

UNIVERSITY OF LJUBLJANA
FACULTY OF MATHEMATICS AND PHYSICS
DEPARTMENT OF PHYSICS



Bojan Hiti

**Radiation Hardness of CMOS detector prototypes
for ATLAS Phase-II ITk upgrade**

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ADVISER: dr. Igor Mandić

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UNIVERZA V LJUBLJANI
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Bojan Hiti

**Sevalna odpornost detektorjev CMOS za
nadgradnjo notranjega sledilnika ATLAS**

Doktorska disertacija

MENTOR: dr. Igor Mandić

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Izvleček

V doktorskem delu je predstavljena študija zbiranja naboja v odvisnosti od sevalnih poškodb v detektorjih CMOS zasnovanih za nadgradnjo (Phase-II) Notranjega sledilnika ATLAS ITk. Preučevani vzorci so bili razviti v štirih vzporednih razvojnih smereh in izdelani v različnih industrijskih procesih. Glavna dejavnika preučevana v tem delu sta začetna upornost senzorja in velikost zbiralne elektrode. Vzorci so bili obsevani z reaktorskimi nevtroni v območju fluenc $10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$ – $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ in s protoni od $10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ – $3.6 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. Zbiranje naboja v vzorcih je bilo opredeljeno z meritvami z metodo e-TCT, radioaktivnim virom β ^{90}Sr in v visokoenergijskem testnem žarku pionov. Meritve učinkovite koncentracije prostorskega naboja za metodo e-TCT kažejo na veliko odvisnost od obsevanja, na katero vpliva tudi učinkovita odstranitev začetnih akceptorjev. Ta poteka počasneje v materialih z nižjo začetno upornostjo in se tipično konča okoli fluence $\sim 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$ v materialu z visoko začetno upornostjo $2 \text{ k}\Omega \text{ cm}$ ter okoli fluence $\sim 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ v materialu z nizko začetno upornostjo $20 \Omega \text{ cm}$. Odstranitev akceptorjev lahko povzroči povečanje osiromašenega področja v senzorju v določenem območju fluenc, kar je bilo opaženo v meritvah z metodo e-TCT in z radioaktivnim virom ^{90}Sr . Meritve v detektorju z majhno zbiralno elektrodo s testnim žarkom so razkrile območja z nizko učinkovitostjo znotraj blazinice po obsevanju. Na podlagi teh rezultatov so bile uvedene spremembe zasnove blazinic, ki bodo po pričakovanjih izboljšale zbiranje naboja v tem detektorju.

Ključne besede:

ATLAS ITk	CERN HL-LHC	Silicijevi detektorji
Detektorji odporni na sevanje	Sevalne poškodbe	Transport nosilcev naboja
Odstranitev akceptorjev	DMAPS	HV-CMOS
HR-CMOS		

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Abstract

This thesis presents a study of charge collection properties and its dependence on displacement damage caused by irradiation in CMOS detector prototypes developed for the phase-II upgrade of the Inner Tracker (ITk) in ATLAS experiment. Investigated samples were developed in four separate development lines and manufactured in different industrial processes. The main design parameters studied in this work are initial resistivity and the size of collection electrode. Samples were irradiated with reactor neutrons to fluences between $10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$ and $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ and with protons to fluences between $10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ and $3.6 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. Charge collection in the samples was characterised with Edge-TCT, radioactive ^{90}Sr beta source and in a highly energetic pion test beam. Measurements of effective space charge concentration with Edge-TCT show significant radiation dependence influenced by initial acceptor removal. Acceptor removal is slower at lower initial substrate resistivity and is typically finished at a fluence of $\sim 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$ in highly resistive $2 \text{ k}\Omega \text{ cm}$ material and $\sim 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ in material with initial resistivity of $20 \Omega \text{ cm}$. Acceptor removal may cause the increase of the depth of depletion zone in certain range of fluences which was observed by both Edge-TCT and ^{90}Sr . Measurements of in-pixel hit detection efficiency with test beam revealed significant efficiency gaps on pixel edges in samples with a small collection electrode after irradiation. These results prompted modifications of pixel design in form of additional implanted structures which are expected to significantly improve detector performance.

Keywords:

ATLAS ITk	CERN HL-LHC	Silicon detectors
Radiation damage	Charge transport	Acceptor removal
Radiation hard detectors	DMAPS	HV-CMOS
HR-CMOS		

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List of acronyms

ATLAS	A Toroidal LHC ApparatuS. 29
BOX	Buried oxide. 56
BSM	Beyond Standard Model Physics. 27
CCE	Charge collection efficiency. 89
CERN	European Organization for Nuclear Research. 23
DMAPS	Depleted Monolithic Active Pixel Sensor. 23, 53
DUT	Detector under test. 145
ENC	Equivalent noise charge. 46
HL-LHC	High Luminosity LHC. 23, 32
HR-CMOS	High resistivity CMOS (detector). 53
HV-CMOS	High voltage CMOS (detector). 53
ID	Inner Detector. 23, 31
ITk	Inner Tracker. 23, 33
LHC	Large Hadron Collider. 23
MAPS	Monolithic Active Pixel Sensor. 39, 52
MIP	Minimum ionising particle. 48, 145
MPV	Most probable value. 48, 89
NIEL	Non Ionising Energy Losses. 60
ROI	Region of interest. 148
S/N	Signal to noise ratio. 46
SCT	Semiconductor Tracker. 31
SM	Standard Model. 27
SOI	Silicon on insulator. 55
TCT	Transient Current Technique. 81, 82
TDAQ	Trigger and Data Acquisition. 30
TID	Total Ionising Dose. 57

Chapter 1

Introduction

Particle colliders are the primary experimental tools in the field of high energy physics that help us probe the properties of elementary particles and search for physics beyond the Standard Model. The Large Hadron Collider (LHC) built by the European Organization for Nuclear Research (CERN) in Geneva is the most powerful particle collider to date, with proton-proton collisions reaching a centre of mass energy of 13 TeV. An integral part of LHC are experiments such as ATLAS, which detect the products of collisions and allow us to reconstruct the underlying physical processes.

To increase the sensitivity to rare processes the LHC will undergo the High Luminosity upgrade (HL-LHC) in the years 2024–2026, which will increase the instantaneous luminosity to $5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, a factor of five above LHC. This ambitious programme will present a major challenge for the experiments that will have to cope with up to 200 simultaneous collisions and a significantly increased radiation damage. ATLAS will therefore undergo a substantial buildup named Phase-II upgrade to be ready for data taking at HL-LHC. One of the main components of the Phase-II upgrade will be replacement of the existing Inner Detector (ID) with a new Inner Tracker (ITk) with a larger silicon surface area, greater radiation tolerance and capability to operate at higher particle rates.

Current state of the art hybrid pixel detectors, consisting of sensor and readout electronics implemented in separate silicon chips, are demanding in terms of production resources due to technologically complex bump bond interconnections. ATLAS CMOS collaboration explored the possibility of using depleted monolithic active pixel sensors (DMAPS) produced in an industrial CMOS process to facilitate the production of large detector volumes required for the outermost ITk Pixel Layer 4.

Monolithic detectors have sensing and readout functionality implemented on the same silicon chip, thus removing the need for bump bonding, while also reducing the material budget. Monolithic concept has been already known for a few decades, but its radiation tolerance and speed of charge collection have been insufficient for use in high radiation environment. Recently rapid development of CMOS sensors has been driven by commercial applications, such as smart phone imaging sensors, which has resulted in several vendors offering processes enabling usage of high bias voltages and/or high resistivity silicon substrates. This allows design of detector elements with significant depletion depth which is necessary for fast charge collection. Charged particle tracking detector production in such high volume industrial process would allow a significantly shorter turnaround time at a fraction of cost of hybrid detectors.

Since ATLAS is pioneering the use of DMAPS in high radiation environment, one of the main challenges for the ATLAS CMOS collaboration is demonstration of sufficient radiation hardness. Radiation damage can be classified in two main categories: damage to the electronics which is predominantly a consequence of ionising dose, and degradation of charge collection due to the damage in silicon lattice. In this thesis extensive studies of charge collection in different DMAPS prototypes developed within the ATLAS CMOS group were carried out after irradiating the samples with neutrons and protons. Different measurement techniques encompassing laser, radioactive sources and highly energetic particle beam were employed for characterisation of samples.

This thesis has the following structure: Chapter 2 introduces the LHC machine, its physics programme, and the ATLAS detector together with the details of Phase-II upgrade. The basics of silicon particle detectors are presented in Chapter 3. Chapter 4 gives an overview of radiation damage in silicon and its effects on particle detectors. DMAPS prototypes developed within the ATLAS CMOS collaboration and investigated in this thesis are presented in Chapter 5. The laboratory setups used to evaluate detector properties with Edge-TCT and radioactive sources are described in Chapter 6, with the results following in Chapter 7. Measurements of detection efficiency with a DMAPS prototype in a test beam are shown in Chapter 8. Finally, the conclusions and outlook are given in Chapter 9.

Chapter 2

The LHC and the ATLAS Experiment

2.1 The Large Hadron Collider

The LHC is a synchrotron accelerator with a circumference of 27 km which can collide two beams of protons with a centre of mass energy of 13 TeV or nuclei of heavy elements such as lead with a centre of mass energy of 2.8 TeV per nucleon [1, 2]. LHC uses a system of four preaccelerators which accelerate the beams to an energy of 450 GeV before injection into the main ring (Figure 2.1). The beams intersect at four points along the LHC ring, called *interaction points* (IP) where collisions occur. Four experiments named ALICE [3], ATLAS [4], CMS [5] and LHCb [6] built around the interaction points detect the products of these collisions.

A core part of the LHC are 1232 NbTi superconducting dipole bending magnets and additional higher order magnets for focusing of the beams. Particles are accelerated with radiofrequency cavities which also longitudinally structure the beams into groups called bunches. The LHC can simultaneously contain up to 2808 colliding proton bunches per beam, spaced at a time interval of 25 ns.

The LHC operation is organised into periods of data taking called Runs, interspersed with maintenance and upgrade periods called Shutdowns (Figure 2.2). In 2019 the LHC is in the state of the Long Shutdown (LS2) after having finished the Run 2 data taking.

An important quantity specifying a collider's performance is the instantaneous

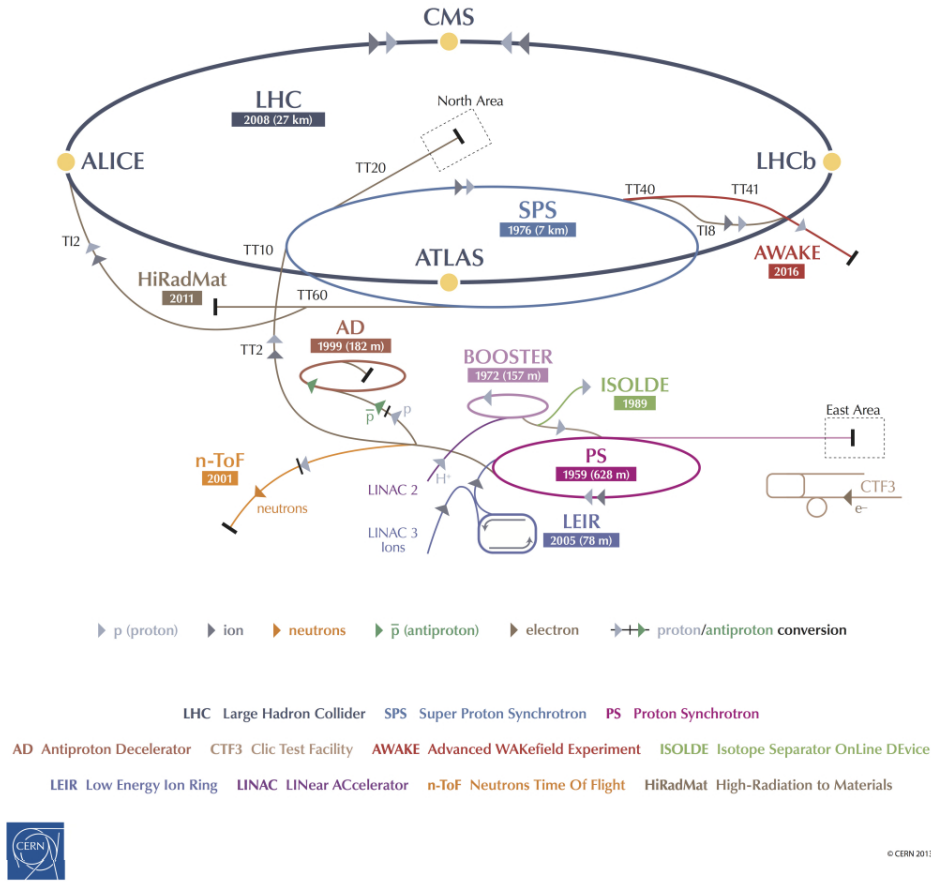


Figure 2.1: Schematic view of the CERN accelerator complex showing the LHC with the four main experiments ALICE, ATLAS, CMS and LHCb, as well as the preaccelerator chain with independent experiments [7].

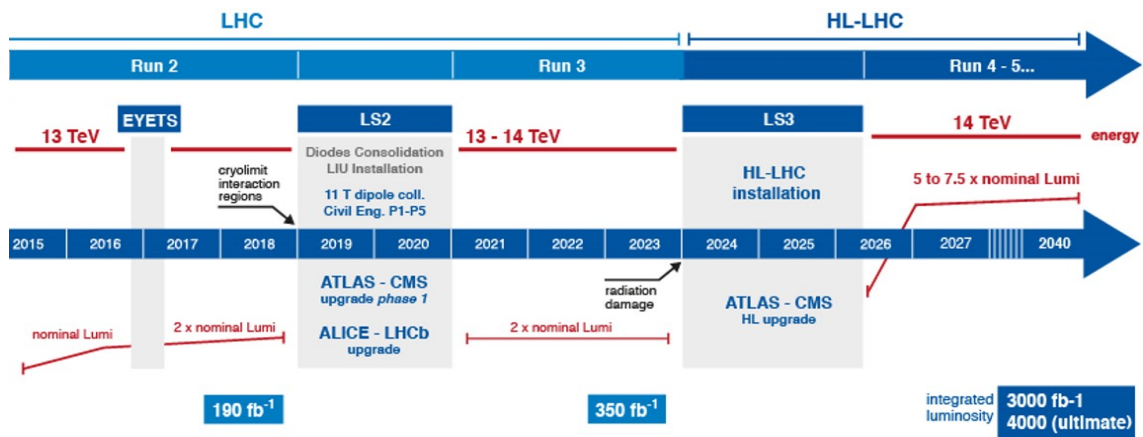


Figure 2.2: Schedule of the LHC operation with data taking (Runs) and maintenance periods (Shutdowns) [8].

luminosity $\mathcal{L}$ which relates event rate $\frac{dN}{dt}$ with the event cross section σ :

$$\frac{dN}{dt} = \mathcal{L} \cdot \sigma. \quad (2.1)$$

The total number of events produced in a given time frame is proportional to the integrated luminosity $\mathcal{L}_{\text{int}}$ which is a time integral of $\mathcal{L}$. The units of $\mathcal{L}_{\text{int}}$ are inverse barns: $1 \text{ b}^{-1} = 0.01 \text{ fm}^{-2}$. The design value of the instantaneous luminosity in proton-proton collisions at the LHC is $1 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [2], but excellent performance of the LHC and the experiments resulted in peak luminosities above $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in Run 2 data taking [9].

However, a higher instantaneous luminosity results in an increased number of proton-proton interactions, called *pile-up*, within an individual bunch crossing. The average value of pile-up during the LHC Run 2 in the year 2018 was 38.3 [9], but it is planned to increase up to 200 during the HL-LHC operation (see Section 2.3). High pile-up causes an increased readout occupancy in the detectors and can eventually result in an irreversible data loss due to insufficient data processing capacities. Moreover, a high density of the collisions makes it challenging to correctly assign the detected collision products to a certain collision vertex. Therefore, a compromise between high luminosity and a feasible detection capability is necessary.

2.1.1 Physics at the LHC

The current theory describing elementary particles and their interactions is *the standard model of electroweak and strong interactions* (SM). It was developed in 1960s and 1970s [10, 11, 12, 13] and describes particles of matter (quarks and leptons) which interact via elementary forces by exchange of gauge bosons. The most recently discovered constituent of the SM is the Higgs boson, a particle of the Higgs field which interacts with massive particles [14, 15, 16, 17]. The SM constituents and their properties are shown in Figure 2.3.

Many theoretical predictions of the SM agree with experimentally observed data to a very high degree of precision. However, the SM does not account for some phenomena such as gravity, the dark matter and dark energy, the neutrino oscillations or the matter-antimatter asymmetry in the universe. Their sources are commonly referred to as *beyond standard model* (BSM) physics or new physics and are one of the main drivers for the modern particle physics experiments. Since BSM processes are expected to occur at very high energies and at low rates, both high collision energy and high luminosity are vital for its discovery. The LHC with its unprece-

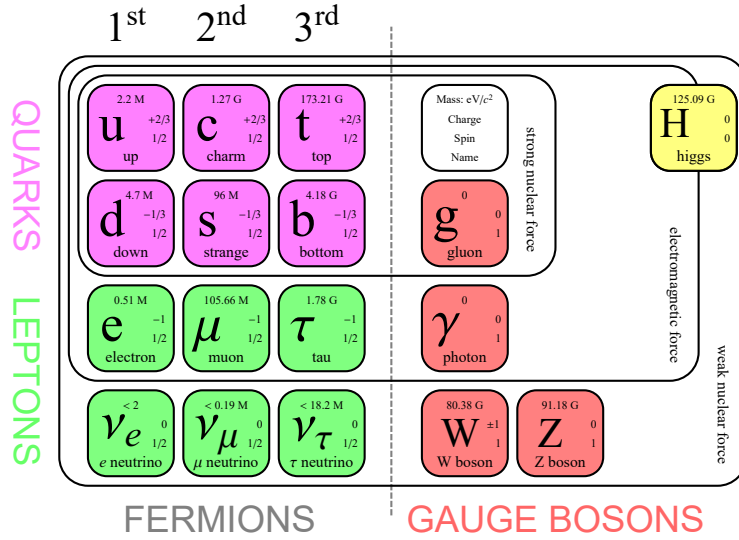


Figure 2.3: Particles of the standard model. Image from [18].

dented collision energy and high luminosity thus provides an excellent environment for such studies.

The research programme at the LHC can be divided in two categories: precision measurements of SM processes and searches for new, yet unobserved phenomena within and beyond the SM. The precision measurements are aimed at studying the known SM processes and determine their parameters such as particle masses or process cross sections. These measurements are vital as SM processes represent a background to potential new physics and it is important to correctly estimate their contribution. Moreover, discrepancies between the SM and experimental data may indicate the nature of new physics. The LHC allows us to study the entire spectrum of the SM, including the heaviest known particles – the top quark, the W and Z bosons and the Higgs boson – and to measure their properties with unprecedented precision. As an example Figure 2.4 shows a summary of p-p production cross sections of several SM processes measured by the ATLAS detector.

The objective of searches in HEP is to look for yet unobserved processes which can originate from the SM or beyond. Experiments at the LHC have made numerous first observations of SM processes such as on-shell light-light scattering [19] and existence of pentaquarks [20]. However, the greatest success to date was the first observation of the Higgs boson by experiments ATLAS and CMS in 2012 [21, 22]. This discovery came as a large success five decades after the theoretical introduction of the electroweak symmetry breaking mechanism [14, 15, 16, 17].

The open questions of the SM suggest existence of other unknown particles, which motivate searches for BSM physics. At the LHC theses are roughly divided

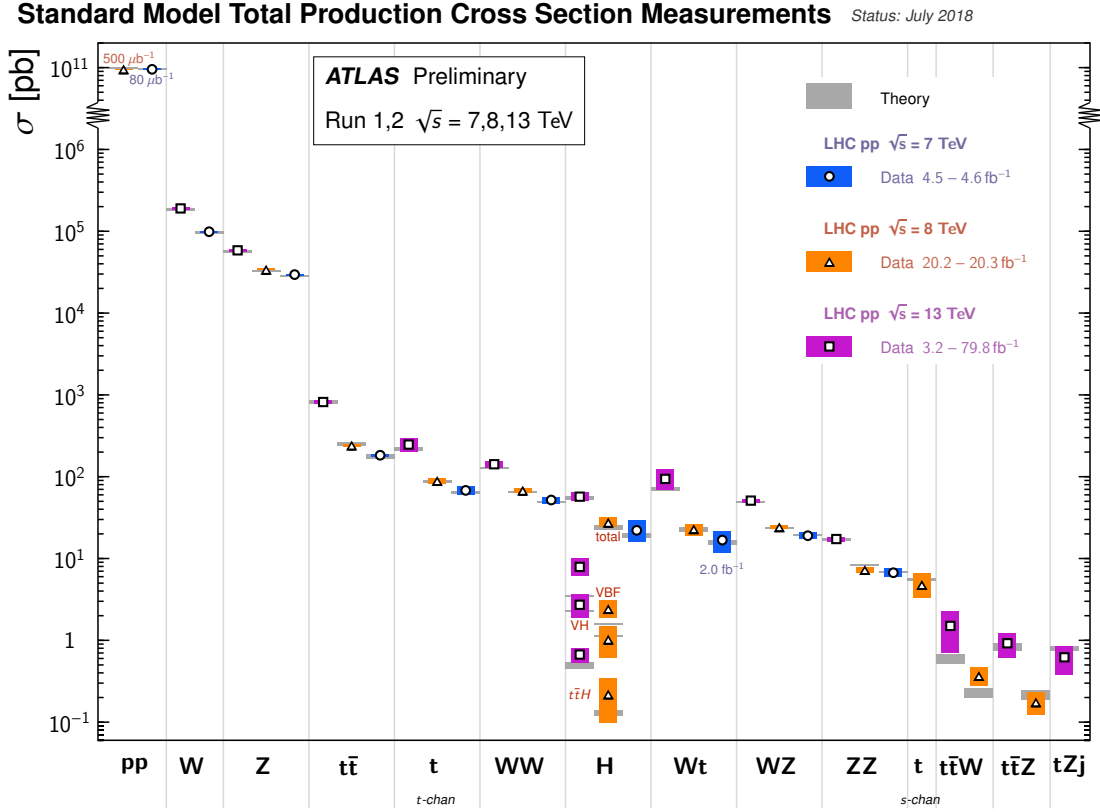


Figure 2.4: Summary of SM production cross sections measured by ATLAS [9].

into two groups: SUSY and exotics. **Supersymmetry** (SUSY) is a theory which proposes elegant solutions to some of the problems not solved by the SM and also predicts existence of supersymmetric partners to SM particles [23]. The lightest SUSY particle is predicted to be stable and is a candidate for the dark matter particle. Exotics cover a broad range of particles predicted by BSM theories which include additional gauge bosons, heavy neutrinos, extra dimensions, multiple Higgs bosons, miniature black holes or gravitons.

No BSM physics has yet been observed at the LHC, but the experimental data allows us to exclude low mass regions and set a lower limit on the mass of new particles. These typically lie in range of few TeV. Further data taking will reduce the statistical errors and increase potential to discover new physics.

2.2 The ATLAS Experiment

A **Toroidal LHC ApparatuS** (ATLAS) is one of the four main experiments at the LHC and together with CMS one of the two general purpose detectors [4, 24]. It has a cylindrical layout with a length of 44 m and a diameter of 25 m consisting of a

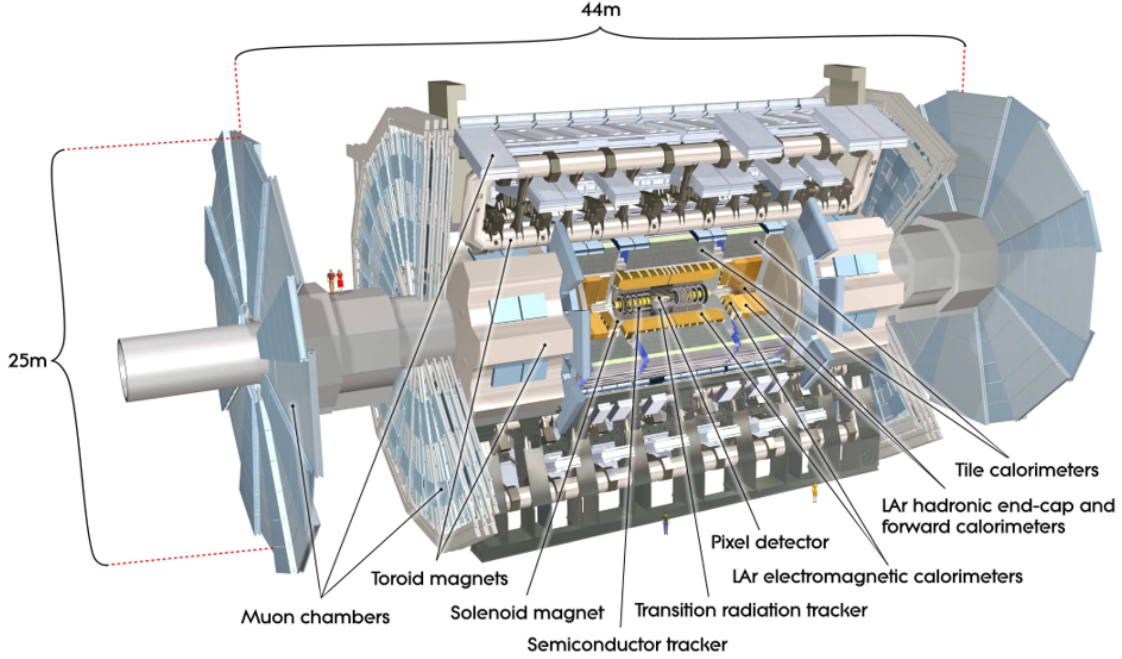


Figure 2.5: The ATLAS experiment with detector subsystems [4].

barrel with two end caps (Figure 2.5). This geometry achieves an almost hermetic coverage around the interaction point.

The layout of ATLAS is driven by the requirement to successfully reconstruct all particles generated by proton collisions. For example a leptonic decay of a top quark $t \rightarrow b\ell\nu$ requires precise tracking to detect the decaying b quark, detection of the lepton, and complete measurement of hadronic jet energies to detect missing energy carried by a neutrino.

The main detector subsystems are thus the Inner Detector for charged particle tracking, electromagnetic and hadronic calorimeters for energy measurements and muon detectors for muon identification and momentum measurement. A superconductive magnetic system consisting of an inner solenoid and an outer toroid provides a complex magnetic field for bending of charged particle trajectories. A three stage real time trigger and data acquisition (TDAQ) system is used for identification of the most interesting events which are retained for further analysis. The trigger system reduces the readout rate from 40 MHz (rate of LHC collisions) to around 200 Hz, which is feasible for storage.

ATLAS uses a Cartesian coordinate system with the origin in the IP, the z -axis given by the beam direction, and the xy -plane (named also the transverse plane) oriented by the positive x -axis showing toward the centre of the LHC ring. Positions in the transverse direction are often given by the radial distance to the IP R and

the azimuthal angle φ . Another commonly used coordinate is the pseudorapidity η , which is a transformation of the polar angle to the z -axis θ :

$$\eta = -\ln \tan(\theta/2). \quad (2.2)$$

For the directions along the beam axis pseudorapidity takes values of $\eta = \pm\infty$ and for $\theta = 90^\circ$ it takes value $\eta = 0$. A useful feature is that every distribution over pseudorapidity is Lorentz invariant for relativistic boosts in z -direction.

2.2.1 ATLAS Inner Detector

The ATLAS Inner Detector (ID) is dedicated to reconstruction of charged particle trajectories [4]. This serves several purposes: calculation of particle momentum from the track's curvature in the magnetic field, charge identification, and determination of the track's vertex (point of origin). The latter plays a role in heavy flavour tagging – detection of long lived hadrons containing c or b quarks, which generate primary and secondary vertices separated by several $100\,\mu\text{m}$.

The ID consists of three subsystems (Figure 2.6): closest to the beam pipe is the silicon Pixel Detector, followed by the silicon microstrip detector (Semiconductor Tracker - SCT) and the straw-tube Transition Radiation Tracker (TRT). The ID is contained within the 2 T solenoid magnet and covers a pseudorapidity range of $\eta < |2.5|$. The silicon sensors are operated at low temperatures around -10°C provided by a CO_2 based cooling system. A multiple layer design ensures particle detection in several points along its trajectory to provide reliable tracking.

The Pixel Detector utilises pixels with a size of $400\,\mu\text{m}$ in the z -direction and $50\,\mu\text{m}$ in φ , while the SCT uses one dimensionally segmented microstrips with a pitch of $80\,\mu\text{m}$ in φ -direction and a length of approximately 12 cm. Strip sensors are assembled in so called stereo modules composed of two sensors rotated relative to each other by a small angle of 40 mrad to provide hit sensitivity along the strip length. Before the beginning of the LHC Run 2 in 2014 an additional innermost layer of pixels, the Insertable B-Layer (IBL), was installed at a radius of 3.2 cm from the interaction point to further improve the tracking performance [25]. The IBL has a pixel size of $250\,\mu\text{m} \times 50\,\mu\text{m}$ and partially employs 3D silicon sensors which is the first large scale experimental use of this type of detector.

The proximity of the interaction point makes the ID – particularly the Pixel Detector – the most exposed part of ATLAS in terms of particle rate and radia-

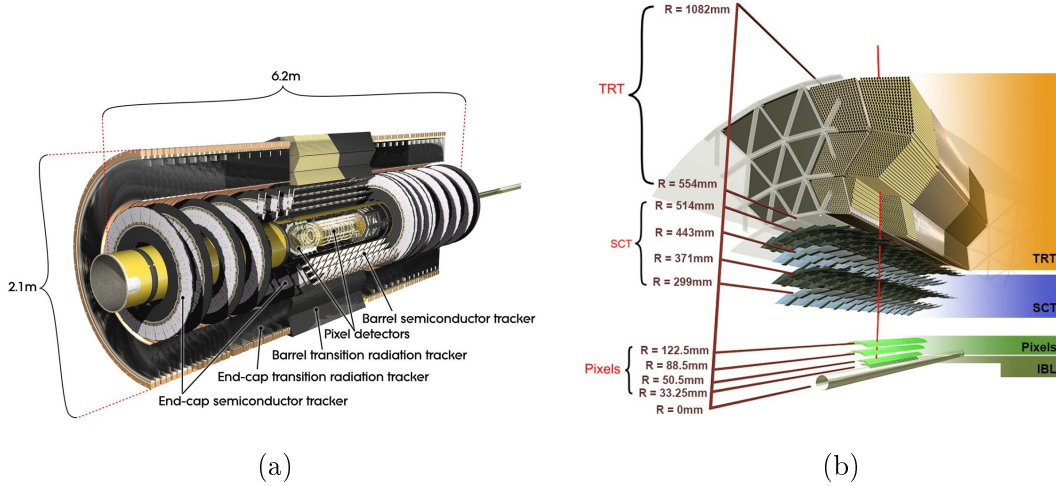


Figure 2.6: a) The ATLAS Inner Detector layout [26]. b) Schematics of the barrel part with radial distances to the interaction point [27].

tion damage. This dictates use of fast and radiation resistant sensors and readout electronics. Moreover, the entire detector layout has to be lightweight to minimise scattering on detector components and provide a good tracking resolution.

2.3 High Luminosity LHC and ATLAS Phase-II upgrade

By the end of the Run 2 in 2018 the LHC delivered an integrated luminosity of 190 fb^{-1} [9]. By the end of Run 3 in 2023 the total delivered luminosity will have reached 300 fb^{-1} . At this point the operation under the same conditions would require an impractically long time to acquire a further statistically significant dataset, as halving of the statistical error for a given measurement would require around ten years. The LHC is therefore planned to undergo a major upgrade in the years 2024–2026 named High Luminosity LHC (HL-LHC, Figure 2.2). This will consolidate the machine for another 10–15 years of data taking in which it will deliver an integrated luminosity up to 4000 fb^{-1} [28].

The nominal peak instantaneous luminosity of the HL-LHC will increase to $5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with the ultimate values reaching up to $7.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and corresponding pileup values 140–200. This is an increase by a factor 5–7.5 compared to the original LHC design values. Collision events will contain an enormous number of particles (Figure 2.7) which will have to be correctly detected and assigned to the right vertices. At present the experiments are not designed for such challenging conditions. The increased detector occupancy and data rates would re-

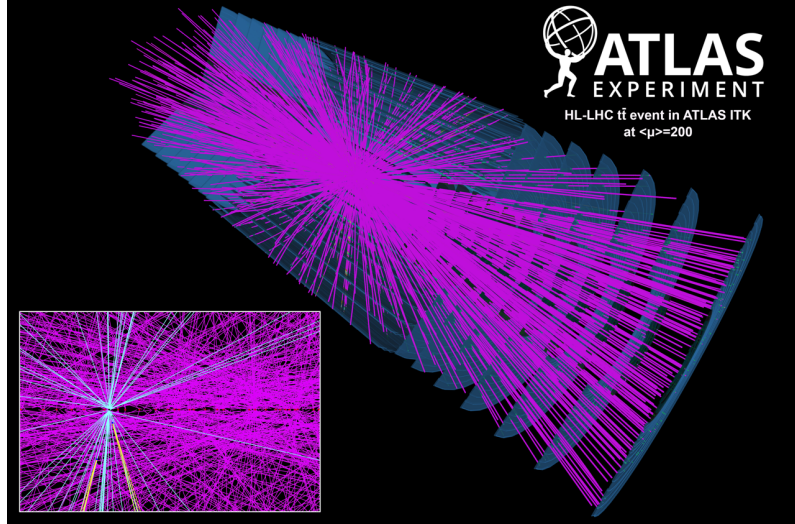


Figure 2.7: Simulated HL-LHC event in ATLAS with 200 simultaneous p - p collisions within a bunch crossing [9].

sult in unacceptably high data losses due to underdesigned short term storage and insufficient data links. The accumulated radiation damage from the higher particle flux would also cause critical degradation of detector performance. The experiments will therefore use the Phase-II shutdown to undergo a large scale upgrade which will prepare them for operation at HL-LHC.

The ATLAS Phase-II upgrade will see upgrades of all major detector subcomponents [29]: improvement of the muon system, addition of a precise timing detector to the calorimeters and a critical upgrade of the TDAQ system. One of the largest parts of the upgrade will be the complete replacement of the existing Inner Detector with a new tracking detector – the Inner Tracker (ITk).

2.3.1 ATLAS ITk

The ATLAS Inner Tracker (ITk) will be an all-silicon replacement for the existing ATLAS Inner Detector. The ITk will consist of silicon pixel and strip detectors, but will omit the TRT. The detectors will be assembled in a so called inclined layout (Figure 2.8), consisting of five pixel and four strip layers in the barrel part, and a large number of layers in the forward part, providing tracking coverage up to $|\eta| = 4$ [30, 31]. The detectors will operate at a temperature of -40°C which will be provided by a new CO_2 cooling system.

The ITk will have to significantly surpass the performance of the current Inner Detector to withstand the harsher conditions at HL-LHC (Table 2.1). The current

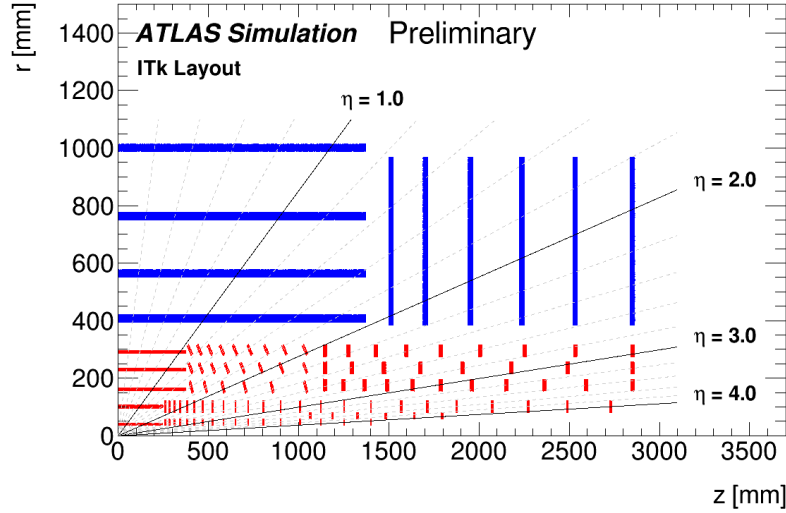


Figure 2.8: Schematic view of the ATLAS ITk layout in one quadrant with pixel detector (red) and strip detector (blue). Interaction point is at (0,0) [30, 31].

ID is designed to operate at peak luminosities of $1 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ over a lifespan of 10 years in which it will record up to 400 fb^{-1} . In terms of radiation damage (see Chapter 4) this translates to a hadron fluence of $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ in the pixel detector and $2 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ in the SCT [32]. The Pixel Detector also has to withstand a total ionising dose of 50 MRad. The high-performance IBL is designed for 850 fb^{-1} , a fluence of $5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ and an ionising dose of 250 MRad. The front end electronics, short term data buffering and output bandwidth of the ID reach saturation at a particle rate of $\sim 1 \text{ MHz}/\text{mm}^2$, which occurs at a luminosity of $3 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ (pile-up ~ 50) at 25 ns bunch crossing time. Higher luminosity results in significant data losses. This performance does not meet the requirements for the HL-LHC.

The ITk will have to withstand 4000 fb^{-1} , a peak luminosity of $7.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and a pile-up of 200. The distribution of the accumulated radiation damage at the end of the ITk lifetime has been evaluated by a simulation shown in Figure 2.9. The innermost pixel layer (Layer 0) is expected to receive a particle flux of $10 \text{ MHz}/\text{mm}^2$, a hadron fluence of $2 \cdot 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ and an ionising dose of 1 GRad (last two numbers include a safety factor of 1.5). To ensure sufficient detector performance newly developed radiation hard sensors will have to be used: 3D sensors in Layer 0 and thinned planar sensors with a thickness of $100 \mu\text{m}$ to $150 \mu\text{m}$ in the outer layers. The pixel detector will also use a new readout chip produced in 65 nm CMOS technology which is under joint development with CMS [33]. Despite the improved components the two innermost pixel layers will have to be replaced after 2000 fb^{-1} at the half of the ITk lifetime due to the extreme radiation damage [30].

The outermost pixel layer of the ITk (Layer 4) will be exposed to a particle flux

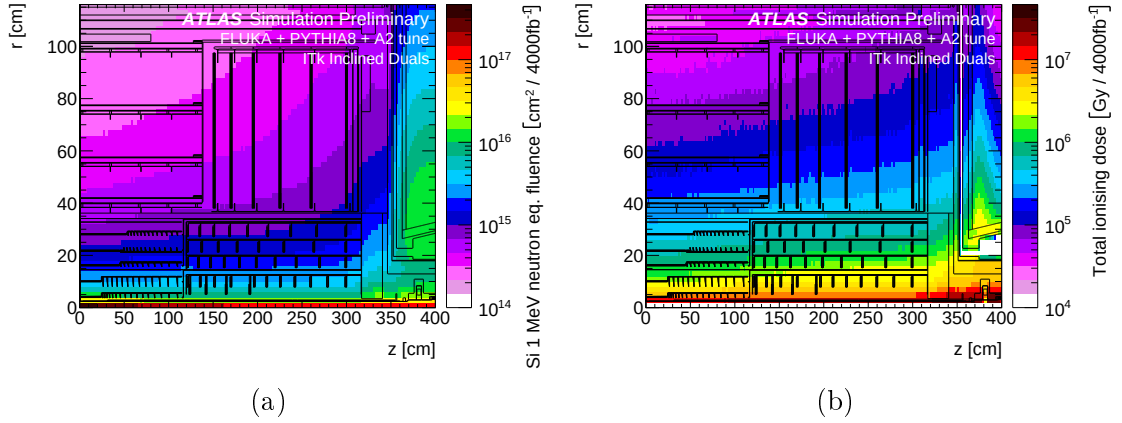


Figure 2.9: Simulated a) fluence and b) dose distributions in the ATLAS ITk after 4000 fb^{-1} at HL-LHC [34].

	Pixels LHC	IBL	HL-LHC Pixel Layer 0	HL-LHC Pixel Layer 4
Particle rate	1 MHz/mm ²	5 MHz/mm ²	10 MHz/mm ²	1 MHz/mm ²
Hadron fluence	$1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$	$5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$	$2 \cdot 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$	$1.5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$
Ionising dose	50 MRad	250 MRad	1000 MRad	80 MRad
Area	1.7 m ²	0.15 m ²	$\approx 1 \text{ m}^2$	$\approx 10 \text{ m}^2$

Table 2.1: Design specifications for different ATLAS pixel detectors [25, 29, 32].

of $1 \text{ MHz}/\text{mm}^2$, accumulating a total fluence of $1.5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ and an ionising dose of 80 MRad. The large surface area of Layer 4 (approximately 10 m^2) has motivated investigations of new detector concepts which would simplify the detector production, such as active CMOS sensors, described in the next Section 2.3.2.

The ITk strip detector will cover a total area of $\approx 160 \text{ m}^2$ and will have to withstand fluences up to $1.2 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ and ionising doses up to 50 MRad (safety factor 1.5 included). The strip detector will also get a greater role in the trigger architecture, as it will contribute already to the first trigger level (Level-0 trigger) [34].

2.3.2 CMOS pixel option for ITk

For pixel detectors at hadron colliders high speed and radiation hardness are paramount. The main technology that has been successfully used for many years and is also the baseline for ITk are so called hybrid detectors. In hybrid pixel modules the electronically passive sensor and the readout electronics are implemented in separate silicon chips interconnected by bump bonding (discussed in 3.4). Since bump bonding is

complex and requires highly specialised production processes, simplifications are desired.

As an alternative to the hybrid solution ATLAS was investigating active CMOS detectors, where the sensor and readout electronics are implemented in the same chip and therefore do not require the complicated hybridisation (bump bonding) step. CMOS sensors have a widespread use in digital imaging and are a well developed technology, which however has to be adapted for application in HEP experiments. The main problem of existing technology is insufficient speed because of slow charge collection resulting also in low radiation tolerance. In particle tracking applications uniform efficiency over entire chip surface is required, which is also not the case for imaging sensors. These are some of technological drawbacks that must be solved to adapt CMOS technology for tracking at ATLAS. Another advantage of CMOS technology is a large number of vendors offering suitable CMOS processes and relatively well available detector grade (high resistivity) silicon wafers. This may result in a significantly faster and cheaper production. In addition, CMOS technology leads to a reduced amount of material in the detector volume, which can result in a better position resolution due to reduced scattering. So far CMOS detectors have been used in the experiments Star [35] and ALICE [36] where fluences and particle rates are by a factor of 100 lower than in ITk Layer 4. Since CMOS detectors have not yet been used in a large experiment with a high radiation and high rate environment it is imperative to demonstrate that they are suitable for reliable operation in the entire lifetime expected for ITk.

ATLAS investigated CMOS detector technology as an option for the outermost pixel layer (Layer 4), which has the largest surface and therefore offers the largest savings of production resources. At the same time performance requirements in terms of data rates and radiation hardness are not as high as in the inner layers. ATLAS studied several different CMOS detector versions for Layer 4 which are presented in detail in Chapter 5.

The CMOS option plans detectors with a small pixel pitch of $\leq 50\,\mu\text{m}$ and a thickness of $25\,\mu\text{m}$ – $100\,\mu\text{m}$. The effect of CMOS Layer 4 on ITk tracking performance was compared to the benchmark $150\,\mu\text{m}$ thick hybrid solution in a simulation [30]. Figure 2.10 shows an example of such comparison in a case of cluster efficiency for single muons. Overall no significant differences have been observed in terms of cluster efficiency, total number of clusters per track, track parameters d_0 , z_0 and q/p_T and track reconstruction performance between the hybrid and the CMOS options, indicating that the CMOS option is viable from the physics point of view.

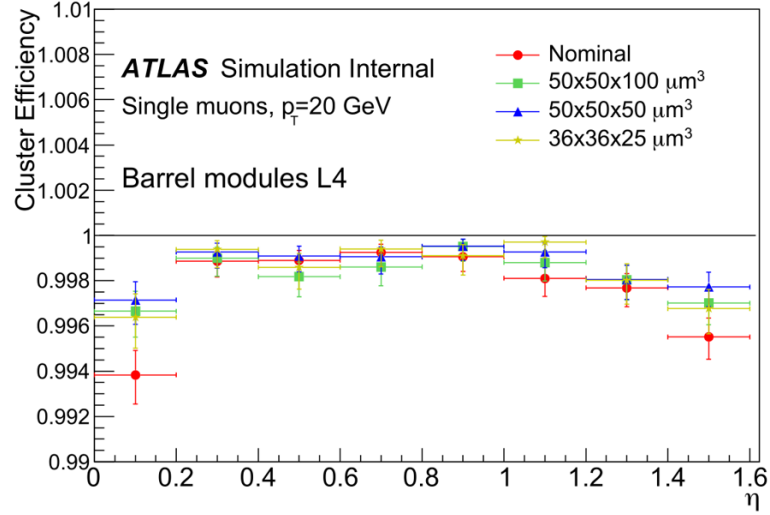


Figure 2.10: Simulated tracking performance of CMOS Layer 4 in ITk. CMOS detectors with pixel pitches $36\,\mu\text{m} \times 36\,\mu\text{m}$ and $50\,\mu\text{m} \times 50\,\mu\text{m}$, and varying thickness were compared to the baseline $50\,\mu\text{m} \times 50\,\mu\text{m}$ hybrid detector with a thickness of $150\,\mu\text{m}$. No significant differences in the efficiency for association of cluster to tracks in Layer 4 were found between different options [30].

A successful operation in the challenging ATLAS environment would prove the maturity of CMOS technology and make it a serious contender for future tracking detectors. This motivated the international detector community to form a large collaboration of institutes within and outside ATLAS with a goal to deliver a functional CMOS module in time for the Phase-II upgrade. This required a substantial amount of R&D, design iterations and testing which have been divided between the institutions to maximise efficiency. A part of the test programme were also studies of radiation effects on CMOS sensors which is the topic of this thesis.

Due to a tight time line of the ATLAS Phase-II upgrade and with the detectors still being in development phase the ATLAS pixel CMOS programme was stopped in March 2019 after having run for more than four years. However, CMOS detectors will be developed further outside of the scope of ATLAS to capitalise on the invested effort and produce a fully functional monolithic CMOS detector.

Chapter 3

Silicon particle detectors

Detectors for tracking applications in high energy physics have to be lightweight, with a high resolution, fast, easily producible and in many cases radiation tolerant. Silicon detectors have all these properties and are well available thanks to the highly developed semiconductor industry. Silicon has therefore been the standard solution for high performance tracking detectors.

This chapter covers the broad topic of silicon detectors from basics to applications in modern experiments. The first part introduces the principles of operation of semiconductor detectors as p-n junctions, the interaction of highly energetic particles with tracking detectors and the properties of signal formation.

The second part of this chapter presents detector solutions for high energy physics experiments: the hybrid modules as the standard option for pixel detectors and the emerging CMOS technology. The most attractive CMOS solution are Monolithic Active Pixel Sensors (MAPS), where the entire detector functionality is implemented on a single silicon chip.

3.1 Silicon as particle detector

3.1.1 Semiconductors

In an isolated atom electrons occupy discrete energy levels defined by the atomic orbitals. When atoms form covalent bonds, atomic orbitals overlap and form new energy states. In crystals, typically consisting of 10^{23} atoms per cm^3 , the overlapping orbitals generate a multiplet of allowed states which form a quasi continuous energy

region. These regions, called energy bands, are described by the energy band model of solids (see e.g. [37]). In a thermal equilibrium at a temperature T the occupation probability for a state with an energy E is given by the Fermi-Dirac statistics:

$$f(E) = \frac{1}{e^{(E-E_F)/k_B T} + 1}, \quad (3.1)$$

where k_B is the Boltzmann constant and E_F is the Fermi energy, at which the occupation probability is exactly 0.5. Energy bands are separated by energy regions where no states are allowed. The energy gap between the last occupied band – the valence band – and the first unoccupied band – the conduction band – is called band gap E_g and determines electrical properties of materials. Based on E_g we classify materials into:

- Conductors, if $E_g = 0$. The valence and conduction bands overlap. E_F is within the valence gap. Electrons can be easily raised into states which enable electrical current to flow.
- Insulators, if $E_g > 3\text{ eV}$. The band gap is too large to allow transitions into conduction band, therefore no current flows under applied electric field. E_F is by convention set in the middle of the band gap.
- Semiconductors, if $E_g < 3\text{ eV}$. E_F is in the middle of the band gap. The band gap is sufficiently small to allow transitions into the conduction band by thermal excitations.

In a semiconductor the transition of an electron into the conduction band leaves a vacancy in the valence band, called *hole*. Electrons and holes can freely move through the crystal lattice, allowing electric current to flow. The resistivity ρ of a semiconductor depends on the electron/hole concentrations n and p , and their mobilities μ_e and μ_h :

$$\rho = \frac{1}{e(\mu_e n + \mu_h p)}. \quad (3.2)$$

Charge carrier concentration in the conduction band of a pure semiconductor is called intrinsic carrier concentration and is strongly temperature dependent.

Silicon is a semiconductor with an indirect band gap of 1.12 eV, an intrinsic carrier concentration of $\sim 10^{10} \text{ cm}^{-3}$ and an intrinsic resistivity of $\rho \approx 230 \text{ k}\Omega \text{ cm}$ at room temperature. The average ionisation energy E_{ion} for generation of an electron-hole pair in silicon is 3.6 eV, which includes the energy of a phonon produced in the process.

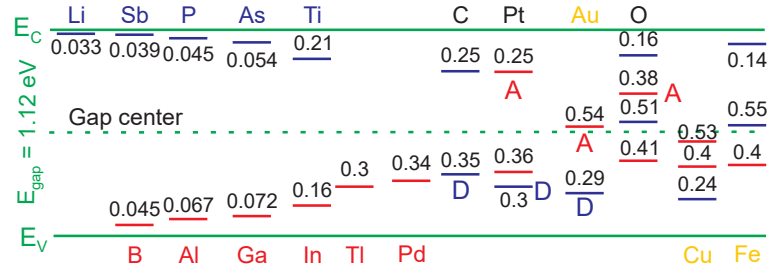


Figure 3.1: Additional energy levels in silicon band gap introduced by impurities. Acceptor states are drawn in red and donor states in dark blue. Useful dopants, most commonly boron (B) and phosphorus (P), add additional levels near the conduction and valence bands, while other states in the mid gap such as those introduced by copper or gold are undesired [38].

3.1.2 Doping of silicon

Electrical conductivity of silicon can be altered by doping – addition of elements from groups III and V of the periodic system which substitute Si atoms in the lattice. Group III dopants such as boron are called *acceptors* and have three valence electrons. To form four covalent bonds they accept an additional electron from a neighbour Si atom and change from a neutral to a negatively charged state. The complementary positively charged defect (hole) is highly mobile and acts as a positive charge carrier. Conversely, dopants from group V (such as phosphorus), called *donors*, have an additional electron which is released into the lattice, leaving a positively charged donor ion. Silicon predominantly doped with acceptors is called p-type and donor doped silicon is called n-type. In addition, silicon wafers also contain low concentrations of other impurities such as oxygen and carbon which are introduced during production process.

The dopant states influence the position of energy bands relative to the Fermi level. In p-type silicon the energy bands shift so that E_F is between the valence band and the acceptor level, while in n-type silicon E_F is between the donor level and the conduction band.

The energies of the states introduced by doping are called shallow states and are typically separated by only a few tens of meV from the valence band (acceptors) or the conductive band (donors) as shown in Figure 3.1. This means that at room temperature with $k_B T = 23 \text{ meV}$ the thermal excitations are sufficient to ionise the majority of dopant atoms and create free charge carriers in the material. Depending on the application the doping concentration range from $\approx 10^{12} \text{ cm}^{-3}$ to $\approx 10^{20} \text{ cm}^{-3}$, which is much higher than intrinsic carrier concentration. Electrical properties of such material, called extrinsic semiconductor, are completely determined by doping.

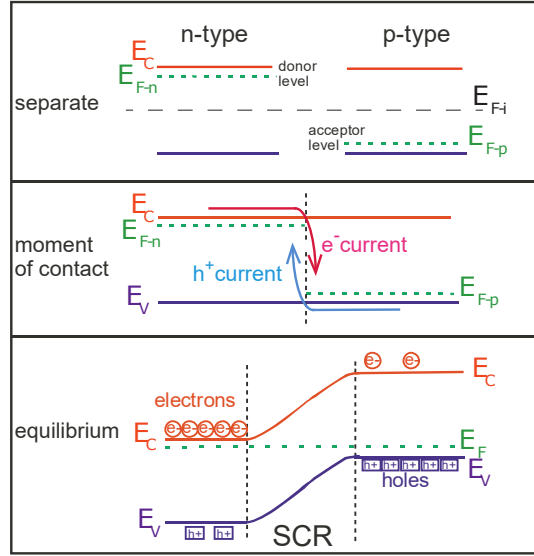


Figure 3.2: The p-n junction. Top: separate n-type and p-type material have a different Fermi level. Middle: theoretical situation at the time of contact between the two types. The Fermi levels equalise by diffusion and recombination of charge carriers. Bottom: emergence of space charge region in thermal equilibrium [38].

3.1.3 The p-n junction

Particle detectors rely on detecting a relatively small amount of e-h pairs deposited in the material by highly energetic charged particles. In a typical $300\text{ }\mu\text{m}$ thick silicon detector approximately 24 000 e-h are deposited on average. In silicon with intrinsic carrier concentration of the order of $\sim 10^{10}\text{ cm}^{-3}$ the additional charge is insignificant, hence pure silicon cannot be used as a detector. A greatly reduced concentration of background free charge carriers can be achieved in a depleted region which forms on the p-n junction in doped silicon.

A p-n junction develops on the interface between p-type and n-type silicon (Figure 3.2). Separated p- and n-type materials have different Fermi levels. On contact, their Fermi levels equalise, leading to the shifting of energy bands. On a microscopic level a gradient in the charge carrier concentration results in diffusion of majority charge carriers into the opposite type material where they recombine. In the process the p-side obtains a net negative charge and the n-side a net positive charge (space charge) due to the immobile acceptor and donor ions. The polarised region depleted of free charge carriers is called a *space charge region* (SCR) or depletion region. Polarisation of SCR results in a built-in electric field that eventually balances the diffusion.

Properties of a p-n junction with acceptor and donor concentrations $N_{A,D}$ are schematically presented in Figure 3.3. They can be calculated by solving the Poisson

equation for the electrical potential V :

$$-\frac{d^2V}{dx^2} = \frac{\rho(x)}{\epsilon_{\text{Si}}\epsilon_0}, \quad (3.3)$$

where $\rho(x)$ is the space charge density in the junction. In an abrupt junction approximation at position $x = 0$ with no free charge carriers in the SCR it holds

$$\rho(x) = \begin{cases} -e_0 N_A & \text{if } -x_p < x < 0; \\ e_0 N_D & \text{if } 0 < x < x_n; \end{cases} \quad (3.4)$$

where $x_{p,n}$ is the width of the SCR in the p-type and n-type material. The potential difference over an unbiased p-n junction is called the built-in potential V_{bi} :

$$V_{\text{bi}} = \frac{e_0}{2\epsilon_{\text{Si}}\epsilon_0}(N_D x_n^2 + N_A x_p^2) \approx 0.5 - 1 \text{ V in silicon.} \quad (3.5)$$

Since the whole system is electrically neutral it also holds

$$N_A x_p = N_D x_n, \quad (3.6)$$

showing that the width of the depleted region on each side is inversely proportional to the doping concentration. In tracking detectors one side (electrode) is typically by several orders of magnitude more heavily doped than the other side (substrate), in which case the depletion of the electrode can be neglected ($x_{\text{electrode}} = 0$) and the doping concentration can be substituted by the effective doping concentration of the substrate N_{eff} . From equations 3.5 and 3.6 it follows that the full width of the depletion zone w is

$$w = \sqrt{\frac{2\epsilon_{\text{Si}}V_{\text{bi}}}{e_0 N_{\text{eff}}}}. \quad (3.7)$$

p-n junction behaves like a diode under application of external electric potential V . In forward bias with p-side connected to positive polarity and n-side to negative polarity the junction becomes conductive when $V > V_{\text{bi}}$.

In particle detectors the depletion zone acts as a sensitive volume with a low background charge carrier concentration. The signal is proportional to the number of charge carriers generated in the depletion zone by the charged particle. Therefore particle detectors are typically operated in reverse mode with the bias voltage much higher than V_{bi} to increase the width of the depletion zone. Equation 3.7 can then be modified to

$$w = \sqrt{\frac{2\epsilon_{\text{Si}}V}{e_0 N_{\text{eff}}}}. \quad (3.8)$$

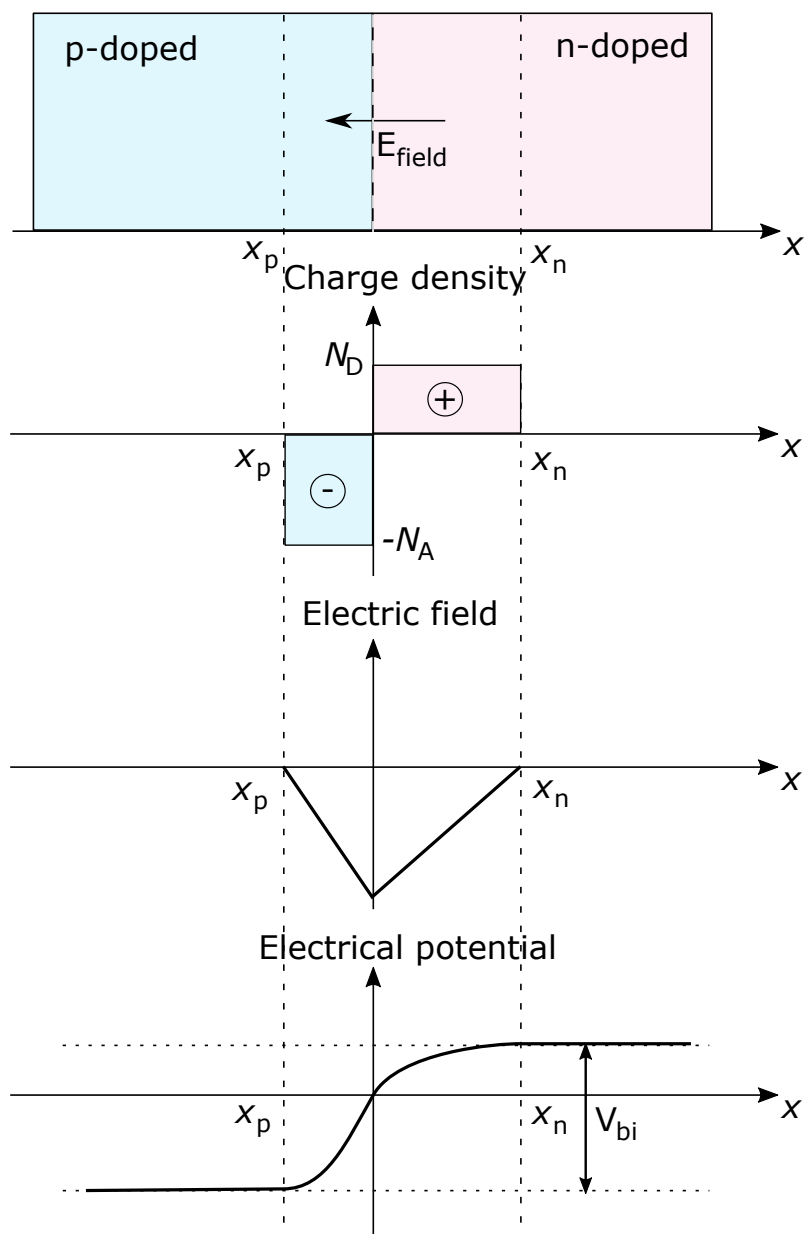


Figure 3.3: Schematics of space charge density, electric field and electrical potential in p-n junction.

