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Design and characterization of an innovative monolithic silicon sensor with additional gain for the ALICE 3 Time of Flight detector

By

Giulia Gioachin

Supervisor(s):

Prof. Stefania Bufalino, Supervisor

Prof. Massimo Masera, Co-Supervisor

Doctoral Examination Committee:

Politecnico di Torino

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Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

Giulia Gioachin
2026

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Acknowledgements

Abstract

Precise Time-of-Flight (TOF) measurements play a fundamental role in Particle IDentification (PID) and event time tagging in High-Energy Physics (HEP) experiments, in particular in low-momentum regions. Therefore, excellent time resolution is mandatory to extend PID capabilities in future detector upgrades. Several experiments will rely on TOF capabilities, including the next-generation heavy-ion experiment named ALICE 3, which will be installed at the Large Hadron Collider (LHC) at CERN. The installation is planned during the Long Shutdown 4 (LS4) of the LHC and it will be ready for the data taking in 2036. The ALICE 3 TOF detector will provide precise PID and, to this aim, the excellent time resolution of 20 ps is required. To meet this challenge, several silicon sensor technologies are currently under investigation, among these, the monolithic approach.

In recent years, Monolithic CMOS Active Pixel Sensors (MAPS) constitute a major step forward in particle detector technology, particularly in tracking systems used in HEP experiments. However, their high-resolution timing capabilities have not yet been completely exploited. A potential solution to this challenge was found by combining the Low Gain Avalanche Diode (LGAD) approach with the advantages of a monolithic sensor. Therefore, the first prototype of monolithic CMOS sensor with additional gain in 110 nm LFoundry technology (also called MADPix) was developed within the ALICE 3 TOF working group in collaboration with the ARCADIA project.

This thesis is focused on the R&D work concerning the design and development of an innovative monolithic silicon sensor, where both simulation and experimental data results are reported. A solid and fully functional simulation chain, combining Technology Computer-Aided Design (TCAD) and Monte Carlo simulations, is employed to investigate the electrical behavior, the gain and timing performance of the proposed devices. Thanks to a careful simulation work, excellent agreement with the experimental data was achieved. This resulted in a robust simulation workflow

capable of accurately reproducing the intrinsic device physics and providing reliable predictive capabilities for future device generations. In addition, in this work the experimental results on the first 110 nm CMOS avalanche detector prototype are shown. A full characterization was performed on sensors from the two sensor productions realized to date, employing both laboratory measurements and tests with particle beams. The timing performance of the MADPix chip was studied during several beam test campaigns that took place at the T10 beamline of the CERN PS, where a beam of protons and pions with a momentum of 10 GeV/c is available. A time resolution of approximately 80 ps was achieved using the latest generation of sensors. In addition, an irradiation campaign was conducted to assess the effects of radiation-induced defects on both gain and timing performance. Although the loss of gain and degradation of time resolution are evident and inevitable when the irradiation levels increase, the operating temperature plays a key role in mitigating these effects. By cooling the detector, the radiation-induced loss of performance can be partially compensated, and the timing resolution can be recovered at the maximum fluence expected for ALICE 3, corresponding to $1 \cdot 10^{13} \text{ } n_{eq}/\text{cm}^2$.

Although still far from the 20 ps requirement of the ALICE 3 TOF system, the results presented in this thesis demonstrate that monolithic CMOS-LGAD detectors are a viable and competitive solution for future fast timing applications. Further technological optimizations are now ongoing to improve the present time resolution. These efforts include the investigation of thinner sensors and optimized device geometries aimed at achieving a more uniform and stronger electric field across the active volume. A new short-loop production has already been submitted using thinner substrates, aiming at achieving an enhanced timing resolution.

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Chapter 1

The ALICE Experiment at the LHC complex

This chapter provides an overview of the experimental and physics context of the ALICE experiment at the CERN Large Hadron Collider. After a brief description of the CERN accelerator complex and its main experiments, the fundamental aspects of heavy-ion collisions and their space–time evolution are introduced. The current ALICE experiment and its detector systems are first presented, followed by an introduction to the future heavy-ion program at the LHC. Finally, the next-generation heavy-ion experiment ALICE 3, which will succeed the present ALICE experiment, is introduced. Since this thesis is based on the experiment upgrade, a detailed description of the detectors composing ALICE 3 is provided.

1.1 The CERN accelerator apparatus and its experiments

The Large Hadron Collider (LHC) is a particle physics research complex at the European Organization for Nuclear Research (CERN) near Geneva. The LHC is the storage ring of the CERN accelerator apparatus and, with its circumference of 26.7 km, was installed in an already existing tunnel between 45 m and 170 m below the surface towards the Léman lake [2]. Designed to explore the fundamental structure of matter and the forces that govern it, LHC provides collisions of protons

and heavy ions at unprecedented energies. The main experiments installed at the CERN LHC are four: A Toroidal LHC ApparatuS (ATLAS) [3], Compact Muon Solenoid (CMS) [4], A Large Ion Collider Experiment (ALICE) [5] and Large Hadron Collider beauty (LHCb) [6]. ATLAS and CMS are the two detectors with the aim to study a wide range of physics beyond the Standard Model, from the Higgs boson to extra dimensions. The LHCb experiment is dedicated to studying the differences between matter and antimatter by investigating particles containing the beauty quark. Finally, the ALICE detector was designed and built to investigate the collisions of nuclei at the ultra-relativistic energies provided by the LHC and to study the matter created under such extreme conditions. To comprehensively understand how each experiment achieves its purpose, it can be useful to explain the mechanism of operation of this accelerator complex which is schematically sketched in Figure 1.1.

During the second long shutdown (LS2) in 2020, the Linear accelerator 4 (Linac4) became the source of proton beams accelerating negative hydrogen ions (H^-) to 160 MeV and driving them to the Proton Synchrotron Booster (PSB). Throughout this process these ions are stripped of their two electrons leaving only protons. They are first accelerated by the Proton Synchrotron (PS) and then by the Super Proton Synchrotron (SPS) achieving an energy of 450 GeV. Thanks this accelerating chain (see Figure 1.1), protons are ready to be injected into the two LHC beam pipes, where one beam circulates clockwise and the other anticlockwise, reaching their final energy in few minutes. Moreover, from the early stages of the LHC conceptual design the inclusion of heavy ion collisions was considered. In particular, lead ions produced from vaporized lead are initially accelerated in Linac3, then accumulated and further accelerated in the Low Energy Ion Ring (LEIR). From there, they follow the same LHC injector chain as protons, reaching their maximum energy.

The two-ring superconducting hadron accelerator, designed to achieve a proton beam energy of 7 TeV, demands a magnetic bending field exceeding 8 T, which is well above the capabilities of superconducting magnets used in previous hadron colliders. This lead to push the existing superconductor technology to its limits, requiring an unprecedented operating temperature of 1.9 K to ensure sufficient operational margins. Moreover, operating at this temperature with superfluid helium not only enhances the magnetic field capacity of the cables but also significantly improves cooling efficiency.[7]. The LHC incorporates an innovative 2-in-1 design concept, where two separate magnetic coils share a common cryogenic system and vacuum

chambers. The beams run in parallel and they are brought into collision only in the interaction regions where the four experimental detectors are positioned.

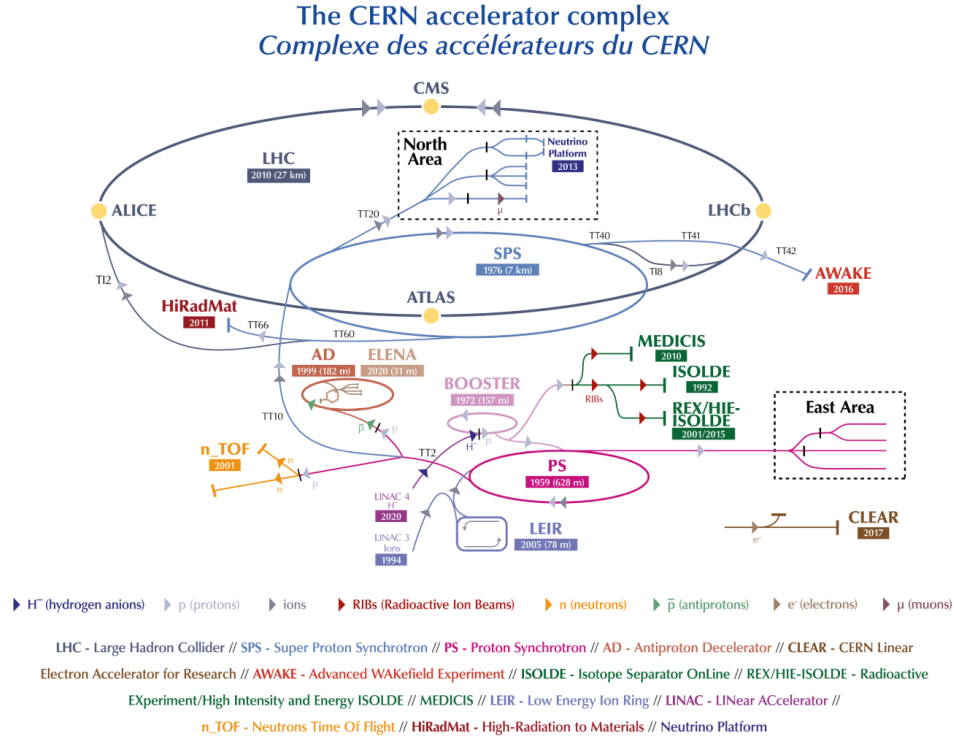


Fig. 1.1 A schematic overview of the CERN accelerator complex and the LHC experiments. Taken from [8].

1.2 Heavy-ion collisions

The Standard Model (SM) of particle physics, which describes the electromagnetic, weak, and strong interactions, provides a quantitative framework for describing the fundamental constituents of matter and their interactions. The theory provides precise predictions for the equation of state of SM matter, the nature of the electroweak and strong phase transitions, and fundamental properties such as transport coefficients and relaxation times. Collisions of heavy nuclei at ultra-relativistic energies, such as those delivered at the LHC, allow to create extreme conditions under which the high-temperature regime of the SM can be accessed in laboratory-based experiments, offering a unique opportunity to probe its non-perturbative thermodynamic proper-

ties.

Quantum Chromodynamics (QCD) is the quantum field theory that governs the strong interaction and constitutes a foundational component of the Standard Model. Since its development in the 1970s, QCD has provided the theoretical basis for understanding the internal structure of hadrons, thereby playing a central role in our description of the fundamental constituents of visible matter. It is formulated to describe the interactions between quarks and gluons (partons), the elementary particles that experience strong interaction, and is characterized by key properties such as asymptotic freedom, where the interaction strength diminishes at high momentum transfers. The strength of the strong interaction, characterized by the coupling constant α_s , varies with the momentum scale of the interaction. Figure 1.2 illustrates the measurements of the QCD coupling $\alpha_s(Q)$ as a function of the energy scale Q .

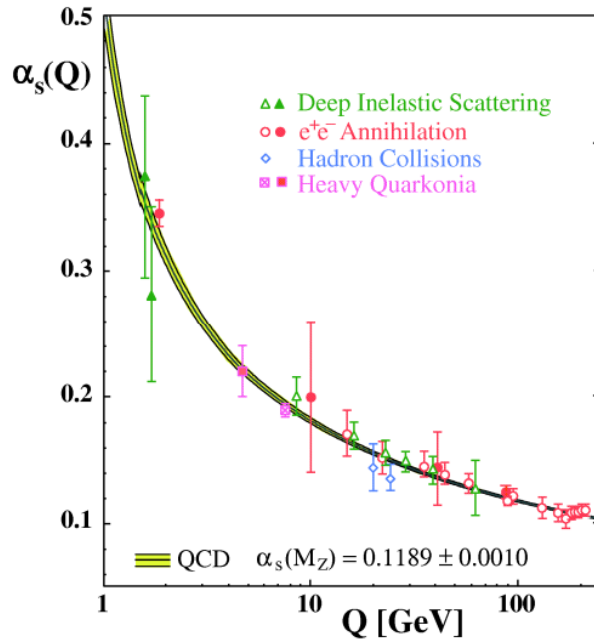


Fig. 1.2 Overview of the measurements of $\alpha_s(Q)$ as a function of the corresponding energy scale Q . Figure taken from [9] and references therein.

At high momentum transfers between partons, the use of perturbative techniques within Quantum Chromodynamics (pQCD) is reliable to describe the process. However, at low momentum scales, the coupling constant increases significantly, making the perturbative expansion invalid and thereby defining the non-perturbative regime of QCD. In this regime, two fundamental phenomena emerge: confinement and the

spontaneous breaking of chiral symmetry. Confinement prevents the isolation of quarks and gluons, which carry the “charge” of the strong interaction (known as colour), such that they cannot be observed as free particles. Only composite objects, known as hadrons, are detectable in experiments. Additionally, the spontaneous breaking of chiral symmetry in this regime is responsible for generating a huge fraction of the mass of hadrons, including protons and neutrons. As perturbative methods fail in this strongly coupled domain, alternative theoretical approaches such as Lattice QCD [10], [11] and Effective Field Theories [12] are required to capture the strongly coupled dynamics of quarks and gluons in non-perturbative regime.

The study of QCD matter can be investigated by creating a many-body system of quarks and gluons at sufficiently high energy densities. When such a system is heated to temperatures exceeding approximately 150–160 MeV (corresponding to over 10^{12} K), a phase transition results between the confined hadronic phase and a deconfined phase, commonly referred to as Quark-Gluon Plasma (QGP), in analogy with the electromagnetic plasma. This deconfined phase, in which quarks and gluons are not bound within hadrons and can propagate freely over distances larger than the size of a nucleus, forms a hot and dense medium and is believed to have existed for approximately 10 μ s following the Big Bang. In this high-temperature phase, the two fundamental properties of low-temperature QCD, confinement and spontaneous chiral symmetry breaking, are no longer manifest. In a baryon-number-symmetric system, the transition phase from a confined (hadronic) towards a deconfined (quarks and gluons) state occurs smoothly at $T \sim 155$ MeV. The corresponding temperature is commonly indicated as “pseudo-critical temperature” T_{pc} . This transition is characterized as a crossover, since no discontinuities appear in the thermodynamic observables and no latent heat is associated with the process. This configuration is of particular relevance as it reflects the conditions of the early Universe, where deconfined quarks and gluons hadronised around the pseudo-critical temperature T_{pc} . Ultra-relativistic heavy-ion collisions, such as those delivered at the CERN Large Hadron Collider, recreate conditions similar to those of the Big Bang, enabling the experimental study of the properties and signatures of the QGP.

The main focus of the research program of the ALICE experiment [13] is to study the strong interaction among particles, the fundamental force responsible for the very existence of atomic nuclei. More broadly, this interaction accounts for approximately 95% of the visible mass of the Universe.

1.2.1 Space-time evolution of a collision

The space-time evolution of ultra-relativistic heavy-ion collisions is typically described as a sequence of distinct stages, which can be factorized as shown in Figure 1.3.

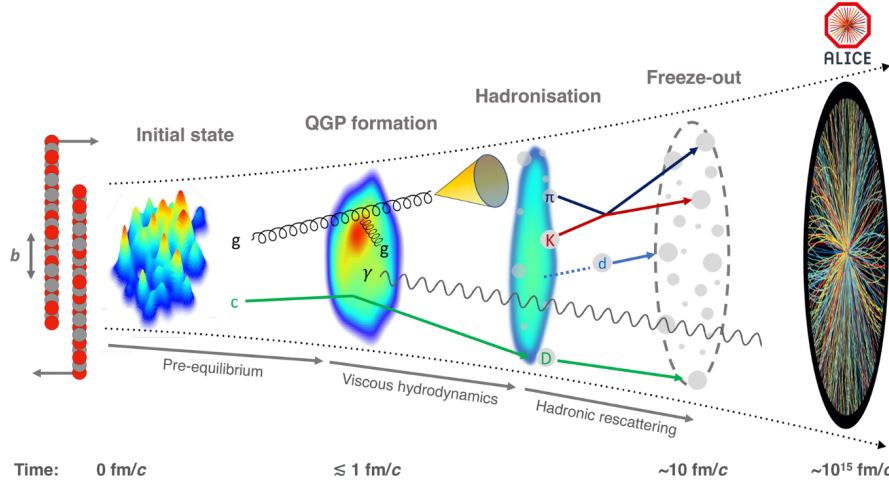


Fig. 1.3 A schematic view of the space-time evolution of a heavy-ion collision at LHC. Taken from [13].

The above figure shows the heavy-ions collision with impact parameter b , which is the distance between the centers of the colliding nuclei. This parameter is related to the number of participating nucleons (N_{part}), which are the nucleons in the nuclei that take part in an inelastic interaction. It also determines the volume of the collision region. The total number of inelastic nucleon–nucleon collisions is referred to as N_{coll} . When b is small, both N_{part} and N_{coll} are large, and vice versa. Nucleons that do not participate in the collision are referred to as spectators and continue to travel approximately along the beam direction following the interaction. Starting from the initial time $t = 0$ fm/c, the onset of the collision, the subsequent evolution can be divided into four phases:

- **Pre-equilibrium phase** ($\tau < 1$ fm/c): This initial phase of the collision is characterized by hard parton–parton scatterings occurring within the overlap region of the colliding nuclei, resulting in the rapid release of energy. These high- Q^2 processes lead to the production of particles with large masses or high transverse momentum. The particle production in this regime can be described

within the framework of perturbative QCD. However, at this stage, the system has not yet achieved thermal equilibrium.

- **Thermalization and Quark–Gluon Plasma formation:** Following the pre-equilibrium stage, the produced particles continue to interact with each other, creating a region of high energy density that rapidly evolves towards a locally thermalized state within approximately $\tau \sim 1 - 2 \text{ fm}/c$. At this point, the energy density exceeds the critical value predicted by lattice QCD, the system undergoes a transition to a deconfined phase of quarks and gluons, known as the quark–gluon plasma (QGP). In this hot and dense medium, the system exhibits collective behavior that can be described by relativistic hydrodynamics. The system expands and cools through inelastic and elastic collisions among its partonic constituents. The expansion continues until the system reaches the pseudo-critical temperature T_{pc} , highlighting the onset of hadronization.
- **Hadronization:** After the expansion phase, as the temperature drops below T_{pc} , the deconfined quarks and gluons recombine into hadrons. This process marks the transition from partonic to hadronic degrees of freedom. The system evolves into a hadronic gas, where the produced hadrons still interact via inelastic and elastic collisions.
- **Chemical and kinetic freeze-out** ($\tau \sim 10 \text{ fm}/c$): After hadronization, the *chemical freeze-out* occurs when inelastic collisions cease, fixing the relative abundances of particle species. However, elastic collisions may still happen and can modify the kinematic properties of the hadrons. Therefore, at a later stage, when the hadrons are sufficiently spaced apart, the system undergoes *kinetic freeze-out*, i.e. elastic collisions also cease and the momentum distributions of the hadrons become fixed. From this point onward, particles stream freely toward the detectors.

These particles propagate outward and reach the ALICE detector approximately $\tau \sim 10^{15} \text{ fm}/c$ after the initial collision. The high-energy beams delivered by the LHC offer an unprecedented opportunity to investigate the properties of the quark–gluon plasma in the laboratory.

However, since the QGP features a small size and short lifetime, it cannot be observed directly. Therefore, identifying appropriate experimental signatures is crucial for studying the formation and properties of the QGP. These signatures are classified

into three types of probes: hard, soft, and electromagnetic. Each of these probes interacts with the medium in different ways, providing complementary information about its formation, evolution, and properties.

- **Hard probes** involve particles or processes with high momentum transfer and originate from the earliest moments of the collision, making them sensitive to the entire evolution of the medium. Since the strong coupling constant α_s is small in these processes, their production rates can be calculated using perturbative QCD. Examples include the production of particles with high p_T and jets.
- **Soft probes** consider the collective behavior of the many particles produced in the later stages of the collision. They provide indirect insight on the phase transition of the QGP. They are characterized by low momentum transfer and have to be treated with non-perturbative methods. They are primarily composed by hadrons containing light quarks with momenta below 2 GeV/c.
- **Electromagnetic probes** such as photons and dileptons (electron–positron or muon pairs), offer the possibility to study in a unique way the QGP because they interact only electromagnetically and thus escape the medium largely undisturbed. These particles carry direct information about the temperature and evolution of the system.

The combined study of these probes allows to reconstruct the space-time evolution of the QGP and to test the predictions of QCD under extreme temperature and energy density conditions.

1.3 The present ALICE Experiment

ALICE is a comprehensive apparatus designed to investigate strongly interacting matter at extreme energy densities and temperatures, with a particular focus on the QGP. By recreating conditions similar to those that existed shortly after the Big Bang, ALICE allows the investigation of how such matter evolves and addresses fundamental questions about the organization of matter and the mechanisms responsible for quark and gluon confinement. The detector is optimized to study hadrons, electrons, muons, and photons produced in the collision of heavy nuclei (such as

Pb-Pb), but the physics program also includes interesting physics cases involving lighter ions or dedicated proton-nucleus (p-Pb) and proton-proton (p-p) runs [5]. The design and configuration of the ALICE detector are driven by the physics requirements and the challenging experimental environment expected in heavy-ion collisions. One of the most critical design constraints is the extremely high particle multiplicities, which may exceed those observed in proton-proton interactions at the same energy by up to three orders of magnitude. A wide dynamic range is required for accurate momentum measurements, from a few tens of MeV/ c to beyond 100 GeV/ c . This is achieved with a minimal material budget, approximately 13% of a radiation length X_0 , reducing the multiple scattering at low transverse momentum. Particle IDentification (PID) across most of this momentum range is crucial, as many key observables depend on the mass or flavor of the particles involved. To achieve this, ALICE employs an extensive set of PID techniques, including specific energy loss (dE/dx), time-of-flight measurements, detection of Cherenkov radiation, electromagnetic calorimetry, muon filtering, and topological reconstruction of decay vertices.

The ALICE detector measures approximately 16 m in height, 16 m in width, and 26 m in length, with a total weight of about 10,000 tonnes. It has been developed and continuously upgraded over nearly thirty years by an international collaboration involving over 2,000 scientists and engineers from more than 160 institutes across 40 countries. The experiment comprises 12 distinct detection systems, each based on specific technologies and optimized according to dedicated performance requirements and design constraints [14]. A schematic of all detectors is shown in Figure 1.4.

ALICE is composed of a central barrel and a forward muon spectrometer. The central barrel is designed to detect hadrons, electrons, and photons, covering a polar angle range from 45° to 135° , and is embedded within a large solenoidal magnet that provides the magnetic field necessary for charged-particle tracking and momentum measurement. Starting from the innermost region of ALICE, the barrel contains an Inner Tracking System (ITS) based on seven layers of ALPIDE Monolithic Active Pixel Sensors (MAPS) [15] which provides high-precision tracking of charged particles near the interaction point. The ITS plays a key role in the reconstruction of primary and secondary vertices and is essential for the identification of short-lived particles through their displaced decay vertices [16].

Surrounding the ITS, the Time Projection Chamber (TPC) is optimized for the full

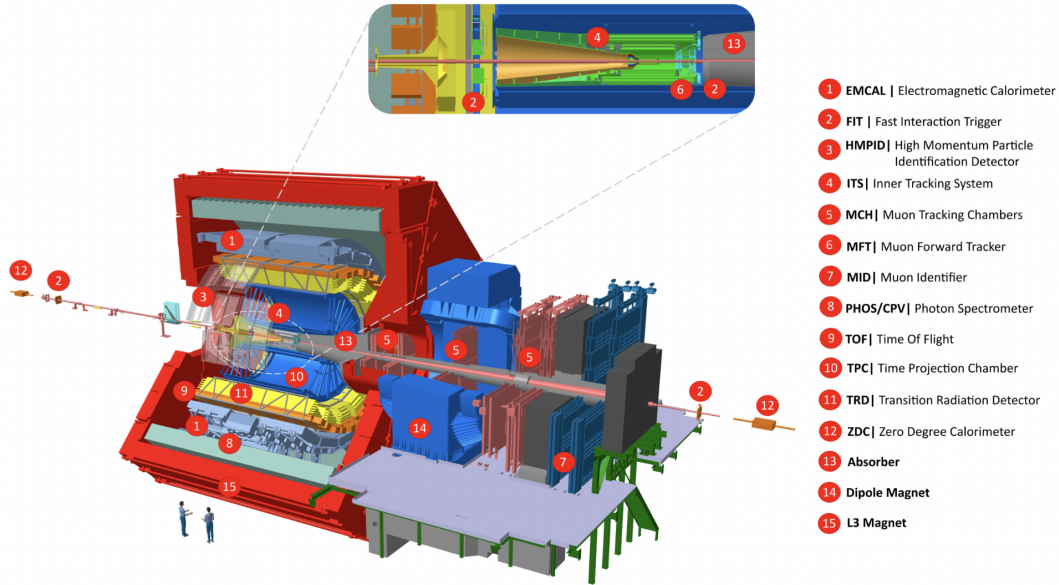


Fig. 1.4 A schematic view of the ALICE detector. Taken from [14].

three-dimensional reconstruction of charged particle trajectories in high-multiplicity environments. The TPC consists of a 90 m^3 cylindrical volume filled with a gas mixture enclosed within a uniform electric field generated by a central cathode disk and two end plates. When charged particles pass through the gas, they ionize producing free electrons. These electrons drift under the influence of the electric field toward the readout Gas Electron Multiplier (GEM) detectors located at both endcaps [17]. The drift time, combined with the known drift velocity, enables a precise reconstruction of the longitudinal (z) coordinate, while the transverse (x , y) position is determined by the segmented readout pads. In addition, the TPC measures the specific energy loss (dE/dx) of charged particles, providing particle identification capabilities. The detector has a very low material budget, enabling it to track low-momentum particles without significant energy loss or multiple scattering. The Transition Radiation Detector (TRD), located outside the TPC, consists of six layers of Multi-Wire Proportional Chambers (MWPCs), each preceded by a radiator made of polypropylene fibers to induce transition radiation. The TRD provides additional spatial points for charged-particle tracking, measures the specific energy loss for particle identification, and detects transition radiation for electron identification at intermediate to high momenta [18].

Even further outward is the Time-of-Flight (TOF) detector, which provides particle identification by measuring the time charged particles take to travel from the inter-

action point to the detector. By combining this timing information with the path length and the momentum measured by the tracking detectors, the TOF provides the separation of different hadron species, such as pions, kaons, and protons, over a wide momentum range, typically up to a few GeV/c. In addition, it enables the identification of electrons at low momentum, where other PID methods are less effective. The TOF system is composed of Multigap Resistive Plate Chambers (MRPCs) and achieves an excellent time resolution of approximately 60 ps [19].

Outside the TOF, there is the High Momentum Particle Identification Detector (HMPID) which consists of seven modules of Ring Imaging Cherenkov (RICH) detectors designed to enhance hadron identification capabilities to higher transverse momenta. It identifies charged hadrons by measuring the Cherenkov radiation emitted as they pass through a liquid radiator [20].

A significant portion of the central barrel acceptance is covered by an Electromagnetic Calorimeter (EMCal) and a Photon Spectrometer (PHOS). The EMCal is a large-area lead–scintillator sampling calorimeter and measures the energy of photons and electrons, crucial to reconstruct jets and high-energy events. The PHOS, with its high granularity and resolution, uses dense and transparent crystals for detecting low-energy photons and neutral mesons.

In order to study the properties of muons, ALICE is also equipped with a Muon Spectrometer, positioned at the end of the detector setup. This subsystem comprises an array of absorbers designed to eliminate hadrons, facilitating the identification of muons. The Muon Spectrometer also features a dipole magnet and a series of tracking chambers, which work in tandem to provide precise measurements of muons produced during the heavy-ion collisions. In addition, Muon Forward Tracker (MFT) is an integral part of the Muon Spectrometer, composed of tracking stations equipped with ALPIDE silicon pixel sensors. These sensors are strategically placed in front of the muon detector to enhance both mass resolution and pointing resolution, which are crucial for the detection of muons from various particle decays [21].

Finally, ALICE also includes several forward detectors located at small angles relative to the beam pipe: the Zero Degree Calorimeter [22], Photon Multiplicity Detector [23], Forward Multiplicity Detector [24], T0 [25] and V0 detectors [26]. These instruments provide essential information on particles produced near the beam axis, helping to determine event centrality, multiplicity, and particle spectra. They also play a crucial role in event selection and triggering for analysis [5].

1.4 From the present to the future heavy-ion program at the LHC

During the LHC Run 1 (2009–2013) and Run 2 (2015–2018), ALICE pursued a rich physics program, significantly improving our understanding of the QCD phase diagram and the properties of the QGP. These efforts led to the discovery of new phenomena, including in the study of J/Ψ production, where evidence was found for a novel production mechanism involving the recombination of deconfined charm and anti-charm quarks. In addition, a dependence of parton energy loss on quark mass was observed within the QGP. These results opened the way to a systematic investigation of the medium properties using charm and beauty quarks as calibrated probes. For a detailed overview of the main results from the ALICE experiment during Run 1 and Run 2, see [27].

In the Long Shutdown 2 (2019-2022) the ALICE experiment underwent significant detector upgrades to fully exploit the potential of the LHC [14]. These upgrades, together with the implementation of a new continuous readout system, enable to handle the high interaction rates expected in Runs 3 and 4, where the integrated luminosity for Pb–Pb collisions will increase in an unprecedented way. ALICE aims to exploit this increased data sample to achieve improvements in the precision of heavy-flavour production measurements and, for the first time at the LHC, to measure the thermal emission of dileptons in heavy-ion collisions. High-precision studies of heavy-flavour hadrons, mainly charm and beauty, will provide enhanced insight into the mass dependence of parton energy loss in the quark–gluon plasma, thereby offering stringent tests of theoretical models of QCD energy loss mechanisms [28]. The future ITS3 detector will enable in Run 4 the first direct measurements involving beauty hadrons with high precision, opening the door to a wide range of novel analyses [29].

Despite the scientific program planned for Runs 3 and 4, key questions will still remain without answers with the current detector capabilities. The final goal of the experiment remains a comprehensive understanding of the complex QCD dynamics in the QGP, including the interplay between parton energy loss, collective flow, hadronisation, and electromagnetic radiation. To achieve this aim, a new generation of experimental tools will be crucial, in particular, to improved some studies such as highly precision beauty measurements, $D\bar{D}$ correlations, azimuthal asymmetry of electromagnetic radiation, chiral symmetry restoration, high-statistics hadronic

physics [1].

To explore the above topics, an innovative detector design is proposed for a new experiment: ALICE 3. This new detector will be composed by ultra-low-mass silicon tracker with excellent spatial resolution and positioned in proximity to the interaction point. Its innermost layers will be located inside the beam pipe, enabling a wide rapidity acceptance. The tracking system will be complemented by exceptional particle identification capabilities, for hadrons, electrons, muons, and photons, across a large range of transverse momenta. The ALICE 3 is designed to collect data during the LHC Run 5 and 6, which are currently scheduled for mid-2036 (for the long-term schedule of the LHC, see Figure 1.5).

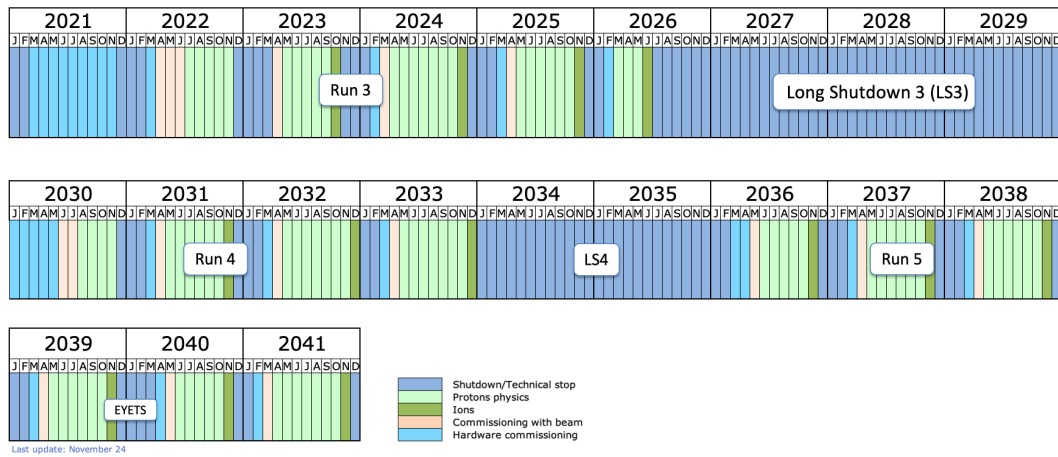


Fig. 1.5 Long-term LHC schedule with the main phases toward the ALICE 3 installation. Taken from [30].

1.5 ALICE 3: a next-generation heavy-ion experiment

ALICE 3 is the next-generation detector that will succeed the present ALICE experiment. The proposed experiment, shown in Figure 1.6, consists of compact and low-mass all-silicon detectors capable of tracking over a wide momentum range. The system is characterized by a retractable vertex detector to enable unprecedented pointing and decay vertex resolution, combined with a compact and lightweight tracking detector. The whole system is integrated with a superconducting solenoid magnet that generates a magnetic field of 2 T, enabling precise tracking of charged

particles. One of the key features of the ALICE 3 detector is its exceptional particle identification capabilities, which allow for the efficient separation and identification of various particle species. Furthermore, ALICE 3 features a continuous data acquisition system, paired with real-time processing capabilities, which ensures that the collected data is analyzed immediately. The detector is designed with an extremely compact geometry in both radial and longitudinal dimensions, providing complete azimuthal coverage up to a pseudorapidity of $|\eta| < 4$. This ensures comprehensive tracking and particle detection across a large phase space.

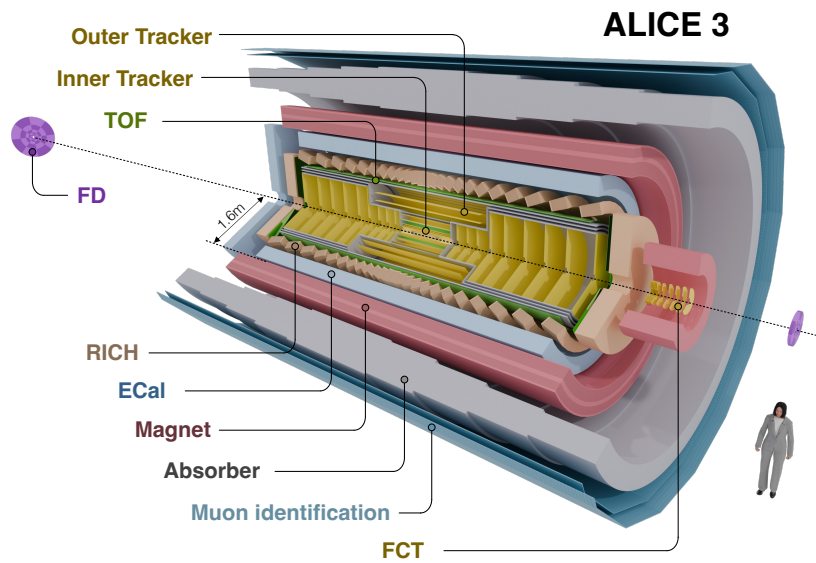


Fig. 1.6 ALICE 3 detector geometry. Taken from [31].

In addition, a better view of the pseudorapidity coverage of the different systems is available in the schematic longitudinal cross-section of the ALICE 3 detector reported in Figure 1.7.

The ALICE 3 layout presented in this thesis is the one reported in the Scoping Document [32] of the ALICE Collaboration. Although other possible detector versions and updates are currently under discussion, such variations would not affect the TOF R&D activities discussed in this work.

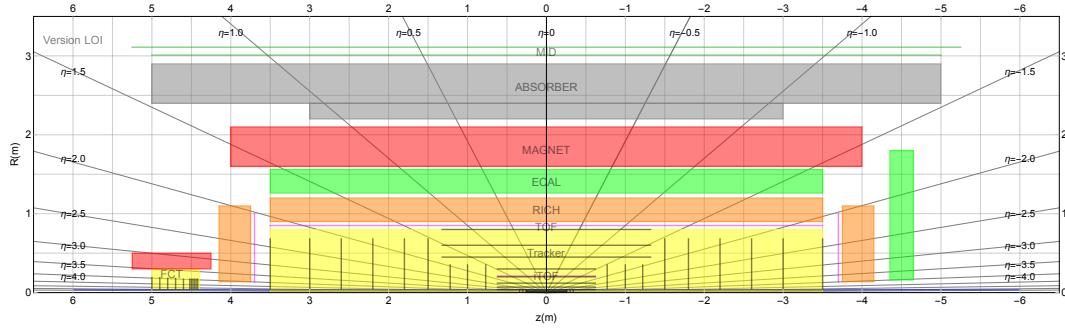


Fig. 1.7 ALICE 3 detector layout: longitudinal cross section. Taken from [31].

