

Silicon Sensors for the Upgrades of the CMS Pixel Detector

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Elwood: *It's 106 miles to Chicago, we got a full tank of gas, half a pack of cigarettes, it's dark... and we're wearing sunglasses.*

Jake: *Hit it.*

THE BLUES BROTHERS

Abstract

The Compact Muon Solenoid (CMS) is a general purpose detector at the Large Hadron Collider (LHC). The LHC luminosity is constantly increased through upgrades of the accelerator and its injection chain. Two major upgrades will take place in the next years. The first upgrade involves the LHC injector chain and allows the collider to achieve a luminosity of about $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. A further upgrade of the LHC foreseen for 2025 will boost its luminosity to $5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. As a consequence of the increased luminosity, the detectors need to be upgraded. In particular, the CMS pixel detector will undergo two upgrades in the next years. The first upgrade (phase I) consists in the substitution of the current pixel detector in winter 2016/2017. The upgraded pixel detector will implement new readout electronics that allow efficient data taking up to a luminosity of $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, twice as much as the LHC design luminosity. The modules that will constitute the upgraded detector are being produced at different institutes. Hamburg (University and DESY) is responsible for the production of 350 pixel modules. The second upgrade (phase II) of the pixel detector is foreseen for 2025. The innermost pixel layer of the upgraded detector will accumulate a radiation damage corresponding to an equivalent fluence of $\Phi_{eq} = 2 \cdot 10^{16} \text{ cm}^{-2}$ and a dose of $\approx 10 \text{ MGy}$ after an integrated luminosity of 3000 fb^{-1} . Several groups are investigating sensor designs and configurations able to withstand such high doses and fluences.

This work is divided into two parts related to important aspects of the upgrades of the CMS pixel detector. For the phase I upgrade, a setup has been developed to provide an absolute energy calibration of the pixel modules that will constitute the detector. The calibration is obtained using monochromatic X-rays. The same setup is used to test the buffering capabilities of the modules' readout chip. The maximum rate experienced by the modules produced in Hamburg will be 120 MHz/cm^2 . For this rate the modules' efficiency has been measured to be 99%. In view of the module production, the energy calibration procedure has been automated. The modules assigned to the Hamburg production center should be completed by the end of February 2016.

For the phase II upgrade, thin silicon sensors with an active thickness of $100 \mu\text{m}$ irradiated with protons up to $\Phi_{eq} = 1.3 \cdot 10^{16} \text{ cm}^{-2}$ have been characterized. The charge collection efficiency has been measured using pad diodes. Charge multiplication effects have been observed for both n- and p-bulk sensors. P-bulk strip sensors with an active thickness of 100 and $200 \mu\text{m}$ have been characterized with a beam test. The signal of these sensors lies between 4000 and 5000 e^- after a fluence of $1.3 \cdot 10^{16} \text{ cm}^{-2}$. The $200 \mu\text{m}$ thick sensors require a higher bias voltage than the $100 \mu\text{m}$ thick sensors to reach this signal height. The threshold necessary to obtain 95% detection efficiency is found to be around 2000 e^- for the $100 \mu\text{m}$ thick sensors.

Kurzfassung

Der Compact Muon Solenoid (CMS) ist ein Universaldetektor am Large Hadron Collider (LHC). Die Luminosität des LHC wird durch Arbeiten am Beschleuniger und seines Injektors kontinuierlich erhöht. Zwei wichtige *Upgrades* werden in den nächsten Jahren stattfinden. Das erste Upgrade betrifft den LHC Injektor und erlaubt es eine Luminosität von etwa $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ zu erreichen. In einem weiteren Schritt wird die Luminosität des LHC weiter auf $5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ erhöht. Als eine Konsequenz der höheren Luminosität müssen ebenfalls die Detektoren verbessert werden. Der CMS Pixeldetektor wird in den nächsten Jahren zwei Upgrades erfahren. Das erste Upgrade (Phase-I) umfasst die vollständige Ersetzung des aktuellen Pixeldetektors im Winter 2016/2017. Der verbesserte Pixeldetektor wird neue Ausleseelektronik besitzen, die eine effiziente Datennahme bis zu einer Luminosität von $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ erlaubt. Diese Luminosität entspricht der doppelten *Designluminosität* des LHC. Die Module, die den vollen Detektor bilden, werden an unterschiedlichen Instituten produziert. Hamburg (Universität und DESY) ist dabei verantwortlich für die Produktion von 350 Pixelmodulen. Das zweite Upgrade (Phase-II) des Pixeldetektors ist für das Jahr 2025 geplant. Die innerste Pixellage des Phase-II Detektors wird nach einer integrierten Luminosität von 3000 fb^{-1} Strahlenschäden entsprechend einer Äquivalenzfluenz von $\Phi_{eq} = 2 \cdot 10^{16} \text{ cm}^{-2}$ und einer Dosis von $\approx 10 \text{ MGy}$ aufweisen. Verschiedene Arbeitsgruppen untersuchen Sensordesigns und Bauformen, die in der Lage sind einer so hohen Dosis und einem so großen Fluenz standzuhalten. Die vorliegende Arbeit ist in zwei Teile aufgeteilt, die sich mit wichtigen Aspekten der verschiedenen Upgrades des CMS Pixeldetektors befassen. Für das Phase-I-Upgrade wurde ein Versuchsaufbau entwickelt, der es ermöglicht, eine absolute Energiekalibration der Pixelmodule durchzuführen. Die Kalibration wird mit Hilfe von monochromatischer Röntgenstrahlung erzielt. Der gleiche Aufbau wird dazu genutzt, die Zwischenspeicherfähigkeiten des Auslesechips der Module zu testen. Die maximale Rate, der die in Hamburg gebauten Module ausgesetzt sein werden, beträgt 120 MHz/cm^2 . Die Moduleffizienz wurde bei dieser Rate zu 99% bestimmt. In Hinblick auf die Modulmassenproduktion wurde die Energiekalibration automatisiert. Die Modulproduktion, die dem Hamburger Produktionszentrum zugeordnet wurde, sollten bis Ende Februar 2016 abgeschlossen sein. Bezüglich des Phase-II-Upgrades wurden $100 \mu\text{m}$ dicke Siliziumsensoren mit Protonen entsprechend $\Phi_{eq} = 1.3 \cdot 10^{16} \text{ cm}^{-2}$ bestrahlt und charakterisiert. Die Ladungssammlungseffizienz wurde mit Hilfe von Pad-Dioden gemessen. Effekte der Ladungsvervielfachung wurden sowohl in n- als auch p-bulk Sensoren beobachtet. P-bulk Streifensensoren, die eine aktive Dicke von 100 und 200 μm aufweisen, wurden in Teststrahlungsmessungen charakterisiert. Das Signal dieser Sensoren liegt nach einer Bestrahlung entsprechend einer Fluenz von $1.3 \cdot 10^{16} \text{ cm}^{-2}$ zwischen 4000 und 5000 e^- . Die 200 μm dicken Sensoren benötigen dabei eine höhere Betriebsspannung als die 100 μm dicken Sensoren um dieselbe Signalthöhe zu erreichen. Der nötige Schwellwert, um eine Nachweiseffizienz von 95% zu erzielen, wurde für die 100 μm dicken Sensoren zu etwa 2000 e^- bestimmt.

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Chapter 1

Introduction

The study of the properties and interactions of subatomic particles is carried out in numerous ways, one of which is the study of the products in collisions of stable particles at accelerators. The Compact Muon Solenoid (CMS) is a general purpose detector at the Large Hadron Collider (LHC). The CMS's physics program is broad, ranging from the study of the standard model to the search of particles predicted by new theories. An important parameter of a collider is its luminosity, a quantity that relates the rate at which a process occurs at the collider to the process' cross section. As the investigation of particle properties is often focused on rare events, the luminosity of the LHC is constantly increased to provide the experiments with a statistical sample big enough to derive conclusions in a reasonable amount of time. The measuring environment at high luminosity hadron colliders is very challenging for the experiments. In particular, the damage caused by ionizing radiation to the detectors and readout electronics and their ability to cope with the high particle multiplicity and track density pose a limit on their operating life.

The precise measurement of particle tracks and their point of origin is fundamental to accomplish the research goals of the experiments. The CMS vertexing and tracking system is based on silicon detectors. Its innermost part consists of a pixel detector. The increase in the luminosity of the LHC will require a replacement of the pixel detector in winter 2016/2017. The upgraded pixel detector will implement new readout electronics that allow efficient data taking up to a luminosity of $2 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, which is a factor of two bigger than the nominal luminosity of the LHC.

An upgrade of the LHC foreseen for 2025 will boost its luminosity to $5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The whole silicon tracking system of CMS will be substituted by a new one able to operate in the radiation environment resulting from such high luminosities. The innermost pixel layers of the silicon tracker will accumulate a radiation damage corresponding to an equivalent fluence of $\Phi_{eq} = 2 \cdot 10^{16} \text{ cm}^{-2}$ and a dose of $\approx 10 \text{ MGy}$ after an integrated luminosity of 3000 fb^{-1} . These values of fluence and dose demand the design of sensors and readout electronics able to operate efficiently during the lifetime of the detector.

The work documented in this thesis is dedicated to the development of quality assurance tests and calibration procedures for the modules produced for the CMS pixel upgrade in winter 2016/2017 and the characterization of silicon sensors with an active thickness of $100 \mu\text{m}$ irradiated up to $\Phi_{eq} = 1.3 \cdot 10^{16} \text{ cm}^{-2}$.

The thesis has the following structure. Chapter 2 presents the LHC and the CMS experiment. Chapters 3 and 4 introduce the basic properties of silicon detectors in tracking and

vertexing applications, and the effects of radiation on these detectors. In chapter 5 the upgrades of the CMS pixel detector are presented. Chapter 6 documents the quality assurance and calibration procedures implemented in the production of pixel modules for the CMS pixel upgrade in winter 2016/2017. In chapter 7 the characterization of highly irradiated thin silicon sensors is presented. Finally, the main results obtained from this work are summarized in chapter 8.

Chapter 2

The LHC and CMS

In the first part of this chapter, the LHC and its high luminosity upgrade are presented. The second part of the chapter is dedicated to the CMS detector and its main sub-systems.

2.1 The Large Hadron Collider

2.1.1 Collider characteristics

The Large Hadron Collider (LHC) is a particle accelerator that collides both protons and lead nuclei. The machine is located in Switzerland and operated by the *Conseil Européen pour la Recherche Nucléaire* (CERN). The accelerator has a circumference of 27 km and is built in a tunnel 100 m underground. The particles in the beams are grouped into bunches, with a minimal bunch crossing period of 25 ns. The design center of mass energy of the collider is 14 TeV for protons and the design luminosity is $1.0 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [1]. Figure 2.1 shows a scheme of the CERN accelerators with the LHC and its injection chain.

The collider delivered nearly 30 fb^{-1} of p-p collisions during the 2011-2012 running period (the so-called Run 1), Run 2 has started in spring 2015. The LHC is currently delivering proton-proton collisions at an energy of 13 TeV. The instantaneous luminosity is $1.5 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, with a bunch spacing of 25 ns [3]. The target integrated luminosity for Run 2 is 100 fb^{-1} [4].

2.1.2 High luminosity upgrade

In order to maximize the discovery potential of the experiments at the collider, a high luminosity upgrade of the LHC is foreseen for 2025 [4]. The upgraded collider is named HL-LHC (High Luminosity LHC); it will maintain the LHC collision energy and its luminosity will range from 5 to $7 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ for p-p collisions. With a bunch spacing of 25 ns this will result in an average of 140 p-p interactions per bunch crossing. In order to achieve this performance many accelerator parts will be replaced, here some examples are reported. The injection chain and the collimators will be upgraded in order to reduce the emittance of the beams. The insertion region magnets will be replaced with ones that can provide a stronger focusing of the beams and are more radiation hard. The need to deal with higher luminosities and beam intensities demands the improvement of the machine protection systems and of the shielding. Crab cavities will be installed to maximize the overlap of the bunches in the interaction regions [4].

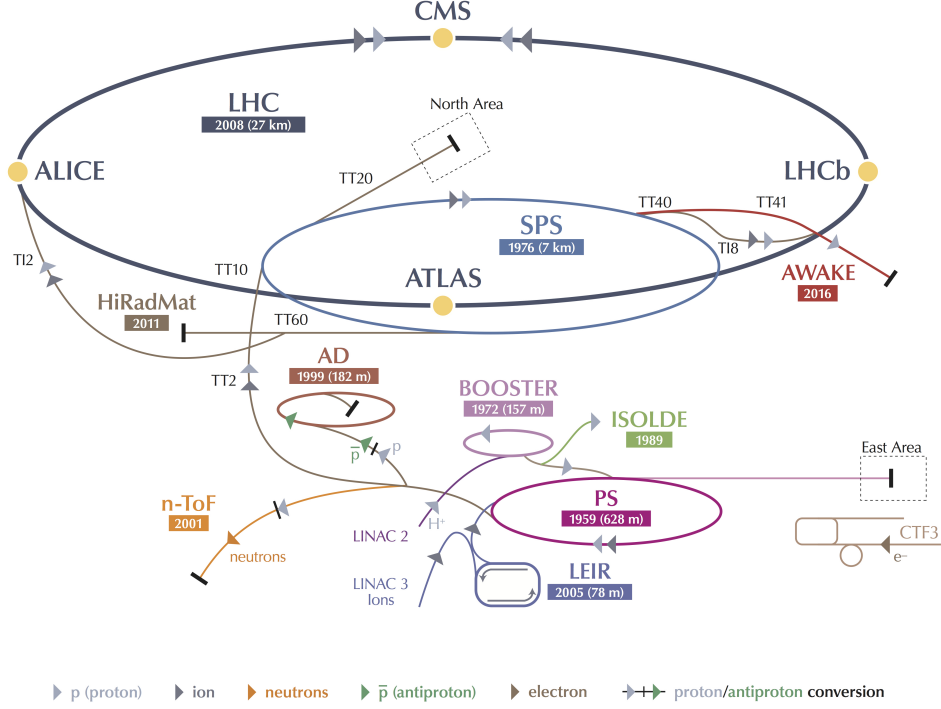


Figure 2.1: The CERN accelerator complex [2].

In order to limit the pile-up in the interaction regions, the accelerator will implement luminosity leveling. This technique is already applied at the LHCb interaction point [5].

2.2 The Compact Muon Solenoid experiment

The Compact Muon Solenoid (CMS) is a general purpose detector [6] built around one of the LHC interaction points. The physics program of the experiment is vast, ranging from testing the standard model to the search for new physics. One accomplishment of the CMS collaboration is the discovery of the Higgs boson. This particle completes the picture of the standard model [7].

To be able to cope with such a wide physics program the detector was designed to be sensitive to a large variety of physics signals. A cutaway view of the detector with its subsystems is shown in figure 2.2.

The detector has a cylindrical geometry with one barrel and two end-cap regions. The barrel region of the detector houses a superconducting solenoid that provides a 3.8 T magnetic field, necessary for the measurement of the momentum of charged particles. The solenoid contains the tracking system, an electromagnetic calorimeter and a hadronic calorimeter. An iron return yoke surrounds the solenoid in the barrel and end-cap regions. The return yoke contains the muon system of the experiment.

The pixel detector The p-p collisions take place in the center of the detector, inside a beryllium beam pipe. The first system that the generated particles encounter is the pixel system. The goal of this system is to measure the primary and secondary vertices of the interactions. This is fundamental for many physics analyses, especially for b- and τ -tagging,

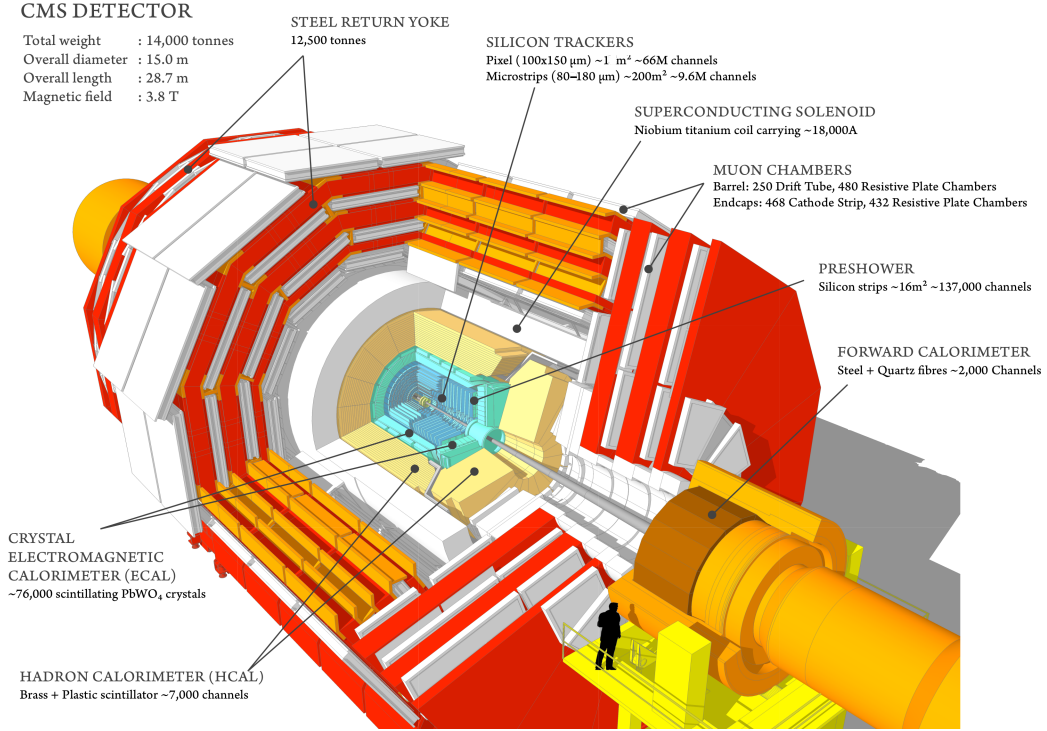


Figure 2.2: A cutaway view of the CMS detector [8].

where the measure of the position of secondary vertices is used to identify the production of these particles.

The CMS pixel detector has a cylindrical geometry. The layout of the detector can be seen in figure 2.3a. The barrel part of the detector is constituted by three layers at 4.4, 7.3 and 10.2 cm from the beam axis. Each end-cap is composed of two discs that cover radii from 6 to 15 cm with the sensors mounted on a turbine-shaped support structure. This detector geometry promotes, together with the CMS magnetic field, charge sharing between the pixels, enhancing the single hit resolution. The total area of the detector is about 1 m^2 , with 0.78 m^2 in the barrel and 0.28 m^2 in the end-caps.

The building blocks of the pixel detector are pixel modules, the exploded view of a barrel module is shown in figure 2.3b. The barrel modules are made of $285 \mu\text{m}$ thick n^+ -in- n silicon sensors, bump bonded to 16 read out chips (ROCs). The pixel pitch is $100 \mu\text{m}$ in the $r - \phi$ direction and $150 \mu\text{m}$ in the z direction. Glued on top of the sensor is the high density interconnect (HDI) together with the token bit manager (TBM) chip. These components are necessary to steer the readout and the communication between the ROCs and the rest of the readout chain. The HDI is connected to the ROCs through wire bonds. The ROCs provide analog pulse height information from each pixel that is traversed by a particle. Due to the readout speed of the ROCs, the hit information can not be read out for each event, so it is stored in analog buffers on the ROCs. The decision of the trigger system determines if the hit information leaves the ROCs. The pixel detector has a total of 66 million readout channels, the vertex resolution is $10\text{--}12 \mu\text{m}$ in each spatial direction [10].

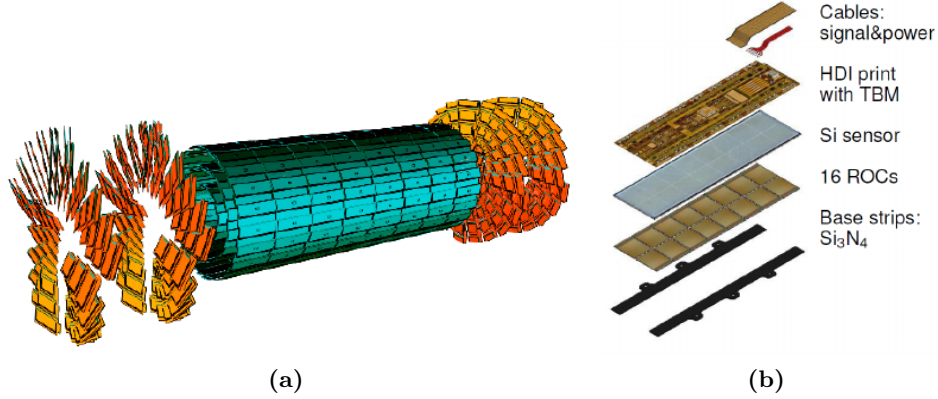


Figure 2.3: Layout of the CMS pixel detector (a) and exploded view of a barrel module (b) [9].

The silicon strip tracker Outside of the pixel system, covering a radius from 20 to 116 cm from the beam axis, there is the strip tracker. The tracker is used to measure the momentum of the charged particles produced in the collisions. The CMS strip tracker is composed of p⁺-in-n sensors, and the strip pitch ranges from 80 to 183 μm in order to accommodate for different hit rates in the detector volume. The readout chips of the strip detector provide analog pulse height information, and the readout is triggered as in the case of the pixel detector. The total area of the strip tracker is about 200 m² divided into 9.5 million channels. The transverse momentum (p_T) resolution of the system is 2.8% for muons with $p_T = 100 \text{ GeV}/c$ [10].

The calorimeter system The strip tracker is surrounded by the calorimeter system. The CMS calorimeters measure the energy of the particles produced at the interaction point and provide shielding for the superconducting solenoid magnet. The main detectors of the calorimeter system are the electromagnetic and hadronic calorimeters.

The electromagnetic calorimeter is a homogeneous calorimeter based on lead tungstate (PbWO₄) crystals read out by avalanche photodiodes in the barrel region and vacuum phototriodes (single-stage photomultiplier tubes) in the end-caps [11]. A pre-shower detector based on lead and silicon strip sensors is placed in front of the end-caps. The total thickness of the pre-shower is 3 radiation lengths (X_0). The calorimeter crystals have a thickness of 25 X_0 . The resolution of the electromagnetic calorimeter is $\sigma_E/E = 2.8\%/\sqrt{E} \oplus 0.126/E \oplus 0.3\%$, with the energy expressed in GeV [12].

The hadronic calorimeter is a sampling calorimeter constituted of many parts. The barrel and end-caps of the calorimeter are placed inside the CMS solenoid. The absorber material used in the barrel and end-caps is brass and the active material is plastic scintillator. The light generated in the scintillators is collected by wavelength shifting fibers and routed to hybrid photodiodes. The barrel hadronic calorimeter has a thickness between 5.8 and 10 interaction lengths (λ_i). The combined resolution of the electromagnetic and hadronic calorimeters for hadronic showers is $\sigma_E/E = 0.85/\sqrt{E} \oplus 0.07$, with the energy expressed in GeV [13]. One other system of the hadronic calorimeter is a $3\lambda_i$ thick tail catcher placed between the solenoid and the muon tracker.

Located outside of the magnetic return yoke is the hadronic forward calorimeter. This calorimeter is composed of iron blocks instrumented with quartz fibers placed parallel to the

beam axis. The energy resolution of the hadronic forward calorimeter is $\sigma_E/E = 1.98/\sqrt{E} \oplus 0.09$, with the energy expressed in GeV [13].

The muon tracker The CMS muon tracker is located inside the iron return yoke of the magnetic system. The muon tracker is based on gaseous detectors that allow the instrumentation of the large area needed for this system. Three types of detectors are used in the system: drift tubes, cathode strip chambers, and resistive plate chambers. The relative p_T resolution of the muon tracker is between 1.3% and 2.0% in the barrel region and 6% in the end-caps, in the range $20 < p_T < 200 \text{ GeV}/c$. The relative p_T resolution in the barrel region is better than 10% up to 1 TeV/c [14].

The trigger system The trigger system of CMS is divided in two parts, the level-1 trigger and the high level trigger. The level-1 trigger (L1) consists of custom designed electronics, and uses data from the calorimeters and muon tracker in order to determine whether the full information about the event will be propagated to the high level trigger. The high level trigger (HLT) is implemented in software and has access to the full event information. Its goal is to determine which events will be preserved for readout and further analysis. The rate reduction capability of the trigger system is designed to be 10^6 [6].

Chapter 3

Silicon detectors in high energy physics

Silicon detectors are widely used in high energy physics experiments. Of particular importance is their application in vertexing and tracking for collider experiments. The low mean ionization energy of these detectors allows thin detector layers, which results in advantages like a fast signal response to traversing particles and a light detector where multiple scattering and photon conversion play a small role. In addition, the use of silicon in the microelectronics industry provides well established methods to produce detectors at an affordable price.

This chapter covers the basic principles of silicon detectors. The chapter is mainly based on references [15, 16, 17, 18] that provide a deeper coverage of the matter.

3.1 Particle detection

3.1.1 Silicon as detector material

Silicon is a metalloid with atomic number 14 and a density of 2.33 g/cm^3 . The outermost orbital of silicon has four electrons, making silicon tetravalent. Silicon can form a covalent crystal with a diamond lattice structure, in which every silicon atom is surrounded by four neighbors. The band structure of silicon is shown in figure 3.1. The energy gap between the conduction and valence band is $E_g = 1.12 \text{ eV}$ at room temperature. Silicon is thus a semiconductor. Electrons can be excited from the valence to the conduction band through thermal excitation or by ionizing radiation. The concentrations of electrons and holes (n and p) are equal to the intrinsic concentration (n_i). At 300 K they assume the value $n = p = n_i = 1.45 \cdot 10^{10} \text{ cm}^{-3}$. The minimum and maximum energy of the conduction and valence band do not have the same position in momentum space, making silicon an indirect semiconductor. The recombination of electrons and holes requires the absorption or emission of phonons.

The resistivity of a semiconductor can be expressed as

$$\rho = \frac{1}{e(\mu_e n + \mu_h p)} \quad (3.1)$$

where e is the electron charge, and μ_e (μ_h) is the mobility of the electrons (holes). The mobility is the quantity that relates the magnitude of the drift velocity v_D to the applied electric field $v_D = \mu E$. Typical values for the mobility of electrons and holes in silicon are $\mu_e = 1350 \text{ cm}^2/\text{Vs}$ and $\mu_h = 450 \text{ cm}^2/\text{Vs}$.

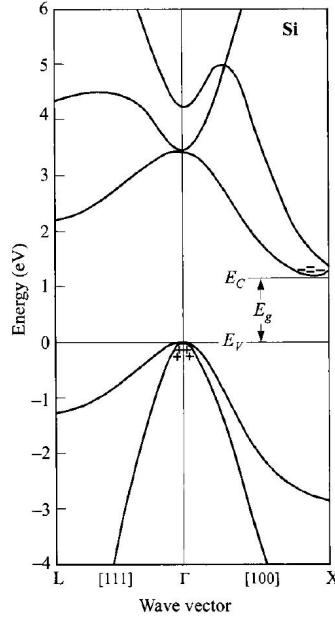


Figure 3.1: Band structure of silicon. E_C and E_V represent the conduction and valence band energy, and E_g the band gap energy. Plus signs (+) and minus signs (-) represent the holes and electrons, respectively. From [15].

It is possible to show that a silicon detector made out of intrinsic silicon is not going to work well at room temperature. Considering an ionization chamber built using silicon as sensitive material, the current due to the free charge carriers (and the noise associated to it) is going to be considerably bigger than the signal produced by a charged particle traversing the silicon crystal. The current passing through the detector can be reduced by cooling the silicon to cryogenic temperatures, but this is not a practical solution for most detector systems.

In order to reduce the current it is necessary to modify the conduction characteristics of the silicon crystal. This can be achieved through the introduction of impurities (dopants) in the silicon crystal. Pentavalent atoms like phosphorous provide an electron that is not used in the bonds with the surrounding silicon atoms. The energy necessary to promote this

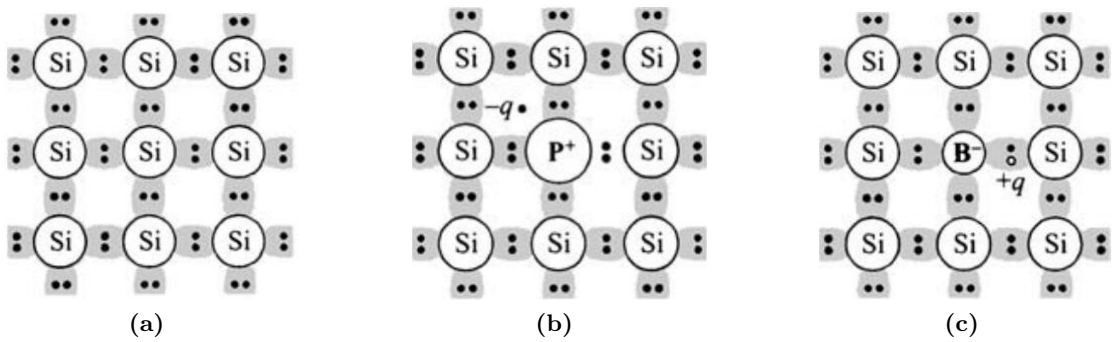


Figure 3.2: (a) Intrinsic silicon. (b) n-type Si with donor (phosphorus). (c) p-type Si with acceptor (boron). From [15].

electron to the conduction band is 0.045 eV, thus, at room temperature, practically all P atoms present in the crystal contribute one electron to the conduction band. The phosphorus atoms remain as fixed positive charges in the silicon lattice. The phosphorus atoms are referred to as donors. Silicon with an excess of electrons in the conduction band is called n-type silicon. The electrons are the majority carriers in n-type silicon. By adding trivalent atoms to the silicon crystal, like boron, the opposite effect is obtained. The boron atoms lack one electron to form the bonds with the four surrounding silicon atoms. An energy of 0.045 eV is necessary to transfer an electron from a silicon atom to a boron atom. This results in a hole in the valence band. The boron atoms remain as fixed negative charges in the silicon crystal and are referred to as acceptors. Silicon with an excess of holes in the valence band is called p-type silicon. A schematic representation of intrinsic, n- and p-type silicon is shown in figure 3.2.

Typical values of the doping concentrations are:

- bulk silicon sensor 10^{12} cm^{-3}
- strip or pixel implant $10^{14} - 10^{16} \text{ cm}^{-3}$
- heavy doping 10^{19} cm^{-3}

For comparison:

- $n_i = 1.45 \cdot 10^{10} \text{ cm}^{-3}$ at 300 K
- silicon atoms $5 \cdot 10^{22} \text{ cm}^{-3}$

The silicon is considered intrinsic if its doping concentration is smaller than the free charge carrier concentration in intrinsic silicon. The resistivity of doped silicon is, for the concentrations listed above, dominated by the presence of dopants. Neglecting the contribution of the minority carriers the resistivity for n-type silicon becomes

$$\rho \approx \frac{1}{en\mu_n} \approx \frac{1}{eN_D\mu_n} \quad (3.2)$$

where N_D is the concentration of the donor atoms. An equivalent formula holds for p-type.

The process of doping silicon is used to produce one of the basic structures of silicon detectors, the p-n junction.

3.1.2 pn-junction

Bringing in contact n- and p-type silicon a pn-junction is created. When the n- and p-type silicon are brought into contact, the free electrons of the n-type silicon diffuse into the p-type, hereby annihilating holes. At the same time holes from the p-type silicon diffuse into the n-type. This creates a region of silicon where no free charge carriers are present, and the fixed charge of the dopants is not compensated. This region is called space charge region (SCR). The diffusion of electrons and holes goes on until the electric field in the space charge region produces a potential difference that stops the diffusion process. This built-in voltage V_{bi} can be expressed as

$$V_{bi} = \frac{kT}{e} \ln \left(\frac{n_{0,n} p_{0,p}}{n_i^2} \right) \approx \frac{kT}{e} \ln \left(\frac{N_D N_A}{n_i^2} \right) \quad (3.3)$$

where T is the absolute temperature, k the Boltzmann constant, $n_{0,n}$ the electron concentration in the n-doped side, $p_{0,p}$ the hole concentration in the p-doped side, and N_A the concentration of acceptor atoms. Typical values of V_{bi} are below 1 V. Figure 3.3 shows the properties of an abrupt pn-junction.

If an external voltage is applied to the pn-junction with the higher potential applied to the n-type silicon and the lower potential to the p-type (reverse bias), the space charge region increases and the contribution of majority carriers to the current traversing the junction is heavily suppressed. This reduces the current enough to allow a practical operation of silicon detectors at room temperature.

3.1.3 Basic sensor

The basic block of a silicon sensor in high energy physics is a pn-junction in reverse bias. To collect the ionization produced by a particle passing through the detector it is necessary to have an electric field inside the silicon crystal. The electric field is confined to the space charge region of the detector. Applying a bias voltage V in the reverse direction to the sensor the thickness of the space charge region, or depletion region, is given by

$$W(V) = \sqrt{\frac{2\epsilon_0\epsilon_{Si}}{e} \left(\frac{1}{N_A} + \frac{1}{N_D} \right) (V + V_{bi})} \quad (3.4)$$

where ϵ_0 is the permittivity of vacuum and ϵ_{Si} is the permittivity of silicon. The doping concentrations at the sides of a pn-junction in silicon sensors are usually very different. This makes the depletion region expand mainly on one side of the junction. Considering a sensor with n-type bulk and that V_{bi} is usually negligible compared to the bias applied to the sensors, equation 3.4 becomes

$$W(V) \approx \sqrt{\frac{2V\epsilon_0\epsilon_{Si}}{eN_D}} \quad (3.5)$$

To exploit the whole sensor thickness for particle detection, it is necessary to expand the depletion region over the whole detector thickness. The voltage at which this happens is called full depletion voltage (V_{dep}). For a sensor of thickness d the full depletion voltage is given by

$$V_{dep} = \frac{eN_D d^2}{2\epsilon_0\epsilon_{Si}} \quad (3.6)$$

Or, as a function of the silicon resistivity

$$V_{dep} = \frac{d^2}{2\epsilon_0\epsilon_{Si}\mu_n\rho} \quad (3.7)$$

The capacitance of a detector of area A as a function of bias voltage assumes the form

$$C = A \frac{\epsilon_0\epsilon_{Si}}{W(V)} \approx \begin{cases} A \sqrt{\frac{\epsilon_0\epsilon_{Si}eN_D}{2V}} & \text{for } V < V_{dep} \\ A \frac{\epsilon_0\epsilon_{Si}}{d} & \text{for } V \geq V_{dep} \end{cases} \quad (3.8)$$

A sketch of the capacitance versus voltage (CV) characteristic of a sensor is shown in figure 3.4. The CV characteristic is often used to determine the depletion voltage of a sensor. A typical procedure is to plot $1/C^2$ as a function of voltage in order to linearize the part of the curve

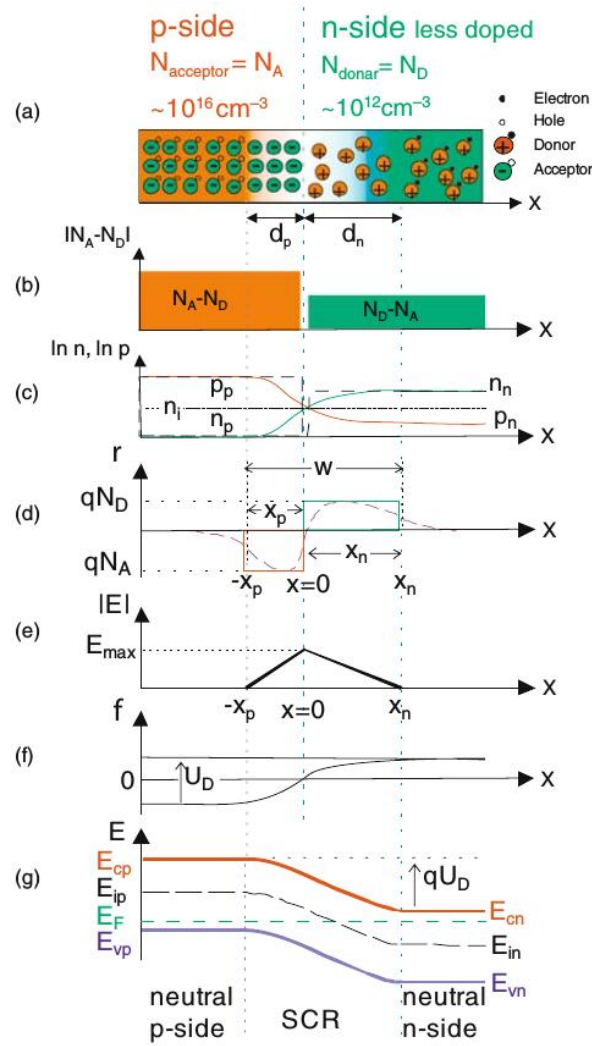


Figure 3.3: Schematic representation of the pn-junction (a) atomic and charge configuration, (b) doping profile, (c) mobile charge density, (d) space charge density, (e) electrical field, (f) electrical potential, (g) electron energy across the pn-junction. All the diagrams refer to the equilibrium state, without any external voltage [16].

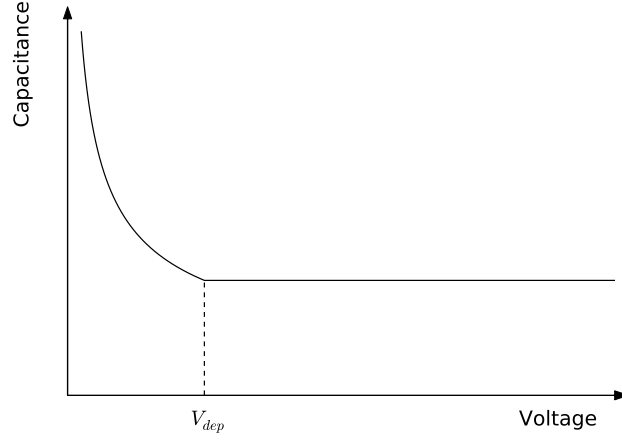


Figure 3.4: Sketch of a typical CV curve.

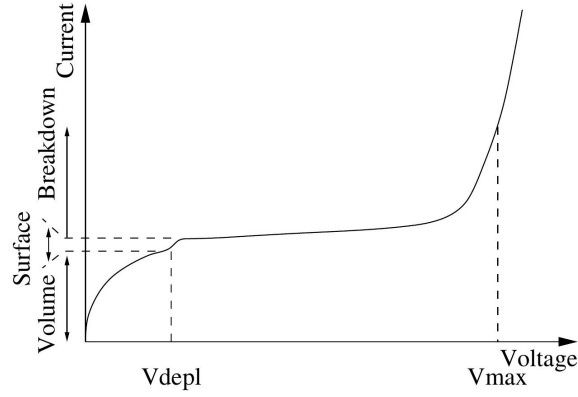


Figure 3.5: Sketch of a typical IV characteristic. From [17].

for $V < V_{dep}$ and better determine the position of V_{dep} . The same result can be achieved by plotting the logarithm of the capacitance as a function of the logarithm of the voltage. Usually silicon sensors are operated at a bias voltage greater than V_{dep} .

An important characteristic of a sensor is the behavior of its current as a function of voltage (IV). A typical IV curve is sketched in figure 3.5. For $V < V_{dep}$ the current grows with the volume of the depletion region. The current traversing the bulk of the sensor is made up by two main components, generation current and diffusion current. The generation current is due to the production of electron hole pairs in the depleted bulk through thermal excitation. The diffusion current is due to majority carriers that manage to diffuse through the potential barrier of the pn-junction. When the sensor reaches full depletion, the surface of the sensor can contribute to the conduction of current. Finally, when the electric field in the sensor is sufficiently high, breakdown occurs and the current suddenly increases with the applied bias voltage. The current drawn by a biased sensor in absence of radiation is called dark current.

The generation current constitutes the biggest part of the dark current. Its behavior as a

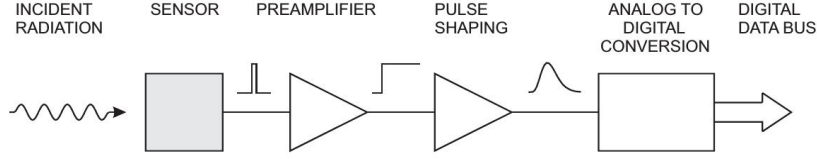


Figure 3.6: Typical elements of the readout electronics for a silicon detector [18].

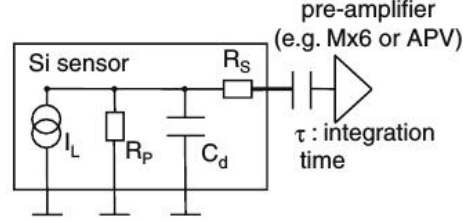


Figure 3.7: Equivalent circuit of a sensor for noise estimation. The principal sources of noise are the dark current I_L , parallel and serial resistance R_P and R_S , and the sensor capacitance C_d [16].

function of temperature, in the range from -30 to $+30^\circ\text{C}$, can be expressed as [19]

$$I(T) = I(T_0) \left(\frac{T}{T_0} \right)^2 \exp \left[-\frac{E_g + 2\Delta}{2k} \left(\frac{1}{T} - \frac{1}{T_0} \right) \right] \quad (3.9)$$

where $I(T_0)$ is the current drawn by the sensor at a temperature T_0 , and $E_g + 2\Delta = 1.21 \text{ eV}$. The factor Δ expresses the contribution of defects in the silicon crystal to the generation of current. The amount of dark current drawn by the sensor approximately doubles every 7 K . This relation holds also for irradiated devices and shows that cooling is an effective way to reduce the dark current.