Large depletion depths are usually achieved by using low doped silicon with small N_{eff} . Detectors where the depletion zone grows over the entire thickness are called *fully depleted* and the smallest bias voltage at which this occurs is called *full depletion voltage* V_{FD} . Typical sensors have a thickness of 300 μm , but can be thinned down to 100 μm to achieve full depletion easier. Smaller thickness is limited by the mechanical integrity of silicon wafers.

In reverse bias the applied voltage results in an electric field in the depletion zone which can be calculated from the Poisson equation. The field is strongest at the p-n interface and reduces at greater distances from the junction. In an unirradiated planar p-n junction the electric field strength reduces linearly with the distance from the junction.

3.1.4 Silicon sensors

Silicon sensors for high energy physics are arrays of reverse biased p-n junctions, segmented into pixels or strips to achieve position sensitivity. Charge carriers released in the depletion zone are separated by the electric field and drift to the respective electrodes. Collection of charge carriers deposited outside of the depletion zone is also possible by diffusion, however this transport is slow ($\gg 100$ ns). The properties of silicon sensors depend on the choice of substrate and electrode polarity. If n⁺-type electrodes¹ are used on the segmented side, the sensor is called n-in-p or n-in-n depending on the substrate type. Conversely p⁺-in-n and p⁺-in-p sensors use p-type collection electrodes. Detectors investigated in this thesis are n-in-p type and use p-type substrates with the depletion region growing from the electrode side.

Leakage current

Reverse biased p-n junction is in essence void of free charge carriers. However, there is a constant thermal generation of e-h pairs which results in the *leakage current*. Leakage current is proportional to the volume of the depleted zone and depends strongly on temperature and band gap E_G [39]:

$$I_L \propto T^2 e^{-\frac{E_G}{kT}}. \quad (3.9)$$

Typical current densities in a few 100 μm thick unirradiated silicon sensor at room temperature are nA/cm² and increase strongly after irradiation to typical values of

¹n⁺ denotes highly doped n-type and material.

$\mu\text{A}/\text{cm}^2$. To prevent a positive feedback loop through ohmic heating – the thermal runaway – irradiated detectors require cooling.

3.1.5 Noise in silicon detectors

Electronic noise limits the minimal detectable signal size and is the source of fake signals, therefore an optimised electronic design of the detector is vital. This section gives a brief overview of noise properties, required for the scope of this thesis, while a more detailed analysis can be found for example in [39].

The parameter describing the detector's noise performance is the signal to noise ratio (S/N). Detector noise is usually specified by the *equivalent noise charge* (ENC), given in electrons, which is the ratio of effective noise voltage on the output and the output voltage for a signal of one electron on the input:

$$ENC = \frac{\sqrt{\langle u_{\text{noise,out}}^2 \rangle}}{U_{\text{out,1 e}^-}} \text{ e}^-. \quad (3.10)$$

The sources of noise in silicon detectors are both sensor and readout electronics. The three main noise contributions are:

- Current noise due to statistical fluctuations of the leakage current in the sensor (*shot noise*);
- $1/f$ voltage noise in the input transistor;
- Thermal current noise in the input transistor.

The characteristic dependence of ENC on the main detector parameters is given by:

$$ENC^2 = \alpha_{\text{shot}} I_{\text{leak}} \tau + \alpha_{1/f} C_D^2 + \alpha_{\text{therm}} \frac{C_D^2}{g_m \tau}, \quad (3.11)$$

with I_{leak} the sensor leakage current, τ the shaping time of the preamplifier, C_d the sensor capacitance and g_m the transconductance of the input transistor. Coefficients α_i describe the size of shot noise, $1/f$ and thermal contributions. As apparent from the above formula, detectors with a higher capacitance feature a higher noise, for example strip detectors have typically higher noise than pixel detectors due to a larger electrode capacitance. Shot noise contribution depends on integration time and leakage current. Leakage current considerably increases with irradiation (Chapter 4.2.2), however in case of LHC the overall effect is not problematic due to a relatively short integration time (25 ns).

3.2 Charged particle interaction with matter

The basis for the detection of particles is their interaction with the detector material which deposits energy and produces electrical signals. The mechanism of energy deposition depends on particle type and its energy. Charged particle with sufficient energy ionises material along its path with minimal disturbance of its trajectory which is ideal situation for tracking. On the other hand electrically neutral particles like photons or neutrons ionise detector material via secondary particles and cannot be tracked in the same way as charged particles.

Ionisation occurs when incoming highly energetic particle knocks out electrons from outer atomic shells in the target, losing energy equivalent to the electron's binding energy in the process. Macroscopically the average ionisation losses per distance travelled are given by the Bethe-Bloch formula (Figure 3.4) [40]:

$$-\left\langle \frac{dE}{dx} \right\rangle = K \rho z^2 \frac{Z}{A} \frac{1}{\beta^2} \left(\frac{1}{2} \ln \frac{2m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 + \frac{\delta(\beta\gamma)}{2} \right), \quad (3.12)$$

ρ	density of the material
K	$4\pi N_A r_e^2 m_e c^2 = 0.307075 \text{ MeV g}^{-1} \text{ cm}^2$
z	charge of traversing particle in units of electron charge
Z	atomic number of absorption medium (14 for silicon)
A	atomic mass of absorption medium (28 for silicon)
$m_e c^2$	rest mass of the electron (0.511 MeV)
β	velocity of the traversing particle in fraction of speed of light
γ	Lorentz factor $1/\sqrt{1-\beta^2}$
I	mean excitation energy (137 eV for silicon)
$\delta(\beta\gamma)$	density correction at high energies

The maximal kinetic energy $T_{\max}$ that can be transferred to an electron by a particle of mass M is approximated by:

$$T_{\max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2}. \quad (3.13)$$

The Bethe-Bloch formula is valid over a wide range of energies corresponding to

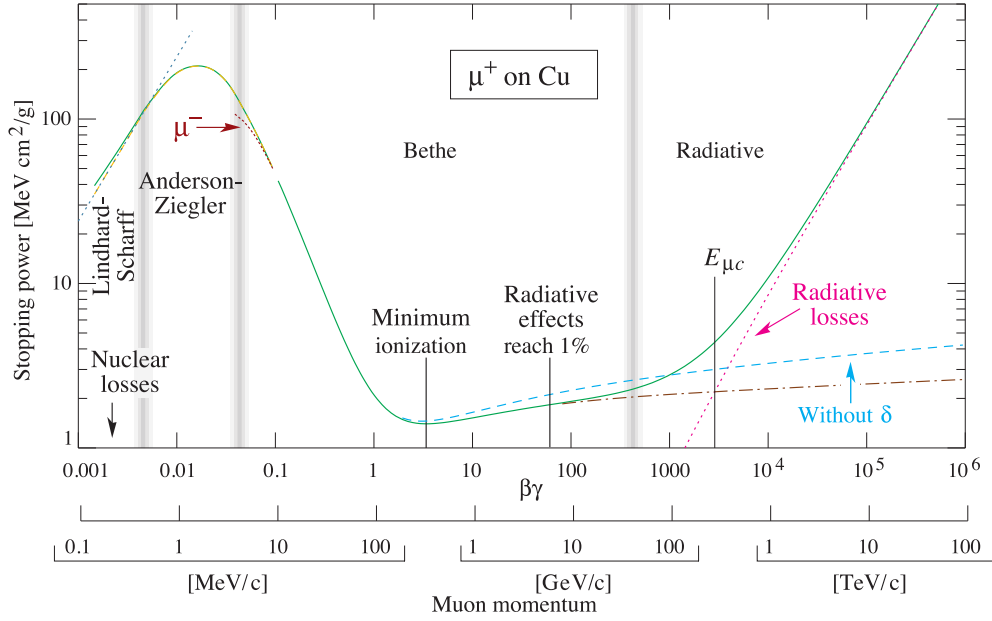


Figure 3.4: Mean energy loss of muons in copper as a function of $\beta\gamma$. Ionisation described by the Bethe-Bloch formula 3.12 is the primary mechanism of energy losses in the range of $\beta\gamma \approx 0.1 - 1000$. Minimum stopping power is reached at $\beta\gamma \approx 2 - 3$. The corresponding particle is a minimum ionising particle (MIP). Figure from [41].

$\beta\gamma \approx 0.1 - 1000$. The ionisation losses have a broad minimum around $\beta\gamma \approx 2 - 3$ which extends up to $\beta\gamma \approx$ few hundred. These particles are called Minimum Ionising Particles (MIP). For $\beta\gamma > 1000$ the dominant mechanism of energy losses is bremsstrahlung, while at $\beta < 0.1$ various other effects not described by the Bethe-Bloch formula dominate. The Bethe-Bloch formula gives the mean value of energy losses in a medium, but actual energy depositions vary due to fluctuations in the number of scattering interactions which follow Poissonian statistics, and varying energy transfer in each scattering event (see for example [39]). The energy loss spectrum is defined by two main contributions: a Gaussian part from numerous scattering events with a small energy deposition, and a part at higher energy depositions corresponding to infrequent central collisions with a larger energy transfer (so called δ -electrons), which results in an asymmetric energy loss distribution. The extent of asymmetry depends on the thickness of the material and particle type and energy. For highly energetic particles in thin material layers such as silicon detectors the distribution is highly asymmetric and can be described by the Landau probability distribution (Figure 3.5) [42]. Since the mean value of the Landau distribution is strongly influenced by fluctuations at high values of energy deposition, the more stable *most probable value* (MPV) is usually used to characterise the spectrum. In silicon ($Z = 14$, $A = 28$, $\rho = 2.3 \text{ g/cm}^2$, $E_{\text{ion},e,h} = 3.6 \text{ eV}$) the mean MIP energy loss is $400 \text{ eV}/\mu\text{m}$, which corresponds to a mean value of $100 \text{ e-h pairs}/\mu\text{m}$ and the MPV of $80 \text{ e-h pairs}/\mu\text{m}$.

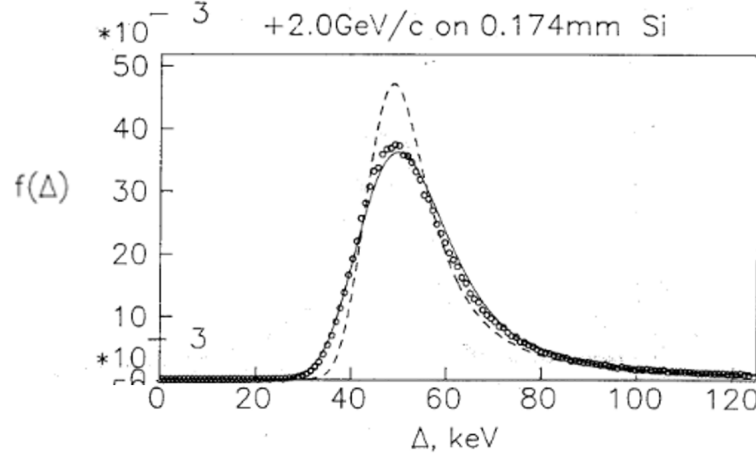


Figure 3.5: Measured energy loss distribution for 2 GeV positrons in 174 μm of silicon, approximation by the Landau function (dashed line) and a more refined model (solid line) [43].

3.3 Shockley-Ramo theorem

The principle of signal formation in silicon detectors is that of an ionisation chamber. The drifting electric charge induces a current in the readout electrodes, which is detected and amplified by the readout electronics. An elegant connection between the velocity of the charge carriers, the device geometry and the induced current was derived by Shockley and Ramo in 1930s [44, 45]. Their theorem was originally developed to explain signal formation in gas chambers, but may also be used in silicon [46]. It gives the following dependence of the induced current I :

$$I = e_0 \vec{v}(\vec{r}) \cdot \vec{E}_w(\vec{r}) \quad (3.14)$$

where $\vec{v}$ is the charge carrier velocity and $\vec{E}_w$ is the weighting field. The weighting field gives the electrostatic coupling between a given electrode and charge at position $\vec{r}$ in the given geometry. It is calculated as $\vec{E}_w = -\nabla U_w$, where U_w is the weighting potential obtained from the Laplace equation in which the sensing electrode is set to a unit potential of 1 and all other electrodes connected to low impedance are set to a potential of 0. For example, in two planar electrodes geometry at a distance d the weighting field is constant $\vec{E}_w = -\frac{1}{d}\vec{z}$. In strip and pixel geometry the largest weighting field is in the proximity of the readout electrode, which is therefore the most important region for signal creation. The trajectory of the charge carrier drift is determined by the actual electric field in the device which has in general a different direction than the weighting field. The difference between the electric and weighting fields is illustrated in Figure 3.6 which represents a 100 μm thick depleted strip detector with the central strip read out.

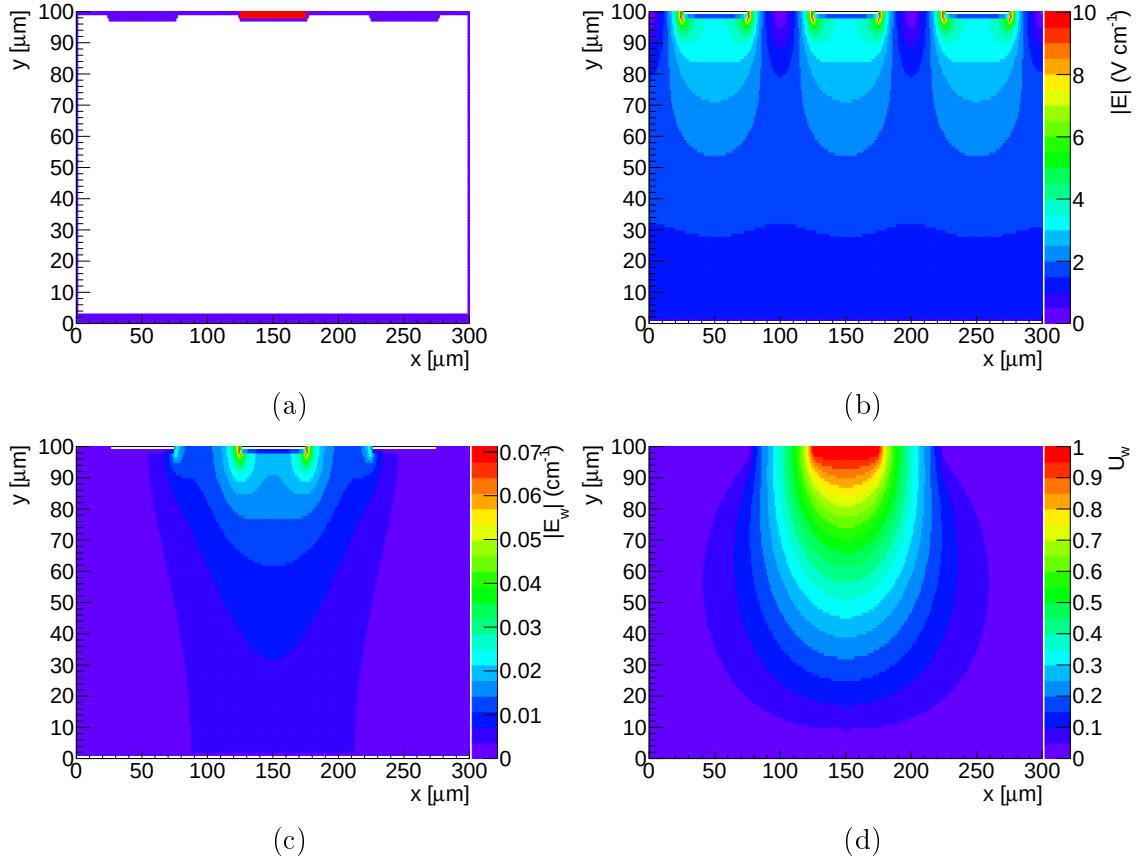


Figure 3.6: Simulation of the electric and weighting fields in a depleted strip detector: a) Side view of the detector with the central strip connected to readout and two neighbouring strips; b) Magnitude of electric field; c) Magnitude of weighting field; d) Weighting potential.

The charge q collected by the sensing electrode is given by the difference in the weighting potential at the start and end positions of the drifting charge e :

$$q = e(U_w(\vec{r}_{\text{end}}) - U_w(\vec{r}_{\text{start}})). \quad (3.15)$$

The total charge is the sum of electron and hole contributions. If the drift finishes on the sensing electrode ($U_w = 1$) the collected charge equals e , whereas the drift finishing on other electrodes ($U_w = 0$) yields a charge of zero. In irradiated detectors charge carriers can get trapped in radiation induced defects (Chapter 4.2.3) and contribute only a fraction of the entire signal, while a finite charge is also induced on neighbouring electrodes.

Experimentally the collected charge can be measured as a time integral of the induced current. For charge carriers drifting towards the sensing electrode the induced current is unipolar with the integral proportional to the collected charge, while for carriers drifting to other electrodes the current is bipolar with a vanishing integral.

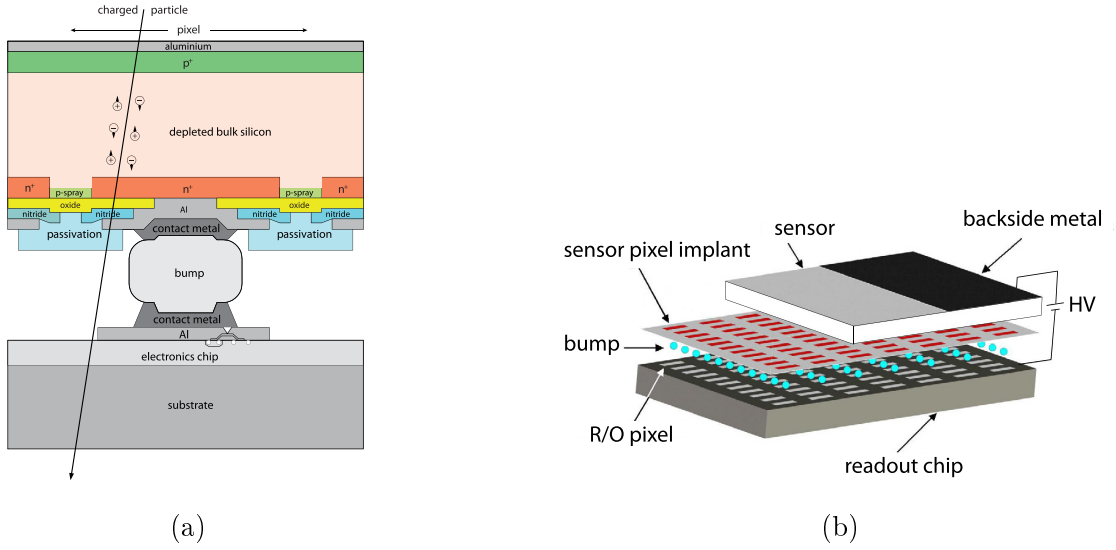


Figure 3.7: Hybrid pixel detector: a) Bump bond interconnection between the sensor and the readout chip in an individual pixel cell; b) Bump bonded pixel detector [47].

3.4 Hybrid pixel detectors

In a pixel detector the sensor has to be equipped with readout electronics, which senses and amplifies the input signals, measures the collected charge and converts hit information into digital format which can be transmitted out of the detector. The most common approach has been the hybrid detector solution, where the readout electronics is implemented on a separate readout chip which is later connected with the electronically passive sensor into one assembly – a detector module [47].

The readout chip consists of an array of readout cells matching the sensor segmentation, allowing individual readout of each pixel. The readout cells provide a fixed electrical potential to the sensor front side, while the high voltage for sensor depletion is applied to the back side. The crucial technological step in production of hybrid pixel detectors is the coupling of the sensor with the readout chip (hybridisation) using bump bonding interconnection technique. The process uses small solder balls (bump bonds) which connect the pixel cells of the two chips, providing electrical and mechanical coupling (Figure 3.7).

Hybrid detectors have proven excellent performance in terms of reliability, radiation hardness and high rate operation, and have been a baseline detector solution for several decades. As such, they will also be used in the ATLAS ITk. One of the main advantages of hybrid detectors is the possibility to separately optimise both detector components to achieve a high radiation tolerance of the sensor and required processing capabilities of the readout chip.

The hybrid approach also has some disadvantages. Using two silicon chips increases the material budget and increases the probability of multiple scattering. The components have to be produced in separate processes, which particularly for sensor are highly customised, correspondingly expensive and available only from few vendors. In addition, bump bonding is a complex process which requires a series of specialised steps and represents a bottleneck in module production. The physical dimensions of the bumps also represents a limit for the minimal possible pixel size that can be bump bonded. The scale of the ATLAS ITk pixel detector and the related production challenges have prompted ATLAS to investigate alternatives to an all-hybrid solution.

3.5 MAPS – Monolithic Active Pixel Sensors

An alternative to standard hybrid pixel modules are active sensors where a part of the readout functionality is implemented within the pixel implants in the sensor. Further extending this concept leads to *monolithic active pixel sensors* (MAPS) where the readout chip becomes redundant as the full signal processing, analogue as well as digital, is implemented in a single silicon chip [47]. MAPS for charged particle tracking are an upgrade of the technology developed for imaging applications such as smartphone cameras and offer several advantages compared to hybrid detectors. Thinner sensors represent a smaller material budget and less multiple scattering, which can lead to improved spatial resolution. In monolithic detectors the bump bonding production step is not needed which is a great advantage in production time as well as cost. Commercial CMOS processes can be adapted for MAPS and these are produced in foundries delivering large quantities of devices which further reduces production time. This is beneficial also for detector development time as time between prototype versions is shorter.

The crucial technological process for MAPS manufacturing is the possibility to implant several nested wells on the surface of the silicon wafers. Implanted p-wells act as the substrate for NMOS transistors while n-wells take this role for PMOS transistors, thus allowing implementation of a full CMOS functionality. Multiple wells also provide electrode shielding, preventing coupling of digital signals into the sensing part (cross talk).

MAPS for HEP applications have already been proposed in 1990s and 2000s [48, 49] and have been successfully used in experiments STAR [35] and ALICE [36]. Schematic pixel cross section in these detectors is shown in Figure 3.8a. The

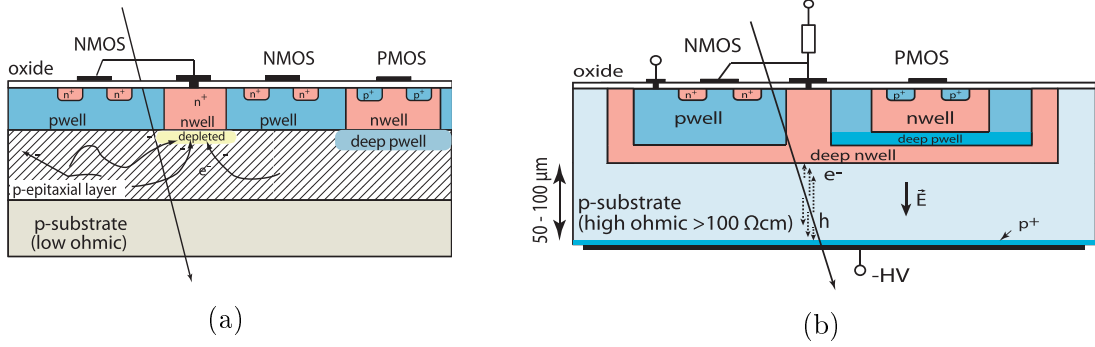


Figure 3.8: Schematics of monolithic active pixel sensors (MAPS): MAPS with charge collection in an epitaxial layer predominantly by diffusion; b) Depleted MAPS (DMAPS) allowing sensor biasing with high voltage (HV) to achieve a sizeable depletion region [47].

sensitive volume is a highly resistive p-type epitaxial layer which also houses the readout electronics. Charge is collected by an n-type implant, while other n-wells housing the PMOS transistors have to be screened by an additional deep p-well implant to prevent parasitic charge collection. The detector is not biased beyond the built in electric field, hence the dominant charge collection mechanism is diffusion. These detectors are not suitable for high rate and high radiation environments such as ATLAS, which require drift based charge collection.

Improved detectors which allow a significant sensor depletion (Figure 3.8b) are known under a common name *depleted MAPS* (DMAPS). Depletion depth depends on material resistivity and the applied bias voltage:

$$d \propto \sqrt{\rho V} \quad (3.16)$$

implying that large depletion can be achieved by either using highly resistive material, high biasing voltage or both. On this basis detectors are sometimes categorised into HR-CMOS (high resistivity CMOS) and HV-CMOS (high voltage CMOS), although the separation is sometimes vague. Typical DMAPS aim at depletion depths in the range of 50–100 μm, but shallower depletion depths down to 20 μm are also possible in designs adapted for low noise.

3.5.1 Large and small readout electrode designs

One of the main considerations in DMAPS design is the size of the collection electrode, which determines the detector capacitance and the length of drift paths for charge carriers. A higher detector capacitance C_d results in a higher noise (see

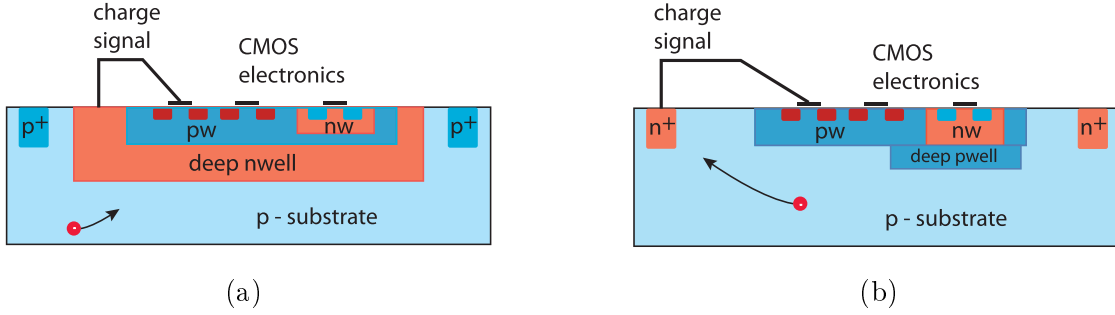


Figure 3.9: Two main approaches to MAPS pixel architecture: a) Large collection electrode with CMOS electronics embedded in the collecting n-well; b) Small collection electrode with the readout implemented in a separate well. Concept a) features shorter drift paths at the expense of a higher detector capacitance compared to b) [47].

Equation 3.11) as well as in a slower detector response time τ_{CSA} :

$$ENC_{\text{th}}^2 \propto \frac{1}{g_m} C_d^2 \quad \text{and} \quad \tau_{\text{CSA}} \propto \frac{1}{g_m} C_d. \quad (3.17)$$

It is therefore desired that the detector capacitance is low. C_d can be compensated with a higher transconductance of the input transistor g_m at the cost of a higher power consumption of the amplifier. The length of the drift path is important to ensure radiation tolerance of the detector. Charge collection in detectors with shorter drift paths is completed faster and is therefore less sensitive to trapping which occurs after irradiation (see Chapter 4.2.3). The choice of pixel architecture is in general a tradeoff between short drift distance and low sensor capacitance.

Two principal DMAPS architectures are called *Large* and *Small collection electrode* designs² shown in Figure 3.9. Both approaches have been investigated for the ATLAS Phase-II upgrade. In sensors with a large collecting electrode, the electrode takes up 50 % or more of the total pixel area (Figure 3.9a). The readout electronics is embedded within the collection n-well. This geometry ensures uniform and relatively short drift paths in all parts of the pixel. The pixel capacitance is of the order of ~ 100 fF which is relatively high [47]. In addition to pixel-to-back-plane and pixel-to-pixel capacitances inherent to every pixel detector, CMOS detectors also feature a capacitance between multiple wells within the collection electrode (Figure 3.10). While its impact on noise and timing performance can be compensated by for example increasing g_m , the inter-well capacitance also acts as a potential coupling between the wells and the collection electrode. This can cause coupling of digital signals into the sensing part, thus producing fake signals, and requires special design

²Sometimes referred to as Large and Small fill factor, although in standard terminology both designs aim for a 100 % detection efficiency, hence a 100 % fill factor.

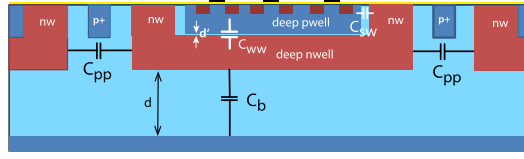


Figure 3.10: Contributions to sensor capacitance in a MAPS with a large collecting electrode, consisting of the capacitance between the pixel and the sensor back side C_b , the inter pixel capacitance C_{pp} and the capacitance between multiple wells within the pixel C_{ww} . The latter can cause coupling of digital signals from the electronics into the sensor unless specifically prevented [47].

measures.

Small collection electrode approach is based on a collection electrode with a size of a few μm and a typical capacitance of 2–3 fF (Figure 3.9b). The readout electronics is placed in a separate p-well and does not contribute to the sensor capacitance. Low capacitance results in significantly lower noise and faster electronic rise time, which allows amplifier design with lower power. The required charge for a satisfactory S/N ratio is also lower so the collection layer can be thinner. Low noise means that the readout electronics can be relatively simple taking up only a small fraction of the pixel area. In general this allows design of smaller pixel pitches.

The main challenge in this geometry is to ensure efficient and fast charge collection in the entire pixel, which requires strong lateral electric fields on pixel edges. Since the back plane and the p-well with electronics act as equipotential planes the generation of lateral fields and full pixel depletion is not straightforward and requires pixel design in a so called modified process with an additional low doped planar n-type layer (see Chapter 5.2) The relatively long drift distances also increase trapping probability in irradiated devices, which is the main limiting factor for radiation hardness of this architecture. This dictates use of small pixels, which on one hand benefits the position resolution, but on the other hand increases charge sharing (less charge per pixel), constraints the amount of electronics that can be packaged within the pixel and increases the power density in the detector due to higher granularity.

3.5.2 SOI sensors

Silicon-on-Insulator (SOI) is an alternative MAPS architecture shown in Figure 3.11 [47, 50]. In SOI devices CMOS circuitry is housed in a dedicated thin silicon layer on the surface which is grown on top of an insulating layer of silicon oxide, called buried

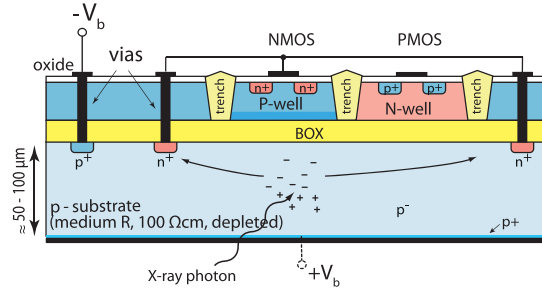


Figure 3.11: Schematics of an SOI MAPS. The depleted sensor substrate is separated from the CMOS layer by the buried oxide (BOX). Sufficient thickness of the CMOS layer is required to prevent back-gate effect on the transistors from charged BOX after irradiation [47].

oxide (BOX). The thick highly resistive substrate acting as a sensor is connected to the CMOS layer by vertical connections (vias). The separation of the sensor and CMOS part allows both large and small collection electrode designs. Developments in vertical (3D) stacking of multiple SOI layers also promise availability of much higher electronics densities in the future.

SOI has some specifics in terms of radiation tolerance due to the BOX layer. Silicon oxide exposed to ionising radiation obtains a net positive electric charge (see Chapter 4.1) and the resulting electric field can change thresholds in adjacent transistors. This is a so called *back-gate effect*. In standard SOI the CMOS layer typically has a thickness of only few 10 nm and is therefore strongly affected by the charge in the BOX. Radiation hard devices mitigate this by using a so called thick film SOI with a thicker CMOS layer ($\sim 1 \mu\text{m}$) or additional implants which screen the oxide charge [51, 52].

Chapter 4

Radiation damage in silicon

In the LHC detectors surrounding the interaction point are exposed to large fluxes of highly energetic particles originating from energy released in proton-proton collisions. These particles cause damage to the detectors and deteriorate their performance. Radiation tolerant detector design to ensure reliable performance until the end of the detector lifetime is therefore paramount. Radiation damage is separated in two main types: ionisation damage and displacement damage. Ionisation damage, also called surface damage, is caused by ionising energy losses of photons and charged particles. It affects silicon oxide and the interface between oxide and silicon on detector surface. Displacement damage is primarily caused by hadrons, which displace silicon atoms from crystal lattice. This is the main source of radiation damage in the bulk with effects on charge collection and leakage current. One consequence of displacement damage is effective removal of initial acceptors. This is an important phenomenon in CMOS detectors and will be discussed in more detail.

4.1 Surface radiation damage

Surface radiation damage or ionisation damage occurs after incident radiation generate electron-hole pairs and thus ionise the medium. Its extent is measured by the total ionising dose (TID) absorbed by the material. TID is measured in units of Gray (Gy = J/kg) or equivalently in rad (1 rad = 0.01 Gy). In the silicon lattice the newly generated charge carriers recombine almost instantaneously, hence no long term effects take place. On the other hand, persistent defects can be generated in silicon oxide SiO₂ and SiO₂-Si interfaces. The decisive factor is extremely low mobility of holes in SiO₂ ($\mu_h \approx 10^{-4}$ – 10^{-11} cm V⁻¹ s⁻¹ [53] compared to electron

mobility of $\mu_e = 20 \text{ cm V}^{-1} \text{ s}^{-1}$ [54]) which prevents the holes from leaving the oxide and recombining [55]. This results in accumulation of trapped holes in the SiO_2 -Si interface, which creates a positive space charge in the oxide.

Since SiO_2 is used in transistors as insulator between the gate electrode and the bulk, these changes have a serious effect on field effect transistor (FET) properties, including shifts in threshold voltage, shifts in the leakage current and reduction of transconductance [39]. This causes performance degradation of analogue and digital parts of the readout chip including risk of false signals and logic failure. In n-in-p sensors accumulation of space charge in the oxide can cause local type inversion of the substrate, creating a conductive channel between the electrodes which causes cross talk between the channels. This behaviour has to be prevented by dedicated p-type implants called p-stop.

Development of integrated circuits technology trends toward miniaturisation of its basic unit – the transistor – which requires thinner gate insulation. This has a positive effect on TID radiation tolerance. With typical gate oxide thickness reduced to few nm, there is a significant probability for trapped holes to escape the traps via the tunnel effect and thus recover some of the radiation damage. More details on surface damage can be found for example in [47, 56, 57].

4.2 Displacement damage

Ionisation damage does not play an important role in silicon bulk, as the original state is recovered as soon as freed charge carriers recombine. The main radiation effect in the bulk is displacement damage, caused by non ionising energy depositions, which occur when an incident particle knocks out an atom from its site in the crystal lattice, creating an interstitial atom (I) and a vacancy (V) – a Frenkel pair [58, 59]. A fraction ($\approx 60\%$ [60]) of interstitials and vacancies recombine on spot, while the rest migrate through the lattice and interact with each other or with impurity atoms, creating *point defects* (examples shown in Figure 4.1). Point defects result in additional energy states – deep levels – in the band gap.

The energy threshold to create a Frenkel pair in silicon is $E_d \approx 20 \text{ eV}$ [61]. If the imparted energy on the displaced atom, called primary knock-on atom (PKA), is sufficiently high, the PKA can displace further atoms creating a *cluster* defect. Events with 1000 or more interstitial-vacancy pairs commonly occur [59].

Point defects and clusters change electric properties of silicon and are hence the

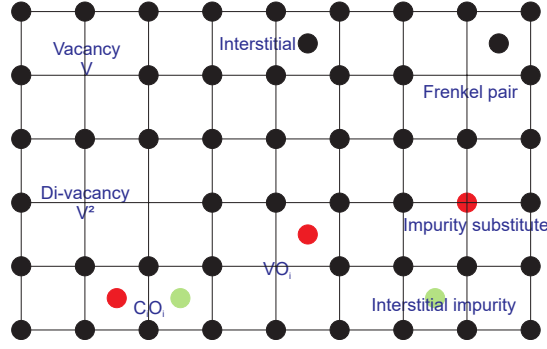


Figure 4.1: Types of point defects in silicon [38].

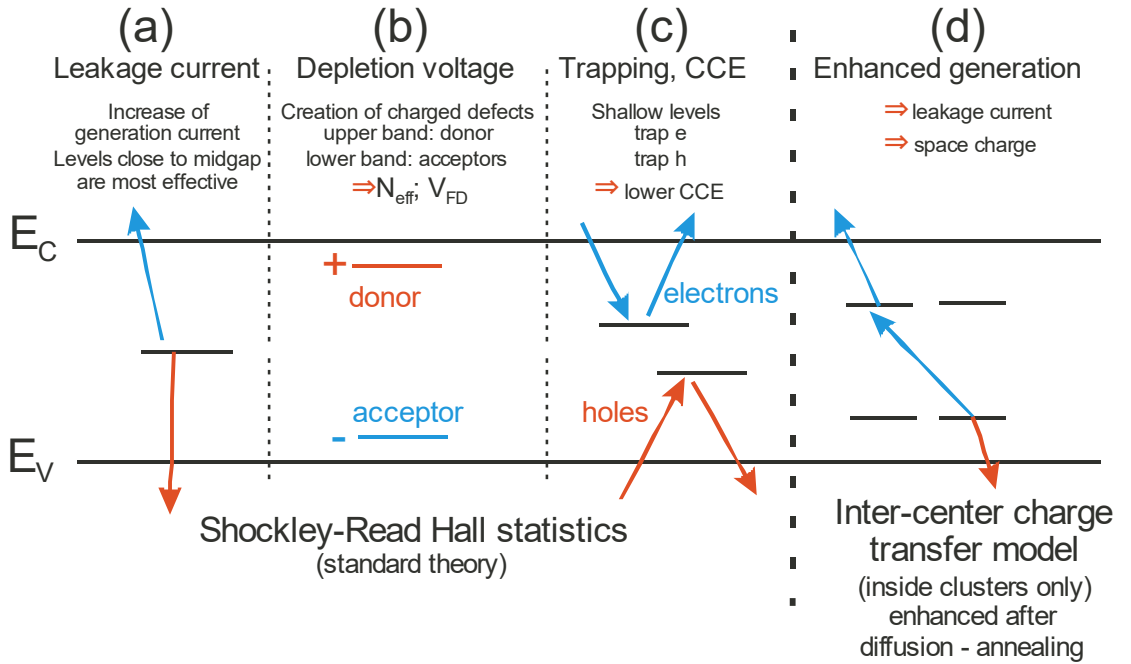


Figure 4.2: Irradiation induced levels in the band gap and their macroscopic effects: a) increased leakage current with main contribution from current generation centres in the middle of the band gap; b) Changes of effective space charge concentration N_{eff} , induced by newly introduced deep levels; c) Increased trapping probability; d) Enhanced effects on leakage current and space charge concentration through inter-centre charge transfer taking place within clusters [38].

source of radiation damage in the bulk. The macroscopic effects of displacement damage (Figure 4.2) are:

- Increase of leakage current;
- Decrease of charge collection efficiency due to defects acting as charge traps;
- Change of effective space charge concentration N_{eff} , affecting sensor depletion.

Since the energy level of the induced defects is higher than the energy of a pure lattice structure, some defects can recover (anneal) with time. Annealing process

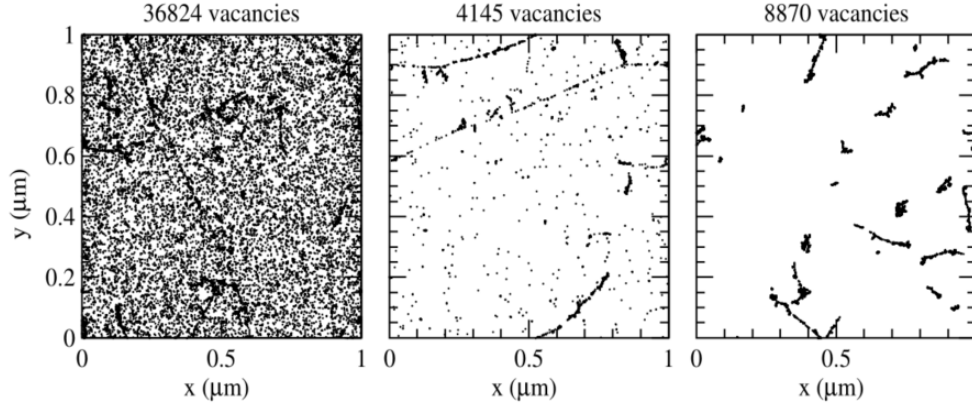


Figure 4.3: Simulated distribution of vacancies generated within 1 μm of silicon by 10 MeV protons (left), 24 GeV/c protons (centre) and 1 MeV neutrons (right). All fluences are $10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ [61].

is strongly temperature dependent. Some defects also form stable complexes in combination with oxygen or phosphorus atoms, which do not anneal over time [38, 39].

The frequency of point defects and clusters depends on the type and energy of the incident particle (Figure 4.3). Hadrons interact via nuclear force with a large energy transfer, which produces point defects and clusters on the end of heavy recoil ranges. For neutrons this is the only reaction mechanism. Charged hadrons in addition interact via long range Coulomb interaction which generates mostly point defects. Highly energetic (GeV) charged hadrons travel deep into the material and generate a larger fraction of point defects, while the damage of protons in the MeV energy range is more similar to neutrons. Displacement damage of electrons is comparably much lower, as the reaction kinematics allows smaller energy transfer to the PKA due to the small electron mass [58].

4.2.1 NIEL hypothesis

A common basis to compare the extent of displacement damage from different sources is established by the *non ionising energy loss* (NIEL) hypothesis. It states that the extent of displacement damage scales linearly with energy imparted in the displacing collision, irrespective of the spatial distribution of the ensuing defects. The total *displacement damage cross section* for a principal particle of energy E is given by [58]:

$$D(E) = \sum_{\nu} \sigma_{\nu}(E) \int_0^{E_R^{\max}} f_{\nu}(E, E_R) P(E_R) dE_R, \quad (4.1)$$

where contributions of all possible displacement processes ν , with cross sections $\sigma_\nu(E)$, are summed. The effects are integrated over all possible PKA recoil energies E_R with $f_\nu(E, E_R)$ the probability density to achieve this energy transfer. The fraction of the recoil energy deposited in form of displacement damage is given by the *Lindhard partition function* $P(E_R)$ [62].

By the above parametrisation, displacement damage can be expressed with a standard quantity which is by convention 1 MeV *neutron equivalent fluence*, denoted Φ_{eq} . The unit of Φ_{eq} is $[\Phi_{\text{eq}}] = n_{1 \text{ MeV, eq}}/\text{cm}^2$ or in short $n_{\text{eq}}/\text{cm}^2$, corresponding to a displacement damage cross section of $D_n(1 \text{ MeV}) = 95 \text{ Mev mb}$ [58]. The proportion of the damage caused by different particles can be expressed by the numerical *hardness factor* κ , which is defined as the fraction of displacement damage relative to the damage caused by the same fluence of 1 MeV neutrons.

The NIEL hypothesis was originally proposed as a robust standard for measurements of damage in the bulk, but does not hold for all processes. It provides accurate values for evolution of the leakage current [58, 63], while the changes of N_{eff} depend significantly on impurity (C and O) concentration in silicon wafer [63], and trap introduction rate changes with particle type by 30–40 % [64]. Acceptor removal studied in this thesis has also been shown to depend on particle type.

4.2.2 Leakage current

Irradiation introduces new states in the band gap, which act as current generation centres and contribute to leakage current. Most effective are energy levels in the middle of the band gap. The leakage current increases linearly with fluence and can for a given volume V be parametrised as:

$$\frac{\Delta I_L}{V} = \alpha \Phi_{\text{eq}}. \quad (4.2)$$

Parameter α designates current related damage rate and depends on the annealing history of the sample and sample temperature. Its value is normally measured at 20° C after *standard annealing* when the effective space charge concentration is minimal (see Section 4.2.4). This is achieved after storing the sample at a temperature of 60° C for 80 min or equivalently for 10 days at room temperature. Under these conditions the value is $\alpha = (3.99 \pm 0.03) \times 10^{-17} \text{ A/cm}$ at 20° C [63]. The universal dependence of leakage current on fluence holds over many orders of magnitude, which is used for calibration of different irradiations to equivalent fluence.

Increased leakage current has several adverse consequences for detector operation. It results in a higher shot noise, scaling with $\sqrt{I_L}$, and consequently in a reduced S/N ratio (see Chapter 3.1.5). In addition, increased leakage current causes higher ohmic losses in the sensor, which can result in uncontrolled sensor heating due to a positive feedback loop – the thermal runaway. To keep the temperature stable sufficient cooling capacities need to be installed.

4.2.3 Charge trapping

Deep levels introduced by irradiation act as traps for drifting charge carriers. If the time in which the trapped charge is released from a defect is greater than the shaping time of the electronics, the charge is effectively lost for detection, leading to a reduced S/N ratio. Irradiation also inhibits charge collection by diffusion, which is in part due to trapping, but also due to increased charge recombination on defects introduced by radiation. This already occurs at low fluences around $10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$.

Trapping is described by the effective trapping time τ_{eff} , which is the characteristic time a charge carrier drifts before being trapped. The trapping rate is to the first order proportional to the concentration of trapping centres, which scales linearly with fluence: $\frac{1}{\tau_{\text{eff}}} = \beta \times \Phi_{\text{eq}}$, with the proportionality factor $\beta \approx 4 \times 10^{-16} \text{ cm}^{-2} \text{ ns}^{-1}$ in p-type silicon [65, 66]. The reduction of an initial charge Q_0 due to trapping is

$$Q_{\text{e,h}}(t) = Q_{0,\text{e,h}} e^{-\frac{t}{\tau_{\text{eff,e,h}}}}. \quad (4.3)$$

With drift saturation velocity of $v_{\text{sat}} \sim 100 \text{ } \mu\text{m}/\text{ns}$, typical trapping times and corresponding drift distances $\lambda = v_{\text{sat}} \cdot \tau_{\text{eff}}$ are:

- $\tau_{\text{eff}}(10^{14} \text{ n}_{\text{eq}}/\text{cm}^2) = 20 \text{ ns}$, $\lambda \gg 300 \text{ } \mu\text{m}$;
- $\tau_{\text{eff}}(10^{15} \text{ n}_{\text{eq}}/\text{cm}^2) = 2 \text{ ns}$, $\lambda = 200 \text{ } \mu\text{m}$;
- $\tau_{\text{eff}}(10^{16} \text{ n}_{\text{eq}}/\text{cm}^2) = 0.2 \text{ ns}$, $\lambda = 20 \text{ } \mu\text{m}$.

In a $300 \text{ } \mu\text{m}$ thick silicon detector the charge loss due to trapping after a fluence of $10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ is of the order of a few percent, but at fluences around $10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ the loss becomes significant (few 10 %), since trapping times become too short for the charge to travel through an entire $300 \text{ } \mu\text{m}$ thick detector. At extremely high fluences $\Phi_{\text{eq}} \gg 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$ charge carriers only drift a few $10 \text{ } \mu\text{m}$ before getting trapped, making it very challenging to achieve a good S/N .

4.2.4 Changes of effective doping concentration

Deep levels act as acceptors or donors and change the effective space charge of the material: $|N_{\text{eff}}| = |N_A - N_D|$, where N_A and N_D are concentrations of charged shallow and deep states acting as acceptors and donors. Typically the majority of radiation induced defects create acceptor-like states (for example $V + V + O \rightarrow V_2O$), leading to net increase of N_A [38]. According to Eq. 3.8 higher N_{eff} results in a higher depletion voltage or conversely less depletion at a given voltage. This is problematic, as the full depletion voltage may not be achievable due to electrical breakdown, while a smaller depletion zone reduces the S/N ratio and hence degrades the detector performance.

In addition to creation of new acceptor states, shallow donor states in n-type material get deactivated ($P + V \rightarrow VP$), reducing N_D [67]. n-type material may therefore convert into p-type, undergoing a so called *type inversion*. n-in-n sensors exploit type inversion to prolong sensor lifetime, as N_{eff} initially reduces and the sensor can be fully depleted at lower voltages for a longer time.

The change of effective space charge $\Delta N_{\text{eff}}(\Phi_{\text{eq}}, t, T) = N_{\text{eff}} - N_{\text{eff},0}$ also depends on annealing history of the sample, with the behaviour parametrised by so called Hamburg model [58, 63]:

$$\Delta N_{\text{eff}}(\Phi_{\text{eq}}, t, T) = N_C(\Phi_{\text{eq}}) + N_A(\Phi_{\text{eq}}, t, T) + N_Y(\Phi_{\text{eq}}, t, T) \quad (4.4)$$

The first contribution $N_C(\Phi_{\text{eq}}) = N_{C0}(1 - \exp(-c_D\Phi_{\text{eq}})) + g_C\Phi_{\text{eq}}$ is the *stable damage*, which does not anneal. In n-type material it can be described as an incomplete donor removal (exponential term) accompanied with acceptor creation with an introduction rate g_C (in p-type material donor removal is replaced by acceptor removal). *Short term* or *beneficial annealing* $N_A(\Phi_{\text{eq}}, t, T)$ describes initial reduction of N_{eff} which caps after 10 days at room temperature, followed by the undesired *reverse annealing* $N_Y(\Phi_{\text{eq}}, t, T)$, when N_{eff} starts to increase again and can even exceed stable damage. In laboratory the annealing process can be quickened by heating up the sample. An equivalent of beneficial annealing (10 days at room temperature) can be achieved by storing the detector at 60° C for 80 minutes – this is the so called *standard annealing*.

The stable damage introduction rate g_C depends on particle type and impurity concentrations (C and O) in the material and is normally measured after standard annealing. The stable damage introduction rate with neutrons is $g_C \approx 0.02 \text{ cm}^{-1}$ with a 10 % spread depending on the material [66]. For charged hadrons this value

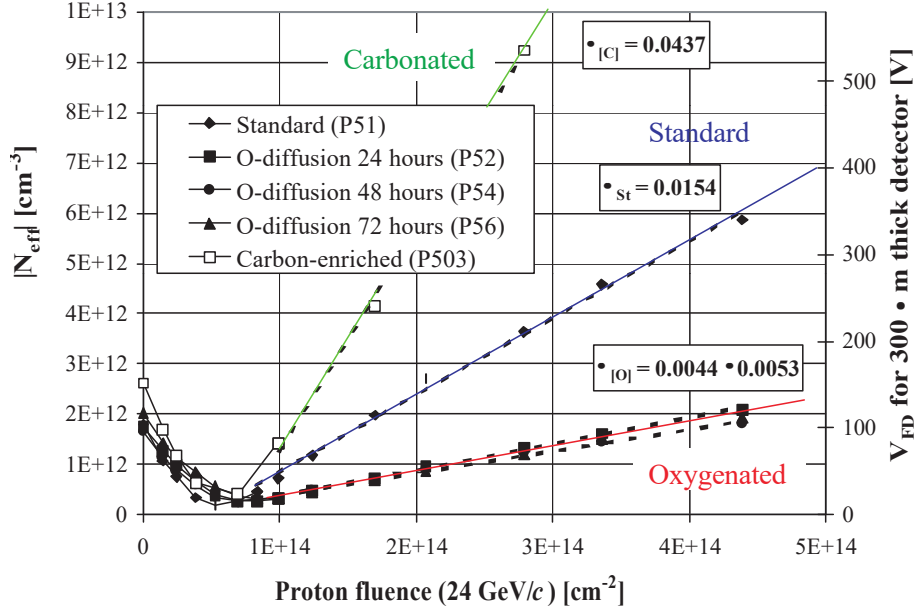


Figure 4.4: Increase of N_{eff} for different materials after proton irradiation. N_{eff} increases more slowly in oxygen rich material and faster in carbonated silicon. Diagram taken from [38] after [63].

can be up to a factor 3 lower in oxygen rich material (Figure 4.4). On the other hand high carbon concentrations increase the acceptor introduction rate [63]. Although more space charge is introduced with irradiation, the ohmic resistivity of irradiated silicon increases because the Fermi level shifts to the middle of the band gap and less free charge carriers are available.

Charge state of radiation induced localized energy levels depend also on temperature and on leakage current. Especially at higher fluences the approximation with uniform space charge is not sufficient to describe the behaviour of irradiated detectors. Trapping of thermally generated charge carriers may lead to change of sign of space charge in a part of the detector – phenomenon also known as *double junction effect* [68]. This is a state with two depletion zones in the sensor – one on the front and one on the back side – with a low electric field in the middle. Double junction is a consequence of trapping of thermally generated charge carriers (leakage current) in the vicinity of their corresponding electrode where their concentration is the highest. The trapped charge locally changes N_{eff} which leads to a local type inversion of the material. Hence, two p-n junctions develop in the material. Double junction is an unwanted effect, as the weighting field at the back side is small and does not significantly contribute to signal, while it reduces the available electric field in the front side of the sensor.

4.2.5 Acceptor removal

Acceptor removal is an important topic in development of advanced silicon detectors using p-type substrate [66, 69, 70, 71]. Analogically to removal of donors, acceptor removal describes electrical deactivation of initial shallow acceptors in the material by irradiation, leading to a reduced N_{eff} [67]. It has recently been established that the relative removal rate depends on initial doping concentration, with higher doped materials undergoing a slower removal, as well as on particle type, with charged hadrons removing the initial acceptors faster.

In standard n-type silicon ($\rho \sim 3\text{--}20\text{ k}\Omega\text{ cm}$) used for n-in-n detectors the initial removal process is finished and radiation induced space charge concentration exceeds the initial concentration already at low fluences below $10^{13}\text{ n}_{\text{eq}}/\text{cm}^2$. Meanwhile, HV-CMOS detectors use intermediate resistivity p-type wafers ($\rho \approx 10\text{--}3000\text{ }\Omega\text{ cm}$), where space charge concentration is reducing up to fluences comparable to the total expected fluence at HL-LHC ($10^{14}\text{--}10^{15}\text{ n}_{\text{eq}}/\text{cm}^2$). In this case the beneficial effects of reduced N_{eff} are present for most of the detector lifetime [72]. Acceptor removal is also a critical topic in LGAD¹ detectors used in timing applications, which rely on charge multiplication in a highly doped p^+ layer. These detectors are sensitive to acceptor removal in the multiplication layer, which causes a lower gain and consequently worse timing resolution [73, 74].

Acceptor removal mechanism

The dependence of active initial acceptor concentration on fluence is usually described by exponentially decaying term with a *removal coefficient* c . The stable damage therefore consists of three terms – the initial concentration $N_{\text{eff},0}$, the removal of initial acceptors and generation of deep acceptors:

$$N_{\text{eff}} = N_{\text{eff},0}(1 - N_c/N_{\text{eff},0} \cdot (1 - e^{-c\Phi_{\text{eq}}})) + g_C\Phi_{\text{eq}}. \quad (4.5)$$

The factor $N_c/N_{\text{eff},0} \in [0, 1]$ is introduced to take into account different materials with varying fraction of acceptors that get removed, describing either a partial ($N_c/N_{\text{eff},0} < 1$) or a complete removal ($N_c/N_{\text{eff},0} \approx 1$).

On microscopic level the source of acceptor removal is interaction of substitutional boron B_s with interstitial silicon atoms $B_s + I \rightarrow B_i$ (vacancy interaction $B_s + V \rightarrow VB$ generates a complex which anneals out at 0°C and plays no role).

¹Low gain avalanche detector

The boron interstitial B_i is highly reactive and forms complexes with other impurities [67, 75, 76]:

- B_iO_i – donor in the upper part of band gap;
- B_iB_sH – acceptor in the lower part of band gap;
- electrically neutral defects.

The net outcome after the above processes is electrically neutralised boron atom. Defects acting as donors contribute a negative space charge, which further enhances the effective removal rate. Conversely, acceptor-like complexes result in an incomplete removal.

Acceptor removal rate depends on the concentration of silicon interstitials, which can also participate in concurrent reactions:

- $I + C_s \rightarrow C_i$ – reduces the interstitial concentration;
- $V + O \rightarrow VO$ – increases the interstitial concentration due to less recombination ($I + V \rightarrow Si_s$ is suppressed by absent V).

The removal rate is hence higher in oxygen rich material and lower in carbon rich material.

Dependence of removal coefficient on $N_{\text{eff},0}$

Recent measurements with CMOS and LGAD detectors have indicated that in materials with a higher initial doping concentration a higher fluence is required to complete the acceptor removal. This can be explained by the fact that every incoming particle can only remove a finite number of initial acceptors. In the limit of high doping concentrations with abundant acceptors the number of removed acceptors after a given fluence is therefore constant irrespective of the actual acceptor concentration, i.e. the fluence required to remove a given fraction of initial acceptors increases in a higher doped material. This implies that acceptor concentration reduces linearly with fluence and not exponentially as presented in Equation 4.5, however the description with an exponential decay has been well established and is usually a sufficient approximation of the behaviour. In materials with a low acceptor density the number of removed acceptors per incoming particle is smaller, since the probability for interstitials to be in sufficient proximity for interaction with relatively scarce acceptor atoms is reduced. This results in a slightly modified acceptor removal regime with a reduced absolute removal rate.