Tracking detectors. The central detector of ALICE 3 is a large silicon tracker, made up of CMOS monolithic active pixel sensors. It is designed to cover a total surface area of approximately 60 m^2 , with sensors distributed across barrel layers and forward disks. To achieve the required pointing resolution, the first hit must be recorded as close as possible to the interaction point, while minimizing the material budget in front of the first layer to minimize multiple scattering. Therefore, the *Inner Tracker* (IT) is divided into two main sections: the *Vertex Detector* (VD) and the *Middle Layers* (ML). The VD comprises three barrel layers and three disks on each side of the interaction point. Surrounding the VD, the ML consists of four barrel layers and is complemented by three disks on either side.

The *Vertex Detector* (VD), illustrates in Figure 1.8, will be positioned inside the beam pipe to enable tracking as close as 5 mm from the primary vertex. It is divided into four movable petals that operate simultaneously and, similar to an iris diaphragm in optics, can contract to a minimum inner diameter of 10 mm. The sensors used to equip the VD and the ML have to provide an intrinsic position resolutions of $2.5 \text{ } \mu\text{m}$ and $10 \text{ } \mu\text{m}$, respectively.

The *Outer Tracker* (OT) is positioned beyond the middle layers and disks of the Inner Tracker, covering the same pseudorapidity range of $|\eta| < 4$. It comprises four barrel layers and six forward disks on each side of the interaction point, covering approximately 50.4 m^2 of active detection area.

The selected technology node for both the Outer Tracker (OT) and Inner Tracker (IT) is the 65 nm CMOS imaging process developed by Tower Partners Semiconductor Co. Ltd. (TPSCo) [33].

Particle Identification detectors. The detectors dedicated to hadron and electron identification are the *Time-of-Flight* and the *Ring Imaging Cherenkov* detector.

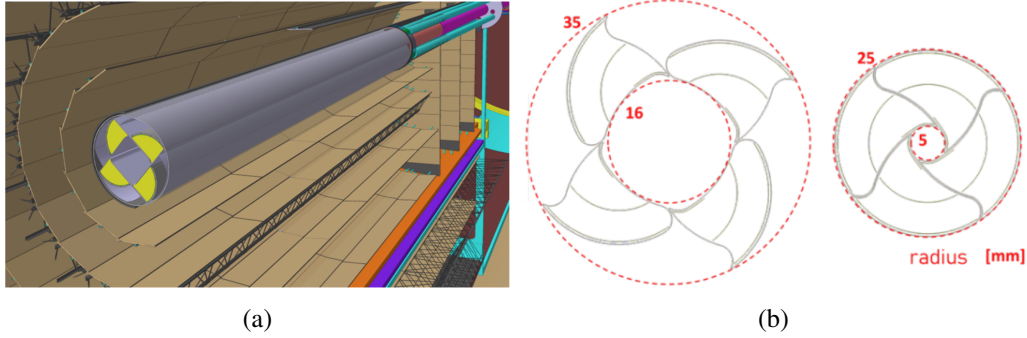


Fig. 1.8 Layout of the Vertex Detector. (a) The IRIS tracker concept inside the beam pipe, while (b) the movable vertex detector can be opened (left) with a radius of 16 mm during the acceleration phase and closed (right) during measurements achieving 5 mm radius.

Complementing each other, they can cover a large p_T range, spanning from 15–60 MeV/ c to several GeV/ c . An overview of the PID performance of these detectors, in terms of pseudorapidity and transverse momentum coverage, is given in Figure 1.9, highlighting the η - p_T regions where particle separation exceeds 3σ significance.

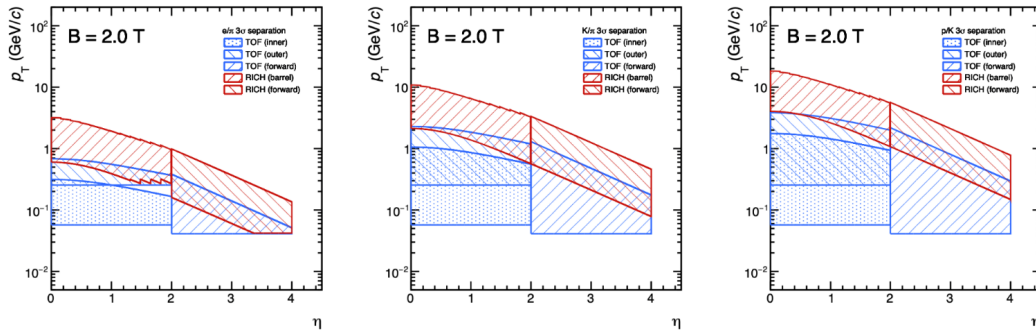


Fig. 1.9 The particle identification performance of the ALICE 3 PID systems is emphasized, showing analytical calculations of the η - p_T regions where a separation better than 3σ can be achieved. From left to right, the plots display electron/pion, pion/kaon, and kaon/proton separation. Taken from [34].

With a time resolution of 20 ps, the Time-of-Flight system comprises: an Inner TOF barrel (iTOF) positioned at a radius of 19 cm, as well as an Outer TOF barrel (oTOF) and forward disks (fTOF). The oTOF is positioned beyond the outermost tracker layer at a radius of 85 cm, while the fTOF disks are located beyond the last tracker disk at $|z| = 370$ cm. In addition, the fTOF can also be used to determine the collision time, providing the time-zero reference for individual particle timing measurements. The TOF detector system, which is the focus of the present thesis, will be described

in detail in Section 2.1.

To further improve the PID beyond the momentum range covered by the TOF, a RICH detector could be necessary. The barrel detector (bRICH), with a pseudorapidity coverage up to $|\eta| < 2$, consists of a 2 cm thick aerogel radiator with a refractive index of $n = 1.03$, positioned 110 cm from the beam and arranged in a barrel configuration with an inner radius of 90 cm. This is followed by a 20 cm gap where there is the photodetectors readout, as shown in Figure 1.10b. Aerogel must be opaque for ultraviolet wavelegths and transparent in the visible range, since most Rayleigh scattering of incoming radiation happens in the UV range. Therefore, the photon detectors used to observe Cherenkov light need to be responsive to visible light, and silicon-based photon sensors present a practical and commercially accessible alternative.

The system is expected to achieve an average Cherenkov angle resolution of 1.5 mrad, enabling electron–pion separation up to 2 GeV/ c and proton discrimination from electrons, pions, and kaons up to 10 GeV/ c . In the forward region, dedicated forward RICH disks (fRICH) with comparable performance but lower refractive index, due to the Lorentz boost, are foreseen at a distance of $|z| = 410$ cm on either side of the experiment, which can cover the pseudorapidity range between $2 < |\eta| < 4$. To improve PID performance minimizing the active area, a possible solution is given by a modular projective cylindrical design, Figure 1.10a.

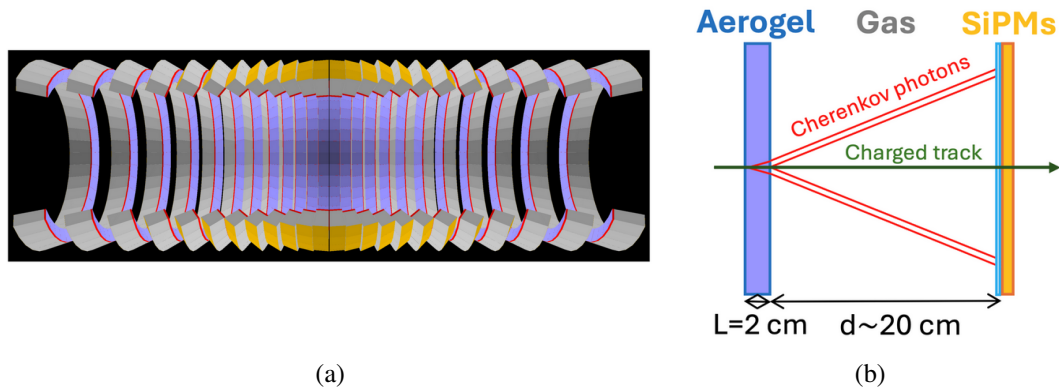


Fig. 1.10 Layout and technology of the RICH Detector. (a) The projective cylindrical bRICH design, and (b) a schematic illustration of the proximity-focusing aerogel configuration.

R&D studies are currently ongoing to assess the possibility of merging silicon photomultipliers (SiPMs) for Time-of-Flight (TOF) applications and Cherenkov

measurements. Recently the SiPMs have demonstrated to have a high detection efficiency thanks to the production of Cherenkov photons within the protective layer [35]. The use of these sensors to determine the arrival time of charged particles opens the possibility of implementing a single sensor layer for both Cherenkov photon detection and time-of-flight measurements, thereby considerably reducing the overall cost of the system. This Cherenkov-based TOF approach can be realized by placing a thin (1–2 mm) layer of solid Cherenkov radiator in front of the SiPMs and utilizing the precise timing of the emitted Cherenkov photons to extract TOF information from the incoming particles. The main limitation of this approach is the decreased overlap between the inner and outer time-of-flight layers, a factor that plays a key role in conducting systematic performance studies.

In ALICE 3, a *Muon Identifier Detector* (MID) is present and combine data from the tracking system with signals from the muon identifier. To enable muon identification, a steel hadron absorber approximately 70 cm thick will be positioned outside the magnet. Two layers of muon detectors are employed to capture muon tracklets (a straight-line segment formed by linking two spatial points measured in two detector layers) and correlate them with tracks reconstructed in the silicon pixel tracker, which provides information on the transverse momentum. The absorber is specifically optimized to efficiently reconstruct J/ψ mesons at midrapidity $|\eta| = 0$, complementing the electron identification capabilities.

The relatively low charged particle rate makes Resistive Plate Chambers (RPCs) or Multi Wire Proportional Chambers a viable and cost-effective options for the system. Nevertheless, an even more promising solution is the use of scintillator bars coupled with wavelength-shifting fibers and read-out by SiPMs, which is currently considered the baseline design.

The *Electromagnetic Calorimeter* (ECal) is designed to provide coverage across the entire barrel and one forward region. The barrel section with a total length of 7 m is positioned between the RICH detector and the magnet cryostat, and it is additionally split into two sections: the innermost region (central barrel) covering the pseudorapidity range $|\eta| < 0.45$ and the adjacent segments (referred to as the outer barrel) spanning $0.45 < |\eta| < 1.6$. The forward endcap instead is implemented as a disk with an inner radius of 0.16 m and an outer radius of 1.8 m. Located downstream of the forward RICH at $z = 4.35$ m, it extends the coverage to the pseudorapidity

interval $1.6 < |\eta| < 4$.

The majority of this range will be equipped with a Pb-scintillator sampling calorimeter, while the central barrel will be a high-precision section constructed from existing lead tungstate (PbWO_4) crystals with SiPM readout to enable precise measurements of χ_c states and low-energy direct photons. Sampling-type calorimeters are commonly employed in high-energy physics (HEP) experiments. The detection elements consist of alternating layers of high-atomic-number passive absorber materials, and active plastic scintillator layers. Scintillation light generated in the active layers is collected and transmitted to the photodetector through wavelength-shifting fibers. Since PbWO_4 crystals exhibit a strong temperature dependence of their light yield, to achieve optimal light output and high energy resolution, the ECal central barrel must be cooled to -25°C with temperature stability maintained at $\sigma_t = 0.1^\circ\text{C}$. Given the tight spatial constraints imposed by the solenoid magnet, the cooling system must be compact and employ thin insulation.

One of the challenging features of ALICE 3 is the capability of detecting photons with extremely low transverse momentum, down to $2 \text{ MeV}/c$. An accurate measurement will be feasible by exploiting the Lorentz boost at high pseudorapidities, $|\eta| \sim 4$. The *Forward Conversion Tracker* (FCT), designed for tracking the $e^\pm$ pairs resulting from ultrasoft photons conversions is composed of silicon pixel disks positioned in the forward region, enabling precise reconstruction of both photon trajectory and its energy. The $e^\pm$ pairs in the presence of a magnetic field are bent with a radius of approximately 10 cm in order to be measured by using a sequence of tracking layers arranged with roughly 2 cm spacing. To maintain high spatial precision for electrons with higher momenta, additional disks are planned with increased separation. These layers can utilize the same silicon pixel technology employed in the ALICE 3 ML, and they should be made as thin as possible to reduce material budget and limit the effects of multiple scattering. Moreover, the silicon layer of the ALICE 3 tracker located just before the FCT can function as an active photon converter, while simultaneously offering tracking data at the point of conversion. Therefore, a separate converter is not necessarily required, since it could degrade both the energy and angular resolution due to multiple scattering and energy loss. Nevertheless, research is still in progress to finalize the setup and assess the viability of the measurement.

Lastly, charged-particle detectors using scintillator tiles coupled with photomultipliers at very forward and backward pseudorapidities, $4 < |\eta| < 7$ will be employed for luminosity measurement and monitoring. They will also help extend the coverage for characterizing event activity or applying veto conditions.

Chapter 2

The ALICE 3 Time-of-Flight detector: candidates technologies

This chapter is dedicated to the Time-of-Flight (TOF) detector of the ALICE 3 experiment and to the silicon sensor technologies considered for its implementation. Firstly, the ALICE 3 TOF system is presented, focusing the attention on the key aspects required to satisfy the physics program of the experiment. The main feature of the TOF system is a demanding timing resolution of 20 ps. In particular, the three main candidate technologies are presented: the Low-Gain Avalanche Diodes (LGADs), the Fully Depleted Monolithic Active Pixel Sensors (FD-MAPS), and the Single-Photon Avalanche Diodes (SPAD). The monolithic approach is the baseline option for the TOF detector, and is the main focus of this thesis. The present state-of-the-art of each technology is described to highlight its advantages and limitations in the context of the requirements of the ALICE 3 TOF detector.

2.1 The ALICE 3 Time-of-Flight system

The TOF system, which constitutes the main focus of this thesis, enables particle identification across the full pseudorapidity range $|\eta| < 4$. With a total area of silicon of 45 m², it comprises an inner and outer layer, and two forward disks on each sides of the experiment.

The primary characteristics and dimensions of the TOF setup are listed in Table 2.1, but its three key aspects can be summarized in: an impressive time resolution

as low as 20 ps (r.m.s.), combined with an extremely low material budget of 1–3% of X_0 and a reduced power consumption of only 200 mW/cm². A significant progress in the timing capabilities of silicon detectors has been achieved in recent year, but an intense and focused R&D program is necessary to design and build a large-scale system as the one required for ALICE 3. Another important aspect regards the requirement of hit rate and radiation tolerance which are relatively moderate in contrast to other detectors at the LHC. This less demanding radiation environment allows for the exploration of a broader range of technological options, including lightweight monolithic silicon sensors, which would be challenging to deploy in high-luminosity experiments such as ATLAS or CMS. In particular, timing systems of ATLAS and CMS rely on highly radiation-hard silicon sensors based on LGAD technology [36], [37], optimized to operate in high pile-up conditions and an extremely harsh radiation and hit-rate environment. As a consequence, technologies that may successfully be employed in the ALICE 3 system, such as SiPMs or CMOS sensors, cannot be straightforwardly adopted. SiPM-based systems, while offering excellent timing resolution, suffer from significant limitations in high-radiation environments. In particular, the dark count rate and noise increase dramatically after exposure to the fluences expected at the HL-LHC, leading to a severe degradation of timing performance and operational stability. Moreover, standard CMOS technologies, although highly attractive for low-material, present limited intrinsic timing resolution, which is insufficient to achieve the 30–40 ps precision required for effective pile-up mitigation in ATLAS and CMS. In addition, radiation-induced damage would significantly affect charge collection efficiency and long-term reliability.

The inner and outer barrels, along with the disks, can utilize identical sensors and front-end electronics. The inner TOF requires a cell dimension of the order of $1 \times 1 \text{ mm}^2$, while the outer TOF uses approximately $5 \times 5 \text{ mm}^2$ cells. The final choice of cell dimensions will primarily depend on the sensor capacitance and associated noise, both of which influence time resolution. To minimize the material usage and the overall cost of the detector, the goal is to construct each TOF element, like inner TOF, outer TOF, etc, by using a single sensor layer, even though the possibility of using two not-aligned silicon layers is still open.

The TOF detector can be divided into five essential components: the sensor, the front-end electronics, which will be discussed later, the Time-to-Digital Converter (TDC), the clock control unit, and the data readout system. Over the past decade,

Table 2.1 Time-of-Flight specifications [1].

	Inner TOF	Outer TOF	Forward TOF
Radius (m)	0.19	0.85	0.15 to 1.5
z range (m)	– 0.62 to 0.62	– 2.79 to 2.79	4.05
Total area (m ²)	1.5	37	6
Pixel size (mm ²)	1×1	5×5	1×1 to 5×5
Particle hit rate (kHz/cm ²)	200	15	280
Material budget per layer (% X_0)	1 to 3	1 to 3	1 to 3
Power density (mW/cm ²)	200	200	200
Time resolution (ps)	20	20	20
Radiation tolerance NIEL (1 MeV n_{eq} /cm ²)	$7 \cdot 10^{12}$	$9 \cdot 10^{11}$	$1 \cdot 10^{13}$
Radiation tolerance TID (rad)	$3 \cdot 10^5$	$2 \cdot 10^4$	$4 \cdot 10^5$

the performance of TDCs has improved significantly. In recent R&D activities, TDCs can operate at sampling rates of several tens of MHz while maintaining power consumption at the level of a few mW per channel. Such TDCs can reach a bin size of 10 ps, corresponding to an r.m.s. quantization noise of approximately 3 ps, which is negligible compared to the system resolution of 20 ps [38]. Moreover, a low-power GigaBit Transceiver (lpGBT), a transceiver ASIC that transmits and receives high-speed data and supports communication between detector front-end electronics and the data acquisition (DAQ) framework, can deliver an LHC clock with 5 ps jitter [39]. The readout will rely on an asynchronous communication between individual pixels and the surrounding periphery to prevent power loss caused by clock signal distribution across the entire matrix. The produced data stream will be gathered at the edge of the chip, serialized, and transmitted off the chip via high-speed serial connections. The Time-over-Threshold (ToT) technique will be used to compensate for time-walk effects while a bandwidth of 1 Gbit/s will be sufficient to allow data transmission. Finally, from the current ALICE TOF system, it is known that the detector can independently determine the event-collision time with a precision of 5 ps during high-multiplicity events, contributing minimally to the overall time-of-flight measurement.

2.2 Candidate technologies

Three silicon technologies have been selected as potential candidates to build the TOF detector, and dedicated R&D are already underway to prove their feasibility: Low-Gain Avalanche Diodes (LGAD), fully depleted CMOS sensors and Single Photon Avalanche Diodes (SPAD).

2.2.1 Low-Gain Avalanche Diodes (LGAD)

Traditional Low Gain Avalanche Detectors are one of the most advanced devices for precision timing in silicon sensors almost able to achieve the strict requirement of the 20 ps time resolution for the ALICE 3 TOF system.

LGADs are *n-in-p* silicon detectors with an extra p^+ doping layer ($\sim 10^{16} \text{ cm}^{-3}$), referred to as the gain layer positioned near the junction to enable a controlled avalanche process, as illustrated in Figure 2.1.

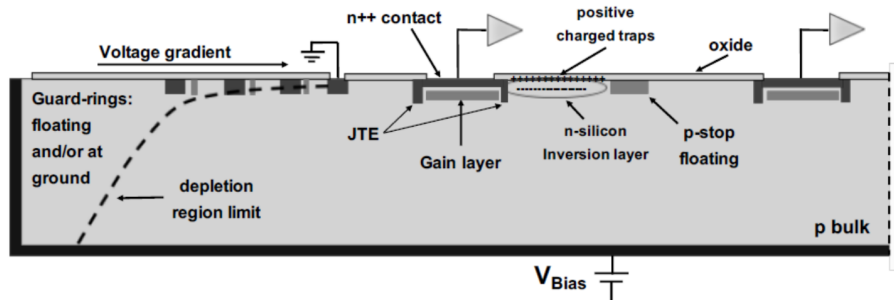


Fig. 2.1 Typical cross section of an LGAD. Image source [40].

Because the p^+ layer is more doped than the surrounding bulk material, it forms a very localized region with a strong internal electric field, which enables charge multiplication and thereby enhances the output signal. The charge multiplication is based on the avalanche mechanism triggered by a carrier (electron or hole) drifted through a region with a sufficiently high electric field ($\geq 300 \text{ kV/cm}$). In this way, the drifting charge acquires kinetic energy sufficient to generate multiple electron-hole pairs through interactions with the crystal lattice. This defines the onset of the avalanche process: iteratively, the newly created charge carriers are further accelerated by the electric field and can produce additional electron-hole pairs. The LGAD design provides a moderate gain, typically in the range of 10-30. A gain of

approximately 20 may represent an optimal value for the operation of LGADs and for achieving the best device performance, as demonstrated in [41].

LGADs commonly employ substrates with thicknesses ranging from 20 to 50 μm . As shown in Figure 2.1, guard rings are located at the periphery of the sensor. These elements, formed by an n^{++} implant, serve to gradually reduce the voltage from the sensor outer edge (held at the bias potential) to the first readout pad, maintained at ground by the readout electronics. Moreover, the gain layer is enclosed by a doped n^{++} region known as the Junction Termination Extension (JTE). This JTE is included in every pad and serves to prevent the gain layer from collecting electron-hole pairs produced by particles traversing the inter-pad region. To electrically separate the n^{++} implants of the pads, an additional p^{++} implant, known as the p-stop, is required. In the absence of p-stops, positive charges at the Si–SiO₂ interface can induce an inversion layer, which would electrically connect all the n^{++} regions, resulting in a short-circuits between the pixels.

As already anticipated, the avalanche process starts when a charge moves through a region with a strong electric field. This phenomenon, commonly referred to as the *impact ionization mechanism*, is represented by Eq. 2.1, where $N_{e,h}(d)$, represents the number of electron-hole pairs produced during the avalanche and depends exponentially on the impact ionization coefficient $\alpha_{n,p}$ and on the distance d traveled by the particle within the high-field region:

$$N_{e,h}(d) = N_{e,h}(0)e^{\alpha_{n,p}d} \quad (2.1)$$

The inverse of α represents the mean free path a carrier travels between successive scattering events generating secondary charges, defined as $\lambda = 1/\alpha$. At a fixed electric field, this mean free path is shorter for electrons (λ_n) than for holes (λ_p). As a result, the electric field can be adjusted to have the multiplication of only electrons. It is possible to describe the gain G as the ratio between the final and the initial quantity of electron-hole pairs:

$$G = \frac{N_{e,h}(d)}{N_{e,h}(0)} \propto e^{\alpha_{n,p}d} \quad (2.2)$$

The signal induced on a given electrode in a detector without internal gain and with a thickness d is based on the Ramo–Shockley theorem [42][43]. Assuming a pixel size much larger than the sensor thickness, the weighting field is a constant

($\vec{E}_w \propto 1/d$) and, if the electric field is high enough, the carriers velocity is saturated (v_{sat}), therefore the initial current can be written as:

$$I_{max} = -q\vec{v} \cdot \vec{E}_w \propto Nq\frac{1}{d}v_{sat} = (n_{e,h}d)q\frac{1}{d}v_{sat} = n_{e,h}qv_{sat} \quad (2.3)$$

where N represent the total number of electron-hole pairs assuming a uniform generation of pairs per micrometer throughout the sensor, and it is given by multiplying the sensor thickness d and the number of electron-hole pairs $n_{e,h}$ generated per unit length. The equation shows an interesting feature of silicon sensors: the peak current in a diode is independent on the detector thickness and depends only on the velocity of the charge carriers. This underlies the limited timing precision of silicon detectors without a gain layer: the signal amplitude is limited by the saturated carrier velocity and the peak value of the weighting field, making it impossible to boost the signal by increasing the sensor thickness.

In a LGAD sensor, electrons enter the gain layer triggering the avalanche multiplication mechanism and generating secondary electron-hole pairs (gain electrons and gain holes). Since the multiplication occurs very close to the cathode, the gain electrons are promptly collected, while the gain holes must drift almost the full sensor depth before reaching the anode, producing most of the resulting signal. Because electrons have a higher drift velocity than holes, by the time the last primary electron arrives at the cathode, the first gain hole is still in transit. Therefore, the signal rises until the last primary electron is collected, remains nearly steady while the first gain hole drifts, and then gradually decreases to zero over a time period determined by the holes velocity. A representative simulated signal of an LGAD, displaying the individual contributions of both primary and secondary electrons and holes, is shown in Figure 2.2.

Following the calculation presented for the diode without a gain layer, it is possible to determine the peak current in a LGAD. In this case as well, N represents the total number of electron-hole pairs. However, since each primary electron generates G additional electron-hole pairs through the gain mechanism, the maximum current I_{max} can be expressed as:

$$I_{max} \propto Nq\frac{1}{d}v_{sat} = (n_{e,h}dG)q\frac{1}{d}v_{sat} = n_{e,h}Gqv_{sat} \quad (2.4)$$

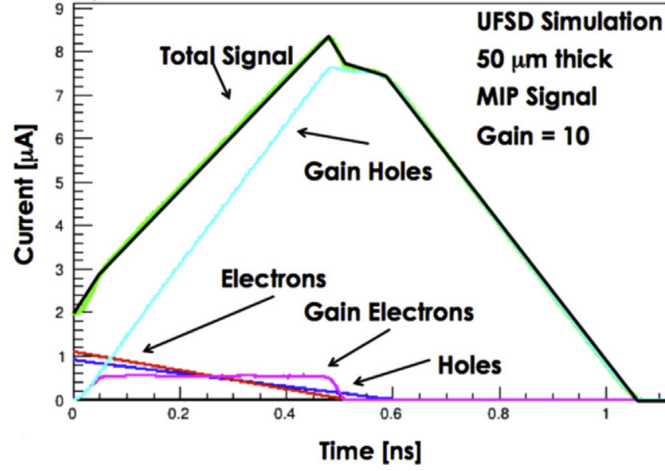


Fig. 2.2 Simulation of the total current with the various current component, generated by a MIP traversing a 50 μm thick sensor. Taken from [44].

Equation 2.4 shows that, under saturated drift velocity conditions, the peak signal current is determined solely by the gain and it is independent of the detector thickness. On the other hand, it is possible to estimate the LGAD current as the quantity of electron-hole pairs dN_{gain} created by primary electrons entering the gain region during a time interval dt . It can be easily demonstrated from [44] that:

$$\frac{dI_{\text{gain}}}{dt} \sim \frac{dV}{dt} \propto \frac{G}{d} \quad (2.5)$$

This highlights another key characteristic of LGADs: the enhancement in signal current caused by the multiplication process is directly proportional to the ratio of gain to sensor thickness (G/d). This means that thin detectors with high gain produce signals with fast *slew rates* (dV/dt , as well described later), making them well-suited for high-precision timing applications. This effect is demonstrated in Figure 2.3, which shows how the signal rise time can be reduced by maintaining a constant gain while adjusting the active thickness of the sensor.

It is possible to conclude that the gain and the sensor thickness determine the signal amplitude and rise time, respectively.

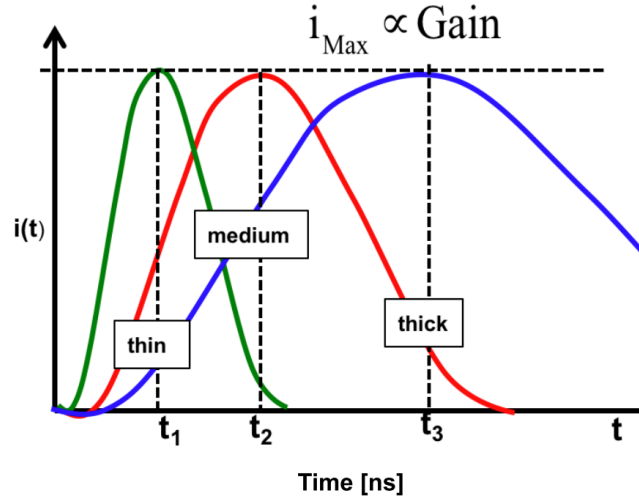


Fig. 2.3 Simulation of the current signals for a fixed gain but different active thicknesses. Taken from [41].

LGAD Temporal resolution

The fundamental aspect of LGAD operation lies in precisely adjusting the electric field to enable a controlled charge multiplication process. They work below the breakdown voltage, which is the maximum reverse-bias voltage that can be applied across the device before entering in a regime of uncontrolled carrier multiplication and excessive leakage current. It is therefore necessary to choose the voltage carefully, in order to find a tradeoff between the breakdown voltage and a bias value high enough to achieve a sufficient enhancement of the signals. At the same time, the dominant contribution affecting the timing precision of an LGAD is the *Landau noise* [41], an intrinsic characteristic of silicon, which reflects the irregular nature of charge deposition within the detector. This phenomenon arises from the non-uniform charge generation along the particle path, which leads to fluctuations in the signal shape. Using thinner substrates helps mitigate the impact of Landau noise. Recent test beam studies [45] have demonstrated that a 35 μm thick LGAD (FBK35) achieves a time resolution of 22 ps at a bias voltage of 240 V, and a 25 μm sensor (FBK25) reaches 25 ps timing precision at 120 V. Meanwhile, a 50 μm thick LGAD shows a time resolution of approximately 30 ps. All the results are shown in Figure 2.4.

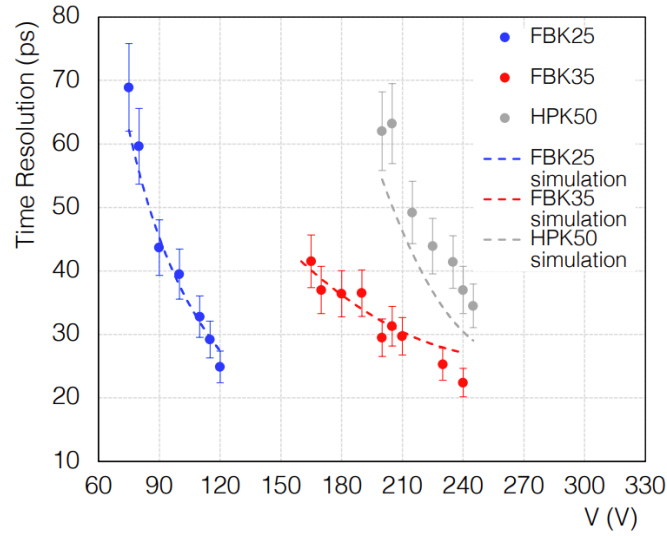


Fig. 2.4 Experimentally measured (circles) and numerically simulated (dashed curves) time resolution results as a function of bias voltage for three different sensor thickness. Taken from [45].

An additional key parameter is the sensor fill factor (FF), which refers to the portion of the detector area that actively contributes to particle detection. The strong electric field created by the gain layer must be carefully confined to prevent cross-talk between adjacent pixels and to reduce the risk of electrical edge-breakdown. Lateral electric field components are managed through the presence of the JTE and p-stops regions at the price of forming dead areas without gain. To overcome this issue and mitigate the gain reduction caused by sensor segmentation, two technological approaches have been developed:

- A promising solution found to overcome the segmentation in LGAD sensors is the use of the Deep Trench Isolation (DTI) technology [46], already applied in the design of CMOS image sensors and SiPMs. It involves shallow trenches into the silicon substrate, usually filled with insulating materials such as silicon dioxide, eliminating the need for p-stop implants and the JTEs at the sensor edges. Prototypes of **Trench-Isolated LGADs** (TI-LGADs) have been fabricated, showing an inter-pad inactive region as small as $\sim 10 \mu\text{m}$, enabling a fill factor approaching 100%.
- An alternative approach involves an advanced version of LGADs known as **Resistive AC-Coupled Silicon Detectors** (RSDs or AC-LGADs), where the gain

layer extends across the entire surface of the sensor, without segmentation[47][48]. The device includes a resistive n^+ layer characterized by a sheet resistance on the order of few $k\Omega$, through which the charge carriers travel. Signal readout is achieved using AC-coupling capacitors, which induce signals on the metal electrodes and enable a fine segmentation. In this approach, both the n-type layer and the gain region are completely spread over the entire sensor surface, enabling a fill factor of 100%.

A key difference compared to traditional LGADs lies in how the signal is generated. The created electron-hole pairs initially induce a charge on the resistive n^+ implant, then they drift toward ground through it. However, the AC metal pads, connected to the readout electronics, provide a lower-resistance path to ground for fast signals than the resistive sheet itself. As a result, these fast signals appear on the AC pads, charging the coupling capacitors. Later, the pads are discharged via the DC contacts.

2.2.2 Fully Depleted Monolithic Active Pixel Sensor (FD-MAPS)

In the LGAD approach, the sensors and readout electronics are manufactured on separate wafers. Two main strategies can be used to interconnect the sensor to the front-end electronics. The first involves aligning the channel layout of the front-end ASIC with the pixel array of the sensor, and linking them via bump-bonding. This method requires the ASIC to match the sensor dimensions, which increases production costs. Although direct bump-bonding between the sensor and front-end channels minimizes parasitic capacitance and inductance, the highest timing resolution achieved with LGADs so far has been using conventional ultrasonic wire bonding between the sensor and the front-end electronics. Given the high manufacturing costs and complicated assembly procedures, monolithic sensors seem to be a promising alternative under these respects.

Unlike standard LGADs, which are built on sensor-grade wafers and rely on custom-designed readout electronics, monolithic sensors can reduce manufacturing costs, decrease the material budget, and simplify the assembly processes typical of hybrid devices, since the front-end electronics is embedded in the same silicon substrate of the active sensor. In recent years, extensive development has been focusing on achieving smaller pixel sizes, low noise levels, and low power consumption in MAPS for tracking applications [49]. However, their capabilities for high-precision timing

have not yet been fully investigated and significant R&D efforts are necessary to this purpose. The present timing resolution of CMOS sensors is of the order of few ns; therefore, it must be significantly pushed to achieve the requirement of 20 ps for the TOF detector.

To achieve high timing performance, fast charge collection is essential, necessitating a fully depleted sensors. Moreover, optimizing the sensor geometry and the corresponding electric field distribution is crucial. Devices with small collection electrodes benefit from low capacitance and improved Signal-to-Noise Ratio (SNR) [50] but suffer from highly non-uniform electric fields, since the drift path lengths are not straight and all equal. This impacts negatively on the time performance of the sensor. On the other hand, larger electrodes improve field uniformity but introduce higher capacitance, reducing the SNR. A promising solution to enhance the SNR involves adding a gain layer beneath the collection electrode, enabling charge multiplication through impact ionization. The integration of the LGAD concept on a monolithic sensor will be extensively discussed in Chapter 4.

2.2.3 Single Photon Avalanche Diodes (SPAD)

The third technology candidate for the construction of the ALICE 3 TOF detector is based on Single Photon Avalanche Diodes, which have been employed for photon detection and counting for several decades. These semiconductor devices feature a doped p–n junction, typically 0.5–2 μm thick, known as the gain region, which is biased above its breakdown voltage. In this configuration, even a single electron or hole entering the region can trigger an avalanche via impact ionization, resulting in a detectable signal. To restore the electric field and return the SPAD to its sensitive state after the diverging avalanche and the breakdown phenomenon, a quenching resistor (Q_R) or external quench circuit connected to the device is used. Although initially designed as single-channel devices, advancements in silicon technology have enabled the integration of many SPADs into two-dimensional pixel arrays. Moreover, based on the architecture of the readout electronics, these systems are referred to either as SPAD image sensors or Silicon Photomultipliers (SiPMs). In the first case, each SPAD pixel is read out individually to generate an image; while, in the second one, the single pixels are connected in parallel through series resistors, forming a unified output channel. In this configuration, the output signal amplitude corresponds to the number of pixels that have triggered, and thus is proportional to the number of

photons incident on the matrix [51]. Figure 2.5 presents a cross-sectional view of a standard SiPM structure.

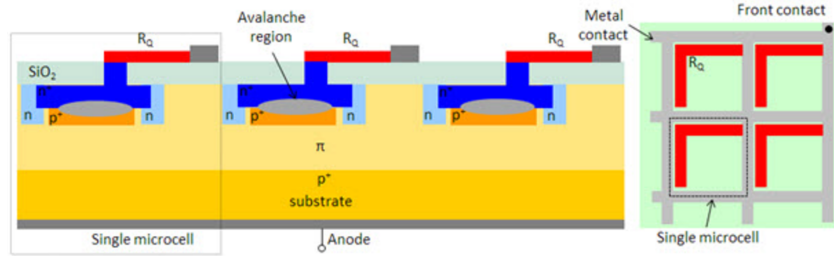


Fig. 2.5 Typical cross section of a SiPM and schematic layout of a matrix on the right. Image source [52].

