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Radiation Damage Studies of Monolithic Silicon Sensors for Particle and Astroparticle Physics Applications

by

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Abstract

The development and characterization of new detector technologies is an important research path in order to facilitate future high energy and astroparticle physics experiments. For both the harsh radiation environment of modern collider experiments and the proton, electron and heavy ion rich environment in the outer earth orbit, the radiation hardness of modern detectors is one of their most important figures of merit. This thesis explores the radiation hardness and optimization of detectors for both space-borne astroparticle physics and modern collider experiments.

In the first part, the radiation hardness of the ULTRASAT space mission's camera is quantified. ULTRASAT is a wide-angle space telescope that will perform deep time-resolved surveys in the near ultraviolet spectrum. ULTRASAT is led by the Weizmann Institute of Science in Israel and the Israel Space Agency and is planned for launch in 2027. The Complementary Metal Oxide Semiconductor (CMOS) camera was designed and built by DESY. The radiation hardness of the CMOS Imaging Sensors was evaluated in terms of both cumulative damage and single event effects. Furthermore, the measured degradation is used to estimate the impact on the detection limits of the camera.

In the second part, the radiation hardness of the depleted monolithic active pixel tracker MALTA is investigated. MALTA is a tracking sensor with a design that targets the ATLAS Inner Tracker outer pixel layer requirements. Several pixel geometries and silicon growing variations have been investigated in order to achieve better tracking performances for the future collider experiments.

Both ULTRASAT and MALTA sensors have been designed and manufactured by Tower Semiconductor in the 180 nm feature size process. This allows for a comparison between the radiation hardness of the two sensors and sets the scene for an overarching discussion of radiation hardness in the context of the two adjacent fields of high energy physics and astroparticle physics and how the lessons learned in each field could be brought together.

Zusammenfassung

Die Entwicklung und Charakterisierung neuer Detektortechnologien ist ein wichtiger Forschungspfad, um künftige Hochenergie- und Astroteilchenphysikexperimente zu ermöglichen. Sowohl für die raue Strahlungsumgebung moderner Collider-Experimente als auch für die protonen-, elektronen- und schwerionenreiche Umgebung in der äußeren Erdumlaufbahn ist die Strahlungshärte moderner Detektoren eine ihrer wichtigsten Leistungsmerkmale. In dieser Arbeit werden die Strahlungshärte und die Optimierung von Detektoren sowohl für die weltraumgestützte Astroteilchenphysik als auch für moderne Beschleuniger-Experimente untersucht.

Im ersten Teil wird die Strahlungshärte der Kamera für die ULTRASAT Weltraummission quantifiziert. ULTRASAT ist ein Weitwinkel-Weltraumteleskop, das tiefe zeitaufgelöste Untersuchungen im nahen ultravioletten Spektrum durchführen wird. ULTRASAT wird vom Weizmann Institute of Science in Israel und der israelischen Weltraumbehörde geleitet und soll 2027 gestartet werden. Die CMOS-Kamera (Complementary Metal Oxide Semiconductor) wurde von DESY entwickelt und gebaut. Die Strahlungshärte der CMOS-Bildsensoren wurde sowohl im Hinblick auf kumulative Effekte als auch auf Einzelereignisse bewertet. Darüber hinaus wird die gemessene Degradation genutzt, um die Auswirkungen auf die Nachweisgrenzen der Kamera abzuschätzen.

Im zweiten Teil wird die Strahlungshärte des Depleted Monolithic Active Pixel Sensor Tracker MALTA untersucht. MALTA ist ein Tracking-Sensor, dessen Design für die Anforderungen der äußeren Pixelschicht des ATLAS Inner Tracker ausgelegt ist. Es wurden verschiedene Varianten der Pixelgeometrie und des Siliziumwachstums untersucht, um bessere Tracking-Leistungen für künftige Collider-Experimente zu erzielen.

Sowohl die ULTRASAT- als auch die MALTA-Sensoren wurden von Tower Semiconductor im 180 nm-Verfahren entwickelt und hergestellt. Dies ermöglicht einen Vergleich der Strahlungshärte der beiden Sensoren und bildet die Grundlage für eine übergreifende Diskussion über die Strahlungshärte im Zusammenhang mit den beiden benachbarten Gebieten der Hochenergiephysik und der Astroteilchenphysik und darüber, wie die in den beiden Gebieten gewonnenen Erkenntnisse zusammengeführt werden können.

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Chapter 1

Introduction

“It’s a dangerous business, going out your door. You step onto the road, and if you don’t keep your feet, there’s no knowing where you might be swept off to.”

— J.R.R Tolkien, *The Lord of the Rings*

The continuous evolution of the instrumentation field, driven by fundamental research (e.g. elementary particle physics) has left an unmistakable mark on the modern world. The development of new detection tools such as the cloud chamber, bubble chamber, wire chamber, gas based detectors, scintillators, solid state detectors etc. has had a tremendous impact on the fields of elementary research. Still, the effect of these developments transcend the field of physics and impact almost every aspect of modern life: medicine, heavy industry, defence sector etc.

Developments of new and more efficient detectors drive fundamental research. A focus needs to be put on instrumentation research and development in collaboration with research institutes and industry partners in order to create the tools necessary for future experiments.

The aim of this thesis is the investigation of the radiation hardness of modern monolithic Complementary Metal Oxide Semiconductor silicon based sensors for both particle and astroparticle physics applications. A focus is made on new tools and algorithms developed for investigating the damage mechanisms of radiation damage in state of the art detectors. In order to expand the field of radiation-hard detectors, several technology variations are investigated and important conclusions regarding the future development of new sensors are drawn. One distinctive opportunity of this study is the ability to bring together the radiation hardness study of similar technologies (Tower, 180 nm feature size, 3.3 V Complementary Metal Oxide Semiconductor (CMOS) Imaging process) for both the fields of particle physics [1] and space-borne astroparticle physics experiments. A final conclusion that brings together the main lessons learned in both studies is pursued at the end of this thesis.

In Chapter 2, an introduction to the principles of radiation detection with a focus on solid state (semiconductors) detectors is made (Section 2.1). Next, silicon is introduced as a material of interest and its desired properties for particle detection are explored (Section 2.2). The electrical junction is introduced and its adaptation for particle detection is discussed (Section 2.3). The modern silicon detector principles are next explored, with a focus on introducing the concept of monolithic and hybrid pixel sensor designs (Section 2.4). Lastly, the basics of charge trapping and charge recombination mechanisms in Silicon (Section 2.5) are explored as a precursor to the effects of radiation damage.

Chapter 3 describes the main concepts associated to CMOS sensors. The basic cell in the

CMOS circuitry, the field effect transistor is introduced and its operation characteristics are expanded (Section 3.1). The basic concepts of CMOS circuitry (Section 3.2) and its implementation for imaging applications is discussed (Section 3.3). Several technology nodes are explored, highlighting their advantages and drawbacks respectively. A detailed discussion of the process employed by the ULTRASAT sensor, the 4T architecture, is made in order to set the scene for the discussion pursued in a following section. The concept of monolithic active pixel sensors (MAPS) is introduced (Section 3.4). The small and large collection electrode MAPS designs are discussed, with a particular focus on the small collection electrode design, which is employed in the MALTA sensor, discussed in further detail in a following section.

Chapter 4 introduces the over-arching topic of the thesis, the radiation damage and radiation hardness of silicon detectors. Initially, the discussion of radiation damage is grounded in terms of two radiation environments: collider and space-borne experiments (Section 4.1). A thorough description of the mechanisms of ionizing cumulative damage (Section 4.2) and non-ionizing cumulative damage (displacement damage) (Section 4.3) is given. The focus of the discussion is put on the physical and parametric changes expected in irradiated silicon sensors. Lastly, a special case of radiation damage, Single Event Effects (Section 4.4) is expanded on. The discussion is focused on the description of soft and hard errors.

Chapter 5 describes the study of the radiation hardness of the ULTRASAT sensor, as part of the ULTRASAT mission radiation qualification work package. The mission is introduced, with a detailed overview of the ULTRASAT camera, as the central piece of the telescope (Section 5.1). A motivation for the mission and its main science goals is briefly introduced (Section 5.2). A detailed description of the ULTRASAT sensor is performed (Section 5.3), introducing the main improvements of the sensor on the commercial 4T CMOS 180 nm Tower Semiconductor CMOS Imaging Sensor technology. The radiation shielding provided by the spacecraft is presented (Section 5.4). Lastly, simulations of the expected particle fluxes in the ULTRASAT mission GEO synchronous orbit (Earth-centered orbit with an orbital period of 24 hours) and their transport through the shielding are performed (Section 5.5). The study of the expected impact of ionizing damage on the mission is pursued with the help of pixel test structures, called SCOUTs (Section 5.6). Extrapolations of the SCOUT data is made for the ULTRASAT mission operational conditions and predictions on the expected mission degradation are made for both the accumulated ionizing and non-ionizing dose during the mission lifetime. The impact of single event effects was also studied with the help of the ULTRASAT sensors (Section 5.7). This study was of particular importance for the ULTRASAT space mission, due to the relatively high flux of heavy ions expected in the GEO orbit. The study of these effects led to the prediction of the expected impact on the mission which in turn led to several critical redesigns of the on-board spacecraft electronics.

Chapter 6 follows the study of the incurred radiation damage and the radiation hardness of tracking sensors designed for future collider experiments. Several sensors were tested, under an R&D project called MALTA. The first MALTA sensor design is initially discussed (Section 6.1). The next generation, MALTA2 is introduced and measurements of the improvements in sensor performance are discussed (Section 6.2). Next, the main tools and techniques employed in the performed studies are described: the irradiation facilities for sensor irradiations (Section 6.3), the beam telescope for the sensor characterization (Section 6.4) and the edge transient current technique set-up employed in the depletion depth study (Section 6.5). The impact of ionizing (Section 6.6) and displacement (Section 6.7) damage on the sensor performance is expanded on, in terms of both pixel and front end degradation. Lastly, an investigation of the depletion depth of both un-irradiated and irradiated MALTA2 sensors was performed (Section 6.8).

Chapter 2

Silicon solid state detectors

“Measure what is measurable, and make measurable what is not so.”

— Galileo Galilei

This section sets the scene by briefly discussing the historical developments in the radiation detection field in Section 2.1. General properties of silicon and why it is a material of interest for particle detection is discussed in Section 2.2. The electrical junction is introduced in Section 2.3 and its adaptation for particle detection is discussed in Section 2.4. Sections 2.5 explores the properties of charge trapping in silicon.

2.1 Radiation Detectors

The field of nuclear physics, is agreed to have been started by the discovery of radioactivity in Uranium salts by Henri Becquerel in 1896. The detector employed by Becquerel to measure the phosphorescence effects of Potassium Uranium Sulfates was the photographic plate. It consisted of a light-sensitive emulsion of silver salts coated on a glass plate, that darkened under the effect of ionizing radiation. Since Becquerel’s discovery, the field of nuclear and particle physics has seen many advancements, but the principle of radiation detection has always stayed the same: ionizing radiation interacts with matter, imparting energy to the medium it travels through. The energy left in a material is then quantified and measured in order to describe the radiation that traveled through the medium.

Semiconductor based detectors take advantage of the extrinsic semiconductor properties of impurity doped materials. The electrical junction formed at the boundary of n and p doped materials can be used for charge collection. This, combined with the developments in the Integrated Circuit (IC) industry, have paved the way to highly complex and application optimized detectors. State of the art semiconductor detectors achieve impressive timing and position resolution capabilities but have relatively high development and manufacturing costs.

The selection of desired detector technology is highly application specific and two typical applications are explored further: accelerator applications, associated to high energy physics experiments and space applications associated with astroparticle physics searches which benefit from the lack of atmospheric attenuation.

Accelerator applications

Modern particle research is driven by special machines (accelerators) in order to perform physics searches. The main properties of accelerators are the accelerated particles (p , e^- , e^+ , ions), the beam energy, the center of mass energy and the integrated luminosity. Of utmost importance for the detector design is the type of collision undertaken during the experiment (e^+e^- colliders, ep , $\bar{p}p$, pp colliders and heavy ion colliders). Experiments operating near the interaction point of such colliders employ multiple specialized detectors in order to cope with the very large luminosities and interaction energies.

General physics experiments (such as the ATLAS [2] and CMS [3] experiments at LHC [4]) aim to resolve the energy of a particle with the help of a calorimeter and measure a particle's momentum by reconstructing its track under the influence of a magnetic field with a tracking detector. Tracking detectors are usually placed as close to the interaction point as possible and as such have very harsh requirements in terms of hit occupancy, radiation hardness, timing and position resolution. Most inner tracker systems use fully semiconductor detectors in order to cope with these requirements.

Space applications

Space applications have both unique challenges and advantages. A clear advantage of a space-borne experiment (especially for ultraviolet imaging applications) is the ability to bypass the atmosphere's shielding effect which attenuates low energy particles and quanta. This comes with multiple disadvantages in terms of mission complexity, weight, power and data transmission limitations etc. Most space missions employ mass and power efficient detectors in order to cope with these limitations. Semiconductor detectors and solid scintillators are usually good candidates for these types of experiments (e.g. the James Webb Telescope [5]).

2.2 Silicon

Silicon makes up about 27.7% of the Earth's crust by mass, making it the second most abundant element on Earth and the eighth most common element in the Universe. Humanity has been aware of this element for thousands of years, it's applications being mainly the fabrication of glass. Being highly reactive to oxygen, the properties of isolated silicon atoms hasn't been investigated until the early 1800's. Jöns Jacob Berzelius is credited for achieving the first pure amorphous silicon substance in 1824 [6].

A silicon atom has 14 electrons and is part of the 14'th group of the periodic table. It has a similar outermost shell configuration to Carbon ($[\text{He}]2s^22p^2$) [6], and thus has four valence electrons ($[\text{Ne}]3s^23p^2$). It has the same number of valence electrons as valence orbitals and can reach its noble gas electron configuration of Argon by forming sp^3 hybrid orbitals ie. SiX_4 derivatives. In this configuration, the silicon atom has four covalent bonds. Silicon forms two structures as represented in Figure 2.1: amorphous silicon (a-Si) and crystalline silicon (c-Si).

Amorphous silicon forms a continuous random network of silicon atoms. Due to its disordered state, not all atoms are fourfold coordinated (all valence electrons satisfied), leading to dangling bonds. These impact the desired electrical properties of the semiconductor material. Additionally, due to the random atom distribution, signal collection through a-Si is generally slower than in its crystalline form. One application of a-Si is thin film solar cells that are able to operate at high temperatures.

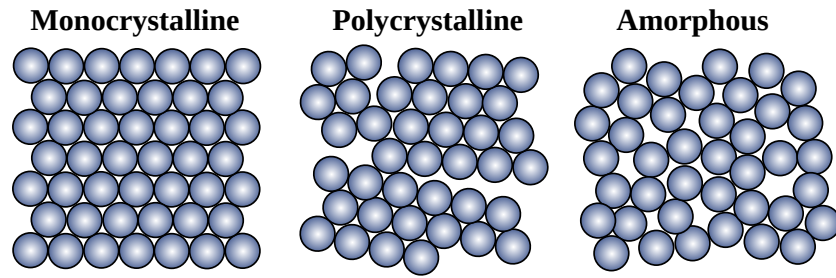


Figure 2.1: Representation of the three atomic configurations of solid state materials: monocrystalline, characterized by a repetition of a unit cell across the entire solid (left); polycrystalline, characterized by a disorderly distribution of unit cells (middle); amorphous, characterized by a random distribution of atoms (right). Figure obtained from [7].

Crystalline materials have a defined periodic arrangement of their atoms. There are two levels of atomic organization that describe a crystal: the unit cell (or lattice structure) and the organization of unit cells (poly or mono crystalline materials). C-Si forms a monocrystalline structure with a unit cell of 16 atoms in a diamond cubic crystal structure. The distribution of Si atoms in a unit cell is shown in Figure 2.2.

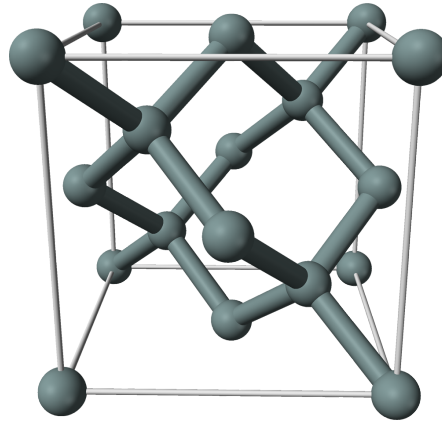


Figure 2.2: Representation of diamond unit cell of c-Si. Figure obtained from [8].

Silicon microelectronics are manufactured from wafers, sliced from a large silicon ingot. Multiple crystal orientations can be achieved by slicing the crystal in different ways. One way to differentiate between crystal orientations are the Miller indices [9]. Each slice will cut through the unit cell in a different way, leading to different electrical, chemical and physical properties. Due to the symmetry of the silicon crystal three unique crystalline orientations can be achieved, as is seen in Figure 2.3. For microelectronic applications, usually the $\langle 100 \rangle$ silicon orientation is used, due to its enhanced electron mobility [10].

Silicon ingots used by semiconductor foundries are large silicon mono-crystals with an uniform crystal orientation. The electrically and optically active silicon used for integrated circuits and/or imaging sensors applications can be achieved through several (often complimentary) growing techniques, explored further in this section.

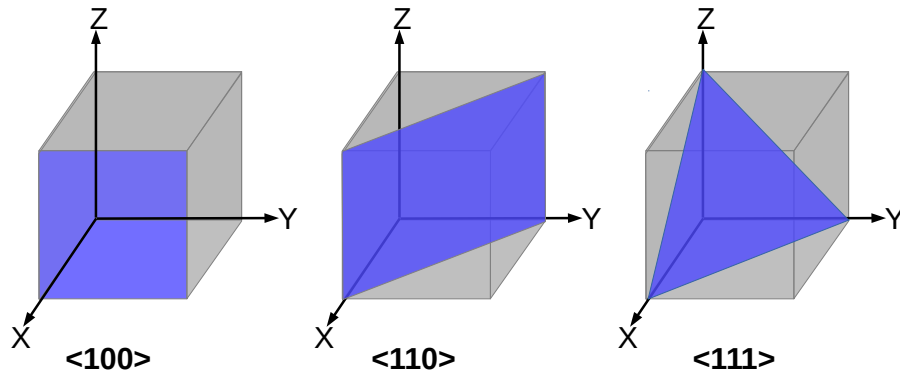


Figure 2.3: Crystal orientations of monocrystalline silicon. The three Miller indices orientations can be seen: $\langle 100 \rangle$ (left); $\langle 110 \rangle$ (middle); $\langle 111 \rangle$ (right).

Czochralski silicon growth

The Czochralski (Cz) growth technique is one of the most common silicon growth techniques for the standardized integrated circuit manufacturing. A schematic of the process is shown in Figure 2.4. Initially, polycrystalline silicon together with a small amount of donor or acceptor impurities (e.g. Arsenic or Phosphorus, depending on the desired doping of the ingot) are added to a crucible. The crucible is then heated up with the help of heating coils, until the melting point of silicon is reached (1414°C) and a “melt” is created. In order to ensure a good mixing of the Si with the impurities, the crucible is kept in constant rotation through a magnet system. Next, a seed crystal that has the desired orientation of the final ingot is placed such that it touches the surface of the melt. Due to the surface tension, layers of Si atoms attach to the seed crystal and once they cool down, they orient themselves to form covalent bonds with the seed and create a large, regular monocrystal. The process is continued by slowly pulling up the seed. In order to ensure a uniform dopant concentration in the ingot, the seed crystal is rotated in the opposite direction of the crucible. A fine tuning of the rotation speed and timing of the retraction of the seed crystal is optimized by each foundry in order to achieve the desired ingot dimensions.

Float zone growth

The main disadvantage of the Czochralski growth technique is the contamination of the melt with Oxygen and Carbon which leads to additional donor impurities in the silicon ingot. The float-zone (Fz) technique is employed for higher purity silicon applications, where the Oxygen and Carbon contamination needs to be avoided. A bar of the polysilicon and dopants is placed in contact with a seed crystal in an inert gas environment. A heating coil is brought near the boundary between the polysilicon bar and seed crystal, such that a controlled localized melting of the bar is achieved. A simplified diagram of this process can be seen in Figure 2.5. When the Si atoms cool down they will orient themselves to the seed crystal and form a monocrystalline structure. This process is repeated across the entire polysilicon bar, by scanning the heating coil in controlled steps. The silicon impurities are highly soluble in the melted silicon, leading to localized higher impurity densities. By sweeping the localized melted silicon across the ingot, the impurities can be effectively drawn in a desired direction and thus be removed from the ingot. In the end, an ultra-pure silicon ingot is formed. The Fz technique is limited in the

length and diameter of the resulting ingots and is thus employed only for specific applications (e.g. thyristors, rectifiers and silicon strip sensors [11][12][13]).

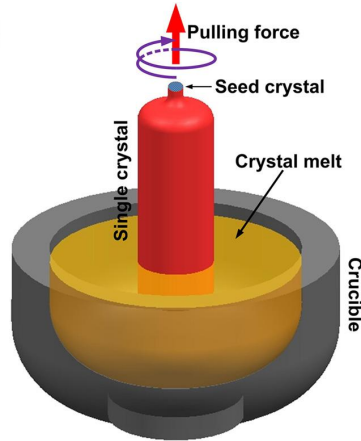


Figure 2.4: Simplified representation of the Czochralski crystal growth technique. Figure obtained from [14].

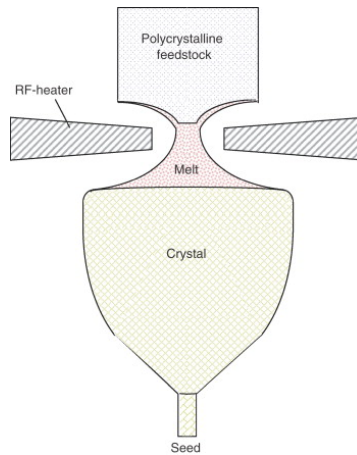


Figure 2.5: Simplified representation of the Float zone (Fz) crystal growth technique. Figure obtained from [15].

Epitaxial growth

Epitaxial (Epi) silicon deposition is the technique of film deposition of silicon on an already grown crystalline structure. This method is usually used for imaging applications, where an ultra pure silicon with a well controlled dopant profile is needed. The basic mechanism of Epi deposition is based on the chemical vapor deposition technique further explored in Appendix A. Additionally, a detailed overview of the steps applied in the wafer fabrication for modern semiconductor devices is presented in the appendix.

2.3 Electrical junction

In order to describe the electrical properties of a solid state material, the concept of an energy band is introduced [16]. An energy band is formed when many atoms are confined in a small space (such as a crystal lattice). Their quantified energy levels become smeared, due to lattice vibrations, called phonons, leading to the formation of energy bands. The electrical properties of a solid state material are described via the two energy bands closest to the material's Fermi level: the conduction and valence bands. In nonmetals, the valence band is the highest energy band which is populated by electrons at 0 K, while the conduction band is the lowest energy band of vacant electron states. The distance between the two bands is called a band gap and represents a region in the energy space where no electron states are allowed.

Figure 2.6 shows the typical band gap structure for metals (left), semiconductors (middle) and insulators (right). Metals are able to conduct electricity, because their conduction and valence bands overlap. Insulators on the other hand have a relatively large band gap, such that electrons can not be easily excited to participate in the electrical conduction. Semiconductors have a smaller band gap than insulators, but still their conduction and valence bands don't touch. Such a semiconductor is called an intrinsic semiconductor.

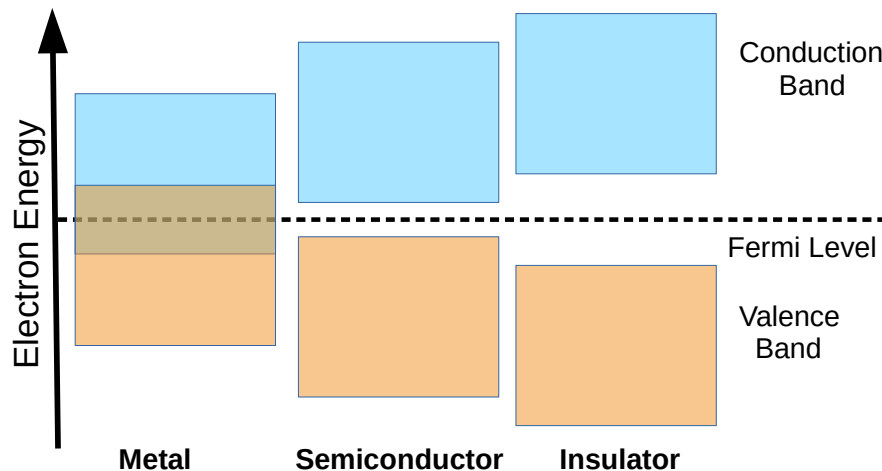


Figure 2.6: Energy band diagram for metals (left), semiconductors (middle) and insulators (right).

In an electrically neutral lattice, the excitation of an electron to the conduction band leads to the formation of an electron-hole pair (EHP). This concept is analogous to the electron ion pairs created in a gas volume when an energy quanta larger than the ionisation potential of an atom is imparted. The EHP formalism implies the existence of a negatively charged free state - the electron and a positively charged free state - the lack of an electron in the lattice. The movement of electrons and holes is similar to the electron-ion pair movement in a gas: electrons are transported in the conduction band and holes are transported in the valence band.

An un-doped silicon crystal has the electric properties of an intrinsic semiconductor. Because all covalent bonds are satisfied in the Si lattice, the electron and hole concentrations are equal, such that the Fermi level is in the middle of the band gap.

Positively doped silicon, or for short p-type silicon, is a silicon crystal with some of the atoms replaced by Group III atoms (e.g. Al, B, In). These have only three valence electrons and thus can form only three covalent bonds. The fourth unsatisfied covalent bond of the neighbouring

Si atom acts as a very shallow hole, that needs an additional electron in order for the atom to fulfill all its valence orbitals. The impurities create an increase in the concentration of holes in the p-type Si, which in turn introduces energy levels in the band gap and shifts the valence band towards the Fermi level. The p-type silicon has mobile positive majority carriers, holes.

A negatively doped, or for short n-type silicon, is doped with Group V atoms that have five valence electrons (e.g. P, As, Sb, Bi). The impurities that settle in the silicon lattice satisfy all four valence bonds of neighbouring Si atoms, but have an additional electron. The dangling electrons increase the electron concentration and introduce energy levels in the band gap near the conduction band, such that the conduction band is close to the Fermi level. The n-type silicon has mobile negative majority carriers, electrons. Semiconductor devices exclusively use the extrinsic form of silicon due to these properties.

The electrical or p-n junction is the building block for all active electrical components. The Figure 2.7 shows a cross-section diagram of an electrical (or p-n) junction. It is an interface that appears at the boundary of two neighboring n and p type semiconductors. As the two regions are “put in contact” (in reality both n and p regions are grown on the same crystal), a diffusion movement of the respective electron and hole majority carriers takes place, in order to satisfy the covalent bonds of the lattice. As initially both crystal regions were electrically neutral, the movement of charge generates an electrically negative region near the p-type silicon and an electrically positive region at the n-type side of the interface. This leads to the generation of an electric field that acts against the diffusion movement of electrons and holes, such that an equilibrium is formed leading to the formation of a region depleted of any charge carriers. This region is called the depleted region or space charge region (SCR) and acts as an insulator between the two sides of the crystal. The electrical potential established at the junction is called the built-in potential and is defined by the following formula:

$$V_0 = V_T \ln \left(\frac{N_A N_D}{n_i^2} \right) \quad (2.1)$$

V_T is the thermal voltage (26 mV at room temperature in silicon [17]), N_A is the acceptor concentration in the p-type semiconductor, N_D is the donor concentration in the n-type semiconductor and n_i is the intrinsic carrier concentration. By solving the Gauss law: $\int \vec{E} \cdot d\vec{A} = \frac{Q}{\epsilon_s}$, $\epsilon_s = 11.7\epsilon_0$, the depletion width is found to be:

$$w = \sqrt{\frac{2\epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) V_0} \quad (2.2)$$

Most modern semiconductor applications employ p-doped wafers. The additional n-type implant that creates the junction is much smaller in size, but higher in doping concentration, such that an asymmetric depletion is formed, $N_D \gg N_A$. The depletion depth is thus proportional to the square root of the doping concentration of the wafer, N_A and the intrinsic junction voltage, V_0 .

$$w = \sqrt{\frac{2\epsilon_s V_0}{e N_A}} \quad (2.3)$$

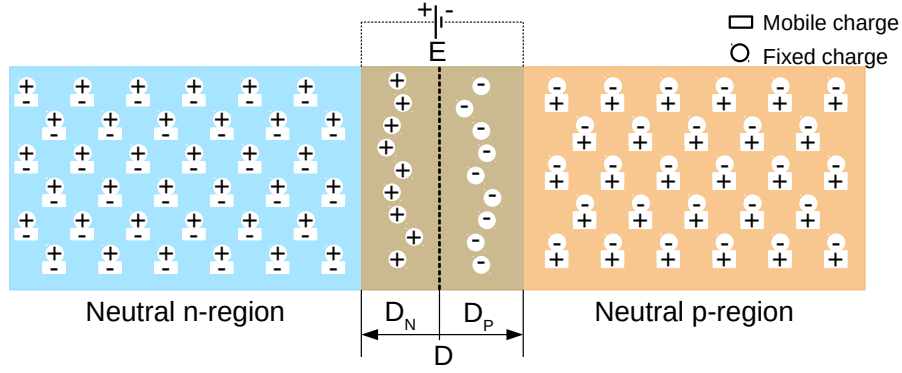


Figure 2.7: Diagram representation of an electrical (p-n) junction, featuring a neutral n and p region and a Space Charge Region of depth D at their intersection.

The doping concentration can be expressed in terms of the resistivity: $\rho = \frac{1}{\mu e N}$, where μ is the major carrier mobility. The depletion depth can than be written as:

$$w = \sqrt{2\epsilon\mu\rho V_0} \quad (2.4)$$

Biasing of the p-n junction

Taking as example a typical n in p Fz silicon diode process, the following approximate concentration numbers can be considered [17]: $N_A = 10^{12} \text{ cm}^{-3}$, $N_D = 10^{16} \text{ cm}^{-3}$. The intrinsic carrier concentration at room temperature is $n_i = 1.45 \cdot 10^{10} \text{ cm}^{-3}$. The built-in potential in this case is derived to be $V_0 = 0.46 \text{ mV}$ and the depletion depth $w = 24 \text{ }\mu\text{m}$. Depending on the application, a larger or smaller depletion depth for a junction may be desired.

Considering the application of a bias voltage between the n and p implants, the current flow through the junction is given by the Shockley equation [18][19]:

$$I = I_0(e^{eV/kT} - 1) \quad (2.5)$$

If the potential difference is such that the generated electric field acts in the same direction as V_0 , a suppression of the depleted region is achieved. This biasing scheme is called forward biasing and large enough voltages lead to the full suppression of the SCR, such that the semiconductor conducts electricity. If the reverse polarity of the biasing is used, such that the electric field acts in the same sense as the charge diffusion, a larger SCR is created. This biasing scheme is called reverse biasing.

The simplest active circuit element is called a diode and is just a p-n junction with ohmic contacts on its sides for biasing. The current-voltage characteristics (IV curve) of a diode is shown in Figure 2.8. For positive values of the bias below the built-in potential V_0 , the current increase is limited, up to a leakage current value. For a certain turn-on value, called V_{ON} , the SCR is fully suppressed and the current increases exponentially with the voltage, according to the Shockley equation. For negative bias values, the current does not increase with larger absolute bias values, due to the Si behaving as an insulator. For a certain value of the negative bias, a breakdown of the diode occurs and is characterized by a large current flow.

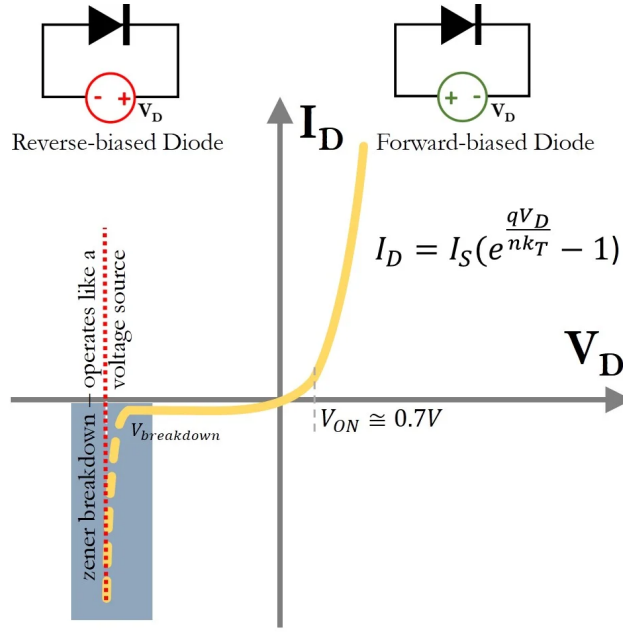


Figure 2.8: IV characteristic of a diode operating in reverse and forward bias mode. Figure obtained from [20].

2.4 Silicon ionizing particle detectors

The space charge region formed at the p-n junction can be used for particle detection as it acts as an ionizing chamber. Ionizing radiation interacts with the lattice bound Si atoms and imparts energy through elastic or inelastic scatterings. For a silicon crystal near 0 K, the energy quanta needed to excite an electron from the valence to the conduction band is equal to the band gap, 1.12 eV. In practice, some of the imparted energy is converted into phonons (lattice vibrations) such that the average ionization energy of a bound electron is 3.6 eV [21]. In the aftermath of a charged particle passing through the detector, multiple EHPs are formed along its track, which act as mobile charges under the influence of two motions: diffusion and drift. The diffusion movement of the generated charges is a relatively slow, random thermal movement towards a region with smaller charge concentration. The drift movement is induced by the electric field generated at the p-n junction and is characterized by the drift velocity, $\vec{v} = \mu \vec{E}$; μ is the mobility of the respective charge and $\vec{E}$ is the electric field. Electrons ionized in the SCR are collected primarily via drift, while all other mobile charges move towards the electrodes via diffusion. As the drift movement has a much smaller characteristic time than the diffusion movement, the former is usually preferred to be the main collection mechanism. Detectors are usually operated in reverse bias mode, in order to facilitate this.

Si detectors offer many advantages over other particle detection techniques: fast charge collection and good time resolution; large material density and large signals generated for small detection volumes; good spatial resolution; radiation hardness; highly developed industrial processes. Several detector technologies have been developed using Si as the sensing volume. Each detector variant aims to improve on one or more sensor properties. For example, high energy physics applications employ both pixel and strip detectors in their trackers. A strip detector has several strip implants placed in series which perform the charge collection. A pixel detector

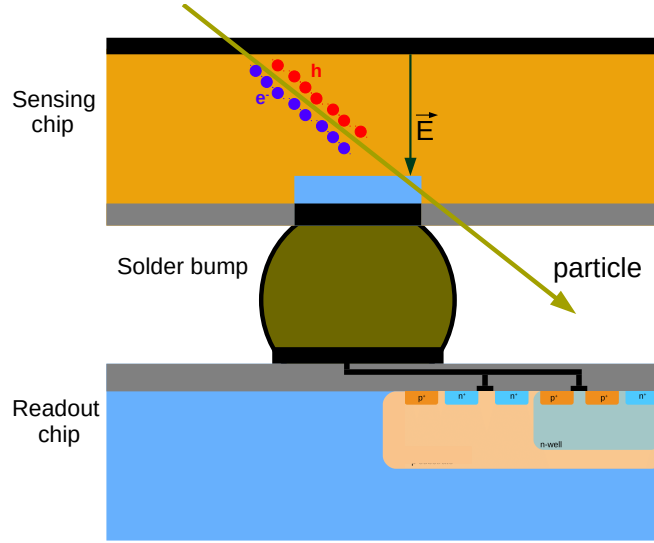


Figure 2.9: Cross-section of a hybrid pixel sensor. The figure highlights a single pixel as part of a sensing chip (top with orange) and a pixelated read-out chip (bottom with blue) usually implemented via an Application Specific Integrated Circuit (ASIC).

has several implants, usually in a two dimensional matrix configuration. Pixel detectors feature better space and time resolution but sport larger manufacturing costs and complexity in terms of readout.

Currently, in the trackers of most complex high energy physics applications, hybrid pixel detector modules are used (e.g. ATLAS Inner Tracker [22] and CMS Inner tracker[23]). Hybrid pixel sensors are made out of two chips. A sensing chip which has a set of independent pixels that collect charge. The signal processing is usually performed by another chip with a pixelated front end. Figure 2.9 shows a cross-section of a hybrid pixel sensor. Each pixel is connected to a front end circuit via a bump bond, special microscopic soldering material placed at the electrical connection of each pixel.

Detectors that combine the sensing and the electronic chips into a single sensor are called monolithic detectors and their fabrication is possible due to the advancements in the production of complementary metal oxide semiconductor structures in the same substrate. A detailed analysis of this technology is investigated in Section 3.4.

2.5 Charge trapping and recombination

The crystal lattice of a semiconductor contains both crystallographic defects (see Appendix A), and defects due to radiation damage (see Chapter 4). These are microscopic physical imperfections that lead to local changes of the electric properties of the lattice. They are called defect centers and are associated with charge generation, recombination or trapping. One model that describes well the behavior of these defects in silicon is the Shockley-Read-Hall (SRH) model [24]. A simplified but accurate model of the impact of these defects can be inferred from their impact on the energy band distribution. Defect centers lead to the creation of energy levels inside the forbidden band gap, giving rise to a number of intermediate energy levels, which act as “stepping stones” for charge between the valence and conduction bands. Figure 2.10 highlights the four mechanisms of charge capture and emission described by the SRH model.

Figure 2.10(a) illustrates the electron capture mechanism, where an electron transitions from the conduction band to a defect level in the forbidden band gap; Figure 2.10(b) illustrates the electron emission mechanism, where a previously trapped electron in a forbidden band gap energy level is emitted back to the conduction band; Figure 2.10(c),(d) shows the analogous processes for holes and the valence band. In the SRH model, the charge recombination is a two step process, where a defect center first captures an electron, followed by the capture of a hole.

Charge trapping is due to a similar process as charge recombination, except the trapped charge gets re-emitted, instead of recombined. Essentially, the only difference between the two phenomena is the different values of the capture cross-sections. From an energy level point of view, this translates to the fact that in the SRH model, charge generation and recombination is associated with “deep” level defects (energy levels near the mid-gap) and charge trapping is associated with shallow level defects (energy levels near the conduction or valence band).

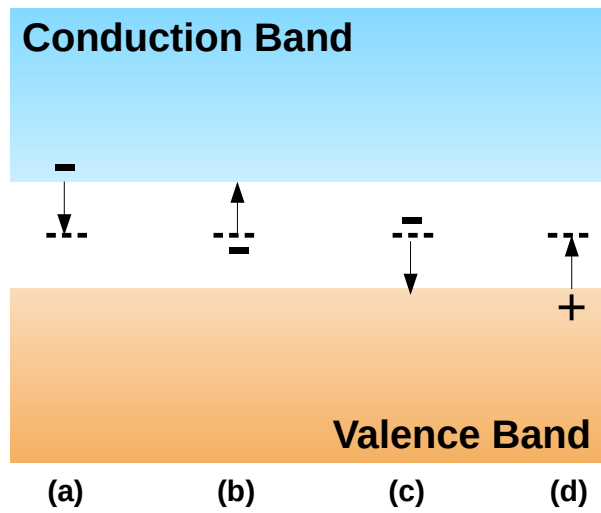


Figure 2.10: Illustration of the four main mechanisms of emission and capture of charge in the SRH model: (a) electron capture; (b) electron emission; (c) hole capture; (d) hole emission. The figure puts these models in context with the energy band model for solid state detectors featuring a conduction (with blue) and valence (with orange) band and a forbidden band gap between them.

While the defect centers in the semiconductor bulk and at the dielectric interface are physically different, it has been shown that their impact is similar, such that both bulk defects and interface states can be modeled in a similar fashion and can lead to similar damage mechanisms for a semiconductor sensor [25].

The fast charge collection (via drift) is essential in preserving the signal amplitude in sensors with a large density of trapped sites. Charge generation leads to the increase in noise and charge recombination leads to charge collection efficiency losses. The effect of trapping can usually be interpreted as a delay in the charge collection, limiting the timing response of a sensor. If traps are present in a p-n junction detector, the mobile charge is characterized by a trapping life time, τ and the collected charge decays as:

$$Q(t) = Q_0 e^{-t/\tau} \quad (2.6)$$

Chapter 3

CMOS Imaging Process

“The best way to predict the future is to invent it.”

— Alan Kay

This section details the fabrication steps and properties of silicon radiation detectors that employ the CMOS process. Section 3.1 details the basic operation of a Field Effect Transistor, the building block of complex integrated circuits. Section 3.2 discusses the basics of CMOS technology and introduces the concept of feature size. Sections 3.3 and 3.4 describe the properties and figures of merit of CMOS detectors for imaging and particle detection.

The main advantage of CMOS detectors is their monolithic design. This implementation is highly complex and is a relatively new branch of detector instrumentation. This development can be attributed to new CMOS imaging processes developed by sensor fabrication companies (e.g. Tower [26], Hamamatsu [27]). By now, the CMOS imaging field has become a mature field of research. The mass production of CMOS imaging sensors have taken over the market share of previous popular technologies, Charge Coupled Devices (CCD) [28]. Furthermore, monolithic sensors offer the most promising prospects for the development of 4D tracking sensors for the future collider experiments (e.g. the Future Circular Collider - FCC [29]).

3.1 The Field Effect Transistor

The Field Effect Transistor (FET) uses a single majority charge carrier in its operation: either electrons or holes. The FET’s greatest advantage is its scalability. This led to the drive towards smaller scales and higher density integrated circuits, contributing to the technological boom of the information era.

The Junction FETs (JFET) were the first field effect transistors to be manufactured on a large scale. Two types of JFETs are distinguished: n-JFETs and p-JFETs, depending on the majority carrier type they employ. As an example, the operational principle of an n-JFET is highlighted in Figure 3.1 and its implementation is further discussed.

A FET features two terminals, named source and drain. The current flow between these is controlled with the help of a third electrical connection, called gate. When the gate is unbiased, the current is able to flow through the n-doped substrate. By applying a positive voltage to the gate (in relation to the source terminal), an enhancement of the built-in SCR takes place, restricting the cross-section of the source-to-drain channel. The voltage value for which the

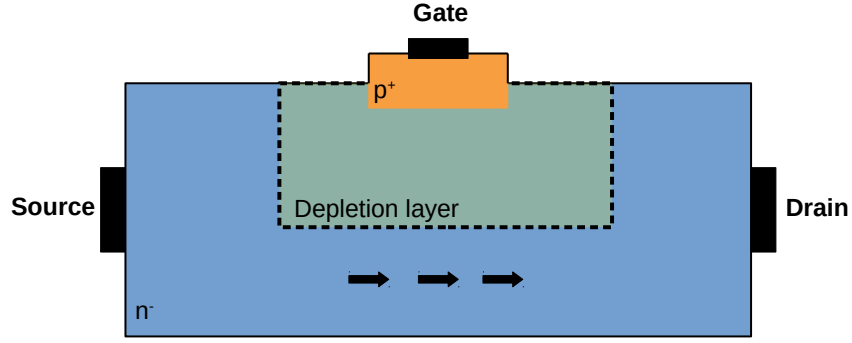


Figure 3.1: Cross-section of an n-type Junction Field Effect Transistor (n-JFET) implemented with three terminals resistively connected to the silicon volumes: gate, source and drain.

device is fully depleted and the current flow between source and drain is stopped, is called the “pinch-off voltage”. Additionally, if a negative voltage is applied to the drain in relation to the source terminal, an asymmetric pinching of the resistive channel takes place. The drain voltage, V_{DS} for which this pinch-off takes place is called the saturation voltage. The saturation voltage of the V_{DS} delimits two working regimes of a JFET: the linear regime, where no pinch off is present and the current increases linearly with the voltage and the saturation regime, characterized by a maximum V_{DS} gain under the action of the gate voltage. The current-voltage (IV) characteristics of a JFET are highlighted in Figure 3.2.

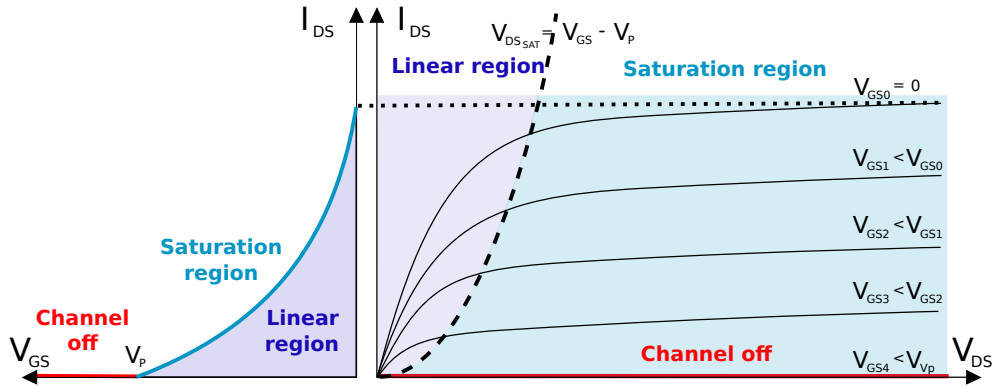


Figure 3.2: IV characteristics of an n-channel JFET. The two working modes: linearity and saturation correspond to the operation of a JFET as a current controlled electric switch and amplifier respectively. Figure obtained from [30].

The usual transistor technology currently employed in integrated circuits is the Metal Oxide Semiconductor Field Effect Transistor (MOSFET). Its work principle is similar to the JFET, where a source and drain are connected via a resistive channel, with a profile that can be manipulated via the action of both the gate-source and the drain-source voltage lines. The main difference from the JFET design is that the gate electrode is capacitively coupled to the semiconductor via an oxide layer (usually SiO_2 for silicon devices) as seen in the cross-section of a typical n-MOSFET device in Figure 3.3.

The resistive channel between the source and drain terminals is not created by physically

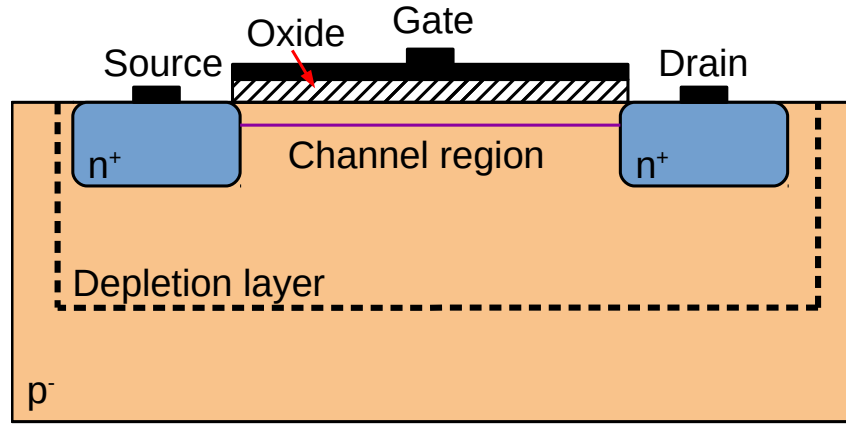


Figure 3.3: Cross-section of an n-type Metal Oxide Semiconductor Field Effect Transistor (n-MOSFET). It is implemented with two terminals resistively coupled to the semiconductor material: source and drain and a capacitively coupled gate terminal.

adding an n or p type implant but rather the energy band properties of the silicon are exploited. Depending on the polarity and magnitude of the gate voltage, three working modes of an n-MOSFET are described in Figure 3.4. Due to the dangling bonds at the Si-SiO₂ interface, an accumulation of positive charge at the interface is naturally present, leading to a downwards shift of the conduction and valence energy bands. This inherently leads to an accumulation of electrons at the interface. If additionally, a positive voltage is applied at the gate electrode, the electron concentration in a Si region near the gate increases, further leading to a shift in the majority carrier concentration. For a large enough gate-source voltage, an area under the gate experiences type inversion, becoming effectively n-doped, creating a “resistive” channel between the source and drain. As in the case of the n-JFET, the application of a Drain Source voltage, changes the profile of the conductive channel, leading to a pinch-off condition for high enough voltages, where the device functions in the saturated regime.

If a negative voltage is applied to the gate electrode, an accumulation of holes is achieved at the Si surface and the device operates in accumulation mode. The operating principles of a p-MOSFET is exactly the opposite of an n-MOSFET, where the accumulation of holes at the surface is used as the resistive connection between the source and the drain terminals.

3.2 Complementary Metal Oxide Semiconductor

Complementary Metal Oxide Semiconductor (CMOS) is a technology that allows the fabrication of both n and p type MOSFETS on the same semiconductor substrate. In order to electrically insulate the transistors, they are placed in deep implants called n or p wells respectively as can be seen in the process cross-section of a simple 2 transistor CMOS structure (Figure 3.5). Modern integrated circuits use the CMOS technology in order to achieve very large densities of transistors that can be then used to implement low level logic for different applications.

One of the main properties of scalability for the CMOS process is the feature size of the process. Moore’s law [31], predicted that the number of transistors per unit area on integrated circuits doubles roughly every two years. In order to maintain this growth, one of the main focuses of the semiconductor industry has been process miniaturization. For planar transistors,

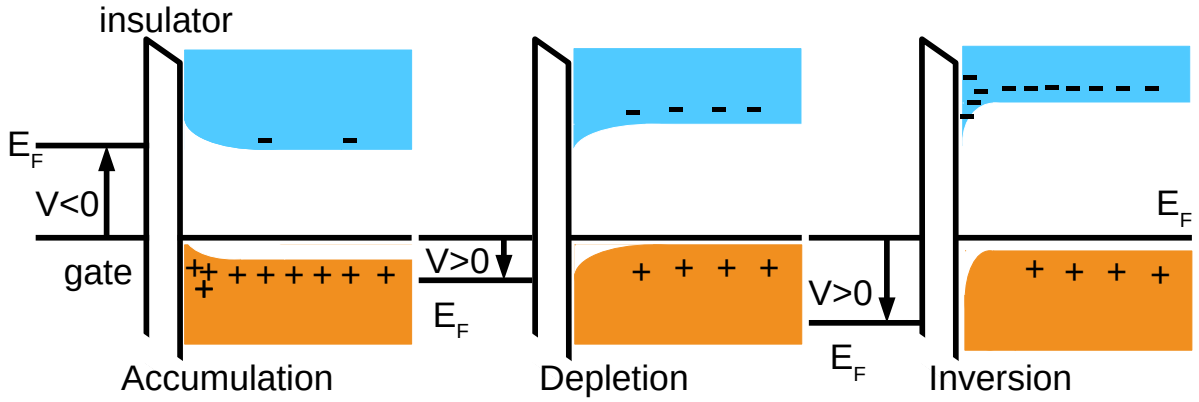


Figure 3.4: Energy band distribution for an n-MOSFET in the three working modes: accumulation (left), depletion (middle) and inversion (right). Each working mode is differentiated by the degree of band bending induced by the accumulated space charge at the gate oxide interface.

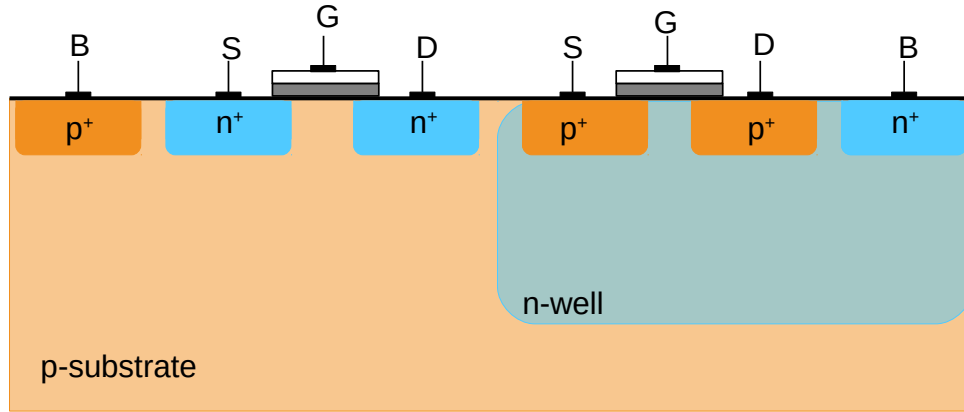


Figure 3.5: Cross-section of the simplest CMOS circuit, formed from an n-MOS and p-MOS device on the same semiconductor substrate. In a p-type substrate CMOS device, p-MOS devices require a deep n-well for electrical insulation. Additionally, in real devices, the entire electrically active MOSFET volume is encapsulated in a dedicated deep p-well in order to ensure the electrical insulation. S stands for the Source node, D stands for the drain node and B stands for the transistor's body.

the feature size was equivalent to the transistor gate length, but for modern transistor architectures, this measurement unit has become slightly ambiguous. The decrease in feature size additionally lowers the oxide thickness and the operating bias voltages, leading to challenges in terms of maintaining operational noise and threshold voltages.

The CMOS process has been quite recently adapted for imaging applications and utilizes the ability of creating deep implants for charge collection and deep wells to insulate in-pixel logic, leading to compact, high granularity devices. The CMOS technology has seen wide spread adoption in recent years, mainly due to the focus of several foundries on providing imaging specific processes. The scalability of the feature size has evolved in parallel to the integrated circuit technology node with state of the art feature sizes for scientific imaging ranging from 180 to 65 nm.

3.3 CMOS Imaging Sensors

In its most usual implementation, the CMOS Imaging Sensor (CIS) uses a p-n junction for converting incident light to electrons and collecting the charge for signal integration. In its original implementation, CIS used passive pixel designs, which employed only a single Select transistor in each pixel. This technology was found to lead to a very low signal to noise ratio (SNR) and was replaced by more efficient pixel designs. In modern implementations, CIS are also known as Active Pixel Sensors (APS), due to the active pixel design, which implies the use of multiple transistor in the pixel FE. A detailed discussion of different modern pixel architectures is pursued further.

3.3.1 CMOS imaging sensor figures of merit

Full Well Capacity

The space charge region that forms at the p-n junction acts as a carrier-depleted region that efficiently separates the radiation induced electron hole pairs. The junction electric field moves the electrons and holes towards the n^+ and p^+ terminals respectively. The SCR can be enhanced or diminished by applying a bias voltage at the junction terminals as described in Section 2.3. If a reverse bias, V_b is applied at the junction terminals, the depletion depth described in Eq. 2.2, becomes:

$$w = \sqrt{\frac{2\epsilon_s}{q} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) (V_0 + V_b)} \quad (3.1)$$

The depth of the space charge region, w acts as a potential well with a capacitance:

$$C = \sqrt{\frac{q\epsilon_0\epsilon_s}{2(V_0V_b(\frac{N_A+N_D}{N_A N_D}))}} \quad (3.2)$$

Such a p-n junction used for imaging is called a photo-diode (PD). In the absence of any illumination, a dark current is diffused from the Si bulk due to the thermal excitation of electrons at room temperature. Under illumination, additional electron-hole pairs are generated in the Si bulk and a dark and photo current are collected in the PD. The accumulation of electrons inside the SCR potential well changes its voltage. In order to quantify the collected charge, the properties of the PD at a known voltage level, V_{RST} need to be recorded. This is achieved via a “reset” value, implemented via an electrical connection of the n^+ terminal to a known voltage value. The most common implementation of a reset is achieved with an n-MOSFET. During the reset operation, the MOSFET is turned on. During charge sampling it is turned off, leaving the PD floating. This gives rise to the alternative name of the junction as the Floating Diffusion (FD).

The signal collected by a PD in an integration time, t is describes by:

$$V_{SIG}(t) = V_{RST} - \frac{Q_{SIG}(t)}{C} \quad (3.3)$$

The number of electrons that can be accumulated in the potential well is defined as the Full Well Capacity (FWC) and represents the amount of charge needed to fully compensate the junction electric field. When the Q_{SIG} approaches this values, the PD becomes saturated. The FWC is an important sensor parameter that needs to be optimized based on the planned application.

Sensitivity

One of the most important properties of a CIS is its sensitivity to light in an application targeted wavelength. The sensitivity, R is defined as the amount of photo-current generated in a sensitiv volume (I_{Ph}) under the illumination of an incident light power, P :

$$R = \frac{I_{\text{Ph}}}{P} \quad (3.4)$$

The measured photo-current is proportional to the amount of ionized electrons, which in turn is given by the effective number of photons incident to the sensor. The light travels through multiple layers of the sensor: dielectric layers, metal layers, passivation, additional coatings which leads to wavelength dependent absorption and reflections. Additionally, the absorption rate of the silicon volume is wave-length dependent and is characterized by the absorption length:

$$L_{\text{abs}} = \Delta z \frac{P}{\Delta P} \quad (3.5)$$

where $\frac{\Delta P}{P}$ is the decrease of light power for a length, Δz . The wavelength dependent absorption of light for silicon is shown in Figure 3.6.

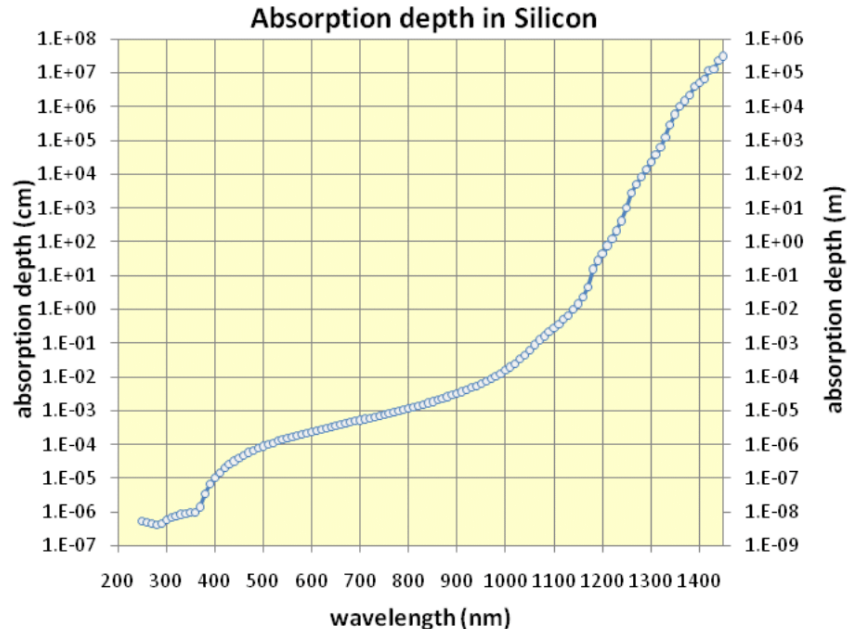


Figure 3.6: Absorption length of light in silicon for multiple wavelengths spanning near-Ultra Violet (NUV) 200 – 380 nm, visible (VIS) 380 – 700 nm and infra-red (IR) >780 nm. Figure obtained from [32].

From a sensor characterization standpoint, it is useful to define the quantum efficiency (η_{QE} or simply QE) as the ratio between the number of photo-carriers (EHP generated by a light source) and the number of incident photons:

$$\eta_{QE} = R \frac{h\nu}{e} \quad (3.6)$$

where h is the Planck constant, ν is the photon frequency and e is the elementary charge.

Noise

The maximization of the signal to noise ratio is a desired achievement for all CIS applications. There are multiple noise sources in modern CMOS imaging sensors. Each active element added to a pixel front end acts as a noise source and its impact needs to be characterized. One important noise source in large scale devices is the Fixed Pattern Noise (FPN). It is defined as the variation in output signal between different pixels (columns or rows) due to fabrication induced process variations. The thermal noise or “kTC” noise is given by the thermal agitation of free carriers in the silicon volume and is proportional to the capacitance of the photo diode. Many other noise sources are associated to state of the art CMOS imaging sensors, such as: Random Telegraph Signal, shot noise, Johnson noise with different degrees of importance depending on the application and technology node.

Random Telegraph Signal

Random Telegraph Signal (RTS) is a noise source associated to the switching between two or more noise levels. It has been correlated with outliers in the pixel noise (colloquially, hot pixel tail) due to the Poissonian distribution of the observed effects. Two types of effects are mainly associated to RTS: Variable Junction Leakage (VJL) and discrete MOSFET channel resistance switching.

The main generation mechanism of VJL is called dark current random telegraph signal (DC-RTS) and is correlated to charge generation mechanisms in the Si bulk or near the Si-SiO₂ interface. The random switching nature of these defects is not yet fully understood and is currently associated to classical Shockley Read Hall (SRH) charge generation centers that randomly fluctuate between two meta-stable states, characterized by different current generation values as highlighted in Figure 3.7.

The main effect of the MOSFET channel resistance switching in modern imaging sensors is associated to the source follower (discrete gain changes) and the reset transistors (discrete reference value changes). Both of these circuit elements are further discussed in Section 3.3.2. In contrast to the DC-RTS, this transient mechanism is well understood [34][35][36][37] and is correlated to the trapping and emission of charge carriers in the inversion layer of a MOSFET. When a minority charge carrier is trapped, the source goes into a low potential state. When it is re-emitted, the source goes into a high potential state. This switching leads to the random resistance changes of the source drain channel, correlated to increased leakage currents for the Reset-RTS component and gain changes for the Source Follower-RTS component.

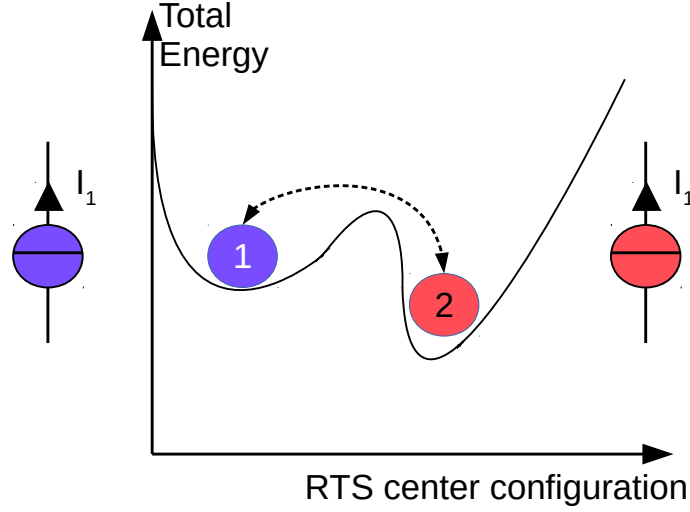


Figure 3.7: Illustration of a dark current random telegraph signal generation mechanism. Two meta-stable SRH generation centers lead to the switching nature of the defects associated to two charge generation rates: I_1 (with blue) and I_2 (with red) [33].

Dynamic range

The Dynamic Range (DR) of a CIS characterizes the operation range of a sensor and is defined as the ratio between the maximum and minimum output signal:

$$DR = 20 \log \frac{V_{\max}}{V_{\min}} [\text{dB}] \quad (3.7)$$

Dark current

The amount of charge collected per second by the PD under no photo-illumination is called the Dark Current (DC) or Dark Current Rate (DCR). While some publications make a distinction between these two, further dark current results in this thesis are always normalized in terms of integration time and all results are shown in terms of electrons per second, such that the two terms can be used interchangeably. The dark current is an important sensor parameter that impacts the full well capacity, the signal to noise ratio and the dynamic range of a sensor. It is associated to charge generation centers in the Si bulk and at the Si-SiO₂ interface, described by the SRH model (see Section 2.5). SRH centers are associated to defects in the Si crystal or the amorphous SiO₂ layer that covers (e.g. the Pre Metal Dielectric - PMD) or surrounds (e.g. Shallow Trench Isolation - STI) the pixel. These are present either as a byproduct of the crystal fabrication or can be induced by radiation as discussed in Sections 4.2 and 4.3. As a consequence, several generation mechanisms for dark current can be identified, depending on the origin of the generated charge and their position relative to the SCR:

- **Direct interface state dark current** is generated by interface states at the Si-SiO₂ interface that are inside the SCR. The generated charge in these centers is collected via

drift, leading to an intense generation contribution [38] that is proportional to the interface area inside the SCR and the number of interface states.

- **Direct bulk dark current** is generated by bulk defects localised in the SCR and is proportional to the depletion volume and the density of defects.
- **Diffusion collected interface state dark current** is due to interface states that generate charge which diffuses to the photo diode. The generated diffusion current is significant only at short distances between the defect centers and photo diode or for very long integration times.
- **Diffusion collected bulk dark current** is similar to the above contribution, induced by bulk defects outside of the space charge region.

Different sensor technology nodes, have one or more DC sources as the main dark generation mechanisms.

3.3.2 The 3T CMOS imaging sensor architecture

The implementation of multiple pixels in a large scale device, requires a readout buffering scheme, containing at least two additional transistors. The column buffering of a pixel is achieved via a Source Follower (SF) that additionally provides signal amplification. The row buffering of a pixel and the last ingredient in order to read-out individual pixels in a large scale device is a row select transistor (usually denoted as SEL). The schematic layout of a 3T pixel [39] can be seen in Figure 3.8.

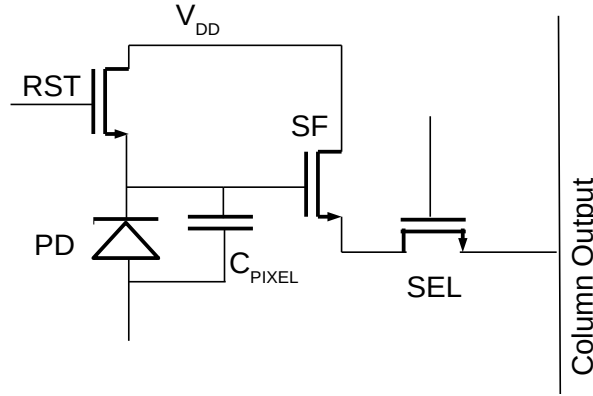


Figure 3.8: Schematic of a typical 3T CMOS imaging sensor pixel front end. The three active elements are: the reset transistor (RST), the Source Follower transistor (SF) and the select transistor (SEL).

Figure 3.9 showcases the cyclical operation of a 3T CIS. At each clock cycle of the sensor, the signal amplitude is recorded for a certain charge collection time (integration time).

The 3T CIS was the first successful, mass-adopted implementation of an APS, but has several limitations. Figure 3.10 shows a typical pixel cross-section. A fundamental problem of the technology node is the electrical connection between the SCR and the oxide: shallow trench isolation and the pre-metal dielectric. Due to the unavoidable imperfect dielectric growth, the Si - SiO₂ interface has several defects (e.g. dangling bonds). The interface dangling bonds act as generation and recombination centers which can lead to a large dark current component.

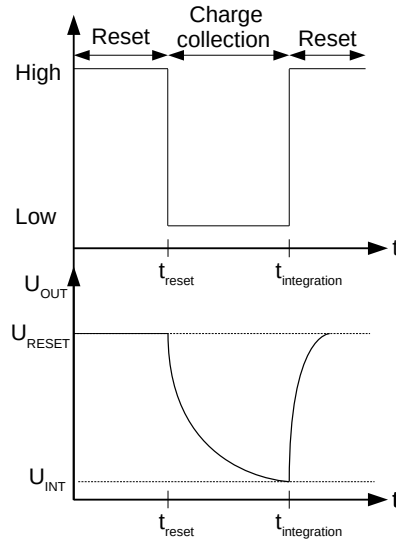


Figure 3.9: Schematic representation of the charge sampling operation of a typical 3T photo diode [40].

Additionally, this technology node is highly susceptible to surface radiation damage (e.g. Total Ionizing Dose). Another limitation is the fact that the photo diode is used for both generation and charge conversion of the incident radiation. The FWC is directly proportional to the PD capacitance C , while the conversion gain is proportional to $1/C$. This leads to a design trade-off and a fundamental limitation of the technology node.

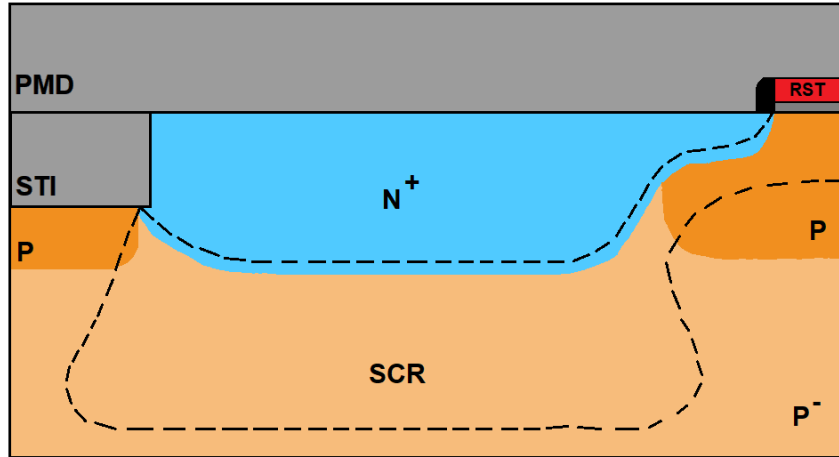


Figure 3.10: Simplified cross-section of a 3T pixel [33]. A complete cross-section would include the other 2 active elements of the front end adjacent to the right of the figure.

3.3.3 The 4T CMOS imaging sensor architecture

The development of better performing CMOS imaging sensors came as a consequence of the development of “no image lag photodiode structures” for interline CCDs [41][42][43][44]. This development proposed the use of charge storage cells in each pixel, that aimed to remove the

problem of residual charge at the Sense Node (SN) (in the 3T CIS design this coincides with the PD implant) after a reset operation. An additional benefit of this, is the implementation of a “true” correlated double sampling (CDS) procedure, drastically limiting the kTC noise of the sensor. This technology was transferred to CMOS imaging sensors in the form of the transfer gate (usually denoted as TG or TX). It acts as an additional transistor introduced in the pixel FE, that controls the flow of charge between the photo diode and the floating diffusion (now a separate implant away from the photo diode that performs the charge conversion). Due to the fact that now, the photo diode performs only the charge collection, it can be redesigned to be “pinned”, leading to the concept of a pinned photo diode, denoted as PPD. In other words, the n-well implant no longer touches the Si-SiO₂ interface and is in fact protected from the oxide surface via highly doped p⁺ implants, called pinning layer. The cross-section of a simplified 4T process is shown in Figure 3.11.

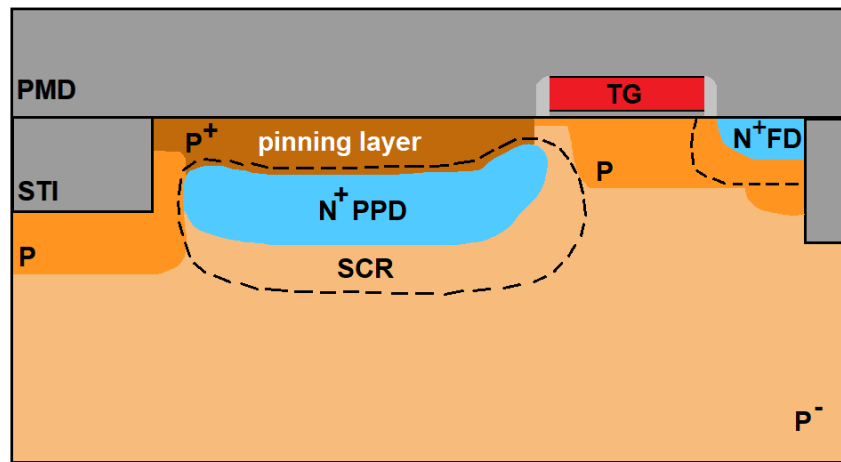


Figure 3.11: Simplified cross-section of a 4T pixel [33]. A complete cross-section would include the other 3 active elements of the front end adjacent to the right of the figure.

The operational principle of a 4T pixel is presented in Figure 3.12. Before charge collection, the transfer gate and the reset transistors are turned on. This leads to a resistive channel forming between the photo-diode and the reset node. An electric field appears at the transfer gate interface, leading to the charge collection initially via drift and subsequently via diffusion. After a t_{reset} time, the photo-diode voltage raises above its pinch-off value, leading to a saturation of the SCR extension. The transfer gate is turned off and the PPD is left floating, leading to the accumulation of the photo and dark currents. The reset transistor is left on, without any impact on the charge collection and awaits the CDS procedure to take place. Before the charge is transferred, the reset transistor is turned “OFF” and a sampling of the sense node is taken by turning on the select transistor. The transfer gate is then turned on and by implementing an optimized electric potential difference scheme ($\phi_{\text{PPD}} < \phi_{\text{TG}} < \phi_{\text{SN}}$), close to 100% of the charge is transferred to the sense node. The second sampling is taken by the operation of the select transistor. The correlated double sampling procedure then subtracts the two values, leading to a large suppression of low frequency noise sources (e.g. 1/f noise, kTC noise).

The decoupling of the detection and conversion stages in the 4T CIS, leads to the ability of customizing the properties of the two stages independently leading to both a large gain and low noise. One downside of the 4T front end is the decreased fill factor (optically sensitive area) of the pixel, due to the additional transistor and metal layer.

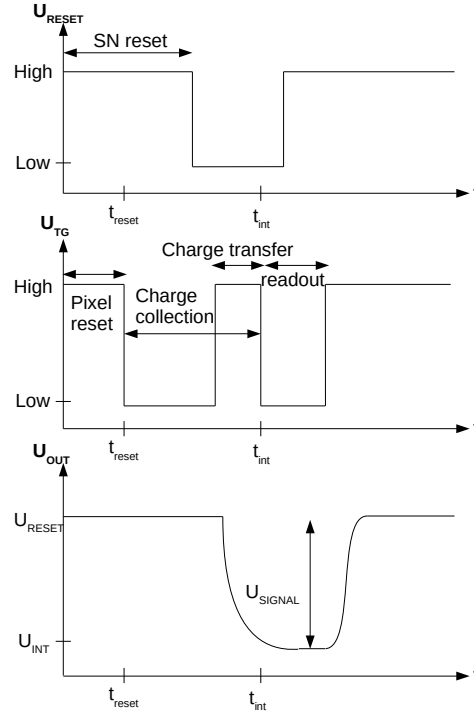


Figure 3.12: Schematic representation of the charge sampling of a 4T CIS.

One of the most important front end parameters for a 4T CMOS imaging sensor is the transfer gate “OFF” bias value (denoted henceforth as both V_{LOTG} or V_{TXL}). As discussed before, its implementation acts as an n-MOSFET, such that a low/ negative voltage leads to its operation into accumulation mode (OFF state) and a large positive bias leads its operation into depletion mode (ON state) (see Section 3.1). The main impact of these two working modes is in the magnitude of the collected dark current. The depletion operation mode is expected to lead to the electrical coupling of the space charge region around the photo-diode to the interface states at the transfer gate pre-metal dielectric. This effect is highlighted in Figure 3.13, using data presented in Reference [45]. It showcases the measured dark current of a 4T CMOS imaging sensor operated at different V_{LOTG} values. In the accumulation mode, the main dark current sources are the diffusion oxide interface and silicon bulk mechanisms, leading to a relatively small noise component. In depletion mode, the main dark current sources are the direct generation mechanism of interface states that lead to a large noise contribution. The presented dark current fall-off at voltages above 0.4 V is due to a transfer gate current compensation effect. These effects are expanded upon in Section 4.2.2.