The above behaviour has been parametrised by a first order model explaining the measured acceptor removal in LGAD detectors [77]. Acceptor removal is treated as a two step process consisting of silicon interstitial generation by irradiation (Φ) and displacement of substitutional boron:

1. $\text{Si}_s + \Phi \rightarrow \text{I}$ with a constant interstitial generation rate;
2. $\text{I} + \text{B}_s \rightarrow \text{B}_i$ with the rate depending on boron concentration N_A .

Once boron is displaced it is considered removed. The removal rate can be governed by either of the two reactions. In materials with high boron abundance the absolute removal rate is limited by interstitial generation and is independent of N_A , while in materials with low N_A the bottleneck is the probability of boron interaction.

In the high density regime with N_A sufficiently high that every interstitial has equal probability to remove an acceptor, the removal rate is

$$\frac{dN_A}{d\Phi} = -N_{\text{Si}} \cdot \sigma_{\text{acc}} = \text{const.} \quad (4.6)$$

with $N_{\text{Si}} = 5 \cdot 10^{22} \text{ cm}^{-3}$ the concentration of silicon atoms in the crystal and σ_{acc} the effective cross section to deactivate an acceptor. According to the two step process described above, this cross section can be parametrised as

$$\sigma_{\text{acc}} = k_{\text{cap}} \cdot N_{\text{Int}} \cdot \sigma_{\text{Si}}, \quad (4.7)$$

with N_{Int} the number of interstitials generated in the scattering, σ_{Si} the cross section of radiation with silicon and k_{cap} the probability for interstitial reaction with an acceptor. The value of k_{cap} encompasses the effects of different impurities (carbon, oxygen, ...) that might intercept the interstitial before it reaches an acceptor, as well as the spatial distribution of interstitials which differs for charged hadrons and neutrons. The initial acceptor concentration N_A^{init} reduces linearly with fluence:

$$N_A = N_A^{\text{init}} - N_{\text{Si}} \cdot \sigma_{\text{acc}} \cdot \Phi. \quad (4.8)$$

The above dependence holds until the low density regime is reached. This model can be linked with Eq. 4.5, which describes the removal by an exponential decay $N_A = N_A^{\text{init}} e^{-c\Phi}$, by introducing a characteristic fluence $\Phi_0(N_A^{\text{init}}) = 1/c$ after which the acceptor concentration drops by a factor e :

$$N_A^{\text{init}} \cdot e^{-1} = N_A^{\text{init}} - N_{\text{Si}} \cdot \sigma_{\text{acc}} \cdot \Phi_0, \quad (4.9)$$

or equivalently

$$\Phi_0 = 1/c = \frac{1 - e^{-1}}{N_{\text{Si}} \cdot \sigma_{\text{acc}}} N_{\text{A}}^{\text{init}}. \quad (4.10)$$

This parametrisation explains smaller removal coefficients c for higher initial doping concentrations. The value of $\sigma_{\text{acc}} = 8.3 \cdot 10^{-22} \text{ cm}^2$ was obtained from a fit of Eq. 4.10 to data with high $N_{\text{A}}^{\text{init}}$ [77].

In the low density regime the probability for the $\text{I} + \text{B}_{\text{s}} \rightarrow \text{B}_{\text{i}}$ process is reduced and depends on the boron concentration. In principle the calculation of the removal rate has to be done differentially, however measurements indicate a non trivial dependence on N_{A} which would require additional assumptions. The behaviour is instead modelled by introducing an effective low density correction to the high density regime (Eq. 4.10) in form of the *proximity function* $D(N_{\text{A}}^{\text{init}})$, so that:

$$\Phi_0 = \frac{1 - e^{-1}}{N_{\text{Si}} \cdot \sigma_{\text{acc}} \cdot D(N_{\text{A}}^{\text{init}})} N_{\text{A}}^{\text{init}}. \quad (4.11)$$

Let a parameter N_0 be the boron concentration at the transition point between low and high density regimes. The proximity function has to have the following limit behaviour: $D(N_{\text{A}}^{\text{init}} \gg N_0) = 1$ and $D(N_{\text{A}}^{\text{init}} \ll N_0) = 0$; which can be described by the ansatz:

$$D_n = \frac{1}{1 + (N_0/N_{\text{A}}^{\text{init}})^{n/3}}, \quad (4.12)$$

where $n \in \mathbb{N}$ is the *proximity factor* defining the behaviour of the low density regime. The values of N_0 and n were determined from the fit of the function 4.11 to measured values of Φ_0 in the doping range $N_{\text{A}}^{\text{init}} = 10^{12}$ – 10^{18} cm^{-3} (Figure 4.5), yielding $n = 2$ and $N_0 = 2.5 \cdot 10^{16} \text{ cm}^{-3}$ [77].

The most intuitive selection of the proximity factor would be $n = 3$, which describes a low density regime with $\frac{dN_{\text{A}}}{d\Phi} \propto -N_{\text{A}}$ and a constant removal coefficient. With the actual proximity factor $n = 2$ the removal is faster, as indicated in Figure 4.5. The reason for this might be that the removed boron forms the donor-like B_iO_i complex which further enhances the net removal effect (removal of acceptor and introduction of donor state) which especially affects low doped materials.

The presented acceptor removal model gives a good qualitative explanation for the value of the removal coefficient. However, the variation between different detector materials shows differences as high as a factor of 2–3 at the same $N_{\text{eff},0}$. Individual characterisation of each wafer type is therefore necessary for precise knowledge about the acceptor removal in a given detector. Summarising, the acceptor removal

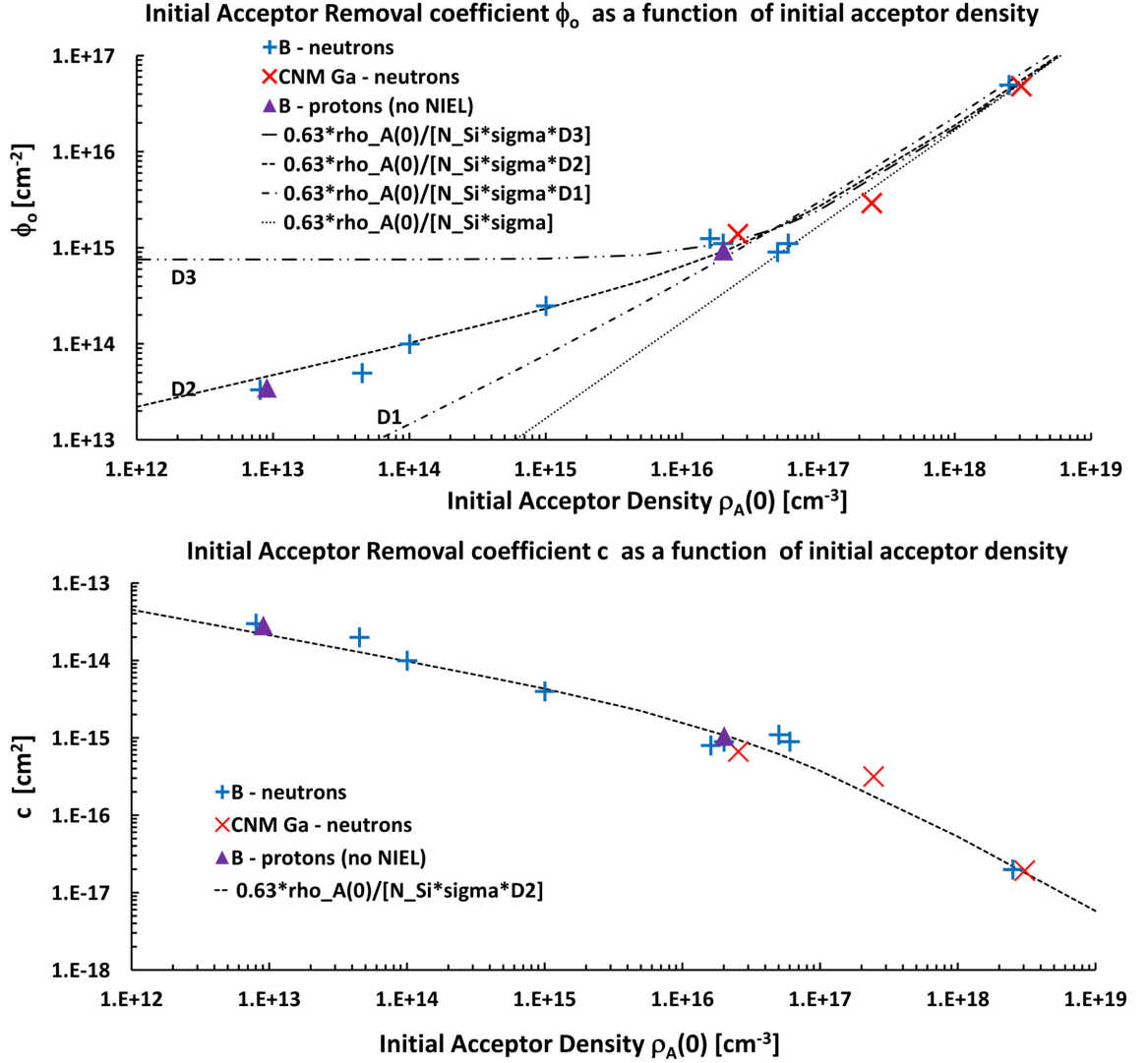


Figure 4.5: Fit of the acceptor removal model (Eq. 4.11) to measured removal coefficients with the proximity function D_n (Eq. 4.12) as a free parameter. Top diagram shows fit results for different proximity factors n , with $n = 2$ describing the data best. Data is obtained with LGAD samples: neutron irradiated material doped with boron (B-n) and gallium (Ga-n), and 24 GeV proton irradiated wafers with boron implants (B-p). Proton fluences are not normalised to Φ_{eq} but use the actual particle fluence instead (160 % of Φ_{eq}) [77].

coefficient can be estimated by the formula:

$$1/c = \Phi_0 = \frac{1 - e^{-1}}{N_{\text{Si}} \cdot \sigma_{\text{acc}}} \left(1 + \left(\frac{N_0}{N_{\text{A}}^{\text{init}}} \right)^{2/3} \right) \cdot N_{\text{A}}^{\text{init}} \quad (4.13)$$

$$N_{\text{Si}} = 5 \cdot 10^{22} \text{ cm}^{-3},$$

$$N_0 = 2.5 \cdot 10^{16} \text{ cm}^{-3},$$

$$\sigma_{\text{acc}} = 8.3 \cdot 10^{-22} \text{ cm}^2.$$

Chapter 5

DMAPS prototypes for ATLAS Phase-II upgrade

At the start of the ATLAS ITk CMOS project DMAPS was a relatively new detector technology. To explore advantages and disadvantages of different DMAPS architectures and establish the optimal detector design the R&D has been divided into several development lines, with prototype names listed below along with vendors offering the corresponding CMOS process:

- LFoundry MonoPix 150 nm – large electrode;
 - TowerJazz MALTA and MonoPix 180 nm – small electrode;
 - ams/TSI ATLASPix 180/350 nm – large electrode;
-
- ams CHESS 350 nm – large electrode, strip CMOS prototype;
 - X-FAB XTB 180 nm – large electrode SOI.

The original programme has been narrowed to the first three options listed above. The X-FAB programme was discontinued in favour of other designs after initial prototyping, while the ams CHESS was a prototype for the ATLAS strip CMOS project, which was not pursued beyond first two prototype chips. Each development line consists of several chips with gradually increasing complexity. Initial submissions typically only feature analogue active part and are equipped with many test structures for studies of individual detector properties. Later submissions contain fully working monolithic chips, although they still consist of several different pixel designs and are not yet final versions suitable for ITk.

The following chapter gives an overview of different development lines. Because of the large number of different chips that have been developed not all are described

in detail in this text. The focus is on the devices that were studied in the scope of this thesis. Other chips are also introduced briefly, while more details can be found in the accompanying references.

5.1 LFoundry 150 nm development line

The LFoundry (LF) 150 nm development line is focused on a HR-CMOS detector with a high initial substrate resistivity of $> 2 \text{ k}\Omega \text{ cm}$ and a large collection electrode. The design targets a high bias voltage of $\approx 250 \text{ V}$, allowing initial depletion depth to exceed $100 \mu\text{m}$. The following chips have been developed in the LFoundry line (Figure 5.1):

- CCPD_LF (2015) – prototype chip;
- LF-CPIX (2016) – demonstrator chip;
- LF-MonoPix01 (2017) – monolithic CMOS chip;

The CCPD_LF [78] is the first prototype based on a CCPD concept with an in-pixel analogue amplifier. The main part of the chip is an array of 24×114 active analogue pixels with quadruple well structure, while several passive diode arrays are also included for material studies. The LF-CPIX chip [79] is an upgraded version of CCPD_LF with improved analogue front end design and additional digital blocks. Both chips are designed for coupling with the ATLAS readout chip FE-I4 [80], either by bump bonding or by gluing.

The LF-MonoPix01 [81] is a fully monolithic chip with a size of $10 \text{ mm} \times 10 \text{ mm}$ based on the previous submissions. The chip uses a digital pixel readout based on column drain architecture, which is a conservative approach used in hybrid detectors with a proven and reliable performance. The pixel size is $250 \mu\text{m} \times 50 \mu\text{m}$ with a relatively large input capacitance of $\approx 400 \text{ fF}$. The minimal discriminator threshold which allows operation below the noise level of $10^{-6}/25 \text{ ns/pixel}$ is $2500 \text{ e}^- \pm 100 \text{ e}^-$ after in-pixel threshold tuning. The front end has a noise level of $190 \text{ e}^- \pm 10 \text{ e}^-$, and a power consumption of $\approx 400 \text{ mW/cm}^2$ [82, 83, 84]. The chip was demonstrated to maintain a good analogue front end performance after a TID of 50 MRad , and to achieve a detection efficiency of 98.9% after a neutron irradiation of $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ [85].

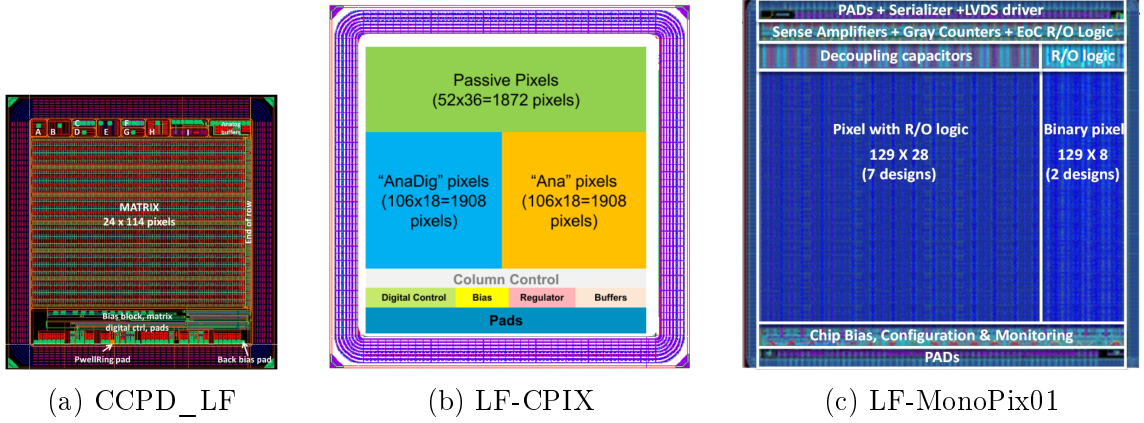


Figure 5.1: CMOS chips in LFoundry development line. a) CCPD_LF prototype chip; b) LF-CPIX demonstrator chip; c) LF-MonoPix01 monolithic CMOS chip. a) and b) are designed as CCPD to be coupled with a readout chip, while c) is fully monolithic. The sensors use a high initial resistivity substrate ($> 2 \text{ k}\Omega \text{ cm}$) and large collection electrode pixel architecture [78, 79, 81].

5.2 TowerJazz 180 nm development line

The TowerJazz (TJ) line is the only ATLAS development line adopting small collection electrode approach. Based on commercial imaging sensor technology, the TowerJazz line is evolved from the ALPIDE chip for ALICE tracking system upgrade [86, 87], adapted for the harsher radiation conditions in ATLAS. The sensitive sensor volume is a 25–30 μm thick epitaxial p-type layer with a high resistivity of $> 1 \text{ k}\Omega \text{ cm}$, which can be biased from the substrate side with relatively low negative voltage in the range of 6–20 V (Figure 5.2). Typical pixel size is below $50 \mu\text{m} \times 50 \mu\text{m}$ and the diameter of the collecting n-well is 2–3 μm which results in a minor pixel capacitance of only $\approx 3 \text{ ff}$, leading to low power, low noise front end designed for operation at a threshold of $300 \text{ e}^- \pm 10 \text{ e}^-$ at a noise occupancy of $10^{-8}/25 \text{ ns}$ per pixel and an ENC of 12 e^- [87, 88]. In-pixel electronics is implemented in a p-well separated from the collection electrode which can be biased with a negative bias voltage up to 6 V to channel electric field lines toward the collection electrode. In addition, n-wells with transistors are shielded by so called deep p-well implants to prevent parasitic charge collection.

A critical challenge for radiation hard devices with a small collection electrode design is depletion of the full pixel area, especially the pixel edges (see 3.5.1). It was proven that the original pixel design in the so called *standard process* shown in Figure 5.2a does not fulfill the radiation tolerance requirements of ATLAS [89, 90], prompting development of a process modification [91]. *Modified process* is based on implanting additional low doped planar n⁻-layer next to the collecting n-well

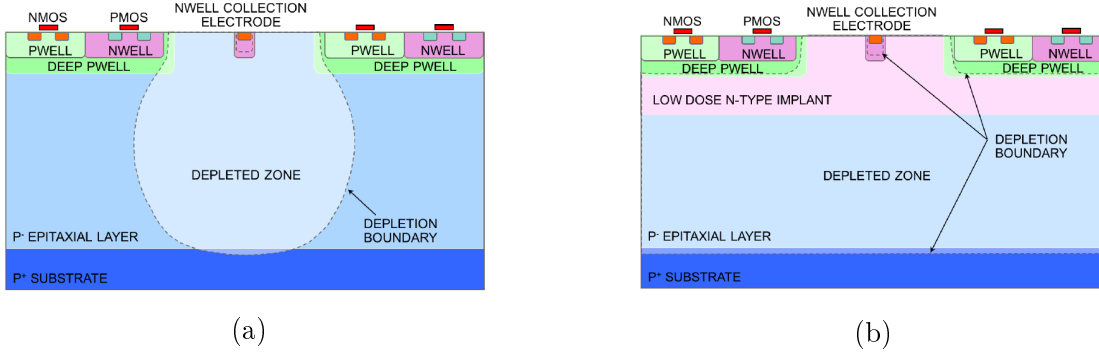


Figure 5.2: Schematics of a small collection electrode pixel produced in the Tower-Jazz process: a) standard process, which has a limited radiation hardness and timing resolution due to the sensor depletion not reaching pixel edges; b) process modification by an additional planar n^- -type layer, which enables simultaneous depletion of the entire pixel area, while maintaining low capacitance [91].

over the entire pixel area (Figure 5.2b). The location of the p-n junction is shifted to the n^- - p^- interface, therefore the entire pixel area is depleted simultaneously. Due to its low doping concentration the n^- layer gets totally depleted and does not significantly contribute to detector capacitance. Modified process shows a significant improvement of the radiation hardness and a faster charge collection, aligned with the ATLAS ITk requirements [89, 90]. The ATLAS programme consists of three chip generations:

- TJ Investigator (2015) – active analogue chip;
- TJ MALTA and TJ MonoPix (2018) – monolithic;
- TJ MiniMALTA (2019) – monolithic;

The Investigator chip is an analogue chip designed to evaluate optimal pixel geometry and consists of more than 250 different pixel designs [90, 92]. The monolithic implementation was made in two different chips, the TJ MALTA [88] and TJ MonoPix [82, 88], which share the same analogue front end design but pursue different readout approaches. TJ MonoPix employs a conservative column drain readout based on the readout of the LFoundry MonoPix chip, while TJ MALTA pursues a novel asynchronous readout architecture which targets a large reduction in power consumption. The TJ MiniMALTA is a smaller, improved version of TJ MALTA chip with improved sensor design and additional digital readout blocks [93].

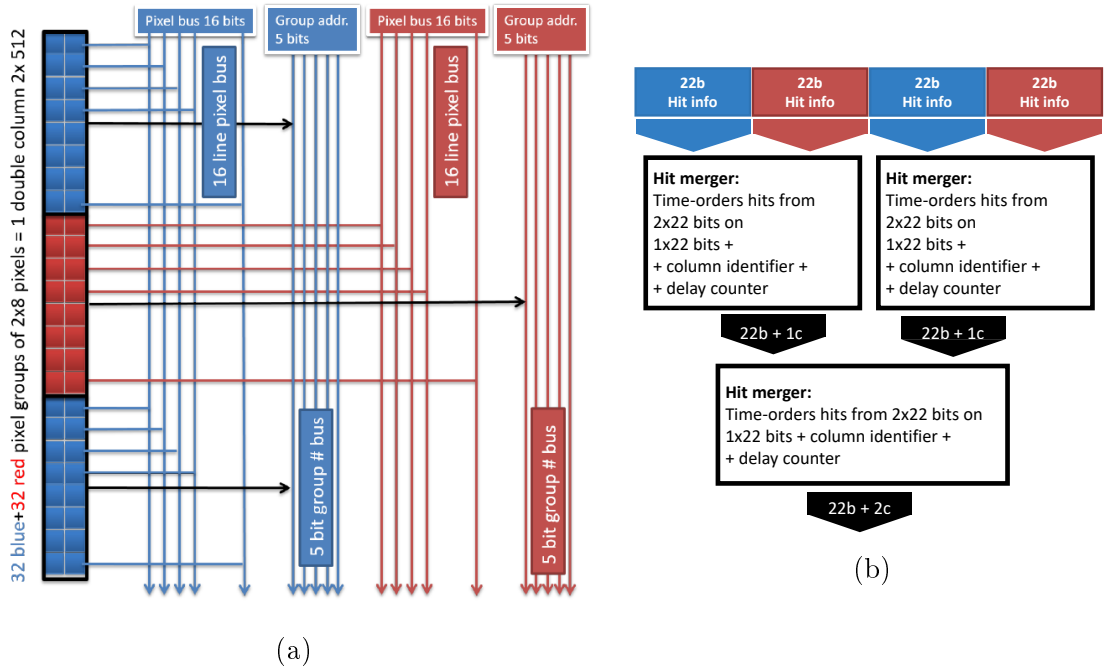


Figure 5.3: Asynchronous readout architecture in TJ MALTA. a) Double column readout: hit pixels in 2×8 pixel groups instantaneously output hit information on the shared data bus which is then propagated into chip periphery. The approach minimises power as it does not require digital clock signals. b) Hit merger logic: asynchronous signals simultaneously arriving into the end of column logic from different data buses are sorted into a sequence by the hit merger [88].

5.2.1 Asynchronous readout architecture in TJ MALTA

TJ MALTA employs a novel asynchronous pixel readout which does not require clock distribution into the pixel matrix [88]. This saves a large amount of power while also eliminating the possibility of the digital clock signal coupling into the analogue front end. Low power consumption means that installed cooling power can be lower, requiring less material and significantly reducing the impact of multiple scattering. Simulations of the digital part of the MALTA chip predict a power consumption of $\approx 10 \text{ mW/cm}^2$, compared to $\approx 100 \text{ mW/cm}^2$ in TJ MonoPix which uses a synchronous column drain architecture. The expected power consumption in the analogue part of both chips is $\approx 70 \text{ mW/cm}^2$.

The matrix in TJ MALTA is subdivided into double columns of 2×512 pixels, which act as independent readout units sending hit information into chip periphery for central processing. Each double column is arranged into groups of 2×8 pixels as shown in Figure 5.3a, which use a 22-bit wide parallel data bus to transmit data to periphery. Alternating pixel groups, indicated as Red and Blue in the schematics, share a common data bus in order to significantly reduce the number of required data lines. Alternation is necessary to correctly reconstruct hits shared between two groups and minimise the probability of two groups simultaneously accessing the data bus. Signals from hit pixels, consisting of 16 bits for the position of the pixel within a group, one reference bit which is active when any pixel in the group fires, and 5 bits for a static group address within the double column, are transmitted instantaneously (asynchronously) upon a hit. Short pulses with a programmable width of 0.5 ns–2 ns are essential to prevent overlapping of concurrent signals on the same data bus, which results in data collisions and corruption. The propagation time of signals through the data bus has a maximal latency of 7.5 ns which depends on the group position within the double column, with a given pixel group having a fixed delay that can be compensated for in the chip periphery.

Measurement of deposited charge in MALTA is based on the time-walk of the signals in the front end, exploiting the fact that of two signals with the same shape, the higher signal will cross a fixed threshold sooner than the lower one. The signal height can be inferred by measuring the delay of the asynchronous pulse, corrected for the propagation delay in the double column, relative to an external reference signal marking the time of arrival (for example bunch crossing signal in LHC). In the LHC conditions the time walk of the lowest triggerred signals shall not exceed 25 ns in order to assign the event to the correct bunch crossing. Measurements show that a minimal threshold that guarantees such in-time operation in MALTA

is $\approx 300\text{ e}^-$.

The circuit in the chip periphery merges signals from all data columns onto a common bus. An arbitration circuit called *hit merger* is used to time-sort hits arriving on different data buses simultaneously in order to prevent data collisions which corrupt the data (Figure 5.3b). In this case one signal is processed normally, while the rest is delayed. The process is repeated on up to 10 levels until all of the signals have been processed, keeping track of the delays by dedicated delay bits. Additionally, double column address bits and time stamp information are added to hit data to correctly identify the event in the reconstruction. The final data is formed into a 40-bit word which is asynchronously transmitted off the chip on a 40-bit wide LVDS bus, allowing data rates up to 5 Gb/s.

5.3 ams/TSI 180/350 nm development line – pixel

The high voltage (HV) CMOS processes offered by ams have been developed for automotive and industrial applications, where HV denotes any voltage level significantly above typical supply voltages in integrated circuits. Detectors produced in the ams 350 nm process in 2007 have been the first application of HV-CMOS technology for particle physics [49]. The ams/TSI development line pursues a large collection electrode design implemented in the following chips:

- CCPDv4 (2015) – prototype;
- H35Demo (2017) – demonstrator chip;
- ATLASpix1 (2017) – monolithic;

The H35Demo has been produced in ams H35 350 nm CMOS process, while the CCPDv4 and ATLASpix1 have been produced in a 180 nm CMOS process. The original foundry ams stopped accepting submissions for HEP after the first version of the ATLASpix1 had been produced. The chip manufacturing was afterwards transferred to the TSI foundry, which uses a compatible 180 nm CMOS process. The standard substrate resistivity in this technology is $20\ \Omega\text{ cm}$, but chips were also produced on higher resistivity substrates of $50\ \Omega\text{ cm}$, $200\ \Omega\text{ cm}$ and $1000\ \Omega\text{ cm}$ in order to achieve larger depletion depths. The samples can be biased with a bias voltage up to 120 V. Tests with the H35Demo chip have been carried out for example in [94]. The monolithic ATLASpix1 has been proven to have a high hit detection efficiency of $> 99\%$ after a neutron irradiation of $1 \cdot 10^{15}\text{ n}_{\text{eq}}/\text{cm}^2$ and a timing resolution of $< 10\text{ ns}$ [95].

5.4 ams 350 nm development line – strip

ATLAS also investigated the possibility of using active strip sensors in the ITk and carried out an evaluation programme which resulted in three prototype chips: HVStrip1, CHESS1¹ and CHESS2. The chips were manufactured in the ams H35 350 nm CMOS process (the same process as used for production of the ams H35Demo pixel chip). Chips were produced on wafers with a standard resistivity of $20\,\Omega\,\text{cm}$, while CHESS2 was also produced on 50, 200 and $1000\,\Omega\,\text{cm}$ substrate. All chips can be biased from the bias rings on the top and allow bias voltages up to $\approx 100\,\text{V}$.

The HVStrip1 and CHESS1 are small chips intended for testing of individual devices on analogue level. They contain several passive test structures, NMOS and PMOS transistors for testing, and small analogue active pixel arrays [96, 97, 98]. The second generation CHESS2 chip is a full reticle size ($18.6\,\text{mm} \times 24.3\,\text{mm}$) for investigations of the readout architecture options in this technology [99]. The chip has a thickness of $250\,\mu\text{m}$ and consists of several triplet arrays with a full digital encoding and readout, test structures for data transmission and multiple passive pixel arrays for material studies. Unfortunately, the active functionality of the CHESS2 chip is compromised by issues in the design. Nevertheless, passive devices can still be characterised and allow comparison to the results with the H35Demo chip.

5.5 X-FAB 180 nm development line

The X-FAB development line studied the performance of SOI sensors produced in the X-FAB 180 nm SOI CMOS process using thick-film SOI technology which makes the electronics resistant to the back gate effect (Chapter 3.5.2). The design allows high bias voltages of up to $300\,\text{V}$ (HV-SOI). Two prototype chips were produced on a $100\,\Omega\,\text{cm}$ p-type silicon substrate in the X-FAB process: the XTB01 and XTB02 [52, 100].

The XTB01 is an active analogue chip designed to investigate the feasibility of the HV-SOI technology for particle detection. The main part of the chip are four independent active pixel matrices with a standardised 3-transistor readout scheme [48]. Testing has demonstrated radiation hardness of the design up to a total ionising dose of $700\,\text{MRad}$ [101, 102], while good charge collection results have been acquired in source and test beam measurements with unirradiated and lightly irradiated ($5 \cdot$

¹CHESS: "CMOS HV/HR Evaluation for Strip Sensors"

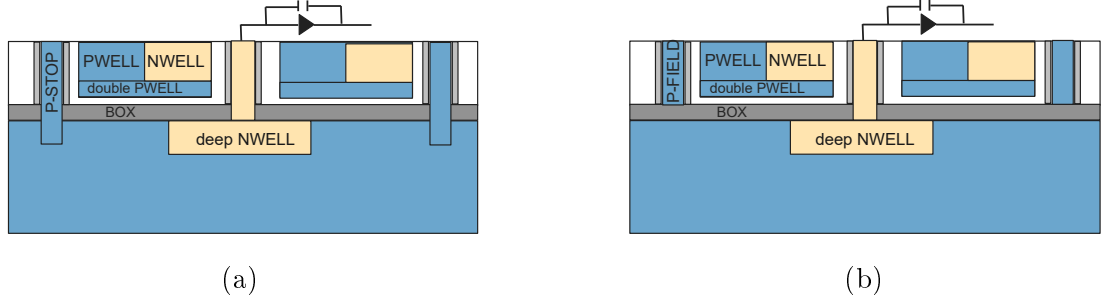


Figure 5.4: Pixel design in the XTB02 chip. The deep n-well collects charge and has to be connected to an external amplifier. The surface layer does not contain transistors but can be nevertheless biased to provide realistic electric fields. The p-stop (a) and p-field (b) implants interrupt a conductive channel which forms under the BOX after irradiation [100].

$10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$ neutrons) chips [100, 102, 103]. The tests revealed an issue with a high leakage current and an early electrical breakdown of irradiated chips, caused by creation of a conductive channel under the BOX due to space charge accumulation on the BOX after TID irradiation.

The subsequently designed XTB02 is intended exclusively for tests of charge collection in the sensor and is a purely passive chip. It consists of several diode structures including pixel matrices with different pixel sizes. The CMOS layer above the BOX does not house any transistors, hence the pixel implants act as normal diodes and have to be connected to an external amplifier. To prevent high leakage current observed in irradiated XTB01 the XTB02 features additional implants called p-stop or p-field, depending on the test structure, which interrupt the conductive channel under the BOX (Figure 5.4). This reduces leakage current after irradiation by a factor 80 compared to XTB01 [100].

Chapter 6

Laboratory setups for charge collection measurements

Good sensor performance after irradiation is one of the vital requirements for particle detectors at colliders, therefore verification of charge collection in prototypes is necessary before the main production. The standard high resistivity ($> 10 \text{ k}\Omega \text{ cm}$) n-type substrate used in hybrid detectors has a known behaviour after irradiation. However, DMAPS tend to use commercially easier available intermediate resistive ($10 \Omega \text{ cm} - 3 \text{ k}\Omega \text{ cm}$) p-type wafers, whose properties after irradiation have not been so well studied in HEP applications. Moreover, pixel structures characteristic for DMAPS, such as nested wells, BOX layer or different collection electrode sizes, may also impact charge collection and these effects have to be investigated. Combined with numerous DMAPS designs, the studies of charge collection are a broad and important topic in the development of these devices.

In this thesis two measurement methods were used to evaluate charge collection in the substrate and characterise the effects of NIEL damage. The *transient current technique* (TCT) uses pulsed laser light to inject charge into the substrate. Focusing the light spot to a sub-pixel dimension allows studies of positional sensitivity of the sensor. One of the most commonly used techniques is Edge-TCT where the laser beam is directed on the thin edge of the detector. This enables measurements of the sensor response to charge generated at different depths and provides information on the size of the depletion region, as well as response uniformity. Laser intensity is tunable, but it is not calibrated and it is set to get clear signals well above the noise level with a wide band amplifier. To achieve this laser pulse typically generates charge several times larger than passage of a MIP.

The second method applied in this thesis is the measurement of collected charge deposited by MIP-like β particles from a ^{90}Sr radioactive source. An appropriate trigger configuration allows selection of events with MIP-like charge deposition, whose signal spectra correspond to those at colliders. However, the method lacks spatial resolution and can be complemented by TCT measurements for more information. The relatively short turnaround time of TCT and ^{90}Sr measurements compared to test beam allows studies with many differently irradiated samples covering the entire fluence range for the given detectors. This chapter describes the instrumentation setups, data acquisition and analysis with these two measurement methods.

6.1 TCT – Transient current technique

The transient current technique (TCT) uses short laser pulses with a duration of several hundred picoseconds to generate free charge carriers in the sensor [104, 105, 106]. The transient signal from the drifting charge can be recorded and allows studies of the signal formation, charge collection, carrier drift velocity and trapping mechanisms in the detector. The absorption coefficient of light in silicon is strongly dependent on the wavelength λ (Figure 6.1). The band gap in silicon is 1.12 eV (corresponding to $\lambda = 1100\text{ nm}$), therefore visible light is absorbed much more than infrared. A few examples of absorption depths d for different wavelengths are:

- Blue light ($\lambda = 400\text{ nm}$): $d = 0.1\text{ }\mu\text{m}$;
- Red light ($\lambda = 660\text{ nm}$): $d = 5\text{ }\mu\text{m}$;
- Infrared light ($\lambda = 1064\text{ nm}$): $d = 1000\text{ }\mu\text{m}$.

Different wavelengths can be used to inject charge into different parts of the sensor. Blue light can probe only the very surface part of the sensor. Red light deposits energy similarly to an alpha particle close to the entry point which is useful to study the drift of a single carrier type – electrons or holes – depending on which side of the sensor the charge is injected. Meanwhile, infrared light behaves similarly to a MIP particle (discounting attenuation) and deposits charge along the intersection of the optical axis with the sensor.

With regard to the orientation of the light source TCT measurements can be done in two ways (Figure 6.2):

- **Surface-TCT** with the laser beam oriented perpendicularly to the sensor surface. The method is also called *Top-TCT*. Schematics 6.2a shows the simplest

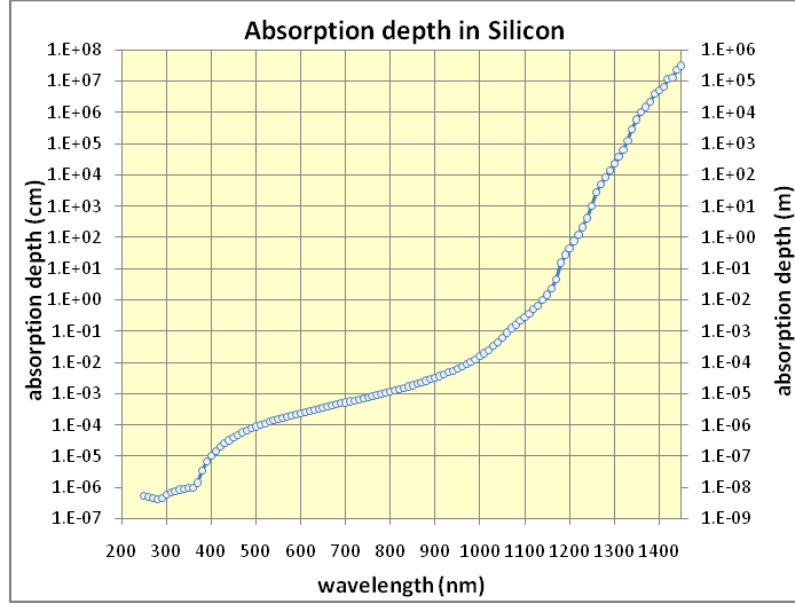


Figure 6.1: Absorption depth of light in silicon [107].

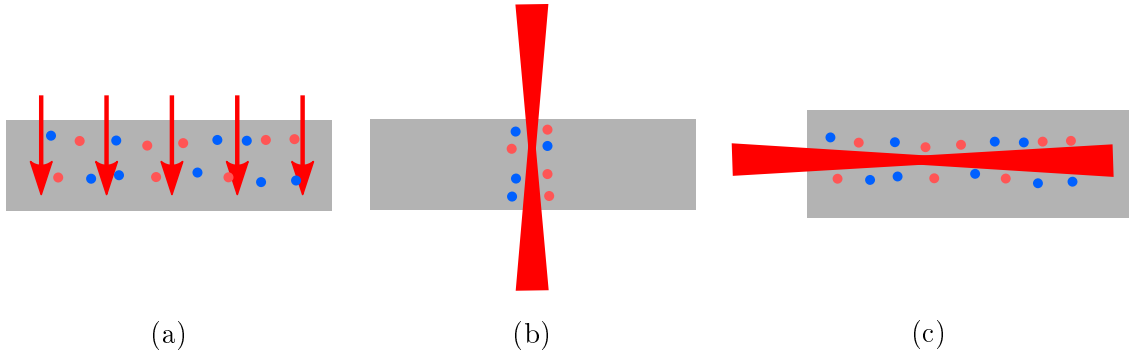
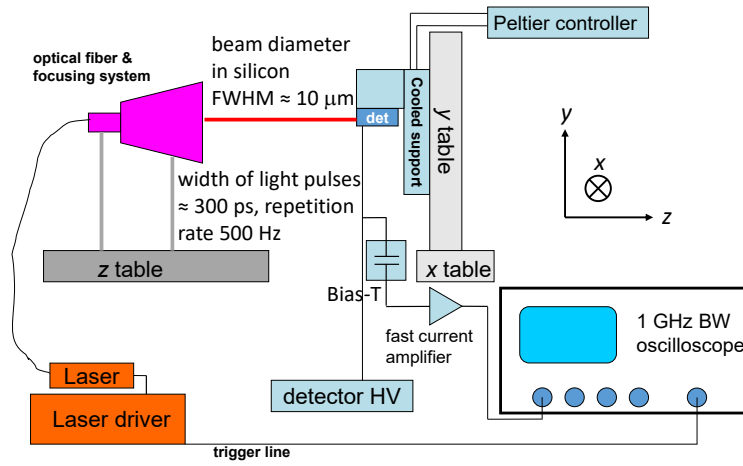


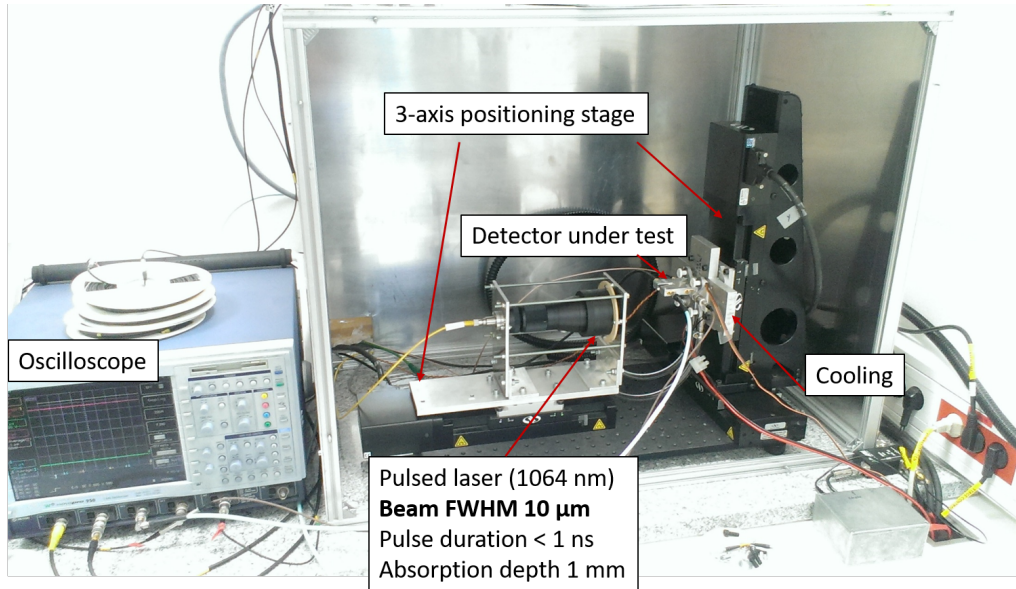
Figure 6.2: Different TCT techniques: a) Top-TCT with uniform illumination; b) Top-TCT with a focused beam, providing position sensitivity; c) Edge-TCT with a focused beam, providing position sensitivity along the sensor depth.

Top-TCT option without any laser focusing. Top-TCT with a focused beam, shown in Figure 6.2b, can be used to measure position dependence of the detector response. Top-TCT measurements are often done with a red laser (absorption depth of few μm), but infrared light can also be used.

- **Edge-TCT** is a method that has been developed in recent years [108, 109]. Focused laser light with a large penetration depth (IR) enters the sensor through the edge, parallel to sensor surface (Figure 6.2c). In this case all e-h pairs are generated at the same depth in the sensor, allowing measurements of charge collection and drift velocity as a function of depth. More details are explained below. Edge-TCT method was the predominantly used TCT method in this thesis.



(a)



(b)

Figure 6.3: TCT measurement setup.

6.1.1 TCT setup

Schematics of the TCT measurement system and a photograph of the setup used in this work are shown in Figures 6.3a and 6.3b. Similar systems produced by Particulars [110] have been used as well and have the same functionality as the presented setup. The sample is mounted on a carrier board which can be oriented either in Top or Edge-TCT position. The carrier is mounted on a support equipped with a Peltier couple which can cool the sample to temperatures below -10°C . The position of the sample in the laser beam is adjusted by positioning stages in three dimensions with a sub-micrometer precision.

The light beam is generated by a laser diode which produces light pulses with a duration of ≈ 300 ps, repetition rate of a few 100 Hz and adjustable intensity which varies by $< 1\%$ during measurements. The light is guided through a single mode optical fibre to an optical system which focuses the beam to a Gaussian shape with a minimal spot size of $\approx 10\text{ }\mu\text{m}$ FWHM¹ and a divergence of $\approx 2^\circ$. The relative light intensity can optionally be monitored by splitting the beam with a semi-permeable mirror and measuring the charge generated by the reflected beam on a photodiode. The laser intensity has to be kept low to avoid the so called plasma effect, which occurs when the amount of injected charge is so high that it significantly distorts the electric field in the sensor, causing deformed signals.

In the simplest case the investigated detector is a passive diode with two electrical contacts. The sensor back side is usually connected to ground potential, while the front side is biased with high voltage (HV). Induced current is measured on the detector front side, where it is superimposed on a HV baseline. The signal line connected to the amplifier input is capacitively decoupled from the high voltage DC component using a "bias-T" element. In case of active detectors the electrical connections are different, as additional low voltage levels are required for supplying the electronics. Since the potential difference between the sensor front side and the low voltage usually cannot exceed a few volts, the front side has to be biased close to the ground potential, while the HV is applied from the back. In this case the bias-T is not strictly necessary.

Signals are amplified with a high bandwidth (1 GHz) current amplifier and recorded by an oscilloscope with an analogue bandwidth of > 700 MHz and a sampling rate of > 5 GS/s (DRS4 [111] or similar). The signals are averaged over 100 pulse repetitions for every acquisition to reduce the noise. The stage movement and data acquisition are controlled by Labview software running on a control PC, allowing automated measurements scanning over different sample positions and bias voltages.

The setup uses a 3-dimensional Cartesian coordinate system with the axes selected as indicated in Figure 6.3a. The xy -axes are defined in the plane perpendicular to the optical axis. In Edge-TCT mounting convention is that the x -axis is oriented along the edge of the sample, parallel to sensor surface, while y -axis is oriented perpendicular to the sensor surface along the sensor depth. The z -axis is oriented along the optical axis of the system.

¹FWHM – Full width at half maximum. $\text{FWHM} = 2.35\sigma$ in a Gaussian distribution.

6.1.2 TCT method and analysis

The underlying equation describing signal formation in silicon detectors is the Shockley-Ramo theorem (see Section 3.3) which describes the induced current on an electrode as a sum of the contributions I_e and I_h of drifting electrons and holes in a weighting field:

$$I_{e,h}(t) = e_0 \cdot N_{e,h} \cdot e^{-t/\tau_{e,h}} \cdot \vec{v}_{e,h}(\vec{r}, t) \cdot \vec{E}_w(\vec{r}), \quad (6.1)$$

where trapping of charge carriers is also taken into account by introducing the effective trapping time $\tau_{e,h}$. In undepleted volume the velocity of charge carriers is $v \approx 0$ due to the slow diffusion transport and, in addition, in irradiated detectors these charge carriers recombine almost immediately. Consequently, charge generated in the undepleted region induces no current and does not contribute to the observed signal. In Edge-TCT this behaviour can be used to estimate the size of the depletion zone.

Figure 6.4 shows an example of an Edge-TCT measurement made with a pixel detector. Induced pulses after charge injection at different distances y from the sensor surface are shown in Figure 6.4a. Induced current is the highest when the charge carriers drift in a large electric and weighting field close to the pixel. At larger injection depths the charge carriers reach this region later, hence the signal peak is delayed. The last waveform measured at injection depth of $y = 180 \mu\text{m}$ does not show a distinguishable pulse, indicating that the material at this depth is undepleted. Charge collected by the electrode is the integral of the induced current:

$$q = \int_0^{t_{\text{int}}} I(t) dt. \quad (6.2)$$

The most commonly used integration time in ATLAS applications is $t_{\text{int}} = 25 \text{ ns}$, defined by the LHC bunch crossing time. Sometimes shorter integration times can also be selected to reduce noise, when induced pulses are appropriately short (in Figure 6.4a $t_{\text{int}} = 10 \text{ ns}$ was used). Figure 6.4b shows collected charge as a function of injection depth for different bias voltages. As for each laser pulse charge carriers are generated at the same depth in the detector the depletion depth can be simply determined from the width of the region that produces observable signals. On the surface side located at $y = 0$ of laser scan in y -direction the edge of the charge collection profile has a width of $10\text{--}20 \mu\text{m}$ which reflects the finite beam diameter. At a fixed bias voltage the collected charge is nearly constant as long as the injection point is well within the depleted region. As the injection point moves towards the end of the depleted region the collected charge gradually starts to reduce. This

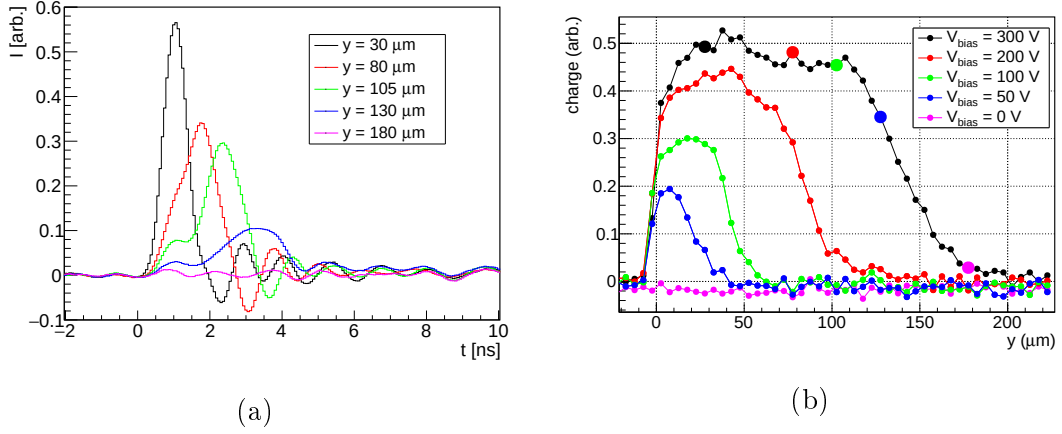


Figure 6.4: Example of Edge-TCT measurements with a partially depleted pixel device: a) induced current pulses depending on the injection depth. Charge injection occurs at $t = 0$. Oscillations come from non matching impedances of the input line and the amplifier; b) collected charge (integrated induced current) at different bias voltages, providing information on depletion depth. Emphasised coloured spots indicate the points where pulses shown in a) were measured. Detector surface is at $y = 0 \mu\text{m}$.

is a consequence of the electric field strength reducing with the distance from the electrode. In addition the slope is reduced due to the finite beam diameter. Because of this the depleted depth cannot be unambiguously defined. In this thesis the depleted depth is by convention measured as the full width at half maximum (FWHM) of the charge collection profile.

Edge-TCT is also well suited for two dimensional scans in xy directions, which reveal regions with high and low charge collection efficiency within the pixel. More examples are given in next chapter. Another quantity which may be estimated with Edge-TCT, although not extensively used in this thesis, is determination of the charge carrier velocity in heavily irradiated detectors. Since all charge carriers are generated at the same depth, the velocity at this depth can be extracted from the induced current using Shockley-Ramo theorem. Immediately after injection trapping can be neglected ($e^{-t/\tau_{e,h}} \approx 1$) and the induced current on the readout electrode is:

$$I(y, t \approx 0) = e_0 N_{e,h} E_w (v_e(y) + v_h(y)). \quad (6.3)$$

The induced current is proportional to the sum of the electron and hole drift velocities at the injection depth. If the velocities are not saturated this measurement enables probing the electric field at a given position using relation $v = \mu E$, where μ is the charge carrier mobility. This method is particularly useful in strip detectors, where the effective weighting field is approximately that of a pad detector $E_w = \frac{1}{d}$. This leads to a position independent conversion factor between induced current and

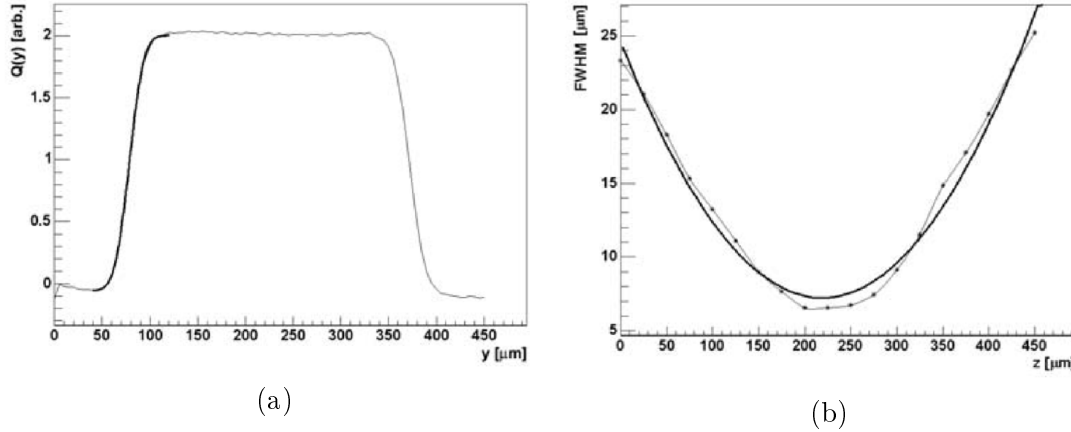


Figure 6.5: Focus finding procedure in Edge-TCT: a) Charge collection profile at a selected z -position with fitted error function on the surface edge; b) Dependence of the FWHM extracted from the fit on z -position. The optimal focus is in the minimum of the parabolic fit, where the charge collection profile has the steepest slope [109].

carrier velocity. In pixel detectors (including CMOS prototypes) the weighting field depends on position and deduction of particle velocity is significantly more complex [108, 109].

Focus finding procedure

Since the laser beam is slightly divergent ($\approx 2^\circ$), the sample has to be first placed in the focal plane of the beam to achieve maximal position resolution. This is done using so called *knife edge technique* with the beam moving from a non sensitive to a sensitive region of the sensor. In Edge-TCT this is usually the detector edge in y -direction, while in Top-TCT the transition between metallised and non-metallised surfaces is mostly used (metal reflects light which prevents generation of e-h pairs). The resulting S-curve of the collected charge gives information about the FWHM of the beam spot at the position of the readout electrode. After each such scan the z -position of the sample is changed by 50–100 μm in order to find the optimal position with the minimal beam FWHM.

At each z -position a charge collection profile like the one shown in Figure 6.5a is measured. The surface edge of the charge collection profile is fitted by the error function to extract the FWHM of the beam (FWHM equals to 2.35σ of the error function). Measured dependence of beam FWHM on z -position is then fitted by a parabola as shown in Figure 6.5b. The optimal z -position is in the minimum of the parabola and corresponds to the maximal slope of the charge collection profile edge.

Typically the beam spot size in this position has a FWHM below $10\text{ }\mu\text{m}$.

6.2 Charge collection measurement with ^{90}Sr

Radioactive strontium-90 (^{90}Sr) is a simple laboratory source of MIP-like particles that can be used for detector tests. The goal of ^{90}Sr measurements is to generate charge in exactly the same way as during detector operation at the collider and to record transient signals, from which charge collection efficiency (CCE) can be measured. Since absolute calibration of measured signals is possible, the results can be used to qualify the detector performance in terms of charge collection. The amount of collected charge is one of the main performance parameters for a silicon detector. Moreover, it allows estimation of the effective depleted depth and comparing the result with Edge-TCT measurements on the same sample.

^{90}Sr is a pure β emitter. It has a short decay chain consisting of two decays: $^{90}\text{Sr} \rightarrow ^{90}\text{Y}$ ($E = 0.546\text{ MeV}$, $t_{1/2} = 28.8\text{ y}$) $\rightarrow ^{90}\text{Zr}$ ($E = 2.28\text{ MeV}$, $t_{1/2} = 64\text{ h}$). The MIP-like particles from the ^{90}Sr source are hence fast electrons from the high energy tail of yttrium decay spectrum. The majority of emitted electrons have relatively low energies, deposit energy significantly faster than a MIP, and have to be excluded from the trigger when measuring MIP spectra.

The measurement setup used for CCE measurements in this thesis is shown in Figure 6.6 [72, 112]. The detector is mounted in an aluminium housing which is in contact with a thermally controlled support plate providing sample cooling down to -10°C . The β particles are collimated by two holes on top and bottom of the 1 mm thick aluminium box, and an additional hole in the cooling plate. A small scintillator with the size of $1\text{ cm} \times 1\text{ cm}$ is positioned below the cooling plate and coupled to a photomultiplier to provide trigger signals. The threshold on the photomultiplier output is selected sufficiently high that only electrons behaving close to a MIP when passing through the sample have sufficient energy remaining to trigger the acquisition. This guarantees a high trigger purity, which exceeds 97% if the sample is larger than the collimator holes so that in all triggered events charge is deposited in the sensitive volume. This configuration allows measurement of small signal to noise ratios. The most probable value (MPV) of electrons from ^{90}Sr source selected in this way is $80\text{ e-h pairs per }\mu\text{m}$, while the mean energy loss is $98\text{ e-h pairs}/\mu\text{m}$ [112]. The samples are connected to a custom made single channel charge sensitive preamplifier with a shaping time of 25 ns . The output waveforms are recorded by an oscilloscope and saved to a computer. The absolute scale of the amplifier output has

To achieve a reasonable event rate of a few Hz the test structures have to be relatively large, of the order of several mm^2 , to ensure a sufficient geometrical acceptance of the incoming radiation. Therefore the measurements are usually not made on single pixels or strips, but on dedicated pad test structures. The large detector capacitance arising from the large surface area increases the noise level of the measurement. A relatively long electrical connection between the sample and the preamplifier further increases the noise level of the setup to approximately 2500 e^- , which is quite high. For example CMOS detectors have a depletion zone with a thickness as small as $30\text{ }\mu\text{m}$, which corresponds to a deposited charge of $\approx 2500\text{ e}^-$ as well. In such a situation noise and signal can not be separated. However, from a sample of events with high trigger purity (i.e. if all recorded events are associated with energy deposition in the DUT) information about the MPV can be extracted as will be explained below.

An example of a CCE measurement² with ^{90}Sr is shown in Figure 6.7. At each setting 2500 individual waveforms, such as one in Figure 6.7a, are acquired. The signals are sampled at a single point at a fixed time in the waveform. To determine the optimal sampling time the average waveform of all 2500 events is calculated (Figure 6.7b). The sampling time for the signal is selected as the peaking time of the average waveform, while noise is sampled before the trigger, where it is causally independent from the signal. The resulting signal and noise spectra are shown in Figure 6.7c.

Charge spectra allow extraction of the collected charge. With sufficiently high S/N ratio the signal spectrum can be fitted with a convolution of a Landau and a Gaussian function (Figure 6.7c), from which the MPV of the collected charge can be determined. The Gaussian from the signal fit has the same standard deviation as the noise spectrum, corresponding to the noise level of the setup.

However, signal size in many CMOS detectors is comparable to the noise level in which case the signal fit has a large uncertainty on the MPV. In such cases the collected charge can be more reliably determined from the shift of the signal spectrum relative to the noise spectrum, since their mean values differ by the average value of the deposited charge (Figure 6.7d). The collected charge can be calculated by taking into account the average charge deposition of $98\text{ e-h pairs}/\mu\text{m}$. This method allows measurement of collected charge with a resolution below the noise level. However, it is essential that in all triggered events charge is deposited within the sensitive region (high trigger purity), otherwise "empty" events lower the mean

²Detector under test is CHESS2 with an initial resistivity of $1\text{ k}\Omega\text{ cm}$ after $10^{14}\text{ n}_{\text{eq}}/\text{cm}^2$ neutron irradiation. Measured MPV is 6400 e^- corresponding to depletion depth of $\approx 80\text{ }\mu\text{m}$.