A SiPM is capable of directly detect light across a broad spectrum, from near-ultraviolet to near-infrared wavelengths. Its configuration supports "simultaneous" photon detection, which allows multiple photons to be measured, facilitating also photon counting. The device is made up of an array of compact, light-sensitive units known as micro-cells (or pixels), all electrically linked in parallel. These micro-cells typically range in size from $10\ \mu\text{m}$ to $100\ \mu\text{m}$, and the total number per device can vary from a few hundred to several tens of thousands. Each micro-cell works as a Geiger-mode Avalanche PhotoDiode (GM-APD), operating above its breakdown threshold. The difference between the applied bias voltage and the diode breakdown threshold is referred to as overvoltage (OV), which is a key parameter to decide the device functions. When a SiPM detects an incoming photon, the generated charge carrier (either an electron or a hole) may initiate an avalanche within the multiplication region. This avalanche process can create between 10^5 and 10^6 charge carriers, which define the internal gain of the sensor. While the purpose of the quenching resistor is to return the APD to its Geiger-mode state after each event. The gain varies linearly with the applied overvoltage and is also influenced by the junction capacitance value [52].

SiPMs are generally regarded as detectors that are not sensitive to charged particles, meaning that signals due to the passage of charged particles typically do not compete with signals generated by incident photons. Nevertheless, researches have shown that SiPMs are capable of directly detect ionizing radiation, even without relying on a photon-producing medium like a scintillator, and achieving a good time resolution [53]. As outlined in [35], the resin layer found on the entrance window of a SiPM (typically added as a protective coating) was identified as the origin of the detected

signal produced during the passage of an ionizing charged particle, due to Cherenkov light being generated within the resin itself. When a charged particle passes through the protection layer, the Cherenkov effect generates a substantial number of photons. Since the resin layer is very thin, these photons reach the SiPM surface within just a few picoseconds of delay. This results in a strong signal, with numerous SPADs firing at once. In recent years, various R&D studies have been conducted, and new developed prototypes featuring alternative protective layers have been evaluated [54]. Latest test beams have been shown the timing performance of SiPMs equipped with a protective resin layer can improve as more SPADs are fired, reaching values below 20 ps when over five SPADs are triggered for MIPs at 10 GeV/c, see Figure 2.6. This capability opens the door to the use of SiPMs for Particle Identification (PID) measurements in upcoming experiments, such as Time-of-Flight systems, which demand both precise timing and accurate tracking capabilities. They could also serve as sensors in RICH detectors, matching their ability to detect photons and identify the particle impact position.

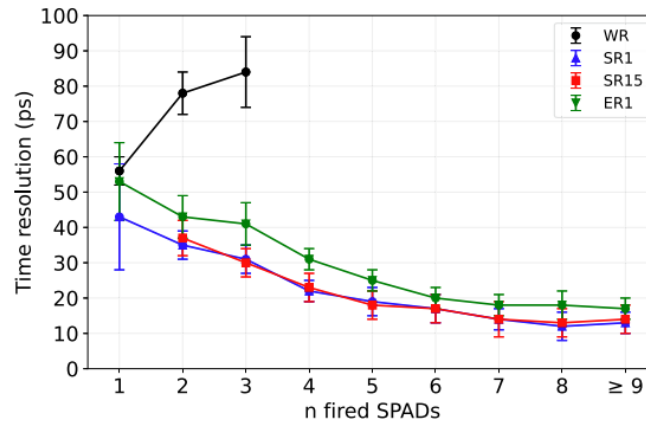


Fig. 2.6 Measured time resolution as a function of the number of firing SPADs for four different sensors: three with a protection layer, in particular silicone Resin 1 mm (SR1), silicone Resin 1.5 mm (SR15) and epoxy Resin 1 mm (ER1); while one without resin (WR). Taken from [54].

These results highlight the crucial role of the protective layer and the contribution of Cherenkov light in enhancing the timing response of SiPMs to passing charged particles.

However, the radiation levels foreseen in the regions designated for the two TOF layers and endcap disks indicate that SPADs are not suitable for being used in the

inner TOF section or in the two disks. As a result, this approach will be further investigated only for the outer TOF layer.

A promising approach would be the development of a sensor capable of efficiently detecting both minimum ionizing particles (MIPs) and individual photons, while also offering excellent timing resolution. Such a device could serve a dual purpose, acting both as a Cherenkov detector and as a Time-of-Flight layer, thereby significantly lowering the overall cost of the detection system. The idea of a Cherenkov-based TOF detector could be realized by placing a thin layer (1–2 mm) of solid Cherenkov radiator in front of the SiPMs, and using the timing data from the Cherenkov photons to determine the TOF of the passing particle [32].

Chapter 3

Monolithic technologies for timing applications

Monolithic detectors constitute a major step forward in particle detector technology, particularly in tracking systems used in HEP experiments. Their development has been driven by the need for faster, lighter, more radiation-tolerant, and cost-effective tracking detectors in increasingly complex experimental environments like those at the LHC. In this chapter, an overview of some of the most recent R&D programs on monolithic silicon detector technologies optimized for time measurements is presented.

3.1 A monolithic silicon sensor

A distinctive feature of a Monolithic Active Pixel Sensors (MAPS) is that the active sensor and readout electronics are integrated on the same silicon wafer, typically using CMOS technology. This is in contrast to hybrid pixel detectors, where the sensor and electronics are separate components bonded together.

The concept of monolithic pixel detectors began to mature in the late 1990s. MAPS consist of an epitaxial (epi) layer, typically 10–15 μm thick, with the electronics layer positioned above it. One recent application of such a design are the ALice Pixel DEtectors (ALPIDE) structures [49], where the charge collection occurs mainly through slow diffusion instead of drift motion. A cross-sectional view of the ALPIDE sensor is reported in Figure 3.1.

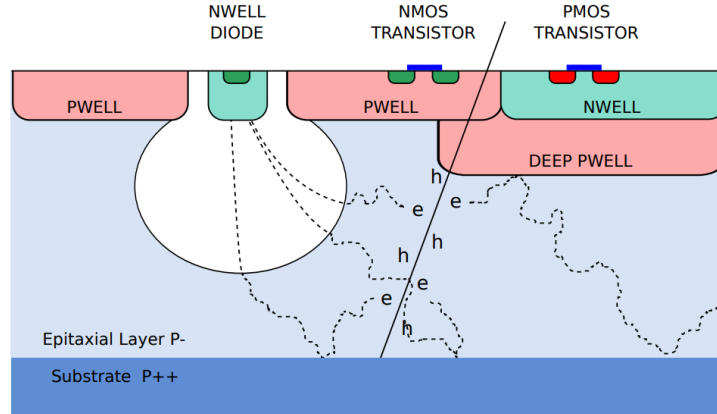


Fig. 3.1 Schematic cross-sectional view of the ALPIDE device. The white zone indicates the depleted region. Taken from [55].

This type of detector can be extremely thin (a total silicon thickness of less than $50\mu\text{m}$ [29]), leading to a sensor material budget roughly ten times lower than that of hybrid pixel detectors, which usually have a total sensor thickness of hundreds of micrometers [40]. Given their small thickness, the undepleted epi-layer and a partial charge collection, the resulting signal is usually quite small.

Recent efforts have demonstrated MAPS as a promising alternative to hybrid pixel detectors. In particular, the development of depleted MAPS (DMAPS) has led to significant improvements in radiation hardness. In these devices, the CMOS electronics is embedded within an isolated well, while the application of a reverse bias voltage creates a depletion region extending from a few to several hundred micrometers. As a result, charge collection occurs primarily through drift rather than diffusion, providing faster response times, larger signal amplitudes, and enhanced radiation tolerance. Efficient charge collection is a key factor in achieving radiation hardness. In irradiated silicon sensors, radiation-induced defects introduce trapping centers that reduce the lifetime of charge carriers. Consequently, rapid charge collection minimizes the probability of carrier trapping, thereby improving the detector performance after irradiation [56].

Monolithic sensors with a partial or a full depletion region have been developed using a variety of process technologies, like the one adopted for the upgrade of the present ITS2, namely the ITS3, that will be installed during the LHC Long Shutdown 3 foreseen in 2026. Starting from the ALPIDE monolithic sensors [49], several efforts are currently devoted to the prototype for the detector upgrade [29]. In the standard

process (Figure 3.2 left), the n-well acting as the charge-collection electrode is not isolated from the epitaxial layer by the deep p-well, allowing it to collect charge directly from the epitaxial region. Conversely, the deep p-well shields the other n-wells, which host the PMOS transistors, preventing them from collecting charge. This isolation enables the integration of a full CMOS circuitry within the pixel and, consequently, to implement more sophisticated readout electronics. Nevertheless, the depletion region begins at the interface between the collection node and the epitaxial layer, and expands with increasing reverse bias voltage. However, obtaining a significant lateral spread of the depletion region deep into the epitaxial material remains challenging.

A possible approach to achieve complete depletion of the sensitive region consists in introducing a large-area, or even planar, junction independent of the collection electrode. In this configuration (Figure 3.2 right), the depletion region originates at the junction and can therefore extend rapidly across the entire pixel area. In particular, a low doped deep n-type implantation has been employed to form a planar junction within the epitaxial layer beneath the pixel array [57]. The implant dose is low enough to allow complete depletion up to the n-well collection electrode under reverse bias voltages of a few volts, resulting in a sensor capacitance of just a few fF.

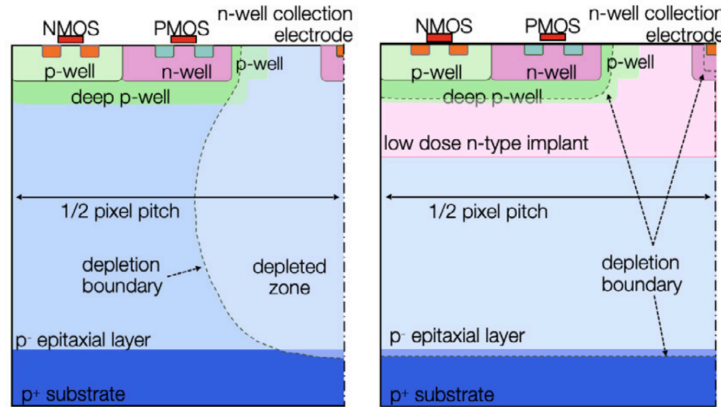


Fig. 3.2 Cross-sections of two different pixel designs: standard (left) and modified (right). In the modified process (right) the deep low dose n-type implant is employed to form a planar junction to extend the depletion region across the entire pixel area. Taken from [58].

Monolithic silicon sensors offer several compelling advantages that make them increasingly attractive for particle tracking applications, such as the dramatic reduction in material budget, the low power consumption and easy large-scale production at relatively low cost. In terms of spatial resolution, monolithic sensors can achieve

very fine pixel pitches (e.g., 20–30 μm), resulting in intrinsic resolutions on the order of 5 μm [59] or better. Those features make them well-suited for applications where precise vertex reconstruction is required. However, their capability regarding time measurement with high resolution has not yet been completely exploited.

3.2 Time resolution of silicon detectors

Precise time measurements depends on the ability of the readout electronics to identify when a particle passes through, based on the signals produced by the sensor. To achieve accurate timing measurements, both the detector technology and the front-end must be carefully selected and designed. The sensor needs to deliver a fast and high-amplitude signal, while the electronics must determine, with minimal uncertainty, a specific point on the waveform corresponding to the particle's arrival time. Multiple factors influence time resolution σ_t and the relevant contributions in a particle detection system can be summarize as follows [40][41]:

$$\sigma_t^2 = \sigma_{LandauNoise}^2 + \sigma_{TimeWalk}^2 + \sigma_{Distortion}^2 + \sigma_{Jitter}^2 + \sigma_{TDC}^2 \quad (3.1)$$

Knowing the target time resolution, the design of both the sensor and the readout electronics can be optimized to minimize each of the contributions in Equation 3.1. In the following, more details are provided for each of these terms.

Landau Noise ($\sigma_{LandauNoise}$)

The Landau component represents the sensor intrinsic limitation imposed by the energy deposition process. When a charged particle crosses a silicon detector produces electron–hole pairs along its trajectory. The non-uniform ionization process introduces fluctuations and irregularity in the signal shape, the so called Landau noise. Since the fluctuations in energy loss are considerable, the resulting signals are not uniform and this variability consequently worsens the time resolution. Two main approaches can be used to mitigate the impact of the Landau term:

- Integrating the output current over a period long enough to include the typical pulse duration. This approach depends on signal integration to smooth out the voltage ramp.

- Employing thinner sensors. In a thin detector, the signal rises steeper thus limiting the effect of amplitude variations on the signal itself.

Time Walk or Time Slewing ($\sigma_{TimeWalk}$)

As for the landau noise term, also this component depends on the non-uniform ionization of particles, since it can lead to variations in signal amplitude. The time-walk effect (also called time slewing) is caused by variations in the amplitude of individual signals, resulting in differences in the threshold-crossing time (Δt) when a constant threshold voltage, V_{th} , is applied. In particular, signals with higher amplitude reach the threshold level earlier than those with lower amplitude, as can be observed in Figure 3.3. For a signal with amplitude S and rise time t_r , the threshold voltage V_{th} is crossed after a delay t_d , as illustrated in Figure 3.3 (right).

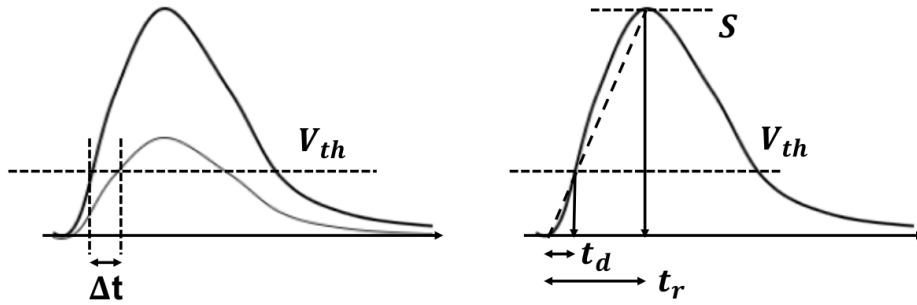


Fig. 3.3 Time walk effect: on the left, two signals cross the fixed threshold with a time delay Δt . On the right, a schematic representation used to evaluate the Time walk contributions. Taken from [40].

Based on the geometric relation $t_d/t_r = V_{th}/S$, the crossing time can be expressed as:

$$t_d = t_r \frac{V_{th}}{S} \quad (3.2)$$

The time-walk component of the timing resolution is then defined as the root mean square (RMS) of t_d [40]:

$$\sigma_{TimeWalk} = [t_d]_{RMS} = \left[\frac{V_{th}}{S/t_r} \right]_{RMS} \quad (3.3)$$

It is therefore straightforward to conclude that enhancing the signal slope (S/t_r) reduces the time-walk contribution.

In order to determine the crossing time and compensate for the time-walk effect, two techniques are employed: the Constant Fraction Discriminator (CFD), and the Time-over-Threshold (ToT) method. The CFD technique does not define the particle arrival time at the moment when the signal amplitude crosses a fixed threshold; instead, it determines the arrival time when the signal reaches a constant fraction of its maximum value [60]. This approach works effectively under the assumption that signals scale linearly with amplitudes, without introducing any shape distortion. The second method, the ToT technique, exploits two timing measurements to estimate the particle arrival time: the time at which the signal surpasses the threshold, t_1 , and the time t_2 at which the signal falls back below it. With this method t_1 is corrected using a function of the time-over-threshold interval $t_2 - t_1$.

Distorsion ($\sigma_{Distortion}$)

The distortion term arises from the non-uniform distribution of the weighting potential and the non-saturated drift velocity of the charge carriers. As previously illustrated in 2.3, the current signal of a sensor can be determined using the Ramo-Shockley theorem, $i \propto qv_d\vec{E}_w$. This equation highlights the key factors to be considered in the design of devices with a good time resolution: the drift velocity v_d and the weighting potential $\vec{E}_w$. Therefore, improving the timing performance of the sensor requires design optimizations aimed at making the **drift velocity** and the **weighting field** as constant as possible, in order to produce uniform signals across the entire sensor area.

A non-uniform **drift velocity** causes variations in the signal shape that depend on where the particle impacts, worsening the overall timing resolution. The most straightforward method to achieve a uniform drift velocity throughout the active region is to maintain an electric field strong enough to saturate the carrier drift velocity. Therefore, at room temperature the sensor bias voltage should ensure an electric field of at least 30 kV/cm across the sensor; while cooling the sensor produces two main effects: it reduces the electric field required to achieve velocity saturation, and it increases the saturated drift velocity. In Figure 3.4 the behavior of the drift velocity as a function of the applied electric field is shown.

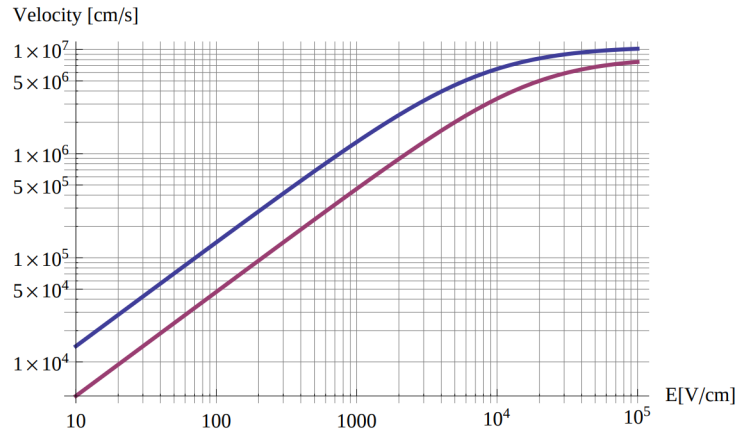


Fig. 3.4 Drift velocity of electrons (in blue) and holes (in purple) as a function of electric field. Taken from [61].

Another important factor concerns the **weighting potential**, which plays a role in the calculation of the induced current. $\vec{E}_w$ represents the interaction between a charge located at a specific point and the readout electrode. It should remain independent of the particle impact position and therefore must be as uniform as possible across the pixel pitch. For this reason, some geometrical optimizations are required to produce smooth weighting fields throughout the sensor. For example, implants as large as the pitch assure a more uniform $\vec{E}_w$, as shown in Figure 3.5.

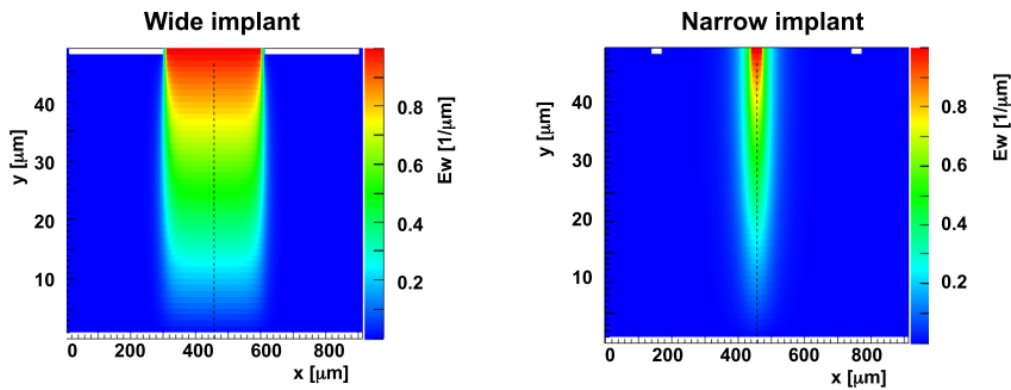


Fig. 3.5 Weighting field maps $\vec{E}_w$ for two different electrode dimensions. For the narrow implant (right), the weighting field is less uniform along the x-direction; this effect improves using a more wide pitch implant (left). Taken from [41].

To summarize, the optimal sensor geometry for high timing resolution applications should resemble a parallel-plate capacitor, with the pixel pitch significantly

larger than the sensor thickness. Under these conditions, both the electric and weighting fields remain highly uniform, ensuring a constant drift velocity and a stable coupling between the charge carriers and the readout electrode.

Jitter (σ_{Jitter})

The jitter component corresponds to the timing uncertainty arising from the premature or delayed triggering of the comparator, caused by noise present either on the signal or within the readout electronics.

If σ_V denotes the standard deviation of the noise influencing the analog pulse, and dV/dt represents the signal slope at the discriminator threshold (also called the **slew rate**), then the jitter can be expressed as:

$$\sigma_{Jitter} = \frac{\sigma_V}{dV/dt} \sim \frac{t_{rise}}{S/\sigma_V} \quad (3.4)$$

As shown in the final part of the equation, assuming a constant slope, the slew rate dV/dt can be approximated as the ratio between the signal amplitude S and the rise time. This simple relation indicates that a balance must be found between competing factors: a faster signal rise and a higher amplitude both contribute to reducing the jitter. On the other hand, large slew rates necessitate broad bandwidths, which consequently amplify noise that should remain as minimal as possible.

TDC (σ_{TDC})

The TDC term denotes the uncertainty linked to the digitization process of the measured time. The TDC converts the time information into discrete time bins of finite width ΔT , determined by the TDC least significant bit (LSB). This process introduces an additional timing uncertainty component equal to $\Delta T/\sqrt{12}$. The uncertainty introduced by the TDC is independent of the sensor properties and since it can be to the order of few ps [38], it is a usually negligible contribution to the total time resolution.

3.3 Monolithic sensor for timing applications

As outlined in the previous sections, the choice of monolithic technology is primarily driven by the requirements for outstanding spatial resolution, low material budget, and radiation hardness: criteria that this technology fully meets. To date, however, no large-scale demonstrator has been produced for HEP applications with specific timing resolution requirements, such as those needed for the TOF detector in ALICE 3. Nevertheless, several R&D projects are currently underway to demonstrate the feasibility of achieving excellent temporal resolutions of the order of tenth ps with these devices.

- Recent research initiatives focused on the development of FD-MAPS with enhanced time resolution. An example is the use of High-Voltage CMOS technology, where high-resistivity wafers enables a full depletion of the charge-sensitive region (exceeding $100\text{ }\mu\text{m}$ in depth) in thinned sensors, thereby improving the tolerance to neutron-induced damage. To this aim, it has been developed a 100 mm^2 pixel detector, named *CACt μ S* (CMOS Active Timing μ -Sensor), specifically designed for precise timing measurements, illustrated in Figure 3.6 [62].

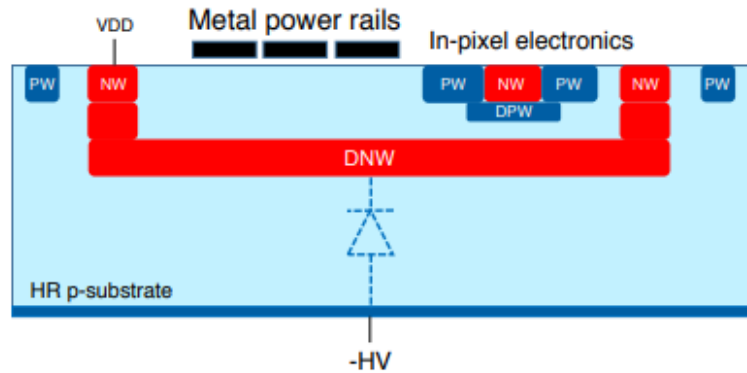


Fig. 3.6 Cross-section of CACTUS pixel showing the in-pixel electronics and the metal power rails. Taken from [63].

A $100\text{ }\mu\text{m}$ -thick sensor, fabricated with the LFoundry 150 nm process technology on a high-resistivity wafer ($R > 2\text{ k}\Omega \cdot \text{cm}$), can achieve full depletion at a bias voltage of -80 V . A fully depleted detector ensures faster charge

collection by drift compared to diffusion-based collection. Moreover, it exhibits enhanced tolerance to neutron and proton irradiation, as charge trapping effects within the damaged crystal lattice are significantly reduced. From timing measurements with a collimated ^{90}Sr source at a distance of 8 cm from the device, a time resolution of 105 ps was obtained using an ad hoc ToT correction [63].

- The upgrade of the CACTUS sensor is represented by the **MiniCACTUS** sensor [64], reported in Figure 3.7. This upgraded device is fabricated in LFoundry LF15A 150 nm technology and it consists primarily of an array of eight passive diodes, each paired with corresponding front-end circuitry located at the column level. In earlier CACTUS devices, the FE electronics were integrated directly within the pixel. However, delivering power across the large pixels in the Y-direction requires metal lines, which introduce substantial parasitic capacitance. To mitigate this effect, MiniCACTUS relocates the FE outside the pixel, although embedding it inside the collecting diode remains technically achievable. In the next fabrication run, the standard high-resistivity wafers were thinned to overall thicknesses of 100, 200, and 300 μm , and then underwent to the backside processing for biasing, including p^+ implantation and metallization, which are crucial to ensure uniform charge collection.

After a first version of the sensor [64], a second one, MiniCactus V2, followed, where an improved separation between the analog and digital signal paths was introduced to reduce the coupling between these two parts. This was achieved by placing the LVDS output drivers in a separate deep N-well, shortening the digital CMOS signal paths, and adding a programmable hysteresis to the discriminator to avoid false retriggering. Moreover, MiniCactus V2 includes two new optimized analog front-ends, CSA2 and VPA. Compared to the original CSA1, they show a slightly better timing performance and a much faster return to baseline (less than 25 ns instead of about 80 ns) [65]. The device has been extensively tested with beam at CERN using 180 GeV/c muons. The best performance has been obtained for sensors with a thickness of 175 μm , for which a time resolution of 60 ps was achieved using $0.5 \times 0.5 \text{ mm}^2$ pixels operated at a bias voltage of -350 V [65].

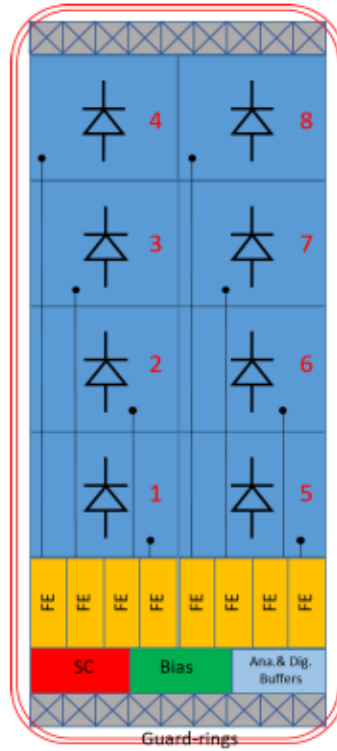


Fig. 3.7 Schematic architecture of MiniCACTUS sensor chip. Taken from [64].

- **FASTPIX: Sub-nanosecond radiation tolerant CMOS pixel sensors**

Another promising R&D, namely the FASTPIX project [66], is represented by a monolithic pixel sensor demonstrator designed using a modified 180 nm CMOS imaging process. This device is aimed at sub-nanosecond time resolution for hits produced by MIPs, employing compact pixels with a pitch of $\leq 20 \mu\text{m}$.

Starting from a standard TowerJazz 180 nm CMOS process (Figure 3.8 left), where a $25 \mu\text{m}$ thick epitaxial layer did not allow an uniform depletion of the active area, a modified process was designed (see Figure 3.8 right) to overcome the limitations of charge collection time caused by diffusion. Depending on whether the particle hits the center or the edge of the pixel, a temporal spread in the charge collection time arises. By reducing the separation between points of charge generation and their collection, the modified process takes an initial step toward improving temporal uniformity, which is achieved through the hexagonal configuration of the collection electrodes. This layout also influences charge sharing in the pixel corners, where only three adjacent pixels are present

rather than four, as found in conventional rectangular layouts. Moreover, a uniform, low-dose n-type implant is used to ensure complete lateral depletion of the $25\ \mu\text{m}$ epitaxial layer. Although in the modified process the charges are primarily transported by drift, the dominant constraint for timing applications is due to the weak electric field in the corner regions. This limitation can be mitigated by engineering a lateral gradient in the doping implants. Such a gradient is generated through design optimizations which include an additional extra-deep p-well implantation and the introduction of a discontinuity in the n-implant near the pixel corner. Together, these modifications establish the desired doping gradient and thereby strengthen the lateral electric field in the corners, see Figure 3.8 (right).

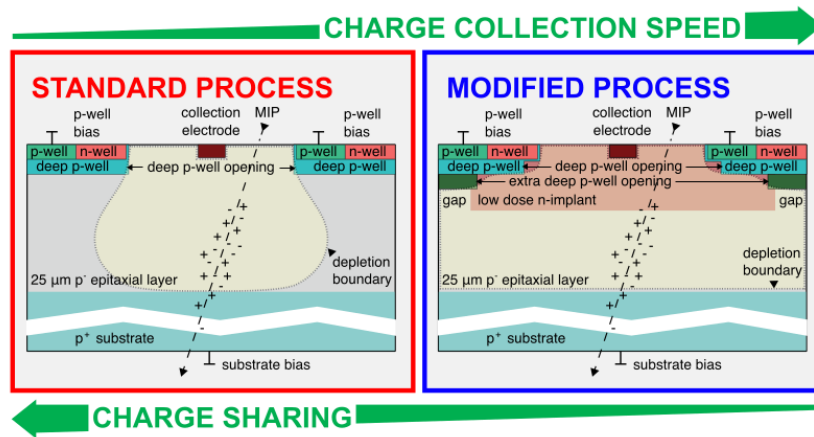


Fig. 3.8 Process variants for FASTPIX sensor. The standard 180 nm CMOS process (left) is compared with the modified process version (right), which features an additional low-dose n-type implant, a gap in the n-profile, a retracted deep p-well and an added extra-deep p-well implantation. By moving from the standard process to the modified one, there is an increase in the charge collection speed as a result of the improvement in the drift component over the diffusion component. On the other hand, to minimizing the distance between charge generation and its collection, the hexagonal pixel layout was chosen leading to a decrease on charge sharing. Image taken from [66].

Different FASTPIX prototypes have been characterized in a dedicated test beam with high-intensity 120 GeV/c pion beam. The process modifications have proven to be crucial for reach down to $1\ \mu\text{m}$ spatial resolution and a timing resolution of the order of 100 ps [66].

- **APTS-OA**

The Multi-Layer-Reticule (MLR1) represented the initial design implemented

using the Tower Partners Semiconductor Co. (TPSCo) 65 nm CMOS process technology [67]. Different prototype chips, each measuring $1.5 \times 1.5 \text{ mm}^2$, were fabricated within the MLR1. Among these, an **Analog Pixel Test Structure (APTS)**, incorporating fast per-pixel buffering based on individual **Operational Amplifiers (OAs)**, was developed to characterize the timing response of the sensors fabricated in this emerging technology. The APTS-OA occupies an area of $1.5 \times 1.5 \text{ mm}^2$ and features a 4×4 matrix of square pixels with a $10 \text{ }\mu\text{m}$ pitch, each connected through direct buffering to the output pads for readout. The APTS was fabricated using three distinct sensor process variants: the standard process, the modified process with blanket implant and the modified one with a gap on the implant [57]. Each modified process started from a conventional imaging CMOS architecture and included specific modifications aimed at achieving faster charge collection and minimizing charge-sharing effects. To study the performance of the APTS-OA in terms of time resolution, detection efficiency, and spatial accuracy, a dedicated test beam campaign was carried out at the CERN–SPS H6 line employing positively charged hadrons with a momentum of $120 \text{ GeV}/c$. The different versions of this chip have been systematically characterized. The results obtained indicate that, although no significant distinction is observed between the modified and the gap-enhanced sensor processes, an enhancement in timing performance becomes evident as the reverse-bias voltage is increased. This is due to the corresponding enhancement of the lateral electric field. In particular, a time resolution of $\sigma_t = 63 \text{ ps} \pm 3 \text{ ps}$ was achieved after the time walk correction, highlighting the improvement achieved by the 65 nm CMOS technology [58] in term of timing performance.

- **MONOLITH Project: Fast SiGe BiCMOS Sensors Without Internal Gain**
The MONOLITH Horizon 2020 ERC Advanced project [68] demonstrated that SiGe heterojunction bipolar transistor (HBT) electronics can enable low-noise, low-power, and ultrafast front-end circuitry. This circuitry can be integrated into a monolithic ASIC to realize a highly efficient detector with outstanding time resolution. The first SiGe monolithic prototype with a time resolution better than 100 ps was produced in the SG13G2 130 nm BiCMOS technology by IHP Microelectronics. In this prototype chip the front-end electronics is hosted in triple wells inside the guard rings and close to the pixels. The device comprises two arrays of hexagonal pixels with side lengths of either

130 μm or 65 μm . The hexagonal geometry was chosen to increase the corner angles, thereby reducing the electric field near the surface and mitigating the risk of premature breakdown. The standard p-type substrate, with a low resistivity of 50 $\Omega\cdot\text{cm}$, is biased with negative high voltage applied both to the top electrode outside the guard rings and to the backside of the die, while the pixels and the triple-well regions are biased at a positive low voltage. The chip was thinned to 60 μm to decrease the resistance of the substrate. The depletion depth is not governed by a backside implant but is instead limited by the wafer low resistivity. Although this approach significantly simplified the fabrication process, it introduces a degradation in timing uniformity, due to the reduced electric field at the interface between neighboring pixels. Laboratory measurements performed with a ^{90}Sr source show a time resolution on the order of 50 ps [69]. This performance in terms of timing is comparable with that of silicon technologies employing an internal avalanche-gain mechanism. The first prototype described above was improved, and the upgraded version of the MONOLITH sensor is shown in Figure 3.9.

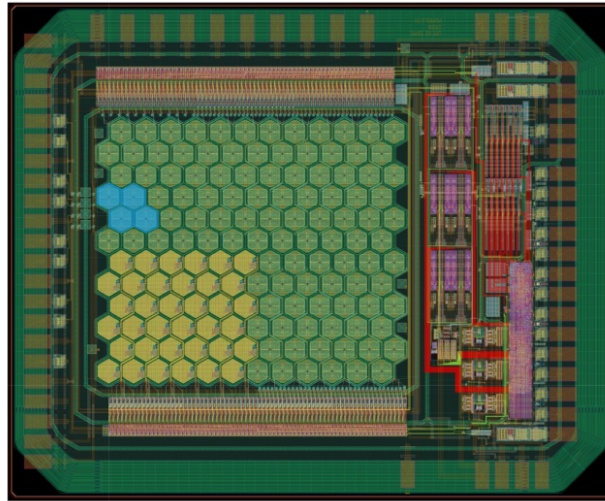


Fig. 3.9 The monolithic prototype, with the four analog pixels used for the time resolution measurements highlighted in blue. The front-end electronics of the digital pixels are positioned along the upper and lower edges of the matrix. Figure taken from [70].

The ASIC matrix in this new version comprises 144 hexagonal pixels, featuring a side length of 65 μm with digital front-ends implemented in the periphery. It also includes four analog pixels (highlighted in blue in Figure 3.9) where the

preamplifier is directly coupled to an analog buffer for oscilloscope readout. Both the front-end electronics and the sensor were modified to solve limitations identified in the earlier design. For the sensor upgrade, low-resistivity substrates incorporating a 50 μm -thick epitaxial layer with a resistivity of 350 $\Omega\text{ cm}$ were employed. Laboratory measurements indicate that the epitaxial layer becomes fully depleted at 70 V. Moreover, the new guard ring layout, together with the higher resistivity of the epitaxial layer, enables stable operation of the device up to 300 V. This extended high-voltage range ensures saturation of the charge carrier drift velocity, thereby optimizing the sensor timing performance.

The full characterization of the prototype was performed with a test beam at the CERN SPS using a 120 GeV/c pion beam. The test was aimed at determining both the detection efficiency and the time resolution of the analog pixels [70]. The detection efficiency of the four pixels was measured with a voltage threshold set to seven times the voltage noise, σ_V , under a power density of 2.7 W/cm² and with a high voltage of 200 V. During the test beam the FE-I4 telescope was used [71]. Due to the intrinsic pointing resolution of the telescope, which causes an apparent inefficiency near the pixel edges, the efficiency was measured within an unperturbed area, defined as the region connecting the centers of the four pixels. The resulting efficiency amounted to $99.8^{+0.07}_{-0.09}\%$ at 2.7 W/cm², remaining above 99.7% across all examined power densities and high-voltage settings. Moreover, with a sensor back biased at -200 V and a threshold set to $7\sigma_V$, the MIP detection timing resolution of a pixel, after applying the time walk correction, is measured to be 20.7 ± 0.3 ps at a front-end power density of 2.7 W/cm². Although a progressive degradation of the timing performance is observed at lower power density, the Device-Under-Test (DUT) remains operable across a broad high-voltage interval, achieving a time resolution spanning between 20 and 25 ps [70].

- **Picosecond Avalanche Detector: Fast SiGe BiCMOS Sensors With Internal Gain**

The Picosecond Avalanche Detector (PicoAD) [72], developed as part of the H2020 ERC Advanced MONOLITH project [68], is a fully depleted, multi-junction silicon pixel device. It is engineered to combine high detection efficiency with excellent time resolution, thanks to the avalanche mechanism occurring in an added, continuous, and deep gain layer.

A schematic cross-section of the PicoAD is presented in Figure 3.10, where the various doping profiles of the layers are shown. The $(NP)_{pixel}$ $(NP)_{gain}$ structure features two highly resistive p-type epitaxial layers separated by a thin n-p junction, the *gain layer*. When a bias voltage is applied, the depletion region extends from two junctions. The junction near the top surface (the pixel junction) serves to isolate the pixels, while the junction near the lower boundary of the depletion region (the gain junction) generates a sufficiently strong electric field to induce impact ionization, producing avalanche gain.