An additional concern for detectors that operate the transfer gate in depletion mode, is the sensitivity to ionizing damage, due to both the accumulation of interface states and positive charge in the oxide. Additionally, the accumulation of oxide charge, is expected to lead to the shift of the operating voltage of the transfer gate towards the depletion regime, further increasing the aforementioned effect.

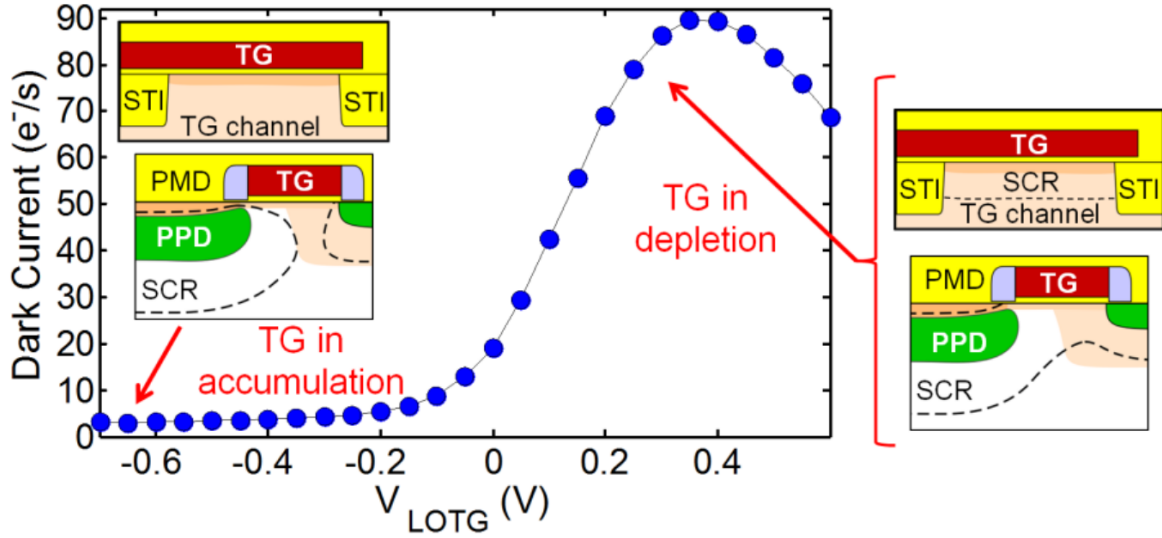


Figure 3.13: Dark current for various transfer gate “OFF” bias voltages, V_{LOTG} . The plot highlights the two operation modes of the transfer gate: accumulation and depletion mode and the corresponding dark current measurements. The plotted data was presented in [45]. Figure obtained from [33].

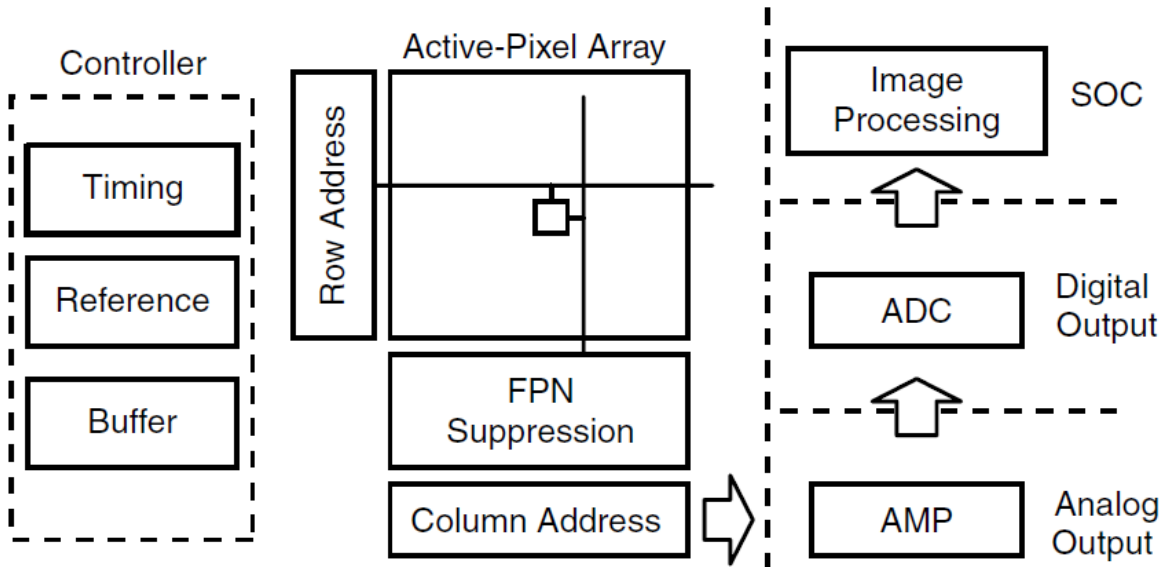


Figure 3.14: Typical read-out architecture of a digital output CIS. In its simplest implementation, the read-out needs to contain the following elements: an active pixel array; row address logic; column address logic; controller circuitry and an analog to digital converter. Additionally, it is desired to implement fixed pattern noise suppression circuits and/or additional image processing on chip. Figure obtained from [46].

3.3.4 Readout architecture of digital output CMOS imaging sensor

This section describes the implementation of a readout circuit for common scientific imaging applications. A typical read-out architecture is presented in Figure 3.14. The read-out is responsible for performing the following tasks: addressing of each pixel, buffering of the signal,

fixed pattern noise suppression, amplification of output signal and digitization. Additionally, thanks to the CMOS process, several controllers can be integrated on the chip, such as clock propagation, timing circuits and other application specific circuits.

The most common read-out implementation of the addressing and signal buffering is the column parallel readout architecture. The read-out of a pixel is triggered by a row select pulse followed by an entire row readout. The processed signals are held in a sample and hold line memory. Several column processors are then assigned for the parallel processing of the signal one row at a time. A shift register is employed as a row scanner in order to scan through the entire array.

The fixed pattern noise suppression circuit aims to minimize the pixel-to-pixel signal variation due to gain differences. One implementation of such a circuit is the additional sampling and subtraction of the PD signal after the reset operation (known as correlated double sampling).

The digitization of the signal is performed by analog to digital converters (ADCs). In the case of the parallel column read-out architecture, each column is routed towards an amplifier and ADC circuit. The timing generator and clock buffering for the sequential array read-out is also usually integrated on chip with the help of peripheral circuits. In order to control the exposure time of the PD, a rolling shutter is usually implemented in the peripheral circuit. The rolling shutter acts as an additional reset scan prior to readout. The time difference between the shutter pulse and the readout pulse is defined as the integration time of the sensor.

3.3.5 Back Side Illumination

In its most common implementation, a CIS collects light after it travels through several layers of a CMOS imaging sensor: passivation, metal layers and inter metal dielectric. This is commonly referred to as Front Side Illumination (FSI) and has several downsides in terms of quantum efficiency. The main loss mechanisms are the reflection off the metal and passivation. Additionally, the inter metal dielectric can refract light at large angles and lead to an increase in the inter-pixel cross talk. One development for the increase of quantum efficiency of this technology has been the decrease of the metal and dielectric thickness layers. Still, this requires multiple development steps and is highly process and technology node dependent.

One way to improve the quantum efficiency of CMOS imaging sensors is the implementation of a Back Side Illumination (BSI) process. A usual process flow is highlighted in Figure 3.15. Starting from a usual FSI wafer, an additional carrier wafer is bonded to the original “front” side. The p^+ silicon of the original wafer is then thinned down to the epitaxial layer. Following, the usual imaging steps are performed on the now “back side” of the wafer. In the past, this process led to very low yields and was highly optimized for specific applications, due to the complex two-side processing. Recent developments in foundry processes have increased the production yield at the wafer scale, leading to large scale implementation of this process [40].

3.4 Monolithic Active Pixel Sensors

The implementation of CMOS technology for detectors for particle physics has led to an independent development branch referred to as Monolithic Active Pixel Sensors (MAPS).

Charged particle detectors have additional requirements compared to their imaging detector counterparts in terms of timing and spatial resolution and especially radiation hardness. MAPS are most commonly used for the non-destructive sampling of incident particles such as timing and tracking layers.

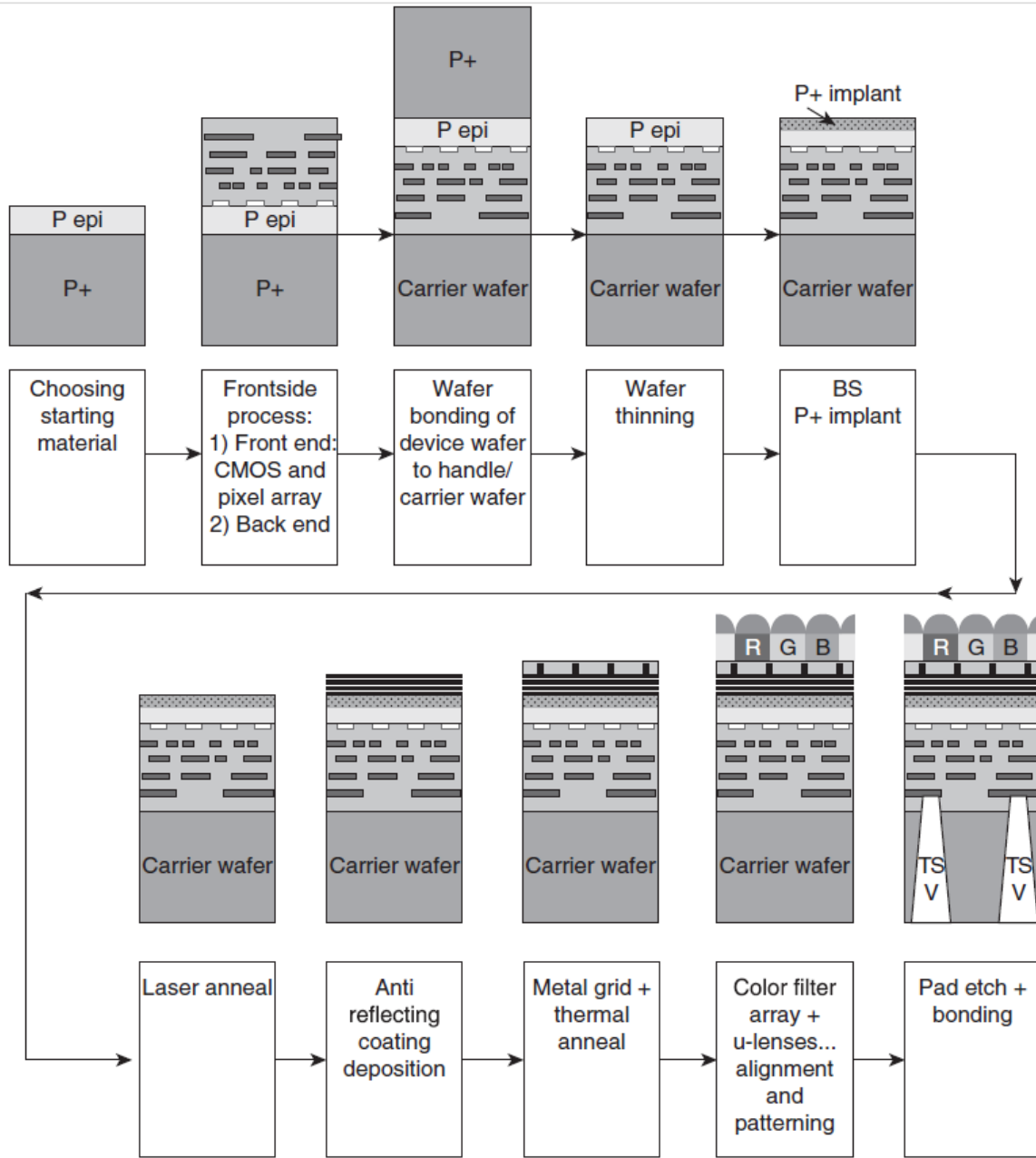


Figure 3.15: Usual flow of a state of the art Tower Semiconductor based Back Side Illumination (BSI) process. The starting point is considered to be a prepared p-type silicon wafer. Figure obtained from [40].

The particle detection mechanism is similar to the light sensing of the CMOS imaging sensors. A high concentration n^+ implant is used as the collection electrode that forms a p-n junction with a lightly doped p-type silicon volume. Two main types of MAPS can be differentiated: low voltage MAPS, also known as Depleted MAPS (DMAPS) or high voltage MAPS or (HV-MAPS). While HV-MAPS showcase promising tracking results [47], the following discussion will focus on DMAPS.

DMAPS, employ a small collection electrode design. This leads to a low capacitance and a large signal to noise ratio for small bias voltages. This severely decreases the power consumption of the sensor which is a sought after property for small radiation length applications, due to the lower requirement imposed on the detector service infrastructure (e.g. cooling). The main downside of this approach is the need for very high resistivity silicon, in order to achieve full device depletion (as is hinted by Eq. 2.2). Additionally, the radiation hardness for large displacement doses is not guaranteed due to the donor removal and p-type compensation effects that severely degrade the depletion propagation through the small collection electrode. Extensive research and development has been performed in order to address the fundamental limitations of this technology [48].

For a long time, these downsides have restricted this technology node to highly customized epitaxial growth processes. Due to relatively recent progress in this field [49], high resistivity ($>3\text{k}\Omega\text{cm}$) Czochralski has also become viable as a Si substrate for MAPS. Another downside of the small collection electrode design is the additional complexity of achieving an effective electrical shielding of the in-pixel active circuits. A typical cross-section of a DMAPS sensor, is shown in Figure 3.16.

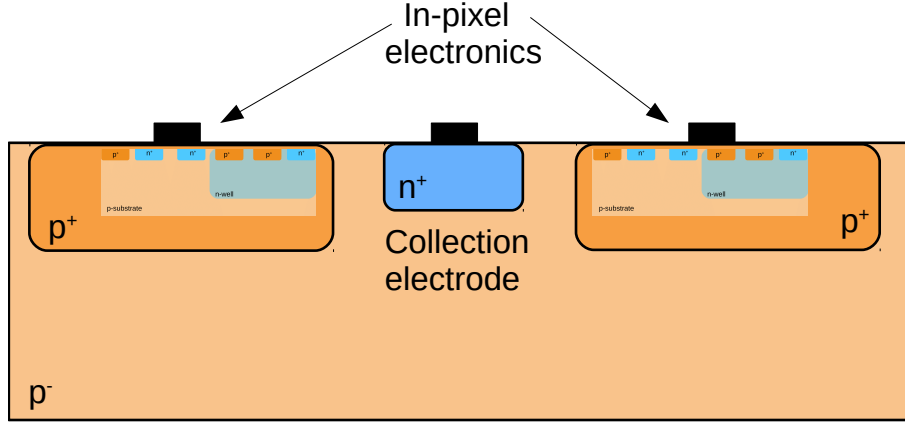


Figure 3.16: Cross-section of a typical small collection electrode DMAPS process. The implants shown are not to scale and are for visualization purposes only.

The main figures of merit for MAPS based tracking sensors are the tracking efficiency, timing resolution and spatial resolution. Additionally, the noise and applied threshold are intrinsic properties of a MAPS that need to be optimized depending on the application. The intrinsic spatial resolution of a MAPS is given by: $\sigma_{\text{in}} = \text{pixel_pitch}/\sqrt{12}$. The spatial resolution can be increased by achieving sensitivity to several pixel hits associated to a detected particle (charge sharing). Time correlated, spatially adjacent hits form a hit cluster and the number of hits is called the cluster size. The tracking efficiency is calculated as the number of matched clusters on a tested device over the number of reconstructed tracks for a well defined spatial and time window (usually called a tracking veto). The track reconstruction usually requires the use of a beam telescope which consists of several tracking planes for particle interpolation.

Chapter 4

Radiation Damage of Silicon sensors

“My name is Ozymandias, king of kings:
Look on my works, ye Mighty, and despair!
Nothing beside remains. Round the decay
Of that colossal wreck, boundless and bare
The lone and level sands stretch far away.”

— Percy Bysshe Shelley, Ozymandias

This section gives an overview of the radiation environments encountered in accelerator and space-borne applications in Section 4.1. In Section 4.2, a discussion regarding the impact of surface damage (oxide ionizing damage or total ionizing dose - TID) in silicon sensors is made. The displacement damage mechanism in silicon sensors is described in Section 4.3. Lastly, the basics of Single Event Effect (SEE) production in modern analog and digital CMOS circuitry is discussed in Section 4.4.

The exposure of silicon sensors to energetic particles and quanta is expected to lead to their performance degradation or even a complete break down of the device functionality. A first classification of radiation damage can be made in terms of cumulative damage (surface and crystal defects) and single event effects.

4.1 Radiation environments

The discussion of radiation damage and radiation hardness of a detector needs to be contextualized in terms of the expected radiation content. This is highly application specific and this section explores two environments of interest for the following studies: collider experiments and space applications.

4.1.1 Collider experiments

High energy physics experiments require large scale accelerators in order to generate high energy and intensity beam lines. Collider experiments investigate the byproducts of beam bunch collisions with the purpose of performing various physics searches. Currently, the state of the art physics searches involve hadron machines that collide high energy protons and/or ions. At the interaction points of these experiments, a very large flux of highly ionizing heavy particles is generated: muons, protons, pions [50].

The two most important sources of radiation in this environment are secondary particles generated after a collision and beam losses in the accelerator. The largest contribution to the total radiation damage of the detectors close to the interaction point, comes from neutrons (from the parton shower tails) and their associated photons.

4.1.2 Space experiments

The space radiation environment is composed from a very broad energy (a few eV to several PeV) and particle type spectrum: e^- , e^+ , γ , H-U. Additionally, the particle content does not scale linearly with the distance from the earth surface and has a large temporal variation linked to the 11 year solar cycle [51]. The three main effects that contribute to the radiation content in Earth’s orbit are:

- Cosmic rays, a low flux of various highly ionized, high energy particles.
- Solar particles (electrons, protons and heavy ions), emitted by the sun.
- The trapped particles in the Earth’s magnetic field, known as the Earth’s radiation belts.

Cosmic Rays

The cosmic ray background is mainly composed of Galactic Cosmic Rays (GCR) and consists of a low flux and wide energy spectrum of heavy, charged particles. They lead to a continuous and mostly isotropic flux of ions with abundances $Z=1-92$. The distribution of particles follows roughly: 85% protons, 14% alphas and 1% heavy ions [52].

Solar particles

The sun acts as a particle source, generating mainly electrons and protons but also in a lower fraction, alpha particles and heavier ions. The charged particle generation can be mostly attributed to geomagnetic storms (colloquially solar flares), but is also characterized by an increase in the radiation background with a temporal dependence. This is due to the sun’s magnetic pole flip every 11 years, leading to a cyclical behavior. Each cycle is characterized by a maximum in solar activity (i.e. number of sun spots) denoted as solar maximum, followed by a solar minimum with close to no solar magnetic activity.

Trapped radiation

The main effect that leads to the charged particle trapping is the magnetic mirroring effect. Figure 4.1 highlights the main principles of magnetic mirroring [53]. Assuming that the earth magnetic field follows an approximate dipole structure, the field lines are “closed”. A particle affected by the Lorentz Force $\vec{F}_L = \vec{v} \times \vec{B}$ will see a larger magnetic field as it approaches the magnetic poles. For a particle with a non-zero $v_{\parallel}$ component, the increase in magnetic field, leads to an $F_{\parallel}$ component towards the region with smaller magnetic fields. This retards the particle and can lead to the mirroring effect. This, combined with a longitude drift component [54] leads to particles trapped on so-called “drift-shells”.

The cross-section of the trapped electron and proton belts are shown in Figure 4.2. These plots have been generated with the help of data from several radiation counters installed on satellites orbiting earth at various orbits [55]. The “bow wave” in the image is due to the

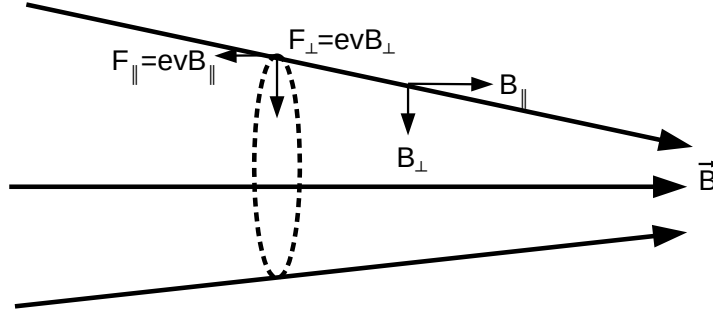


Figure 4.1: Representation of the magnetic mirroring process. Figure obtained from [53].

impact of the sun that is leftwards in relation to Earth. The contours encapsulate points with an equal average integrated particle flux. Protons with energies above 10 MeV are plotted on the left side and electrons with energies above 1 MeV are plotted on the right side.

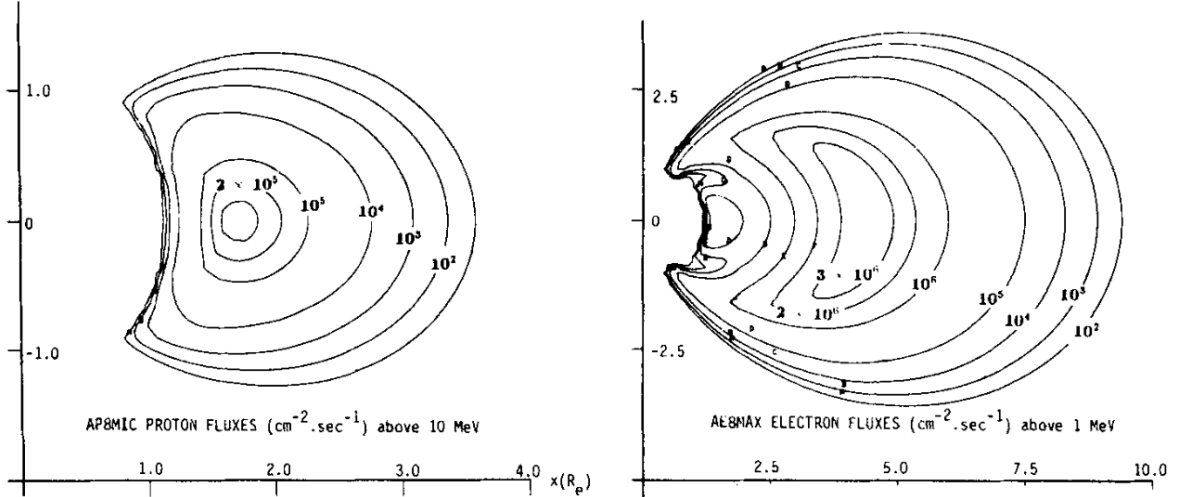


Figure 4.2: Representation of the Earth's radiation belts according to the AP8 and AE8 models. Average omni-directional integral fluxes above energy thresholds are shown. Figure obtained from [55].

The trapped electron belt can be divided into an inner zone and an outer zone showing an asymmetric distribution towards the earth poles. Two flux maxima are observed, highlighting an important electron flux contribution at lower orbits, with a monotonous variation in flux towards further orbits. The trapped proton belt flux shows a monotonous decay with the distance from earth.

4.2 Total Ionizing Dose

This subsection gives a thorough description of the physical processes associated to ionizing damage in the silicon oxide. It aims to describe and de-convolute the different effects that can appear in both the pixel structure and the active elements implemented on the sensor (MOSFET impact). The description of the signature and expected magnitude of each defect source will

further be contextualized in the total ionizing damage study of both the ULTRASAT sensor (Section 5.6) and the MALTA sensor (Section 6.6).

Total Ionizing Dose also known as ionizing damage or surface damage is caused by directly ionizing particles (e.g. photons, electrons, charged heavy particles) or indirectly ionizing particles (e.g. neutrons) via recoils. The passage of such particles through the Si lattice, generates electron-hole pairs that can be separated by an electric field and accumulate at a sensor's collection electrode. While the silicon lattice is immune to this type of damage, the silicon oxide is not. The ionization of the SiO₂ can lead to cumulative radiation damage. The mechanism of the radiation damage is extremely complex and currently no unified model that explains all the observed phenomena exist. Multiple models are further presented in order to form a picture of the radiation damage mechanisms associated to TID in silicon sensors.

4.2.1 The physics of ionizing damage

The case of a typical n-MOS structure is further analyzed. The dielectric layer under the gate electrode is considered as the ionizing damage sensitive volume. The generation of electron-hole pairs due to direct or indirect ionization depends on the energy of the incident particle and the ionization energy of the material in question. The absorbed dose in terms of a sensor's mass dm, is defined as:

$$D = \frac{\Delta E}{dm} [\text{Gy} = 1\text{J/kg}] \quad (4.1)$$

and is measured in Gy or rad, $\text{rad} = 10^{-2} \text{ Gy}$. For an accumulated ionizing energy ΔE , a number of free space charges are generated, given by the generation rate:

$$g_0 = \frac{\Delta E}{E_{\text{ion}}} \quad (4.2)$$

For SiO₂, the ionization energy is $E_{\text{ion}} = 18 \text{ eV}$ and $g_0 = 8.2 \times 10^{14} \text{ EHP/Gy/cm}^3$. Assume further, the case of a highly penetrating ionizing particle. Its passage through the gate dielectric, leads to the creation of N_{eh} EHPs given by:

$$N_{\text{eh}} = A \cdot d_{\text{ox}} \cdot g_0(\text{SiO}_2) \cdot D \quad (4.3)$$

where A is the gate area, d_{ox} is the dielectric thickness and D is the accumulated dose.

Depending on the gate voltage, an electric field, E_{ox} is present in the oxide, leading to the separation of the generated electrons and holes. A fraction of the EHPs recombine through one or more mechanisms:

- **geminate recombination.** For low densities of generated EHPs, a recombined pair is the same as the one created. This recombination mechanism dominates for low ionizing particles such as electrons and photons.
- **columnar recombination.** For high densities of generated EHPs, charges can recombine with any carrier. This recombination mechanism dominates for highly ionizing particles such as heavy ions or protons.

As a consequence, the estimation on the number of EHPs generated in the oxide needs to take into account a fractional yield f_H : $N = N_{eh} \cdot f_H$. The fractional yield for several particle species and oxide electric fields, is highlighted in Figure 4.3. The A group is associated with geminate recombination and the B group with columnar recombination.

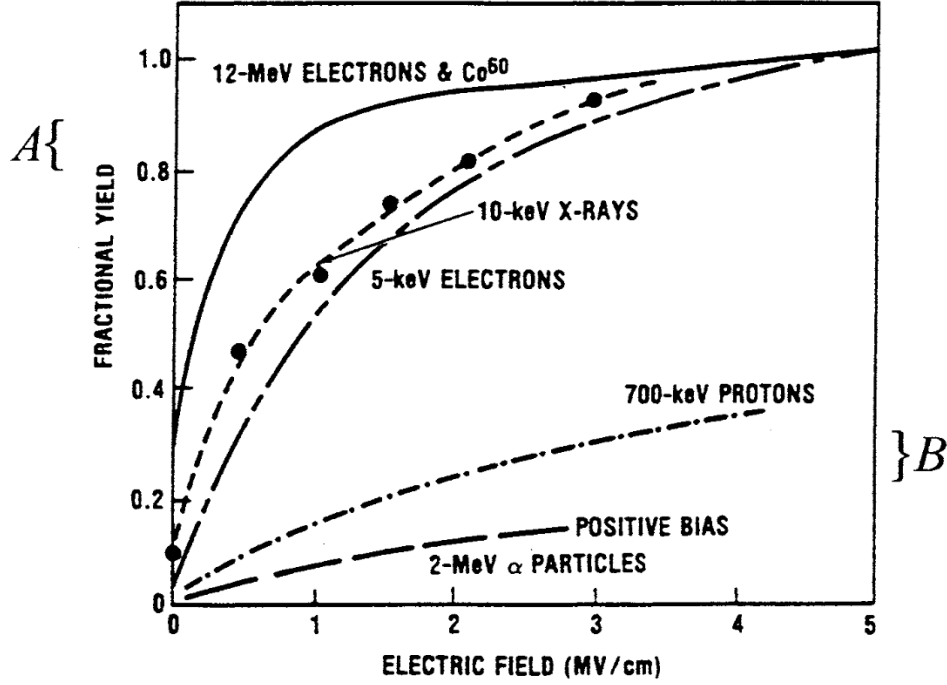


Figure 4.3: Fractional yield versus oxide electric field at room temperature for several particle species. The A group marks the species dominated by geminate recombination and the B group marks the columnar recombination dominated group. Figure obtained from [56].

The room temperature thermal velocity of electrons and holes is vastly different in the oxide. The electrons are characterized by a zero-field mobility of $20 \text{ cm}^2/\text{V} \cdot \text{s}$, while for the holes its only $1.6 \cdot 10^{-5} \text{ cm}^2/\text{V} \cdot \text{s}$. As a consequence, following their thermalization process, the electrons move towards the gate electrode, outside the oxide, within a short time window ($\sim 1 \text{ ps}$), while the hole movement is highly dispersive and has highly variable characteristic times between seconds and hours. The movement of holes is described by the Continuous Time Random Walk model and includes both a temporary capture of holes in shallow traps and a polaron hopping mechanism (holes polarize the dioxide structure locally and the transport of this polarization across the oxide is associated to the hole movement)[57][58][59][60][61][62][63][64][65].

The holes move towards the Si-SiO₂ interface leading to two effects: trapped oxide charge and interface states. These lead to intermediary silicon energy levels between the oxide valence and conduction bands. Induced energy levels near the mid gap act as charge traps for both holes and electrons, leading to a trapped oxide charge layer. The concentration of these defects is highest near the Si interface, with the trapped charge distribution centroid reported to be 4 – 5 nm away from the interface [66]. Both holes and electron traps have been found at the interface with vastly different capture cross-sections: hole trap density: $\sim 10^{-13} \text{ cm}^2$ and electron trap density: $\sim 10^{-17} \text{ cm}^2$ [67].

Additionally, to the SiO₂ traps, interface states (charge traps at the physical Si-SiO₂ in-

terface) can appear after irradiation. There are multiple models associated to different defect centers that model the density of interface states. More information regarding these models can be found in the following references: [68], [69], [70], [71], [72], [73], [74], [75].

The sensitivity of a certain oxide layer to ionizing damage is correlated to microscopic defects in the SiO_2 and especially at the Si-SiO_2 interface. A brief description of some of the most important defects is presented below.

Intrinsic defects are deviations from the ideal tetrahedral SiO_2 network that act as precursors to trapping centers under the action of an outside source, e.g. radiation. Some of the most important intrinsic defects are:

- Oxygen vacancies ($\text{Si}-\text{Si}$) are precursors to the E' centers in the SiO_2 bulk [76].
- Strained Si-O-Si bonds lead to dangling bonds (also denoted as P_b centers) at the Si interface [77].

Extrinsic defects are associated to contaminants in the SiO_2 that satisfy the imperfections (e.g. dangling bonds) at the Si interface. The most common impurity is hydrogen which leads to two basic extrinsic defects: acceptor-like Si-OH and donor-like Si-H defects [76].

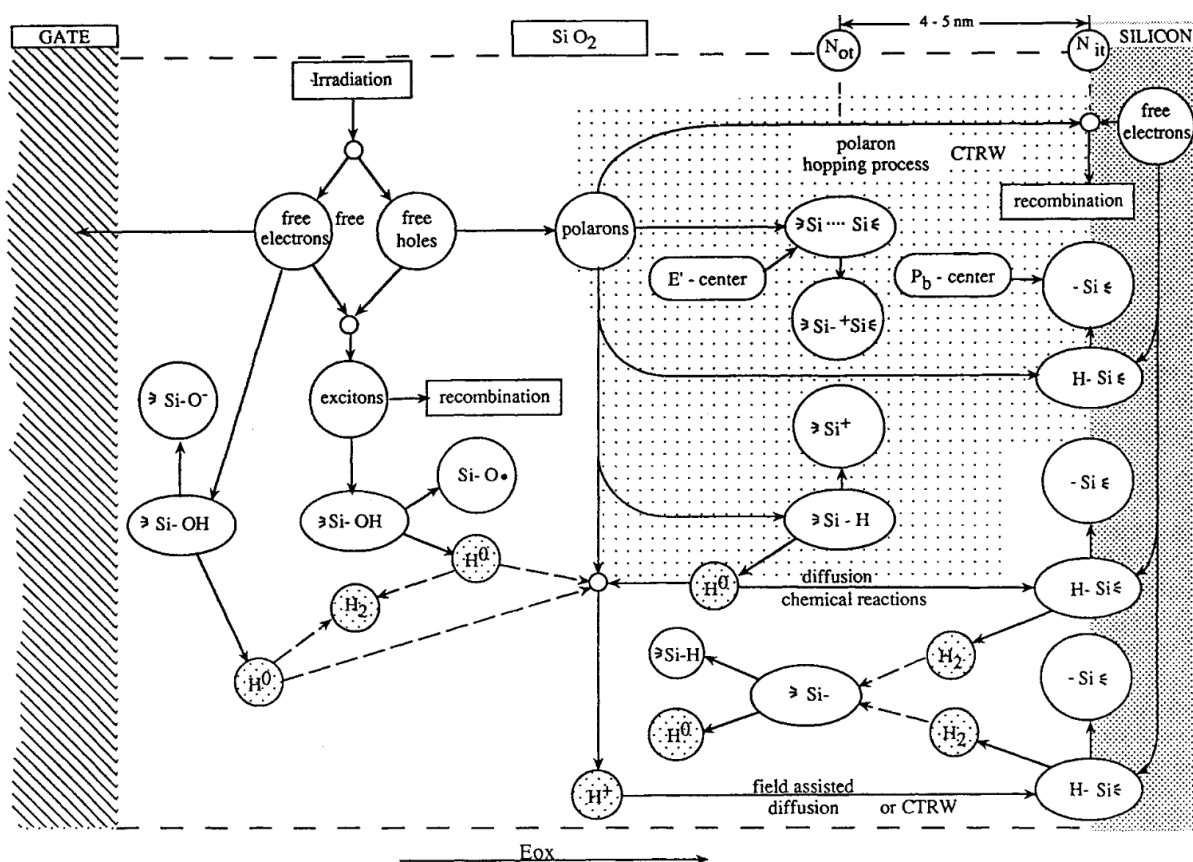


Figure 4.4: Diagram of physical processes leading to the accumulation of charge in the oxide and at the oxide-silicon interface for irradiated silicon sensors. Figure obtained from [78].

Figure 4.4 gives a visual support to the different ionization damage mechanisms described so far. To summarize, ionizing radiation excites SiO_2 molecules in the oxide. A fraction of the

generated EHPs survive the immediate recombination, leading to free electrons and holes. Free electrons and excitons, can lead to the formation of electron traps by breaking extrinsic defect precursors: e.g. Si-OH ($\text{Si-OH} \rightarrow \text{Si-O}^- + \text{H}^0$). The holes are transported towards the silicon interface via the polaron hopping mechanism, some getting trapped in E' - centers leading to trapped oxide charge. Some holes form interface states, while others get recombined with the free silicon electrons via the tunneling effect. The free neutral hydrogen atoms (H^0) generated from the Si-OH bonds can recombine with other H^0 atoms in order to form H_2 molecules or H^+ atoms via the interaction with a polaron. Both forms of free hydrogen move through diffusion and/or drift towards the Si interface, leading to the formation of dangling bonds with the help of free Si electrons ($\text{SiH} + \text{hole} \rightarrow \text{Si}^+ + \text{H}^0$). The reverse reaction of H^0 with SiO_2 atoms recombining to stable Si-OH or SiH is also possible.

4.2.2 Degradation mechanisms of TID

As has been highlighted in the above section, the two main consequences of ionizing damage in Si devices are the accumulation of positive charge in the oxide bulk, Q_{ox} , and the accumulation of interface states at the Si-SiO₂ interface, N_{it} . The parameter impact of this damage mechanism is studied for the case of CMOS circuitry. The MOSFET and the pixel array impact is each independently considered.

MOSFET impact

MOSFETs are particularly sensitive to TID due to the field effect operation through the gate dielectric, which is inherently sensitive to charge buildup. The accumulation of Q_{ox} and N_{it} leads to a change in the flat band voltage of a MOS structure. In MOSFETs, the most important impact of TID comes in terms of an operating voltage shift. In the case of an n-MOSFET, the application of a positive gate bias, leads to the buildup of positive charge in the oxide, which in turn bends the energy bands of the Si as is shown in Figure 3.4. This leads to the operation of the MOSFET in a more pronounced inversion mode, which in extreme cases can lead to the inability of turning off a transistor at its nominal operating voltage. In this case, a larger negative “off bias voltage” would need to be applied to the gate electrode in order to recover the normal transistor operation. In the case of p-MOSFETs, the buildup of positive charge is diminished, due to the negligible hole movement towards the Si-SiO₂ interface. As a consequence, the p-MOSFETs are expected to be more radiation hard than their n-MOSFETs counterparts. The threshold voltage shift of a MOSFET under the impact of TID, is given by:

$$\Delta V_{\text{th}} = \Delta V_{\text{ox}} + \Delta V_{\text{it}} \quad (4.4)$$

ΔV_{ox} is the voltage shift due to the oxide charge build-up and ΔV_{it} is the voltage shift due to interface state trap sites. The voltage shift of each component is further dependant on each charge buildup mechanism, such that:

$$\Delta V_{\text{th}} = -\frac{1}{C_{\text{ox}}} \cdot (\Delta Q_{\text{ox}} + \Delta Q_{\text{it}}) \quad (4.5)$$

Here, C_{ox} is the oxide capacitance and $\Delta Q_{\text{ox}}, \Delta Q_{\text{it}}$ are the amount of charge accumulated via each mechanism. From this, it follows that the voltage shift of a MOSFET is proportional

to the amount of trapped charge, which in turn is proportional to the thickness of the oxide, as is shown in Eq. 4.3. An additional benefit of very thin oxides, is the electron tunneling effect from the silicon. Near the interface, electrons tunnel with sufficiently high probability, leading to the recombination of hole trapped sites. This effect was studied and highlighted in Reference [79] for MOS capacitors showing a flat-band voltage change due to TID following a $\sim t_{\text{ox}}^2$ dependence for larger thickness oxides and a clear suppression of the damage mechanism at lower oxide thicknesses, attributed to the electron tunneling effect.

The buildup of interface states is also correlated to an increase in the source-to-drain leakage current and the over-all noise behaviour of a MOSFET. For transistors operated in the deep inversion mode, a change in operating voltage can lead to changes in its transconductance, affecting the properties of analog circuits.

Pixel impact

As many radiation defects are technology specific, only a general picture of the most important defect mechanisms is drawn in this section. A detailed treatment of the defects investigated in the study of this thesis will be discussed in the respective Chapters 5 and 6.

MAPS for particle physics are designed for harsh radiation environments (~ 100 Mrad), and hence employ radiation hard techniques in the pixel design. The main radiation effect expected in MAPS is an increase in sensor noise, and decrease in charge collection efficiency.

CMOS imaging sensors are usually less radiation hard, due to the standardized imaging processes employed by large foundries that do not emphasize radiation hardness. Several significant figures of merit are expected to be impacted after exposure to TID. The dark current is expected to see the largest impact due to the charge generation centers associated to the formation of Si-SiO₂ interface states. The charge collection efficiency and full well capacity expect a second order impact magnitude.

The most important defects in terms of dark current generation are studied further for the 4T CIS operated in the accumulated (Figure 4.5) and depleted (Figure 4.6) transfer gate modes. The oxide trapped charge accumulation is denoted via red crosses (traps with major influence) if they contribute to the direct dark current generation or yellow crosses (traps with minor influence) if they contribute to the diffusion collected dark current. The interface states are marked as white X's (states with major influence) or green (states with minor influence) based on the same considerations as for the trapped oxide charge. Three TID values are considered, defined as: Low TID (0.5 – 1 kGy(SiO₂)); Moderate TID (1 – 10 kGy(SiO₂)); High TID (10 – 50 kGy(SiO₂)). The definition of these dose limits is made based on the following references: [80][81][82][83].

Operation in accumulated mode. Figure 4.5 shows the main expected degradation mechanisms that take place in an irradiated 4T sensor operating in accumulated transfer gate mode. At low TID, the pinning of the diode is maintained and only a small dark current contribution is due to the interface states near the pre-metal dielectric. Further irradiation can lead to the extension of the SCR towards the region in the vicinity of the transfer gate where the photo-diode n⁺ implant is closer to the oxide. This leads to a large dark current contribution coming from direct interface DC generation, proportional to the transfer gate width. Higher irradiation doses (>50 krad), can extend the SCR across the entire interface, leading to a very large dark current across the entire photo diode, proportional to the total implant area.

Operation in depletion mode. Figure 4.6 shows the main expected degradation mechanisms that take place in an irradiated 4T sensor operating in depleted transfer gate mode. Due

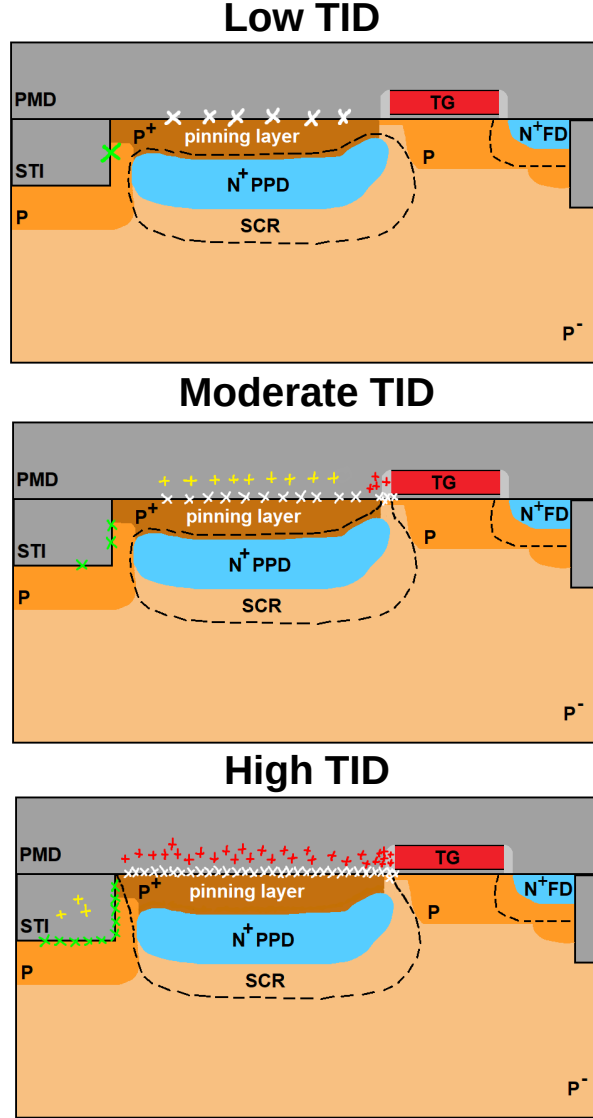


Figure 4.5: Illustration of the pixel dark current generation centers for a 4T CIS operating in accumulated transfer gate mode for three TID doses: low (top picture); moderate (middle picture) and high (bottom picture). These figures were generated based on a literature review for irradiated 4T CIS devices [33].

to the open channel between the photo-diode and the floating diffusion at low TID, interface states at the transfer gate oxide have an important impact on the dark current, contributing to the direct generated interface DC. An additional contribution can also come from diffusion collected interface states and oxide charge buildup at both the pre-metal dielectric and shallow trench isolation. As the TID is increased, more interface states and charge buildup contributes to the total dark current. For very large doses, similar to the accumulation transfer gate operation mode, the SCR extends to the pre-metal dielectric, leading to a very large DC contribution coming from the interface states and oxide charge buildup.

As the above qualitative interpretation suggests, 4T sensors with a transfer gate operating in depleted mode are more sensitive to TID at lower doses (the low dose definition matches the

expected ULTRASAT lifetime ionizing dose, see Section 5.5).

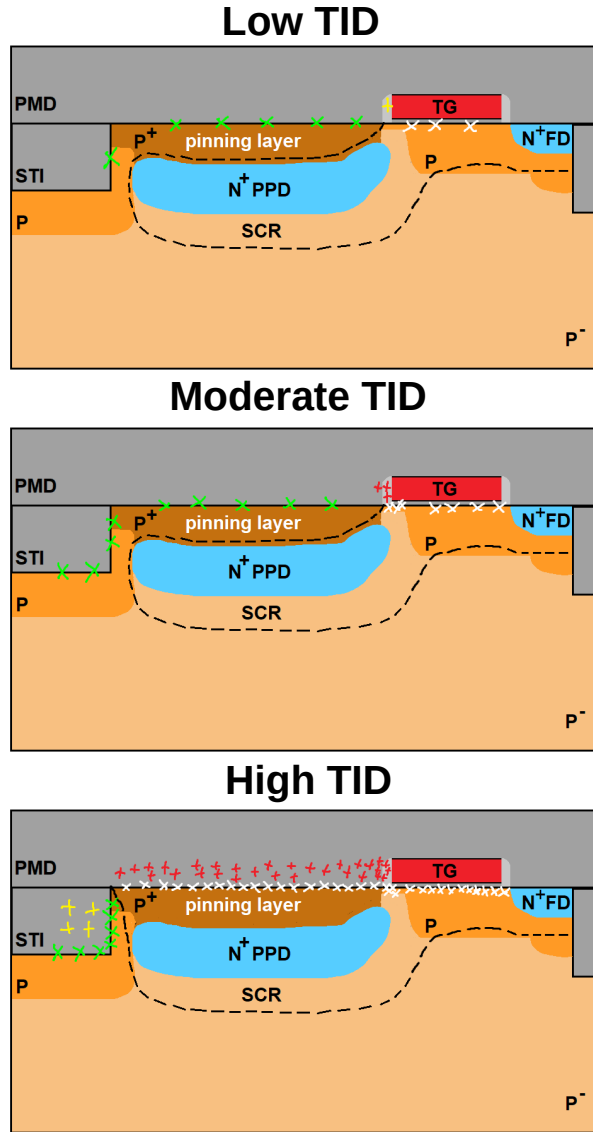


Figure 4.6: Illustration of the pixel dark current generation centers for a 4T CIS operating in depleted transfer gate mode for three TID doses: low (top picture); moderate (middle picture) and high (bottom picture). These figures were generated based on a literature review for irradiated 4T CIS devices [33].

The accumulation of oxide and interface charge, leads to the inversion of the p-doped implants near the oxide, which in turn expands the SCR. Naively, this implies an increase of the photo diode capacity, and thus an increase in the FWC. In practice there are several mechanisms competing against the growth of the effective FWC. The first order compensating effect is the increase in dark current that can severely limit the effective full well capacity with a second order effect coming from the increase in transfer gate leakage current.

4.3 Displacement Damage Dose

Similar to the previous subsection, a comprehensive description of displacement damage and the associated physical mechanisms in silicon based detector is described. A focus is made on the impact of the pixel properties (charge collection, noise increase) and the doping changes associated to highly irradiated devices. This section is used to motivate the radiation hardness results obtained for the MALTA sensors (Section 6.7) and contextualize the predicted impact of displacement damage for the ULTRASAT sensor (Section 5.5.2).

Displacement damage in Si sensors is associated to physical atomic lattice displacement. These can arise due to crystallographic defects or inelastic nuclear scattering of incident particles with lattice atoms. In order to generate displaced atoms through inelastic scattering, the interaction needs to impart at least 24 eV to a silicon atom. This energy threshold can be reached by high energy gamma interactions (via the Compton effect) or more efficiently, by massive particles, such as protons, neutrons and heavy ions. Electrons and high energy gammas are associated to single defect sites, while heavy particles are associated to defect clusters (several defects in close proximity).

4.3.1 The physics of displacement damage

The main mechanism of radiation induced displacement damage is the production of Frenkel pairs [84]. The physical dislocation of a Si atom from the lattice, leads to a vacancy and interstitial atom pair. Both the vacancy and the interstitial are highly mobile in silicon. Some of them recombine, while others migrate inside the Si lattice until they form single or clustered defect centers.

Vacancies have a chemical affinity to Group V atoms, such as P or As, often recombining in the form of vacancy-defect pairs. Similarly, interstitials have a chemical affinity to Group III atoms, such as B, leading to trapped interstitial impurities. Both of these defect centers are electrically active, giving rise to energy levels inside the band gap. Figure 4.7 shows an illustration of the atomic configuration of several vacancies and interstitials with contaminants in semiconductors. Additionally, their induced energy levels inside the band gap is also plotted. The energy of each level is shown relative to the closest energy band.

4.3.2 The NIEL hypothesis

Unlike TID, the displacement damage is not directly proportional to the total energy absorbed. It is dependent on both the particle type and energy. For example, 1 MeV neutrons are associated to highly clustered defect sites, 10 MeV protons are associated to a uniformly distributed damage, while 24 GeV protons are associated with a mix of both [86].

A scaling method to the damage incurred by a standard particle is desired. Several standards exist in different fields: 1 MeV electrons, 1 MeV neutrons. Such a standardized approach of displacement damage needs to take into account the kinematics of both low and high energy interactions of different particles in terms of both the first displaced atoms, called the primary knock-on atoms (PKA) and their propagation inside the lattice. Reference [87] links the number of generated Frenkel pairs to the energy imparted by a particle to the PKA. If the transferred energy is large enough, it can travel far into the material bulk, leading to several other lattice interactions. PKAs displaced by neutrons are known to have a recoil energy ranging from 2 keV to several MeVs. PKAs induced by protons and electrons in the MeV range have a broad energy spectrum with an important low energy contribution. For low energy deposition interactions

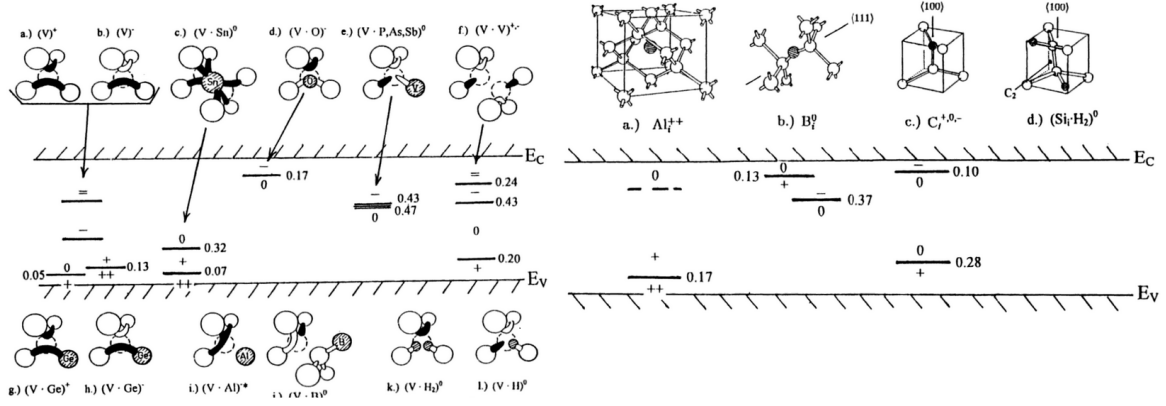


Figure 4.7: Diagram of the most common vacancy and interstitial pairs with impurities encountered in silicon. The energy levels and the chemical structures associated to the electronic states of each defect center is also shown. Figure obtained from [85].

(e.g. ~ 125 keV electrons), the recoil energy of the PKA is low enough to not lead to other secondary interactions.

Remarkably, a good linear relationship between the energy deposited in the material and the device degradation was found for several particle physics detectors with varying technology nodes. The various differences between different PKAs do not appear in the device characterization. This behaviour is known as the Non-ionizing Energy Loss (NIEL) hypothesis [88] and is a useful scaling mechanism for device characterization. One plausible explanation for this behaviour could be the many collisions between several PKAs, leading to a loss of information of the original PKA spectrum. Figure 4.8 shows the equivalent Displacement Damage Dose (DDD) equivalent in terms of 1 MeV neutrons for various particles and energies usually encountered in accelerator applications.

4.3.3 Degradation mechanisms of displacement damage

Displacement damage is correlated to intermediary energy levels in the silicon band gap, as was shown in Figure 4.7. Defect centers with energy levels near the mid-gap lead to charge generation and recombination. The cross-section of these phenomena is proportional to the free carrier concentration, such that carrier generation dominates for centers in the depleted volume of a sensor and charge recombination dominates for centers in the un-depleted volumes. Additionally, shallow defects (i.e. defect centers with energy levels close to the conduction or valence bands) can lead to minority or majority carrier trapping which degrades the timing and quantum efficiency performance of a device. Additionally, due to the different affinities of vacancies and interstitials discussed in Section 4.3.1, displacement damage can lead to doping concentration changes. The main effects of displacement damage in Si sensors are discussed below using simplistic parametrizations.

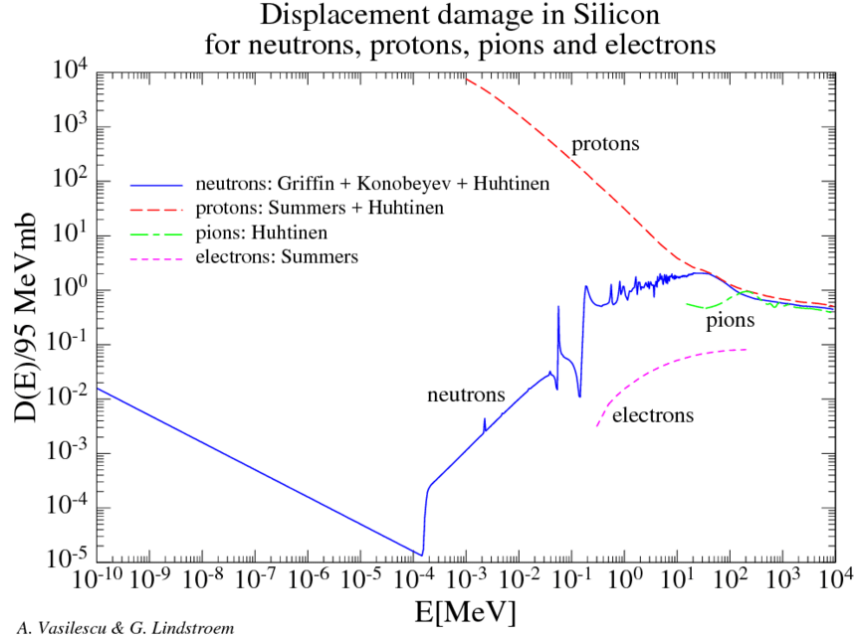


Figure 4.8: Displacement damage equivalent for a 1 MeV neutron versus particle energy for: electrons, protons, neutrons and pions. The data has been compiled by Reference [89] and is based on the experimental data collected by the following publications: [90], [91], [92], [93]. Figure obtained from [94].

Increase in leakage current

The mid-gap states inside the space charge region, lead to charge generation, which is associated to a larger current flow through the reverse biased junction. This is usually known as leakage current and its increase due to irradiation at room temperature is given by:

$$I = I_0 + \alpha \cdot \Phi \cdot w \quad (4.6)$$

where I_0 is the bias current before irradiation, α is a damage coefficient dependent on particle type (e.g. $\alpha = 3 \cdot 10^{-17} \text{A/cm}$ for 650 MeV protons [95] and $\alpha = 4 \cdot 10^{-17} \text{A/cm}$ for 1 MeV neutrons [96]), ϕ is the radiation fluence and w is the depleted volume.

The leakage current has a strong temperature dependence, given by [17]:

$$I(T) \sim T^2 \exp^{-E/2kT} \quad (4.7)$$

This formula models well the radiation damage centers within the depleted silicon bulk and ionizing damage that induces interface states in electrical contact with a sensor's space charge region. The temperature scaling of diffusion dominated trapped charge transport has been reported in other publications [97], and was found to have a highly diminished contribution at low temperatures.

Doping changes

Doping changes of irradiated sensors have been measured for relatively high NIEL doses ($\sim 10^{13} \text{ 1 MeV } n_{\text{eq}}/\text{cm}^2$). N-doped Si has been observed to decrease in doping concentration after

severe irradiation (appearing as intrinsic Si) and even switching to effectively p-doped Si (type inversion). The compensation of n-doping concentration is attributed to the donor removal effect [98]. The change in doping is explained by the highly mobile vacancies formed after irradiation, that due to their chemical affinity to group IV elements, preponderantly form vacancy - donor (e.g. V-P) groups. The vacancy-donor complexes are not as electrically active, as the donor atoms, leading to an effective donor concentration removal. The type inversion can be explained by di-vacancies (V-V) complexes that act as acceptor-like states, compensating the donor-like states in n-type silicon. At a certain irradiation fluence, the acceptor states dominate, effectively turning the Si to p-type. While, the inverted Si does not behave exactly as a p-doped Si (it is not associated to the creation of free holes [99]), the impact on the space charge is similar to a change in the effective doping concentration, N_{eff} .

The type inversion, does not require a change in applied bias polarity, but has an impact on the depletion voltage for a diode detector:

$$V = \frac{e}{2\epsilon} |N_{\text{eff}}| d^2 \quad (4.8)$$

For n-type Si the change in space charge is parameterized as:

$$\Delta N_{\text{eff}} = N_n - N_{\text{rd}} \left(1 - \exp^{-g_c \Phi} \right) - g_c \Phi \quad (4.9)$$

and for p-type Si:

$$\Delta N_{\text{eff}} = N_p + g_c \Phi \quad (4.10)$$

N_n and N_p are the doping concentrations before irradiation, N_{rd} is the concentration of removable donors ($\sim 0.7N_n$ for float-zone Si), g_c is a particle dependent parameter ranging from $g_c = 0.022$ [100], to $g_c = 0.047$ [101].

The double junction effect

The double junction is an effect mainly studied in irradiated Fz silicon sensors. This effect has also been observed in irradiated Cz silicon sensors [102]. A schematic representation of the formation of the double junction for a symmetrical p-n junction is shown in Figure 4.9. When no deep electron or hole traps are present in the silicon and a large enough bias voltage is applied at the junction, a fully depleted device with an uniform electric field distribution is expected. In turn, the distribution of the free carrier concentration in both the n and p regions follow:

$$\begin{aligned} n(x) &= \frac{j_n(x)}{e v_{\text{dr}}^n(E(x))} \\ p(x) &= \frac{j_p(x)}{e v_{\text{dr}}^p(E(x))} \end{aligned} \quad (4.11)$$

where j_n and j_p are the thermal generated electron and hole currents respectively, v_{dr}^n and v_{dr}^p are the drift velocities of the electrons and holes, e is the elementary charge and $E(x)$ is the electric

field distribution. Next, we consider the existence of uniformly distributed electron and hole traps across the volume, induced by radiation or imperfections in the silicon growth technique. The differences in free carrier concentrations lead to non-uniform steady state filling of the deep traps: negative charge accumulates in the n^+ region and positive charge accumulates at the p^+ contact.

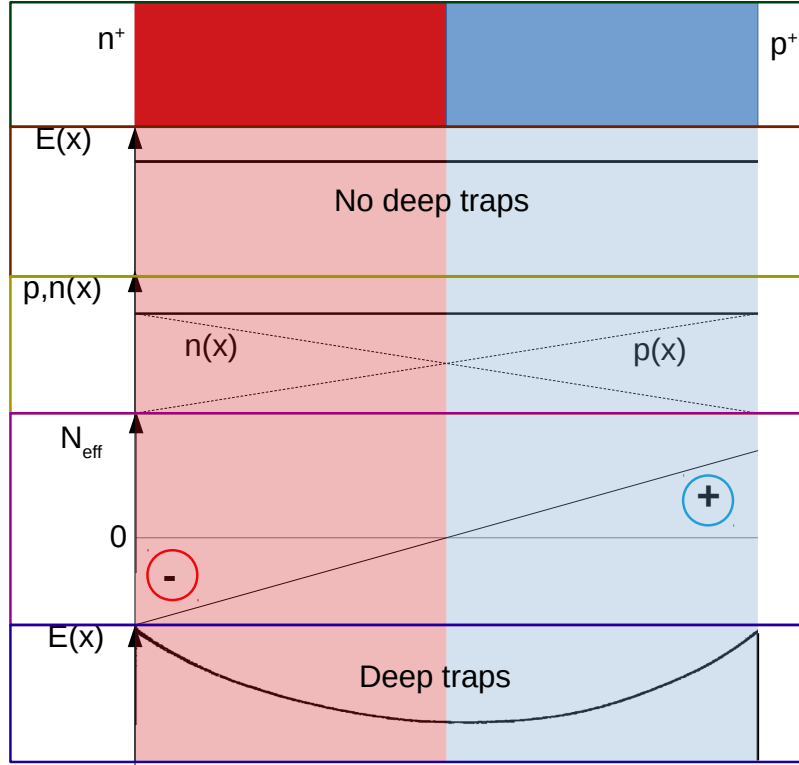


Figure 4.9: Schematic representation of a symmetric junction double junction structure assuming an uniform charge trap distribution [103].

The localized increase in trapped charge, leads to a larger local electric field according to the Poisson equation:

$$\text{div}E = -eN_{\text{eff}}/\epsilon\epsilon_0 \quad (4.12)$$

Finally, the local electric field increase leads to a double peak distribution towards the n^+ and p^+ terminals.

4.4 Single Event Effects

Single Event Effects (SEE) are not caused by the accumulation of radiation damage, but rather are associated to a single high energy deposition event in an active component's sensitive volume (usually at one of its nodes, e.g. Source, Drain for transistors). Unlike, cumulative damage, SEE's mostly affect the digital and analog circuitry in a sensor and not the pixel itself. They

are caused by transient events in the Si bulk, usually attributed to highly energetic cosmic particles or heavy ions. As a consequence, these effects are of a great concern for space-borne missions where the atmospheric shielding is limited. There are several mechanisms documented in literature through which highly energetic particles imparting a large amount of charge to the Si or the SiO₂ can lead to electrical malfunction of Si devices: Single Event Snapback, Single Effect Dielectric Rupture, Single Event Effect Gate Rupture [104]. The following sections focus on the two main effects affecting modern CMOS sensors: Single Event Upsets (SEU) and Single Event Latch-ups (SEL). SEUs are “soft” errors, leading to bit flips in memory circuits that can be fixed by overwriting the memory to its original state and SELs are “hard” errors, leading to high current states that can be removed only by power cycling the affected circuit. Both the upset and latch-up effects will be studied in the context of the ULTRASAT sensor’s SEE qualification in Section 5.7.

4.4.1 Single Event Upsets

Consider a typical CMOS bi-stable memory cell that transitions from an “on” to an “off” state via a current pulse. A similar transition can be induced by a particle depositing charge at the node of the MOSFET. The amount of charge deposited in the Si, in order to lead to a flip of the bi-stable cell, is known as the critical charge, Q_c .

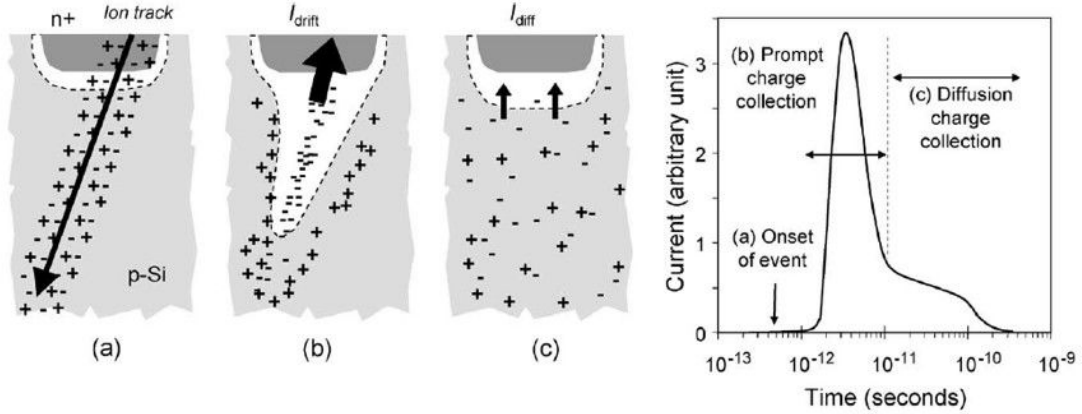


Figure 4.10: Current pulse generation in a p-n junction due to a single charged ion. The left-most three panels show a diagram of a transient event at a transistor node induced by a highly ionizing particle: (a) A particle strikes close to a transistor node; (b) The prompt charge collection is performed via two mechanisms: charge drift movement in the space charge region near the node and a funnel charge collection associated to an effective enlargement of this region due to the additional localized electric charge; (c) charge collection via diffusion movement. The right panel highlights the expected current pulse generated at the transistor node associated to such an event. Figure obtained from [105].

Figure 4.10 shows the current pulse generation in a p-n junction, that models the interaction of an ionizing particle passing through a transistor node of a bi-stable memory cell. The collected charge is due to three effects: prompt drift (a), prompt funneling, due to a field enhancement in depth correlated to the large amount of generated charge (b) and delayed diffusion (c). Similar to the charge collection of a pixel, the particle leads to a current pulse at the node that can lead to a switch in the memory cell’s state.

As was hinted above, a change in a memory cell (bit flip), takes place if the energy deposited near a transistor node bypasses a threshold value called critical charge, Q_c . As the injected

charge is dependent on the energy transfer rate of a particle, it is useful to introduce the Linear Energy Transfer (LET):

$$\text{LET} = \frac{dE}{dx} [\text{MeV cm}^{-1}] \quad (4.13)$$

It is usually useful to normalize this quantity to the density of a material such that the above equation can be rewritten for silicon:

$$\text{LET}[\text{Si}] = \frac{dE}{dx} \rho = 2.33 \cdot 10^{-3} \frac{dE}{dx} [\text{MeV cm}^2/\text{mg}] \quad (4.14)$$

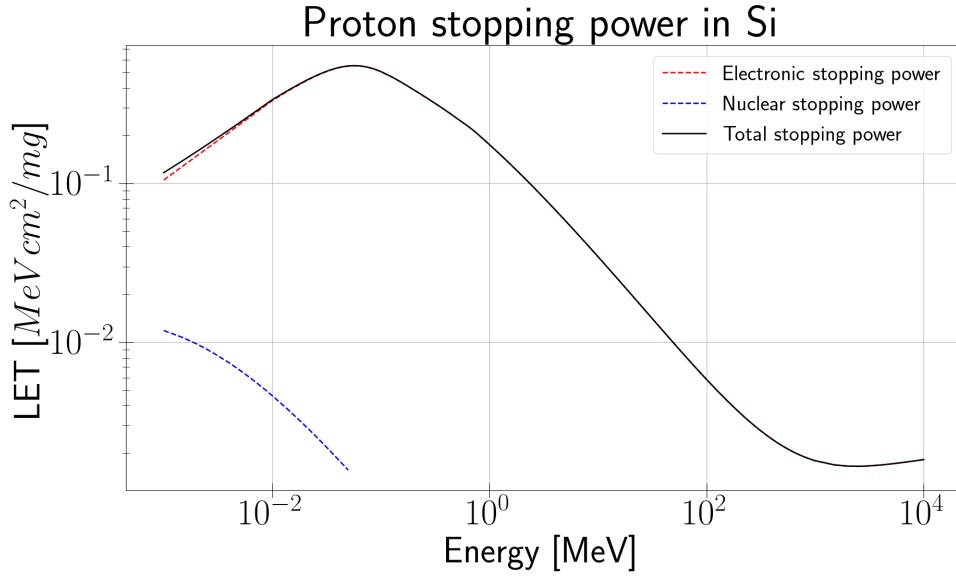


Figure 4.11: The linear energy transfer of protons in silicon. The electronic (dashed red line) and nuclear (dashed blue line) stopping powers are plotted together with the total energy transfer component (solid black line). The data for the plot has been sourced from the PSTAR NIST database [106].

Figure 4.11 shows the dependence of proton energy to its LET in silicon for two components: the electronic stopping power (dominated by Coulomb scattering) and the nuclear stopping power (dominated by nucleus inelastic scattering). The majority of the energy imparted to the silicon lattice comes in the form of ionizing effects, with small contributions to the total energy transfer at low proton energies due to nuclear inelastic scatterings. Due to the complex particle interaction in matter, the amount of charge generated at a circuit's sensitive node is considered linear in relation to the LET and not its energy.

Next, consider the case of a memory cell array formed from completely identical bi-stable memory circuits characterized by a critical charge, Q_C . As the LET of impinging particles is proportional to the amount of generated charge in the Si bulk, there exists an LET for which a charge $Q \geq Q_C$ forms in the active silicon volume. This is known as the onset LET and is denoted as LET_0 . The critical charge can then be written as:

$$Q_C = (\text{LET}_0 \cdot z \cdot \rho \cdot e) / X \quad (4.15)$$

where z is the sensitive depth of the MOSFET (the space charge region, the funnel and the delayed diffusion length), $\rho = 2.32 \text{ g/cm}^3$ is the Si density, $e = 1.602 \times 10^{-19} \text{ C}$ is the elementary charge and $X = 3.6 \text{ eV}$ is the ionization potential of silicon [107].

Making a further approximation, that the delayed diffusion movement is significant, than the sensitive area of a memory cell can be approximated to its area. From this assumption it follows that the upset sensitivity of a memory cell is completely described by LET_0 [$\text{MeV cm}^2/\text{mg}$] and the area of the device, σ_{lim} [cm^2] known as the limiting cross-section.

The probability of the upset for the memory cell array is then given by the Heaviside step function:

$$f(x) = \begin{cases} \sigma_{\text{lim}}, & x \geq \text{LET}_0 \\ 0, & x < \text{LET}_0 \end{cases} \quad (4.16)$$

For real devices, these approximations are often too restrictive, and the upset probability can be described more accurately by the 4-parameter Weibull function:

$$f(x) = \sigma_{\text{lim}}(1 - e^{-(x-\text{LET}_0)/l})^k \quad (4.17)$$

The scale and shape parameters, l and k lead to a “smearing” of the Heaviside function. The smearing is often attributed to process variations between cells and the stochastic nature of the energy deposition of heavy ionizing particles. In practice, the σ_{lim} derived from experimental data is smaller than the component physical size, due to a small delayed diffusion contribution. In fact, measurements of σ_{lim} that approach the physical size of a component are often times an indication of under-counting of upset events in the experimental data.

4.4.2 Single Event Latch-up

The close proximity of n-MOSFET and p-MOSFET structures in the same substrate leads to the creation of parasitic bipolar n-p-n and p-n-p structures. Additionally, these parasitic structures can couple together to form a parasitic thyristor p-n-p-n.

Figure 4.12 (left side) shows a schematic representation of a parasitic thyristor structure that can appear in CMOS circuitry. The neighbouring n and p wells lead to the connection of the positive V_{DD} and V_{SS} lines. A thyristor acts as a Silicon-Controlled Rectifier, which is a circuit that can be latched to conduct a large current via the control of a small current. The operational principle of a parasitic thyristor is highlighted in Figure 4.12 (right side). The positive anode (the V_{DD} rail) is connected to the source of the p-n-p transistor and the negative cathode (the V_{SS} rail) to the drain of the n-p-n transistor. The J_1 and J_3 junctions are forward biased, but no current flows through the structure, because the J_2 junction is reverse biased. If a positive bias is applied to the p-bulk or a negative bias is applied to the n-bulk, the J_2 is turned on leading to a direct current connection between the anode and the cathode. The gate bias leads to a current through the n-p-n transistor that in turn leads to the opening of the p-n-p transistor in a feedback loop connection. If the gate bias is then removed, the connection persists, leading to the latching behaviour associated to a Silicon-Controlled Rectifier. The initial biasing condition of the parasitic thyristor can be caused by a short-lived transient event in the circuit, that in turn leads to a latched circuit state that persists even after the transient disappears. To summarize the above discussion, a latch-up in a CMOS circuit can occur if the

following conditions are satisfied:

- n-MOSFET and p-MOSFET built in p or n-wells respectively are in physical contact.
- Both parasitic bipolar transistors have their emitter-base junctions forward biased.
- A positive feedback loop can be created in the bulk, i.e. the gain product: $G_{npn} \cdot G_{pnp} > 1$.
- The injected gate current is greater than the current latch value of the thyristor (defined as the current value for which the Silicon-Controlled Rectifier latches).

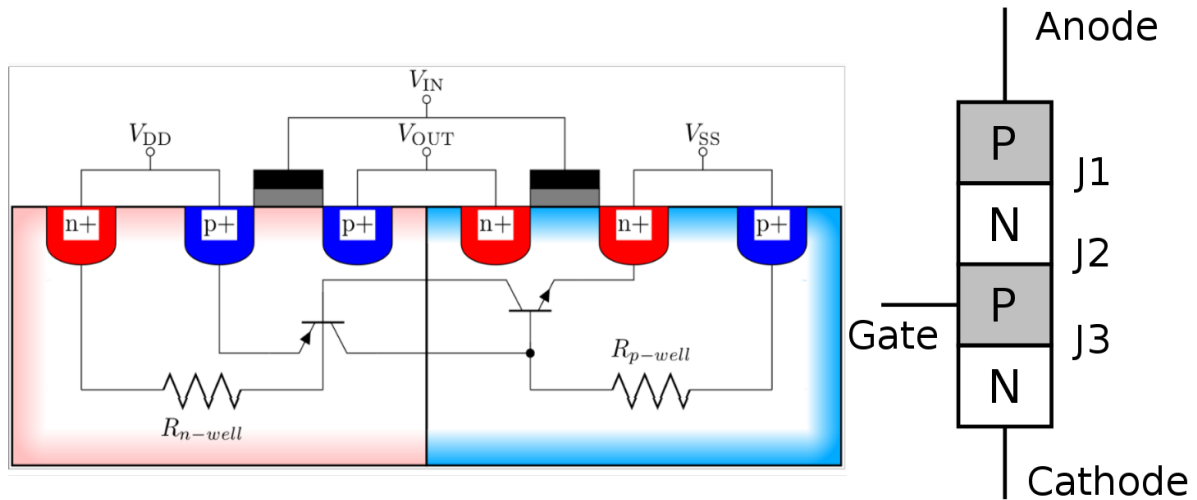


Figure 4.12: Schematic representation of a parasitic thyristor structure that can take place in CMOS circuitry. Figure obtained from [108].

Following the above final condition for the formation of a latch-up, it can be seen that similar to an upset, a latch-up can be associated to a critical value of an injected charge. The injected charge can be due to highly ionizing particles (e.g. protons, pions, heavy ions) and as such, the latch-up sensitivity of CMOS devices is an important parameter in environments with high fluences of such particles. As the definition of a latch-up-sensitive component is not as straight forward as in the upset case, there is no direct indication that the same model that can be applied for the upsets can also be rigorously applied for latch-ups. An approximation is made by assuming that latch-ups are defined by a single critical current (associated to a critical charge) value and a similar thyristor gain value in the entire circuit.