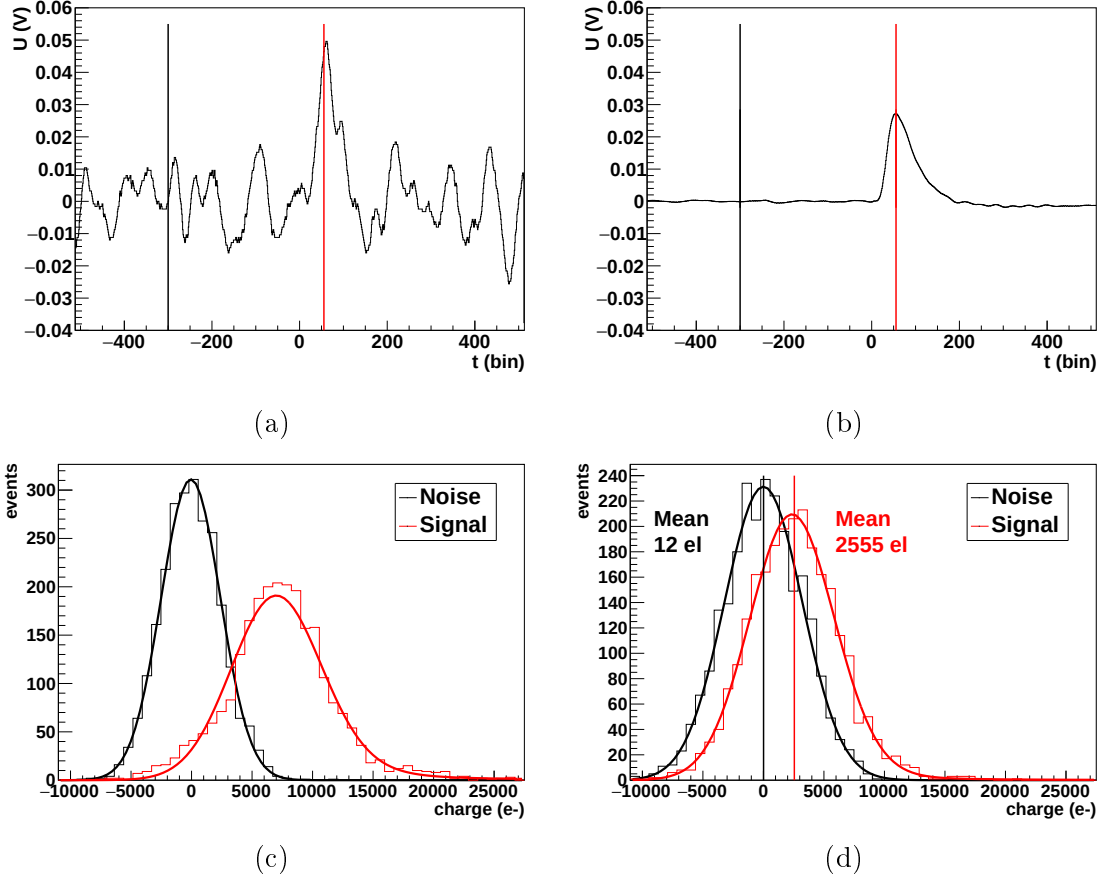


Figure 6.7: Example of CCE measurement with ^{90}Sr : a) Individual waveform at the output of amplification chain. Red and black lines denote the sampling times for signal and noise respectively. Note the high noise level; b) Average of 2500 waveforms. The sampling time for the signal is selected at the maximum of this waveform, while noise sampling time is selected before the pulse; c) Calibrated charge spectrum of signal (red) and noise (black) fitted with a convolution of Landau and Gaussian function, and a Gaussian function respectively. The signal MPV is $6300 e^-$. Due to high trigger purity the signal spectrum has no noise peak around zero, i.e. in all events the triggering particle passed through the sensitive region; d) Signal and noise charge spectra in a sample with less collected charge. Due to a large uncertainty of the Landau fit the collected charge is determined from the shift of the mean value of the signal spectrum relative to the noise spectrum. The measured mean charge is $2500 e^-$, corresponding to an MPV of $\approx 2000 e^-$.

value of the spectrum, resulting in a smaller measured value than it actually is. For this reason the size of the investigated detector has to be large enough compared to the scintillator to provide a 100 % geometrical acceptance of the triggering particles.

Chapter 7

Results of charge collection measurements

This chapter presents the studies of charge collection in irradiated CMOS detectors using TCT and ^{90}Sr techniques. Different prototypes from four ATLAS CMOS development lines were evaluated in the scope of this thesis. In the beginning of the chapter the irradiation process and facilities are briefly introduced, followed by the results from different development lines. At the end the results are summarised and an overview of detector properties, in particular acceptor removal behaviour, is presented.

7.1 Irradiation of samples

Displacement damage was introduced into the samples by irradiation with neutrons and with protons. Neutron irradiations were performed at Jožef Stefan Institute's research TRIGA reactor by inserting the samples into the reactor core through dedicated irradiation channels [113, 114]. Free neutrons from nuclear reactions deliver NIEL radiation damage uniformly over the entire sample volume. The majority of NIEL damage ($> 99\%$) is introduced by fast neutrons with kinetic energy above 100 keV. Desired fluences are achieved by adjusting reactor power, which is proportional to neutron flux, and time of insertion. Irradiations to fluences above $10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ were made with the reactor operating at the maximal thermal power of 250 kW and at a neutron flux of $1.54 \cdot 10^{12} \text{ n}_{\text{eq}}/\text{cm}^2/\text{s}$. For lower fluences the reactor power was reduced to lower the neutron flux and increase irradiation time. The uncertainty on the delivered fluence is $\leq 10\%$. The flux is in addition monitored by

standardised measurements of changes of leakage current in dedicated diodes [63]. During the irradiation samples are also exposed to TID from background gamma rays amounting to 1 kGy per $10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$.

Temperature of silicon during irradiation is over 40° C due to background radiation of the reactor. After the sample is recovered from the core it is kept in a freezer except for brief intervals during transport, mounting and testing, which in total do not exceed 3 hours at room temperature.

Proton irradiation is performed by inserting the sample in a proton beam generated by an accelerator. Proton beams typically have a small Gaussian cross section of $\sigma \sim 5 \text{ mm}$ centered to a desired spot on the sample. To achieve a uniform irradiation over large detector area the sample can be moved through the beam in a carefully planned scanning procedure. However, this approach is more complex and requires a significantly longer irradiation times, hence it was not applied to samples in this thesis. With fixed samples precise positioning within the beam is vital to ensure that the desired fluence is deposited in the targeted test structure.

Samples in this work were irradiated at two facilities: the PS synchrotron at CERN with the proton beam energy of 24 GeV [115] and the LANSCE linac in Los Alamos with the proton beam energy of 800 MeV [116]. In both facilities the beam energy is sufficiently high that a stack of multiple samples can be inserted in the beam at the same time without attenuating the proton flux. The received fluences were determined after the irradiation from activation of an aluminium foil irradiated together with the samples. Protons deposit a larger TID than neutrons at the same equivalent fluence because of their electric charge. Typical TID values for 24 GeV protons are approximately 30 kGy per $1 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$. Proton irradiations took several days, during which the samples were held at room temperature. After irradiation samples were stored in a freezer.

Most measurements with irradiated sample were done twice, before annealing and after the end of beneficial annealing. During the standardised annealing procedure the samples were heated up to 60° C for 80 minutes. This is equivalent to annealing for approximately 10 days at room temperature which corresponds to the end of so called beneficial annealing when minimum of full depletion voltage in moderately irradiated silicon pad detectors is observed (Chapter 4.2.4). Proton irradiated samples underwent certain amount of annealing already during irradiation during which they were held at room temperature.

7.2 Results with LFoundry prototypes

LFoundry CMOS prototypes (Section 5.1) use the large collection electrode design and employ both high resistivity and high voltage to achieve a large depletion depth in the sensor. In the context of this thesis charge collection in passive test structures was evaluated. Characterisation of two different chip versions were made using Edge-TCT and charge collection measurements with ^{90}Sr .

The first set of measurements was made with CCPD_LF chips produced on a substrate with initial resistivity of $2\text{ k}\Omega\text{ cm}$ [117]. Investigated passive test structures A and F are shown in Figure 7.1. Each test structure was contacted with wire bonds. Structure A consists of five n-type implants connected together to form a $250\text{ }\mu\text{m} \times 250\text{ }\mu\text{m}$ pad-like diode. Structure F consists of 3×3 pixels with dimensions of $125\text{ }\mu\text{m} \times 33\text{ }\mu\text{m}$, of which the outer eight are grouped together, while the central one can be connected separately. The goal of this configuration is to enable measurement at "typical" pixel conditions with minimal effects of the chip edge. Pixels in structure F have a more complex implant structure with several wells designed for housing readout electronics in active pixels, but are left empty in this passive device. Samples were produced on a $700\text{ }\mu\text{m}$ thick wafers with two subsets thinned to a thickness of $300\text{ }\mu\text{m}$ and $100\text{ }\mu\text{m}$. The unthinned samples can be biased from the top surface of the sensor through a p-type ring that surrounds all test structures. Thinned samples have a processed and metallised back plane which allows sensor biasing from the back. Maximal bias voltage that can be applied before electrical breakdown is $\sim 100\text{ V}$ before irradiation and up to 150 V in irradiated samples. All test structures are surrounded by an n-type ring which horizontally constrains the electric field and thereby the sensitive volume, and can be biased separately. However, biasing the n-type ring results in a much higher leakage current which effectively limits the bias voltage to 40 V . Measurements above this voltage had to be done with the n-ring left floating. This affected the shape of the depletion region which was wider with an unbiased n-type ring, but it did not significantly change the depletion depth [117].

The second set of measurements was performed with a "Test Structures" chip produced at a later point together with the LF MonoPix on a substrate with initial resistivity of $3\text{ k}\Omega\text{ cm}$ [118, 119]. The investigated passive structure "B", shown in Figure 7.2 is an array of 15×6 pixels with a pixel size of $250\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$ and a multiple well design. Signal routing is similar as in CCPD_LF with a single pixel within the matrix that can be contacted separately, while the surrounding pixels are connected together and routed to another pad. Samples come in two thicknesses: $700\text{ }\mu\text{m}$ without processed back plane, and thinned to $200\text{ }\mu\text{m}$ with metallised back

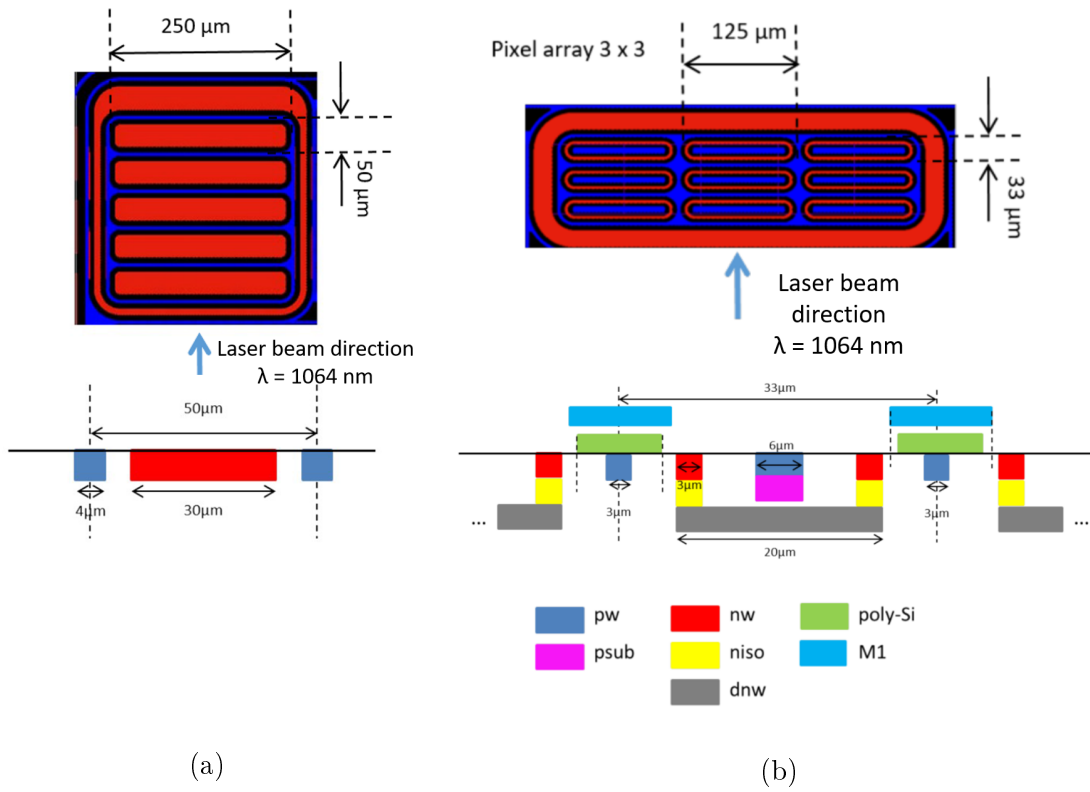


Figure 7.1: Passive test structures on LFoundry CCPD_LF: a) Structure A consisting of five pixel implants connected together and surrounded by an n-type ring; b) Structure F, a 3×3 pixel array. Central pixel can be contacted separately. Implant structure is more complex as indicated on the cross section below the picture [117].

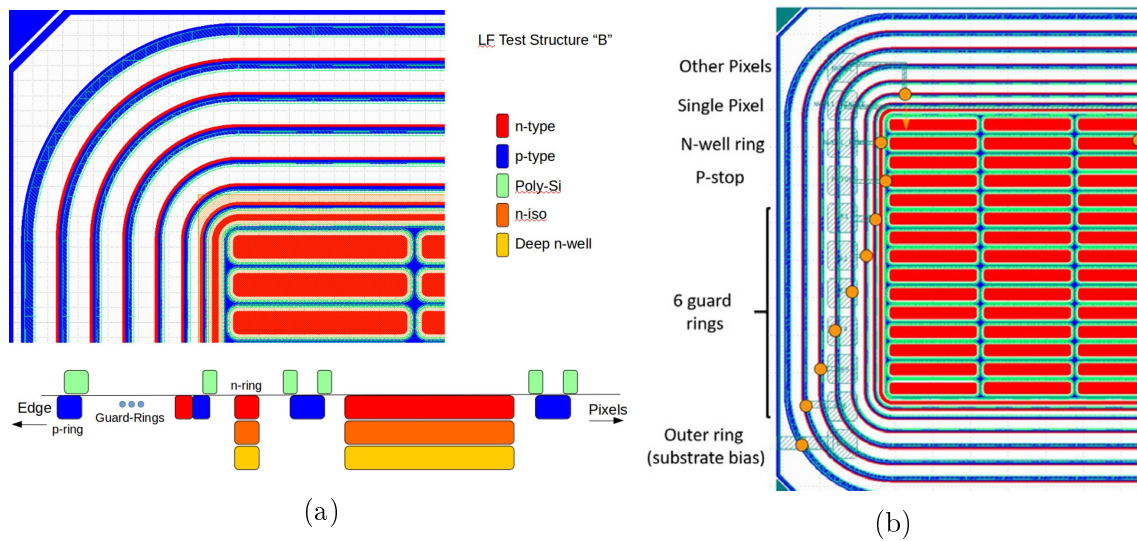


Figure 7.2: Passive test structures on LFoundry "Test Structures" chip: a) Detail of the test structure B, showing guard ring geometry and implant cross section; b) Larger section of the test structure B including wire bond pads [118].

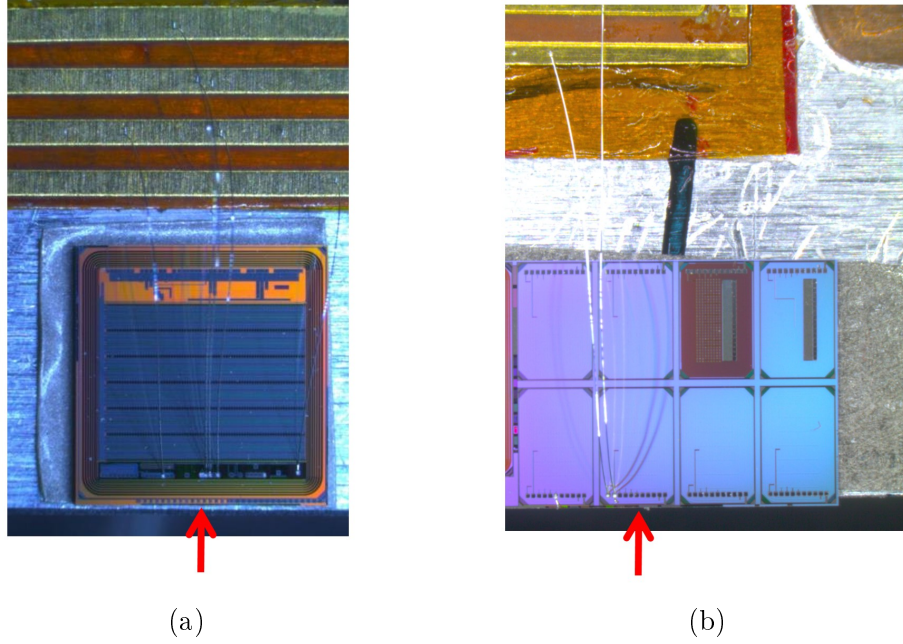


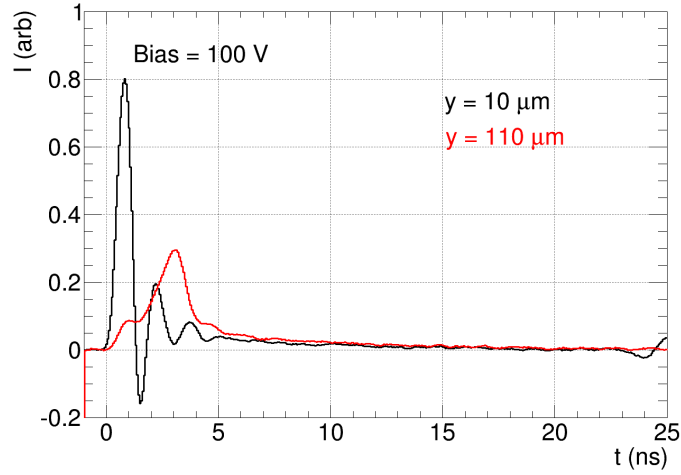
Figure 7.3: Photograph of LFoundry CMOS prototypes CCPD_LF (a) and the Test Structures chip (b) mounted and wire bonded for measurements. The arrow indicates the laser beam direction in Edge-TCT [118].

plane, which can be biased from the top and from the back respectively. Improved high voltage tolerance allows bias voltages up to 250 V before breakdown. The size of the test structure B ($1.5 \text{ mm} \times 0.75 \text{ mm}$) is sufficient to also allow performing ^{90}Sr measurements with the setup presented in Chapter 6.2.

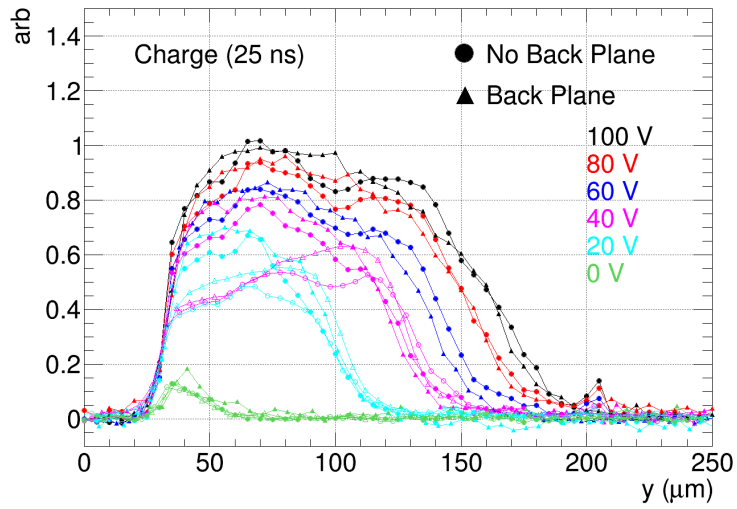
Detectors were irradiated with neutrons in Ljubljana TRIGA reactor. The $700 \mu\text{m}$ and $300 \mu\text{m}$ thick CCPD_LF samples were irradiated to fluences ranging from $1 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ to $8 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. Since only two samples of each thickness were available, irradiation was made in steps, taking into account the fluence accumulated during previous irradiation steps. After each step measurements before and after standard annealing (80 min at 60°C) were performed. The $100 \mu\text{m}$ thick CCPD_LF were irradiated to fluences between $1 \cdot 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$ to $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ (two samples per fluence), while the TS samples were irradiated from $1 \cdot 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$ to $2 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ (one sample per fluence). Since these samples were available in greater numbers, different samples were used for different fluences.

7.2.1 Edge-TCT measurements with CCPD_LF

Detectors were mounted and wire bonded on carrier boards as shown in Figure 7.3. Conductive glue was used to connect the back sides to ground potential, while the detector front side was biased with high voltage. Samples were moved in the laser



(a)

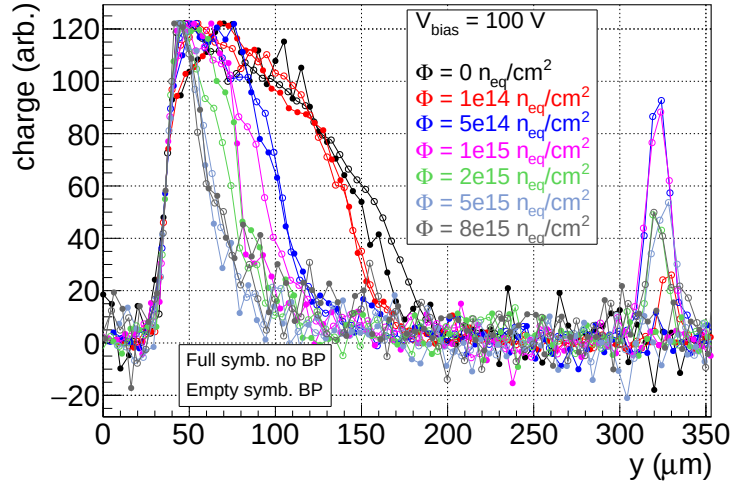


(b)

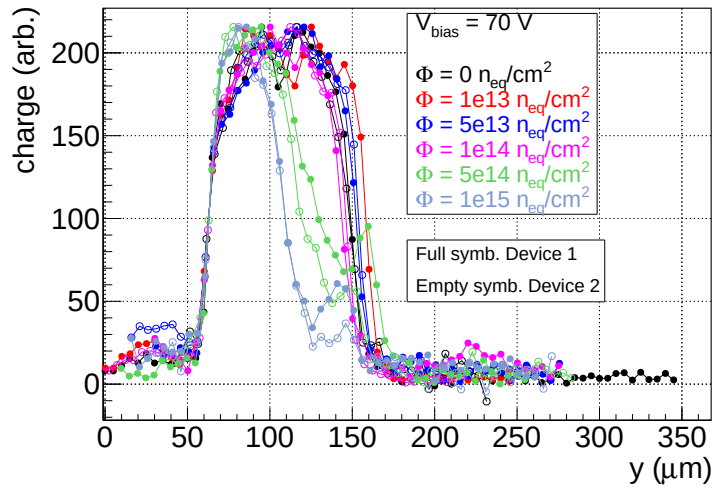
Figure 7.4: a) Induced current pulses in CCPD_LF for charge injection at two different distances from the surface; b) Profile of collected charge in y -direction, calculated as integral of induced pulses over 25 ns. Beam is centered on the middle of the test structure in x -direction. Chip surface is around $y = 30 \mu\text{m}$. Data points represented with full and empty symbols represent measurements with biased and floating n-type ring respectively [117].

beam focused to a beam spot size of $\text{FWHM} < 10\ \mu\text{m}$ with a step of $5\ \mu\text{m}$ in x and y directions, and transient pulses were recorded. Figure 7.4a shows an example of two induced pulses recorded in test structure A measured at injection depths of $10\ \mu\text{m}$ and $110\ \mu\text{m}$ relative to chip surface. In x -direction the beam was positioned at the centre of the structure. The oscillations observed after injection close to the surface are caused by non-perfect matching of the cable and amplifier impedance. The pulse originating from injection point close to the surface has a shorter peaking time and is shorter, reflecting a higher charge carrier velocity and larger weighting field at this position. However, the integral of both pulses over $25\ \text{ns}$, representing the collected charge, is almost identical. Figure 7.4b shows an example of resulting charge collection profiles in y -direction. Depletion zone grows from the chip surface located at $y = 30\ \mu\text{m}$. There are only small variations of the amount of collected charge from different depths in the depleted volume which may be the effect of imperfections on the edge surface, as it was not polished. No significant differences between charge collection profiles in thinned and unthinned samples were observed. The growth of depletion zone with bias voltage is also clearly visible.

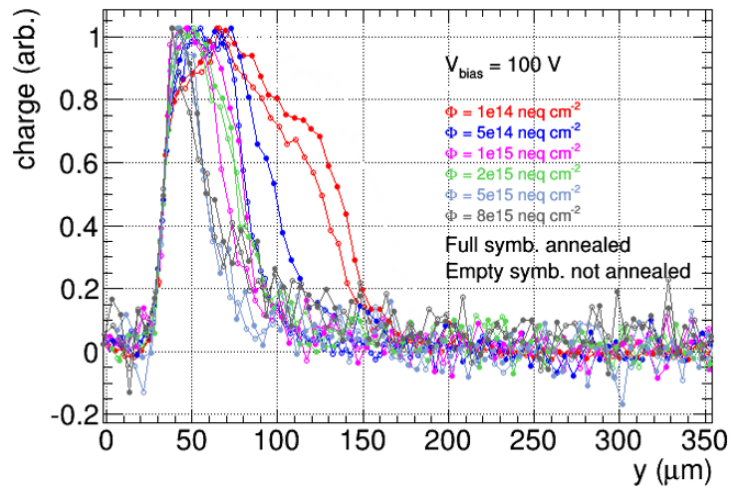
One of the main goals of Edge-TCT measurements is a systematic measurement of depletion depth and its dependence on bias voltage and irradiation fluence. Measurements were carried out on test structure A with floating n-ring to allow higher bias voltages up to $\sim 100\ \text{V}$. Laser beam was centered in the middle of the test structure in x -direction and moved along the y -direction, while bias voltage was varied in steps of $5\text{--}10\ \text{V}$ so that a one dimensional scan was performed at each bias voltage. Charge collection profiles for different fluences measured at a high bias voltage are shown in Figures 7.5a ($700\ \mu\text{m}$ and $300\ \mu\text{m}$) and 7.5b ($100\ \mu\text{m}$). The sample surface is located at the left flank of the profiles which are rescaled so that they have the same maximal height. The measurements were done after beneficial annealing which increases the width of the charge collection profiles by up to 20% compared to measurements before annealing (Figure 7.5c). The charge collection profiles in $700\ \mu\text{m}$ and $300\ \mu\text{m}$ thick samples have a width well below sample thickness indicating that the samples are partially depleted. The profile width is similar in both samples and decreases with fluence which is a consequence of introduction of additional acceptor states by irradiation resulting in increased N_{eff} . Even at the highest fluence of $8 \cdot 10^{15}\ \text{n}_{\text{eq}}/\text{cm}^2$ a sizable collecting region is still visible. In $300\ \mu\text{m}$ thick samples there is an additional charge collecting region around $y = 320\ \mu\text{m}$, which appears due to the electric field appearing near the back side contact. The field may be the consequence of p-p^+ doping gradient and/or of the double junction effect (Chapter 4.2.4). The $100\ \mu\text{m}$ thick samples up to the fluence of $1 \cdot 10^{14}\ \text{n}_{\text{eq}}/\text{cm}^2$ are fully depleted at the bias voltage of $70\ \text{V}$. At higher fluences charge collection efficiency at



(a)



(b)



(c)

Figure 7.5: Charge collection profiles measured with annealed CCPD_LF chips: a) 700 μm and 300 μm chips; b) 100 μm thick chips; c) profiles before and after annealing [117].

the back of the device drops and high efficiency region starting from top electrode the gets smaller with increasing fluence because depletion zone shrinks due to higher N_{eff} . Depletion depth was estimated from the width of charge collection profiles by measuring the full width at half maximum (FWHM). Since the profiles in Figure 7.5 have a gradual slope on the substrate side, the choice of the cutoff fraction introduces a systematic uncertainty on the depletion depth. The magnitude of this effect was estimated by measuring the full width at two additional threshold values of 40 % and 60 % of maximum, yielding different depletion depths that were used to estimate the measurement uncertainty in subsequent analysis.

Depletion depth measured as explained above at different bias voltages is shown in Figure 7.6. Depletion depth increases with bias voltage but, as already observed in Figure 7.4b, reduces with fluence. In 100 μm thick samples the depletion depth grows with bias voltage until full sensor depletion is reached. The full depletion voltage V_{FD} can be defined as the voltage of the kink between flat and increasing part of the curve in Figure 7.6b. V_{FD} is the lowest after a fluence of $5 \cdot 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$ which is a consequence of initial acceptor removal. At higher fluences V_{FD} increases which is compatible with the measurements on thicker samples. Taking into account the abrupt junction approximation (Equation 3.8) the dependence of depletion depth w on bias voltage can be described by the function:

$$w = w_0 + \sqrt{\frac{2\epsilon\epsilon_{\text{Si}}}{e_0 N_{\text{eff}}}} V_{\text{bias}}, \quad (7.1)$$

where an additional term w_0 is introduced based on experimentally observed offset at 0 V [72, 117]. A typical value of $w_0 \sim 10 \mu\text{m}$ encompasses several factors: in the first place substrate depletion by the built-in voltage and widening of the charge collection profile due to a finite beam width, but also potential beam reflections on sample surface, non-abrupt doping profile, and in unirradiated detectors charge collection by diffusion. It has been shown that the effect of the finite beam width can lead to an overestimated depletion depth when depletion depths are small compared to the beam spot size ($w < 1.5$ beam FWHM) [120, 121]. However, the scaling of measured depletion depth with $\sqrt{V_{\text{bias}}}$ is still the same and can be used to extract N_{eff} .

Equation 7.1 was fitted to data with N_{eff} and w_0 as free parameters. In unirradiated samples the fitted value of $N_{\text{eff}} = 8 \cdot 10^{12} \text{ cm}^{-3}$ corresponds to the substrate resistivity of 1.7 k Ω cm which is not far from the nominal wafer resistivity of 2 k Ω cm and verifies the validity of this method. The uncertainty on measured N_{eff} was estimated from the variance of the fit result when function 7.1 was fitted to depletion depth measured at 40 % and 60 % of the maximum of the charge collection profiles.

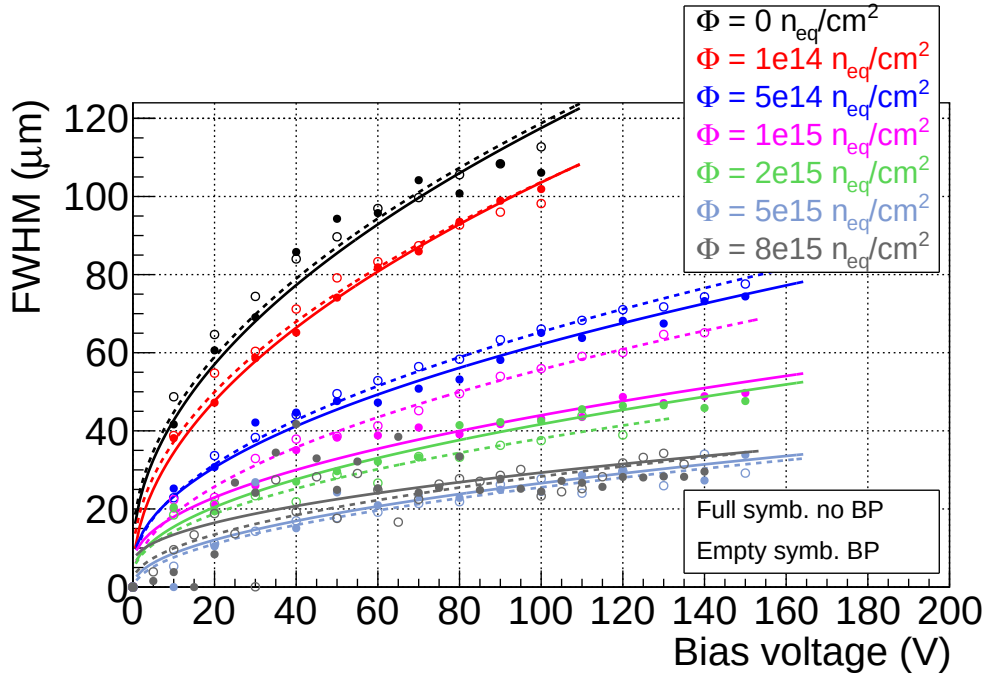
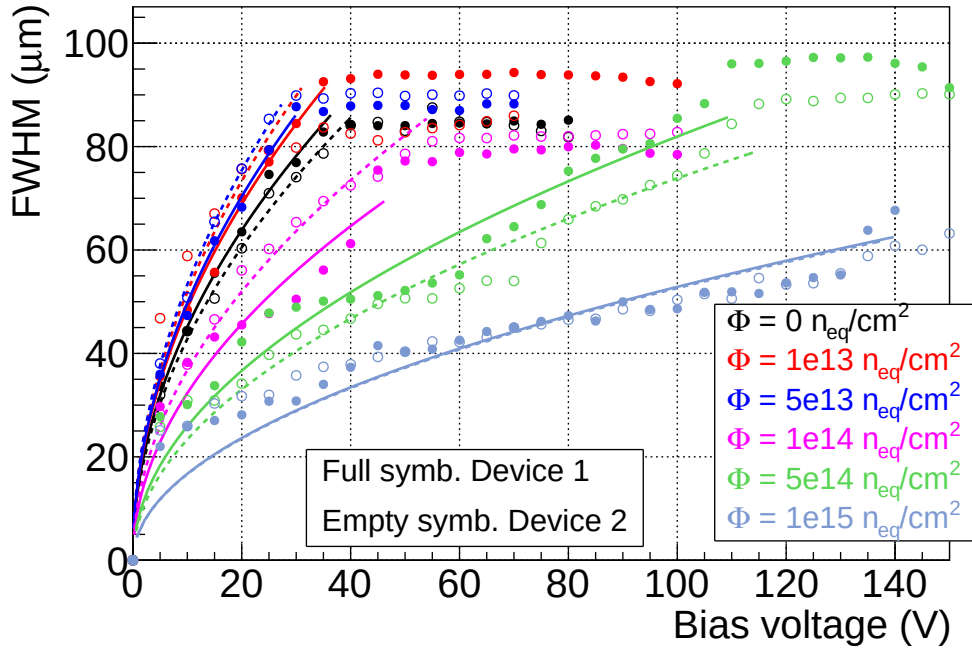
(a) Sample thickness 700 μm (no BP) and 300 μm (BP)(b) Sample thickness 100 μm

Figure 7.6: Dependence of depletion depth (FWHM of charge collection profiles) on bias voltage in differently irradiated CCPD_LF samples. 100 μm thick samples shown in figure b) could be fully depleted at fluences $\leq 5 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$. Full depletion voltage initially decreases with irradiation up to the fluence of $5 \cdot 10^{13} \text{ n}_{\text{eq}}/\text{cm}^2$ due to acceptor removal. At fluences above $1 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ the initial acceptor removal is completed and the depletion depth at a given voltage decreases. Data points were fitted with the function 7.1 to extract N_{eff} [117].

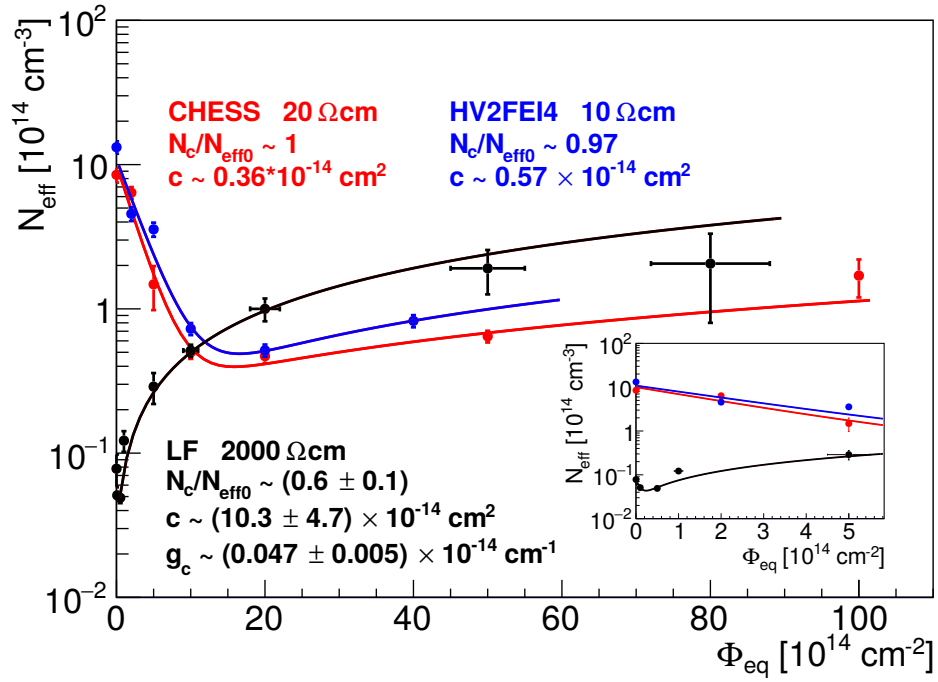


Figure 7.7: Evolution of N_{eff} with neutron fluence in CCPD_LF (black line). Two other CMOS prototypes with a 100 times lower initial resistivity are included for comparison [72]. Inset diagram shows low fluence behaviour below $1 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ where acceptor removal can be observed. At higher fluences N_{eff} converges towards similar values for all samples. The data was fitted with the function 4.5 with the fit results shown in the diagram [117].

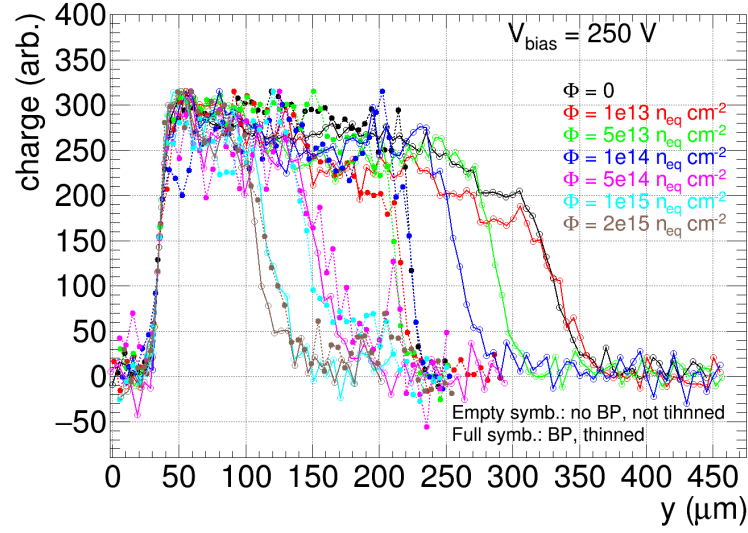
The measured values of N_{eff} at different fluences are shown in Figure 7.7. For comparison the diagram also shows values of N_{eff} in two other CMOS prototypes produced on low resistivity substrates ($10\ \Omega\text{cm}$ and $20\ \Omega\text{cm}$) [72]. While the initial N_{eff} differs by two orders of magnitude, it converges to approximately the same value after a fluence of $1 \cdot 10^{15}\ \text{n}_{\text{eq}}/\text{cm}^2$ and follows roughly the same trend at higher fluences. N_{eff} in CCPD_LF initially reduces up to the fluence of $5 \cdot 10^{13}\ \text{n}_{\text{eq}}/\text{cm}^2$. This is in contrast to the lower resistivity chips where the initial acceptor removal is finished at a much higher fluence above $10^{15}\ \text{n}_{\text{eq}}/\text{cm}^2$. This behaviour demonstrates faster removal in high resistivity material as discussed in Chapter 4.2.5. The data points are fitted with the function 4.5 which parametrises acceptor removal:

$$N_{\text{eff}} = N_{\text{eff},0}(1 - N_{\text{c}}/N_{\text{eff},0} \cdot (1 - e^{-c\Phi_{\text{eq}}})) + g_{\text{C}}\Phi_{\text{eq}}.$$

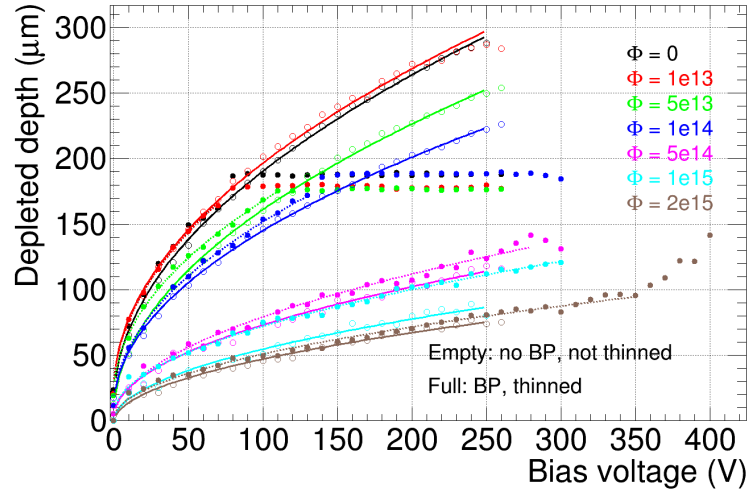
The free parameters of the fit are the fraction of removed initial acceptors $N_{\text{c}}/N_{\text{eff},0}$, acceptor introduction rate g_{C} and acceptor removal coefficient c . The fitted value of $N_{\text{c}}/N_{\text{eff},0} = 0.6$ indicates a partial acceptor removal. The value of the acceptor introduction rate $g_{\text{C}} = 0.047\ \text{cm}^{-1}$ is significantly higher from the value of $g_{\text{C}} = 0.02\ \text{cm}^{-1}$ found in literature for p-type silicon [66]. However, the fit overestimates the measurements at the two highest fluences, which are more compatible with a g_{C} value of $0.03\text{--}0.04\ \text{cm}^{-1}$.

7.2.2 Edge-TCT measurements with "Test Structures" chip

Edge-TCT measurements with the "Test Structures" chip were made on the $1.5\ \text{mm} \times 0.75\ \text{mm}$ test structure B (Figure 7.2a) with the single pixel connected to the readout. Unthinned samples with a thickness of $700\ \mu\text{m}$ were biased through a p-type ring on the sensor surface, while the thinned samples with a thickness of $200\ \mu\text{m}$ were biased through the back plane. Measured Edge-TCT profiles depletion depth are shown in Figure 7.8. The charge collection profiles have almost the same height over the entire probed sensor depth. This is due to the relatively large size of the test structure which results in more uniform electric fields without edge effects. The high substrate resistivity and high applicable bias voltage above $250\ \text{V}$ result in depletion depth exceeding $80\ \mu\text{m}$ even at the highest tested fluence of $2 \cdot 10^{15}\ \text{n}_{\text{eq}}/\text{cm}^2$. Full sample depletion in the $200\ \mu\text{m}$ thick sample can also be observed at fluences below $1 \cdot 10^{14}\ \text{n}_{\text{eq}}/\text{cm}^2$. The width of the charge collection profiles falls monotonously with the fluence. No initial acceptor removal is observed, possibly because the initial material resistivity is so high that the removal is already finished at fluences below the first measured point at $1 \cdot 10^{13}\ \text{n}_{\text{eq}}/\text{cm}^2$.



(a)



(b)

Figure 7.8: Edge-TCT measurements with LF "Test Structures" sample: a) Charge collection profiles at different fluences. The profiles are normalised to the same height; b) depletion depth. At low fluences the 200 μm thick samples are fully depleted. [118].

Figure 7.8b shows the measured depletion depth fitted with the function 7.1. Up to the full depletion voltage the depletion depth is similar for thinned and unthinned samples. The only significant difference is the depletion depth at the fluence of $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ where the unthinned sample has a smaller depletion depth. However, the difference is probably due to device-to-device variation. The fit of function 7.1 to the measurements with the unirradiated sample yields the value of N_{eff} corresponding to initial substrate resistivity of $3 \text{ k}\Omega \text{ cm}$, which is compatible with the specifications.

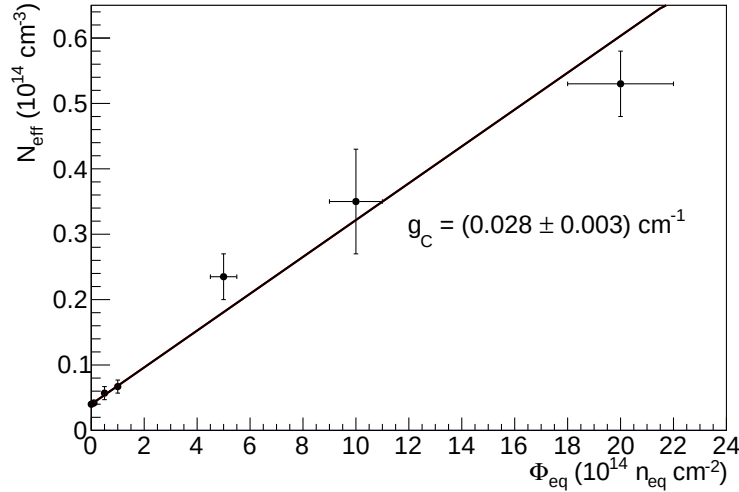


Figure 7.9: Evolution of N_{eff} with received neutron fluence in LF "Test Structures" chip. Since the initial substrate resistivity is higher than in CCPD_LF ($3 \text{ k}\Omega \text{ cm}$), initial acceptor removal is not observed as it is completed below the lowest fluence [118].

The values of N_{eff} extracted from the fit of the data are shown in Figure 7.9. Since no acceptor removal can be observed the data were fitted only with the linear term describing introduction of stable effective acceptors:

$$N_{eff} = N_{eff,0} + g_C \Phi, \quad (7.2)$$

with g_C as a free parameter. The fitted value of $g_C = (0.028 \pm 0.003) \text{ cm}^{-1}$ is slightly higher than the literature value of $g_C = 0.02 \text{ cm}^{-1}$ [66], similarly as measured with CCPD_LF samples.

7.2.3 Two dimensional Edge-TCT measurements

Figure 7.10 shows a two dimensional scan of test structure F with all nine pixels connected to the readout. The measurements were made before irradiation (Figure 7.10a) and after irradiation to $5 \cdot 10^{15} \text{ n}_{eq}/\text{cm}^2$ (Figure 7.10b) at a bias voltage of 40 V . In Figure 7.10a the sample surface is at $y = 40 \mu\text{m}$ and the depletion zone is approximately $100 \mu\text{m}$ deep (up to $y \approx 140 \mu\text{m}$). A uniform response without gaps between pixels is observed. In the heavily irradiated sample a relatively uniform response is likewise observed. Depleted zone shrunk to a depth of $\approx 40 \mu\text{m}$ is still visible. Measured structure size of $\approx 350 \mu\text{m}$ in x -direction is compatible with the pixel pitch of $3 \times 125 \mu\text{m} = 375 \mu\text{m}$.

In the unirradiated sample the largest charge is measured at beam positions

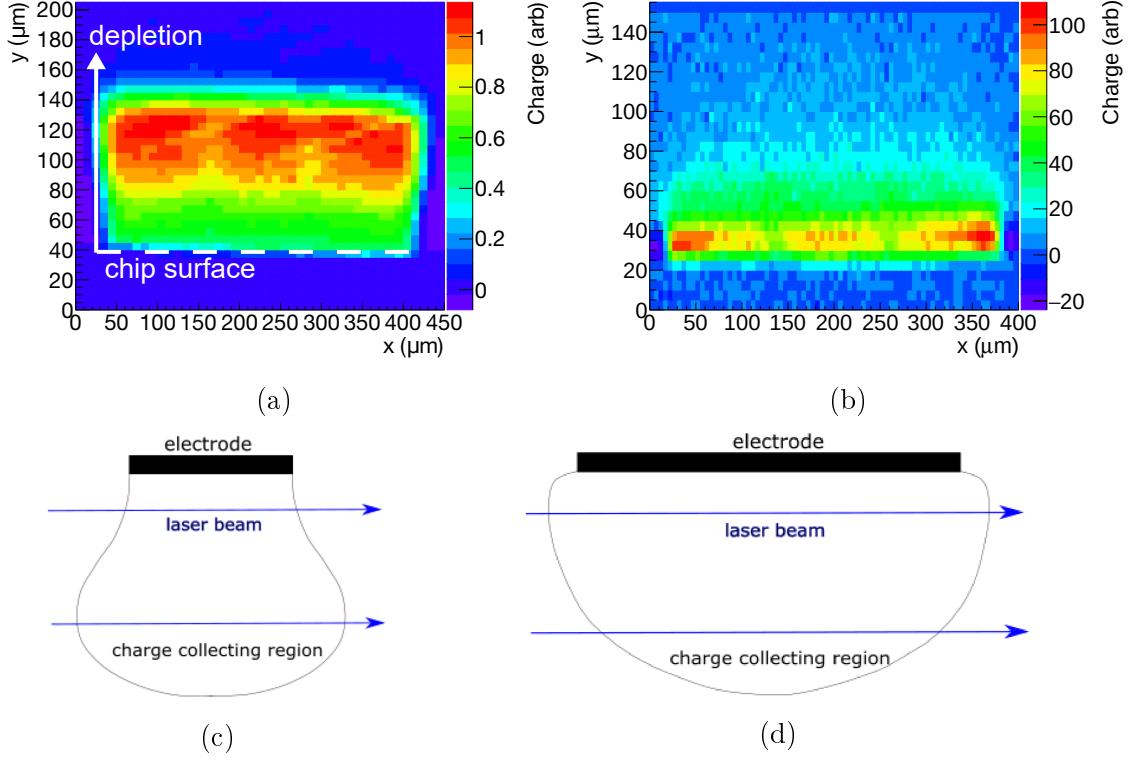


Figure 7.10: Two dimensional Edge-TCT scan of a 3×3 pixel array F in CCPD_LF at $V_{\text{bias}} = 40 \text{ V}$: a) Unirradiated sample; b) Sample irradiated to $5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. Sample surface is around position $y = 40 \mu\text{m}$ in a) ($20 \mu\text{m}$ in b)) and depleted zone grows in y -direction. The response between pixels is relatively uniform with no critical gaps on pixel edges. The depleted zone is still visible even after heavy irradiation. The n-type ring surrounding the test structures to horizontally constrain the electric field was biased in these measurements. Figures c) and d) illustrate the small structure effect responsible for larger signals at larger injection depths. When the depletion depth is smaller than the transverse structure size the depletion zone has a shape as shown in figure d) and the intersection length of the laser beam with depletion region does not increase with depth. If the depletion depth is large compared to electrode dimension the depletion zone has a "pear" like shape, so charge from a longer stretch of laser beam is collected at larger y [117].

far from the surface between injection depths of $90\text{ }\mu\text{m}$ and $130\text{ }\mu\text{m}$. This is an artifact arising from the relatively small size of the tested structure, which has also been observed with numerous other samples. An explanation is illustrated in Figures 7.10d and 7.10c. When the depletion depth is small compared to the lateral dimensions of the test structure the depletion zone has a roughly constant width, resulting in a flat charge collection profile. However, when the depth of the depletion zone exceeds the characteristic scale of the test structure the shape of the charge collecting area of the readout electrode expands in the direction of the laser beam. In the particular case the characteristic dimension is the array size in z -direction, which is $3 \times 33\text{ }\mu\text{m} = 100\text{ }\mu\text{m}$. The electric field starts to expand laterally into undepleted volume, caused by the repulsion of the electric field lines, forming a "pear" shaped depletion zone with a larger width deeper in the sample. Since the amount of detectable charge in Edge-TCT scales with the length of the laser path in the depleted zone, more charge is available for collection from deeper in the sample, hence larger signals are detected. This effect is very specific for small test structures. In large pixel arrays no such effects are expected, since symmetry dictates a vertical electric field with no lateral expansion of the depleted zone.

7.2.4 ^{90}Sr measurements with "Test Structures" chip

The "Test Structures" chip was furthermore used for charge collection measurements with ^{90}Sr setup described in Chapter 6.2. All pixels in the test structure B were connected together to form a pad detector. Examples of spectra measured with samples before irradiation and after irradiation to $5 \cdot 10^{13}\text{ n}_{\text{eq}}/\text{cm}^2$ at the maximal bias voltage before electrical breakdown ($\approx 250\text{ V}$) are shown in Figure 7.11. As the DUT is too small for good collimation in this setup it was not possible to select clean sample of events, so both signal and noise peaks are visible. But since the peaks are well separated, reliable estimation of charge collection by ^{90}Sr electrons is possible. The spectra are fitted with a convolution of Landau and Gaussian function allowing extraction of the most probable value (MPV). In the unirradiated $700\text{ }\mu\text{m}$ thick sample (Figure 7.11a) the MPV is $20\,000\text{ e}^-$. Assuming the most probable charge deposition of $80\text{ e}^-/\mu\text{m}$ this corresponds to a depletion depth of $\approx 250\text{ }\mu\text{m}$ which is consistent with Edge-TCT measurements. In the unirradiated $200\text{ }\mu\text{m}$ thick sample (Figure 7.11b) the MPV is $13\,700\text{ e}^-$, which is 15 % less than expected for a fully depleted $200\text{ }\mu\text{m}$ thick detector. However, Edge-TCT measurements in Figure 7.8b also indicated depletion depth below $200\text{ }\mu\text{m}$. After irradiation the MPV in the $200\text{ }\mu\text{m}$ thick sample (Figure 7.11d) is $13\,300\text{ e}^-$, which is only slightly less than before irradiation. However, the collected charge in the irradiated $700\text{ }\mu\text{m}$ thick

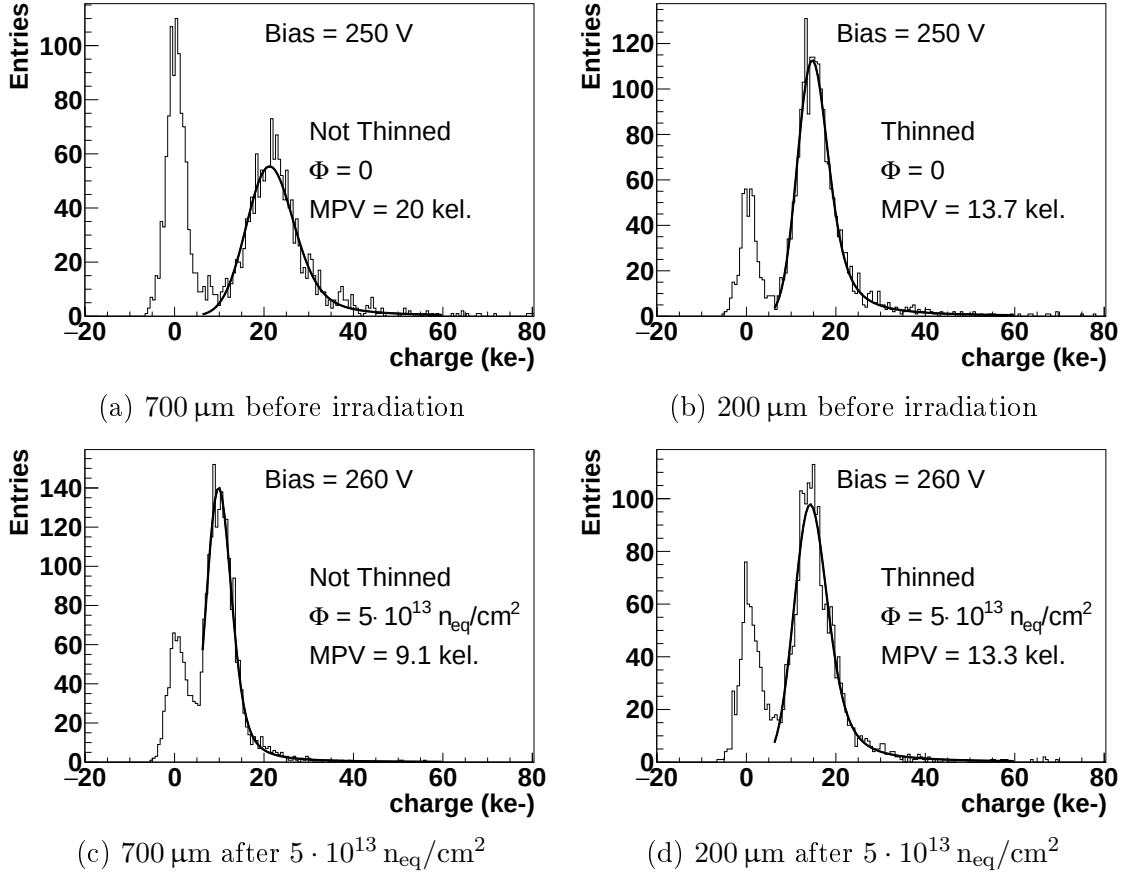


Figure 7.11: ^{90}Sr charge spectra measured with LFoundry "Test Structures" samples. Charge in the unthinned sample reduces significantly after irradiation [118].

sample (Figure 7.11c) reduces by more than 50 % to an MPV of only 9 100 e^- . This difference in behaviour between the unthinned and thinned samples has been consistently observed at all fluences as shown in Figure 7.12. The thinned sample could be fully depleted up to the fluence of $1 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$. At higher fluences full depletion could not be achieved, however higher breakdown tolerance after irradiation allowed higher bias voltages, up to 470 V after the highest fluence. The collected charge in a fully depleted sample is around 13 000 e^- and slightly reduces by up to 10 % compared to pre-irradiation. A charge above 5 000 e^- can be collected in partially depleted samples at all fluences up to $2 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. In unthinned samples the collected charge reduces much faster with irradiation – from 20 000 e^- before irradiation to 7 000 e^- after a fluence of $1 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$. At higher fluences the charge is even smaller so the peak of the Landau distribution cannot be clearly separated from the noise peak and the MPV cannot be determined.