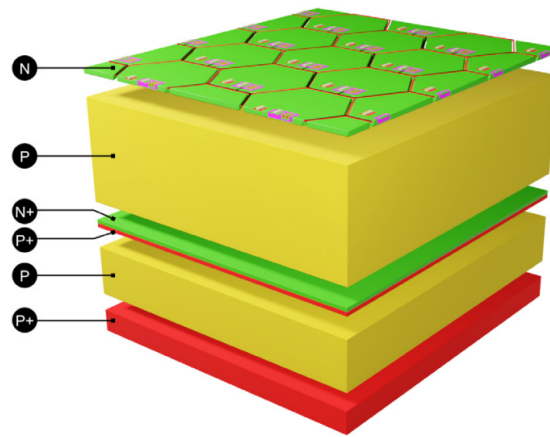


Fig. 3.10 PicoAD detector schematic layout with the deep p^+-n^+ junction constituting the continuous gain layer. Image taken from [73].

When a MIP hits the sensor, it produces electron–hole pairs within the two epitaxial layers through ionization. The primary electrons, created in the region above the gain layer, drift toward the top electrodes producing secondary charges. The holes migrate in the opposite direction, where no amplification occurs. Therefore, it is possible to distinguish three different regions, from the surface to the back of the sensor: the *drift region*, the *gain layer region*, and the *absorption region*. The *drift region*, corresponding to the P-doped layer between the pixels and the gain region, is the region where primary charges and secondary electrons propagate. Their motion within this area generates the predominant fraction of the signal current in the pixel. Adjacent to this is the thin, uniform gain implant, which produces an avalanche as electrons pass through it. A significant advantage is that the absorption region may be engineered to be arbitrarily thin, reducing the statistical fluctuations in the collection of the charge, without significantly increasing the pixel capacitance.

Moreover, unlike Low-Gain Avalanche Detectors where the gain layer is segmented, the uniformly implanted gain region extends across the entire sensor and sustains a homogeneous electric field. As a result, it enables the use of smaller pixel dimensions without compromising the uniformity of the amplification.

The prototype developed by IHP, using the SG13G2 130 nm SiGe BiCMOS process, was fabricated on boron-doped wafers exhibiting a resistivity of $0.1 \Omega \cdot \text{cm}$. It features a $5 \mu\text{m}$ -thick epitaxial absorption layer positioned beneath the gain region, together with a $10 \mu\text{m}$ -thick epitaxial drift layer located above the gain implant. The device is an array of hexagonal pixels with a side length of $65 \mu\text{m}$ and an inter-pixel distance of $10 \mu\text{m}$. Four pixels, connected to charge-sensitive amplifiers and equipped with analog output buffers, were characterized with a pion beam of $180 \text{ GeV}/c$ momentum at the CERN SPS facility. Equally to the measurements performed on the Monolith prototype [70], a detection efficiency of 99.9% was evaluated for the three different conditions of power consumption [74]. Regarding the timing performance, the better resolution achieved, after the time walk correction, was $17.3 \pm 0.4 \text{ ps}$ at $2.7 \text{ W}/\text{cm}^2$ of power consumption with a slightly worsening for lower power densities [74].

All the R&D described in the present chapter demonstrates the potential to achieve timing resolution of the order of tenths of ps, although none can currently be considered a large-scale demonstrator. Moreover, a CMOS detector implementing an additional junction to provide a tunable gain within the sensor represents a promising approach. Combining the LGAD approach with the advantages of a monolithic design could bring several advantages. In this context, the PicoAD project [72] represents one of the first R&d efforts exploring this direction. However, a fully integrated avalanche detector built using standard CMOS manufacturing techniques has not been realized so far. A potential solution to this challenge is offered by an innovative sensor, developed using LFoundry 110 nm technology, as employed within the ARCADIA project. My thesis focuses on the design and characterization of these devices.

Chapter 4

A First 110 nm CMOS Avalanche Detector Prototype: design and simulation

This chapter outlines the design and modeling of the first prototype of a CMOS sensor produced in a 110 nm commercial process by LFoundry with additional internal gain. The simulation tools and the simulation chain used to study the device are also described. In particular, the Synopsys Sentaurus Technology CAD (TCAD) tool [75] and Monte Carlo simulations were extensively employed to achieve a comprehensive investigation of the sensor behavior. The first prototype chip was designed in collaboration with the ARCADIA project.

4.1 The ARCADIA baseline technology

The *ARCADIA* (Advanced Readout CMOS Architectures with Depleted Integrated Sensor Arrays) project focused on the design and manufacturing of FDMAPS sensors implemented in the LFoundry 110 nm commercial CMOS technology with 1.2 V transistors. Profiting on the expertise and insights gained during the previous SEED project (Sensor with Embedded Electronics Development), the ARCADIA team succeeded in producing three different runs from 2020 to 2023. This technology is designed for fully depleted regime, in order to take advantage of drift-driven charge collection. The readout circuitry relies on a flexible, modular architectural layout

and can function in a low-power configuration to satisfy the energy-consumption constraints required in the low-rate and low-power conditions typical of space applications.

The n-on-n sensor, reported in Figure 4.1, is based on a small n-type collection electrode implanted on an n-doped substrate and surrounded by a p-well and a deep p-well, which host the front-end electronics (pMOSFETs in n-wells and nMOSFETs in p-wells), isolating it from the underlying sensor substrate. Moreover, the deep p-wells avoid the n-wells from competing with the n^+ electrodes in gathering the charge as a collection electrode. The n^+ pixels are biased with a positive voltage, whereas the backside p^+ electrode is polarized by applying a negative potential, creating a depleted region that cover the entire thickness of the sensor.

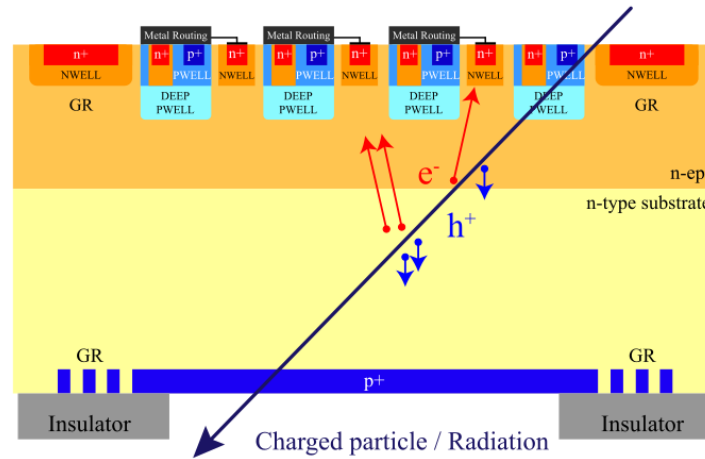


Fig. 4.1 Schematic cross-section of a FDMAPS pixel sensor. On the surface, the n-wells that capture the electrons are illustrated in red, whereas the p^+ backside electrode appears in blue with the aim to collect the holes. Image source [76].

Different nominal substrate thicknesses, 48 μm , 100 μm and 200 μm , have been fabricated, and the possibility to achieve full substrate depletion for all of them was confirmed experimentally. If thinner substrates are needed to accelerate charge collection and to improve the device timing capabilities, thicker ones can provide a larger quantity of generated charge when MIPs cross the detector, as well as increased efficiency, which is essential for detecting X-rays with energies between 1 and 20 keV.

Wafers featuring an active region with a nominal thickness of 48 μm were produced starting from p^+ handle-wafers, where an n-type epitaxial layer followed by a

second one, more heavily doped, was sequentially grown to form the active volume. Subsequently, the p-type substrate was gradually thinned.

Concerning the thicker thicknesses, high-resistivity n-type substrates were employed. The 100- μm -thick active substrate presents a uniform p^+ layer on the backside surface produced by implanting boron atoms and activating them through laser annealing. This creates the device pn junction from which the sensor depletion starts. For a thickness of 200 μm , in addition to the implantation of p^+ layer on the rear side of the wafer, an additional backside lithography step was performed to define a set of termination structures composed of floating guard rings. The inclusion of floating guard rings prevents problems associated with breakdown at the junction edges, thereby allowing the application of the negative bias voltage needed to deplete the substrate from the backside p-type contact. Specifically, the guard rings reduce the electric-field peak at the junction, smoothing the gradients in the electrostatic potential.

The punch-through effect occurs when the voltage applied to the backside electrode exceeds a certain threshold, referred to as V_{PT} , resulting in a hole current flowing between the front-side p-wells/deep p-wells and the p^+ doped electrode located at the bottom of the sensor. Special attention was required to keep the punch-through current under control when the sensor reached full depletion. The punch-through control could be achieved either by raising the bias applied to the pixel sensor nodes or by increasing the doping of the n-type implant beneath the p-wells. Because the sensors needed to be directly coupled with low-voltage electronics and the thin transistor gate oxide demands a low voltage, the latter approach was selected, introducing an n-doped epitaxial layer with a lower resistivity than the substrate into the process sequence [76].

The ARCADIA Main Demonstrator chip

The wafer reticle contained multiple active detectors with integrated electronics, along with a set of test structures without the front-end circuitry (the so called passive structures) designed to characterize the production process (i.e. the sequence of fabrication steps used to realize the structures) and the detector working point independently of the electronics. Although during the different engineering runs the reticle was modified, a main demonstrator chip was always present. The ARCADIA Main Demonstrator (MD) chip consists of a 512×512 pixel matrix, with 25 μm

pixel pitch, organized in double columns and covering an area of $1.28 \times 1.28 \text{ cm}^2$. The demonstrator, designed for charged-particle tracking, features an event-driven readout scheme. Each pixel integrates the analog and digital blocks required to amplify and discriminate the signal generated by a detected particle, and to record and transmit the corresponding pixel address. The sensor architecture aims for extremely low power consumption, around 20 mW/cm^2 at a particle flux of 100 MHz/cm^2 , to allow operation with simple air cooling. Another important design goal is the capability to further decrease the sensor power density to roughly 5 mW/cm^2 or even less under low hit-rate conditions such as those encountered in space applications [77].

Figure 4.2 depicts the geometry of a single ARCADIA MD pixel, using a 3D TCAD model domain (i.e. the physical simulated region of the device). The Figure shows a single pixel characterized by a small n-type collection electrode, sized $(25 \times 25 \times 50) \mu\text{m}^3$ positioned on the surface, which becomes electrically insulated only once the substrate is fully depleted. To investigate the tracking performance and timing capabilities of the chip, an extended simulation region was considered in order to study both the cluster-size distribution and the charge-collection efficiency within the pixel matrix [78].

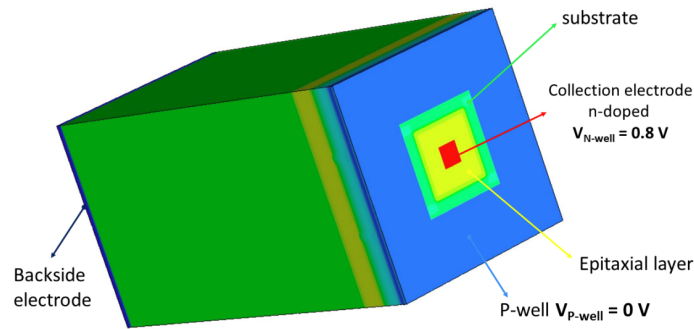


Fig. 4.2 Three-dimensional single pixel design in TCAD simulation domain of the ARCADIA Main Demonstrator chip. The color mapping corresponds to the dopant concentration. Taken from [78].

Particular attention was devoted to the electric field distribution and to the weighting potential profile within the pixel matrix, since both play a crucial role in charge transport and signal formation. In reference [79], a first estimation of the sensor

time capability was studied by considering MIP particles crossing the central pixel of a pixel array. Preliminary investigations suggested that these sensor concepts could provide time resolutions on the order of a few ns. The achieved resolution remained far from the 20 ps target required by ALICE 3 TOF, thereby motivating the development of a new sensor technology specifically optimized for ultra-fast timing performance.

4.2 The ARCADIA Fully Depleted CMOS sensors with an internal gain

Several factors motivated the collaboration to investigate a new sensor concept optimized for timing applications. The goal is to develop a monolithic CMOS sensor able to provide ultra-fast timing performance not only for HEP experiments, but also for all other applications requiring an excellent time resolution. As anticipated in previous chapters, the time response is mainly influenced by the following parameters:

1. **Sensor thickness:** this is one of the most important factor. Thinner sensors exhibit reduced Landau fluctuations (see Section 3.2), thereby yielding an improved timing resolution. In addition, e-h pairs generated by a crossing particle travel a shorter drift distance before being gathered, resulting in a faster collection. However, a thinner detector also implies a lower energy deposition by the particle, which produces less charge at the pixel electrode and therefore degrading the SNR.
2. **Electric field and weighting potential:** the electric field has to be high enough to assure saturated drift velocity of the charge carriers reducing the collection time. This requires the sensor to operate in a fully depleted condition. Moreover, an optimized sensor geometry is essential to obtain a weighting potential profile as uniform as possible across the pixel pitch. In this way the induced current is independent of the particle position.
3. **Sensor capacitance:** devices employing small collection electrodes exhibit reduced capacitance; however, they typically exhibit highly non-uniform electric fields, which subsequently can limit the time resolution capability. On

the other hand, sensors with larger electrodes provide a more uniform electric field distribution, but also an increased capacitance which reduce the SNR.

4. **Signal slew rate:** for fixed noise conditions and sensor capacitance, the jitter (Section 3.2) can be reduced by enhancing the signal slew rate. This can be achieved either by increasing the amplifier operating current or by multiplying the charge generated inside the sensor. The former approach is almost impractical in large-scale experiments employing multichannel architectures, as the resulting power density would rapidly exceeds acceptable values. Therefore, implementing amplification directly inside the sensor requires the development of a novel CMOS sensor concept.

A novel CMOS sensor architecture, developed within the ARCADIA collaboration and the ALICE 3 TOF working group, combines the avalanche charge multiplication of LGADs with the advantages of monolithic devices, with the goal of significantly enhancing the timing performance of these sensors. Owing to these characteristics, it represents a promising solution and it is currently considered the baseline technology for the TOF system of the ALICE 3 experiment.

4.2.1 Sensor concept

The proposed approach is based on the FD-MAPS technology developed within the ARCADIA collaboration using a modified LFoundry 110 nm CMOS process, with the aim of realizing a monolithic LGAD sensor, hereafter referred to as CMOS-LGAD. To this purpose, an additional doped implant was added underneath the collection electrode. A schematic cross-section of the ARCADIA pad sensor is shown in Figure 4.3 (left). The structure consists of a high-resistivity n-type substrate, followed by a more heavily doped layer and a backside pn junction that enables the depletion region to extend from the bottom of the sensor, allowing full depletion of the active volume. In the original ARCADIA fabrication process, CMOS readout circuitry could be integrated within the p-wells and n-wells positioned adjacent to each collection electrode. This configuration operates at a low bias voltage and can thus be directly DC-coupled to the preamplifier stage.

The modified layout, including the addition p⁺-doped gain layer, is illustrated on the right hand side of Figure 4.3. This added layer creates an high electric field region that enables the charge multiplication through impact ionization, as for LGADs

(Section 2.1). As in the standard process, the substrate consists of a high-resistivity layer upon which a second, thinner n-type epitaxial one is grown. Also in this case, a sufficiently negative bias voltage is applied to the backside p^+ implant in order to fully deplete the entire active region and ensure charge collection by carrier drift. In this modified architecture, however, a high positive voltage must also be applied to the front side electrode in order to control the gain. This bias depletes the p^+ -doped gain layer and generates the strong electric field necessary to charge multiplication. As a consequence, the drift field and the multiplication field can, in principle, be tuned independently, whereas in conventional APDs and LGADs a single bias voltage simultaneously governs both fields. Since the collection electrode operates at a much higher bias voltage than the CMOS readout electronics, the front-end preamplifier must be AC coupled to the detector. Therefore, a decoupling capacitor and a bias resistor are implemented to deliver the high voltage to the top electrode, while the CMOS electronics operates at their nominal bias voltage of 1.2 V [80]. In addition, each pixel is surrounded by an n^+ guard ring, which ensures complete substrate depletion and simultaneously prevents premature breakdown phenomena at the periphery of the active region.

Within the ARCADIA project, several fully depleted sensors with active thicknesses of 48, 100 and 200 μm and different sensor geometries were produced. However, only the 48 μm thick sensors were analyzed, since both simulations and experimental measurements indicate that thinner devices provide better time resolution.

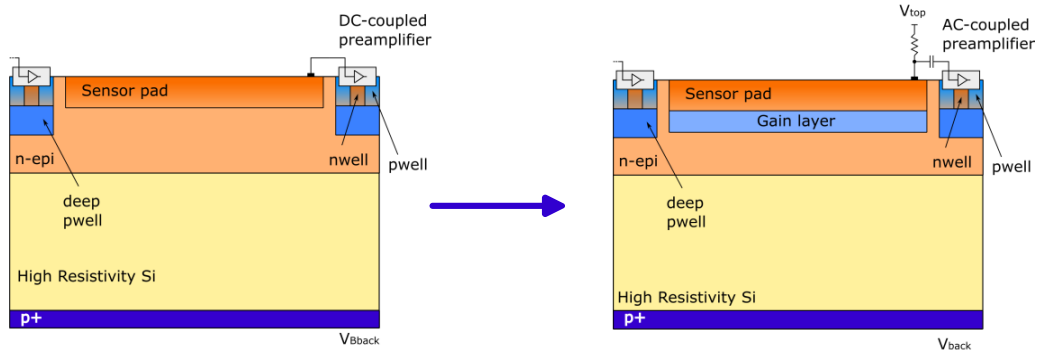


Fig. 4.3 A schematic cross-section of a DC-coupled pixel without gain (left) and an ARCADIA AC-coupled pixel with a gain layer underneath the collection electrode (right). Image source [80].

It is reported in Figure 4.4 a 2D TCAD simulation domain of a 48 μm -thick pixel designed by the author. The image is intended to help the reader better understand

the device and its component. More details on the simulation will be provided in the Chapter 6.

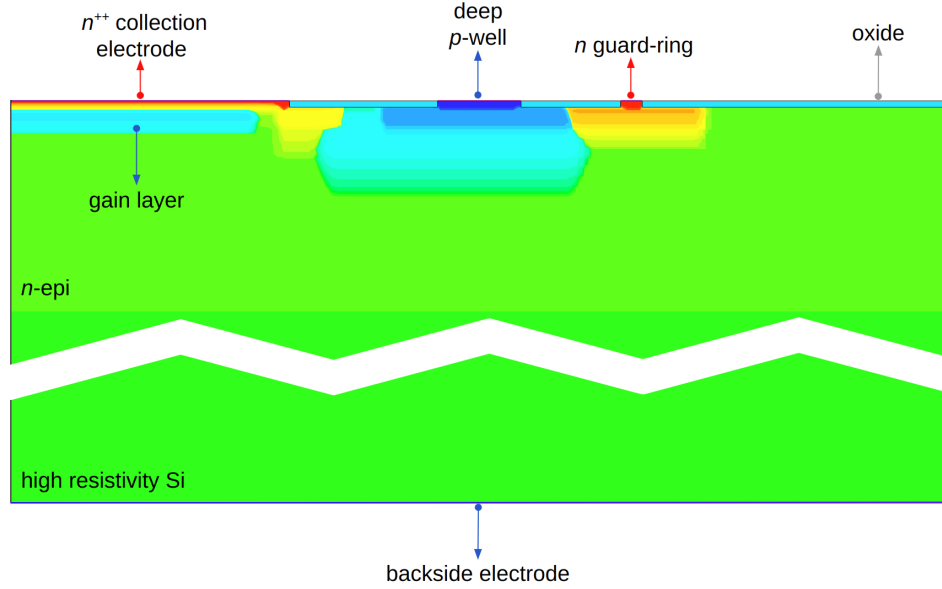


Fig. 4.4 2D TCAD simulation domain of the ARCADIA half pixel cross-section with gain. The color mapping corresponds to the dopant concentration.

Pixel termination layouts

The prototype features two distinct pixel configurations, labeled as A1 and A2, shown Figure 4.5. The different layouts have been implemented to study the efficiency of the charge collection and the relative temporal response at the pixel edges.

- **A1 layout:** in this configuration, the deep p-wells are in direct contact with the gain layer implant, resulting in an enlarged multiplication region. As a consequence, even primary charges generated beneath the deep p-wells can undergo multiplication while drifting toward the gain layer and subsequently being collected at the n^+ electrode. This leads to a larger average collected charge, since multiplication occurs throughout the entire pixel. Nevertheless, these carriers reach the n^+ implant with a measurable delay compared to those produced in the central region of the pixels and, as a result, degrade the timing performance of the device.

- **A2 layout:** a small gap is present between the deep p-wells and the gain layer, resulting in an edge termination similar to the one of a conventional LGAD sensor. This layout implies that some of the charges generated near the periphery may follow drift paths that cross the gap and reach the collection electrode directly, bypassing the gain layer and therefore not undergoing multiplication. In this case, a more uniform response within the active region is expected, which consequently results in a reduced multiplication volume. In addition, A2 layout allows signals generated within the gain region to be distinguished from peripheral signals, i.e. those that are not multiplied. By differentiating fast and slow signals and selecting only the fast contributions, an improved time resolution is foreseen for the A2 layout.

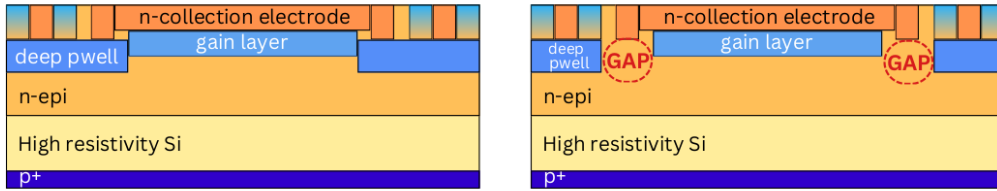


Fig. 4.5 Cross-section of the ARCADIA pixel with gain having different termination layouts: A1 layout on the left, A2 layout on the right. Red dashed circles highlight the gap region between deep p-wells and gain layer. Taken from [79].

In the third and last ARCADIA engineering run, delivered at the end of April 2023, the first prototypes with internal gain were produced. Several structures were fabricated in order to investigate the proposed sensor concept and to study the effects of different sensor geometries and gain implants. Structures with integrated electronics (hereafter referred to as active devices), and structures without integrated electronics (passive devices), were both included in the fabrication run.

The process design was guided by TCAD-based 2D simulations, which were used to define the gain implantation doses and the relevant geometrical parameters [80]. In particular, different gain layer implantation levels were implemented in the fabricated prototypes in order to experimentally assess their impact on the device performance, with the aim of covering a gain in the range of interest of 10-25. These gain values are expected to provide a substantial improvement in the signal-to-noise ratio (SNR) without introducing excessive non-uniformity arising from fluctuations within the gain layer. As observed in APDs and LGADs, even minor variations in the implanted

dose can markedly influence the gain. Consequently, precise control of the implanted gain profiles is crucial for the successful fabrication of the proposed structures. A trade-off in the gain value is therefore required: the gain must be sufficiently high to improve the signal-to-noise ratio, but not so high as to compromise uniformity and control of the gain in large-area sensors.

The main characteristics of the passive and active CMOS-LGAD structures fabricated during the ARCADIA engineering run 3 are summarized in Table 4.1. The different pixel pitches reported for the passive structures correspond to the different geometries that were produced in the fabrication run; further details on these geometries are provided in the next chapter. Four different gain layer implantation doses were implemented in order to investigate the impact of the gain layer doping on the sensor performance.

Table 4.1 Summary of the characteristics of the CMOS-LGAD structures fabricated in the ARCADIA engineering run 3.

Structure type	Thickness [μm]	Pixel pitch [μm^2]	Gain layer doses
Passive	48, 100, 200	250×70 , 250×250	4
Active	48, 100, 200	250×100	4

4.3 Simulation tools

To evaluate the performance of monolithic CMOS sensors, dedicated simulation tools are used to analyze signal formation and support the design optimization of these prototypes. An overview of the simulation tools employed will be presented, followed by a description of the developed simulation chain that integrates the TCAD software with a Monte Carlo framework to study the devices. All TCAD and Monte Carlo simulations discussed in the following chapters were performed using the Open Computing Cluster for Advanced Data Manipulation (OCCAM), operated in collaboration between the University of Torino and INFN Torino, and funded by the “Compagnia di San Paolo.”

4.3.1 Introduction to Technology Computer-Aided Design (TCAD) simulations

TCAD software is a numerical simulation tool that allows us to design prototypes through simulations, providing the capability to model highly complex geometries including a wide range of physical effects. It predicts the electrical behavior of semiconductor devices in response to externally applied electrical, thermal, or optical boundary conditions imposed on the structure, without requiring the fabrication and testing of a physical prototype. TCAD has the aim to describe the movement of electrical carriers and the generation of the electromagnetic field resulting from this motion, making the two phenomena inherently coupled, as the electromagnetic field can influence carrier transport.

The typical procedure of the Synopsys Sentaurus TCAD tool [75] can be summarized as follow:

1. The device geometry must be precisely defined. To achieve this, it is essential to assign accurate dimensions to the various doping regions, material layers, and electrodes, as well as to specify the doping concentrations for each distinct region. It is possible to import each doping profile from external files, where the doping concentrations are specified as a function of the depth relative to the surface of the device. These files can be supplied directly by silicon foundries enhancing the reliability of the simulation results, because the simulated device structures can more accurately reflect the actual fabricated devices.
2. After establishing the sensor structure, it is essential to define an appropriate mesh discretization for the simulation domain by selecting suitable element sizes and types. In particular, the computational time and the required resources for a simulation depend both on the total number of nodes and elements within the mesh of the simulation domain. Furthermore, the size of the mesh elements influences the approximate numerical solution of the discretized equations governing the device physical behavior; and thus, the precision of the simulation results. By default, Sentaurus employs triangular elements for 2D meshes and tetrahedral elements for 3D mesh generation. Finer mesh elements are applied in specific regions of the device to properly resolve critical sensor features, while a coarser mesh is used over the rest of the simulation domain. Regions for mesh refinement are typically selected in areas characterized by

steep electric-field gradients, high electric-field magnitudes, sharp doping concentration gradients, or high current densities. For the simulations discussed in the subsequent chapters, the mesh was locally refined based on variations in the doping concentration. As a result, the element dimensions are minimized in regions where the doping gradient is steeper, whereas in areas with nearly uniform doping, the mesh is relaxed to reduce computational effort.

3. To accurately reproduce the device behavior, a set of physical models was defined in the simulations. These models describe the generation and recombination of charge carriers (for example the Shockley-Read-Hall (SRH) model was employed in the performed simulations), the carrier lifetimes, define how the electron and hole mobilities vary as functions of the overall dopant concentration and changes in temperature, or evaluate the charge multiplication.
4. Subsequently, an appropriate numerical method required to solve the discretized equations representing the sensor physical behavior must be chosen. In this work, the semiconductor equations were discretized and solved using the finite element method (FEM) [81], see below for details.
5. Using the chosen numerical method, TCAD software calculates the numerical solution of the equations at the mesh nodes, ensuring also continuity of the solution within each mesh element and across neighboring elements.
6. Finally, each computed nodal value is saved together with a set of output parameters associated to the device electrodes.

Concerning points 3. and 4., it is useful to provide a detailed explanation. TCAD simulations rely on solving the semiconductor model equations, which consist of a coupled system of Poisson, transport, and continuity equations. The Poisson equation describes the relationship between the electric field and the distribution of charge carriers within the material. Various formulations of the transport equations were already implemented and accessible in TCAD: the Boltzmann transport equations, the hydrodynamic equations, quantum mechanical approaches, or the classical drift-diffusion model. The latter equation, which was employed in all the simulations performed below, expresses the total electron and hole current densities as the union of two distinct components corresponding to drift and diffusion processes. Finally, the continuity equations enforce charge conservation by ensuring that the net

flux of charges entering and leaving a region is balanced by changes in the carrier concentrations within the material.

The combination of these three sets of partial equations allows the comprehensive modeling of the electrical behavior of the simulated devices. Therefore, to solve the problem the software reduces the overall computational complexity by discretizing the equations in both space and time, and by replacing the original partial differential equations with equivalent systems of ordinary differential equations. A Finite Element (FE) discretization strategy is employed for this purpose, although the specific implementation details fall outside the scope of this work. More details can be found in [81]. At this point the software can proceed iteratively with a solver to find the numerical solution of the system of equations. In this thesis Newton based solver [82] was employed to solve a system of nonlinear equations by linearizing it around the current solution and updating it until convergence is reached.

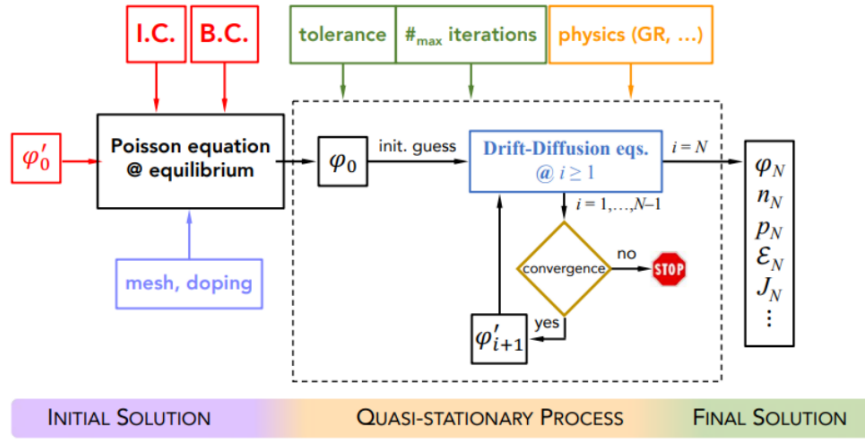


Fig. 4.6 Schematic representation of the TCAD algorithm, provided courtesy of M. Mandurino.

The TCAD workflow is illustrated schematically in Figure 4.6. When the algorithm succeeds in identifying a solution within a finite number of iterations, the system is said to converge. Conversely, non-convergence may arise from various issues, such as an excessively small threshold parameter or a not well-defined mesh, which is a crucial factor for the convergency. If the mesh is too fine, the simulation may fail to converge due to limited computational resources, whereas a coarse mesh can also find convergence difficulties because it can not adequately represent the physical properties in regions where steep variations in electrostatic potential, electric field,

or doping concentration are present.

However, TCAD needs a considerable computational time by each event. In this context, integrating the TCAD framework with a Monte Carlo simulation tool, an essential method in HEP that accounts for the stochastic nature of particle interactions, proves highly beneficial.

4.3.2 Allpix²: a Monte Carlo simulation framework

Allpix² [83], [84], [85] is a open-source, modular and lightweight framework merging the modeling of how materials influence particle interactions with a comprehensive description of the subsequent motion of the generated charge carriers. Each simulation is composed of multiple modules, each configured with its own parameters, which are executed in sequence for every individual event being simulated. The framework is composed of four primary components, which collectively constitute the Allpix Squared simulation environment:

- **Core:** The core manages the fundamental operations of the framework, including module initialization, supplying the geometry, managing communication between modules, and executing the sequence of simulated events.
- **Modules:** A module consists of a collection of methods executed within the simulation chain. Modules are implemented as independent libraries and are dynamically loaded by the core as required during runtime.
- **Objects:** Objects constitute the data transmitted between modules through the messaging infrastructure supplied by the core.
- **Physics:** In many cases, multiple modules rely on the same fundamental physics models, which are maintained independently from the modules. These modules describe the the physics of semiconductor devices, such as material properties, charge carrier mobility and lifetime, or impact ionization.
- **Tools:** Allpix Squared offers a collection of header-only “tools” which include Runge-Kutta solver [86], a class of numerical integrators for solving ordinary differential equations, implemented with the support of the Eigen3 library, and the mesh converter. This last tool converts adaptive meshes from finite-element simulations into a regularly spaced grid.

Allpix² provides interfaces to other external software packages for carrying out specific tasks within the overall simulation chain. A remarkable example is Geant4 [87], a widely adopted toolkit for modeling particle interactions with matter. Within Allpix², Geant4 serves as one of the available modules for simulating the initial energy deposition in the sensor by ionizing radiation.

The major advantage of Allpix² is given by its capability to combine the TCAD simulations with a Geant4 simulation of particle interactions with matter, while accurately taking into account the stochastic characteristics of the initial energy deposition. The capability to import TCAD static electric fields enables realistic modeling of signal formation within a Monte Carlo framework, at a significantly lower computational cost than full transient TCAD simulations, while simultaneously incorporating stochastic phenomena such as Landau fluctuations. Thereafter, a simplified charge transport procedure is employed, using the electrostatic field map produced by the TCAD simulation to represent the complex internal electric-field distribution of the sensor. A key difference between the two simulation software packages is their treatment of the electric field. In TCAD, the electric field and space-charge region are dynamically updated to reflect local variations caused by charge transport. Conversely, in the Monte Carlo framework, the electric field and weighting potential are kept constant after import. This fixed-field assumption substantially reduces both computational time and processing demands.

4.3.3 Simulation chain

The simulation workflow in Allpix² is organized through configuration files and several modules, each responsible for a different step in the simulation flow, which are executed sequentially for every individual event. A single run comprises multiple events (i.e. 1000 or 10000 events in these simulations), where each event corresponds to the passage of one or more particles through the sensor. The overall simulation workflow is illustrated schematically in Figure 4.7



Fig. 4.7 A schematic representation of the simulation flow employed in this thesis, derived from the combined use of TCAD and Allpix². The abbreviations EF, EP, and WP refer to the electric field, electrostatic potential, and weighting potential, respectively.

First of all, it is necessary to define the type of the detector assembly (monolithic or hybrid device) and its geometry with some information concerning the sensor thickness and dimension, together with the position and orientation in the global reference frame.

The next conceptual step regards the definition of the internal electric field. This field may be defined analytically or imported from a TCAD simulation, as in the case of all the studies reported in this work. The electrostatic field produced by TCAD is converted into a uniformly spaced mesh through the Mesh Converter tool included in the framework, to speed up the following steps. The tool input comprises two files: one specifying the coordinates of each mesh vertex, and the other containing the corresponding field values at these vertices. The process generates a single output file representing the uniform mesh, as opposed to TCAD simulations, employing a barycentric interpolation method to evaluate the field vector at each new point. The user may specify the number of divisions in the new mesh. As for TCAD simulations, when choosing this value, it is important to recognize that a finer mesh will substantially increase the simulation time, whereas an excessively coarse mesh might compromise accuracy. Consequently, an appropriate balance between precision and computational cost must be maintained. Not only the electric field, but also the electrostatic potential and doping concentration map inside the structure are imported from TCAD and fed into the converter tool to obtain a regular mesh.

Once geometry and fields are defined, the detector is ready to host particle transport, which in this work is delegated to *DepositionGeant4* module, an interface to Geant4 that enables the simulation of energy deposition by the incoming radiation (e.g. single electrons, pions, photons) that interacts with the material. The energy deposited in the sensor is converted into electron–hole pairs according to the silicon ionization energy. Moreover, all simulations presented in this work employed the *Photon Absorption Ionization (PAI)* model to provide a realistic description of energy-loss fluctuations in thin detector layers.

The subsequent phase is the charge transport simulation, where the *TransientPropagation* module is exploited to simulate the signal formation and the propagation of e-h pairs. The propagation comprises an interplay between drift and diffusion mechanisms. The drift contribution is determined using the charge carrier velocity obtained from the corresponding mobility, which can be chosen among a list of available models. The diffusion component, instead, is taken into account through the Einstein relation [88], which directly proportional to the root mean square of the

temperature and the carrier mobility.

The charge transport is parameterized in each time step, where the charge induced (4.1) on a electrode n is evaluated using the Shockley–Ramo theorem [43][42] by computing the change in weighting potential map between the carrier's current position x_1 and its preceding position x_0 :

$$Q_n^{ind} = \int_{t_0}^{t_1} I_n^{ind} dt = q(\psi(x_1) - \psi(x_0)) \quad (4.1)$$

where ψ is the function describing the weighting potential used to calculate the induced current on the pixel. The computation of the weighting potential on the interested electrode can be evaluated by maintaining all the electrodes at their respective bias voltages, and by applying a small additional increment ΔV to the interested one, and subsequently evaluating the resulting change in the electrostatic potential [89]. In particular:

1. two TCAD simulations were performed in which the interested electrode was biased at V_0 and at $V_0 + \Delta V$.
2. The resulting electrostatic potential maps are then subtracted, and the output is normalized such that the value equals to 1 is applied at the electrode of interest and 0 at all remaining electrodes.

Allpix² allows the implementation of charge multiplication by impact ionization through several models available. To model the impact ionization, the number of e–h pairs generated by multiplication is determined for each propagation step and for every charge carrier using a random sample drawn from a geometric distribution. This approach implements a stepwise representation of the avalanche mechanism.