An effect that leads to “soft latch-ups” has been associated to upsets. In this particular case, a latch-up is not followed by a global I_{DD} current increase, but rather to a local increase in current near a latched logic cell. This local current increase can in turn propagate to the circuit primary outputs, leading to global current increases. The main difference between a soft latch-up and the classical latch-up mechanism is the current drawn. A smaller current draw is expected for soft latch-ups. Additionally, several soft latch-up sites can appear concurrently in different parts of the circuit, leading to the gradual increase in I_{DD} over time.

Chapter 5

Radiation qualification of the ULTRASAT camera

ULTRASAT stands for Ultra-Violet Transient Astronomy Satellite. It is a space-borne mission planned for launch in 2027. The mission is led by the Weizmann Institute of Science (WIS) and the Israel Space Agency (ISA) in collaboration with DESY and NASA. At the heart of the telescope, there is a CMOS camera built in the 180 nm Tower Semiconductor feature size process designed by DESY.

In Section 5.1, an overview of the planned operation of the ULTRASAT satellite is presented. An emphasis on the camera and the optical supporting structures is made. The main scientific goals of the mission are briefly discussed in Section 5.2. No details regarding the astrophysical and cosmological context and impact of the observations is made, as this is outside the scope of this thesis. Section 5.3 gives an in depth explanation of the ULTRASAT sensor operation and sets the scene for the radiation hardness results presented in the further sections. Section 5.6 details the TID study of pixel test sensors, called SCOUTs and provides impact estimations for the mission operation. Section 5.7 details the SEE testing of the ULTRASAT sensor. Finally a prediction of the expected in-orbit single event effect rate is made. Overarching conclusions on the radiation qualification of the ULTRASAT mission and the radiation hardness of the technology node employed in the ULTRASAT sensor are made in Section 5.8.

5.1 The ULTRASAT mission

The ULTRASAT mission is planned for launch to the Geostationary Transfer Orbit (GTO) in 2027. The spacecraft comprises of two components: the ULTRASAT telescope and a propellant propulsion system with a total mass of ~ 1100 kg [109]. After its initial transit orbit, the mission will self-perform a transfer to the geosynchronous orbit (referred as GSO or GEO) and will operate for a minimum of 3 years and up to 6 years (limited by propellant fuel for orbit adjustments). A continuous, real-time data rate transfer of ~ 5 Mbps will be achieved with the help of several high-gain antennas mounted on the spacecraft.

The ULTRASAT telescope will have a large field of view (204 deg^2) and a large sensitivity (22.5 AB limiting magnitude - proportional to the light flux at 5σ detection of three co-added images of 300 s integration time) in the near UV band (230 – 290 nm). The telescope is planned to operate in multiple modes described in more detail in Section 5.2. In order to cope with the strict sensitivity requirements of the mission, the design of all telescope components have

been optimized. The ULTRASAT telescope is functionally divided into three parts: the Optical Tube Assembly (OTA), the baffle and the camera.

5.1.1 The ULTRASAT Optical Tube Assembly

Figure 5.1 highlights the design of the ULTRASAT OTA. The assembly is based on a Schmidt telescope design [110]. A set of two lenses made of fused silica and CaF_2 act as an approximately achromatic pair in the NUV band pass. The refracted beam is then reflected on a spherical mirror. The focus is achieved with the help of several field flatteners. Lastly, a Sapphire filter is used to suppress the light components outside of NUV (out of band suppression). The aperture of the telescope will be 330 mm, leading to a wide field of view of 204° .

Optical aberrations are kept low by the OTA design and the strict flatness requirements ($\pm 10\mu\text{m}$) of the ULTRASAT camera.

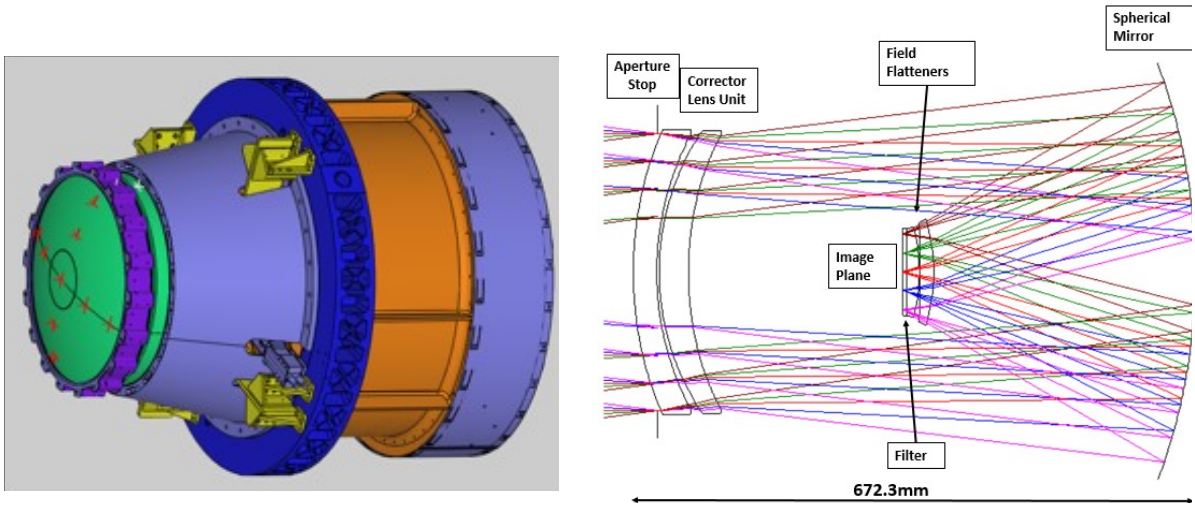


Figure 5.1: ULTRASAT Optical Tube Assembly (OTA) computer aided design diagram (left) and ray-trace layout (right). Figure obtained from [111].

5.1.2 The ULTRASAT baffle

Figure 5.2 (left) shows a Computer Aided Design (CAD) diagram of the ULTRASAT baffle. It is fabricated from 4.2 mm thick aluminium sheets and its interior is coated with Acktar “vacuum black” paint. It is designed to suppress stray light, reduce the trapped electron flux and the Cherenkov radiation generated by their passing through the telescope lenses. The baffle is attached to the telescope aperture at a slanted angle of 20° . This allows the telescope to point $>70^\circ$ from the sun without a significant increase in background light. Additionally, in order to limit the scattered light from the Earth and the moon, an internal vane structure was implemented in the baffle as can be seen in Figure 5.2 (right) [111].

5.1.3 The ULTRASAT camera

The ULTRASAT camera is composed of the detector assembly, showcased in Figure 5.3 and the Remote Electronics (RE) (its design is described in detail in Reference [112]). The RE is responsible for the sensor read out and the communication with the spacecraft.

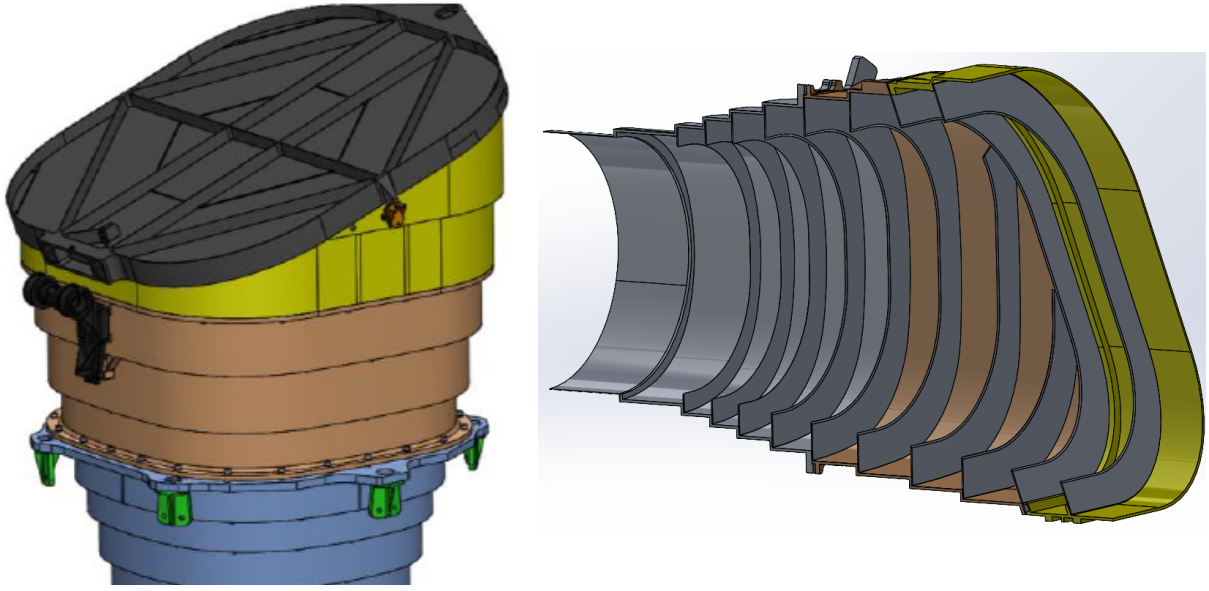


Figure 5.2: ULTRASAT baffle with the protective trap door closed (left) and baffle cross-section, highlighting its vane structure for optimized stray light capture (right). Figures obtained from [111].

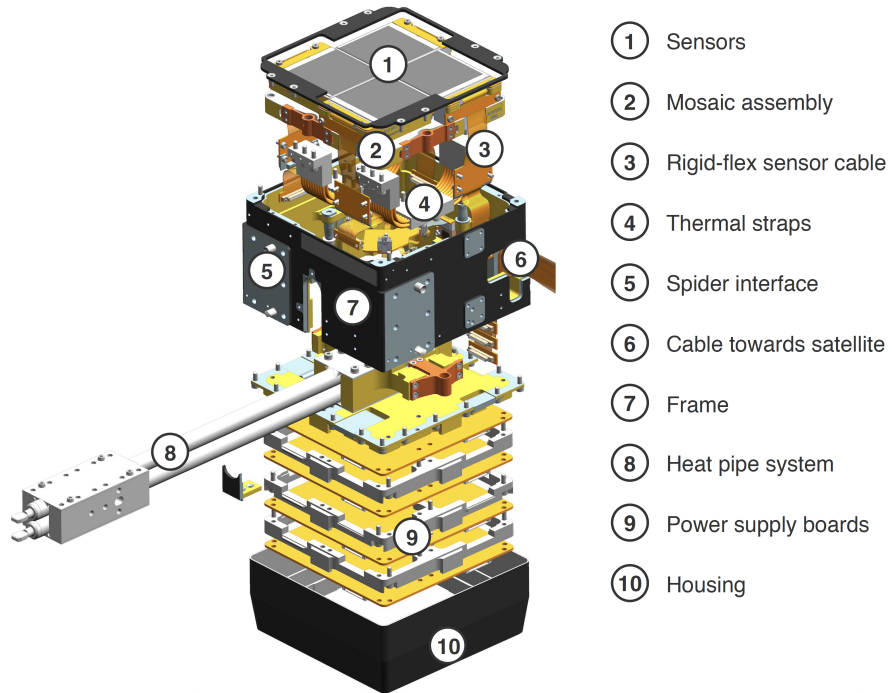


Figure 5.3: Exploded view of the ULTRASAT detector assembly design. Figure obtained from [111].

The detector assembly contains several elements:

1. **Sensors.** The camera contains four Back Side Illuminated (BSI), dual gain 4T CMOS imaging sensors, whose design is expanded in Section 5.3. Each sensor has an area of $47.135 \times 50.080 \text{ mm}^2$, 22.4 megapixels leading to a camera sensitive area of $90 \times 90 \text{ mm}^2$.

2. **Mosaic assembly.** The four sensors are mounted on a mosaic assembly designed by Semiconductor Technology Associates (STA) [113]. The sensors are glued to the mosaic in a 2-buttet configuration, with all the peripheral electronics pointing outwards from the camera center, decreasing the dead space. Several temperature sensors and heaters are placed on each imaging sensor. They are interfaced to the spacecraft, creating a control loop which can adjust the sensor temperature (<1 K thermal gradient stability) in flight.
3. **Rigid-flex sensor cables.** The sensors are wire-bonded to rigid-flex sensor cables using aluminum wedge wire bonding, mounted perpendicular to the sensor plane, in order to maintain a compact design.
4. **Thermal straps.** The sensors will be operated at 200 ± 1 K during observations. Additionally, decontamination procedures are planned where the temperature of the detector assembly will be elevated to ~ 343 K [111]. The cooling of the sensors is realised via thermal straps connected to interfaces provided by the spacecraft in the form of several heat pipes. This design is used in order to mechanically decouple the mosaic from the distribution system.
5. **Spider interface.** The detector assembly will mechanically interface with the telescope via four “spider” interfaces.
6. **Cable towards satellite.** The sensor’s slow control is preformed via a Serial Peripheral Interface (SPI). Its primary role is loading the sensor configuration to the on-chip micro-controller unit (MCU). The data acquisition will be performed via a Low Voltage Differential Signaling (LVDS) line.
7. **Frame.** The Invar frame is designed to ensure mechanical integrity and provides the required interfaces towards the spacecraft.
8. **Heat pipe system.** Provides the thermal interface to the spacecraft.
9. **Power Supply boards.** Provide the seven low noise pixel power supplies and digital and analog additional lines to the sensor.
10. **Housing.** The housing structure is based on a milled hollow box design. It is made from Invar in order to match the thermal expansion coefficient of the frame.

The RE contains four Field Programmable Gate Arrays (FPGA) each controlling one of the four sensors. It interfaces with the spacecraft via three interfaces: a direct current power line (28 – 45 V); Universal Asynchronous Receiver / Transmitter (UART) line to receive commands from the spacecraft and a link to send the acquired data.

5.1.4 Sensitivity

As mentioned in Section 5.1.1, the optical design aims to increase the sensitivity of the telescope in the operational band (220 – 290 nm). Additionally, the telescope will be imposed several pointing restrictions away from the most luminous background sources: $>70^\circ$ away from the Sun, $>48^\circ$ away from the Earth limb and $>35^\circ$ away from the Moon. The sensitivity of the telescope in and outside of the operational band has been simulated and measured by one of the ULTRASAT collaboration partners [111].

The optical throughput of the main OTA components is shown in Figure 5.4. The spherical mirror (left plot) has a large out of band suppression and a high reflection throughput in the operational wave band. Similar results are observed for the sapphire filter (right plot), with a lower suppression factor at larger wavelengths (>1000 nm) which is improved upon in upcoming studies. Considering additionally, the Quantum Efficiency of the sensor, which was estimated by Ref [114], the total ULTRASAT throughput is shown in Figure 5.5. A throughput of $\sim 30\%$ is expected for the operational band, which is compatible with the mission requirements.

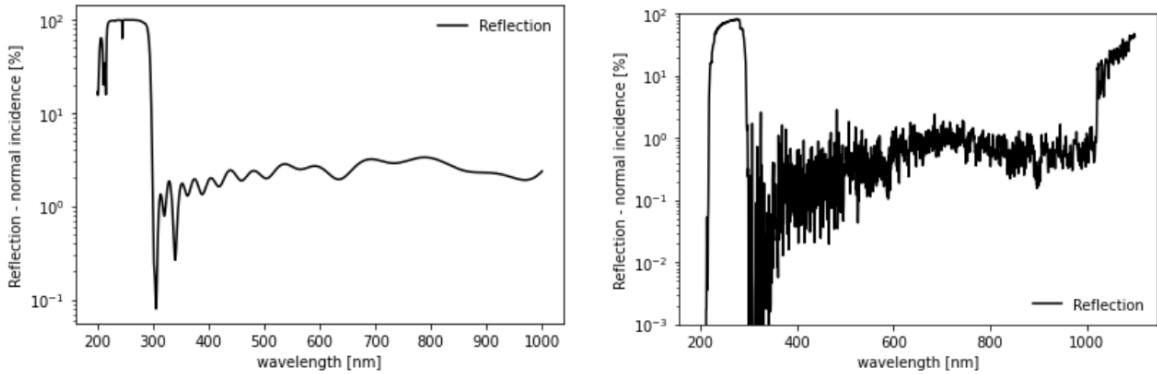


Figure 5.4: ULTRASAT spherical mirror reflection throughput (left). Sapphire filter optical throughput (right). Figures obtained from [111].

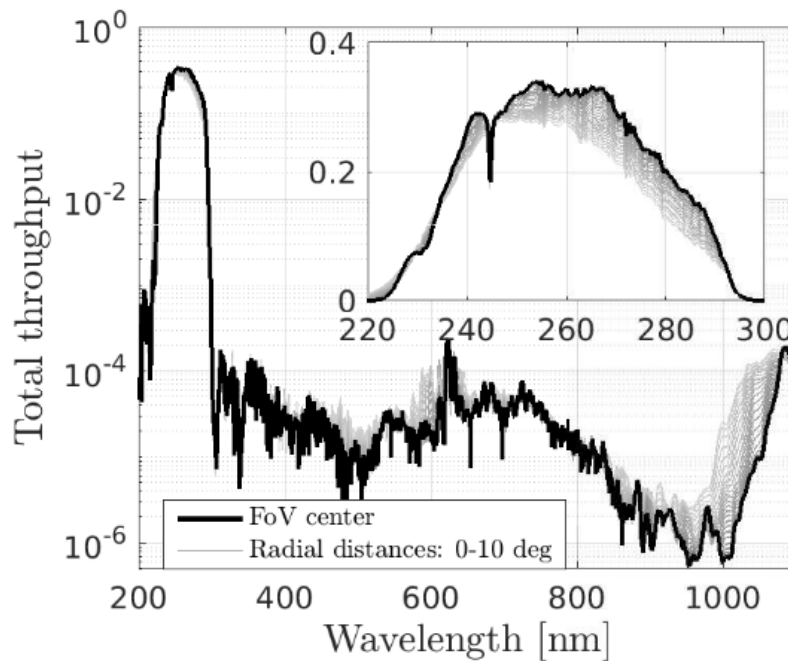


Figure 5.5: ULTRASAT total throughput considering all contributions from the Optical Tube Assembly (OTA) and sensor quantum efficiency. Figure obtained from [109].

The leading noise sources that are expected to impact the ULTRASAT mission have been investigated in Reference [109] and a summary of their findings is presented in Table 5.1. The

main background component has been estimated to be the zodiacal light [115]. This component is already highly suppressed by the baffle and the limited inclination ranges of the mission. A value of $27 \text{ e}^-/\text{pix}$ has been estimated for the conservative case of a perpendicular pointing in relation to the Sun. The Cherenkov radiation is the second order background contribution. This component is already suppressed by the baffle design, but can dominate in the low wavelength background spectrum [116]. The stray light component is highly suppressed by the tilted baffle design and the pointing restrictions of the telescope. The only expected sources are reflections from Earth and the Moon. The instrumental noise components have been estimated from preliminary results and design specifications, with the largest components expected to come from the sensor’s dark current and readout noise.

Table 5.1: ULTRASAT simulated background for a single 300s integration time frame at operational temperature [109].

Source	Variance [e^-/pix]
Zodiacal	27
Cherenkov	15
Stray light	12
Dark current	12
Readout noise	6
Electronic cross talk	2
Gain	1
Quantum Yield	<1
Total	75

The estimated resulted sensitivity, leads to limitations of the detectable light sources, quantified via the limiting magnitude AB. The signal to noise ratio (SNR) for several source magnitudes and radial inclinations is plotted in Figure 5.6. The improvements in SNR associated to a radial inclination of 5° is associated to the properties of the ULTRASAT telescope optics [109]. Following the sensor testing, the main impact of the sensor parameters after irradiation will be related back to the sensor SNR and limiting magnitude presented in Figure 5.6.

5.2 ULTRASAT Science

The ULTRASAT mission will perform time domain surveys in the NUV band for large fields of view looking primarily for transient, short-lived events. The number of observable transient events is proportional to the celestial volume observable per unit time, defined as grasp. Figure 5.7 highlights that the ULTRASAT mission has a comparable grasp to the Vera Rubin Observatory (VRO) and 300 times larger grasp than the GALEX mission. ULTRASAT additionally is poised to image a relatively unique spectral band (220 – 290 nm), leading to several scientific goals described further.

5.2.1 ULTRASAT imaging modes

The ULTRASAT telescope is planned to be operated in two survey modes: continuous survey and target of opportunity (ToO). In the continuous survey mode, the telescope will be pointed to a volume of space and is planned to take continuous frames for a predetermined amount of

time. If a ToO trigger is sent to the spacecraft, the survey is interrupted and the telescope slews (with a slew rate of $>0.5^\circ \text{ s}^{-1}$) towards its target.

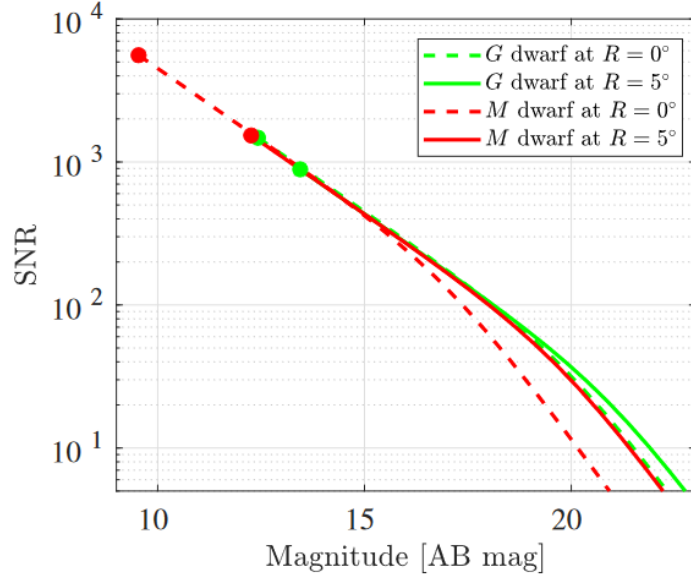


Figure 5.6: ULTRASAT estimated signal to noise ratio for M dwarf (red dwarf), G dwarf (yellow dwarf) light sources at various radial inclinations: 0° and 5° . The dots mark the saturation limit for each curve. Figure obtained from [109].

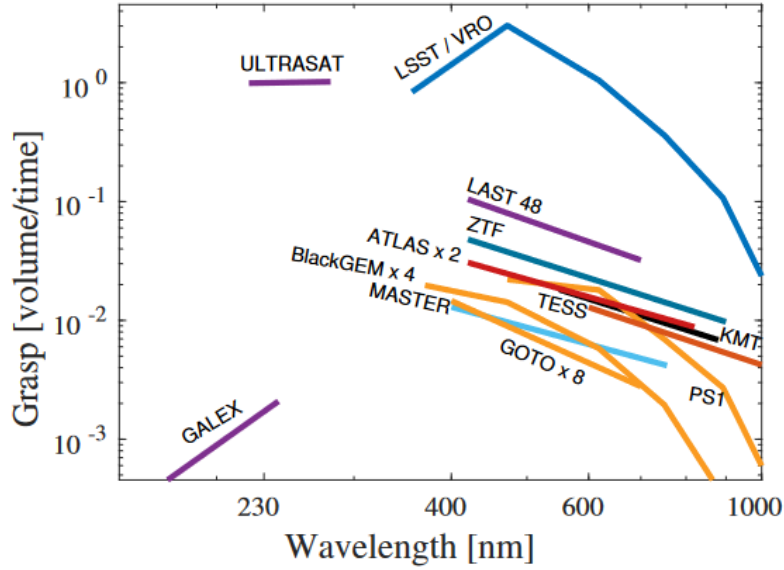


Figure 5.7: The grasp (volume accessible in unit time) accessible for previous, future and current space missions with sensitivities in various wavelength ranges (VRO/LSST [117]; LAST [118]; ZTF [119]; ATLAS [120]; Pan-STARRS [121]; KMTNet [122]; TESS [123]; Black-GEM [124]; MASTER [125]; GOTO [126]; GALEX [127]). Figure obtained from [109].

5.2.2 ULTRASAT science goals

ULTRASAT will be able to detect transient events in a large volume of space. The primary science objectives are: early detection of Gravitational Wave (GW) sources, characterizing the death of massive stars, advancements in cosmology, investigation of the generation mechanism of Gamma Ray Bursts (GRB), investigation of stars and stellar remnants, exoplanet studies, Tidal Disruption Events (TDE), Active Galactic Nuclei and general galaxy studies.

As most GW sources are initially hot, it is expected for them to have a NUV EM counterpart that can be used for the early detection of these events. The ULTRASAT telescope will send alerts to several dedicated GW detectors with coordinates to the event position. The detection of the NUV spectral band additionally presents information on the abundance of elements ejected during these events. The fast detection of a Supernova will also lead to a deeper understanding of the properties of the star and its explosion.

A complete overview of ULTRASAT's science goals is presented in Reference [109]. A review of all the expected measurements of the ULTRASAT mission was compiled and can be seen in Table 5.2.

Table 5.2: ULTRASAT Science highlights. Table was made based on the estimation of Reference [109].

Source Type	# Events per 3 yr mission
Supernovae(SNe)	
Shock break-out of core collapse SNe	>40
Early (shock cooling) of core collapse SNe	>500
Superluminous SNe	>250
Type Ia SNe	>1000
Compact Object Transients	
Emission from Gravitation Wave events	~25
Tidal disruption events	>300 (high-cadence)
	>4500 (low-cadence)
Quasars and Active Galactic Nuclei (AGN)	
Continuous UV lightcurves	>7500
AGN-related flares and transients	>100
Stars and Exoplanets	
Active and flaring stars	$>4 \times 10^5$
White dwarfs	$>3 \times 10^4$
RR Lyrae	>1000
Nonradial hot pulsators	>250
Eclipsing binaries	>400
Galaxies and Clusters	
All Sky Survey - galaxies	$>10^8$
Gamma Ray Bursts (GRB)	
GRBs occuring in-field	~30
Orphan Afterglows	>30
Solar System	
Asteroids and other small bodies	$>10^4$

5.3 The ULTRASAT sensor

In order to cope with the ULTRASAT mission sensitivity requirements highlighted in Section 5.1, the sensor design has been chosen to comply with the following specifications:

- **Quantum efficiency** $>60\%$ in the 220 – 290 nm wavelength band.
- **Dark current** $<0.026 \text{ e}^-/\text{pix/s}$ at the operational temperature of 200 K.
- **High Dynamic Range (HDR)** achieved via a dual gain design with a low gain ($7.4 \text{ } \mu\text{V/e}$ conversion gain and 140 – 155 Ke full well capacity) and high gain measurement ($80 \text{ } \mu\text{V/e}$ conversion gain and 16 – 21 Ke full well capacity).
- **Electronic cross-talk** $<0.01\%$.
- **Photo Response Non-Uniformity (PRNU)** of 3 – 5%.
- **TID** radiation hardness up to 100 krad
- **SEL** immunity up to $60 \text{ MeVcm}^2/\text{mg}$

The sensor has been fabricated by Tower Semiconductor in the 180 nm feature size, aluminium backend, 3.3 V CMOS Imaging process, employing 8 inch wafers. The active thickness of the sensor consists of $\sim 4 \text{ } \mu\text{m}$ thick epitaxial silicon, with an additional $\sim 700 \text{ } \mu\text{m}$ of low resistivity silicon for mechanical stability. The total die dimension is $47.135 \times 50.080 \text{ mm}^2$ with an active area of $45 \times 45 \text{ mm}^2$ implemented with a 4738×4738 pixel array. Each pixel is a square $9.5 \times 9.5 \text{ } \mu\text{m}^2$, with most of the area filled by the PPD implant, leading to a large fill factor. Due to the fixed mask size employed in the processing of the sensor, stitching of several blocks has been employed to reach the large sensor area required by the ULTRASAT mission. The stitching diagram of the ULTRASAT sensor can be seen in Figure 5.8 and highlights the following functional blocks:

- A, B, C, F, I - Seal rings and well closures
- D - Row decoders
- E - Pixel array
- G - The digital control block and Input/Output (I/O) pads
- H - Analog to Digital Converter blocks and I/O pads

The wafers are post-processed with a Back Side Illumination (BSI) process (see Section 3.3.5) that insures a large quantum efficiency in the operational waveband. A further increase in quantum efficiency has been achieved through the careful optimization of several dielectric layers on top of the pixel array, called Anti Reflective Coating (ARC) described in detail in Reference [114]. In the same study, an important infra-red stray light source has been found to originate from the sensor's peripheral circuitry. This has led to the implementation of a post processing trench isolation between the pixel array and the peripheral circuitry.

The architecture of the ULTRASAT sensor can be seen in Figure 5.9. The main functional components of the sensor are: the pixel array, the row decoder, the readout block containing the analog to digital converters, multiplexers, logic encoders and LVDS output buffers and the programmable controller unit.



Figure 5.8: The ULTRASAT stitching diagram for a front side illuminated sensor. The backside illuminated equivalent diagram is mirrored.

5.3.1 The ULTRASAT sensor pixel array

The pixel design closely follows the 4T CIS design described in Section 3.3.3. In order to extend the dynamic range of the ULTRASAT sensor, an additional low-gain capacitor and a switching transistor (SEN) have been introduced, leading to the so-called 4T dual-gain pixel design. A schematic of the ULTRASAT front-end design is shown in Figure 5.10.

The pixel front end is powered via six metal lines that control the voltages applied to the pixel active elements. The operational values of the front end voltages are given in Table 5.3. The Transfer Gate (TX) is split into two separate lines for even and odd columns. This allows the simultaneous transfer of low and high gain data. The optimization of the voltages is an ongoing effort for both the electrical and optical testing of the sensor and the final operational bias values are expected to change for its in-flight configuration.

Table 5.3: Current ULTRASAT front end nominal voltage supplies.

Pixel supply	Low level [V]	High level [V]	Explanation
RST	0	3.8	“ON”/“OFF” values for the RST transistor
SEL	0	3.8	“ON”/“OFF” values for the SEL transistor
SEN	0	3.8	“ON”/“OFF” values for the SEN transistor
TX1	0	3.3	“ON”/“OFF” values for the Transfer Gate (TX) transistor of odd columns
TX2	0	3.3	“ON”/“OFF” values for the Transfer Gate (TX) transistor of even columns
VDD_SF	N.A.	3.3	Source Follower voltage
VDD_RST	0	3	Reset reference voltage

The sensor’s integration time can be varied between 10 – 600 s, with a nominal value of 300 s. The pixel readout concept can be visualized in Figure 5.11. The pixel operation can be

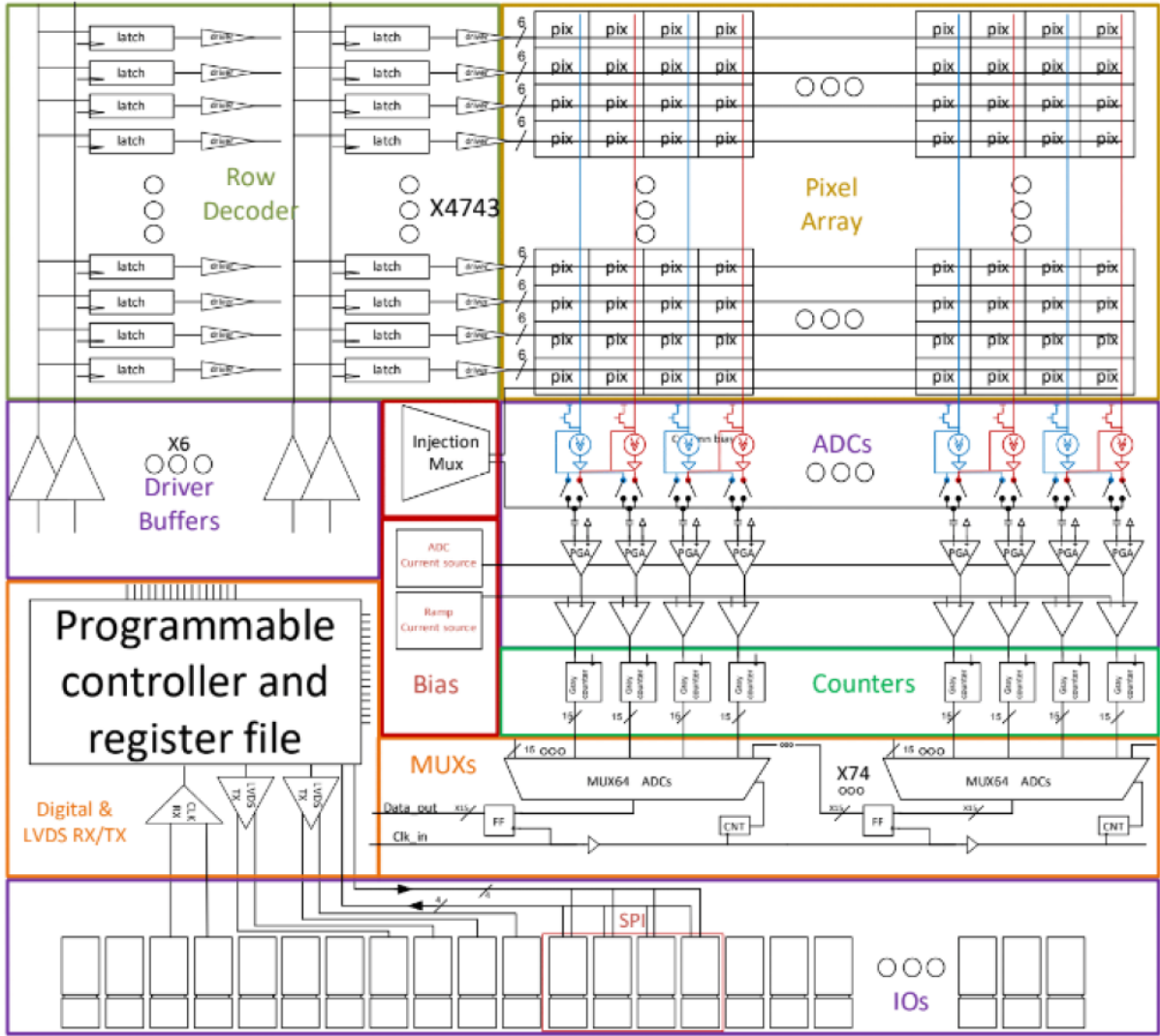


Figure 5.9: ULTRASAT sensor architecture.

divided into three modes: charge integration (defined by the integration time), pixel readout (~ 0.35 ms) and pixel reset (~ 1 ms).

Prior to charge integration, a reset step of the photo-diode and the floating diffusion is performed. This is achieved by setting high the TX, SEL and RST voltage lines. This ensures the return of the photo diode voltage to the reference VDD RST value. After the reset time of ~ 1 ms, the SEL line can be set to low in order to limit the electronic noise and the TX is set to low to decouple the photo diode from the reset voltage. As described in Section 3.3.3, the accumulation of photo-charge leads to a change in the photo diode voltage that is proportional to the accumulated charge. In order to read out a pixel, the SEL is set to high. The Reset Transistor voltage line is kept high in order to perform the Correlated Double Sampling (CDS) measurements right before the charge sampling. This operation is known as a “true” CDS procedure. Before the end of the integration time, the low gain (LG) reset sample is performed. This is followed by turning the SEN line low, isolating the low gain capacitor and performing a high gain (HG) reset sampling. After the integration window ends, the TX is pulsed in order

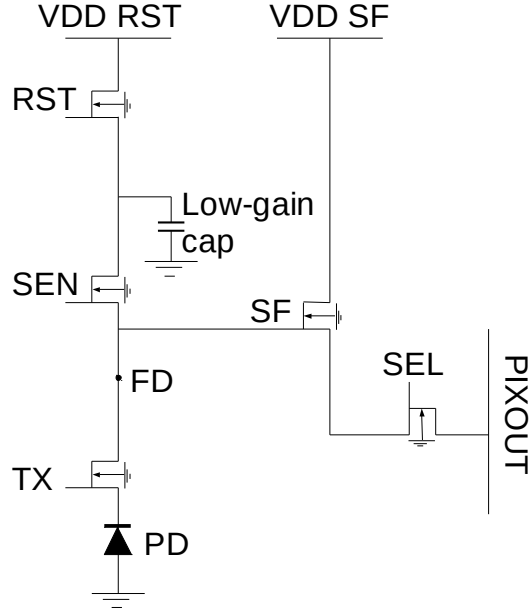


Figure 5.10: The ULTRASAT pixel front end, featuring a 4T dual-gain design.

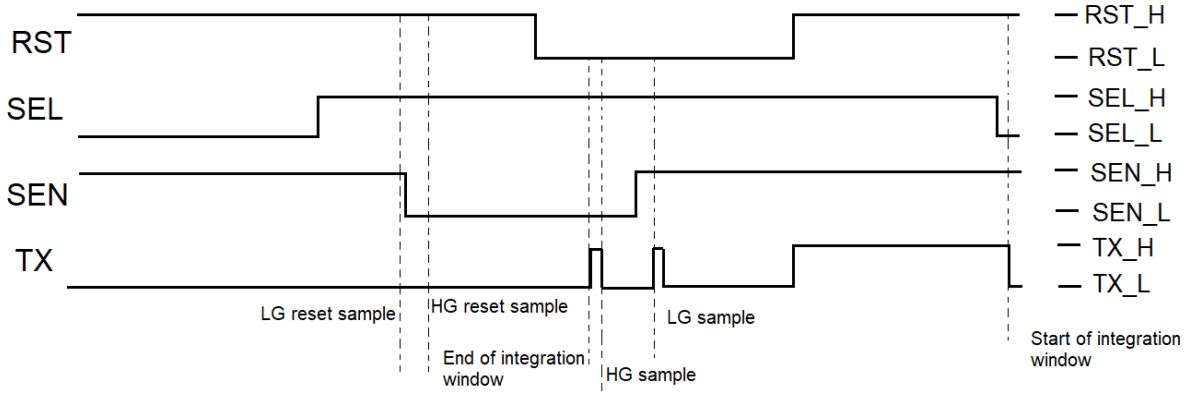


Figure 5.11: Timing diagram of the ULTRASAT sensor's readout scheme.

to acquire a high gain charge sample. By setting the SEN transistor to high, the TG is pulsed again and the low gain sample is taken. This is followed by the initial reset phase leading to the cyclical performance of the front end.

For each pixel, four samplings are performed: one sampling of the reference reset value and a sampling of the charge value for the low and high gain. The true CDS procedure significantly diminishes the kTC and Fixed Pattern Noise (FPN). The two corrected analog values for the low and high gain are then sent to the analog to digital converters for digitization.

5.3.2 The ULTRASAT periphery

The row decoder is a logic block that decodes the row address generated by the digital block and drives the pixel voltage lines. Both the row decoders and the analog to digital converters

are powered via a separate analog power rail (VDDA).

The readout block connects each pixel array column to a 14 bit analog to digital converter that digitizes the two analog signals from the pixel. The digitized data is sent to a FIFO (First in First out register) and encoded into two 10 bit words, one for each gain mode. The serialized data is then piped through two LVDS lines to the remote electronics.

The programmable controller is a fully digital block responsible for setting the sensor configuration (e.g. integration time) and is powered by a separate digital power rail (VDDD). The commands are sent to the digital block via a Serial Peripheral Interface port.

5.4 ULTRASAT radiation shielding

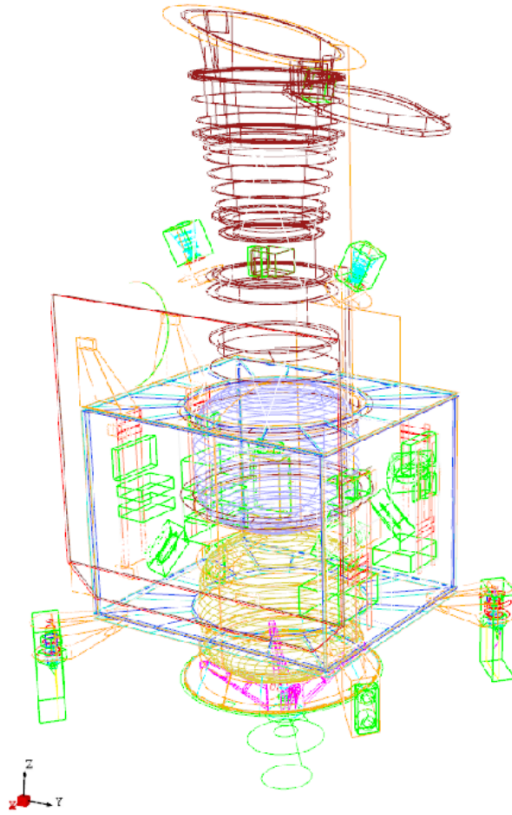


Figure 5.12: Wire frame diagram of the ULTRASAT spacecraft using the 2021 satellite assumptions. The model was used by IAI for simulating the ULTRASAT shielding.

Figure 5.12 shows the satellite elements considered in the simulation of the total shielding of the camera. This shielding simulation has been performed by one of the project partners, IAI in February 2021 and is part of an internal study of the ULTRASAT mission. In this simulation, a simplified geometrical model of the ULTRASAT structure and its subsystems was built in accordance with the understood mechanical model at that time. While some revision of this model took place, no major payload redesigns occurred, such that the accuracy of the calculated radiation shielding is not impacted. In this simulation, the units have an aluminum equivalent thickness correlated to their mass and density. The tanks (Fuel tank, Oxidizer tank

and Helium tank) are modeled according to their shapes and masses with equivalent aluminum wall thickness. The tanks are taken as empty (dry).

The computed shielding of the camera in 6 directions is given in Table 5.4. The shielding thickness in the vertical plane ($\pm Z$) is significantly larger than in the horizontal plane ($\pm X, Y$). As was highlighted in Section 4.1.2, the particle flux components in the GEO orbit are expected to be isotropic, with the exception of the solar particle flux. Due to the limited pointing space of the ULTRASAT mission, the solar particle flux will mostly travel through the horizontal plane of the telescope. This leads to a good approximation of the shielding of the ULTRASAT mission to the effective value of 5.05 mm for all un-isotropic flux components. Nonetheless, in the following sections, the radiation damage estimation includes effective shielding variations in order to highlight the possible impact of additional shielding or the impact of unexpected un-isotropies in the in-orbit radiation flux.

Table 5.4: Equivalent Aluminum shielding of the detector assembly in the ULTRASAT spacecraft. The equivalent shielding in the 6 Cartesian coordinates is given. Additionally, the equivalent spherical shielding is derived via a ray tracing algorithm employed by IAI with the help of the Systema 4.9 software with the DOSRAD solver.

+X [mm]	+Y [mm]	+Z [mm]	-X [mm]	-Y [mm]	-Z [mm]	Total equivalent thickness [mm]
3.94	3.68	34.95	3.43	3.72	19.86	5.05

5.5 ULTRASAT mission radiation environment

Section 4.1.2 showcased the main radiation sources expected in Earth’s orbit. As the different contributions coming from Galactic Cosmic Rays (GCR), trapped particles and solar particles vary with several mission parameters: the orbit, the mission shielding and the mission timing, a detailed simulation of the different particle contents has been performed for the ULTRASAT mission. In this purpose, both the SPENVIS [128] and the CREME96 [129] simulation tools have been employed.

5.5.1 ULTRASAT orbit

The ULTRASAT GEO orbit has been simulated using the default parameters of the SPENVIS program [128]. The values of these parameters are included in Appendix C. Figure 5.13 shows the evolution of the orbital parameters in time, for a 24 h orbit period. The change in altitude showcases the slightly elliptical orbit expected at GEO orbit. As expected, the latitude and longitude parameters are constant for a synchronous orbit.

5.5.2 ULTRASAT simulated particle flux

The particle flux for GCRs, solar particles and trapped proton flux depending on the solar cycle have been simulated. The shielding transport simulation has been performed using the model designed by BIRA-IASB [128]. The SPENVIS framework has been used to generate the predicted particle fluxes during the space mission operation, using the following models for the flux simulation:

- GCR: CREME-96 Sol. Min (1977)
- Solar particles: ESP-PSYCHIC (H-U)
- Traped proton flux: AP-8 MIN; trapped electron flux: AE-8 MIN

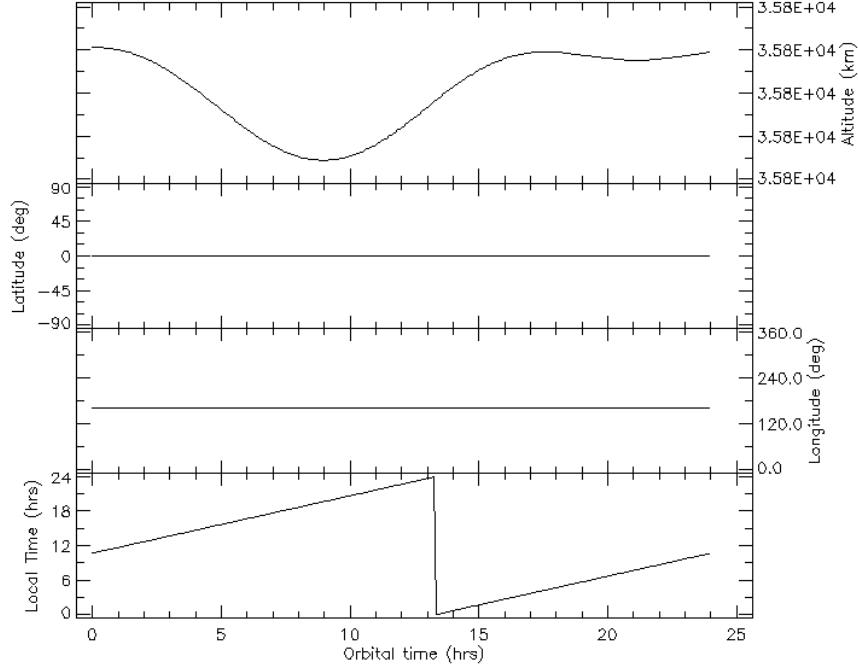


Figure 5.13: The ULTRASAT simulated GEO orbit parameters. The plot was created with the help of the SPENVIS program [128].

The chosen models for the trapped and solar particle fluxes account for the 11-year solar cycles by considering a mix of the solar minimum and solar maximum states across the mission lifetime. The mix of solar states for future mission times can be made with the help of prediction tools that extrapolate the increase/decrease in solar activity (in terms of number of sun spots) based on the data recorded for previous years. Figure 5.14 shows the results achieved with such a tool. The grey contour represents the expected number of sun spots in the next 11 years. In contrast, the GCR model used contains only the solar minimum component of the flux, providing a worst case flux estimation. This is anyway expected to provide accurate results due to the minimal shielding effect of the heliosphere for highly energetic particles.

The galactic cosmic ray: CREME-96 Solar Minimum model

The CREME-96 model is based on data collected by satellites between 1986 and 1987, corresponding to a solar minimum period. As the GCR particle flux is inversely modulated by the heliosphere magnetic field, this period matches a GCR maximum and serves as a realistic worst case scenario of GCR flux contribution for a space mission. As the GCR flux is additionally modulated by the Earth magnetosphere, the respective particle propagation needs to be taken into account. This is achieved by the model developed by 1992 Nimik et al. [131] that gives a

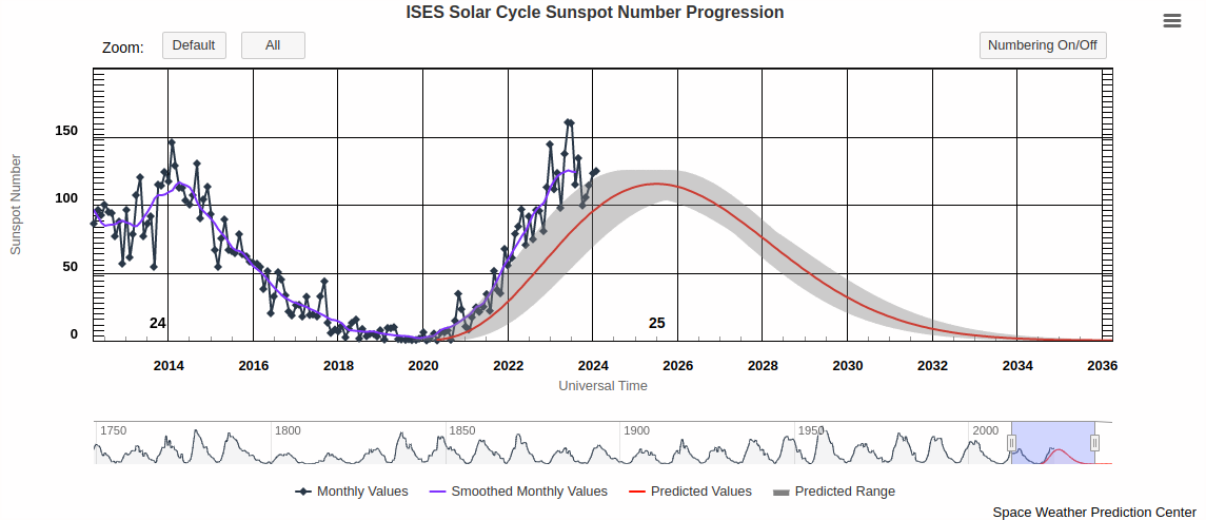


Figure 5.14: The observed and predicted Solar Cycle, depicted in terms of the number of sunspots from [130]. The black line represents the monthly averaged data and the purple line represents a 13-month weighted, smoothed version of the monthly averaged data. The mean forecast for the current solar cycle (Cycle 25) is given by the red line. This is based on the results of an international panel convened in 2019. In February, 2023 the plot was modified to show the full range of the 2019 Panel prediction as the gray shaded region. This takes into account expected uncertainties in the cycle start time and amplitude. The picture was obtained as a screen capture from the website of Reference [130].

parametric expression of this modulation dependent on the number of sun spots. This effect is included in the simulation.

Several other models can be used to represent the expected contributions of the GCR flux. A comparison of the CREME96 model and several others available in the SPENVIS framework: CREME86, ISO15390 and Nimmik 1996 is presented in Figure 5.15 in terms of the predicted proton flux.

The differences in the low energy proton fluxes between the different models appear due to the inclusion or exclusion of the anomalous cosmic ray fluxes, which is due to neutral atoms getting ionized and subsequently accelerated after their interactions with the heliosphere. The CREME96 and the Nimmik 1996 include this component. Other differences between the models are caused by small variations in the parametrization of the particle propagation through the heliosphere. The CREME86 model uses a cruder sinusoidal modulation of the solar cycle which leads to less accurate results. The CREME96 model was chosen in this study in order to maintain result compatibility with the CREME [128] online simulation tool.

The solar particle ESP-PSYCHIC model

One model that gives accurate estimations for both the proton and heavy ion solar fluxes is the ESP-PSYCHIC model. It is based on the measurements of three cycles of the sun: cycle 20-22. The inclusion of the data from all three cycles is very important due to the large variance between them [132], insuring an increased accuracy of the simulation. The solar electron flux was found to not propagate through the spacecraft radiation shielding and thus is considered to not contribute to the total particle flux on the detector assembly.

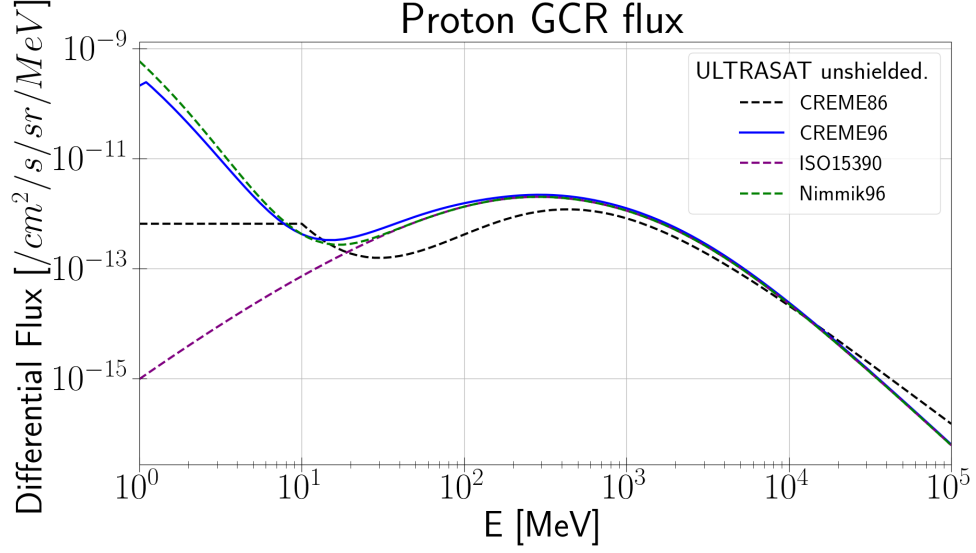


Figure 5.15: The simulated proton flux outside the ULTRASAT mission (no radiation shield) for several GCR models: CREME86 (dashed black line), CREME96 (solid blue line), ISO15390 (dashed purple line) and Nimmik 1996 (dashed green line).

The AP-8 and AE-8 models

The AP-8 and AE-8 models describe the trapped proton and electron content for a specific orbit. The model relies on the measurements performed by several space missions and the orbit dependent fluxes are highlighted in Figure 4.2.

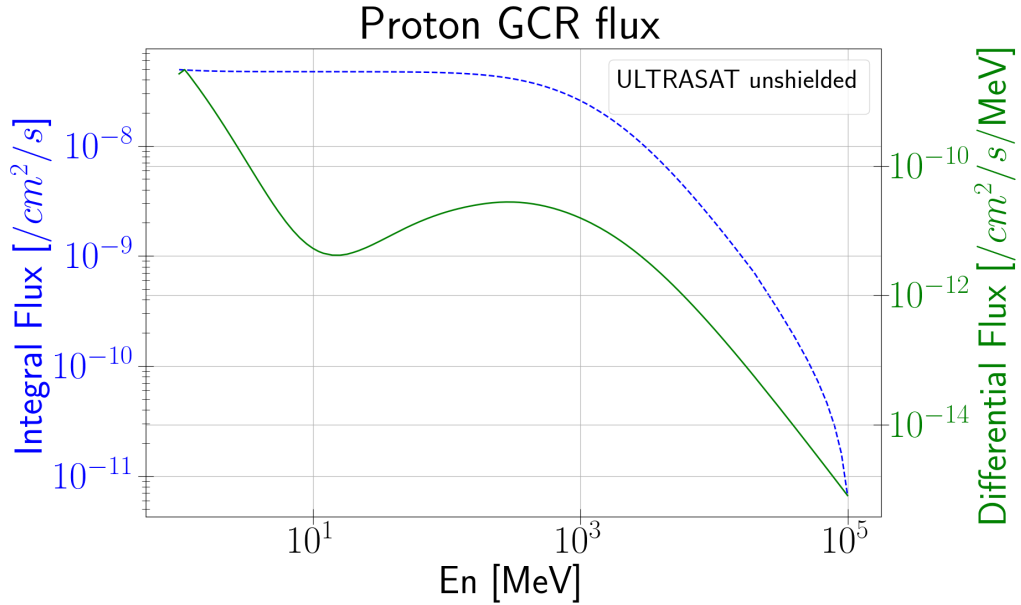


Figure 5.16: The simulated galactic cosmic ray proton flux outside the ULTRASAT mission (no radiation shielding) for the CREME96 model. Both the differential (green) and integrated (blue) fluxes are represented in terms of the proton energy.

Simulation results

A useful quantity for the representation of the particle flux is the integral particle flux, defined as the number of particles with an energy above a defined value. In Figure 5.16, the integral and differential fluxes are plotted for the GCR simulated proton flux.

The contribution of both protons and heavy ions to the total GCR particle flux is highlighted in Figure 5.17 in terms of their linear energy transfer. In the following discussion, the integral LET spectrum will be preferentially used.

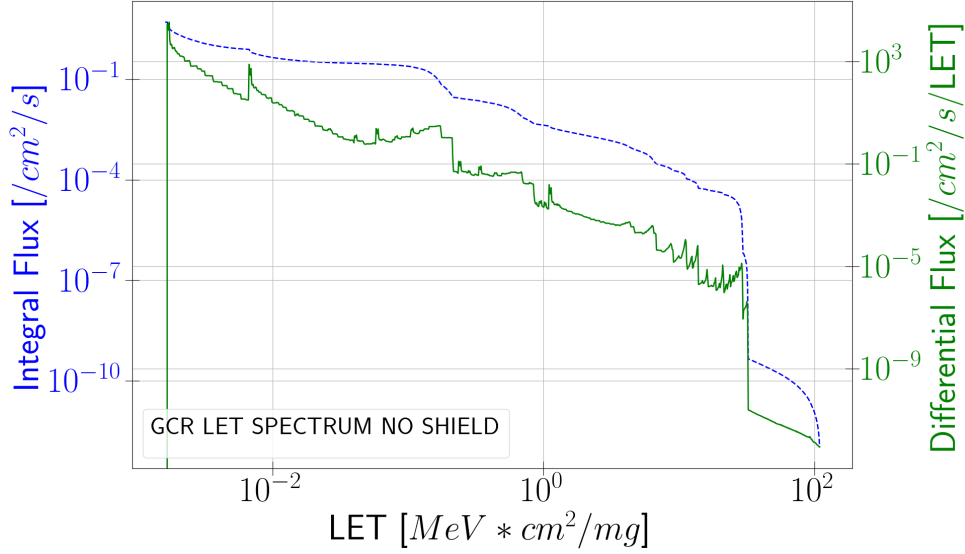


Figure 5.17: The simulated cumulative proton and heavy ion flux outside the ULTRASAT mission (no radiation shielding) for the CREME96 model. Both the differential (green) and integrated (blue) fluxes are represented in terms of the particle LET.

The cumulative effect of all three radiation components expected in the GEO orbit: GCR, trapped protons and electrons and solar particles is plotted in terms of their LET in Figure 5.18. The simulation highlights that at low LETs the trapped proton flux dominates, while at higher LETs the solar particle flux is the most important component.

The simulation of the particle transport through different shield thicknesses is shown in Figure 5.19. This highlights that even a small amount of shielding leads to a significantly diminished particle flux. This effect is associated to a significant low energy component of the particle flux that gets completely absorbed in the ULTRASAT mission shielding. Indeed, further increase of the shielding has a diminishing effect on the particle attenuation due to several competing effects: the shielding diminishes an incident particle's energy via non-elastic nuclear scattering and Coulomb scattering, leading to the complete capture of some particles, but also to the LET enhancement of other particles (e.g. Figure 4.11). This effect can be clearly seen in Figure 5.19 via the crossing of the 5 mm and 35 mm effective shielding lines at high LET ($\sim 20 \text{ MeV cm}^2/\text{mg}$).

Considering the effective shielding of the ULTRASAT mission (5.05 mm), the contribution of the various particle fluxes is plotted in Figure 5.20. The contribution of the solar particles is significantly diminished by the radiation shield, leading to no significant contribution to the total flux. At low LETs, the solar particle flux dominates the integral flux, while at large LETs, the GCR and solar particle contributions are similar, mainly due to the limited amount of heavy

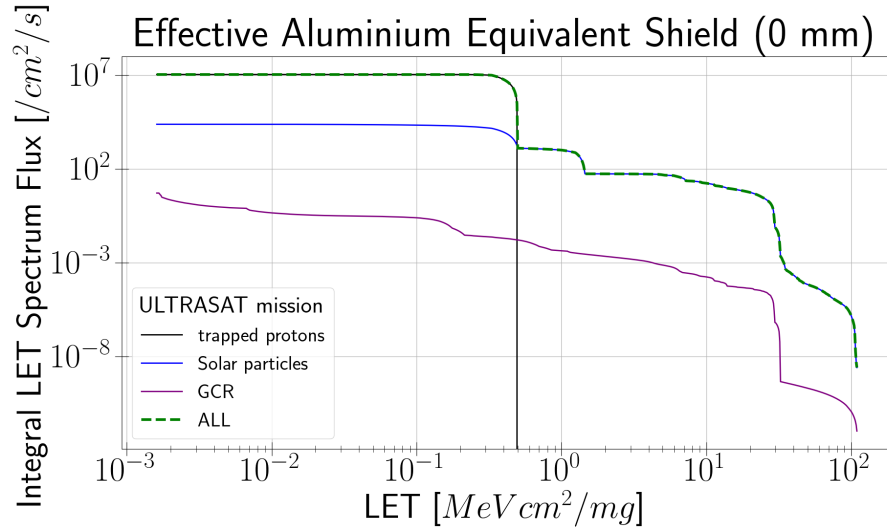


Figure 5.18: The simulated LET particle flux outside the ULTRASAT mission (no radiation shielding) for the three particle sources expected in GEO orbit: trapped particles (black line), solar particles (blue line), GCR (purple line) and their cumulative contribution (green dashed line).

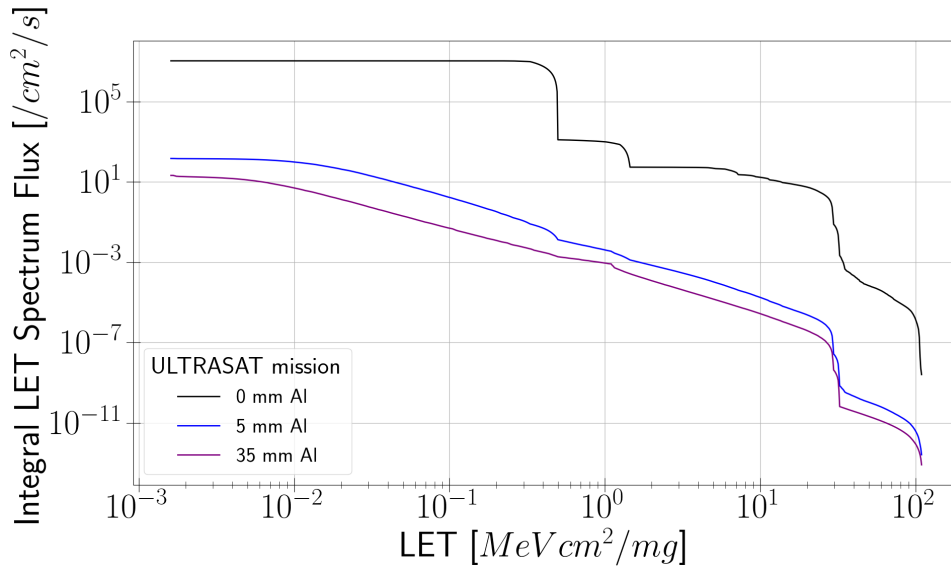


Figure 5.19: Integral total flux (GCR, solar particles and trapped particles) in GEO orbit versus LET for multiple shielding configurations: no shielding black line (0 mm); ULTRASAT effective shielding blue line (~ 5 mm) and maximum ULTRASAT shielding along the z axis, purple line (35 mm).

ions in both fluxes. The integral flux highlights that a highly diminished large LET component is expected ($<10^{-2}$ part/cm²/s), especially for particles with LETs larger than 1 MeV cm²/mg.

Using the integral flux simulation and their propagation through the ULTRASAT spacecraft shielding, a simulation of the expected cumulative surface and bulk damage has been performed using the SHIELDDOSE-2 and the JPL Si [128] models respectively. Both models are applicable for simple geometries: finite slab or spherical shielding for a homogeneous material. The SHIELDDOSE-2 is based on the Monte Carlo ETRAN code described in detail in Reference

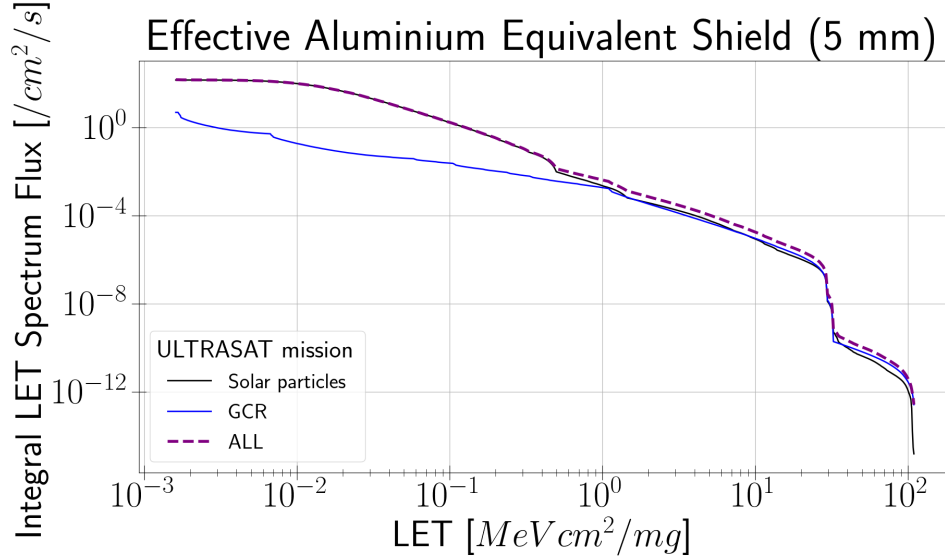


Figure 5.20: Integral flux in GEO orbit versus LET for the ULTRASAT effective shielding (5.05 mm). Multiple components to the total flux are drawn: solar particles (black line); GCR (blue line) and total flux (purple dashed line).

[133] and considers the electron energy loss via inelastic scattering and bremsstrahlung, angular deflections of electrons due to multiple scattering by atomic electrons, penetration, diffusion of secondary bremsstrahlung photons and delta ray electrons and coulomb scattering of impinging protons. The simulation takes into account only the electron and proton fluxes, due to the small contribution from the heavy ion flux to the cumulative ionizing damage. The main contributions of the particle fluxes and their simulated interactions with the spacecraft materials is highlighted in Figure 5.21. For effective shielding values < 5 mm, the trapped electron flux is dominant, while at larger shielding values, the total ionizing effect is mostly caused by both bremsstrahlung and solar protons.

These simplified models are appropriate for use in the ULTRASAT mission, thanks to the good understanding of the equivalent shielding of the detector assembly highlighted in Table 5.4. For this purpose, two techniques have been employed for simulating the expected accumulation of ionizing damage during the maximum 6 years operation time of the ULTRASAT mission. The first approach used was the transport of the respective flux through each of the six Cartesian coordinates relative to the detector assembly via the finite slab technique, which assumes a one directional particle distribution through a fixed thickness of a homogeneous material (aluminium). The second approach used was the transport of the particle flux through a spherical effective shielding. Both simulation techniques and the predicted dose in krad for various mission lifetimes is highlighted in Figure 5.22. A match within 20% between the two methods is achieved. The plot highlights that a dose of ~ 20 krad is expected to be accumulated after the 3 years of ULTRASAT in-orbit operation and a dose of ~ 50 krad is expected to be accumulated after 6 years.

The estimation for the cumulative displacement damage incurred during a mission time of 3 years has been performed by considering the particle transport through the effective spherical shielding of the spacecraft and the results have been related to the NIEL damage dose curves by JPL Si. Similarly to the ionizing damage estimation, only the proton flux has been considered

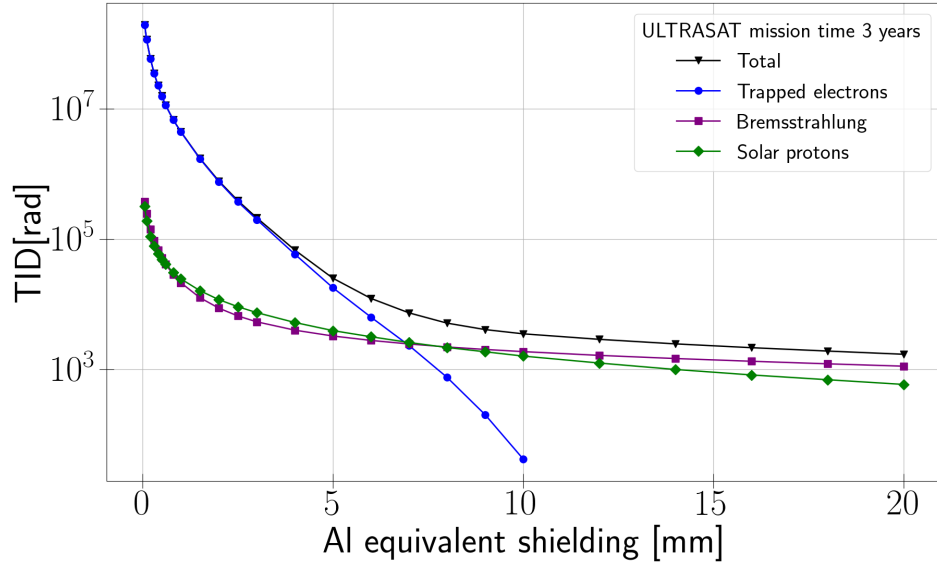


Figure 5.21: Total ionizing dose depth curve for the ULTRASAT mission. The main particle interactions leading to ionizing effects in the silicon oxide are shown for several aluminium equivalent spherical shielding values. The main contributions to the total accumulated ionizing dose are considered to be the trapped electrons (blue line and circles) and their bremsstrahlung resulting from the interactions with the spacecraft (purple line and squares) and solar protons (green line and rhombus). The total value is highlighted with black line and triangles.

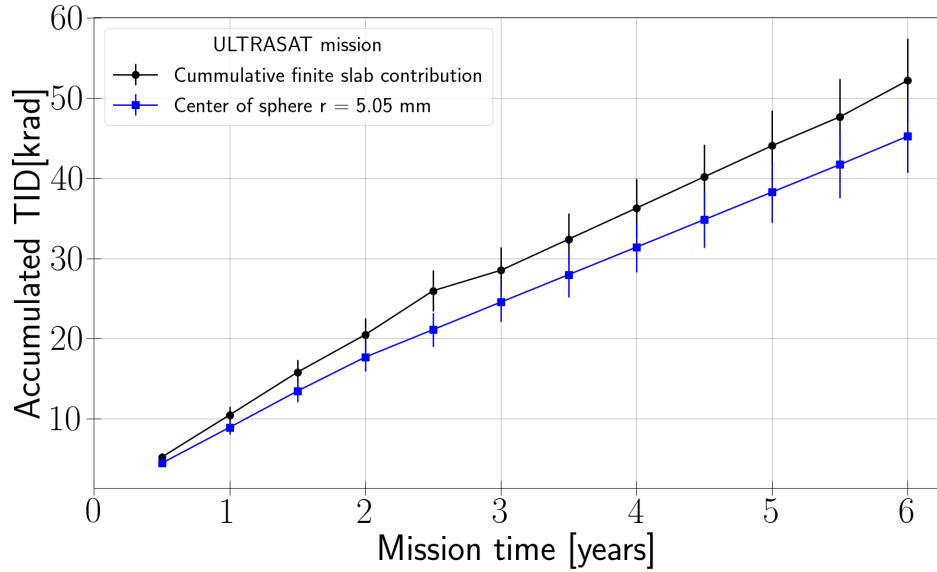


Figure 5.22: Accumulated TID for two shielding simulation techniques: the finite slab (black line and circles) and effective spherical shielding (blue line and squares) for several mission times, up to the maximum of 6 years. The finite slab technique was simulated with the help of a Monte Carlo code which assumes a directional particle flux through a slab of defined thickness for each Cartesian coordinate. The effective spherical technique is based on similar Monte Carlo code, which assumes an isotropic particle flux transported through a homogeneous spherical shielding defined by a radius r , called the effective shielding. The estimation assumes the spacecraft launch in early 2027 (1st of January 2027).

to meaningfully contribute to the accumulation of displacement damage (the electron flux can be ignored in this simulation due to the small displacement cross-section and the heavy ion flux can be ignored due to the small flux contribution). For comparison value with other radiation damage studies, the NIEL dose curve has been converted from the usual 10 MeV proton damage equivalent adapted by the JPL Si model, to 1 MeV neutron damage equivalent using the Summer and Huhtinen [134], [135] damage curves from Figure 4.8. The NIEL damage depth dose curve for the ULTRASAT mission after 3 years is presented in Figure 5.23. The trapped proton flux is completely absorbed at shield thicknesses <0.5 mm and thus only the solar proton flux contributes to the total displacement damage dose. For the spherical aluminium equivalent shielding of the detector assembly in the spacecraft, a dose of $\sim 10^{10}$ 1 MeV neutron equivalent / cm^2 is expected. This can be further correlated to the damage factor $g(\text{Si}) = 10^{-11}$ [136], (following the NIEL hypothesis, see Sec. 4.3.2) such that the equivalent damage expected in terms of Charge Transfer Efficiency (ΔCTE) is:

$$\Delta\text{CTE} = g(\text{Si}) \int_0^\infty \text{NIEL}(E) \frac{d\Phi(E)}{dE} dE \quad (5.1)$$

where $\text{NIEL}(E)$ is the non-ionizing energy loss equivalent of a particle species at a certain energy, $\Phi(E)$ is the energy dependent particle flux and E is the particle energy.

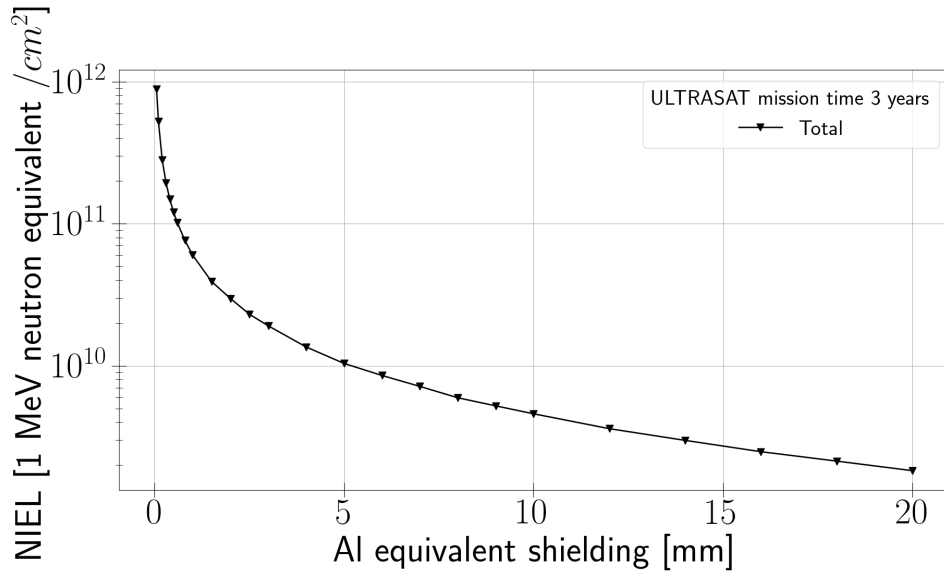


Figure 5.23: The displacement damage dose curve due to NIEL interactions in the ULTRASAT sensor after 3 years in GEO orbit for several spacecraft shielding values. The estimation assumes the spacecraft launch on 1st of January 2027.

Figure 5.24 shows the expected degradation of the ULTRASAT sensor charge transfer efficiency (CTE) after several years in GEO orbit. The showcased plateau is correlated to the diminished solar proton flux after ~ 2 years of mission time, due to the sun entering its minimum emission cycle (solar minimum). A degradation of at most 2% in charge transfer efficiency is expected due to displacement damage.