The signal generated in the sensor is usually read out by an electronics chain as depicted in figure 3.6. The amplitude of the signal produced in the sensor is first amplified, a shaper makes the pulse shape suitable for digitization and finally the signal amplitude (or charge) is digitized. Many other components can be part of the chain, like buffers, discriminators and so on. The preamplifier is usually placed as close to the sensor as possible in order to avoid pick-up noise in the connection.

The noise of a detector is usually expressed as equivalent noise charge (ENC) given in electrons. A schematic representation of the noise sources in a silicon detector is shown in figure 3.7. The total noise of the sensor is given by the sum of the noise components

$$ENC = \sqrt{ENC_{C_d}^2 + ENC_{I_L}^2 + ENC_{R_P}^2 + ENC_{R_S}^2} \quad (3.10)$$

where C_d is the detector capacitance, I_L the dark current, and R_P , R_S the parallel and serial

resistance. The different components of the noise can be expressed as

$$\begin{aligned}
 ENC_{I_L} &= \frac{e}{2} \sqrt{\frac{I_L t_p}{q_e}} \\
 ENC_{R_P} &= \frac{e}{q_e} \sqrt{\frac{kT t_p}{2R_P}} \\
 ENC_{R_S} &= C_d \frac{e}{q_e} \sqrt{\frac{kT R_S}{6t_p}} \\
 ENC_{C_d} &= a + bC_d
 \end{aligned} \tag{3.11}$$

where t_p is the signal peaking time, e the Euler number, and q_e the elementary charge. The factors a and b are specific to the preamplifier. The slope b is determined by the voltage noise of the preamplifier $u_{n,amp}$

$$b \approx \frac{u_{n,amp}}{t_p} \tag{3.12}$$

The dominating contribution to the noise depends on the sensor type. The design of the sensor and of the readout electronics greatly affects the ENC of a detector.

3.1.4 Energy deposition in silicon

The mean rate of energy loss (or stopping power) for charged heavy particles traversing a medium is given by the Bethe-Bloch equation. For a particle of charge z , the mean energy loss in a medium with atomic number Z and atomic mass A is described by

$$\left\langle -\frac{dE}{dx} \right\rangle = 4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A \beta^2} \left[\frac{1}{2} \ln \left(\frac{2m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} \right) - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right] \tag{3.13}$$

where N_A is the Avogadro's number, r_e the classical electron radius, m_e the electron mass, c the speed of light in vacuum, $\beta = v/c$, $\gamma = \sqrt{\frac{1}{1-\beta^2}}$, W_{max} the maximum kinetic energy transferred to a free electron in a collision, I the mean excitation energy, and $\delta(\beta\gamma)$ the density correction. W_{max} for a particle of mass M can be described as

$$W_{max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/M + (m_e/M)^2} \tag{3.14}$$

The description of the stopping power for electrons and positrons requires a different treatment than the one for heavy particles. The energy loss due to collisions however is not very different for electrons and heavier particles.

The mean rate of energy loss for electrons and muons in silicon is shown in figure 3.8. For both particles the energy loss rate reaches a minimum around $\beta\gamma = 3$. The minimum of the stopping power lies at about 1.6 MeV cm²/g. A particle that loses energy at this rate is named minimum ionizing particle (MIP).

For electrons the stopping power at high momentum is dominated by radiative energy losses. The energy loss by collisions with the electrons and nuclei of the medium is however almost constant for a wide momentum range. Figure 3.9 shows the different components of the stopping power of electrons in silicon.

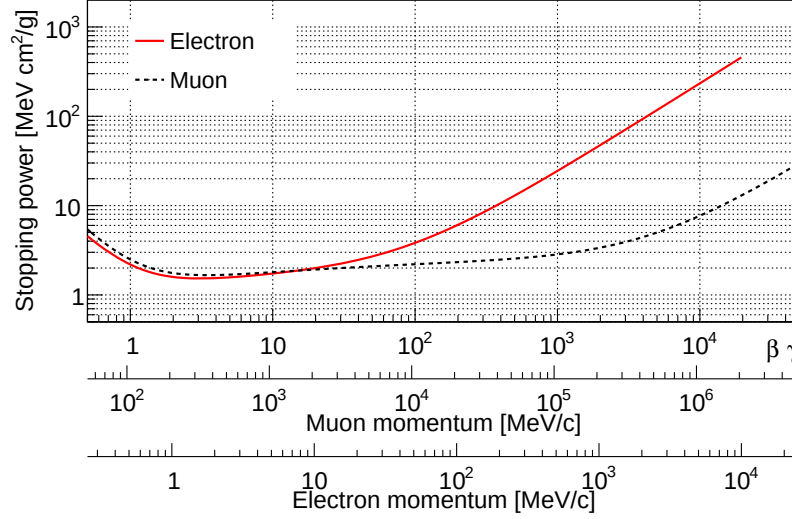


Figure 3.8: Stopping power of silicon for electrons and muons. The data for muons are from [20] which is based on [21]. The data for electrons are from [22] which is based on [23].

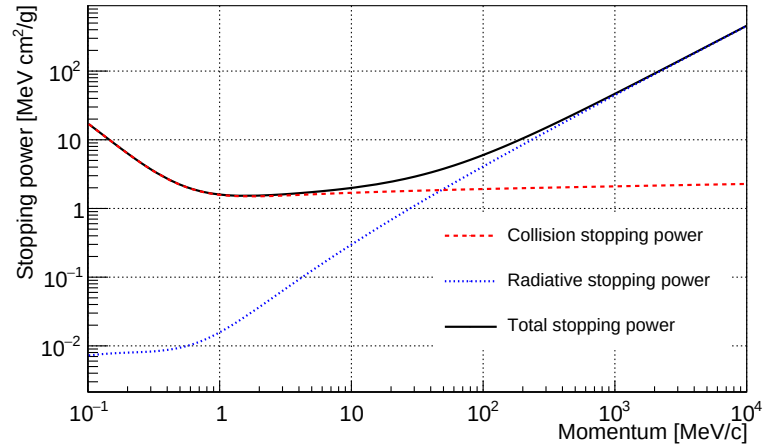


Figure 3.9: Different components of the stopping power of silicon for electrons. The collision stopping power is similar to the one of heavy particles. Data from [22] that is based on [23].

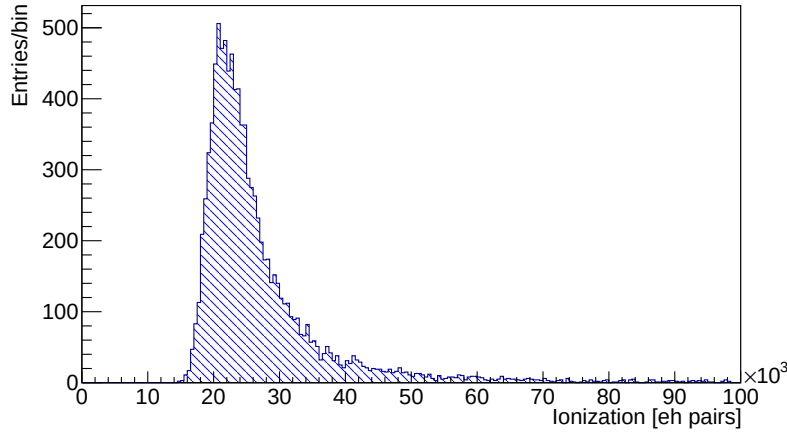


Figure 3.10: Simulated distribution of the ionization spectrum produced by 300 MeV muons in 300 μm of silicon. The simulation code is described in [27].

A charged particle passing through silicon produces ionization in the silicon crystal by promoting electrons from the valence to the conduction band. The energy necessary to produce an electron hole pair in silicon is 3.67 eV at room temperature [24].

The energy loss spectrum of charged particles in silicon can be described using a Landau distribution [25]. A better description of the spectrum is provided in [26]. Figure 3.10 shows a simulated distribution of the ionization produced in 300 μm of silicon by 300 MeV muons. The simulation code is described in [27] and is partly based on [26]. The tail of the distribution is due to electrons that undergo a hard collision with the ionizing particle. These electrons, also called δ -rays, propagate into the silicon producing ionization.

Silicon detectors can also be used to detect photons. The interaction of photons in matter follows

$$I = I_0 e^{-\mu x} \quad (3.15)$$

where I is the intensity of a photon beam of intensity I_0 after traversing a thickness x of material. μ is the attenuation coefficient for the considered material and photon energy.

The way photons interact with silicon is influenced by the photon energy. Figure 3.11 shows the different contributions to the attenuation coefficient of silicon as a function of photon energy. For energies below 100 keV the photoelectric effect is the dominant contribution to the attenuation coefficient. In this energy region the silicon sensors can be used to measure the energy of the incident photons. A photon interacting through photoelectric effect results in one electron that carries the photon energy minus its extraction energy. This electron propagates into the silicon crystal producing ionization. If the electron does not escape the detector volume, it produces an amount of ionization that is proportional to its energy, allowing a measure of the impinging photon energy.

3.2 Position sensitive detectors

This section describes the principal features of strip and hybrid pixel detectors. The selection is motivated by the technological choices of the experiments operating at high luminosity hadron colliders.

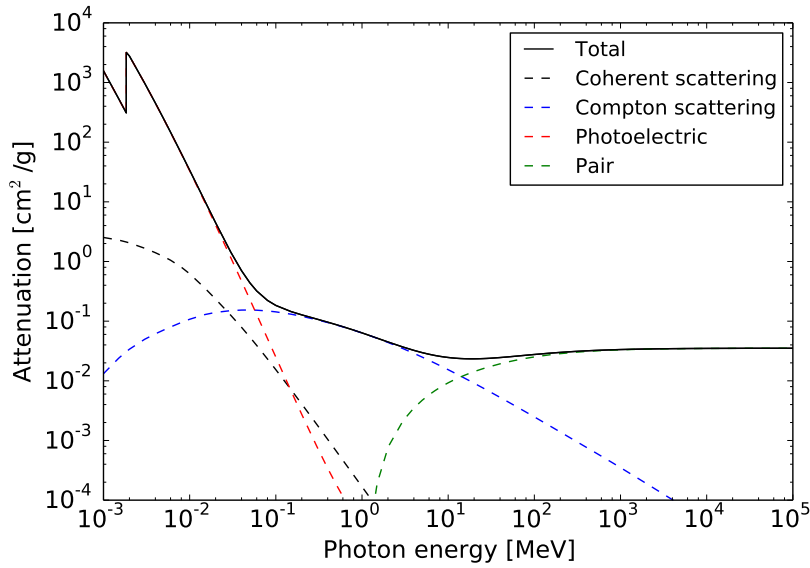


Figure 3.11: Attenuation coefficient of photons in silicon. Data taken from [28].

3.2.1 Strip detectors

Position sensitivity can be achieved by segmenting the pn-junction in one direction, effectively dividing the detector in several diodes. Strip detectors measure the position of a traversing particle in one direction. A sketch of a strip detector is shown in figure 3.12. The charge induced on the strip implants is usually read out by capacitively coupled (AC) metal electrodes that are connected to the readout electronics through ultrasonic wire bonding. Direct coupling (DC) between the strip implants and metal electrodes can be also used. The typical thickness of strip sensors ranges between 200 and 300 μm , with a strip pitch ranging from 50 to 200 μm . The ENC of strip detectors is usually around $1000 e^-$, this figure being dominated by the contributions from the strip capacitance and the dark current.

Dividing the back side of the sensor in strips, it is possible to measure the position of traversing particles in two directions. However, if two particles traverse the sensor at the same time there is no way to determine the particle's position unambiguously. To provide an unambiguous determination of the particles position in such a scenario and to perform measurements at higher track densities, pixel detectors are usually employed.

3.2.2 Hybrid pixel detectors

By segmenting the pn-junction in two directions a pixellated sensor is created. Hybrid pixel detectors are characterized by the production of sensor and readout electronics on different substrates. They are the usual choice in high luminosity hadron collider experiments given their radiation tolerance. A sketch of a hybrid pixel detector is shown in figure 3.13. The connection between the pixels and the readout electronics is usually established using bump bonding. The electronics is usually directly (DC) coupled to the pixel implant. Given the channel density in pixel detectors it is unpractical to read out the whole pixel matrix. The readout electronics often implements zero suppression, achieved by applying a threshold

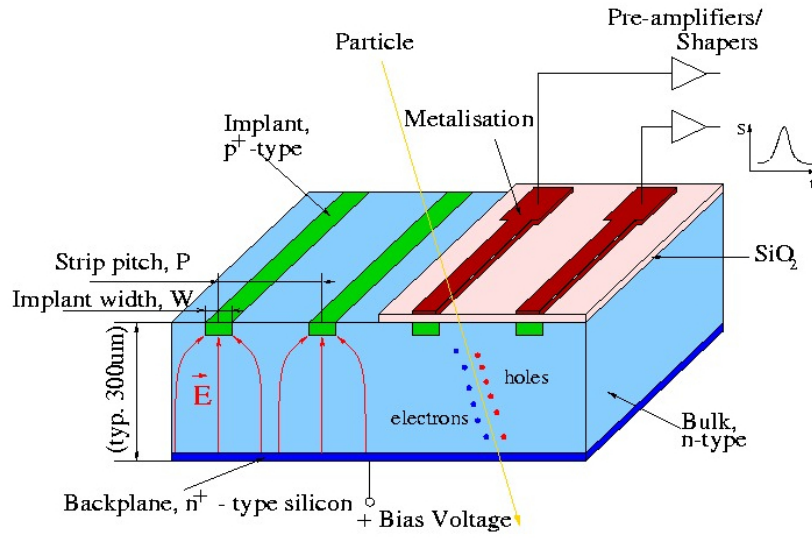


Figure 3.12: Sketch of a n-bulk strip sensor. From [29].

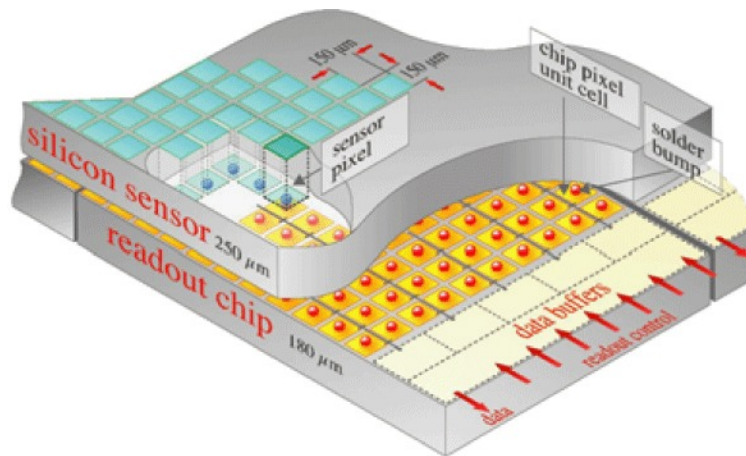


Figure 3.13: Sketch of a hybrid pixel detector. From [30].

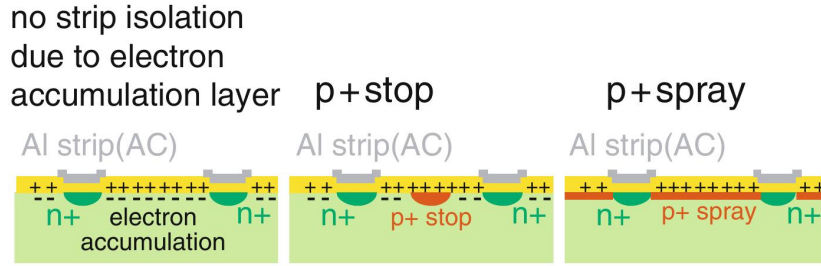


Figure 3.14: Schematic representation of a detector without isolation (left), with p-stop (center), and p-spray isolation (right). The bulk material can be either p- or n-doped. From [16].

on the measured signal. The typical thickness of pixel sensors is around $300\text{ }\mu\text{m}$, with a pixel pitch ranging from 50 to $200\text{ }\mu\text{m}$. The ENC of hybrid pixel detectors is usually around 100 e^- . The height of the threshold implemented in the electronics is however often determined by other factors like electronic cross talk.

3.2.3 Isolation of strips and pixels

The silicon dioxide layer that covers the silicon sensor presents usually a fixed positive charge. This positive oxide charge increases with irradiation (see section 4.2). The presence of the oxide charge can result in the formation of an electron accumulation layer that compromises the isolation of the strips and pixels in p-bulk and n^+ -in-n sensors. This situation is shown in the left part of figure 3.14.

To maintain interstrip (interpixel) isolation, a portion of p-doped silicon is placed between the strips (pixels). The p-doped silicon provides fixed negative charges that interrupt the electron accumulation layer and compensate the positive oxide charge.

The p-doped silicon is usually introduced in the form of p-stop (figure 3.14, center) and p-spray (figure 3.14, right). In the p-stop implementation the p-doped silicon is well localized and encloses the strips or pixels. The p-spray consists in a homogeneous doping of the silicon between the strips or pixels.

The production of sensors with p-stop isolation is usually more complex than the one of p-spray isolated sensors. However the p-spray can result in the creation of high electric field regions between the p-doped silicon and the strips (or pixels). To overcome this problem the doping concentration of the p-spray can be reduced in the region close to the strips (or pixels), this technique is called moderated p-spray.

3.3 Fabrication techniques

The silicon crystals used for the production of silicon detectors are mainly grown using the float zone (FZ) and Czochralski (Cz) techniques.

In the float zone growth, shown in figure 3.15a, an ingot made of poly-crystalline silicon (poly-silicon) is attached to a seed crystal, then a radio frequency (RF) coil melts the poly-silicon starting from the seed side and moving to the other end of the ingot. The silicon crystallizes after the passage of the RF coil following the crystal orientation of the seed crystal

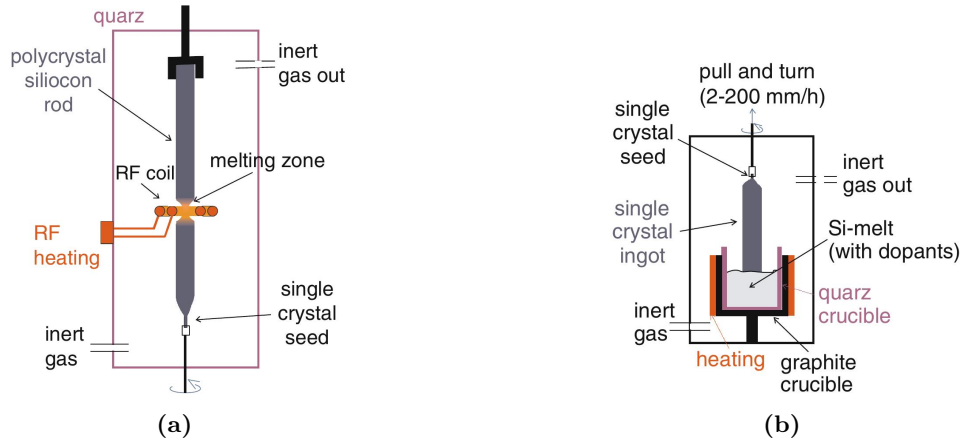


Figure 3.15: Float zone (a) and Czochralski (b) techniques to grow silicon crystals. From [16].

Figure 3.15b shows the Czochralski growth technique. In the Czochralski method the silicon is melted in a quartz crucible, and a seed crystal is lowered to touch the surface of the melted silicon to initiate the crystallization. The crystal is then pulled upwards and turned. The silicon crystal grows layer by layer as it is pulled out of the melted silicon bath.

The result of the FZ and Cz growth is a single silicon crystal of cylindrical shape. Impurities are added to the poly-silicon and in the melted silicon to dope the silicon crystal.

The silicon crystals are cut along the transverse axis to produce wafers. The wafers undergo the implantation and photolithographic steps that are necessary to produce a sensor.

A different method to produce silicon crystals is through epitaxial growth. A wafer produced using the float zone or Czochralski techniques is used as substrate and seed to start the growth of the silicon crystal. A gaseous silicon compound is used as the source of silicon. This gas reacts with the silicon wafer bonding Si atoms to the wafer. The obtained crystal has the same orientation as the seed (wafer) crystal. The doping is achieved by adding different gases to the silicon compound used in the growth. This growth technique can be used to create thin detectors. The wafer used as substrate usually has a very low resistivity while the epitaxial silicon has high resistivity. In this way the substrate does not affect the operation of the sensors produced on the epitaxial silicon. The substrate wafer offers also mechanical support to the epitaxial silicon. Thin ($< 150 \mu\text{m}$) wafers are usually quite fragile.

The pn-junctions necessary to create detectors are produced by ion implantation. The patterning of the implantation is achieved through the manipulation of the thickness of the silicon dioxide present on the wafer. This, as well as the shaping of the metal electrodes, is done using photolithographic procedures similar to the ones used in microelectronics.

3.4 Detector systems

In order to employ silicon detectors in high energy physics experiments, all the services necessary for the detector operation must be provided. The detectors must be positioned in space with high accuracy and stability. The electronics must be supplied with power and the sensors with bias voltage. The data produced by the detectors has to be carried outside the detector volume to the counting room. Finally the heat produced by the sensors and electronics must be removed from the detector. A discussion of these fundamental parts of

a detector system is out of the scope of this introductory chapter. However it is clear that to fulfill all the tasks listed above some material, in the form of cabling, pipes, mechanical structures and so on, must be placed into the detector volume. The choice of the materials to be employed in a detector system is constrained by their interaction with the particles that are to be detected. In particular the trajectory of the particles can be modified by traversing material. This process is named multiple scattering. The modification of the particle trajectory can degrade the resolution of a tracking device. The angular deflection experienced by a particle of unitary charge after traversing a material layer can be expressed as [24]

$$\Theta_{RMS} = \frac{0.0136[\text{GeV}/c]}{p} \sqrt{\frac{x}{X_0}} \left[1 + \ln \left(\frac{x}{X_0} \right) \right] \quad (3.16)$$

where p is the particle momentum, x the thickness of the traversed material, and X_0 its radiation length. From equation 3.16 it is possible to evince that materials with a large X_0 should be preferred in tracking applications. In order to reduce the demand on cooling and power cables, the power consumed by the readout electronics has to be minimized.

The solutions found in order to optimize the performance of a tracking system are various and strongly constrained by the different experimental environments. Some of the optimizations adopted in the CMS pixel upgrade are discussed in chapter 5.

Chapter 4

Radiation damage of silicon detectors

The operation of silicon detectors in tracking applications results in the degradation of the sensor properties due to radiation damage. Both the crystal structure and the surface layer of silicon dioxide are affected by radiation. These effects result ultimately in the modification of several detector properties:

- Increase of leakage current
- Change of the doping concentration
- Charge carrier trapping
- Modification of the electric field in the sensor

In this chapter the mechanisms and the effects of radiation damage on silicon sensors are explained. The evolution in time of the characteristics of the irradiated sensors is also covered.

This chapter is mainly based on [31, 16, 32].

4.1 Bulk damage

4.1.1 Damage mechanism

The damage produced in the bulk of silicon detectors is produced through the displacement of a primary knock on atom (PKA) that undergoes a hard collision with the traversing particle. The PKA is displaced from its position in the lattice and, depending on its energy, it can propagate into the detector producing ionization and knocking other atoms off their lattice sites. The PKA can produce other energetic knock on atoms, producing large displacement damage in a small volume, which results in defect clusters. Figure 4.1 shows the damage produced by a silicon PKA with a recoil energy $E_R = 50$ keV. The ionizing energy loss of particles and PKAs does not contribute to the damage of the silicon crystal. The bulk damage depends on the non-ionizing energy loss (NIEL).

Figure 4.2 illustrates different kinds of defects that can be produced in the silicon lattice.

Figure 4.1: Simulation of a damage cascade from a PKA with $E_R = 50$ keV. The track of the PKA is shown in red and the additionally displaced atoms (vacancies) in blue. From [33].

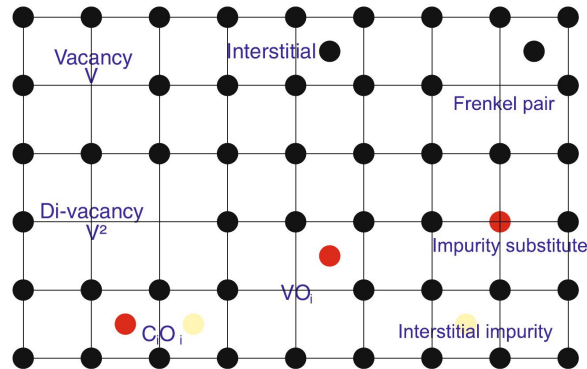
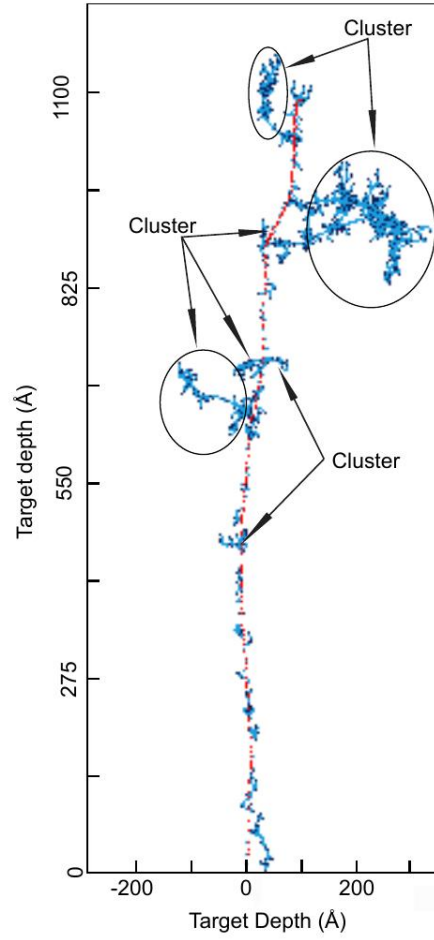


Figure 4.2: Schematic representation of some defects in silicon. As abbreviation, vacancies are labeled V, interstitials I, di-vacancies V_2 . Impurities are labeled with their atomic sign, their index defines their position as substitute or interstitial, e.g. O_i or C_i . From [16].

The recoil energy E_R of the PKA ranges from the binding (or displacement) energy of the lattice $E_d \approx 25$ eV to

$$E_R^{max} = 4E \frac{m \cdot m_{Si}}{(m + m_{Si})^2} \quad (4.1)$$

derived in the non-relativistic approximation. E is the kinetic energy of the incoming particle of mass m , and m_{Si} is the mass of a silicon atom.

A useful quantity to express the bulk damage is the displacement damage function $D(E)$, related to the NIEL through

$$D(E) = \frac{A}{N_A} \left. \frac{dE}{dx} \right|_{\text{non ionizing}} \quad (4.2)$$

where A is the atomic mass of silicon.

The displacement damage function can be expressed as

$$D(E) = \sum_{\nu} \sigma_{\nu}(E) \int_{E_d}^{E_R^{max}} f_{\nu}(E, E_R) P(E_R) dE_R \quad (4.3)$$

where $\sigma_{\nu}(E)$ are the cross sections of the processes that lead to a displaced atom for a particle with energy E , $f_{\nu}(E, E_R)$ is the probability for a reaction with cross section σ_{ν} to produce a recoil atom with energy E_R , and $P(E_R)$ is the Lindhard partition function [34] that expresses the fraction of E_R that results in displacement damage.

The damage efficiency D_{eff} for a fluence spectrum $\Phi(E)$ is expressed in equation 4.4. In order to compare the bulk damage produced by different kinds of radiation, the damage efficiency is expressed as the fluence of 1 MeV neutrons resulting in the same amount of displacement damage in the lattice

$$D_{eff} = \int D(E) \Phi(E) dE = D_{\text{neutron}}(1 \text{ MeV}) \cdot \Phi_{eq} \quad (4.4)$$

with

$$\Phi_{eq} = k \Phi_{tot} = k \int \Phi(E) dE \quad (4.5)$$

where k is the so called hardness factor that is characteristic of the kind of radiation causing the damage

$$k = \frac{\int D(E) \Phi(E) dE}{D_{\text{neutron}}(1 \text{ MeV}) \int \Phi(E) dE} \quad (4.6)$$

Figure 4.3 shows the displacement damage for different particle types and energies normalized to the displacement damage of 1 MeV neutrons, that is 95 MeVmb.

The defects produced in the silicon lattice by the PKA can move inside the lattice and interact with each other and with the impurities present in the silicon. This kind of behavior alters the properties of the silicon detectors over time after irradiation and is called annealing. The rate of the reactions responsible for the alterations is a strong function of temperature. To predict the behavior of a detector after irradiation it is typical to study the evolution of its properties with annealing at high temperatures. This simulates the effect of longer annealing times at temperatures close to room temperature.

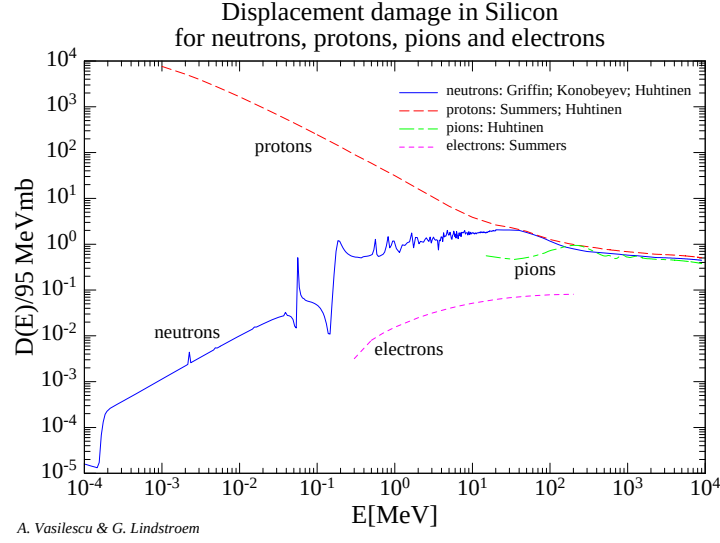


Figure 4.3: Displacement damage for different particle types and energies. From [35].

4.1.2 Effects on the detector

The defects created by displacement damage result in additional levels in the band gap. These levels affect the performances of the detector. Figure 4.4 summarizes the effects produced by these levels.

Dark current The increase in dark current due to irradiation is found to be proportional to Φ_{eq}

$$\Delta I(T) = \alpha(T) \Phi_{eq} V \quad (4.7)$$

where V is the detector volume, and the proportionality factor α is called the current related damage rate. The left part of figure 4.5 shows that this relation holds across several orders of magnitude in fluence and for different silicon materials.

The annealing behavior of the current related damage rate is shown in the right part of figure 4.5. The data are described using

$$\alpha(t, T_a) = \alpha_0 + \alpha_1 e^{-\frac{t}{\tau_1(T_a)}} - \beta \ln \frac{\Theta(T_a)t}{t_0} \quad (4.8)$$

where T_a is the annealing temperature, t the annealing time, and $t_0 = 1$ min. The values of the parameters obtained through the fit are presented in [31].

Doping concentration The effective doping concentration is modified by irradiation. The dopants introduced during the production of the sensor can be neutralized by interacting with defects. The levels created in the band gap can act as dopants. The sum of these effects is reflected in the effective doping concentration N_{eff} , that is related to the depletion voltage through (see equation 3.6)

$$|N_{eff}| = \frac{2\epsilon_0\epsilon_{Si}V_{dep}}{ed^2} \quad (4.9)$$

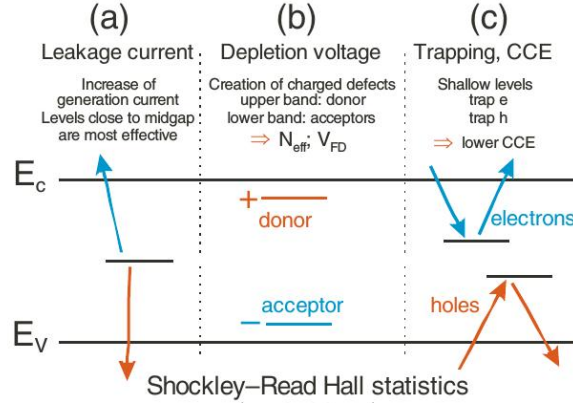


Figure 4.4: Effect of different energy levels in the band gap. (a) Levels close to the middle of the band gap enhance dark current generation and decrease the life time of the charge carriers, (b) Charged defects can act as acceptors or donors, modifying the doping of the detector. (c) Shallow levels with trapping times larger than the detector's electronics' peaking time cause a reduction of the measured pulse height. From [16].

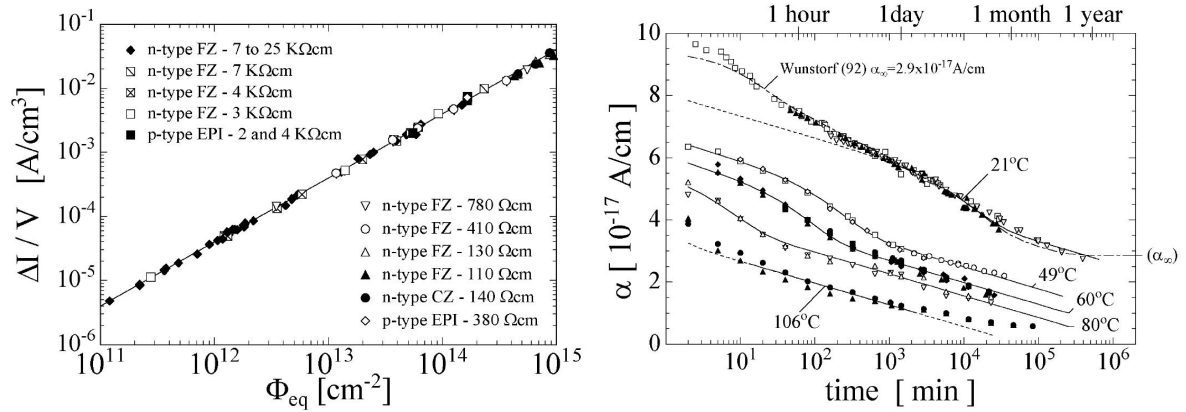


Figure 4.5: Left Fluence dependence of dark current for different silicon materials. The current was measured after a heat treatment for 80 min at 60 °C and is scaled to a sensor temperature of 20 °C. Right Current related damage rate α as a function of accumulated annealing time at different temperatures. From [31].

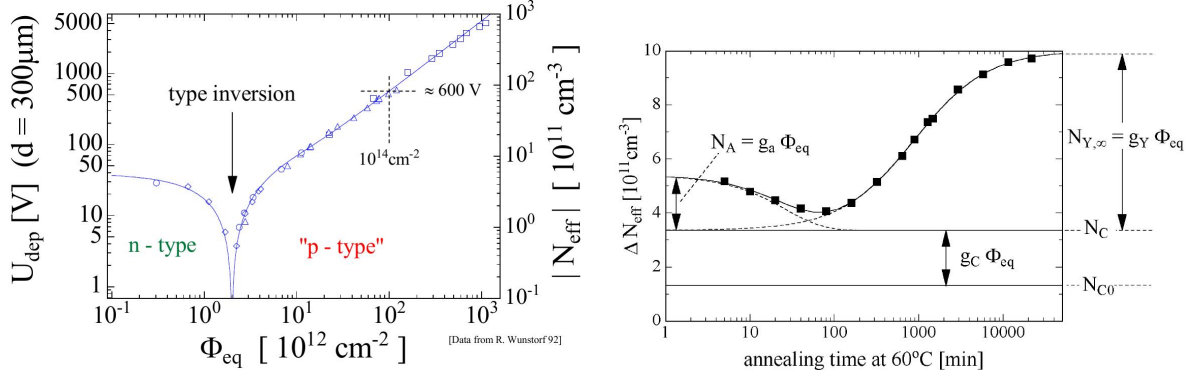


Figure 4.6: *Left* Change of the N_{eff} of a detector as measured immediately after irradiation [36, 37]. *Right* Annealing behavior of ΔN_{eff} . The sample was irradiated to a fluence of $1.4 \cdot 10^{13} \text{ cm}^{-2}$ [31].

The change of N_{eff} and V_{dep} with fluence is shown in the left part of figure 4.6. The sensor starts with a n-bulk and its doping changes with neutron irradiation until it acts like a p-bulk sensor. After type inversion, the depletion voltage increases with fluence.

The right part of figure 4.6 shows the annealing behavior of the variation in effective doping concentration, defined as

$$\Delta N_{eff}(\Phi_{eq}, t(T_a)) = N_{eff0} - N_{eff}(\Phi_{eq}, t(T_a)) \quad (4.10)$$

where N_{eff0} is the doping concentration before irradiation. The annealing behavior of ΔN_{eff} can be described with

$$\Delta N_{eff}(\Phi_{eq}, t(T_a)) = N_C(\Phi_{eq}) + N_A(\Phi_{eq}, t(T_a)) + N_Y(\Phi_{eq}, t(T_a)) \quad (4.11)$$

The different components of the annealing of ΔN_{eff} are explained below. The full set of values of the parameters used in the description of the annealing of ΔN_{eff} is given in [31].

- Stable damage part, N_C

This component of ΔN_{eff} does not change with annealing

$$N_C = N_{C0} (1 - e^{-c\Phi_{eq}}) + g_C \Phi_{eq} \quad (4.12)$$

- Short term annealing, N_A

The short term, or beneficial, annealing reduces N_{eff} , lowering the depletion voltage. This term can be described using a sum of exponential functions

$$N_A = \Phi_{eq} \sum_i g_{a,i} e^{-\frac{t}{\tau_{a,i}}} \quad (4.13)$$

However, for practical detector operation, only the exponential with the largest time constant is relevant, reducing the sum to a single term. The time constant of the short term annealing is about 2 days at room temperature.

- Reverse annealing, N_Y

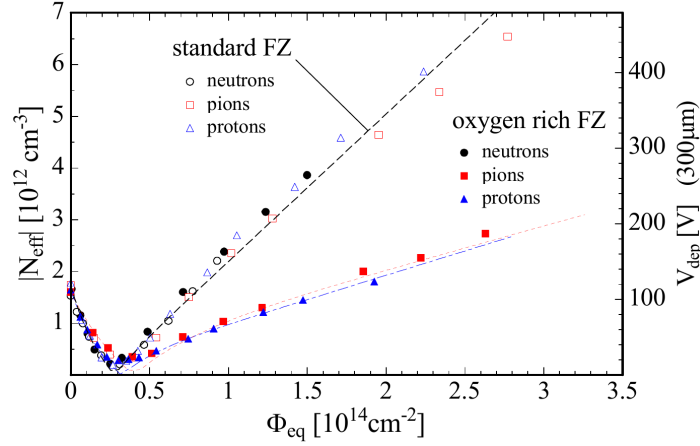


Figure 4.7: Comparison between standard and oxygen rich silicon [37].

The reverse annealing has a detrimental effect on the detector. N_{eff} increases with annealing time, and so does the depletion voltage. The reverse annealing is described by

$$N_Y = N_{Y\infty} \left(1 - e^{-\frac{t}{\tau}}\right) \approx N_{Y\infty} \left(1 - \frac{1}{1 + t/\tau}\right) \quad (4.14)$$

with $N_{Y\infty} = g_Y \Phi_{eq}$. The time constant of the reverse annealing is about 350 days at room temperature.

The annealing behavior of ΔN_{eff} constrains the operating detector temperature and the amount of time the detector can be kept at room temperature during maintenance periods. By cooling the detector to -7°C the time constant of the reverse annealing increases by a factor of ≈ 190 . This makes cooling a very effective way to reduce the effects of reverse annealing. It is therefore a normal procedure to keep the detector cold even during maintenance periods, when possible.

It has been shown that the change of N_{eff} in silicon with a high oxygen content is smaller than the one in standard silicon for irradiation with protons and pions. For neutron irradiation, however, there is no difference between oxygen rich and standard silicon. This violation of the NIEL scaling of bulk damage is attributed to the difference in the kind of defects created by different particles. These effects are shown in figure 4.7.

Since the radiation traversing the detectors at hadron colliders is composed of both charged and neutral hadrons, oxygen rich silicon is used as detector material given its radiation hardness for charged hadrons.

Charge carrier trapping and charge collection efficiency The charge collection efficiency (CCE) is defined as the ratio of the charge collected by a detector and the charge deposited in the detector by radiation. For the study of irradiated detectors, the charge collected by a non-irradiated detector is normally taken as normalization factor with the assumption that $CCE = 1$ for non-irradiated sensors.