Chapter 5

First CMOS-LGAD engineering run: sensor design and full characterization

This chapter describes the design and full characterization of the first production of monolithic CMOS-LGAD sensors. Monte Carlo simulations are used to evaluate the sensor time resolution with both nominal and tuned doping profiles, considering different scan strategies across the sensor surface. The electrical and dynamic characterization of passive test structures is carried out to study the device performance and to assess the gain value of the structure. The chapter continues with the description of the Monolithic CMOS Avalanche Detector PIXelated (MADPix), presenting the chip layout, the readout architecture, and the laboratory tests. Finally, the sensor time resolution is measured with particle beams at the T10 beamline of the CERN PS, before and after applying the Focused Ion Beam (FIB) technique to improve the chip performances.

All the Monte Carlo simulations and the data analysis described in this chapter were carried out by the author of this thesis. Furthermore, the author actively participated in all the measurements presented in this work, contributing significantly to the test beam campaigns.

The procedure concerning Focused Ion Beam has been carried out at Nanofacility Piemonte Istituto Nazionale di Ricerca Metrologica (INRiM), a laboratory supported by the "Compagnia di San Paolo" Foundation, and at QR Laboratories, INRiM, a micro a nanofabrication lab.

5.1 Monte Carlo simulation studies: run 3 with nominal doping profiles

In accordance with the methodology outlined in the Section 4.3, both TCAD and Monte Carlo studies were carried out on a prototyping structure of the first engineering run dedicated to the R&D of the ALICE 3 TOF. Namely, a 2D simulation domain was first implemented on TCAD to obtain the electric field profile of the device featuring the A2 layout (see Figure 4.5). The designed sensor used for these simulations has a pitch of $140\ \mu\text{m}$ and a thickness of $48\ \mu\text{m}$ to simulate the short side of a rectangular pixel. Indeed, this side was currently chosen to assess how limiting the electric field distribution was along the shorter side of the rectangle, and its impact on the breakdown phenomenon. Although the simulated domain is slightly larger than the actual sensor geometry, this choice was intentionally made for exploratory studies aimed at investigating some electric field effects at the center of the active area while decoupling it from the electrostatic effects induced by the guard rings. In this framework, the gain layer dimensions were kept realistic. By placing the guard rings farther from the active region, their functional role is preserved without significantly affecting the pad behavior, thereby approximating an almost infinite sensor geometry.

Following the simulation chain outlined in the previous chapter, this information was used as input to Allpix² to compute the weighting potential map and the relative induced signals. Monte Carlo simulations were exploited to evaluate the gain and the intrinsic timing resolution of the sensors with nominal gain produced in this first run, namely the run 3.

These first simulations were performed exploiting the nominal doping profile of the gain layer supplied by the foundry. The sensor was polarized with 35 V at the collection electrode on the top, while applying -40 V on the p^+ backside implant. The Monte Carlo simulation employs a uniformly spaced grid with a bin size of 50 nm in all directions, selected as a balance between computational efficiency and accuracy in gain layer sampling.

The electric field and the weighted potential map, obtained with the simulation, are reported in Figure 5.1. In particular, Figure 5.1a presents the electric field distribution inside the structure, highlighting a pronounced high-field region (in yellow) close

to the gain layer implant. Figure 5.1b shows the weighting potential map used to compute the induced signal via the Shockley-Ramo theorem as explained in 4.3.3.

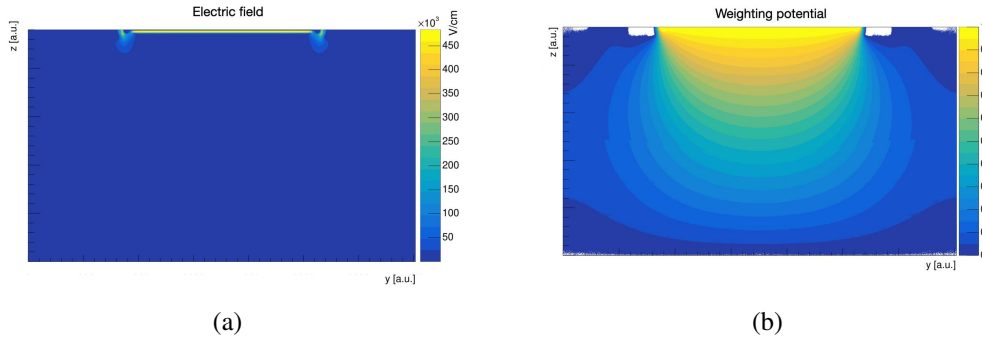


Fig. 5.1 Simulated electric field (left) and weighting potential map (right) obtained using Allpix², for an individual pixel based on the A2 layout and with a thickness of 48 μm .

Once the electric field profile has been determined, Allpix² is employed to simulate the charge collection. In this procedure, a beam of 180 GeV pions (MIPs) is first uniformly injected and then randomly injected into the pixel as the incident particle. The particle direction is perpendicular to the pixel area. Charge carrier propagation is described using the extended Canali mobility model [90] while impact ionization is described by the Okuto–Crowell model [91]. Finally, the induced charge is computed using a time granularity of 0.5 ps to maintain a high level of precision in its determination.

5.1.1 Position scan on the surface

A set of simulations was carried out using pions impinging at different fixed positions in order to quantify the Landau term (Eq. 3.1), since the beam illumination is localized on the surface. In Figure 5.2, the cross-section of the simulated pixel is shown. The induced signal, the gain, and the time resolution were studied starting from the pixel center ($x = 0$) and gradually moving toward the boundary in steps of 10 μm . The pions are incident orthogonally on the sensor surface, and the beam-like source is assigned a narrow size of 1 nm to guarantee identical impact positions within the pixel. One thousand events were simulated for each impact position, and the gain was evaluated by comparing signals simulated with and without the multiplication mechanism enabled.

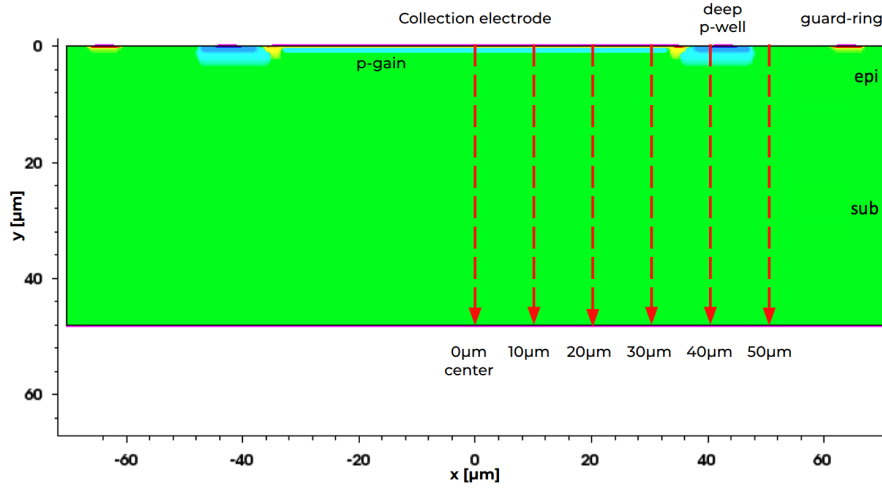


Fig. 5.2 Cross section of the ARCADIA pixel simulated in TCAD, featuring a gain layer and layout A2. The different particle impact positions are indicated by red dashed arrows. TCAD simulations courtesy of M. Mandurrino.

In Figure 5.3, the average signal waveforms for pions impinging at the pixel center are compared for the cases with the multiplication mechanism disabled (black line) and enabled (red line). The two conditions show distinct signal shapes: when multiplication is disabled, a triangular-like waveform is observed, while the activation of the multiplication mechanism results in a higher total collected charge and therefore a larger area under the waveform. This behavior is expected and is also consistent with previous studies performed on hybrid LGAD sensors, as reported in Figure 2.2.

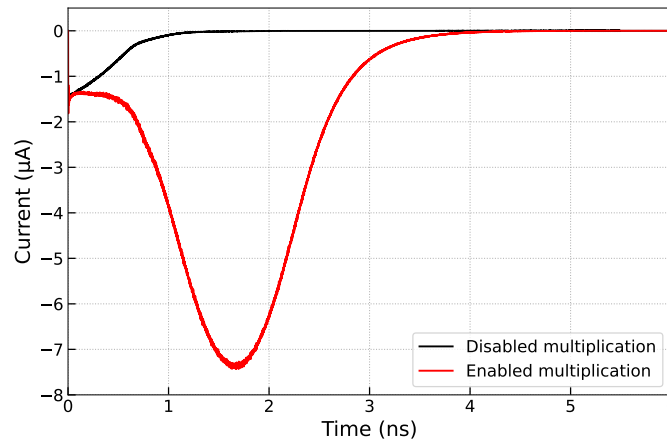


Fig. 5.3 Average waveforms calculated for 1000 events with pions impinging orthogonally in pixel center ($x = 0$). Waveforms are reported for enabled (in red) and disabled (in black) multiplication mechanism.

The current induced on the collection electrode has also been simulated for the different positions reported in Figure 5.2. The impact ionization mechanism was activated, and the average waveforms obtained for all the impinging points are reported in Figure 5.4. From the pixel center up to roughly $30\ \mu\text{m}$, the effect of gain on the waveform shape is clearly visible. Toward the periphery, the collected charge decreases, the signal amplitude drops, and the waveform shape changes significantly. The purple and black curves show the largest deviations, due to the absence of gain in these cases.

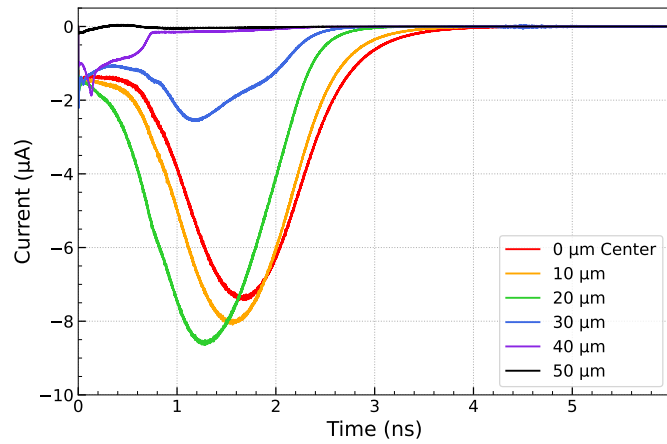


Fig. 5.4 Average waveforms from 1000 events for different impinging positions when the multiplication mechanism is enabled.

The gain was calculated as the ratio of the collected charge with multiplication enabled to the collected charge without multiplication for each impact position. The collected charge was computed by directly integrating each waveform over the full signal duration, so that this area represents the total charge collected for a single event. The resulting charge values were then accumulated into a histogram, describing the event-by-event distribution of the collected charge. In Figure 5.5, the collected charge distributions corresponding to the central impinging position, with multiplication enabled and disabled, are reported. The distributions exhibit a characteristic asymmetric shape due to fluctuations in energy deposition. The Most Probable Values (MPVs) of the red and black distributions were extracted from this histogram by performing a fit with two Landau functions. The same procedure was applied to the distributions of the charge collection simulated at different impact distances from the center of the sensor.

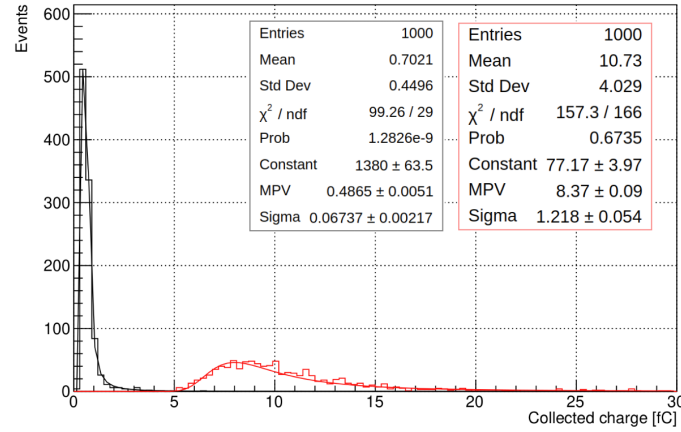


Fig. 5.5 Charge collection distributions obtained from simulations for the central impact position, with multiplication enabled (red) and disabled (black). A Landau fit is superimposed on each distribution.

The gain as a function of impact position was then determined as the ratio of the MPV of the distribution with gain to the MPV of the distribution without the multiplication mechanism enabled, evaluated at each position.

The result is shown in Figure 5.6, where the multiplication gradually decreases as the particle impact position approaches the edge outside the gain region. A slight increase in the gain is observed at approximately $20 \mu\text{m}$ from the center of the pixel. This behavior suggests the presence of a non-uniform electric field distribution within the active area, which will be discussed in more detail in the following sections.

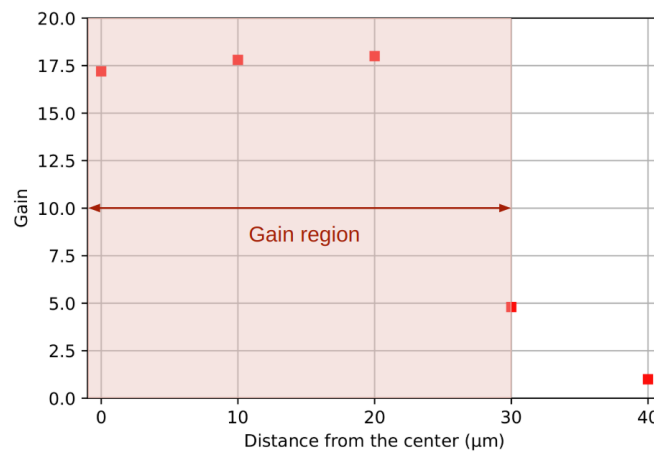


Fig. 5.6 Gain calculated as a function of the impinging position of pions using data simulated with Allpix² for a sensor with A2 layout.

Time resolution analysis

To conclude this study, the time resolution of these impact positions was estimated. The procedure used to obtain the time resolution can be summarized as follows:

1. For each event, the waveform is integrated over the full signal duration, yielding the collected charge as a function of time. This results in an S-shaped curve, which rises from 0 to the total collected charge in that event.
2. The obtained S-curves are then normalized to the total charge in each event, as illustrated in Figure 5.7 as an example.
3. Several thresholds are applied as fixed CFD values of the normalized collected charge. For each threshold, the crossing time distribution of the signal is derived from the normalized S-curve, and the time resolution is evaluated as the standard deviation of each distribution.

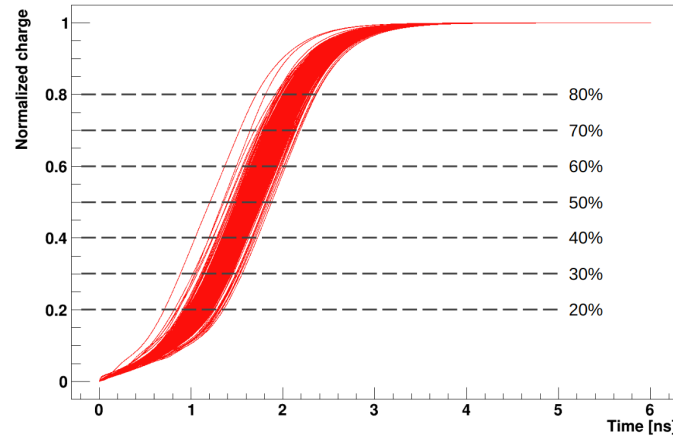


Fig. 5.7 Normalized collected charge over the full signal duration. The dotted lines indicate the fixed thresholds used in the CFD algorithm to estimate the time resolution. This plot is an example to illustrate the method adopted for the time resolution estimation. In this specific case, the distribution refers to particles impinging at the center of the sensor.

Figure 5.8 shows the time resolution as a function of the fixed threshold for different particle impact positions. As the distance from the pixel center increases, the time resolution deteriorates accordingly.

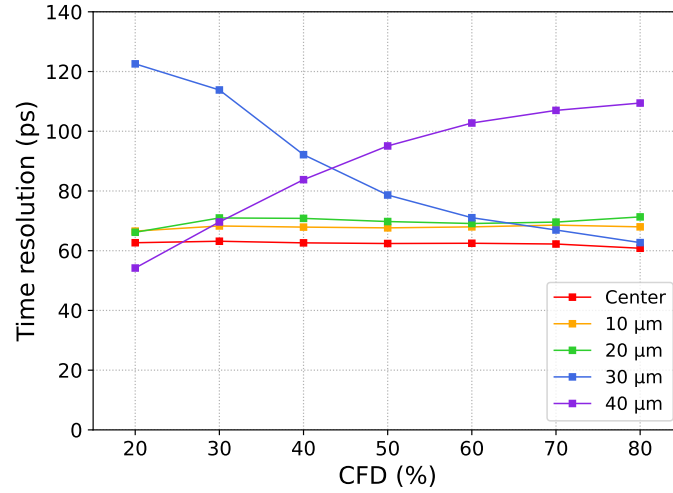


Fig. 5.8 Simulated time resolution evaluated for five different particle impact positions as a function of the applied CFD threshold.

In particular, when the particle crosses the sensor at $30\ \mu\text{m}$ from the center (blue curve), its behavior deviates from that observed at smaller impact distances. In this case, the time resolution gradually decreases as the CFD fraction increases. This unusual trend is caused by a very broad and scattered crossing-time distribution at small CFD values, resulting in a large standard deviation. The effect is likely related to the considerable S-curve spread observed in the initial part of Figure 5.9. This interaction point ($30\ \mu\text{m}$ from the center) is located at the edge of the gain layer, where the electric field is non-uniform. The gain is reduced but still present. Electrons follow vertical trajectories and are collected by the top electrode, while the holes are slower and their motion has a lateral component. As a result, the initial signal generated by the holes is lower than that of the central signals, increasing later when the holes move toward the back electrode. This low signal is more sensitive to variations due to the granularity of charge deposition, leading to a larger time resolution at low CFD percentages. At high CFD values, however, all the primary charges have been multiplied, and the multiplied holes have crossed the region with non-uniformity, resulting in a more uniform signal.

Concerning the purple curve ($40\ \mu\text{m}$ from the center), the particle impinges outside the gain layer, producing a signal without gain. The charge collection is faster, as shown by the average signal in Figure 5.4, and it is mainly due to electrons. Therefore, the initial part of the signal appears more uniform, since it is mainly dominated by the collection of electrons toward the top electrode. As a result, the

time resolution is relatively poor at low CFD thresholds. At later times, a slower signal component emerges, associated with carrier velocities no longer close to saturation, a less uniform weighting field, and the presence of a horizontal drift component. The combined effect of these factors, together with the granularity of the charge deposition, leads to an improvement in timing performance as the CFD threshold increases.

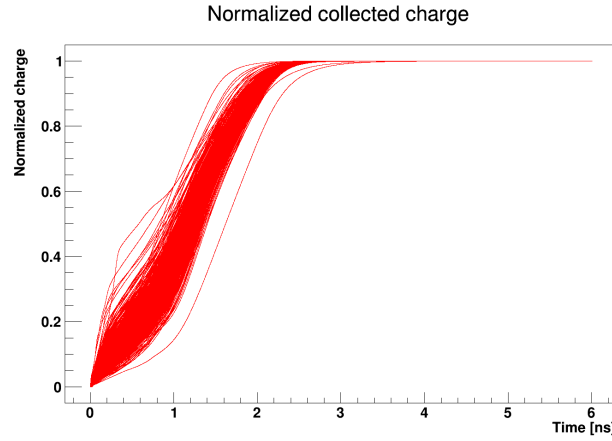


Fig. 5.9 Normalized collected charge over the full signal duration for particles impinging on the sensor at a distance of $30\ \mu\text{m}$ from the center. In particular, a larger spread of the S-curves can be observed, resulting in a higher time resolution at low CFD threshold values.

5.1.2 Random scanning

A second simulation study was focused on evaluating the time resolution for a pion beam randomly impinging on a square source with a $50\ \mu\text{m}$ side length, located $25\ \mu\text{m}$ from the pixel center. In this configuration, only half of the pixel was illuminated to reduce the computational time. Random scanning is essential to account for the distortion term, which has a significant impact on the timing resolution (see Eq. 3.1). This term reflects a possible non-uniformity of the weighting potential depending on the impact point, or a unsaturated carrier velocity.

The simulation was performed on ten thousand events to ensure good statistical precision, and Figure 5.10 shows the corresponding collected charge distribution. A double-peaked structure is observed. Indeed, when the particle traverses the edge of the structure and charge carriers are generated beneath the termination region, the resulting signal is not multiplied, producing the left peak. Otherwise, the charge carriers undergo multiplication, giving rise to the second peak on the right. This

effect is enhanced by the simulated A2 termination, where a small gap exists between the deep p-wells and the gain layer implant, allowing carriers to reach the collection electrode directly without traversing the gain layer and undergoing multiplication.

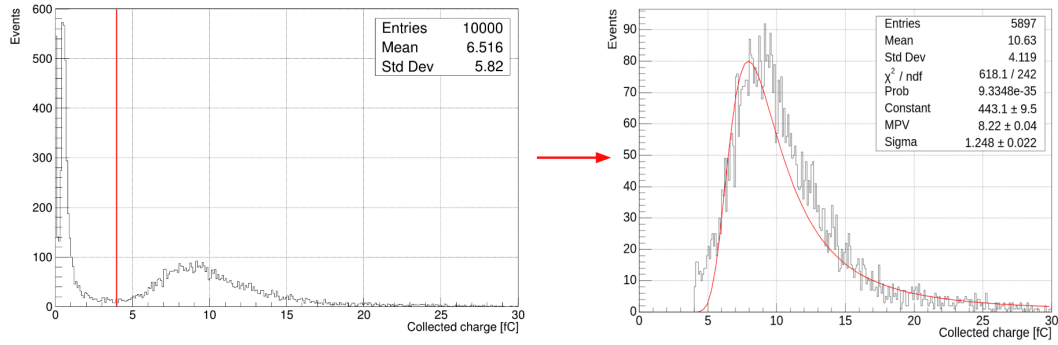


Fig. 5.10 Charge collection distributions for 10000 events simulated with pions randomly impinging on a square source with a $50 \mu\text{m}$ side length, located at $25 \mu\text{m}$ from the pixel center (left). A cut is applied at 4 fC (red line) to select multiplied signals. The resulting charge distribution after selecting multiplied events is shown (on the right) together with a Landau fit.

To consider only the multiplied signals associated to charges generated and collected inside the pixel central region, a threshold cut at 4 fC was applied (marked by a red line in Figure 5.10). The resulting distribution is shown on the right of the same figure.

The time resolution, computed using only the multiplied events, was then evaluated following the same procedure used for the fixed-position simulation and it is reported in Figure 5.11.

The differences in timing resolution as a function of the applied CFD threshold between the fixed-position (Figure 5.8) and random-position (Figure 5.11) simulations can be attributed to the interplay between charge collection dynamics, signal formation, and position-dependent weighting fields. When particles impinge at a fixed position, such as the geometrical center of the sensor, the induced current signals are highly uniform from event to event. The charge deposition profile, the carrier drift paths, and the avalanche multiplication process are almost equal. Moreover, in each event, the generated carriers experience nearly identical electric and weighting fields. As a consequence, the signal rise time, the total collected charge and the induced signal shape exhibit minimal fluctuations. Under these conditions, the CFD

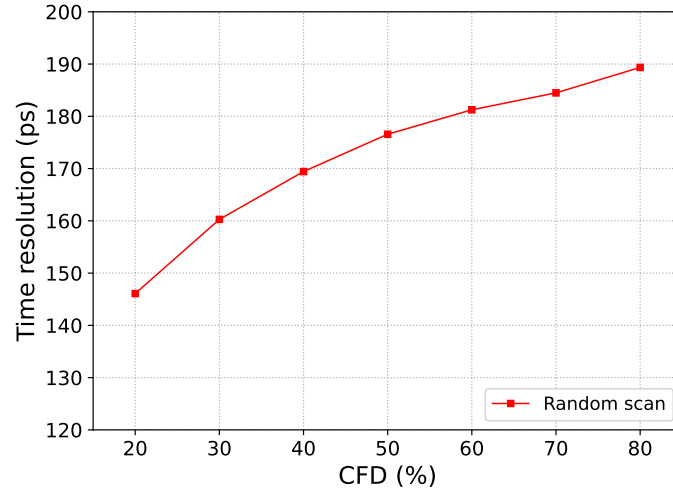


Fig. 5.11 Simulated time resolution on A2 layout and with MIPs impinging randomly on a square source having a $50\ \mu\text{m}$ side length and placed at $25\ \mu\text{m}$ from the pixel center.

technique samples a nearly identical portion of the signal waveform for different events, resulting in a time resolution that is approximately independent of the chosen CFD fraction.

Conversely, when particles are injected at random positions across the sensor surface, significant event-by-event variations arise in the signal formation process. The local gain, the effective thickness of the multiplication region, the local weighting field experienced by the charges, and carrier velocities all depend strongly on the impact position. Events occurring in regions with stronger electric fields produce faster-rising signals, whereas events originating in lower-field regions produce slower signals. This spatial non-uniformity leads to a broader distribution of signal rise times and shapes. The effect becomes more pronounced at higher CFD fractions, which correspond to later portions of the waveform where fluctuations in charge collection time, primarily due to hole drift away from the multiplication layer, are more significant. Consequently, the timing resolution not only degrades compared to the fixed-position case but also exhibits a clear dependence on the CFD fraction, increasing monotonically with higher CFD values.

In summary, the degraded and CFD-dependent resolution observed in the random-position simulations is driven by position-dependent variations in gain and weighting-field effects. These results emphasize the critical role of spatial uniformity in the multiplication layer and electric field configuration for achieving optimal timing performance in silicon sensors.

The analysis of the crossing-time distributions revealed an unexpected double population, as shown in Figure 5.12.

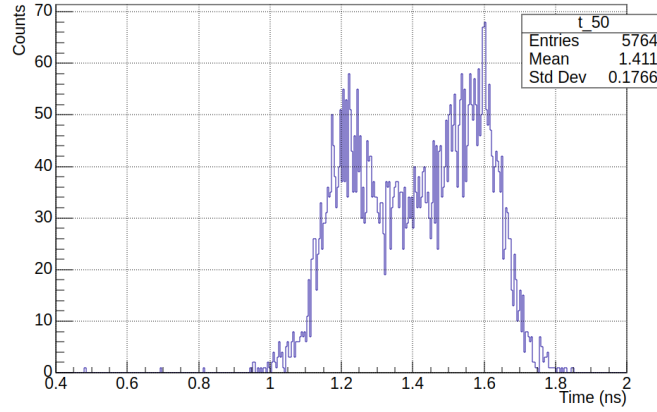


Fig. 5.12 Crossing time distribution at 50% of CFD for MIPs randomly impinging on the surface. A double population can be well identified.

This phenomenon was investigated in detail by analyzing the Time of Arrival (ToA) as a function of the particle impact position, ultimately providing a direct explanation for the origin of the double-population structure observed in the crossing-time distribution. The ToA versus impact position map, in Figure 5.13, shows that signals originating near the center of the sensor exhibit delayed arrival times, which can be attributed to a local depression of the electric field. In this central region, charge carriers experience reduced drift velocities, leading to longer drift times before reaching the high-field gain layer where avalanche multiplication occurs. As a consequence, the onset of the induced current signal is delayed compared to events generated in regions with stronger electric fields. When particles are injected at random positions across the sensor surface, events from the central low-field region and from the higher-field peripheral regions are both present. This naturally leads to two distinct timing regimes. Events generated outside the central field-depressed region produce faster signals that cross the CFD threshold earlier, forming the early crossing-time population. In contrast, events originating near the sensor center experience delayed charge transport and avalanche multiplication, resulting in later threshold crossings and the formation of a second delayed population.

Therefore, the observed double population in the crossing time distribution can be directly linked to the dependence of the ToA from the impact position and consequently

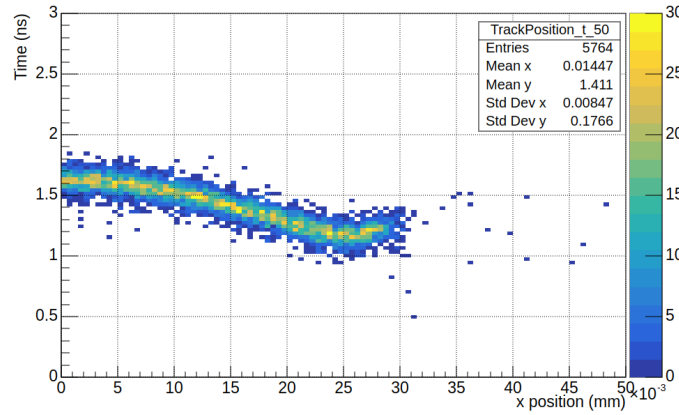


Fig. 5.13 ToA as a function of the particle impact position for the random-position simulation, taken at 50% of CFD.

to the non-uniform electric field in the sensor. The central field depression introduces a well-defined population of delayed signals, while regions with higher electric fields produce faster signals. This correlation demonstrates that the degradation of the timing resolution observed in random-position simulations is driven mainly by intrinsic non-uniformity in the electric field and weighting potential configuration. This leads to the conclusion that mitigating electric field depressions is crucial for suppressing the formation of multiple timing populations and achieving optimal time resolution in sensors.

5.2 Characterization of run 3 passive structures

As anticipated in Section 4.2.1, ARCADIA run 3 was the first engineering run produced in 110 nm technology featuring internal gain. It comprised both passive test structures without integrated electronics and active sensors with integrated CMOS readout circuitry. This section describes the first test campaign conducted for the full characterization of the passive structures, together with a discussion of the obtained results. The main purpose of this campaign was to demonstrate the feasibility of adding a gain layer to this sensor technology, and to validate the fabrication process.

Multiple passive test structures were manufactured, differing in pixel termination geometry: ARCADIA 250A1, 250A2, and 250G1 structures. The first two adopt rectangular pads with the same geometry as the active device, characterized by

a $250\text{ }\mu\text{m} \times 70\text{ }\mu\text{m}$ active area, whereas the G1 devices employ square pads of $250\text{ }\mu\text{m} \times 250\text{ }\mu\text{m}$, resulting in a larger fill factor. The A1 and A2 layouts have already been presented in Section 4.2.1, while the G1 layout shares the A1 design but includes additional holes in the metal layer, enabling optical measurements.

5.2.1 Electrical characterization

A microscopic image of the passive pixel arrays for the three different termination geometry is shown in Figure 5.14, where the rectangular or square pixel shapes are clearly visible. The three structures feature four front side electrodes on the chip surface (indicated with red arrows) that, from left to right, correspond to the external p-well, the n-type charge collection electrode (top electrode), the internal p-well, and the n-type guard ring.

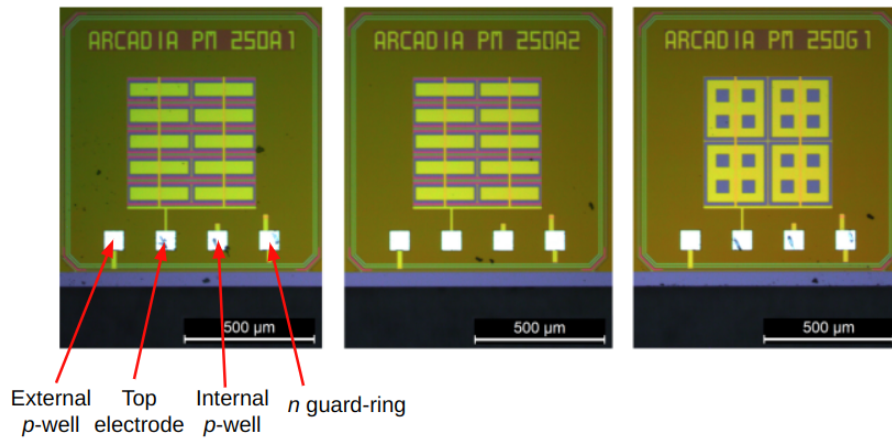


Fig. 5.14 A microscopic image of three passive pixel arrays: (from the left to the right) ARCADIA 250A1, 250A2, and 250G1 structures. Image taken from [92]

In these matrices, all collection nodes are connected in parallel to a single readout electrode, which is used to apply a positive bias voltage to guarantee the avalanche multiplication. The internal p-well pad provides the ground reference during the measurements; accordingly the p-well voltage was fixed at 0 V. The guard ring was biased to a dedicated voltage to collect current diffusing from the volume surrounding the test structure. Finally, a fourth pad can be used to apply a negative bias to the external p-well [92].

All the electrical measurements discussed in this section were performed using

a probe station with needles connected to a HP 4156A Precious Semiconductor Parameter Analyzer [93]. The trend of the topside and backside currents for different devices are illustrated in Figure 5.15 and Figure 5.16, respectively, as a function of the applied reverse bias voltage on the back. Results are shown for both the A1 (blue curves) and A2 (red curves) pixel layouts. During the measurements, the voltage applied to the top electrode was fixed at 35 V, while the guard ring electrode was biased at 3 V.

In Figure 5.15, it can be observed that at low backside voltages the current is high, corresponding to incomplete depletion of the device. As the reverse bias is increased, the sensor reaches full depletion, marked by a steep drop in the curve (colored regions). The corresponding top current is then quite small and is entirely due to the dark current of the pn junction. The different behavior of the A1 and A2 layouts can be attributed to their geometric differences: the gap in the A2 termination shifts the depletion voltage to higher values (around -35 V), compared to -25 V for the A1 device. The subsequent increase in current around -48 V is associated with the onset of edge breakdown at the junction borders, which is also confirmed by a significant increase in the guard ring current (not shown) over the same voltage range. These breakdown voltages define the maximum allowable voltage that can be applied to the collection electrode for proper device operation.

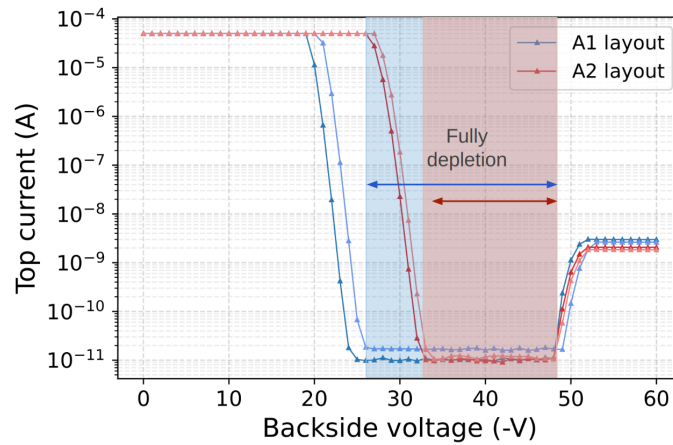


Fig. 5.15 Topside current as a function of the negative reverse bias voltage applied on the back electrode for A1 (blue curves) and A2 (red curves) layouts. Two test structures for each layout were measured. The collection electrode voltage was biased at 35 V, while the guard ring at 3 V.

Figure 5.16 is useful for studying the onset of punch-through phenomenon. As explained in Section 4.1, this effect occurs when the voltage applied to the backside electrode exceeds a certain threshold, causing a hole current to flow between the top and back p-implants. For the structures considered in this thesis, punch-through begins once the applied backside bias reaches about -40 V. This "knee" is followed by a plateau indicating that the compliance current set for the p-well channel was reached in order to prevent potential damage to the sensors. Nevertheless, the backside current continues to evolve with increasing bias voltage, and the onset of breakdown becomes clearly visible at approximately -48 V. The punch-through voltage generally defines the maximum allowable backside bias for proper sensor operation, although slightly higher voltages may be applied if temperature and power consumption are carefully monitored.

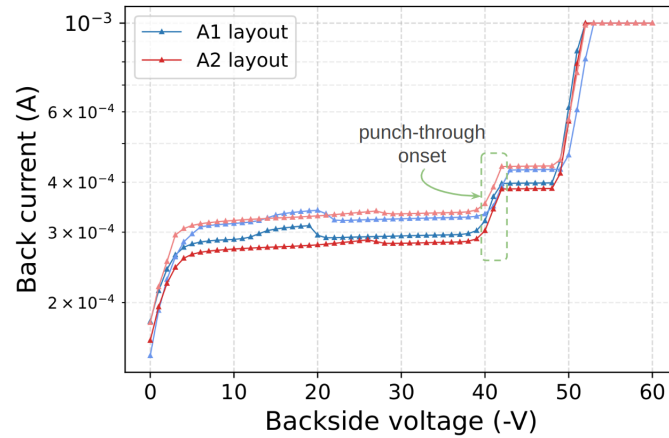


Fig. 5.16 Backside current as a function of the negative reverse bias voltage applied on the back electrode for both A1 (blue curves) and A2 (red curves) layouts. Two test structures for each layout were measured. The collection electrode voltage was biased at 35 V, while the guard ring at 3 V.