Additionally, the increase in dark current has also been observed to follow a linear relationship with accumulated dose and is given by the damage factor [137]:

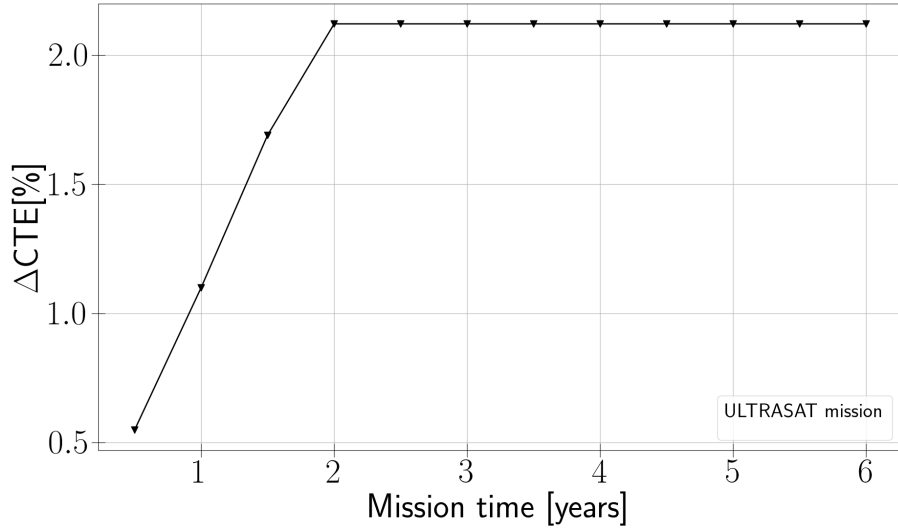


Figure 5.24: Relative expected degradation of the ULTRASAT sensor charge transfer efficiency (CTE) after several years of mission operation. The estimation assumes the spacecraft launch on 1st of January 2027.

$$K_{\text{dark}} = \Delta G / D_d \quad (5.2)$$

where ΔG is the radiation induced increase in electron-hole pairs dark generation and D_d is the displacement damage dose. Reference [138] has found for several silicon sensors, that $K_{\text{dark}} = (1.9 \pm 0.6 \times 10^5 \text{ carriers/cm}^3/\text{s}/(\text{MeV/g}))$. Integrating for the volume of the sensitive ULTRASAT pixel ($361 \mu\text{m}^3$), the dark current damage coefficient at 300 K becomes:

$$K_{\text{dark}}(300\text{K}) = 7.22 \times 10^{-5} \text{e}^-/\text{s}/(\text{MeV/g}) \quad (5.3)$$

Considering the bulk current generation rate dependence on temperature highlighted in Equation 4.7, the damage coefficient for a middle band charge generation center at the operational temperature of the ULTRASAT mission (200 K) becomes:

$$K_{\text{dark}}(200\text{K}) = 5 \times 10^{-10} \text{e}^-/\text{s}/(\text{MeV/g}) \quad (5.4)$$

The increase in dark current at the ULTRASAT operational temperature for several years in orbit is shown in Figure 5.25. Due to the same assumption of linear dependence to the accumulated dose (as in the case of the charge transfer efficiency degradation), the same data trend is observed. The dark current estimation includes only the displacement damage component and is expected to be much higher when additionally considering ionizing effects. At most, a doubling effect on the dark current is expected at operational temperature due to the incurred displacement damage dose.

The abrupt plateau in both Figure 5.24 and 5.25 is due to limitations in the estimation of the solar proton flux. The ESP-PSYCHIC model considers a mix between solar minimum and solar

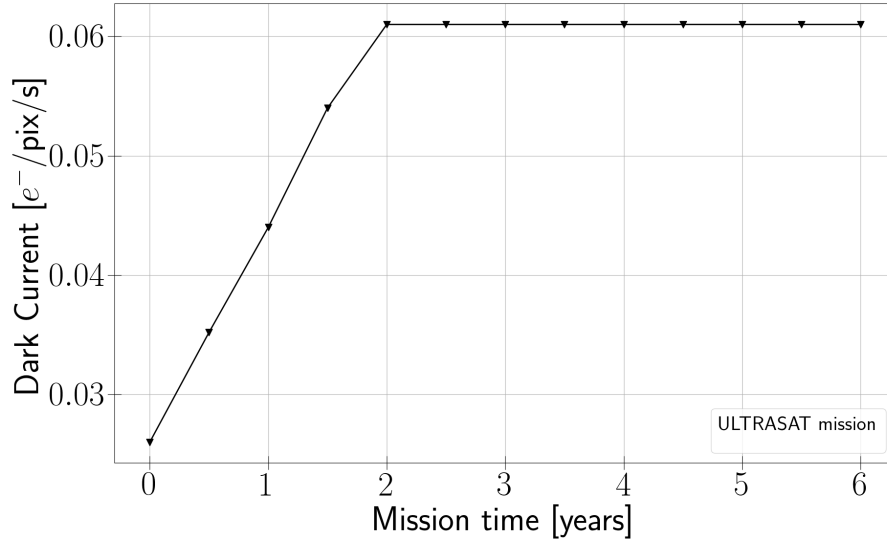


Figure 5.25: Dark current increase due to the displacement damage, excluding ionizing effects for several in-orbit years of the ULTRASAT mission.

maximum phases depending on the space mission timing in relation to the solar cycle. Figure 5.26 highlights this effect, showing that a delayed mission launch (~ 2029) would lead to no significant charge transfer efficiency or dark current degradation, due to the mission operating only during the solar minimum period.

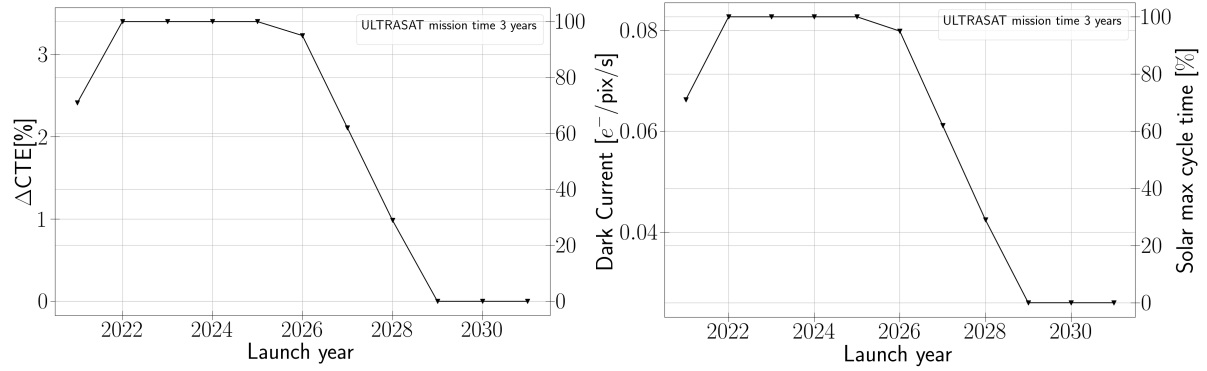


Figure 5.26: Relative charge transfer efficiency degradation (left) and dark current (right) for 3 years of mission time and several mission launch dates starting from 2021 to 2031. Additionally, the percentage of time in which the sun would be in its solar maximum phase during the mission time is highlighted on the right y axis.

It is expected that the TID induced damage will have a larger impact on the sensor dark current and noise. As a consequence, it has been prioritized to be tested as part of the radiation qualification of the ULTRASAT camera.

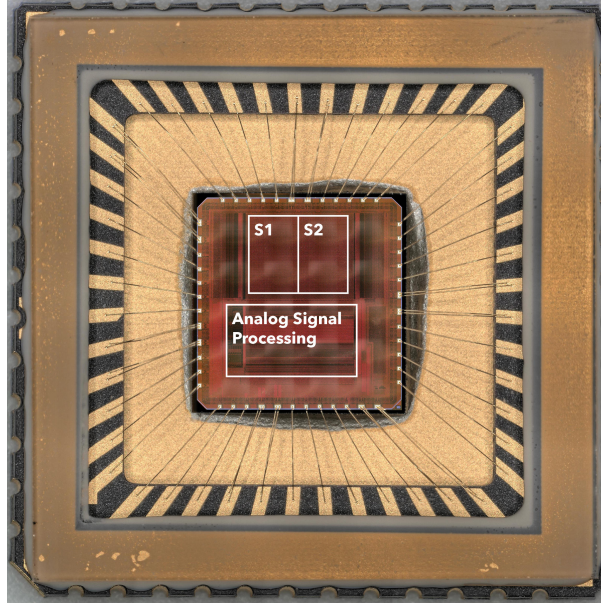


Figure 5.27: Tiled SCOUT sensor. Two arrays featuring different pixel geometries are identified: S1, the standard array (left) and S2, the in-pixel guard ring array (right). The picture was also used in Reference [114].

5.6 Ionizing damage study on pixel test structures

Due to the time intensive process of producing and tiling the ULTRASAT sensors, a preliminary ionizing damage study has been performed on pixel test structures provided by Tower Semiconductor. Their initial purpose has been the testing of several anti-reflective coatings for the final sensor design and to verify the pixel design for NUV measurements. Due to the similar pixel designs of the two sensors, the SCOUTs were also tested in order to perform a first order characterization of the ionizing damage hardness of the flight grade sensors. The test sensors are called SCOUTs and are offered by Tower with the full analog image acquisition on chip and analog output buffers for off-chip signal digitization. A read-out board has been designed with a sensor socket. This allows for the relatively fast testing of several samples. The tiled sensors are wire bonded and packaged as can be seen in Figure 5.27.

The pixel test structures employed in this study use the same 4T CMOS imaging sensor back side illumination process as the ULTRASAT sensors, but do not implement the additional dual gain readout. They feature a matrix of 640×480 pixels and a pitch of $4 \times 4 \mu\text{m}^2$. The array is divided in two parts, with two different pixel geometries: with and without an in-pixel guard ring as highlighted in Figure 5.27. As the ULTRASAT sensor will not contain an in-pixel guard ring, only one half of the test structure's matrix has been considered in this study.

While the pixel pitch and the analog pixel front end varies slightly between the SCOUTs and the ULTRASAT sensor, the oxide thickness, the backside processing and the implant and metal depositions are identical. Furthermore, the charge collection and integration is similar between the two sensors. This lends a good motivation to the performance of this preliminary study and is expected to have reference value to the ULTRASAT sensor. The main figures of merit investigated in this study are the dark current and the sensor read noise (see Section 4.2).

5.6.1 SCOUT Voltage Biasing

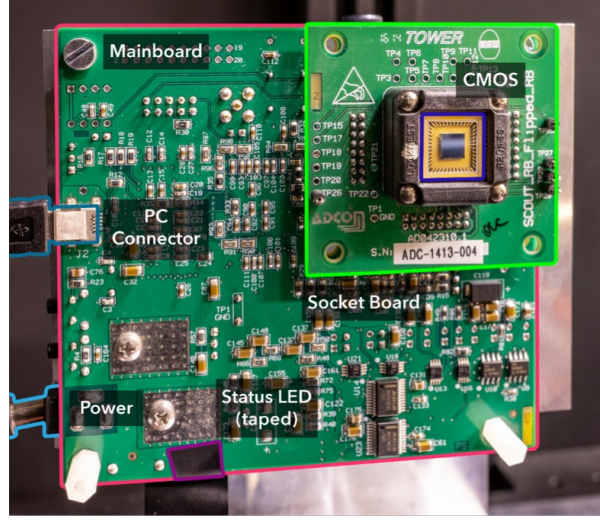


Figure 5.28: SCOUT readout, featuring a main board (highlighted with red) and a socket board (highlighted with green). The picture was also used in Reference [114]

The voltages applied to the analog, digital circuitry and the pixel front end have been tuned to minimize the sensor’s dark current. The voltage levels are controlled through the main-board as can be seen in Figure 5.28. The SCOUT voltage values are close the nominal values for the ULTRASAT sensor. During irradiation, in order to create the worst-case ionizing damage accumulation, the voltages have been set at the highest operational values as suggested by the MIL-STD-883 standard [139]. Both the nominal and worst case values are shown in Table 5.5 and will be further referenced in this Section as nominal and worst-case bias.

Table 5.5: SCOUT front end nominal and worst case voltage values.

Pixel Supply	Nominal value [V]	Worst value [V]	Explanation
V-REF	0.69	0.69	Analog Reference Value
VDD-A	3.6	3.6	Analog power
V-RST-L	0	0	“OFF” value for the RST transistor
V-RST-H	4	4.5	“ON” value for the RST transistor
V-TX-L	0	0	“OFF” value for the transfer gate transistor
V-TX-H	3.3	3.8	“ON” value for the transfer gate transistor
VDD-SF	3.3	3.8	Source Follower power
V-AD_offset	1.6	1.6	Offset for the post ADC signal processing

5.6.2 SCOUT experimental set-up

In order to achieve an accurate estimation of the dark current degradation, SCOUTs were characterized both before and after irradiation. All measurements have been performed at room temperature. This is an important limitation of the experiment, as the significantly larger room temperature (compared to the ULTRASAT operational temperature, 200 K) during the

irradiation and testing is expected to lead to some degree of annealing of the radiation damage. Only a conservative estimate can thus be made on the TID impact. In order to limit the magnitude of these effects, all samples have been measured (before and after irradiation) at the irradiation facility. Some longer measurements, as in the case of the Random Telegraph Signal study, have been performed after several weeks/months. The effect of the room temperature annealing of these samples was not found to be large.

A picture of the experimental set-up can be seen in Figure 5.29. In order to ensure the proper light insulation of the sensor for dark current measurements, a special aluminium box has been designed in order to house the daughter-board. A cut out in the box has been introduced above the sensor in order to reduce the radiation attenuation. A thin aluminium foil and a black tape is applied on the inside of the box's cutout. The box is further insulated with the help of several aluminium foil layers which minimize light leakage especially near the cable feed-through.

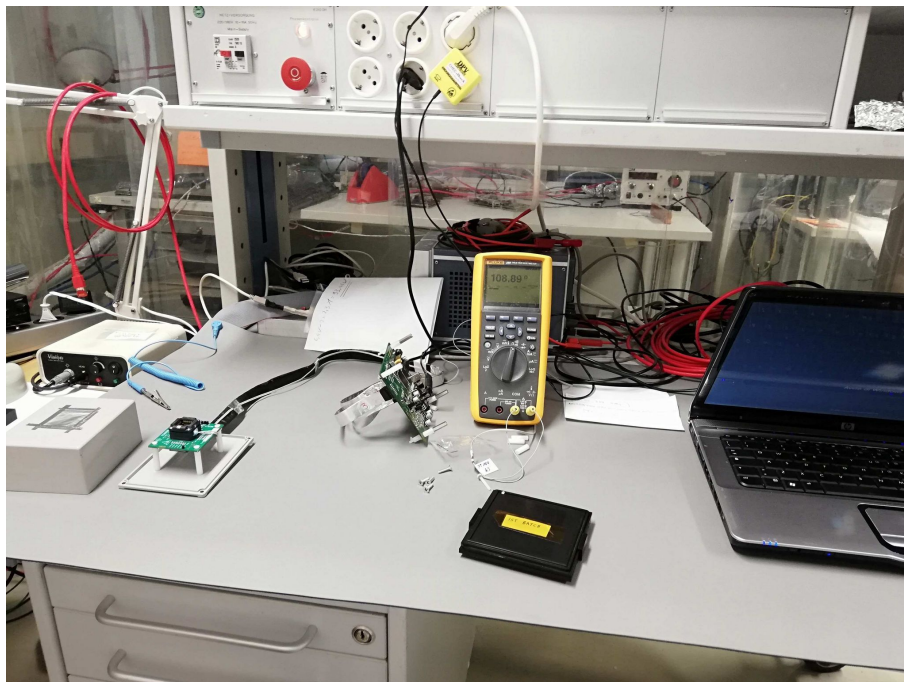


Figure 5.29: Picture of the SCOUT laboratory experimental set-up in a clean room environment at DESY. The aluminium box shielding of the daughter-board (from stray light) can be seen with the cover removed on the left side.

The mother-board contains several radiation sensitive active components that could be damaged by the exposure to radiation. A ~ 1 m shielded cable has been designed in order to separate the mother and daughter board. In the irradiation environment, the mother-board was appropriately shielded behind several lead/steel blocks. A PT100 temperature sensor has been installed on the daughter-board and the temperature has been remotely recorded via a FLUKE multi-meter.

5.6.3 Irradiation facilities

While the TID is proportional to an ionizing particle's energy, the particle species / quanta energy has an important impact on the irradiation source selection. For the SCOUT testing, a Co-60 gamma source has been chosen. The large quanta energy of radioactive Cobalt insures

a homogeneous energy deposition inside both the surface and deep ($\sim 4 \mu\text{m}$) oxides of the back side illuminated samples. Additionally, as can be seen in Figure 4.3 a fractional yield close to 1 can be obtained for this irradiation technique, leading to lower ionizing effect uncertainties. The Co-60 spectrum has two peaks at: 1.17 and 1.33 MeV, leading to absorption lengths much larger than the optically active range in the SCOUTs ($< 10 \mu\text{m}$).

Two facilities have been used for the TID irradiations: the Helmholtz-Zentrum Berlin (HZB) Wansee [140] and the CC-60 facility at CERN [141]. The experimental set-ups and radioactive sources at the HZB (left image) and CC-60 (right image) facilities can be seen in Figure 5.30. Both Co-60 sources are housed in lead barrels that effectively shield them in their respective “OFF” position. The source can then be brought upwards from the barrel via a pulley system, in their respective “ON” position. The HZB Co-60 source has cylindrical symmetry, while the CC-60 source acts as a point-like conical distributed source. Both sources provide a uniform radiation field ($\pm 10\%$) with a small dose uncertainty (5%).

The aluminium box, housing the Device Under Test (DUT) is placed close to the source in order to maximize the dose rate and minimize the irradiation time. The dose rates at various DUT positions for several irradiation campaigns performed at both the HZB and CC-60 facilities are highlighted in Figure 5.31. The irradiation campaigns were performed across several years, leading to small changes in recorded dose rates, due to the relatively small Co-60 half-time (5.3 years). Despite this, the change in dose rate is within 10% for all campaigns at both HZB and CC-60 facilities, such that no significant dose rate dependent effects are expected.

Several SCOUT samples have been irradiated and measured. The samples vary in terms of the anti-reflective coating deposited on the sensor surface but are otherwise identical, barring any wafer to wafer variations. The results gathered with different samples are expected to be comparable. The procedure for acquiring an average dark current value for a sample requires several data processing steps that are described in Appendix B.



Figure 5.30: Co-60 source at HZB (left) and CC-60 (right). Additionally, the experimental set-ups can be seen in each figure.

5.6.4 DC before irradiation

Figure 5.32 shows the distribution of mean dark current (left) and its dispersion (right) for several non-irradiated SCOUTs. The samples are differentiated in terms of their wafer provenience in order to provide a qualitative description of the wafer-to-wafer dark current variation. The

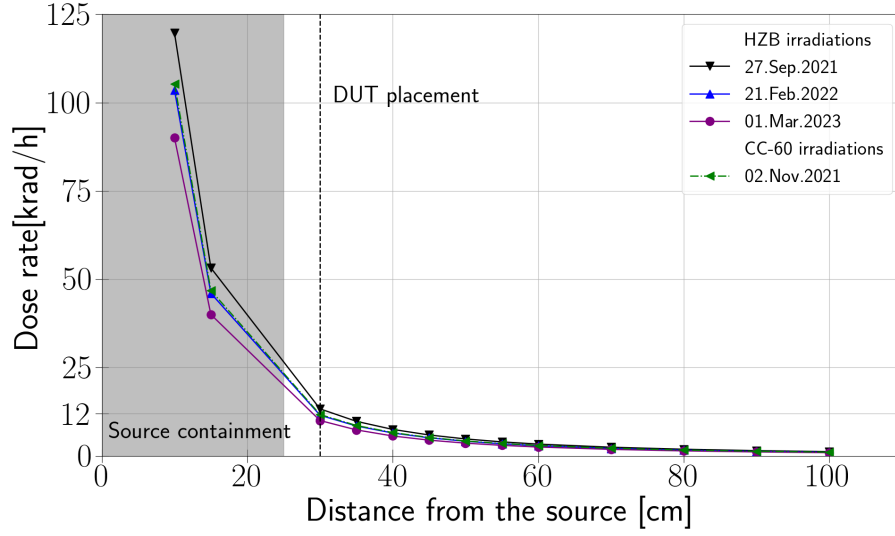


Figure 5.31: The dose rate measured with an ionization chamber at different times for both the HZB and CC-60 Cobalt-60 sources for several devices under test - source distances. The shaded grey block represents the estimated internal source containment. The position of the tested device in relation to the source is marked with a dashed line.

dark current values at room temperature range from $200 - 370 \text{ e}^-/\text{s}$. The variations between measured samples can be attributed to differences in environmental conditions between measurements and no large wafer-to-wafer variation is observed. The dispersion for most samples is within 15%.

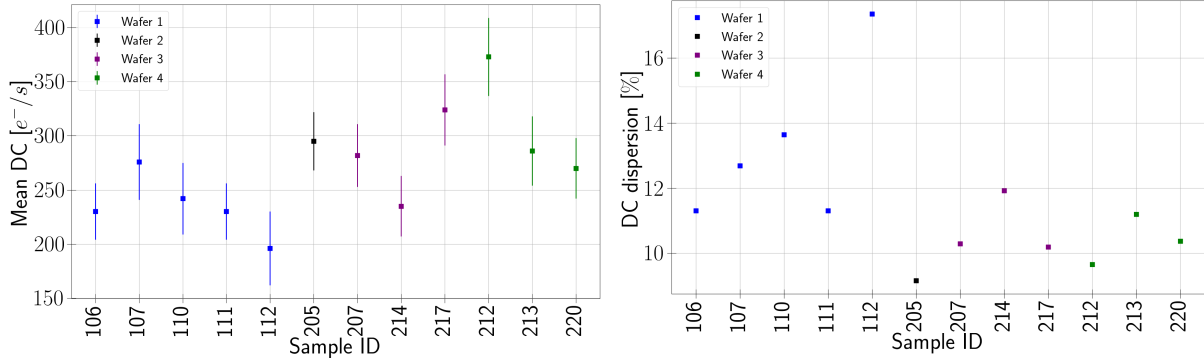


Figure 5.32: The mean dark current measured for a 1 s integration time of several SCOUT samples (left). The error bars are given by the standard deviation of the dark current distribution. The dark current dispersion (defined as $\sigma/\mu \times 100$) is plotted on the right for several SCOUT samples. All the measurements have been performed at the irradiation facility before any exposure to radiation. The sample IDs are arbitrary values given to the samples after a visual inspection performed at DESY, corresponding to four different wafers highlighted with different colors: blue, black, purple and green.

The linear response of the SCOUT sensors has been investigated for several integration times. Figure 5.33 shows the mean dark current without any gain calibration for several integration times. The linearity fit highlights the sensor's performance in terms of integration time. As was found in Reference [114], the linearity holds up to an integration time of $\sim 3 \text{ s}$, after which non-linear effects start to dominate.

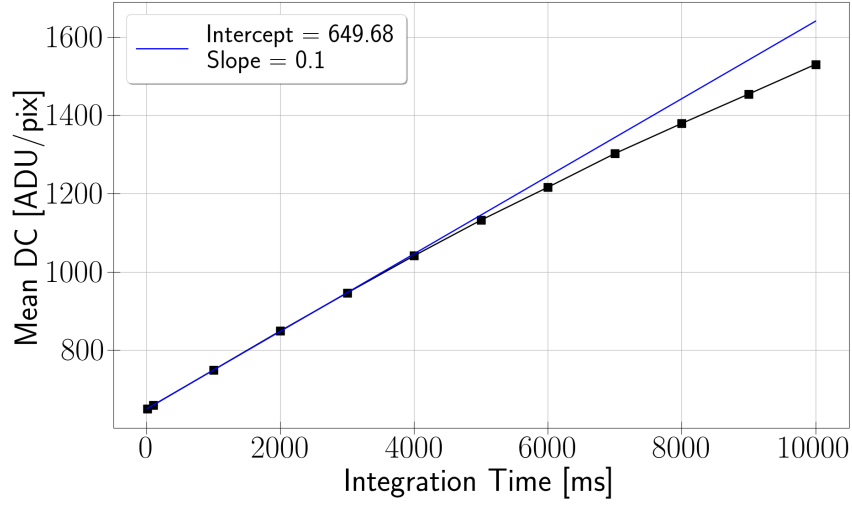


Figure 5.33: Mean dark current in Arbitrary Digital Units (ADU) for several integration times for a SCOUT sensor. The linearity fit is also shown with blue, highlighting a well behaved linear sensor response up to 3 s integration time.

Figure 5.34 shows the 2D map of a SCOUT sample imaged for a 1 s integration time. The image represents the average of 20 consecutive dark frames. The clear column pattern is investigated quantitatively via two projection plots along X and Y. The relative deviation from the mean is represented for both directions and it shows that under no illumination, the sensor has a large ($\sim 10\%$) column to column signal variation associated to fixed pattern noise. The row to row variation is much smaller ($\sim 3\%$). The column FPN is a well documented effect [142] in CMOS circuitry associated to process variations in the column amplifiers.

The sensor dark current variance has been investigated by analyzing its response for several consecutive frames. Two distinct noise types are defined: temporal and spatial noise. The temporal noise is defined as a pixel's signal variation in time. Figure 5.35 (left) shows a 2D map of the temporal noise. An average temporal noise of $19.3 \pm 3.7 \text{ e}^-/\text{s}$ has been recorded. A few outlier pixels extend the noise curve to larger values as can be seen in Figure 5.35 (Right). The Inverse Cumulative Distribution Function (ICDF) is introduced as the probability that a variable X takes a value less or equal than x : $\text{ICDF}(x) = P^{-1}(X \leq x)$. The ICDF of the temporal noise distribution provides a straight forward visualization of non-Gaussian effects, associated with in-pixel transients which will be used later in this section.

The spatial noise, is defined analogously to its temporal counterpart, as the deviation in the total sensor noise with time. This highlights the over-all stability of the sensor for several consecutive frames and is especially important for long measurements of many consecutive frames. Figure 5.36 highlights the spatial noise stability across several frames. The average spatial noise is $42.3 \pm 0.4 \text{ e}^-$, showing that the dark current is relatively stable for long measurements and records no strong temperature variations.

The read noise of the sensor is defined as the noise in the pixel signal for $\sim 0 \text{ s}$ integration of the dark current. The read noise sources are expected to be the in-pixel transistors and the peripheral circuitry. For the SCOUT sensors there is no direct way of probing the read noise. An indirect measurement can be made through the acquisition of very low integration time (1 ms) frames. This ensures a minimal noise contribution from the dark current, leading to a dominant noise component from the read-out circuitry (i.e. read noise). Figure 5.37 shows the

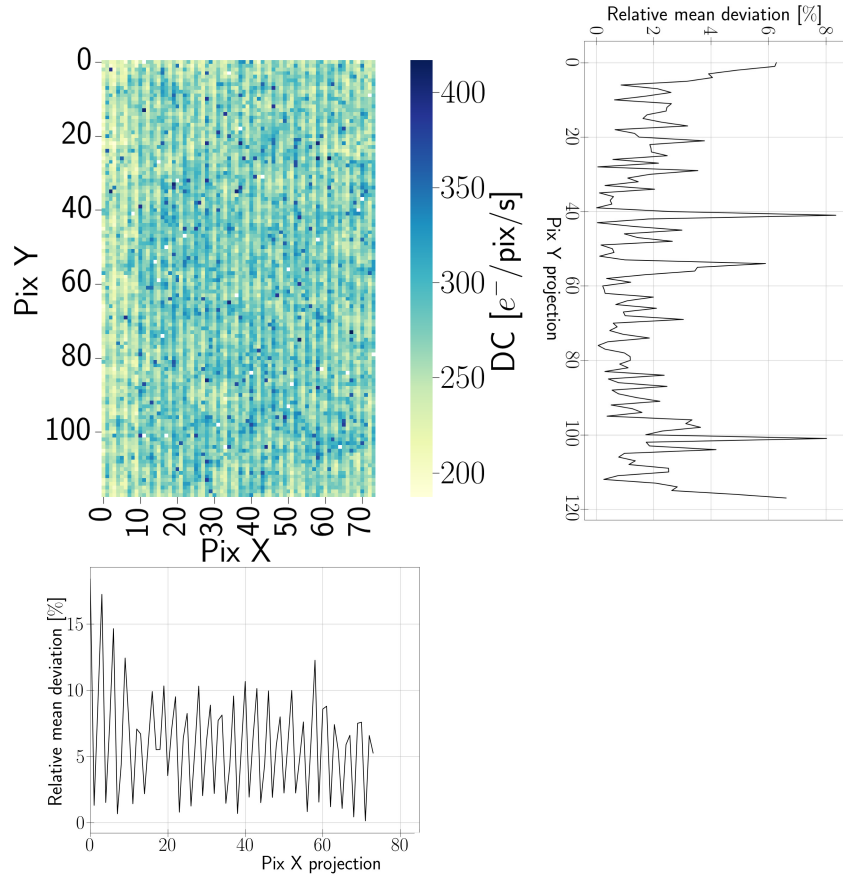


Figure 5.34: Average 2D dark current map of a SCOUT sample for a 1 s integration time and 20 consecutive frames. Additionally, the X and Y projections of the map are shown, highlighting the relative deviation from the mean of the column and row averages respectively.

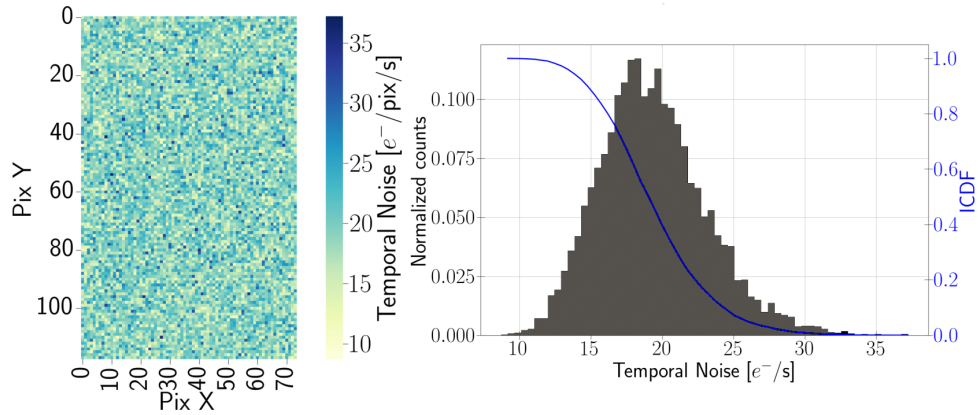


Figure 5.35: The temporal noise 2D map of a SCOUT (left). The normalized density histogram of the temporal noise distribution (right). Additionally, the Inverse Cumulative Distribution Function of the histogram is overlaid, with blue.

read noise distribution of a SCOUT. It will be further shown in this section that this indirect measurement method is impacted by the limited charge collection and can lead to inaccurate

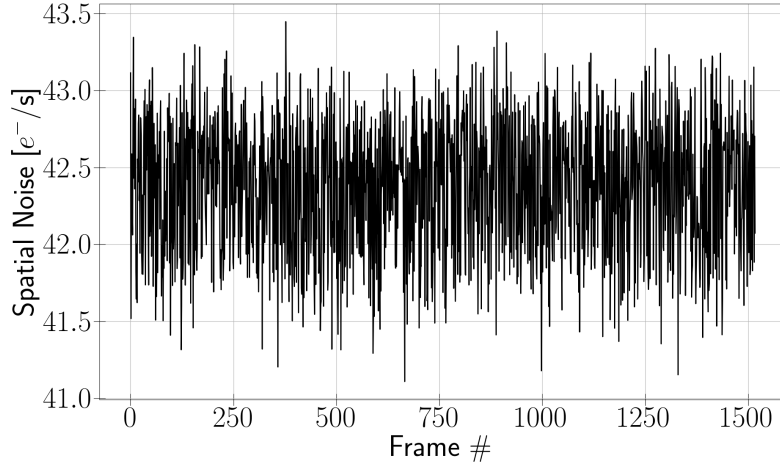


Figure 5.36: The spatial noise distribution across 1500 consecutive frames measured for a SCOUT sample at 1 s integration time.

measurements after irradiation.

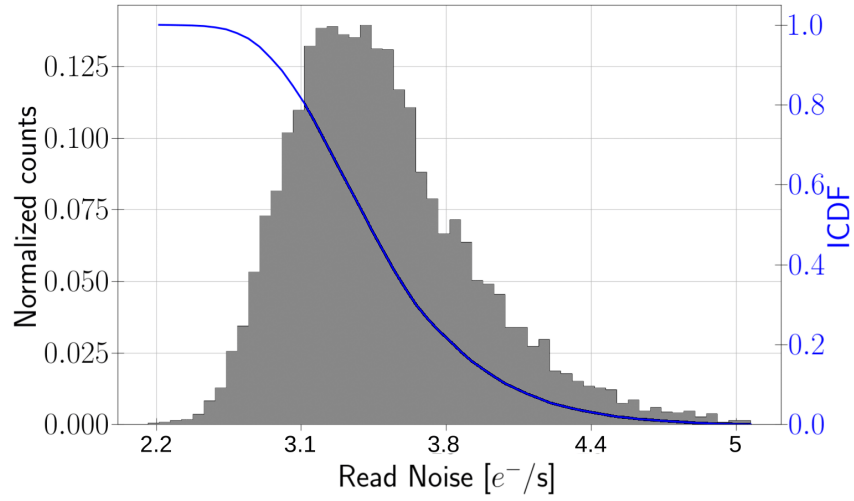


Figure 5.37: The read noise distribution computed from several frames for a SCOUT sample at 1 ms integration time.

5.6.5 TID induced damage on the SCOUT sensors

The results discussed in this section were additionally published in the paper proceedings appended to the thesis as Paper I.

Dark current degradation

Figure 5.38 shows several 2D maps of a non-irradiated and irradiated sample at several TID values. At 0 krad, the column FPN is clearly visible. After irradiation, the pattern disappears, due to the elevation of the dark current variance above the column amplifier 10% process variation. As expected, the radiation damage is evenly distributed across the pixel sensor. The

removal of the column FPN can be clearly seen in Figure 5.39 (left), associated with the smaller mean dispersion. The mean dispersion of the Y projection as seen in Figure 5.39 (right) remains largely unchanged. The relative mean deviation for the X and Y projections become similar in scale (2 – 3%) after irradiation.

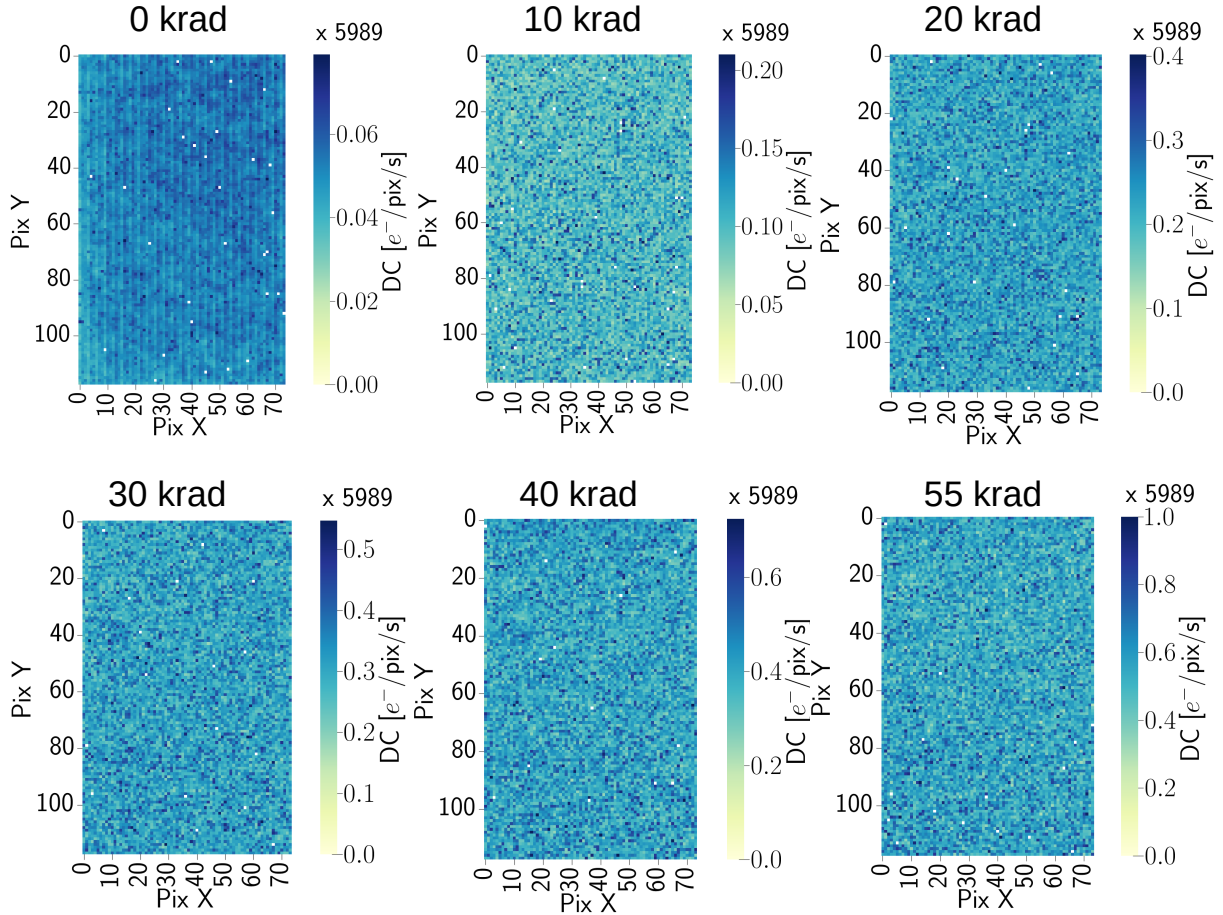


Figure 5.38: 2D dark current map of a SCOUT sample for a 1 s integration time at several irradiation doses: 0, 10, 20, 30, 40, 55 krad. The empty bins represent outlier pixels with values above or below 5σ .

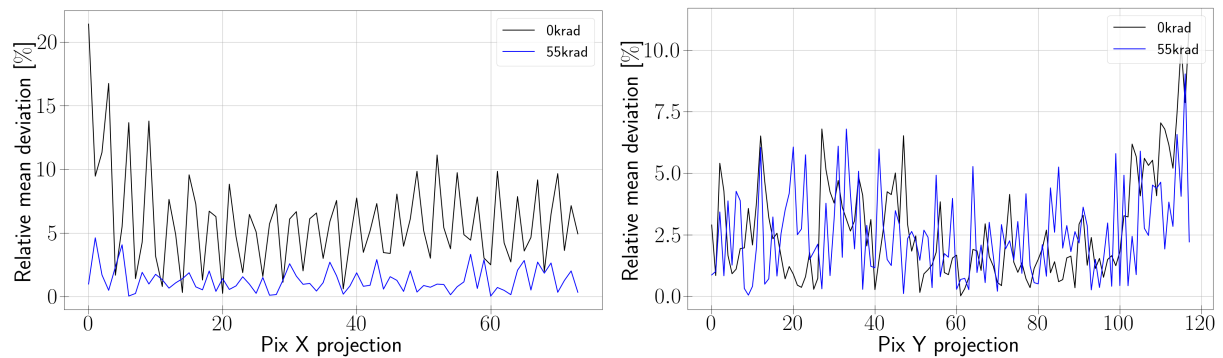


Figure 5.39: The column (X) projection (left) and the row (Y) projection (right) of the 2D maps for the non-irradiated (black line) and the 55 krad TID (blue line) measured points.

A better understanding of the pixel dark signal distributions after irradiation can be achieved by plotting the dark histograms for each irradiation step as can be seen in Figure 5.40. The histograms are fit with a probability distribution function (PDF) and their mean and standard deviation computed. Before irradiation (0 krad), a Gaussian distributed dark signal is recorded. As the TID increases, a departure from the normal distribution is observed (10 – 20 krad). For the highest TID values (30 – 55 krad), the return to a normal distribution is achieved. The source of this behaviour was not initially understood and constituted one of the main investigations of this study.

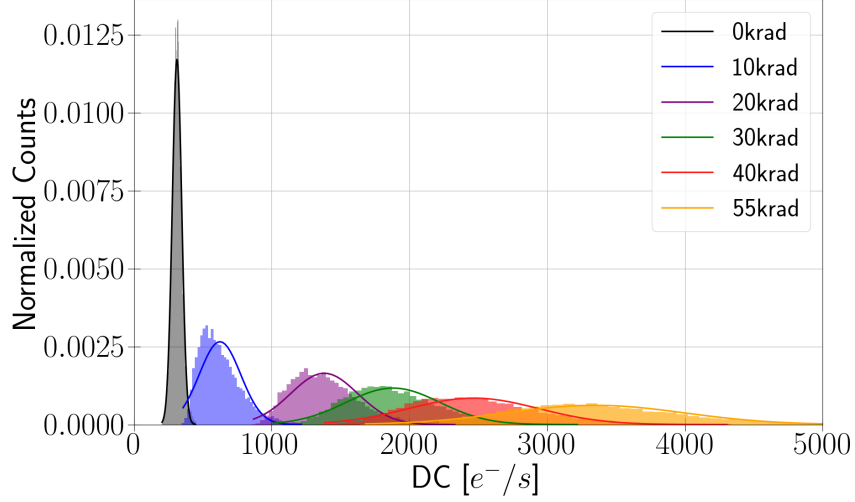


Figure 5.40: Dark histograms for a SCOUT sensor irradiated at several TID values: 0 krad (black line and histogram), 10 krad (blue line and histogram), 20 krad (purple line and histogram), 30 krad (green line and histogram), 40 krad (red line and histogram), 55 krad (orange line and histogram).

The increase in the dark current mean with TID is approximately linear as can be seen in Figure 5.41. The observed linearity is explained by the expected trapped oxide charge and interface states proportionality with the absorbed dose (Equation 4.3). As already discussed in Chapter 4, these are correlated to the parametric degradation observed in irradiated sensors.

Temporal noise degradation

Figure 5.42 shows the temporal noise increase with the accumulated dose. As the dose increases, a more pronounced distribution tail can be observed. This is a clear indication of a transient effect in the pixel sensor which scales with the accumulated dose. This correlation additionally serves as an explanation for the elevated kurtosis of the dark current distributions in the intermediate dose values (10 – 20 krad), but does not seem to be consistent with the observations for elevated doses (30 – 55 krad).

The existence of a transient noise source in the temporal noise distributions of the irradiated SCOUT sensors served as a first indication of the existence of a Random Telegraph Signal (RTS) noise source. In order to isolate the origin of this noise source, the read noise degradation has been additionally investigated.

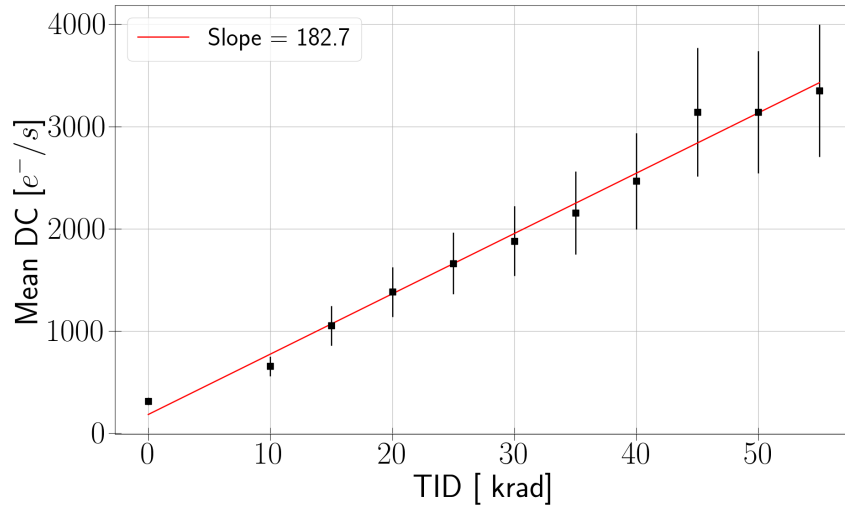


Figure 5.41: Mean dark current of a SCOUT sensor irradiated to several doses. The error bars are defined as the standard deviation of the dark current.

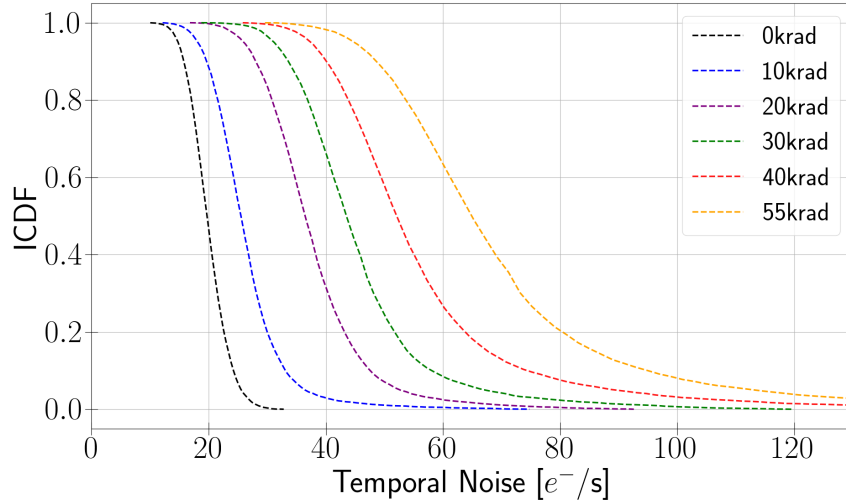


Figure 5.42: Inverse cumulative distribution function of the temporal noise for a SCOUT irradiated to several TID values: 0 krad (black line), 10 krad (blue line), 20 krad (purple line), 30 krad (green line), 40 krad (red line), 55 krad (orange line).

Read noise degradation

After irradiation, the read noise has been measured in a similar fashion as described in Section 5.6.4. Figure 5.43 shows the apparent increase in read noise with the accumulated TID. While an increase in measured read noise can be observed with elevated TID, the lack of a distribution tail, indicates that the transient effects are localised at the pinned photo diode - sense node region.

The read noise investigation shows a similar trend to the dark current in Figure 5.40. The intermediate dose values lead to a small asymmetric effect, while the large dose leads to a larger more symmetric effect. This, is an indication that the read noise measurement is convoluted with an important integration time dependent component accumulated in the small integration

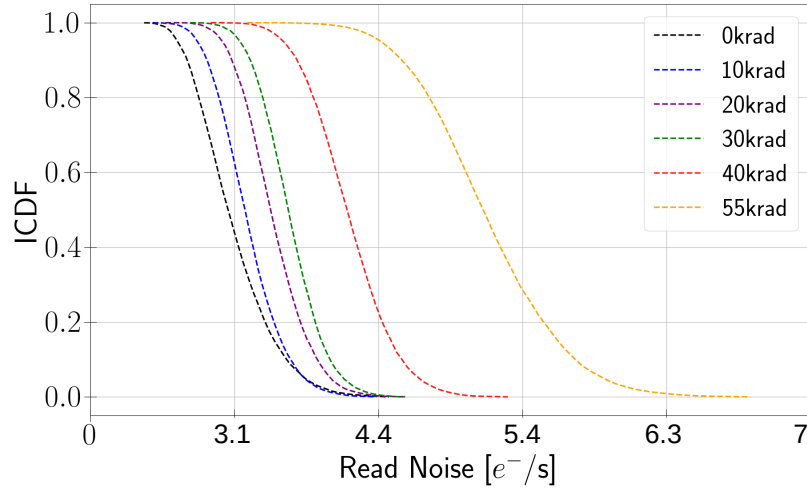


Figure 5.43: ICDF of the read noise of a SCOUT sensor for several TID values: 0 krad (black line), 10 krad (blue line), 20 krad (purple line), 30 krad (green line), 40 krad (red line), 55 krad (orange line).

window. This result raises the possibility of an inaccurate estimation of the read noise.

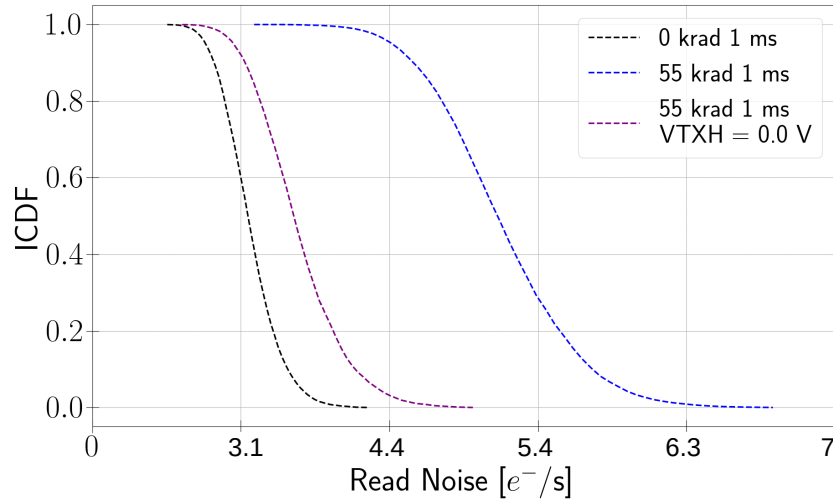


Figure 5.44: ICDF of the read noise for a non-irradiated (black dashed line) and irradiated at 55 krad SCOUT sensor. Two techniques are used for deriving the read noise: minimizing the integration time to 1 ms (blue dashed line) and the additional setting of the high transfer gate voltage to 0 V (purple dashed line).

An alternative read noise investigation technique has been developed, which involves setting the voltage level of the high transfer gate (VTXH) to the ground level. This is an effective way to “shut off” the charge collection. An investigation of the effect of this technique compared to the small integration time technique for an irradiated and un-irradiated sample is shown in Figure 5.44. The VTXH= 0V measurement point shows that the read noise degrades only by a small margin due to TID. The previously observed jumps in read noise for higher TID values (Figure 5.43) are most probably an artifact of the partial charge collection at the sense node. Following from Figure 5.41, this effect is expected to be enhanced at higher irradiation doses.

Figure 5.45 shows the variance versus mean plot of a 20 krad irradiated SCOUT. The

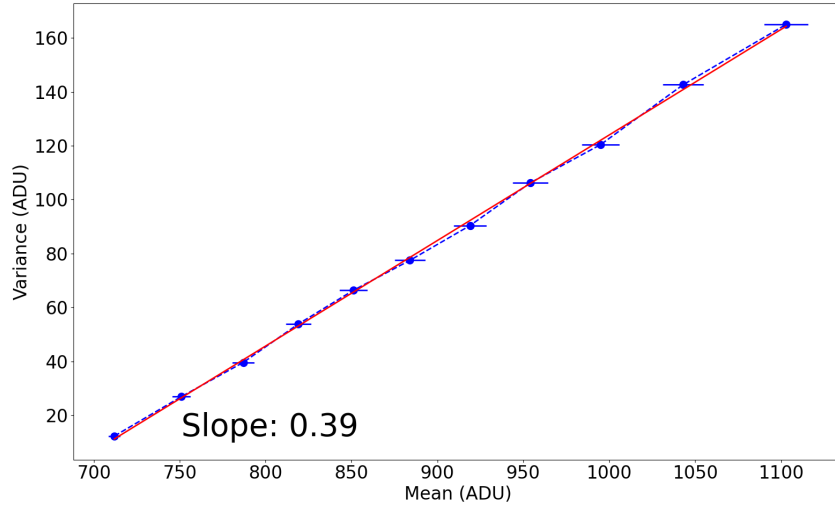


Figure 5.45: Signal variance versus the signal mean in ADU's for a 20 krad irradiated SCOUT sensor at 15°C. The slope of the plot yields the gain of the sensor in ADU/e^- .

extracted slope of the plot coincides to the gain [143] of the sample: $K = 0.39 \pm 0.04 \text{ ADU}/e^-$. The manufacturer reports a gain of $0.42 \text{ ADU}/e^-$ before irradiation.

These results highlight that the pixel front end and the periphery circuitry is not significantly affected by radiation damage. It appears to be localized near the pixel's photo-diode - sense-node.

Random Telegraph Signal

In the previous sections, the temporal noise signature was attributed to a transient effect, correlated to random telegraph signal (RTS). In order to gain a better understanding of the radiation defect source, a thorough investigation of the sensor's RTS has been performed. RTS meta-stable states are characterized by long lifetimes, such that the measurements before and after irradiation have been performed for many consecutive frames (1000 – 30000 frames). Due to the time sensitive nature of measurements performed at irradiation facilities, a dedicated study of the minimum amount of frames for which the RTS characteristics can be accurately identified has been performed and is presented in Appendix B.

This study treats each pixel as an independent diode detector. The existence of several meta-stable dark current levels is correlated to the notion of a ground level, defined as the lowest meta-stable noise level that the pixel occupies during a measurement window. Because each pixel is analyzed independently, several “ground levels” can be defined for a sensor. The variance of the ground level distribution can be higher than the expected Gaussian variance. This is motivated by the inability to distinguish between a “true” ground level and an excited state for a finite measurement time of a randomly distributed lifetime event. Meta-stable noise levels associated to telegraph signal have been reported to have lifetimes varying from seconds, to several weeks [144].

As an example, Figure 5.46 shows the signal in ADUs extracted from a single pixel for an irradiated sensor. The consecutive monitoring of the pixel's dark signal highlights the transition to and from an elevated signal level.

The statistical treatment of the radiation induced effect in the SCOUT sensors relies on the

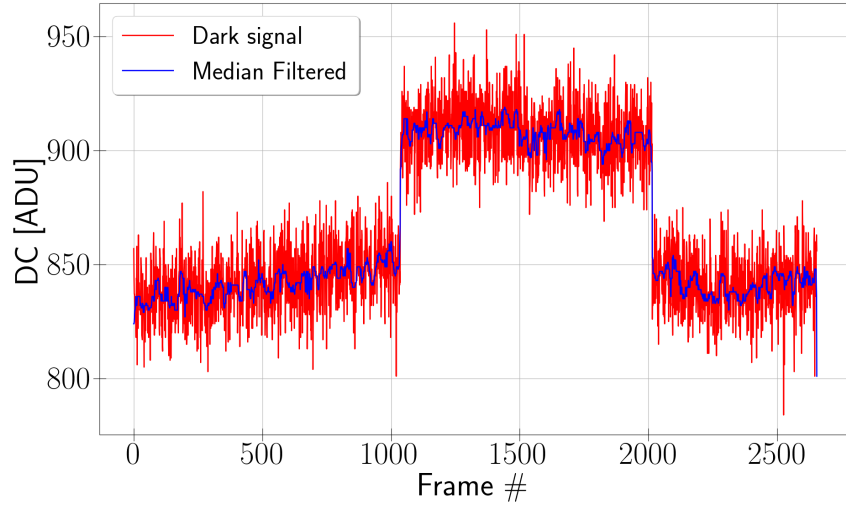


Figure 5.46: Dark signal (red line) of a pixel for a SCOUT sensor irradiated at 20 krad for several consecutive frames. Over-layed (blue line), the median filtered (kernel of 17) signal values are plotted to better showcase the signal trend. The plot highlights the existence of a two-level random telegraph signal in a pixel.

individual detection and analysis of random telegraph signals in each pixel. In order to expedite this process, an automatic filtering and threshold detection algorithm of the acquired data has been developed in the python programming language based on References [145] and [146].

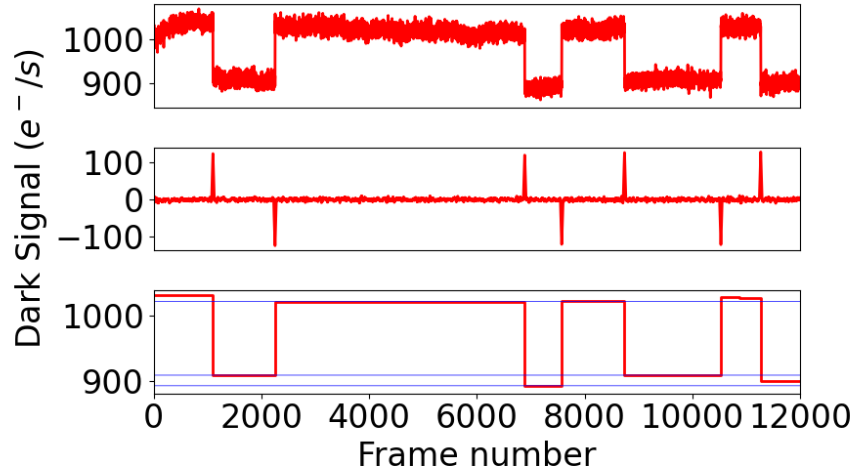


Figure 5.47: Illustration of the detection algorithm for random telegraph signals. The first box at the top shows a pixel's signal for several consecutive frames taken with a 20 krad irradiated SCOUT for an 1 s integration time. The second box (in the middle) shows the filtered signal. The third box on the bottom is the reconstructed signal from which the amplitude and timing properties are extracted. Blue lines represent the detected meta-stable signal levels.

The method aims to separate the Gaussian component of the noise from the RTS correlated jumps. The method fails beneath a detection threshold, where the transient amplitudes can not be distinguished from the Gaussian noise. An example of the functionality of the detection

algorithm is presented in Figure 5.47. Multiple frames are taken in the same sensor configuration (integration time and bias voltages) and the temporal variations for each pixel are monitored. In order to average out the contributions of the Gaussian noise and contrast the signal jumps, the following step shaped filter is applied to the signal:

$$H(z) = \sum_{i=0}^{L/2-1} \left(\frac{2}{L}z^{-i}\right) - \sum_{j=L/2}^{L-1} \left(\frac{2}{L}z^{-j}\right)$$

The convolution creates triangle pulses with the height of the signal amplitude whenever a leading or falling edge is encountered. In order to distinguish between Gaussian noise fluctuations and “real” RTS transitions, the filter length, L needs to be tuned. Ideally, a self tuning mechanism should be employed in order to optimize the filter length for each pixel. The tuning procedure should ensure that the filter length is always smaller than the minimum lifetime of the transitions. Due to the large computational complexity of the procedure, a fixed value of $L=50$ was found to be sufficient for the study at hand.

The detection algorithm assumes that the Gaussian noise standard deviation σ_G and the RTS noise standard deviation σ_{RTS} components are uncorrelated. The signal standard deviation, σ_S can be written as:

$$\sigma_S = \sqrt{\sigma_G^2 + \sigma_{RTS}^2}$$

The smallest RTS transition that can be detected with this method needs to satisfy $A > \sigma_S$, where A is the largest step amplitude. Considering the worst case scenario, when equal time is spent on all transition levels, $\sigma_{RTS} < A/2$, the detection threshold is:

$$\sigma_S < \sqrt{\sigma_G^2 + A^2/4} < A$$

From this follows that the minimum detection threshold is $A > \frac{2}{\sqrt{3}}\sigma_G$. The automatic threshold detection procedure is achieved by segmenting the in-pixel noise into slices without RTS transitions, estimating the σ_G component. The edge of each slice is marked as a possible detected event. If the detection condition is fulfilled, the transition is identified and its parameters (amplitude and time constant) are recorded. A simplified signal shape is then reconstructed.

Section 3.3 discussed the existence of several RTS mechanisms associated to the Variable Junction Leakage (VJL) mechanism (associated to DC-RTS) and MOSFET channel resistance switching correlated to the source follower and reset transistors. Each noise source has several different signatures and can be identified in terms of its magnitude for each pixel. The magnitude of the DC-RTS is integration time dependent, while the magnitude of the Source Follower-RTS and the Reset-RTS are expected to be dependent on the respective transistor bias voltage.

While, the plot showcased in Figure 5.44 gives a good first indication that the noise is dominated by DC-RTS, the investigation of the temporal noise integration time dependence can show if any pixel is additionally affected by other RTS sources. Figure 5.48 shows several correlation plots of the temporal noise dependence on integration time for both non-irradiated and 20 krad irradiated SCOUTs. The non-irradiated correlation plots show an expected uniform distribution given by the Gaussian smearing of the signal variance that is shifted upwards for larger integration times. After irradiation, the Gaussian smearing is additionally convoluted with the randomly distributed RTS transitions. Several pixels show a higher temporal noise at lower integration times, but the data trend, especially for the 10 s integration time, clearly shows

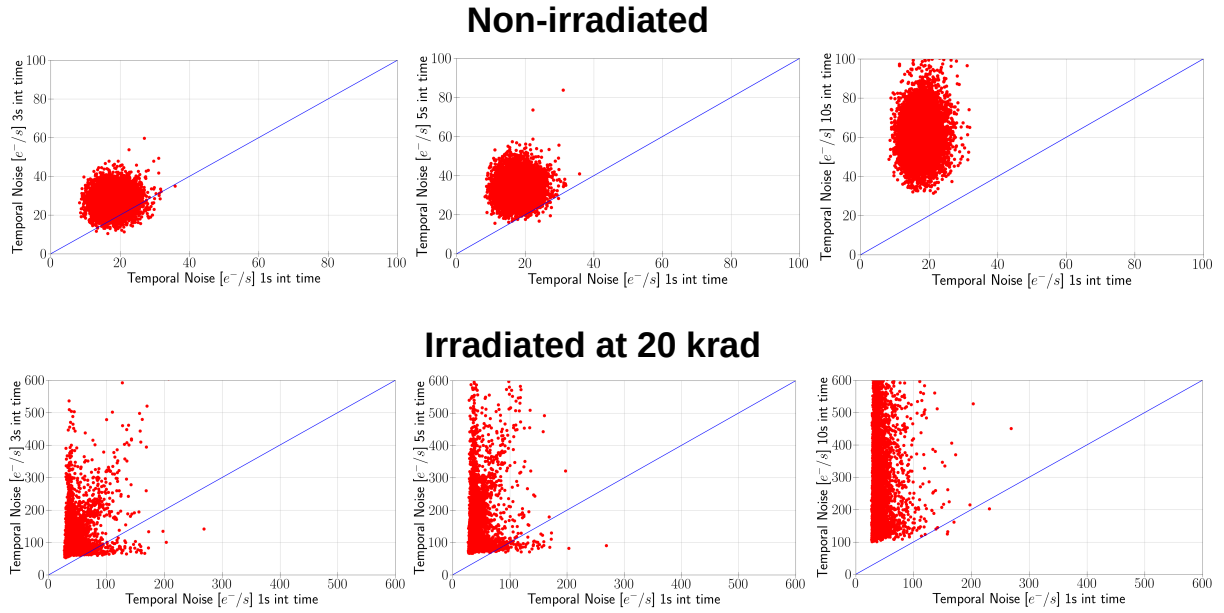


Figure 5.48: Correlation plot between temporal noise and integration time of the sensor for both an un-irradiated and 20 krad irradiated SCOUT sensor. An integration time of 1 second is used for the data points on the X axis and an integration time of 3 s (left), 5 s (middle), 10 (right) seconds is used for the data points on the Y axes. Points that don't follow the blue line have a majority noise component that is integration time dependent.

that the vast majority of pixels have a dominating integration time dependent temporal noise component. Some pixels (~ 7 out of a total of 8732 pixel array) seem to follow the correlation curve (blue line) which could be an indication of some pixels being affected by MOSFET channel resistance switching, but it clearly is not a dominating effect in the SCOUT sensors.

Figure 5.49 shows the 2D distribution of detected meta stable noise levels for SCOUTs irradiated to several TIDs. The multi-level transitions observed are attributed to several defect centers in a pixel that get randomly activated in a coincidence window matching the measurement time [147]. At low irradiation doses (TID < 1 krad), the bi-level transitions dominate. Additionally, the flagged pixels appear clustered, indicating a systematic effect across the pixel matrix or a detection algorithm false flagging. At higher doses, several signal levels are recorded (up to 11 levels in a single pixel). Figure 5.50 shows the distribution of detected signal levels for several irradiated SCOUT sensors. The distribution follows an approximate exponential decay, characterized by a very small numbers of pixels with large numbers of RTS levels.

The percentage of pixels that showcase RTS for several radiation doses is presented in Figure 5.51. Already at 5 krad, close to 100% of the pixels exhibit detectable RTS transitions. The difference in the number of pixels with observable RTS for several TIDs is attributed to both the random activation of the radiation defects and the exponential decay distributed RTS amplitudes. Only transitions that rise above the minimum detection threshold can be detected.

The maximum RTS amplitude is defined as the maximum of the transition step distribution (for a pixel) between consecutive meta-stable noise levels. It can be used to infer information on the physical properties of the defect centers. While, only information regarding the worst-impacting defect in the pixel is available, this is a good approximation, as highlighted in Reference [148].

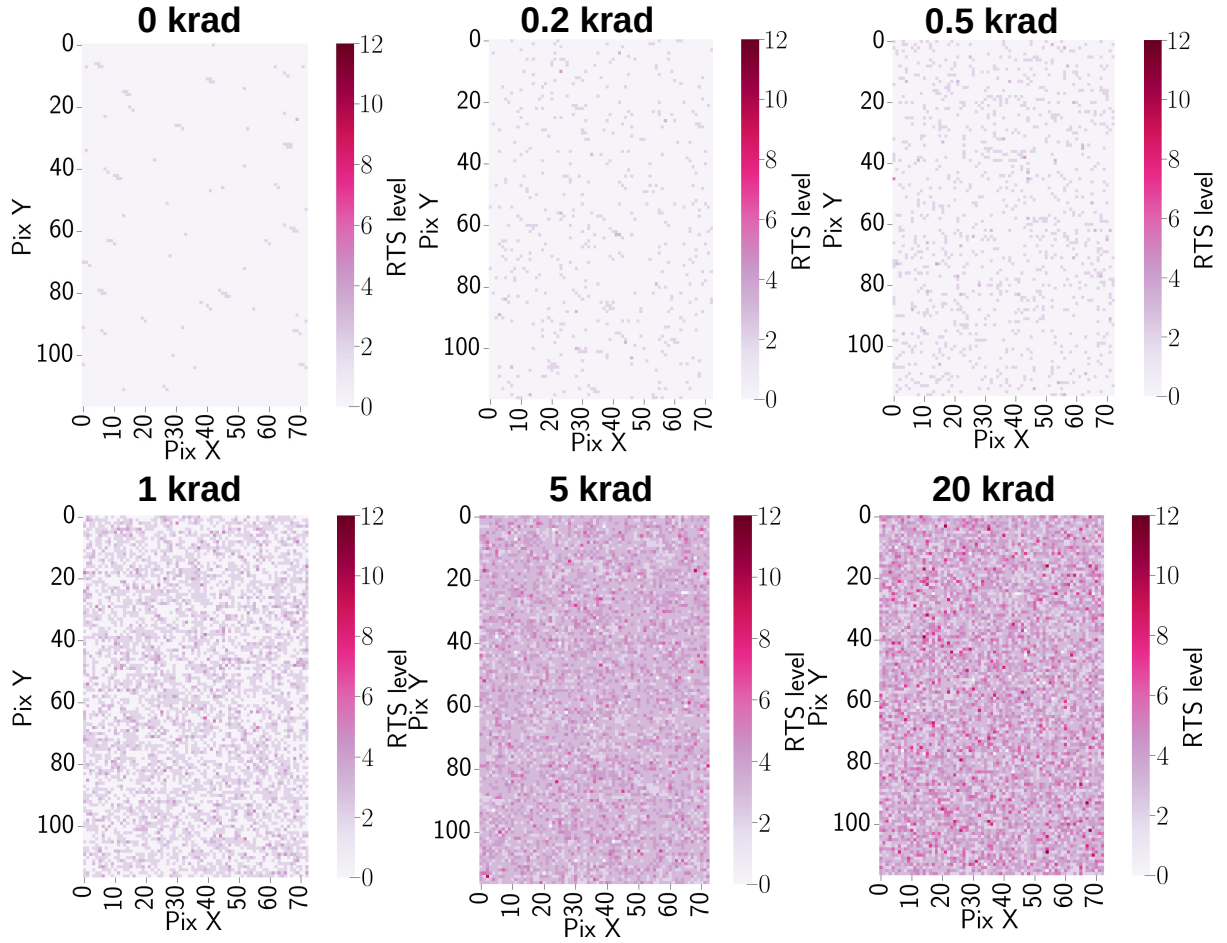


Figure 5.49: The number of detected meta-stable levels identified as RTS for each pixel projected over the 2D SCOUT sensor map. Several 2D distributions are plotted for both an un-irradiated sample and several irradiation doses: 0.2, 0.5, 1, 5, 20 krad. Empty bins are pixels for which no meta-stable noise levels (above a pixel's respective ground state) have been detected.

Figure 5.52 shows the distribution of RTS maximum amplitudes for multiple TID values. The maximum amplitude distributions follow an exponential decay in the semi-logarithmic scale, with a cut-off at low amplitudes, due to the inherent detection threshold:

$$f(x) = k\lambda * \exp(-\lambda x) \quad (5.5)$$

While a shift towards higher amplitudes can be seen at larger irradiation doses, all distributions follow a similar decay constant $1/\lambda$, in the range of $40 - 50 \text{ e}^-/\text{s}$. As the λ parameter is correlated with the signature of RTS [149], it is apparent that similar defects contribute to the measured noise at all irradiation levels. A slight elevation of the $1/\lambda$ coefficient is observed for the 20 krad irradiated SCOUT, which was also observed by other publications [149] and was hypothesized to be correlated to the increase in number of radiation defects per pixel leading to larger apparent maximum amplitudes.

Correlating these results to the dark histograms presented in Figure 5.40, a clear picture

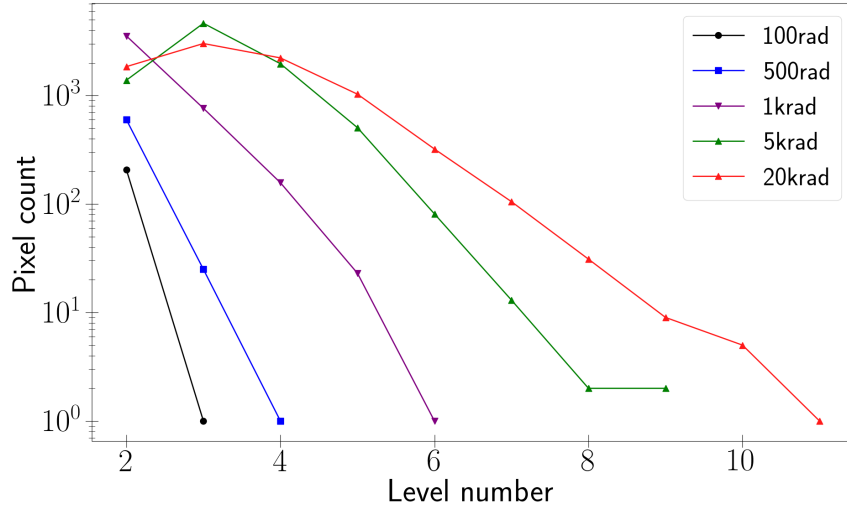


Figure 5.50: Distribution of the number of meta-stable noise levels detected for several irradiated SCOUTs at various TID values: 100 rad (black line), 500 rad (blue line), 1 krad (purple line), 5 krad (green line), 20 krad (red line).

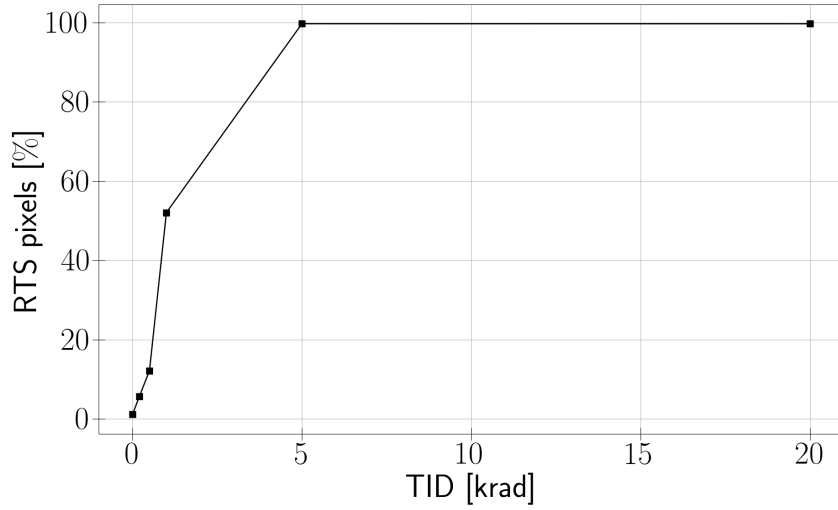


Figure 5.51: Percentage of identified pixels with at least two distinct signal levels for several irradiated SCOUTs at multiple irradiation doses: 0, 0.2, 0.5, 1, 5, 20 krad.

of the TID damage mechanism can now be formulated. The dark current mean dispersion for SCOUTs irradiated at several TIDs is shown in Figure 5.53. The large increase in dispersion at low irradiation doses can be explained by the small percentage of pixels with RTS levels above the Gaussian noise. These appear as large noise and low statistics events in the temporal noise distribution. This leads to the departure from the normal distribution in Figure 5.40. At large enough TID values (>5 krad), the median of the RTS maximum amplitude distribution raises above the Gaussian noise. As a consequence, the DC-RTS becomes the main noise source in most pixels of the array. The large number of observable signal transitions in each pixel, effectively smear the ground level. The Poisson distributed RTS effect approaches a Gaussian distribution, leading to the observed (elevated) plateau in the dark current dispersion at large TID's.

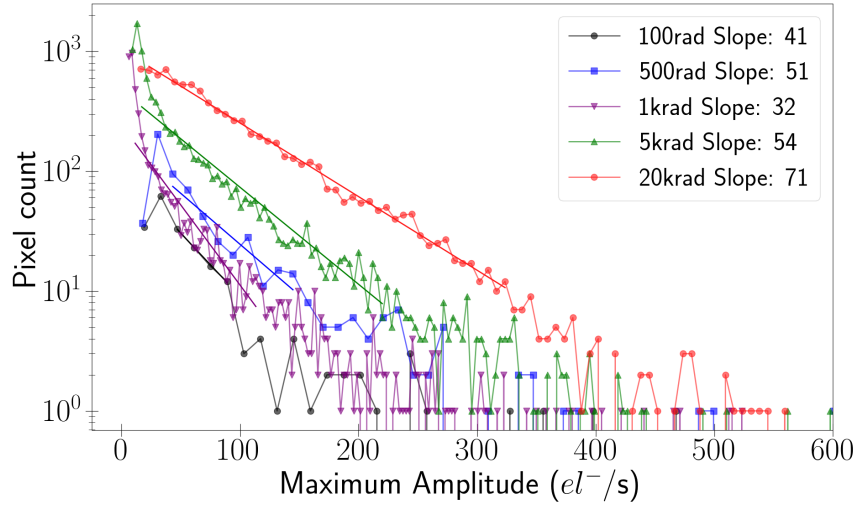


Figure 5.52: Distribution of the maximum RTS amplitudes for irradiated SCOUT samples at various TID values: 100 rad (black line), 500 rad (blue line), 1 krad (purple line), 5 krad (green line), 20 krad (red line). An exponential decay fit is performed for the statistically relevant regions of the plot, above the detection threshold. These regions were manually chosen for each data set. The slope value showcased in the legend corresponds to the $1/\lambda$ of the exponential decay distribution.