The main causes of the degradation of charge collection efficiency with irradiation are partial depletion of the sensor and the trapping of the charge carriers. If an amount of charge

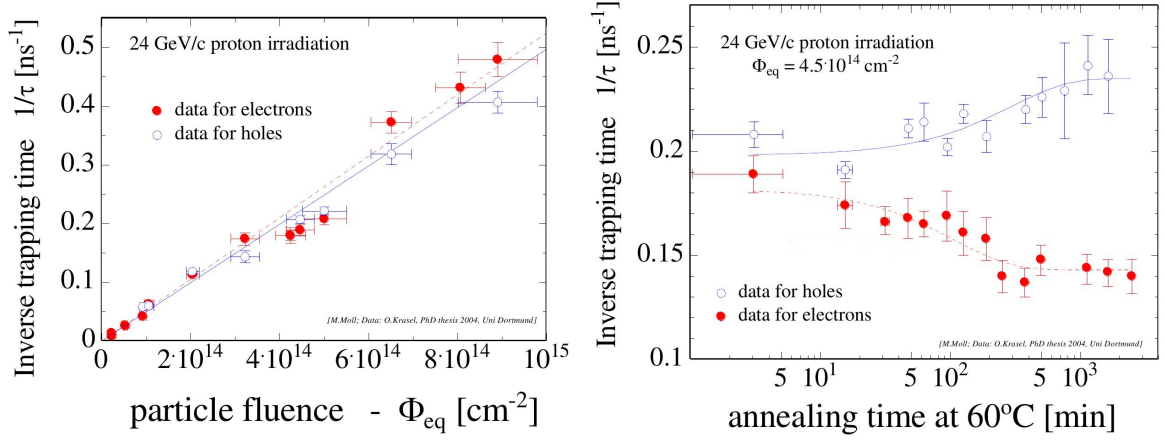


Figure 4.8: Inverse trapping time and its annealing after irradiation [38, 39].

$Q_{0e,h}$ is produced in the sensor, after a time t the free charge is reduced to

$$Q_{e,h}(t) = Q_{0e,h} e^{-\frac{1}{\tau_{eff\,e,h}} t} \quad (4.15)$$

due to trapping. $\tau_{eff\,e,h}$ express the effective trapping time for electrons and holes and its inverse is proportional to the number of defects in the silicon and thus to the bulk damage

$$\frac{1}{\tau_{eff\,e,h}} \propto \Phi_{eq} \quad (4.16)$$

This relation is shown in the left part of figure 4.8.

The annealing behavior of the inverse trapping time is shown in the right part of figure 4.8. The inverse trapping time decreases for electrons and increases for holes with the annealing time.

Electric field The trapping of the electrons and holes flowing through the detector while conducting the dark current can modify the electric field in the sensor. At equilibrium the trapped electrons and holes contribute to the space charge of the detector and influence its electric field. The field configuration presents a maximum at each side of the detector. The model that describes this effect is illustrated in [40]. The electric field configuration is depicted in figure 4.9.

4.2 Surface damage

4.2.1 Damage mechanism

Silicon dioxide covers the surface of silicon sensors and is used to produce MOS transistors and capacitors in the readout electronics. The damage mechanism explained here affects both sensors and readout electronics.

The surface damage is due to ionization and not atom displacement. Particles traversing the silicon dioxide create ionization in the same way as they do in silicon. The electrons, due to their mobility $\mu_{e,SiO_2} \approx 20 \text{ cm}^2/\text{Vs}$, escape the SiO_2 volume through drift or diffusion. The

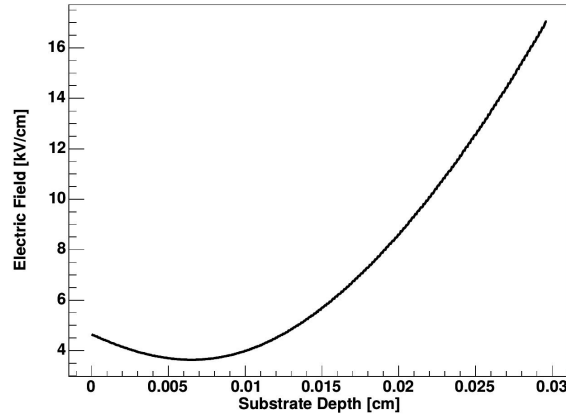


Figure 4.9: Simulated electric field of a sensor irradiated to $2 \cdot 10^{14} \text{ cm}^{-2}$. The field is influenced by the trapped electrons and holes [39].

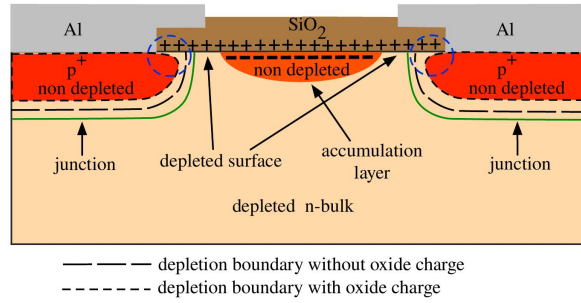


Figure 4.10: Accumulation layer of electron due to surface damage [41].

holes have a lower mobility $\mu_{h, \text{SiO}_2} \approx 2 \cdot 10^{-5} \text{ cm}^2/\text{Vs}$ and are easily trapped in the defects of the silicon dioxide. The amount of defects in the SiO_2 is maximum at the Si-SiO_2 interface. The probability for holes to detrapp from defects is very low, so the irradiation results in an increase of the fixed positive charge in the silicon dioxide.

4.2.2 Effects on the detector

The presence of a fixed positive charge in the silicon dioxide affects the electric field in the sensor and can result in an electron accumulation layer at the Si-SiO_2 interface (see figure 4.10). The presence of the electron accumulation layer increases the interstrip (interpixel) capacitance, increasing the noise of the detector.

In the case of an n-bulk sensor, the presence of an electron accumulation layer can result in high electric field regions in the sensor that can lead to electrical break down. The high field regions are located between the electron accumulation layer and the strip (pixel) implants. The high field is the result of the potential difference between the implants, which are grounded, and the accumulation layer, which is floating. A simulation of these effects is shown in figure 4.11. The effect of surface damage in n-bulk sensors can be mitigated by designing the sensor to reduce the magnitude of the electric field between the implants and the accumulation layer.

For a p-bulk sensor the surface damage can lead to the loss of isolation of the junctions

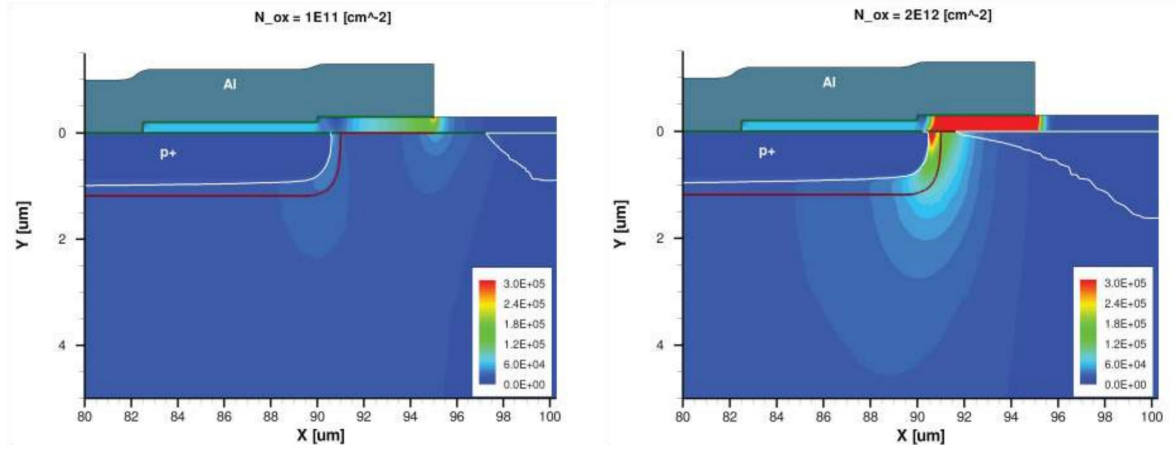


Figure 4.11: Simulated magnitude of the electric field (color coded) in a n-bulk sensor for different values of the oxide charge. The boundary of the depletion regions is shown as a white line. The development of a high field region is evident in the right picture [41].

that form strips or pixels. In addition the electric field of the sensor can be affected as shown in figure 4.12, with field lines passing through the dioxide instead of terminating on the strips (pixels). This affects the charge collection of the sensor as discussed in [42].

The effects of annealing on the surface damage appear to be small and are not treated in this introductory chapter.

In the design of sensors for the HL-LHC both the effects of bulk and surface damage must be taken into account.

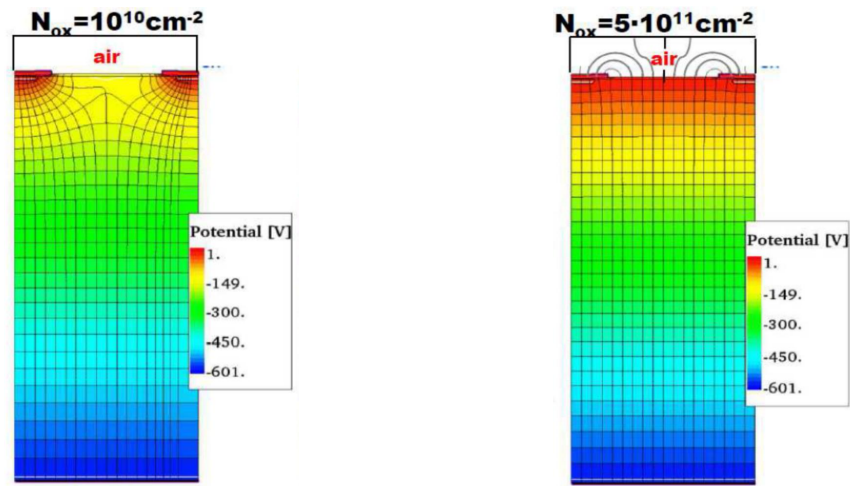


Figure 4.12: Simulated electric field and potential in a p-bulk sensor for different values of the oxide charge. The sensor has p-spray isolation with a doping of $2.5 \cdot 10^{11} \text{ cm}^{-2}$. In the right picture the field lines do not terminate anymore on the junctions [42].

Chapter 5

Upgrades of the CMS pixel detector

5.1 Phase I pixel upgrade

The pixel detector currently installed in CMS is designed to operate up to a luminosity of $1 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with a 25 ns bunch spacing, resulting in an average pile-up of 25. The LHC is expected to exceed this value of luminosity in 2016. The main effect of the increased luminosity on the detector will be a loss of tracking efficiency caused mainly by the size of the buffers in the readout chip and the communication speed of the pixel modules with the electronics in the counting room.

The phase I pixel upgrade will overcome these problems and allow an efficient data acquisition up to a luminosity of $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The main focus of the upgrade is therefore on the readout chip and the communication speed of the data acquisition system. In addition, the material budget of the upgraded detector will be reduced in comparison to the present one. The upgraded detector is planned to be installed in the winter of 2016/17.

The main source of information for this section is [43]. This section is focused on the solutions implemented in the barrel part of the detector, since Hamburg University is involved in the production of pixel modules for this part of the detector.

5.1.1 Detector layout

The layout of the upgraded detector consists of 4 layers in the barrel region and 3 end cap disks on each side of the barrel. The chosen geometry provides a four-hit coverage for $|\eta| < 2.5$. A comparison between the current and upgraded detector is shown in figure 5.1.

The innermost layer of the barrel part of the detector (layer 1) is placed at a radius of 3 cm from the interaction point and the outermost (layer 4) at 16 cm. The positions of layer 2 and 3 are similar to the ones in the present detector. The total sensitive surface of the barrel pixel is 1.24 m^2 .

The forward part of the detector provides tracking at a radius between 4.5 and 16.1 cm. The location of the first disk along the beam line is 29.1 cm from the interaction point, the third disk is placed at 51.6 cm. The sensors in the end caps are arranged in a turbine-like geometry in order to enhance the charge sharing between the pixels and hereby improve the hit resolution. The total sensitive surface of the end caps is 0.35 m^2 .

A comparison of the amount of material present in the tracking volume for the current and upgraded detector is shown in figure 5.2. The amount of material in the tracking volume is reduced in the upgraded detector despite the presence of an additional pixel layer. The

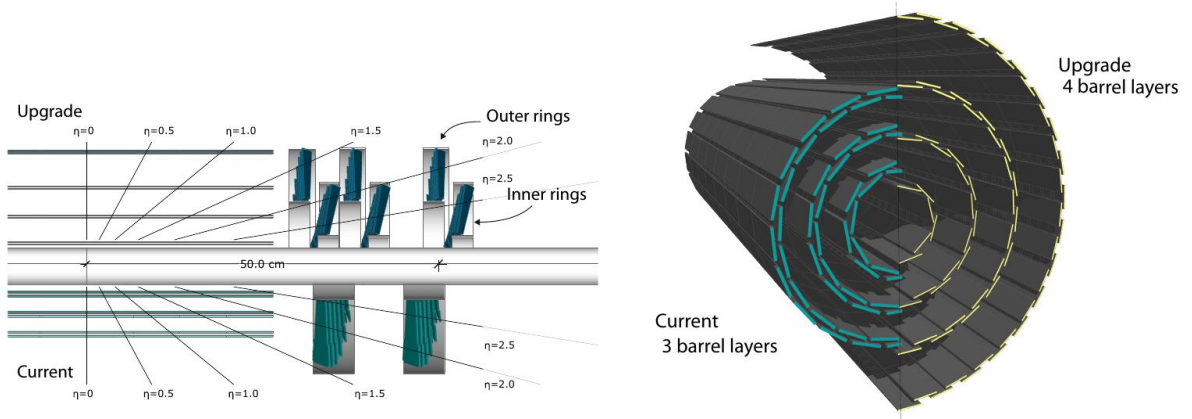


Figure 5.1: Comparison of the layout of the upgraded and present pixel detector. From [43].

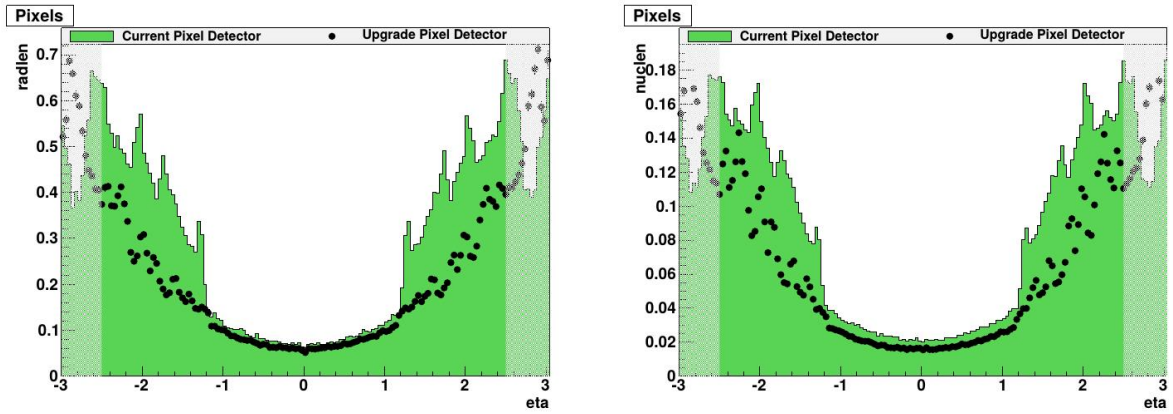


Figure 5.2: Amount of material present in the tracking volume for the upgraded (dots) and current (green bars) pixel detectors. The material is shown in units of radiation length (left) and nuclear interaction length (right) [43].

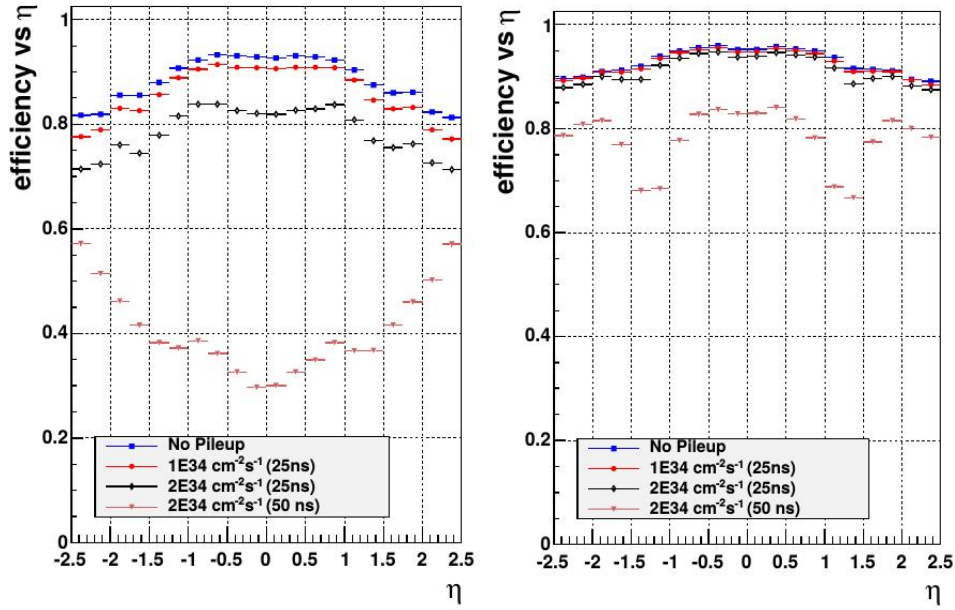


Figure 5.3: Comparison of the tracking efficiency between the current (left) and the upgraded (right) detector extracted from the simulation of $t\bar{t}$ events at $\sqrt{s} = 14$ TeV for different beam conditions. From [43].

Luminosity [$\text{cm}^{-2}\text{s}^{-1}$]	Bunch crossing time [ns]	Average pile-up
$1 \cdot 10^{34}$	25	25
$2 \cdot 10^{34}$	25	50
$2 \cdot 10^{34}$	50	100

Table 5.1: Summary of the average pile-up for the beam conditions depicted in figure 5.3.

main improvements come from the use of two-phase CO_2 cooling that requires smaller pipes than the ones employed in the present detector, and the placement of unsensitive components outside of the tracking volume.

5.1.2 Expected performance

The expected performance of the upgraded pixel detector has been evaluated using simulations. Figure 5.8 shows a comparison of the tracking efficiency defined as

$$\text{Tracking efficiency} = \frac{\text{Number of truth tracks matched to reconstructed tracks}}{\text{Number of Monte Carlo truth tracks}} \quad (5.1)$$

between the current and upgraded pixel detector for different operating conditions. The data used to obtain the plots are from a sample of generated $t\bar{t}$ events with a center of mass energy of 14 TeV. Table 5.1 summarizes the average pile-up for the beam conditions depicted in figure 5.3.

The tracking efficiency of the current pixel detector is slightly degraded at a luminosity of $1 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (25 ns bunch crossing time) with respect to the no pile-up scenario. For higher pile-up the efficiency drops considerably. Regarding the upgraded detector, very little

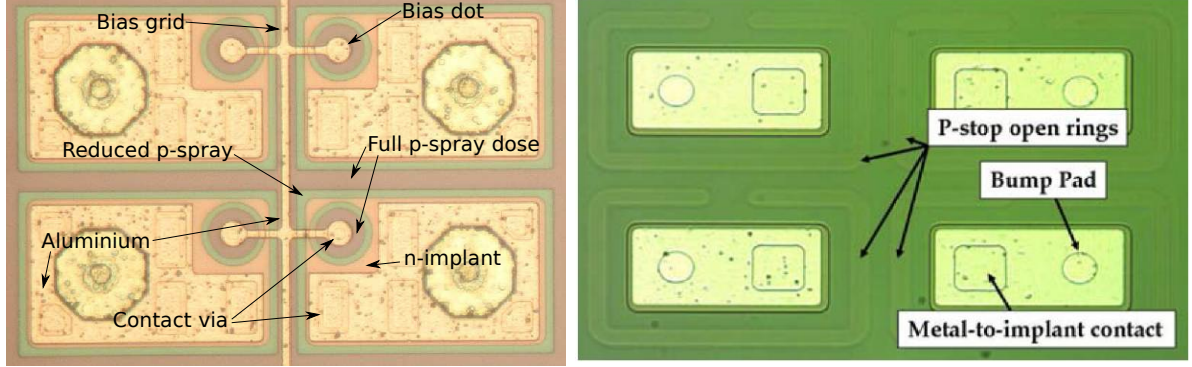


Figure 5.4: BPIX (left) and FPIX (right) pixel design. The BPIX design employs p-spray isolation and a bias grid to establish electrical contact to the pixels. The FPIX design employs p-stop isolation with an opening to allow electrical connection between the pixels. From [43].

efficiency is lost at $2 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ with a bunch crossing time of 25 ns. However, the tracking efficiency of the upgraded detector drops for a luminosity of $2 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and a bunch crossing time of 50 ns.

5.1.3 The pixel sensor

The pixel sensors employed in the upgrade have the same design as the ones used in the current pixel detector. The sensors are made of oxygen rich float zone silicon and have a thickness of $285 \mu\text{m}$. The sensors follow an n^+ -in- n design, where the pixels are made of n^+ implants produced on an n -doped substrate. The pn-junction is obtained by producing a p^+ implant on the back side of the sensor. The back side of the sensor also includes a series of guard rings that allow a gradual drop of potential between the the p^+ implant, biased up to 600 V, and the edge of the sensor that is at ground potential. Maintaining the edge of the sensor at ground potential eliminates the risk of electric discharges between the sensor and the readout chip. The pixels have an area of $100 \times 150 \mu\text{m}^2$ ($r - \phi \times z$). The pixel design is different for the sensors to be used in the barrel (BPIX) and forward (FPIX) parts of the detectors. Figure 5.4 shows a picture of four pixels of the BPIX (left) FPIX (right) sensors.

The BPIX design employs moderated p-spray to insulate the pixels. All the pixels on a sensor are connected using punch through structures to a bias grid. The bias grid allows the identification of defective sensors through electrical tests. In addition, in the case of a missing bump bond connection, the potential of the unconnected pixel is maintained close to the one of its neighbors, avoiding distortions of the electric field in the sensor.

In the FPIX design p-stop is used for the pixel isolation. Each pixel is surrounded by a p-stop implant with an opening. The opening of the p-stop provides an electrical connection between the pixels. The positive oxide charge produces an electron accumulation layer that forms a resistive connection between the pixels. As for the BPIX sensors, this connection is used to control the potential of the pixels in the case of missing bump bonds.

In order to avoid insensitive regions, the pixels that cover the areas at the boundary of two readout chips have their size increased to 2 or 4 times the usual pixel size. This is done to accommodate for the design and mechanical tolerances of the readout chips in the pixel modules (see figure 5.8). A picture of the pixels at the corner of two readout chips is shown

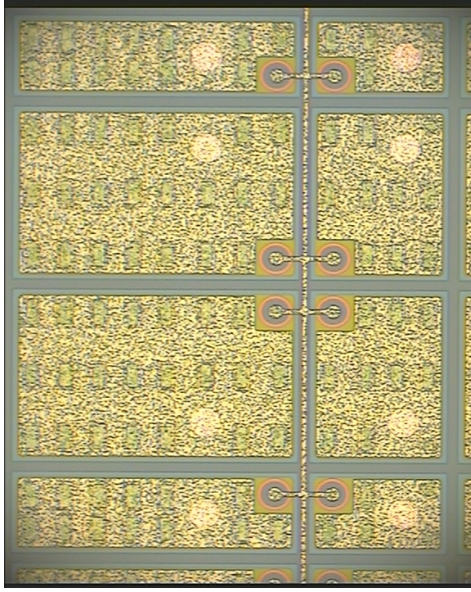


Figure 5.5: Different pixel sizes in a BPIX sensor at the corner of two read-out chips, see figure 5.8.

in figure 5.5.

The integrated luminosity that will be recorded by the upgraded detector is estimated to be 500 fb^{-1} , resulting in an equivalent fluence of $3 \cdot 10^{15} \text{ cm}^{-2}$ for the innermost pixel layer. Since the system is not designed to withstand such a fluence, the innermost pixel layer will be substituted every 250 fb^{-1} . Even so, the sensors of the innermost layer will receive the highest fluence in the upgraded detector, $\Phi_{eq} = 1.5 \cdot 10^{15} \text{ cm}^{-2}$.

The most probable value of the collected charge for BPIX sensors is shown in figure 5.6 for different fluences and particle types. The data was obtained irradiating sensors bump bonded to a readout chip from the current pixel detector. The irradiation was performed after bump bonding in order to avoid the annealing effects induced by the thermal treatment of the sensors during the bump bonding procedure. The variations of the signal observed for a specific value of voltage and fluence are due to the tolerances on the sensor thickness, that is $285 \pm 15 \mu\text{m}$, and the fluence accuracy. The value of the collected charge reaches 10000 e^- at a bias voltage of 600 V after a fluence of $1.1 \cdot 10^{15} \text{ cm}^{-2}$. This signal value allows an efficient operation of the upgraded pixel detector.

5.1.4 The readout chip

The readout chip (ROC) used in the upgrade is an evolution of the one employed in the current pixel detector and is produced using the same 250 nm CMOS process. Two kinds of ROCs will be used in the upgraded detector, one for the innermost barrel layer, and one for the rest of the detector. Both ROC types feature the same architecture.

The ROC layout is shown in figure 5.7. The ROC consists of a matrix of 52×80 pixel unit cells (PUC) organized in 26 double columns (DC). The pixels in a double column share the same buffer units, located in the ROC periphery (bottom part of figure 5.7). The periphery of the ROC also contains the digital to analog converters (DAC) that are used to regulate the chip behavior and the interfaces to communicate with the outside world.

The signal produced in the sensor is processed in the PUC by a charge sensitive preamplifier and shaper. The shaper output is evaluated by a comparator whose threshold is adjusted

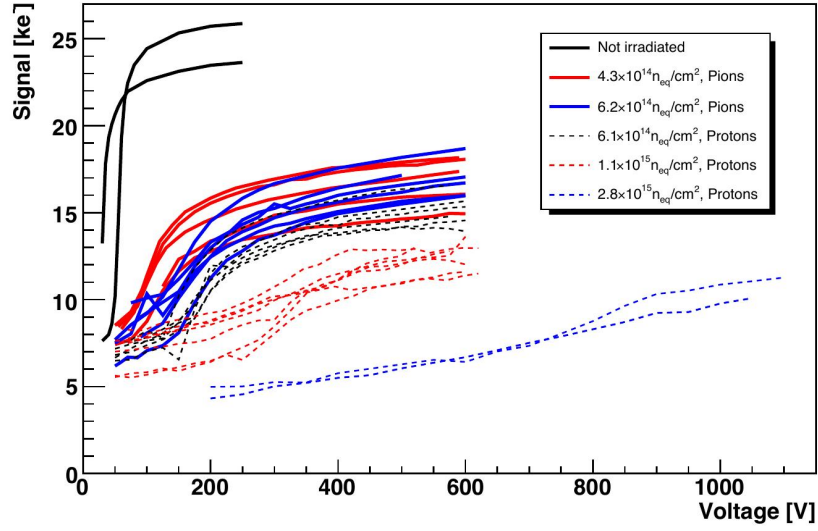
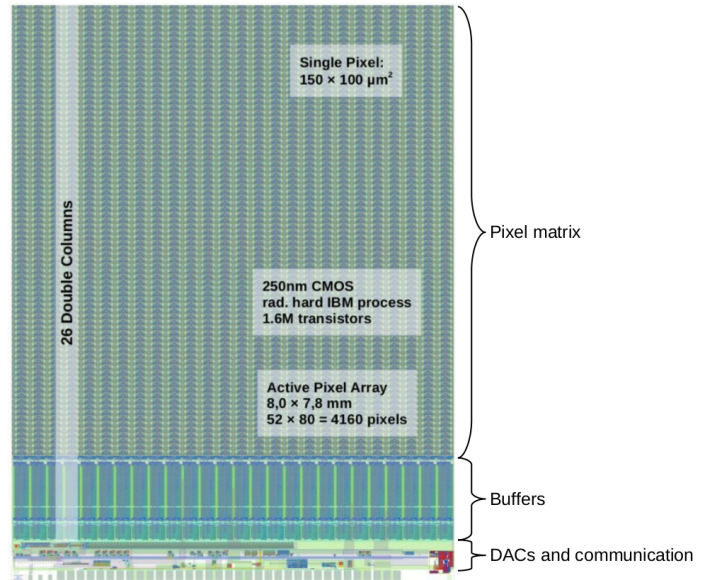


Figure 5.6: Most probable signal value for BPIX sensors irradiated with different particle types. The signal reaches $10000 e^-$ at a bias voltage of 600 V for the modules irradiated to $\Phi_{eq} = 1.1 \cdot 10^{15} \text{ cm}^{-2}$. From [43].

Figure 5.7: ROC layout. From [44].



in each pixel through a 4 bit register in the PUC (trim bits). If the signal exceeds the comparator threshold, a signal is sent to the DC periphery to book a place in the time stamp buffer. The readout of the pixels hit in the double column starts and the PUCs with a hit send their address and an analog signal representing the pulse height to the row address and pulse height buffers, respectively. The hit information is stored in the buffers until the CMS trigger system decides whether to keep the event. In case a trigger signal is received for the event, the data is sent to the ROC periphery to be digitized and stored in a first in first out (FIFO) memory. The readout of the ROCs in a module is steered by the token bit manager (TBM) chip. When the ROC receives the signal to initiate the transmission of the data, all the hits of one event are sent out.

The main improvements of the ROC for the detector upgrade with respect to its predecessor are:

- Extended buffer size

The time stamp buffer has been increased from 12 to 24 cells, while the pulse height and row address buffers have been increased from a depth of 32 to 80.

- Digital readout

The ROCs present in the current detector use a 40 MHz analog data transmission protocol based on 6 analog levels for the pixel address. An analog signal contains the pulse height information. The data from the ROCs are digitized in the counting room.

The ROCs used in the upgrade employ a digital communication protocol with a speed of 160 Mbit/s. The pulse height information is digitized on the ROC.

- Improved analog performance

The threshold applied to the ROCs in the current pixel detector is limited by cross talk. Several precautions have been taken in order to reduce the cross talk and allow the use of lower threshold settings. A threshold value of $\approx 1800 e^-$ can be achieved without inconveniences using the upgraded ROC.

The digital readout and the augmented buffer size will limit the data loss of the system. The lower threshold of the new ROC extends the fluence at which the modules can be operated by making the ROC sensitive to the smaller signal from the sensor.

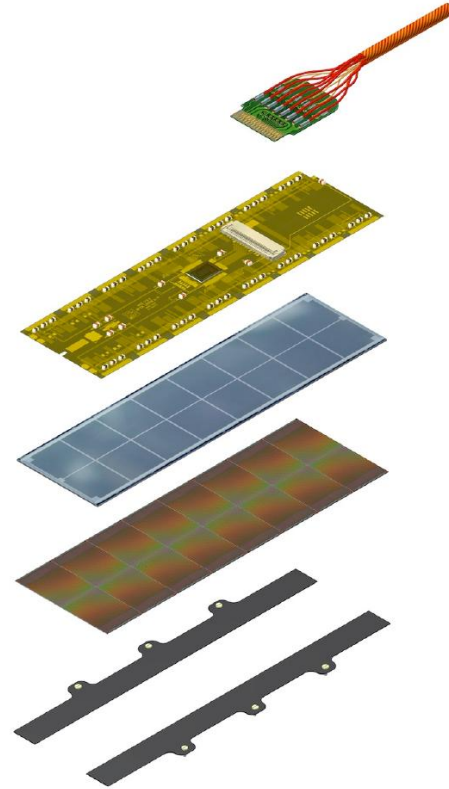
In addition to these improvements, the ROC used for the innermost layer will implement a faster transfer of the hit information from the PUC to the buffers and an improved buffer logic.

To test the ROC functionality and provide a reference to determine the ROC settings, an internal calibration signal is used to inject charge at the preamplifier input of each PUC. The amount of injected charge is controlled through a DAC named Vcal. The calibration signal is used to determine the threshold of the ROC and to provide a common scale for the pulse height measured by each PUC. The absolute calibration of the DAC register that regulates the amount of injected charge is discussed in section 6.5.

5.1.5 The pixel module

The structure of the pixel module used in the upgraded detector is similar to the one used in the current detector. The upgraded detector has three different types of modules. One

Figure 5.8: Exploded view of the BPIX module for layers 2 to 4. From [45].



kind of module is used in the innermost barrel layer, one is used in the other barrel layers, and one for the end caps.

Figure 5.8 shows an exploded view of the modules used in the barrel layers 2 to 4. The module has a pixel sensor bump bonded to 16 ROCs, which are connected through wire bonds to a circuit layer glued on top of the sensor. The circuit layer, called high density interconnect (HDI), distributes power and control signals to the ROCs and the bias voltage to the sensor. One of the components of the HDI is the token bit manager chip. The TBM chip manages the communication between the ROCs and the external world. The TBM steers the ROCs readout through a token signal that is passed through groups of ROCs. The hit information is transferred from the ROCs to the TBM at a speed of 160 Mbit/s, the TBM aggregates the hit information and transmits it out of the module at 400 Mbit/s. The communication speed achieved between the modules and the counting room is a key parameter to avoid data losses. The module is mounted to its support structure in the detector using base strips glued to the ROCs.

The modules for the innermost layer of the barrel pixel are equipped with two TBM chips and a different ROC version to cope with the higher rate. Both the module for the innermost layer and end cap have a different mounting mechanics than the base strips shown in figure 5.8.

The modules needed for the detector upgrade are under production in several institutes in Europe and America. The module production chain used in Hamburg is explained in chapter 6.

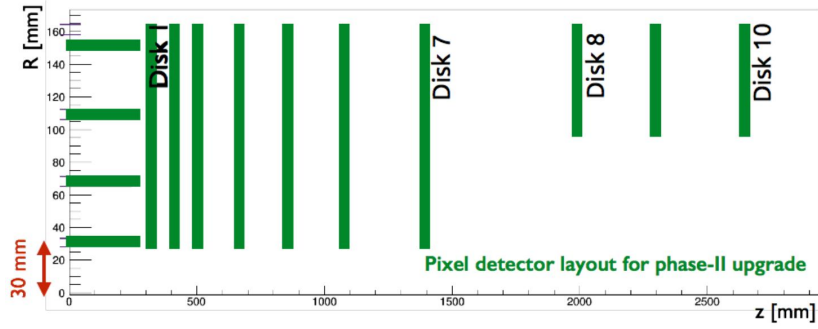


Figure 5.9: Proposed layout for the phase II pixel upgrade [46].

5.2 Phase II pixel upgrade

Data taking in the environment of HL-LHC will require the installation of a new pixel detector in 2025. The average pile-up foreseen for a luminosity of $5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with a bunch crossing time of 25 ns is 140, too high for an efficient data taking with the phase I pixel detector.

5.2.1 Detector layout

The proposed layout of the upgraded detector is shown in figure 5.9. The detector consists of 4 barrel layers and 10 end cap disks that extend the tracking to $|\eta| \approx 4$. The total area of the detector will be $\approx 4 \text{ m}^2$.

5.2.2 The pixel sensor

The sensor material to be used in the phase II upgrade is still a matter of investigation. The innermost layer of the pixel detector will accumulate a fluence $\Phi_{eq} = 2 \cdot 10^{16} \text{ cm}^{-2}$ and a dose of $\approx 10 \text{ MGy}$ after 3000 fb^{-1} [47]. These values of dose and radiation damage are unprecedented, therefore new designs and sensor materials have to be found to operate in such conditions. The sensors being investigated are currently 3D silicon sensors and thin planar silicon sensors with a thickness between 75 and 200 μm .

3D silicon sensors present the advantage over planar silicon sensors that the distance the charge carriers have to drift is decoupled from the sensor thickness. A schematic of a 3D silicon sensor is shown in figure 5.10. The electrodes that collect the charge are produced vertically through the silicon thickness, and are typically placed at a distance of 50 μm . The sensor thickness is usually around 300 μm , therefore the charge deposited in the sensor by a ionizing particle is the same as in a typical silicon sensor. The small drift distance reduces the effects of trapping on the charge collection after irradiation. The small distance between the electrodes makes it possible to achieve high electric fields in the sensor even at small bias voltages. These effects enhance the radiation hardness of 3D silicon sensors. The possibility to produce implants vertically in silicon makes it possible to reduce the insensitive region at the edge of the sensors, as shown in figure 5.10. The sensors that implement this design are usually named active edge sensors. The production of 3D silicon sensors is more complex than the one of planar sensors, which makes the cost of 3D sensors significantly larger than the one of planar sensors.

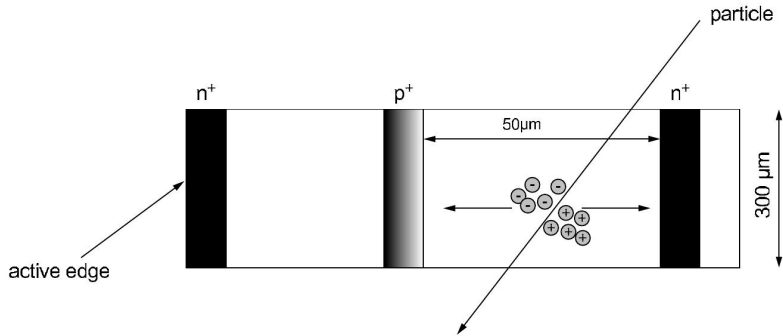


Figure 5.10: Schematic representation of a 3D silicon sensor. The drift distance of the charge carriers is small compared to planar silicon sensors. From [17].

A study of the radiation hardness of thin silicon sensors is presented in chapter 7.

In order to maintain the occupancy of the detector at a reasonable level the pixel area will be $2500 \mu\text{m}^2$. The shape of the pixels will probably be either $50 \times 50 \mu\text{m}^2$ or $25 \times 100 \mu\text{m}^2$. The choice will be driven by the performance of the detector in simulations.

5.2.3 The readout chip

The readout chip will have to withstand a dose of $\approx 10 \text{ MGy}$ and a hit rate of $\approx 2 \text{ GHz/cm}^2$. A collaboration has been formed to develop the readout chip for the ATLAS and CMS pixel detectors [48].

The chip will be produced using a 65 nm CMOS technology. The design of the chip is under development. A first demonstrator chip is expected for 2017.

Chapter 6

Module production for the phase I pixel upgrade

The production of the upgraded pixel detector is shared between multiple production centers. The forward pixel modules are produced by American institutes. The barrel pixel modules are produced in Europe, the production being shared between different institutes. The modules of the outermost layer of the barrel pixel detector are produced by German institutes; one half of the modules needed for this layer is produced by DESY (*Deutsches Elektronen-Synchrotron*) and the University of Hamburg. A total of 350 modules, including spares, must be produced in Hamburg. In this chapter the module production in the Hamburg production center is explained. In order to achieve a good yield many quality assurance tests are performed. The quality assurance tests in use at the University of Hamburg are introduced in this chapter. The completed modules are tested and calibrated using X-rays; these tests are illustrated in the last part of the chapter.

6.1 Production chain in Hamburg

The steps of the module production at the Hamburg production center are illustrated in figure 6.1.

The module production starts with the bump-bonding of the readout chips (ROCs) to the sensor. The sensor wafers are produced by CiS¹ and shipped to PacTech² where the under bump metallization (UBM) is deposited and the wafers are diced. The ROC wafers are produced by IBM and the ROCs are tested on-wafer at PSI. They are then sent to PacTech where they receive the UBM and are diced. Diced sensors and ROCs are sent to DESY. The bump-bonding is executed in a clean room at DESY. The first step of the bump-bonding consists of the deposition of a solder ball for each pixel onto the sensor. The solder balls have a diameter of 40 μm , which are individually melted by a laser pulse and deposited on the sensor using a blast of nitrogen. This procedure is quite time consuming since 66560 solder balls have to be deposited on each sensor. The solder ball deposition cannot be parallelized and sets the upper limit for the throughput of the production chain to two modules per day. The next step consists of the flip-chip bonding of the ROCs to the sensor. The ROCs' functionality is tested before they are mated with the sensor. The ROCs are individually

¹Forschungsinstitut für Microsensorik GmbH, www.cismst.org/en/

²<http://www.pactech.de/>

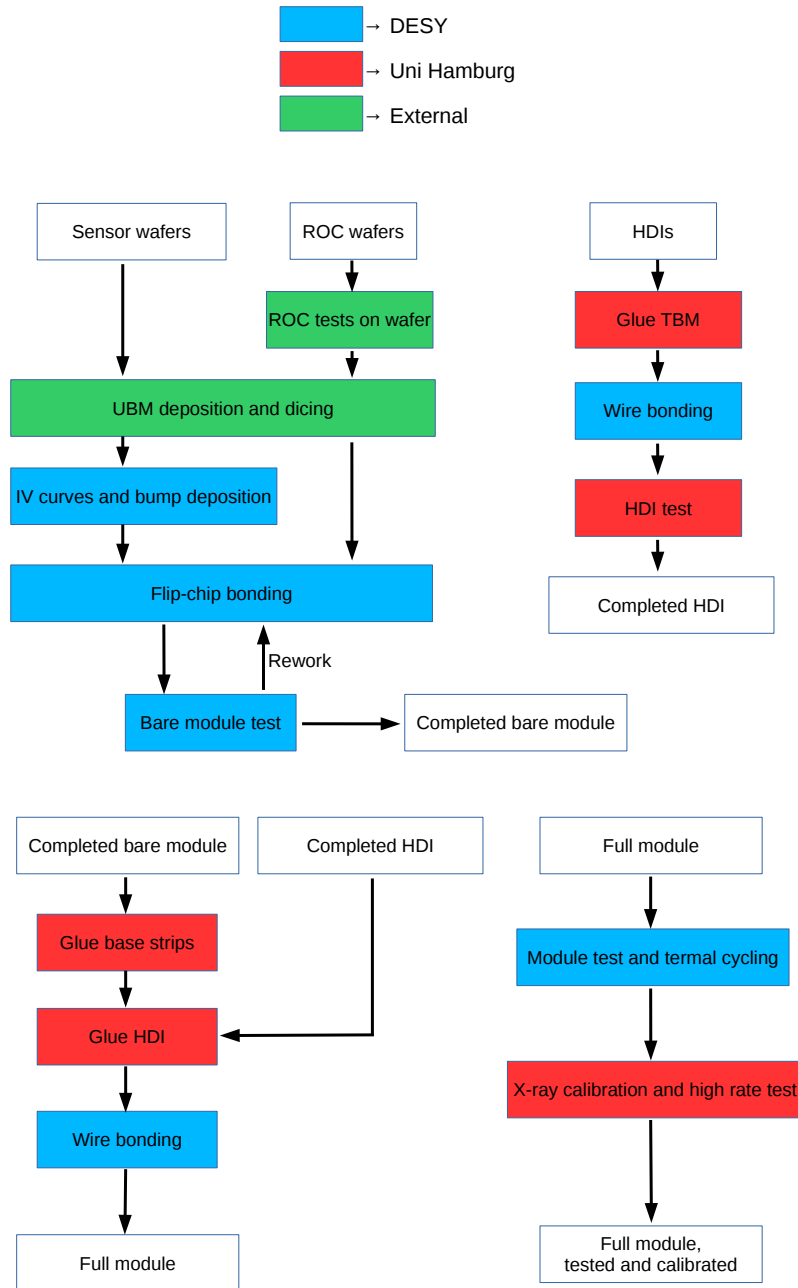


Figure 6.1: Production chain of the barrel modules at the Hamburg production center.

placed on the sensor by a dedicated machine that heats both the sensor and ROC and applies pressure to the ROC to achieve a good contact. The temperature used in this process is below the melting point of the solder. The assembly of the sensor and ROCs, called bare module, is then heated to about 230 °C to re-flow the solder balls, which ensures a good contact of the balls to both the sensor and the ROCs and relieves mechanical stress. Each ROC in the bare module is tested in a probe station. In the case that one ROC has been damaged during the bump-bonding procedure it is possible to replace it. The sensor is heated up and the faulty ROC is detached and replaced with a working one. The bare modules are then moved to the university site to receive the HDIs.