5.2.2 Dynamic characterization and investigation on the gain implant

After the electrical characterization, the dynamic behavior of the passive pixels was tested with an optical setup in collaboration with the Trento Institute for Fundamental Physics and Applications (TIFPA). A fast pulsed IR laser emitting at 1060 nm, capable of producing pulses with a FWHM of approximately 100 ps and a focused spot of about 10 μm FWHM, was employed. The characterization was performed by

illuminating the backside surface of the device through a hole made in the Printed Circuit Boards (PCBs), on which the chips were glued and wire-bonded. Thanks to this optical setup, the gain was evaluated as the ratio between the charge collected by a structure with internal gain and that collected by a reference device without a gain implant. Figure 5.17 shows the collected charge measured on a matrix with A2 layout obtained by integrating the acquired signals for different applied topside voltages.

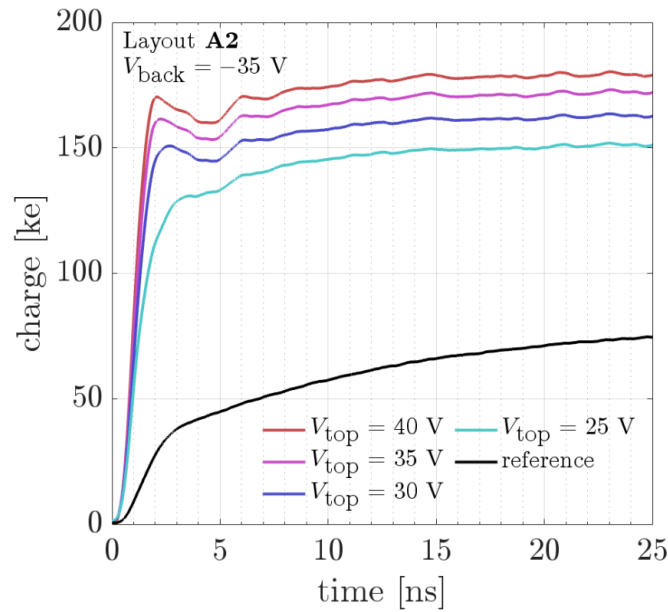


Fig. 5.17 Collected charge as a function of time measured using a 1060 nm pulsed IR laser for a test structure with A2 layout. The colored curves correspond to a device with internal gain at different top voltages, while the black curve refers to a reference device without internal gain. Image taken from [94]

The ratio of the charge collected in devices with gain to that obtained from the reference structure indicates a multiplication factor of approximately 2.5, whereas a gain in the range of 10–25 was expected. Furthermore, the collected charge increases only marginally with the applied top voltage, providing additional evidence of low gain.

A simulation study based on a 2D TCAD framework was designed to investigate the gain layer implant. Since the capacitance variation with applied bias voltage can provide relevant information on this implant, the $C(V)$ characteristics were used as a

benchmark for validating the gain calculations. The results reported in Figure 5.18a show that the capacitance simulated with the nominal profile (black solid line) of the first engineering run with gain does not match the experimental data (dots). Good agreement is achieved by introducing a significant shift in the gain implant toward the sensor frontside (red solid line). Since a shallower gain layer corresponds to a lower multiplication factor, this shift may explain why the measured gain was lower than expected [94].

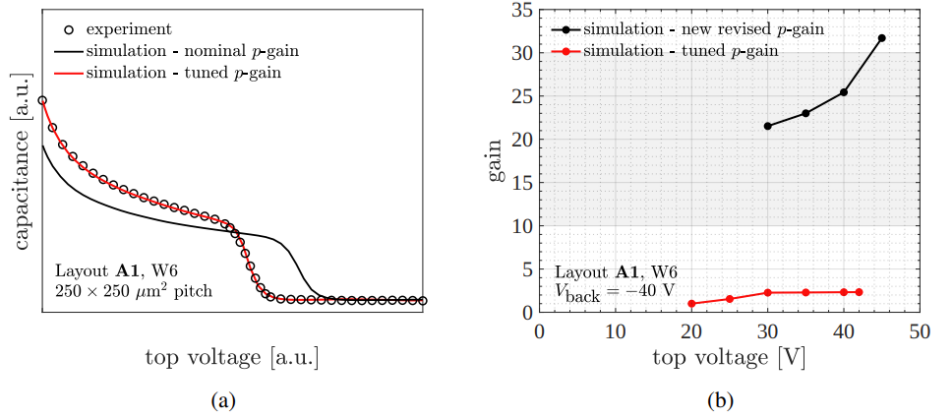


Fig. 5.18 (a) Lateral $C(V)$ characteristics of a test structure with internal gain: simulated (lines) and measured data (dots) are shown for comparison. (b) Gain as a function of the top voltage obtained from simulations using the tuned p-gain implant (red), and with the updated profile proposed for the subsequent short-loop run (black). Taken from [94].

To validate this hypothesis, an additional TCAD simulation was performed to compute the gain G as a function of the top bias voltage, employing the optimized implantation profile (corresponding to the red line in Figure 5.18a) as an input parameter. Charge carriers were injected perpendicularly to the sensor surface, and the corresponding $G(V)$ curve is reported in Figure 5.18b. The gain obtained using the tuned parameters (red line) ranges between 2 and 3, which is substantially lower than the expected values of 10–25 and consistent with the results presented in Figure 5.17. This suggests that some parameters were mismatched during the fabrication process. Indeed, a verification of the process flow by the foundry confirmed that the ion implantation energy was set to 30% of the values used in the design phase [94]. Despite this limitation, the study was very useful in demonstrating the feasibility of implementing the LGAD concept in the 110 nm technology developed by LFoundry and in verifying its proper operation. Finally, it confirmed the reliability of the simulation tools.

5.3 Monte Carlo simulation studies: run 3 with tuned doping profiles

The results presented in this Section were obtained from Monte Carlo simulations using as input the TCAD profiles performed with the tuned parameters discussed in Section 5.2. The simulated structure has the same layout described in Section 5.1, but with a shallower gain implant introduced to better reproduce the design of the real sensor. As described above, the electric field profile obtained from TCAD was imported in Allpix² and combined with the weighting potential map to compute the induced signal on the collection electrode. The bias voltages were set to 45 V at the top collection electrode and -40 V at the backside electrode, and a beam of 180 GeV pions was used as the simulation source.

For this study, the same simulation flow described in Section 5.1 was followed. A set of simulations scanning the sensor surface was performed, using the same impinging positions shown in Figure 5.2. For each impact point, 1000 events were simulated. Figure 5.19 shows the average waveforms for all scan positions. The most evident feature of these waveforms is their triangular shape, which closely resembles the signals obtained when the multiplication mechanism is disabled, indicating the low gain associated with the tuned doping profiles. As in the previous study, moving towards the periphery the induced signal shape change significantly, further highlighting the absence of effective gain.

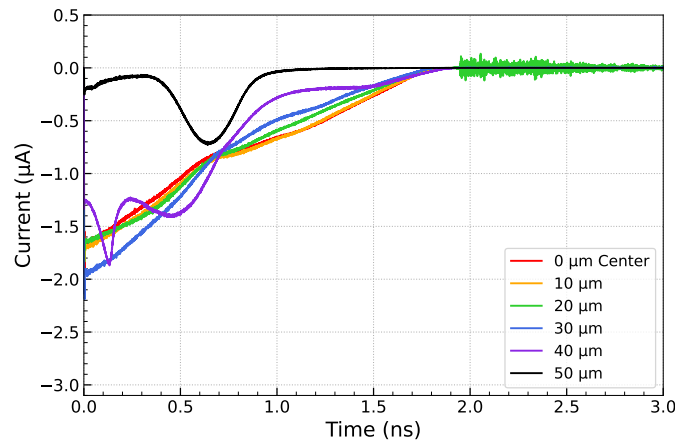


Fig. 5.19 Average waveforms from 1000 events for different impinging position after tuning the gain implant.

Adopting the same method described in Section 5.1, the sensor gain was evaluated as a function of the impact position. The results are shown in Figure 5.20. The gain was computed as the ratio between the MPV of the collected charge distribution obtained with multiplication enabled and that obtained with the multiplication mechanism disabled. The results confirm the expectations from both TCAD simulations and experimental data, yielding a gain value of about 2 and supporting the reliability of the Monte Carlo framework.

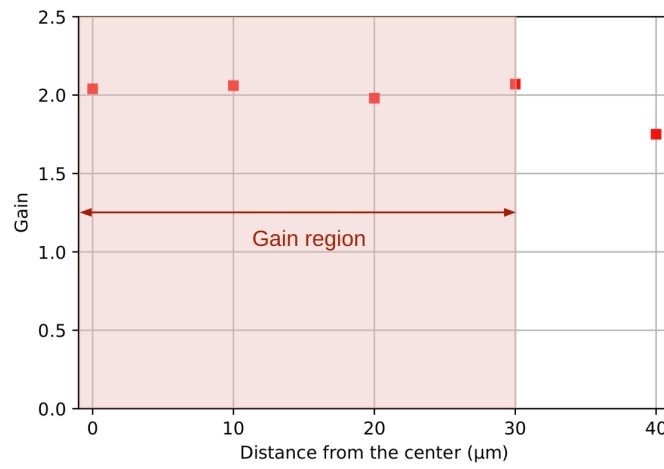


Fig. 5.20 Gain as a function of four impinging position obtained with Monte Carlo simulations for the A2 structure after the tuning of the gain implant profile.

To complete the simulation campaign, 10000 events randomly impinging on the surface were simulated using a square source with a side length of $100\ \mu\text{m}$, placed in the pixel center, in order to estimate the overall time resolution of the sensor. The average waveforms obtained using two different Monte Carlo tools (Allpix² and Garfield++ [95]) show a very good agreement, as reported in Figure 5.21.

Figure 5.22 shows the charge distributions and the effect of enabling charge multiplication. When multiplication is active, the most probable value shifts toward higher values, while a shoulder appears at lower collected charges. This shoulder, labeled (1) in Figure 5.22, can be described by a Landau–Gaussian convolution and is attributed to the A2 layout, where charges generated at the pixel periphery do not undergo multiplication.

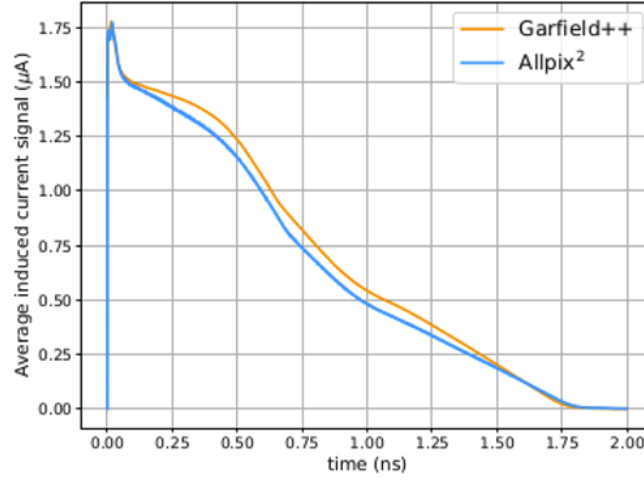


Fig. 5.21 Average waveforms of 10000 simulated events, impinging randomly on the surface, obtained using two different Monte Carlo tools (Allpix² and Garfield++). Garfield++ results are courtesy of U. Follo. Image taken from [79]

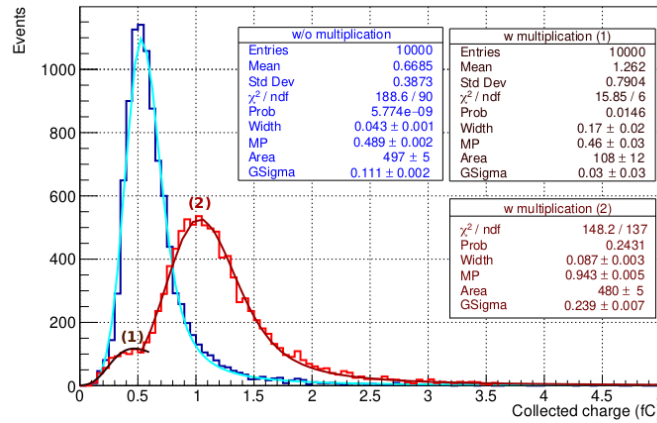


Fig. 5.22 Simulated collected charge distributions without (in blue) and with (in red) the multiplication model enabled. The red distribution exhibits a primary component, labeled (2), together with a shoulder, labeled (1), which is attributed to signals that do not undergo multiplication. Image taken from [79]

Figure 5.23 shows the overall time resolution, demonstrating excellent agreement between the two tools within 10% [79].

The simulation results discussed above provided a first estimation of the intrinsic time resolution of this innovative technology benefiting from the high statistics provided by the Monte Carlo approach. They also served as a valuable benchmark

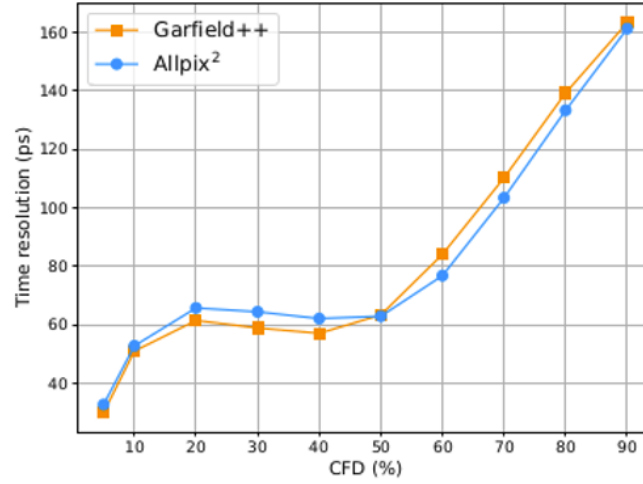


Fig. 5.23 Overall time resolution simulated using the CFD algorithm, comparing the two frameworks: Allpix² in blue and Garfield++ in orange. Garfield++ results are courtesy of U. Follo. Taken from [79]

for validating the simulation methodology, showing strong agreement between the outputs of the two Monte Carlo frameworks.

5.4 A Monolithic CMOS Avalanche Detector PIXelated (MADPix)

This section is dedicated to the first prototype of a Monolithic CMOS Avalanche Detector PIXelated (MADPix) featuring internal gain and fabricated using a commercial 110 nm CMOS technology. The prototype, integrating on-chip electronics, was developed using the LFoundry 110 nm process within the ALICE 3 TOF working group in collaboration with the ARCADIA project.

5.4.1 Chip layout

The layout of MADPix is shown in Figure 5.24. This first prototype has overall dimensions of $16.4 \times 4.4 \text{ mm}^2$ and consists of two symmetric adjacent regions, referred to as top and bottom. Each region contains four matrices, with each matrix comprising 64 pixels arranged in 8 rows and 8 columns. The four matrices are

different and they are labeled as: A1_*a*, A2_*a*, A1_*b*, and A2_*b*. The A1 and A2 labels correspond to the two termination layouts presented in Section 4.2.1, while the subscripts *a* and *b* indicate two different coupling capacitor connecting the sensor to the amplifier input. A distinctive feature of this technology, as reported above, is the AC coupling solution used to connect the pixel to the electronics, necessary due to the large difference in operational voltages. In particular, the library capacitor provided by the foundry is certified to operate up to 30 V, while the top electrode must be biased to higher voltage to reach the desired gain and its best working point. Consequently, a fully custom capacitor (layout *b*) was developed with a different metal layers and an increased spacing between the plates in order to prevent electrical breakdown.

Due to size constraints, the chip was designed with only 64 analog output pads on the top and 64 on the bottom. As a result, the outputs of four 3.3 V buffers, one for each matrix, share a common output pad.

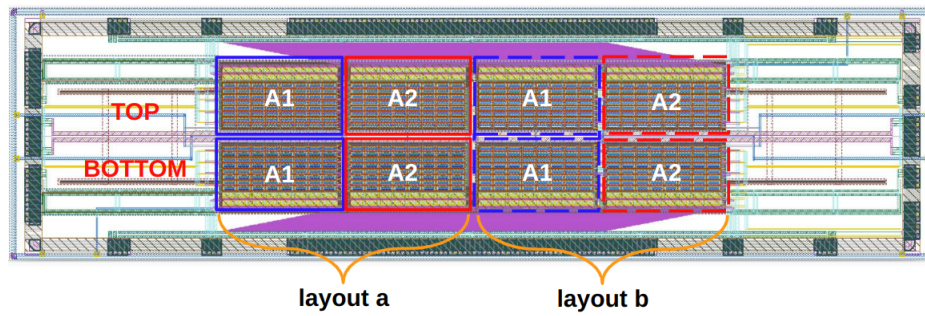


Fig. 5.24 Layout of the MADPix chip. The device is divided into two symmetric sections, TOP and BOTTOM, which are symmetric with respect to the horizontal axis. Each section contains four matrices, with each matrix of an array of 8×8 pixels. The matrices differ in both the pixel sensor layout (A1 and A2) and the design of the coupling capacitor connected to the readout electronics (solid or dashed line).

A single matrix is shown in Figure 5.25: on the left, the 64 rectangular pixels with dimensions of $100 \times 250 \mu\text{m}^2$ are visible. These pixels are similar to those of the ARCADIA 250A1 and 250A2 passive structures, but with a larger short-side pitch adopted in the active design to accommodate the integrated readout electronics. More precisely, 1.2 V front-end electronics is integrated within an $8 \times 250 \mu\text{m}^2$ deep p-well located along the long side of the rectangular pixel and separating two neighboring pixels. On the opposite side, a bias resistor is implemented to provide the required voltage. The integration of the electronics at the pixel border justifies

the larger dimension of the short side in the active structures ($100\ \mu\text{m}$) compared to the passive ones, where a $70\ \mu\text{m}$ pitch is sufficient.

For the ALICE 3 TOF application, the required pixel granularity corresponds to a maximum pixel pitch of $1\ \text{mm}$. Since the intrinsic time resolution strongly depends on the ratio between the electrode size and the sensor thickness, a detailed study of the collection electrode is essential to minimize the contribution of the distortion term to the time resolution. The initial target pixel pitch for the first tape-out was set to $250\ \mu\text{m} \times 250\ \mu\text{m}$. However, due to diffusion density limitations imposed by the submission, the pixel dimensions were subsequently reduced to $250\ \mu\text{m} \times 100\ \mu\text{m}$. A possible implementation of the final detector concept foresees a 2×2 pixel matrix, with each pixel featuring dimensions of $250\ \mu\text{m} \times 250\ \mu\text{m}$, thus covering an active area compatible with the TOF granularity requirements. At this stage, however, the sensor layout is still under investigation, and dedicated simulations are currently ongoing to optimize the detector geometry and define the final sensor configuration.

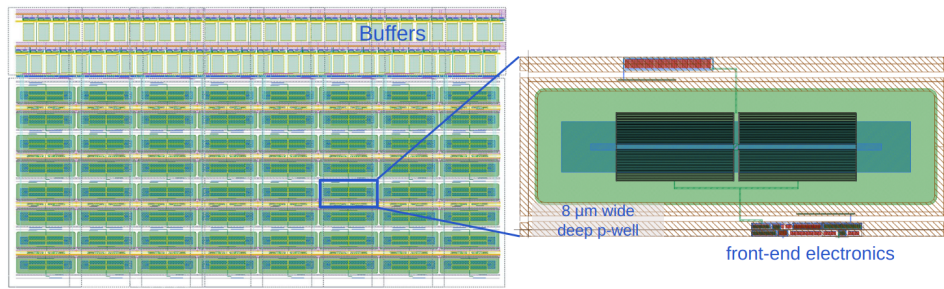


Fig. 5.25 Zoom of the MADPix layout. On the left, the matrix with the array of 8×8 pixels where is visible together with the $3.3\ \text{V}$ buffers. On the right, a zoom of a single pixel with the $1.2\ \text{V}$ front-end electronics integrated within an $8 \times 250\ \mu\text{m}^2$ deep p-well positioned along the long side is reported.

5.4.2 Readout architecture

The readout electronics comprises an initial amplification stage followed by a buffer that drives the amplifier output out to the chip. Figure 5.26 presents a schematic representation of the electronic readout chain. The top electrode is biased at $V_{top} = V_b - R_b I_{top}$ and it is AC-coupled through C_{c0} to a transimpedance amplifier. The amplified signal is subsequently buffered to the output pad through a second amplification stage located at the periphery of the matrix.

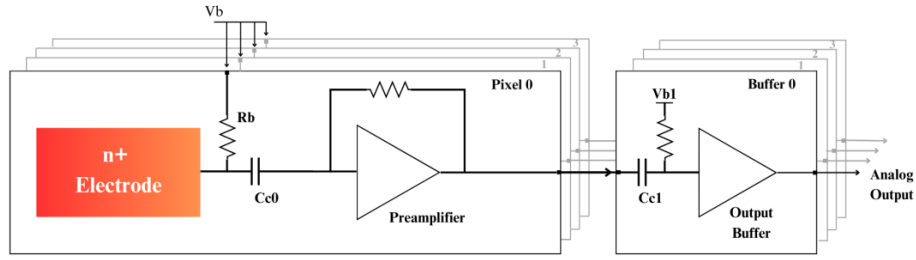


Fig. 5.26 Diagram of the single-channel readout electronics. The top electrode is AC-coupled through C_{c0} to a transimpedance amplifier implemented with 1.2 V transistors, and it is biased at V_{top} thanks to the bias resistor R_b . Outside each matrix, a buffering stage based on 3.3 V transistors drives the analog signal toward the output pads. Image taken from [96]

A schematic representation of the readout electronics is presented in Figure 5.27. The in-pixel preamplifier consists of a cascoded common-source amplifier, followed by a differential amplifier with unitary gain required to decouple the amplification stage from the output load capacitance. The front-end is subsequently connected to an output buffer realized as a source follower enclosed by two transistors acting as switches (S1 and S2). Contrary to the in-pixel front-end, which was designed with 1.2 V transistors, 3.3 V MOSFETs were selected for this stage. As for the sensor the presence of two distinct power domains prevents a direct connection. Therefore, the output buffer is AC-coupled to the front-end electronics through the capacitor C_{c1} . Unlike the in-pixel circuitry, the 3.3 V buffers are located outside each matrix but within an external guard ring. This key element surrounds each matrix and, when biased, is able to collect charges generated at the periphery, ensuring a low dark current.

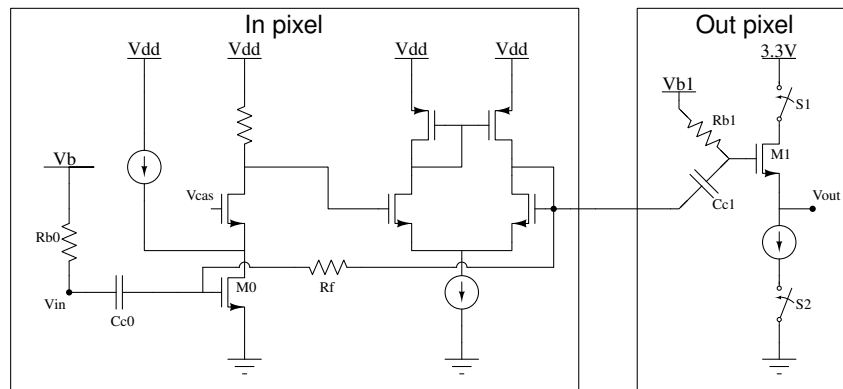


Fig. 5.27 Block diagram illustrating the in-pixel front-end circuitry and the subsequent output buffer implemented outside the pixel matrices. Taken from [94]

The in-pixel front-end consumes 0.18 mW per pixel, corresponding to a power density of 7.2 mW/mm^2 (given the pixel dimensions of $100 \times 250 \mu\text{m}^2$). Each output buffer stage draws a current of $500 \mu\text{A}$, leading to a power consumption of 1.65 mW per channel.

5.4.3 Readout board

A dedicated custom PCB Test Board (TB), shown in Figure 5.28, was developed to characterize the MADPix chip. Its main purpose is to provide and configure all bias currents and voltage levels required by the electronic circuitry. As for the chip, the PCB is partitioned into two sections: top and bottom. The upper section hosts four analog buffers, each driving a 50Ω transmission line that can be connected to an oscilloscope through SMA cables. The lower one contains four Low-Voltage Differential Signaling (LVDS) buffers operating as discriminators, whose outputs are connected to an external FPGA that manages the board through two flat cables.

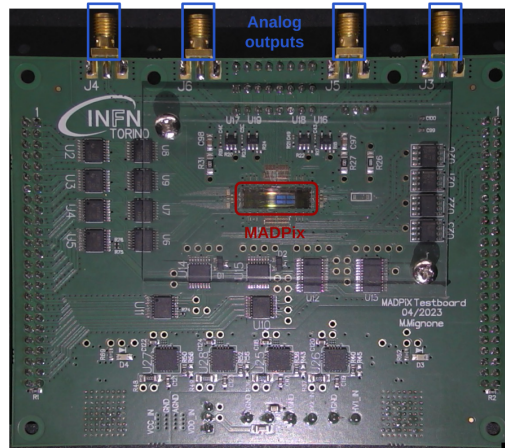


Fig. 5.28 Image of the readout test board developed at INFN Torino for chip characterization.

5.4.4 Characterization in laboratory

I-V measurements

The first measurement to verify the correct operation of the chip concerns the electrical characterization performed on a probe station as illustrated in Section 5.2.1. The backside and p-well currents as a function of the back electrode are shown in

Figure 5.29. For this test the top electrode was biased a fixed voltage of 45 V while the guard ring at 9 V. The measurements were carried out for both the A1 and A2 layouts; however, from this point onward, only the characterization of the A2 design is presented, as it was developed to achieve improved time resolution.

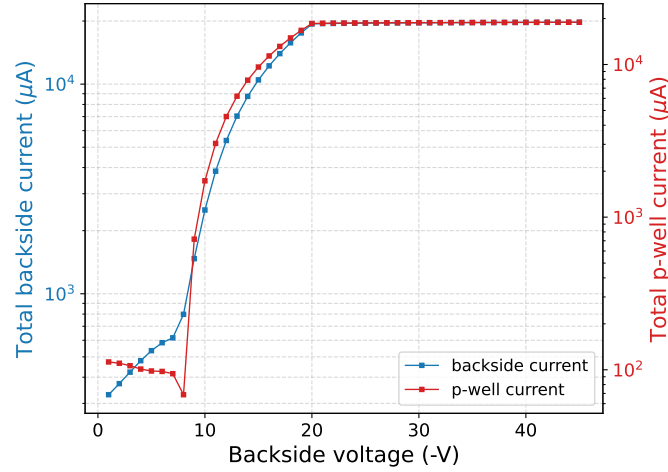


Fig. 5.29 In blue, the backside total chip current versus the reverse bias voltage of the back. In red, the total p-well current always as a function of the backside voltage. The top electrode was left to a fixed voltage of 45 V while the guard ring at 9 V.

The back electrode current (blue curve in Figure 5.29) is the one which flows from the p^+ back implant and rises sharply because of the punch-through effect, which usually appears at bias voltages greater than 10 V. However, this current increases at approximately -7 V due to a floating guard ring located outside the pad frame, i.e. in close proximity to the silicon edge where the chip is diced. During the dicing process, some low-resistance paths can form, leading to an increase in the border current that would have been collected if the guard ring had been properly biased. Therefore, the punch-through onset is not visible in this plot.

In the same Figure 5.29, it has been reported also the p-well current fixed at 0 V as a function as the reverse bias voltage of the back. The behavior of the p-well current is similar to the one of the backside electrode, showing a strong relation and communication between the two implant which would cause the punch-through phenomenon.

In Figure 5.30 the topside current per single pixel as a function of the backside voltage is reported. This current flows at the collection electrode and its behavior

brings information on the breakdown mechanism when it happens. In the initial part of the curve, the sensor is not yet fully depleted, resulting in a conductive path between the two topside n-doped implants: the electrode and the surrounding guard ring. Once the sensor reaches full depletion, the topside current drops to low values, corresponding to the dark current, and it reaches a plateau at approximately -20 V. The current not collected by the floating external guard ring contributes to an increase in the topside current, which rises around -7 V in correspondence with a growth in the backside current. As a result, the depletion voltage shifts to higher backside bias values.

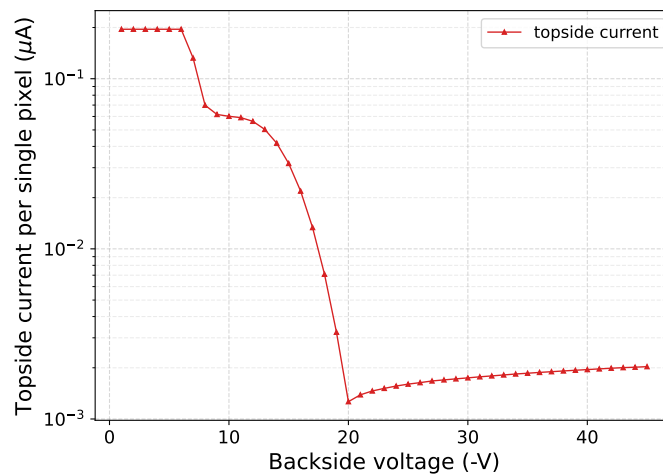


Fig. 5.30 Topside current per single pixel as a function of the negative bias voltage applied to the back. The top electrode was biased at a fixed voltage of 45 V while the guard ring at 9 V.

Finally, the top current is also reported as a function of the top bias voltage to appreciate the breakdown onset, see Figure 5.31. An increase of the characteristic is visible and it is due to the multiplication process, which leads to the breakdown phenomenon at around 35 V.

Laser characterization

The same setup described in Section 5.2.2 was employed to evaluate the jitter contribution to the sensor time resolution. Laser characterization allows this contribution to be studied while avoiding the influence of the Landau and distortion terms, provided that a uniform illumination over a small area is used.

To perform this characterization the time difference between the chip output signal,

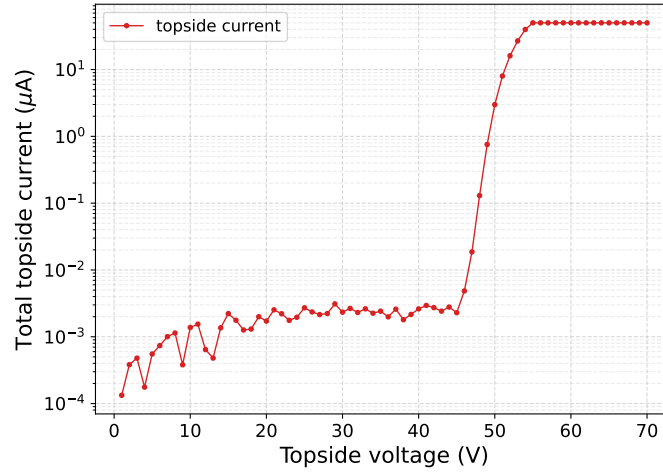


Fig. 5.31 The topside total chip current as a function of top bias voltage. The backside electrode was biased at a fixed voltage of -20 V while the guard ring at 9 V.

measured at 50% of its amplitude, and the laser trigger was evaluated [94]. The electronic jitter was estimated as the standard deviation of this time distribution. Initially, the laser intensity was adjusted to deliver a charge equivalent to that deposited by a MIP, corresponding to a signal amplitude of approximately 10 mV. Subsequently, the intensity was increased to ensure that the MADPix signal remained sufficiently high, allowing an amplitude scan. The results are shown in Figure 5.32 and it is evident that the jitter contribution decreases as the signal amplitude is increased through higher laser power, achieving a value of about 50 ps.

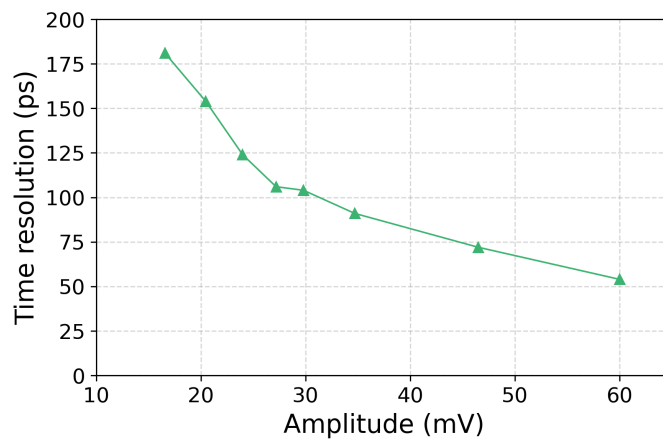


Fig. 5.32 Time resolution evaluated with the laser setup to study the jitter contribution. The backside was biased at -30 V while the top electrode was biased at 40 V.

5.4.5 First in-beam measurement

Test beam setup

The timing performance of the MADPix chip was studied during several beam test campaigns conducted since 2023. All tests took place at the T10 beamline of the CERN PS where a positive hadron beam, primarily composed of protons and pions with a momentum of $10 \text{ GeV}/c$, is available. The experimental setup used during the tests (illustrated in Figure 5.33) consists of a four-plane telescope enclosed in a dark box exposed to the beam. For the measurements only two planes are relevant: one for the DUT and the other for the timing reference, provided by a fast hybrid LGAD with a known timing resolution.

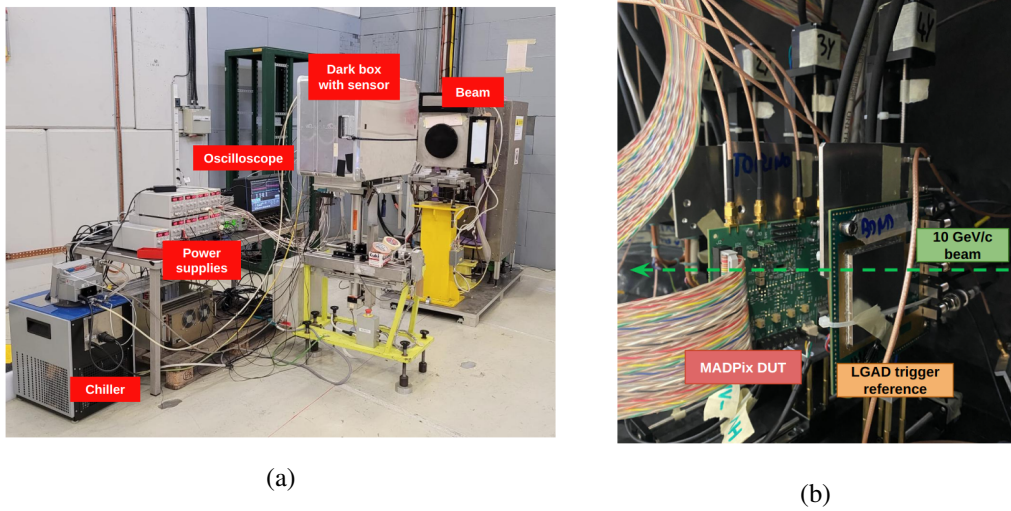


Fig. 5.33 (a) Photo of the test beam setup used at the T10 beamline of the CERN PS. (b) Two telescope planes where the DUT and the timing reference were mounted using the micro-moving stages placed inside the dark box.

Each plane can be moved using micro-moving stages in the x-y plane, which is perpendicular to the beam direction. The stages can be remotely controlled with a spatial precision of $10 \text{ }\mu\text{m}$, and this feature allowed the alignment of the two sensors for the measurements. In the last test beam, the setup also included a chiller to control and stabilize the temperature in the region where the chip was mounted. A temperature scan was performed to study the sensor response as a function of temperature. The entire setup, including power supplies, oscilloscope, and FPGA, was remotely controlled from a PC connected via Ethernet. LabVIEW

tools were used for data acquisition and data storage, as well as for bias voltage and current configuration. The signals from three neighboring MADPix pixels were read out and recorded simultaneously with the signal provided by the hybrid LGAD. Data acquisition was performed using a Teledine LeCroy WaveRunner 9404M-MS oscilloscope with a sampling rate of 20 GS/s, an analog bandwidth of 4 GHz, and 8-bit vertical resolution. Given the limitation of the oscilloscope to read out simultaneously only four channels, three channels were assigned to MADPix signals, while the final one served for the reference plane. The oscilloscope contribution to the overall measured time resolution was negligible, allowing a direct analysis of the sensor time resolution. In particular, its contribution is about 14 ps, estimated as the time binning (50 ps) divided by $\sqrt{12}$. The use of linear interpolation between the points around the threshold further reduces the effective timing uncertainty to a few picoseconds. This makes the oscilloscope contribution negligible compared to the measured time resolution. Full LGAD and DUT waveforms were acquired and analyzed offline.

In the following sections, the method used to analyze the data collected during the test beam campaigns will be described, and the obtained results will be discussed.

Collected charge

By sampling the entire analog waveform, it was possible to reconstruct the collected charge distribution as shown in Figure 5.34. The charge is determined from the peak of the amplitude signal normalized by the electronics gain obtained from post-layout simulations. The resulting distributions are fitted using a Landau–Gaussian convolution.