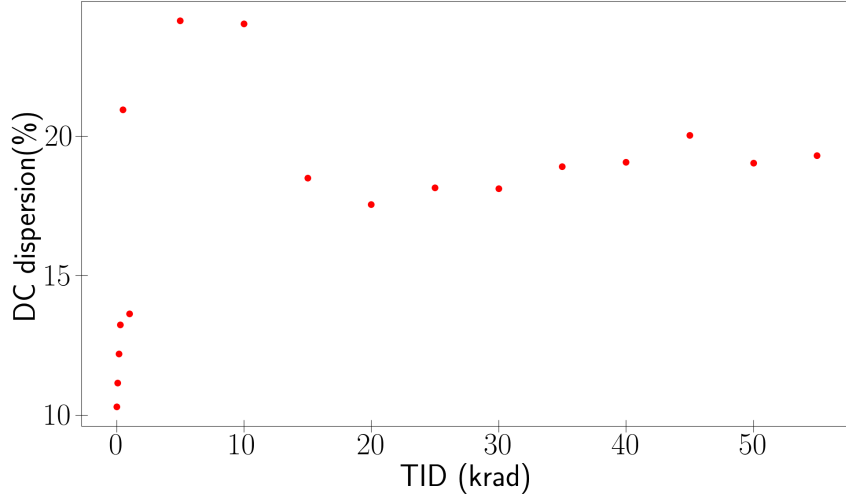


Figure 5.53: Dark current dispersion for SCOUT sensors irradiated at several TID values: 0, 10, 20, 30, 40, 55 krad.

This result highlights that at relatively small doses for the ULTRASAT mission (>5 krad), the DC-RTS noise source is expected to dominate. The large impact of TID on the measured DC-RTS was not initially expected, and was not taken into account into the sensor design. It can be correlated to the operation of the VTXL line at 0 V (see Figure 3.13). This operation mode is not expected to lead to the transfer gate operation in accumulation (especially after irradiation) and as a consequence, a large TID impact is foreseen for these sensors. Unfortunately, the SCOUT sensors could not be biased at negative values for the transfer gate, such that this effect could not be mitigated. Similarly, the ULTRASAT sensors were designed with the low transfer gate line grounded, such that no voltage tuning of this line is possible.

Simulation of the RTS detection algorithm efficiency

A simulation of the RTS detection algorithm efficiency has been developed. It includes a Gaussian noise component modeled after the measured dark current variance in un-irradiated SCOUTs and an RTS noise component. The latter is implemented through the addition of an exponentially distributed noise source with $1/\lambda$ decay constant and random distributed time constants. For simplicity, only bi-level signal transitions are considered.

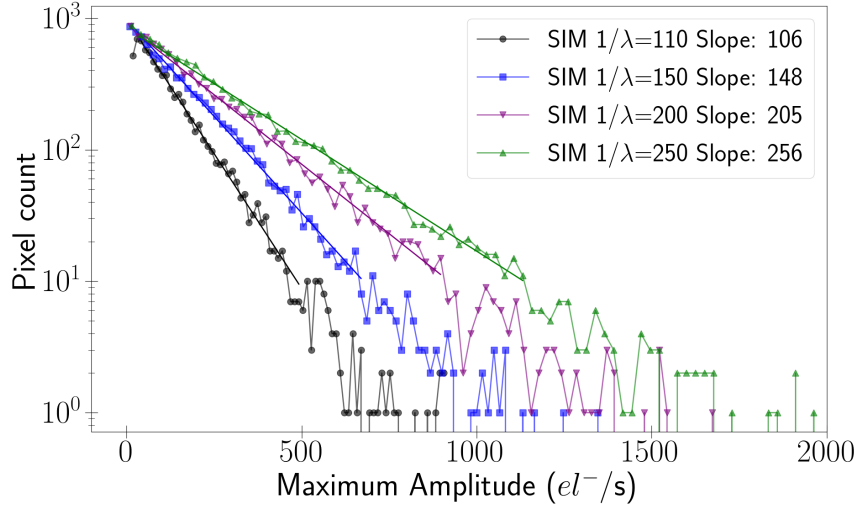


Figure 5.54: Simulated maximum amplitude distributions derived for data sets with exponential decay coefficients ($1/\lambda$): $1/\lambda = 110$ (black line), $1/\lambda = 150$ (blue line), $1/\lambda = 200$ (purple line), $1/\lambda = 250$ (green line).

Figure 5.54 shows the accurate reconstruction (within 10%) of the RTS amplitude distribution for various decay constants. For the lower decay constant, $1/\lambda = 110$, the detection threshold is visible in the plot (low maximum amplitude values), indicating that small amplitudes get lost in the simulated Gaussian noise. Additionally, the simulation closely follows the data for a 20 krad irradiated sensor at a similar decay constant as can be seen in Figure 5.55. This serves as a validation step of the simplifications made in the simulation.

Integration time and temperature dependence

The relation of these results to the ULTRASAT sensors needs to take into account the differences in the operational integration time (300 s for the flight grade sensor) and temperature (200 K). A study of the impact of integration time and temperature on the random telegraph signal is further described.

Figure 5.56 shows the distribution of RTS maximum amplitudes for a 20 krad irradiated SCOUT at several integration times. The RTS amplitude distributions λ coefficients increases with the integration time, as expected from Figure 5.48. The linear increase in the median RTS maximum amplitude distribution with integration time is further highlighted in Figure 5.57.

The temperature scaling depends on the activation energy of the radiation induced defect centers. The activation energy has been measured in a dedicated study. This assumes that the generation rate of free carriers is thermally activated and the variation of the defect cross-section and band-gap height is negligible. An approximate measurement of the charge generation rate can be inferred from the median of the maximum amplitude distribution [148].

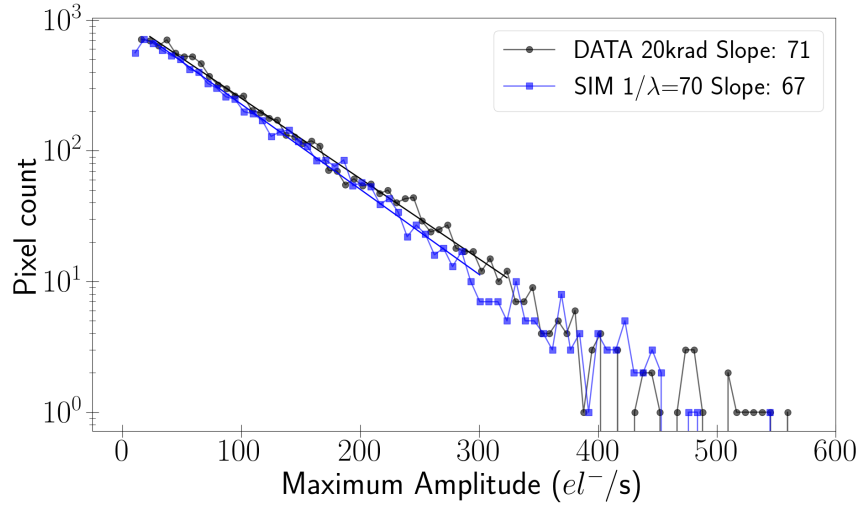


Figure 5.55: Simulation (blue line and squares) and data (black line and circles) for data sets with similar $1/\lambda$ exponentially distributed RTS amplitudes.

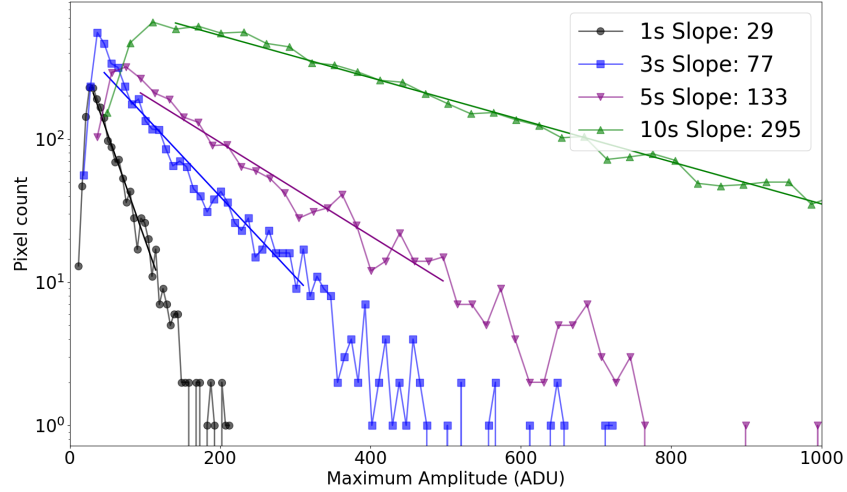


Figure 5.56: RTS maximum amplitude distribution for a SCOUT sensor irradiated at 20 krad measured at several integration times: 1 s (black line), 3 s (blue line), 5 s (purple line), 10 s (green line). The values of the measured RTS amplitudes are presented in ADUs and the values of the $1/\lambda$ are highlighted in the top right corner.

The activation energy is calculated from the slope of an Arrhenius plot [150]. It is an empirical relation that can be applied to thermally activated effects. The temperature dependence of a reaction rate can give information on the underlying activation energy of the physical effect. The median of the RTS maximum amplitude distribution is considered as the rate constant. The Arrhenius equation can then be written as:

$$\lambda = A e^{\frac{-E_a}{kT}} \quad (5.6)$$

A is a temperature independent constant, E_a is the activation energy, k is the Boltzmann constant and T is the absolute temperature.

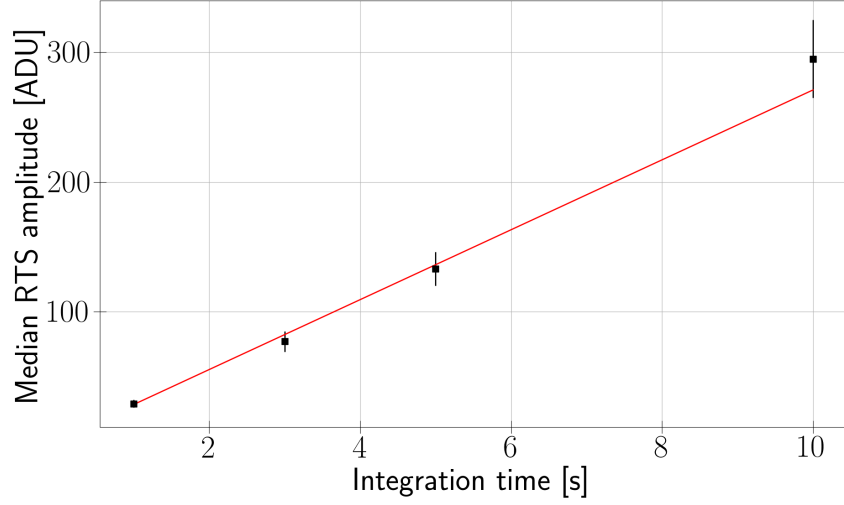


Figure 5.57: Median of the RTS maximum amplitude distribution for a SCOUT sensor irradiated at 20 krad measured at several integration times. The error bars are determined by considering the systematic 10% detection precision.

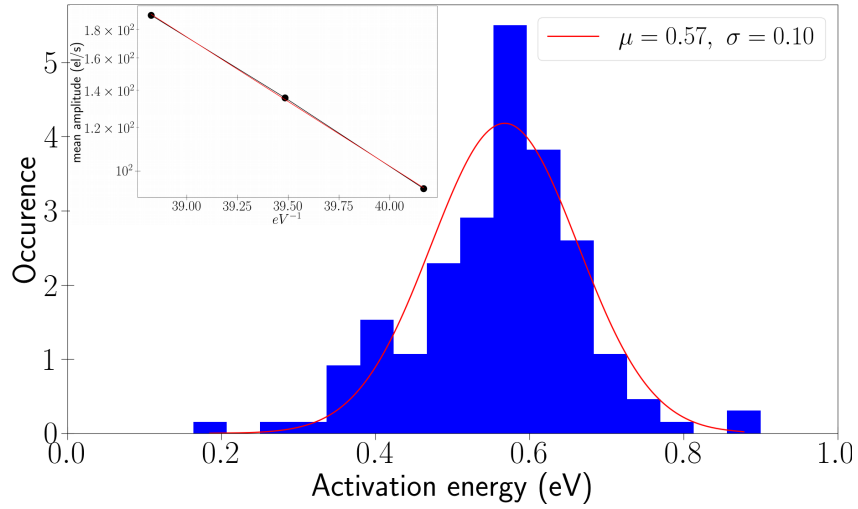


Figure 5.58: Activation energy histogram for a 20 krad irradiated SCOUT. Each bin is derived from the slope of an Arrhenius plot (an example is shown in the top left). The statistics used for the histogram is 151 events. The relatively small number of statistics is due to the difficulty of “following”, a bi-level transition across multiple measurements. Most pixels either showcase complex RTS level distributions (>2) at high temperatures or have indistinguishable RTS noise levels at low temperatures. The median and standard deviation of the distribution are used to extract the activation energy, $E_a = 0.57 \pm 0.10$ eV.

In order to keep the complexity of the calculations low, only bi-level transitions have been considered, leading to relatively low statistics. Figure 5.58 shows the histogram of activation energies computed in the temperature range of $15 - 25^\circ\text{C}$ for 151 pixels. An activation energy $E_a = 0.57 \pm 0.10$ eV is extracted. The value close to the midgap shows that deep traps are involved in the meta-stable charge generation process, strongly indicating a classic Shockley Read Hall generation mechanism as discussed in Section 2.5.

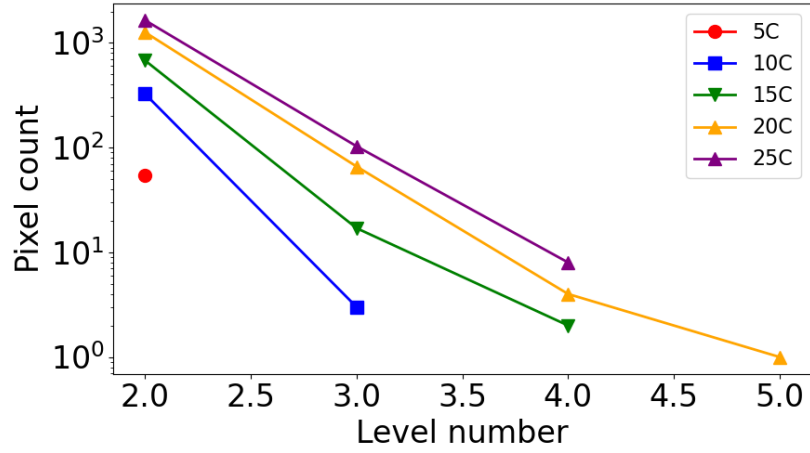


Figure 5.59: Distribution of the number of RTS levels detected in a 20 krad irradiated SCOUT sensor at several temperatures: 5°C (red line), 10°C (blue line), 15°C (green line), 20°C (yellow line), 25°C (purple line).

The distribution of meta-stable noise levels detected in a 20 krad irradiated SCOUT at different temperatures is shown in Figure 5.59. The number of multi-level transitions is found to decay with temperature. The maximum amplitude distribution for several temperatures is shown in Figure 5.60. As expected, a decrease of the exponential slope is observed with temperature.

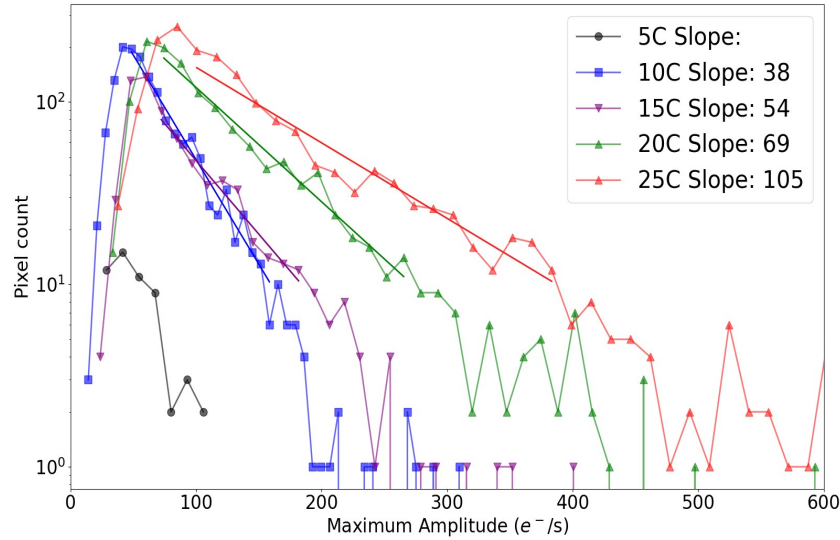


Figure 5.60: Maximum RTS amplitude distribution of a 20 krad irradiated SCOUT sensor at several temperatures: 5°C (red line), 10°C (blue line), 15°C (green line), 20°C (yellow line), 25°C (purple line). For each curve, the $1/\lambda$ coefficient is quoted in the top right corner. The exponential decay fit could not be performed for the 5°C measurement point due to the low number of observable signal levels.

Taking into account that the radiation induced defect centers are temperature activated, the relation between the median RTS maximum amplitude distribution and temperature is expected to follow: $\sim T^2 e^{(-E/2kT)}$ [17]. The measurement points gathered for several temperatures (5 –

27° C) are shown in Figure 5.61 and results have been extrapolated for the ULTRASAT mission operational temperature. A median RTS amplitude of $0.4 \pm 0.02 \text{ e}^-/\text{s}$ is estimated for the ULTRASAT operational temperature of 200 K for a 20 krad irradiated SCOUT sensor.

Scalability of results for the ULTRASAT sensor

This subsection explores the scalability of the SCOUT sensor results, to the ULTRASAT sensor considering the differences in the sensor's design. The differences between the two sensors are: pixel pitch ($4 \times 4 \text{ } \mu\text{m}^2$ for SCOUT sensors and $9.5 \times 9.5 \text{ } \mu\text{m}^2$ for the ULTRASAT sensors), dual-gain read-out (implemented only for the ULTRASAT sensor) and the on-chip digital processing (implemented only for the ULTRASAT sensor).

The dominant transient noise component has been correlated to a pixel's photo diode/ sense node and was further associated to the dielectric under the transfer gate. While, the digital processing of the ULTRASAT sensor has not yet been tested in terms of radiation hardness, it is currently assumed that it will not introduce an important dark current degradation to the sensor as it employs space qualified, radiation hard active elements. For the same reasons, the additional transistor and capacitance in the ULTRASAT pixel front end is not expected to lead to a miss-match of the results for the two sensors.

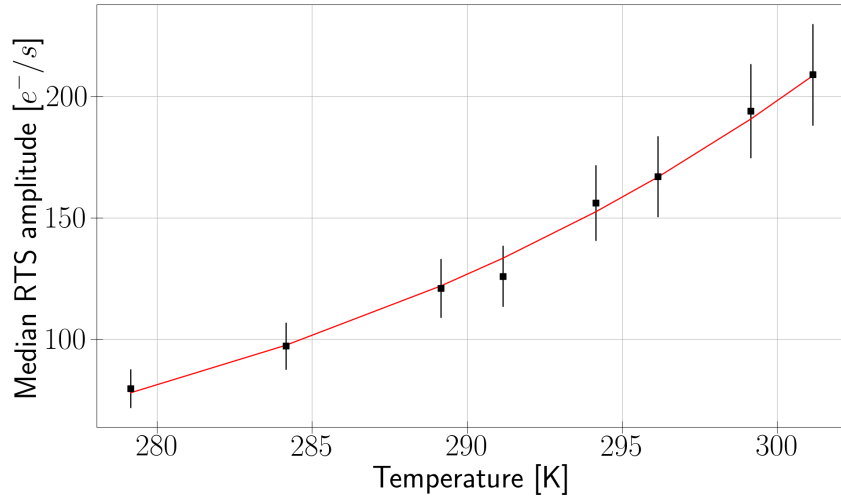


Figure 5.61: Median of the maximum RTS amplitude distribution of a 20 krad irradiated SCOUT for several temperatures. The function: $f(T) = T^2 e^{(-E/2kT)}$ fits the data. The error bars are determined by considering the systematic 10% detection precision.

The vastly different pixel sizes between the two sensors brings a slightly more complex problem, where the scalability of the SCOUT observations should be brought to question. For a homogeneous radiation source, the number of interface defect centers associated to the transfer gate scale with its area. Still, only defect centers with an electrical connection to the floating diffusion implant, meaningfully contribute to the measured dark current. The floating diffusion implant size does not scale with pixel size and is expected to be the same for the two sensors. As a consequence, the number of interface states is expected to be proportional only to the transfer gate width and not its length. This is an important distinction, as the transfer gate width is not expected to change between the two pixel designs. Furthermore, the increase in dark current for irradiated 4T CMOS imaging sensors was shown to have a definitive stronger dependence

on the transfer gate width rather than its length in Reference [33]. Thus, the results gained for the SCOUT sensors are expected to be directly compatible to the ULTRASAT sensors.

TID impact estimation for the ULTRASAT mission

The impact of RTS on the ULTRASAT mission is correlated to the magnitude of the DC ground level. If the signal jumps are within the Gaussian noise, its impact is expected to be minimal. Figure 5.62 shows the ratio between the RTS maximum amplitude and DC ground level for multiple temperatures for a sensor irradiated at 20 krad. The linear, flat dependence between the two effects highlights that the DC generation mechanism (associated to the the ground level) follows a similar temperature scaling as the RTS.

This result has been further confirmed by an independent study on the activation energy of the charge generation centers associated to the observed dark current (before irradiation) performed by Tower Semiconductor. They found a dark current activation energy of 0.55 eV for non-irradiated SCOUT samples. The match between the activation energy of the RTS defect centers and the DC shows that both effects are expected to follow the same temperature dependence. The relative impact of RTS can thus be scaled down to the ULTRASAT operational temperature.

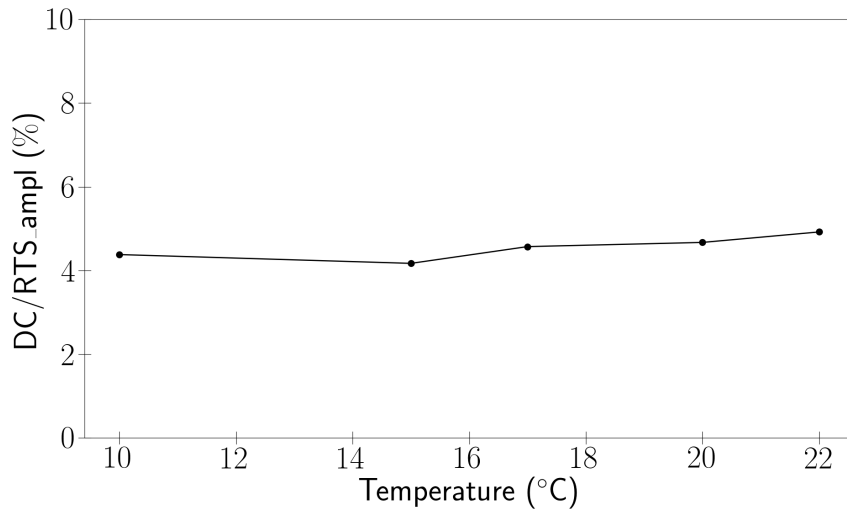


Figure 5.62: Ratio of maximum RTS amplitude and DC ground level versus temperature for a SCOUT irradiated at 20 krad.

Due to the limited parameter space available in the TID testing of the SCOUT sensors, several extrapolations and assumptions have been made:

- The TID accumulation in the ULTRASAT spacecraft is known and described in Figure 5.22.
- The magnitude of the irradiation effects is linear with the accumulated dose and can be scaled by a constant factor as shown in Figure 5.41.
- The main radiation effect that degrades the sensor noise is the DC-RTS which can be visualised in Figure 5.40.

- The DC-RTS is thermally activated, with an activation energy, $E_a = 0.56 \pm 0.10$ which is similar in scale with the activation energy of the DC defect centers, highlighted in Figure 5.62.
- The DC-RTS median amplitude increases linearly with integration time as is highlighted by Figure 5.57.
- The DC-RTS median amplitude decreases with temperature as shown in Figure 5.61.
- The magnitude of the DC-RTS amplitudes detected in the SCOUT sensors are compatible with the expected degradation in the ULTRASAT sensors. This assumption is motivated by the expected localization of the ionizing defects near the transfer gate pre-metal dielectric. Its width is expected to be similar for both the SCOUTs and the ULTRASAT sensor.
- The degradation in the signal to noise ratio of the mission is estimated for the signal from a monochromatic point-like source of magnitude m_{AB} in the operational band of the ULTRASAT mission. The magnitude to flux conversion is performed for a flux in Janski: $m_{AB} = -2.5 \lg f + 8.9$ with a pass-band in the ULTRASAT operational band-wave. The expected signal in the sensor is calculated assuming a quantum efficiency: $QE = 65\%$, a transmission of 30% , a bandwidth of $600 \text{ \AA}$ and an integration time of 300 s , which is compatible with the results shown in Figure 5.6.

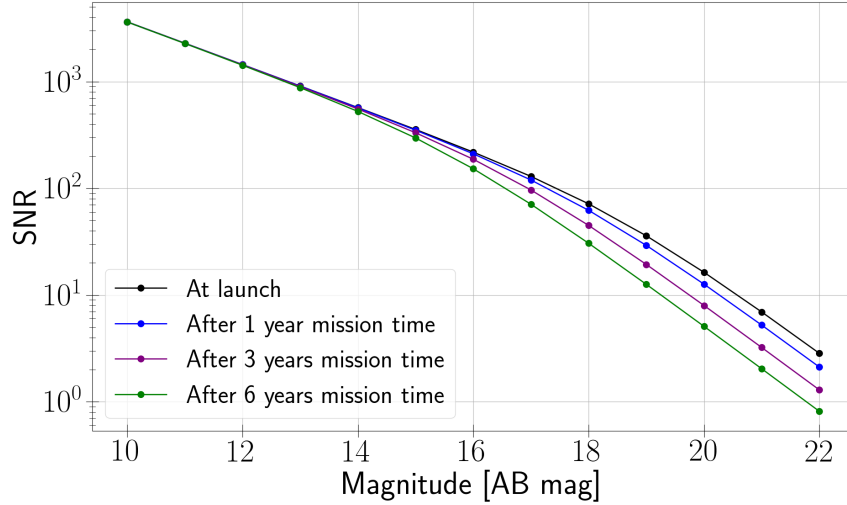


Figure 5.63: Predicted signal to noise ratio (SNR) for several m_{AB} magnitudes of monochromatic point-like sources. The degradation due to RTS is considered as an uncorrelated additional noise source which scales with the accumulation of TID for various mission life times. The plot assumes a mission launch in early 2027.

The expected signal to noise ratio degradation is highlighted in Figure 5.63. The DC-RTS has a large impact for low intensity sources (magnitude > 20 AB) but is expected to not have a large impact on high intensity sources (magnitude < 15 AB). Considering the detection limit of the ULTRASAT mission of $SNR = 5$, after three years of in-orbit operation, the camera will lose sensitivity to the faintest stars, with magnitudes up to 20.3 AB mag. After six years, the camera can expect to lose its detection sensitivity for sources up to 20 AB mag. This is further

shown in Figure 5.64, where the SNR= 5 limiting magnitude is not expected to drop under a magnitude of 20 AB.

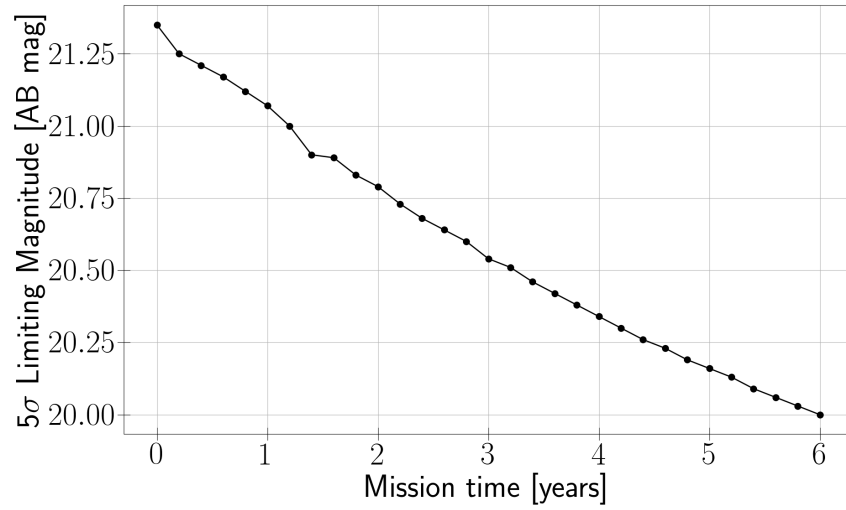


Figure 5.64: The SNR= 5 limiting magnitude for several mission times considering the DC-RTS degradation and assuming a launch in early 2027.

Considering the increase in noise and drop in charge transfer efficiency due to displacement damage, the drop in signal to noise ratio for a mission time of 3 years is shown in Figure 5.65. As expected, the ionizing damage mechanism seems to dominate.

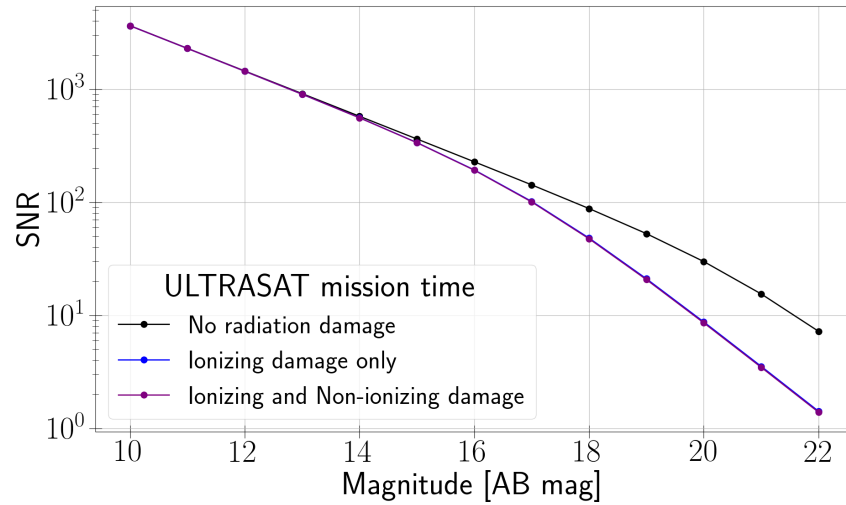


Figure 5.65: The SNR for several magnitudes of a monochromatic point-like source with a pass-band in the ULTRASAT operational wave-band for a mission time of 3 years, assuming the spacecraft launch in early 2027. The SNR before any radiation damage is plotted with black, the SNR considering only ionizing damage with blue and the SNR considering both ionizing and non-ionizing effect with purple. The blue and purple lines align due to their similar scale.

5.7 Single Event Effect study of the ULTRASAT sensor

The results discussed in this section were additionally published in the paper proceedings appended to the thesis as Paper II.

The Single Event Effect impact on the ULTRASAT sensor has been tested by exposing the sensor to heavy ions. The two effects investigated are Single Event Upsets (SEU) that affect the on-chip memory array or the sensor configuration registers, and the Single Event Latch-ups (SEL) which can appear in the digital or analog peripheral circuitry of the sensor. The memory cell array is implemented as an array of latches, 768×9 bit with an average footprint of $90.25 \mu\text{m}^2$ and the CPU registers are implemented via 260 flip-flops with an average footprint of $147.6 \mu\text{m}^2$, of which 115 were investigated. The digital block of the ULTRASAT sensor has an area of 10 mm^2 . The sensor manufacturer quotes a latch-up immunity of $60 \text{ MeV cm}^2/\text{mg}$. The heavy ion beam line was chosen in order to reach the qualification dose ($60 \text{ MeV cm}^2/\text{mg}$) +10%. Following a successful application through the RADNEXT collaboration [151], 12 beam hours have been awarded at the RADEF cyclotron facility in Jyväskylä Finland [152].

5.7.1 Experimental set-up

The experimental set-up for the SEE monitoring of the ULTRASAT sensors requires only a minimal version of the sensor read-out scheme. This is primarily due to the fact that the imaging of the pixel array was not employed during the test due to its assumed SEE immunity. This is because the functional implementation of the in-pixel front end was achieved with only n-MOSFET active elements. A mechanical mount has been designed in order to interface with the facility mounting plate and also comply with the facility's weight limitation of 5 kg. As such, the experimental set-up presented in Figure 5.66 consists of the ULTRASAT sensor, wire bonded to a flex Printed Circuit Board (PCB), connected to a Sensor Bias Board (SBB). The SBB is controlled via an EFM32 micro-controller which sets the values of the voltage lines via several digital to analog converters. Additionally, the micro-controller monitors telemetry data outputted by the sensor. An additional FPGA was used for performing a reset operation on all pixels after each power reset, in order to ensure that no electrical malfunction takes place in the pixel array. The micro-controller board is powered via a 5.5 V, 3 A power supply, while the FPGA is powered via an USB line to a lab PC. All data transfer to the PC was performed via dedicated USB UART lines.

The telemetry data of interest for the Single Event Effect testing are the analog and digital currents (latch-up testing) and the memory state of each memory cell of interest on the sensor (memory and register upset testing). The sensor currents are monitored via two registers, which were programmed to group the sensor currents into one “high” current power domain (VDDD, VDDA, VDD_{SF}) and a “low” current group (all the others). The telemetry measurements are performed with a control software at a relatively low rate of 5 Hz. The monitoring of memory upsets is performed by initially writing and then constantly reading out the entire memory array in the memory controller unit (MCU) with the same frequency. The same procedure is also performed for the sensor control registers.

In order to be able to recover the normal sensor operation after a latch-up induced high current sensor state, a latch-up monitoring and recovery procedure has been implemented with the help of the EFM32 micro-controller logic. It implements a (software) switch with a configurable current threshold ($I_{\text{thr}} = 100 \text{ mA}$ above baseline) and a time-over-threshold counter as follows. Every time the current measurements of the high current group (VDDD+VDDA+VDD_{SF}) ex-

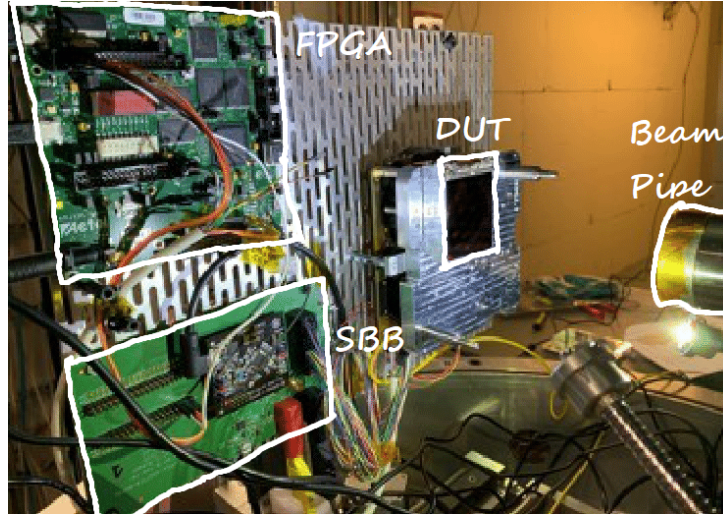


Figure 5.66: Single event effect testing set-up at the RADEF facility. The exposed sensor is mounted on a plate near the beam pipe. It is wire bonded to a flex PCB, which in turn connects to the remote electronics on the backside of the mounting. The FPGA and SBB are also mounted on the same plate. Before the commencement of the measurements, the plate is brought closer to the beam pipe, such that the sensor is only a few millimeters away from the beam pipe.

ceeds I_{thr} , an over-threshold-counter is incremented. When this counter exceeds a specified value (10 consecutive samples), the switch activates, turning off the VDDD and VDDA supplies. Simultaneously, the micro-controller stops filling a monitoring FIFO with current measurements. The time-over-threshold mechanism prevents rapid switching of the supplies in the presence of transient current spikes, ensuring that the switch remains stable and latch-up conditions are effectively detected. By following this latch-up prevention methodology, the sensor can be adequately safeguarded during irradiation. The continuous monitoring of the supply current, combined with the configurable threshold and time-over-threshold settings, ensures timely detection and mitigation of latch-up occurrences, minimizing potential harm to the sensitive electronics. Before performing the measurement campaign, the sensor's latch-up protection mechanism was tested in terms of cosmic-ray impact and noise transients. During a continuous operation for more than 100 hours, no latch-up was detected.

During the measurement, the digital and analog lines VDDD and VDDA have been set at the highest operational value: 3.6 V and all other lines have been grounded. This experimental design choice was selected in order to insure that only the digital and analog lines contribute to radiation induced current spikes, isolating any other transients, considered as second order effects in terms of testing prioritization. The design choice was influenced by a technical limitation of the circuitry, which provided only two monitoring registers for the sensor's current values. As the circuit is highly complex, it is difficult to perform a simulation in order to gauge the impact of over-currents of different magnitudes. It is expected that over-currents larger than 1 A can lead to a quick degradation of the digital circuitry if the sensor is not power-cycled within a few milliseconds.

5.7.2 Test facility

The RADEF facility at Jyvaskyla offers several ion cones. Each cone consists of several ions with similar mass to charge ratios. This allows users of the beam-line to quickly switch between ions. Additionally, the high energy of the ion cone permits the operation of the experiment in air. Before an irradiation, a single ion species is selected, ensuring a mono-energetic beam.

The LET distribution versus penetration depth of the ions employed in the experiment were simulated by the facility and are shown in Figure 5.67. The broad Bragg peaks of the beamline ensures a uniform dose deposition within the limited thickness of the $\sim 4 \mu\text{m}$ epitaxial layer. The surface LET of the beam is thus a good estimation for the effective energy deposition inside the device. An LET increase beyond this value for an ion can then be achieved by either tilting the sensor, thereby increasing the penetration depth or by attenuating the beam with additional Kapton layers. A visual representation of the effect of adding multiples of $25 \mu\text{m}$ thick Kapton layers can be seen in Figure 5.67 via the dashed gray lines. The configuration of ion and Kapton layers used during the test beam experiment can be seen in Table 5.6.

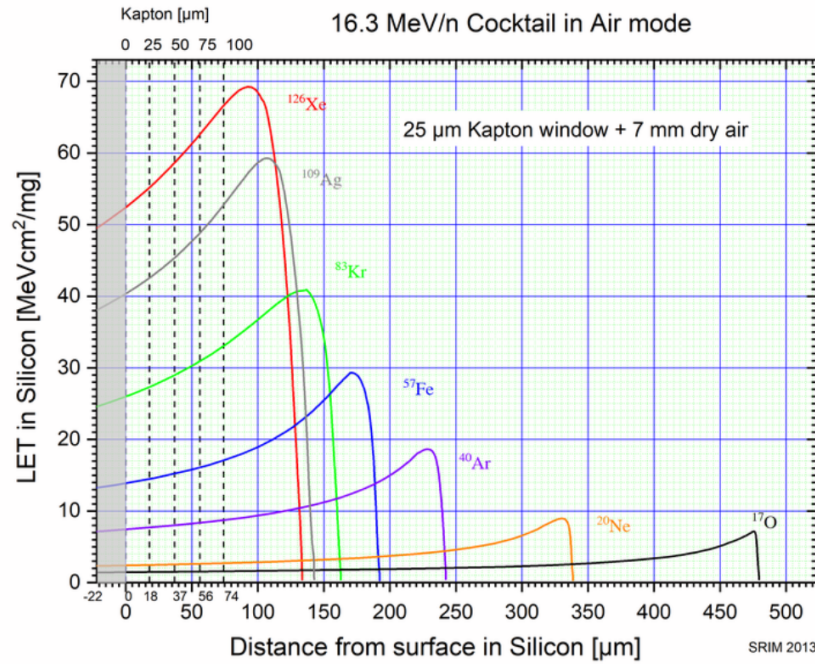


Figure 5.67: LET curves of the 16.3 MeV/u RADEF ion cones for silicon in air. Vertical dashed lines show the effective Device Under Test (DUT) surface positions when 25, 50, 75 and 100 μm of Kapton is added between the beam window and the DUT. Note: Ag ions were not available at the time of the testing campaign. Figure obtained from [152].

An electromagnetic shutter allows for the quick beam stop after the detection of a latch-up event in order to limit the unnecessary accumulation of radiation damage on the sensor. An optimized test plan has been drafted and successfully implemented in order to perform an efficient measurement campaign. The detailed test plan is described in Appendix D.

The SEE test execution was accompanied by several hardware implementation errors, which affected the pre-planned time budget for performing the measurements. As a consequence, only two sectors of the ULTRASAT sensors were tested: Sector 1 and Sector 2. No events were recorded for Sector 2, showing that the analog to digital converters and the pixel array are

Table 5.6: List of ions and number of Kapton layers used during the SEE testing of the ULTRASAT sensor. Only ions used to collect statistically significant data sets are shown.

Ion	# of Kapton layers	LET [MeV cm ² /mg]
¹²⁶ Xe	4	67
¹²⁶ Xe	2	58
¹²⁶ Xe	0	53
⁸³ Kr	4	33
⁸³ Kr	0	25
⁵⁷ Fe	0	13

latch-up immune up to 65 MeV cm²/mg. Unfortunately, Sector 4 was not investigated, such that the row decoder's contribution remains unknown, but they are not believed to have a leading order contribution. Sector 1, on the other hand, has shown a SEE sensitivity both in terms of latch-ups and upsets well under the expected qualification dose of 60 MeV cm²/mg. Single event effects correlated to the heavy ion beam have been measured in the sensor down to 13 MeV cm²/mg.

5.7.3 Single Event Effect cross-sections

The impact magnitude of the single event effects can be described via their cross-section, which is defined as the probability that after a particle interaction in the sensor, a state change of the circuit takes place. The cross-sections shown further are calculated via the following steps:

- The number of events are counted (SEs via the current measurements, SEUs via the memory and register write-read cycles).
- The number of particles per cm² incident to the sensor is calculated from the flux reported by the facility integrated for the measurement time. The flux is measured by the facility along the beam-pipe and processed by a simulation that accounts for the air plus Kapton tape attenuation (see Figure 5.67). The fluence uncertainty is believed to be <10%.
- The cross-section is derived as the ratio of these two numbers. In the case of the memory and register upsets, the cross-sections per bit [cm²/bit] have been derived. This accounts for the 6912 individual memory cells and 115 monitored registers.

Two sensors from the same wafer were irradiated during the campaign and are further referred to as DUT1 and DUT2.

Two fitting techniques have been employed on the experimental data: the Least Squares Estimation (LSE) [153] and the Maximum Likelihood Estimation (MLE) [154]. A detailed description of their implementation is given in Appendix E.

Single event upset cross-section

The memory array and control register upsets are each described via a separate cross-section motivated by their different circuit implementation. The cross-section of the SEUs in the memory array of the DUT1 is showcased in Figure 5.68. The data points are fit with both the MLE and LSE methods and yield a good fit convergence, R²>99%. The few measured data points

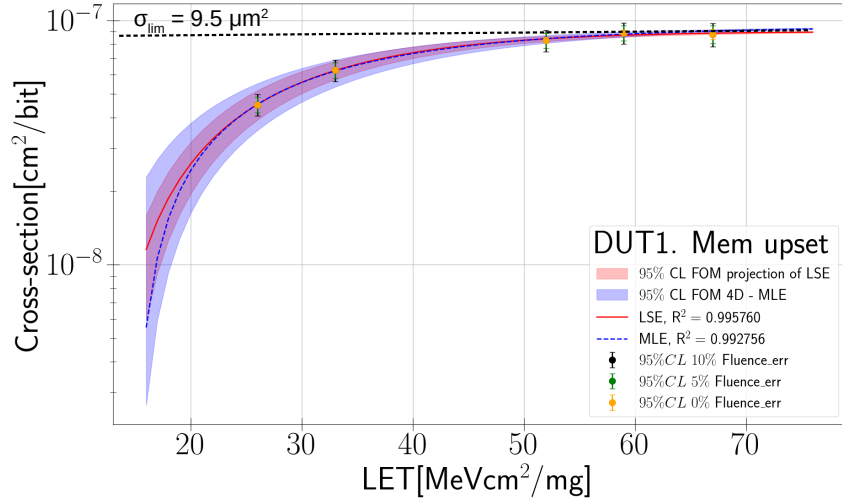


Figure 5.68: Memory Upset cross-section versus LET for DUT 1. Two fitting methods have been employed: the Least Squares Estimation (LSE) (with red) and Maximum Likelihood Estimation (MLE) (with blue). The fit contours are provided for a 95% confidence level. Additionally, the magnitude of error bars has been investigated by varying the assumed particle fluence error from 10% to 0%. The derived limiting cross-section is additionally highlighted with a dashed black line.

at low LETs ($<24 \text{ MeV cm}^2/\text{mg}$), lead to an increase in the fit contour at low values. The MLE fit has a larger contour at low LET's due to the important contribution of the Poisson fluctuations in low statistics measurement points. An investigation of the error bar magnitude was performed in order to gauge the possibility of data over fitting. Several error bars (see Appendix E) are defined by varying the flux variance from 0 – 10%. The large variations between the different error bars indicate that the estimated cross-section variance is dominated by the flux uncertainty. The initially assumed 10% flux fluctuation is an overestimation. Considering a flux uncertainty close to 0%, the appearance of data over fitting vanishes. Both fitting methods yield a well defined limiting cross-section, $\sigma_{\text{lim}} = 9.5 \text{ } \mu\text{m}^2$ and a less well defined onset LET in the range of 10 – 18 $\text{MeV cm}^2/\text{mg}$.

The same analysis chain performed on the DUT 2 data set is shown in Figure 5.69. Fit convergence issues are found when the lowest LET point is considered. Additionally, a well-defined fit contour is no longer found. The trend of this data set indicates that there is a higher cross-section at lower LET in the second DUT. The low LET measurement point was taken only for DUT2, so there is no clear indication that the discrepancy highlights a variation in the two sensor sensitivities or a low LET SEU enhancement for all ULTRASAT sensors. In fact, there is some evidence for the latter, due to the good (2σ or $O(10\%)$) match between the two DUT cross-sections highlighted in Figure 5.70.

Figure 5.71 shows the cross-section versus LET for register upsets. It highlights that both data sets match within 2σ and an enhanced cross-section for lower LET's for DUT 2 is observed. It is also clearly visible that this data set is not showing the typical turn-on behaviour. One explanation for these unexpected data trends could be the lack of optimization for upset monitoring. As the latch-up detection was the main goal of the experiment, the beam flux was optimized to ensure its accurate detection. As a consequence, a systematic effect could be the under-counting of upsets, especially at large LETs, due to the a high event frequency.

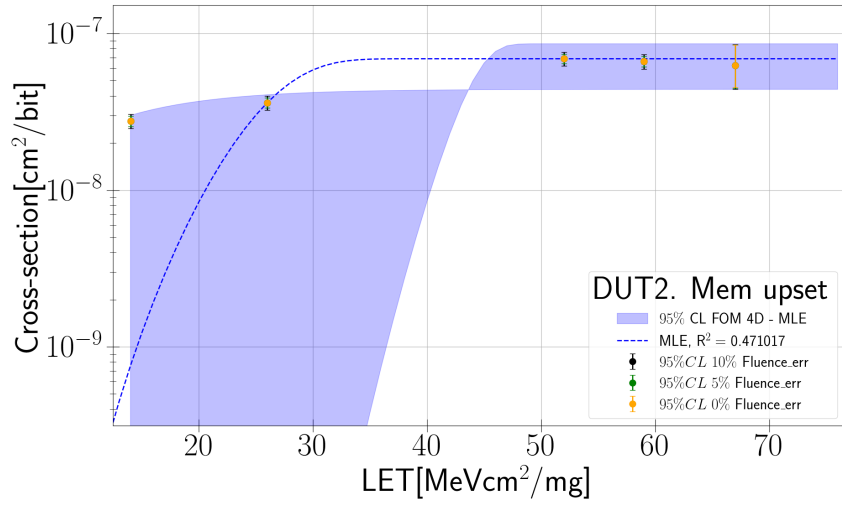


Figure 5.69: Memory Upset cross-section versus LET for DUT 2. A fit could be performed only with the MLE method. The fit converges only by ignoring the low LET point. Divergencies in the contour estimation appear for low LET values and a low R^2 of 47% is observed.

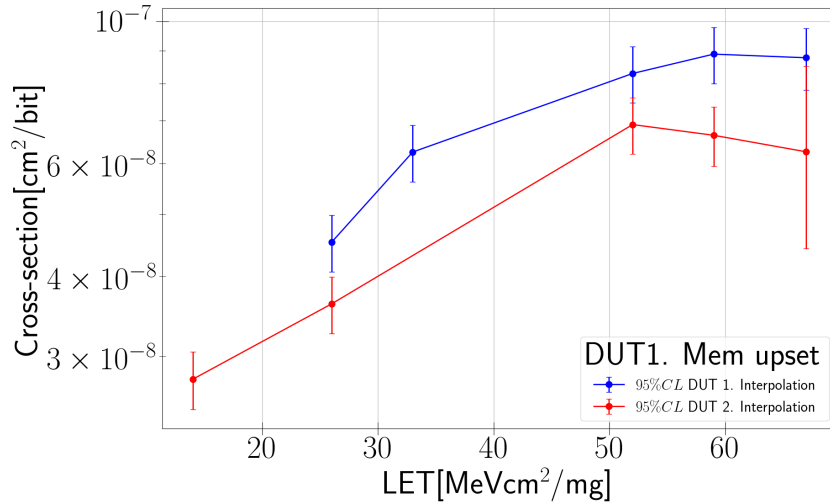


Figure 5.70: Memory single event upset cross-sections versus LET for the two DUT's: DUT1 with blue and DUT2 with red.

Single event latch-up cross-section

Figure 5.72 shows the interpolated SEL cross-section for both DUTs. Both data sets show a dramatic departure from a Weibull-like turn-on curve, resembling an exponential increase in cross-section at higher LETs.

Due to the departure of the data from the theoretically expected Weibull shape for both upsets and latch-ups, the statistical treatment of the cross-section has been performed using the Heaviside formula shown in Equation 4.16. The only parameters of interest in this approach are the LET_0 and σ_{lim} , which can not be easily derived from the acquired data set. One possible definition for these parameters is the minimum LET for which events are detected (LET_0) and the maximum cross-section detected (σ_{lim}). For simplicity, only the DUT1 data set is considered.

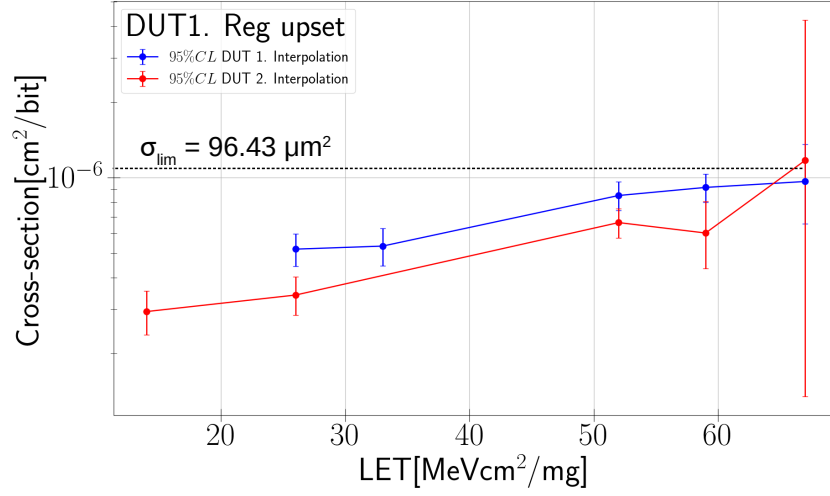


Figure 5.71: Register upset cross-sections versus LET for both measured DUT's: DUT1 with blue and DUT2 with red. The derived limiting cross-section is additionally highlighted with a dashed black line.

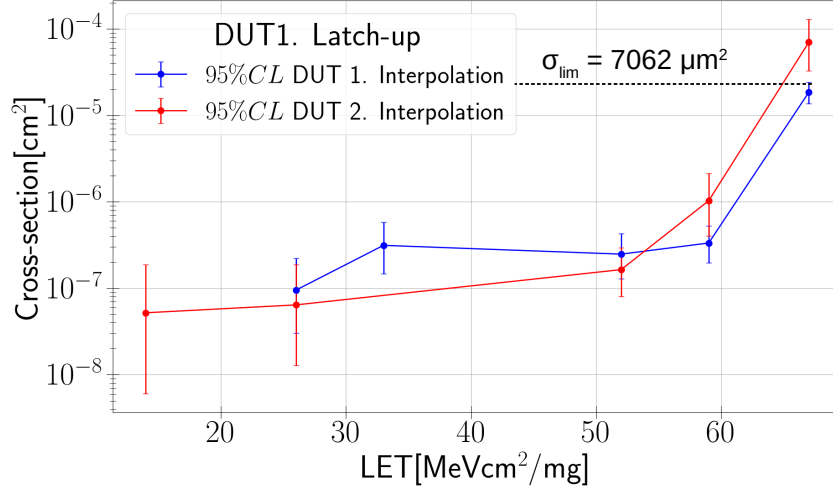


Figure 5.72: Latch-up cross-section versus LET for both DUTs: DUT1 with blue and DUT2 with red. The derived limiting cross-section is additionally highlighted with a dashed black line.

The values of the LET_0 and σ_{lim} for the three investigated effects are showcased in Table 5.7.

In the following sections, the cross-section data is used to derive single event effect rate estimations for the ULTRASAT mission. A detailed description of the rate estimation calculation is given in Appendix F.

5.7.4 Single event upset impact estimation

As was showcased in Section 5.7.3, the current data sets do not fully bound either the low nor the high LET ranges for both investigated DUTs. As a consequence, several rate estimations have been performed considering variations of the LET_0 and σ_{lim} parameters. These range from a best to worst case scenario defined by the following parameter variations:

- The turn-on of the cross-section curve, LET_0 , can vary between the lowest LET value for

Table 5.7: Heaviside function parameters derived for the different effects detected in the ULTRASAT sensor.

SEE	LET_0 [MeV cm ² /mg]	σ_{lim} [μm^2]
Memory upset (MEM SEU)	13	9.5
Register upset (REG SEU)	13	96.4
LET	13	7062.7

which events were detected, 13 MeV cm²/mg, and an arbitrarily low LET value (1 MeV cm²/mg). This values was chosen in order to avoid the contribution of the large proton flux to the total rate, which was considered a too-pessimistic estimation.

- σ_{lim} can vary between the value of the largest cross-section found by the SEU measurements and the physical area of the affected circuit block. In the case of the memory circuits, the limiting cross-section from the data is 9.5 μm^2 and the average area of a memory cell is 90.25 μm^2 . In the case of the register circuit, the limiting cross-section from the data is 96.43 μm^2 and the largest average cell area is 147.6 μm^2 .

The best case scenario is defined as the case where the experimental data gathered, fully describes the sensor's SEE characteristics. The worst case scenario is defined through the fundamental limitations on the limiting cross-section, defined by the respective component sizes and the onset LET of 1 MeV cm²/mg.

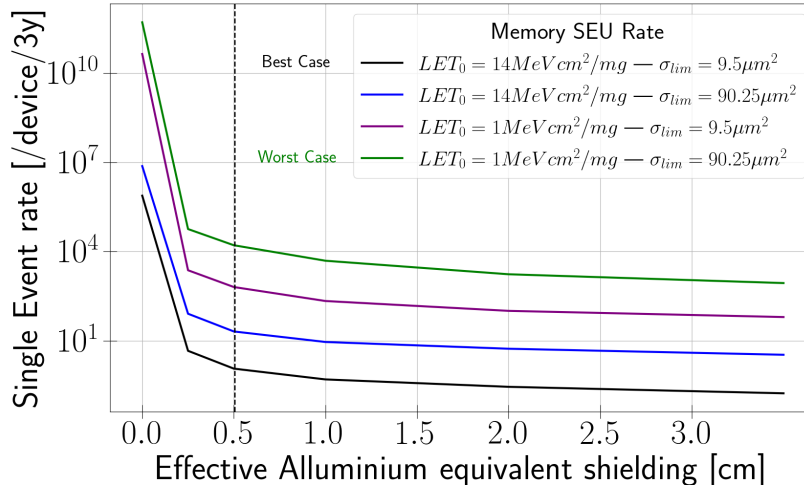


Figure 5.73: Event rate versus effective shielding thickness for memory upsets (from DUT 1). Multiple cases for the Heaviside fit parameter are chosen to give an estimation for the best case scenario (black line) and a worst case scenario (green line). The blue and purple lines provide intermediary cases by considering a mix between best and worst case parameters. The dashed vertical line marks the ULTRASAT effective shielding as per the 2021 IAI simulation.

Figure 5.73 shows the integrated rate deduced for DUT 1 for a predicted mission lifetime of 3 years. The black curve shows the impact of different shielding configurations for the best case scenario. The purple and blue curves showcase intermediary cases with a mix between best

and worst case scenario of LET_0 and σ_{lim} . The green curve highlights the worst case scenario. Several orders of magnitude difference between the worst and best case estimation is induced by the large expected high energy proton flux which is not stopped by the shielding. It can have an important contribution to the SEE rate for larger sensitive volumes and smaller onset LETs.

It is also noteworthy that Figure 5.73 shows that the shielding impact on the derived rates is relatively modest above the effective value of 5.05 mm. Only at smaller values ($\lesssim 3$ mm), the SEE rate increases significantly.

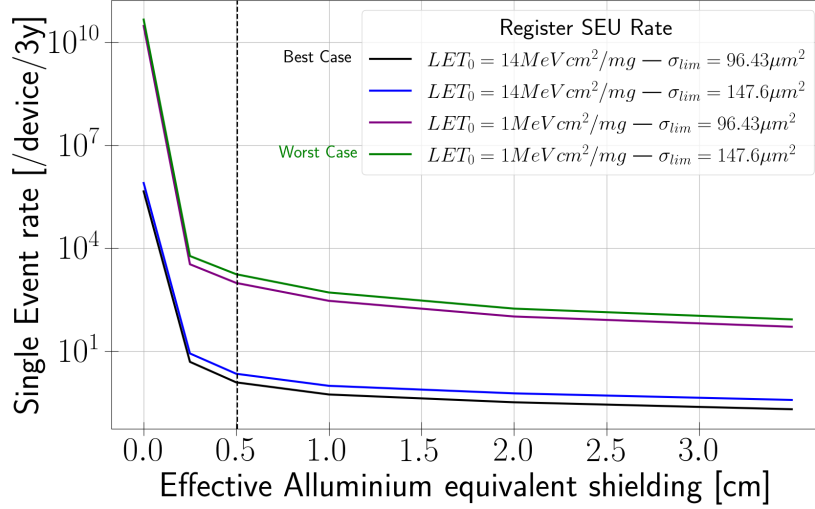


Figure 5.74: Event rate versus effective shielding thickness for register upsets. Multiple cases for the Heaviside fit parameter are chosen to give an estimation for the best case scenario (black line) and worst case scenario (green line). The blue and purple lines provide intermediary cases by considering a mix between best and worst case parameters. The dashed vertical line marks the ULTRASAT effective shielding as per the 2021 IAI simulation.

Figure 5.74 shows a similar parameter scan for the register SEUs. The LET_0 parameter has a larger impact than σ_{lim} on the predicted rate. As for the memory upset results, multiple orders of magnitude are seen between the best and worst case scenarios.

5.7.5 Single event latch-up impact estimation

The theoretical model applied for the upset rate calculation is not rigorously applicable for the latch-ups. This is due to the different formation mechanism of a latch-up and due to the ill-defined latch-up sensitive volume as compared to the case of memory cells or registers. As a consequence, the σ_{lim} parameter space is very large (with a maximum of 10 mm^2 , the geometrical area of the digital block). The parameter variations were done in the range of: LET_0 values of 1 and 13 $\text{MeV cm}^2/\text{mg}$ and σ_{lim} values of $7.06 \times 10^{-5} \text{ cm}^2$ and 0.1 cm^2 .

Figure 5.75 shows the integrated latch-up rate for the mission lifetime in the four scenarios of LET_0 and σ_{lim} . Given the lack of a turn-on behavior of the measured cross-section, the current approach yields potentially inaccurate predictions even for the smallest rates shown in the figure. In order to understand the deviation of the data set from the theoretically expected behavior, a further investigation of the SELs was pursued.

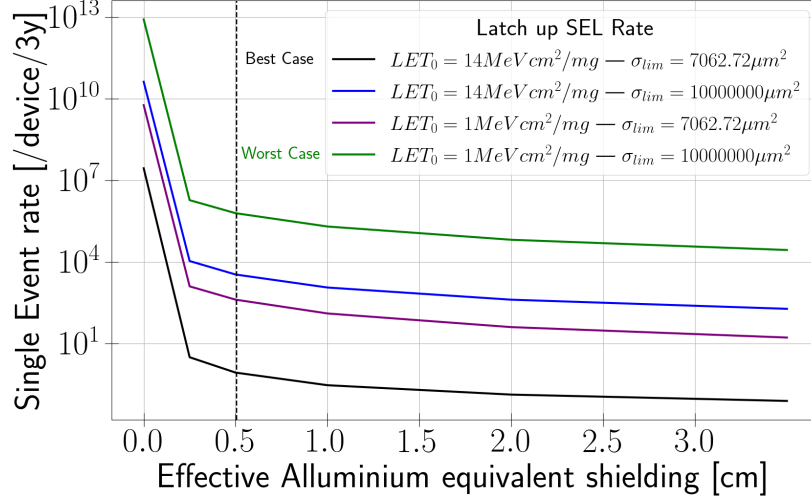


Figure 5.75: Event rate versus effective shielding thickness for SEL's. Multiple cases for the Heaviside fit parameters are chosen to give an estimation for a best (black line) and a worst case scenario (green line). The blue and purple lines provide intermediary cases by considering a mix between best and worst case parameters. The dashed vertical line marks the ULTRASAT effective shielding as in the 2021 IAI simulation.

As mentioned before, the latch-up detection is based on monitoring over-currents, in a combined fashion from the VDDD, VDDA, VDD_{SF} domains. A first understanding of the latch-up data set can then be derived by looking at the distribution of over-currents detected at the onset of a latch-up event.

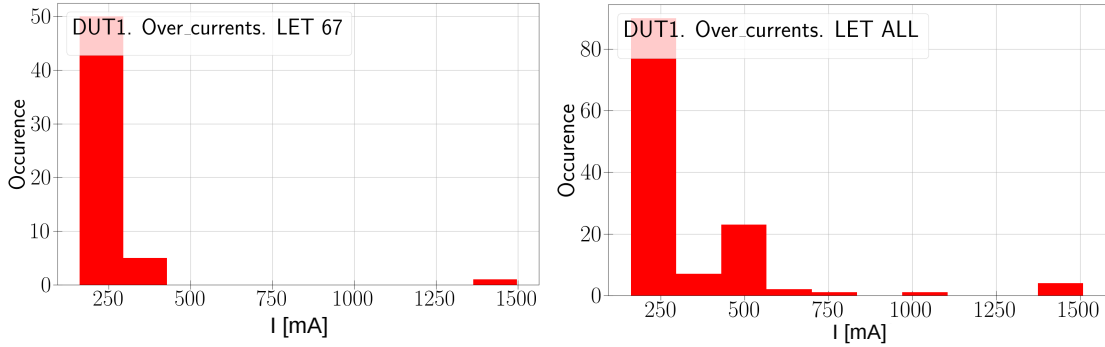


Figure 5.76: Histogram of the monitored over-currents for the latch-up events detected while irradiating with particles at LET of 67 MeV cm²/mg (left plot) and for all LET points (right plot).

Figure 5.76 shows the distribution of the detected over-currents for all measurement points (right plot) and only the highest LET measurement point (67 MeV cm²/mg) (left plot). A trend in the data can be seen, which indicates that higher energy depositions lead to lower over-currents. We interpret this as an indication of two latch-up mechanisms: a “classical” latch-up mechanism that leads to the creation of circuit latch-up states at large over-currents (≥ 250 A), and a micro latch-up mechanism that leads to only a circuit element latching up which leads to a smaller current increase. This is further evidenced by the gradual step-like increase in the drawn current for some detected over-current events. This effect was observed for

one of the highest LET measurement points by momentarily turning off the latch-up protection mechanism. This effect was associated with several consecutive micro latch-ups [155]. This measurement was performed only once due to the inherent risks associated with the disabling of the latch-up safety mechanism and were not recreated for any other LETs. Figure 5.77 shows the latch-up cross-section divided into a “low” LET regime ($<59 \text{ MeV cm}^2/\text{mg}$) with blue and a “high” LET regime ($>59 \text{ MeV cm}^2/\text{mg}$) with black. By dividing the data set into two different latch-up mechanisms, the current model rate estimations are more realistic.

For the “high” LET latch-up case, the onset LET is fixed $\text{LET}_0 = 59 \text{ MeV cm}^2/\text{mg}$ and σ_{lim} is varied between the measured value of $1.95 \times 10^3 \mu\text{m}^2$ (best case) and the total physical area of the MCU, 10 mm^2 (worst case). The predicted rate is then found to be between 4.03×10^{-3} events for the best case scenario and 1.92×10^2 events for the worst case scenario for the 3 year mission lifetime.

In the “low” LET latch-up case, the σ_{lim} is fixed at the measured cross-section of $31.9 \mu\text{m}^2$, LET_0 is varied between 1 (worst case) and $13 \text{ MeV cm}^2/\text{mg}$ (worst case). This leads to a rate prediction between 8.09×10^{-4} in the best case scenario and 5.62×10^{-1} in the worst case scenario for the 3 year mission lifetime.

While the current data set contains multiple limitations due to the unexpected low and high LET sensor behaviour, absolute best and worst case rate boundings can be made for the ULTRASAT mission. Table 5.8 summarizes the up-to-date estimations of the upset and latch-up predicted rates using the current data set and the known average sensitive component sizes and assuming the 2021 effective satellite shielding.

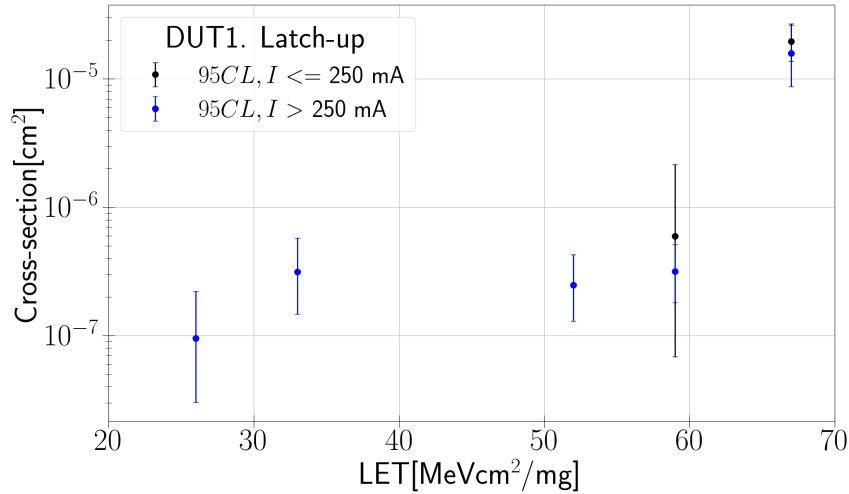


Figure 5.77: Cross-section versus LET for the latch-up events detected for one of the measured DUTs (DUT 1). The data points that measured over-currents larger than 250 mA (blue) and over-currents smaller than 250 mA (black) are plotted.

The SEL [ALL LET] values are grayed out because splitting the data set into low and high LET regions was found to yield more realistic estimates. The LOW and HIGH rates in the table are to be added together, in order to reach a total SEL rate. The large error bars in the predicted rate for the SEUs are motivated by the lack of clear understanding of the impact of low LET particles on the event cross-section. This uncertainty is planned to be studied in a secondary measurement campaign.

These results have driven an effort of designing and implementing a fast and efficient latch-up

Table 5.8: Summary of the best and worst case predicted rates for the ULTRASAT mission, considering a launch in early 2027 and a mission lifetime of 3 years.

SEE	Case	Predicted Rate [# of events/ mission lifetime]
MEM SEU	Best Case	1
	Worst Case	16174
REG SEU	Best Case	1
	Worst Case	1732
SEL [ALL LET]	Best Case	8.63E-1
	Worst Case	6.27E+5
SEL [LOW LET]	Best Case	8.09E-4
	Worst Case	5.62E-1
SEL [HIGH LET]	Best Case	4.03E-3
	Worst Case	1.92E+2

detection and mitigation mechanism for the ULTRASAT sensors. The relatively low predicted latch-up rate will not degrade the performance of the sensor. The SEUs are not expected to lead to large impacts on the mission performance even though the expected event rate could be relatively high. Any image corruption or temporary operation loss of the camera due to SEUs is not expected to lead to a large data acquisition degradation of the satellite.

5.8 ULTRASAT Conclusions

This section detailed the studies of predicting the impact of radiation damage on the sensors for the ULTRASAT space mission. Reliable predictions on the particle fluxes expected in orbit have been made showing a large impact from both trapped and solar particles. Their contributions has however been found to be highly suppressed by the ULTRASAT spacecraft shielding. A particle transport simulation through the calculated equivalent shielding of the space mission has found that for 3 years of GEO orbit operation after a launch in early 2027 an ionizing dose of 20 – 30 krad and a displacement damage dose of $\sim 10^{10}$ 1 MeV n_{eq}/cm^2 will be incurred. In the case of further mission launch delays, it was found that the particle flux can change. Only the predicted displacement damage estimation was found to have a significant impact for mission launches later than 2027. Its suppression is correlated to the solar minimum cycle. As a consequence, the predicted particle flux was found to provide an accurate estimation for the ULTRASAT mission conditions.

The cumulative effect of the displacement damage was estimated with the help of parametric degradation equations. Assuming the validity of the NIEL hypothesis, a prediction on the charge transfer efficiency of 2% and at most a doubling of the bulk generated dark current at operational temperature is expected.

The cumulative effect of TID was estimated with the help of a systematic study of pixel test structures, called SCOUTs. The radiation testing with Co-60 gamma sources of several similar samples (>12) showed that the sensors were more sensitive to ionizing damage than initially expected. The main impact of the incurred TID was related to the sensor’s dark current. The main source of radiation damage was attributed to dark current random telegraph signal and was correlated to the operation of the pixel’s transfer gate at ground in its off state. A

literature review [156] found several studies which show that the operation of the transfer gate in pinned photo diode CMOS Imaging Sensors at non-negative bias voltages leads to an “always on” resistive channel between the photo diode and sense node (depletion mode). A dedicated algorithm for the detection and analysis of Random Telegraph Signal was developed in the python programming language with the aim to perform large statistics studies on the observed Poissonian distributed random effect.

The results gained for the SCOUTs were extrapolated to the ULTRASAT sensors. This was highly non-trivial due to the many differences in the two sensors. Firstly, due to the similar fabrication process, the radiation damage incurred in SCOUTs was assumed to be proportional to the ULTRASAT sensors. This assumption was found to be plausible due to the assumed origin of the radiation defects. Comparing the results to an RTS overview paper [33], the most probable defect location was attributed to the pre-metal dielectric under the Transfer Gate, which is expected to have a similar width for both the SCOUT and the ULTRASAT sensor.

The linearity of the SCOUTs were found to hold for integration times up to 3 s, such that an extrapolation had to be done for the expected integration time of the ULTRASAT sensors of 300 s. Lastly, a dedicated activation energy study of the radiation induced RTS defect centers was performed to gauge their temperature scaling. An activation energy of 0.56 ± 0.10 eV was found, showing a very good match to the expected Shockley-Read-Hall mechanism of deep defects in the silicon mid-gap.

Employing several assumptions, the results gained for the SCOUTs were scaled to the in-orbit operational conditions of the ULTRASAT sensor. The impact of the DC-RTS on the scientific mission was made in terms of the sensor’s signal to noise ratio degradation. It was estimated to impact the detection threshold of the mission for an arbitrary monochromatic source, lowering the sensor’s limiting AB magnitude from 21.27 to 20.5 AB mag after three years of TID degradation. This result should be interpreted in relative terms, as a thorough light source consideration was not pursued in this thesis as was the case of the SNR and limiting magnitude results in Reference [109]. Additionally, displacement damage was found to lead to negligible effects in terms of the SNR degradation.

During the mission life-time several decontamination procedures are planned. During these, the camera’s temperature will be raised to ~ 343 K for several days. This is expected to lead to an improvement of the sensor parameters previously degraded by radiation.

In the second half of this chapter, the impact of single event effects on the ULTRASAT space mission was estimated. An unique investigation technique for poorly bound data sets of SEE sensitive devices was designed. For most experiments [157][158][159], a dedicated radiation hard design severely limits the statistics of the data gathered during a heavy ion beam-line test. In our case, we collected large data sets, that allowed us to gain a deeper understanding of the radiation sensitivity of the technology nodes employed.

The rate estimation bounding in terms of best and worst case scenarios allowed for the formulation of absolute rate estimations for the final ULTRASAT mission. Furthermore, the development of independent analysis tools (for data fitting and rate estimation) have allowed a deconstruction of the final rate results. They shed light on the main particle species and energy domains that could impact the operation of the space mission. This analysis can further be used for optimizing future measurement campaigns in terms of the scanned parameter space.

5.9 Outlook

Before the launch of the mission, a dedicated TID testing campaign is planned on several (>2) ULTRASAT sensors. The test campaigns will follow a similar test flow as presented in this thesis and will aim to validate the radiation damage predictions extrapolated from the SCOUT results. Additionally, neutron irradiation campaigns are planned in order to gauge the true impact of the displacement damage on the sensor parameters.

Preliminary optical measurements of the ULTRASAT sensor showed that a small amount of pixels are affected by a similar RTS noise source (as observed for the SCOUT sensors) even for non irradiated samples. Additionally, ULTRASAT sensors irradiated with heavy ions were measured in terms of their dark current degradation. The exposed pixel array was found to have an elevated average dark current value. The sector exposed to a TID close to 55 krad, recorded only saturated pixels at room temperature, showing some concerning results. This result further highlighted the urgency of performing the TID testing on the flight grade sensors. Furthermore, it raised concerns on the possible elevated effect of the displacement damage contribution to the total dark current degradation.

The single event effect test results have led to several changes to the space mission. A hardware latch-up protection has been designed within the remote camera electronics to ensure a fast ($<1 - 2$ ms) power cycle of the sensor in the case of a prolonged over-current sensor state.

A second SEE measurement campaign was planned and performed at the SIRAD facility [160] in Padova, Italy with the aim of characterizing the low (<13 MeV cm²/mg) and high LET (>65 MeV cm²/mg) SEE cross-sections. This will further increase the accuracy of the SEE rate estimations. Additionally, during this test, the ULTRASAT sensor sector which contains only the row decoders and pixel array was investigated in order to unequivocally find the source of the latch-ups (which is currently assumed to be the digital circuitry of the sensors' micro controller unit). In order to gain further information regarding the source of the latch-ups in the ULTRASAT sensor, the analog power supply was varied between 3.6 and 2.5 V. This was expected to impact the occurrence of transient analog current spikes due to erroneous bit configurations (induced by upsets), which at the moment is a contested effective latch-up source within the ULTRASAT collaboration. Lastly, the two investigated DUTs were placed with a relative orientation of 90° between them. This technique compounded with the relative tilt of the detector assembly in relation to the heavy ion beam will give a measurement on the X and Y dimensions of the sensitive volumes for both upset and latch-ups. The data gained during this campaign is currently being analyzed and the results are planned to be used in a publication which is currently being prepared. Preliminary data show evidence of two latch-up mechanisms that match relatively well the “low” and “high” over-current assumption made in this thesis. The elevated latch-up cross-section at large LETs is currently attributed to an upset-induced high current state in the analog domain, which can be recovered from via a memory re-write operation.