The University of Hamburg receives the high density interconnect circuits (HDIs) directly from the vendor³. The HDIs are electrically tested before shipment. The TBM (token bit manager) chips are tested and shipped already diced to Hamburg. The TBM chips are glued to the HDIs and the assembly undergoes wire-bonding at DESY. The HDIs with TBM are then tested for functionality (see section 6.4).

The base strips and the HDI are glued to the bare module at the University of Hamburg. The wire bonds between the ROCs and the HDI are placed at DESY.

The completed module undergoes functionality tests and several thermal cycles from 20 to -25°C in order to assure that the mechanical stress due to thermal dilatation will not damage the module when operated in the detector.

The module is then calibrated and tested using X-rays. The ROCs are calibrated in energy using monochromatic X-rays and the buffers of each double column are tested using a high rate beam of X-rays. These procedures are described in sections 6.5 and 6.6.

6.2 Visual inspection of sensor wafers

In order to identify defects on the sensors that would not show up in the electrical measurements described in section 6.3, the sensors of five wafers received a full visual inspection under the microscope. The sensors were inspected on both the n- and the p-side for damages or imperfections such as scratches, holes in the passivation or problems in the metallization. One example of a defect in the passivation on the n-side of a wafer is shown in figure 6.2. The depicted defect is a hole in the passivation that leaves the metallization of two pixels and of the bias grid exposed. This kind of defect would lead to the creation of a short circuit between the two pixels and the bias grid during the UBM deposition. It would then be impossible to correctly measure the signal from these pixels in the detector.

The number of defective pixels observed in the visual inspection is 5, distributed over 15 sensors. Therefore the observed defects are present at a $5 \cdot 10^{-6}$ level. The visual inspection of sensors under the microscope is extremely time consuming and revealed a good quality of the sensors. This quality assurance test has being dismissed for the module production.

6.3 IV/CV measurements of sensors

The IV characteristic of the sensors on wafers is used to determine at an early stage whether a wafer will receive the UBM and be diced. Wafers with at least two good sensors are further processed and the rest are rejected. The classification of the sensors and wafers

³<http://hightec.ch/>

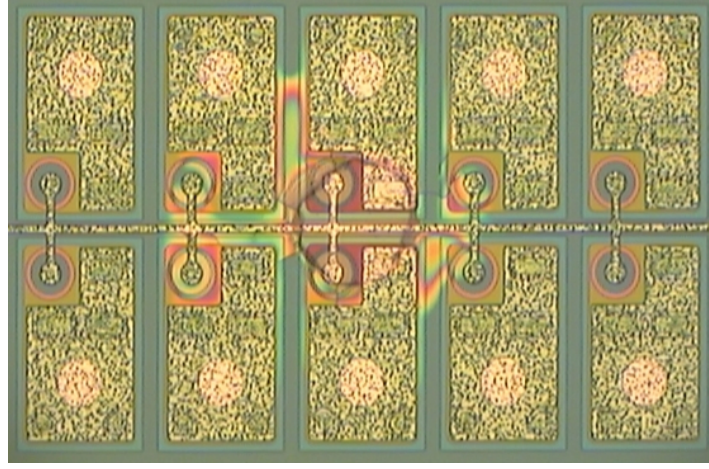


Figure 6.2: Defect in the sensor passivation on the n-side.

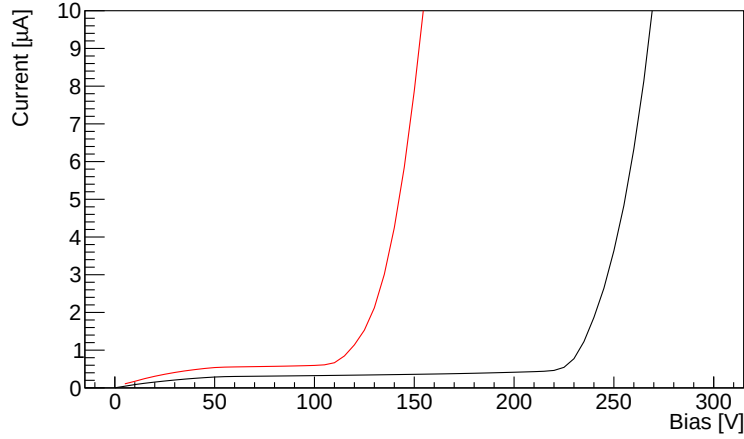


Figure 6.3: Comparison of IV curves for a good and a bad sensor. The curve in black fulfills the conditions in equation 6.1. The red curve show a breakdown at around 110 V, too low to fulfill the requirements of the sensor production.

is done by the manufacturer, CiS in this case. A good sensor must have a current of less than $2 \mu\text{A}$ at 150 V bias, the current being scaled for a sensor temperature of 20°C , and the ratio of the current at 150 V bias and 100 V bias must be less than 2. These conditions are summarized in the following equation.

$$\begin{cases} I(150 \text{ V}) < 2 \mu\text{A} \\ I(150 \text{ V})/I(100 \text{ V}) < 2 \end{cases} \quad (6.1)$$

The first row of equation 6.1 ensures that the current drawn by the sensor is at a reasonable level while the second row excludes sensors with a low breakdown voltage. Figure 6.3 shows the IV characteristics of two sensors evaluated using equation 6.1.

The IV and CV characteristics of two sensor batches have been measured before wafer dicing in order to cross check the manufacturer data and the resistivity of the ingot. The measurement requires contacting both the n- and p-implants of the sensors. The wafers are

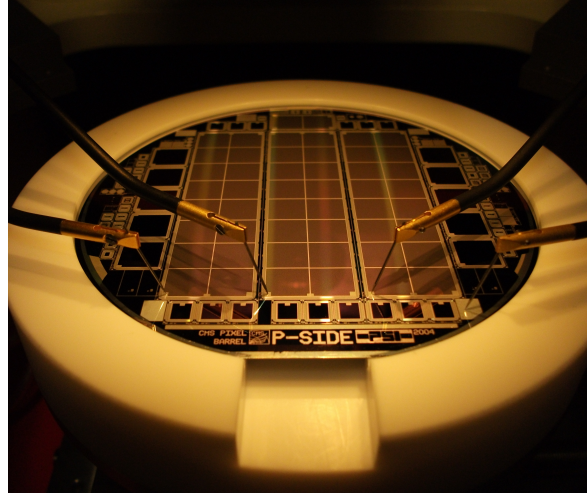
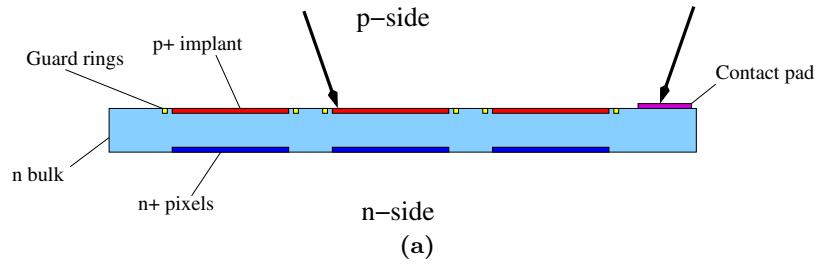


Figure 6.4: Schematic of the needle placement on wafer (a). Picture of the setup (b).

placed with the p-side upwards on a Teflon chuck that supports the wafers at the rim in order to avoid scratches on the n-side. The contact of the n-implant is achieved through a contact pad on the p-side. The contact pad consists of a p⁺-implant that forms a junction with the n-bulk, this junction is biased in the forward direction during the measurement. A schematic of the contacts on the wafer is shown in figure 6.4a, while a picture of the setup is shown in figure 6.4b.

A temperature sensor placed close to the Teflon chuck measures the air temperature, and this value is used to scale the sensor current. This method is assumed to be correct since the wafers are in thermal equilibrium with the air in the room. The IV curves of one of the sensor batches are shown in figure 6.5. The IV characteristic of the sensors that do not satisfy equation 6.1 are drawn in red.

A comparison of the IV characteristic of one sensor measured by the manufacturer and at the university setup is shown in figure 6.6. The curves are in good agreement.

The parameters used to determine if a sensor is good for further processing have been compared. Figure 6.7a shows the comparison of the current values measured at 150 V bias. Figure 6.7b shows the comparison of the slope of the IV curves defined as $I(150\text{ V})/I(100\text{ V})$. Both measurements show a good agreement between the manufacturer and the university measurements. The difference present in the value of the slope of some IV curves (figure 6.7b) has a small effect in the sensor classification. In the batch shown in figure 6.7, 15 bad sensors were identified by the vendor and 17 are classified as bad from the university measurements. The mismatch in the identification of bad sensors is therefore 2/75 sensors. The overall wafer

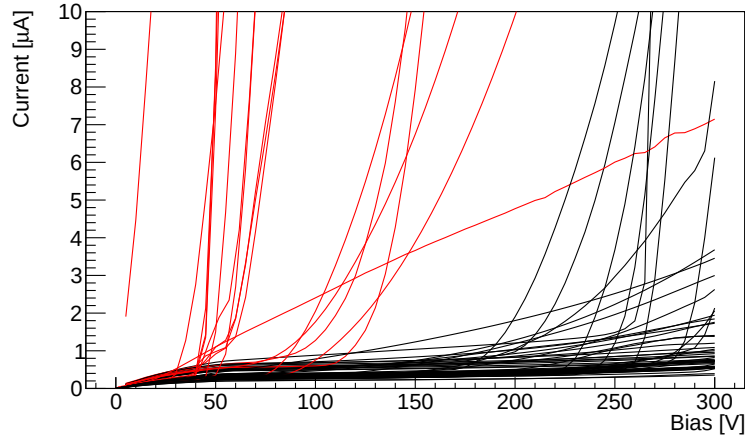


Figure 6.5: IV curves of a sensor batch, the bad sensors (see equation 6.1) are marked in red. The current is scaled to a sensor temperature of 20°C.

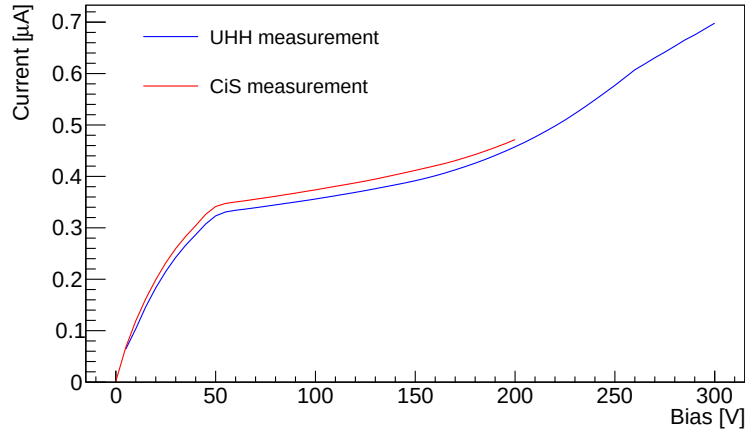


Figure 6.6: Comparison of the IV characteristic of one sensor measured by the producer and at the university setup. Both curves are scaled to a sensor temperature of 20°C.

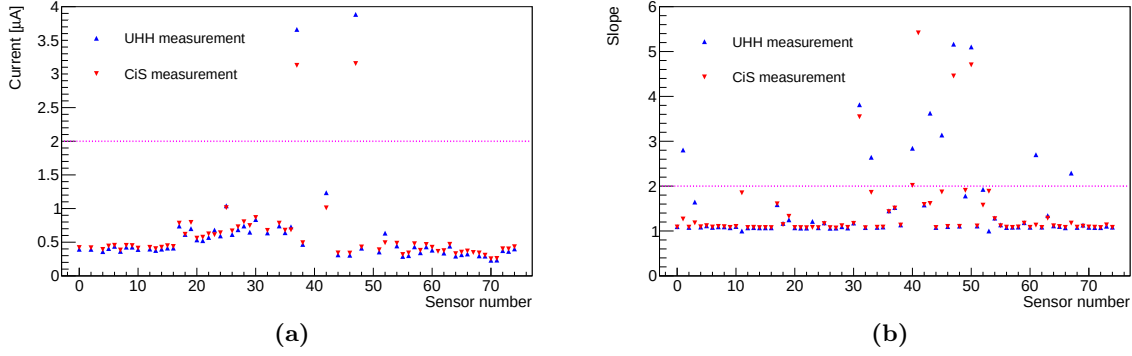


Figure 6.7: Comparison of the current at 150 V bias (a) and slope (b) of the IV curves measured in the university setup and by the manufacturer for one sensor batch. The current values are scaled to a sensor temperature of 20°C. The dashed line marks the limit that defines a good sensor. Some points are outside the range of the plots.

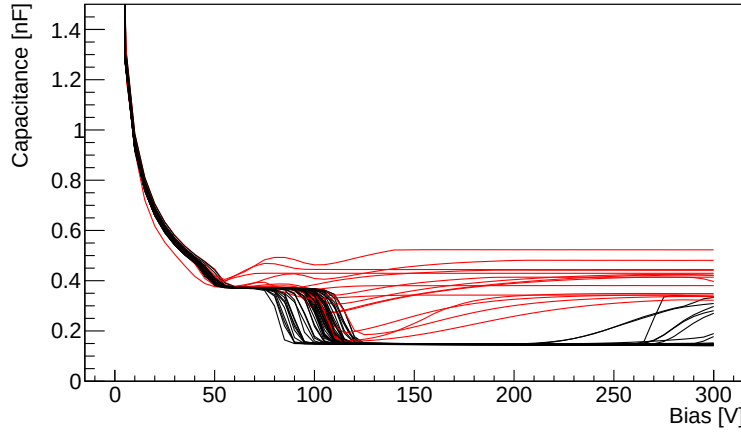


Figure 6.8: CV curves of a sensor batch, the bad sensors (see equation 6.1) are marked in red.

classification is identical for the vendor and university measurements.

The CV curves for one sensor batch are shown in figure 6.8. The CV characteristics have been measured with a frequency of 10 kHz, with the LCR meter working under the hypothesis of a parallel RC circuit. The depletion voltage is around 50 V, corresponding to a bulk resistivity of 5.8 kΩcm.

The CV curves present two plateaus. In order to check that this feature is not a consequence of the measurement being performed on a wafer with multiple structures, the CV characteristic of a diced sensor has been measured. The CV curve is shown in figure 6.9a, where the points represent the measurement. The sensor has the same design of the upgrade sensors but comes from a different ingot, thus the different depletion voltage (around 80 V). The two plateaus are also present in the diced sensor. The conductance-voltage (GV) characteristic of the sensor, also measured with the LCR meter under the parallel RC circuit hypothesis, is shown in figure 6.9b.

The CV and GV characteristics can be described, for this frequency, with the model

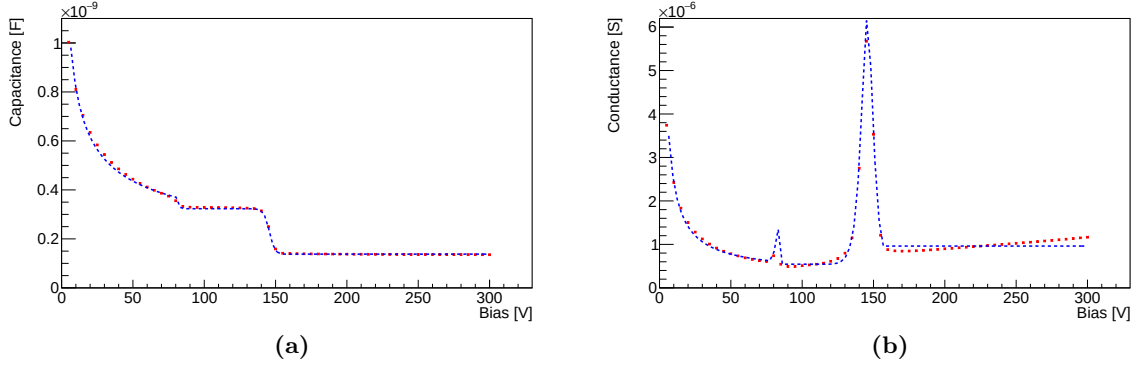


Figure 6.9: Capacitance vs. voltage (a) and conductance vs. voltage characteristics of a diced sensor. The points represent the measured data and the dashed line the model. The frequency used for the measurement is 10 kHz.

depicted in figure 6.10.

To describe the data the impedance of the circuit is calculated and then the values of capacitance and conductance are extracted. In the circuit the pixel and bias dot implants are represented by a variable capacitance and resistor connected in series. The values of capacitance and resistance representing the pixel implant are a function of bias voltage and evolve with the thickness of the depletion region (see chapter 3). The impedance of the bias dot is, due to geometrical considerations, proportional to the impedance of the pixel implant. The transition from the first plateau to the second can be ascribed to the depletion of the silicon between the pixel implants and the scribe line implant. This results in the pinch-off of the connection provided by the undepleted bulk between the two implants. This connection is represented in the model by a variable resistor connected in parallel with a capacitor. The capacitor represents the capacitance between the implants. The value of the resistor grows exponentially when the pinch-off occurs and then saturates when the channel between the implants is fully depleted. The pinch-off of the channel between the pixel implant and the bias dot is modeled in the same way. The scribe line implant on the n-side of the sensor is represented by a resistor connected in series with a capacitor. Finally a resistor is added in series to the rest of the components to represent the connections between the LCR meter and the silicon sensor. The result from the model is depicted in figure 6.9 by the dashed line. The parameters of the model have been optimized by a simultaneous fit of the CV and GV characteristics. The presence in the model of the pinch-off of the channel between the pixel and bias dot implants is necessary in order to achieve a correct description of the curves in the region close to the depletion voltage.

The correct description of the CV and GV characteristic by the model presented above confirms the hypothesis that the presence of a second plateau in the CV characteristics is caused by the pinch off of the connection provided by the undepleted silicon between the pixel matrix and the scribe line implant. The parameters extracted from the fitting procedure are not listed here since they are not meant to provide a precise measurement of the sensor properties. Test structures can be characterized in order to precisely determine the properties of the sensor material and design.

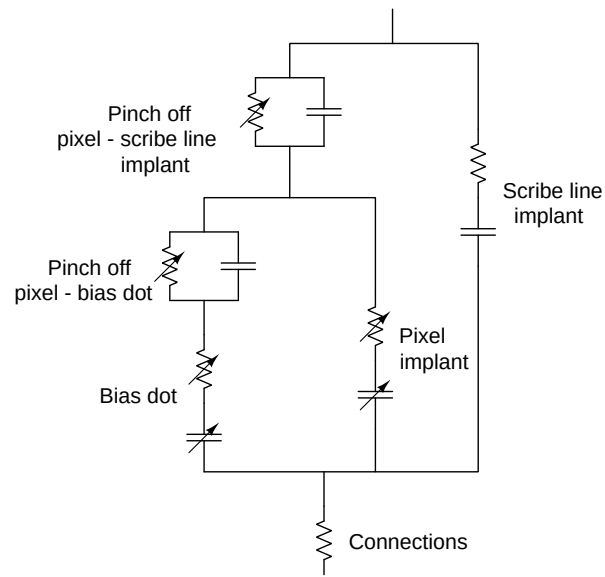


Figure 6.10: Circuit model used to describe the CV and GV curves of figure 6.9.

6.4 HDI test

The HDI with TBM is a crucial component of a pixel module. All the communication, powering and biasing of the module pass through the HDI and TBM. The HDIs wire-bonded to a TBM are tested before being glued to the bare modules. This prevents wasting good bare modules by gluing a faulty HDI onto them. The setup used for the test is shown in figure 6.11. The HDI is connected to the test setup using reserved pads that are contacted using spring loaded needles.

During the test all the tasks of the HDI are checked. First, it is checked that the TBM chip draws the right amount of current. Then the communication with the TBM is checked by observing on the oscilloscope the signal that the TBM sends back to a digital test board. This ensures that the data produced by the ROCs can be correctly transferred from the module to the rest of the readout chain. The signals that the TBM distributes to the ROCs are inspected on the oscilloscope. The signals are checked for shape and amplitude. The signal amplitude must be big enough to have definite logic states for the ROCs. The presence of undesired patterns would result in errors in the communication with the ROCs. An example of a good signal seen during the test is shown in figure 6.12.

Since the powering of the ROCs is also done through the TBM, the voltages supplied to the ROCs are measured with a multimeter. The sensor bias is supplied through the HDI, the connection of the bias line is checked.

6.5 Energy calibration using X-rays

One of the last steps in the module production is the energy calibration of the internal test signal used by each ROC (see section 5.1.4). The calibration is achieved by illuminating the full modules with monochromatic X-rays produced by stimulating fluorescence in metal targets. Through this calibration it is possible to express the noise and the threshold of the ROCs in units of e^- charge. This is an important information for the simulation of the

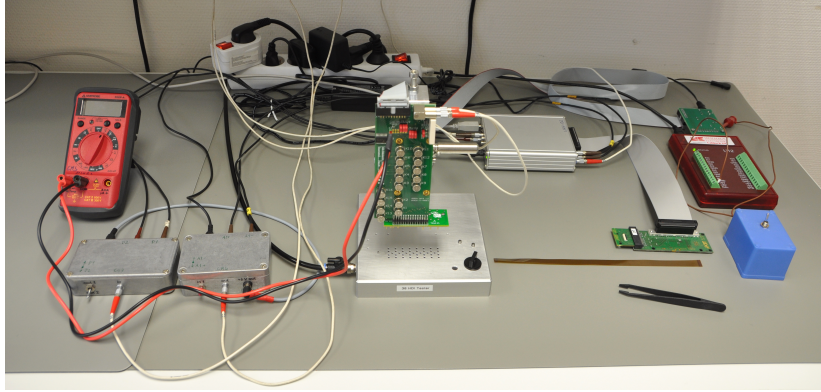


Figure 6.11: Setup for the HDI test. The chuck that holds the HDI and the needles to contact it occupies the center of the picture, the digital test board is in the background. The oscilloscope and the computer that complete the setup are not present in the picture.



Figure 6.12: The oscilloscope traces show a signal distributed from the TBM to the ROCs (yellow and blue), the synchronization signal (pink) generated by the digital test board, and the signal that the TBM sends back to the test board (green).

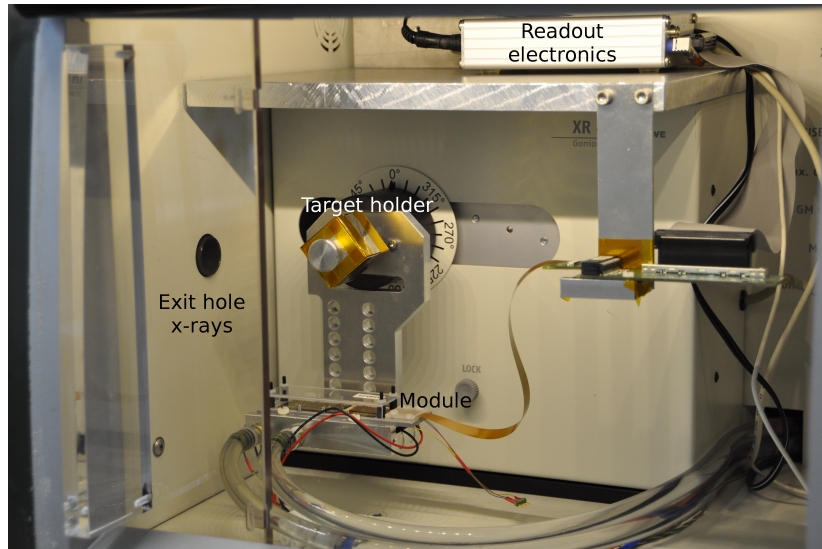


Figure 6.13: Setup for X-ray calibration. The module is illuminated by the fluorescence X-rays emitted by a metal target. The X-ray tube is behind the left wall of the experimental volume.

detector. In addition the energy deposited in the sensors can be expressed on the same scale on the whole pixel detector. This makes it possible to use the pixel detector in analyses relying on dE/dx measurements.

6.5.1 The calibration setup

The setup used for the calibration is based on a commercial X-ray box⁴ and is shown in figure 6.13. It consists of a X-ray tube generating X-rays that are distributed in energy in a bremsstrahlung spectrum (see figure 6.31). The acceleration voltage and the current of electrons in the X-ray tube can be steered independently, with the maximum voltage being 35 kV and the maximum current 1 mA. The X-rays from the tube illuminate a metal target that generates fluorescence X-rays. The energy of the fluorescence lines must be high enough to produce a signal in the silicon sensor above the ROC threshold. At the same time the ionization energy of the electronic shells involved in the emission of the fluorescence lines must not exceed the maximum energy of the X-rays emitted by the X-ray tube. The shells' ionization energy must also be low enough to provide a sufficient rate of fluorescence X-rays for the calibration. Four metal targets that fulfill these requirements are used for the calibration: Zn, Mo, Ag, and Sn. The measure of the ionization produced in the silicon sensor by their K_α fluorescence line is used in the calibration. The energy of the K_α lines of the metal targets, together with the ionization that they generate in silicon is summarized in table 6.1. The metal targets are mounted on a target holder that can rotate allowing an automated exchange of the target in use. The module that is being calibrated is placed on a cooling plate where Peltier elements and the fluid from a chiller stabilize its temperature.

⁴See www.phywe.de.

Element	K_α line energy [eV]	Ionization in Silicon [eh pairs]
Zn	8627.4	2396.5
Mo	17426.8	4840.8
Ag	22076.6	6132.4
Sn	25157.7	6988.3

Table 6.1: Energy and ionization in silicon for the fluorescence lines of the elements used in the calibration [49, 50]. The values reported in the table correspond to the mean of the $K_{\alpha 1}$ and $K_{\alpha 2}$ lines of each element.

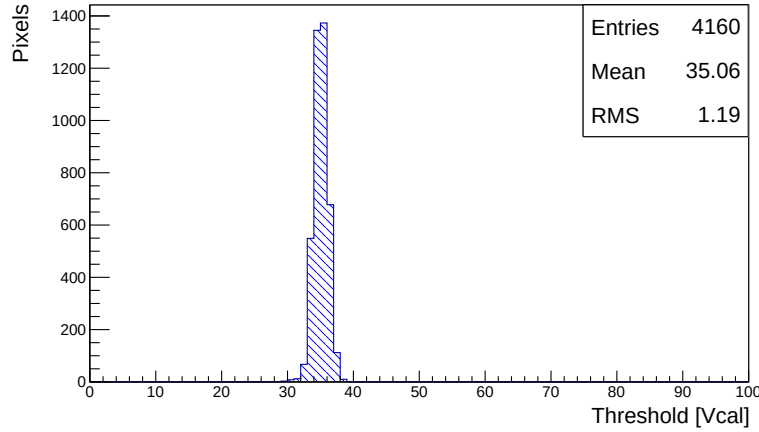


Figure 6.14: Threshold distribution of one ROC. The goal threshold was set to 35 Vcal.

6.5.2 Module preparation for the calibration

The modules must be prepared for the calibration in the same way as for the data taking in CMS. First, the analog part of the ROCs is set up. The working point of the preamplifier and shaper of each channel is fixed by tuning the current drawn by each ROC. Then the timing of the calibration signal is tuned in order to enable it to be used in the next configuration steps. The thresholds of the channels are set through DAC registers on the ROC that act on all the pixels and then trimmed on a pixel basis using the trim bits. The calibration signal is used to measure the thresholds at each step of the procedure and the value of its DAC register (Vcal) is used to express the threshold value. The threshold distribution of the pixels of one ROC is shown in figure 6.14. The goal threshold was set to be 35 Vcal. The DAC registers controlling the amplifiers between the analogue buffers in the double columns are then adjusted to ensure a good dynamic range within the analog to digital converter (ADC) range. Finally the response of each pixel to different injected pulse heights is measured and described using the equation

$$PH_{ADC} = p_3 \left[\text{erf} \left(\frac{PH_{Vcal} - p_0}{p_1} \right) + p_2 \right] \quad (6.2)$$

where PH_{ADC} is the pulse height measured by the ADC on the ROC, PH_{Vcal} is the injected pulse height in units of the Vcal DAC, and erf is the error function. An example of the fit is shown in figure 6.15. A finer scan is performed in the region where the fluorescence spectra are measured in order to improve the description of the pixel response. This final measure

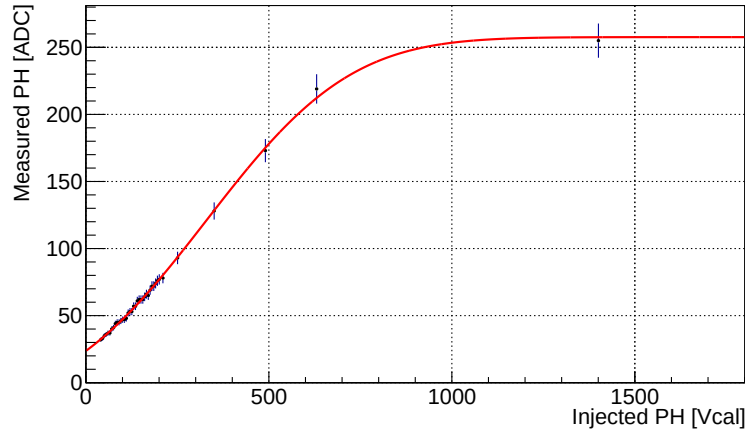


Figure 6.15: Fit of the pulse height calibration for one pixel.

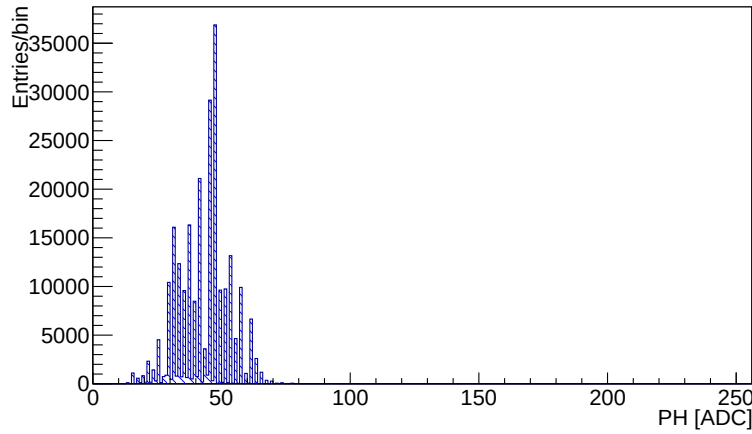


Figure 6.16: Spectrum of the Mo target as measured from the ADC.

allows all the pulse height measurements from the pixels in one ROC to be expressed using a common scale, namely the DAC of the calibration signal, Vcal. An example of a fluorescence spectrum as measured from the ROC's ADC is presented in figure 6.16. Only if the pixel wise calibration is applied is it possible to reconstruct the spectrum correctly. The spectrum obtained applying the calibration is shown in figure 6.17b.

6.5.3 Calibration procedure

The calibration procedure is rather simple. First, the fluorescence spectra of the four metal targets are measured. The module acquires data for 100 s for each target. The trigger is random, with a rate of 100 kHz. An example of the fluorescence spectra recorded by a ROC is shown in figure 6.17. The spectra of Mo, Ag, and Sn present two peaks. The peak at lower energies and the distribution of entries between the peaks is background caused by X-rays that scatter inside the box that contains the targets and the module. The peak at higher energies is the K_α line of the metal target. The background is not visible in the Zn

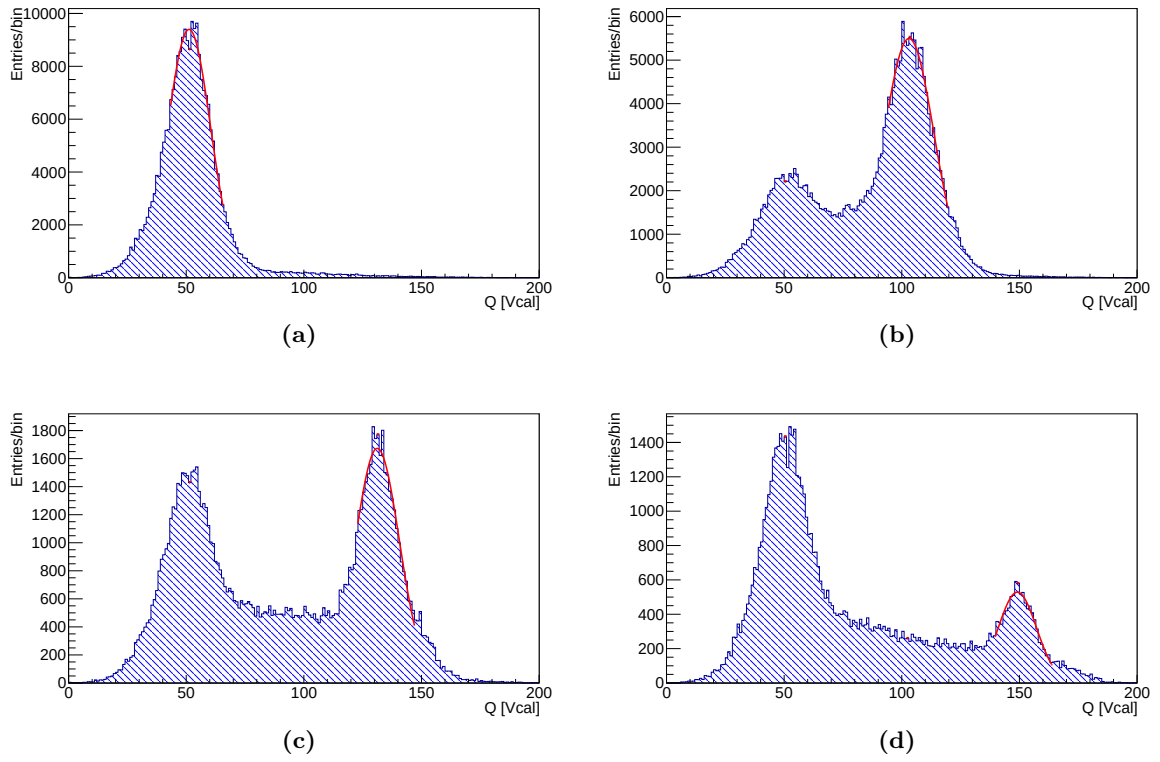


Figure 6.17: X-ray spectra used for the energy calibration. The metal targets are (a) Zn, (b) Mo, (c) Ag, and (d) Sn.

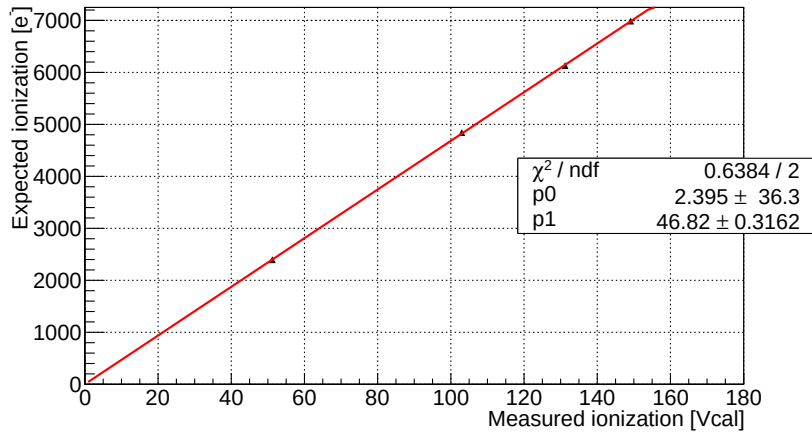


Figure 6.18: Calibration fit of one ROC.

spectrum since the rate of its K_α line is higher than the background rate. The contributions of other fluorescence lines to the measured spectra can be disregarded since their rates are much smaller compared to the K_α line. The peaks corresponding to the K_α lines of the targets are described using a Gaussian function as shown in figure 6.17. The fit interval has been chosen so that the description of the peak is least affected by the background. A combined fit to the background and fluorescence peak has been tested. Since only a negligible variation of the fitted peak position was observed at the expense of a more complex fitting procedure, no description of the background is used in this work. The mean value of the Gaussian defines the ionization measured by the ROC for photons with energy corresponding to the K_α line of the target. The expected ionization produced in Si by photons with the energies of the fluorescence lines of the different targets is then plotted against the measured ionization as shown in figure 6.18. The relation between expected and measured ionization is linear and can be described by

$$I_e = p_0 + p_1 \cdot I_{Vcal} \quad (6.3)$$

where I_e and I_{Vcal} are the expected and measured ionizations, respectively.

6.5.4 Rate effects

The stability of the measurements necessary for the calibration with respect to the trigger rate and X-ray hit rate has been tested using a single chip module. This kind of module contains one ROC and a sensor that is one sixteenth of a full sensor. No HDI or TBM is necessary for the operation of such an assembly. This provides a homogeneous rate of X-rays over the sensor. Figure 6.19 shows the measured ionization for the Mo line as a function of trigger rate. No trend is visible.

The ROCs of one module experience different rates of X-rays due to the components present on top of the sensor, namely the HDI with its passive components, the TBM and the cable. A hit map using the fluorescence spectrum of Mo is shown in figure 6.20. The module cable with its connector can be seen in the left part of the picture, the TBM surrounded by the bond pads can be seen in the center of the module. The passive components on the HDI appear as purple rectangles. A part of the conductor lines of the HDI can also be seen in the

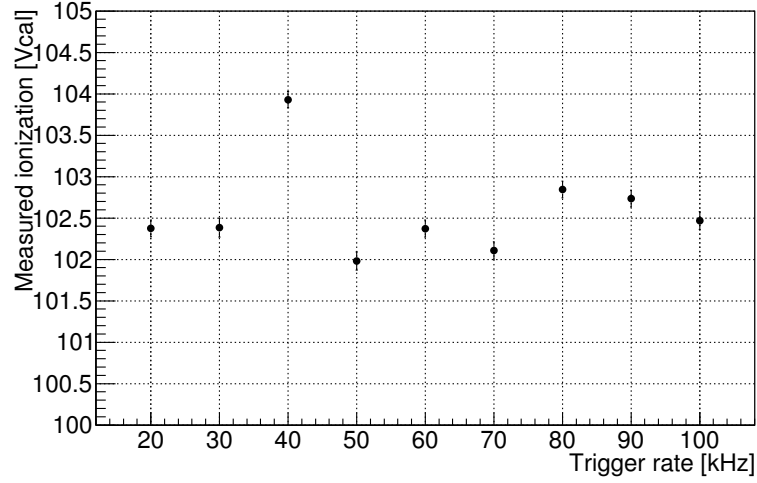


Figure 6.19: Measured ionization for the Mo target as a function of the trigger rate of the ROC. No trend is visible.

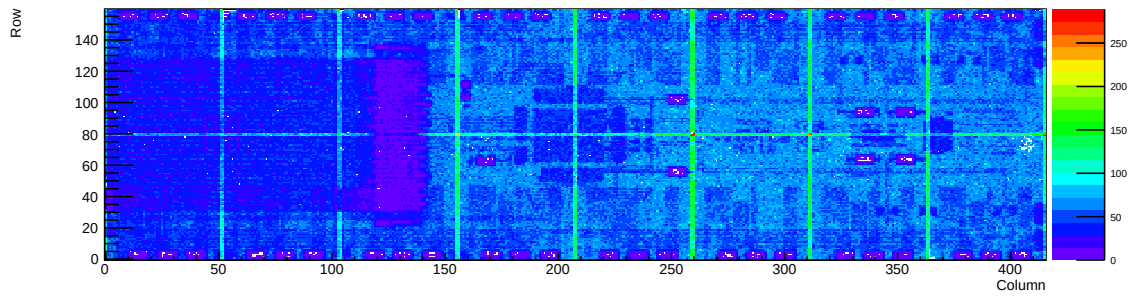


Figure 6.20: Hit map for a full module using X-ray illumination with the Mo target.