Figure 5.34a shows the measured charge distributions for a sensor with the A2 layout, and with the collection electrode voltage set to 30 V and 45 V. As the voltage increases, the most probable value of the distribution rises by approximately a factor of 2.2, indicating the onset of gain activation and the good agreement with the results obtained from laser measurements (see Section 5.2.2). Figure 5.34b compares the results obtained for the A1 and A2 structures at the same collection electrode voltage of 45 V. The slight difference in the MPVs may be attributed to small fluctuations in the electronics gain, while the discrepancy observed in the low-charge tails is likely due to the different terminations of A1 and A2 layouts. In fact, for the A1 layout the avalanche multiplication can also occur at the edges of the sensor. In contrast, in the

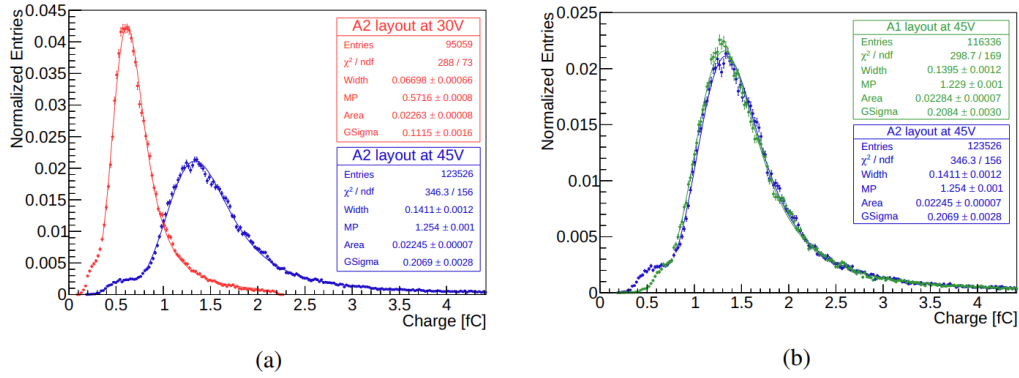


Fig. 5.34 (a) Collected charge distributions measured for the A2 structure at two different top bias voltages, 30 V (red) and 45 V (blue). (b) Comparison of the collected charge distributions for structures with A1 (green) and A2 (blue) layout. Top bias voltage and backside bias were fixed at 45 V and -30 V, respectively. Figure taken from [94]

A2 layout a gap allows particles to reach the collection electrode directly, without traversing the gain layer and multiplying.

Evaluation of time resolution

For the experimental evaluation of the MADPix time resolution two different analysis methods were adopted: the Constant Fraction algorithm (or CF algorithm) and the fixed threshold algorithm, also called Leading Edge (LE). In both cases the time walk correction described in Sec. 3.2 was applied. In the first approach, the time of arrival (ToA) of a particle is measured as the time when the signal crosses a fixed fraction of its amplitude. In the second method, the ToA is defined as the moment when the signal crosses a specified threshold, expressed in mV, as shown in Figure 5.35. For the timing reference plane, the ToA was extracted as the time at which the signal crosses 30% of its amplitude, using the algorithm described in [45].

The time difference between MADPix (t_{DUT}) and the reference ($t_{reference}$) is shown as a function of the DUT signal amplitude (DUT ampl) in Figure 5.36a. The corresponding distribution was fitted using the function in Eq. 5.1, and the measured data were subsequently corrected by subtracting the fitted value.

$$t_{DUT} - t_{reference} = a + \frac{b}{(DUT \text{ ampl})} + \frac{c}{(DUT \text{ ampl})^2} \quad (5.1)$$

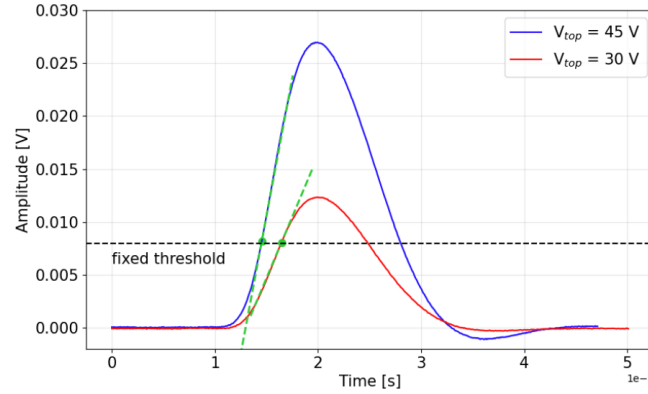


Fig. 5.35 Example of LE algorithm. Average recorded over 300 events at collection electrode voltages of 45 V (blue) and 30 V (red). The plot illustrates an example of a fixed threshold of 8 mV used in the LE algorithm and the slope at the crossing point. Figure taken from [94]

The distribution of the time difference obtained using the LE algorithm with a 5 mV as threshold is shown in Figure 5.36b. The light blue distribution corresponds to the measurements before the time walk correction, while the dark blue distribution shows the results after applying the correction.

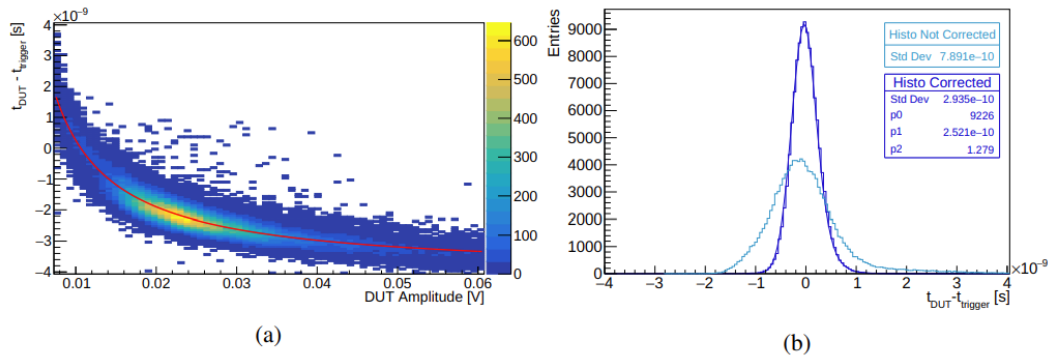


Fig. 5.36 (a) 2D histograms of the time difference between the MADPix and the timing reference plane as a function of the DUT signal amplitude. The red line shows the fit used for time walk correction. (b) Time difference distributions $t_{\text{DUT}} - t_{\text{reference}}$ before (light blue) and after (dark blue) the time walk correction. The superimposed fit, used to evaluate the time resolution, is shown for the corrected distribution, where p_1 corresponds to σ and p_2 is related to the right heavy-tail parameter of the q-Gaussian. Figure taken from [94]

To extract the sensor time resolution the corrected time difference distributions were fitted using an asymmetric q-Gaussian function. This approach allows the tails to be properly modeled. The LGAD reference resolution was then removed by quadratic

subtraction from the sigma.

Figure 5.37 shows the timing resolutions obtained using the CF (on the right) and the LE (on the left) algorithms after the time walk correction. Generally, the correction for time walk is not required for the CF method because the timing pick-off is, to first order, independent of the signal amplitude. However, residual time walk might still be present due to variations in the signal shape and rise time, arising for example from position-dependent charge collection. For this reason, the correction was applied in any case in order to minimize any residual correlation between the reconstructed time and the signal amplitude. The correction function described in Eq. 5.1 was adopted, since it provides a good description of the data and an effective compensation of the residual time walk contribution.

Concerning the LE method, the time stamp is assigned when the signal crosses a fixed voltage threshold. Since signals with larger amplitudes cross this threshold earlier than smaller ones (as can be noted in Figure 5.35), the measured time depends on the amplitude signal. This amplitude-dependent shift must be corrected, typically using time-over-threshold or amplitude information. For the LE method, the minimum threshold was chosen to be at least $5 \sigma_{\text{noise}}$, while the maximum threshold was set to avoid a deterioration of the slew rate.

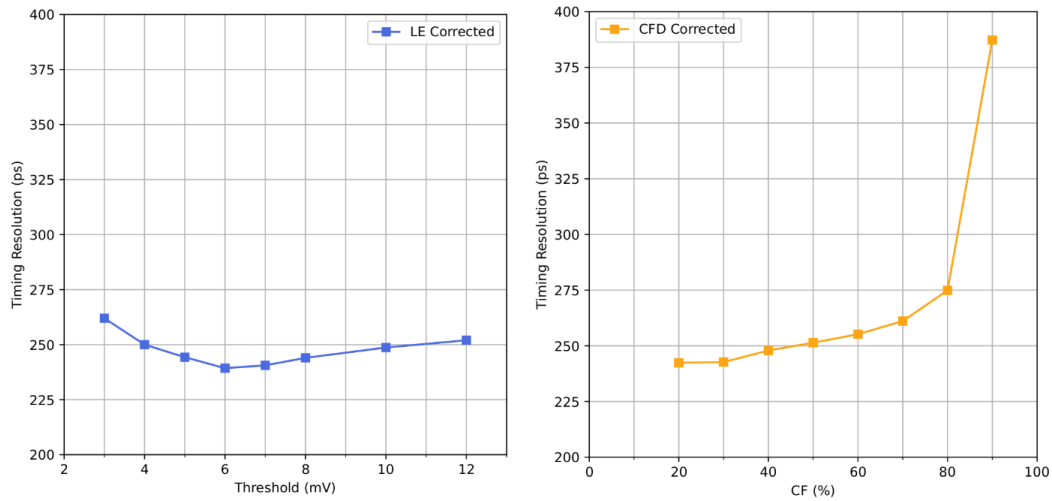


Fig. 5.37 (left) Time resolution measured for the A2 structure using the fixed threshold algorithm; (right) time resolution obtained using the CF method. In both cases, the time walk correction was applied.

The results obtained with the two methods are comparable, with a slightly better performance achieved using the LE method. Indeed, in the following sections the

LE algorithm were always chosen.

Figure 5.38a shows the time resolution achieved using the fixed threshold method for the A2 layout structure for two different top bias voltage, i.e. at 30 V and 45 V. By increasing the top polarization, an improvement of about 25% of the timing performance is observed. When V_{top} is set to 30 V, the multiplication effect is largely suppressed, resulting in a lower average signal amplitude. As a consequence, the time resolution begins to degrade for thresholds above 6 mV, where the signal slope decreases (as illustrated in Figure 5.35), leading to an increased jitter contribution. In contrast, when V_{top} is set to 45 V, the signal slope remains constant over the entire threshold range, leading to stable timing performance.

The time resolution measured for A1 and A2 structures at the same top bias voltage is compared in Figure 5.38b, showing a slight performance advantage for the A1 layout. This improvement may be attributed to the different sensor design and the larger multiplication region in the A1 layout.

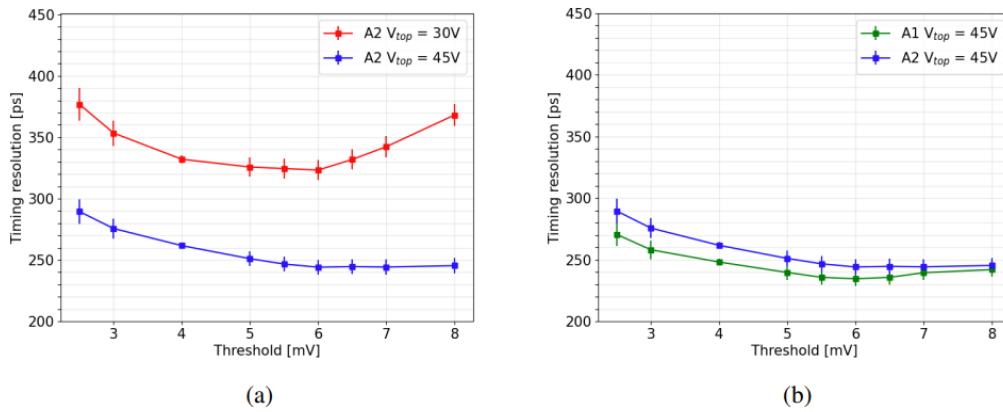


Fig. 5.38 (a) Time resolution evaluated using the LE method for the A2 layout at two different top bias voltages: 30 V (red) and 45 V (blue). (b) Time resolution for the two termination layout, A1 (green) and A2 (blue), at V_{top} 45 V. A backside bias of -30 V was applied. Taken from [94]

The best time resolution achieved is 234 ± 6 ps for the A1 structure and 244 ± 6 ps for the A2 layout. Both results were obtained applying a fixed threshold of 6 mV after the time walk correction. In Figure 5.38, the error bars at 30 V represent the standard deviation of the time resolution measured for four separate pixels hosted on the same chip. This relative uncertainty was then propagated to the measurements

obtained at 45 V.

From a design perspective, the A2 layout should provide better time resolution. Nevertheless, the low gain measured in this run limits the clear discrimination between particles incident on the border regions and those collected beneath the electrode.

5.4.6 Second test beam campaign

In June 2024, a new test beam was conducted at the T10 beamline of the CERN PS using a positive hadron beam with a momentum of 10 GeV/ c . The experimental setup and analysis methods were the same as those described for the previous test beam. Measurements were performed on the same chips but with an increased top bias voltage applied to the collection electrode. In the first test beam, a more conservative voltage range was adopted to minimize the risk of premature and unwanted sensor breakdown. However, the time resolution of about 230 ps obtained in the first test could not be explained by the jitter contribution alone, which was estimated to be around 130 ps for a signal amplitude of 25 mV (see Section 5.4.4). This indicated that the sensor itself was the main factor limiting the measured resolution. For this reason, the top bias voltage was increased up to 60 V during the second test campaign.

Time resolution

Figure 5.39 shows the time resolution for a single pixel of the A2 layout structure as a function of the top (5.39a) and back (5.39b) bias voltage. The resolution was estimated using the fixed threshold algorithm. As expected, increasing the topside voltage improves the time resolution by producing a stronger and more uniform electric field, which also leads to an enhanced gain. In this case, a time resolution of about 150 ps was achieved (see Figure 5.39a).

It can be observed that, for the highest top bias voltage, the best timing performance was achieved at lower values of V_{back} . Therefore, by plotting the time resolution as a function of the back bias voltage (see Figure 5.39b), an unexpected trend can be observed. It is well known that increasing the back voltage expands depleted region of the sensor, resulting in a stronger electric field and higher carrier drift velocities, approaching the saturation velocity. Under these conditions, an improvement in

timing performance would normally be expected. However, as shown in the plot, the opposite behavior is observed: increasing the back voltage actually worsens the time resolution.

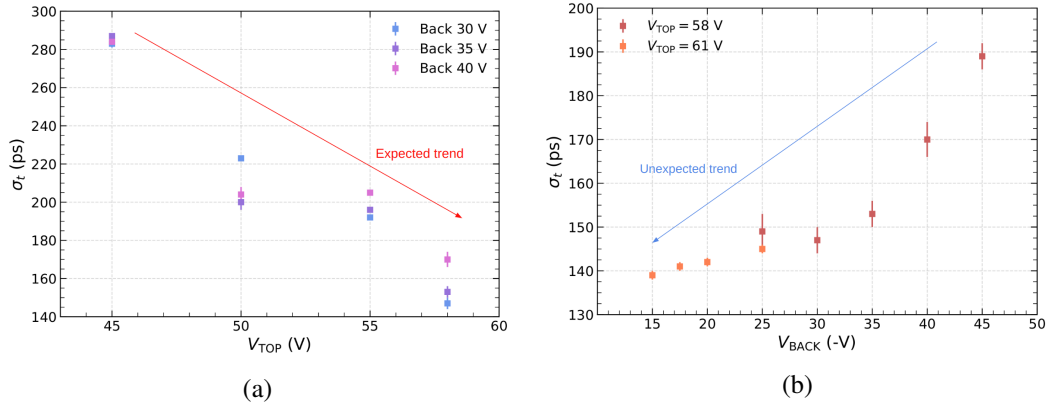


Fig. 5.39 (a) Time resolution as a function of the top voltage for different backside polarization: -30 V, -35 V, -40 V. (b) Time resolution versus the backside electrode polarization for two different V_{top} . In both figures the uncertainties associated to the time resolution are the statistic errors evaluated from the q-Gaussian fit applied on the corrected time difference distribution. All the results were obtained using the LE method applying a fixed threshold.

This unusual behavior was attributed to the extremely high backside current, observed in Figure 5.29, caused by the external guard ring surrounding the matrices, which remained floating in the sensor design.

5.4.7 FIB: Focused Ion Beam technique

The floating guard ring caused a large substrate current, resulting in a degradation of the time resolution and an increase in power consumption. A solution was studied and identified to connect this structure to a fixed potential. The adopted technique implied the use of a Focused Ion Beam (FIB) [97] available at the National Metrology Institute (INRiM) in Torino. The FIB system is a versatile micro- and nano-fabrication tool widely used in materials science and semiconductor physics. It employs a finely focused beam of ions to locally modify, remove, or deposit material with nanometer scale precision. In our case, the FIB provided a powerful method to access buried structures and to implement connections without the need to manufacture new wafers production, thus reducing the fabrication costs.

A focused beam of energetic ions (Ga^+ ions accelerated to tens of keV) interacted

with the material, causing transfer momentum to the lattice atoms and leading to several possible effects such as sputtering or implantation. By scanning the ion beam over the surface in a controlled manner, it was possible to selectively remove or modify material at predefined locations. Thanks to the dual-beam system in a single chamber, the used instruments combine both FIB and Scanning Electron Microscopy (SEM) which, detecting secondary electrons generated during ion–sample interactions, enabled high-resolution imaging (SEM images are reported in Figure 5.40). Once the area beneath the floating guard ring was identified using SEM images, a hole could be created in the device by sequentially removing the passivation and metal layers of the chip. This process continued until the metal implant associated with the target structure was reached (Figure 5.40b). This step required precise depth control to avoid unintentional damage to the structure itself or to nearby functional regions of the sensor. The use of in situ SEM imaging in a dual-beam FIB–SEM system enabled continuous monitoring of the process.

Once the floating structure was exposed, a metal deposition induced by the ion beam was performed to establish an electrical connection between the guard ring and an external contact pad, corresponding to the internal guard rings biased at 9 V. A metal–organic gas (platinum-based) was introduced into the chamber through a needle and locally decomposed by the ion beam, resulting in the deposition of a conductive metallic layer in the hole and along the path for the pad, as illustrated in Figure 5.40c and 5.40d. This deposited metal line provided a reliable electrical contact, enabling the bias of the previously inaccessible structure.

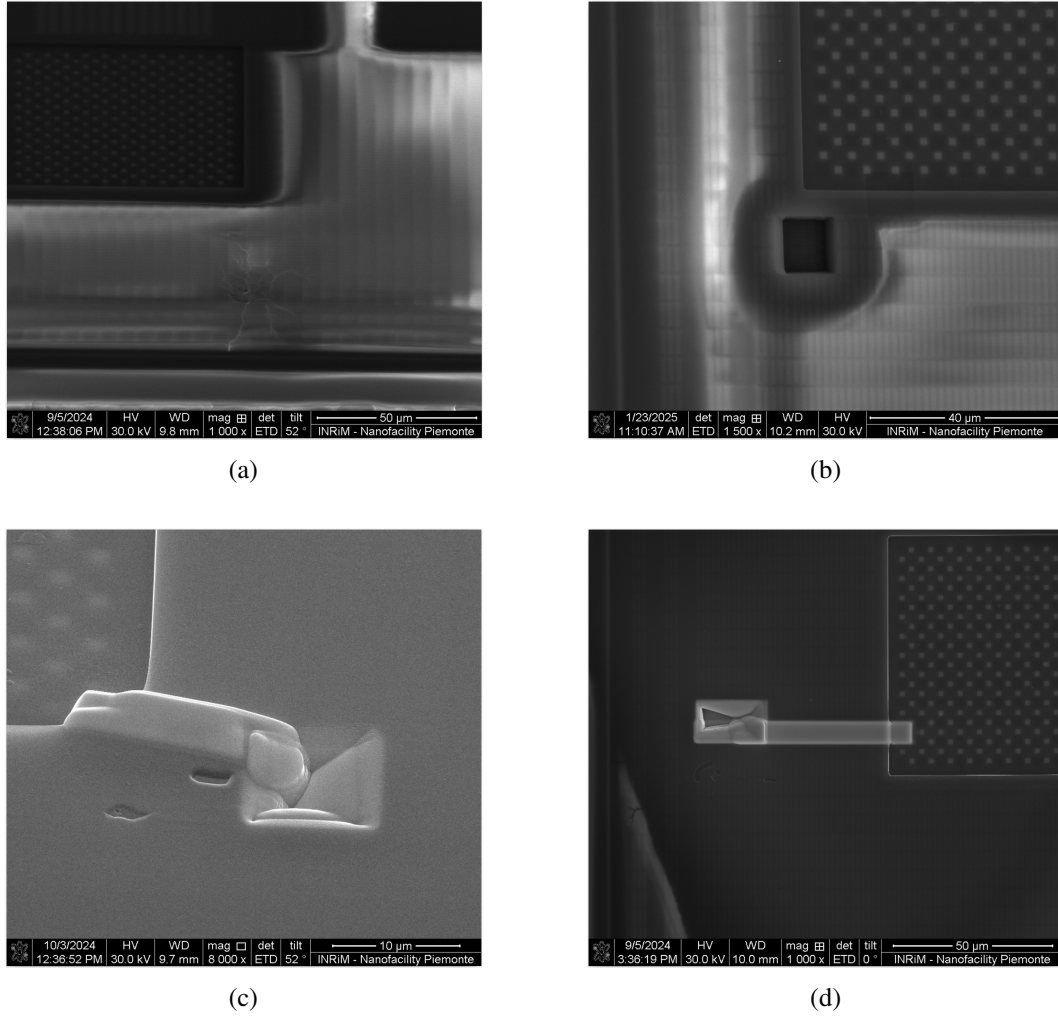


Fig. 5.40 SEM images taken during the FIB process carried out at the INRIM institute in Torino. Image (a) shows the structure before any operation, while in (b) the hole dug performed with the Ga^+ ions beam near the pad to be connected. In (c) and (d) the Pt deposition is visible. Such a process is used to contact the floating guard ring with the internal one to establish electrical connection along the path.

Once this operation was completed, a new electrical characterization of the sensor was performed to verify that the process had succeeded without damaging the sensor. In particular, I-V measurements were performed on different devices with FIB and the results are reported in Figure 5.41. In Figure 5.41a, the back electrode current is reported for three Test Board: before (TB2) and after (TB1 and TB4) using the FIB. For TB1 and TB4, this current was significantly reduced of approximately two orders of magnitude. This also corresponded to a reduction in power consumption and allowed the onset of punch-through to be identified at approximately -35 V.

Figure 5.41b shows the top current as a function of the top bias voltage in order to individuate the breakdown point. Also in this case, the current was presented both before (TB2) and after (TB1 and TB4) the FIB process, showing an advantage in the onset of breakdown, which is thus shifted to higher voltages, even more than 70 V for the TB1.

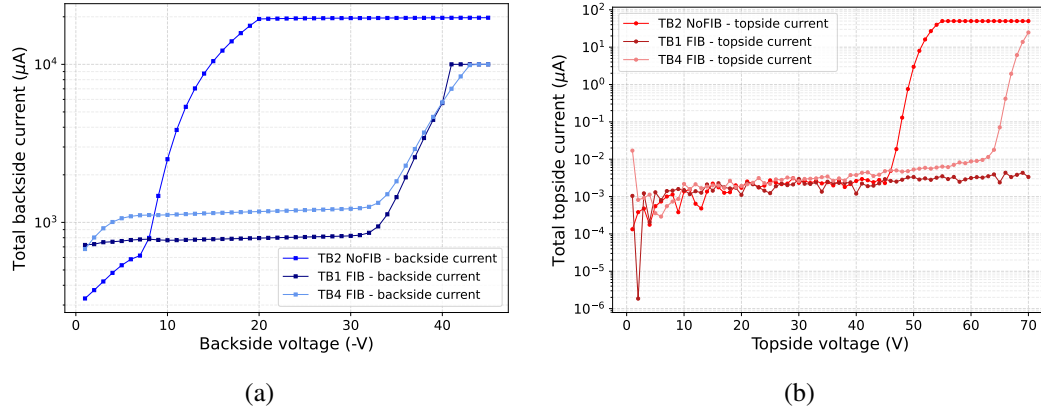


Fig. 5.41 (a) Backside current versus the backside voltage before and after the FIB process. The top collection electrode was biased at 45 V while the guard ring at 9 V. (b) The topside total chip current as a function of top bias voltage before and after the FIB process. In the device where the FIB technique was performed, the backside electrode was operated at a fixed voltage of -30 V and the guard ring at 9 V.

TB1 and TB4 were then tested with a particle beam to perform new time resolution measurements, which were carried out using the same experimental setup and the fixed threshold algorithm. Figure 5.42 shows the time resolution of a single A2 pixel as a function of the top (5.42a) and back (5.42b) bias voltages. In both plots, the estimated σ_t is reported for two electronics configurations: the standard configuration, where the in-pixel front-end consumes 0.18 mW per channel (see Section 5.4.2); and the boosted configuration, in which the front-end electronics operate at a higher current to improve performance, resulting in a power consumption of 0.28 mW per channel. After the FIB operation, the expected trend of the σ_t was confirmed: by increasing the backside bias voltage the timing performance slightly improves reaching then constant values. The topside bias voltage was fixed at 66 V, near the breakdown onset, as shown in Figure 5.41b. It can be observed that the timing performance is considerably improved after the connection of the floating guard ring, achieving a time resolution of 100 ps.

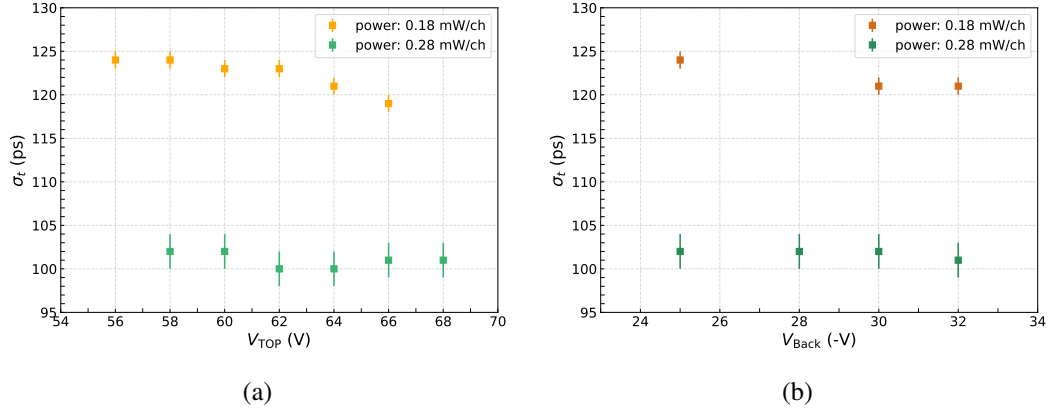


Fig. 5.42 (a) Time resolution as a function of the top voltage for two electronics configuration: standard (yellow) and boosted (green). The backside bias polarization was fixed at -32 V, just before the punch-through onset, as shown in Figure 5.41a. (b) Time resolution versus the backside electrode polarization for standard (orange) and boosted (green) configuration. The uncertainties associated to the time resolution are the statistic errors evaluated from the q-Gaussian fit applied on the corrected time difference distribution. Moreover, all the results were obtained using the LE method applying a fixed threshold.

Although still far from the 20 ps requirement of the ALICE 3 TOF system, this was an extremely good result. Based on the knowledge gained so far about this new technology, a new sensor production with higher gain was submitted.

Chapter 6

CMOS-LGAD run 3.2: enabling sub-100 ps time resolution

In Chapter 5, the first prototype of a monolithic sensor with an internal gain, fabricated using a commercial 110 nm CMOS technology, has been presented. As shown in that chapter, a reduced ion implantation energy during the production phase led to an internal gain lower than expected. Nevertheless, this first production was extremely useful to prove the feasibility of implementing the LGAD concept in the sensor technology developed by the ARCADIA collaboration.

To overcome the discussed gain limitations, a new short-loop run, named run 3.2, with increased gain was submitted to the foundry. Since the design and architecture of the chips remained unchanged and only the gain was improved, it was possible to use the same production masks while a wider range of gain splits was investigated. In this chapter, a comprehensive study of simulation, characterization, and radiation hardness of the sensors produced in run 3.2 was performed. The characterization of passive structures is reported first, including electrical measurements and preliminary gain evaluation. Monte Carlo and TCAD simulations are then employed to investigate the sensor behavior with both nominal and tuned doping profiles. In particular, TCAD matching studies are performed to tune simulation and experimental results. The chapter continues with the full characterization of MADPix, showing the state-of-the-art of its time resolution. To conclude, the chapter outlines the effects of radiation damage on CMOS-LGAD sensors. Finally, a description of the irradiation campaign, followed by the characterization in the laboratory and with a particle beam on the irradiated sensor, is reported.

6.1 Characterization of run 3.2 passive structures

The short-loop run 3.2 of ARCADIA was delivered in September 2024 and, as for the previous production, it comprised both passive test structures and active sensors with CMOS readout electronics integrated. For this second run, a larger number of gain-dose splits were requested from the foundry, as reported in Figure 6.1. This plot shows the expected gain values for the different p-gain implantation dose splittings requested to cope with uncertainties and variability during the fabrication process. The dose splitting D represents the reference dose (+0%), while five additional splits with a dose of -10%, -6.7%, -3.3%, +3.3%, and +6.7% with respect to the reference one were produced. Moreover, one split with no gain implant was added, as a reference, to evaluate the real gain of the structures during tests. In the following, mainly the results obtained for the -3.3%, 0%, and +3.3% gain layer dose splits are reported, as these allow to achieve the desired gain, ranging from 6 to 20.

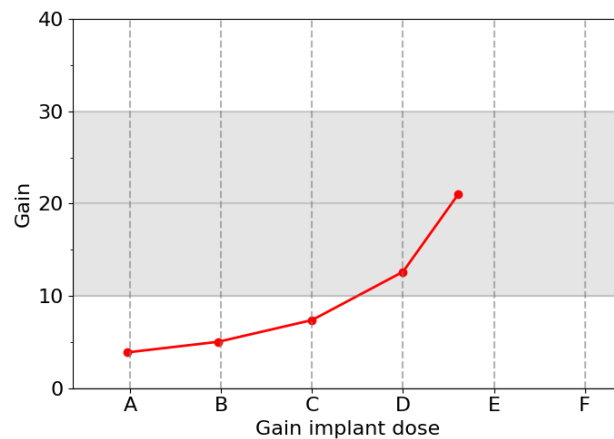


Fig. 6.1 Expected gain values for different p-gain implantation dose splittings required for the foundry for the short-loop run 3.2. The dose splitting D is the reference dose for the gain implant. Courtesy of L. Pancheri.

A total amount of 25 wafers was produced, and the Table 6.1 reports the corresponding wafer ID number and the split dose for the main tested structures.

Table 6.1 Wafer ID number and the corresponding p-gain implantation dose splitting.

Gain dose split	Wafer ID
-6.7%	16
-3.3%	11
+0%	15 , 07
+3.3%	08 , 12
+6.7%	13
No Gain	09 , 17

6.1.1 Electrical characterization and preliminary gain evaluation

The measured test structures have the same geometry as the one described in Section 5.2.1, and the approach used for the electrical characterizations performed on these sensors is also explained in the same Section. The topside and backside currents measured for devices with different gain splits, identified by the wafer ID number (see Table 6.1), are shown in Figure 6.2 and Figure 6.3, respectively, as a function of the reverse bias voltage applied to the backside. Results are reported for both the A1 (blue curves) and A2 (red curves) pixel layouts. In these measurements, the voltage applied to the top electrode was fixed at 45 V, while the guard ring electrode was biased to 9 V.

In Figure 6.2, the full depletion of the sensor is highlighted by the steep decrease of the curves, reaching dark current values of 40-60 pA. The A1 structures (Figure 6.2a) reach the depletion suddenly without differences among the several p-gain dose splittings. On the other hand, as shown in Figure 6.2b, the A2 termination shifts the depletion voltage to slightly higher values with differences based on the gain split. The less the implant is doped, the higher the voltage at which the later depletion occurs. The subsequent increase in current around -40 V is associated with the onset of punch-through, as also indicated by the significant increase in the backside current observed in Figure 6.3.

The onset of the punch-through phenomenon for both A1 and A2 layout designs is shown in Figure 6.3. For these devices, the punch-through begins once the applied backside voltage reaches about -40 V without differences between the two termination layouts, suggesting that this effect is only related to the backside operation.

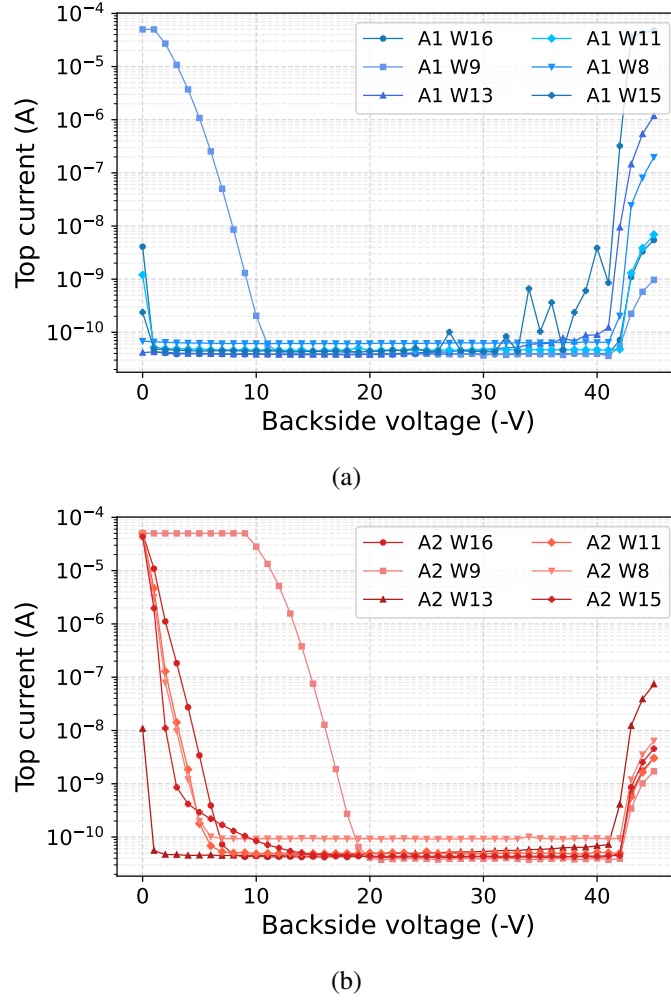


Fig. 6.2 Topside current as a function of the reverse bias voltage applied on the back electrode for both A1 (a) and A2 (b) layouts. The collection electrode voltage was biased at 45 V, while the guard ring was at 9 V.

IR illumination

In order to have a first gain estimation of the new short-loop sensors, I-V measurements of the topside current were performed with a probe station illuminating the device with a uniform and continuous source in the IR wavelength range (940 nm). The use of an IR LED allowed for a controlled generation of electron-hole pairs within the silicon bulk, since this wavelength is able to penetrate in depth of the order of tens of microns. This method relies on comparing the top electrode current of a sensor featuring the gain layer, $I_{top}^{w/gain}(V)$, with that of a reference device without internal gain, $I_{top}^{w/o\ gain}(V)$, while both are continuously illuminated by the same IR

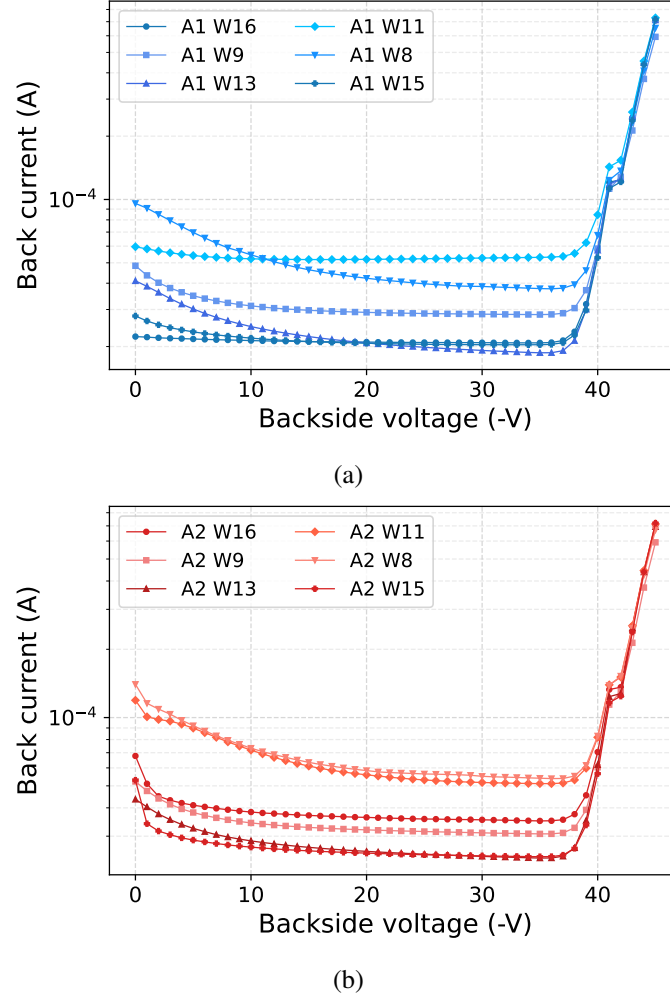


Fig. 6.3 Backside current as a function of the reverse bias voltage applied on the back electrode for both A1 (a) and A2 (b) layouts. The collection electrode voltage was biased at 45 V, while the guard ring was at 9 V.

source. In the absence of charge multiplication, the generated current is directly proportional to the number of primary charge carriers produced by the incident radiation and collected by the electrodes. Conversely, in a sensor with the gain layer, the high electric field present in the multiplication region triggers impact ionization processes, leading to an increase in the measured current. Therefore, the sensor gain G can be evaluated as the ratio of the measured currents:

$$G = \frac{I_{top}^{w/o \text{ gain}}(V)}{I_{top}^{w \text{ gain}}(V)} \quad (6.1)$$

This approach provided a preliminary estimate of the internal gain, allowing a comparison with the value expected from the design specifications provided to the foundry. However, this method does not yield an absolute gain measurement, as it may be affected by systematic effects such as differences in illumination or charge-space effects. Therefore, a better gain characterization requires measurements with a laser, or a radioactive source, or a test beam, as will be reported in Sec. 6.5.2.