An additional test venue for SEEs is the use of a pulsed laser for scanning the ULTRASAT sensor. This technique would be especially desirable to be employed for the ULTRASAT sensors due to the back side imaging process which allows for direct laser penetration to the electronics sensitive layer, bypassing the metal lines. Such a study could aim to find a better bounding on the sensitive volumes of the upset affected memory cells and find sensitive volumes of localized latch-up sources. These measurements could additionally be elevated to quantitative results in terms of cross-section determination for several effective LETs controlled by the laser intensity. This step however would be highly non-trivial and would require a calibration of the laser

intensity to an effective LET value, which can be further complicated by non-linear effects associated to large intensity beams (e.g. Two Photon Absorption [161]).

Chapter 6

Radiation damage study of the MALTA tracking sensor

This chapter describes the design and iterative development of the MALTA sensor. Initially, the ALIPDE pixel design is discussed and its development towards more radiation hard designs is explored. Section 6.1 details the design and operation of the MALTA sensor. Section 6.2 introduces the next iteration of the MALTA sensor, MALTA2 and explores its improved design and performance in terms of threshold, noise and tracking efficiency. Sections 6.3, 6.4 and 6.5 introduce the tools, experimental set-ups and irradiation facilities employed for the radiation hardness studies of the MALTA2 sensor. Section 6.6 explores the TID radiation hardness of the sensor and Section 6.7 investigates the displacement damage hardness. Section 6.8 pursues a detailed study of the sensor's depletion depth, correlating it to the previous results as the main radiation hardness parameter for a monolithic tracking sensor.

MALTA stands for Monolithic ALICE To ATLAS. The collaboration aimed to translate the ALICE Pixel Detector (ALPIDE) design for the ALICE Inner Tracking System (ITS) to the ATLAS Inner Tracker (ITk) for the High Luminosity LHC (HL-LHC) upgrade. The sensor design aims to provide a high tracking efficiency, in a binary hit/no hit information scheme. The charge information of a hit, for example via Time over Threshold (ToT) is not implemented in the sensor design.

The ALICE experiment replaced their entire inner tracker with a fully MAPS based detector during the second long shutdown of the LHC in 2019. The advantages of a fully monolithic detector have already been explored in Section 3.4. The sensor was designed [162] in the Tower 180 nm imaging process for an Epi grown thin silicon layer with a thickness between 18 - 40 μm and a resistivity between 1 - 8 $\text{k}\Omega\text{cm}$. A thin gate oxide of 3 nm was employed in order to limit the impact of TID on the operational voltages of the on-chip active elements [163][164]. The pixel is based on the small collection electrode ($\sim 2 \mu\text{m}$, 2 fF capacitance) design discussed in Section 3.4. A cross-section of the pixel can be seen in Figure 6.1. As the figure suggests, the small collection electrode leads to a non-planar junction and a partially depleted pixel volume.

6.1 The MALTA sensor

The MALTA sensor builds upon the ALPIDE design, adapting it for the ATLAS outer pixel layers harsher radiation hardness requirements. While the planned ITk upgrade will employ hybrid pixel sensors [165], the MALTA sensor R&D follows the same design requirements in

order to show the viability of the technology for current and future collider experiments. The outer barrel of the ITk is planned to remain operational up to 4000 fb^{-1} of accumulated luminosity. The expected accumulated dose during the Phase II upgrade both in terms of TID and displacement damage was simulated by the ATLAS collaboration and summary results are shown in Figure 6.2. The outer pixel layers (highlighted in the plot with black boxes) expect an end of life dose of $1.5 \times 10^{15} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$ NIEL and $\sim 100 \text{ Mrad}$ TID. Additionally, a good timing response is needed in order to achieve the rigorous timing requirements imposed by the 25 ns LHC bunch crossing and a high-speed readout architecture to cope with the high hit rates of $2 \text{ MHz}/\text{mm}^2$. These additional requirements, have motivated the developments discussed further.

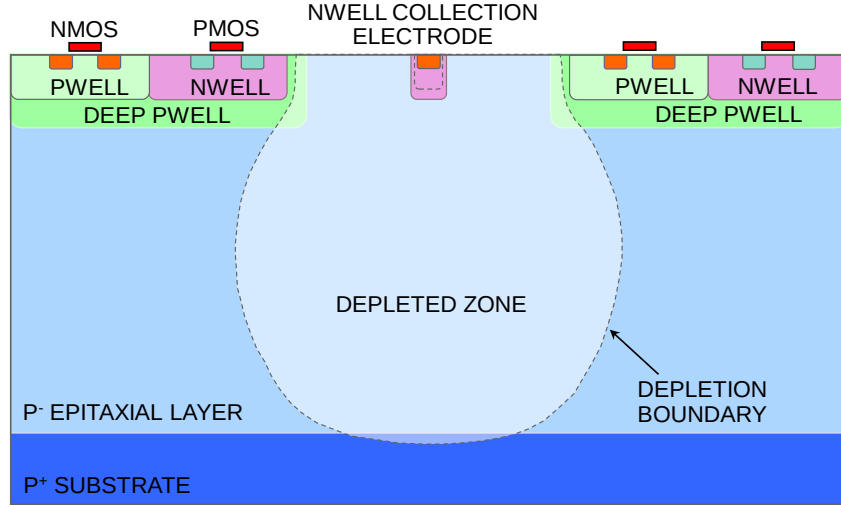


Figure 6.1: Cross-section of the process of the small collection electrode pixel implemented in the ALPIDE chip.

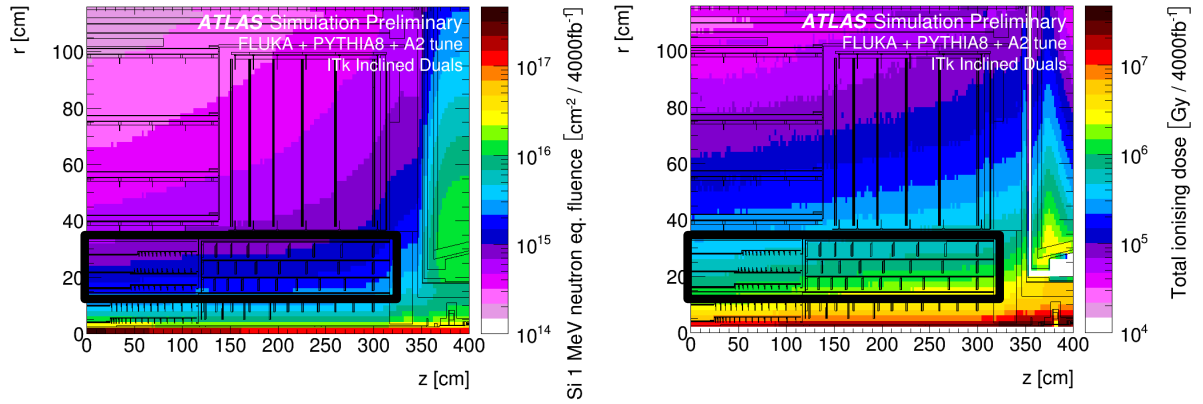


Figure 6.2: 1 MeV neutron equivalent fluence (left) and total ionising dose (right) per 4000 fb⁻¹ of integrated luminosity in the ATLAS Inner Tracker. More information on the simulation can be found at Reference [166]. The black rectangles highlight the outer pixel layer of the ATLAS ITk which matches the initial target of the MALTA development.

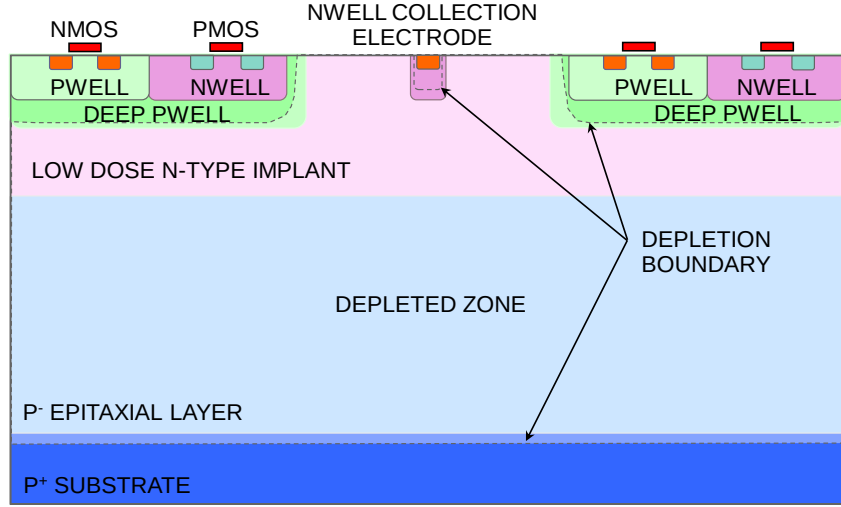


Figure 6.3: Cross-section of the modified process, implementing a small electrode pixel, as in the original ALPIDE chip. The additional low dose n-type implant (also referred to as n- layer) is expected to extend the junction to the full pixel size.

6.1.1 The modified standard process

The additional timing and radiation hardness requirements for the MALTA sensors have motivated the implementation of an additional relatively low doping concentration n-type implant underneath the n-well in which the collection electrode resides. Figure 6.3 shows the cross-section of the modified process, often called the “modified standard” or STD for short. The n-type implant is selected to have a sufficiently low dose, such that it can be depleted at low bias voltages (-6 V), leading to no significant input capacitance increase. The main effect of the STD process is the creation of a planar junction which extends across the entire pixel volume.

The MALTA sensor implements a 512×512 pixel array, with a symmetrical pixel of $36.4 \times 36.4 \mu\text{m}^2$ and a total sensing area of $2 \times 2 \text{ cm}^2$. The sensor was initially implemented only on epitaxial silicon of varying thickness: $25\text{--}30 \mu\text{m}$. It is divided into 8 sectors that implement several modifications highlighted in Figure 6.4. Two pixel reset schemes have been considered: a diode reset and a p-MOS reset. The diode reset leads to a more compact design. It is implemented as a small p-well in the n-well collection electrode but has the drawback that the reset current depends on the leakage current. Alternatively, the p-MOS reset has a significantly larger footprint but the reset current is fixed by a bias current I_{RESET} . An octagonal collection electrode is implemented in all designs with varying size ($2 - 3 \mu\text{m}$), which slightly impacts the input capacitance of the front end. The separation between the n-well and the p-well was also varied between 3.5 and $4 \mu\text{m}$. A larger spacing leads to a higher punch-through current threshold and a smaller sidewall junction capacitance. Lastly, two shapes of the p-well implant have been considered, denoted as medium and maximum p-well extension.

The biasing of the sensor is performed by applying two voltages called SUB and PWELL in addition to all the voltage lines for the analog and digital pixel front end. The SUB voltage is applied on the sensor backside, while the PWELL voltage is applied to the well that contains the in-pixel electronics.

S0	S1	S2	S3	S4	S5	S6	S7
diode reset	diode reset	diode reset	diode reset	PMOS reset	PMOS reset	PMOS reset	PMOS reset
2 μm el. size	2 μm el. size	3 μm el. size	3 μm el. size	3 μm el. size	3 μm el. size	2 μm el. size	2 μm el. size
4 μm spacing	4 μm spacing	3.5 μm spacing	3.5 μm spacing	3.5 μm spacing	3.5 μm spacing	4 μm spacing	4 μm spacing
med. deep p-well	max. deep p-well	max. deep p-well	med. deep p-well	med. deep p-well	max. deep p-well	max. deep p-well	med. deep p-well

Figure 6.4: The MALTA sensor sectors differentiating between different pixel geometries.

6.1.2 MALTA Analog Front End

The analog front end of the MALTA sensor inherits the pixel hit discrimination architecture of the ALPIDE sensors [167]. The schematic of the analog front end is presented in Figure 6.5. The working principle of the front end is based on the charge transfer from a large to a small capacitance. The collection electrode acts as a diode that collects the input charge (Q_{IN}) produced by an incident particle. The discharging of the diode into the reset circuit (input capacitance of ~ 230 aF) generates a negative pulse $\Delta V_{\text{PIX_IN}} = Q_{\text{IN}}/C_{\text{IN}}$, which is fed into the M1 transistor gate. The M0 transistor acts as a current source (IBIAS). If the operational point of the M3 transistor is tuned appropriately, the M1 transistor functions as a source follower, effectively transferring the source charge to the OUTA terminal. The voltage pulse at the OUTA terminal is given by:

$$\Delta V_{\text{OUTA}} = \frac{Q_{\text{source}}}{C_{\text{OUTA}}} = \frac{C_{\text{S}}}{C_{\text{OUTA}}} \Delta V_{\text{PIX_IN}} \quad (6.1)$$

C_{OUTA} is given by the parasitic capacitance of the OUTA branch. The signal at V_{OUTA} has a large amplification if $C_{\text{S}} \gg C_{\text{OUTA}}$. The M2 transistor acts as a cascode in order to limit the input capacitance of the input transistor M1 (given by the Miller effect [168]).

The matching of the operational point of the M3 transistor is difficult, so a low frequency feedback circuit is used. The M4 transistor is biased via a current I_{THR} , much smaller than I_{BIAS} . Its purpose is to minimize the $I_{\text{BIAS}} + I_{\text{THR}}$ on the M3 transistor and adjust its operating point. Additionally, the M4-M5 transistor branch define the OUTA baseline. After a particle hit, the OUTA is set to high, reducing the M5 transistor voltage. As a consequence, I_{THR} is forced to charge up the M3 transistor, discharging the OUTA signal, leading to a return to baseline. The VCASN supply defines the baseline and the I_{THR} defines the speed of the return to baseline. A secondary gain mechanism is implemented by connecting the C_{S} capacitance to the feedback loop. Part of the source charge travels to the M3 transistor and gets amplified

due to its transconductance. In order to cope with large signals (large amplitudes and wide charge collection), a voltage clipping mechanism has been implemented via the M6 transistor. The VCLIP voltage defines the threshold of the clipping mechanism, which ensures that large charge events have a fast return to baseline.

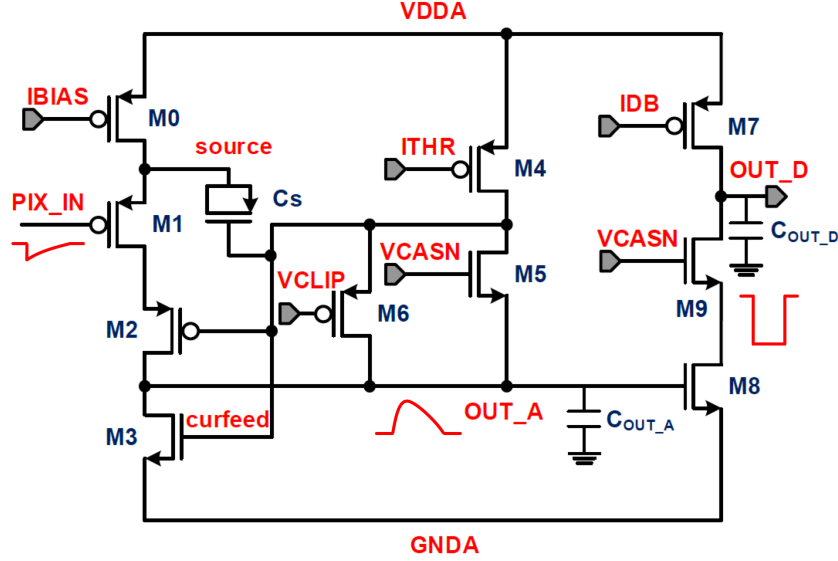


Figure 6.5: Schematic of the MALTA analog front end circuit based on the ALPIDE front end [167], [169]

Lastly, a discriminator branch is implemented with the help of the M7-M9 transistors. The branch acts as a current comparator with a threshold set via the IDB line and baseline set by VCASN. The M9 transistor acts as a cascode in order to limit the output capacitance. The current through M8 increases due to the pulse on OUTA. If it bypasses the IDB current, then a pulse of variable length ($V_{REF} = 0.5 - 2$ ns) is transmitted to the digital OUTD node. The threshold setting leads to an efficient hit detection if it raises sufficiently above the noise of the sensor.

The threshold of MALTA2 can be measured with an in-pixel charge injection test capacitance (~ 300 aF). The pixel threshold is measured as the 50%-occupancy point of the hit occupancy (number of times a hit is generated by an injected charge) versus the injected charge “S-curve”. The electron calibration is achieved via special analog pixels placed on the edge of the active pixel matrix. They are able to output the OUTA voltage, bypassing the comparator branch and the in-pixel digitization. Figure 6.6 shows the energy calibration performed with a Fe-55 radioactive source. The calibration is achieved by matching the ratio of amplitudes for the two $k-\alpha$ and $k-\beta$ peaks to the difference of the two peak energies: 5.19 and 6.49 keV. The optimal low threshold operation of the MALTA front end has been found to be $\sim 200 e^-$.

6.1.3 Asynchronous readout

The MALTA sensor’s pixel matrix is effectively divided into 256 parallel double columns. Each double column is in turn divided into 32 groups of 16 pixels as shown in Figure 6.7. The double column readout ensures that clusters of pixels that span multiple pixel groups can be distinguished. Following a particle hit, a pixel generates a reference pulse of varying length as

described in Section 6.1.2. Following, a 22 bit word is generated in the digital front end, which consists of: bit 0 - the reference, bits 1 – 16 - the pixel address, bits 17 – 21 - the group address. If multiple hits within a group are detected in a window of <2 ns, several bits are set to high in a MALTA word. Usually, in-group clusters are sufficiently separated in time, in order to form distinct words. The double column bus has an 18.6 mm height. In order to be able to calibrate the timing difference between different groups (due to their word propagation time) the words are stored in NAND gates acting as buffers. At the end of the double column, the hits are merged on a $22 + 1$ bit wide bus, where the additional bit encodes the “parity” of the original column bus. The merging of all 256 double columns is performed in a similar fashion. Words that arrive simultaneously are delayed via a priority arbitration stage which keeps track of the delay by adding 3 delay count bits. The double column ID is encoded via 8 additional bits. The synchronization with the LHC bunch crossing can be achieved with the help of 2 bunch ID bits. Finally, 4 chip ID bits can be added to distinguish between different sensors. The 40 bit wide word is summarized in Table 6.1 and is further transmitted via 40-bit wide parallel Low Voltage Differential Signalling (LVDS) drivers operating at up to 5 Gbps. The data is transmitted to an FPGA First In First Out (FIFO) buffer memory and saved on the disk of a lab PC.

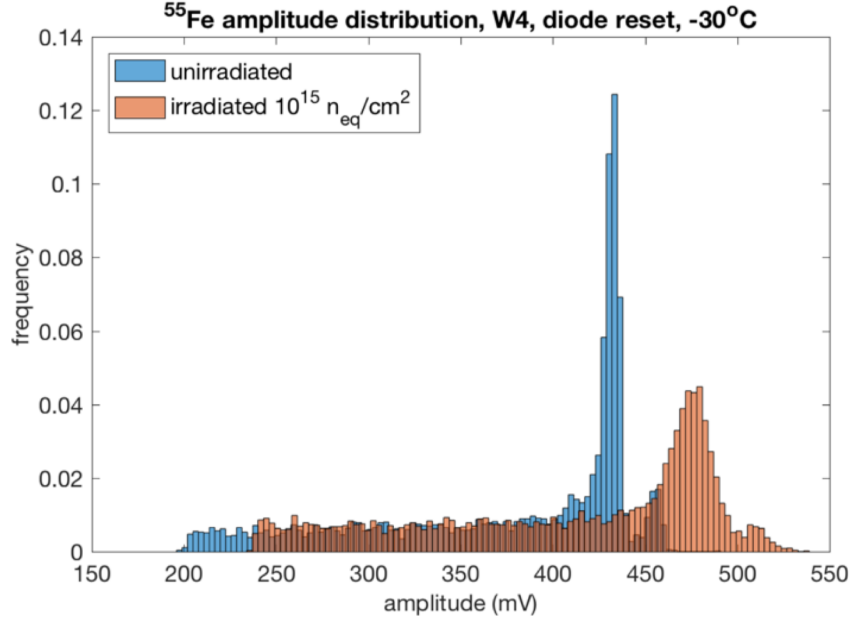


Figure 6.6: Energy calibration of the MALTA sensor using special analog output pixels. Result for an un-irradiated (blue bins) and a 1×10^{15} 1 MeV n_{eq}/cm^2 irradiated (orange bins) sensor are presented [170].

The readout architecture is fully asynchronous, requiring no external clock. Each group with a hit above threshold is transmitted to the readout independently of the other pixel groups. The main advantage of this is the further reduction in power output. Reference [171] calculates a total analog power of 238 mW, a total digital power of 12 mW and a periphery digital power of 267 mW, for a total power consumption per sensor of 514 mW. It further compares the performance of the MALTA chip to an equivalent synchronous readout design, the MONOPIX sensor [172], achieving a digital power consumption 20 times lower than its counterpart.

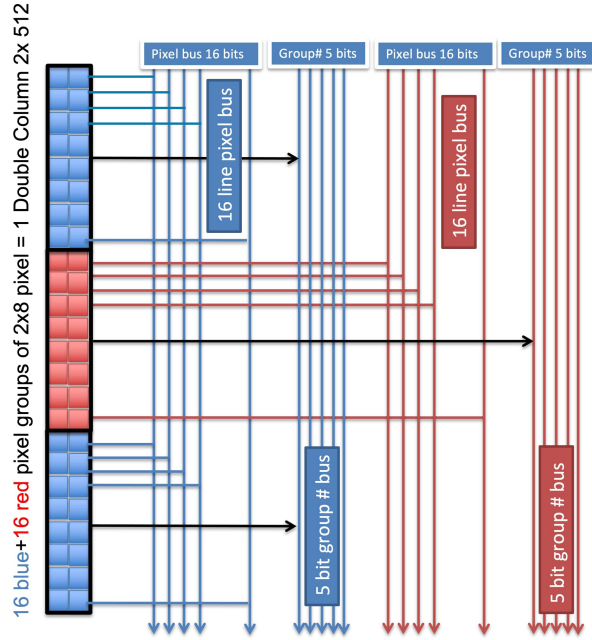


Figure 6.7: The MALTA asynchronous readout architecture.

Table 6.1: MALTA 40 bit word composition.

BIT #	ID
0	Reference
1-16	Pixel Address
17-21	Group Address
22	Group Parity
23-25	Delay Count
26-33	Double Column ID
34-35	Bunch Crossing ID
36-39	Chip ID

6.2 MALTA2

MALTA2 is the second generation of Tower 180 nm DMAPS. It is approximately half the size of the MALTA sensor, with an active area of 224×512 pixels and 18.33 mm^2 . Each sensor contains a single pixel geometry, based on the Sector 3 of the MALTA sensor: diode reset, $3 \text{ }\mu\text{m}$ collection electrode size, $3.5 \text{ }\mu\text{m}$ deep p-well spacing and medium deep p-well extension. The NGAP and XDPW pixel modifications shown in Figure 6.8 have been adapted to the new sensor design together with the modified front end of the mini-MALTA sensor. The pixel modifications have been shown to improve the radiation hardness, by increasing the charge collection efficiency in the pixel corners [173]. Improvements to the slow control have been implemented to streamline the chip communication. MALTA2 samples on both Epi and high resistivity Cz substrates are available. A picture of a MALTA2 sample can be seen in Figure 6.9. In the figure, one can find the power pads which distribute the power to the sensor, the slow control and digital to analog converters that control the front end current and voltage lines, the merging and arbitration logic

which merges the data from each of the 256 double columns and the LVDS output which pipes the data away from the sensor. The remaining sensor area is occupied by the pixel array.

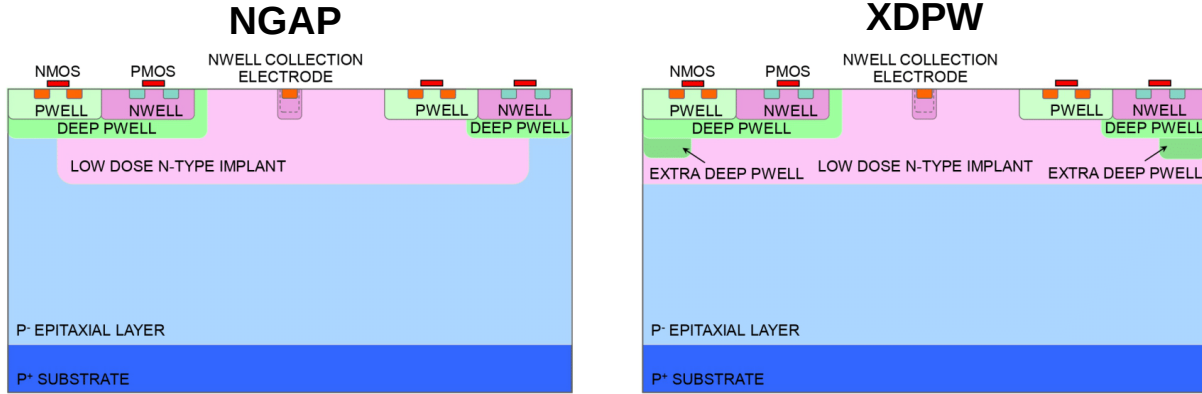


Figure 6.8: Cross-section of the modified process where the planar n-type implant has a gap at the pixel corners - NGAP (left) and an extra deep p-well is added to the pixel edge - XDPW (right).

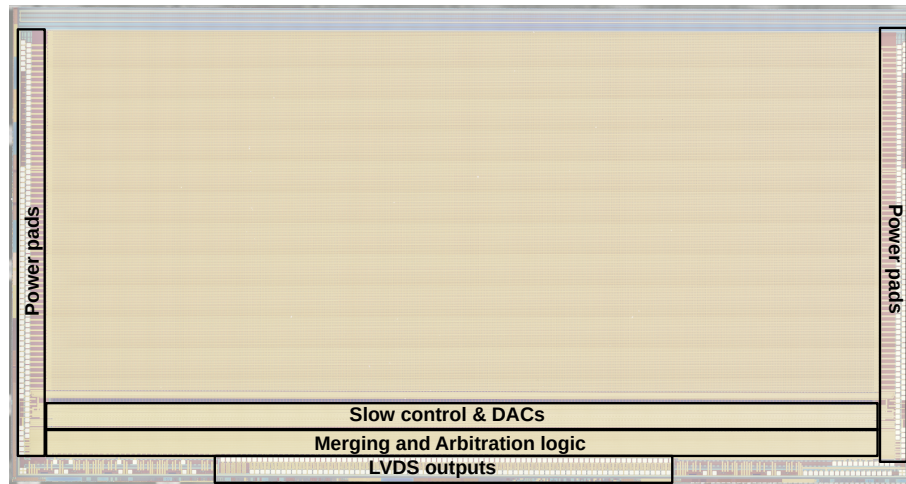


Figure 6.9: The MALTA2 sensor. On the left and right sides of the sensor, the power pads are highlighted. On the bottom of the sensor, the Slow control & DACs, the Merging and Arbitration logic and the LVDS output blocks are highlighted.

6.2.1 MALTA2 improved front end

The improved front end implemented in the MALTA2 sensor can be seen in Figure 6.10. Its operation remains similar as in the case of the MALTA sensor, but brings improvements in terms of Random Telegraph Signal suppression, gain and signal to noise ratio increase and a decrease in the operational threshold and its dispersion.

A diode reset is implemented in all pixels via the diode D_0 shown in the figure. It provides a continuous reset mechanism by holding the collection electrode voltage. The diode is biased at ~ 1 V accounting for the leakage current in the V_{RESET} bias. After a particle hit, a negative voltage step ΔV leads the reset diode to conduct more current, causing the input node to return to its original value in ~ 200 μs .

One improvement in the MALTA2 front end comes in the form of a cascoded M3 transistor, that decouples the M4 transistor from the output. This allows its resizing without incurring large capacitance penalties. Larger transistor gate sizes lower the noise but also increases the capacitance [174]. The size of the M4 transistor and the input transistor M1 have been optimized to limit the Random Telegraph Signal noise in an iterative manner [175]. The size of the M1 transistor was increased to $0.18 \mu\text{m}^2$ and the M4 transistor to $2.4 \mu\text{m}^2$.

The gain of the front end has been increased by increasing the C_S capacitance. Due to the coupling of the C_S to the low frequency feedback loop provided by the M5-6 branch, the gain acts as a high-pass filter at low frequencies with a pass band that extends from 15 kHz to 10 MHz [174]. The C_S capacitance is implemented with the help of a p-MOS transistor whose source, bulk and drain are connected together in order to benefit from the capacitance of the MOS structure in deep inversion. A gate area of $14.24 \mu\text{m}^2$ was chosen for the C_S element which significantly increases its capacitance to $\sim 114 \text{ fF}$. This effectively widens the amplifier pass band towards lower frequencies, where the input signal dominates, effectively raising the signal to noise ratio of the circuit.

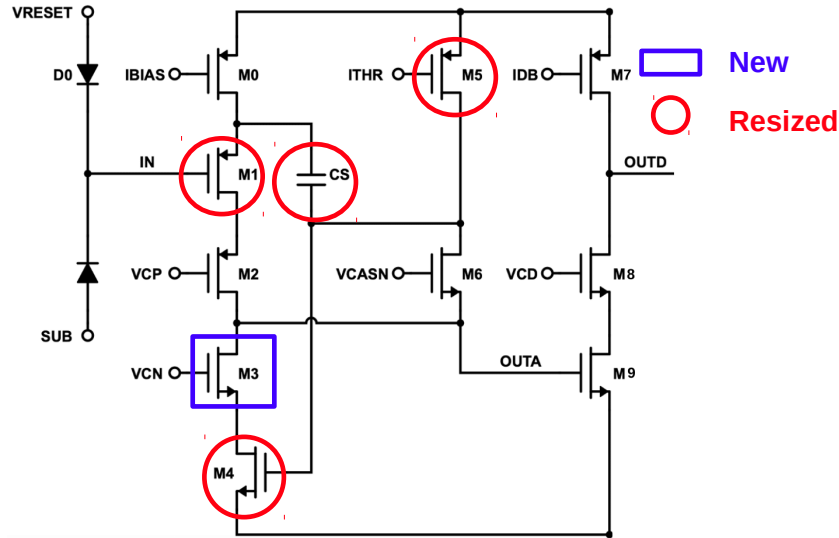


Figure 6.10: Diagram of the MALTA2 front-end. Components highlighted with a blue square were introduced in the latest design, while the red circles denote resized components.

Lastly, the threshold dispersion of the circuit was lowered, shifting the operational point to $\sim 100 e^-$. This is achieved in part thanks to the lower noise but also via lowering the pixel-to-pixel transistor mismatch, which is known to scale down with the square root of their area [176]. The largest impact of this effect was found to originate from the M5 and M6 transistors, which control the speed of the feedback loop's return to baseline and the amplifier baseline value respectively. The M5 transistor was implemented with a large gate area transistor of $20 \mu\text{m}^2$. The M6 transistor needs to be kept small in order to not impact the amplifier output capacitance.

The improvements of the MALTA2 front end have been investigated in terms of threshold and noise [177] in Figure 6.11 for the Sector 3 of MALTA and MALTA2 samples. The threshold scan has been performed at the same electron equivalent threshold value of $350 e^-$. A slightly lower threshold dispersion is achieved for the MALTA2 sample. Nonetheless, both sample's threshold dispersion is under the design specification of 10%. A large impact on the recorded

noise was observed when comparing the 2 samples. The MALTA2 sample achieves a large suppression of the pixel noise outliers observed previously for the MALTA sensor. The main sources of noise in the MALTA2 sensor have been investigated via a small-signal AC noise analysis [174] and have been found to contribute in the following proportions: M1 thermal noise (53%); M4 thermal noise (36%); D1 shot noise (2.5%); M6 thermal noise (2%); M5 thermal noise (1.75%).

Previously, the MALTA sensor employed an Ethernet-like protocol. The clock tree was not implemented as foreseen and configuration of the detector was challenging. In order to send commands, the power supply needed to be toggled between two different voltage values, as decreasing the supply voltage allowed to reduce the speed of the clock and helped with loading the registers. This approach proved to be too slow and could not perform full array threshold scans. A slow control change has also been implemented in the mini-MALTA and MALTA2 sensor by incorporating a shift register [178]. The shift register-based slow control enabled a more efficient configuration of the chip, unlocking the ability of performing full matrix threshold and noise scans.

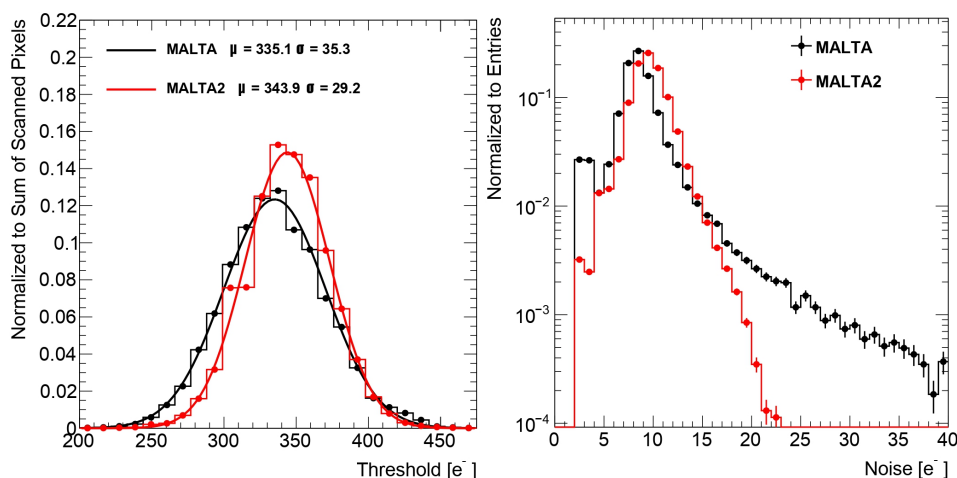


Figure 6.11: Threshold (left) and noise (right) distributions of a MALTA (black curve) and MALTA2 (red curve) sample. The root mean square values of the noise distributions are around 3.5 and 2.25 for MALTA and MALTA2 respectively.

Figure 6.12 shows the 2D threshold and noise distribution for a MALTA2 sensor. The noise is uniformly distributed across the entire sensor, while the threshold is uniformly distributed along the column (Y) direction. A slight variation along the rows (X) can be observed and is attributed to the way the bias is distributed across the sensor. As was shown in Figure 6.9, the power pads are placed on the left and right sides of the pixel array. A power drop of ~ 12 V is thus expected towards the matrix center. In order to counteract this effect, several mirroring stages (at every 32 columns) are placed in the Digital to Analog Converter (DAC) region, leading to the small observed threshold variation.

The several 7-bit DACs that control the front end are linear in most of the operational range (1-127 ADU). For example, the linearity of the IBIAS DAC can be seen in Figure 6.13. From an operational stand-point, the main parametric change incurred from the variation of these DAC settings is a change in threshold. In the following sections, several DAC configurations have been used, but their impact on the threshold is always measured by performing a threshold scan.

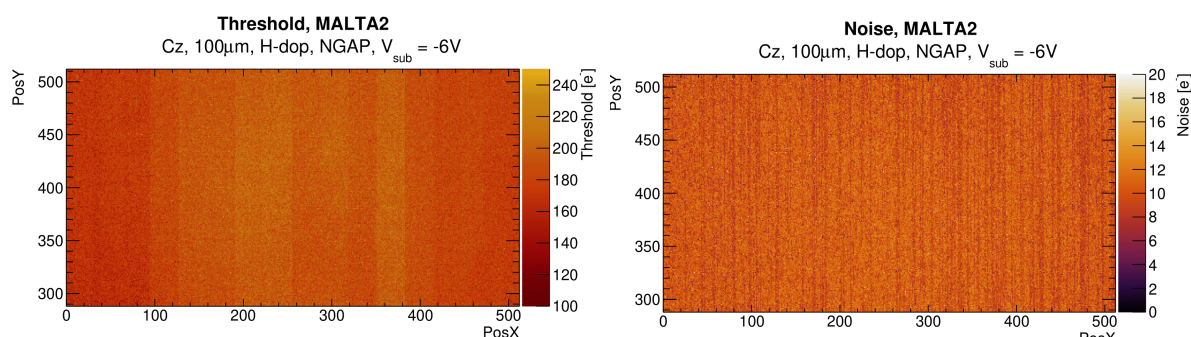


Figure 6.12: Threshold (left) and noise (right) 2D distributions for a MALTA2 sample.

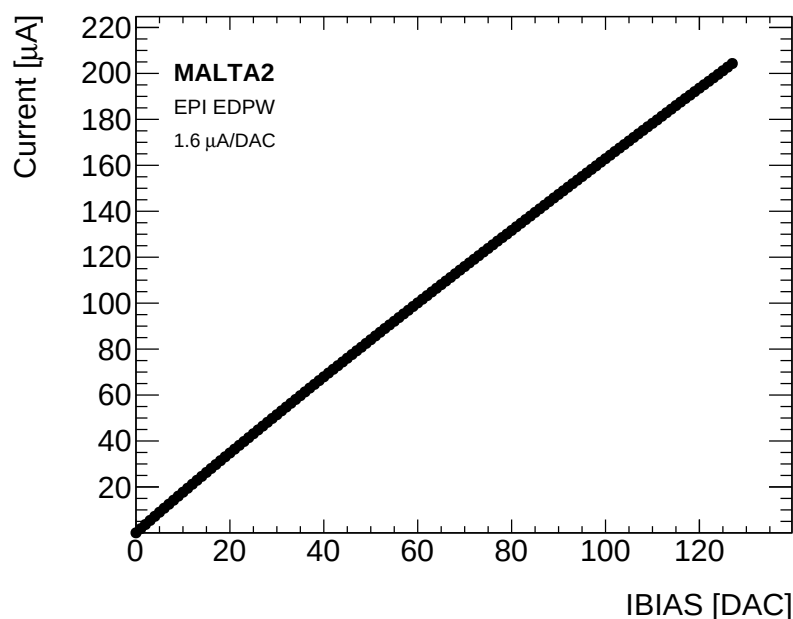


Figure 6.13: IBIAS current characteristic curve generated at the respective DAC value. Measurements were performed on MALTA2 Epi sample with XDPW modifications and low doping concentration of the n-layer and a thickness of 100 μm . SUB and PWELL were both set to -6 V and operating at room temperature. Measurements were performed with a Keithley 2400 at the monitoring pins.

6.2.2 MALTA2 sample variation summary

Several samples have been investigated with various pixel geometries, different deep n-layer doping and different sensor configurations. Below are listed the various differences between samples:

- **Silicon growth technique.** Two different silicon growth techniques were employed for MALTA sensors: epitaxial (Epi) and Czochralski (Cz).
- **Pixel geometry.** Three different pixel geometries were implemented for MALTA sensors: modified standard (STD), gap in the n-layer (NGAP) and extra deep p-well (XDPW). The NGAP and XDPW were found to lead to the same results.

- **Doping concentration of the deep n-layer.** Four different doping concentrations of the deep n-layer were used, denoted as low, moderate, high and very high doping. The value of these is confidential and unfortunately can not be shared.
- **Back processing.** Three different back processing methods for Cz samples were implemented: regular backside, conductive glue and back metallization.
- **Active depth thickness.** Several different active depth thicknesses have been implemented: 25 – 30 μm for Epi samples and 100 – 300 μm for Cz samples.
- **Irradiation dose.** Multiple sensors were irradiated to different doses: $1 - 5 \times 10^{15} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$ and up to 100 Mrad.

6.2.3 MALTA2 Efficiency and Cluster Size

The tracking efficiency and cluster size as a function of the applied SUB and threshold configuration was studied for non-irradiated samples. For both Epi and Cz MALTA2 samples, a uniform efficiency across the entire sensor was measured above 99.6%. Figure 6.14 shows the 2D full matrix efficiency map of a Cz, 300 μm NGAP MALTA2 sample operated at -6 V in SUB and PWELL.

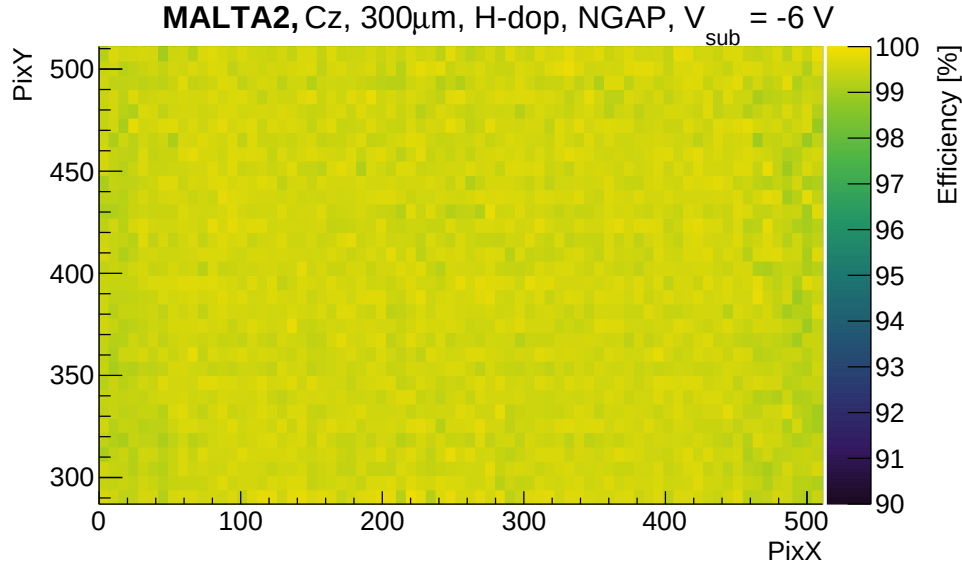


Figure 6.14: 2D Efficiency map of the entire matrix of non-irradiated MALTA2 Cz, 300 μm thickness sample operated at -6 V SUB and PWELL. The threshold corresponds to 150 e^- and the average efficiency to 99.6%.

The additional active thickness of Cz samples, leads to larger cluster size formations in the measured samples. The cluster size growth is expected to dominate at low thresholds, where the maximum amount of shared charged events can be detected. A comparison between similar Epi and Cz MALTA2 samples was performed and is shown in Figure 6.15. A much larger cluster size is gained for the Cz sample at the lowest threshold configuration of 130 e^- , while at larger thresholds, the improvement is minimal.

For MALTA2 Cz samples, the increase in SUB enhances the in-pixel electric field, leading to a more efficient charge collection and charge sharing between pixels. As a consequence, the

measured average cluster size increases with the absolute value of SUB as can be seen in the measurement of a MALTA2 Cz, 300 μm thickness NGAP sample in Figure 6.16. The average threshold of each measurement point is additionally quoted in the plot and shows that a constant configuration within the 10% measured threshold dispersion is achieved for all measurement points.

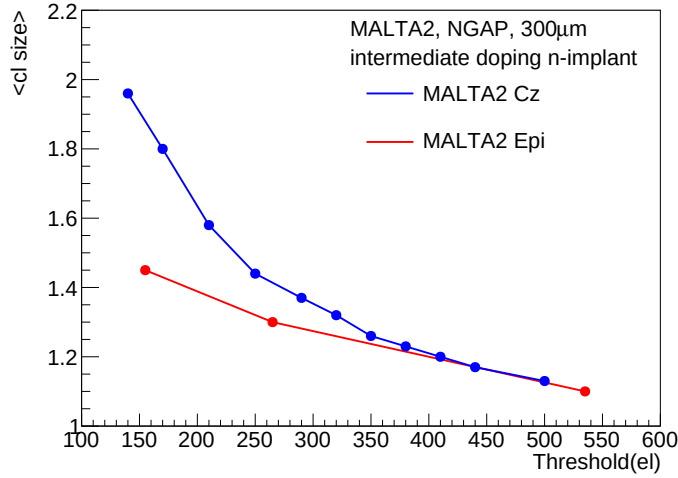


Figure 6.15: Average cluster size of two MALTA2 samples: Epi 30 μm (red line) and Cz 300 μm thickness (blue line), NGAP and intermediate doping of the deep n-layer for several threshold configurations. The Cz sample reaches a cluster size of 2.25 ± 1 for 130 e^- threshold and the Epi sample reaches a cluster of 1.45 ± 0.01 for 155 e^- .

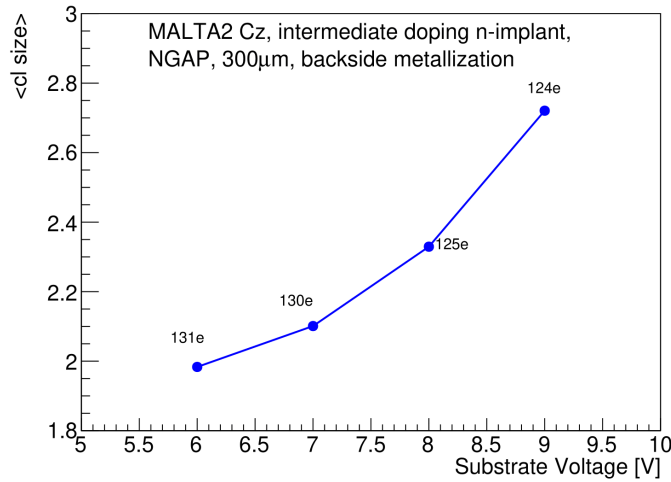


Figure 6.16: Average cluster size of a MALTA2 Cz, 300 μm thickness NGAP, intermediate doping of the deep n-layer sample versus absolute value of the SUB voltage. The PWELL was biased at -6 V. The threshold configurations for each measurement point was around 130 e^- .

6.3 Irradiation facilities

In order to gauge the radiation hardness of MALTA sensors, several samples have been irradiated with both neutrons and X rays. The neutron irradiation was performed at the TRIGA Mark II reactor at the Jozef Stefan Institute (JSI) [179] up to 5×10^{15} 1 MeV n_{eq}/cm^2 fluence with an approximate neutron flux of $10^{12} \text{ cm}^{-2}\text{s}^{-1}$. After dicing, bare samples are sent for irradiation at room temperature. After a room temperature annealing of several days, the samples are shipped to CERN and stored at -20°C until the samples are wire bonded. The wire bonding process implies the application of a conductive glue (Staystik 571 [180]) on the sensor's backside which is annealed at a temperature of 170°C for 1 minute. The elevated temperature applied to the sensor during wire bonding is not expected to lead to a large annealing effect of the radiation damage due to the limited exposure time. After wire bonding, the sensors are stored and operated at a constant temperature of -20°C , ensuring that the radiation defects remain "frozen into" the measured samples.

The X ray irradiation was performed at CERN with a 100 kV X-ray generator using a Tungsten target with a dose rate of 1 Mrad/h. Samples have been irradiated up to a TID of 150 Mrad.

6.4 The MALTA telescope

A beam telescope is typically used in high energy physics detector experiments in order to characterize tracking detectors. Beam telescopes provide a trigger for data taking and the capability of track reconstruction and time tagging through several tracking planes. They can be further used to characterize the efficiency and cluster size of a device under test.

The MALTA and mini-MALTA variants were tested at various beam lines using different provided beam-line user telescopes: 180 GeV proton beam at the Super Proton Synchrotron (SPS) facility in 2018, 2.5 GeV electron beam at ELSA 2019, 4 GeV electron beam at DESY 2019 and others. The spatial and timing resolution of the available telescopes and the difference in beam particle content between testbeam campaigns have motivated the design of a full MALTA based telescope at the SPS beam line, CERN. The MALTA telescope was designed as a permanent fixture in the H6 North Area (NA), one of the secondary beam areas at SPS. The beam line benefits from a high energy (180 GeV) mixed hadron beam, permitting the constant operation of the MALTA telescope as a parasitic user. The particle flux and beam collimation is controlled by the main user of the experiment and ranges between 2×10^{15} and 4.5×10^{16} particles per SPS spill [181].

The MALTA telescope is composed of six MALTA-based tracking planes and a scintillator for fast timing reference. A cold box cooled down via a JULABO FP50-HE air-cooled chiller can house up to two Devices Under Test (DUT). A dry air line is provided at the beam line and is necessary in order to maintain a low humidity environment. This is especially important when operating the DUTs at low temperatures in order to avoid ice formation on the sensors. A picture of the telescope can be seen in Figure 6.17. The placement of telescope planes in relation to the DUT can also be seen in schematic form in Figure 6.18. The substrate type (Epi, Cz) and the pixel geometry (STD, NGAP, XDPW) have been chosen for each tracking plane in order to optimize the spatial and timing resolution of the telescope. The two closest planes to the DUTs, plane 3 and plane 4 implement a thick (300 μm) Cz STD samples in order to maximize their cluster size. The other planes employ thinner (100 μm) Epi or Cz planes in order to limit the particle scattering.

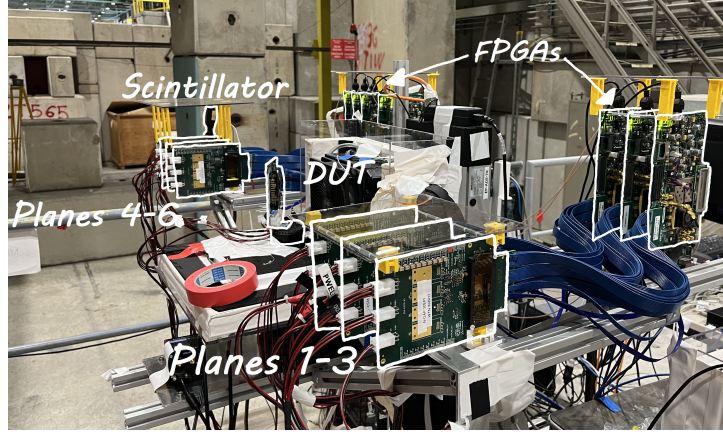


Figure 6.17: Side picture of the MALTA telescope.

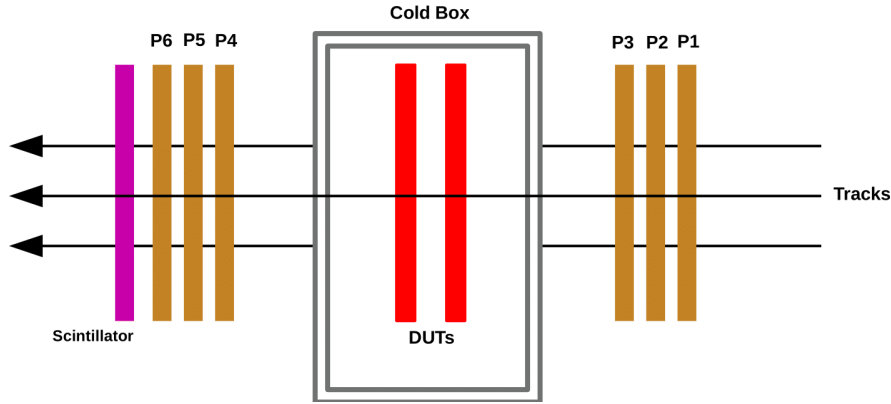


Figure 6.18: Schematic view of the MALTA telescope.

The telescope planes and the DUT's position are controlled via two independent linear stages with mobility in both the perpendicular and horizontal directions in relation to the beam. A rough alignment of the tracking planes and the DUTs is insured before data acquisition with the help of an alignment laser. A fine alignment is implemented manually by visually inspecting the telescope live monitoring plots. Additionally, a rotational stage can be implemented inside the cold box for tilting of the DUT with respect to the beam. This technique was employed in the inclined tests described in Section 6.8.1.

Each tracking plane and DUT is connected via a flexible HPC FMC cable to a Xilinx Kintex (KC-705) or Virtex (VC-707) commercial FPGA. The FPGAs are further connected to a custom built Trigger Logic Unit (TLU). The operation of the TLU is highlighted in Figure 6.19. When an event is detected, a MALTA plane sends a fast signal (shown in red) to the TLU. The TLU can be customized to take signals from up to four planes and merges them. The coincidence of the several signals is performed with an AND gate, where a programmable coincidence time window is implemented. This is important due to the variable MALTA signal widths on the charge deposition (5 – 15 ns). The larger the coincidence window, the higher the trigger rate. ⁹⁰Sr source measurements found a saturating effect of the trigger rate for a coincidence window of 25 ns [182]. The scintillator provides a precise time tagging of the generated trigger with a time resolution of ~100 ps. The trigger signal (Level 1 Accept - L1A) is sent from the TLU to

all the tracking planes and the DUTs in order to start the data taking via the standard readout (see Section 6.1.3).

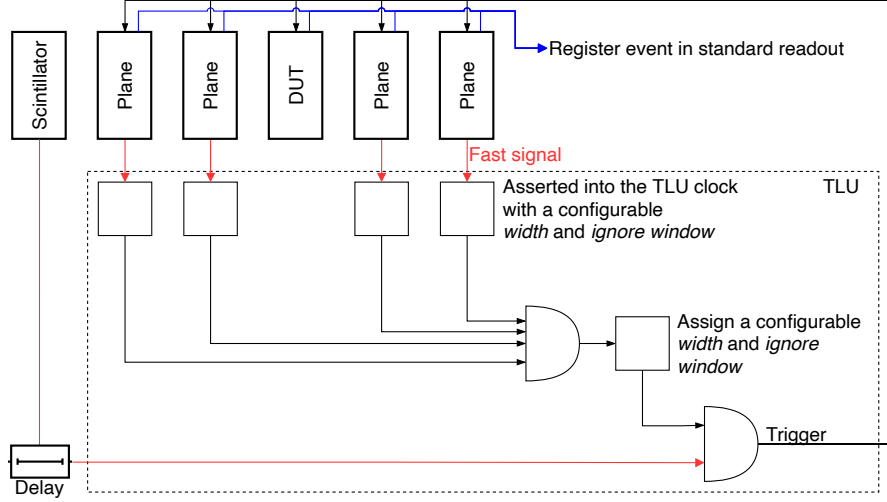


Figure 6.19: Diagram of the TLU's processing logic of the MALTA fast signals for triggering and data recording.

The offline data analysis is performed with the help of a software package called Proteus [183]. As an input, it receives the raw data as hits per event in the form of n-tuples [184] and groups spatial and temporal adjacent hits into clusters. Next, an offline plane alignment is performed by minimizing the χ^2 distribution of the track residuals. A “geometry file” which contains the coordinates of the telescope and DUT planes is generated with the corrected plane alignment in relation to three rotational degrees and two translational degrees. Next, a track fitting algorithm is performed which searches for clusters in each plane and generates linear regression fits for each equivalent track. The identified tracks are now interpolated with the DUT. Clusters detected in the DUT at a maximum distance of 80 μm (2.5 times the pitch, 36.4 μm) from a reconstructed track are matched to it. Following, a characterization of the efficiency, cluster size and timing resolution of DUTs can be performed.

6.5 Edge Transient Current Technique

The transient current technique employs a highly focused pulsed laser. Each laser pulse induces a transient current inside a sensor. By integrating the generated charge, qualitative and/or quantitative information about the electric field can be derived. By scanning the laser over several positions within a sensor, information about the distribution of the electric field can be inferred. The Edge Transient Current Technique (E-TCT) offers a unique perspective in terms of sensor testing. By shining the laser on the sensor's edge, information about the electric field distribution in the depth coordinate can be gathered.

6.5.1 Experimental set-up

The experimental set-up was installed in the Particulars laser enclosure [185] at Humboldt University, Berlin as can be seen in Figure 6.20. An L-shaped mounting bracket was designed in order to interface the MALTA2 carrier board to a linear stage with horizontal mobility. The

FPGA is also connected to a mechanical support that moves with the carrier board. A pulsed infra red laser (1064 nm wavelength, 500 Hz frequency) was used. The laser is transported through an optical fiber to the laser optics and is shone on the sensor with the laser head marked in Figure 6.20. The laser head can be moved up and down in order to achieve a focused beam on the sensor's edge.

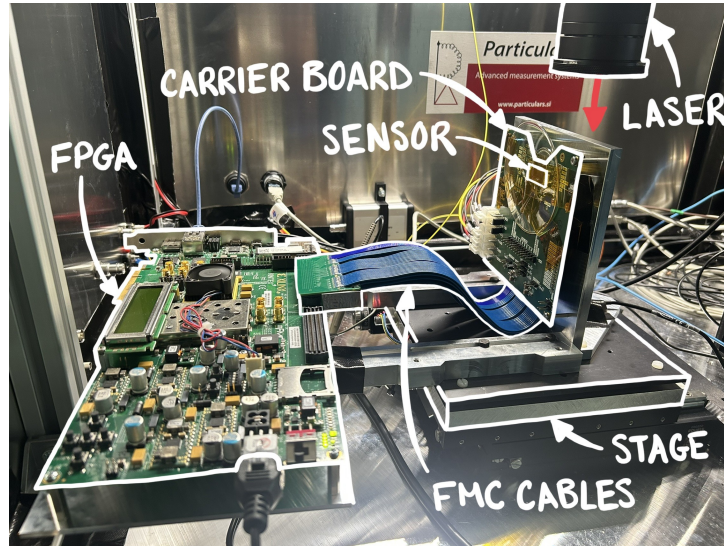


Figure 6.20: Edge transient current technique experimental setup. It consists of a sensor wire bonded to a specially designed PCB with a cut-out which allows for laser penetration. The sensor slow control is performed with an FPGA and the analog readout is performed with a probe to an oscilloscope. We thank Alexandra Savino, a former DESY summer student, for the graphics and the photo.

The sensor is connected with an FMC cable to a Xilinx Kintex (KC-705) board similar to the test beam set-up. However, this connection is not used for reading out data, but rather only for programming the DAC values of the sensor before a measurement. Only the analog component of the read-out is of interest in this investigation and as such, special analog pixels placed on the MALTA2 sensor's edge have been investigated with the help of a Tektronix P6248 differential probe connected to an Tektronix MSO66B oscilloscope.

The original MALTA2 board had to be redesigned in order to allow the laser to reach the sensor's edge. A cut-out was introduced in the PCB and most electronic components have been moved away from the sensor. The circuit around the sensor's wire bonds was kept the same. A picture of a standard PCB (left) and a modified PCB for E-TCT (right) can be seen in Figure 6.21.

6.5.2 Edge polishing of MALTA 2 samples

In order to insure a uniform laser beam on the sensor edge, the sensors were edge polished before wire bonding. A detailed polishing procedure is described in Appendix G.

The polished sensor has a smooth surface with no visible defects except minor scratches that are inevitably introduced by the cleaning procedure. A “before” (left) and “after” (right) picture of a polished MALTA2 sample can be seen in Figure 6.22. As can be seen in the microscope picture of a MALTA2 sensor's edge after polishing, some rounding is introduced towards the sensor back contact, while the sensor top remains un-rounded. The edge rounding towards the backside is not expected to lead to significant effects for most sensor configurations.

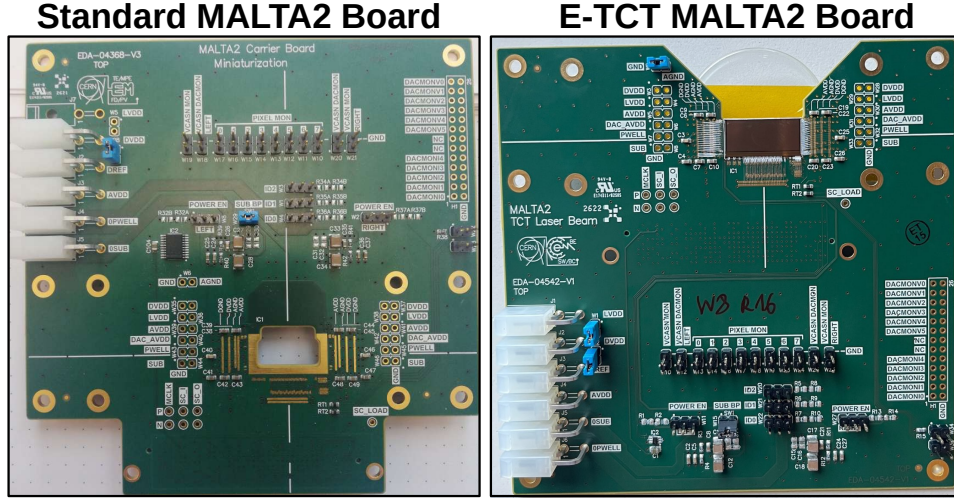


Figure 6.21: Standard MALTA2 carrier board (left) and the MALTA2 carrier board layout for E-TCT (right) with a wide opening at the top.

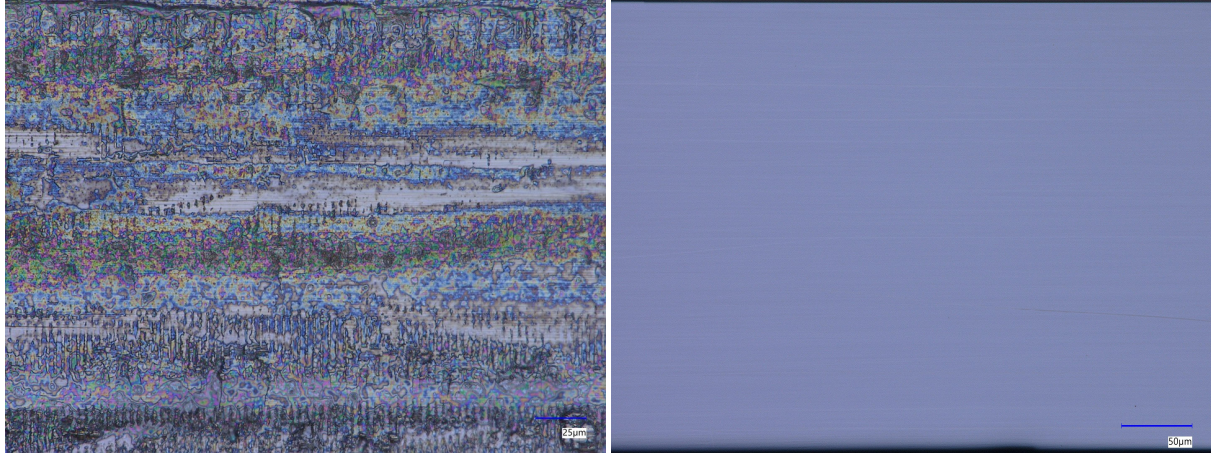


Figure 6.22: MALTA2 sensor edge before polishing (left). MALTA2 sensor edge after polishing (right). Images were taken with a Keyence digital microscope.

6.5.3 Data acquisition

A python based framework for automatic data taking has been developed to interface with both the oscilloscope and the linear stages. A screenshot of a live monitoring plot during a measurement can be seen in Figure 6.23. The average maximum amplitude for each measurement is shown for the pitch, depth and height axes. Each measurement point contains the average of 200 consecutive wave-forms detected above an oscilloscope trigger threshold of 30 – 40 mV for one of the special analog pixels. Figure 6.24 shows a recorded waveform. The relatively large full width at half maximum (FWHM) value (~ 50 ns) of the waveform highlights a slow charge collection which could be associated with a large density of trap sites or an important diffusion movement component.

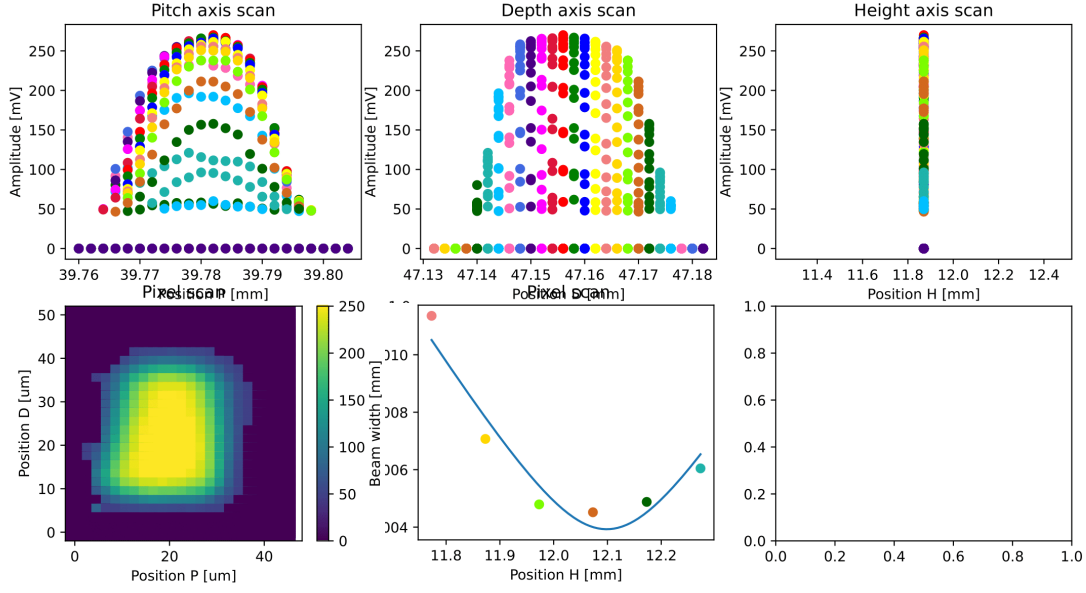


Figure 6.23: Screen capture of a monitoring plot for an edge transient current technique scan for an Epi MALTA2 sample.

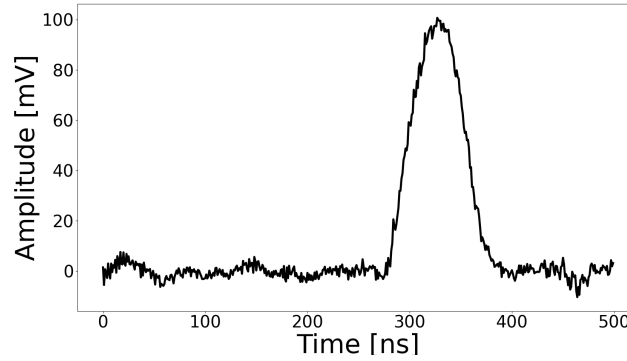


Figure 6.24: Amplitude waveform recorded with an oscilloscope of an Epi MALTA2 sample. The background was subtracted by averaging the noise dominated time bins up to 150 ns.

6.5.4 Laser focus

In order to increase the precision of the experiment, the smearing of the Gaussian distributed laser beam was minimized. This was achieved by finding the minimum spot size with the help of a focus scan. The focus scan implied the measurement of the signal change for a systematic variation of the laser head height [186].

The scanning of the sensor is performed by illuminating the pixel edge with the laser head and moving the linear stage in two axes (pitch and depth). Figure 6.25 shows an expanded view of a pixel cross-section and highlights the two axes of movement of the stage: the pitch (across the sensor length) and depth (in the silicon bulk) axes. Additionally, the laser head can be moved on the height axis (down the matrix of the sensor).

To measure the width of the beam, the laser is shone across the edge of a pixel. The signal

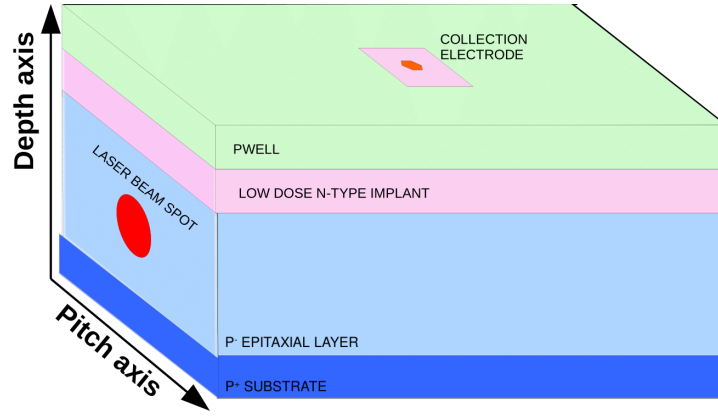


Figure 6.25: Expanded view of a MALTA pixel cross-section. The orientation of the pitch and depth axes are marked and the laser spot position on the sensor edge is highlighted.

turn-on near the pixel collection electrode gives a quantitative measurement of the beam width via the error function [187]:

$$f(x, A, \mu, \delta) = A \left(\operatorname{erf} \left(\frac{x - \mu}{\delta} \right) + 1 \right), \quad (6.2)$$

$$\operatorname{erf} \left(\frac{x - \mu}{\delta} \right) = \frac{2}{\sqrt{\pi}} \int_0^{\frac{x - \mu}{\delta}} e^{-\tau^2} d\tau \quad (6.3)$$

The fitting parameter A is proportional to the maximum of the charge profile and μ to the position of the edge corner. The beam width is deduced from the width parameter of the error function δ as $w = \sqrt{2}\delta$ [187]. Figure 6.26 shows a depth scan near the collection electrode for a laser focus configuration. The focus scan consists of measuring multiple laser widths at different laser heights, shown in Figure 6.27. The data is fitted with a waist function for a Gaussian beam:

$$w(z) = w_0 \sqrt{1 + \left(\frac{z - z_0}{z_R} \right)^2} \quad (6.4)$$

The minimum spot size is found to be $4.4 \pm 0.4 \mu\text{m}$ and the Rayleigh length, $z_R = 163 \pm 16 \mu\text{m}$, ensuring a constant beam profile for samples diced close to the pixel array.

6.6 TID radiation hardness of the MALTA2 sensor

Due to the large number of active elements in the MALTA2 FE, the TID radiation hardness of the sensor was extensively studied in the range of $0 - 150 \text{ Mrad}$. The main impact is expected to come in terms of threshold, noise and signal amplitude degradation. If these effects are severe, it could further impact the tracking efficiency. The systematic study of the measured degradation in MALTA2 sensors is investigated in this section. Due to the front end complexity, the source of the radiation damage can not be exactly pin-pointed and several possible causes are suggested.

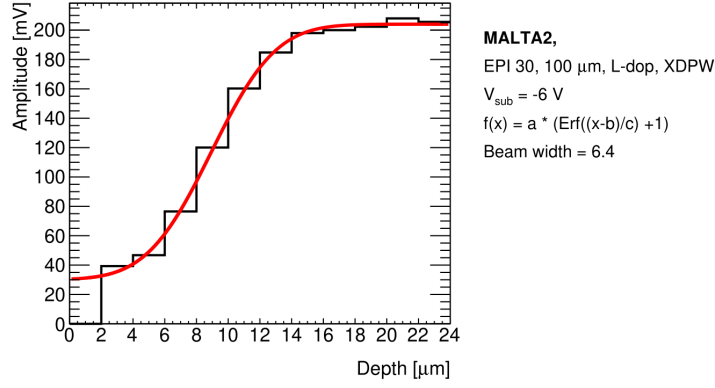


Figure 6.26: The beam width measurement plot for a focus configuration. The average amplitudes were recorded for multiple measured signals induced with the E-TCT laser at different depths in the pixel, near the collection electrode for a fixed height. The data fit is an error function.

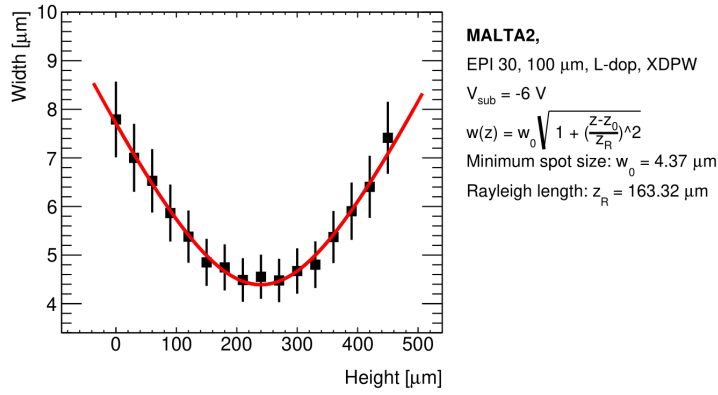


Figure 6.27: The focus scan performed for a MALTA2 sample. The width calculated through the error function fit of multiple focus configurations is plotted versus the height position of the laser head. The data fit is a waist function for a Gaussian beam from which the best focus position and smallest beam width are extracted. The error bars are computed from the error function fit covariance of the beam width.

6.6.1 Threshold, noise and signal amplitude degradation

An Epi XDPW MALTA2 sample has been systematically irradiated with X-rays in the experimental set-up described in Section 6.3. After each irradiation step, the analog front-end characteristics were investigated by exposing the special analog output pixels to a Fe-55 source. Additionally, after the last measurement point at 100 Mrad was taken, an accelerated annealing step (40°C for 55 minutes) was employed to gauge its effectiveness in recovering the original sensor performance.

Figure 6.28 shows the degradation in the measured signal amplitude for the $k-\alpha$ and $k-\beta$ Fe-55 spectral lines. An approximate semi-log drop in the amplitude can be observed for accumulated TIDs up to 1 Mrad, followed by a diminished effect up to 100 Mrad. Additionally, the annealing performed shows a slight improvement in the signal amplitude.

A saturating effect of ionizing radiation damage at 1 Mrad TID has been observed in several irradiated samples [188] and has been attributed to a feature of the MOSFET technology node.

This could be due to the shift of several n-MOSFETs in the front end to deep inversion for a TID of 1 Mrad.

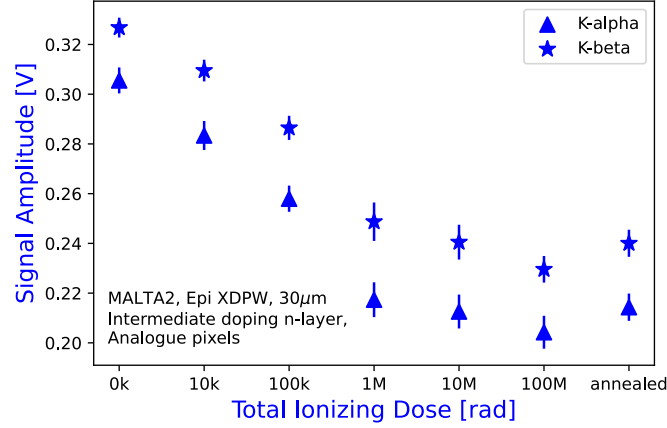


Figure 6.28: Average amplitude of the recorded $k-\alpha$ and $k-\beta$ Fe-55 spectral line as a function of accumulated TID. The amplitude of the signal was measured with respect to the baseline calculated 100 ns before the rising edge of the signal.

One possible cause for the signal amplitude drop could be the voltage shift in the voltage and current DACs. One especially important voltage line is VCASN. A value change of this line can lead to a change of the open-loop amplifier baseline and thus a large change in the measured signal amplitude. Figure 6.29 however shows a small deviation of the voltage DAC characteristic curve for TID's up to 150 Mrad. The impact on the front end is thus assumed to be due to parametric changes of the active circuit components. A source for the degradation can not be identified due to the circuit complexity.