Since Edge-TCT measurements show no significant difference in depletion depth of thinned and unthinned samples (before full depletion of thinned samples), the amount of available charge is the same. These results therefore indicate a degraded

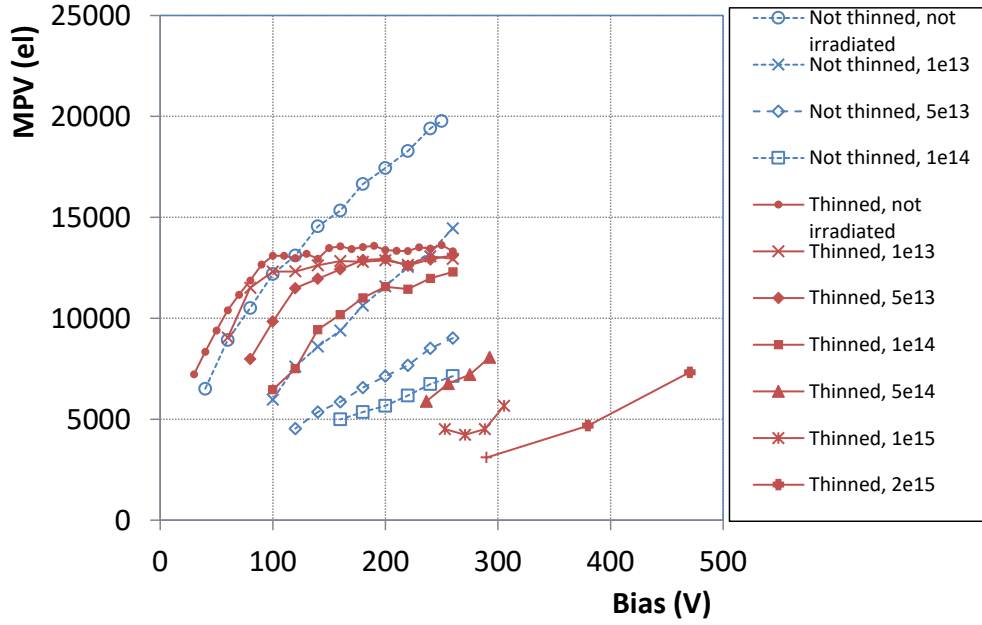


Figure 7.12: Dependence of collected charge from a ^{90}Sr MIP on bias voltage in unthinned samples (blue) and thinned samples with a processed back plane (red) [118].

charge collection in the unthinned samples. The reason for the different collection efficiency arises from different biasing layout of the detectors as illustrated in Figure 7.13. Unthinned samples are biased from a p-type ring on top of the chip, while the thinned samples are biased from a metallised back plane. The drift path of holes in unthinned detectors ends on the surface, while in thinned detectors holes drift towards the back plane. According to the Shockley-Ramo theorem a full charge collection is achieved when charge carriers drift over the entire weighting potential. Before irradiation the ohmic resistivity of the material is sufficiently low that the weighting potential on the boundaries of the depleted volume is the same as on the corresponding collecting electrode even if a part of the substrate in between is undepleted. Because of that the biasing configuration does not have an impact before irradiation.

After irradiation the ohmic resistivity of the material increases and boundaries of depletion zone are no more at the weighting potential of the electrodes. In case of top bias the zero weighting potential for holes is at the p-type ring on chip surface. However, the drift path of holes leads through a region within the substrate with a low electric field (Figure 7.13a) and long drift time, so there is a high probability that they get trapped before reaching the electrode. Trapped charge carriers do not contribute the full signal hence less charge is measured. In samples biased through the back plane the zero weighting potential is at the back plane. In case of full depletion this coincides with the depletion zone boundary, whereas in partial

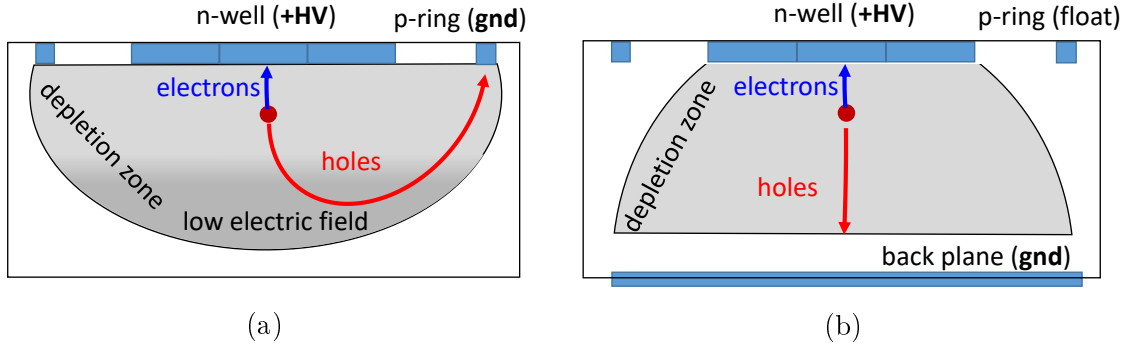


Figure 7.13: Charge carrier drift in a detector biased from the top (a) and from the back plane (b). In a top biased detector holes can be trapped in the low field region and do not drift through the entire weighting field, resulting in less collected charge.

depletion it is still closer to the boundary than in a detector biased from the top. Trapping therefore does not have so much impact on collected charge as in top biased samples. The measurements clearly indicate beneficial effects of back plane processing on charge collection. However, the above measurements were made with a pad structure, where the weighting field is uniform. In pixel devices the weighting field is significantly different – the field is largest close to the readout electrode and most of the charge is collected from the carrier drift in this region. It is therefore expected that while thinning and back plane processing is still beneficial, top biasing does not have as large adverse effect as measured here on charge collection in pixel devices.

7.3 Results with CHESS2

CHESS2 (Section 5.4) has been designed as a prototype of strip detector in CMOS technology and manufactured by *ams* [122]. The basic readout unit is an active striptlet, also called pixel, with a size of $630\text{ }\mu\text{m} \times 40\text{ }\mu\text{m}$. There are several structures on the CHESS2 chip. In the three main active arrays multiple (32×1) striptlets are interconnected to form 20 mm long strips. Passive test structures investigated in this work are located in a dedicated test sector outside of the main arrays as shown in Figure 7.14. Edge-TCT measurements were made on a 3×3 passive striptlet (pixel) array with the standard pixel dimensions of $630\text{ }\mu\text{m} \times 40\text{ }\mu\text{m}$ located on the edge of the device. Charge collection measurements with ^{90}Sr were made with the so called Large Array of interconnected implants with a total size of $1.2\text{ mm} \times 1.2\text{ mm}$. Chips are produced on four different substrates with initial resistivities of 20, 50, 200 and $1000\text{ }\Omega\text{ cm}$, covering the full resistivity range of CMOS detectors. Samples are

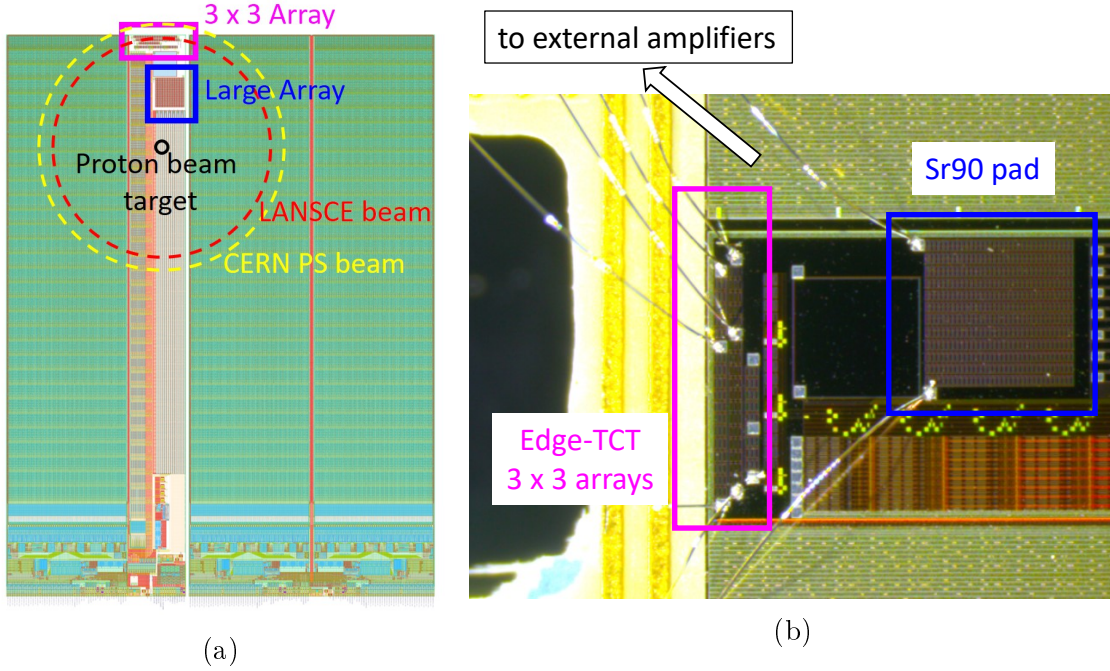


Figure 7.14: The CHESS2 chip: a) chip layout. The chip consists of three large monolithic arrays and a collection of test structures located in a test sector in the middle. The schematics indicates the two test structures used in this work, as well as the position and size (σ) of the beam during proton irradiation; b) Closeup of test structures used for Edge-TCT and ^{90}Sr measurements. The sample is glued to a carrier board and test structures connected with wire bonds can be seen in the picture

thinned to a thickness of $250\text{ }\mu\text{m}$, but the back plane is not processed. The samples are instead biased from the top via p-type rings surrounding the test structures. Chips are designed to withstand a high bias voltage of 120 V .

CHESS2 samples were used in an extensive irradiation study employing both neutron and proton irradiation. A summary of the delivered fluences is given in Table 7.1 [123]. Neutron irradiation up to a maximal fluence of $2 \cdot 10^{15}\text{ n}_{\text{eq}}/\text{cm}^2$ was performed at Ljubljana TRIGA reactor, while irradiation with protons was performed at CERN PS and LANSCE (see section 7.1) up to a maximal nominal fluence of $3.6 \cdot 10^{15}\text{ n}_{\text{eq}}/\text{cm}^2$. The targeted centre and spot size of the beam during proton irradiation is shown in Figure 7.14a. However, we suspect that during irradiation at LANSCE the beam centre was displaced with respect to the targeted position so that the fluence received by the investigated test structures was less than nominal. This assumption is based on I-V measurements in LANSCE samples which show a leakage current lower by about an order of magnitude compared to samples irradiated in PS. Moreover, results of Edge-TCT and ^{90}Sr measurements presented below are also more compatible with lower fluences in LANSCE samples.

Table 7.1: List of irradiated CHESS2 samples.

CHESS2 neutron fluences

$\Phi_{\text{eq}}(10^{14} \text{ n}_{\text{eq}}/\text{cm}^2)$	1	3	5	10	20
20 $\Omega \text{ cm}$	Ljubljana				
50 $\Omega \text{ cm}$					
200 $\Omega \text{ cm}$					
1000 $\Omega \text{ cm}$					

CHESS2 proton fluences

$\Phi_{\text{eq}}(10^{14} \text{ n}_{\text{eq}}/\text{cm}^2)$	4.2	7.8	8.7	14	36
20 $\Omega \text{ cm}$	CERN PS	LANSCE	CERN PS	n.a.	n.a.
50 $\Omega \text{ cm}$	n.a.		n.a.	LANSCE	
200 $\Omega \text{ cm}$	CERN PS		CERN PS		
1000 $\Omega \text{ cm}$			n.a.	n.a.	

7.3.1 Edge-TCT measurements with CHESS2

Edge-TCT measurements were made with laser focused to a beam spot size with $\text{FWHM} < 10 \mu\text{m}$ and movement step of $5 \mu\text{m}$. Collected charge was measured by integrating the transient pulses over an interval of 10 ns to reduce noise compared to the standard integration time of 25 ns.

Neutron irradiation

Charge collection profiles across the pixel centre measured in neutron irradiated samples are shown in Figure 7.15. In 20 $\Omega \text{ cm}$ substrate the depletion depth is less than $50 \mu\text{m}$ up to a fluence of $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, but after a fluence of $2 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ it grows significantly to $90 \mu\text{m}$. In samples with initial resistivity of 50 $\Omega \text{ cm}$ the depletion depth before irradiation is $\approx 30 \mu\text{m}$, while in the irradiated chips it is consistently above $50 \mu\text{m}$ with the maximum of $\approx 80 \mu\text{m}$ reached after a fluence of $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. The 200 $\Omega \text{ cm}$ substrate shows the smallest dependence of depletion depth on fluence of all tested materials, with the depletion depth exceeding $50 \mu\text{m}$ in all samples and reaching a maximum of $70 \mu\text{m}$ after a fluence of $5 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$. In the samples with the initial resistivity of 1000 $\Omega \text{ cm}$ the profiles in unirradiated samples could not be measured due to an early electrical breakdown. In irradiated samples the width of charge collection profiles reduces with fluence. The 200 $\Omega \text{ cm}$

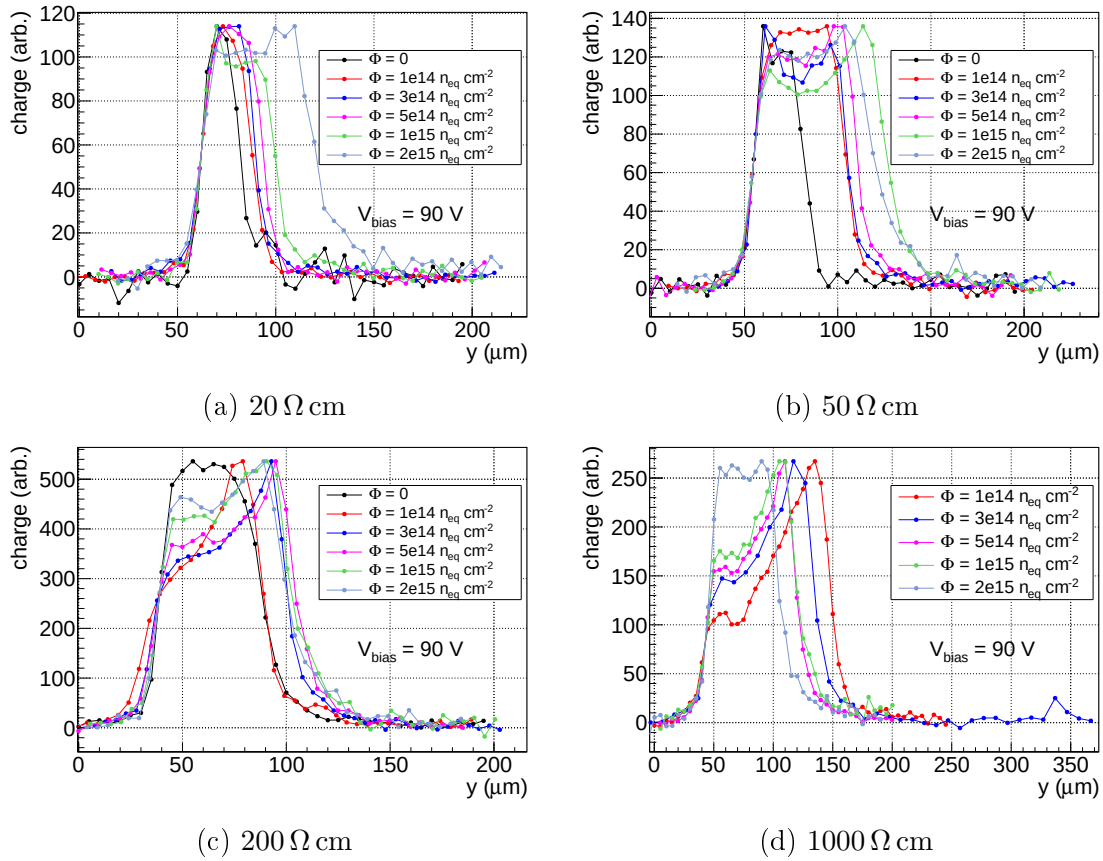


Figure 7.15: Edge-TCT charge collection profiles in neutron irradiated CHES2 chips of different initial substrate resistivities. Chip surface is on the left flank of the charge collection profile. The beam was positioned in the centre of the pixel in x -direction.

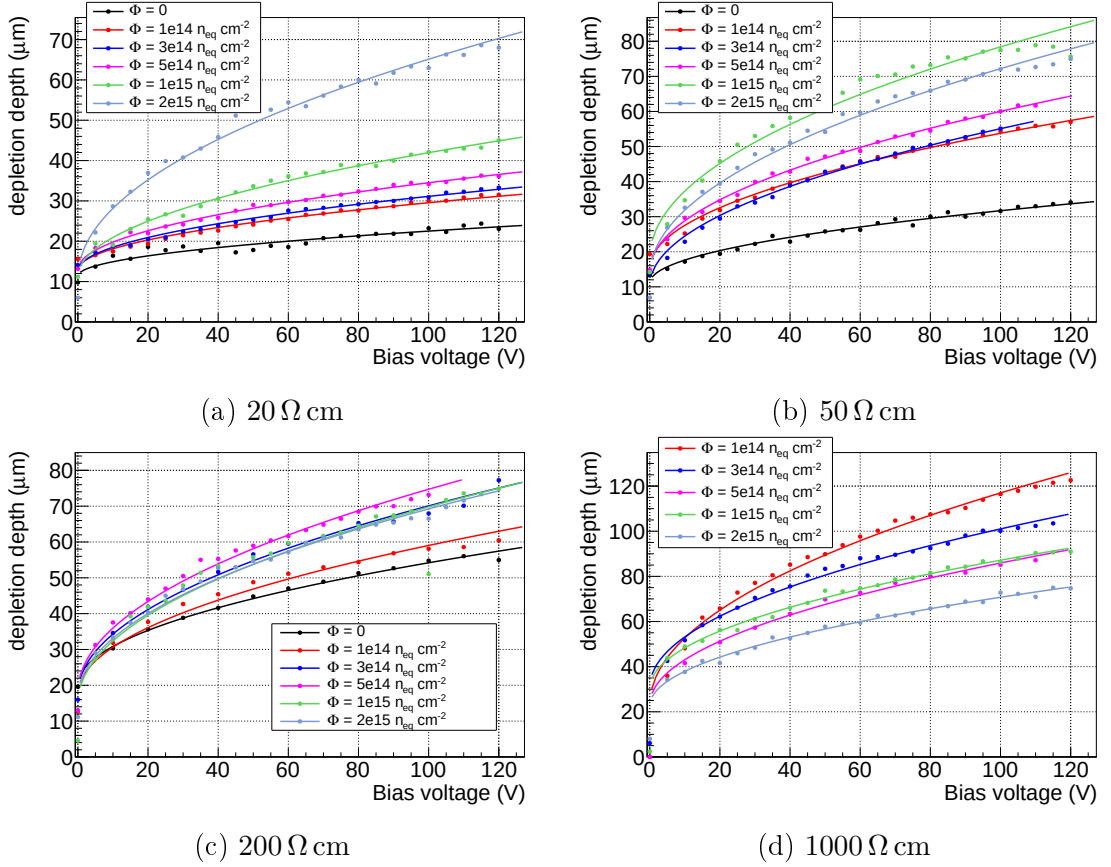


Figure 7.16: Depletion depth in neutron irradiated CHESS2 chips. Data is fitted with Formula 7.1.

and 1000 Ωcm samples feature significantly larger signals at the back side of the depletion zone, which is the consequence of the "small structure" effect observed also in LFoundry samples (Figure 7.10c). The evolution of charge collection profiles with fluence in different samples is consistent with the faster acceptor removal in materials with higher initial resistivity.

As described before, depletion depth can be estimated from the width of charge collection profile. In 20 and 50 Ωcm substrates the depletion depth is defined as FWHM of the profiles, while in 200 Ωcm and 1000 Ωcm the depletion depth is measured as FWHM of the left (surface) flank of the profiles to compensate for the small structure effect. Measurement uncertainty is estimated from the variance of depletion depth evaluated from the profile width at 40 % and 60 % of the maximal value instead. Measured depletion depths are shown in Figure 7.16. The data points were fitted with the function $w = w_0 + \sqrt{\frac{2e\epsilon_{\text{Si}}}{e_0 N_{\text{eff}}}} V_{\text{bias}}$ (Equation 7.1), taking into account the empirically established offset w_0 at 0 V. N_{eff} extracted as a free parameter from the fits is shown in Figure 7.17. N_{eff} of different materials converges towards the same value with increasing fluence as the initial acceptors get removed. In CHESS2 this occurs around the highest fluence of $2 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. The data

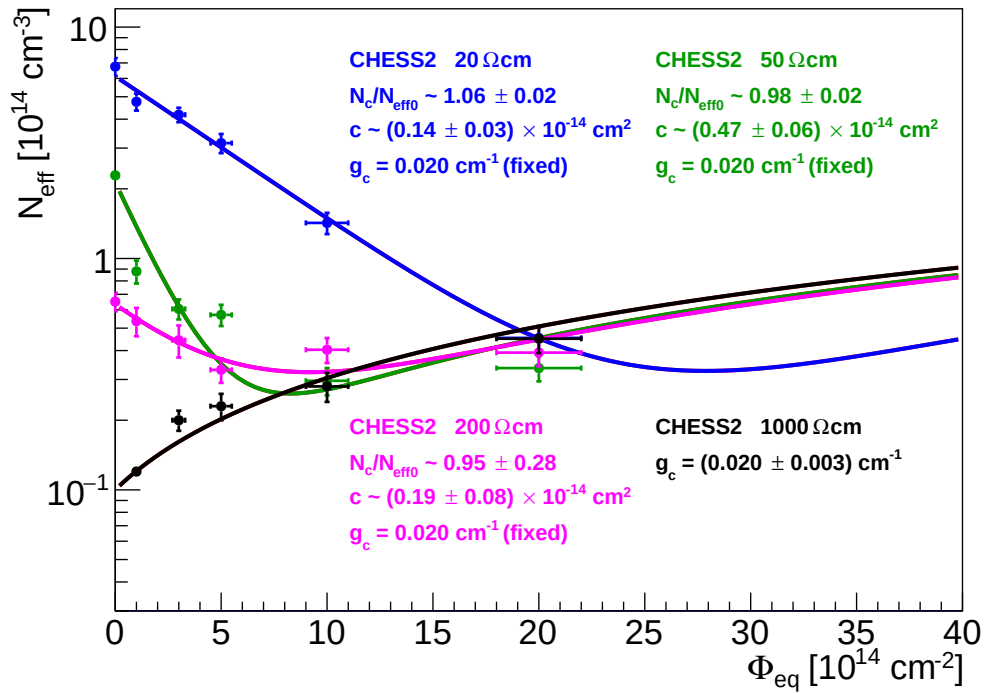


Figure 7.17: Evolution of N_{eff} with received neutron fluence in CHESS2 chips. Acceptor removal is observed in chips with the three lowest initial substrate resistivities. Data is fitted with equation 4.5. In samples with the highest initial resistivity only acceptor introduction term was taken into account, since initial acceptor removal is already completed below $1 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$.

for the 20, 50 and 200 $\Omega\text{ cm}$ material is fitted with the Equation 4.5 parametrising acceptor removal:

$$N_{\text{eff}} = N_{\text{eff},0}(1 - N_c/N_{\text{eff},0} \cdot (1 - e^{-c\Phi_{\text{eq}}})) + g_C\Phi_{\text{eq}},$$

with $N_{\text{eff},0}$, N_c and c as free parameters and $g_C = 0.02\text{ cm}^{-1}$ fixed to the literature value [66]. In all three samples the acceptor removal is complete, i.e. $N_c/N_{\text{eff},0} \approx 1$. The values of the acceptor removal coefficient c are $(0.14 \pm 0.03) \cdot 10^{-14}\text{ cm}^2$ (20 $\Omega\text{ cm}$), $(0.47 \pm 0.06) \cdot 10^{-14}\text{ cm}^2$ (50 $\Omega\text{ cm}$) and $(0.19 \pm 0.08) \cdot 10^{-14}\text{ cm}^2$ (200 $\Omega\text{ cm}$). These values are compatible with $c = (0.5 \pm 0.2) \cdot 10^{-14}\text{ cm}^2$ (50 $\Omega\text{ cm}$) and $c = (0.3 \pm 0.3) \cdot 10^{-14}\text{ cm}^2$ (200 $\Omega\text{ cm}$) measured with the ATLASpix pixel chip using the same substrate [94]. The value of c in the 200 $\Omega\text{ cm}$ material is comparatively small and less than in 50 $\Omega\text{ cm}$ material. This indicates a slow removal and hence a very constant depletion depth in this material. Removal coefficients for all three initial resistivities are by more than an order of magnitude smaller than in the high resistivity 2000 $\Omega\text{ cm}$ LFoundry sample ($c = 10.8 \cdot 10^{-14}\text{ cm}^2$), where removal is much faster. The acceptor removal term is omitted in the fit of the data for 1000 $\Omega\text{ cm}$ material ($N_c = 0$), due to the lack of measurements below the fluence of $1 \cdot 10^{14}\text{ n}_{\text{eq}}/\text{cm}^2$ which is the typical fluence where removal is completed in high resistivity material. Instead the data was fitted with the acceptor generation term g_C as a free parameter, yielding a value of $g_C = (0.020 \pm 0.003)\text{ cm}^{-1}$, which is consistent with literature.

Proton irradiation

Depletion depths in proton irradiated samples are shown in Figure 7.18. Compared to neutron irradiated samples the depletion depths are much larger, reaching over 100 μm at certain fluences in all samples. There is a significant difference in depletion depth of samples irradiated to fluences of $8.7 \cdot 10^{14}\text{ n}_{\text{eq}}/\text{cm}^2$ (CERN PS) and $7.8 \cdot 10^{14}\text{ n}_{\text{eq}}/\text{cm}^2$ (LANSCE). This is because the test structures in samples irradiated at LANSCE probably received a lower fluence than quoted. The test structures were positioned at the fringe of the beam during irradiation (Figure 7.14a) which makes the delivered fluence very sensitive to small displacements in the beam.

The values of N_{eff} from the fit of the Equation 7.1 to proton data are shown in Figure 7.19. In samples irradiated at PS the values of N_{eff} are well below the values in neutron irradiated samples, indicating a faster acceptor removal with protons. The effect is most prominent in 20 $\Omega\text{ cm}$ samples where N_{eff} in proton and neutron samples is different by a factor of 10. The values of N_{eff} in LANSCE samples are not always compatible with PS samples, since their fluences are probably

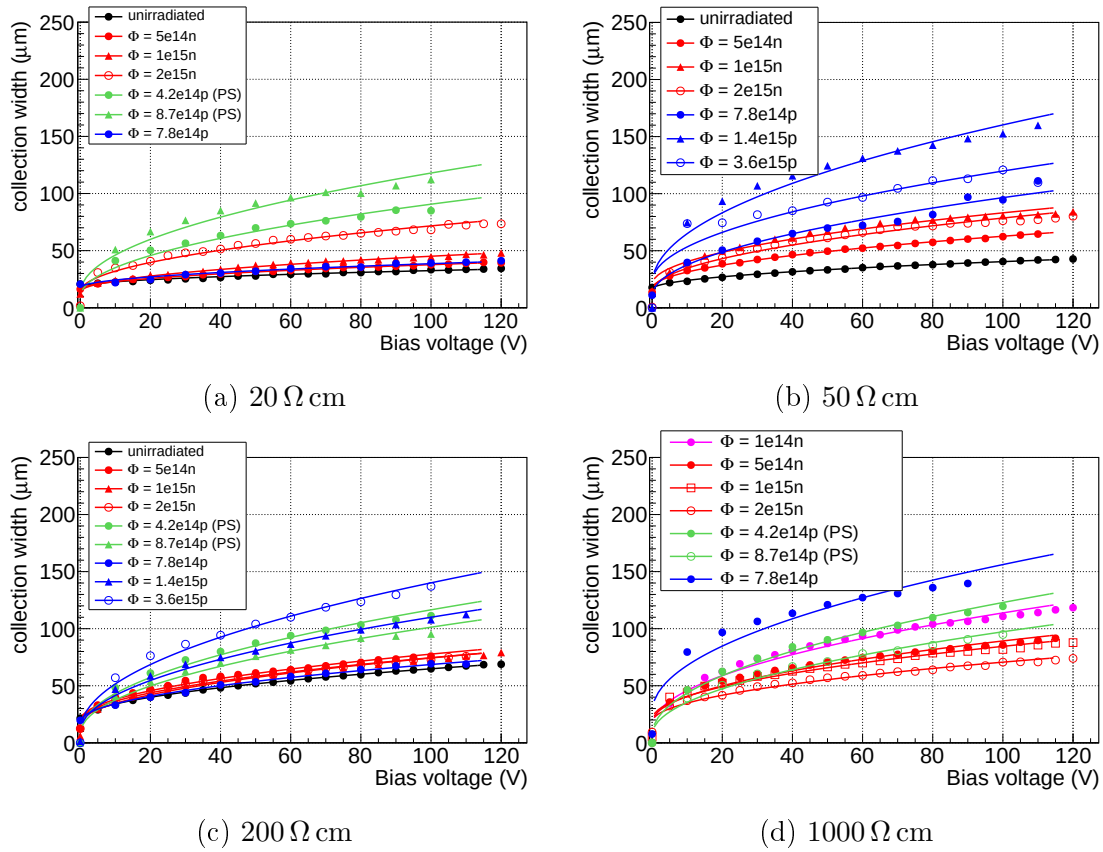


Figure 7.18: Depletion depth in CHES2 samples irradiated with protons at CERN PS (green) and LANSCE (blue), along with data for unirradiated (black) and neutron irradiated samples (red). Depletion depth in proton irradiated samples is larger than in neutron irradiated samples at similar fluences.

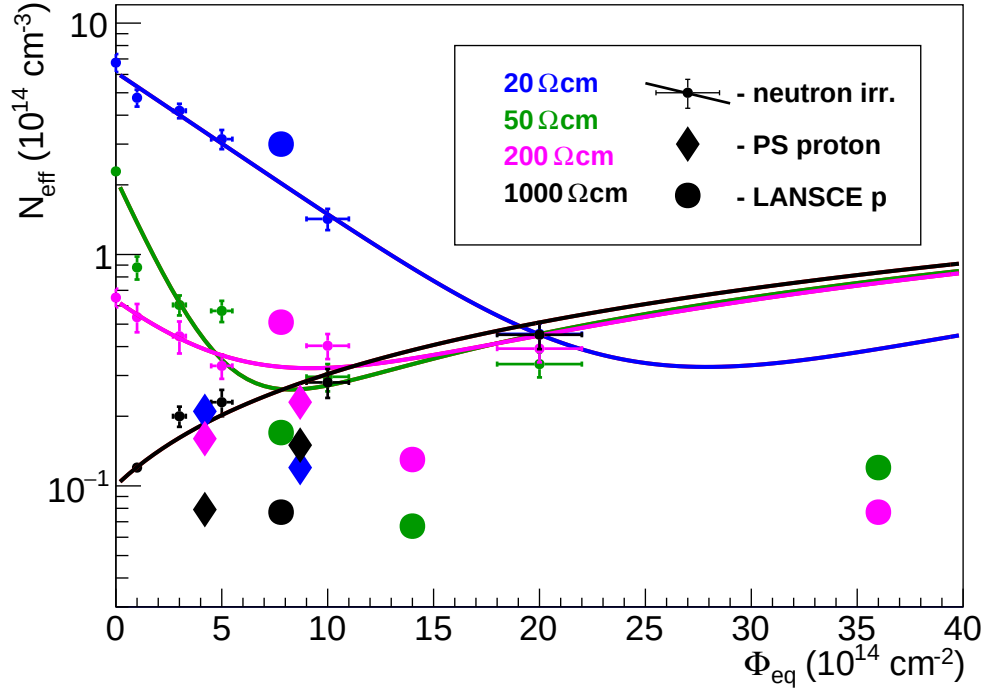


Figure 7.19: Evolution of N_{eff} with proton irradiation (large markers) compared to data for neutron irradiated samples. N_{eff} after proton irradiation is typically very low, less than at any point during neutron irradiation, indicating a fast removal and slower introduction rate g_C with protons. LANSCE fluences are probably overestimated as discussed in the text.

overestimated. Nevertheless, N_{eff} in LANSCE samples with initial resistivities of 50 and 200 Ωcm is significantly lower than neutron data, confirming the faster acceptor removal with protons. Moreover, the data at high fluences also indicates lower acceptor introduction rate g_C , which can be explained by the high concentration of oxygen in the Czochralski grown silicon of the substrate [63] (Figure 4.4). The values of N_{eff} in samples with initial resistivity of 1000 Ωcm irradiated to $4.2 \cdot 10^{14}$ and $7.8 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ are below the values extrapolated for an unirradiated sample, indicating acceptor removal even in this high resistivity material. Due to a small number of measurement points and a large uncertainty on fluence the acceptor removal model was not fitted to data.

7.3.2 ^{90}Sr measurements with CHES2

Charge collection measurements with the CHES2 chips are more difficult than with the LFoundry chip (Section 5.1), as the sensor depletion and hence available charge is smaller due to a lower substrate resistivity and lower bias voltages. Due to the low signal to noise ratio the mean collected charge has to be used instead of the MPV

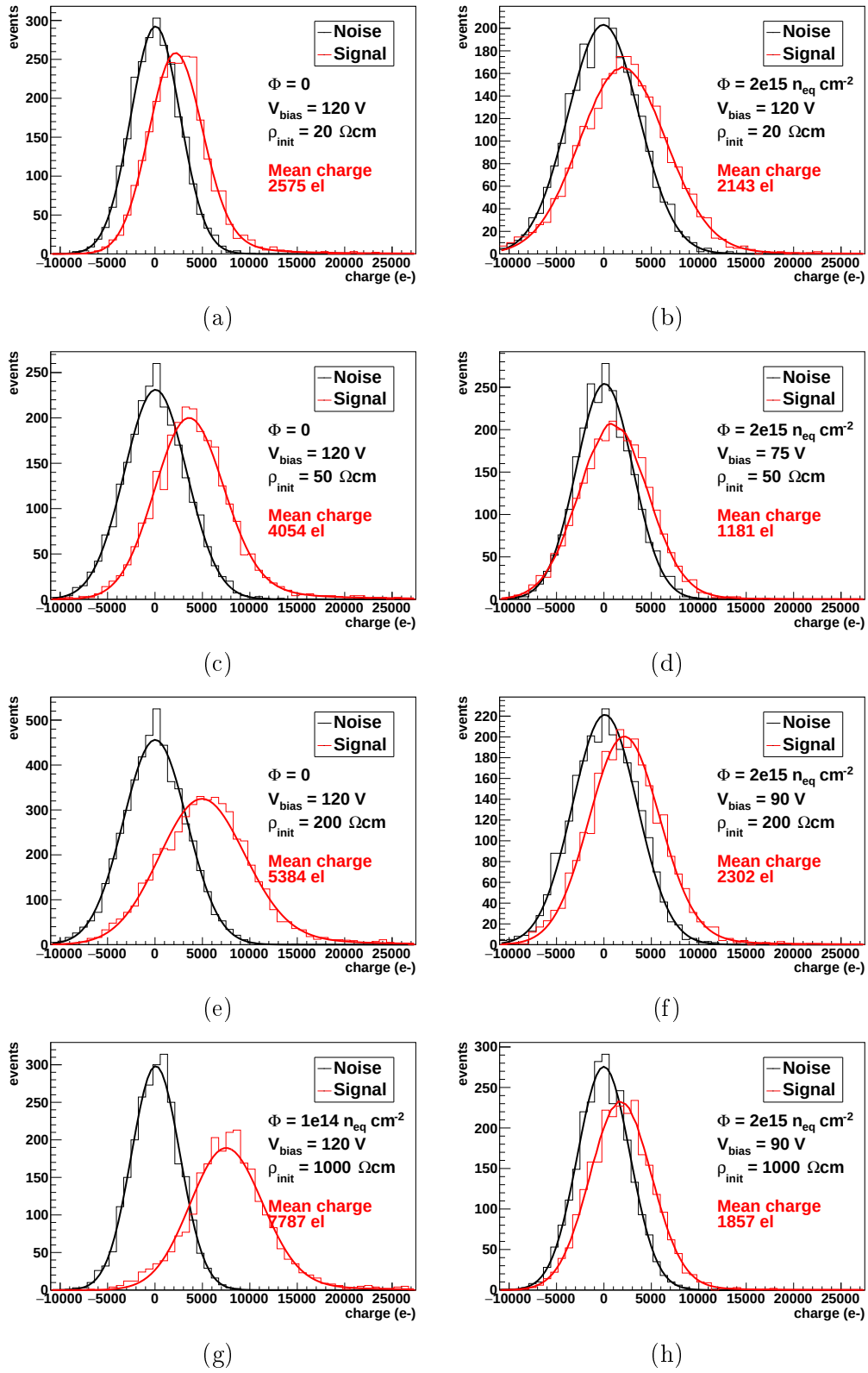


Figure 7.20: ^{90}Sr charge spectra measured with CHESS2 chips of different initial substrate resistivity before and after neutron irradiation to $2 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$.

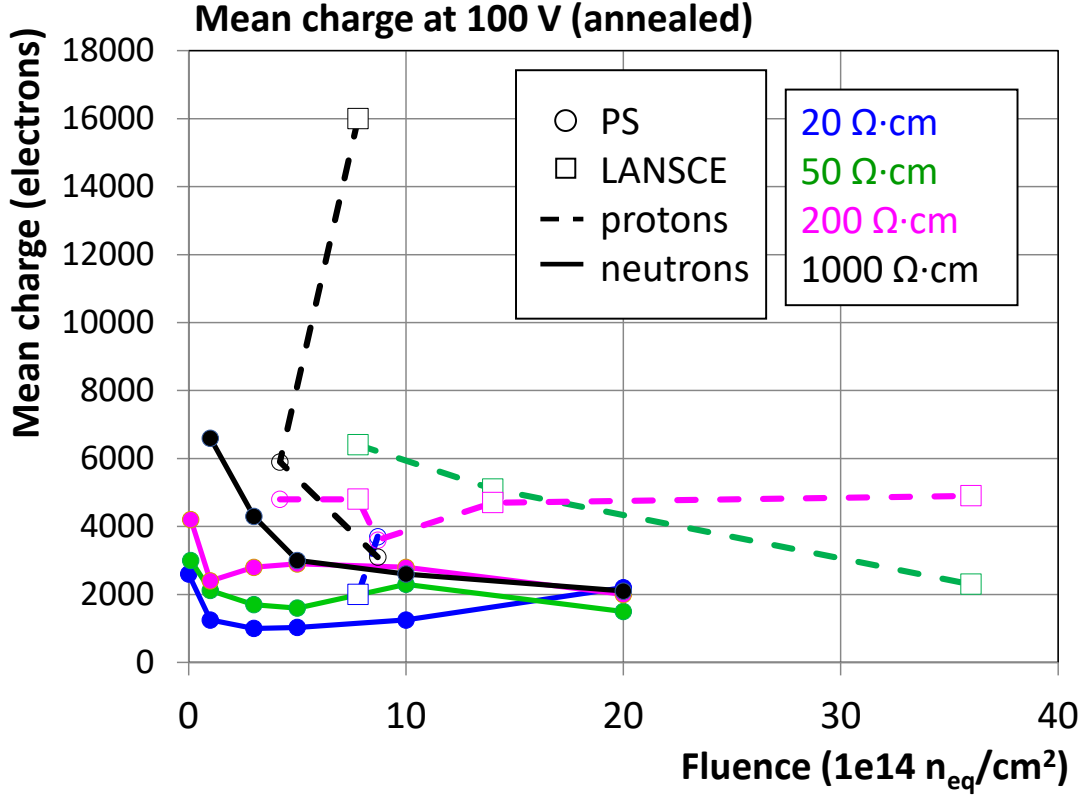


Figure 7.21: Mean charge deposited by a ^{90}Sr MIP in differently irradiated CHESS2 chips. Charge collected in proton irradiated samples is consistently larger than in neutron irradiated samples, and at certain fluences also larger than before irradiation. The 200 Ωcm substrate gives the most constant response with the measured charge never dropping below 2000 e^- . Based on LFoundry data (Section 7.2.4) and Edge-TCT measurements the amount of collected charge in pad structures can be significantly increased by biasing the sample via back plane.

values. The mean charge deposition with MIP-like ^{90}Sr electrons is $100 e^-/\mu\text{m}$. Examples of ^{90}Sr MIP spectra for unirradiated and neutron irradiated samples at a fluence of $2 \cdot 10^{15} n_{eq}/\text{cm}^2$ are presented in Figure 7.20 and show a clear degradation of collected charge after irradiation.

A summary of the collected charge for all samples and fluences for both proton and neutron irradiation is shown in Figure 7.21. The collected charge after proton irradiation is significantly higher than after neutron irradiation to the same fluence in all samples which is consistent with the larger depletion depths observed with Edge-TCT. After the first neutron irradiation step the collected charge reduces by $\approx 1000\text{--}2000 e^-$ with respect to unirradiated samples. This is because before irradiation a fraction of charge is collected by diffusion, but after the first fluence of $1 \cdot 10^{14} n_{eq}/\text{cm}^2$ this contribution is already completely suppressed. In neutron irradiated samples with initial resistivities of 20–200 Ωcm the collected charge temporarily increases at intermediate fluences due to acceptor removal and related increase of

depletion depth. The most consistent charge collection is observed in $200\ \Omega\text{cm}$ samples where a mean charge above 2000e^- is collected at all fluences. In samples with an initial resistivity of $2\text{k}\Omega\text{cm}$ a mean charge over 2000e^- is also measured at all fluences, but this material suffers an early electrical breakdown before irradiation. The sample also has to be designed for a larger amplitude dynamic range, since larger signals are expected before irradiation due to higher resistivity. A mean charge of 2000e^- corresponds to a depletion depth of $20\ \mu\text{m}$, which does not agree with depletion depths exceeding $50\ \mu\text{m}$ measured by Edge-TCT. This inconsistency can be attributed to the top biasing scheme and was also observed in LFoundry samples (Section 7.2.4). It is expected that more charge will be collected with a "real" pixel detector where pixels are not connected together, since the weighting field in such devices is more favourable.

7.4 Results with X-FAB XTB02

The test chip X-FAB XTB02 is produced in SOI technology (Chapter 5.5) on a p-type substrate with an initial resistivity of $100\ \Omega\text{cm}$. The test structure 2A investigated in this work (Figure 7.22) is a 4×4 pixel array with a pixel size of $110\ \mu\text{m} \times 100\ \mu\text{m}$ [124]. The n-type collection electrodes underneath the buried oxide layer (BOX) have a size of $40\ \mu\text{m} \times 50\ \mu\text{m}$. The output signals are routed to two separate bond pads, one for a single central pixel and the other one for the remaining 15 pixels. Two additional wire bond contacts are used for biasing of the p-wells with CMOS electronics (called LOGIC layer), and the P-FIELD structure used for inter pixel insulation. The chip has a thickness of $700\ \mu\text{m}$ with no processed back plane. The sensor can be biased to a maximal bias voltage of 300V using the outermost guard ring on the sample surface as the bias electrode. In a standard biasing configuration the collecting n-well and the LOGIC layer were biased to the same potential, while the P-FIELD structure was floating. Tests with different biasing schemes are presented later in the chapter. A single sample available for tests was progressively irradiated with neutrons in Ljubljana TRIGA reactor in six steps up to a final total fluence of $1 \cdot 10^{16}\text{ n}_{\text{eq}}/\text{cm}^2$. Measurements were carried out after standard annealing (80 min at 60°C) after every fluence step [124].

Measurement of depletion depth and estimation of N_{eff}

Edge-TCT charge collection profiles at the bias voltage of 300V are shown in Figure 7.23a and display a behaviour typical for acceptor removal. The width (FWHM)

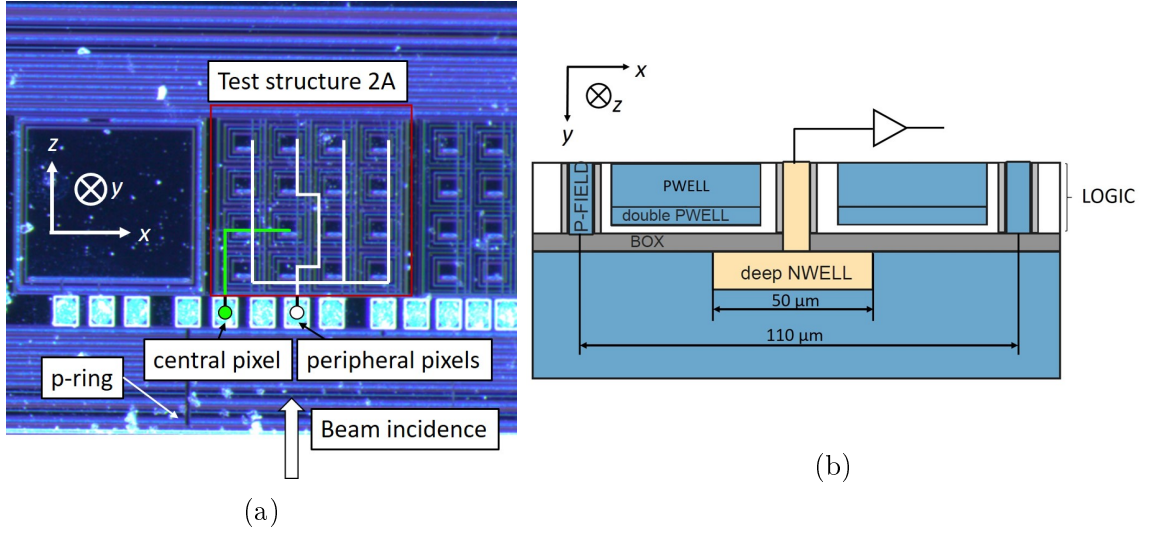
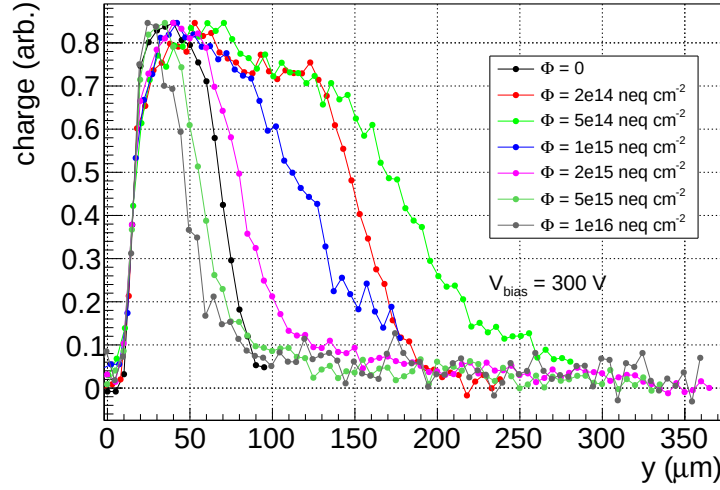


Figure 7.22: X-FAB XTB02 chip: a) pixel array 2A; b) schematics of the pixel [100]. The P-FIELD structure and the layer housing the p-wells (LOGIC) can be biased separately [124].

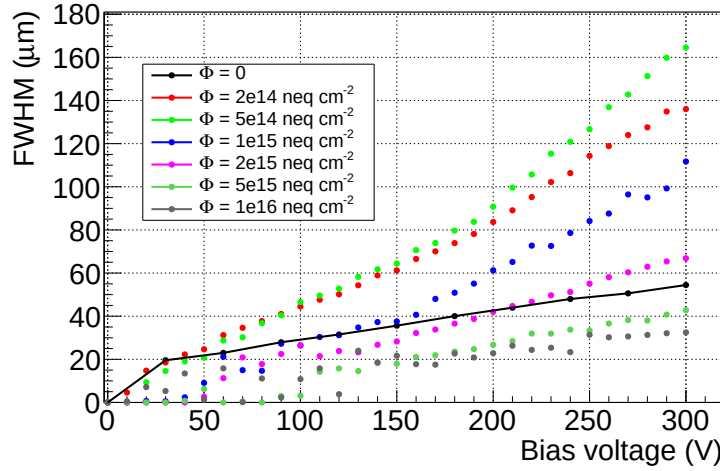
of the profile increases from $\approx 50 \mu\text{m}$ before irradiation to the maximal width of $\approx 150 \mu\text{m}$ after a fluence of $5 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$, at which effective space charge concentration stops falling due to initial acceptor removal. At higher fluences the width starts to shrink again due to additional space charge introduction, reaching $\approx 30 \mu\text{m}$ at the final fluence of $1 \cdot 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$. Depletion depth estimated as FWHM of charge collection profiles is shown in Figure 7.23b. In the unirradiated samples the depletion depth scales approximately with $\sqrt{V_{\text{bias}}}$ which is consistent with the abrupt junction approximation. However, this is not the case in irradiated samples, where depletion zone grows faster than $\sqrt{V_{\text{bias}}}$. Moreover, at fluences above $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ a significant depletion zone is only detected above a threshold voltage of $\sim 30 \text{ V}$. The reason for this behaviour is not understood, but it is probably related to the effects of electric field generated by charge trapped in the BOX as a consequence of irradiation. Since the data does not follow the abrupt junction model, an approximation is used to estimate the space charge concentration: N_{eff} is extracted from the formula 3.8 evaluated at the maximal bias voltage of 300 V :

$$w = \sqrt{\frac{2\epsilon\epsilon_{\text{Si}}}{e_0 N_{\text{eff}}} V_{300 \text{ V}}}. \quad (7.3)$$

Applying the above procedure to measurements with the unirradiated sample yields a value of $N_{\text{eff},0} = 1.3 \cdot 10^{14} \text{ cm}^{-3}$ which is consistent with the $100 \Omega \text{ cm}$ resistivity of the substrate. Extracted values of N_{eff} are shown in Figure 7.24 together with the values for LFoundry CCPD_LF (high substrate resistivity) [117] and ams CHESS (low substrate resistivity) [72] for comparison. The XTB02 produced on an intermediately resistive material features a behaviour midway between the other two sam-



(a)



(b)

Figure 7.23: Measurements of depletion depth with X-FAB XTB02: a) charge collection profiles at 300 V. Sample surface is at $y = 20 \mu\text{m}$; b) dependence of depletion depth on bias voltage. Except in unirradiated sample the behaviour does not follow the $\sqrt{V_{\text{bias}}}$ dependence. Instead, N_{eff} was estimated from the depletion depth at $V_{\text{bias}} = 300 \text{ V}$ [124].

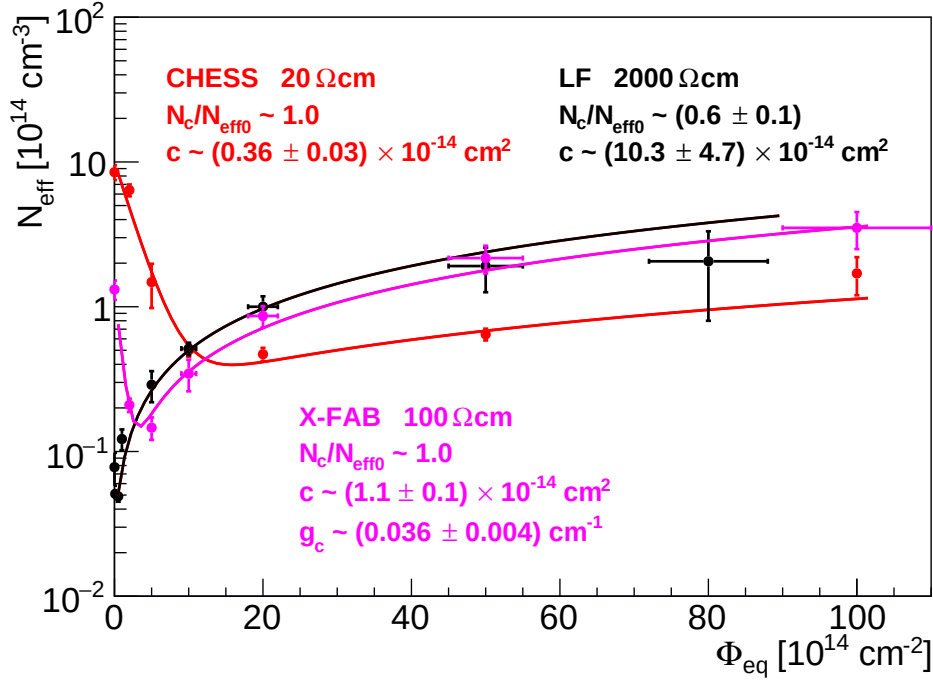


Figure 7.24: Evolution of N_{eff} with neutron fluence in X-FAB XTB02 [124]. Two other CMOS prototypes are included for comparison [72, 117].

ples. The initial acceptor removal is completed around a fluence of $5 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$ resulting in N_{eff} reduced by a factor of 10 from the initial value. At higher fluences the space charge introduction rate is similar to the LFoundry CCPD_LF. The data were fitted with the acceptor removal parametrisation 4.5:

$$N_{\text{eff}} = N_{\text{eff},0}(1 - N_c/N_{\text{eff},0} \cdot (1 - e^{-c\Phi_{\text{eq}}})) + g_C\Phi_{\text{eq}},$$

with $N_c/N_{\text{eff},0}$, c and g_C as free parameters. The results of the fit indicate a complete acceptor removal ($N_c/N_{\text{eff},0} = 1$) with a removal constant of $c = (1.1 \pm 0.1) \cdot 10^{-14} \text{ cm}^2$. Since the procedure of determining N_{eff} from Equation 7.3 depends on an arbitrarily selected voltage of 300 V, the values of N_{eff} are ambiguous. However, the evolution of N_{eff} with fluence shows the same trend for any voltage and extracted value of c using, for example, a reference voltage of 200 V differs from the above value by less than 10%. The space charge introduction rate $g_C = (0.036 \pm 0.003) \text{ cm}^{-1}$ is larger than the literature value of 0.02 cm^{-1} [66]. This could be due to a systematic offset introduced by the procedure to calculate N_{eff} from depletion depth at 300 V, since the sample does not follow the abrupt junction approximation. However, a similar value was also measure in LFoundry samples.

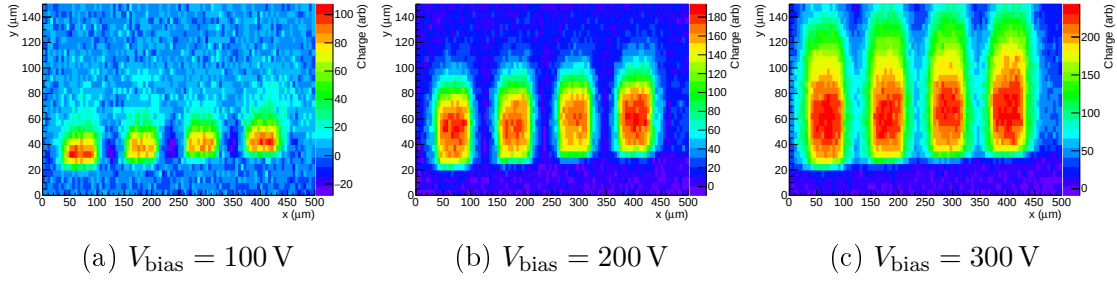


Figure 7.25: Two dimensional Edge-TCT scans on XTB02 at different bias voltages. The sample is irradiated to a fluence of $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. Chip surface is at $y = 25 \mu\text{m}$.

Two dimensional Edge-TCT measurements

Figure 7.25 shows an example of a two dimensional charge collection map of a sample irradiated to a fluence of $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ at bias voltages between 100 V and 300 V. The measurement demonstrates the large increase of depletion depth with bias voltage which can also be seen in Figure 7.23b. More importantly, the measurement reveals efficiency gaps between pixels whose width coincides with the size of the area not covered by the charge collecting n-well implant. Further scans at different fluences are shown in Figure 7.26. Efficiency gaps were observed after all irradiation steps, but not in an unirradiated sample. The efficiency gaps are a problem in detectors that target near 100 % particle detection efficiency.

The efficiency gaps are related to the SOI pixel architecture with the logic layer housing the electronics acting as a parasitic collecting electrode. Although the logic layer is separated from the bulk by the buried oxide (BOX) it can modify the electric field in the sensor and collect charge similar to an AC coupled detector. Since the LOGIC node is not connected to the readout, the collected charge is not detected. This hypothesis was verified by reading out the induced current on the LOGIC contact, which yielded an inverse of the charge collection maps shown in Figures 7.25 and 7.26 with highly efficient regions in between pixel implants.