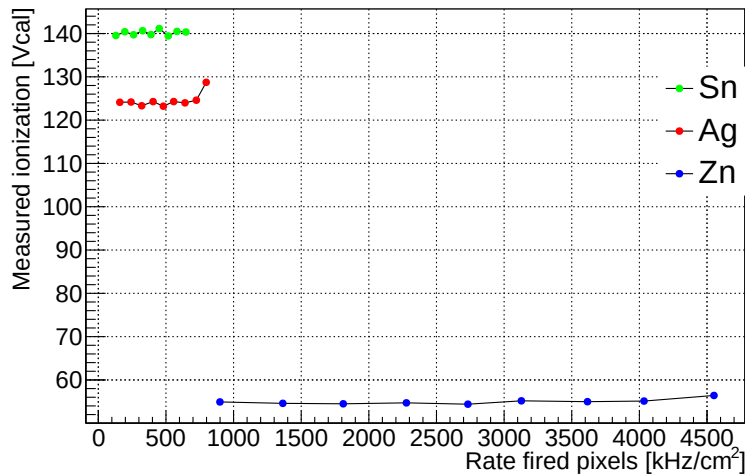


Figure 6.21: Measured ionization for different targets as function of the rate of X-ray impinging on the sensor. No trend is visible.

picture. The green areas that appear between the ROCs are the big pixels that have a size of two or four times the area of the other pixels. The overall illumination of the module with the fluorescence X-rays is homogeneous.

The value of the measured ionization for different metal targets as a function of the rate of impinging X-rays has been studied. The rate of X-rays achieved at the module position is influenced by many factors:

- The X-ray tube to target distance
- The target to module distance
- The energy of the fluorescence line
- The maximum energy of the X-rays from the tube
- The electron current in the X-ray tube

Keeping the geometry of the system and the acceleration voltage of the X-ray tube fixed, the tube current was varied in order to obtain different rates of fluorescence X-rays. Figure 6.21 shows the value of measured ionization for different metal targets as a function of the X-ray rate, no trend is visible. The Zn target achieves higher rates than the Ag and Sn because of the lower energy of its K_{α} line and its bigger area. The Zn target was not cut to its final dimension at the time of the test.

6.5.5 Stability measurement

The reproducibility of the fluorescence spectra measurements has been tested. The fluorescence spectra of the Mo target has been measured several times over a time of about 4.5 hours. Each measurement had a data acquisition time of 100s and was taken using a 100 kHz trigger frequency. The measured ionization from the Mo line is plotted for each ROC as a function of time in figure 6.22, and no trend is visible. The standard deviation of the

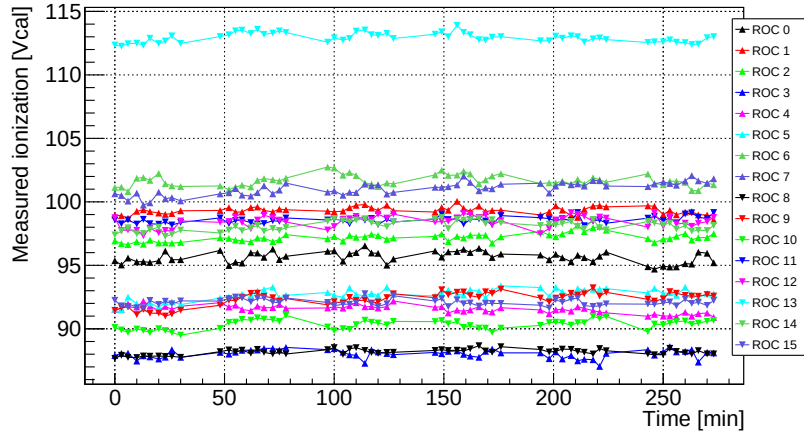


Figure 6.22: Stability of the Mo line measured using one module. The measurements from all the ROCs are plotted over a time of about 4.5 hours. No trend is visible.

distribution of the measured ionization has been measured for each ROC. Its average value corresponds to 0.4 Vcal. This value corresponds to the uncertainty on the measurements of ionization of a fluorescence line in the calibration setup.

6.5.6 Temperature effects

The impact of the module temperature on the spectra measurements has been studied. The modules will be used in the CMS pixel detector at a temperature of about -15°C , while the energy calibration is performed at room temperature in order to save cooling time and to keep the setup simple. Part of the measurements presented in this section required the use of a plastic box flushed with dry air positioned around the module in order to avoid condensation on the module. The plastic box is fairly transparent to the X-rays, the only effect it produces is a small reduction of the rate of X-rays impinging on the sensor. The energy calibration is not affected, as a comparison between figure 6.18 (for which the box was not necessary) and figure 6.26 (measured with the box in place) shows.

First, the effects caused by varying the module temperature on the fluorescence spectra has been studied. Figure 6.23 shows how the fluorescence spectrum of Mo is affected by changing the module temperature. The whole distribution gets shifted, without a change in shape. The behavior of the measured ionization of the Mo line as a function of temperature is shown for all the ROCs of a module in figure 6.24. The relation between temperature and measured ionization is linear. The temperature dependence of all the ROCs has been described using a linear function. The average slope is $-4.9 \pm 0.1 \text{ Vcal}/^{\circ}\text{C}$.

Repeating the steps listed in section 6.5.2 to adjust the ROC settings at each temperature, the temperature dependence shown in figure 6.24 is eliminated. Figure 6.25 illustrates this situation. Describing the temperature dependence for each ROC with a linear function an average slope of $0.015 \pm 0.007 \text{ Vcal}/^{\circ}\text{C}$ is obtained.

By adjusting the ROC settings for the temperature the energy calibration remains constant. Figure 6.26 shows the calibration obtained at -15°C for the same ROC shown in figure 6.18 where the ROC temperature is 17°C . The parameters of the calibration are equal within the errors. The calibration of the ROCs of one module has been repeated at different

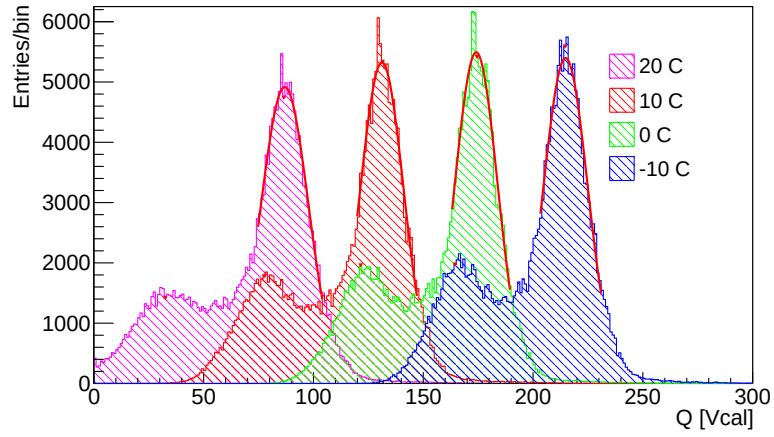


Figure 6.23: Spectrum of the Mo target measured at different module temperatures, the ROC settings being the ones obtained at 18 °C.

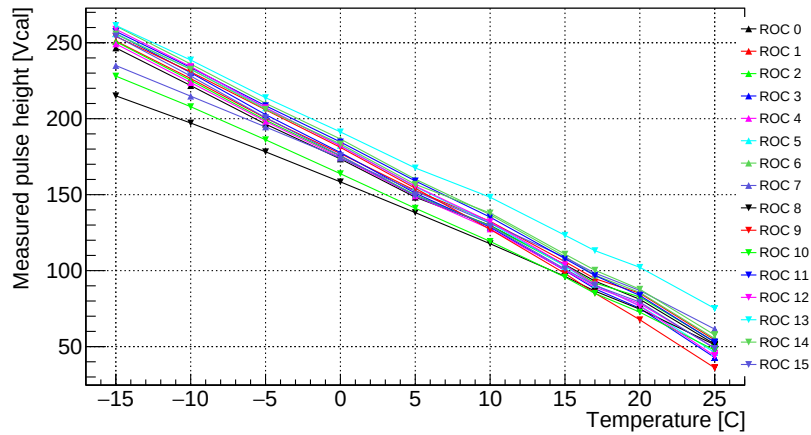


Figure 6.24: Measured ionization of the Mo target as a function of the module temperature. The ROC settings are the ones obtained at 18 °C.

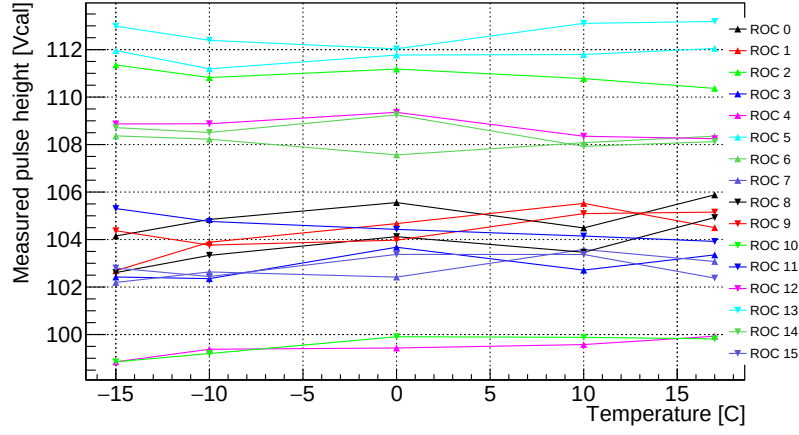


Figure 6.25: Measured ionization of the Mo target as a function of the module temperature. The ROC settings are adjusted at each temperature.

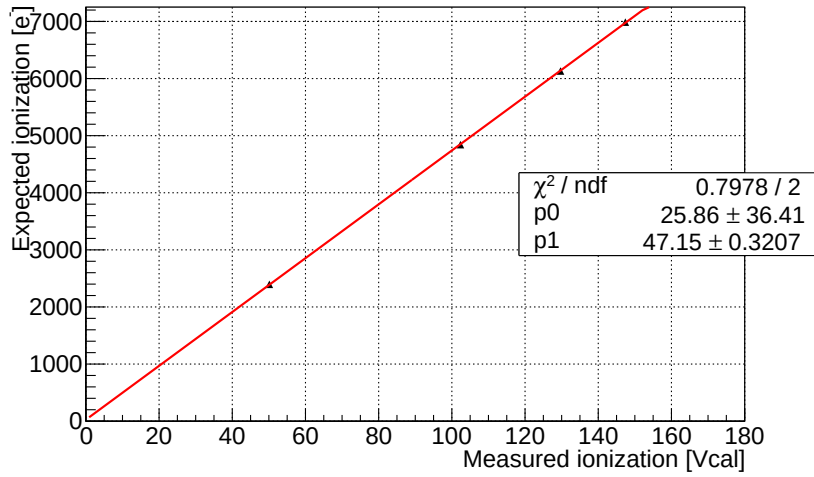


Figure 6.26: Calibration fit of one ROC at -15°C . The ROC is the same used for figure 6.18, where the temperature was set to 17°C . The parameters obtained at 17°C are $p_0 = 2 \pm 36 e^-$ and $p_1 = 46.8 \pm 0.3 e^- / \text{Vcal}$. The fit parameters are not influenced by temperature.

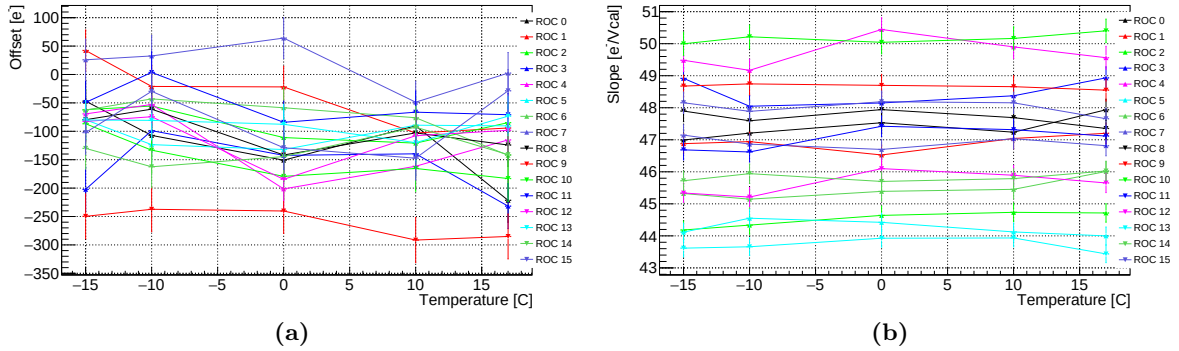


Figure 6.27: Offset (a) and slope (b) of the calibration fit for the ROCs of a module as a function of the module temperature. No trend is visible.

temperatures adjusting the ROC settings for each temperature. The offset and slope of the calibration fits are shown in figure 6.27. No trend is visible.

The energy calibration of the ROCs in a module is constant with temperature provided that the ROC settings are adjusted to the module temperature. Therefore the calibration can be executed close to room temperature and used at the operating temperature of the modules inside the CMS pixel detector.

In view of the module production, the calibration procedure has been fully automated. The time required to calibrate a module is ≈ 30 min.

6.6 High rate test

In order to test the correct functioning of the buffers in the ROC periphery, the efficiency of each double column is tested using a beam of X-rays. The module under test is held in the beam of X-rays produced by the tube as shown in figure 6.28. The ROCs' buffers are filled by the X-rays hits and at the same time several test pulses are sent to each pixel. The double column efficiency is defined as the ratio of the sent and measured test pulses.

In order to characterize the setup, the rate of X-rays at the position of the module during the test has been measured as a function of the current in the X-ray tube. For the measurements presented in this section the tube voltage was fixed to 35 kV. The rate has been estimated using two methods. The photo current induced in the sensor by the X-ray beam gives a measure of the rate of X-rays given the knowledge of the X-ray spectra. The rate of fired pixels measured using a module also gives an estimation of the rate of X-rays.

The rate measurements have been carried out using a single chip module. The absence of a HDI on this kind of module simplifies the measurement since the rate is uniform over the sensor surface.

Figure 6.29 shows the photo current drawn by the sensor of a single chip module as a function of the current in the X-ray tube. The relation between the two currents is linear. To proceed with the rate estimation, the knowledge of the spectrum of X-rays interacting with the pixel sensor is required. The X-ray spectrum produced by the electrons impinging on the W anode of the X-ray tube has been simulated using the GEANT4⁵ software. An accurate

⁵<http://geant4.cern.ch/>

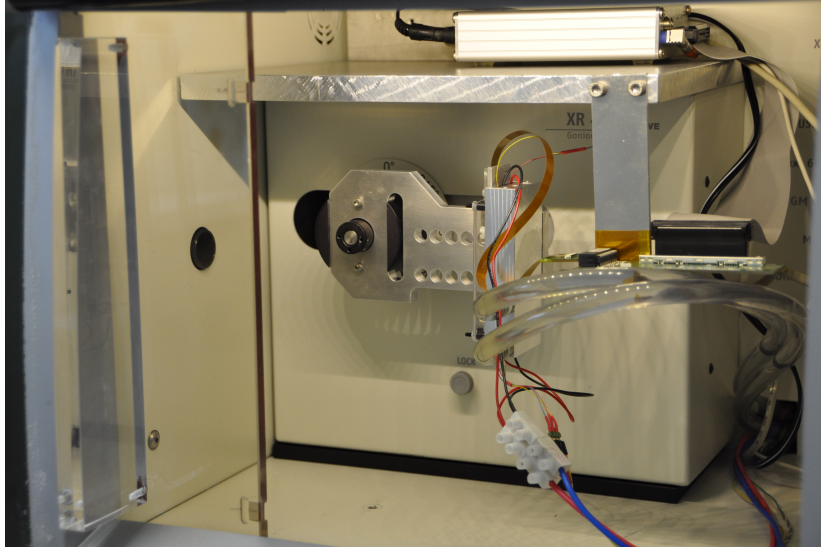


Figure 6.28: Module positioned in the direct X-ray beam in the calibration setup.

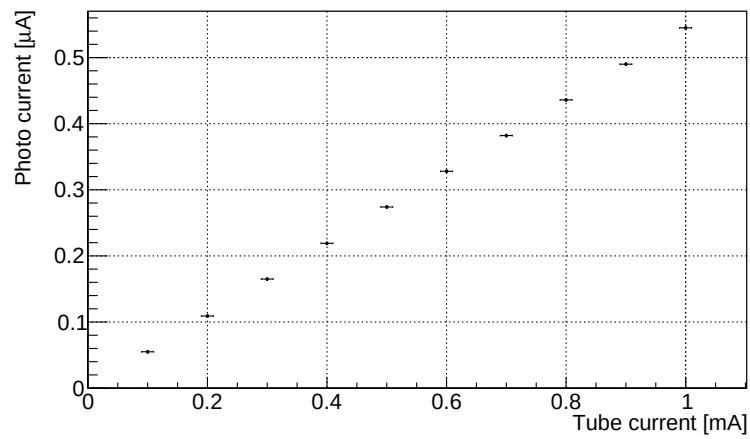


Figure 6.29: Photo current of a pixel sensor as a function of the X-ray tube current.

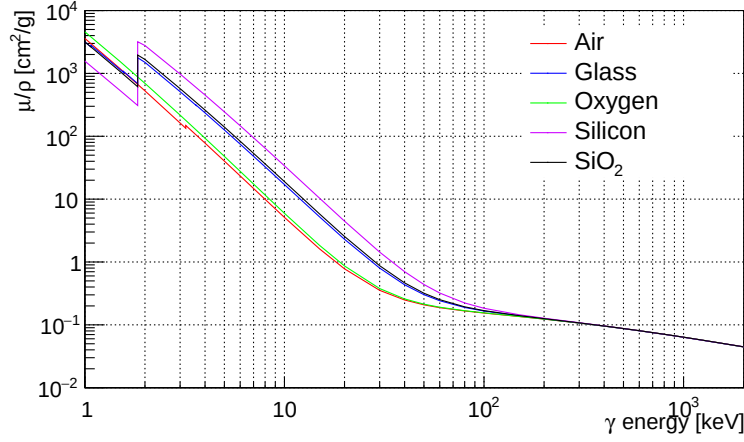


Figure 6.30: Absorption coefficients for the materials used in the determination of the X-ray spectra [52, 28].

Material	Thickness [cm]
Glass	0.035
Air	20
SiO ₂	$5 \cdot 10^{-5}$
Si	0.0285

Table 6.2: Thickness of the materials used in the determination of the X-ray spectra.

description of the X-ray spectra can be achieved by using the right simulation packages as shown in [51]. The setup of the simulation consists of a beam of electrons with a kinetic energy of 35 keV that is directed on to a W target. The energy spectrum of the photons produced in the process is shown in figure 6.31. The absorption of the X-rays in the glass of the X-ray tube, in air, in silicon dioxide and in the silicon sensor is calculated using the absorption coefficients shown in figure 6.30. Table 6.2 lists the thicknesses of material considered in the spectra estimation. Figure 6.31 shows the spectrum of X-rays transmitted through the glass of the X-ray tube, and the one of X-rays that interact in the pixel sensor. With the knowledge of the spectrum of X-rays interacting in the pixel detector, the photo current drawn by the sensor can be converted into the rate of X-rays impinging on the detector.

The estimation of the X-ray rate counting the fired pixels is a straightforward measurement. The threshold of the module was set to $1750 e^-$, corresponding to a photon energy of 6.3 keV. The effect of the module threshold on the measurement is therefore negligible. The rate measured by the module has to be corrected for the module efficiency.

Figure 6.32 shows the rate measurements done exploiting the two methods explained above. The line representing the rate of X-rays measured through the fired pixels is an extrapolation from the fit of different measurements taken with the tube current set at 0.1 and 0.2 mA. The choice of this region is dictated by the difficulty of measuring the module efficiency at rates higher than 350 MHz/cm^2 . The values of the rate estimated with these different methods are in good agreement.

The measurement of double column efficiency as a function of rate is shown in figures 6.33 and 6.34. The data shown represent two ROCs that are part of the same module. The

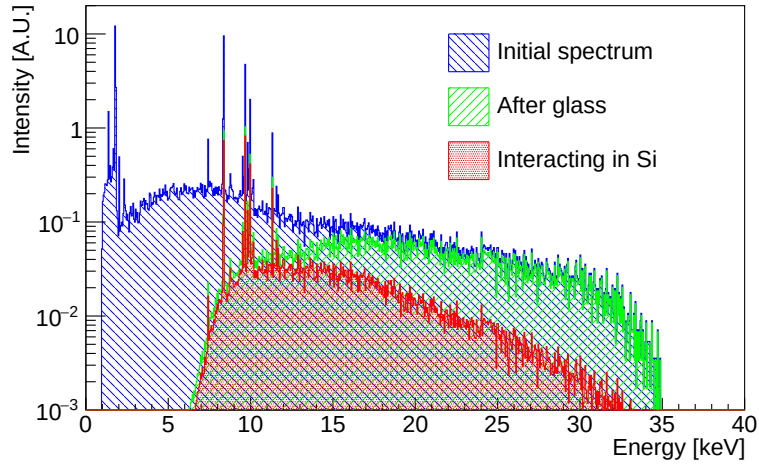


Figure 6.31: Simulated spectrum of X-rays generated by 35 keV electrons impinging on a W target (blue). Spectrum of X-rays transmitted through the glass of the X-ray tube (green). Spectrum of X-rays interacting in the silicon sensor (red).

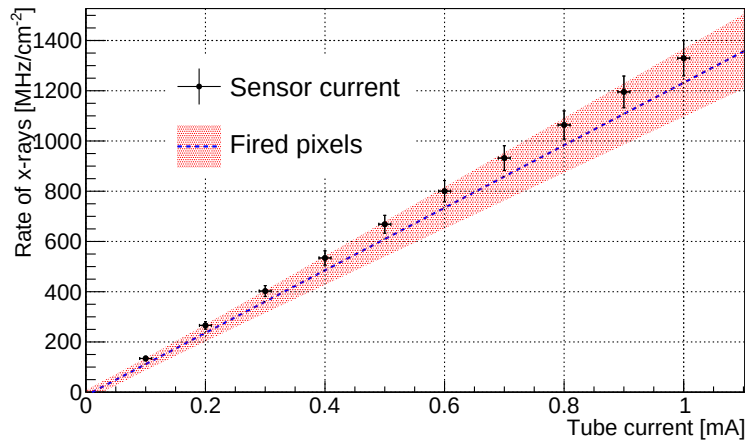


Figure 6.32: Measurement of the rate of X-rays impinging on a single chip module as a function of the current of the X-ray tube. The rate has been measured using the sensor photo current (dots) and the rate of fired pixels (dotted line).

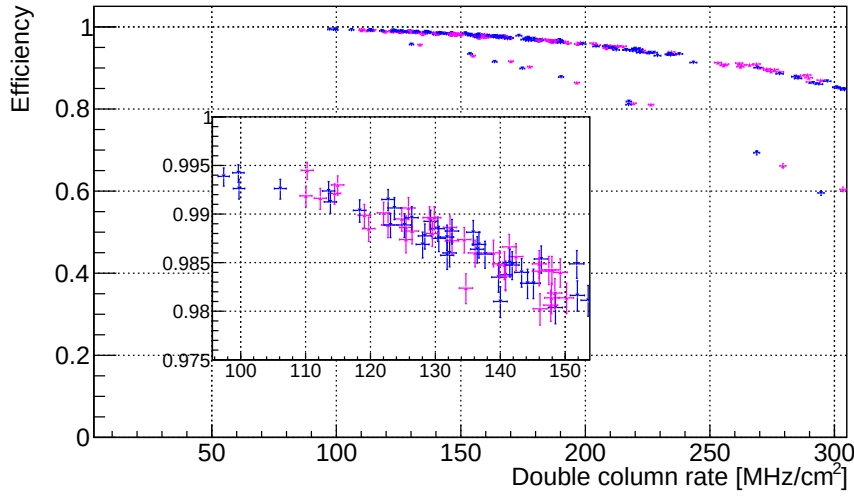


Figure 6.33: Double column efficiency as a function of the X-ray rate for two ROCs (represented in different colors). The series of points lying at lower efficiencies belong to the double columns with bigger pixels. The insert shows a zoom of the plot around 120 MHz/cm², that is the highest rate expected for this type of module.

efficiency has been measured by illuminating the module with different rates of X-rays. The presence of the HDI on top of the pixel sensor lowers the rate of X-rays impinging on the detector and makes the rate non-uniform on the double columns (see figure 6.35).

From figure 6.33 it is possible to see how the efficiency of the double columns follows the same behavior in the two ROCs. The maximum rate of particles foreseen for this kind of module in the pixel detector is achieved in the second pixel layer and is 120 MHz/cm², the efficiency at this rate is 99%. There is a group of double columns that exhibit a lower efficiency compared to the rest. These are the double columns with the big pixels. Given the bigger area of these double columns they have to process more hits than the others for the same rate of impinging X-rays. Expressing the rate in pixels per event per double column, the behavior of the efficiency as a function of rate becomes the same for all the double columns, as shown in figure 6.34.

The high rate achieved in the direct X-ray beam allows the measurement of detailed hit map of the modules in a short amount of time. With this information, missing bump bonds can be identified. Figure 6.35 shows the hit map of a module measured in the direct beam. The features of the HDI with its active and passive components appear as blue and violet areas. The big pixels are brighter than their neighbors, and the missing bump bonds appears as white dots. A group of missing bump bonds can be seen on the right part of the picture.

The test stands and calibration setups necessary for the production of the module for the pixel phase I upgrade of CMS at the Hamburg University have been prepared and characterized. The module production is ongoing. The modules assigned to the Hamburg production center should be completed by the end of February 2016. At the time of writing this thesis, 47 modules have been produced. Of the produced modules, 40 qualify for the installation in the upgraded pixel detector.

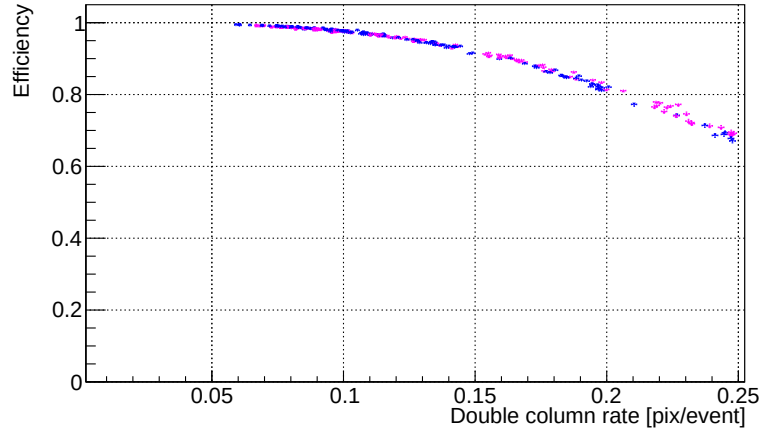


Figure 6.34: Double column efficiency as a function of the X-ray rate for two ROCs (represented in different colors). Once the rate is expressed in pixels per event per double column, big and regular pixels show the same behavior.

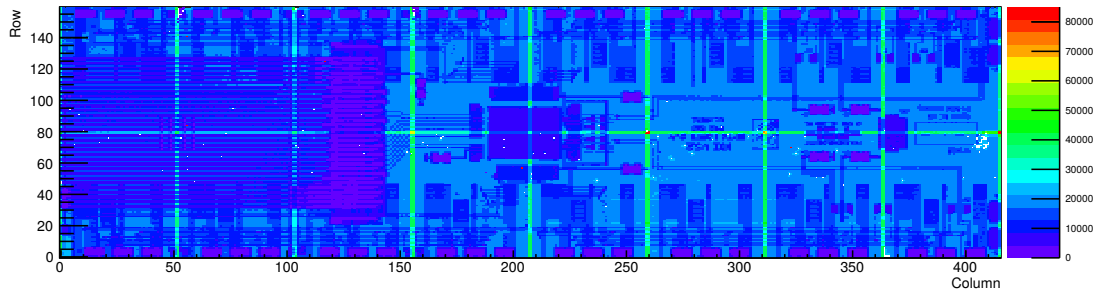


Figure 6.35: Hit map of a module in the direct beam. A few missing bump bonds can be seen as white dots.

Chapter 7

Thin planar silicon sensors for the phase II pixel upgrade

The high luminosity upgrade of the LHC will require the installation of a pixel detector in CMS whose innermost layer can withstand fluences as high as $2 \cdot 10^{16} \text{ cm}^{-2}$. The planar silicon sensor technology is well established in the tracking and vertexing applications but was never employed in such a challenging radiation environment. Several groups studied the radiation hardness of planar silicon. A partial summary of the obtained results is shown in figure 7.1 that illustrates the evolution of the signal produced in different sensors as a function of the accumulated fluence. The sensors with a thickness of $300 \mu\text{m}$ show a rapid degradation of the signal with fluence, while thinner devices do not show such a signal decrease.

This chapter illustrates the studies accomplished on highly irradiated thin silicon sensors obtained by epitaxial growth. The aim of the study is to assess which are the operational limits of thin silicon sensors produced through the planar process. Pad diodes and strip sensors have been characterized in the study. The pad diodes are used to determine the evolution with the accumulated fluence of the dark current, sensor capacitance and charge collection efficiency. The strip sensors measurements are focused on the determination of the amount of collected charge and its distribution for different accumulated fluences. The epitaxial growth technique allows to produce thin sensors with a good mechanical stability due to the presence of the growth substrate. In addition, the different doping concentration of the sensor and the growth substrate provides a well defined active thickness. The first part of the chapter is dedicated to measurements performed on pad diodes, while the second part illustrates the results from a beam test of strip sensors.

7.1 Diode measurements

7.1.1 Sensors and irradiation

The diodes used in this study have been produced by Hamamatsu¹ on oxygen rich epitaxial silicon. Both p- and n-bulk diodes have been studied. The diodes have an active area of $0.5 \times 0.5 \text{ cm}^2$. The epitaxial silicon is grown on a highly doped substrate with orientation $\langle 100 \rangle$ and a thickness of $220 \mu\text{m}$. The substrate resistivity is $18 \cdot 10^{-3} \Omega\text{cm}$ [54]. The sensors are produced on a $100 \mu\text{m}$ thick epitaxial layer. The resistivity of the epitaxial layer has

¹<http://www.hamamatsu.com/us/en/index.html>

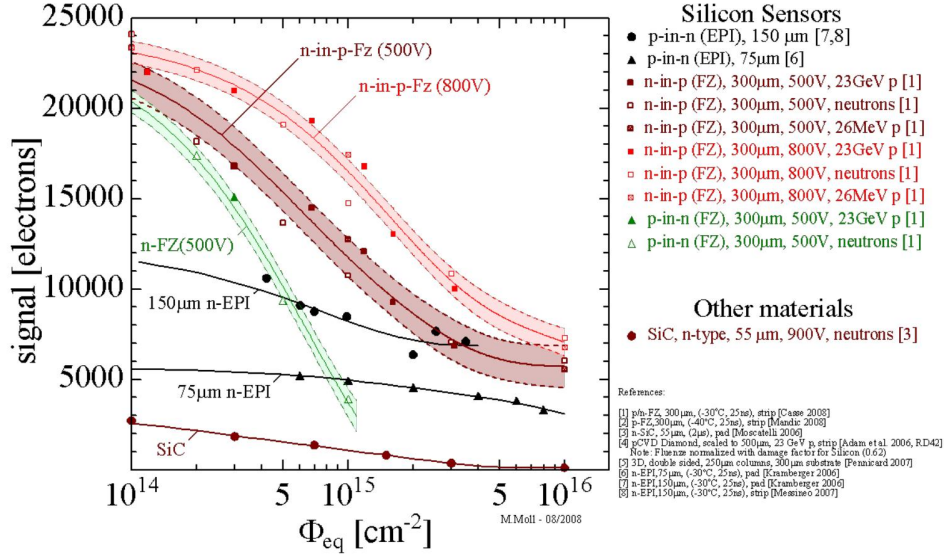


Figure 7.1: Signal produced in different planar sensors by minimum ionizing particles as a function of fluence. The signal produced in 300 μm thick sensors (red and green curves) degrades rapidly with fluence, thinner sensors show a less severe degradation of the signal [53].

been estimated using the CV characteristic of the diodes and has been found to be between 1 and $1.5 \cdot 10^3 \Omega\text{cm}$ for both the p- and n-bulk sensors. The difference in the resistivity of the substrate and epitaxial layer is assumed to avoid any influence of the substrate in the measurements of diode characteristics. In order to define the diode volume, a current collection ring surrounds the diode junction. The current collection ring is kept at the same potential as the junction electrode during the measurements of the IV and CV characteristics. To insulate the diode junction from the current collection ring, p-spray isolation has been used in the p-bulk diodes.

The diodes have been irradiated at the CERN PS² with 24 GeV/c protons (hardness factor $k = 0.62$). The irradiation steps were $\Phi_{eq} = 1.5 \cdot 10^{15}, 3 \cdot 10^{15}$, and $1.3 \cdot 10^{16} \text{ cm}^{-2}$. The irradiation was performed without cooling and bias. The precise determination of the annealing status of the sensors is not straightforward. The radiation damage created at the beginning of the irradiation anneals for the rest of the irradiation time, while the damage created in the last part of the irradiation experiences a short annealing time. The annealing status of the sensors after irradiation is estimated to correspond to approximately 15 days at 20°C for the highest fluence.

7.1.2 IV and CV characteristics

The IV characteristic of the diodes has been measured before and after irradiation. Figure 7.2 shows the IV characteristic of the diodes with p-bulk. The measurements have been performed at 20°C before irradiation and at 0°C after irradiation. The IV characteristics shown in this section have been scaled to a sensor temperature of 20°C. Figure 7.3 shows the IV characteristics of the diodes with n-bulk.

The IV characteristics of both p- and n-bulk diodes before irradiation does not show a

²<https://irradiation.web.cern.ch/irradiation/irrad1.htm>

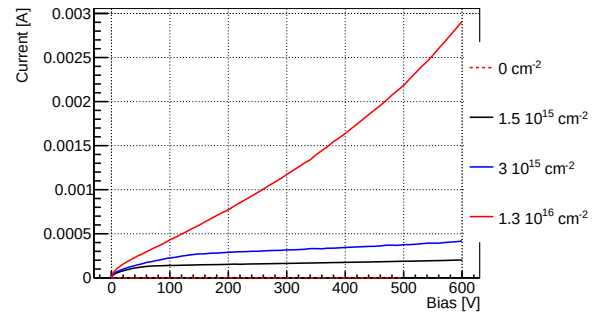
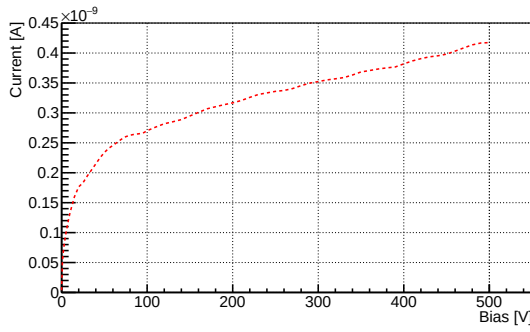


Figure 7.2: IV characteristic of a sample p-bulk sensor before irradiation (left). IV characteristics of the p-bulk sensors after irradiation (right).

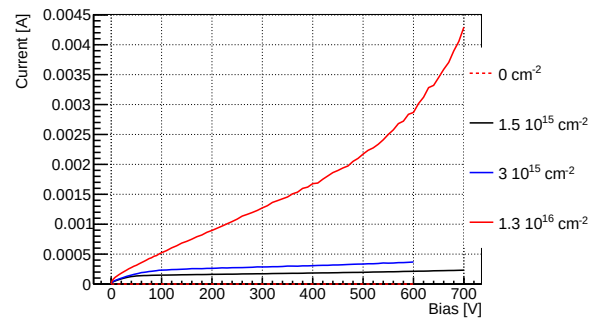
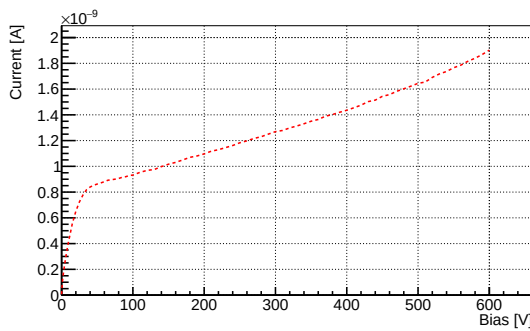


Figure 7.3: IV characteristic of a sample n-bulk sensor before irradiation (left). IV characteristics of the n-bulk sensors after irradiation (right).

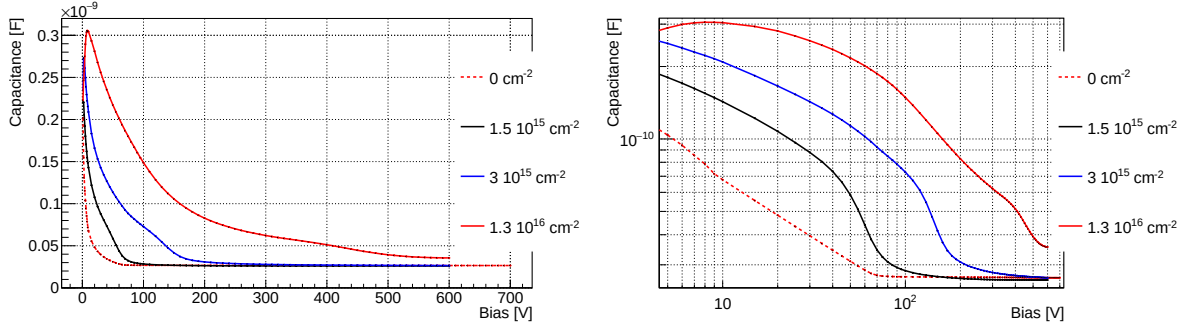


Figure 7.4: CV characteristic of the p-bulk sensors. The curves are plotted in linear (left) and double logarithmic scale (right) to better show their features.

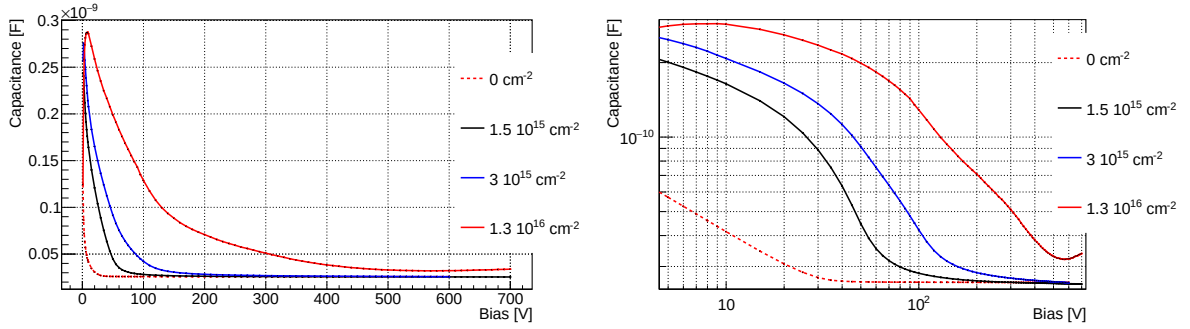


Figure 7.5: CV characteristic of the n-bulk sensors. The curves are plotted in linear (left) and double logarithmic scale (right) to better show their features.

saturation of the current after the full depletion of the sensor is achieved. The full depletion voltage has been estimated to be around 70 V for p-bulk diodes and 30 V for n-bulk diodes. This behavior can be explained by trap assisted tunneling [55] contributing to the generation current.

The IV characteristics after irradiation show similar features for p- and n-bulk diodes. The values of dark current are similar. The shape of the IV characteristics show a “soft breakdown” for the highest irradiation step.

The CV characteristic of the diodes has been measured in the same conditions as the IV characteristic. The CV characteristic has been measured using a frequency of 1 kHz. The capacitance values have been estimated using the hypothesis of the sensor being represented by a parallel RC circuit. The CV characteristics of p-bulk diodes are shown in figure 7.4, while the ones of n-bulk diodes are shown in figure 7.5.

For both sensor types the depletion voltage (see section 3.1.3) increases with the accumulated fluence. The shape of the CV characteristics of the sensors irradiated to $1.3 \cdot 10^{16} \text{ cm}^{-2}$ is different than the others. A peak appears at bias values close to 20 V and the capacitance never reaches the value of the non-irradiated devices. The latter effect can be attributed to the influence of the dark current on the CV measurement. The rapid increase of the dark current with the applied bias voltage causes the measured value of capacitance to appear larger. The shape of the CV characteristic at such high fluence forbids a meaningful determination

Annealing step	Annealing time at 20°C
10 min at 60°C	3.3 days
80 min at 60°C	27 days
30 min at 80°C	4.4 months
120 min at 80°C	17 months

Table 7.1: Correspondence between annealing steps and accumulated annealing time at 20°C. The conversion is done using the formula for the annealing of dark current and the parameters from [31].

of the depletion voltage.