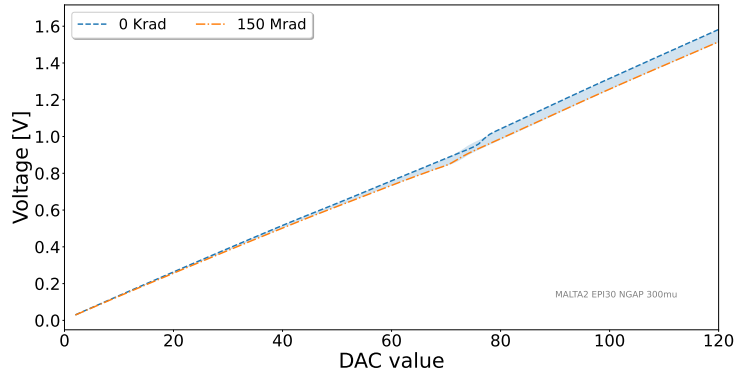


Figure 6.29: Voltage characteristic curve of the VCASN digital to analog converter generated at the respective DAC value over the TID range: 0 – 150 Mrad.

The change in gain of the irradiated MALTA2 sample was estimated with the help of an Fe-55 source and was defined as the difference in signal amplitude over the difference in deposited charge between the two $k-\alpha$ and $k-\beta$ peaks. Figure 6.30 shows the change in sensor gain for TID's up to 100 Mrad. The increase in gain is correlated to an increase in capacitance, possibly

due to the formation of an oxide space charge which limits the depletion around the collection electrode. A similar saturating trend at 1 Mrad is observed as previously seen in Figure 6.28.

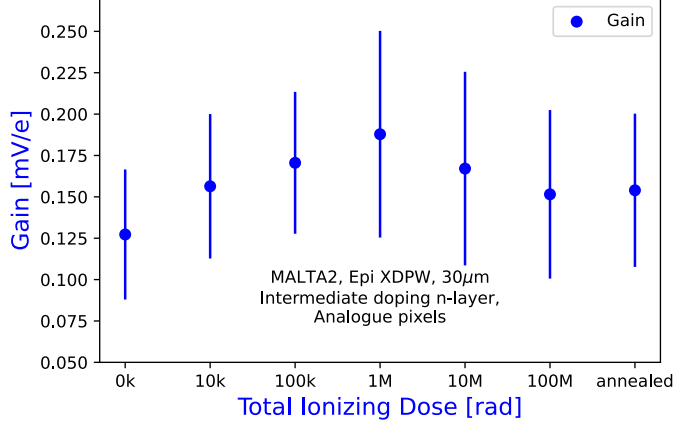


Figure 6.30: Average gain of the analog front end over the TID range 0 – 100 Mrad. Additionally, a measurement point after an accelerated annealing step (40° for 55 minutes).

The impact of TID on threshold was studied both in terms of the shift of a certain configuration but also in terms of the minimum operating threshold. Figure 6.31 (left) shows the decrease in threshold (due to the gain and capacitance increase) with elevated TID. The original threshold configuration is regained by manually adjusting the front end parameters. Figure 6.31 (right) shows that a targeted threshold value of 200 e^- can be maintained (via manual adjustments) for several TID values up to 150 Mrad.

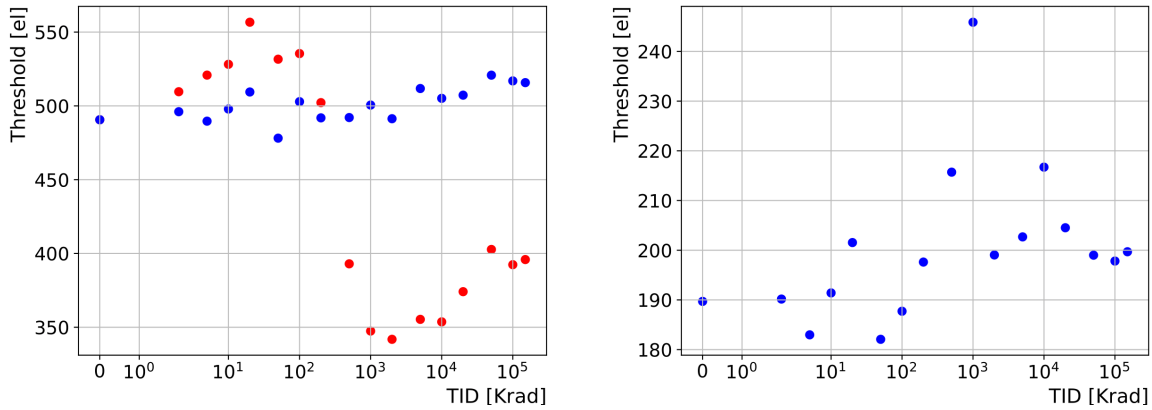


Figure 6.31: Threshold value of a constant DAC configuration (red points) and manual readjustment of front end parameters (blue points) for several TID values (left). Threshold value around a targeted 200 e^- operational value achieved via manual adjustment for several TID values (right).

An increase in noise has also been observed in irradiated mini-MALTA samples at elevated TID values and are discussed in Reference [189]. A mean noise of 21 e^- has been measured for a TID value up to 80 Mrad, well below the targeted threshold of 100 – 200 e^- .

6.6.2 Tracking degradation

As the impact on the noise is minimal and the threshold change can be recovered after TID accumulation, close to no impact on the tracking is expected. Indeed, Figure 6.32 shows that the impact on both tracking efficiency and cluster size after irradiation to 100 Mrad is lower than 2%.

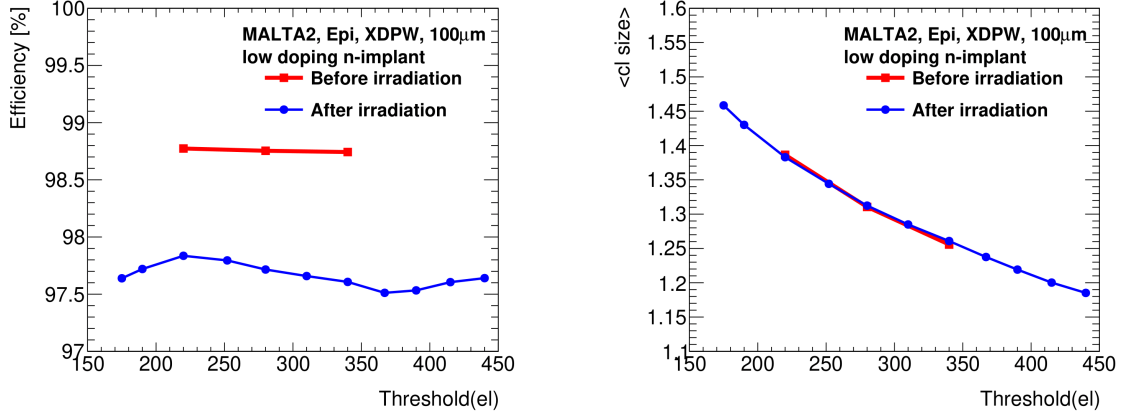


Figure 6.32: Tracking efficiency (left) and cluster size (right) before (red line and points) and after irradiation (blue line and points) to 100 Mrad TID.

6.7 Displacement damage radiation hardness of the MALTA2 sensor

The results discussed in this section were additionally published in the peer reviewed paper appended to the thesis as Paper III.

The displacement damage radiation hardness of the MALTA2 sensor was estimated with the help of neutron irradiation of several samples in the range of $1 - 5 \times 10^{15} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$. An impact on the threshold, noise and tracking efficiency was observed and the results are discussed further below.

6.7.1 Threshold and noise degradation

The MALTA2 front end is not expected to be severely impacted by displacement damage. Still, a threshold decrease was observed for a constant sensor configuration at elevated irradiation doses [190] as is highlighted in Figure 6.33. The observed drop in threshold is correlated to a change in the input capacitance and consequently a change in the sensor gain. The donor removal effect which is expected to take place in samples irradiated above $1 \times 10^{15} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$, leads to the decrease in the effective doping of the deep n-type implant. This in turn was found to lead to a decrease of the effective collection electrode size due to local depletion changes [191]. Furthermore, it leads to a decrease of the input capacitance of the FE, increasing the signal to noise ratio of the sensor. The perceived beneficial effect of the radiation is counteracted by several competing factors: the increase in noise, the decrease in charge transfer efficiency and a reduction of the depletion volume.

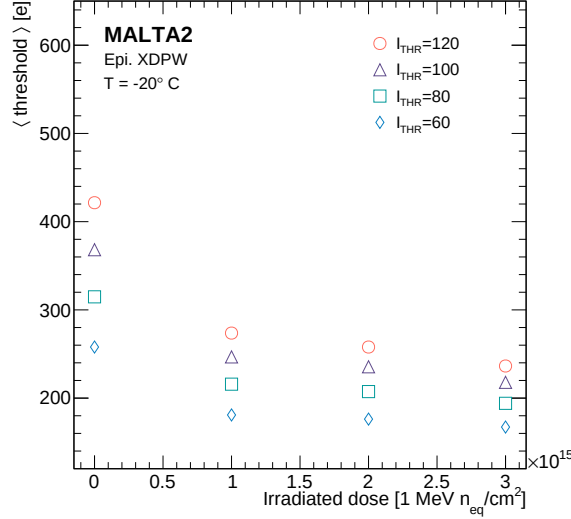


Figure 6.33: The average threshold value of Epi XDPW MALTA2 samples for several threshold configurations induced by the change of the ITHR DAC and for several irradiation doses.

The lowest threshold configuration for an un-irradiated and $3 \times 10^{15} \text{ 1 MeV } n_{eq}/\text{cm}^2$ irradiated Epi XDPW MALTA2 sample is shown in Figure 6.34 (left). Even after irradiation to an elevated dose, a threshold $\sim 100 \text{ e}^-$ can be applied to the sensor. A slight increase in the threshold dispersion can be observed. The noise distribution for the lowest threshold configuration before and after irradiation is shown in Figure 6.34 (right). As expected, a noise increase is gained after irradiation. However, no large pixel noise outlier contribution is observed even after elevated irradiation doses, indicating no important Random Telegraph Signal noise component. During testing, the impact of the noise is mitigated by masking the noisiest pixels. The pixel masking is an iterative procedure customized for each sensor such that the minimum amount of pixels are masked (< 100), while a noise smaller than 40 Hz is achieved.

These results indicate that the front end can be operated in its nominal mode even after irradiation to $3 \times 10^{15} \text{ 1 MeV } n_{eq}/\text{cm}^2$. Still, the induced noise can lead to the operation of some samples at elevated threshold configurations.

6.7.2 Czochralski and substrate propagation improvements

An Epi MALTA2 sample irradiated to $2 \times 10^{15} \text{ 1 MeV } n_{eq}/\text{cm}^2$ has been measured with the help of the MALTA telescope. The average efficiency after irradiation for several threshold and SUB bias configurations is shown in Figure 6.35. As expected, the efficiency increases for lower threshold configurations. The increase in SUB leads to an increase in efficiency (86%) up to -10 V , followed by a slight decrease. The decrease in efficiency above -10 V is correlated to a saturating effect in the depletion volume growth, where higher SUB values lead only to an increase in noise, decreasing the measured efficiency. This result, indicates a process limitation of the radiation hardness of Epi MALTA2 samples. As a consequence, the radiation hardness R&D efforts of the MALTA collaboration have mainly focused on Cz MALTA2 samples.

The main benefits of Cz have already been discussed in the previous sections. The ability to deplete a larger silicon volume, comes at the price of applying larger bias values. The

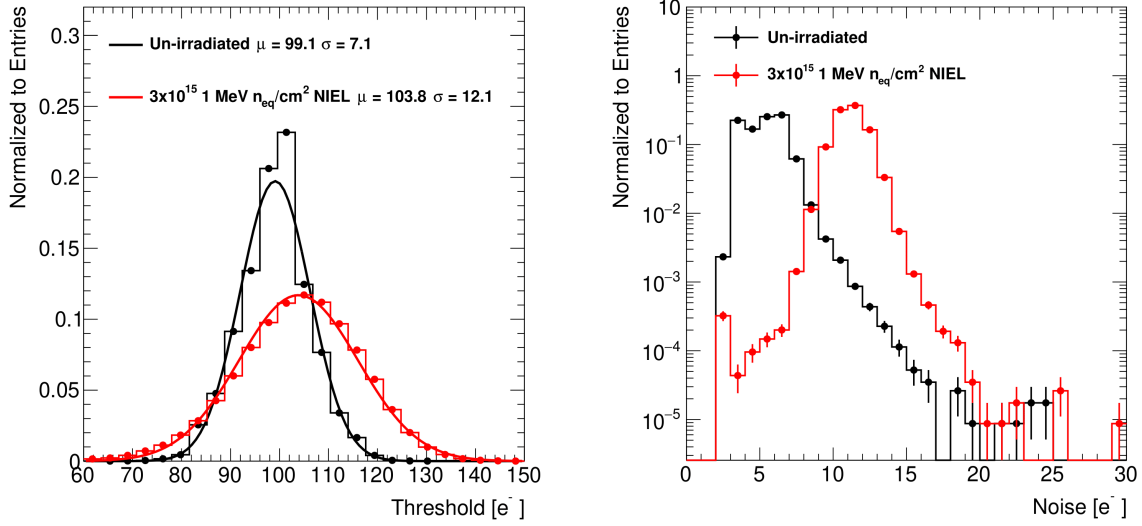


Figure 6.34: Lowest threshold configuration distribution (left) and noise distribution for the lowest threshold configuration (right) of un-irradiated (black curve) and 3×10^{15} 1 MeV n_{eq}/cm^2 irradiated (red curve) Epi XDPW MALTA2 samples.

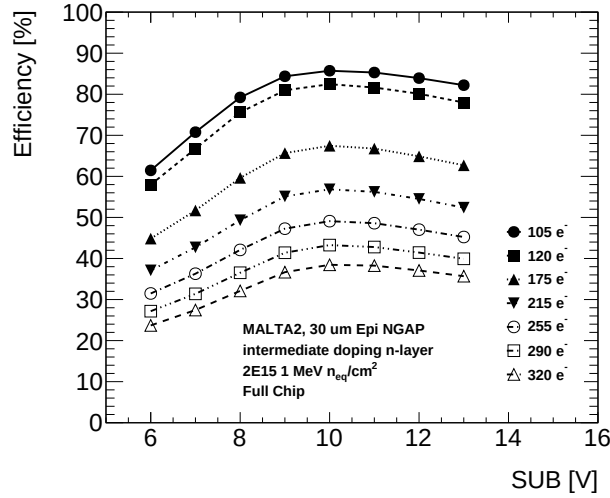


Figure 6.35: Average efficiency of 2×10^{15} 1 MeV n_{eq}/cm^2 irradiated Epi, NGAP, 30 μm thickness MALTA2 sample. The sample was operated at -6 V PWELL and several threshold and SUB values.

initial MALTA2 Cz design involved no backside processing, achieving the SUB bias distribution through an ohmic contact with the metallized pads of the carrier board. Furthermore, the carrier boards for the MALTA2 samples have been designed with a cut-out under the sensor in order to reduce particle scattering in the beam line experiments. A uniform voltage propagation could be achieved across the entire matrix for non-irradiated samples, as seen in Figure 6.14. However, after irradiation up to 3×10^{15} 1 MeV n_{eq}/cm^2 , a uniform propagation is no longer observed. Figure 6.36 shows the 2D efficiency map of an irradiated Cz MALTA2 sample operated at -50 V. The efficient spots match the electrical contacts of the carrier board.

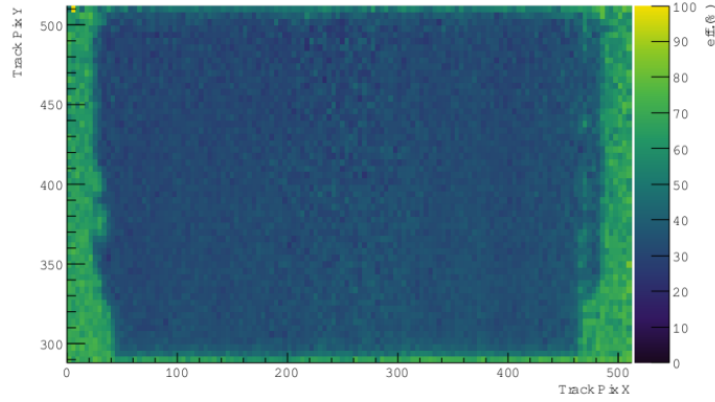


Figure 6.36: 2D efficiency map of an 3×10^{15} 1 MeV n_{eq}/cm^2 irradiated Cz NGAP 100 μm thickness MALTA2 sample with regular backside, at -50 V SUB and -6 V PWELL.

In order to propagate the SUB voltage to the entire pixel matrix, a conductive glue (Staystik 571) has been applied across the entire backside. Unfortunately, the thermal anneal of the glue created gaps within it, as air bubbles remained trapped. This effect was observed through microscope images and was correlated to the 2D efficiency map of an 1×10^{15} 1 MeV n_{eq}/cm^2 irradiated Cz XDPW, 100 μm MALTA 2 sample in Figure 6.37. The trapped bubbles lead to poor electrical contact, which in turn lead to localized efficiency drops. Still, some areas with good electrical contact are achieved and are marked with red boxes. These are employed in computing the average efficiency of the irradiated samples in the respective fiducial areas. A similar pattern was observed across several samples for which the conductive glue was applied.

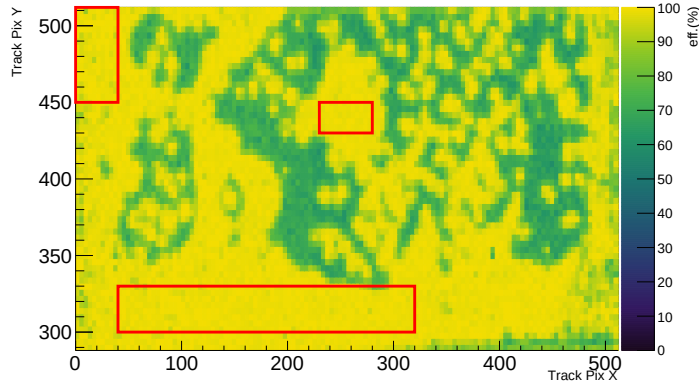


Figure 6.37: 2D efficiency map of an 1×10^{15} 1 MeV n_{eq}/cm^2 irradiated Cz NGAP 100 μm thickness MALTA2 sample with conductive glue at -12 V SUB and -6 V PWELL. The red boxes match the fiducial area for which the efficiency was considered.

The average efficiency in a fiducial region for several irradiated Cz samples was investigated and is highlighted in the set of plots of Figure 6.38. The threshold and SUB was varied between several values in order to create a parameter space (threshold and bias) in which a large hit efficiency ($>95\%$) is recovered.

At relatively low doses (1×10^{15} 1 MeV n_{eq}/cm^2) an efficiency over 98% is achieved at -10 V SUB for multiple sensor configurations. At elevated displacement damage doses, the substrate

voltage needs to be increased in order to achieve a similar depletion volume due to the carrier removal in the n-doped layer. A hit efficiency of $>96\%$ is achieved for 2×10^{15} and 3×10^{15} 1 MeV n_{eq}/cm^2 at -25 V and -55 V SUB respectively.

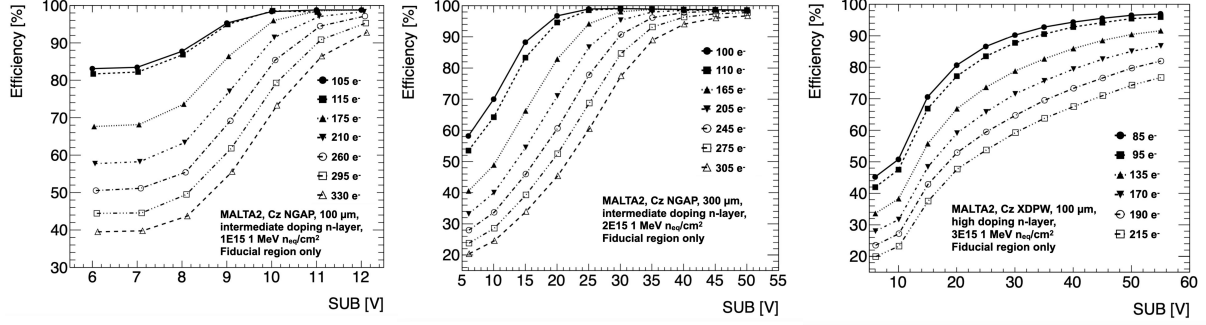


Figure 6.38: Average efficiency of 1×10^{15} 1 MeV n_{eq}/cm^2 (left), 2×10^{15} 1 MeV n_{eq}/cm^2 (middle) and 3×10^{15} 1 MeV n_{eq}/cm^2 (right) irradiated MALTA2 Cz samples. The quoted efficiency corresponds to fiducial regions where good electrical contact is guaranteed.

In order to extend the promising radiation hardness results presented above to the full pixel matrix, a post processing back metallization procedure was employed. The backside metallization process was performed by Ion Beam Services (IBS) [192]. The sample is initially thinned, after which boron is implanted for an improved electrical contact. In the last step, a 1 ± 0.1 μm thick aluminium is deposited on the backside of the sample. Figure 6.39 shows a Scanning Electron Microscope (SEM) image of a cross-section of a MALTA2 sample with backside metallization.

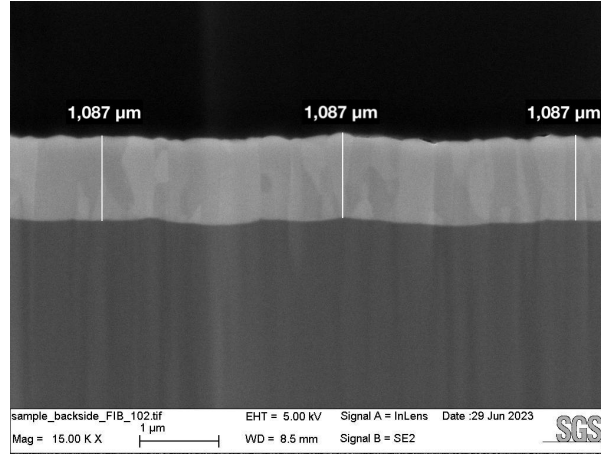


Figure 6.39: Cross-sectional SEM image of a MALTA2 sample with backside metallization. The light grey area indicates the 1 μm thick aluminium layer.

A 3×10^{15} 1 MeV n_{eq}/cm^2 irradiated, back metallized Cz MALTA2 sample was measured. The full chip efficiency can be seen in Figure 6.40, highlighting the successful implementation of the procedure. The missing bins in the middle of the chip are due to several masked pixels.

Figure 6.41 compares the performance in terms of efficiency and noise of two similar irradiated MALTA2 sensors with regular backside for a fiducial region of the sensor (open markers) and back metallization (closed markers). Over-layed on the plot, the black and red dashed lines

match the requirements of the ATLAS ITk pixel upgrade. This shows the clear improvement in radiation hardness for back metallized samples and is attributed to a very good propagation of the SUB voltage across the entire pixel matrix. Additionally, several threshold configurations are found for which both the noise occupancy and efficiency are below 40 Hz and above 95% respectively.

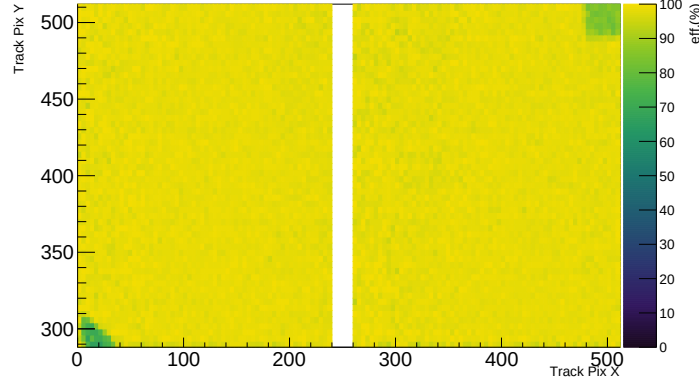


Figure 6.40: 2D efficiency map of an 3×10^{15} 1 MeV n_{eq}/cm^2 irradiated Cz NGAP 100 μm thickness MALTA2 sample at -50 V SUB and -6 V PWELL. Pixels at the sample center have been masked in order to reduce the noise.

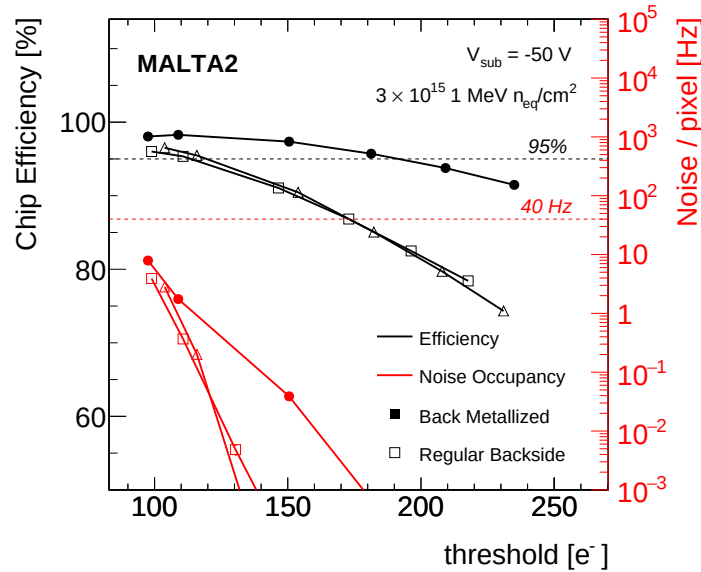


Figure 6.41: Average efficiency (in black) and noise occupancy (in red) of 3×10^{15} 1 MeV n_{eq}/cm^2 irradiated MALTA2 Cz samples. The samples were operated at -50 V SUB and -6 V PWELL. Two sensors had a regular backside (open markers) and one was back metallized (closed markers).

Figure 6.42 gives an overview of the performance of several irradiated samples in the range of $1 - 3 \times 10^{15}$ 1 MeV n_{eq}/cm^2 with several backside treatments. The samples showcased differ in terms of several parameters (doping of the n-type implant, geometry modification and thickness) and the results should not be directly compared in order to infer quantitative

information regarding the radiation hardness improvement. Still, the results give an overview of the radiation hardness trends discussed in detail in this section and showcase the importance of the backside processing in order to achieve large efficiencies at relatively lower SUB values.

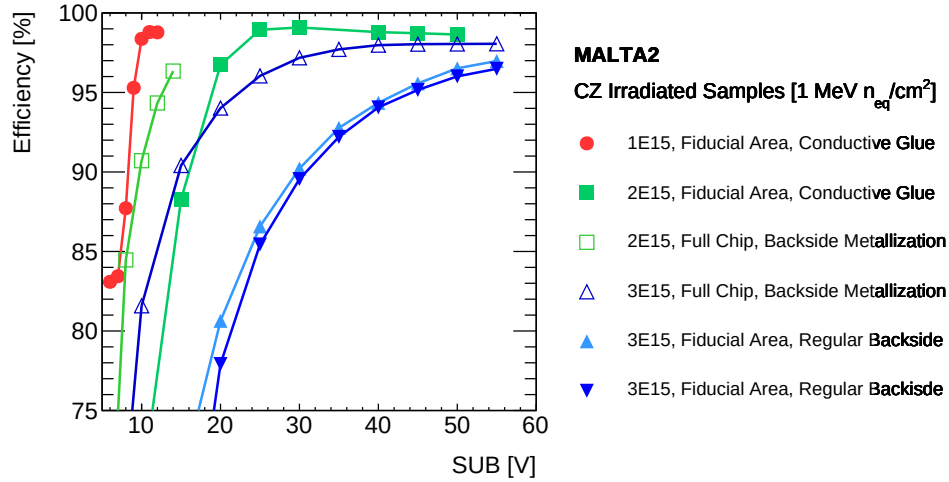


Figure 6.42: Summary plot of the average efficiency of irradiated samples in the range of $1 - 3 \times 10^{15}$ $1 \text{ MeV } n_{\text{eq}}/\text{cm}^2$ with several backside treatments. Samples differ in several parameters such as doping of the n-type implant, geometry modification and thickness.

6.7.3 Doping of the deep n-layer improvements

A high efficiency for the 3×10^{15} $1 \text{ MeV } n_{\text{eq}}/\text{cm}^2$ irradiated MALTA2 Cz sample, was recovered only for samples with larger doping of the deep n-layer. A study of the impact of the doping concentration of the n-layer was further developed.

For the highly irradiated MALTA2 samples, two doping concentration values of the deep n-type implant have been implemented in the sensor design. These are denoted as high doping (H-dop) and very high doping (VH-dop) and refer to their relative difference in implantation dose (approximately 70%). The increase in doping of the n-layer was found (via TCAD simulations [191]) to lead to a decrease in the depletion layer around the collection electrode. This is correlated to an increase in capacitance and noise. Still, careful increases in the doping level have been found to not lead to a large impact on the threshold and noise as can be seen in Figure 6.43, which compares the threshold and noise distribution for the H and VH doping samples. The slight decrease in threshold and increase in noise between the H and VH doped samples, is attributed to sample-to-sample variance. The increase in the deep n-layer doping concentration is not found to lead to a large noise or threshold penalty.

A uniform efficiency across the entire chip was found for a 1×10^{15} $1 \text{ MeV } n_{\text{eq}}/\text{cm}^2$ irradiated back metallized VH-doping Cz MALTA2 sample and is highlighted in Figure 6.44.

A clear improvement in the radiation hardness was found for the VH doped sample after irradiation up to 3×10^{15} $1 \text{ MeV } n_{\text{eq}}/\text{cm}^2$. The average efficiency for several threshold configurations for both a H and a VH doped n-layer irradiated sensors is shown in Figure 6.45. Compared to the high doped sample, the very high doped sample reached an efficiency 8% larger for SUB values above -40 V . Additionally, the VH doped sample reached the required 95% efficiency target already for a SUB bias of -20 V . This result is promising in terms of the

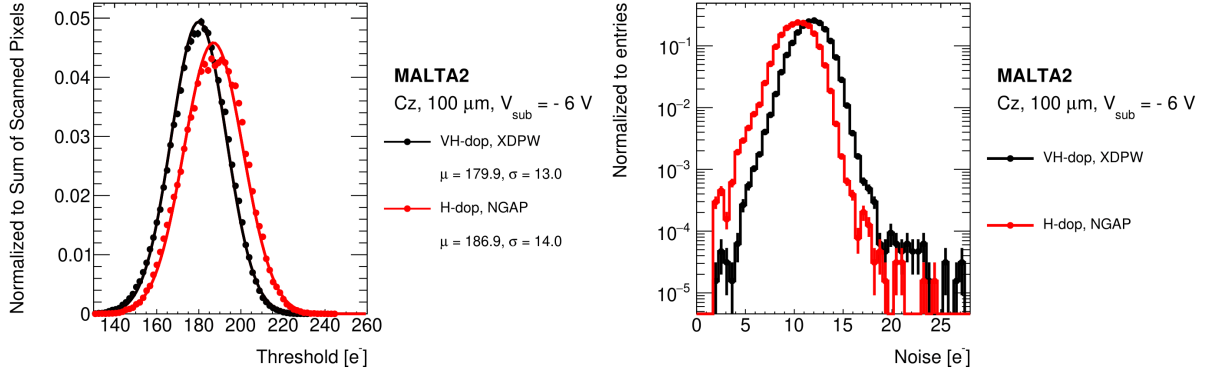


Figure 6.43: Threshold (left) and noise (right) distributions of two non-irradiated Cz MALTA2 samples with a very high doping of the deep n-layer (black) and high doping of the deep n-layer (red).

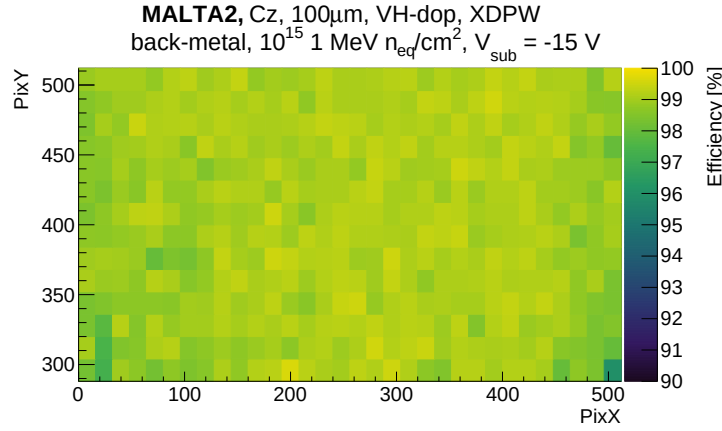


Figure 6.44: 2D efficiency map of the entire matrix of an $1 \times 10^{15} \text{ 1 MeV } n_{\text{eq}}/\text{cm}^2$ irradiated Cz XDPW, 100 μm thickness VH doping of the deep n-type layer MALTA2 sample. The SUB was -15 V and the PWELL was -6 V .

power dissipation optimization of future MALTA sensor designs.

The radiation hardness improvements brought by the increase in the deep n-layer doping highlights that the main radiation damage mechanism in the MALTA2 sensor is the donor removal effect. The radiation hardness improvements come from compensating this effect at large irradiation doses.

6.7.4 Radiation hardness at $5 \times 10^{15} \text{ 1 MeV } n_{\text{eq}}/\text{cm}^2$

Several regular backside H and VH doped samples have been irradiated to the elevated dose of $5 \times 10^{15} \text{ 1 MeV } n_{\text{eq}}/\text{cm}^2$, in order to gauge the feasibility of pushing the current technology node to larger radiation doses. An efficiency up to 50% was found for the $5 \times 10^{15} \text{ 1 MeV } n_{\text{eq}}/\text{cm}^2$ VH doping irradiated MALTA2 sample. A comparison plot between this result and the ones obtained previously for lower irradiation doses is shown in Figure 6.46. An important feature of this plot is the fact that the efficiency trend does not saturate at the maximum SUB value of -55 V . This shows that a larger average efficiency could be gained by increasing the SUB which could be facilitated by achieving a larger punch-through current threshold.

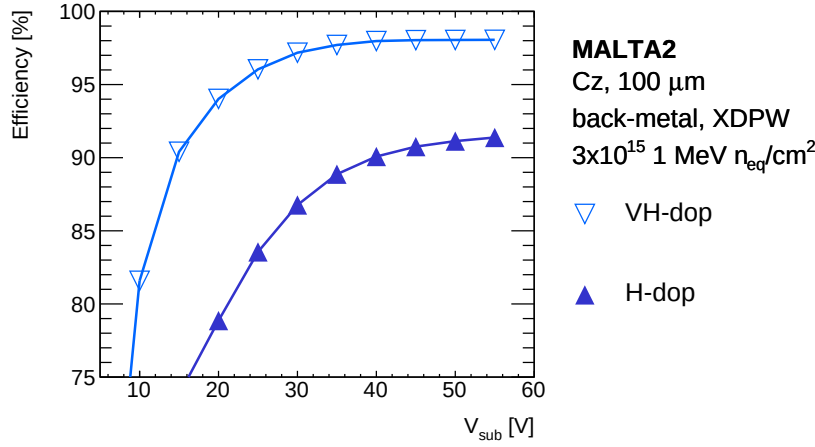


Figure 6.45: Average efficiency versus bias voltage for two 3×10^{15} 1 MeV $n_{\text{eq}}/\text{cm}^2$ irradiated Cz MALTA2 samples. One sample has a high doping of the deep n-type layer and the other sample has a VH doping concentration.

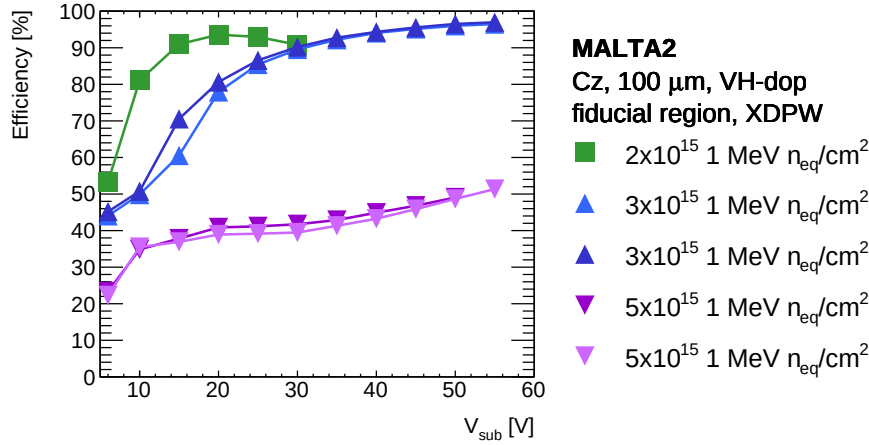


Figure 6.46: Average efficiency of several irradiated Cz, XDPW, VH-dop MALTA2 samples versus SUB. The operating threshold of all the samples is between 100 and 200 e^- .

Additionally, the 5×10^{15} 1 MeV $n_{\text{eq}}/\text{cm}^2$ shows improvements in efficiency for higher doping concentrations of the deep n-layer as seen in Figure 6.47. Another strategy for increasing the radiation hardness of the MALTA2 sensor at very large radiation doses, could be the further increase in concentration doping of the deep n layer. However, the continued doping increases could lead to large noise penalties. A balance between radiation hardness and a low input capacitance should be optimized in the future iterations of the MALTA sensor.

6.8 Depletion depth studies of the MALTA2 sensor

The results discussed in this section were additionally published in the paper proceedings appended to the thesis as Paper IV.

In all the radiation damage studies for the MALTA2 sensor, the over-arching parameter degradation which impacts all of the sensor's figures of merit is the depletion depth. The depleted

volume of a sensor is known to grow with the square root of the applied bias (Equation 2.4) and shrink with the accumulation of displacement damage dose. A thorough understanding of the depletion volume dimensions of a sensor is paramount in achieving a satisfactory understanding of the underlying radiation damage effects which in turn lead to the observable sensor parametric changes in the previous sections.

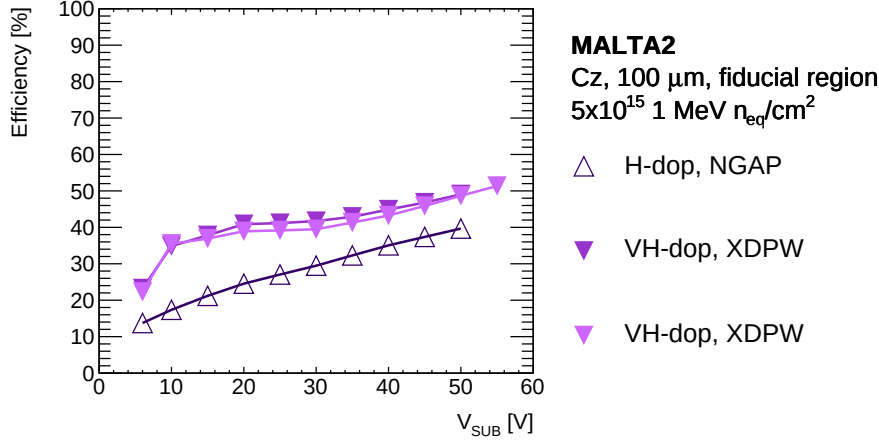


Figure 6.47: Average efficiency of three 5×10^{15} 1 MeV n_{eq}/cm^2 irradiated Cz MALTA2 samples. One sample has a high doping of the deep n-layer and the other two had a very high doping of the deep n-layer.

Usually, for hybrid sensors that physically decouple their sensing and read-out into two separate chips, the depletion size can be inferred from the saturating value of the quadratic inverse capacitance, $1/C^2$ value with applied bias voltage, commonly known as a CV curve. Due to the complex implementation of the MALTA2 monolithic sensor, such a simple investigation is not possible. Two indirect investigation methods for the depletion volume of MALTA2 sensors have been explored: the grazing angle technique and the E-TCT.

6.8.1 Grazing angle studies of MALTA2

The grazing angle technique [193] uses a geometrical model that correlates the depletion depth of a sensor to the increase of the average cluster size due to the inclination of incident charged-particles (mixed hadron beam from the SPS facility) as can be seen in Figure 6.48:

$$Cl_{size\perp}(\tan \alpha) = \frac{d}{p} \tan \alpha + Cl_{size\perp}(0) \quad (6.5)$$

$Cl_{size\perp}$ is the cluster size projected on the axis perpendicular to the axis of rotation, d is the active depth, p is the pixel pitch and α is the track angle. The active depth of a sensor configuration can be calculated from the slope of the increase in cluster size with the tangent of the track angle. A smearing of the estimated depth is expected at the boundary of the junction, where an electric field gradient is expected. As a consequence, the active depth estimation approaches the depletion depth of the sensor when the diffusion component of the collected charge is minimized. In order to generate inclined tracks through the sensor, the DUT was placed on a Thorlabs rotating stage controlled via a K-Cube Brushed DC Servo Motor Controller that allowed the systematic rotation of the sensor.

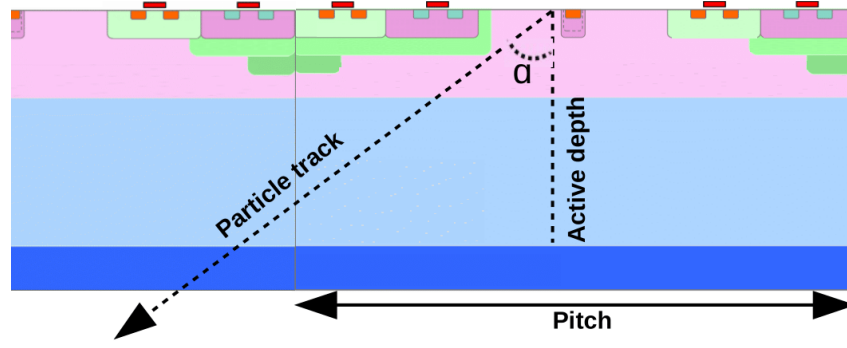


Figure 6.48: Schematic principle of the grazing angle technique.

At small angles, the diffusion component of cluster formation is dominant, while at large angles the cluster formation due to angled particle tracks is dominant. Figure 6.49 shows the projections in the perpendicular (blue line and circles) and parallel (red line and squares) directions relative to the axis of rotation of the average cluster size. The parallel projection remains almost constant with the increase in the track angle. At larger angles, a slight increase in cluster size is noticed. It is correlated to both a tilt in the DUT plane and a larger total deposited energy of hits that lead to an increase in charge sharing. The perpendicular projection increases with the rotation angle. The increase is characterized by a diffusion dominated regime (angles $< 30^\circ$) and a linear (in terms of the tangent of the angle) regime (angles $> 30^\circ$).

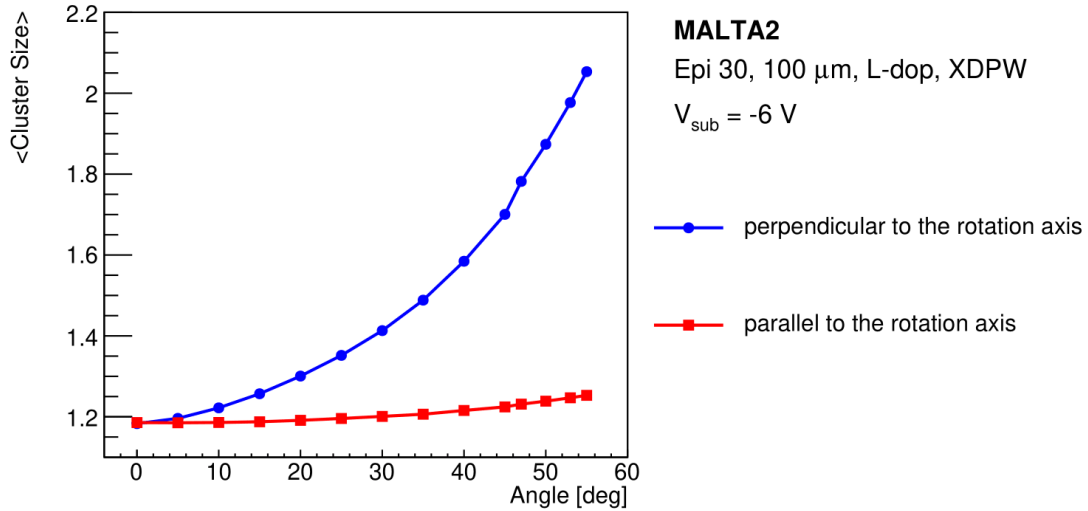


Figure 6.49: Average cluster size projected on the perpendicular and parallel axis of rotation vs the angle of rotation for a MALTA2 sample.

MALTA2 epitaxial

A 30 μm thick NGAP, highly-doped n-layer Epi MALTA2 sample has been investigated with the grazing angle technique. The total sample thickness is 300 μm , which includes the low resistivity silicon substrate for mechanical stability. The low resistivity substrate is not expected to contribute to charge collection and it can not be depleted at the nominal SUB value of -6 V . Several threshold and bias configurations have been used in order to probe the dependence of

the calculated active depth on these parameters and is shown in Figure 6.50. A drop in active depth is observed for lower threshold configurations. This effect is not directly associated to a decrease of the depletion volume, but rather highlights the magnitude of the inter-pixel charge sharing. Increased thresholds, will lead to the inability of observing low charge hits, leading to a drop in the observable cluster size which is further reflected in the grazing angle technique as a drop in the measured active depth. The magnitude of the inter-pixel charge sharing was studied in a dedicated energy loss study and the results are currently being prepared for publication.

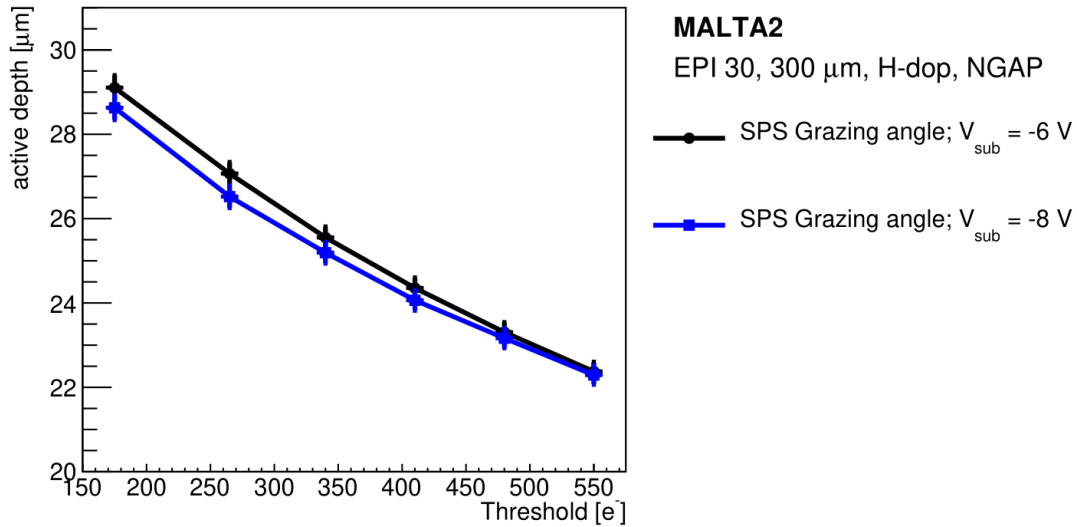


Figure 6.50: Active depth versus threshold in electrons measured with the grazing angle, performed with a 180 GeV mixed hadron beam at SPS CERN.

The active depth dependence on the bias voltage shows that the increase in SUB does not lead to an increase of the active depth. The systematic drop in the active depth for -8 V SUB is associated to an elevated noise level of the sensor which degrades the cluster size measurement. For the lowest threshold configuration, an active depth close to the Epi physical size of $30\text{ }\mu\text{m}$ is found. This is an important result, as it confirms the initial assumptions for the Epi MALTA2 samples, in terms of achieving “full depletion” at a small bias voltage of -6 V. One caveat to this statement is the technique’s ability to only probe the depletion in the depth axis. The depletion propagation across the pixel pitch can not be studied with this method, such that the statement on full depletion is made considering only the depth component.

MALTA2 Czochralski

Several non-irradiated and irradiated MALTA2 Cz samples have been investigated with the grazing angle technique. The Cz samples are of special interest as the study of their active depth can give preliminary information on the resistivity of the p-type bulk and its change with elevated displacement damage doses.

The measured active depth of a non-irradiated $300\text{ }\mu\text{m}$ thick, NGAP high doped deep n-layer Cz MALTA2 sample is shown in Figure 6.51. The larger threshold dependence of the Cz sample, compared to the previous Epi result is motivated by the increased charge sharing of the larger signals generated in Cz. The cluster size growth is induced by both angle track effects

and charge diffusion effects. As a consequence, the threshold dependence of the active depth leads to a large uncertainty on the estimation of an accurate active depth value.

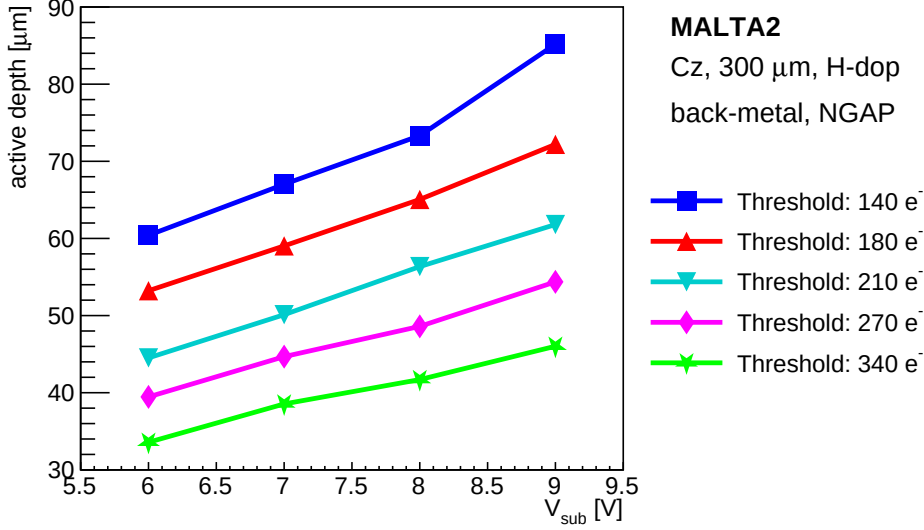


Figure 6.51: Active depth measured through the grazing angle technique of a non-irradiated MALTA2 sample (Cz, NGAP, 300 μm thick, high doping of the n-layer, back metallized) at -6 V PWELL bias and multiple SUB Voltage and sensor threshold configurations.

An increase with the SUB in the measured active depth can be observed for all threshold configurations. The increase in depth with bias voltage roughly follows the expected parametric depth formula: $d = 0.3[\mu\text{m}] \times \sqrt{\rho V_b}$ [17], where d is the depletion, ρ is the resistivity of the p-type substrate and V_b is the applied bias. Considering the several investigated threshold configurations, the resistivity of the p-type substrate is between 1 – 8 $\text{k}\Omega\text{cm}$. Reference [194] performed a similar study on the CLICTD sensor, which shares the same Tower fabrication reticle, and has the same Cz substrate as the MALTA sensor. The active depth presented in that publication indicates a substrate resistivity close to 3 $\text{k}\Omega\text{cm}$.

An 1×10^{15} 1 MeV $n_{\text{eq}}/\text{cm}^2$ irradiated 100 μm thick, XDPW with high doping of the deep n-layer, Cz MALTA2 sample was investigated in a similar fashion. Figure 6.52 shows the measured active depth versus SUB for several threshold configurations. Only high efficiency ($>90\%$) configurations are considered to lead to a meaningful sensor performance description. For low efficiency configurations, the cluster size formation through inclined tracks penetrating multiple pixels is convoluted with other effects: pixel boundary effects, non-uniform charge propagation. As a consequence, the grazing angle technique produces a less accurate active depth estimation for these configurations.

As with the previous results, the active depth varies with the applied threshold and increases with the bias voltage. For all threshold configurations, a saturating effect in the measured active depth is observed. A direct comparison between the irradiated and non-irradiated results can not be made due to the unfortunate mismatch in sample thicknesses. The plateau in depletion at several threshold configurations further shows that the active depth to threshold dependence is just an artifact of the observation technique. Using the same depletion depth to p-type resistivity parametrization as before, the resistivity of the substrate after 1×10^{15} 1 MeV $n_{\text{eq}}/\text{cm}^2$ irradiation is found to be between 0.5 – 2 $\text{k}\Omega\text{cm}$. Relating these results to the change in p-type

concentration due to neutron irradiation parametrization in Equation 4.10, the damage factor g_c is found to be in the range of 0.0075 – 0.03. Reference [101] found a damage factor between 0.022 – 0.047, which is close to our estimation.

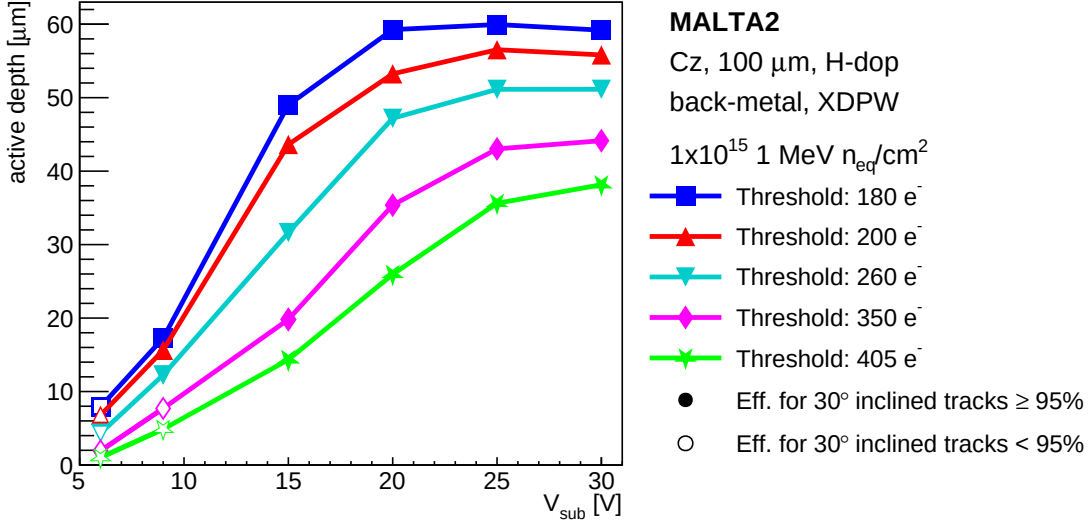


Figure 6.52: Active depth measured through the grazing angle technique of an irradiated MALTA2 sample (Cz, XDPW, 100 μm thick, high doping of the n-layer, $1 \times 10^{15} \text{ 1 MeV } n_{eq}/\text{cm}^2$, back metallized) at -6 V PWELL bias and multiple SUB Voltage and sensor threshold configurations. The data points with an efficiency larger than 95% for tracks traversing the sensor at 30° inclination are denoted with closed markers, while those with an efficiency lower than 95% are denoted with open markers.

The grazing angle technique provides a relatively easy venue for the investigation of a sensor's active depth. It allows a straight-forward implementation in a test beam experiment with the help of a rotating stage. During the testing of the MALTA2 sensor and especially for Cz samples, the magnitude of the diffused charge was found to have a large contribution on the measurements. In order to achieve a measurement of the depletion in the MALTA2 sensor, independent of the various front end effects, a dedicated study of analog output pixels with the help of a pulsed laser has been undertaken.

6.8.2 E-TCT studies of MALTA2

Several Epi and Cz MALTA2 samples have been scanned with the help of a 4 μm wide infra-red pulsed laser, described in detail in Section 6.5. The laser width matches the telescope position resolution, leading to compatible results. The intensity of the laser was configured before each measurement in such a way to not saturate the pixel output. By avoiding the saturation of the front end, the signal output (waveform) amplitude can be considered proportional to the deposited charge. Additionally, the integral of the waveform was also calculated and a good match between the amplitude and integral of the waveforms was found.

MALTA2 epitaxial

An Epi, 30 μm thick, XDPW, low doping of the deep n-layer MALTA2 sample was polished following the procedure detailed in Section 6.5.2. The total sample thickness is 100 μm, which

includes the low resistivity silicon substrate for mechanical stability.

A systematic study of the monitored signal amplitude in terms of the applied SUB was performed and the resulting edge scan of a single pixel is shown in Figure 6.53. The maximum in the collected amplitude is correlated to the maximum charge collection efficiency, associated to the location of the collection electrode and is consistent across all bias voltages. The area with large charge collection efficiency, gives qualitative information about the shape of the electric field inside the pixel. A larger electric field is found in the vertical and horizontal dimensions relative to the position of the collection electrode. This leads to the approximate “T” shape of the large amplitude distribution seen in the four panels of Figure 6.53. This effect has already been predicted with the help of TCAD simulations in Reference [173]. The regions with a small recorded amplitude are correlated to un-depleted regions of the epitaxial volume and give a measurement of the inefficiencies in the depletion propagation across both the depth and the pitch axis of the pixel. Red boxes have been fit to each pixel in order to estimate the absolute position of the pixel relative to the data. The fitting procedure took into account the 4 μm Gaussian beam smearing, aligning the box relative to the charge collection profile maximum, identified as the position of the collection electrode.

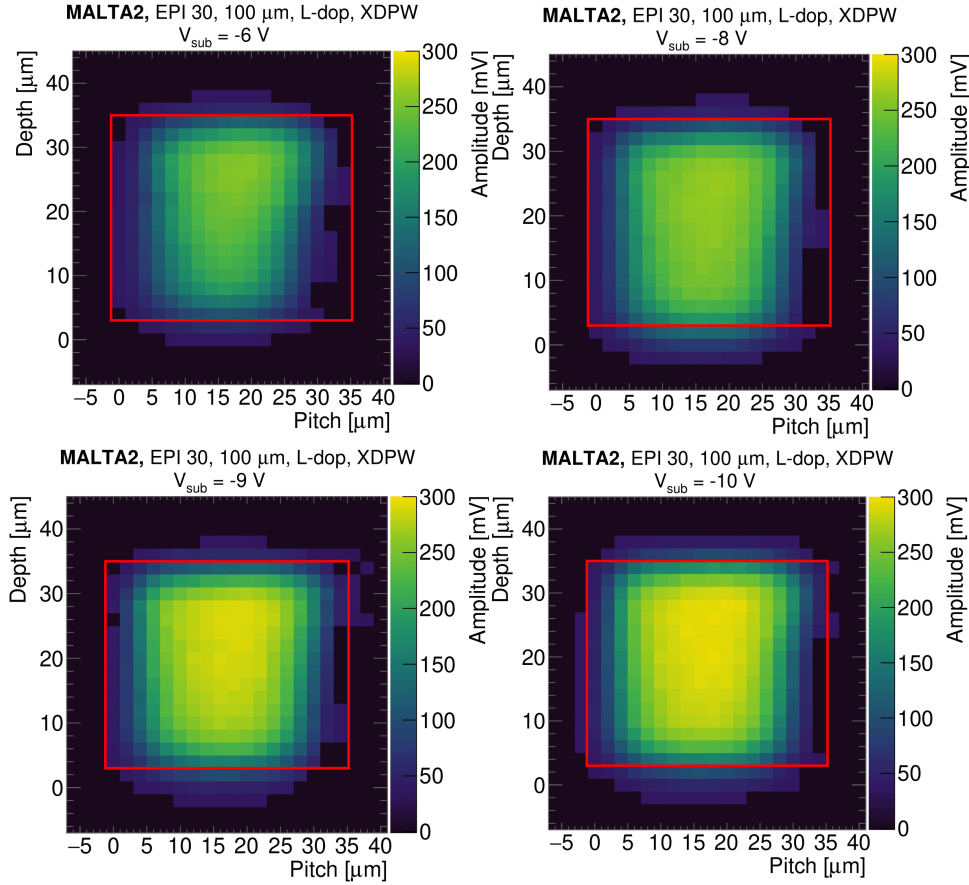


Figure 6.53: 2D distributions of the analog signal amplitudes induced with the E-TCT set-up for several SUB values: -6 , -8 , -9 , -10 V . The red box shows the estimated position of the pixel ($36.4 \mu\text{m}$ pixel pitch and $30 \mu\text{m}$ of Epi thickness) aligned to the maximum amplitude measured. The orientation of the plot is such that the collection electrode sits at the top of the plot and the sensor edge on the left.

A quantitative measurement of the depletion propagation inside a pixel is achieved by computing the FWHM of the projection across both axes. The two projections are plotted in Figure 6.54 and 6.55. In both sets of plots, the top plot shows the data normalized to the maximum value of the -10 V bias measurement point and the bottom plot shows the data normalized to each distribution maximum.

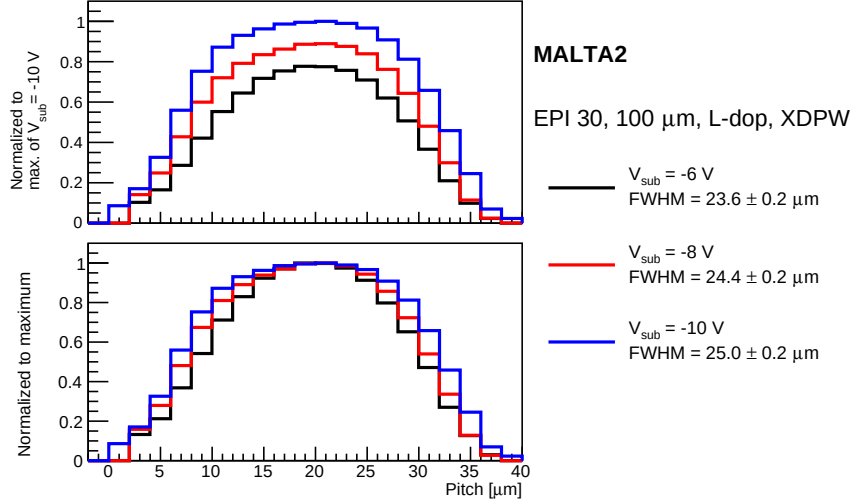


Figure 6.54: Projection on the pitch axis of the measured amplitude distribution induced with the E-TCT setup for multiple SUB Voltage values. Two normalization procedures are performed on the data. A normalization to the maximum value of the -10 V SUB bias amplitude distribution is performed in the top plot and a normalization to the respective maximum amplitude of the distributions in the bottom plot. The normalization constants at different SUB values are: 0.77 at -6 V, 0.89 at -8 V, 1 at -10 V. Additionally, the full width at half maximum of the data is quoted in order to highlight the magnitude of the pixels depth depletion.

Both normalizations in the pitch projections of Figure 6.54 highlight a symmetric distribution around the pixel CE. This is expected due to the octagonal electrode and symmetrical pixel pitch design [173]. The lateral depletion is calculated as the FWHM of the projection distribution. The estimation of the depletion is additionally convoluted with the Gaussian smearing of a $4 \mu\text{m}$ wide beam. The lower amplitudes at smaller bias values are compatible with fewer collected charges. As expected, a larger bias voltage leads to larger collected amplitudes. A systematic increase of the lateral depletion is observed with an increase in the bias voltage, from $23.6 \mu\text{m}$ at -6 V, to $25 \mu\text{m}$ at -10 V. The lateral depletion can be improved by further optimization of the electrical field design, in order to achieve the full $36.4 \mu\text{m}$ lateral dimension.

Unlike the pitch projection, the depth projection in Figure 6.55 shows an asymmetrical distribution. It is characterized by a rapid increase near the collection electrode, followed by a plateau and a slower decrease further in the silicon bulk. The normalization of the upper figure shows the increase in measured amplitude with bias voltage, due to the increase of the electric field strength. The bottom normalization highlights that at larger bias voltages, the depth distribution has a “flatter” plateau after the sharp increase near the collection electrode (depth $\sim 30 \mu\text{m}$). This is an indication of a more uniform electric field in depth at higher bias voltages. The depletion depth estimation remains relatively unchanged for the various bias

voltages, suggesting that the epitaxial layer is fully depleted in depth at -6 V and only an increase in the electric field strength is achieved by increasing the bias voltage. This result is compatible with the grazing angle technique showcased in Figure 6.50.

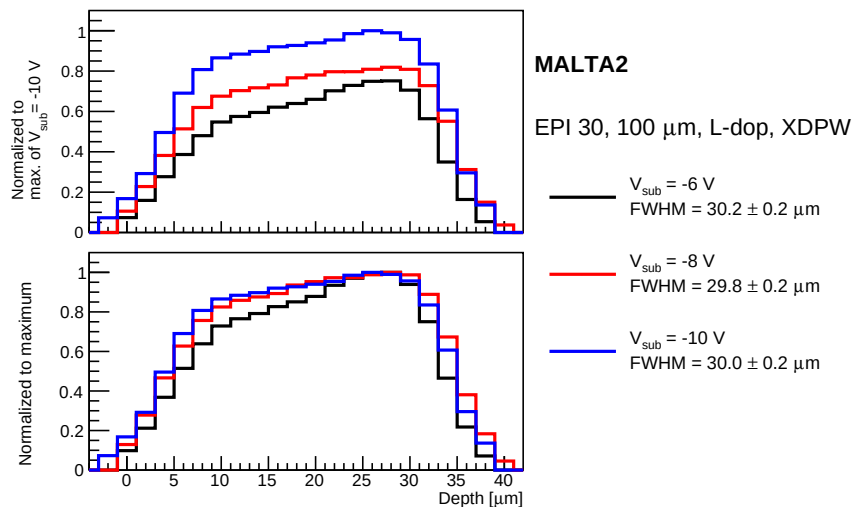


Figure 6.55: Projection on the depth axis of the measured amplitude distribution induced with the E-TCT setup for multiple SUB Voltage values. Two normalization procedures are performed on the data. A normalization to the maximum value of the -10 V SUB bias amplitude distribution is performed in the top plot and a normalization to the respective maximum amplitude of the distributions in the bottom plot. The normalization constants at different SUB values are: 0.75 at -6 V, 0.81 at -8 V, 1 at -10 V. Additionally, the FWHM of the data is quoted in order to highlight the magnitude of the pixels depth depletion.

MALTA2 Czochralski

A non-irradiated, 100 μm thick, XDPW with high doping of the deep n-layer Cz MALTA2 sample was investigated with the E-TCT. The sample did not undergo the polishing technique employed for the Epi sample. Still, through microscope investigations it has been found that the sensor's edge didn't have significant damage.

Figure 6.56 shows the 2D scans performed for one of the analog pixels of the Cz MALTA2 sample. When the sample is biased at -6 V SUB, a similar efficient charge collection pattern is gained to the one found for the Epi MALTA2 sample. For larger bias voltages, a growth of an efficient charge collection inside the silicon bulk is observed, increasing in size for higher SUB values. The sharp change in bin content for some of the measurement points is an artifact of the data acquisition procedure. When operating the sensor under a high pulse frequency laser, the front end can latch, leading to a high current state and rendering the measurements un-physical. The sensor scanning is done row wise first and as a consequence, the affected bins appear along one or several rows. During data analysis, the affected data points are removed and the empty bins are merged, leading to some of the visual artifacts. Only few such events took place during the data acquisition, such that their contribution is minor to the entire data set.

A quantitative analysis of the pitch and depth depletion components was also pursued.

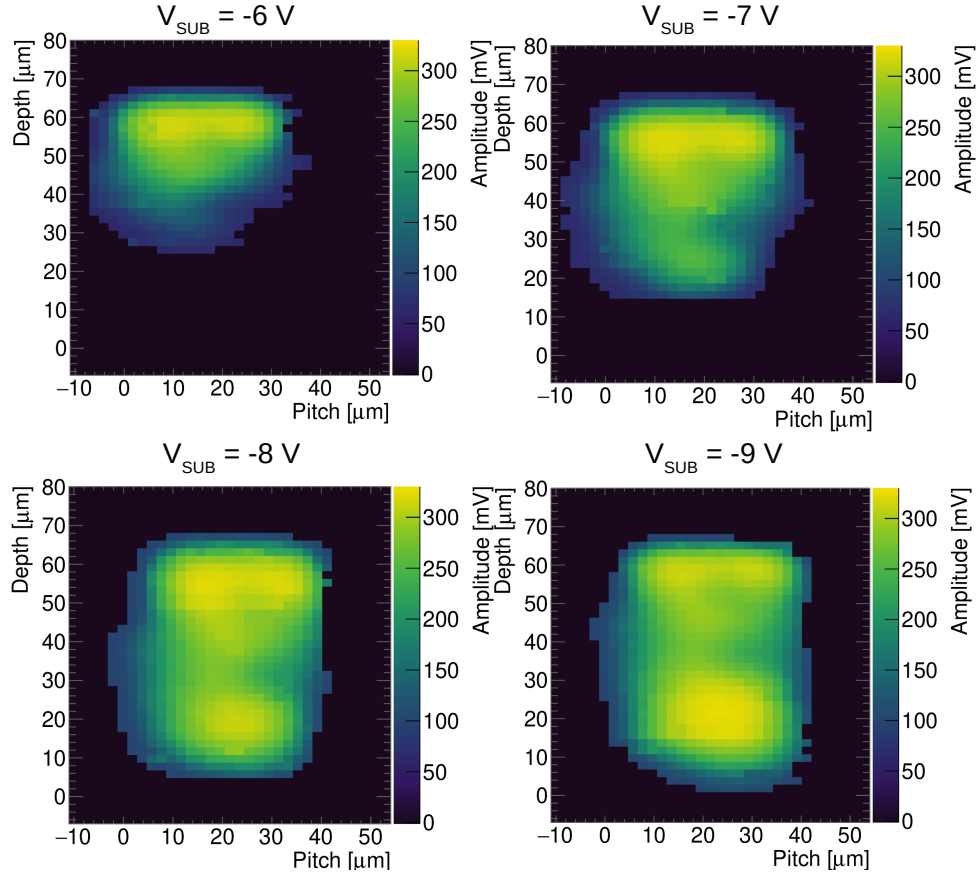


Figure 6.56: 2D distributions of the analog signal amplitudes induced with the E-TCT set-up for several SUB values: -6 , -7 , -8 , -9 V for a Cz MALTA2 sample. The orientation of the plot is such that the collection electrode sits at the top of the plot and the sensor edge is on the left.

Figure 6.57 shows the pitch projection of the measurement points highlighted in Figure 6.56. A lateral depletion ($\sim 36 \mu\text{m}$) matching the entire pixel pitch ($36.4 \mu\text{m}$) was found for all SUB values. A slight asymmetry is seen at low bias voltages which could be due to the data acquisition malfunctions described above or due to the asymmetric design of the deep p-well cut-out of the MALTA2 design. A symmetric pitch depletion distribution is gained at larger bias voltages, -9 V.

Figure 6.58 shows the depth projection of the plots showcased in Figure 6.56. Unlike the measurements for the Epi MALTA2 sample, a large increase in the depletion in the depth axis is observed. A doubling effect of the depletion depth value is gained for bias voltages between -6 and -9 V. Additionally, a saturating effect takes place at -8 , -9 V SUB which highlights that a further increase in bias would not lead to a large increase in depletion. However, the saturating trend in the depth axis could be also due to a poorer bias voltage propagation due to the lack of back metallization of the sample. This effect was however studied with the help of a threshold scan, which showed that for -9 V SUB, a uniform threshold distribution is achieved for the entire pixel matrix. As a consequence, the voltage propagation effect is not expected to be the leading order effect in the observed results.

At low bias voltages, the depth depletion is characterized by a fast increase, followed by a much shallower decrease in the silicon bulk. This behavior is expected for large, partially

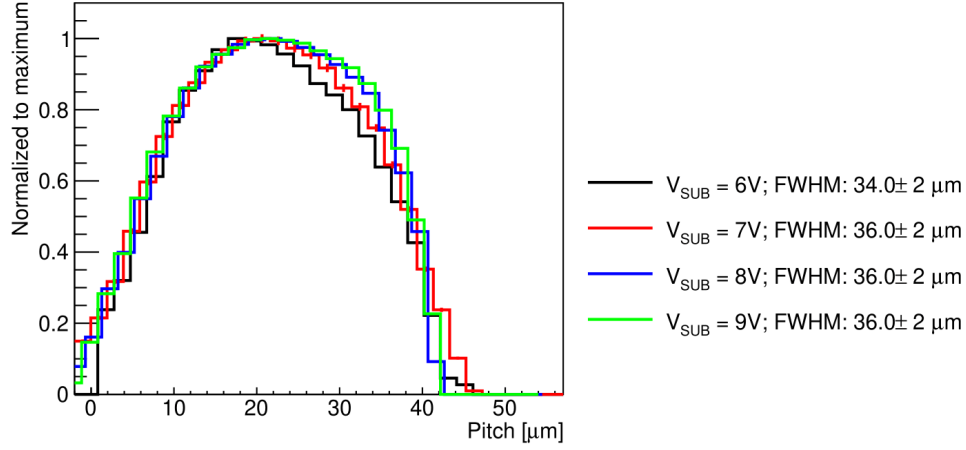


Figure 6.57: Projection of the pitch axis of the measured amplitude distribution induced with a pulsed laser for a 100 μm thick, XDPW, un-irradiated, with high n-doping of the deep n-layer Cz MALTA2 sample.

depleted silicon volumes, where the region between depleted and un-depleted silicon is not well defined and an electric field gradient exists. This result brings a degree of validation for the assumptions postulated in Section 6.8.1, relating to the large depletion depth uncertainty observed for Cz MALTA2 samples with the help of the grazing angle technique. For larger bias voltages, a second peak forms inside the silicon bulk.

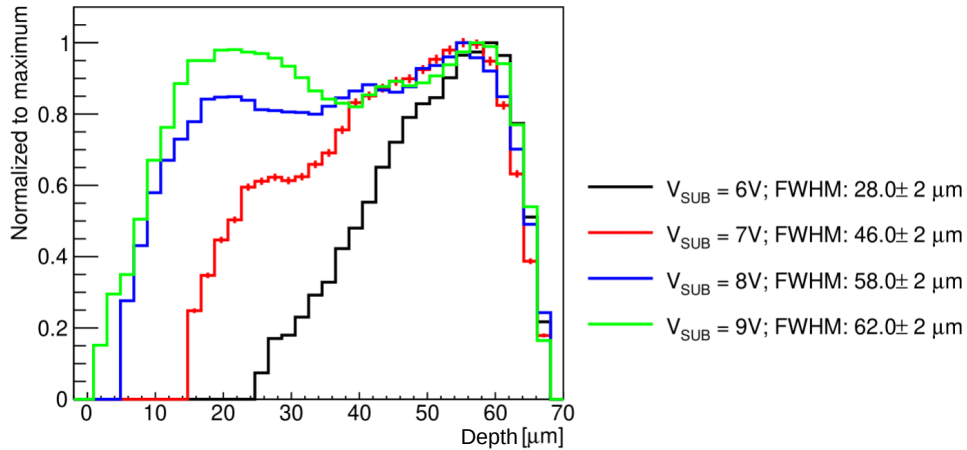


Figure 6.58: Projection of the depth axis of the measured amplitude distribution induced with a pulsed laser for a 100 μm thick, XDPW, un-irradiated, with high n-doping of the deep n-layer Cz MALTA2 sample.

The double peak structure observed in the data is similar to the double junction effect observed in neutron irradiated Fz silicon sensors [195] discussed also in Section 4.3.3. Most descriptions of the double junction effects are made for neutron irradiated Fz silicon sensors.