The electrons collected by LOGIC finish their drift on the BOX layer where the charge transport effectively stops. Accumulated electrons then slowly discharge via the collection n-wells. The exact mechanism of charge transport on the BOX was not investigated in this thesis, but measurements indicate it takes place on a time scale of $1 \mu\text{s}$ and it is sensitive to irradiation. This can be observed in waveforms in Figure 7.27 showing induced pulses on a μs time scale. The current from the carrier drift in the substrate takes place in the first 10 ns and is truncated from the figure as it is by a factor 100 larger from the scale of the diagram. In the first 10 ns the signal from an efficient region directly underneath the BOX (red) is unipolar with

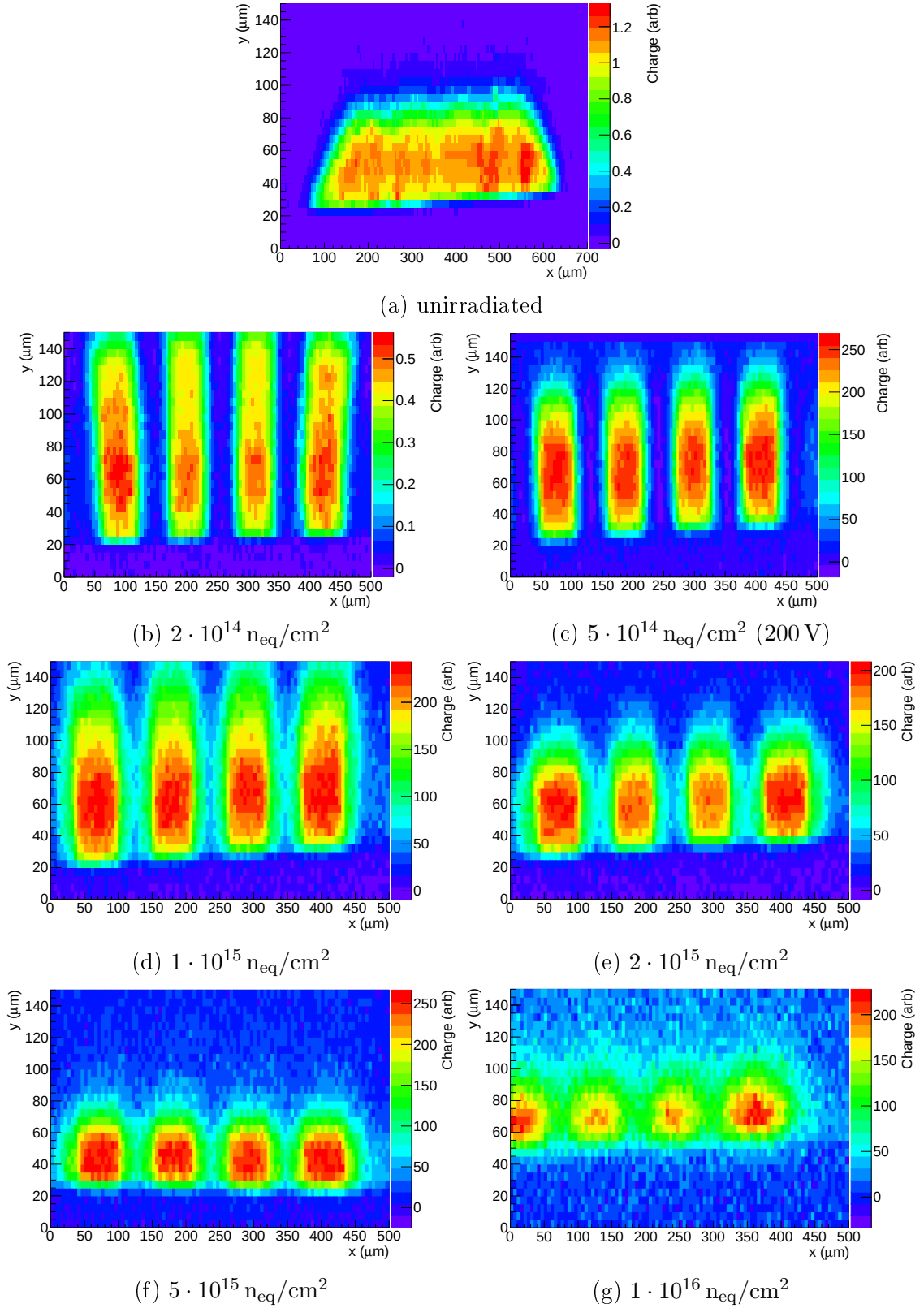


Figure 7.26: Two dimensional Edge-TCT scans on XTB02 irradiated to different fluences. Measurements are made at the maximal bias voltage of 300 V (except at the fluence of $5 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$).

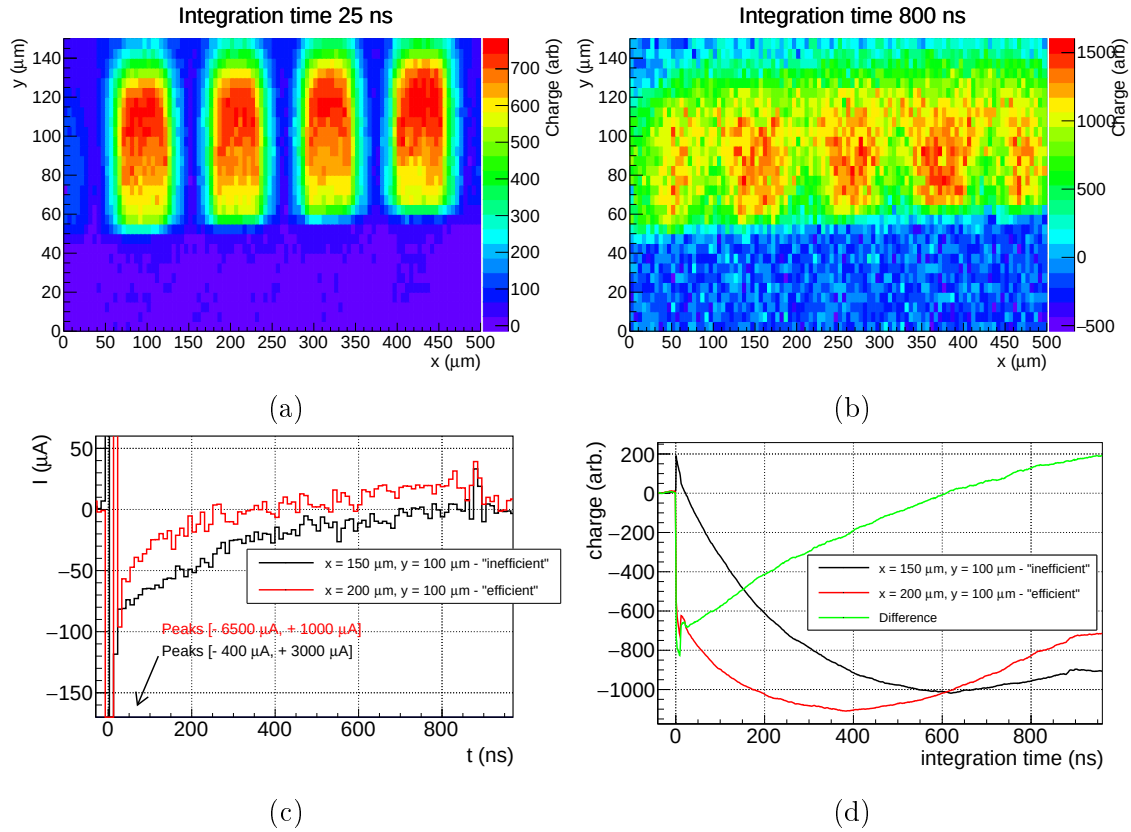


Figure 7.27: Dependence of charge collection uniformity on integration time in XTB02 irradiated to a fluence of $5 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$. Figures a) and b) show charge collection maps at 25 ns and 800 ns integration times with significantly better uniformity after longer integration. Figure c) shows induced pulses from an efficient (red) and inefficient region (black) from figure a). The current in first 10 ns is truncated. Figure d) shows the integrals of both pulses depending on integration time and their difference (green) [124].

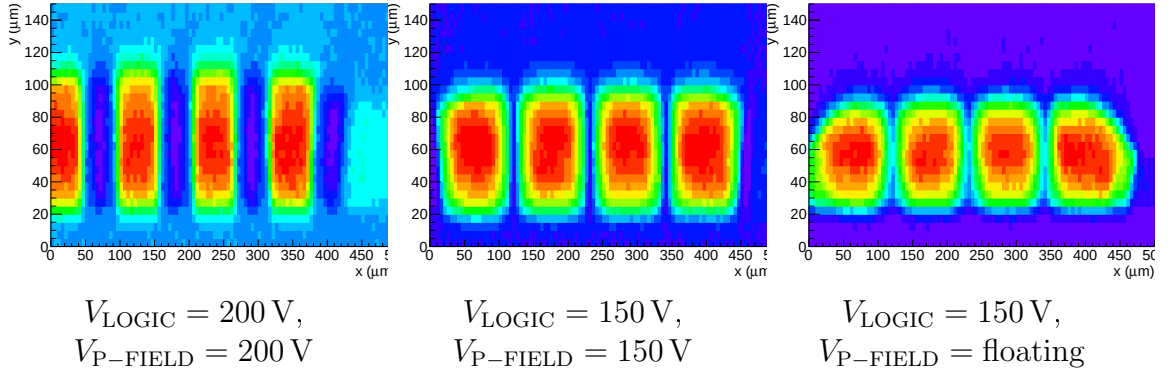


Figure 7.28: Charge collection maps in XTB02 for different configurations of bias voltages on the LOGIC and P-FIELD implants. Collecting n-wells are biased to 200 V. Different configurations impact the size of efficiency gaps between pixels as well as depletion depth. Sample was irradiated to a fluence of $5 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$.

an integral corresponding to the collected charge, while the bipolar signal from the inefficient region (black) has a vanishing integral. However, over a period of $1 \mu\text{s}$ the current after charge injection in inefficient region is consistently larger, leading to both integrals equalising after an integration time of 600 ns. At longer integration times the integral from an inefficient region even surpasses the integral from an efficient region. This leads to a significantly better charge collection uniformity on larger time scales. The reason for a sizeable discharge current even after injection into the efficient region is the segmentation into pixels in z -direction (i.e. along the laser beam which extends under several pixels in Edge-TCT configuration) with the inefficient volume between the pixels producing the discharge current. The inter-pixel efficiency gaps are not present in the unirradiated sample. The probable reason is that the BOX layer acquires a positive space charge due to the TID during irradiation. Positively charged BOX attracts negatively charged electrons and effectively stops their drift. In the original unirradiated material BOX is not charged, hence the electrons can freely drift to the collection n-well.

A possibility to mitigate the effects of parasitic charge collection is operation at a different biasing configuration. If the logic layer is biased below the n-well potential the electric field lines close to the surface bend toward the collection n-wells resulting in a higher efficiency. Figure 7.28 shows tests with different bias voltages on LOGIC and P-FIELD structures. Biasing LOGIC 50 V below the n-well potential results in significantly smaller efficiency gaps, while the biasing of P-FIELD also slightly modifies the shape of the sensitive region. Besides the smaller efficiency gaps the alternative biasing schemes also result in smaller depletion depths. This is probably related to modifications of the electric field caused by charge trapped in the BOX.

It has to be noted that the above measurements were made with a passive chip

with no implemented readout electronics. Operation in one of the alternative biasing configurations is more complicated in an active device, since the n-well signals have to be routed to the input transistor, resulting in large potential differences between both nodes (~ 50 V in the above case). This could be overcome by AC coupling of the readout electrode to the electronics. Viability of an AC design sustaining potential difference of the order of 50 V between the collection electrode and the electronics has been demonstrated for example in the TowerJazz MonoPix CMOS chip [83]. Another promising SOI concept is double SOI (DSOI) which employs two silicon-on-insulator layers separated by two BOX layers [125, 126]. The intermediate SOI layer screens the substrate from the top SOI housing the electronics, resulting in reduced cross talk and parasitic charge collection. This approach has not been investigated in the scope of ATLAS CMOS programme.

7.4.1 Simulation of charge collection in a SOI device

The hypothesis explaining the origin of efficiency gaps in XTB02 by parasitic charge collection of the SOI layer was tested with a simulation of charge collection using the KDetSim simulation tool [127, 128]— a ROOT based library for signal simulation in a fixed detector geometry. KDetSim takes the electrode configuration, boundary conditions and (contrary to several other simulation tools) space charge concentration as inputs and calculates the electric and weighting potentials by numerically solving the corresponding Poisson and Laplace equations on an orthogonal mesh using a finite element method. Local modifications of the electric field due to injected charge (plasma effect) are neglected. Injected charge is divided into basic units called buckets, which are individually propagated through the detector as point charges, taking into account the local electric field and random diffusion. Each bucket contributes to the induced current according to the Shockley-Ramo theorem. Signals induced by electrons and holes are treated separately and can be summed in the end.

Simulation of an SOI device was carried out in a simplified geometry (Figure 7.29) to reduce complexity while maintaining the main characteristics of the problem. The SOI device in simulation is translation invariant in z -direction, i.e. has a strip geometry, with three readout electrodes with a size of $50\text{ }\mu\text{m}$ and a pitch of $100\text{ }\mu\text{m}$. Above the electrodes a $1\text{ }\mu\text{m}$ thick insulating layer and a $3\text{ }\mu\text{m}$ thick biased silicon layer representing the BOX and LOGIC layers are situated. The charge carrier mobility in the BOX layer is set to zero, so that particles entering the BOX are stopped. Readout electrodes and LOGIC can be biased separately, while a conductive back plane at a depth of $100\text{ }\mu\text{m}$ acts as a back bias contact. The XTB02 has a

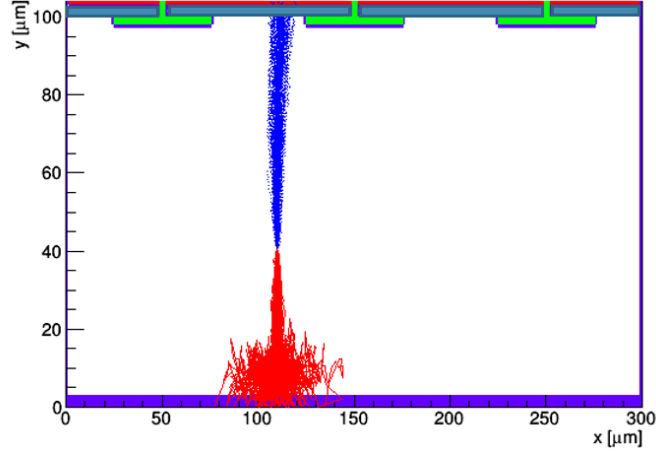


Figure 7.29: SOI device simulated in KDetSim. Drift of electrons (blue) and holes (red) are shown after point injection at $y = 40 \mu\text{m}$. Device is partially depleted, resulting in diffusion of holes once they leave the depleted zone ($y < 20 \mu\text{m}$). Collection electrodes (green) and LOGIC layer (red, $y = 105 \mu\text{m}$) can be biased to different potentials.

thickness of $700 \mu\text{m}$ and is biased from the top, however for the purpose of the simulation both configurations were treated as equivalent. This assumption is justified if conductivity of undepleted silicon is sufficiently high that the entire substrate is at the same electrical potential. Measurements with LFoundry chips in section 7.2.4 show that this is not entirely correct. However, we believe that this has a minor influence on the effects investigated in this simulation. Mirror boundary conditions with electric field lines parallel to detector edges were set on the boundaries of the simulated volume. The space charge concentration was defined in accordance with the abrupt junction approximation with a constant concentration of $1.1 \cdot 10^{14} \text{ cm}^{-3}$ in the depleted region and zero otherwise. The boundary of the depleted region was determined as the point where the electric field reaches zero. The electrical potential on the sensing electrodes were set to zero, while the bias voltage on the back plane was arbitrarily set to -130 V resulting in partial depletion with the depletion depth of $80 \mu\text{m}$. Three different configurations were selected for biasing of the LOGIC layer: 0 V (same potential as collection electrodes), -50 V and floating.

Charge collection efficiency was evaluated by generating 100 charge buckets with a point injection and integrating the induced pulses over 25 ns . Charge trapping was neglected as typical collection times were short (below 2 ns). The point of injection was varied with a step size of $5 \mu\text{m}$ in x and y directions to generate two dimensional charge collection maps shown in Figure 7.30. The results are consistent with Edge-TCT measurements. When LOGIC is biased to the same potential as the collection electrodes, electron drift trajectories are almost perpendicular to the detector surface and hence often end with on the BOX, resulting in efficiency gaps.

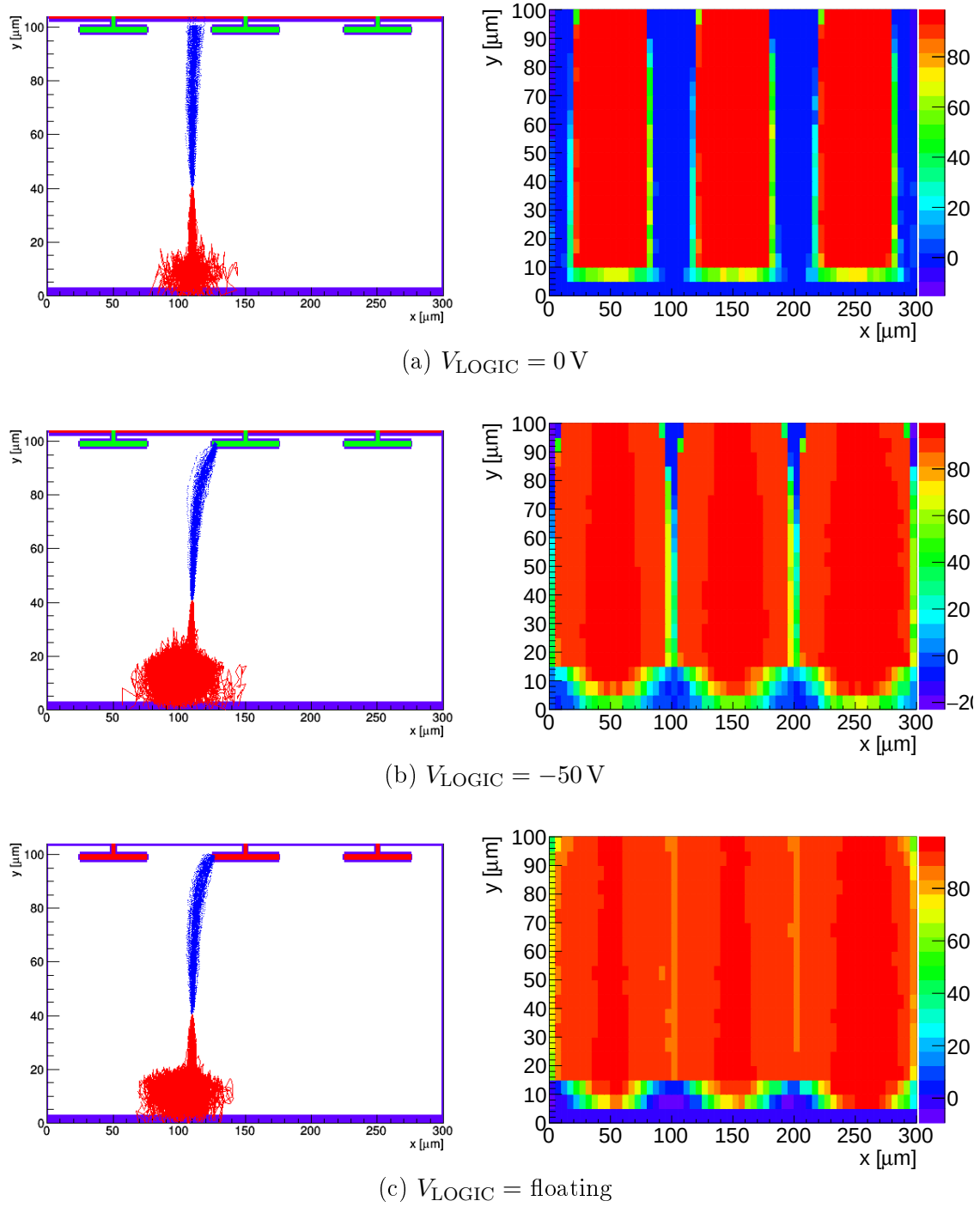


Figure 7.30: Simulated charge carrier trajectories and charge collection efficiency in a SOI device for different biasing configurations of the LOGIC layer. Collection electrodes are at zero electric potential, while the back plane is at -130 V .

When LOGIC is biased 50 V below the n-well potential or left floating, the charge carrier trajectories bend in the vicinity of the electrodes, thus improving charge collection efficiency. However, the changes in depletion depth observed at different biasing configurations in Figure 7.28 were not reconstructed in the simulation.

7.5 Results with TowerJazz Investigator

Detectors produced in TowerJazz CMOS technology use a small electrode pixel design which relies on small pixel sizes in the range of 20–50 μm and small depletion depth of $\approx 30 \mu\text{m}$. Since the beam spot size in conventional TCT measurements has a FWHM of $\approx 10 \mu\text{m}$, the measurements are made on the limit of the resolution. For this reason TCT measurements targeted simpler goals, focusing on qualitative assessment of charge collection within pixels and its evolution with irradiation.

Edge-TCT measurements in this thesis were made with the TJ Investigator chip produced in modified TowerJazz process with a 30 μm thick sensing layer and an additional low doped n-type layer to enhance charge collection (discussed in Section 5.2). The chip has a size of 5.722 mm $\times$ 5 mm and consists of 2×134 independent structures called mini matrices (Figure 7.31a) which employ different pixel designs varying in pixel pitch, the size of the collection electrode, the distance between the electrode and the surrounding electronics (so called spacing) and the shape of the deep p-well which shields the n-wells with transistors [90, 92]. Each mini matrix consists of an array of 10×10 pixels equipped with a charge sensitive amplifier (current integrator). The central 8×8 pixels can be read out (Figure 7.31b), while the outermost pixels are used to eliminate edge effects – they are operated under the same conditions as the rest, but are not read out. All mini matrices are connected in parallel to 64 readout wire bonds on the chip (one per pixel). A configurable internal selector circuit is used to switch between the mini matrices, connecting the output signals from a single matrix at a time to the output. The array of 134 matrices on the top side of the chip is mirrored on the bottom side with an additional circuitry which allows electronic charge injection in the pixel. This feature does not work due to connection problems and was not used in testing.

Chips come in two versions with differently doped n-type layer (high and low doping concentration) which is expected to affect charge collection efficiency. Measurements were made with unirradiated chips and chips irradiated with neutrons in Ljubljana to four different fluences between $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ and $1 \cdot 10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$. The investigated structures were pixel arrays 2 and 129 with pixel sizes of $20 \mu\text{m} \times 20 \mu\text{m}$

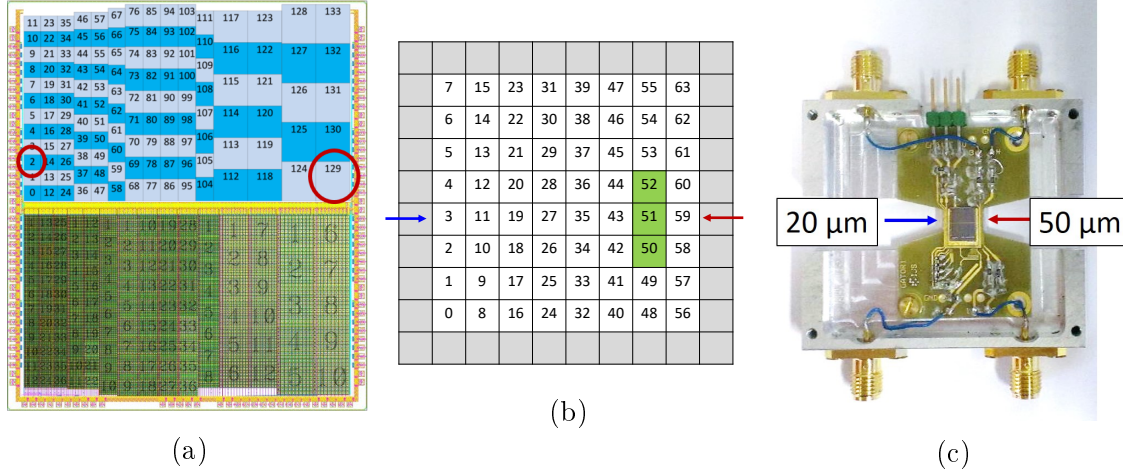


Figure 7.31: TowerJazz Investigator chip: a) chip schematics indicating investigated pixel arrays 2 (pixel size of $20\ \mu\text{m} \times 20\ \mu\text{m}$) and 129 ($50\ \mu\text{m} \times 50\ \mu\text{m}$); b) schematics of a 10×10 pixel array. Pixels in the outermost frame cannot be read out, while the outputs of central 64 pixels are routed out in parallel. In Edge-TCT measurements pixels 50, 51 and 52 were read out in separate channels; c) chip mounted on an Edge-TCT test board. Arrows indicate the laser beam direction during tests of matrices 2 and 129.

and $50\ \mu\text{m} \times 50\ \mu\text{m}$ respectively (Figure 7.31c). Pixels in these arrays have the largest spacing between the readout electrode and the surrounding p-well, which is considered to be the worst case in terms of charge collection due to the difficult lateral depletion of the pixel. The pixel arrays consist of 10×10 pixels of which three neighbouring pixels were read out in three separate channels. The biasing voltage for the depletion of sensing epitaxial layer was applied between the collection electrode, which is at $\sim 0\text{ V}$ potential, and the back side of the epitaxial layer, as well as the p-well surrounding the collection electrode. Both structures can be biased to a maximal voltage of -6 V , which is significantly less than in other CMOS samples.

An example of an Edge-TCT waveform showing the output of the charge sensitive amplifier (integrator) in the pixel is shown in Figure 7.32. A periodic reset signal to prevent output saturation takes place before $t = -150\text{ ns}$. The oscillation following the reset signal is stabilised around $t = -100\text{ ns}$. The output signal then linearly falls due to the integration of a constant leakage current. Charge injection with the laser pulse occurs at the time $t = 25\text{ ns}$, resulting in a voltage step (modified by the transfer function of the electronics). The size of the signal can be determined from a linear fit of the waveform before and after charge injection using the slope of the first line for both fit functions. Signal size is calculated from the difference in the vertical intercept of both fit results. The output signals from the chip were connected directly to an oscilloscope without a second stage amplifier. A $1\text{ M}\Omega$ input impedance had to be used in order not to overload the output current drivers on

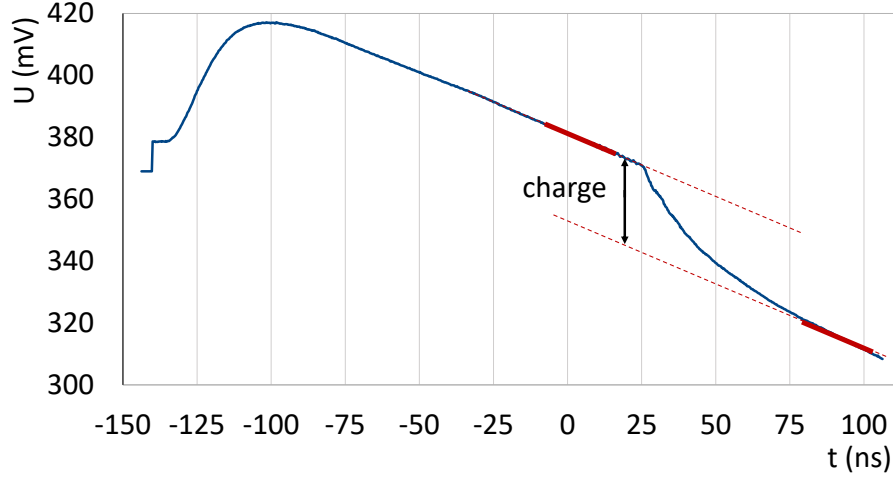


Figure 7.32: Output of the charge sensitive amplifier in TowerJazz Investigator. At $t = -150$ ns the amplifier is reset resulting in output oscillation until $t = -100$ ns. The slope in the time interval $[-100$ ns, 25 ns] is due to integration of the leakage current. Charge injection takes place at $t = 25$ ns causing the step in the output waveform. Collected charge is obtained from a linear fit of the waveform before and after charge injection using the same slope for both lines. Collected charge is proportional to the difference of the two intercepts.

the chip.

Charge collection was investigated with two dimensional Edge-TCT scans. Figure 7.33 shows a measurement on the $20\text{ }\mu\text{m} \times 20\text{ }\mu\text{m}$ pixel size array with a sample irradiated to $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ and biased to the maximal voltage of -6 V. Signal maps of individual channels show a clear separation of pixels. Summed signals from the three pixels are shown in Figure 7.33d. In x -direction the resulting structure features a relatively uniform response within the positional resolution of the measurement. In y -direction the highest response comes from a narrow region with a thickness of $10\text{ }\mu\text{m}$. This is at least in part because on the top and bottom edge the relatively large beam spot is not fully contained within the epitaxial layer, therefore producing less signal in the sensitive region. The dimensions of the observed signal region roughly coincide with the size of three pixels ($60\text{ }\mu\text{m}$ wide and $30\text{ }\mu\text{m}$ deep).

Figures 7.34 and 7.35 show charge collection maps in $50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$ pixels in samples with a low and highly doped n-type layer respectively irradiated to $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. A significant increase of signal size with bias voltage can be observed in both samples, indicating that adapting the design to accommodate even higher bias voltages would benefit charge collection. In y -direction both samples feature a two peak structure with a high collected charge in front and in the back side of the depletion zone and a less efficient region in between (Figures 7.34f and 7.35f). The effect is more pronounced in the sample with a low doped n-layer. Measurements

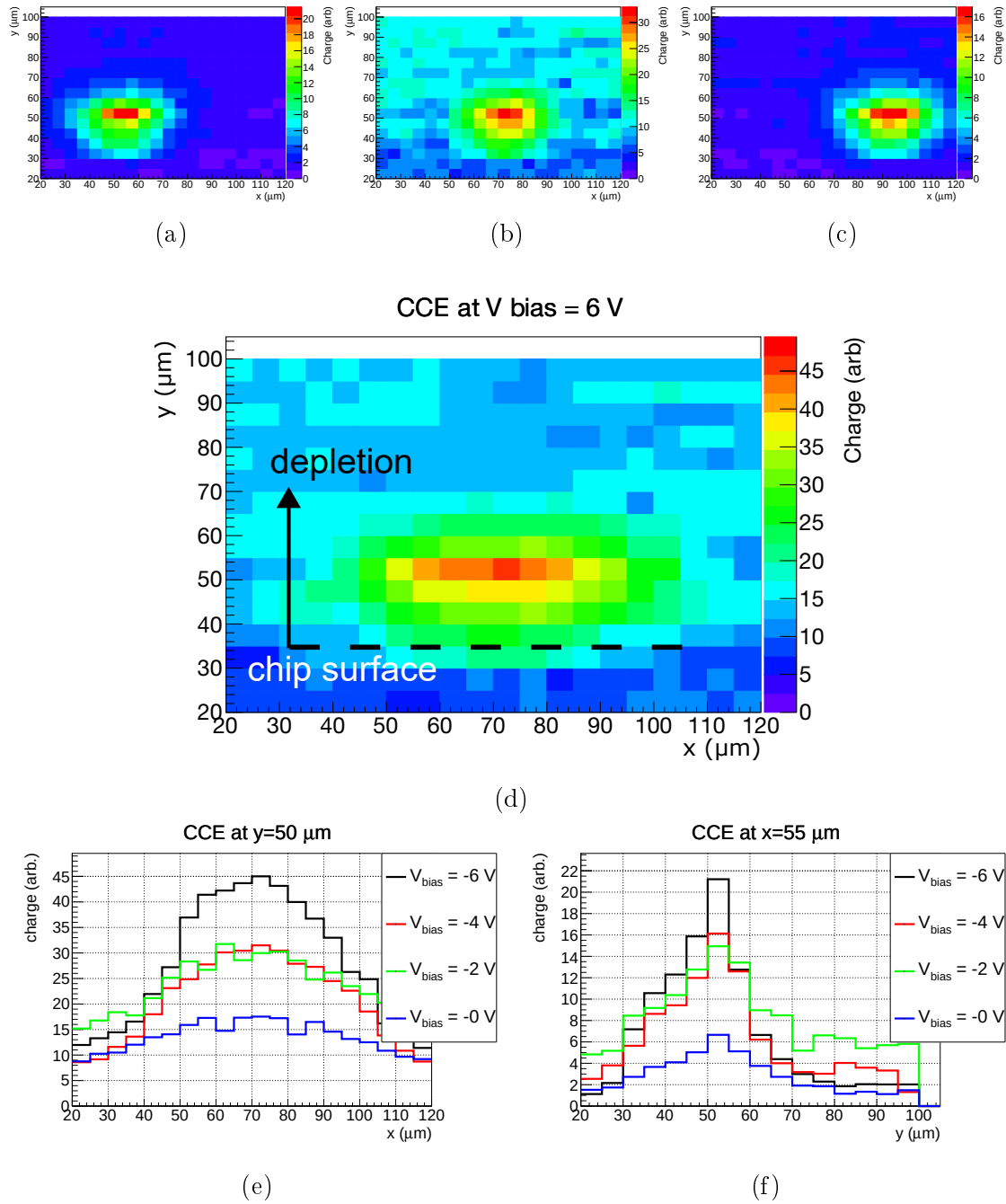


Figure 7.33: Edge-TCT scan on $20 \mu\text{m} \times 20 \mu\text{m}$ pixels of a $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ sample (low n-layer doping) biased to 6 V. Figures a), b) and c) represent signals from individual pixels, which are summed up in Figure d). The size of the signal region of $60 \mu\text{m} \times 30 \mu\text{m}$ is consistent with the device dimensions. Figures e) and f) are cross sections of the 2-dimensional signal map along x and y directions for different bias voltages.

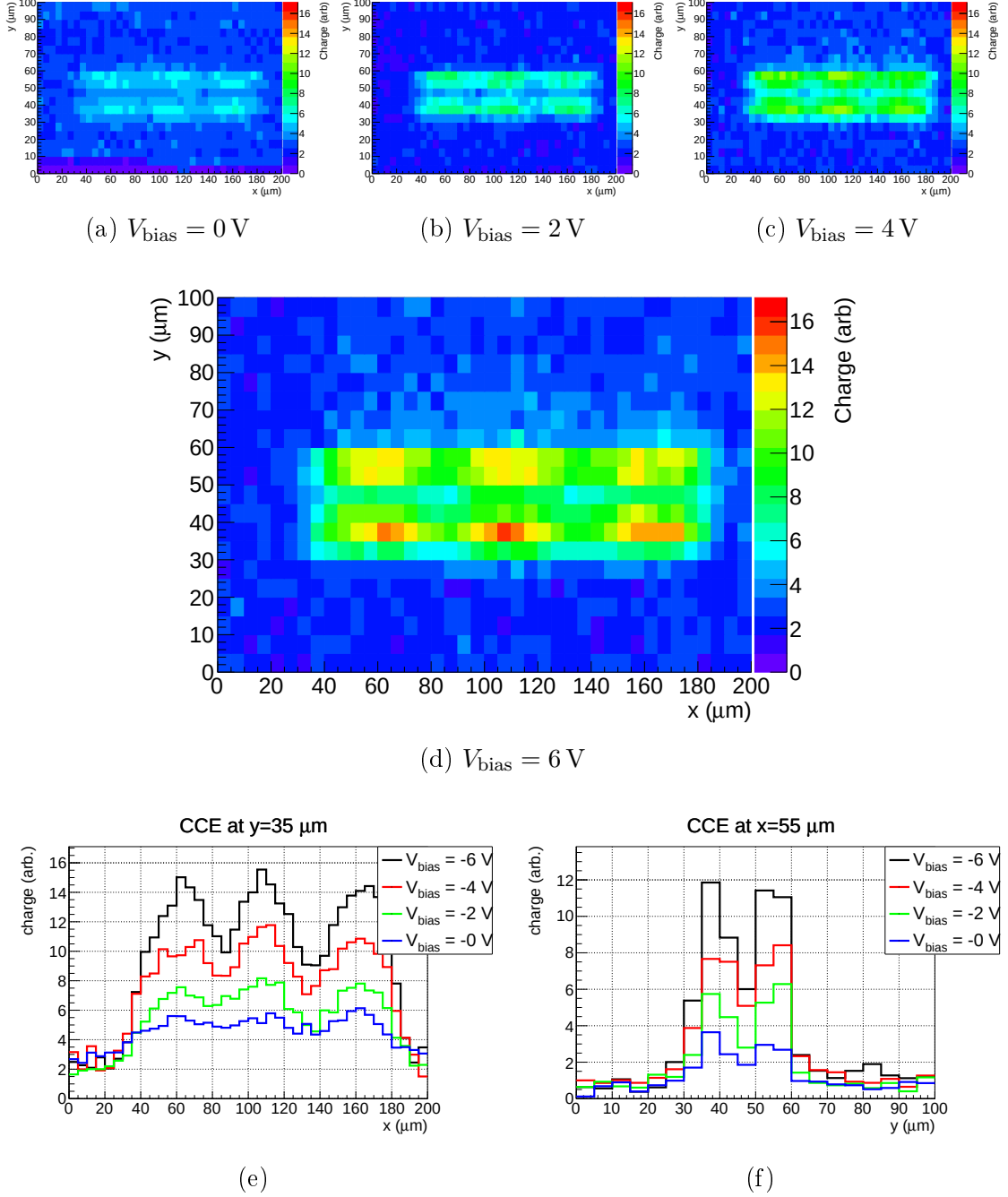


Figure 7.34: Edge-TCT scan on $50 \mu\text{m} \times 50 \mu\text{m}$ pixels of a $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ sample with a low doped n-type layer at different bias voltages.

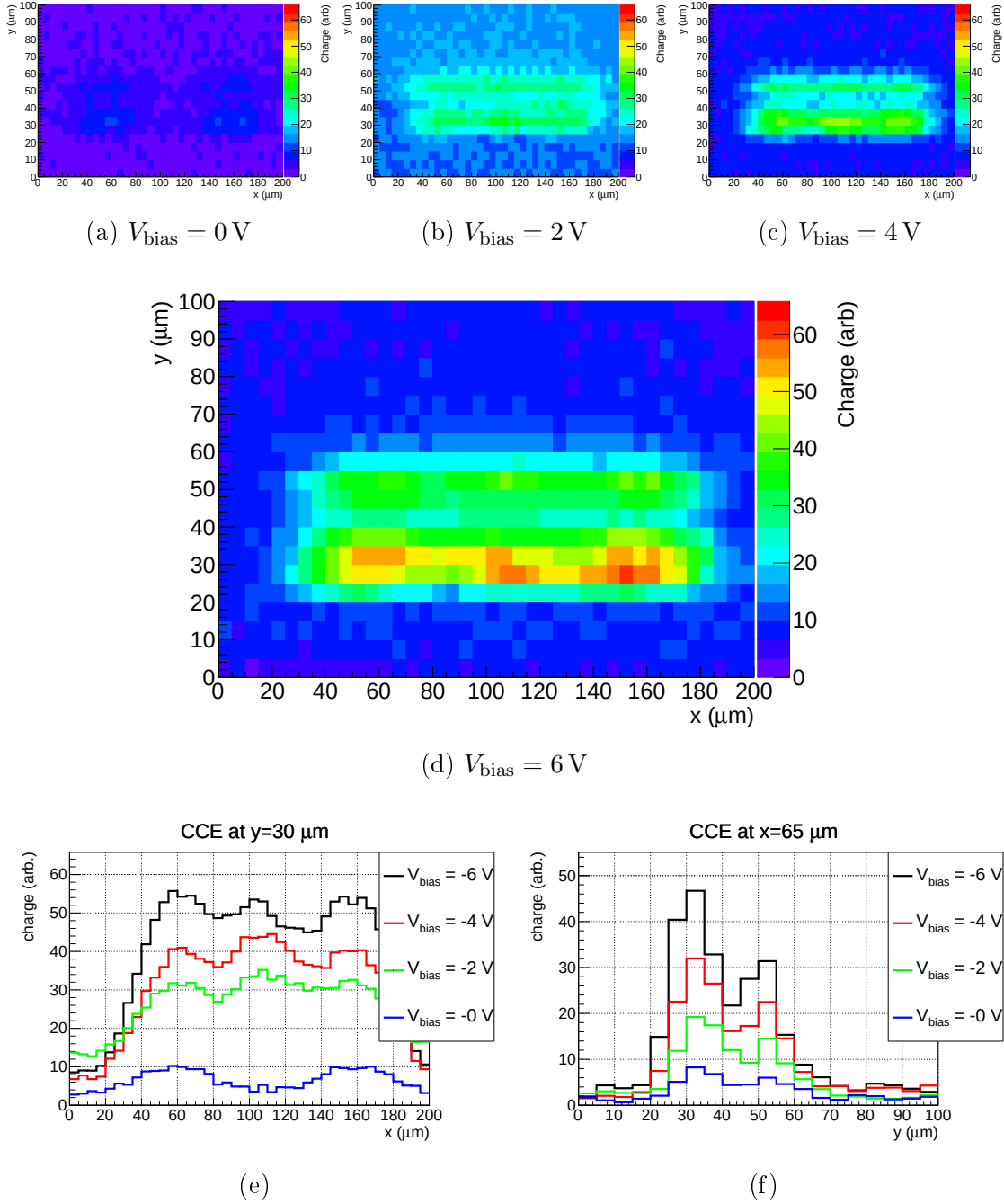


Figure 7.35: Edge-TCT scan on $50 \mu\text{m} \times 50 \mu\text{m}$ pixels of a $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ sample with a highly doped n-type layer at different bias voltages.

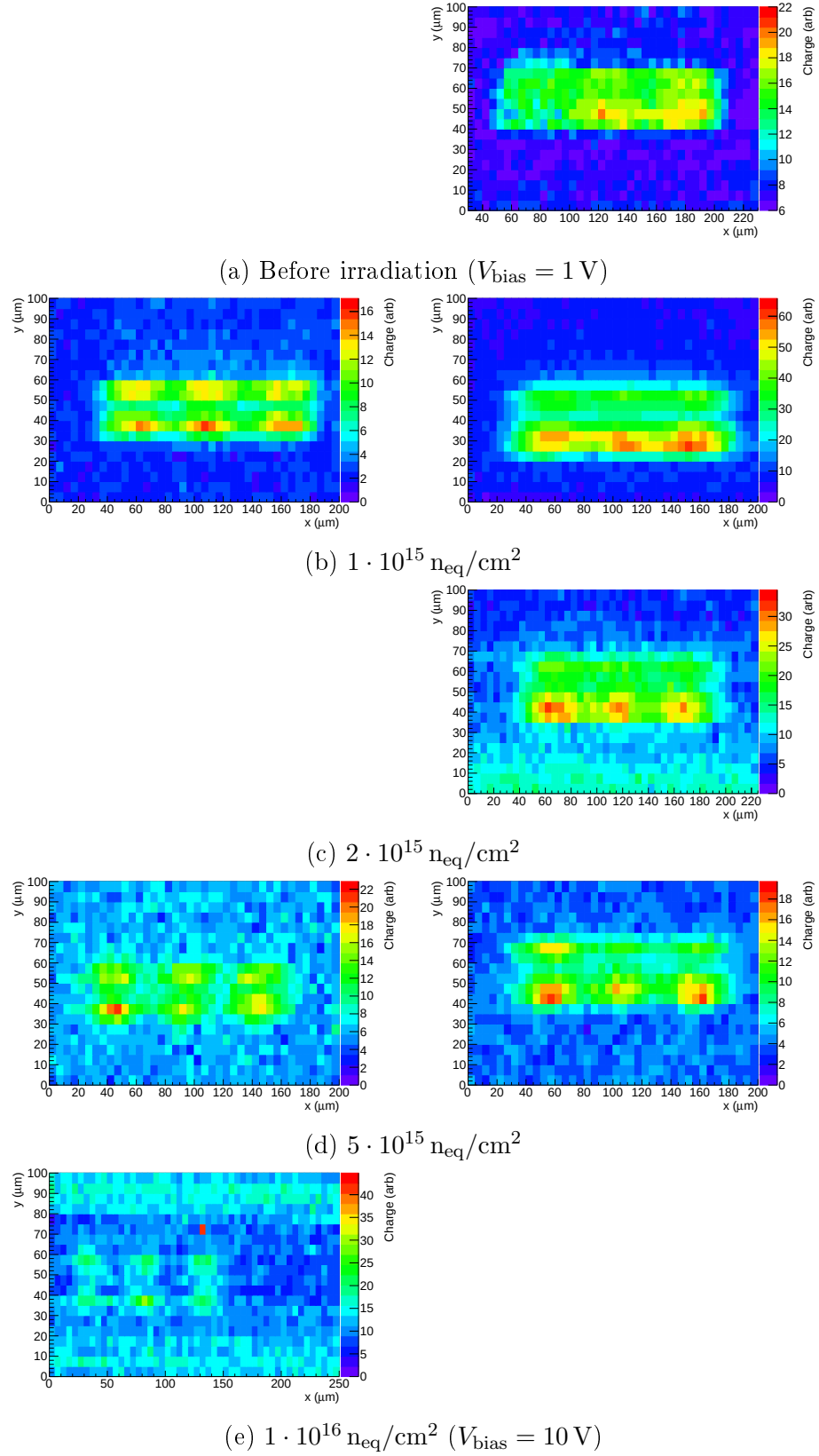


Figure 7.36: Comparison of charge collection in $50 \mu\text{m} \times 50 \mu\text{m}$ pixels with low doped (left) and high doped n-type layer (right) irradiated to different fluences. Measurements were done at $V_{\text{bias}} = 6 \text{ V}$ unless otherwise noted. Missing measurements are due to non functional samples. Note different scales on the x -axis.

also indicate non-uniformity in charge collection between pixels with lower signals detected on pixel edges. This is the consequence of the inherently challenging sensor depletion in small electrode design. Regions with the worst charge collection are probably pixel corners, although sample orientation in Edge-TCT does not enable to separate the contributions from the corners and the sides of the pixel. The efficiency gaps are slightly larger in the low doped sample (Figures 7.34e and 7.35e), indicating that higher doping of the n-layer is favourable for charge collection.

Evolution of charge collection with neutron fluence is shown in Figure 7.36 for both low and highly doped samples. Measurements with some of the samples are missing due to several samples not functioning after being mounted on the sample board. Efficiency gaps on pixel edges become wider with increasing fluence. Measurements at fluences of $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ and $5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, which could be made with both low and highly doped samples, confirm that the efficiency gaps are smaller in the samples with the highly doped n-type layer. However, after the fluence of $5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ the charge collection efficiency is already severely degraded.

7.6 Summary of acceptor removal in CMOS detectors

The presented measurements have shown that charge collection in HV-CMOS prototypes can be beneficially affected by initial acceptor removal, potentially resulting in larger depletion depths and more collected charge after irradiation. Measured values of the acceptor removal coefficient c for differently doped substrates after neutron irradiation are summarised in Figure 7.37, combining data from this work and previous research [72, 129]. In general the acceptor removal is completed at lower fluences in higher resistivity materials, although the removal rate can vary significantly between different materials of similar initial resistivity. This is most likely due to different substrate compositions in wafers from different manufacturers. The largest outliers in this work are the $20 \Omega \text{ cm}$ and $200 \Omega \text{ cm}$ substrates of CHES2 chip, where acceptor removal is slower than in other similar materials. Nevertheless, the values are consistent with those from the H35DEMO chips [129] which are produced by the same manufacturer, demonstrating the consistency of the Edge-TCT method. The diagram 7.37 also includes prediction of the acceptor removal coefficient by the simple acceptor removal model presented in 4.13. The predictions of the model are in a rough agreement with most of the measurements. It has to be noted that this parametrisation is based on empirical assumptions (such

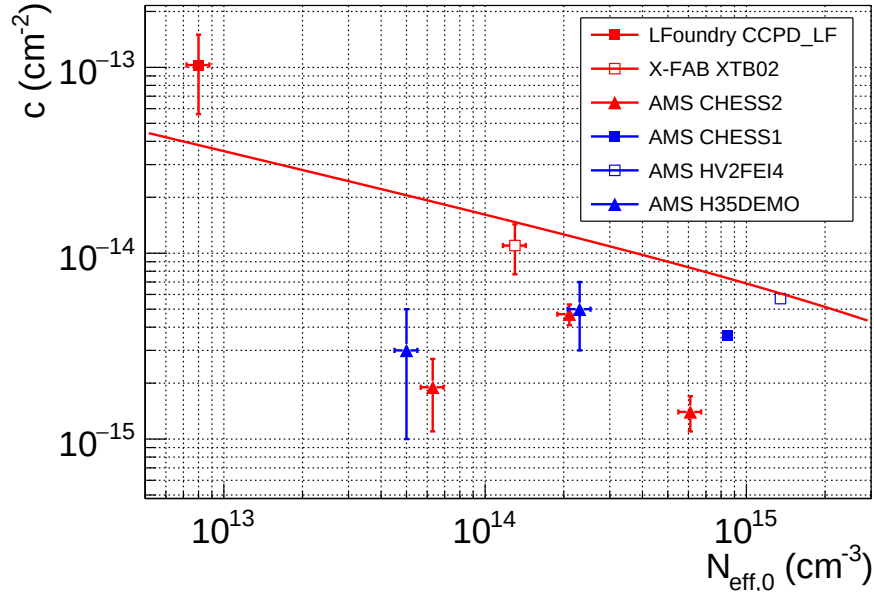


Figure 7.37: Dependence of acceptor removal coefficient on initial space charge concentration in HV-CMOS samples characterised in the scope of this thesis (red) and reference measurements with HV-CMOS (blue) [72, 129]. The line is a prediction by the basic acceptor removal model (4.13) [77].

as selection of the density factor) and is extrapolated from larger initial doping concentrations, so its predictions have to be taken with a margin of tolerance. In general the initial resistivity alone is not sufficient to predict the acceptor removal rate exactly, but can nevertheless serve as a guideline for a rough approximation. For proton irradiation the removal coefficients could not be determined due to scarcity of proton irradiated samples and uncertainty of irradiation fluence for LANSCE samples. However, measurements with proton irradiated samples indicate a faster acceptor removal and a slower space charge introduction rate compared to neutron irradiation. This is compatible with measurements performed with proton irradiated LGAD detectors, which show consistently faster acceptor removal than neutron irradiated samples [73, 130]. These effects are favourable in terms of charge collection in HV-CMOS detectors as they ensure larger depletion depths and hence more available charge. The difference in removal rates probably comes from different spatial distribution of defects induced by different particles, which changes the probability for interstitial-boron interaction (the underlying reaction of acceptor removal).

CMOS prototypes for ITk layer 4 have to be designed to withstand a typical fluence of $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. The right choice of initial substrate resistivity can help to optimally exploit acceptor removal in this fluence range. In samples with high initial resistivity above $1 \text{ k}\Omega \text{ cm}$ the removal with neutrons is completed below a fluence of $1 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$. Subsequently the depletion depth reduces significantly compared to

unirradiated samples, hence such detectors have to cope with a large drop of charge with irradiation. Moreover, some highly resistive wafers seem to be less resilient to electrical breakdown and require more careful high voltage design. In highly doped materials with initial resistivity around $10\ \Omega\text{cm}$ initial acceptor removal is the main driver of changes in space charge concentration, but the removal is slower and completes above $1 \cdot 10^{15}\ \text{n}_{\text{eq}}/\text{cm}^2$. Due to the high initial doping concentration the initial depletion depth is relatively small, but increases with irradiation, which is helpful to counter the degradation of charge collection due to radiation damage. The downside of low resistive materials is the relatively small amount of charge available initially, which requires electronics adapted for lower signals. The optimal material for the given fluence range in terms of charge collection therefore seems to be intermediately resistive material with initial resistivity around $100\ \Omega\text{cm}$. This material provides more charge at low fluences compared to the low resistive substrate, while at higher fluences the amount of charge is boosted by acceptor removal. Measurements show that up to a fluence of $2 \cdot 10^{15}\ \text{n}_{\text{eq}}/\text{cm}^2$ the depletion depth in such material is larger than in unirradiated samples. Moreover, the relatively constant signal size throughout the detector life time could also slightly facilitate the design of readout electronics.

A specific case in terms of material properties are detectors with a small collection electrode produced on an epitaxial silicon layer of a fixed thickness. Such detectors rely on an additional low doped n-type layer implanted on sensor surface to ensure depletion of pixel edges. The sensitivity of this implant to irradiation could not be clearly observed by Edge-TCT due to a limited spatial resolution. However, since a potential type inversion into p-type material would be detrimental for the functionality of such detectors, further studies including both neutron and proton irradiation may be necessary. An alternative method of measuring the efficiency of such detectors with high resolution in a test beam is presented in next chapter.

Chapter 8

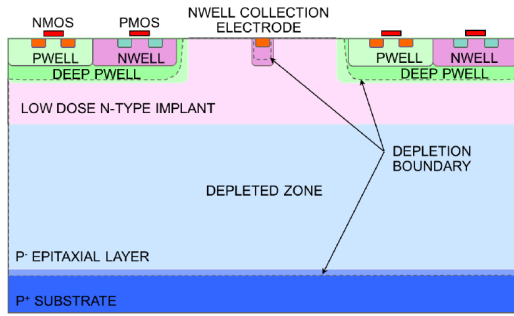
Test beam efficiency measurement with TowerJazz MALTA

Laboratory measurements provide useful information about detector performance, however for a full detector qualification measurement of detection efficiency in a test beam is required to determine detection efficiency of the entire sensor area. In this work a test beam measurement with a monolithic TowerJazz MALTA detector was carried out and is presented in this chapter.

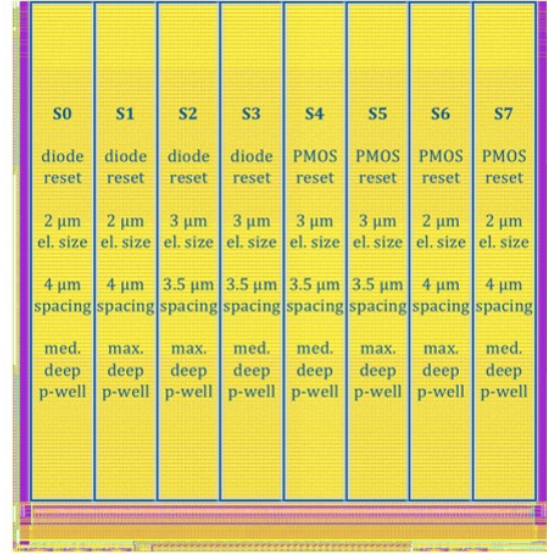
The test beam was performed at CERN SPS North Area H6 beam line. The SPS is the last preaccelerator stage of the LHC, but also supports other experiments. For test beam experiments proton beam from the SPS impacts on a fixed target, providing a secondary beam of pions from ensuing collisions. Pions with an energy of 180 GeV were extracted and directed on the detector under test (DUT). At this energy pions behave like minimum ionising particles (MIP) in terms of energy deposition in the material. The trajectories of traversing particles were reconstructed with a beam telescope with a sub pixel precision, allowing a position sensitive measurement of detector response.

8.1 Tested samples

Measurements presented in this chapter were carried out with TowerJazz MALTA samples with a small collection electrode produced in a modified 180 nm TowerJazz process with a uniform low doped n-type layer across the entire pixel matrix (Figure 8.1) [131]. The chip consists of an array of 512×512 pixels with a size of $36.4 \mu\text{m} \times 36.4 \mu\text{m}$ subdivided into eight sectors with different pixel types varying in the type



(a)



(b)

Figure 8.1: Schematics of the TowerJazz MALTA sample: a) Pixel cross section in modified TowerJazz process; b) Chip layout with eight sectors (64×512 pixels each) with different pixel variants. Test beam measurements were primarily made with sectors S2 and S3 [88, 131].

of reset circuit, electrode size, spacing between the electrode and the p-wells with electronics, and p-well depth. Sectors S2 and S3 have shown the best performance in the current prototype version of the detector and were in focus of this investigation. The right side of the chip (S4–S7) was not functional in this version. Measurements presented here were made with two chips from the first two batches (December 2017 and June 2018): an unirradiated sample (designated W6R6, second batch), and a sample irradiated with neutrons to a fluence of $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ (W4R2, first batch). The second batch features improved powering connections in the slow control circuitry compared to the first version, but there is no notable difference in the functionality of both versions.

Average noise occupancy in the samples operated in normal configuration is of the order of $10^{-4}/25 \text{ ns}$ per pixel, which is significantly above the design specifications of $10^{-6}/25 \text{ ns}$ [30]. This is because samples from the initial submissions suffer from several drawbacks in the chip functionality. Due to a problem in chip powering scheme, the circuit responsible for chip configuration – so called *slow control* – is not fully functional and does not reliably execute commands sent to the chip. One of the main issues is inability of masking individual (noisy) pixels. Presence of a few ($\approx 0.01\%$) noisy pixels in the chip causes extremely high activity level at low discriminator thresholds. This prevents correct operation of the hit merger circuit designed for processing simultaneous events from different parts of the matrix and

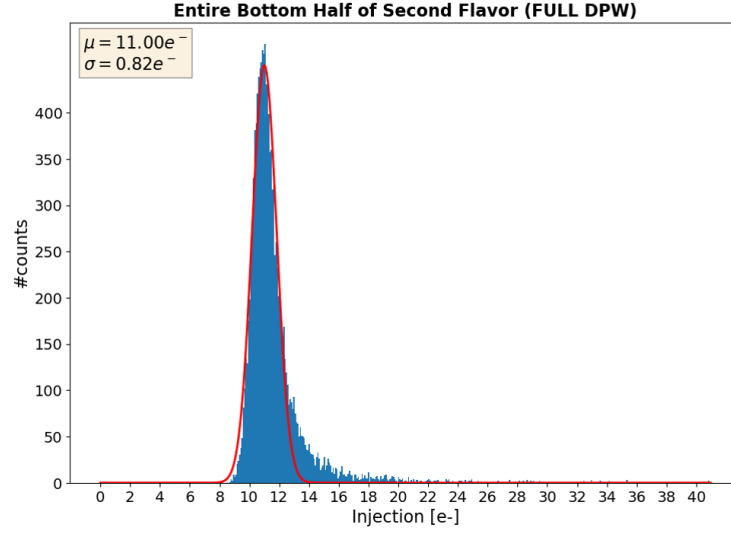


Figure 8.2: Equivalent noise charge in TowerJazz front end. The non-Gaussian tail at high values is due to random telegraph signal noise and forces chip operation at larger thresholds. The measurement is made with TJ MonoPix, but the same behaviour is observed in TJ MALTA [83].

avoiding data collisions (see Chapter 5.2.1). A solution is to operate the chip with the merger disabled, accepting the risk of data collisions, and setting the threshold sufficiently high to reduce the frequency of noise hits. However, due to inability to mask noisy pixels the overall noise occupancy is still high. Another problem is the presence of a non-Gaussian tail in the noise spectrum, caused by random telegraph signal (RTS) noise in transistors (Figure 8.2) [132]. RTS noise (also called popcorn noise) is related to trapping of charge carriers in individual defect sites within the transistor, which causes a transition between two discrete voltage levels. Its impact is larger in smaller transistors, where single states can influence the signal substantially. In MALTA the absence of an in-pixel threshold adjustment circuit forces operation at higher thresholds. Improvements of these issues are discussed at the end of this chapter.

The chips were tested under different configurations to determine optimal operating conditions. Bias voltage was varied between -10 V and -20 V on the sensor back side (substrate) and 0 to -6 V on the p-wells. The front end was operated at different settings corresponding to discriminator thresholds up to 600 e^- (highest threshold). The lowest threshold was 250 e^- in unirradiated chip and 350 e^- in irradiated chip. The threshold levels were determined in laboratory by injecting a series of voltage pulses into the preamplifier input over a known capacitance and extracting the threshold level, dispersion and noise level from the response S-curve.

8.2 Experimental setup

Telescope used in this work, called KarTel [133], consists of seven reference detector planes mounted in two clusters called telescope arms (3 + 4 planes) with the DUT placed between them (Figure 8.3). Six sensor planes are high resolution Mimosa-26 detectors [134] with a pixel pitch of $18\,\mu\text{m} \times 18\,\mu\text{m}$ and a total size of 1152×576 pixels. The seventh sensor plane is a silicon sensor coupled to an FEI4 readout chip with a pixel pitch of $250\,\mu\text{m} \times 50\,\mu\text{m}$ and a size of 80×336 pixels. The FEI4 module is a part of the trigger system, generating a fast trigger signal called HITOR whenever one of designated pixels is hit. The pixel pattern can be selected, thus allowing to set up a sensitive area, called region of interest (ROI). ROI can be used to constrain the trigger to tracks in a certain area, typically a few MALTA sectors. Data acquisition in the Mimosa-26 planes, the FEI4 module and the DUT is triggered by a coincidence of the signals from two scintillators coupled to photomultipliers and the HITOR signal to ensure trigger purity.