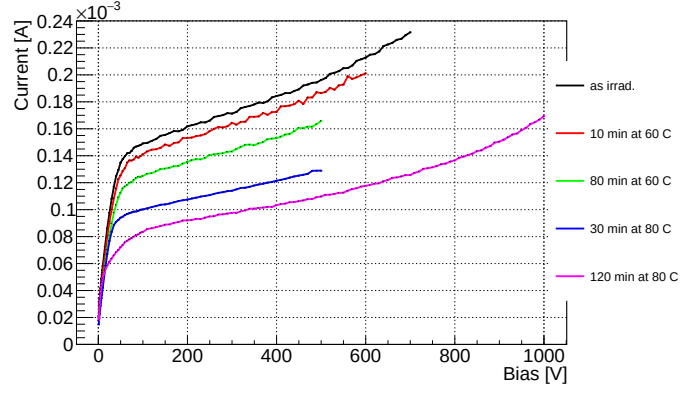
The effects of the annealing on the IV and CV characteristics are shown in figure 7.6 and 7.7 for two n-bulk diodes that have accumulated a fluence of $1.5 \cdot 10^{15} \text{ cm}^{-2}$ and $3 \cdot 10^{15} \text{ cm}^{-2}$, respectively. The conversion of the accumulated annealing time to annealing time at 20°C is shown in table 7.1, where the conversion is made using the formula for the annealing of the dark current, with the parameters taken from [31]. For both diodes the current decreases with annealing time. The CV characteristics are little affected by an annealing time of 10 and 80 minutes at 60°C. This effect can be explained by the fact that the annealing performed in the laboratory is comparable with the one already received by the sensors during irradiation. For an accumulated annealing time of 30 minutes at 80°C the effect of beneficial annealing can be seen for both the sensors. Finally after 120 minutes at 80°C the curves are dominated by the reverse annealing and the depletion voltage is larger than the one presented just after irradiation.

7.1.3 Charge collection efficiency

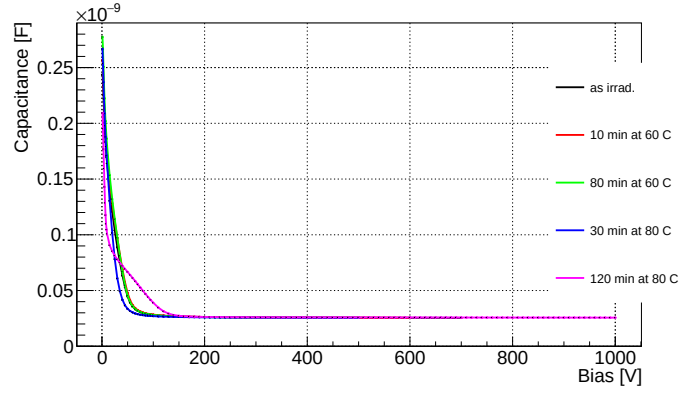
The charge collection efficiency (CCE) of the diodes has been measured by producing electron-hole pairs in the sensors with an infrared laser with a wavelength of 1060 nm. The absorption length of infrared light in silicon is much larger than the sensor thickness, thus the ionization is created uniformly along the sensor thickness. The signal induced in the sensor is amplified and subsequently digitized by an oscilloscope. The waveforms are averaged 512 times in the oscilloscope to reduce the effects of noise. More information about the setup can be found in [56]. The waveforms of a p-bulk diode before and after irradiation are shown in figure 7.8.

The waveforms are integrated over a 30 ns time interval, starting 3 ns before the peak position. The baseline is integrated over the 30 ns preceding the time interval where the peak is integrated. The integral of the baseline is subtracted from the integral of the peak. The CCE is obtained by normalizing the peak integral after baseline subtraction to the integrated signal of a non-irradiated sensor. The normalization is determined by applying the procedure described above to a non-irradiated sensor. The mean value of the integral of the pulses recorded with bias between the depletion voltage and 600 V is used to normalize the data.

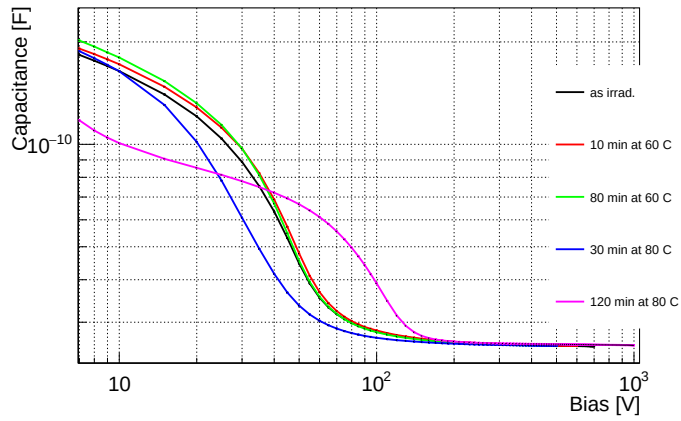
The CCE of p- and n-bulk diodes is shown in figure 7.9 and 7.10. The plots show measurements performed at 0 and -20°C . The CCE of p-bulk sensors exceeds unity at high bias voltages for diodes irradiated to $3 \cdot 10^{15}$ and $1.3 \cdot 10^{16} \text{ cm}^{-2}$. This effect is a manifestation of charge multiplication happening in the sensor. The basic mechanism of the process is multiplication of charge carriers due to impact ionization in a high field region. This effect has already been observed for similar devices and irradiations to the ones described in this section [56]. The charge multiplication effect that enhances the values of CCE is also present



(a)

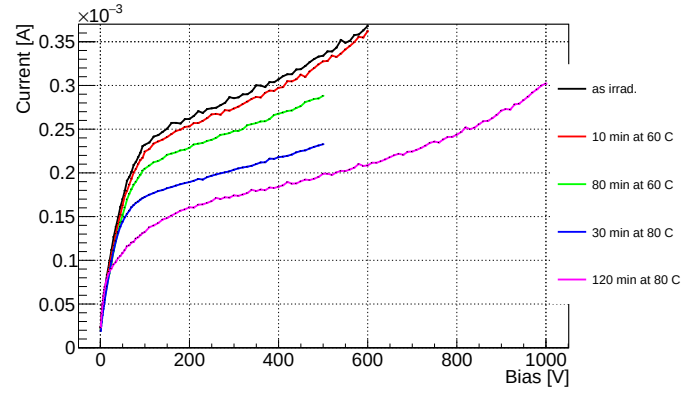


(b)

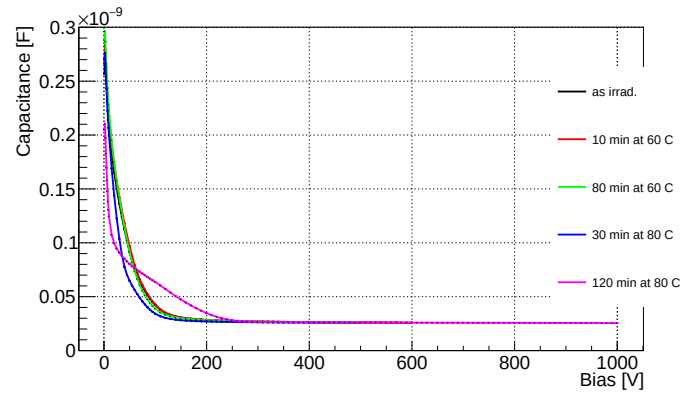


(c)

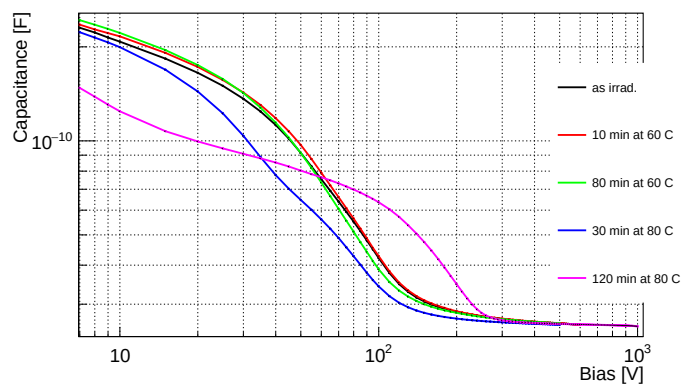
Figure 7.6: IV (a) and CV (b-c) characteristics of a n-bulk diode irradiated to $\Phi_{eq} = 1.5 \cdot 10^{15} \text{ cm}^{-2}$ for different accumulated annealing times.



(a)



(b)



(c)

Figure 7.7: IV (a) and CV (b-c) characteristics of a n-bulk diode irradiated to $\Phi_{eq} = 3 \cdot 10^{15} \text{ cm}^{-2}$ for different accumulated annealing times.

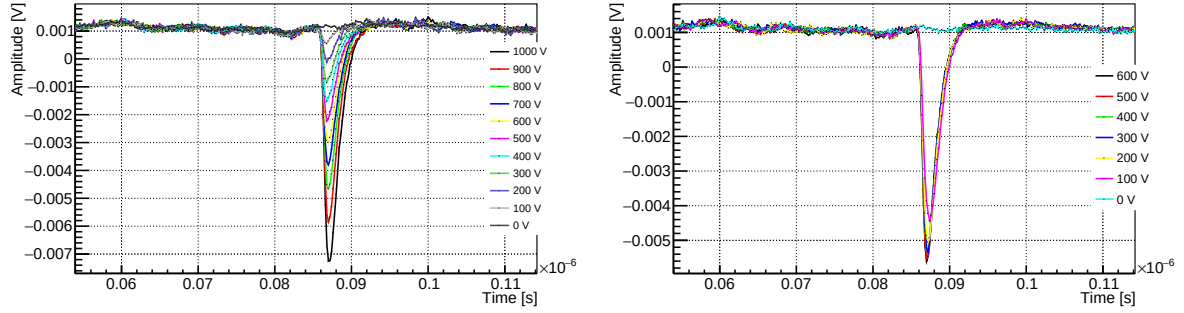


Figure 7.8: Waveforms obtained in the CCE measurement of a p-bulk diode. The waveforms are measured for a diode irradiated to $\Phi_{eq} = 1.3 \cdot 10^{16} \text{ cm}^{-2}$ (left) and a non-irradiated diode (right).

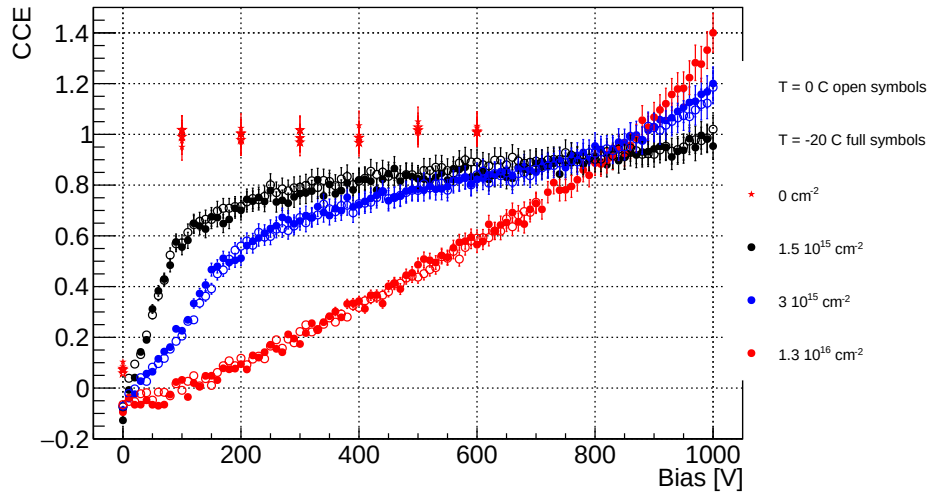


Figure 7.9: Charge collection efficiency of p-bulk diodes before (stars) and after irradiation (circles). The open symbols represent measurements performed with a sensor temperature of 0°C , the full symbols refer to a temperature of -20°C .

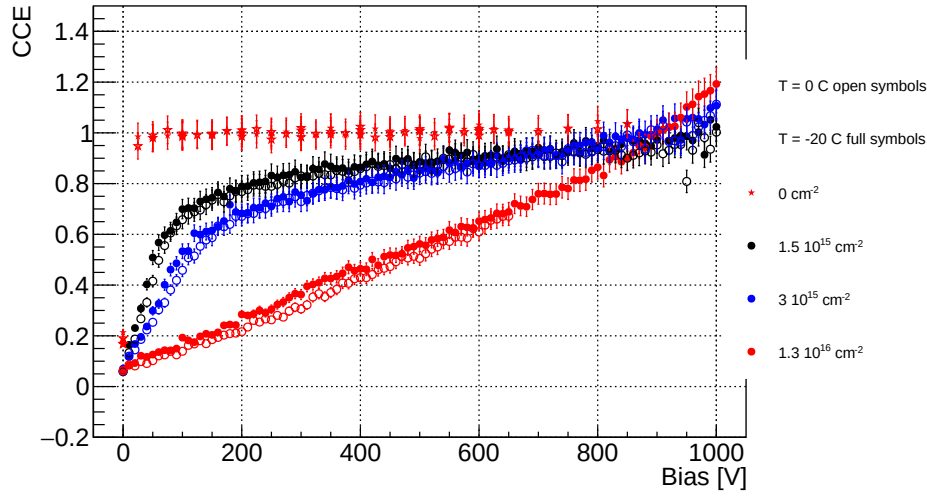


Figure 7.10: Charge collection efficiency of n-bulk diodes before (stars) and after irradiation (circles). The open symbols represent measurements performed with a sensor temperature of 0°C , the full symbols refer to a temperature of -20°C .

in the dark current. This can explain the “soft breakdown” of the IV characteristic shown in figure 7.2. The CCE of the sensors irradiated to 1.5 and $3 \cdot 10^{15} \text{ cm}^{-2}$ show a kink when the full depletion voltage is reached. The position of the kink in the CCE curves corresponds to the one in the CV characteristics shown in figure 7.4. The CCE of the sensor irradiated to $1.3 \cdot 10^{16} \text{ cm}^{-2}$ does not show such a kink and does not saturate.

Similar conclusions can be drawn for the CCE of the n-bulk sensors. However, the magnitude of the CCE at 1000 V bias is not as big as for the p-bulk sensors. This can be explained by the fact that holes (collected in the n-bulk sensors) have a lower probability than electrons to produce impact ionization [57].

The effects of annealing on the CCE characteristics of two n-bulk diodes irradiated to 1.5 and $3 \cdot 10^{15} \text{ cm}^{-2}$ are shown in figure 7.11 and 7.12. The CCE of both sensors is hardly affected by an accumulated annealing time of 30 minutes at 80°C . For an accumulated annealing time of 120 minutes at 80°C the CCE of the sensors is affected in a similar way as the CV curves presented in figure 7.6 and 7.7. It is not possible to draw conclusions on the stability of charge multiplication effects after long annealing times by studying the effects of annealing on the CCE of the diodes presented in figure 7.11 and 7.12.

The characterization of diodes shows the onset of charge multiplication at a fluence of $3 \cdot 10^{15} \text{ cm}^{-2}$ for bias voltages close to 1000 V. The shape of the CV characteristics of diodes irradiated to $1.3 \cdot 10^{16} \text{ cm}^{-2}$ does not allow a determination of the diode’s depletion voltage. The CCE of such highly irradiated sensors does not present the typical saturation usually present when the applied bias exceeds the sensor’s depletion voltage.

7.2 Beam test at the DESY II facility

To study the properties of highly irradiated thin sensors, a series of beam test measurements has been carried out using strip detectors. The choice to use strip sensors to investigate

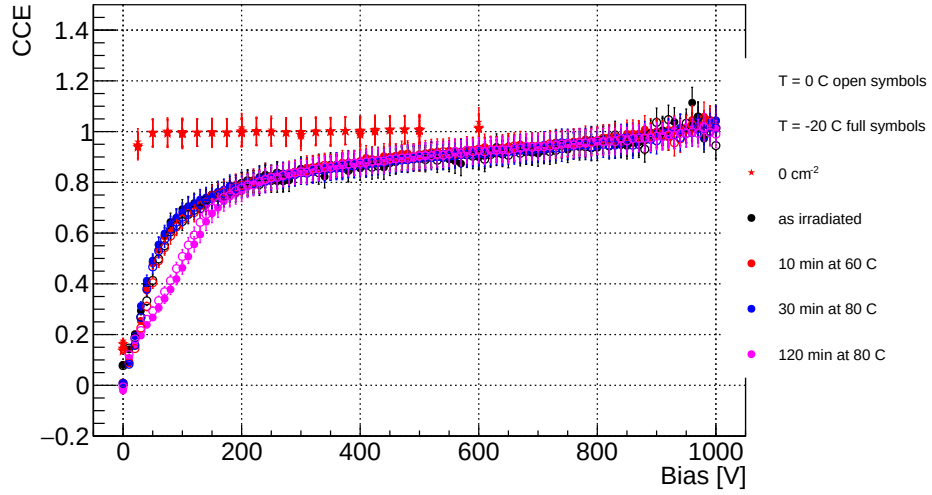


Figure 7.11: CCE of a n-bulk diode irradiated to $\Phi_{eq} = 1.5 \cdot 10^{15} \text{ cm}^{-2}$ measured at different annealing times.

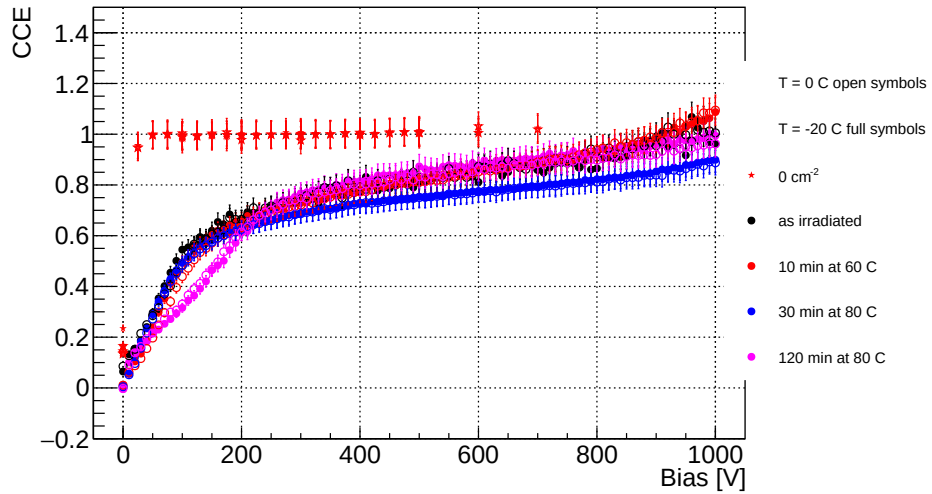


Figure 7.12: CCE of a n-bulk diode irradiated to $\Phi_{eq} = 3 \cdot 10^{15} \text{ cm}^{-2}$ measured at different annealing times.

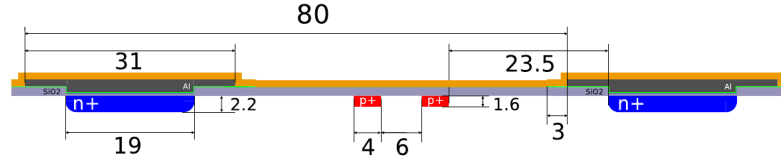


Figure 7.13: Cross section of a p-bulk strip sensor with p-stop isolation. Two strips are represented. The distances are in μm . From [60].

materials and fluences for pixel detector applications is motivated by the technology used to connect the pixel sensors to the readout electronics. The bump bonding procedure used in hybrid pixel detectors requires the use of thermal treatments for both the sensor and the readout electronics with temperatures in the order of 200°C . This forbids the interconnection of readout electronics and sensors after irradiation since the sensor would experience an annealing equivalent to a rather long time at room temperature. By bump-bonding the sensors and electronics before irradiation, the readout electronics would receive a high radiation dose and therefore its operation would be modified or compromised. At the time of the irradiation there was no readout chip thought to be able to sustain the dose accumulated during the irradiation necessary to achieve a fluence of $\approx 10^{16} \text{ cm}^{-2}$ on the sensor. The interconnection of strip sensors to the readout electronics does not involve thermal treatments, leaving the annealing status of the sensor unchanged. This allows the irradiation of sensors prior to their connection to the readout electronics.

Strip sensors present higher noise than hybrid pixel sensors. The typical noise level of hybrid pixel detectors is about 100 e^- , while for strip sensors the noise is about 800 e^- before irradiation. The difference is mainly due to the bigger area of the strips that imply higher leakage current and capacitance per channel with respect to pixel detectors. The noise of the sensors increase with irradiation. To improve the separation of the noise and signals induced by particles, the tracking information provided from a beam telescope is used.

Another difference between strip and pixel sensors is the configuration of their electric and weighting³ fields. This difference will require confirmation of the results obtained with the strip sensors using pixel sensors.

7.2.1 Sensors and irradiations

The strip sensors used in the test beam are produced on the same $100 \mu\text{m}$ thick epitaxial silicon used for the diodes. Both p- and n-bulk sensors have been used in this study. The tested p-bulk sensors implemented both p-spray and p-stop isolation. A section of a p-bulk strip sensor with p-stop isolation is shown in figure 7.13. The strip pitch is $80 \mu\text{m}$, with the strip metallization capacitatively coupled to the strip implants.

The sensors consist of 64 strips surrounded by a bias ring and a current collection ring. The strip length is 25 mm and the active sensor width is 5.12 mm . The sensor layout is shown in figure 7.14.

The strip sensors have been irradiated at the CERN PS to the same fluences used for the diodes. In addition, some sensors have been irradiated with 800 MeV/c protons (hardness

³The weighting field defines the relation between the charge movement in the sensor and the current induced on the sensor's electrodes [58, 59].

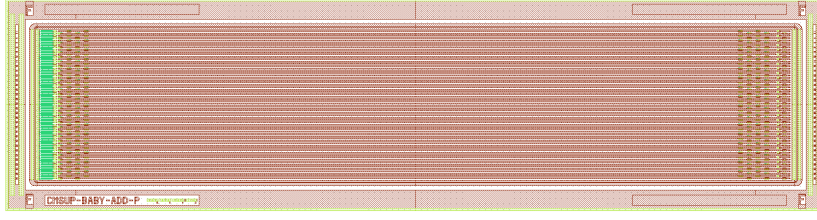


Figure 7.14: Layout of the strip sensors. The sensors are made of 64 AC coupled strips. The total active area is $25 \times 5.12 \text{ mm}^2$.

factor $k = 0.71$) at the LANSCE facility⁴ to a fluence $\Phi_{eq} = 10^{15} \text{ cm}^{-2}$.

In order to test different sensor thicknesses, strip sensors produced on magnetic Czochralski (MCz) and float zone (Fth) silicon with a physical thickness of $200 \mu\text{m}$ have been characterized in the beam test. The design of these sensors is identical to the one of the sensors produced on epitaxial (Epi) silicon. The $200 \mu\text{m}$ thick sensors have been irradiated at the CERN PS to a fluence $\Phi_{eq} = 1.3 \cdot 10^{16} \text{ cm}^{-2}$.

7.2.2 Setup

The beam test measurements have been performed at the DESY II facility⁵. A monochromatic beam of electrons with momenta between 3 and 5 GeV/c has been used to characterize the sensors. The tracks of the particles traversing the sensor under test are measured by the Datura or ACONITE pixel telescope [61], depending on the beam line used. The sensor under test is enclosed in a light-tight box flushed with nitrogen where it can be cooled down to -28°C . The sensor housing can be rotated with respect to the beam to study the effect of different particle incidence angles. The setup in the beam area can be seen in figure 7.15.

The sensor is read out using the ALiBaVa system [62], based on the readout chip of the vertex detector of the LHCb experiment [63]. The readout system records the analog information from its 256 channels for each event. Both positive and negative signals can be processed, allowing the readout of n- and p-bulk sensors. A strip sensor connected to the readout electronics is shown in figure 7.16. The sensor is connected to the readout chip through a series of pitch adapters. The strip sensor is placed on a PCB that provides bias to the sensor's backside. The bias filter can be seen on the right side of the picture. The PCB is placed on a copper block that provides thermal contact to the cooling loop present in the light-tight box. The cooling fluid circulating in the loop is kept at a stable temperature by a chiller. Both the cooling loop and the copper block have a hole below the sensor to minimize the amount of material traversed by the beam, and therefore multiple scattering. A thermometer is mounted on the sensor PCB. The usual temperature of the sensors during measurements was 20°C for the non-irradiated sensors, around -27°C for the sensors irradiated to $1.3 \cdot 10^{16} \text{ cm}^{-2}$, and -20°C for the other sensors.

The readout of both the strip sensor and the telescope is triggered by the coincidence of the signals of four scintillators placed in pairs before and after the telescope. The scintillators also define the geometrical acceptance of the system. As the data acquisition systems of the strip sensor and telescope are independent, the synchronization of the data streams of these systems is achieved through the common trigger logic.

⁴<http://lansce.lanl.gov/>

⁵<http://testbeam.desy.de/>

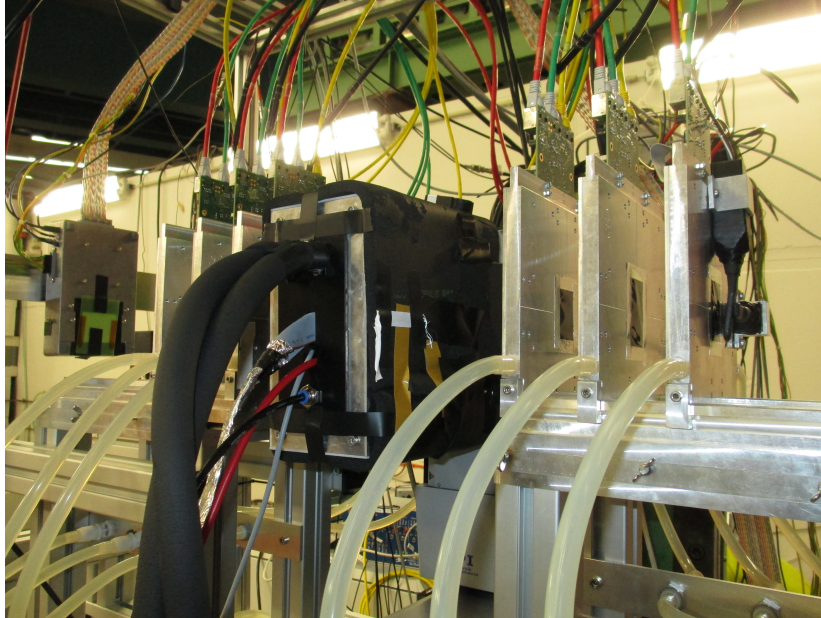


Figure 7.15: Beam test setup. The electron beam comes from the right. The objects encountered by the beam are: trigger scintillators, three telescope planes, the sensor under test, three telescope planes, and trigger scintillators (hidden by the last three telescope planes in the picture).

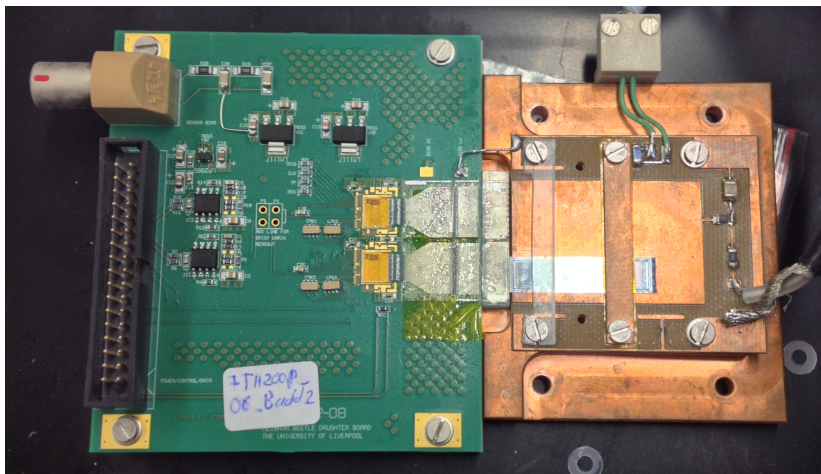


Figure 7.16: Strip sensor on the cold block connected to the readout electronics.

The integration times of the ALiBaVa system and the telescope are very different. The telescope registers tracks in the $115\text{ }\mu\text{s}$ that follow the passage of the particle that triggered the readout of the system. The data of the strip sensor are divided in blocks of 25 ns with only one block being read out for each event. The strategy to overcome this difference is explained later in this chapter.

The reference system used at the beam test is right handed, with the z axis pointing in the beam direction, and the y axis pointing to the ground. The strips are positioned parallel to the x axis. The incidence angle of the incoming particles is expressed as the angle between the particle trajectory and the normal to the strip sensor plane, so that 0° incidence corresponds to normal incidence.

7.2.3 Analysis procedure

Signal processing The procedure illustrated below follows the steps also described in [64]. The pedestals of the channels of the strip readout system have been measured for each combination of sensor, bias, and temperature by taking data without particles traversing the sensor. The pedestal measurements for a $100\text{ }\mu\text{m}$ thick epitaxial sensor irradiated to $3 \cdot 10^{15}\text{ cm}^{-2}$ are shown in figure 7.17. The pulse height distribution measured for each channel can be described by a Gaussian function. The mean value of the Gaussian lies close to the center of the analog to digital converter (ADC) range to give the possibility to measure both positive and negative signals. The pedestal width is mainly influenced by the capacitance at the input of the channel and by the common mode noise⁶, therefore the channels connected to the strip sensor show a larger width of the pedestal distribution compared to the rest of the channels. This feature is exploited to determine which channels have been correctly connected to the readout electronics.

In order to measure the signal and noise of the strip sensors the signal digitized by the readout electronics has to be processed following the procedure illustrated (for one event) in figure 7.18. First the pedestal position is subtracted from the pulse height of each channel. The pulse heights of the channels that are not connected to the readout electronics are set to 0. The common mode noise is estimated by fitting the pulse height of the connected channels with a linear function of the channel number. An iterative procedure ensures that the channels with a signal produced by a traversing particles are excluded from the fit. The choice of describing the common mode noise as a function of the channel number is dictated by the fact that the pulse height information of the readout chip channels is serialized for its transmission from the readout chips to the digitizing electronics. Since the pulse height of the channels is transmitted one after the other, high frequency noise can produce a different shift in amplitude for different channels.

After applying the corrections described above, the noise of the sensors can be estimated using the data gathered without particles traversing the detector. Figure 7.19 shows the noise distribution for a single channel connected to a p-bulk epitaxial sensor irradiated to $1.3 \cdot 10^{16}\text{ cm}^{-2}$ biased to 800 V. The noise distribution is centered around 0 and can be described by a Gaussian function. The standard deviation of the noise distribution of a channel is referred in the following as the channel's noise. The noise of the channels of a p-bulk epitaxial sensor irradiated to $3 \cdot 10^{15}\text{ cm}^{-2}$ and biased to 800 V is shown as a function of channel number in figure 7.20. The noise has very similar values for all the channels connected to the readout

⁶The common mode noise is defined here as a coherent shift of the pulse height measured by different channels.

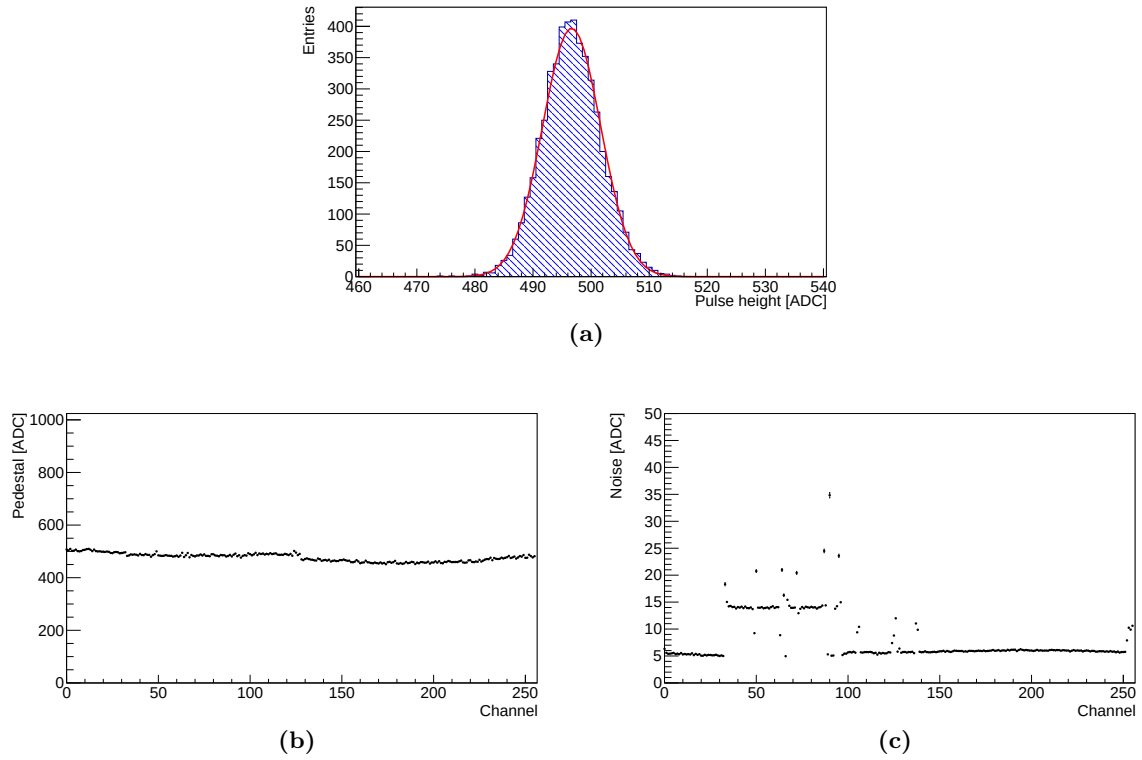


Figure 7.17: (a) Distribution of pulse height for a single channel in a run without beam. The distribution can be described by a Gaussian function. (b) Position of the mean of the pedestals over the channels. (c) Standard deviation of the pedestal distribution over the channels. The channels connected to the strip sensor show a bigger pedestal width due to the capacitance of the sensor and common mode noise. The data has been measured using a $100\text{ }\mu\text{m}$ thick p-bulk epitaxial sensor irradiated to $3 \cdot 10^{15}\text{ cm}^{-2}$ biased to 800 V.

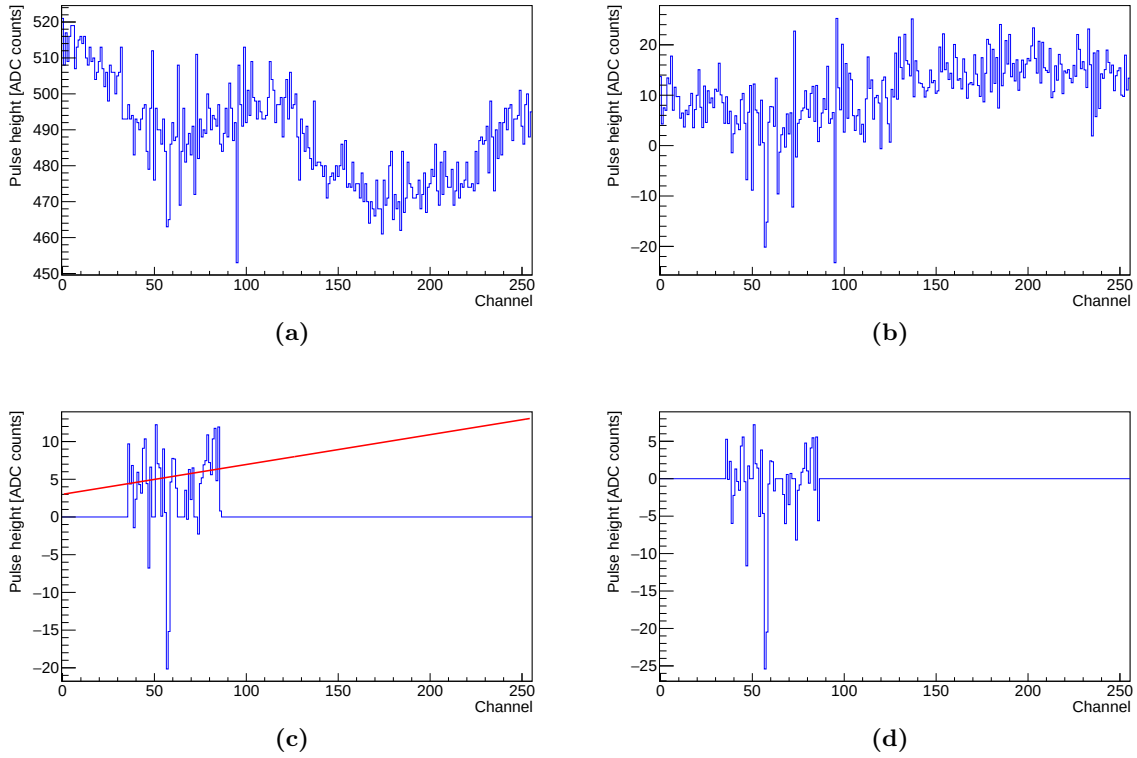


Figure 7.18: Signal processing for the strip sensors. (a) Raw pulse height measured for one event for all the ALiBaVa channels. (b) The pedestal position of each channel is subtracted. (c) The pulse height of the non connected channels is set to 0, and the common mode noise (represented by the red line) is estimated. (d) Pulse height after common mode subtraction. The event shown contains the signal of a particle passing through the sensor close to channel 60. The data has been measured using a $100\text{ }\mu\text{m}$ thick p-bulk epitaxial sensor irradiated to $3 \cdot 10^{15}\text{ cm}^{-2}$ biased to 800 V.

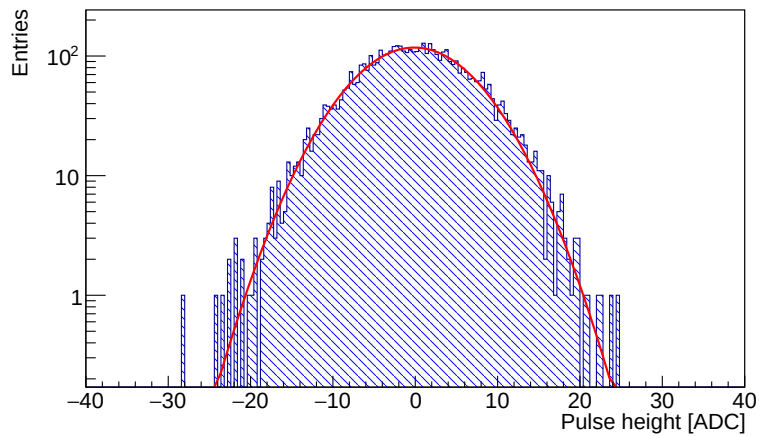


Figure 7.19: Single channel noise distribution of a p-bulk epitaxial sensor irradiated to $1.3 \cdot 10^{16}\text{ cm}^{-2}$ biased to 800 V. The distribution is centered around 0 and can be described using a Gaussian.

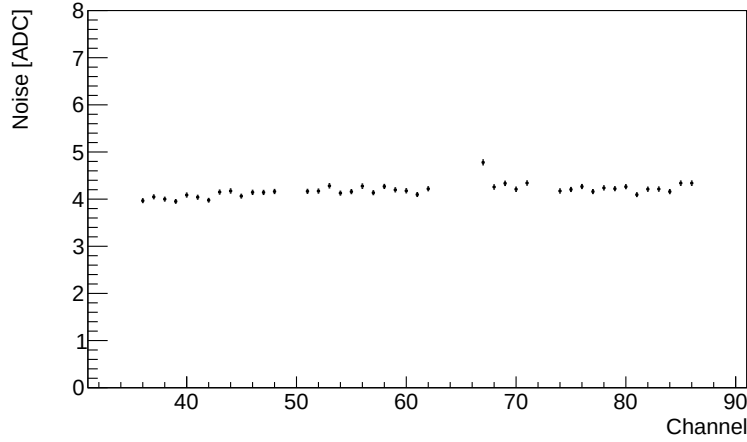


Figure 7.20: Single channel noise as a function of channel number for a p-bulk epitaxial sensor irradiated to $3 \cdot 10^{15} \text{ cm}^{-2}$ and biased to 800 V.

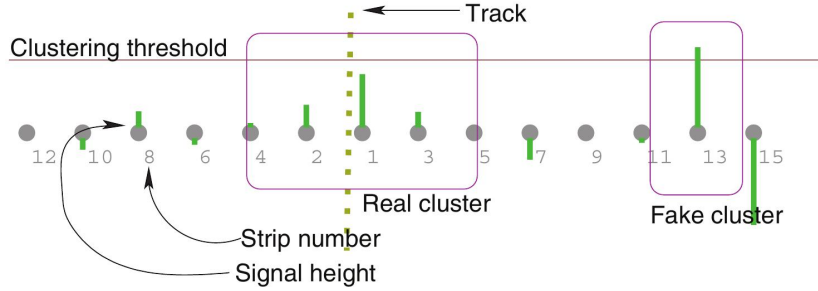


Figure 7.21: Comparison between track based clustering and threshold based clustering. The cluster definition used in the following is the one depicted on the left, with a cluster defined as a group of five strips with the central strip being traversed by a particle [65].

electronics.

The strip sensor is aligned to the beam telescope using the tracks from the beam particles. The impact position of the particles on the strip sensor is estimated at this stage by using a clustering algorithm based on the signal to noise ratio recorded by the strip sensor. During the data analysis the presence of an asymmetric cross talk between the channels of the strip readout electronics was noticed. A correction for the cross talk has been implemented in the signal processing procedure. The alignment procedure and cross talk correction are described in [64]. The precision of the alignment procedure is between 20 and 30 μm for all the runs.