The Cz growing process can lead to several defects in the silicon which could in turn induce a similar effect as seen in irradiated Fz. One main difference in the observed defects for the Cz MALTA2 sample, is that the second peak does not appear at the edge of the 100 μm thick sample, but rather it appears inside the silicon bulk. This can be explained by the lack of a second implant on the sample backside, which limits the formation of a second junction there. The additional junction in the silicon bulk could be generated by an accumulation of mobile trap sites, which under the effect of the enhanced electric field lead to a local accumulation of positive charge. This effect, in turn can lead to a screening of the electric field, limiting the propagation of the depletion in depth. This interpretation of the results matches the projections of the scans both in depth and in pitch. In the 2D plots of Figure 6.56 an additional effect can be observed in the pitch orientation, where two localized efficient charge collection areas can be identified to the left and right of the pixel center. This effect can be explained in the double junction effect framework, as a local increase in the electric field, due to the existence of trapped charge at the deep p-well - deep n-well junctions. Still, due to the lack of a p-type implant on the backside of the tested sample, a rigorous double junction interpretation of the experimental data can not be justified.

Another possible explanation for the observed data is a non planar extension of the space charge region in partially depleted sensors. This could be further correlated to a bulging effect in the deep bulk dimension of the pixel, leading to an increase in the measured charge.

The validity of both assumptions is planned to be further tested with the help of additional samples. The measurement of a back metallized sample will give information about the possible double junction effect. The back metallization should impact the double peak structure observed in the signal and effectively shift the maximum towards the backside. Additionally, the measurement of thinned samples (50 μm thick Cz) could give more information on the possible non-planarity of the space charge region in the silicon bulk. Finally, a thorough understanding of the physical effects could be achieved with the help of TCAD simulations.

While the given interpretations partially match the results, the complexity of the pixel design does not lead to a clear proof of the existence of these effects. The lack of sample polishing could lead to some localised laser reflection. The magnitude of this effect is however assumed to be insignificant due to the well behaved measured waveforms (showing no secondary reflection or absorption peaks) across the entire sensor surface of interest.

For both the Epi and Cz MALTA2 samples, the results between the grazing angle and the edge transient current techniques match on a qualitative level. Additionally, for the Epi sample, a similar depletion depth was gained with both techniques.

For the grazing angle study of Cz MALTA2 samples, the large charge sharing inherent to this substrate has led to inaccurate measurement of the depletion depth, leading to a large threshold dependence. The E-TCT found values for the depletion within the estimation of the grazing angle technique.

Additional inclined sensor benefits

Independently of the grazing angle technique, the sensor inclination brings several improvements to the sensor performance in terms of spatial resolution and efficiency after irradiation.

The larger cluster sizes associated to inclined tracks are correlated to an increase in the spatial resolution of the sensor. The spatial resolution improvements are mainly found for the axis perpendicular to the rotation axis. This effect is highlighted in Figure 6.59. An improvement in the spatial resolution is gained in the X projection (perpendicular to the rotation axis) for

angles up to 30° , followed by a large apparent degradation at large angles. As expected, the resolution in the Y projection (parallel to the rotation axis) remains mostly unchanged with the increase in angle. A slight decrease in the Y projected resolution is observed at very large angles ($>50^\circ$) with a similar hypothesized source as the effect observed in the Y projection of the cluster size of Figure 6.49. The poorer resolution in the X axis for angles above 35° is not correlated to a physical change in the measured spatial resolution. It is rather correlated to the cluster position definition in the offline data analysis. The cluster position is defined as the center of gravity of the cluster, without an additional weighting scheme from the individual hit time tagging. This effect in turn leads to large root mean square values of the track residual distributions for large angles.

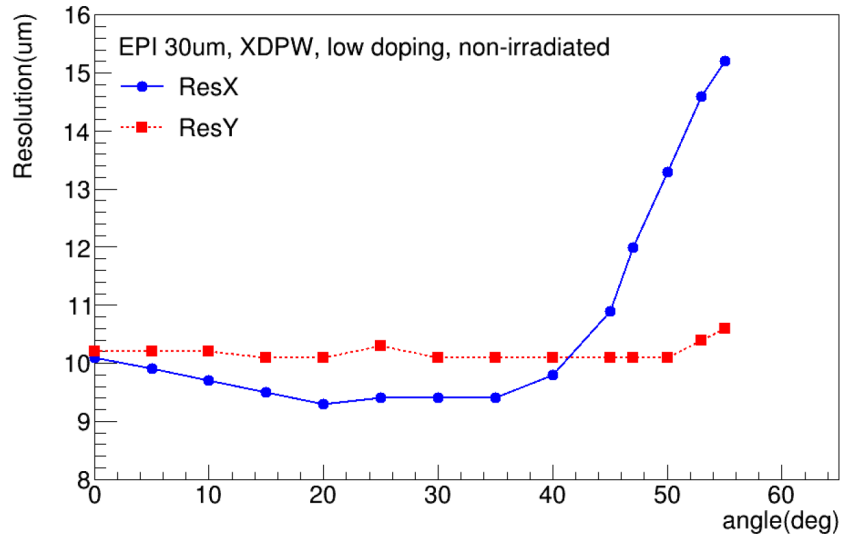


Figure 6.59: Spatial resolution of an Epi, 30 μm thick, XDPW, low doping of the deep n-layer MALTA2 sample. The resolution in both the X - perpendicular to the rotation axis (blue line and circles) and Y - parallel to the rotation axis (red line and squares) projections are plotted. The spatial resolution is defined as the RMS of the track residual distributions in both X and Y axes.

In order to gain more accurate measurements of the improvement of the spatial resolution for large angles, a time-weighted cluster position definition should be considered. Reference [194] performed a similar study and found a similar trend in their spatial resolution data for inclined sensors. They found that the weighted cluster position definition improves the spatial resolution at low angles but does not have a large effect at larger angles. Instead, they associate the poorer measured spatial resolution at large angles to the un-optimized operation of their front end at large signals associated to the inclined particle tracks.

The sensor inclination has also been found to improve the efficiency in non-efficient sensor configurations of irradiated MALTA2 sensors. Figure 6.60 shows the improvement of the sensor efficiency with the increase of the inclination angle for several SUB values. The improvement of the efficiency is much more pronounced at the lowest SUB value, -6 V. This is mainly due to the fact that the small depletion depth associated to this configuration benefits most from the additional charge induced by the inclined tracks. With the increase in SUB and the related increase in depletion, a larger deposited charge is formed inside the sensor, leading to overall larger signal amplitudes.

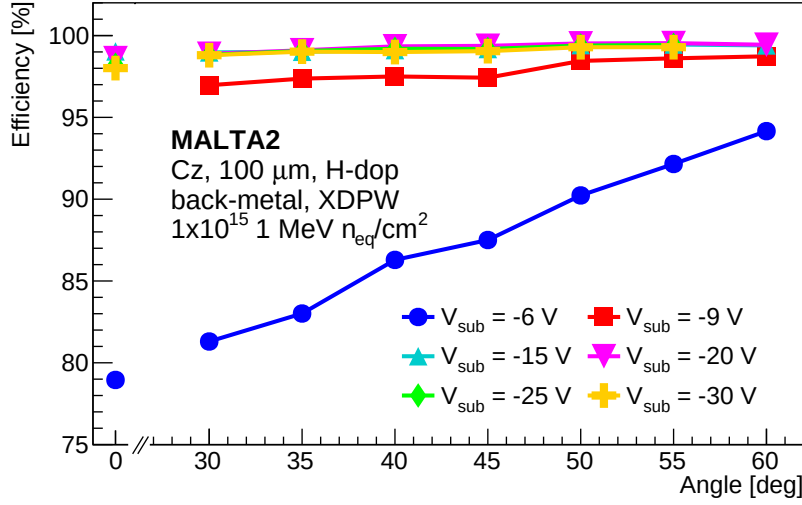


Figure 6.60: Average efficiency of a 1×10^{15} 1 MeV n_{eq}/cm^2 Cz, 100 μm thick, XDPW, high doping of the deep n-layer MALTA2 samples for several SUB values and inclined angles.

6.9 MALTA Conclusions

This section provided a snapshot of the MALTA collaboration R&D efforts and argued the current design choices of the MALTA2 sensor. Several developments mainly focused on radiation hardness were introduced and their impact on the sensor in terms of threshold, noise and tracking efficiency was measured through both laboratory measurements and test beam campaigns spanning several years (2021 and currently ongoing).

Several sensor variations were investigated in order to quantify their improvements and in turn learn more about the physical impact that the radiation damage has on the MALTA2 sensors.

Wafers from two silicon growing techniques were used: epitaxial, with a 25 – 30 μm thick very high resistivity active silicon layer and Czochralski, leading to a 100 – 300 μm of high resistivity silicon layer. MALTA2 samples were successfully implemented on both substrates. Epi MALTA2 samples were found to be fully depleted at low bias voltages (-6 V), while Cz samples required larger voltages for an equivalent performance. As a consequence, Epi based sensors can be efficiently operated in less radiation harsh environments, but irradiation up to 2×10^{15} 1 MeV n_{eq}/cm^2 already showed a low tracking efficiency (85%) even for larger SUB values (>10 V). In contrast, Cz based MALTA2 sensors show a poorer performance at low bias voltages (<10 V), but a much improved performance at larger bias voltages, recovering large efficiencies ($>98\%$) for irradiated samples up to 3×10^{15} 1 MeV n_{eq}/cm^2 , due to the larger charge collection volume.

The pixel geometry was varied between three processes called STD, NGAP and XDPW. While the STD process employed in Cz samples was found to lead to larger cluster sizes and

better spatial resolution, it was shown that it also leads to large tracking efficiency losses in the pixel corners after irradiation. The NGAP and XDPW modifications were found to bring a definitive improvement in terms of radiation hardness. Both modifications were found to have a similar impact (investigated via TCAD simulations [173]), by shaping the electric field away from the inefficient regions in the pixel corners.

The usual (ohmic contact) substrate bias propagation for MALTA2 Cz samples was found to not lead to an uniform efficiency map after sensor irradiation. This effect was mainly correlated to a cut-out in the PCB under the sensor which aimed to decrease particle scattering in telescope-based beam experiments. A first modification to this process was the application of an electrically conductive glue on the entire sensor surface for a better voltage propagation. However, this process was found to not yield good results due to the trapping of air bubbles under the glue during its curing procedure. Lastly, uniform full-array tracking efficiency results were gained by performing a post processing back side metallization procedure on MALTA2 samples. Large tracking efficiency, full pixel matrix results for 3×10^{15} 1 MeV n_{eq}/cm^2 Cz MALTA2 samples were gained for this post-processing modification.

In order to further increase the tracking efficiency of Cz MALTA2 samples irradiated to 3×10^{15} 1 MeV n_{eq}/cm^2 , doping concentration variations of the deep n-layer were investigated. It was found that a 70% increase in doping concentration led to an 8% tracking efficiency increase for a heavily irradiated sample (3×10^{15} 1 MeV n_{eq}/cm^2). This observation also highlights that the main radiation damage mechanism incurred in highly irradiated MALTA2 sensors comes in the form of the donor removal effect, which severely impacts the (originally) relatively lightly doped deep n-layer. Samples irradiated to 5×10^{15} 1 MeV n_{eq}/cm^2 showed a similar tracking efficiency improvement with the doping concentration increase, highlighting the possibility for further improvements in future sensor designs.

In order to gain a better understanding of the radiation hardness results on the MALTA2 sensor, two indirect depletion depth measurements were performed: the grazing angle technique at the SPS mixed hadron beam line and the Edge Transient Current Technique with a pulsed laser at the Humboldt University.

For Epi MALTA2 samples, the depletion depth studies confirmed the assumptions already made on the sensor performance, finding a full depth depletion already at -6 V in SUB. More surprising was the investigation of the lateral depletion component (also called pitch depletion), which found that at -6 V only $23.6 \mu m$ are depleted, increasing to $25 \mu m$ at -10 V from a potential $36.4 \mu m$ pixel pitch dimension. Additionally, it was found that larger bias voltages increase the electric field uniformity in the pixel's depth, which is expected for a fully depth depleted sensor.

The study of the depletion of Cz MALTA2 samples was found to be less straight-forward. This was mainly correlated to the increased charge sharing in these sensors. A large threshold dependence was found for the grazing angle technique study. This led to relatively large error bars in the estimation of the depletion depth. Before irradiation, the p-type substrate resistivity was found to be between $1 - 8 k\Omega cm$. The study of an irradiated sample further allowed the bounding for the neutron damage constant (correlated to the silicon resistivity increase) to $0.0075 - 0.03$. The E-TCT study of similar Cz MALTA2 samples found results that match the bounding predicted by the grazing angle technique. Furthermore, a double peak structure in the silicon depth was found in the analog pixel output. This effect was correlated to the double junction effect observed initially in irradiated Float zone silicon sensors and was further associated to deep traps introduced in the silicon bulk during the Czochralski silicon growth. An alternative explanation was given, assuming a possible bulging of the depletion volume in

depth.

Further studies are planned on both non-irradiated and irradiated MALTA2 Cz samples in order to provide validation for these results. The edge transient current technique is expected to provide further insight on the physical mechanisms of radiation damage. Additional grazing angle test beam experiments are planned for highly irradiated samples ($> 2 \times 10^{15}$ 1 MeV $n_{\text{eq}}/\text{cm}^2$). This experimental venue will provide a deeper understanding on both the depletion extension after irradiation, but also on the doping changes of the p-type silicon bulk.

Chapter 7

Conclusions

“Do you remember the Shire, Mr. Frodo? It’ll be spring soon. And the orchards will be in blossom. And the birds will be nesting in the hazel thicket. And they’ll be sowing the summer barley in the lower fields... and eating the first of the strawberries with cream. Do you remember the taste of strawberries? - Sam asked Frodo as they approached their doom.”

— J.R.R Tolkien, The Lord of the Rings

This thesis has focused on describing the radiation hardness studies of two sensors manufactured in the same technology node: Tower Semiconductor 180 nm feature size for 3.3 V CMOS Imaging process. These two sensors are planned to be employed in vastly different applications: the ULTRASAT imaging sensor for in-orbit near-ultraviolet spectrum measurements and the MALTA tracking sensor for track reconstruction at the inner radii of collider experiments. As a consequence, their pixel and front end design is different: the ULTRASAT sensor employs a close to commercial 4T dual-gain CMOS Imaging Sensor design, while the MALTA sensor uses a highly customized monolithic active pixel sensor with a small collection electrode design. Due to these differences, the testing procedures were customized for each sensor. The radiation hardness figures of merit considered for the ULTRASAT sensor were the dark current, charge transfer efficiency, noise, sensor linearity and uniformity, while for the MALTA sensor were the comparator threshold, noise and tracking efficiency. Additionally, the radiation environments expected for both sensors are different: the MALTA sensor is planned for implementation at the inner radii of hadron collider experiments which could expect a lifetime dose accumulation of ionizing effects up to 100 Mrad and displacement damage up to 1.5×10^{15} 1 MeV n_{eq}/cm^2 for current collider experiments, while the ULTRASAT sensor expects a lifetime accumulation of ionizing damage up to 55 krad and displacement damage in the order of $\sim 10^{10}$ 1 MeV n_{eq}/cm^2 .

The TID sensitivity study of test structures for the ULTRASAT sensor highlighted a possible large impact of the ionizing radiation damage for TIDs as low as 5 krad in terms of dark current random telegraph signal. In contrast, the MALTA sensor’s parameters were not found to severely degrade to TIDs up to 100 Mrad. This large discrepancy in “effective radiation hardness” is very hard to explain in an unitary fashion due to the complex sensor’s design and operation, but some observations are further made.

The main difference between the two sensors comes in terms of their operation principles. The ULTRASAT sensor is a 4T CMOS imaging sensor, while the MALTA sensor has a charge collection resembling a 3T CMOS imaging sensor. Naively, the lack of diode pinning in the MALTA sensor could lead to a larger dark current source from the large oxide interface contact

area between the space charge region and the pre-metal dielectric translating to a poorer signal to noise ratio. While this is partially true, the operation of the front end of the MALTA sensor brings several inherent radiation hardness improvements. The ULTRASAT sensor collects the charge generated in a pixel volume and transfers it in the form of a voltage pulse to an analog to digital converter. In this case, a low variance dark current component does not severely impact a measurement, unless saturation effects take place. The MALTA sensor, similarly collects charge and generates a voltage pulse. Instead of aiming to quantify the amount of charge collected, the voltage pulse is amplified and compared to a reference (via a current comparator) outputting binary hit/ no hit information. This output scheme offers a big advantage in terms of ionizing radiation damage hardness in the sense that the only impact of the dark current increase occurs if the signal induced in a pixel bypasses the comparator threshold (order of $\sim 100 e^-$ for MALTA2). The ULTRASAT sensor's ionizing damage was mainly localized in the pixel, showing no large impact in the read-out noise for a TID up to 55 krad. In turn, the MALTA TID impact up to 150 Mrad was mainly associated to parametric changes in the front end transistors operation. This was not found to lead to significant tracking parameters degradation.

An additional discrepancy between the two sensors is their different charge collection integration times. This is a fundamental limitation of the two sensor's applications and their signal to noise ratio optimization. The ULTRASAT sensor will take 300 s integration time images (in order to be able to image faint astronomical sources), with a discrete reset and global shutter read-out operation. In contrast, the MALTA2 sensor employs a continuous reset mechanism (in order to cope with the 25 ns bunch crossing requirement of LHC) and asynchronous read-out, which leads to an integration time in the order of 10's of ns, drastically limiting the collected radiation induced dark current.

Another difference between the two sensors is their active silicon thickness. The ULTRASAT sensor's active thickness is only 4 μm in order to be sensitive to near-UV light, while the MALTA sensor requires much thicker substrates for particle detection (30 μm Epi and up to 300 μm Cz). The thicker substrates implemented by the MALTA2 sensor, ensure a large signal to noise ratio even after severe irradiation. In contrast, the relatively small charge accumulated by the ULTRASAT sensor, poses fundamental limitations on its signal to noise ratio.

In terms of displacement damage, the ULTRASAT sensor is expected to not see a large degradation up to its life-time dose $\sim 10^{10}$ 1 MeV $n_{\text{eq}}/\text{cm}^2$ while, MALTA2 showed radiation hardness up to 3×10^{15} 1 MeV $n_{\text{eq}}/\text{cm}^2$. The main impact in both sensors is expected to come in terms of their charge transfer efficiency degradation. As this is directly linked to charge trapping sites in the sensor's space charge region, the amount of charge transfer efficiency loss in both sensors is expected to scale with the incurred displacement damage dose and lead to a comparable effect in both sensors. However, the impact on the sensors's signal to noise ratio would be vastly different due to the large difference in sensor thickness and generated charge (during an operation cycle of the pixel).

The ULTRASAT sensor was found to be sensitive to single event upsets and latch-ups induced by heavy ions with linear energy transfers down to 13 MeV cm^2/mg . While not yet categorically proven, this sensitivity was associated to the implementation of a micro controller unit directly on the sensor. The MALTA2 sensor implements a shift register based slow control and does not have a digital block in the sensor. Thus, it does not expect any significant contribution from single event effects. Another advantage of the MALTA sensor in terms of single event effect immunity is the radiation content at collider experiments. Unlike space applications, hadron collider experiments do not expect large fluxes of heavy ions with large LETs, but rather a large hadron flux, which could lead to single event effects only via secondary

ionizing effects. Additionally, such experiments are usually built underground which provides additional shielding from high LET galactic cosmic rays.

Several additional measurements are planned to be performed for both the ULTRASAT space mission and the MALTA tracker collaboration. These measurements will be complementary to the results shown in this study and will aim to provide additional validation and an expanded understanding of the observed radiation defects.

The ULTRASAT sensor will perform a dedicated Total Ionizing Dose test campaign. This, will aim to validate the results predicted through the SCOUT testing. A secondary Single Event Effect measurement campaign was already performed on two ULTRASAT sensors and the data is currently being analyzed. The preliminary data analysis highlights the benefits of a third measurement campaign, although this is not yet confirmed and is subject to change in the near future. An additional measurement planned for the Single Event Effect testing of the ULTRASAT sensors is the use of the Transient Current Technique in order to induce a large amount of charge in a small ($9.5 \times 9.5 \mu\text{m}^2 \times 4 \mu\text{m}$), well-defined volume of the sensor. This experiment could provide a much better position resolution of the latch-up and upset sensitive volumes. This would both improve the understanding of the physical processes that occur in the sensor during a single event effect and lower the width of the error bar for the in-orbit single event rate estimation.

The MALTA2 sensor will continue to be tested in both test beam environments and with the help of the Edge Transient Current Technique. More measurements with the MALTA telescope are planned in order to provide validation on the grazing angle results showcased in this study. Of exceptional interest, is the study of very highly irradiated samples $2 - 5 \times 10^{15} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2$ for inclined tracks. The grazing angle technique, will provide a measurement on the p-bulk compensation concentration and a measurement of the expected depletion depth. These measurements will bring an important validation step for the technology node of MALTA2 Czochralski samples for future collider applications. Edge Transient Current Technique measurements are also planned to be performed on non-irradiated, back-metallized polished Czochralski samples, leading to a better understanding of the observed depletion enhancement in the silicon bulk. Irradiated samples are also planned to be measured in the near future, in order to provide complementary results to those gained with the grazing angle technique.

In conclusion, two sensors built in the same technology node but with vastly different designs and targeted applications have been investigated in terms of their radiation hardness. While different in many aspects, parallels between the two result sets have been drawn. Both sensors have been found to be relatively radiation hard up to their respective application goals, showing promising results. These results are encouraging for the further development of radiation hard monolithic CMOS sensors for both imaging and tracking applications.

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Abbreviations

3T	Three transistor CMOS Imaging process
4T	Four transistor CMOS Imaging process
ADC	Analog to Digital Converter
AGN	Active Galactic Nuclei
ALICE	A Large Ion Collider Experiment
ALPIDE	ALICE Pixel Detector
APS	Active Pixel Sensor
ARC	Anti Reflective Coating
ATLAS	A Toroidal LHC Apparatus
BSI	Back Side Illumination
CAD	Computer Aided Design
CCD	Charge Coupled Device
CDS	Correlated Double Sampling
CE	Collection Electrode
CIS	CMOS Imaging Sensor
CL	Confidence Level
CMOS	Complementary Metal Oxide Semiconductor
CMS	Compact Muon Solenoid
CTE	Charge Transfer Efficiency
CTRW	Continuous Time Random Walk
CVD	Chemical Vapor Deposition
CV	Capacitance Voltage (curve)
Cz	Czochralski (crystal growth technique)

DAC	Digital to Analog Converter
DAQ	Data Acquisition
DA	Detector Assembly
DC-RTS	Dark Current Random Telegraph Signal
DCR	Dark Current Rate
DC	Dark Current
DDD	Displacement Damage Dose
DMAPS	Depleted Monolithic Active Pixel Sensor
DR	Dynamic Range
DSNU	Dark Signal Non-Uniformity
DUT	Device Under Test
E-TCT	Edge Transient Current Technique
EHP	Electron Hole Pair
EM	Electro-Magnetic
EoC	End of Column
Epi	Epitaxial (substrate growth technique)
FCC	Future Circular Collider
FD	Floating Diffusion
FET	Field Effect Transistor
FE	Front End
FIFO	First In First Out (register)
FOM	Figure of Merit
FOV	Field of View
FPGA	Field Programmable Gate Array
FPN	Fixed Pattern Noise
FSI	Front Side Illumination
FWC	Full Well Capacity
FWHM	Full Width at Half Maximum
Fz	Float zone (crystal growth technique)

GCR	Galactic Cosmic Ray
GEO	Earth centered orbit with a 24 hour period
GRB	Gamma Ray Burst
GTO	GEO Transfer Orbit
GUI	Graphical User Interface
GW	Gravitational Wave
HDR	High Dynamic Range
HG	High Gain
HL-LHC	High Luminosity LHC
HV-MAPS	High Voltage Monolithic Active Pixel Sensor
HZB	Helmholtz Zentrum Berlin
ICDF	Inverse Cumulative Distribution Function
IC	Integrated Circuit
IP	Interaction Point
IR	Infra Red
ISA	Israeli Space Agency
ITS	(ALICE) Inner Tracking System
ITk	(ATLAS) Inner Tracker
IV	Current Voltage (curve)
JFET	Junction Field Effect Transistor
L1A	Level 1 Accept (trigger)
LET	Linear Energy Transfer
LG	Low Gain
LHC	Large Hadron Collider
LSE	Least Squares Estimation
LS	Long Shutdown
LVDS	Low Voltage Differential Signaling
MALTA	Monolithic ALICE to ATLAS
MAPS	Monolithic Active Pixel Sensor

MCU	Micro Controller Unit
MIP	Minimum Ionizing Particle
MLE	Maximum Likelihood Estimation
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MOS	Metal Oxide Semiconductor
MPV	Most Probable Value
NA	(SPS) North Area
NGAP	gap in the n-layer MAPS process
NIEL	Non-Ionizing Energy Loss
NUV	Near-Ultra Violet
OTA	Optical Tube Assembly
PCB	Printed Circuit Board
PC	Personal Computer
PDF	Probability Distribution Function
PD	Photo Diode
PKA	Primary Knock-on Atom
PMD	Pre-Metal Dielectric
PPD	Pinned Photo Diode
PRNU	Photo Response Non-Uniformity
QE	Quantum Efficiency
RE	Remote Electronics
RF	Radio Frequency
RMS	Root Mean Square
RPP	Rectangle Parallelepiped
RST	Reset transistor
RTA	Rapid Thermal Anneal
RTS	Random Telegraph Signal
RD	Research and Development
SBB	Sensor Bias Board

SCR	Space Charge Region
SEE	Single Event Effect
SEL	Single Event Latch-up
SEM	Scanning Electron Microscopy
SEN	Gain mode transistor
SEU	Single Event Upset
SF	Source Follower
SNR	Signal to Noise Ratio
SNe	Supernovae
SN	Sense Node
SPI	Serial Port Interface
SPS	Super Proton Synchrotron
SRH	Shockley Read Hall
STA	Semiconductor Technology Associates
STD	modified standard MAPS process
STI	Shallow Trench Isolation
SUB	Substrate Voltage
SV	Sensitive Volume
SW	Software
TCAD	Technology Computer Aided Design
TCT	Transient Current Technique
TDC	Time Domain Converter
TDE	Tidal Disruption Event
TG/TX	Transfer gate transistor
TID	Total Ionizing Dose
TLU	Trigger Logic Unit
ToO	Target of Opportunity
ToT	Time over Threshold
UART	Universal Asynchronous Receiver/Transmitter

ULTRASAT	Ultra Violet Transient Astronomy Satellite
USB	Universal Serial Bus
UV	Ultra Violet
VJL	Variable Junction Leakage
VRO	Vera Rubin Observatory
WIS	Weizmann Institute of Science
XDPW	extra deep p-well MAPS process

Appendix A

Wafer processing

Chemical vapor deposition

The two main Chemical Vapor Deposition (CVD) mechanisms employed in the Epi deposition are pyrolysis (chemical reaction induced by heat alone) and reduction (chemical reaction with hydrogen). The principle of silicon deposition via CVD employs a Si based gas deposited on a Si wafer. In the case where a SiO₂ layer exists on top, the Si is deposited in its polycrystalline form. If the native oxide layer is etched away and the Si atoms are deposited with an appropriate amount of energy, they are able to and orient themselves on the Si surface such that they form appropriate covalent bonds to the crystal, leading to a monocrystalline structure. The silicon deposition rate is directly proportional to the deposition temperature. In turn, a large deposition rate can lead to crystal defects and Epi film cracks. The most used CVD process in CMOS fabrication is the silicon tetrachloride source chemistry:



The most attractive feature of this reaction is that it is reversible. The Epi deposition employs a well cleaned Si wafer. Air purging at room temperature is performed with N₂ gas. A heating up to the process temperature is next performed, followed by an initial etching of the Si with HCl gas, leading to some SiCl₄ molecules. As silicon tetrachloride accumulates in the vessel, the silicon deposition of the reaction starts to dominate. The Si deposition (left side of the chemical formula) is at all times balanced by the Si etching (right side of the chemical formula), such that a controlled deposition is achieved. Additionally, an Epi film doping process can be employed. By introducing dopant vapors to the CVD mixture, a well controlled doping of the epitaxial film can be achieved.

Crystallographic defects

The Si crystals used for semiconductor application require a very low crystal defect density. Still, multiple crystal defects can develop in the growing process even for the best controlled processes. For the Cz and Fz growing techniques the most common crystal defects are point defects, dislocations and growth defects. Point defects refer to either a contaminant in the silicon lattice or a “vacancy”, which refers to the lack of a Si atom in the lattice. Dislocations are misplaced unit cells in the crystal. They can occur from physical strains of the crystal that propagate further in its depth. Growth defects are structural defects that appear during the

crystal growth. Some examples of these are crystal slips, where two crystal planes are misaligned or twinning, where the crystal grows in two different directions from the same interface. During the growth process, investigation steps are employed.

Epitaxial deposition additionally has several defect sources. Some of the most common defects that can appear during the Epi deposition are hazing induced by oxygen contamination and leads to an impure Si film; spikes are centers of accelerated deposition caused by surface contaminants. Two major concerns for the high temperature CVD processes are the auto-doping and the out-diffusion processes. Auto-doping of the growing film occurs when dopants from the wafer diffuse into the growing film, leading to changes in the Epi doping. Additionally, out-diffusion is the same process but occurs at the Epi layer-wafer interface.

Wafer processing

Silicon wafers are the end product of the silicon growing process and the starting point for all semiconductor fabrication plants. Si wafers have very strict requirements and tolerances in order to comply with highly standardized process steps. The first processing step of a silicon ingot is the diameter grinding, to ensure a uniform diameter of the ingot along its length. Next, a “major flat” is ground in the silicon ingot along one of the major crystal planes as a demarcation point for future processing steps. Secondary flats are usually ground in the ingot to easily distinguish between different crystal orientations and conductivities (n or p -type). The convention of flats can be seen in Figure A.1 and was regularly used for wafers up to 150 mm in diameter. Modern processes do not always employ this convention, but will have at least a notch to demarcate the major crystal plane for the lithographic process alignment.

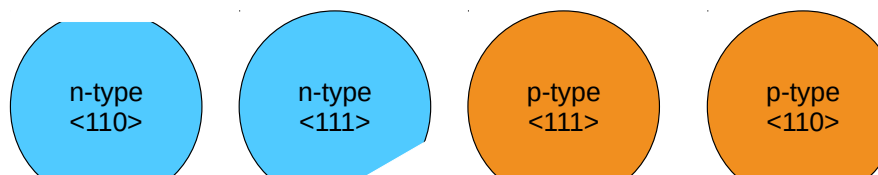


Figure A.1: Convention of flats ground in the silicon ingots before wafer slicing for two crystal orientations: $\langle 110 \rangle$, $\langle 111 \rangle$ and two doping profiles: n and p-type.

The wafer slicing is performed with a thin circular steel saw coated with diamonds or a wire saw. The saw is tightened onto a circular frame, providing the needed rigidity for achieving thin, flat wafers. A typical 200 mm diameter wafer has a 725 μm thickness. Flatness is one of the most important properties of a wafer. Any bows or warps of a wafer will lead to distortions in the lithographic process. In order to achieve flat wafers, a first lapping procedure is implemented, a mechanical rough polishing step is employed. Next, a chemical mechanical polishing step is performed which uses both etching reagents as well as a slurry of silica in a “alkaline slurry”. By carefully controlling the introduction of the wafer in this substance, a very good polishing of the wafer is achieved. Lastly, the edge is ground such that no chipping or mechanical damage can propagate through the wafer. SiO_2 is grown on top of the wafer which is then carefully packaged for transport to the semiconductor fabrication plant.

The wafer fabrication process starts from the sliced, polished wafer and leads to a populated wafer, usually with multiple chips. The four basic operations performed on a wafer to achieve

this are: layering, patterning, doping and heat treatments:

- **Layering** is the process of growing (e.g. SiO_2) or depositing (e.g. aluminium) a substance on the wafer. It is an essential step in the photo-litographic processing of the wafer by depositing photo resistive material that is then etched away selectively via masks.
- **Patterning** is the most essential step in semiconductor manufacturing. It implies the use of a series of steps that either selectively remove or add certain layers from the wafer surface. Patterning is achieved through reticles or masks in combination with the photo-litographic process. Careful alignment and defect control is important in order to not lead to distortions or misplaced patterns on the wafer surface that can lead to severe electrical and optical issues.
- **Doping** is the process of adding donor or acceptor atoms to the silicon lattice in order to create n or p type regions. The doping can be achieved through two techniques. Thermal diffusion exposes the Si to dopant containing vapors. By heating up the Si to $\sim 1000^\circ \text{C}$ the dopants diffuse in the Si lattice. The other doping technology employed by Si fabs is ion implantation and usually implies the use of a low energy (few keV to 100's of MeV) cyclotron beam that accelerates dopant atoms and implants them inside the Si lattice. The implant position is controlled by energy tuning of the ion beam (translated to the Bragg peak position [196]).
- **Heat treatments** are processes that involve the heating up of the wafer without any material removal. This step is essential in multiple fabrication processes, like the implant diffusion annealing step after ion implantation at about 1000°C .

These four basic operations are sequentially used by Si fabrication plants in order to achieve a certain circuit design on a wafer. The process of designing and creating a wafer with a certain circuit involves multiple design steps:

- Electrical circuit designed to perform desired task.
- Layout of the circuit components aided by a Computer Aided Design (CAD) system.
- Creation of multiple reticles or photo-masks (quartz plate with chrome deposited on top in a certain pattern) for each processed layer in the Si wafer.
- Alternating steps between layering, patterning, doping and heat treatment in a process designed by the foundry.

Appendix B

ULTRASAT total ionizing dose data processing

An uniform data acquisition of the SCOUT DC study has been utilised across all campaigns in order to ensure comparable results. The “basic” data acquisition procedure involves the variation of the integration time in the range of 1 - 1000 ms in order to gauge the linearity of the sensor response. For each integration time, several frames (>20) are acquired in order to account for statistical fluctuations. The first frame of each integration time set is discarded in order to mitigate the effect of errors that can appear on the slow control side and impact the correct setting of the integration time. Each integration time set is then averaged pixel-wise and a “master frame” for each integration time is created. Each master frame contains pixel values in ADU’s which have the contribution of the DC convoluted with the “bias value”, i.e. the reference voltage level V_{REF} . In order to subtract the ADU value equivalent to the V_{REF} voltage, the intercept of the DC vs integration time linear fit is computed (see Figure 5.33). The corrected DC ADU values are then calculated by subtracting the bias value intercept. Finally, the value in e^-/s is found by dividing with the gain measured as $K = 0.42ADU/e^-$:

$$DC[e^-/s] = DC[ADU/s]/K \quad (B.1)$$

The accurate measurement of the dark current random telegraph signal signature requires the acquisition of several consecutive frames. Due to the often time sensitive nature of the irradiation campaigns, a well understood optimization of the necessary statistics for Random Telegraph Signal (RTS) characterization has been performed. This involved a single RTS measurement set of an irradiated sample which contained several consecutive frames. Data subsets with different lengths have been selected and the variation of the median of maximum amplitude distribution has been measured as a function of the segment length. The Relative deviation in measured median has been defined as the relative data quality and its decay for varying data segment lengths is showcased in Figure B.1. Based on this study, RTS measurements performed at irradiation facilities involved 1000 consecutive frames, incurring an uncertainty of 20% in the measured RTS median maximum amplitude distribution.

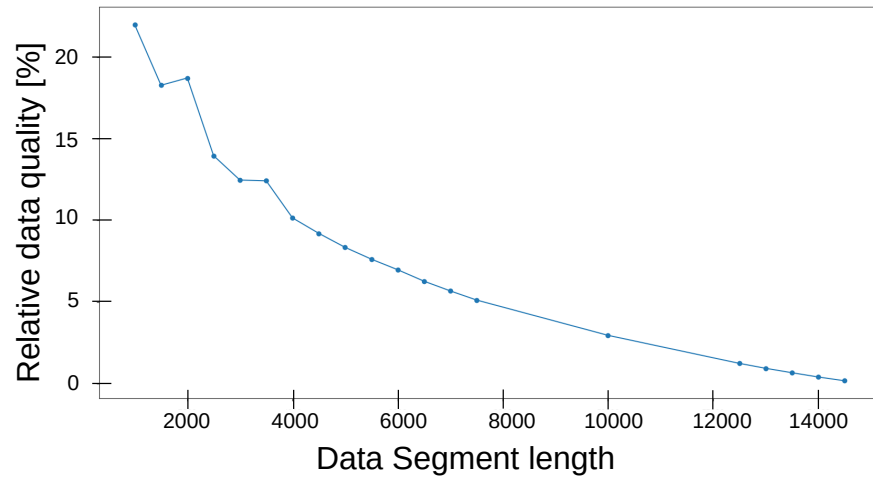


Figure B.1: The relative data quality decay for smaller data sub sets, defined as the number of consecutive frames analyzed for measuring the median RTS maximum amplitude distribution. We thank Clara Dima for her work as a DESY summer student, which was instrumental in realizing this plot.

Appendix C

Orbital parameters for the ULTRASAT mission

Initially, the ULTRASAT satellite will be launched to the GEO transfer orbit (GTO). The mission, will then perform a self-transfer to the GEO synchronous orbit in a time frame smaller than 1 month. During this period, the telescope will not be operated and the radiation damage incurred is not expected to be significant. The orbit parameters used to simulate the GEO synchronous orbit of the ULTRASAT mission are:

- Orbit type: geostationary
- Apogee: 35793.23 km
- Perigee: 35793.23 km
- Inclination: 0.00°
- R. A. Ascending Node: 99.44°
- Argument of Perigee: 0.00°
- True Anomaly: 160.00°
- Period: 23.93 hrs
- Number of orbits: 1.00
- Duration: 1.00 days
- Segment length: 1095.00 days
- Semi latus rectum: 42164.23 km
- Semi major axis: 42164.23 km
- Eccentricity: 0.00
- Mean motion: 6.30 rad/day
- Integration step: 0.50°
- Time intervals:
60.0 s below 20000.0 km
240.0 s between 20000.0 km and 80000.0 km
3600.0 s above 80000.0 km

Appendix D

Single Event Effect test plan

Due to the high cost and limited availability of heavy ion beam time, an optimized test plan has been implemented. The test plan aimed to prove the latch-up protection of the ULTRASAT sensor, verify the latch-up immunity dose specified by the manufacturer and characterize the signature of the SEE for LET's under the qualification value ($65 \text{ MeV cm}^2/\text{mg}$) in the case that events are detected. Additionally, to provide an estimation on the sensor to sensor variation, two ULTRASAT sensors have been measured.

A square beam spot of $2 \times 2 \text{ cm}^2$ size has been chosen for the irradiation campaign. The ULTRASAT sensor has been divided into four sectors which can be separately exposed to the heavy ion beam with the help of a linear stage with both X and Y mobility. The beam alignment to each sector was achieved with the help of a charge couple device camera located at the other side (in relation to the DUT) of the RADEF beam line. The four sectors defined for the ULTRASAT sensor irradiation campaign can be seen in Figure D.1. Sector 1 contains the digital block (digital domain - VDDD), half of the analog to digital converter block (analog domain - VDDA), half of the Row decoder block (analog domain - VDDA) and a quarter of the pixel array (VDD_{SF} domain); Sector 2 contains the other half of the analog to digital converter block and a quarter of the pixel array; Sector 3 contains only the pixel array; Sector 4 contains a quarter of the pixel array and the other half of the row decoder blocks.

As has been already discussed, the VDD_{SF} power domain is assumed to be latch-up immune due to the exclusive n-MOSFET pixel front end implementation. Due to the large density of MOSFET's in the digital block, the initial assumption was that the digital domain is more sensitive to SEEs. As a consequence, the ULTRASAT sensor testing focused on measurements of the Sector 1, with additional measurement on other sectors planned for validation of some of the other power domains.

Latch-ups are not expected to induce permanent damage assuming a correct implementation of a protection circuit. Still, the interaction of heavy ions with the device oxide is expected to yield an accumulated ionizing dose. An estimation [197] of the ionizing dose expected per impinging heavy ion was made in Table D.1.

The target fluence of heavy ions to be accumulated during the experiment has been defined in relation to the maximum in-orbit dose of 55 krad. Considering the average TID per ion of $2.54\text{E} - 7 \text{ krad}$, a maximum fluence per sector has been defined as $2\text{E}8 \text{ u/cm}^2$.

The prediction of an appropriate particle flux is important to be made as soon as possible in the course of the experiment, in order to optimize the data acquisition process. The low value of the flux is defined by the limited beam time, while the high value of the flux is given by the occurrence rate of single event effects (e.g. a very high upset rate $\gg 5 \text{ Hz}$ can lead to

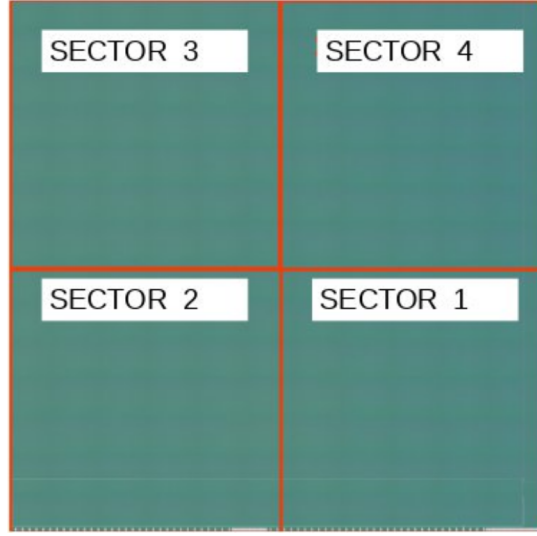


Figure D.1: The four sectors division of the ULTRASAT sensor, as part of the SEE measurement campaign.

Table D.1: Table: TID induced in the SiO₂ per incident heavy ion.

Heavy ion	TID/u [Gy]	TID/u [krad]	<TID/u> [krad]
¹²⁶ Xe ⁴⁴⁺	$3.11E - 6$	$3.11E - 7$	$2.54E - 7$
⁸³ Kr ²⁹⁺	$3.13E - 6$	$3.13E - 7$	
⁵⁷ Fe ²⁰⁺	$3.28E - 6$	$3.28E - 7$	
⁴⁰ Ar ¹⁴⁺	$2.63E - 6$	$2.63E - 7$	

a large error overwriting cross-section, considering the memory read frequency of 5 Hz). The optimal flux selection followed the flow chart shown in Figure D.2. For each LET measurement point, the flux is initially set to the minimum flux available ($1E3$ u/cm²/s). If the single event effect cross-section is larger than (Read Frequency= 5 Hz)/Flux, a debugging step is employed to ensure that no systematic effect exists in the read-out circuitry that leads to event false-flagging. If the cross-section is smaller than the threshold value, the flux is increased in orders of magnitude steps until either a threshold is bypassed or the maximum planned flux of $1E5$ u/cm²/s is reached.

The first flux calibration was performed on the highest LET value that is expected to yield the highest single event effect cross-section. After this step, several other lower LET particles will either re-employ the flux calibration technique or inherit a set value, depending on the initial flux calibration (e.g. a low flux could be appropriate for high LET measurement points, while low LET points could be tuned to higher fluxes).

The planned statistics for each measurement point, was defined in terms of a fluence budget (related to the maximum fluence of $2E8$ u/cm²), due to the unknown flux calibration and SEE rate. Before proceeding with the experiment the following dose budgets have been defined: $1E8$ accumulated fluence for the highest LET point (65 MeV cm²/mg) and $1.5E7$ for all other LET points.

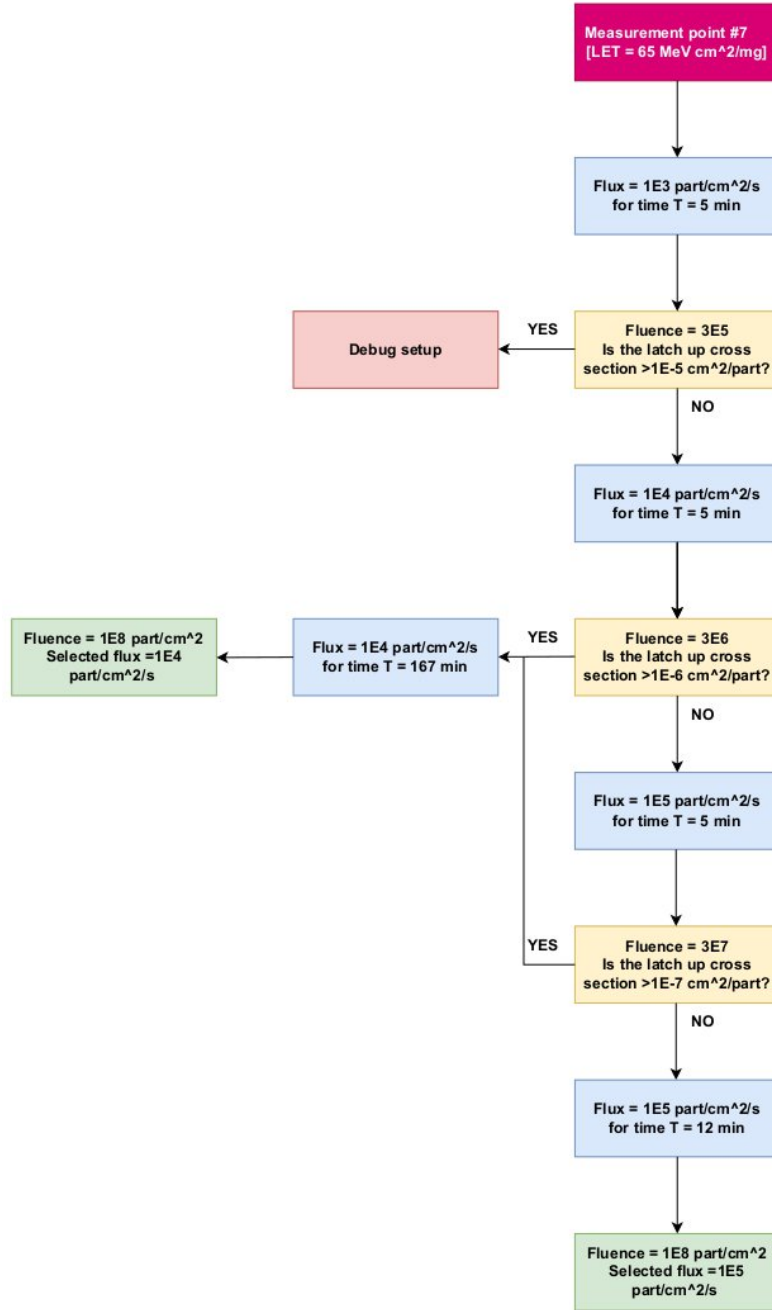


Figure D.2: Flow chart that details the selection of the optimal flux value for each LET heavy ion measurement point.

Appendix E

Data Fitting and Error Bars definition

The increase in the cross-section in respect to a particle LET can be described via a “turn-on” curve which is modelled by the 4-parameter Weibull function in Equation 4.17.

Two fitting techniques have been employed on the experimental data: the Least Squares Estimation (LSE) [153] and the Maximum Likelihood Estimation (MLE) [154]. The LSE method is implemented via the scipy python library and offers a quick fitting method of the experimental data. The MLE method is a more robust fitting approach, allowing the selection of multiple confidence level estimations and more flexible parameter space scans of the fit parameters. This is especially important for non-convergent fits of incomplete data sets. Additionally, the MLE method takes into account the Poissonian fluctuations on event counts, giving a more accurate treatment of low statistics measurement points.

The MLE method developed allows a 2-dimensional and 4-dimensional parameter space optimization of the fit parameters. The intended use of the algorithm implies an initial 2-dimensional scans of the fit parameters for initial fit guesses, followed by a fine 4-dimensional fit parameter space scan in order to find the best fit values. Figure E.1 shows an example of a 2-dimensional scan for the scale and shape Weibull fit parameters. The best fit is highlighted with a red box and is represented by the minimization of the log likelihood ratio:

$$\mathcal{L} = \prod_{i=1}^n P(x_i, \mu = F_i \sigma_{lim} W(LET_i, LET_0, l, k)) \quad (E.1)$$

F is the fluence, W is the 4-parameter Weibull function and P is the Poissonian distribution:

$$P(x, \mu) = e^{-\mu} \times \frac{\mu^{-x}}{x!} \quad (E.2)$$

Additionally, a confidence contour can be defined at a desired confidence level, as is represented through the black shape. In order to project the 2-dimensional contours to the confidence band in the 4-dimensional fit, a maximization of a figure of merit (FOM) that is a good SEE estimator [198] is performed:

$$FOM = \frac{C\sigma_{lim}}{(LET_0 + w * (0.288)^{1/s})^2}$$

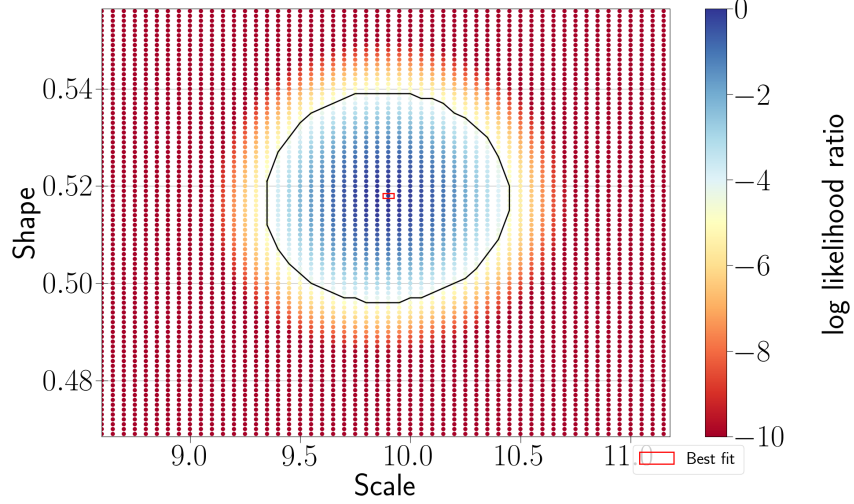


Figure E.1: Parameter space scan of the shape and scale Weibull fit parameters for fixed σ_{lim} and LET_0 values. The best fit point is highlighted with the help of a red box. The 95% confidence level parameter space estimation is given by the black circle.

The error bar estimation includes the contribution of the flux uncertainty, δF and the variance of the number of events, δN . The number of events is expected to follow a Poissonian distribution and is defined as the χ^2 distribution for a 95% confidence level as per the ESCC standard [199].

$$\frac{\delta\sigma}{\sigma} = \sqrt{\left(\frac{\delta N_{events}}{N_{events}}\right)^2 + \left(\frac{\delta F}{F}\right)^2}$$

δN_{events} is calculated as an asymmetric lower and upper limit on the 95% confidence level derived from the inverse of the left and right -tailed of the chi-squared distribution respectively.

Appendix F

Single Event Effect rate estimation

The predicted single event effect rate R is calculated as the product between the event cross-section and in-orbit particle flux integrated over all possible tracks that can go through the circuit sensitive volume:

$$R = \int \int \int f(L, \Theta, \Phi) \cdot S(Q_C / L, \Theta, \Phi) \sin \Theta dL d\Theta d\Phi$$

Here, f is the incident particle flux, which if assumed isotropic, $f(L, \Theta, \Phi) = f(L)$, and S is the LET dependent cross-section. Depending on the geometry of the Sensitive Volume (SV), the track inclination can have a significant impact on the single event effect rate, such that the angular integration ($\sin \Theta dL d\Theta d\Phi$) is important. This point is highlighted further in this section in Figure F.6.

Usually, the above integral is difficult to compute for real devices due to the complex geometry of the sensitive volume. A simplification can be made by assuming that the sensitive volume has a Rectangular Parallelepiped (RPP) shape. Its sensitive volume is: $V = A \cdot h$, where A is the sensitive area which is bounded by experimental measurements or component size provided by the manufacturer and h is the sensitive depth which can be inferred from tilted heavy ion measurements or more usually is an a priori known dimension. For the ULTRASAT sensor, the manufacturer reported the implementation of the digital circuitry as a “sea of logic nodes” within a deep well implant of $\sim 1 \mu\text{m}$ depth. A further simplification of the integral computation can be made by assuming that the charge generation in the sensitive volume is proportional to the particle LET and a chord, defined as a particle track through the volume. This assumption is called the chord-length model [200], which defines the differential per-bit rate as:

$$dR = A C(l) f(L) dL dl \tag{F.1}$$

l is the chord length and $C(l)$ is the chord length distribution, defined as the probability that a chord has a length greater than l . The angular integration is then reduced to a simple integration over a distribution of chords in a sensitive volume and over an LET flux.

The formalism for finding the chord-length distribution in a three dimensional cube was developed by [201] and [202]. Reference [200] extends this formalism to an arbitrary rectangular parallelepiped volume (a, b surface dimensions) and derives the following solution (the C_3 and C_4 solutions are only approximations due to the complexity of the computation):

$$\begin{aligned}
C_1(l) &= \frac{8(a+b)}{\phi A} \left(\frac{h\phi}{4} - \frac{2hl}{3(a+b)} + \frac{\phi ab}{4(a+b)} - \frac{2l}{3} + \frac{3l^2}{8(a+b)} \right), 0 < l \leq h \\
C_2(l) &= \frac{8(a+b)}{\phi A} \left(\frac{h\phi}{4} + \frac{2l}{3}(d-1) - \frac{h}{2} \sin^{-1} d - \frac{h^2 d}{6l} \right. \\
&\quad \left. - \frac{h^2}{4(a+b)} - \frac{h^2}{4(a+b)l^2} \left(\frac{1}{6} h^2 - \phi ab \right) \right), h < l \leq a \\
C_3(l) &= \frac{8(a+b)}{\phi A} \left(\frac{hb}{a+b} \left(\frac{\phi}{4} + \frac{hd}{2} - \frac{1}{2} \sin^{-1} d \right) \right. \\
&\quad \left. + \left(\frac{\phi ab}{2(a+b)} - \frac{a^2}{2(a+b)} \right) \left(\frac{h^2}{2l^2} \right) - \frac{2bl}{3(a+b)}(1-d^3) \right), a < l \leq b \\
C_4(l) &= C_3(l) \frac{(a^2 + b^2 + h^2)^{1/2} - 1}{(a^2 + b^2 + h^2)^{1/2} - b}, b < l \leq \sqrt{a^2 + b^2 + h^2}
\end{aligned} \tag{F.2}$$

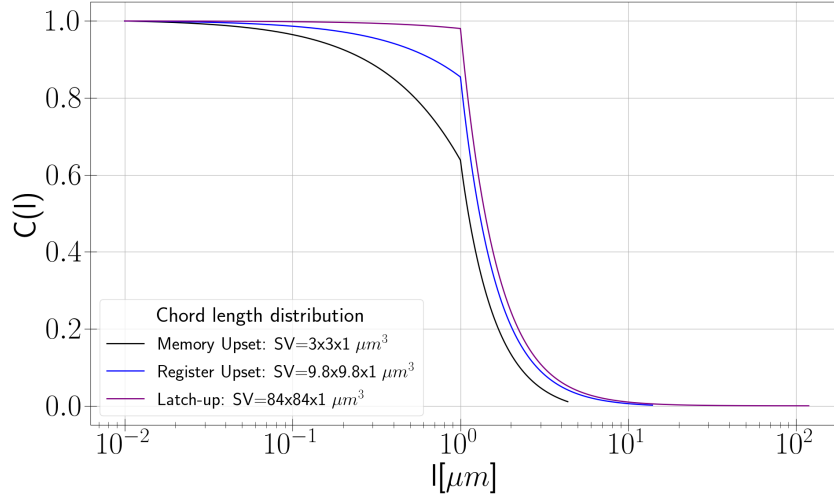


Figure F.1: Distribution of the chord probability $C(l)$ for several sensitive volumes implementing the chord length model: (black) the sensitive volume for the memory upsets; (blue) the sensitive volume for the register upsets; (purple) the sensitive volume for the latch-ups. The sensitive volumes are derived from the experimental data bounding in the RPP assumption.

Figure F.1 shows the derived $C(l)$ distributions for the sensitive volume of the three single event effects investigated in the ULTRASAT sensor. The sensitive volume for each effect was derived from the experimental data summarized in Table 5.7 as : $\sqrt{\sigma_{\text{lim}}} \times \sqrt{\sigma_{\text{lim}}} \times \text{depth}$.

The track length for which the charge deposited is larger than the critical charge, (defined in Equation 4.15) is shown in Figure F.2. The plot can be further used for calibrating the energy deposited for various chord lengths.

Figure F.3 shows the energy deposited (defined as the integrated LET for the value of the chord) in a sensitive volume bounded by the experimental data for both perpendicular (w.r.t. the RPP surface) particles (denoted as minimum deposition) and particles that create the largest chord through the volume (denoted as maximum deposition). For the SEU curves, a change of about an order of magnitude between the two fringe cases is observed, while for the SEL, a change of two orders of magnitude is recorded. The consequence of this effect can be seen in

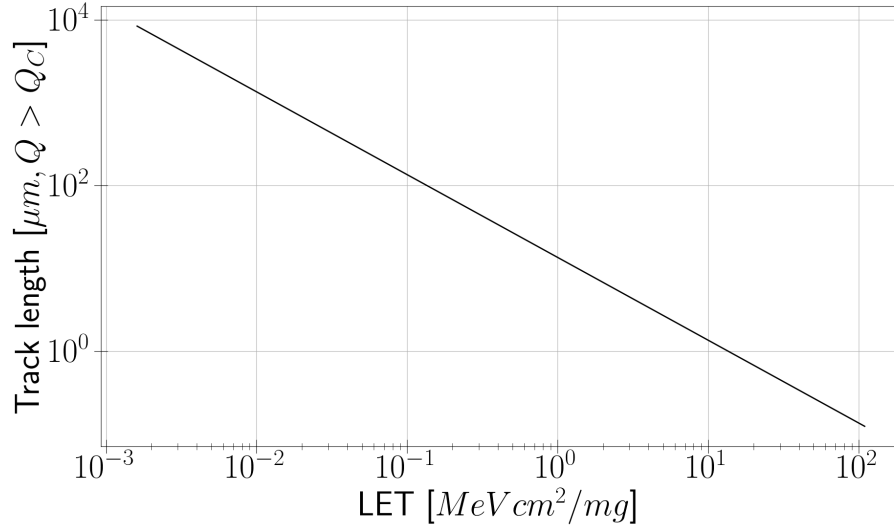


Figure F.2: Track length associated to a charge deposition larger than the critical charge of the circuit versus a particle's LET.

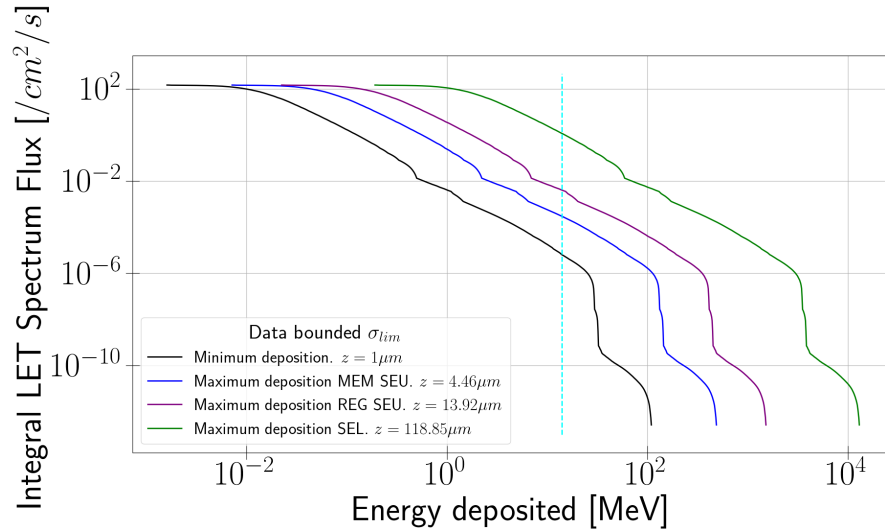


Figure F.3: The energy deposited across several chords of fixed length for the integral LET spectrum flux in $1/\text{cm}^2/\text{s}$. The chords corresponding to different sensitive areas are plotted: (black) perpendicular path; (blue) maximum distance in a cell associated to memory upsets; (purple) maximum distance in a cell associated to register upsets; (green) maximum distance in a cell associated to latch-ups. The teal line corresponds to the onset LET derived from the experimental data.

the effective shift of the onset LET, defined to be LET_0 (teal dashed line). Considering only perpendicular tracks through the sensor, a flux of particle with an energy deposition of 14 MeV is expected to be $\sim 10^{-5} / \text{cm}^2/\text{s}$. For the maximum chord value of particles in the memory SEU circuit, the effective flux increases to $\sim 10^{-4} / \text{cm}^2/\text{s}$, for the register SEU circuit it increases to $\sim 10^{-2} / \text{cm}^2/\text{s}$ and for the entire latch-up sensitive domain it increases to $\sim 10 / \text{cm}^2/\text{s}$. This effective shift of the onset LET is accounted for only by considering the chord distribution inside a sensitive volume. The fluxes shown at this point are considered only in relative terms. Final

rate estimations are rigorously determined in Sections 5.7.4 and 5.7.5

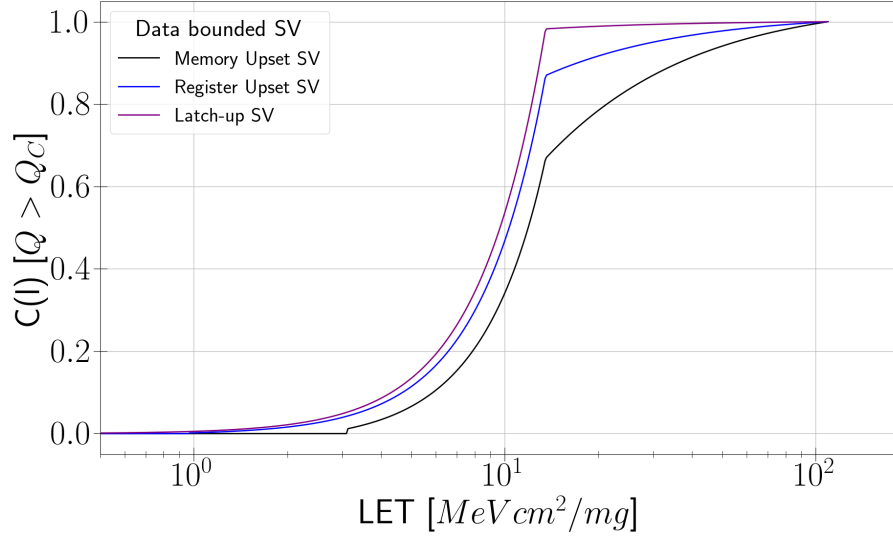


Figure F.4: Chord length distribution calibrated for LET calculated for the: (black) memory upset sensitive volume; (blue) register upset sensitive volume; (purple) latch-up sensitive volume. The sensitive volumes are bound by the experimental data.

Figure F.4 shows the LET calibrated chord length distribution. The calibration curve can be further used to derive a differential rate, as can be seen in Figure F.5. In the case of the memory and register SEU's, the differential rate is distributed around the data bounded onset LET, $LET_0 = 14 \text{ MeV cm}^2/\text{mg}$. A slight asymmetry towards low LET values is attributed to the long chords that travel through the sensitive volume and impart a large amount of energy. The latch-up differential rate is dominated by the low LET component due to the very large sensitive volume and the chord lengths associated with it.

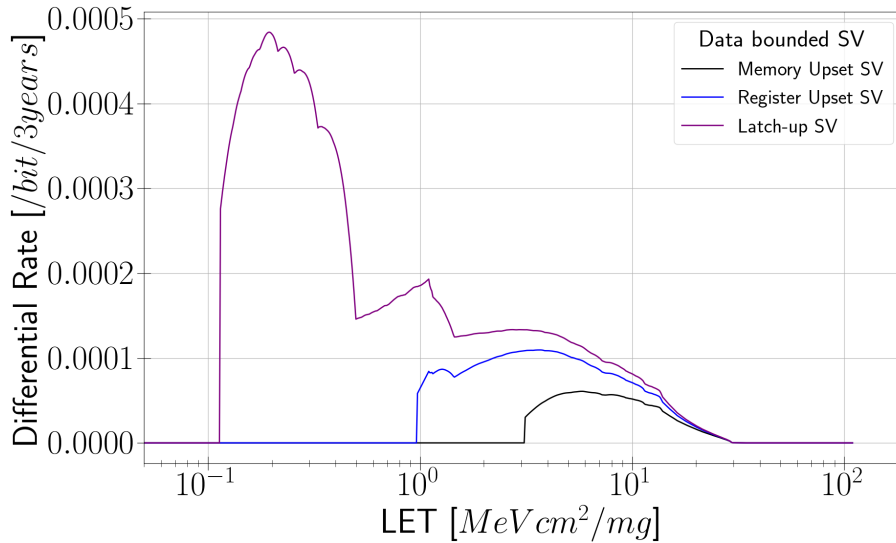


Figure F.5: The differential rate per bit for the cumulative flux during a mission life time of 3 years versus LET for the three single event effects detected in the ULTRASAT sensor: (black) memory upsets; (blue) register upsets; (purple) latch-ups.

Figure F.6 aims to quantify the inaccuracies of a simplistic rate estimation that only takes into account perpendicular particle tracks. The same analysis chain was run considering only the memory upsets with both the above mentioned method (called ‘RPP algorithm’ in the plot) and a simple multiplication of the cross-section and flux data. In the RPP formalism, an integral rate (/device) of 4.47 events for a mission life time of 3 years was found, while the simplistic approach yielded a much lower value of 0.13 events.

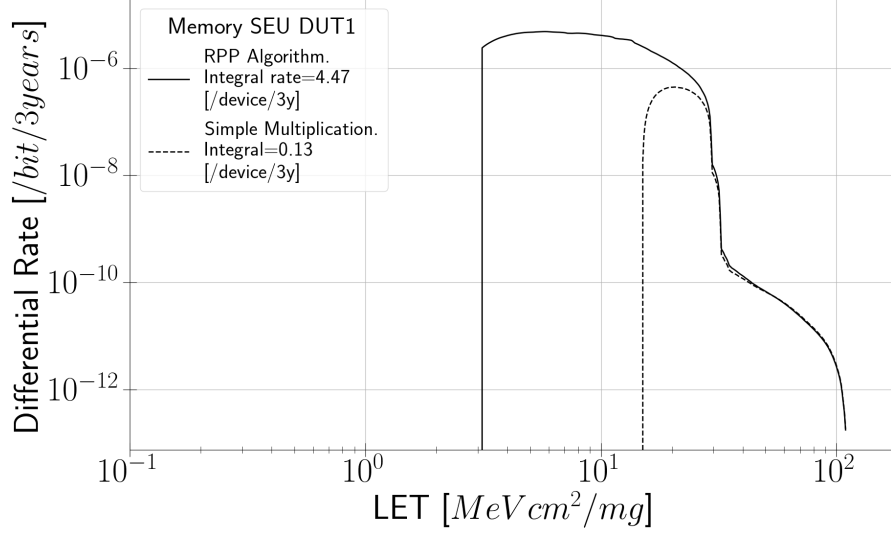


Figure F.6: Differential rate of the memory upsets versus LET calculated through the RPP algorithm (black line) and through a simplified multiplication that takes into account only perpendicular particle tracks (black dashed line).

Two online tools that implement chord-length models have been used, CREME96 and SPENVIS. The rate estimations quoted further have been made with the help of these tools. These results have been cross checked via the independently developed analysis chain presented above. A match between these two within 50% was achieved. The discrepancy is motivated by the approximate chord-length solution employed in the developed algorithm.

Appendix G

Edge polishing of the MALTA2 sensor

The edge polishing aims to remove any structures left behind from the sensor dicing and create a uniform and smooth surface. The two dicing procedures employed on different MALTA2 samples are: blade and stealth dicing. Usually, the blade dicing leads to a smoother surface, which requires smaller polishing times. The stealth dicing [203][204] is expected to lead to many laser ablation artifacts, that present themselves on the sensor edge as deep trenches ($\sim 3 - 5\mu m$). Additionally, MALTA2 samples can have different thicknesses ($50 - 300\mu m$). The thinner the samples, less polishing time is required, but more care needs to be put for the mechanical stability of the sensor.

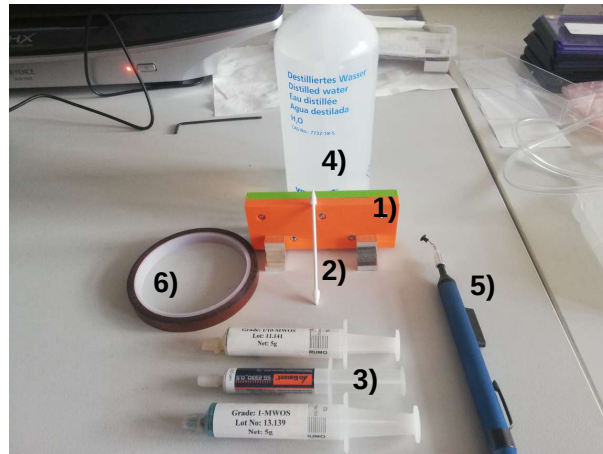


Figure G.1: Polishing equipment.

The equipment employed in the edge polishing of the sensor are:

1. A 3D printed holding block formed of two plastic blocks that can be brought together by multiple screws. One of the holding blocks has been designed with two approximately $2 \times 2cm^2$ grooves of 100 and $300\mu m$ thickness, to be used for different MALTA2 thickness samples.
2. Clean room cotton buds that do not disintegrate after repeated use.

3. Fine granularity diamond paste.
4. De-ionized water and/or alcohol for cleaning the sensor edge.
5. Suction cap pen for sensor manipulation.
6. Kapton tape for fixing the polished sensor.
7. Microscope for imaging of the polishing progress.



Figure G.2: Microscope pictures of the MALTA2 sensor on the plastic holding blocks. The images are used in the alignment of the polished sensor to the edge of the holding blocks. (Left) a 3D picture of the sensor edge in relation to the two holding blocks. The image has been performed with a Keyence Digital microscope via the depth composition technique. (Right) top view of the sensor kapton taped to one of the holding blocks.

The polishing procedure is as follows:

1. The holding blocks are thoroughly cleaned to remove any residue from previous polishing.
2. A MALTA2 sample is placed with the help of a suction cup in the 100 or 300 μm groove and fastened in place with the help of several kapton tapes. The correct alignment of the sensor in relation to the plastic block is very important (preferably this step should be performed under a microscope as is shown in Figure G.2). The sensor edge should be sticking out from the plastic blocks only by a few μm 's. The two blocks are then brought tightly together, effectively “sandwiching” the sample. This is necessary in order to transfer the mechanical stress induced by the polishing on the sensor to the holding blocks.
3. A drop of diamond paste is applied to the cotton. A cotton bud is used to gently rub the sensor surface by applying a small amount of force perpendicular to the sensor. Any inclination of the cotton bud can lead to sensor edge rounding, which severely degrades the laser uniformity. The cotton bud shall be swapped for a new one after a few minutes of use. Depending on the sensor thickness or dicing procedure, this step should be continued for 15 – 30 minutes, followed by an investigation of the polishing progress.

4. Before investigating the progress of the polishing, a thorough cleaning of the sensor edge is required. Firstly, a clean room tissue paper wet with several drops of de-ionized water and/or alcohol is used to wipe the sensor edge. Depending on the amount of diamond paste and/or polishing time, several cleaning steps need to be performed. Lastly, when the sensor edge is deemed as clean, a dry wipe is used to dry off the edge. The cleaning of the edge shall be performed with care in order to not further scratch the edge with the large granularity sensor fragments generated by the previous polishing step. The best procedure for cleaning is to perform a “dabbing motion” rather than wiping the edge length wise.
5. The previous 3. and 4. steps are performed on a small ~ 10 mm surface near the left and right edges of the sensor, where the analog pixels are placed. The polishing of the middle of the chip is not required. Once, both sides of the chip have been polished, the sensor is carefully removed from the holding blocks. In case some water and/or diamond paste has infiltrated on the front or back side of the sensor, the sensors are placed on clean room tissues and slowly cleaned with a similar “dabbing motion” described in step 4.

Appendix H

List of Publications

The content showcased in this thesis has been additionally published and/or referenced in the following conference proceedings and peer-reviewed journal articles:

1. **Paper I. Total Ionizing Dose effects on CMOS image sensor for the ULTRA-SAT space mission**
Nucl. Instrum. Meth. A 1054 (2023) 168463
Corresponding Author
2. **Paper II. Preliminary results of the Single Event Effect testing for the ULTRASAT sensors**
In the review process for Nucl. Instrum. Meth. A arXiv: 2407.03789 astro-ph.IM (2024)
Corresponding Author
3. **Paper III. Radiation Hardness of MALTA2, a Monolithic Active Pixel Sensor for Tracking Applications**
IEEE Transactions on Nuclear Science 70 (2023) 2303-2309
Corresponding Author
4. **Paper IV. Depletion depth studies with the MALTA2 sensor, a depleted monolithic active pixel sensor**
Nucl. Instrum. Meth. A 1063 (2024) 169262
Corresponding Author
5. **Radiation hardness of MALTA2 on Czochralski substrates**
Eur. Phys. J. C 84 251 (2024)
Co-author
6. **The scientific payload of the ultraviolet transient astronomy satellite (ULTRASAT)**
arXiv:2208.00159 (2023)
Co-author
7. **Development of a large-area, light-weight module using the MALTA monolithic pixel detector**
Nucl. Instrum. Meth. A 1047 (2023) 167809
Co-author

8. **Future developments of radiation tolerant sensors based on the MALTA architecture**
JINST 18 03 (2023) C03013
Co-author
9. **Timing performance of radiation hard MALTA monolithic pixel sensors**
JINST 18 03 (2023) C03011
Co-author
10. **MALTA-Cz: A radiation hard full-size monolithic CMOS sensor with small electrodes on high-resistivity Czochralski substrate**
JINST 18 09 (2023) P09018
Co-author
11. **Performance of the MALTA telescope**
Eur. Phys. J. C 83 581 (2023)
Co-author
12. **MALTA monolithic pixel sensors in TowerJazz 180 nm technology**
Nucl. Instrum. Meth. A 1057 (2023) 168787
Co-author
13. **Recent results with radiation-tolerant TowerJazz 180 nm MALTA sensors**
Nucl. Instrum. Meth. A 1041 (2022) 167390
Co-author
14. **Quad-module characterization with the MALTA monolithic pixel chip**
Nucl. Instrum. Meth. A 1064 (2024) 169306
Co-author
15. **Development of the radiation-hard MALTA CMOS sensor for tracking applications**
PoS VERTEX2023 (2024) 048
Co-author

Declaration of Independent work for inclusion in the thesis (see § 7/4)

I declare that I have completed the thesis independently using only the aids and tools specified. I have not applied for a doctor's degree in the doctoral subject elsewhere and do not hold a corresponding doctor's degree. I have taken due note of the Faculty of Mathematics and Natural Sciences PhD Regulations, published in the Official Gazette of Humboldt-Universität zu Berlin no. 42/2018 on 11/07/2018.