Mimosa-26 sensors use a rolling shutter readout scheme with the readout cycle duration of $115.2\,\mu\text{s}$. In this period multiple particles usually traverse the telescope, resulting in multiple recorded tracks in reference planes. Since the DUT only records the response to the particle that triggered data acquisition but not to the others within the $115.2\,\mu\text{s}$ time frame, it is essential to correctly identify the matching track, while discarding the rest. This is the second use of the FEI4 module, which time stamps the hits with a precision of $25\,\text{ns}$, providing the necessary time resolution required to discern between the tracks (anchoring).

The asynchronous digital output of MALTA DUTs, presented in Chapter 5.2.1, was recorded with a custom readout system based on the Xilinx VC707 FPGA board and fast algorithms [135, 136, 137]. During the measurements one or two MALTA DUTs were inserted into the telescope at a time. Unirradiated samples were kept at room temperature, while irradiated ones were cooled to a temperature of $\approx -20^\circ\text{C}$ with a silicon oil chiller. Cooled samples were kept in a thermally insulated container flushed with nitrogen to prevent air moisture condensation.

8.2.1 Track reconstruction and selection

Synchronisation of events in the telescope, FEI4 and DUT data streams, and subsequent track reconstruction and analysis were carried out with Judith/Proteus software framework [133]. An absolute Cartesian coordinate system defined by x -

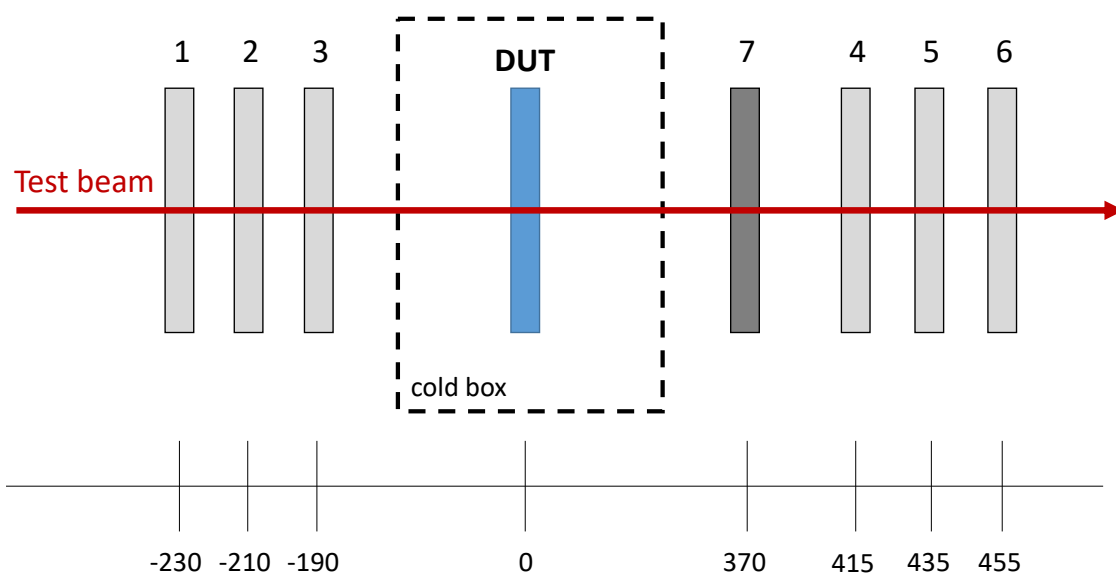
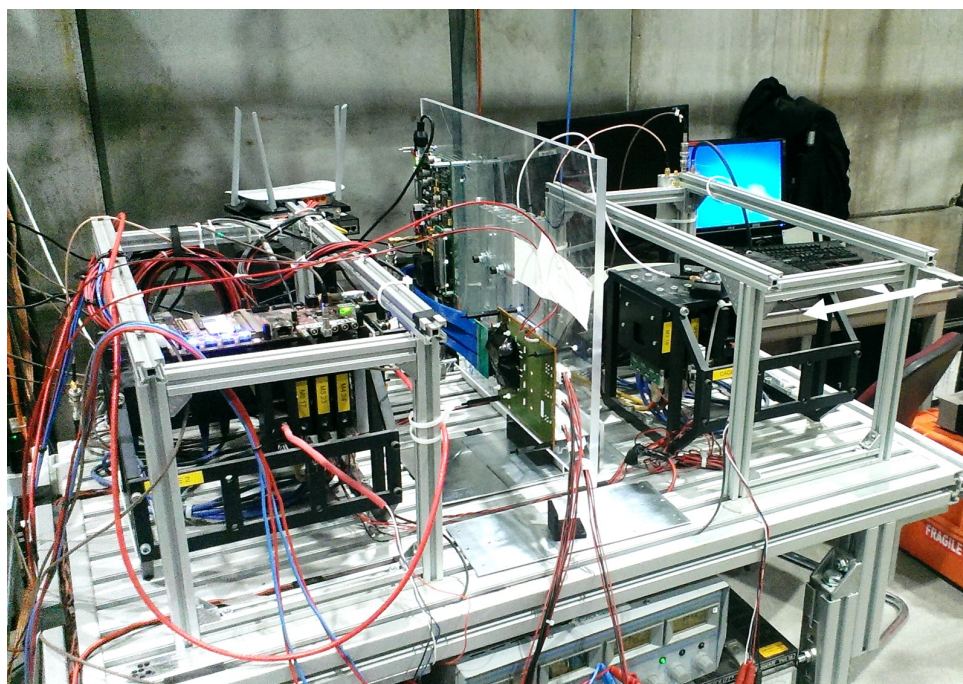


Figure 8.3: KarTel beam telescope in the test beam. Each telescope arm consists of three Mimosa-26 sensors (marked with 1–6). The FEI4 module (7) for triggering and time anchoring is located in the downstream arm. The board with an unirradiated MALTA DUT is in the centre. Thermally insulated housing was used for irradiated samples which had to be cooled. Dimensions in the schematics are given in mm. Arrow indicates beam direction.

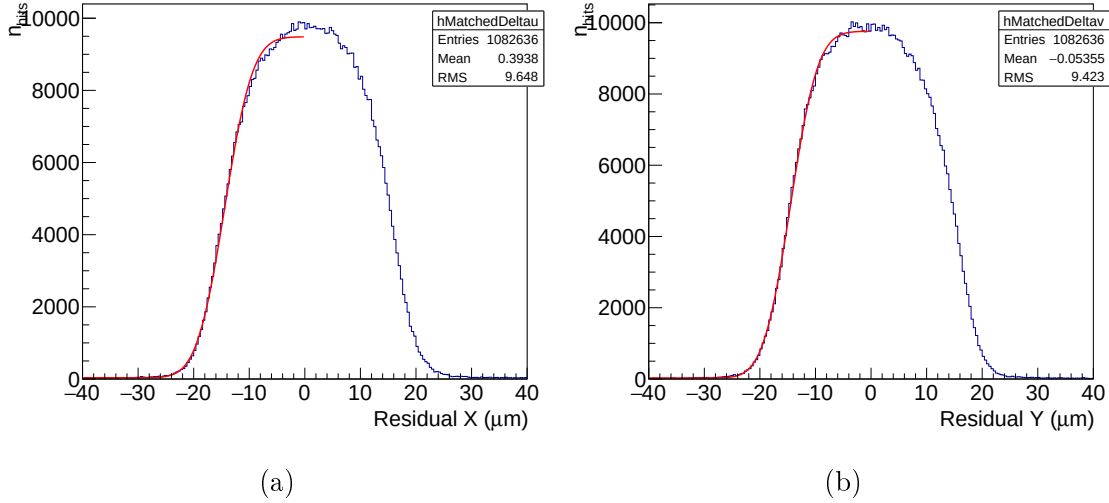


Figure 8.4: Distribution of residuals between interpolated track position and single pixel cluster positions on a MALTA DUT in x - and y -directions. The fitted Gaussian error function corresponds to a spatial resolution of $4\text{ }\mu\text{m}$ in each direction.

and y -axes perpendicular to beam direction and z -direction along the beam axis was used throughout the analysis. Hits in adjacent pixels were grouped into clusters with the cluster position defined as the center of gravity of the deposited charge. In Mimosa-26 and MALTA binary hit information was used (hit/no hit), while the FEI4 module measured the deposited charge with a 4-bit resolution. Correlated clusters in telescope planes belonging to the same track were found by taking the hits in the first plane and, assuming nearly horizontal tracks, propagating the track seed to subsequent planes, searching a narrow area around the predicted hit position for a matching cluster. Tracks were selected by requiring a cluster in all seven reference planes, thus automatically fulfilling the anchoring functionality of the FEI4 module. The majority of events have only one cluster in the FEI4 plane due to its short readout window, hence at most one track fulfills the condition of seven correlated clusters. The fraction of events with exactly one reconstructed track is approximately 30%. In the majority of remaining events no track fulfills the requirement for a hit in all seven planes, mostly due to inefficiency of Mimosa-26 planes. These events cannot be used in the analysis. Events with more than one reconstructed track represent less than 1% of the dataset and were discarded to avoid ambiguity. Tracks were reconstructed using a straight line fit in three dimensions.

Precise positions of the telescope planes relative to each other, vital for precise track reconstruction, were determined in two alignment stages. The first stage called Coarse Alignment is based on comparing the differences in x - and y -positions (residuals) of all possible hit combinations in two consecutive reference planes. Clusters belonging to the same track have correlated positions, resulting in a narrow

($\sim 100\ \mu\text{m}$) residual distribution, while the distribution for random cluster combinations is much wider ($\sim 10\ \text{mm}$). Coarse Alignment applies a relative offset in x - and y -directions to each reference plane so that the peak of the residual distribution is centered at zero. The second stage called Fine Alignment is made for one plane at a time using tracks reconstructed from the remaining planes as a reference. Distribution of residuals between the cluster position and track intercept in the designated plane is minimised using χ^2 method, which yields fine tuned positions in x - and y -directions and the rotation angle around the z -axis. The procedure is repeated in multiple (≈ 20) iterations to achieve convergence of the position parameters. Once the telescope planes are aligned the same procedure is also carried out for the DUT. The spatial resolution of aligned telescope was estimated from one dimensional residual distributions between the track intercept and cluster position on a MALTA DUT, using only clusters with one hit pixel (Figure 8.4). The residual distribution is a rectangular window with a width of $36.4\ \mu\text{m}$ (pixel pitch) convolved with a Gaussian function due to finite measurement resolution. Left slope of the distributions was fitted with a Gaussian error function, yielding width parameter (spatial resolution) of $\sigma = 4\ \mu\text{m}$ in x - and y -directions.

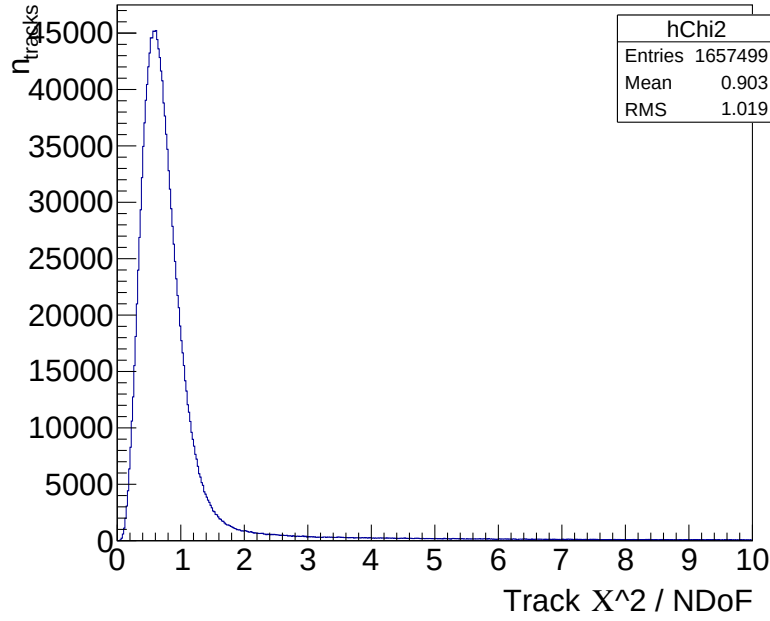
The distribution of the reduced χ^2 value from the track reconstruction fit is shown in Figure 8.5. The distribution has a mean value of 0.9 and a root-mean square of 1.0, indicating the reliability of the reconstruction procedure. To ensure precise track reconstruction only tracks with reduced $\chi^2 < 3$ were selected for further analysis. To avoid edge effects on the matrix boundaries events with track position on an edge pixel in the DUT were discarded, thus the final size of the fiducial area was 62×510 pixels per sector.

8.2.2 Efficiency calculation

Track positions and detector response were histogrammed in two dimensions representing the detector area. Hit detection efficiency η was measured in each bin as the ratio of the number of tracks with an associated cluster in the DUT over the total number of tracks in a given histogram bin:

$$\eta(x, y) = \frac{N_{\text{tracks with cluster}}(x, y)}{N_{\text{all tracks}}(x, y)} \quad (8.1)$$

Clusters were associated with tracks based on spatial proximity: if the distance between the interpolated track intercept in the DUT and the nearest cluster centre was below $40\ \mu\text{m}$ the events were matched, otherwise the track did not have an associ-


 Figure 8.5: Example of reduced χ^2 distribution of track reconstruction fit.

ated cluster. The in-pixel sensitivity of the detector was determined by mapping an entire pixel array in a 2×2 pixel cell shown in Figure 8.6. Four different areas were used for evaluating the performance in different parts of the pixel. The area called *Full Cell* has the size of a pixel pitch and contains corners of four different pixels (equivalent of one full pixel). The area *Centre* with a side of one half pixel pitch is centered around the collection electrode. The remaining two areas highlighted in blue in Figure 8.6 each contain one pixel corner and are used to evaluate asymmetry within the pixel. Measurement uncertainty in a selected area was estimated from statistical fluctuations with efficiency treated as a binomially distributed variable with a standard deviation of:

$$\sigma_{\eta}(x, y) = \sqrt{\frac{\eta(x, y)(1 - \eta(x, y))}{N_{\text{all tracks}}}}, \quad (8.2)$$

where $N_{\text{all tracks}}$ is the number of tracks in the given area. Typical numbers of tracks per bin using a bin size of $2 \mu\text{m} \times 2 \mu\text{m}$ is between 40 in runs with a smaller number of events (for example Figure 8.7) and 800 in runs with high statistics (Figure 8.9). With this binning the areas outlined in Figure 8.6 covering a quarter of a pixel consist of 81 histogram bins and hence at least 3000 tracks.

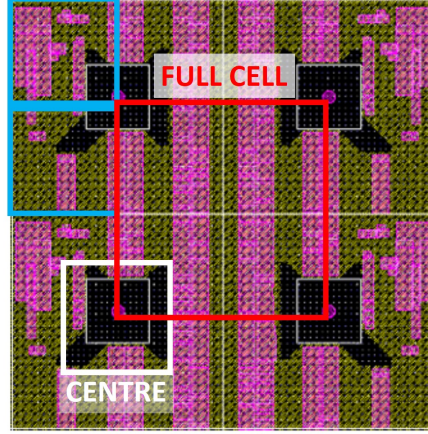


Figure 8.6: 2×2 pixel cell used for evaluation of detection efficiency. Four outlined areas were used to determine efficiency in different parts of the pixel. Collection electrodes are located in the corners of the square marked FULL CELL.

8.3 Efficiency measurement

8.3.1 Efficiency of unirradiated sample

Figure 8.7 shows in-pixel hit detection efficiency of sector S3 in unirradiated MALTA sample operated at the bias voltages of -15 V and -6 V on the substrate and p-wells respectively and different discriminator thresholds between $250 e^-$ and $600 e^-$. At the lowest threshold the efficiency is uniform across the entire pixel area with an average value of 96.4%. At higher threshold levels the efficiency starts to decrease on pixel edges, while efficiency in the centre increases, resulting in an average pixel efficiency of 97.2% at threshold value of $400 e^-$ and 94.7% at the threshold value of $600 e^-$.

The efficiency drop on pixel edges is due to charge being distributed between adjacent pixels – so called *charge sharing* – resulting in less charge available in individual pixels and hence smaller signals which do not exceed the threshold. The extent of charge sharing can be seen in Figure 8.8 which shows the average cluster size depending on track position. At the lowest threshold of $250 e^-$ the average cluster size is slightly above 1 in the pixel centre, around 2 on pixel edges, and almost 3 in pixel corners. At higher thresholds the average cluster size on the edges and corners reduces due to signals not exceeding the threshold.

The higher detection efficiency in pixel centres at higher thresholds is an uncommon effect caused by the problems in the asynchronous MALTA readout. Since the chip is operated with the disabled merger module, simultaneous hits from dif-

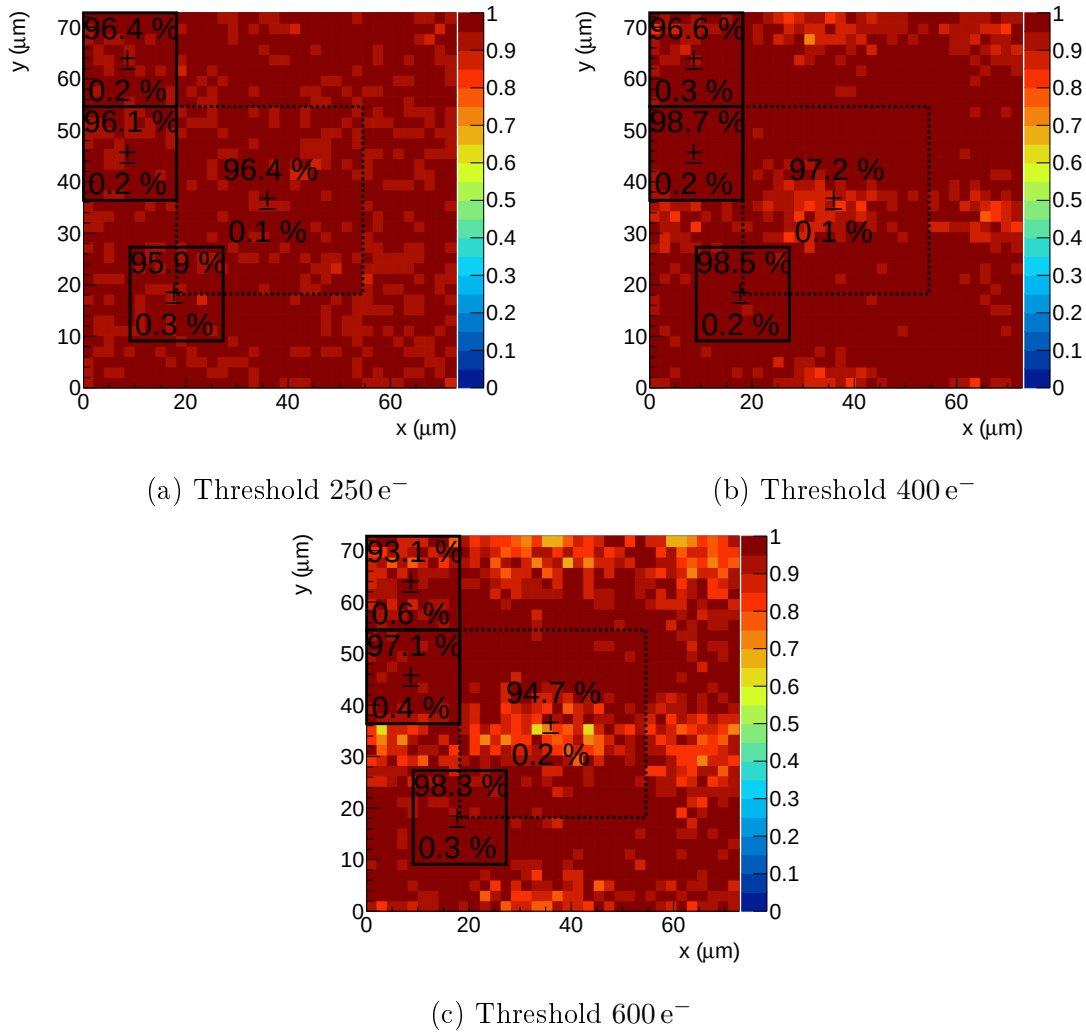


Figure 8.7: In-pixel efficiency of sector S3 (2×2 pixel cell) in unirradiated MALTA chip at discriminator thresholds of: a) 250 e^- ; b) 400 e^- ; c) 600 e^- . Chip is operated at $V_{\text{bias}} = 15\text{ V}$.

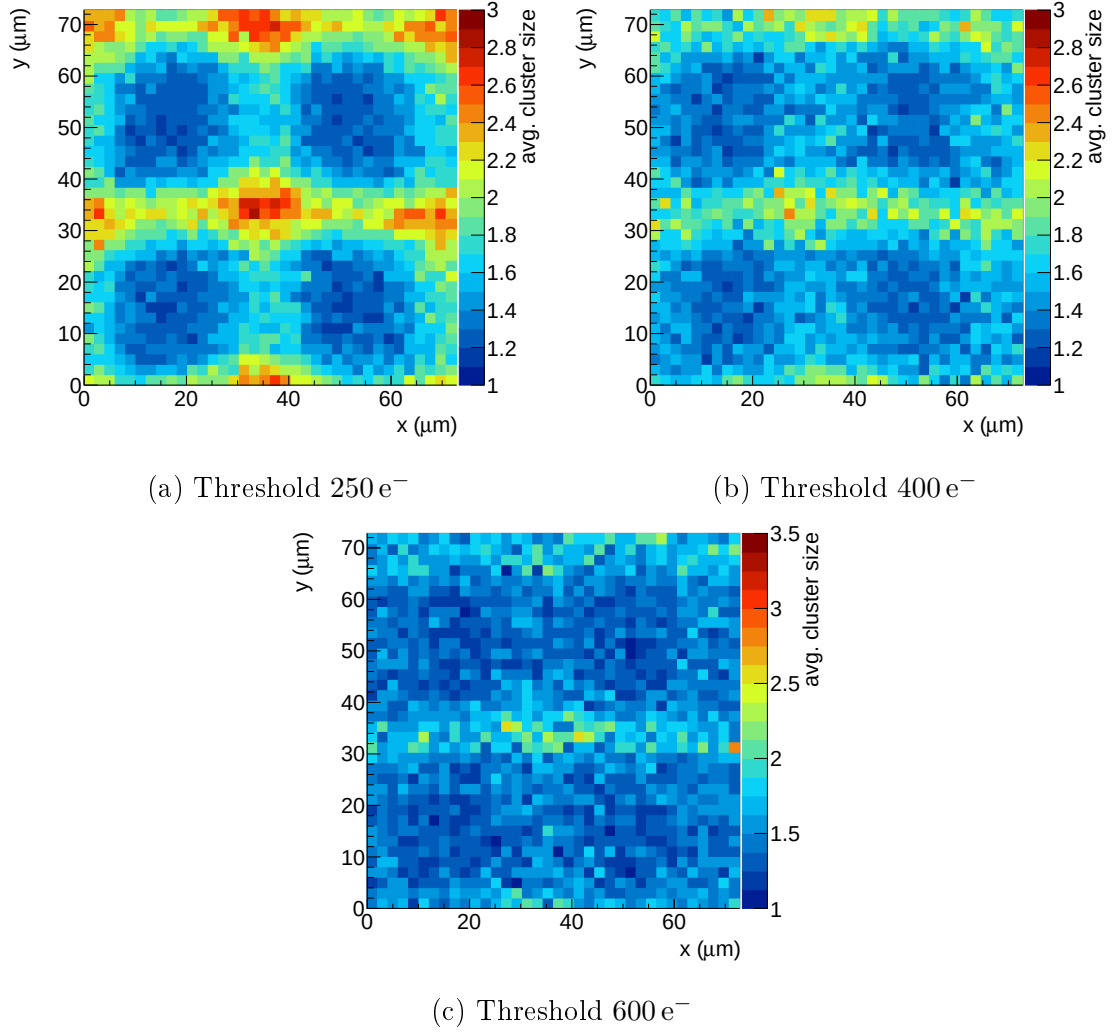


Figure 8.8: Dependence of average cluster size on discriminator threshold in unirradiated MALTA chip.

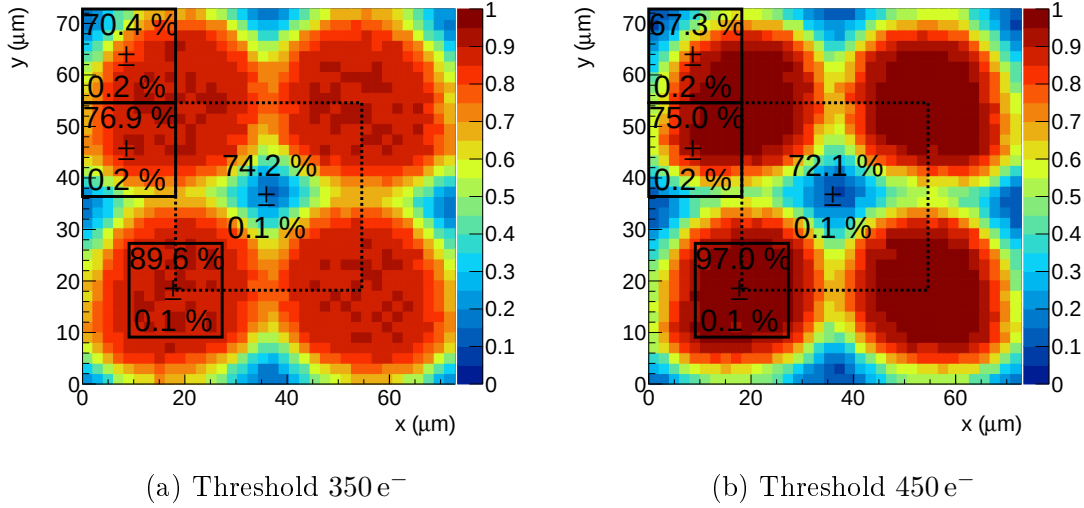


Figure 8.9: In-pixel efficiency of sector S3 (2×2 pixel cell) in a MALTA chip irradiated to a fluence of $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ at discriminator thresholds of: a) 350 e^- ; b) 450 e^- . Chip is operated at $V_{\text{bias}} = 15 \text{ V}$. Efficiency in the pixel centre is reduced at a lower threshold due to data collisions.

ferent parts of the pixel matrix are not processed correctly and result in wrongly interpreted hit location. This can for example happen with a signal from a hit pixel and a random signal from a noisy pixel. In the test beam measurement such data collisions manifest as detection inefficiency. Since the problems in the chip slow control prevent masking individual noisy pixels such occurrences are relatively frequent. The probability for a random noise exceeding a given threshold is higher at lower threshold, hence the efficiency drop due to data collisions is higher at low threshold configuration.

8.3.2 Efficiency of irradiated sample

Hit detection efficiency in a MALTA sample irradiated to $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ was investigated at threshold values between 350 e^- and 450 e^- . Due to an increased noise level after irradiation the chip could not be operated under lower thresholds without severely increasing the noise rate. Figure 8.9 shows in-pixel hit detection efficiency of sector S3 with the chip operated at threshold values of 350 e^- and 450 e^- and the standard bias voltage of -15 V on the substrate and -6 V on the p-well.

The results show a significant degradation of charge collection efficiency especially in the pixel corners where the efficiency drops to almost zero. The average pixel efficiency is reduced to 74.2% at the threshold of 350 e^- and 72.1% at the threshold of 450 e^- , while the respective efficiencies in the pixel centres are 89.6% and 97.0% . Moreover, the shape of the efficient region is slightly asymmetric with

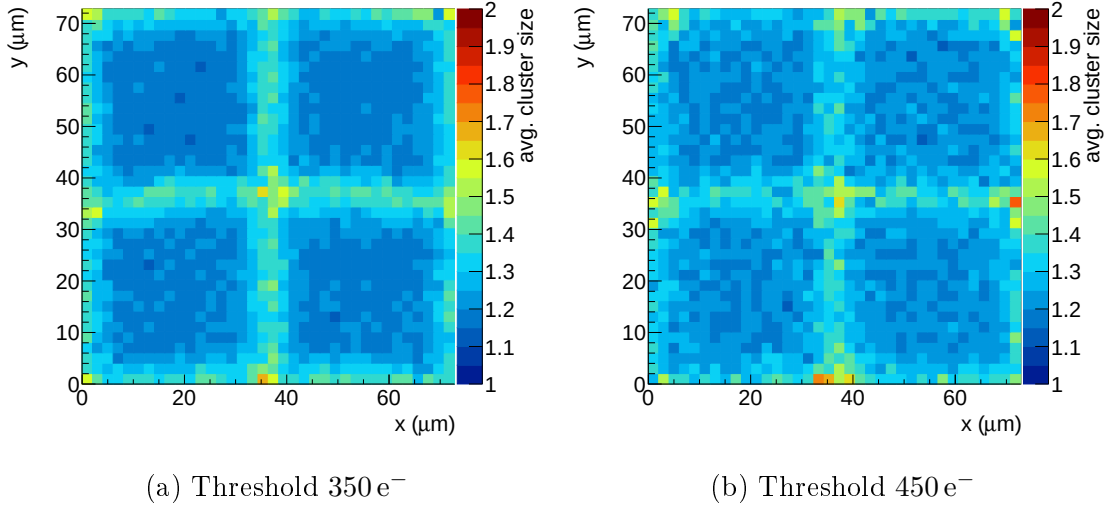


Figure 8.10: Dependence of average cluster size on discriminator threshold in MALTA chip irradiated to $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$.

the efficiency of pixel corners varying by 5–10 %. This is because of the asymmetric shape of pixel implants which is briefly discussed later. The reason for the critically reduced efficiency in the irradiated sample is charge trapping which occurs because the electric field strength is insufficient for a fast charge collection on pixel edges. This is augmented by the problems in the detector readout which force operation at non optimal (high) thresholds and further reduce detector sensitivity to small signals, which are common on pixel edges due to charge sharing. The efficiency loss in pixel centre at low threshold due to data collisions is similar to the unirradiated chip. Overall the lower threshold outweighs the disadvantage of more frequent data collisions, as the average pixel efficiency is slightly higher at lower thresholds. The reduced charge collection efficiency on pixel boundaries is also reflected in the average cluster size shown in Figure 8.10 which does not exceed the value of 1.6 in any part of the pixel. This is significantly lower compared to the values in an unirradiated sample.

The measurements presented above were made with the sector S3 of the MALTA chip. Measurements were also made with the sector S2 which features a deeper p-well implant. Figure 8.11 shows a comparison of the performance of both sectors. The size of the efficient region in S2 is smaller than in sector S3 and has a circular shape opposed to an asymmetric shape in S3. This is correlated to size and shape of the gap in the p-well which separates the collection electrode from the readout electronics in the pixel (black area in Figures 8.11c and 8.11d). The design with a larger gap displays a better charge collection. This information has motivated further research how to exploit different implant configurations to improve charge collection [138]. The solutions are presented in Section 8.4.

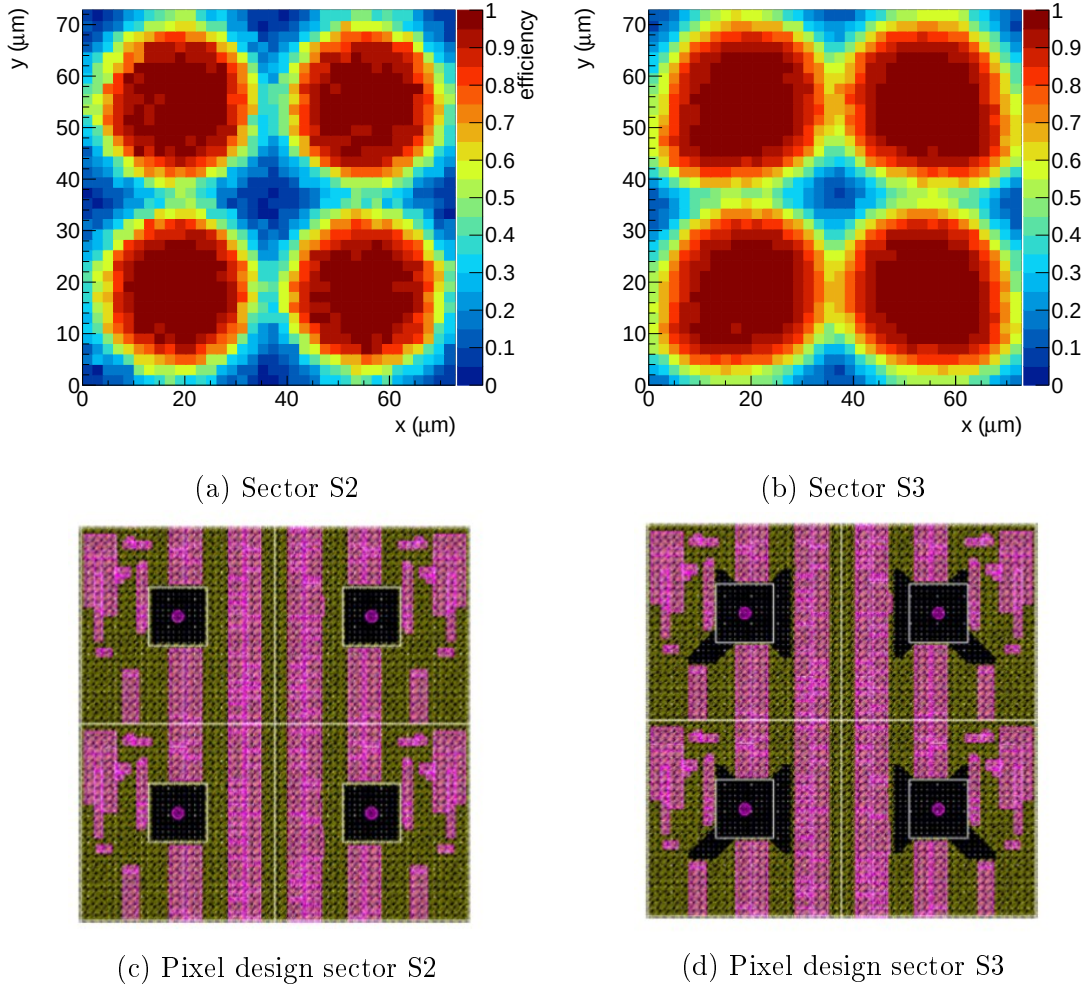


Figure 8.11: Comparison of in-pixel efficiency in sectors S2 (a) and S3 (b) of irradiated MALTA chip. The shape of highly efficient regions coincides with the shape of the gap in the p-well around the collection electrode shown as black area on figures c) and d).

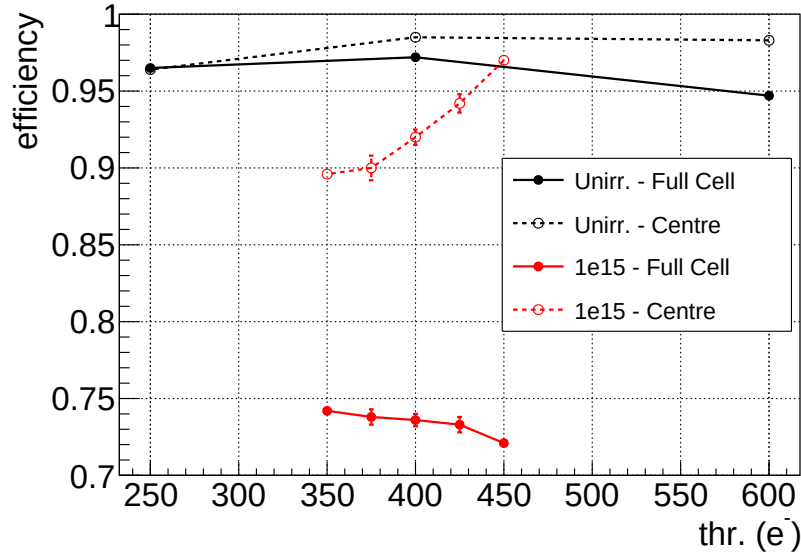
8.3.3 Dependence of efficiency on threshold and bias voltage

A summary of hit detection efficiency in sector S3 measured at different thresholds and bias voltages is shown in Figure 8.12. The values are given for the entire pixel cell and for the central area around the collection electrode. Figure 8.12a gives the dependence of efficiency on threshold at the bias voltage of 15 V. In the unirradiated sample the maximal efficiency is reached at a threshold of 400 e^- ($> 98\%$ in the centre and $> 97\%$ overall). At a threshold of 250 e^- the efficiency is lower mainly because of reduced efficiency in the centre (96%), which occurs due to data collisions. At the threshold of 600 e^- the central efficiency is the same as at 400 e^- threshold, however the overall efficiency is reduced to 94.7% due to losses on the edges. These two competitive effects are more pronounced in the irradiated sample where a similar behaviour is observed – the overall efficiency reduces with increasing threshold from 74% at 350 e^- to 72% at 450 e^- , while the central efficiency increases from 89% to 97% at the same respective thresholds. Above measurements were made with p-wells biased to 6 V. Tests with p-wells biased to 3 V in irradiated sample have shown a performance drop with efficiency reduced by $\sim 2\%$ in the centre and $5\text{--}10\%$ on pixel edges.

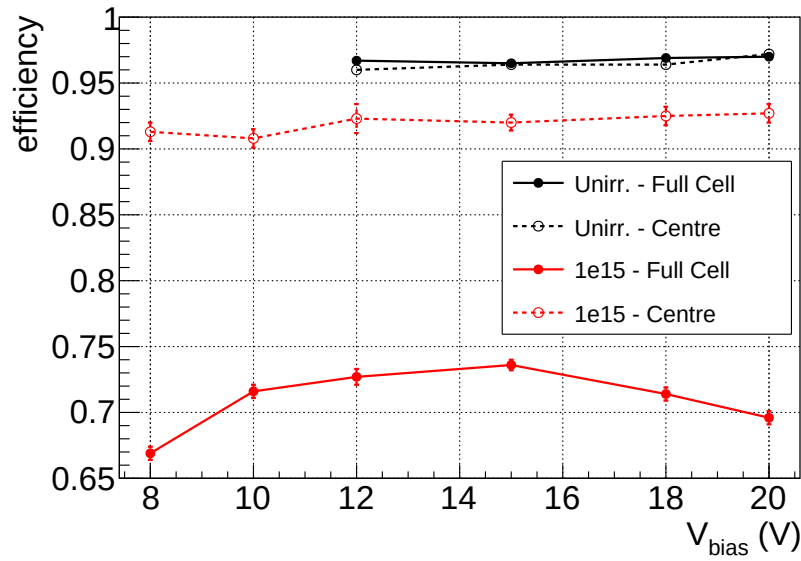
The dependence of efficiency on bias voltage is shown in Figure 8.12b. The measurements were taken at a constant threshold of 250 e^- in the unirradiated sample and 400 e^- in the irradiated sample. In the unirradiated sample the overall and central efficiency have a roughly constant value of $\approx 97\%$ in the entire voltage range between 12 V and 20 V. In the irradiated sample the central efficiency increases slightly with voltage – from 91% at 8 V to 93% at 20 V. However, the full pixel efficiency peaks at the bias voltage of 15 V. The reason for the efficiency drop at lower voltages is weaker electric field which results in slower charge collection and more charge trapping. The behaviour at voltages above 15 V is more complicated and was explained by simulation presented in [138]. For efficient charge collection from the pixel edges the lateral component of the electric field is vital. In case the applied bias voltage is too high the electric field lines are almost perpendicular to the detector surface, therefore the lateral component is smaller than at moderate bias voltages, resulting in a lower efficiency on pixel edges.

8.4 Further development

The test beam campaign with TowerJazz MALTA provided initial insights into the functionality of the chip, but also identified several issues which limit the chip per-



(a)



(b)

Figure 8.12: Dependence of in-pixel efficiency of sector S3 on a) threshold and b) substrate bias voltage in MALTA chip before and after irradiation. Measurements in a) were taken at $V_{\text{bias}} = 15 \text{ V}$ and measurements in b) at a threshold of $250 e^-$ (unirradiated) and $400 e^-$ (irradiated chip).

formance. These disadvantages were addressed in the next design iteration called MiniMALTA [93]. The non functional slow control, which was a significant problem in MALTA resulting in data losses and forcing operation at high thresholds, has been fixed in MiniMALTA. Additionally, the operation of MALTA at low threshold levels has been compromised by the random telegraph signal noise in the front end. This has been attributed to an undersized front end transistor which has been enlarged in MiniMALTA. This modification together with the ability to mask noisy pixels has allowed operation at a threshold of 200 e^- after a fluence of $1 \cdot 10^{15}\text{ n}_{\text{eq}}/\text{cm}^2$, which is a major improvement complying with the original design specifications of the chip.

Another challenge for the small electrode design is efficient charge collection over the entire pixel. While MALTA introduces process modification with the additional n^- layer, the test beam has shown that inefficient regions in pixel corners are still a problem. The influence of the p-well shape on charge collection in different pixel designs (Figure 8.11) has inspired two further improvements to boost charge collection shown in Figure 8.13 which have been implemented in MiniMALTA:

- Addition of an extra deep p-well implant on pixel edges;
- Introduction of a gap in the n^- layer on pixel edges.

Both modifications are aimed at increasing the lateral electric field near the sensor surface and thereby improve charge collection on pixel boundaries. Both approaches require minor adaptations of the production process and are relatively simple to implement. The time dependence of induced current in different designs before and after irradiation was evaluated in a TCAD simulation [138] summarised in Figure 8.14. The induced current in the pixel was simulated after charge deposition by a MIP traversing the pixel corner, which is the worst case scenario in terms of charge collection. The results indicate significantly faster charge collection in both improved pixel designs with peaking time reduced from $\approx 8\text{ ns}$ in the baseline design to $\approx 3\text{ ns}$ in the improved designs. This is a significant gain particularly in the irradiated sample, as such detectors are significantly less sensitive to charge trapping. The simulation also shows a significant effect of pixel size on the speed of charge collection. For example, a pixel size of $28\text{ }\mu\text{m} \times 28\text{ }\mu\text{m}$ results in about twice shorter peaking times compared to pixels with the original size of $36.4\text{ }\mu\text{m} \times 36.4\text{ }\mu\text{m}$ [138], thus reducing the pixel size may be an important element of future designs. First tests with MiniMALTA have confirmed the benefits of the improvements listed above, indicating an average hit detection efficiency of $\approx 98\%$ over the entire pixel in detectors irradiated to $1 \cdot 10^{15}\text{ n}_{\text{eq}}/\text{cm}^2$ [93].

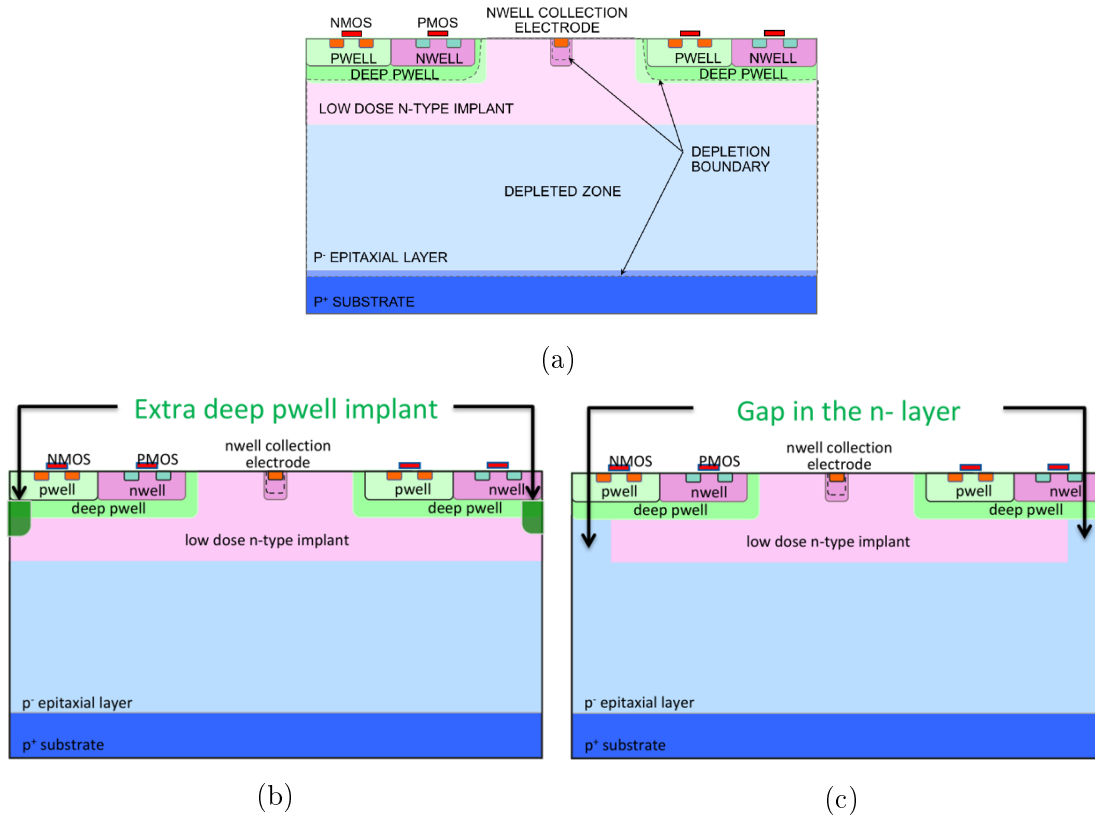


Figure 8.13: Proposed modification of TowerJazz pixel design to improve charge collection in irradiated samples: a) Baseline TowerJazz modified process; b) Additional deep p-well implant; c) Gap in the n-layer. Modifications b) and c) aim to increase lateral electric field on pixel borders. Figures made after [138].

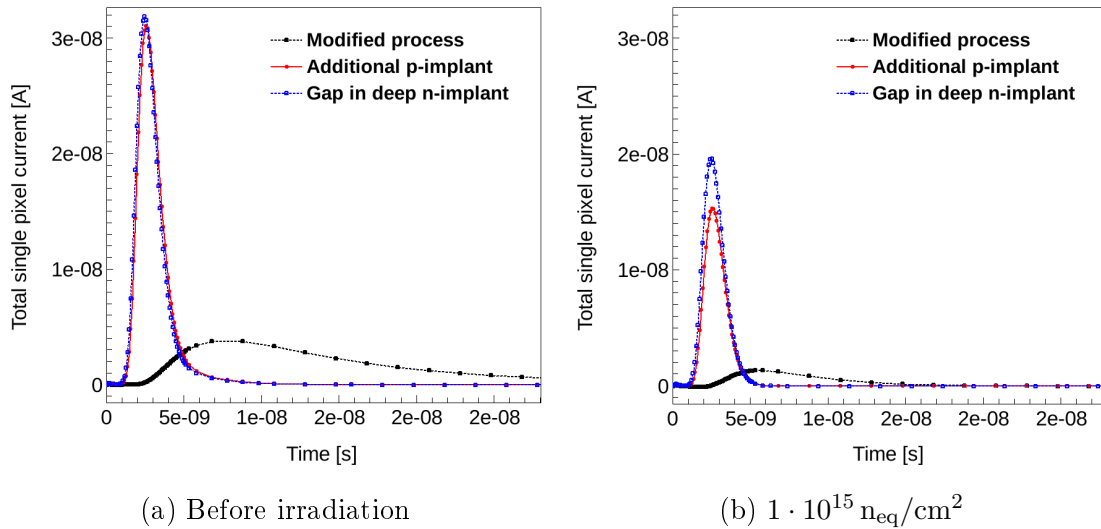


Figure 8.14: Simulation of induced current in different TowerJazz pixel designs after MIP equivalent charge is injected into pixel corner: a) unirradiated detector; b) detector irradiated to $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. Pixels with improved design feature significantly faster pulses which are less affected by trapping [138].

Chapter 9

Summary and outlook

The High Luminosity upgrade of the LHC (HL-LHC) scheduled in the years 2024–2026 aims at increasing the instantaneous luminosity up to $7.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, exceeding the original LHC design value by a factor of 7.5, and will result in unprecedented collision rates of up to 200 simultaneous proton-proton collisions. ATLAS experiment at the LHC will undergo an extensive upgrade called Phase-II in order to prepare for these challenging conditions. A major part of the upgrade will be the replacement of the existing Inner Detector with a new all-silicon Inner Tracker (ITk). ATLAS CMOS collaboration was established to evaluate an alternative for the standard hybrid pixel detector for the outermost ITk Pixel Layer 4, targeting a simpler approach without the technologically complex bump bonding.

The proposed solution is use of Depleted Monolithic Active Pixel Sensors (DMAPS) based on industrial high voltage (HV) and/or high resistivity (HR) CMOS technologies which have seen rapid development for commercial applications in recent years. These processes allow combination of sensor and readout functionalities in the same silicon wafer. The HV/HR component provides sensor depletion for drift based charge collection essential for high radiation environment. ATLAS has focused on development of a so called monolithic detector containing the sensor together with the full readout circuitry – analogue as well as digital part – on a single chip. Such detectors can be produced in an industrial process which reflects in a significantly faster and cheaper detector production. In addition, smaller amount of detector material and lower cooling requirements reduce particle scattering, which can result in a superior spatial resolution compared to hybrid detectors. With these benefits DMAPS based trackers have a potential to become the main detector technology for future colliders.

For Pixel Layer 4 ATLAS CMOS collaboration has pursued several DMAPS development lines exploring different sensor concepts varying in design approaches such as readout architecture, pixel pitch and size of collection electrode (large vs. small electrode design), and choice of initial substrate resistivity. Prototypes of sensors produced in silicon-on-insulator (SOI) geometry and CMOS strip sensors have also been developed. Since DMAPS have never been used in high radiation environment similar to ATLAS ITk, which will receive an expected lifetime fluence of $1.5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ in Pixel Layer 4, one of the main concerns is demonstration of sufficient radiation tolerance. Radiation damage in detector bulk caused by neutrons and protons and its effects on charge collection were studied in this thesis.

In partially depleted silicon detectors depletion depth depends on bias voltage V_{bias} and effective space charge concentration N_{eff} and scales as $\propto \sqrt{V_{\text{bias}}/N_{\text{eff}}}$. In unirradiated material N_{eff} is defined by the initial doping concentration (i.e. initial resistivity) and changes with generation of electrically active defects by radiation. In highly resistive material (3–20 k Ω cm) typical for hybrid detectors the dominant process is introduction of positive space charge from additional acceptor states with concentration proportional to received fluence. However, in commercially available p-type material used for DMAPS with initial resistivity ranging between 10 Ω cm and few 1000 Ω cm the effect of initial acceptor removal, which describes electrical deactivation of boron dopants through generation of a B_iO_i complex, plays an important role. Acceptor removal reduces N_{eff} which results in increase of depletion depth and larger signals at a given bias voltage. Removal is completed either with the removal of all initial acceptors (complete removal) or when no further states are effectively removed (partial or incomplete removal). The fluence at which this process is finished depends on material, with removal completed faster in higher resistivity silicon. In DMAPS the acceptor removal may span over a fluence range of 10^{13} – $10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$, which coincides with the expected lifetime fluence for Pixel Layer 4, indicating that beneficial effects of acceptor removal can be relevant in the entire lifespan of this detector.

In this thesis evolution of N_{eff} with fluence was evaluated in several DMAPS prototypes irradiated with neutrons or protons in a fluence range of 10^{13} – $10^{16} \text{ n}_{\text{eq}}/\text{cm}^2$. Detectors were characterised with Edge Transient Current Technique (Edge-TCT) which uses a focused infra red laser beam with a diameter below 10 μm to inject charge into the sensor at a fixed distance from the surface through the detector edge. Fast readout electronics is used to detect induced current from drifting charge carriers, providing information on the size of sensitive volume, i.e. depletion depth, and N_{eff} . Acceptor removal coefficients were determined for neutron irradiated prototypes on substrates with initial resistivities of 20, 50, 200 and 1000 Ω cm

(ams CHES2), 2–3 k Ω cm (LFoundry) and 100 Ω cm SOI (X-FAB). Near complete or complete removal was observed in most samples. In material with initial resistivity above 1000 Ω cm acceptor removal was finished below a fluence of $5 \cdot 10^{13}$ n_{eq}/cm², while in 20 Ω cm substrate the removal was completed above a fluence of $3 \cdot 10^{15}$ n_{eq}/cm². In intermediate resistivity material acceptor removal was completed at fluences within this interval. In proton irradiated samples acceptor removal coefficient could not be determined due to insufficient number of data points, but measurement indicate that protons remove initial acceptors faster and introduce less additional deep acceptor states than neutrons. Measurements in this thesis indicate that detectors with initial resistivity around 100 Ω cm have the smallest variations of N_{eff} with fluence in the entire fluence range of ITk Layer 4. Despite a distinct trend of faster acceptor removal in higher resistivity substrate, variations in materials from different vendors are large and dedicated studies are required for precise determination of N_{eff} evolution in each particular substrate.

Passive pad diodes in LFoundry and CHES2 samples were further characterised in a setup with a radioactive ⁹⁰Sr beta source, which allows selection of events with MIP-like charge deposition in the sensor. The signal spectra show collected charge increasing with fluence in several samples, indicating larger depletion zone due to acceptor removal. In detectors with bias voltage applied to structures on sensor surface, not the backside, the signal size after irradiation is smaller than expected from the depletion zone size measured with Edge-TCT. This is due to holes getting trapped in a low electric field volume and not traversing the full weighting field. In a pixel detector with each pixel read out individually the expected degradation would be significantly smaller due to a favourable weighting field.

Edge-TCT was additionally used to assess signal uniformity within the pixel. Significant efficiency gaps were observed in the X-FAB SOI detector, which suffers from parasitic charge collection by the structure above the buried oxide housing readout electronics. This hypothesis was confirmed by a simulation. Measurements were also conducted with TowerJazz Investigator samples with a small collection electrode geometry and a very small pixel size of ≤ 50 μ m on the limit of Edge-TCT resolution. The results show efficient regions in the pixel centre close to collection electrode, and less efficient regions on pixel edges where signal strongly degrades with irradiation.

In the scope of this thesis small collection electrode design was further studied in a test beam with a monolithic TowerJazz MALTA chip. Measurements of hit detection efficiency were made before irradiation and after a neutron irradiation of $1 \cdot 10^{15}$ n_{eq}/cm². The detector designed for operation at a threshold of 200 e⁻ had to

be operated at a higher threshold of $\geq 250\text{ e}^-$ (unirradiated) and $\geq 350\text{ e}^-$ (irradiated) due to problems in chip design. In addition, detection efficiency was reduced due to data collisions in the readout arising from the same issues. Unirradiated sample has a uniform in-pixel efficiency of $\approx 97\%$. After irradiation the detector shows a critical efficiency degradation on pixel boundaries, with the average pixel efficiency below 75% . Meanwhile efficiency of the central 25% of pixel area is between 90% and 97% depending on the threshold, and is limited by the loss due to data collisions. These results have led to improvements of pixel design with implant modifications aimed at increasing electric field, and hence efficiency, on pixel edges. These improvements together with the fixes of the readout electronics have been implemented in the TowerJazz MiniMALTA chip.

In March 2019 ATLAS decided against using CMOS option in the ITk, since none of the detector designs had been developed to a sufficiently advanced stage to fit into the tight time line for the Phase-II upgrade. Nevertheless, the R&D within the ATLAS CMOS collaboration has led to a rapid progress of CMOS based sensors for high radiation environment that has been recognised within and beyond ATLAS. DMAPS development in TowerJazz, ams and LFoundry processes has been continued outside ATLAS in order to take advantage of the previous research and deliver a fully functional DMAPS. For example, recent test beam results with the ams ATLASpix show promising efficiency and timing resolution which would fulfill the specifications for ITk Layer 4. The recently submitted TowerJazz MiniMALTA has also fixed the major issues identified in MALTA and shows very promising performance in the test beam. DMAPS development for ATLAS also synergised with detector development for future linear colliders such as Compact Linear Collider (CLIC) and International Linear Collider (ILC) which require high resolution, low material budget and moderate radiation tolerance. For these applications DMAPS are a very attractive option.

This work has presented an extensive study of charge collection properties in numerous irradiated DMAPS prototypes using Edge-TCT, ^{90}Sr and test beam. On one hand the measurements provided insights into charge collection properties of these detectors, while on the other hand also generated feedback to chip designers that led to design improvements. Moreover, the measurements have demonstrated the importance of acceptor removal which takes place over a large fluence range due to the choice of relatively low substrate resistivity in DMAPS. Acceptor removal benefits DMAPS as it results in increased depletion depth and larger signals, and might therefore play a considerable role in the design of future silicon detectors.

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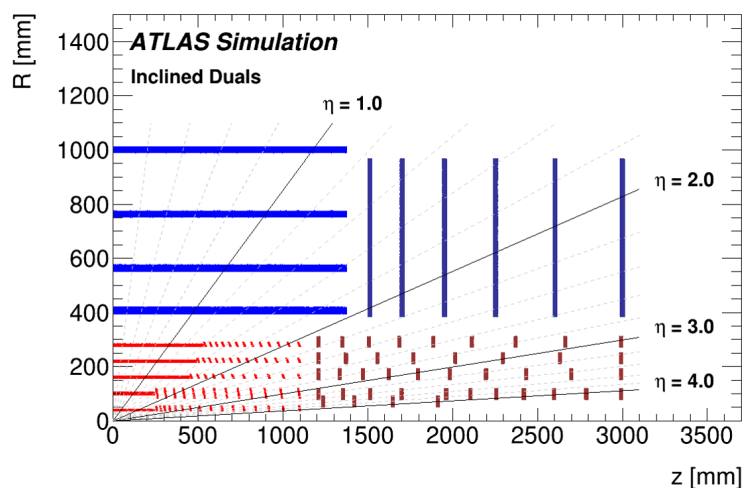
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Razširjeni povzetek v slovenskem jeziku

Veliki hadronski trkalnik (LHC) [1, 2] Evropske organizacije za jedrske raziskave (CERN) je največji in najmočnejši trkalnik delcev kadarkoli zgrajen. LHC medsebojno trka protone pospešene do težiščne energije $\sqrt{s} = 13 \text{ TeV}$, iz katere lahko nastanejo novi, težji delci, ki jih opisuje *standardni model fizike delcev* [10, 11, 12, 13]. Največji uspeh LHC-ja do sedaj je odkritje Higgsovega bozona [21, 22], ki so ga napovedale že teorije v 1960-ih letih [14, 15, 16, 17]. Poleg tega pri visokih energijah trka obstaja možnost za nastanek novih delcev oziroma procesov, ki jih standardni model ne opisuje in jih poznamo pod skupnim imenom *nova fizika*. Te pojave pričakujemo glede na nekatera fizikalna opazovanja, ki jih standardni model ne more uspešno razložiti, npr. naravo temne snovi in temne energije, kvantno-mehansko naravo gravitacije, maso nevtrinov in asimetrijo med snovjo in antisnovjo v vesolju. S trkalnikom LHC so neločljivo povezani fizikalni eksperimenti, ki zaznavajo produkte trkov in nam s tem omogočajo vpogled v fizikalne procese med interakcijami delcev. Eden od štirih glavnih eksperimentov LHC-ja je detektor ATLAS [4, 24], ki je izpopolnjen za zaznavanje čim večjega nabora procesov pri protonskih trkih.