Charge distribution The analysis of the charge distribution measured by the strip sensors uses the tracks recorded by the telescope. The clusters are defined as groups of five strips centered on the one traversed by a particle. The cluster charge is the sum of the signal of the five strips. The definition of the clusters is shown in figure 7.21, where the track based clustering is compared to a threshold based clustering. The features of the track based clustering are extensively explained in [65]. The main advantages with respect to a threshold based clustering are:

- Absence of cuts on the signal measured by the strip sensors.

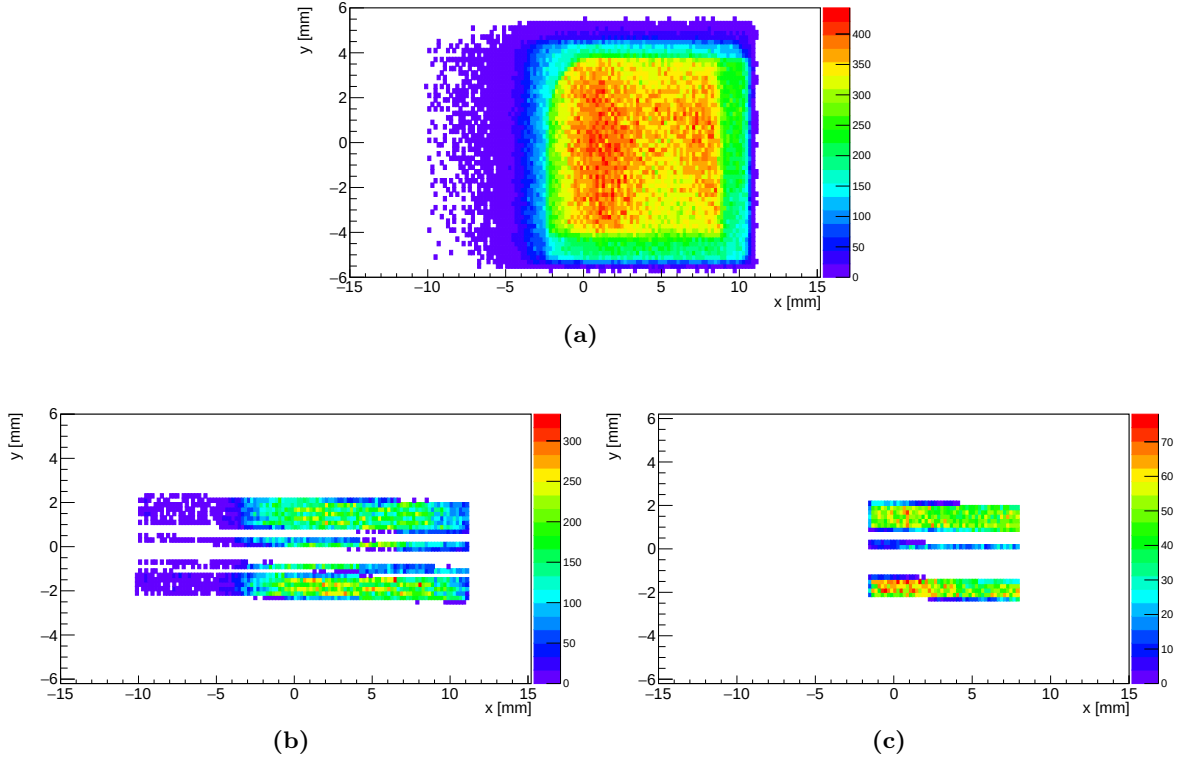


Figure 7.22: Beam spot at the strip sensor position as measured by the telescope (a). Hits on the strip sensor used for the alignment (b). Position of the tracks used in the analysis (c). The data has been measured with a non-irradiated p-bulk sensor biased to 300 V.

This avoids biasing the measured charge distribution to high charge values.

- Noise rejection.

Irradiated sensors may present high noise levels able to produce a signal above the clustering threshold, resulting in “fake clusters”.

The selection of the tracks used in the analysis starts by applying geometrical cuts on the extrapolated track position on the strip sensor. The cut on the horizontal position of the tracks (in the direction parallel to the strips) is determined using the distribution of hits used in the alignment of the strip sensor to the telescope. The cut on the vertical track position is determined by requiring that the track is passing through a strip surrounded on each side by two strips connected to the readout electronics. To overcome the different integration times of the telescope and strip sensor readout, only the events where all tracks fulfill the geometrical cuts mentioned above are selected for the analysis. In this way the cluster charge on the strip sensor can be evaluated for each track. The cluster with the highest charge is assumed to belong to the track traversing the strip sensor at the right time to be recorded by the readout electronics. The effect of the geometrical cuts on the track distribution at the strip sensor position is shown in figure 7.22. The empty regions in the track distribution on the strip sensor are due to strips that were not correctly connected to the readout electronics. Figure 7.23 shows the number of tracks per event before and after applying the geometrical cuts. The mean number of tracks per event is close to one after

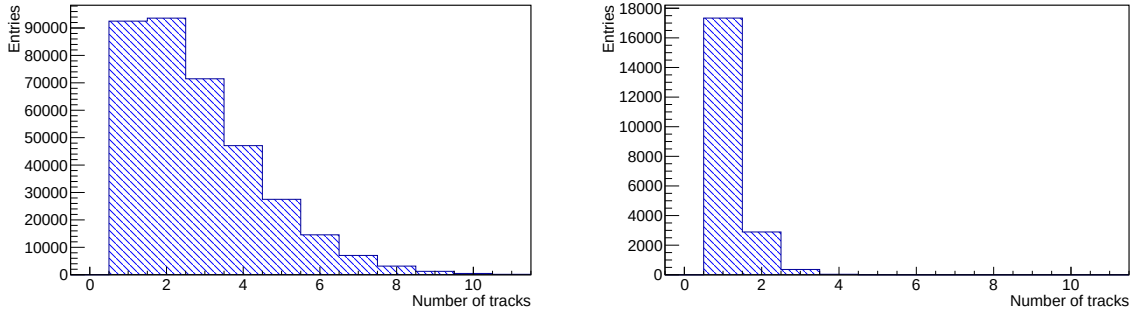


Figure 7.23: Tracks per event before (left) and after the geometrical cuts (right). The mean track multiplicity goes from 2.79 to 1.18 tracks per event, the standard deviation of the distributions goes from 1.68 to 0.44 tracks per event. The data has been measured with a non-irradiated p-bulk sensor biased to 300 V.

the geometrical cuts are applied. Therefore the assumption that, in case of more than one track fulfilling the geometrical cuts, the cluster with the highest signal belongs to the track traversing the strip sensor at the right time to be recorded by the readout electronics does not introduce a significant bias in the analysis.

The readout chip used in the ALiBaVa system features a synchronous and an asynchronous part. The preamplifier and shaper of each channel are always active and independent of the chip clock. The signal after the preamplifier and shaper is sampled synchronously to the clock and stored in a buffer to preserve it until the trigger decision is received. Since the particles impinge on the strip sensor at a random time with respect to the readout clock, the signal amplitude registered by the readout electronics is dependent on the time elapsed between the particle traversing the sensor and the electronics sampling the shaper output. The pulse shape of the signal after the preamplifier and shaper is shown in figure 7.24. The horizontal axis is the phase between the signal from the trigger scintillators and the clock of the readout system. The pulse height is estimated by describing the cluster charge distribution for each value of phase with the convolution of a Landau and a Gaussian distribution, the plotted value is the most probable value of the Landau distribution. The phase is measured by a time to digital converter in the ALiBaVa system. The measuring interval of 100 ns is obtained by reading out different buffer positions after the trigger signal is received. Only one buffer position is read out for each event.

The different phase between trigger and clock of the readout system results effectively in a phase dependent amplification of the signal from the strip sensor. The data used in the analysis should have a similar amplification factor, therefore a cut on the phase is applied. Only the events with a phase contained in a 10 ns interval centered on the maximum of the amplification chain pulse shape are used in the analysis. The cut on the phase is adjusted for each run.

In addition to the cuts mentioned above, it is required for the clusters used in the analysis that the strip presenting the maximum pulse height is the one to which the track is pointing or one of its neighbors.

The signal distribution obtained for a non-irradiated sensor is shown in figure 7.25. The distribution is composed of two contributions, the signal from the sensor that follows an asymmetrical distribution peaking around 50 ADC counts, and some entries close to 0 ADC.

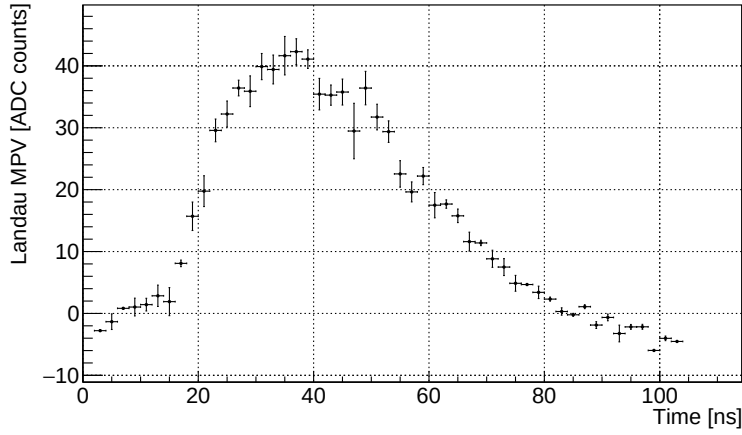


Figure 7.24: Pulse shape of the signal after preamplifier and shaper. The data has been measured with a non-irradiated p-bulk sensor biased to 300 V.

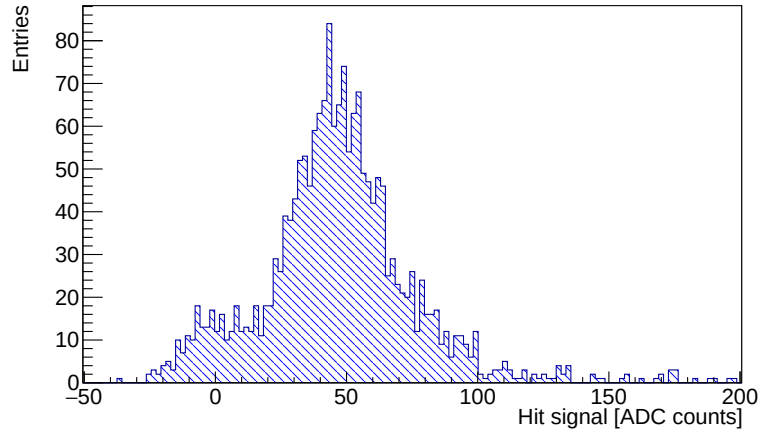


Figure 7.25: Signal distribution of a non-irradiated p-bulk sensor biased to 300 V. The sensor temperature was 20°C with a normal particle incidence.

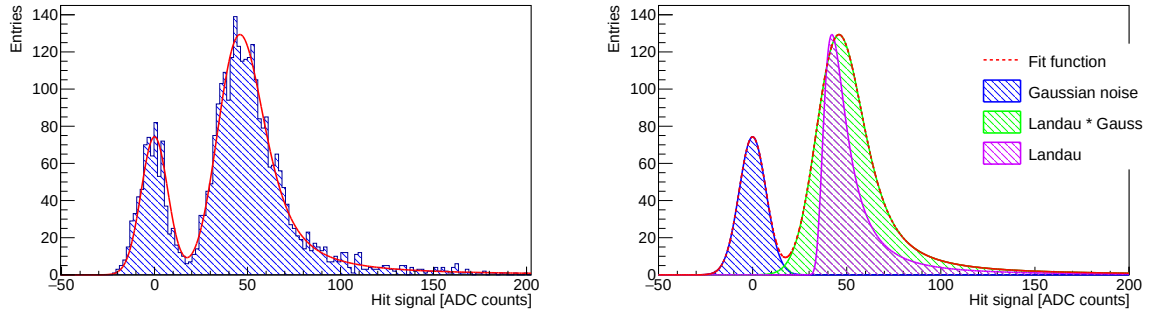


Figure 7.26: Signal distribution of a non-irradiated p-bulk sensor biased to 300 V (left), the sensor is kept at a temperature of -20°C with the particles from the beam traversing it with an inclination of 25° , the angle being defined between the sensor normal and the particle track. The different components used in the description of the charge distribution are showed on the right.

The entries close to 0 ADC are considered to be due to tracking inefficiencies. In the case of one event where the track corresponding to the particle triggering the readout is not reconstructed, the other tracks of the same event can pass the analysis cuts and contribute to the distribution with one cluster that is constituted by noise.

Description of the charge distribution The charge distribution recorded by the strip sensors is described using a convolution of a Landau and a Gaussian distribution plus the contribution of the noise summed over five strips for the entries close to 0 ADC. The implementation of the Landau Gaussian convolution used to describe the data can be seen at [66], while the algorithm used for the implementation of the Landau distribution is described in [67].

The Gaussian part of the convolution is mainly composed of two contributions. The distribution of the ionization produced in the sensor is broader than a Landau distribution [26]. In addition, the noise of the sensor and readout system produces a smearing of the charge collected by the sensor.

The free parameters of the Landau Gaussian convolution are:

- The width parameter of the Landau distribution
- The most probable value (MPV) of the Landau distribution
- The integral of the convolution
- The standard deviation of the Gaussian distribution

The entries around 0 ADC are considered to be noise and are described with a Gaussian distribution. The mean value and the standard deviation of the Gaussian distribution are fixed using the mean and standard deviation obtained by describing the distribution of the noise summed over five strips with a Gaussian distribution. The normalization of the Gaussian is left as a free parameter in the fit. The total number of free parameters to be optimized in the fitting procedure is five. The charge distribution of a non-irradiated sensor and the components used to describe it are shown in figure 7.26. The most probable value of the Landau distribution is used in the following to characterize the strip sensors.

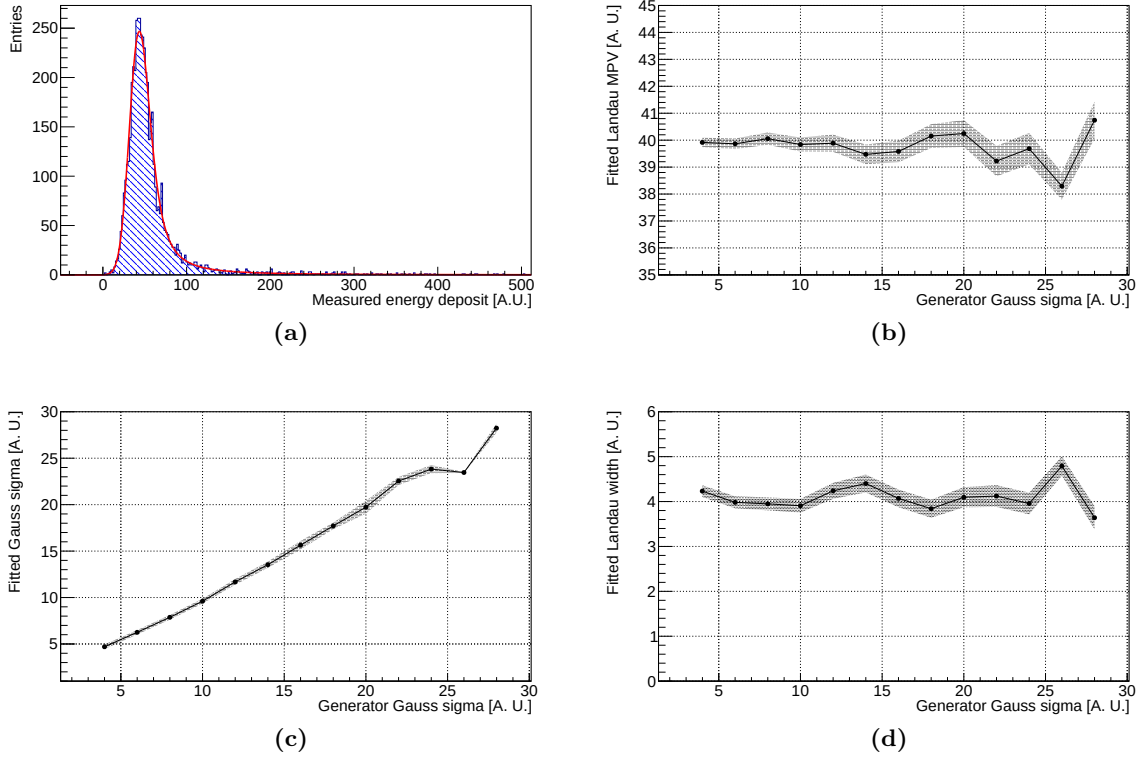


Figure 7.27: (a) Generated Landau Gaussian convolution distribution for a standard deviation of the Gaussian distribution (σ) of 10 and its fit. The number of entries generated for each distribution is 5000. (b) Fitted Landau MPV as a function of the Gaussian σ used to generate the distribution. (c) Fitted Gaussian σ as a function of the σ used to generate the distribution. (d) Landau width as a function of the σ used to generate the distribution. The shaded area in (b-c-d) represent the uncertainty on the parameters estimated by the fitting routine.

The ability of the fitting algorithm to determine the correct parameters of the Landau distribution has been tested by generating different Landau Gaussian convolutions where the parameters of the Landau distribution are kept fixed and the standard deviation of the Gaussian distribution is varied. The results of this test are shown in figure 7.27 where a Landau distribution with a MPV of 40 and a width of 4 was convoluted with different Gaussian distributions. For each distribution 5000 entries were generated and the fitting procedure used for the data is applied neglecting the contribution of the noise around 0. The fit routine is able to estimate correctly the parameters of the generated distribution for values of the standard deviation (σ) of the Gaussian distribution used in the convolution smaller than 20. The choice of a MPV of 40 and a width of 4 for this test is motivated by the fact that these are the typical values in ADC counts of the parameters used to describe the charge distributions measured by the strip sensors. The values of the Gaussian σ presented by the data are always smaller than 20 ADC.

Temperature correction The gain of the readout chip used in the ALiBaVa setup depends on the chip temperature. In order to compare the data of strip sensors operated at different temperatures, the signal measured from the sensors must be corrected for the difference in the

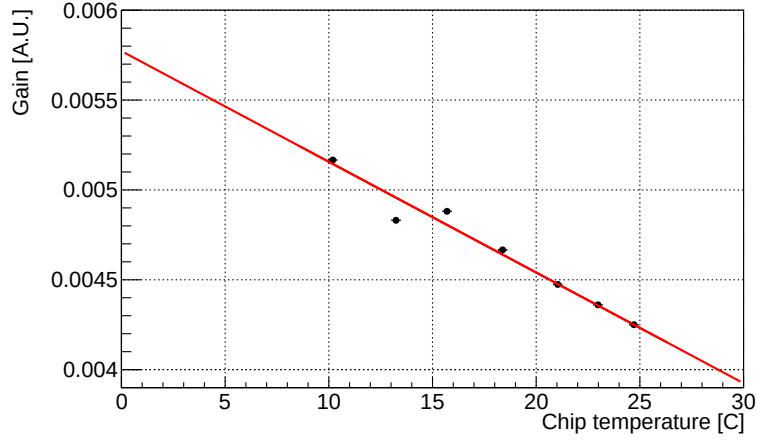


Figure 7.28: Gain as a function of chip temperature measured using the charge injection circuit of the readout chip. The data was measured with a non-irradiated epitaxial p-bulk sensor.

chip gain. A sensor placed in the proximity of the readout chips allows their temperature to be monitored during data taking. During the data taking the chip temperature ranged from 24°C when the sensor temperature was maintained at 20°C to 6°C for a sensor temperature of -28°C . For the majority of the runs the sensor temperature was set to -20°C corresponding to a chip temperature of 10°C . The dependence of the gain on the chip temperature has been determined using the charge injection circuitry of the readout chips. The results obtained for a non-irradiated p-bulk sensor are shown in figure 7.28. The dependence of the gain on the chip temperature has been parametrized using a linear function $G = p_0 + p_1 \cdot T$. The values of the parameters obtained by the fitting procedure are $p_0 = (5.77 \pm 0.02) \cdot 10^{-3}$, and $p_1 = (-6.1 \pm 0.1) \cdot 10^{-5} \text{ 1/}^{\circ}\text{C}$. The parametrization obtained with this measurement technique does not provide a good description of the data measured during the beam test. Two charge distributions were measured with a non-irradiated sensor in the exact same conditions except for the sensor temperature. The parametrization from the data shown in figure 7.28 does not provide a temperature correction good enough to make the parameters extracted from the charge distributions coincide.

To produce a better estimation of the dependence of the chip gain as a function of its temperature, the expected charge distribution for the two runs mentioned above was simulated using the software described in [27] and compared to the measured charge distributions. The simulation takes into account all the physical processes that lead to the generation of electron-hole pairs. The data has been measured at the test beam with a non-irradiated p-bulk sensor biased to 300 V with the particles from the beam traversing it with an inclination of 25° , the angle being defined between the sensor normal and the particle track. The measurement were performed with a chip temperature of 10 and 24°C .

The simulated charge distribution has been obtained by simulating the passage of 10000 electrons with a momentum of $5 \text{ GeV}/c$ through a $353 \mu\text{m}$ silicon layer. The thickness corresponding to the total sensor thickness of $320 \mu\text{m}$ corrected for the angle of incidence of the particles. Since it is not possible to alter the position and angle of the incoming particles in the simulation program, the active volume is chosen to mimic an incidence angle of 25° . The charge distribution is reconstructed considering only the ionization produced in the volume

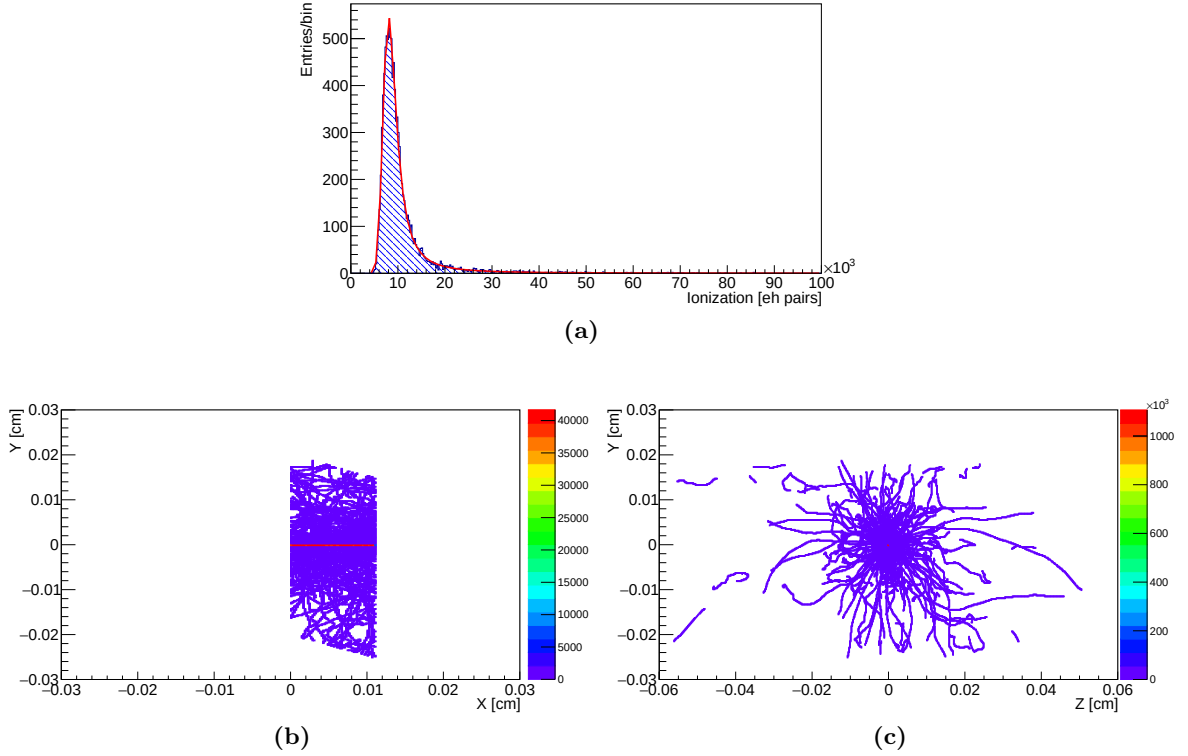


Figure 7.29: Simulated ionization distribution of 5 GeV/c electrons in one epitaxial sensor used at the beam test (a). Position of the ionization deposits in the XY and YZ planes (b-c). The electrons enter the silicon at (0, 0, 0) moving parallel to the X direction. The volume considered to produce the charge distribution corresponds to the one under five strips and an active thickness of 100 μm after considering a particle incidence angle of 25° . The reference system used in the simulation differs from the one used for the beam test data. The strips are parallel to the Z axis in the simulation's reference system.

corresponding to five strips and an active thickness of 100 μm after the incidence angle of the particle is considered. The charge distribution has been described using the same Landau Gaussian convolution fitting routine used for the data. The value of the Landau MPV and the mean ionization are used to estimate the temperature dependence of the chip gain. The simulated charge distribution and position of the ionization in the silicon layer are shown in figure 7.29.

The Landau MPV and the mean ionization measured at the beam test are compared to the ones of the simulated charge distribution to estimate the gain. The mean ionization is estimated for the beam test measurements by subtracting the noise peak from the charge distributions using the parameters from the fit function illustrated above. The gain as a function of chip temperature is shown in figure 7.30. The dependence of the gain on the chip temperature has been described using a linear function. The parameters obtained from a combined fit of the gain estimated using the Landau MPV and the mean of the charge distributions are $p_0 = (5.926 \pm 0.08) \cdot 10^{-3} \text{ ADC/e}^-$, and $p_1 = (-4.8 \pm 0.4) \cdot 10^{-5} \text{ ADC/e}^-/\text{ }^\circ\text{C}$. The parameter values obtained with this method are not compatible with the ones determined using the charge injection.

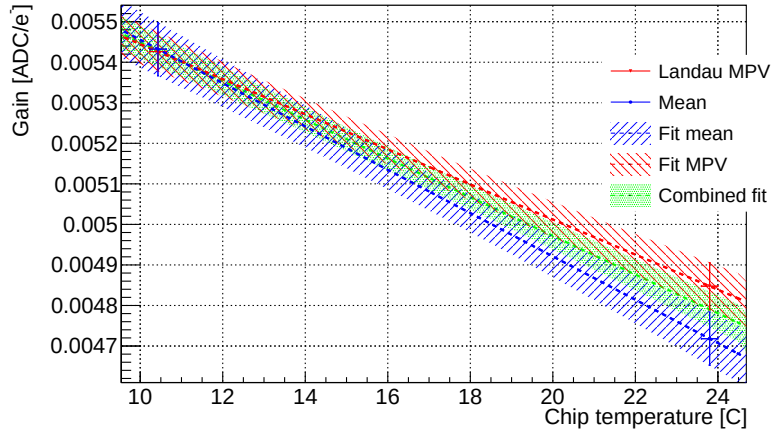


Figure 7.30: Gain as a function of chip temperature measured using the beam test data. The dependence of the gain from the chip temperature is fitted using the gain estimation from the Landau MPV and the mean of the distributions (in red and blue, respectively). The combined fit using both estimations is represented in green. The shaded areas represent the uncertainties.

The temperature correction estimated using the beam test data works satisfactorily for the measured charge distributions. Figure 7.31 shows the charge distributions used in the determination of the gain dependence on the chip temperature. The measured distributions have been scaled to the gain corresponding to a chip temperature of 10°C . The charge is expressed in units of electrons. This value of the chip temperature has been chosen since it is close to the temperature at which the majority of the measurements has been performed. The width of the charge distribution measured with a chip temperature of 24°C is larger than the one measured at 10°C due to the different gain values and the fact that the electronic noise of non-irradiated sensors is dominated by sources that are independent of the chip temperature.

ADC calibration The conversion coefficient from ADC counts to electrons has been determined in a similar way as the gain for the temperature correction. The measured charge distributions of the non-irradiated p-bulk sensors with particles impinging on the sensors at different angles have been used to determine the conversion factor. All the measured distributions have been scaled to a chip temperature of 10°C . A simulation similar to the one shown in figure 7.29 has been produced for incidence angles of 0° (normal incidence), 25° and 51° . Both the Landau MPV and the mean of the charge distributions have been used to determine the conversion factor. The fit of the conversion factor is shown in figure 7.32. The obtained value is $183 \pm 1 \text{ e}^{-}/\text{ADC}$.

Figure 7.33 shows the charge distribution of a p-bulk sensor with p-stop isolation irradiated to $1.3 \cdot 10^{16} \text{ cm}^{-2}$ and biased to 800 V after temperature correction with the collected charge expressed in electrons. The different components of the fit of the distribution are also shown.

Noise estimation The noise of the strip sensors has been measured by using the telescope to determine which strips were not traversed by particles. The noise distributions of the single channels are described by a Gaussian distribution. The standard deviation of the Gaussian expresses the noise level of the channel. The single channel noise appears to be dominated,

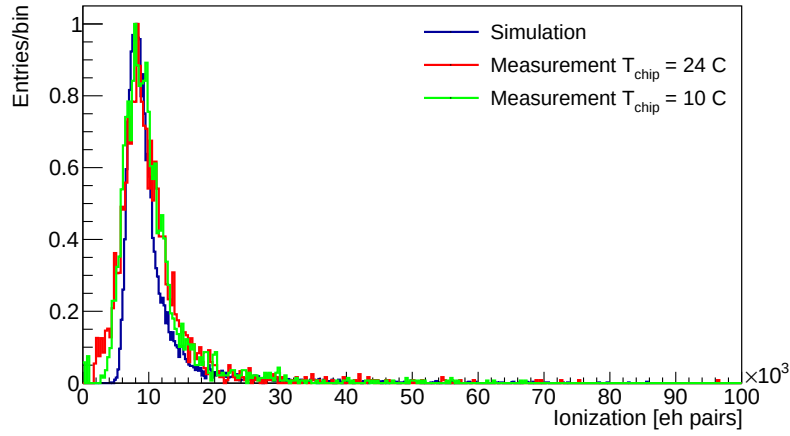


Figure 7.31: Distributions used in the determination of the dependence of the gain on the chip temperature. The measured distributions have been scaled to a chip temperature of 10°C, their charge is expressed in electrons.

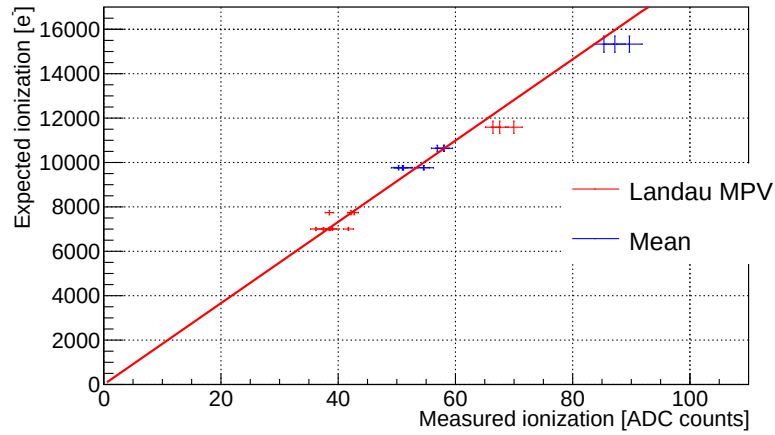


Figure 7.32: Estimation of the conversion factor between ADC counts and electrons.

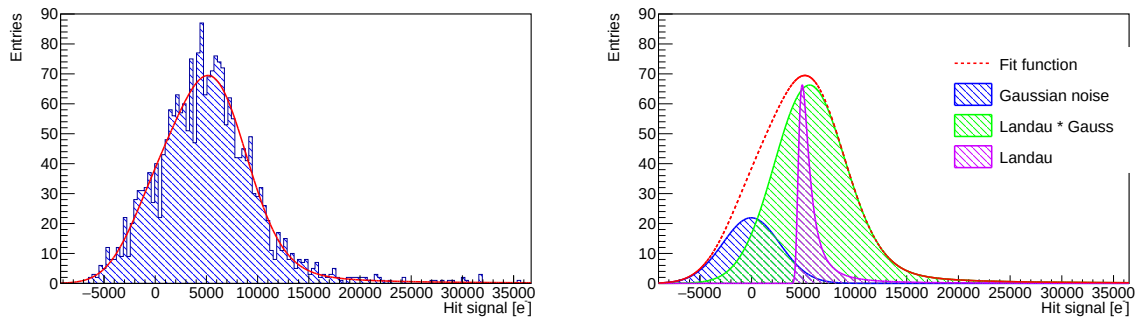


Figure 7.33: Charge distribution of a p-bulk epitaxial sensor with p-stop isolation irradiated to $1.3 \cdot 10^{16} \text{ cm}^{-2}$ and biased to 800 V (left) and the components of the fit function used to describe the distribution (right).

for bias voltages up to 600 V, by the sensor capacitance and noise sources not related to the sensor and readout chip. Therefore the single channel noise is not corrected for temperature.

In order to provide the parameters necessary for the description of the charge distribution, the noise of groups of five strips has been determined for each sensor for each combination of temperature and bias voltage. The five strip noise distribution is described using a Gaussian as for the single channel noise. The five strip noise is corrected for the chip temperature since the parameters estimated from it are used in the description of the signal distribution, where a temperature correction is applied.

Charge distribution of the seed strip and efficiency The operation of a pixel detector often requires the use of zero suppression that is usually implemented by applying a threshold on the signal measured by the single channels. The reduction of the collected charge with irradiation and the modification of the shape of the distribution of the collected charge for single channels can lead to inefficiencies in the particle detection once a threshold is applied. The inefficiency caused by applying a threshold on the detector can be estimated by observing which fraction of entries is lost by applying a cut on the signal distribution of the seed strip. Since the seed strip is not defined in the clustering algorithm used in the beam test data analysis, the seed strip is considered to be the one presenting the highest signal in a cluster. As explained above, the strip with the highest signal in a cluster is either the one closest to the particle track or one of its neighbors.

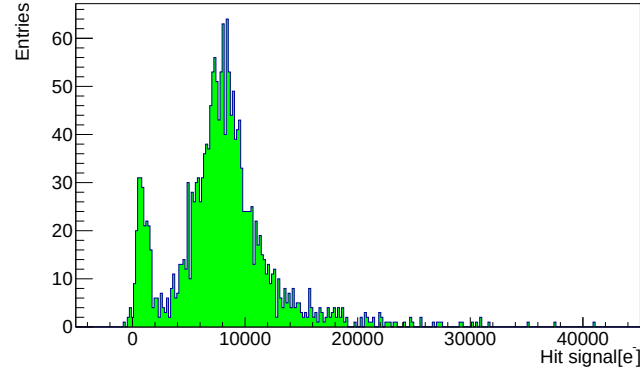
As for the cluster charge distribution, a noise contribution is present in the charge distribution of the seed strip. The noise distribution can be measured by considering the highest signal in the groups of five strips used to determine the five strips noise distribution. The noise contribution can then be subtracted from the charge distribution of the seed strip. The factor used to scale the noise distribution in the subtraction procedure is the ratio of the integrals over a region close to 0 e^- of the noise and charge distribution of the seed strip. Figure 7.34 shows the charge distribution of non-irradiated and irradiated p-bulk sensors as well as the noise distribution of the irradiated sensor, and the effect of the noise subtraction on the charge distribution.

The results regarding the loss of efficiency due to a threshold are presented in the next section.

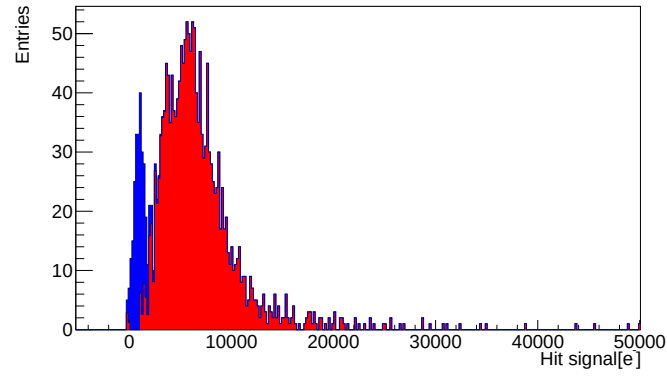
7.2.4 Results

In this section the results from the beam test measurements of the strip sensors are presented. The results are focused on the p-bulk sensors since the n-bulk sensors presented micro-discharges after irradiation [64]. This made the alignment of the n-bulk sensors with the telescope problematic and prone to failures. As a result very few runs of the n-bulk sensors resulted in a satisfactory alignment. The occurrence of micro-discharges in the n-bulk sensors is thought to be an effect of the surface damage produced during irradiation. The effect of micro-discharges could probably be mitigated or avoided by a modification of the strip sensor design.

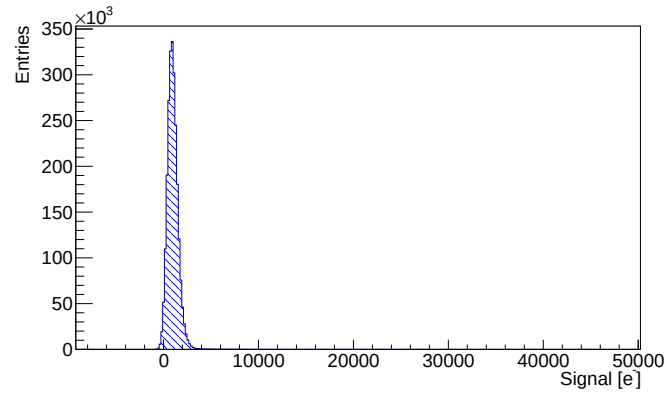
Signal The value of the variables used in the description of the charge distributions of the p-bulk sensors are shown in figure 7.35. The distributions have been measured with the particles having a normal incidence to the sensors. The most probable value of the Landau distribution decreases with irradiation and increases with the applied bias voltage. The epitaxial sensors



(a)



(b)



(c)

Figure 7.34: (a) Charge distribution of the seed strip for a non-irradiated p-bulk epitaxial sensor. (b) Charge distribution for the same kind of sensor irradiated to $3 \cdot 10^{15} \text{ cm}^{-2}$. The measured charge distribution is represented in blue, the red distribution is obtained after noise subtraction. (c) Noise distribution of the seed strip of the irradiated sensor, used for the noise subtraction.

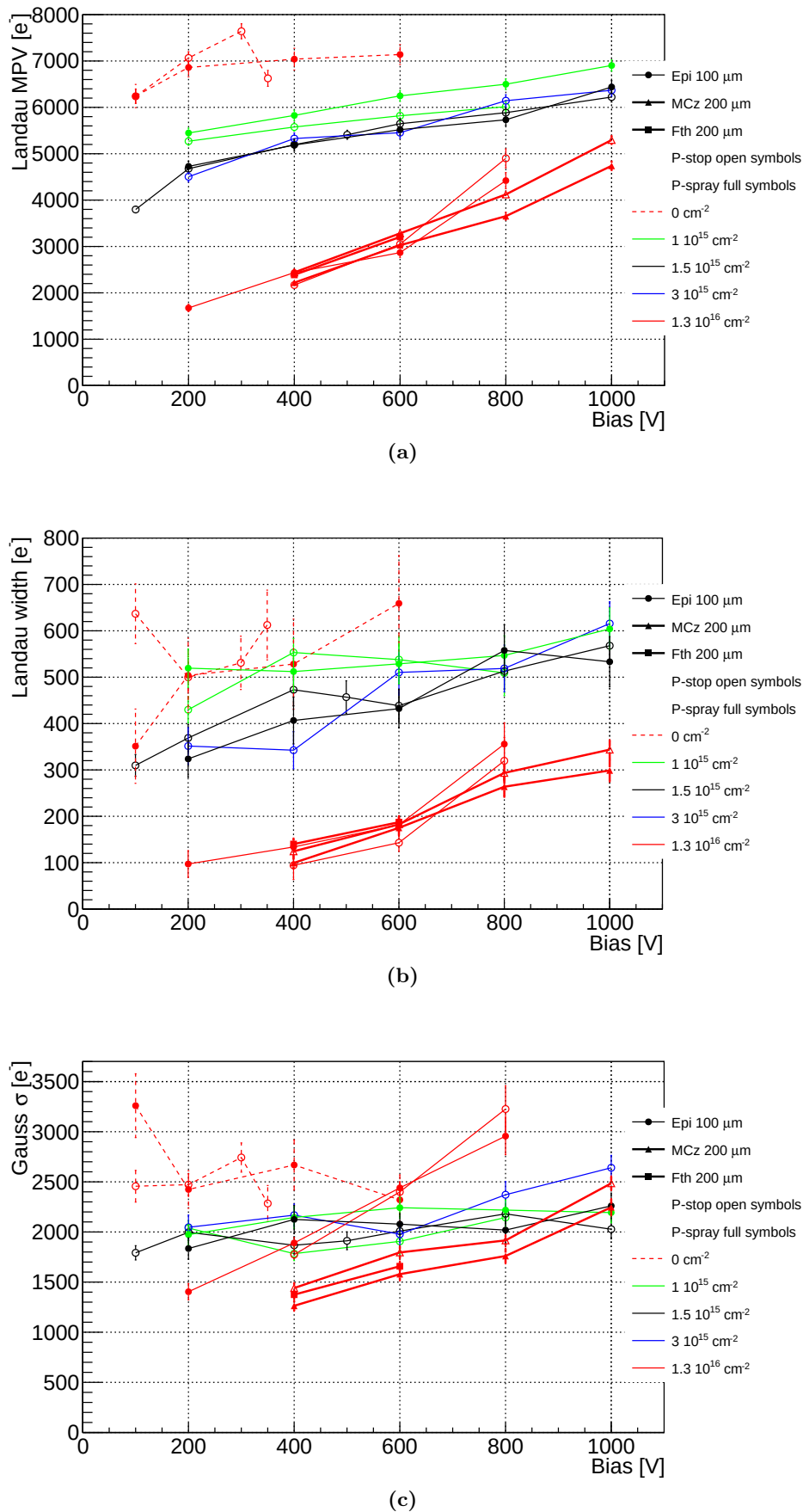


Figure 7.35: Variables used to describe the charge distributions of the p-bulk sensors with the particle impinging on the sensor with normal incidence. (a) Landau MPV, (b) Landau width, and (c) Gaussian σ of the convolution.