Ker so pričakovani sipalni preseki σ pri procesih nove fizike zelo majhni, je za možnost njihovega zaznavanja potrebno veliko število trkov. Sorazmernost med sipalnim presekom in hitrostjo ustvarjenih dogodkov na trkalniku $\frac{dN}{dt}$ opisuje *trenutna luminoznost* $\mathcal{L}$ v zvezi $\frac{dN}{dt} = \mathcal{L} \cdot \sigma$, skupno število ustvarjenih dogodkov pa je sorazmerno z *integrirano luminoznostjo* $\mathcal{L}_{\text{int}} = \int \mathcal{L} dt$. LHC je zasnovan za delovanje pri trenutni luminoznosti $1 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, tako do bo trenutnem obdobju delovanja načrtovanem do leta 2024 pričakovana količina proizvedenih trkov ustrezala integrirani luminoznosti 400 fb^{-1} . Po tem obdobju bi delovanje pri nespremenjenih pogojih postalo nepraktično zaradi izredno dolgega časa potrebnega za statistično pomembno povečanje obsega podatkov. Z namenom doseganja še večje količine trkov bo LHC v letih 2024–2026 izboljšán v t.i. *Nadgradnji za visoko luminoznost* (HL-LHC) [28], ki bo omogočala delovanje pri trenutni luminoznosti $5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, v skrajnem



Slika 9.1: Shema razporeditve silicijevih modulov v nagnjeni porazdelitvi v enem kvadrantu detektorja ATLAS ITk. Rdeče plasti predstavljajo blaziničaste, modre pa linijske detektorje [30].

primeru pa celo pri $7,5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, in cilja na skupno integrirano luminoznost 4000 fb^{-1} v desetih letih zbiranja podatkov. Obratovanje pri teh ekstremnih pogojih bo predstavljalo izredno obremenitev za eksperimente, saj bodo morali v povprečju zaznati produkte kar 200 istočasnih trkov. Poleg tega bodo zaradi večjega števila trkov poškodbe detektorja zaradi sevanja znatno večje od vrednosti, za katere so zasnovani trenutni detektorji.

Zaradi omenjenih dejavnikov bo eksperimente na LHC-ju v času nadgradnje HL-LHC potrebno izboljšati. Pri detektorju ATLAS bodo v tem obdobju, imenovanem *nadgradnja Phase-II*, izvedene številne izboljšave. Ena največjih novosti bo zamenjava obstoječega Notranjega detektorja (ID) [4], namenjenega zaznavanju sledi nabitih delcev, z novim *Notranjim sledilnikom* (ITk) [30, 34], ki bo v celoti zgrajen iz silicijevih detektorjev. ITk bo od vseh detektorskih sistemov najbližje točki trka in bo pokrival prostor od žarkovne osi oddaljen med 36 mm in 1000 mm. Detektorji v ITk bodo razporejeni plastovito v t.i. nagnjeni ureditvi (Slika 9.1), ki sestoji iz blaziničastih detektorjev v notranjih plasteh in linijskih detektorjev v zunanjih plasteh. V osrednjem delu odmaknjenem od žarkovne osi za kot večji od $15\text{--}30^\circ$ bodo detektorji razporejeni v obliki koncentričnih cevi (5 plasti blaziničastih in 4 plasti linijskih detektorjev), pri ostrejših kotih pa v številnih obročih. Površina vseh blaziničastih detektorjev v ITk bo s približno 10 m^2 znatno presegla trenutnih 1.8 m^2 v ID. Največja površina detektorjev v cevastem delu bo potrebna za zunanjo *Plast 4*¹, ki bo zaradi največje oddaljenosti od točke trka hkrati izpostavljena najmanjšemu toku delcev in poškodbam zaradi sevanja. Zaradi zahtevne in drage

¹V cevastem delu ITk so plasti oštevilčene od 0 do 4.

izdelave velike količine blaziničastih detektorjev potrebnih za Plast 4 je bila znotraj eksperimenta ATLAS ustanovljena *Kolaboracija ATLAS CMOS*, ki je preučevala možnost alternativnega postopka izdelave blaziničastih detektorjev.

Običajni blaziničasti detektorji so zgrajeni po hibridnem principu, v katerem sta senzor za zaznavanje delcev in čitalna elektronika izdelana na dveh ločenih rezinah silicija naknadno povezanih s krogličnimi povezavami na nivoju posameznih blazinic [47]. Postopek krogličnih povezav je tehnološko zahteven in časovno potraten, poleg tega pa so hibridni detektorji dragi zaradi senzorja iz izredno čistega silicija z upornostjo 3–20 k Ω cm, ki mora biti izdelan v posebnem uporabniku prilagojenem postopku. Alternativa hibridnim detektorjem, ki jo je raziskovala Kolaboracija ATLAS CMOS, so *osiromašeni monolitni aktivni blaziničasti senzorji* (DMAPS) izdelani v industrijskem procesu CMOS [48, 49]. V monolitnem detektorju sta zaznavni del in čitalna elektronika združena na eni sami silicijevi rezini, zato kroglične povezave niso potrebne. Kompaktna zasnova vezja z manjšim šumom omogoča uporabo manj čistega silicija z upornostjo 10–3000 Ω cm, ki je komercialno bolj razpoložljiv. V primerjavi s hibridnimi detektorji DMAPS med drugim omogočajo zasnovo manjših blazinic in manjšo porabo moči, zaradi česar je potrebno manj materiala za hlajenje sledilnika in je posledično sipanje delcev manjše. Te prednosti obetajo izboljšano ločljivost sledenja. Senzorji izdelani v tehnologiji CMOS so v zadnjem desetletju doživeli velik razcvet zaradi široke uporabe v potrošniški elektroniki, npr. v kamerah pametnih telefonov. Zaradi občutljivosti na sevalne poškodbe neposredni prenos te tehnologije v fiziko visokih energij sicer ni možen, vendar nekateri izdelovalci ponujajo procese, ki omogočajo uporabo visoke napetosti na senzorju in/ali visoko upornega materiala. Takšni senzorji imajo veliko osiromašeno področje, v katerem nosilci naboja potujejo v električnem polju, in so s tem odporni na sevalne poškodbe. Izdelava detektorjev v industrijskem procesu z velikimi količinami omogoča prihranke pri času izdelave in ceni v primerjavi s hibridnimi detektorji. Ker DMAPS doslej še niso bili uporabljeni v velikem obsegu v okolju z ATLAS-u primerljivo stopnjo sevanja, je ena glavnih zahtev pred njihovo uporabo prikaz njihove zadostne sevalne odpornosti, kar je tudi cilj tega doktorata.

Za razumevanje sevalnih poškodb je najprej potrebno poznavanje načina delovanja polprevodniških detektorjev delcev. Ti temeljijo na zbiranju električnega naboja – v siliciju parov elektron-vrzel (e-h) – ki ga nabiti delci ustvarijo z ionizacijo vzdolž svoje poti skozi material. Hitrost odlaganja energije hitrih nabitih delcev v materialu opisuje Bethejeva formula [40], ki uvede pojem *minimalno ionizirajočega delca* (MIP) za delce z vrednostjo relativističnega faktorja $\beta\gamma$ med 2 in nekaj 100. V siliciju MIP z največjo verjetnostjo odloži energijo 400 eV/ μm , ki ustreza 80 parom e-h/ μm . Za zaznavanje te razmeroma majhne količine naboja je potrebno delova-

nje v stanju z nizko ravnovesno gostoto nosilcev naboja, zato so silicijevi detektorji izdelani na osnovi p-n stika priklopljenega v zaporni smeri. p-n stik temelji na dveh različno dopiranih plasteh silicija, od katerih ena vsebuje presežek akceptorjev (p-tip), druga pa presežek donorjev (n-tip). Na območju spoja zaradi selitve nosilcev naboja pride do nastanka *osiromašenega področja*, v katerem prostih nosilcev naboja praktično ni. Zaradi posledične polarizacije materiala se ustvari električno polje, ki proste nosilce nemudoma odstrani iz osiromašenega območja. To lastnost izkoriščajo detektorji za zbiranje naboja, ki ga v osiromašenem območju ustvarijo visokoenergijski delci. Ker osiromašeno območje deluje kot občutljivi del, njegova velikost odločilno vpliva na velikost signala. V detektorjih je navadno ena plast (zbiralna elektroda) bistveno močnejše dopirana od druge plasti (substrat). V takšnem primeru je širina osiromašenega območja w podana z enačbo:

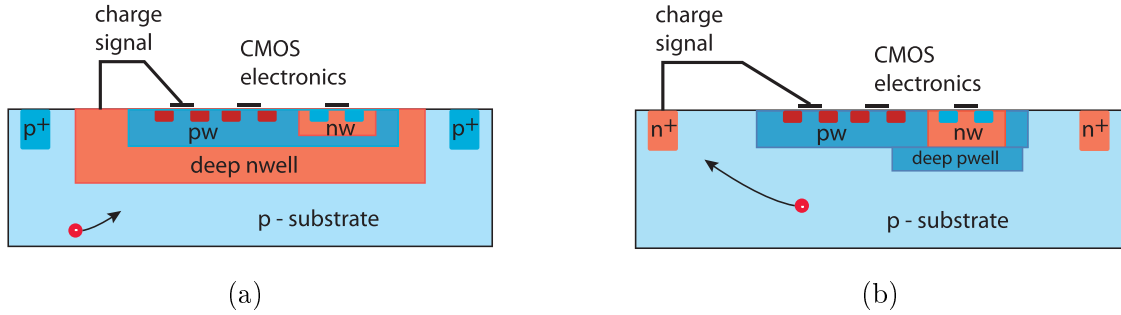
$$w = \sqrt{\frac{2\epsilon\epsilon_{\text{Si}}V_{\text{bi}}}{e_0N_{\text{eff}}}}, \quad (9.1)$$

kjer je ϵ influenčna konstanta, ϵ_{Si} dielektričnost silicija, V_{bi} pritiskljena električna napetost v zaporni smeri, e_0 osnovni naboj in N_{eff} *efektivna gostota prostorskega naboja* v substratu. V neobsevanih detektorjih je N_{eff} sorazmerna z gostoto dopantov v substratu, oziroma obratno sorazmerna z upornostjo materiala.

V silicijevih detektorjih izpostavljenim visokoenergijskemu sevanju pride do poškodb materiala zaradi tvorjenja defektov. Sevalne poškodbe delimo v dve glavni kategoriji:

- poškodbe zaradi *skupne ionizacijske doze* (TID), ki jo odložijo fotoni ter nabiti delci in povzroči poškodbe elektronike zaradi nabijanja SiO_2 v tranzistorjih [55];
- poškodbe zaradi izbitja atomov iz silicijeve kristalne rešetke, ki jo pretežno povzročijo hadroni [58, 59]. Njene posledice so povečan temni tok v detektorju, pasti, ki ujamejo nosilce naboja preden dosežejo zbiralno elektrodo, in spremembe N_{eff} . Ti dejavniki vplivajo na količino zbranega naboja v detektorju. Merilo za stopnjo poškodb zaradi izbitja je ekvivalentna fluenca Φ_{eq} z enoto $1 \text{ MeV n}_{\text{eq}}/\text{cm}^2$, ki je ekvivalent poškodbam, ki jih v materialu povzroči tok enega nevtrona z energijo 1 MeV na 1 cm^2 .

Plast 4 sledilnika ITk bo v načrtovani življenjski dobi predvidoma prejela skupno ionizacijsko dozo 80 MRad in fluenco $1,5 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$. Ta doktorat se osredotoča na določitev posledic poškodb v DMAPS zaradi izbitja atomov v tem območju fluence. Velik poudarek je na določitvi efektivne gostote prostorskega naboja, ki je



Slika 9.2: Shema detektorjev DMAPS z a) veliko; b) majhno zbiralno elektrodo. Prednost velike elektrode so krajše poti potovanja naboja in enakomerna rast osiromašenega področja na račun večje kapacitete detektorja [47].

v materialu tipa p določena s tremi prispevki opisanih z enačbo:

$$N_{\text{eff}} = N_{\text{eff},0}(1 - N_c/N_{\text{eff},0} \cdot (1 - e^{-c\Phi_{\text{eq}}})) + g_C\Phi_{\text{eq}}. \quad (9.2)$$

Prvi prispevek je začetna koncentracija atomov akceptorja $N_{\text{eff},0}$ določena z nivojem dopiranja substrata. Člen $g_C\Phi_{\text{eq}}$ opisuje ustvarjanje dodatnih akceptorskih stanj s koncentracijo sorazmerno s prejeto fluenco [63, 66]. Tretji prispevek imenovan *efektivna odstranitev začetnih akceptorjev*² opisuje električno deaktivacijo atomov akceptorja, navadno elementa bora, do katere pride zaradi izbitja atoma bora iz kristalne rešetke in tvorjenja kompleksa B_iO_i v medkristalnem prostoru. Komplex B_iO_i ima lastnosti donorja [67, 75, 76], zato se N_{eff} zmanjša, kar je ugodno za detektorje DMAPS, saj se s tem poveča globina osiromašenega območja in velikost signalov (Enačba 9.1). Efektivni delež vseh začetnih akceptorjev, ki so odstranjeni, podaja koeficient $0 \leq N_c/N_{\text{eff},0} \leq 1$, hitrost odstranitve s prejeto fluenco pa opisuje *koeficient odstranitve akceptorjev* c . Meritve z naprednimi silicijevimi detektorji [72, 77] nakazujejo, da je c odvisen od začetnega dopiranja in da je v močno dopiranih materialih za odstranitev akceptorjev potrebna višja fluenca. Zaradi velikega učinka, ki jih lahko ima odstranitev akceptorjev na delovanje DMAPS, je pomembno natančno opredeliti njen potek v različnih vzorcih.

Vzorci preiskovani v tem delu so bili razviti v okviru Kolaboracije ATLAS CMOS, ki je v vzporednih razvojnih procesih razvila več vrst DMAPS. Različne zasnove so bile izdelane pri različnih proizvajalcih, med sabo pa se med drugim razlikujejo po tipu CMOS procesa, geometriji blazinic, vrsti čitalne arhitekture in začetni upornosti substrata. Opravljene so bile tudi študije z detektorji zgrajenimi v arhitekturi *silicij na izolatorju* (SOI) in s prototipi linijskih detektorjev v tehnologiji CMOS. Ena glavnih snovalskih odločitev je izbira med t.i. zasnovama z veliko ali majhno zbiralno elektrodo (Slika 9.2). Detektorji z veliko zbiralno elektrodo, ki zaseda večji

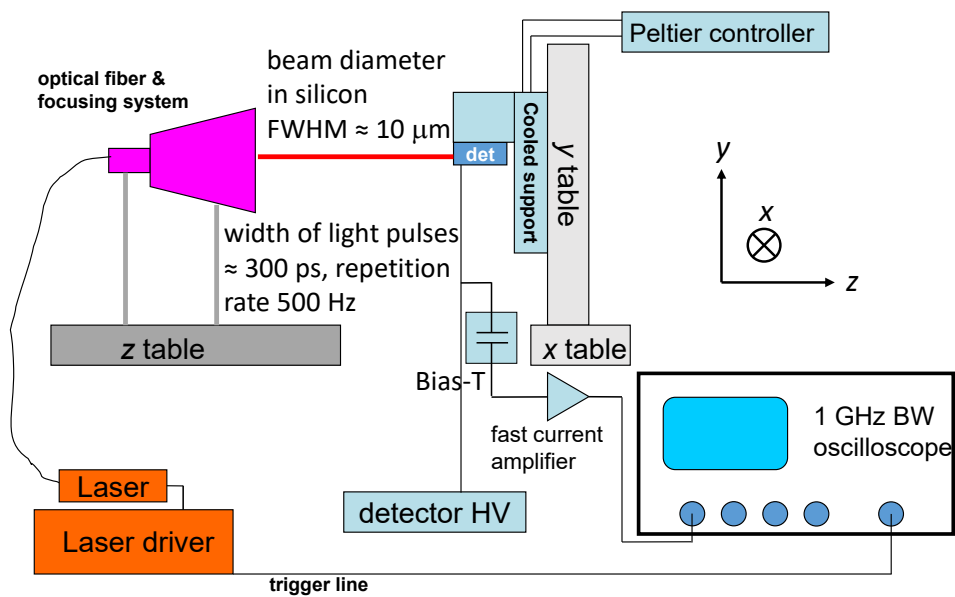
²Kratko *odstranitev akceptorjev*.

del površine celotne blazinice, so ustaljen koncept v hibridnih detektorjih, kjer velika zbiralna elektroda omogoča enakomerno rast osiromašenega območja po celotni površini blazinice in kratke poti potovanja naboja. Zaradi tega je odziv senzorja enakomeren in precej odporen na sevanje, vendar je kapaciteta blazinice razmeroma velika (nekaj 100 fF). To povzroči počasnejši odziv senzorja in višji nivo šuma, ki ju je potrebno kompenzirati z višjo električno močjo, kar lahko predstavlja težave pri hlajenju in posledično ločljivosti sledilnika. Pri detektorjih z majhno zbiralno elektrodo velikosti nekaj μm je kapaciteta detektorja minimalna ($\sim 5\text{ fF}$), zaradi česar imajo hiter odziv in omogočajo uporabo preprostejših čitalnih vezij z nizko močjo. Njihova slabost je težavno osiromašenje celotne prostornine blazinice in dolge poti potovanja naboja, kar lahko povzroči neučinkovitost detektorja, sploh po obsevanju. Razvojne smeri DMAPS v Kolaboraciji ATLAS CMOS opredeljene s ponudnikom in vrsto CMOS procesa, začetno upornostjo substrata in tipom geometrije zbiralne elektrode so:

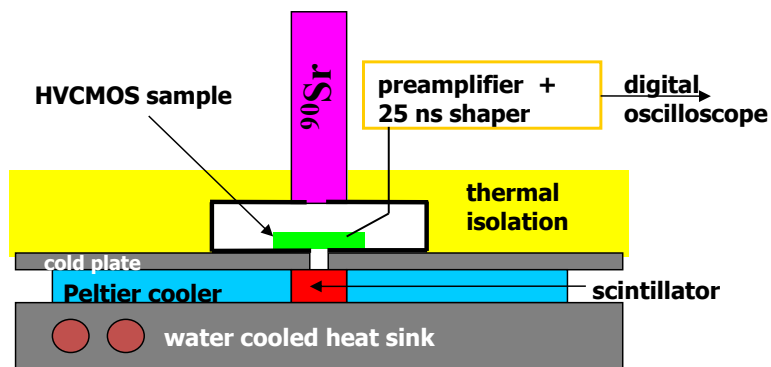
- LFoundry 150 nm, 2–3 k Ω cm, velika zbiralna elektroda [78, 79, 81];
- ams/TSI 180/350 nm, 20–1000 Ω cm, velika zbiralna elektroda [94, 96, 99];
- TowerJazz 180 nm, 1 k Ω cm (epitaksialno), majhna zbiralna elektroda [88, 89];
- X-FAB 180 nm, 100 Ω cm (SOI), velika zbiralna elektroda [52, 100].

V tem doktorskem delu so bile opravljene meritve zbiranja naboja z vzorci iz vsake od zgornjih skupin. Vzorci so bili obsevani z reaktorskimi nevtroni na Institutu Jozef Stefan [113, 114] v območju fluenc $1 \cdot 10^{13}\text{ n}_{\text{eq}}/\text{cm}^2$ – $1 \cdot 10^{16}\text{ n}_{\text{eq}}/\text{cm}^2$ ter s hitrimi protoni na pospeševalnikih PS v CERN-u [115] in LANSCE v Los Alamosu [116] v območju fluenc $4 \cdot 10^{14}\text{ n}_{\text{eq}}/\text{cm}^2$ – $3,5 \cdot 10^{15}\text{ n}_{\text{eq}}/\text{cm}^2$. Za meritve zbiranja naboja v laboratoriju sta se uporabljali tehniki e-TCT³ in meritve zbiranja naboja z radioaktivnim virom ^{90}Sr (Slika 9.3). Metoda TCT obsega širok nabor tehnik, ki namesto visokoenergijskih delcev za ustvarjanje naboja v detektorju uporabljajo pulzirano lasersko svetlobo [104, 105, 106]. Odziv detektorja se določi iz meritev prehodnega toka (angl. Transient Current Technique – TCT), ki se ga zajame s hitro merilno elektroniko. Po teoremu Shockleyja in Rama [44, 45] je integral influenciranega toka na merilni elektrodi enak naboju, ki ga ta elektroda zbere. Metoda e-TCT temelji na vbrizgavanju naboja z ozkim žarkom premera $< 10\text{ }\mu\text{m}$, ki v detektor vstopa s strani (Slika 9.3a) [108, 109]. Na ta način se ves odloženi naboj nahaja na točno določeni globini v senzorju, kar omogoča določitev odziva posameznega dela znotraj volumna blazinice z visoko ločljivostjo. Tako je možno preprosto izmeriti velikost osiromašenega območja, saj v obsevanih detektorjih le to proizvede znatne signale. Pomanjkljivost metode TCT je, da količina vbrizganega naboja ni umerjena, saj

³angl. Edge Transient Current Technique

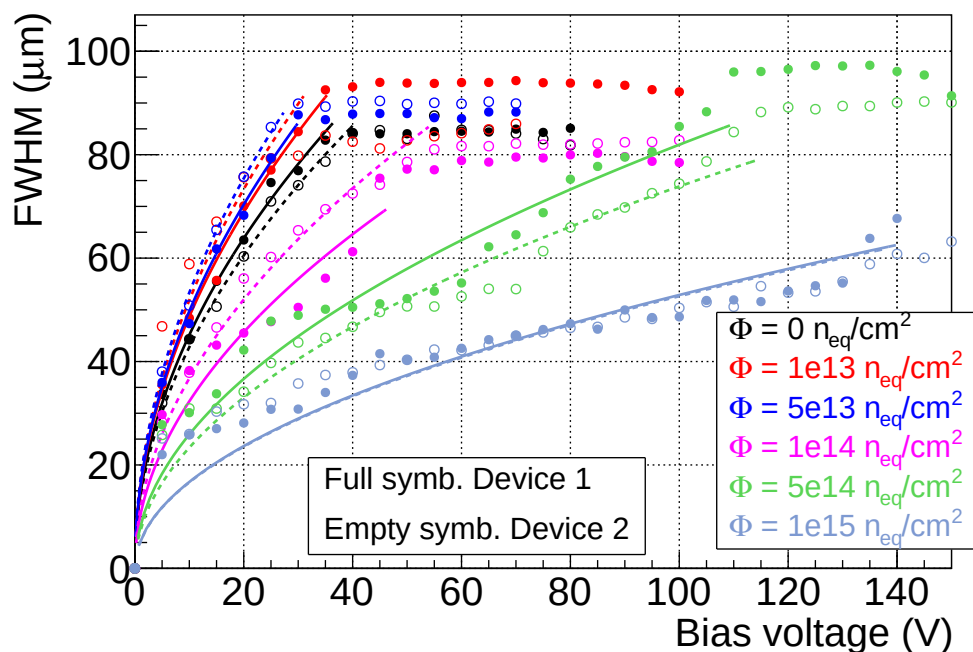


(a)



(b)

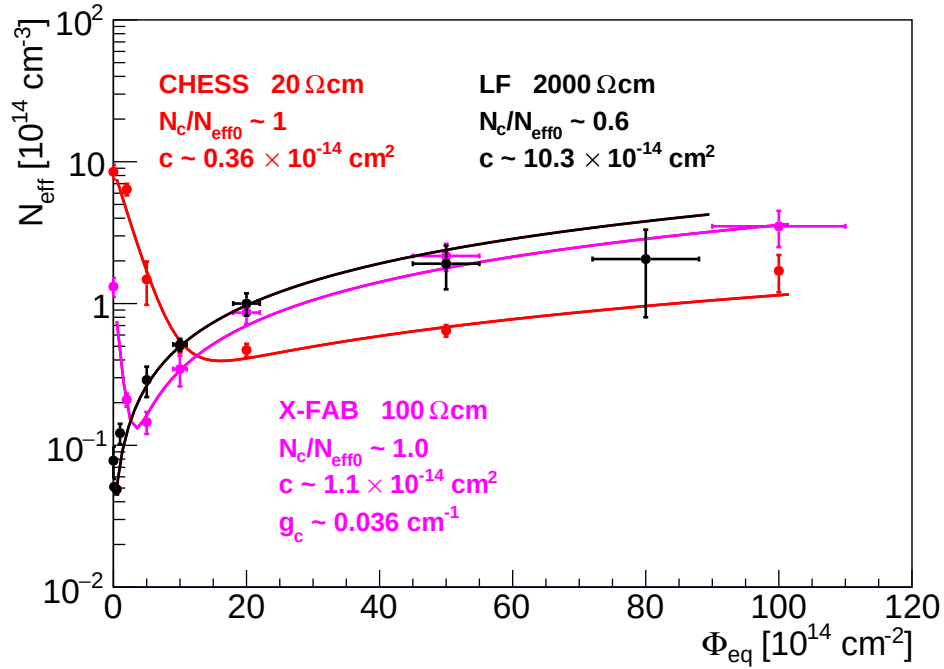
Slika 9.3: Shemi merilnih naprav za: a) meritve z metodo e-TCT; b) meritve zbiranja naboja s ^{90}Sr [72].



Slika 9.4: Primer meritve širine osiromašenega območja v odvisnosti od zaporne napetosti z metodo e-TCT v detektorju LFoundry z začetno upornostjo $2 \text{ k}\Omega \text{ cm}$ in debelino $100 \mu\text{m}$ [117].

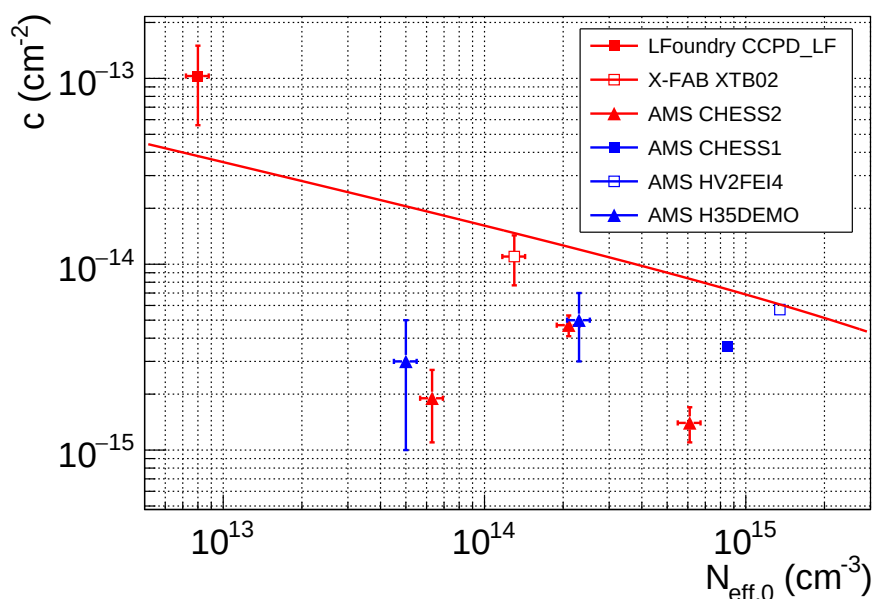
je lahko intenziteta laserske svetloba poljubna. To dodatno informacijo je možno pridobiti z meritvijo zbranega naboja s ^{90}Sr , ki je vir elektronov iz radioaktivnega razpada β s skupno energijo $2,26 \text{ MeV}$. Del elektronov iz visokoenergijskega dela spektra se obnaša podobno kot MIP, zato je količina odloženega naboja znana. Takšne dogodke je možno izbrati s proženjem zajema s fotopomnoževalko postavljeno za testiranim detektorjem, kot je prikazano na Sliki 9.3b. Naboj zbran na detektorju v času 25 ns je nato zaznan s prilagojenim ojačevalcem in zabeležen z osciloskopom.

Primer meritve širine osiromašenega območja v odvisnosti od zaporne napetosti z metodo e-TCT je prikazan na Sliki 9.4. Preiskovani detektor je prototip iz serije LFoundry z začetno upornostjo $2 \text{ k}\Omega \text{ cm}$ in debelino $100 \mu\text{m}$. Iz meritev je razvidno naraščanje širine osiromašenega območja z napetostjo do točke, ko je osiromašena celotna debelina detektorja. Do tega pride najhitreje v vzorcu obsevanem z nevtroni na fluenco $5 \cdot 10^{13} \text{ n}_{eq}/\text{cm}^2$, kar kaže na zmanjšanje N_{eff} zaradi odstranitve akceptorjev. Pri višjih fluencah do popolnega osiromašenja pride šele pri višjih napetostih zaradi dodatnih akceptorskih stanj, ki povečajo effektivno gostoto prostorskega naboja. S prilagajanjem Enačbe 9.1 na podatke pri napetostih pod napetostjo popolnega osiromašenja je možno določiti vrednost N_{eff} pri vsaki fluenci. Primer poteka N_{eff} z nevtronsko fluenco v različnih materialih je prikazan na Sliki 9.5. V detektorju LFoundry [117] pride pri najnižjih fluencah do zmanjšanja prostorskega naboja zaradi odstranitve akceptorjev, vendar je zaradi nizke stopnje



Slika 9.5: Primer izmerjenih vrednosti N_{eff} v odvisnosti od fluence za prototipe DMAPS za različnimi začetnimi upornostmi substrata [72, 117, 124].

dopiranja potek kmalu dominiran z nastankom novih akceptorskih stanj. V vzorcu X-FAB z začetno upornostjo $100 \, \Omega \text{ cm}$ [124] je odstranitev akceptorjev končana pri višji fluenci okrog $5 \cdot 10^{14} \text{ n}_{\text{eq}}/\text{cm}^2$, nato pa je potek N_{eff} podoben kot pri detektorju LFoundry. Pri detektorju CHES z začetno upornostjo $20 \, \Omega \text{ cm}$ pa je odstranitev akceptorjev končana šele pri fluenci $1 \cdot 10^{15} \text{ n}_{\text{eq}}/\text{cm}^2$ [72]. Iz prilaganja funkcije 9.2 podatkom je možno določiti delež odstranjenih akceptorjev in koeficient odstranjevanja akceptorjev c . Pri večini preučevanih vzorcev je delež odstranjenih akceptorjev enak 1, pri ostalih pa se giblje med 0,5 in 1. Koeficienti odstranitve akceptorjev pri nevtronskem obsevanju izmerjeni v tem delu so v odvisnosti od začetne koncentracije dopiranja prikazani na Sliki 9.6, kjer so primerjani z vrednostmi izmerjenimi v drugih prototipih DMAPS. Opazen je splošen trend zmanjševanja vrednosti c z naraščajočim dopiranjem, vendar zaradi velikih razlik med materiali ni možno parametrizirati splošne odvisnosti. Izmerjene vrednosti se grobo ujemajo z napovedjo preprostega modela izdelanega na podlagi meritev z detektorji LGAD, ki so dopirani v koncentracijah nad 10^{16} cm^{-3} ($< 1 \, \Omega \text{ cm}$) [77]. Podobne meritve so bile izvedene tudi z vzorci ams CHES2 obsevanimi s protoni, vendar zaradi manjšega števila razpoložljivih fluenc ni bilo mogoče določiti koeficientov odstranitve akceptorjev. V grobem so meritve pokazale, da protoni začetne akceptorje odstranijo znatno hitreje kot nevtroni, poleg tega pa ustvarjajo nova akceptorska stanja počasneje. Zaradi tega je N_{eff} v protonsko obsevanih vzorcih veliko nižji kot pri primerljivi nevtronski fluenci, kar je s stališča DMAPS ugodno, saj to omogoča večjo širino osiromašenega

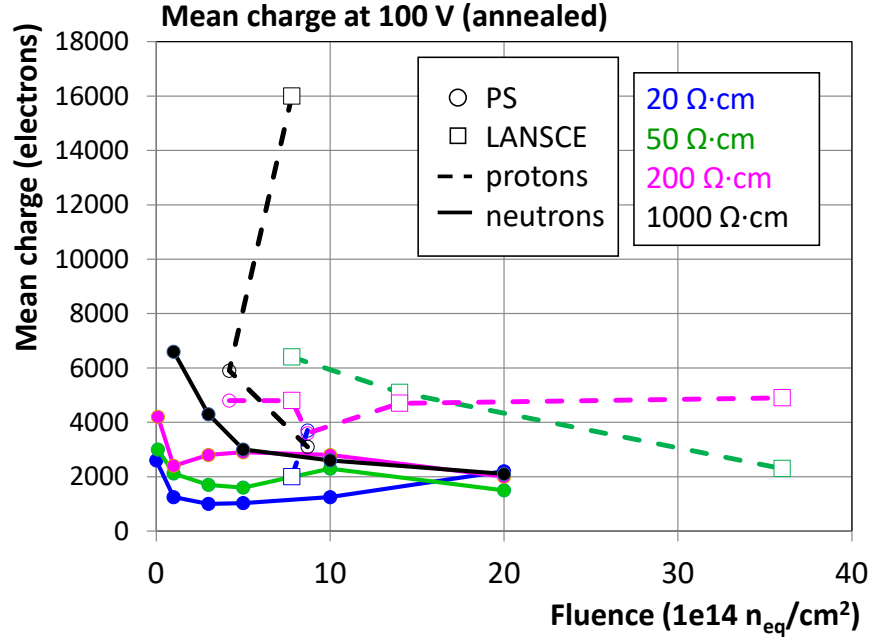


Slika 9.6: Izmerjene vrednosti koeficienta odstranitve akceptorjev v odvisnosti od začetne koncentracije akceptorjev v materialu. Podatki predstavljeni z rdečimi točkami so bili izmerjeni v okviru tega dela [117, 123, 124], modre točke pa predstavljajo meritve z drugimi prototipi DMAPS [72, 94]. Rdeča črta predstavlja napoved modela odstranjevanja akceptorjev izdelanega na podlagi visoko dopiranih ($> 10^{16} \text{ cm}^{-3}$) detektorjev LGAD [77].

območja.

Poleg meritev z e-TCT je bilo v nekaterih vzorcih izmerjeno še zbiranje naboja s ^{90}Sr . Slika 9.7 prikazuje takšno meritev z detektorji ams CHESS2 izdelanih v štirih različicah začetne upornosti. Iz meritve je razvidno, da je v neobsevanih vzorcih zbranega več naboja kot po prvem koraku nevtronskega obsevanja. Razlog za to je zbiranje naboja ustvarjenega izven osiromašenega območja, ki skozi detektor potuje z difuzijo. Ta način transporta je zelo občutljiv na sevalne poškodbe, zato njegov prispevek po obsevanju izgine. Pri višjih nevtronskih fluencah je razvidno naraščanje količine zbranega naboja, kar je posledica odstranitve akceptorjev. Od vseh vzorcev je signal najbolj stabilen v detektorju izdelanem na substratu z upornostjo $200 \Omega \text{ cm}$, kjer povprečni zbran naboj nikoli ne pade pod 2000 elektronov. Na detektorju z visoko začetno upornostjo $1 \text{ k}\Omega \text{ cm}$ je sicer pri nizkih fluencah na razpolago več naboja, vendar se pri fluenci nad $5 \cdot 10^{14} n_{\text{eq}}/\text{cm}^2$ ta vrednost izenači z $200 \Omega \text{ cm}$ vzorcem. V vzorcih obsevanih s protoni so jasno razvidne posledice manjše količine efektivnega prostorskega naboja v primerjavi z nevtronsko obsevanimi vzorci, saj je količina zbranega naboja veliko večja, celo znatno višja kot v neobsevanih vzorcih.

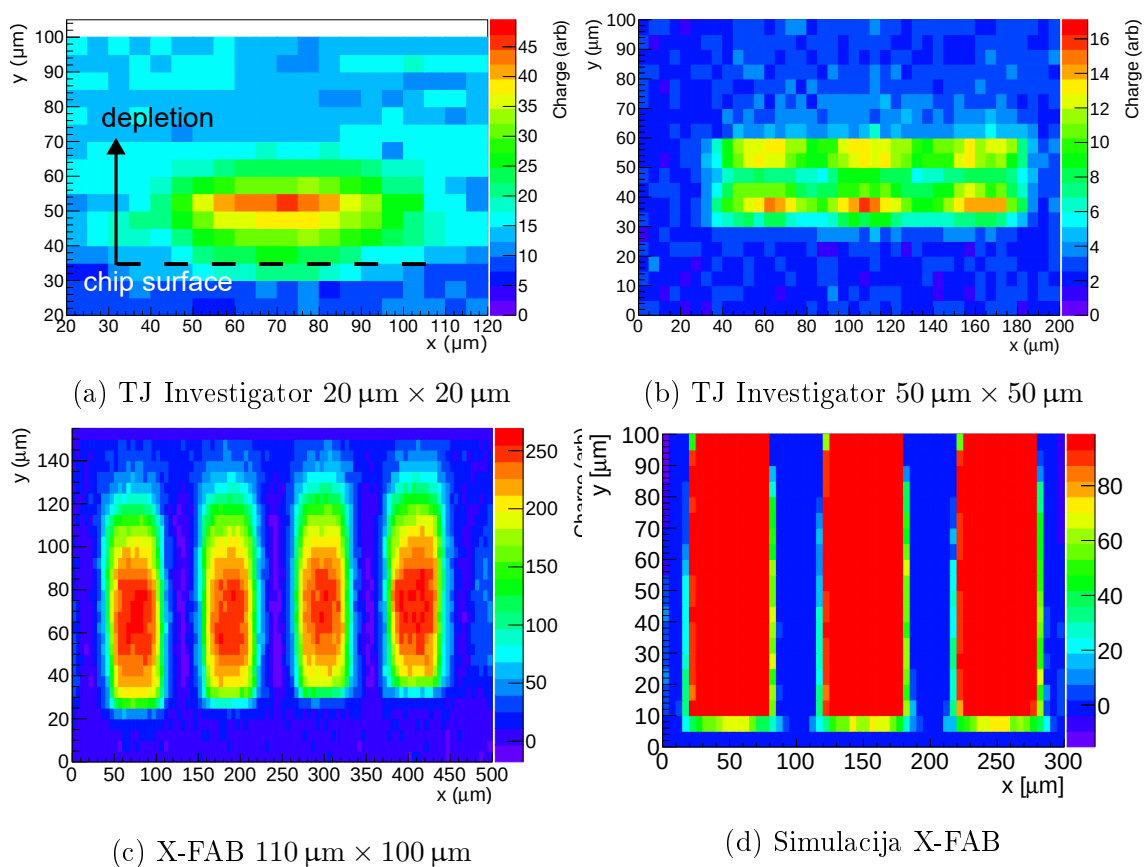
Metoda e-TCT je bila uporabljena tudi za določitev enakomernosti signala po celotni blazinici, ki je bila izvedena s premikanjem žarka v dveh dimenzijah. Primeri



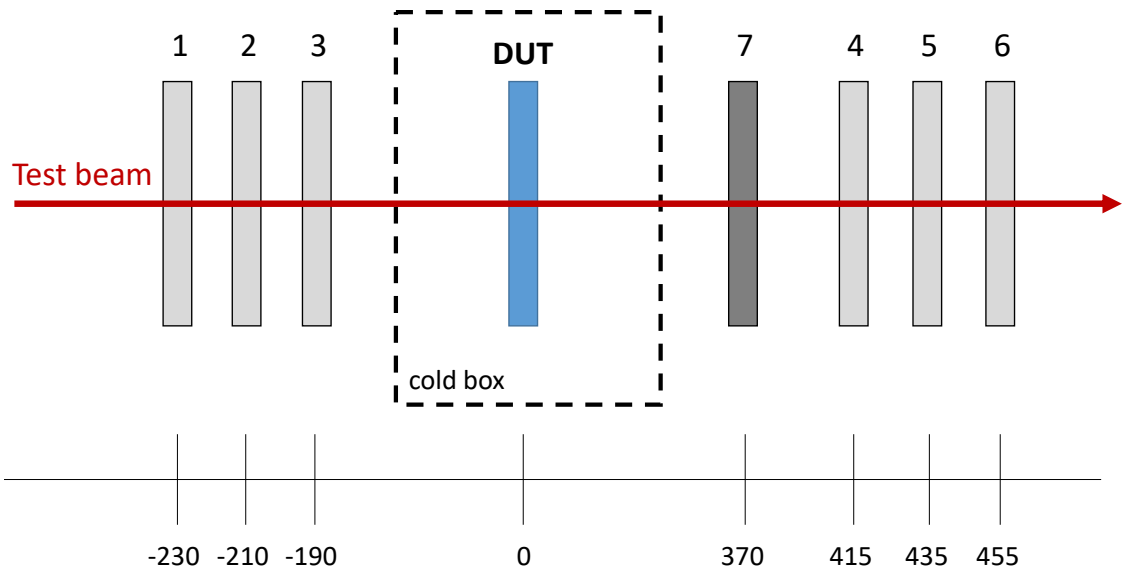
Slika 9.7: Povprečna količina zbranega naboja izmerjena s ^{90}Sr v detektorjih ams CHESS2 z različnimi začetnimi upornostmi v odvisnosti od fluence. Polna črta predstavlja meritve z nevtronsko obsevanimi vzorci, črtkana črta pa s protonsko obsevanimi vzorci [123].

meritev so prikazani na Sliki 9.8. Sliki 9.8a in 9.8b prikazujeta meritev z vzorcem TowerJazz Investigator z velikostjo blazinice $20\text{ }\mu\text{m} \times 20\text{ }\mu\text{m}$ oz. $50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$ izdelanega v geometriji z majhno bralno zbiralno elektrodo in obsevanega z nevtronsko fluenco $1 \cdot 10^{15}\text{ n}_{\text{eq}}/\text{cm}^2$. Na sliki so vidne tri blazinice, ki so bile povezane na bralno elektroniko. Površina silicijeve rezine se nahaja na spodnjem delu občutljivega območja, osiromašeno področje pa narašča v smeri osi y . Zaradi zelo majhnih blazinic je bila meritev izvedena na meji pozicijske občutljivosti, vendar so vseeno razvidna področja z različno količino zbranega naboja. Pri blazinicah z velikostjo $50\text{ }\mu\text{m} \times 50\text{ }\mu\text{m}$ je vidna večja količina zbranega naboja v osrednjem delu blizu zbiralne elektrode, medtem ko je na robovih blazinic ta nekoliko nižja. Podoben primer je prikazan na Sliki 9.8c narejeni z vzorcem X-FAB z velikostjo blazinic $110\text{ }\mu\text{m} \times 100\text{ }\mu\text{m}$ izdelanega v tehnologiji SOI in obsevanega na fluenco $5 \cdot 10^{14}\text{ n}_{\text{eq}}/\text{cm}^2$. Na sliki so štiri blazinice, ki jih ločujejo področja z majhno količino zbranega naboja. To je posledica parazitskega zbiranja naboja na delu detektorja namenjenemu bralni elektroniki, ki pa ni povezan z zbiralno elektrodo. Posledica tega so navidezno neučinkovita območja, ki jih je potrebno odstraniti s prilagoditvijo zasnove. Parazitsko zbiranje naboja je bilo potrjeno tudi z orodjem KDetSim [127], ki simulira zbiranje naboja v detektorjih s poljubno geometrijo. Rezultati simulacije prikazani na Sliki 9.8d se kvantitativno ujemajo z meritvijo z e-TCT.

Druga zvrst meritev v okviru tega doktorata je bila določitev učinkovitosti mo-



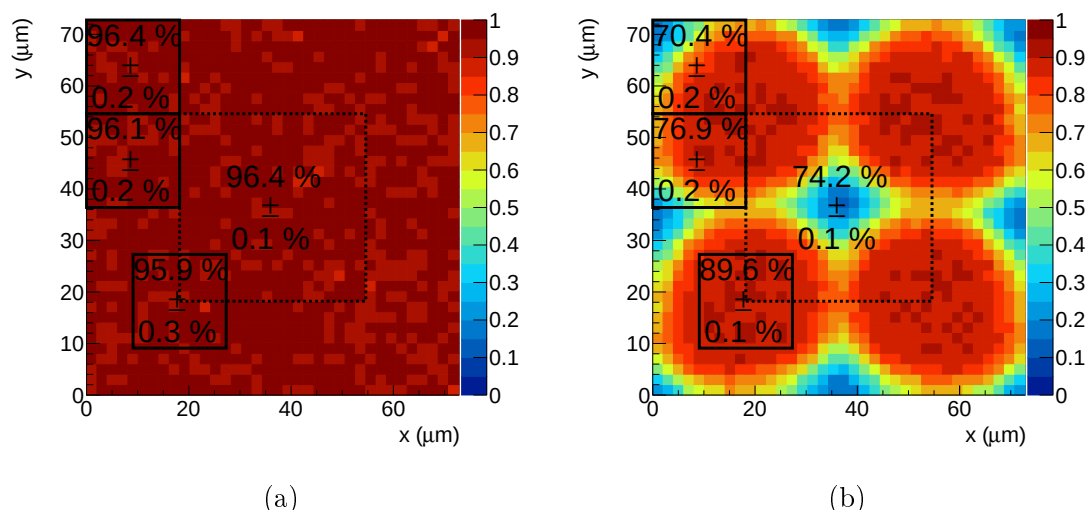
Slika 9.8: Meritve enakomernosti zbranega naboja znotraj polja blazinic z metodo e-TCT: Sliki a) in b) sta narejeni z vzorcem TowerJazz Investigator z majhno zbiralno elektrodo obsevanem z nevtroni do fluence $1 \cdot 10^{15}\ \text{n}_{\text{eq}}/\text{cm}^2$, Slika c) pa z vzorcem X-FAB obsevanem z nevtronsko fluenco $5 \cdot 10^{14}\ \text{n}_{\text{eq}}/\text{cm}^2$. Slika d) je rezultat simulacije zbiranja naboja v detektorju podobnem detektorju c) in kaže enaka območja z nizko učinkovitostjo med blazinicami.



Slika 9.9: Shema žarkovnega teleskopa KarTel za meritve v testnem žarku. Preiskovani detektor (DUT) je nameščen med zaznavnima ravninama 3 in 4 v hlajenem ohišju. Dimenzije so v mm.

nolitnega detektorja TowerJazz MALTA z visokoenergijskim testnim žarkom na pospeševalniku SPS v CERN-u. TowerJazz MALTA je izdelan v arhitekturi z majhno zbiralno elektrodo in velikostjo blazinic $36\ \mu\text{m} \times 36\ \mu\text{m}$, za čitanje podatkov pa uporablja inovativen sistem, ki za delovanje ne potrebuje razdeljevanja urinega signala v polje blazinic in s tem zmanjša električno moč čipa za več kot 50 % [88]. V tem delu so predstavljene meritve z dvema vzorcema: neobsevanim in nevtronsko obsevanim na fluenco $1 \cdot 10^{15}\ n_{\text{eq}}/\text{cm}^2$. Nepredvidene napake v zasnovi čipa so povzročile, da vzorci niso mogli delovati v idealnem območju nastavitve. Zaradi težav v napajanju vezja za konfiguracijo čipa iz čitalnega sistema ni bilo možno izločiti blazinic z visokim šumom, kar je vodilo v zasičenost bralnega sistema na čipu. V izogib tem težavam je bilo vzorce treba nastaviti na manjšo občutljivost, pri kateri je bil najnižji zaznavni prag namesto na predvideno vrednost $200\ e^-$ nastavljen na $250\ e^-$ v neobsevanem in $350\ e^-$ v obsevanem vzorcu.

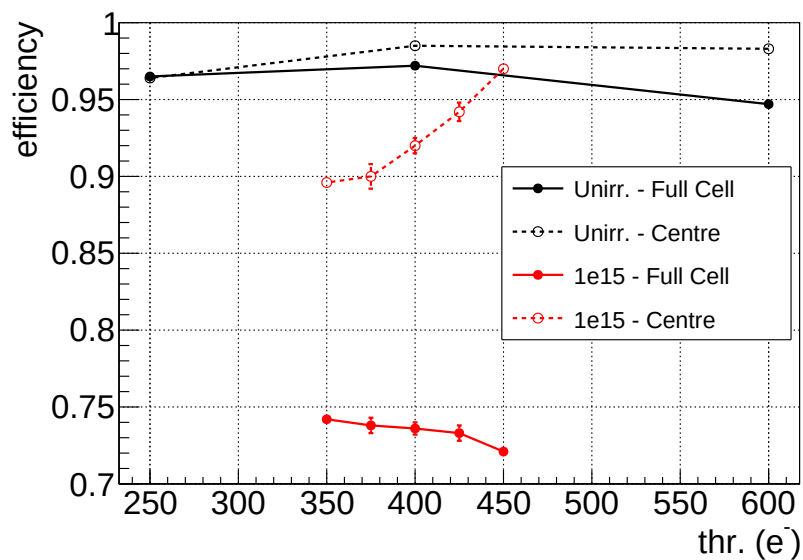
Meritve so bile opravljene z žarkom pionov z energijo $180\ \text{GeV}$ in lastnostmi delcev MIP. Trajektorije delcev so bile določene z uporabo žarkovnega teleskopa KarTel [133], ki sestoji iz sedmih zaporednih visokoločljivostnih zaznavnih ravnin (6 detektorjev Mimosa-26 [134] + 1 detektor z bralnim čipom FEI4) postavljenih na obeh straneh preiskovanega detektorja (Slika 9.9). Prikazana postavitve omogoča določitev presečišča sledi delcev MIP z detektorjem z ločljivostjo $\sigma = 5\ \mu\text{m}$. V rekonstrukciji podatkov s programsko opremo Judith/Proteus [133] so bile izbrane samo sledi zaznane v vseh sedmih ravninah teleskopa, poleg tega pa so bili izločeni dogodki z več kot eno sledjo, ki je ustrezala temu kriteriju. Učinkovitost vzorca



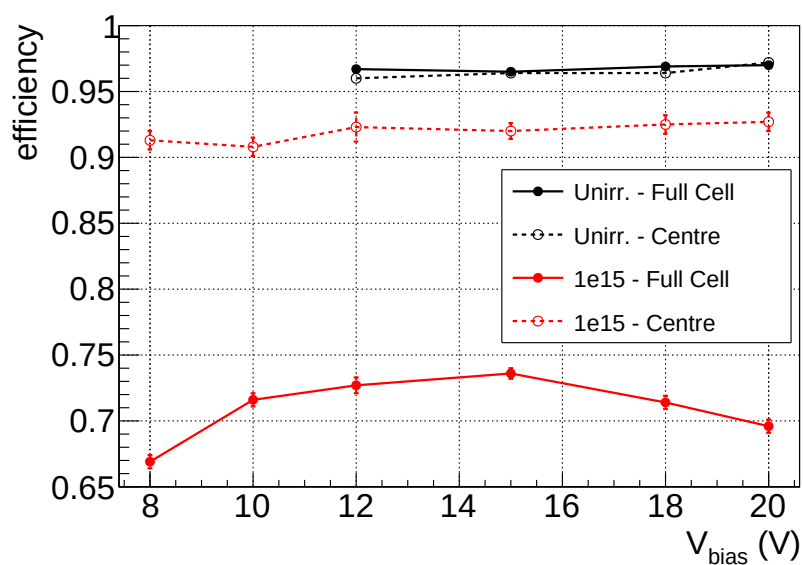
Slika 9.10: Izmerjena učinkovitost zaznavanja delcev v detektorju TowerJazz MALTA, predstavljena v polju 2×2 blazinic: a) pred obsevanjem pri pragu $250 e^-$; b) po obsevanju z $1 \cdot 10^{15} n_{eq}/\text{cm}^2$ pri pragu $350 e^-$. Pritisnjena zaporna napetost je 15 V.

je bila definirana kot razmerje med številom sledi povezanih z zaznanim dogodkom v preučevanem vzorcu in skupnim številom sledi v izbranem območju. Za večjo preglednost je bila učinkovitost celotnega polja preslikana v celico velikosti 2×2 blazinici. Primer meritve učinkovitosti neobsevanega in obsevanega vzorca je prikazan na sliki 9.10. V neobsevanem vzorcu je učinkovitost zaznavanja enakomerna s povprečno vrednostjo 96,4 % znotraj blazinice, medtem ko so v obsevanem vzorcu jasno opazna območja na robovih blazinic z nižjo občutljivostjo. Povprečna učinkovitost blazinice v obsevanem vzorcu je v prikazanem primeru 74,2 %, pri čemer znaša učinkovitost v osrednjem delu blazinice, ki predstavlja 25 % površine okoli zbiralne elektrode, 89,6 %, v kotih blazinice pa je vzorec skoraj popolnoma neučinkovit. Do neučinkovitosti na robovih pride zaradi šibkega električnega polja, ki ni zadostno za hitro zbiranje naboja. Posledično se nosilci naboja ujamejo v pasti, ki jih povzroči sevanje, zato se zbran naboj zmanjša, kar je splošen problem zasnove z majhno zbiralno elektrodo. V osrednjem delu blazinice je izmerjena učinkovitost višja pri višjem pragu občutljivosti. To je možno razložiti z izgubo podatkov zaradi zasičenosti čitalnega sistema, ki se z naraščanjem praga občutljivosti niža zaradi nižjega nivoja prepuščenega šuma.

Učinkovitosti detektorja MALTA pri različnih pragovih zaznave in različnih zapornih napetostih so prikazane na diagramu 9.11. Neobsevan detektor doseže najvišjo učinkovitost 97,0 % pri zaznavnem pragu $400 e^-$, na različne zaporne napetosti pa je razmeroma neobčutljiv. V obsevanem detektorju se povprečna učinkovitost celotne blazinice zmanjšuje z večanjem praga, učinkovitost osrednjega dela pa s



(a)



(b)

Slika 9.11: Učinkovitost detektorja TowerJazz MALTA pred in po obsevanju v odvisnosti od a) praga na predojačevalcu in b) pritiskjene zaporne napetosti. Meritve a) so bile narejene pri zaporni napetosti 15 V in meritve b) pri pragu 250 e^- v neobsevanem in 400 e^- v obsevanem vzorcu. Polna črta predstavlja povprečno učinkovitost celotne blazinice, črtkana črta pa povprečno učinkovitost osrednjih 25 % površine blazinice v okolici zbiralne elektrode.

pragom narašča. To je posledica zgoraj opisanih procesov – pri nizkem pragu je zaznanih več dogodkov na robovih detektorja, kjer je na razpolago manj naboja zaradi ujetja v pasti. Obenem se z nižanjem praga zvišuje stopnja izgube podatkov zaradi zasičenja čitalnega vezja, kar je prevladujoči proces v osrednjem delu blazinice, kjer je ujetja v pasti razmeroma malo. Odvisnost učinkovitosti od zaporne napetosti v obsevanem detektorju doseže najvišjo vrednost 74,2 % pri napetosti 15 V. Pri višjih napetostih učinkovitost pade, ker postane električno polje v blazinici slabše usmerjeno proti zbiralni elektrodi in je zato na robovih zaznanih manj signalov. Opisani rezultati so bili pomemben vir povratnih informacij načrtovalcem čipa MALTA, ki so na podlagi zgornjih meritev predlagali izboljšave v zgradbi blazinice. Te temeljijo na spremembi implantiranih struktur, ki povečajo bočno komponento električnega polja ter s tem znatno povečajo učinkovitost na robovih blazinic [139]. Te spremembe so bile skupno z odpravljenimi napakami v elektronskem vezju, ki so onemogočale delovanje pri nizkih pragovih zaznavanja, izvedene v čipu MiniMALTA. Prvi rezultati meritev v testnem žarku kažejo na bistveno izboljšanje delovanja z učinkovitostjo nad 98 % v obsevanih vzorcih [93].

Marca 2019 se je kolaboracija ATLAS odločila, da zaradi prekratkih časovnih rokov ne bo uporabila detektorjev DMAPS za izgradnjo Plasti 4 v sledilniku ITk, saj nobena ob razvojnih smeri do takrat še ni razpolagala s prototipom s polno funkcionalnostjo zahtevano za ATLAS. Nekatere skupine vseeno nadaljujejo z razvojem, da izkoristijo vloženo delo in dosedanje raziskave. Detektorji DMAPS imajo kljub temu svetlo prihodnost, saj so zanimivi tudi za uporabo na prihodnjih pospeševalnikih, kot sta npr. načrtovana Kompaktni linearni trkalnik (CLIC) in Mednarodni linearni trkalnik (ILC), ki zahtevata visoko ločljivost sledenja in zmerno odpornost na sevanje.

Obsežna študija detektorjev DMAPS izvedena v okviru tega doktorata je z uporabo merskih metod e-TCT, ^{90}Sr in testni žarek raziskala lastnosti zbiranja naboja v obsevanih detektorjih. Hkrati so meritve služile kot vir povratnih informacij snovalcem detektorjev, ki so na podlagi rezultatov lahko izboljšali sevalno odpornost vzorcev. Ena glavnih tem tega dela je opredelitev odstranitve začetnih akceptorjev, ki lahko odločilno vpliva na velikost osiromašenega območja v območju fluenc $10^{13}\text{--}10^{15}\text{ n}_{\text{eq}}/\text{cm}^2$. Zaradi koristnega vpliva na delovanje sledilnih detektorjev bo upoštevanje odstranitve akceptorjev verjetno imelo pomembno vlogo v zasnovi prihodnjih detektorjev.