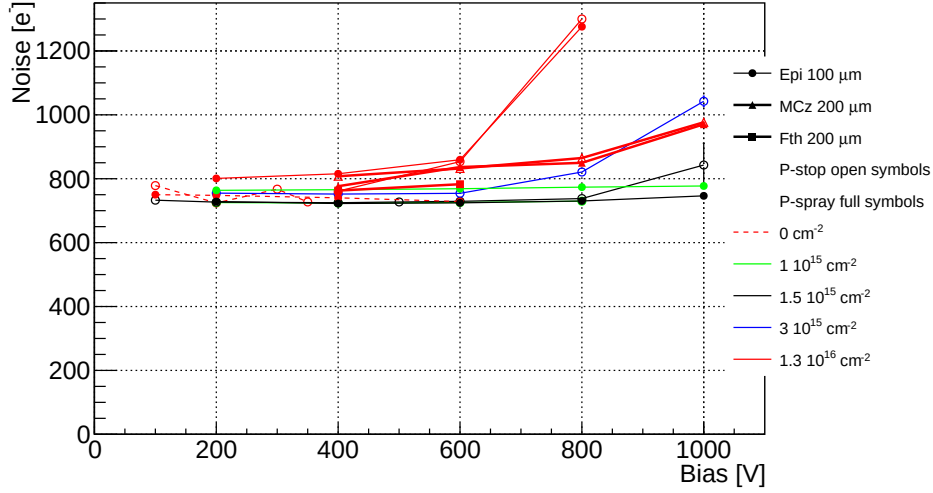


Figure 7.36: Single channel noise of the p-bulk sensors.

irradiated to 1.5 and $3 \cdot 10^{15} \text{ cm}^{-2}$ behave in almost the same way. This can be a consequence of the different annealing status they have since the irradiation was performed without cooling. The Landau MPV of the epitaxial sensors irradiated to $1.3 \cdot 10^{16} \text{ cm}^{-2}$ show a steep increase between 600 and 800 V bias that might indicate the onset of charge multiplication, as observed in pad diodes. The value of the Landau MPV reached by the $100 \mu\text{m}$ thick epitaxial sensors biased to 800 V is compatible with the one reached by the $200 \mu\text{m}$ thick magnetic Czochralski sensors biased to 1000 V .

No difference can be observed between the sensors with p-spray and p-stop isolation.

The Gaussian σ used in the convolution and the Landau width are bigger for the non-irradiated sensors due to the temperature correction.

The plots of the quantities necessary to describe the charge distributions for each measured particle incidence are shown in appendix A.

For normal incidence, the most probable value of the Landau distribution lies between 4000 and 5000 e^- after a fluence of $1.3 \cdot 10^{16} \text{ cm}^{-2}$. These signal values, if confirmed using pixel sensors, are promising for an application of planar thin sensors at the HL-LHC.

Noise The mean value of the single channel noise of the p-bulk sensors is shown in figure 7.36. For bias voltages up to 600 V the noise figure of the strip sensors is dominated by the sensor capacitance and external noise sources, with the sensor current playing a marginal role in the noise figure. The noise of the $100 \mu\text{m}$ thick sensors irradiated to $1.3 \cdot 10^{16} \text{ cm}^{-2}$ shows a steep increase between 600 and 800 V bias, a similar behavior as observed with the Landau MPV for the same sensors. For bias voltages greater than 600 V , the $200 \mu\text{m}$ thick sensors irradiated to $1.3 \cdot 10^{16} \text{ cm}^{-2}$ show a lower noise than the $100 \mu\text{m}$ thick ones that received the same fluence.

It is worth remembering that the noise expected from hybrid pixel detectors built using thin silicon sensors is smaller than what is presented in figure 7.36.

The five strip noise of the p-bulk sensors is shown in figure 7.37. The behavior of the sensors is similar to the one seen for the single channel noise except for the non-irradiated

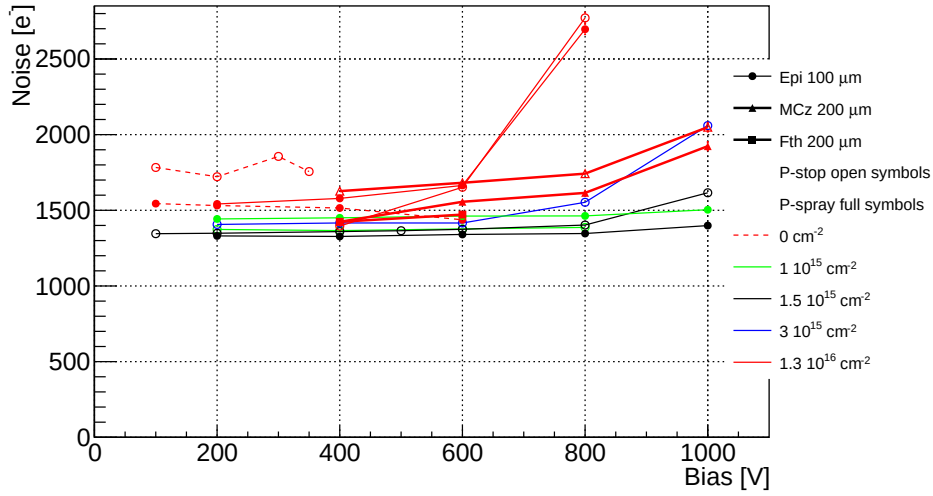


Figure 7.37: Five strip noise of the p-bulk sensors.

sensors that have a larger noise than many of the irradiated sensors. This effect is the product of the different chip temperature at which the measurements were performed (and so gain values) and the fact that the electronic noise of non-irradiated sensors is dominated by sources that are independent from the chip temperature.

IV characteristic The IV characteristics of the p-bulk strip sensors are shown in figure 7.38. The current has been normalized to a sensor temperature of -20°C since the majority of the measurements was performed at that temperature. All the sensors have the same area, therefore the current measured for the $200\text{ }\mu\text{m}$ thick sensors is generated in a volume two times bigger than the one of the $100\text{ }\mu\text{m}$ thick sensors. Despite this the current drawn by the $100\text{ }\mu\text{m}$ thick epitaxial sensors irradiated to $1.3 \cdot 10^{16}\text{ cm}^{-2}$ is bigger than the one drawn by the $200\text{ }\mu\text{m}$ thick sensors. The shape of the IV of the highly irradiated epitaxial sensors is similar to the one of the irradiated diodes that present charge multiplication. These two observations support the hypothesis that charge multiplication is playing a role in the charge collection of $100\text{ }\mu\text{m}$ thick strip sensors irradiated to $1.3 \cdot 10^{16}\text{ cm}^{-2}$.

Charge collection between strips The uniformity of the charge collection between the strips has been studied using the information of telescope tracks. The sum of the charge collected on the left and right strips with respect to the impact point of the track on the sensor is defined as $Q_{LR} = Q_L + Q_R$. The sensor's pitch has been divided in six intervals of $13\text{ }\mu\text{m}$ each. For each interval, a distribution of the collected charge Q_{LR} has been determined. In order to enhance the amount of data present in the distributions, the whole sample was summed in three distributions that cover half of the sensor's pitch. The procedure is done under the assumption that the amount of collected charge is distributed symmetrically between the strips. The maximum of the distribution for each position has been estimated by describing the distribution with a Gaussian function. The temperature correction and conversion of the collected charge in units of electrons were not applied in this part of the analysis since this study is focused on determine how strong is the dependence of the collected charge on

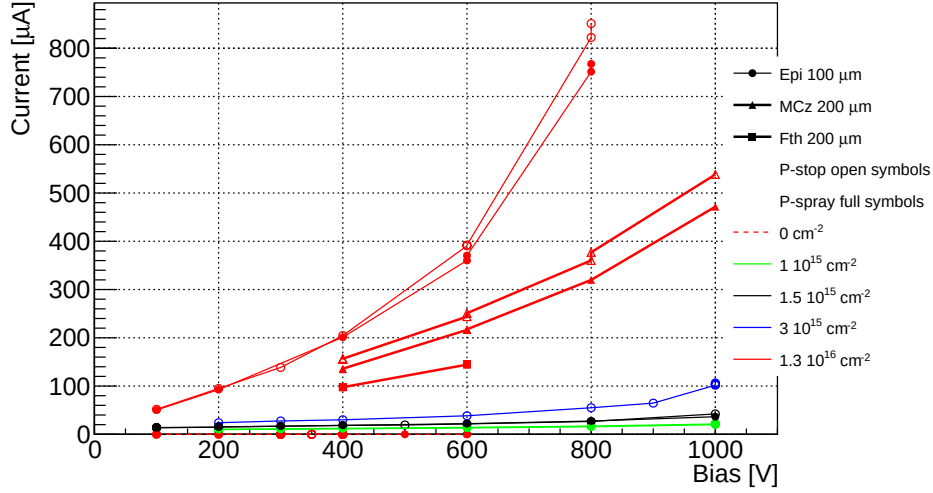


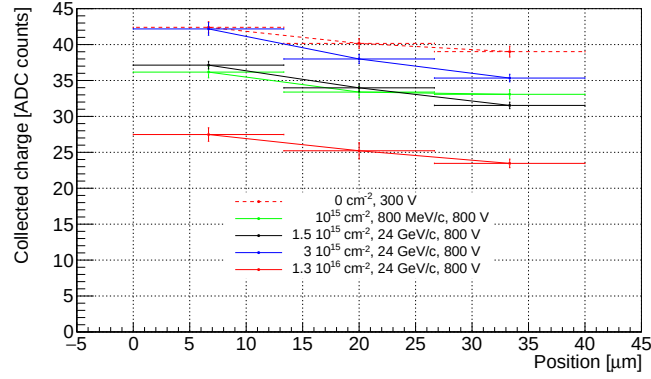
Figure 7.38: IV characteristics of the p-bulk strip sensors at the beam test, scaled to -20°C .

the hit position relative to the strips. The results obtained for normal particle incidence are shown in figure 7.39, where 0 and $80\text{ }\mu\text{m}$ on the horizontal axis correspond to the center of the strip implants, and $40\text{ }\mu\text{m}$ is therefore the point furthest away from the strip implants. The behavior of the collected charge as a function of the hit position has been described using a parabola, expressed in the form

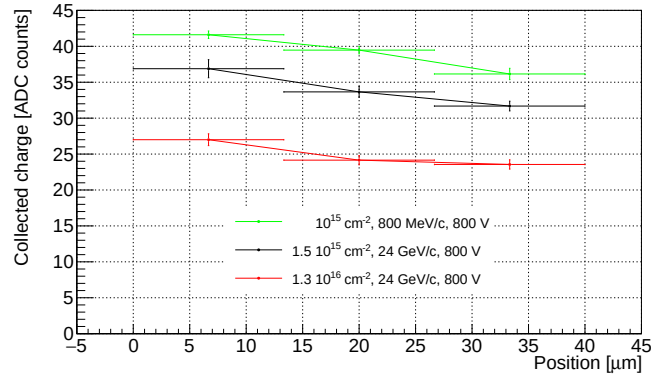
$$f(x) = p_0 + p_1(x - 40)^2 \quad (7.1)$$

where p_0 and p_1 are the parameters optimized by the fitting routine, and x is expressed in μm . The quantity $(f(0) - f(40))/f(40)$ is used to express the variation of the charge collected in the proximity of the strip implants and in the position between them. The values assumed by this quantity for different fluences are shown in figure 7.40. The amount of charge collected when a particle traverses the sensor in proximity of the strip implants is bigger than the amount collected when a particle traverses the sensor further away from the strips. This effect is enhanced by irradiation. The points at $1 \cdot 10^{15}\text{ cm}^{-2}$ correspond to the irradiation performed with 800 MeV/c protons, while all other fluences are obtained irradiating the sensors with 24 GeV/c protons. From the present analysis it is hard to draw a solid conclusion on the observed increase of the charge loss between strips. It could be an effect increasing with fluence which levels off above $3 \cdot 10^{15}\text{ cm}^{-2}$. Or it could be an effect dependent on the proton energy, stronger for higher proton energy. Further measurements are necessary to clarify this point.

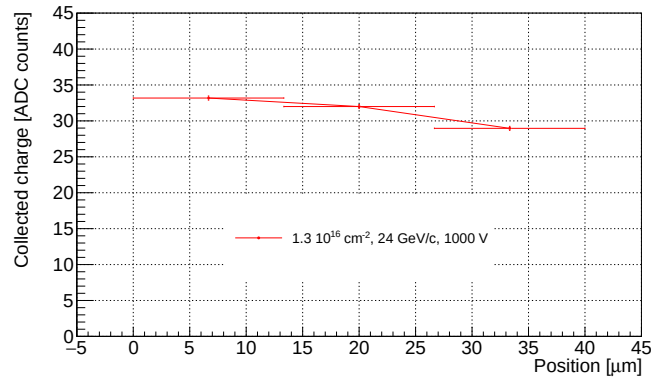
Threshold to obtain 95% detection efficiency Using the charge distribution of the seed strip illustrated above, it is possible to determine which threshold can be applied to a sensor maintaining a certain efficiency. The value of the threshold that results in a 95% detection efficiency has been measured for the p-bulk sensors characterized at the beam test. The value of 95% efficiency (instead of e.g. 99%) has been chosen to reduce the influence of the noise subtraction from the charge distribution. The results for normal particle incidence are shown in figure 7.41. The value of the threshold decreases with irradiation and increases with



(a)



(b)



(c)

Figure 7.39: Maximum of the signal distribution measured in different positions relative to the strip implants. Only half of the pitch is shown. Results are shown for 100 μm thick p-bulk sensors with p-stop (a) and p-spray isolation (b). (c) shows the same quantity for a 200 μm thick p-bulk MCz sensor with p-stop isolation.

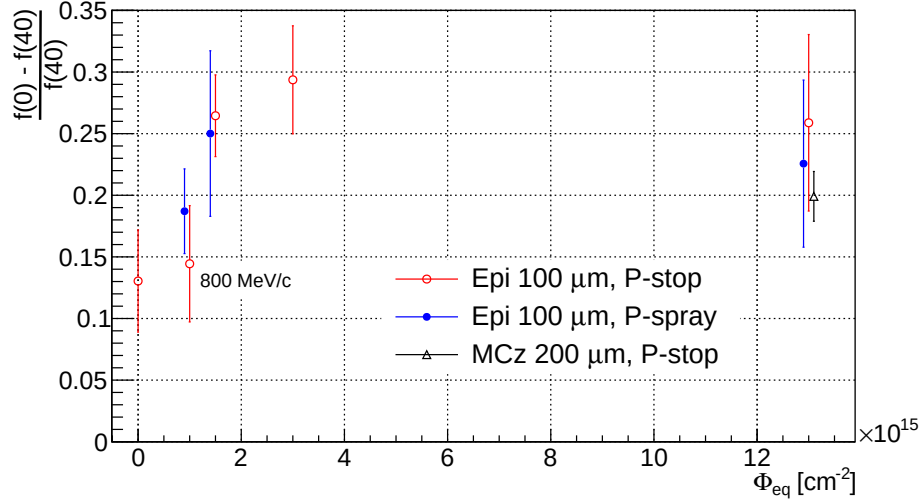


Figure 7.40: Variation in the charge collection as a function of the accumulated fluence. The points have been staggered on the horizontal axis to better show their values and error bars. The points at $1 \cdot 10^{15} \text{ cm}^{-2}$ represent sensors irradiated with 800 MeV/c protons. The points at higher fluences are obtained from irradiations using 24 GeV/c protons.

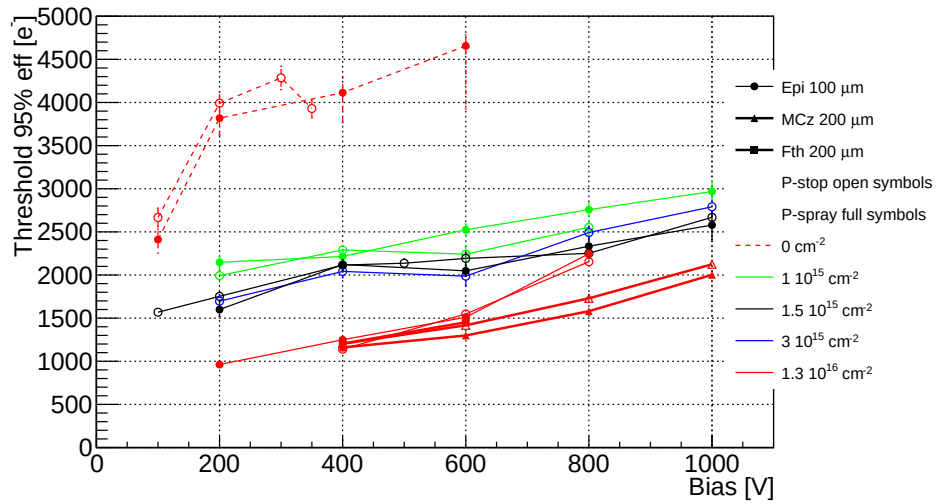


Figure 7.41: Threshold to achieve 95% efficiency for the p-bulk sensors.

the voltage. At a fluence of $1.3 \cdot 10^{16} \text{ cm}^{-2}$ the sensors with a thickness of $200 \mu\text{m}$ require a lower threshold than the $100 \mu\text{m}$ thick sensors despite the fact that the Landau MPV assumes similar values for these sensors.

The estimated threshold value to obtain 95% efficiency for each measured particle incidence is shown in appendix A.

The measured values of threshold, if confirmed with pixel sensors, are promising. For comparison, the readout chip used in the phase I pixel upgrade can be operated with a threshold of $\approx 1800 \text{ e}^-$ before irradiation, and the chip being designed for the Atlas and CMS phase II pixel upgrade should have a threshold of $\approx 1000 \text{ e}^-$ [48]. The amount of noise that would be above threshold has not been measured since the noise figure of the strip sensors is not representative of the expectation for pixel sensors.

7.3 Outlook

The work started with the measurements of highly irradiated thin diodes and strip detectors has to be expanded and supported by additional measurements. Since strip sensors have a different weighting field than pixel sensors, the measured values of collected charge and thresholds exposed above have to be confirmed by using a pixel sensor. The stability in time of the charge multiplication effects observed in diodes and strip sensors have to be confirmed through annealing studies. The study of sensors irradiated at fluences between $3 \cdot 10^{15}$ and $1.3 \cdot 10^{16} \text{ cm}^{-2}$ would provide a better understanding of the observations made for sensors irradiated to $1.3 \cdot 10^{16} \text{ cm}^{-2}$. A comparison between 100 and $200 \mu\text{m}$ thick sensors irradiated to fluences below $1.3 \cdot 10^{16} \text{ cm}^{-2}$ can provide useful information for the decision regarding the thickness of the sensors to be used in the phase II pixel upgrade. Finally, a better understanding of the charge multiplication effects can be gained by performing edge-TCT measurements on the irradiated diodes or by grazing angle measurements [68] in beam test.

Chapter 8

Conclusions

Phase I pixel upgrade In order to maintain an efficient data taking, the CMS pixel detector will undergo a series of upgrades to cope with the increase in the LHC luminosity. The phase I pixel upgrade will take place in winter 2016/2017. The main reason for this upgrade is the data loss expected when the luminosity will exceed $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The upgrade consists in the replacement of the current pixel detector with a lighter one equipped with improved readout electronics. The upgraded detector will provide an efficient data taking up to $2 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The modules that will constitute the upgraded detector are being produced at different institutes. The University of Hamburg and DESY are responsible for the production of the half of the modules that will constitute the outermost layer in the upgraded detector. This corresponds to 350 modules, including spares. The production chain in Hamburg has been established. The modules assigned to the Hamburg production center should be completed by the end of February 2016. Several quality assurance tests have been implemented in the production chain to assess the quality of the modules. The energy calibration of the pixel modules is achieved by using monochromatic X-rays. A calibration setup has been built using a commercial X-ray box. The influence of various parameters on the calibration has been investigated. The trigger rate and rate of the fluorescence X-rays impinging on the detector have been found to have no influence on the energy calibration. The module temperature affects the energy calibration. However, once the calibration has been measured for one temperature, the calibration can be translated to a different temperature by adjusting the working point of the module readout electronics. The buffering capabilities of the readout electronics are also tested using X-rays. For this test the modules are held in the direct X-ray beam. The maximum rate that will be experienced by the type of modules produced in Hamburg is 120 MHz/cm^2 (for the second pixel layer), and for this rate the efficiency of the module has been measured to be 99%. At the time of writing this thesis, 47 modules have been produced. Of the produced modules, 40 qualify for the installation in the upgraded pixel detector.

Phase II pixel upgrade The high luminosity upgrade of the LHC will result in a luminosity of $5 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. To cope with this challenging measuring environment, a new silicon tracker will be installed in CMS. The innermost pixel layer of the new tracking system will accumulate a radiation damage corresponding to $\Phi_{eq} = 2 \cdot 10^{16} \text{ cm}^{-2}$ and a dose of $\approx 10 \text{ MGy}$ after an integrated luminosity of 3000 fb^{-1} . Thin silicon sensors with an active thickness of $100 \mu\text{m}$ irradiated with protons up to $\Phi_{eq} = 1.3 \cdot 10^{16} \text{ cm}^{-2}$ were characterized. The charge collection

efficiency (CCE) was measured using pad diodes. Charge multiplication effects was observed for both n- and p-bulk sensors. The stability of the CCE with annealing was studied using an n-bulk diode irradiated to $\Phi_{eq} = 3 \cdot 10^{15} \text{ cm}^{-2}$. For this fluence, the CCE appears to be stable for annealing times up to 120 minutes at 80°C. The latter result does not allow to draw conclusions on the charge multiplication effects observed for higher irradiations and p-bulk diodes. Strip sensors with a pitch of 80 μm were characterized in a beam test with electrons. The signal of the sensors has been described using a convolution of a Landau and a Gaussian distribution. The most probable value of the Landau distribution lies between 4000 and 5000 e^- for the p-bulk sensors after being irradiated to $1.3 \cdot 10^{16} \text{ cm}^{-2}$. The development of the dark current, the signal, and noise of the highly irradiated p-bulk sensors with the applied bias voltage suggests that charge multiplication effects play a significant role in the production of the measured signal. The threshold necessary to obtain 95% detection efficiency has been found to be around 2000 e^- for the highly irradiated p-bulk sensors. The n-bulk strip sensors could not be characterized in the beam test since they presented micro-discharges and could not be correctly aligned to the beam telescope used in the analysis. The occurrence of micro-discharges in the n-bulk sensors is thought to be an effect of the surface damage produced during irradiation. The effect of micro-discharges could probably be mitigated or avoided by modifying the strip sensor design. In the beam test p-bulk strip sensors with an active thickness of 200 μm irradiated to $\Phi_{eq} = 1.3 \cdot 10^{16} \text{ cm}^{-2}$ were characterized. When compared to the 100 μm thick sensors, these sensors present a similar position of the most probable value of the Landau distribution and a smaller noise level. The bias voltage required by the 200 μm thick sensors to achieve this signal value is higher than the one used for the 100 μm thick sensors. Since the weighting field is different in diodes, strip, and pixel sensors, the results obtained for thin pad diodes and strip sensors must be confirmed using pixel detectors. However, from the measurements performed in this work, thin silicon sensors produced with a planar process are promising candidates for the production of pixel detectors for the HL-LHC.

Appendix A

Summary plots for different particle incidence angles at the beam test

In this appendix the plots presented for normal particle incidence in chapter 7 are shown for all the incidence angles used in the beam test. The sensors represented in the plots have a p-doped bulk due to difficulties encountered in the measurements of n-bulk sensors, see section 7.2.4. The incidence angle of the incoming particles is expressed as the angle between the particle trajectory and the normal to the strip sensor plane, so that 0° incidence corresponds to normal incidence. Figures A.1, A.2, and A.3 show the parameters used to describe the five strip cluster charge distribution for different incidence angles. In these figures (a) shows the Landau MPV of the charge distribution of the five strip clusters, (b) the Landau width, and (c) the Gaussian σ used in the convolution. Figure A.4 shows the threshold to obtain 95% detection efficiency for all incidence angles used in the beam test.

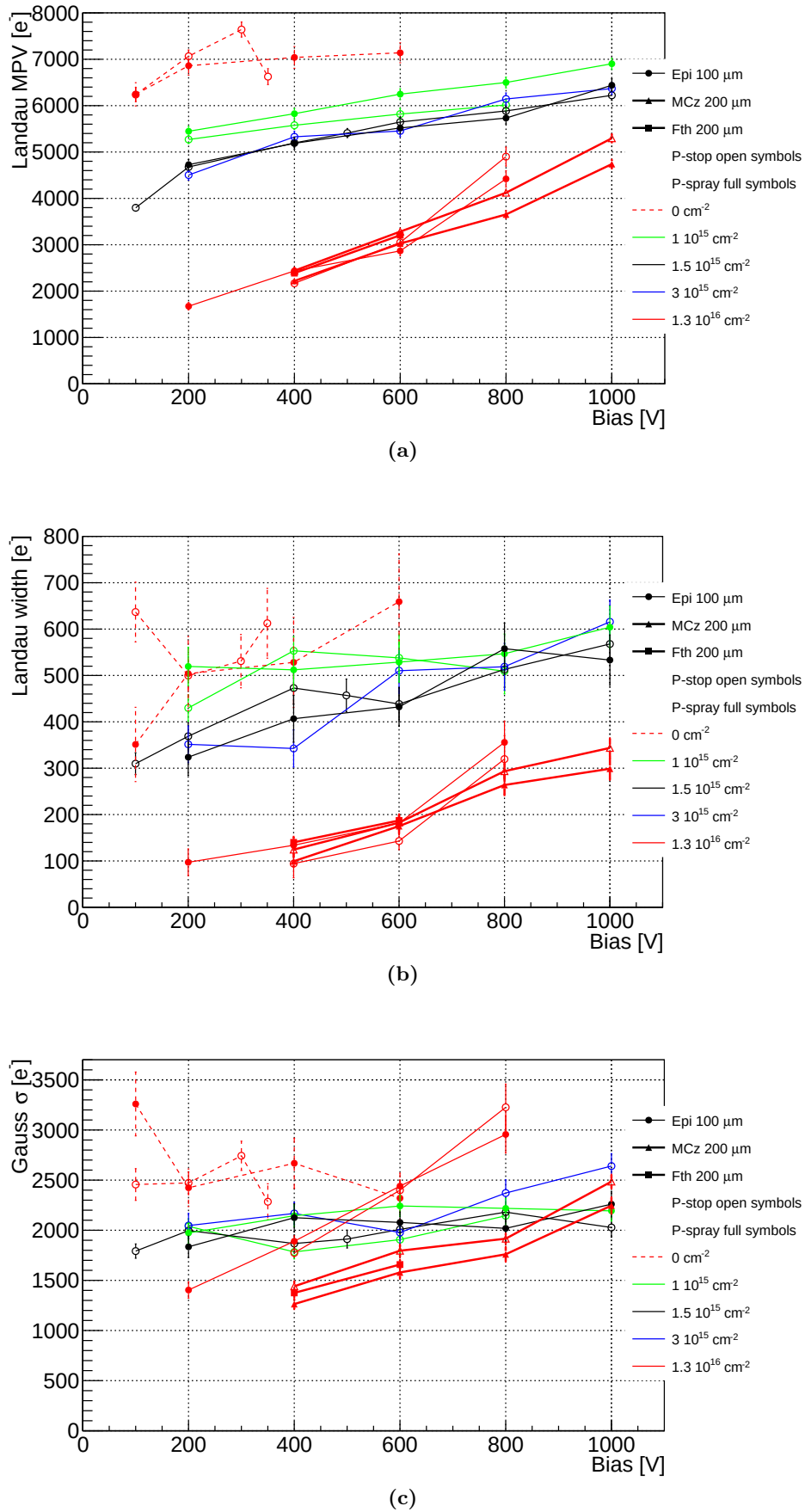
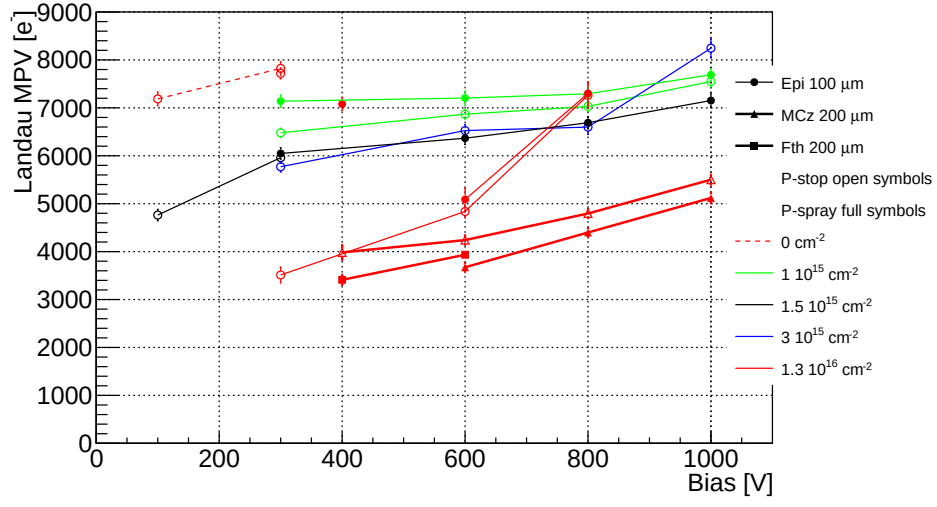
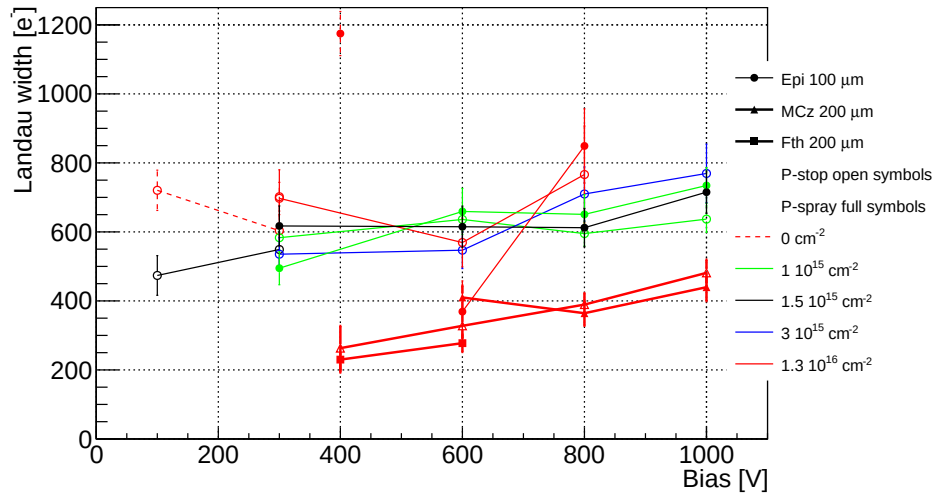


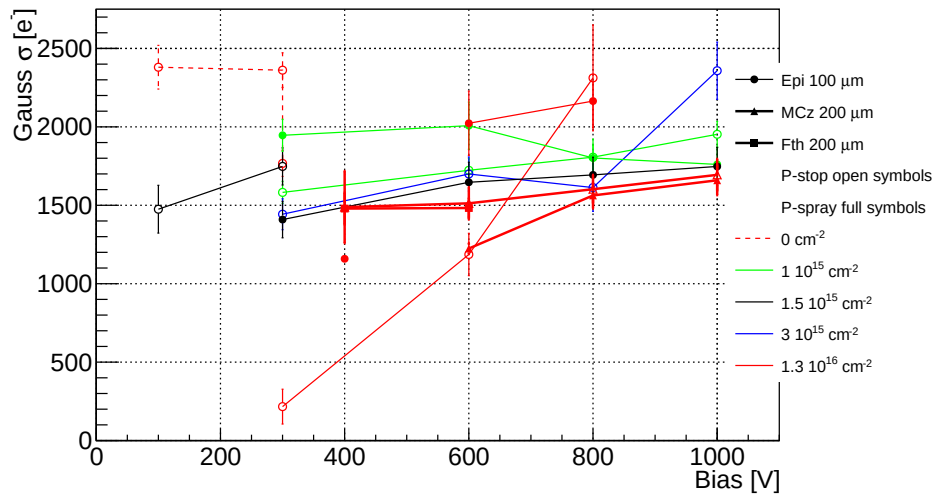
Figure A.1: Parameters measured at 0° incidence.



(a)



(b)



(c)

Figure A.2: Parameters measured at 25° incidence.

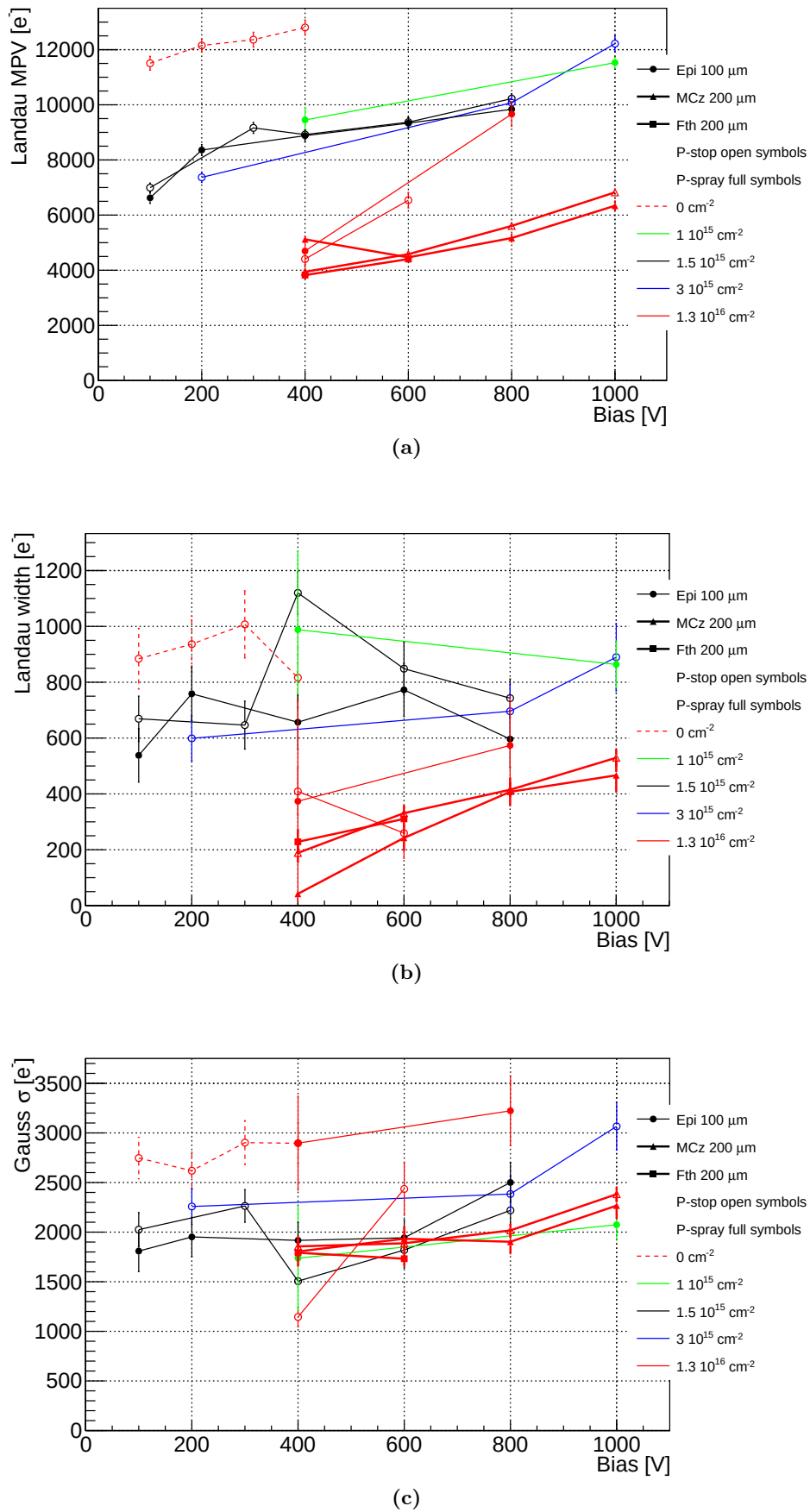


Figure A.3: Parameters measured at 51° incidence for the 100 μm thick sensors, the parameters have been measured with a 32° incidence for the 200 μm thick sensors.

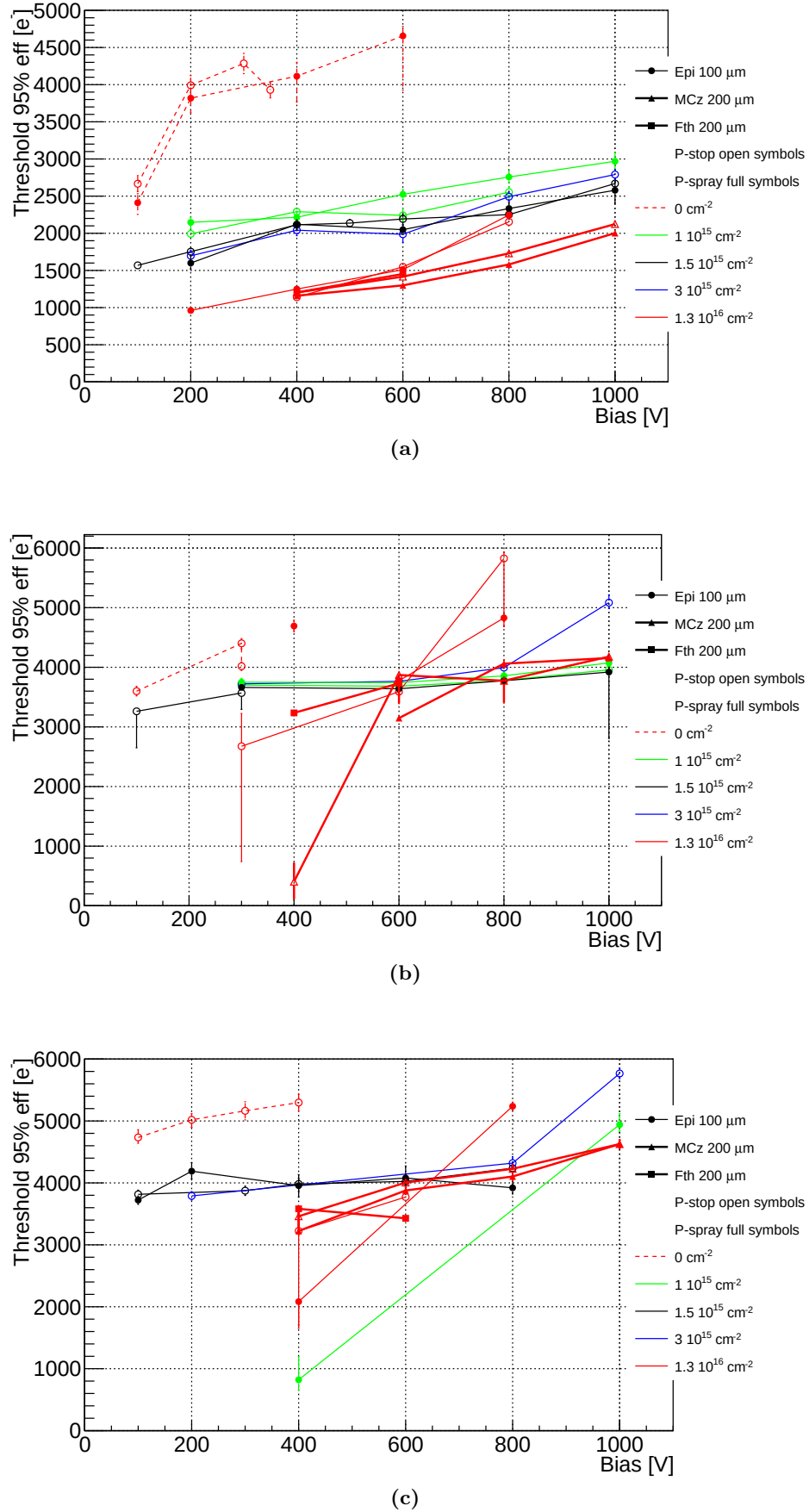


Figure A.4: Threshold to achieve 95% detection efficiency for different incidence angles. (a) Normal incidence. (b) 25° incidence. (c) 51° incidence for the 100 μm thick sensors, and 32° incidence for the 200 μm thick sensors.

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I'm a leaf on the wind. Watch how I soar.

SERENITY

Eidesstattliche Versicherung
Declaration on oath

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertationsschrift selbst verfasst und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe. I hereby declare, on oath, that I have written the present dissertation by my own and have not used other than the acknowledged resources and aids.

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