Figure 6.4 reports the topside current as a function of the top bias voltage for several sensors with different p-gain dose splittings (different wafer ID numbers), both with IR illumination disabled (solid line) and enabled (dashed line). For the curves with IR light switched on, it can be noted that the current values are higher since a large generation of electron–hole pairs occurs. After the increase of the current due to the multiplication process, the breakdown phenomenon can be appreciated at about 65 V for all the structures. This means that it is not a gain breakdown, which would vary depending on the doping split, but rather an edge breakdown occurring at the borders of the junction. In this chapter, only the A2 layout measurements are reported.

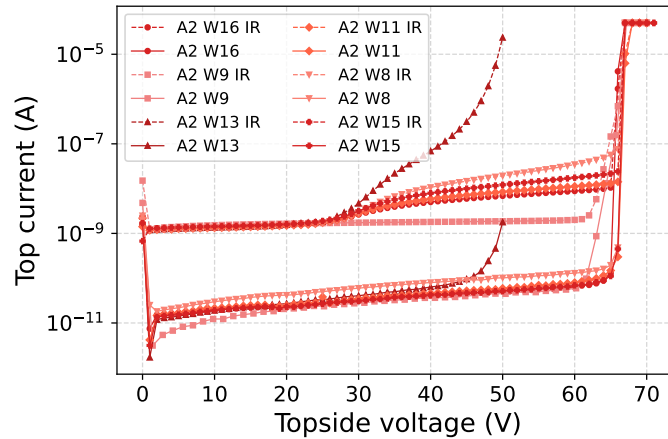


Fig. 6.4 Topside current as a function of the top bias voltage. The backside electrode was biased at -35 V while the guard ring was at 9 V. Different wafer ID numbers correspond to different p-gain dose splittings and for each dose splitting the measurements with IR illumination disabled (solid line) and enabled (dashed line) are reported.

The value of the gain was evaluated using Eq. 6.1 and the results are presented in Figure 6.5. It can be clearly noted that as the top voltage varies, the electric field and, thus, the gain increase. It can also be observed that all wafers exhibit well-distinguishable gain values within the expected range.

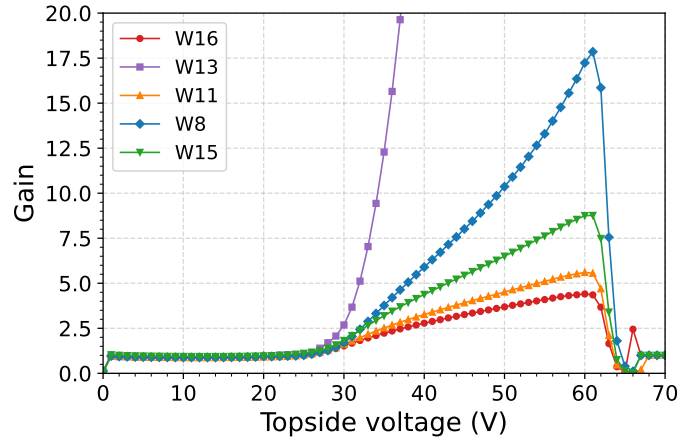


Fig. 6.5 First gain estimation using a continuous IR illumination for different wafers with different gain split. The backside electrode was biased at -35 V while the guard ring was at 9 V.

Thanks to this short-loop production, the measured gain for these monolithic sensors is now in agreement with the expectations.

6.2 Monte Carlo simulation studies: run 3.2 with nominal doping profiles

In accordance with the procedure followed in Chapter 5, both TCAD and Monte Carlo studies were carried out for the structures of the short-loop run 3.2. As a first step, a 2D simulation domain was implemented on TCAD to obtain the electric field profile of the device featuring the A2 layout. The design is the same of the sensor simulated in Figure 5.2 with a pitch of $140\ \mu\text{m}$ and a thickness of $48\ \mu\text{m}$. These first simulations were performed exploiting the nominal doping profile of the implants supplied by the foundry. The structure was biased applying -25 V on the p^+ backside electrode, while a voltage scan was performed on the collection electrode. After obtaining the electric field maps from TCAD, these were used as input in Allpix², which adopts a regular mesh for its maps, computes the weighting potential profiles, and provides the relative induced signals through the Shockley-Ramo theorem. As for the simulation studies described in Section 5.1, a beam of 180 GeV pions (MIPs) was injected into the pixel as the incident particle source. Charge carrier propagation is described using the extended Canali mobility model [90], while the impact ioniza-

tion mechanism is described by the Okuto–Crowell model [91]. Finally, the induced charge is computed using a time granularity of 0.5 ps.

Firstly, pions were impinged orthogonally on the surface with a beam-like source featuring a narrow width of 1 nm at the pixel center ($x = 0$). Figure 6.6 shows the average signal waveforms of 1000 events for three different top bias voltages: 45 V, 50 V, and 55 V. The effect of the gain on the waveform trend is clearly visible: by increasing the top bias voltage, the electric field increases, leading to the activation of the multiplication mechanism, which becomes higher. Moreover, it can be observed that at 45 V the signal is significantly slower respect to the other two voltages, indicating that the charge carriers require a longer time to reach the collection electrode.

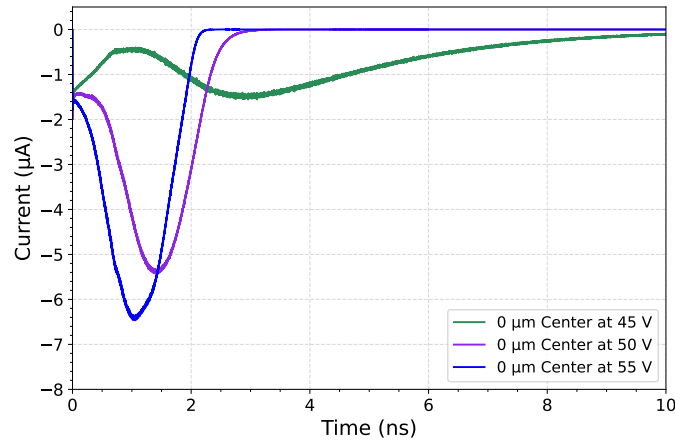


Fig. 6.6 Average waveforms from 1000 events impinging in the pixel center for different topside voltages: 45 V, 50 V, and 55 V.

This is linked to a local depression of the electric field that causes the carriers to slow down, preventing them from reaching their saturation velocity, as illustrated in Figure 6.7. In this figure, the electric field maps are shown on a logarithmic scale for a top bias voltage of 45 V applied to the collection electrode (left), and for a voltage of 55 V on the right. By increasing the collection electrode voltage the depression disappears almost completely, resulting in a faster signal as confirmed in Figure 6.6.

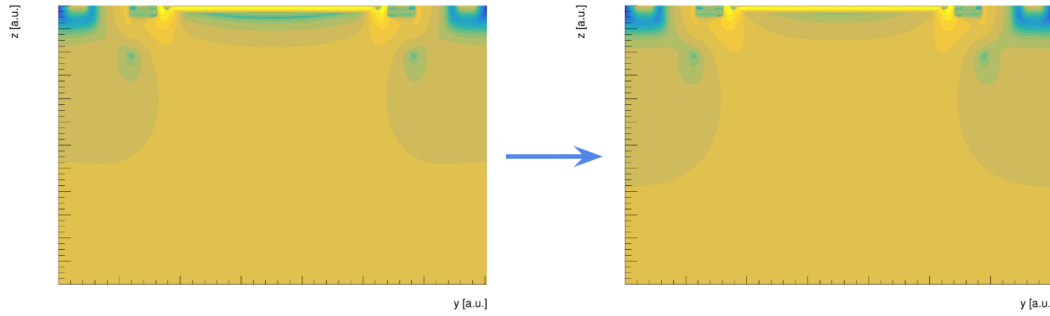


Fig. 6.7 Simulated electric field profiles for two topside voltages: 45 V, on the left, and 55 V, on the right.

To conclude this study, the simulation of the time resolution was performed. The method used to determine the time resolution is the one explained in Section 5.1.1. Figure 6.8 shows the time resolution as a function of the CFD thresholds for three topside bias voltages (45 V, 50 V, and 55 V) and for particles incident at the pixel center. For the lower bias condition, the time resolution is worse respect to the two other cases, which achieve approximately 60 ps. This is again due to the local electric field depression, which also degrades the timing performance of the sensor because of the reduced electric field below the gain layer.

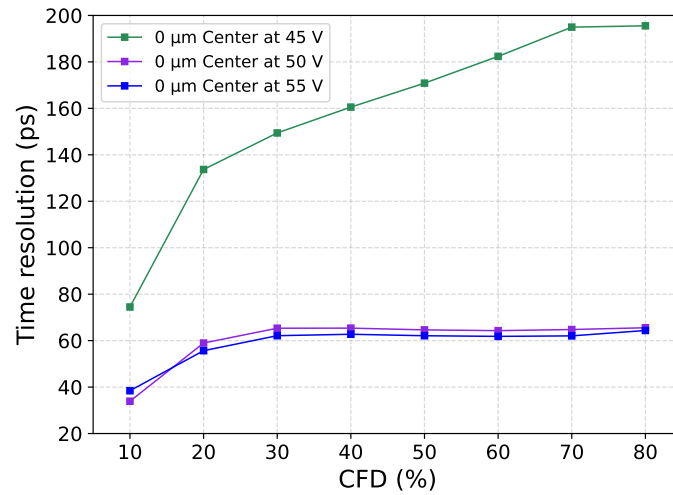


Fig. 6.8 Simulated time resolution estimated as a function of the CFD thresholds. The results are presented for the same topside bias voltages of Figure 6.6.

To ensure the complete disappearance of the electric field depression, the top bias voltage should be further increased. Moreover, as indicated by the I-V characteristics

of the passive structures shown in Figure 6.4, the breakdown is expected to occur only at top bias voltages above 65 V. Therefore, extending the simulations to higher top voltages would be desirable. However, convergence issues encountered during the TCAD simulations prevented the extension of the simulations to higher bias voltages. This limitation is likely related to the use of nominal doping implant profiles, which may differ from the actual post-fabrication profiles due to process uncertainties. Consequently, a more accurate determination of these parameters is necessary to obtain simulations that better reproduce the experimental data.

6.3 TCAD simulation studies

In order to achieve a precise tuning of the parameters required for the sensor simulation, the simulated I-V characteristics were matched to the experimental measurements. In particular, the tuning study was performed using the $I_{top}(V_{top})$ characteristics measured on the passive structures belonging to wafer W8, corresponding to a dose split of +3.3%.

As a first step, the sensor geometry was designed using a 2D TCAD simulation domain, where a single pixel with a pitch of 120 μm and a thickness of 48 μm was implemented. The starting point for the layout definition was the Graphic Data System (GDS), which contains the detailed technological and geometrical parameters of the device provided to the foundry. All the key aspects of the sensor were reproduced as faithfully as possible, including the active region, implants, and contact structures, in order to ensure a realistic representation of the fabricated device. All doping implants were included in the simulation and positioned according to their nominal locations as specified in the GDS. Particular attention was paid to preserving the relative distances and overlaps between the different implants, as these parameters have a strong impact on the electric field distribution inside the device. The simulation domain was defined along the short side of the rectangular pixel. This choice was motivated by the need to investigate the device breakdown mechanism, which is expected to be dominated by the electric field configuration at the pixel edges and within the junction termination region. Focusing on the short side enhances its impact on the breakdown behavior, enabling a more detailed analysis of the electric field distribution while keeping the computational cost of the simulations under control.

A non-uniform mesh was employed to accurately resolve regions characterized by large gradients in electric field, electrostatic potential, and doping concentration. In particular, a fine mesh was defined near the gain layer and the implant termination regions, where high electric fields are expected to develop and vary rapidly. The mesh spacing in these regions was selected to ensure numerical stability and accurate field calculations. More specifically, the mesh was locally refined according to the doping concentration gradients: the element dimensions were minimized in regions with steep doping variations, while a coarser mesh was adopted in areas with nearly uniform doping to reduce the computational effort. Conversely, a coarser mesh was used in the substrate bulk, where the electric field varies more smoothly. This choice reduces the simulation time without significantly affecting the accuracy of the results. The mesh element size directly influences the numerical approximation of the discretized equations governing the device physical behavior, enabling a detailed description of the electric field evolution and breakdown mechanisms, while providing a reliable basis for comparison with the experimental measurements. Subsequently, quasi-stationary simulations were performed. In these simulations, the applied voltages were gradually increased using very small predefined increments to ensure numerical convergence. At each simulation step, the Poisson equation was solved iteratively at every mesh node according to the selected voltage step size. Figure 4.4 shows the design of the 2D TCAD simulation domain based on the A2 termination layout. For simplicity, in Figure 6.9 the zoom of the sensor topside is reported.

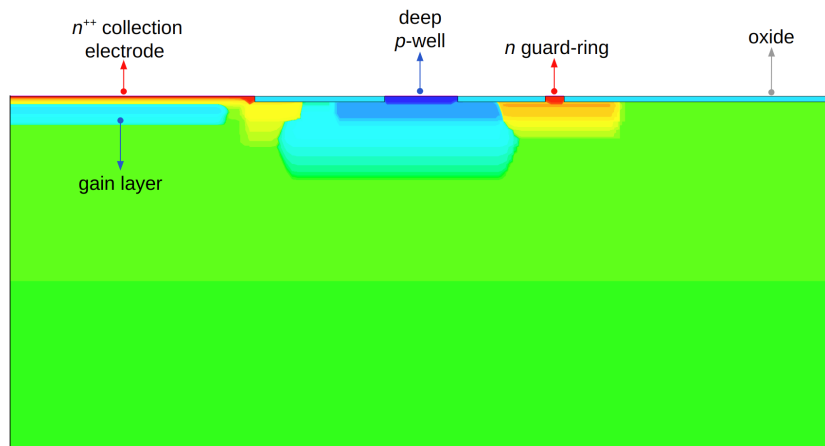


Fig. 6.9 Zoom of the TCAD 2D simulation domain of the pixel. The topside part of the device is reported here, and the key elements are highlighted.

6.3.1 I-V simulations and matching with experimental data

In the TCAD simulations, a voltage of 9 V was applied to the n -implant guard ring, while the deep p-wells containing the CMOS electronics were kept at 0 V. Moreover, a SiO₂ layer was included on the surface in order to reproduce the real device configuration as accurately as possible, since the silicon oxide layer can influence the electrical characteristics of the sensor.

Quasi-stationary simulations were performed to evaluate the pixel I-V characteristics by systematically varying several design parameters, including the implant doping profiles and their concentration levels. Initially, the simulations were carried out using the nominal doping concentrations, without any preliminary tuning, in order to establish a well-defined reference configuration for the sensor and evaluate its baseline electrical behavior. Starting from this initial configuration, I-V simulations were performed. First, a backside voltage scan was carried out while keeping the other bias conditions fixed. This preliminary scan aimed to identify the punch-through voltage of the device. The results of this study were then used to define an appropriate biasing scheme for the subsequent simulations. In particular, by determining the voltage range in which punch-through occurs, a safe operating point for the sensor could be identified.

Once the backside operating point had been properly established, this bias voltage was fixed, and the study was then focused on the top contact. A new set of I-V simulations was performed, with the topside voltage progressively increased in order to investigate the breakdown phenomenon. The sweep was extended until convergence issues appeared, typically due to high-field effects and increased carrier multiplication. Under these conditions, the device operates in a strongly nonlinear regime, and numerical instabilities may rise before the physical breakdown is fully captured. If not properly managed, this can limit the predictive capability of the simulation. From a theoretical standpoint, convergence issues in TCAD simulations arise from the strong nonlinear coupling between Poisson's equation and the carrier continuity equations, which becomes particularly pronounced under high electric-field conditions. Near breakdown, the impact ionization model introduces carrier generation terms that depend exponentially on the local electric field, leading to steep spatial gradients in both carrier concentrations and electrostatic potential. Consequently, convergence failure in the breakdown regime does not necessarily

indicate non-physical device behavior, but rather reflects numerical limitations in handling extreme nonlinearities.

Figure 6.10 shows the $I_{top}(V_{top})$ curve obtained without any preliminary tuning. Comparison with experimental data indicates that breakdown is expected to occur at approximately 65 V, whereas the simulation fails to converge at lower voltages, highlighting the need to match the simulated behavior against the measured response.

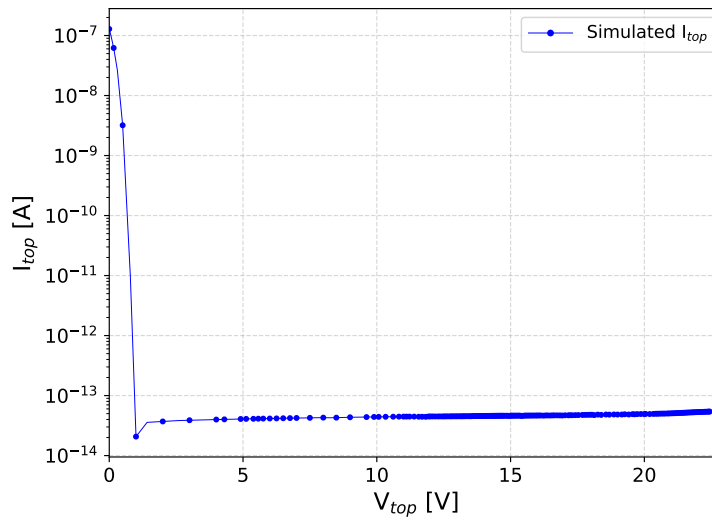


Fig. 6.10 Simulated top current I_{top} as a function of the top voltage V_{top} using TCAD simulation tool. The simulation was performed adopting the nominal doping concentrations without any preliminary tuning.

To mitigate convergence issues in TCAD simulations, a careful adjustment of both physical and numerical parameters was performed. One of the adopted strategies involves controlling the solver stability during the sweep. To achieve this, the voltage at the top contact was increased in fine steps, allowing the Newton-based solver to track the continuous evolution of the solution. This approach was particularly important in the vicinity of breakdown, where small voltage variations can induce large changes in carrier densities and current levels. The breakdown analysis was performed by gradually enabling advanced physical models, with particular emphasis on impact ionization mechanisms, which are essential for reproducing avalanche multiplication effects. To this end, the choice of avalanche multiplication models is crucial. These are commonly described using empirical or semi-empirical impact

ionization formulations that relate the ionization coefficients of electrons and holes to the local electric field. Among these, the van Overstraeten–de Man model [98] represents one of the most widely adopted approaches for silicon-based devices and it is often used as a reference in breakdown simulations. Its relative simplicity and robustness make it particularly suitable for drift–diffusion-based simulations, allowing a stable and computationally efficient description of avalanche breakdown. Another approach is the one provided by the Okuto–Crowell model [91], which takes into account the influence of lattice temperature and carrier energy on the ionization process.

Another parameter to consider is the mesh, as its refinement influences both the convergence and the accuracy of the simulation. While fine meshes are needed to accurately capture steep field variations, excessively fine or poorly graded meshes in high-field regions can lead to numerical instability. Therefore, the mesh was carefully optimized with a trade-off study: a local refinement was applied only where needed and a smoother transition in mesh density was adopted elsewhere.

Another important factor affecting convergence is the thickness of the epitaxial layer. Extremely thin layers or abrupt interfaces can generate steep potential gradients, making the system of equations more prone to divergence. A study of the epi-layer thickness was performed to determine if a smooth transition between regions helps to stabilize the numerical solution.

However, the most important parameters affecting convergence are those related to the implant profiles, including both the dopant concentration and the lateral spread of the implanted regions. In practice, the lateral diffusion of the gain layer, deep p -well, and n -type collection electrode was carefully tuned. Slightly smoothing the dopant distributions reduces sharp gradients in carrier density and electric field, thereby significantly improving the stability of the Newton solver, especially near breakdown.

Similarly, the nominal dopant concentrations of the substrate, epi-layer, and gain layer were occasionally adjusted within physically reasonable bounds to prevent excessive local fields that can induce solver divergence.

The carrier lifetime was deliberately tuned to improve the agreement between simulated leakage currents and experimental measurements. Adjusting the carrier lifetimes in the device, within physically realistic ranges, can increase or decrease the leakage current levels to match observed device behavior, ensuring that the

simulation results faithfully represent the experimental data.

After several iterative adjustments and careful testing of all relevant parameters, including implant profiles and diffusion, doping levels, mesh density, carrier lifetimes, and the avalanche model, it was possible to eliminate convergence issues and successfully extend the simulations into the high-bias and breakdown regimes. This approach enabled the generation of I–V characteristics that accurately reproduce the experimentally observed breakdown behavior, achieving an almost perfect match between simulated and measured data, as shown in Figure 6.11. The simulated result (blue curve), obtained using the Overstraeten–De Man impact ionization model [98] with calibrated carrier lifetimes, shows excellent agreement with the experimental measurement (red curve). The close matching across the entire voltage range is achieved through careful tuning of the doping implant doses and their spatial dispersion, demonstrating the accuracy of the physical modeling and parameter optimization adopted in the simulations. Consequently, the results accurately reflect the intrinsic device physics without numerical artifacts and provide a reliable basis for further analysis and device optimization.

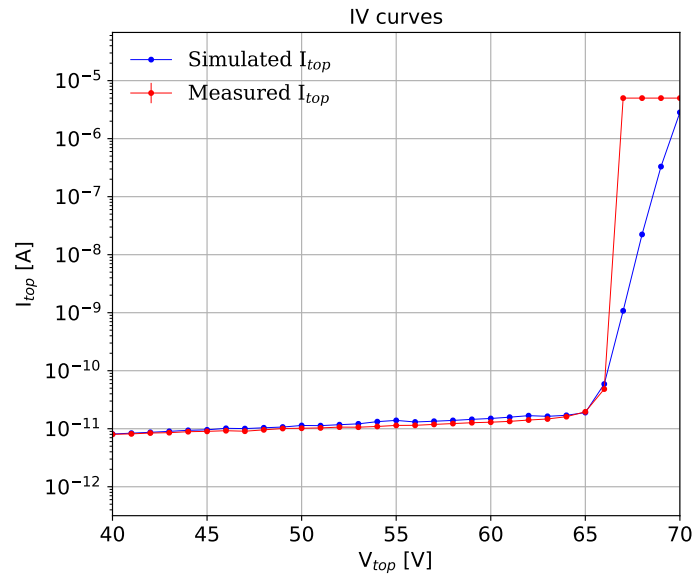


Fig. 6.11 Comparison between TCAD simulated and measured top current I_{top} as a function of the top voltage V_{top} . The simulated data (blue curve) closely follow the measured results (red curve) across the investigated voltage range, capturing both the low-current region and the sharp current increase at higher bias voltages.

The careful optimization of simulation parameters is essential not only to ensure that the results of the current short-loop are accurate and reliable, but also because the parameter tuning provides valuable guidance for future production runs. The information gained from this study can be directly applied to possible process adjustments and design refinements, enabling predictive reliability in subsequent device generations.

6.4 Monte Carlo simulation studies: run 3.2 with tuned doping profiles

New results from Monte Carlo simulations, using input maps from the TCAD simulations with the tuned parameters, are presented in this section. The simulated structure has the same geometry as the one described in the TCAD study (Section 6.3). The doping and later dispersion of the implants, such as other simulation parameters, have been tuned to better reflect the real device. As previously discussed, the electric field profile from TCAD was imported into Allpix² and used, together with the weighting potential map, to calculate the induced signal on the collection electrode. The bias voltages were fixed at 65 V on the topside electrode, at -35 V on the backside electrode, and at 9 V on the guard ring. Figure 6.12a illustrates the electric field distribution in linear scale, while Figure 6.12b shows the same distribution in logarithmic scale. A pronounced high-field region (in yellow) close to the gain layer implant is clearly visible, highlighting the suppression of the electric field depression observed in the previous maps in Section 6.2.

In Figure 6.13 the weighting potential map, used to compute the induced signal via the Shockley-Ramo theorem, is reported. The Allpix² simulation uses a uniformly spaced grid with a bin size of 50 nm in all directions.

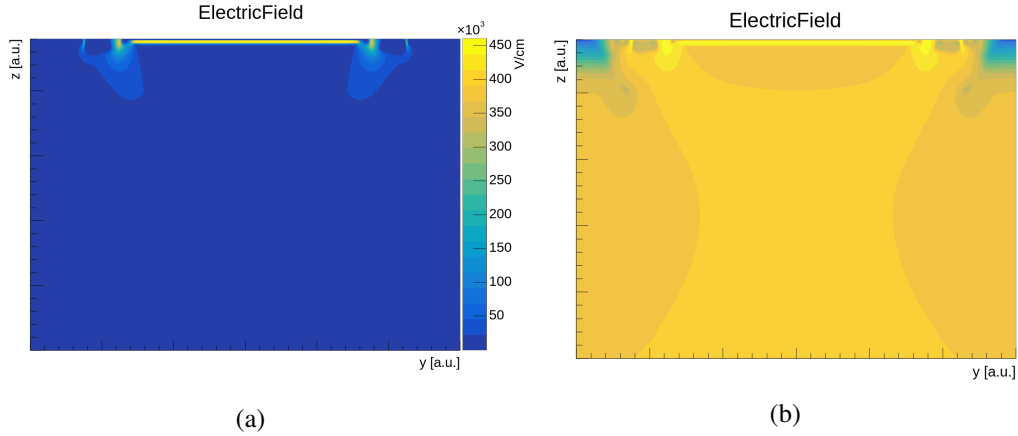


Fig. 6.12 Simulated electric field (a) and the same map in log scale (b), for a single pixel based on layout A2 and $48\ \mu\text{m}$ thickness, using the tuned parameters obtained from the TCAD matching study. The collection electrode voltage was biased at 65 V, the backside at -35 V, while the guard ring at 9 V.

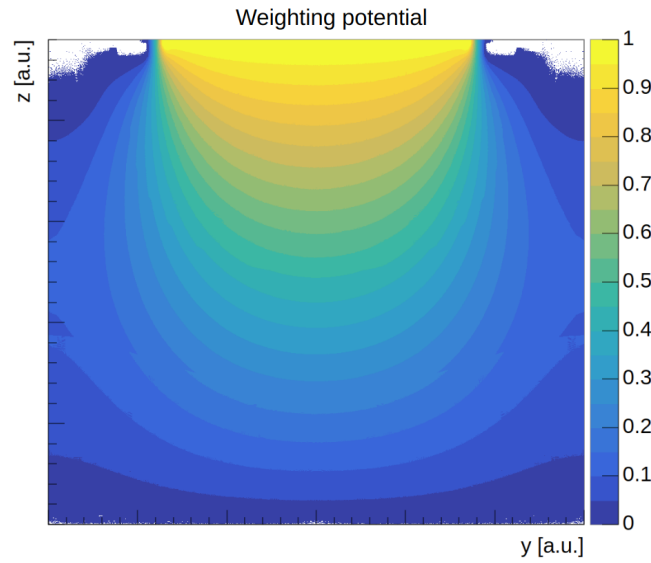


Fig. 6.13 Simulated weighting potential map in Allpix² using the TCAD maps with tuned parameter after the matching study.

As done previously, a beam of 180 GeV pions was used as the incident source for the simulation, impinging either uniformly on specific points or randomly. The Okuto–Crowell model was used to evaluate the impact ionization mechanism, and the induced charge is computed using a time granularity of 0.5 ps.

6.4.1 Position scan on the surface

A set of simulations was performed for different pion impact positions. Starting at the pixel center ($x = 0$) and progressively shifting toward the edge with steps of $10\ \mu\text{m}$, as illustrated in Figure 6.14, the induced signal, the device gain, and its time resolution were analyzed. The pions hit the sensor surface perpendicularly, and a very small width of $1\ \text{nm}$ was assigned to the beam-like source to ensure identical crossing positions within the pixel. For each impact position, 1000 events were simulated.

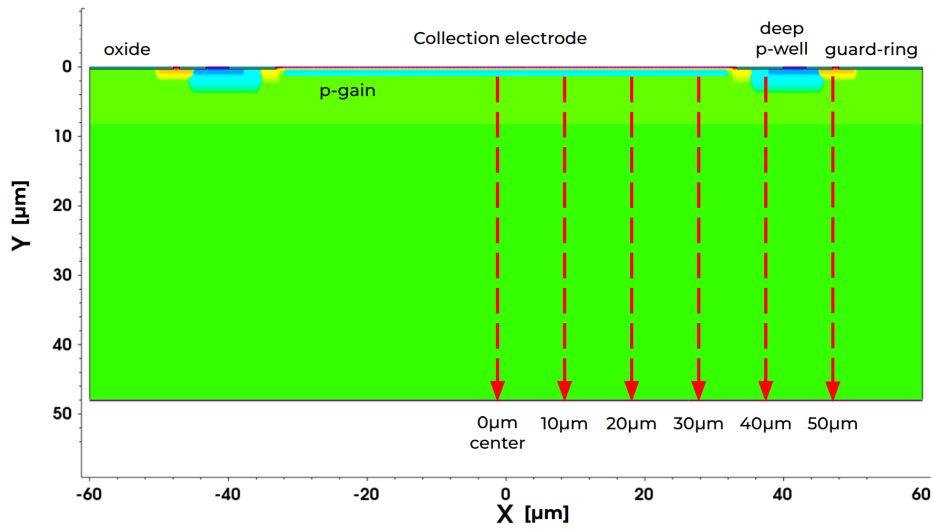


Fig. 6.14 Cross-section of the short side pixel simulated in TCAD, showing a gain layer and layout A2. The different particle impact positions are indicated by red dashed arrows.

At this point, the induced current signal on the collection electrode was simulated, and Figure 6.15 shows the average waveforms for all impinging points. For particles impinging in the region surrounding the collection electrode, the influence of the gain on the waveform evolution is clearly visible. The signals originating from the central region are slower, due to a residual non-uniformity of the electric field that results in a local field depression and consequently slower charge transport, as already observed in Figure 5.1.2. Shifting toward the periphery results in a reduction of the collected charge: the signal amplitude decreases and the induced signal shape changes, as in the black curve, which exhibits the largest deviation due to the absence of gain.

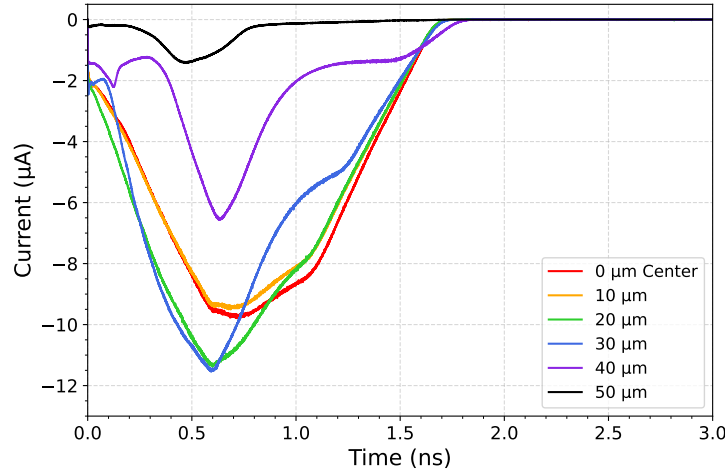


Fig. 6.15 Average waveforms from 1000 events at different impact positions on the surface: from the center ($x = 0$) to the pixel edge.

Following the procedure described in Section 5.1.1, the gain was evaluated, for each impact position, as the ratio between the collected charge with multiplication enabled and the collected charge without multiplication. The collected charge is obtained by integrating each waveform over time and building an event-by-event charge histogram, whose asymmetric distribution is thus fitted with a Landau function to extract the MPV. The MPV values are then used to estimate the sensor gain. The gain as a function of the position was evaluated using a point-like approach and it is shown in Figure 6.16. The results show that the multiplication progressively decreases as the MIP impinging position approaches the edge and moves outside the gain region.

To conclude, the time resolution as a function of the chosen threshold and for different impinging positions of the particles is shown in Figure 6.17. As for the previous studies, when the impinging position moves away from the pixel center, the timing performance gets worse. Also in this study, as already seen in Section 5.1.1, when a particle crosses the sensor at $40 \mu\text{m}$, the trend deviates from those observed at smaller impact positions. This behavior is attributed to a broad crossing time distribution, resulting in a large standard deviation, and it is likely caused by the significant S-curve spread observed at low CFD thresholds. Since the interaction occurs in a region where the electric field is non-uniform, the gain is reduced, although still present. As a result, the signal in this region becomes more sensitive to fluctuations

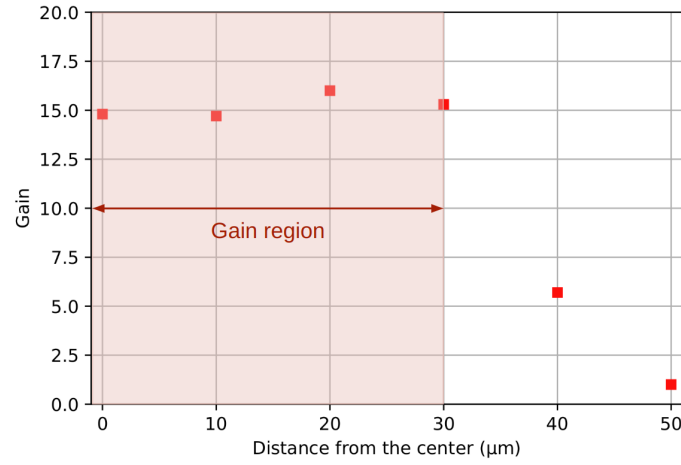


Fig. 6.16 Gain as a function of different impinging position estimated with Allpix² simulations using the tuned maps for run 3.2.

related to the granularity of the charge deposition, leading to a degradation of the time resolution at low CFD thresholds.

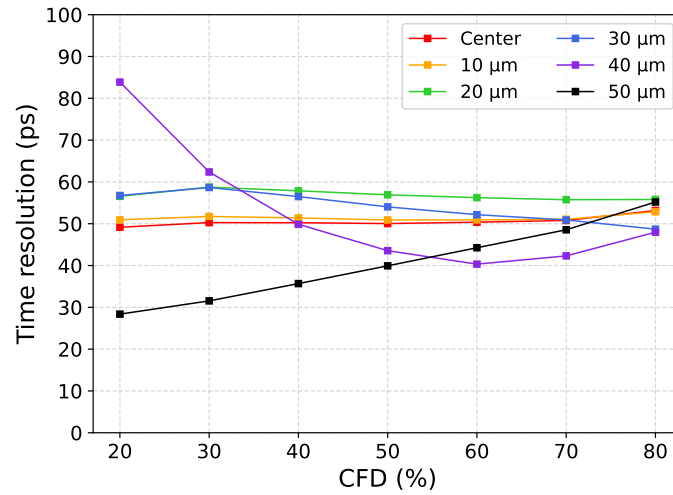


Fig. 6.17 Simulated time resolution as a function of the applied CFD threshold for different particle hit positions.

6.4.2 Random scanning

To fully characterize the sensor and take into account also the distortion term, 10000 events were simulated with particles impinging randomly on the sensor surface using a square source with a side length of $100\ \mu\text{m}$ and centered on the pixel. In this

configuration, it is possible to consider the non-uniformity of the weighting potential based on the impact point, and a possible non-saturated carrier velocity.

As for Section 5.1.2 a double population of the collected charge was found. This corresponds to signals with and without charge multiplication, depending on whether carriers cross the gain layer or are generated beneath the termination region. This effect is enhanced in the A2 termination due to a gap that allows carriers to reach the collection electrode without undergoing multiplication. Also in this case, a threshold cut at 4 fC was applied to the collection charge distribution, selecting only multiplied events from the pixel central region, and the corresponding time resolution is reported in Figure 6.18.

As explained in Section 5.1.2, the timing performance deteriorates compared to the one at fixed positions, such as in $x = 0$, as expected. The worsening of the time resolution is caused by position-dependent variations in gain and weighting-field effects, highlighting the importance of the spatial uniformity in the multiplication layer and the electric field distribution for achieving optimal timing performance.

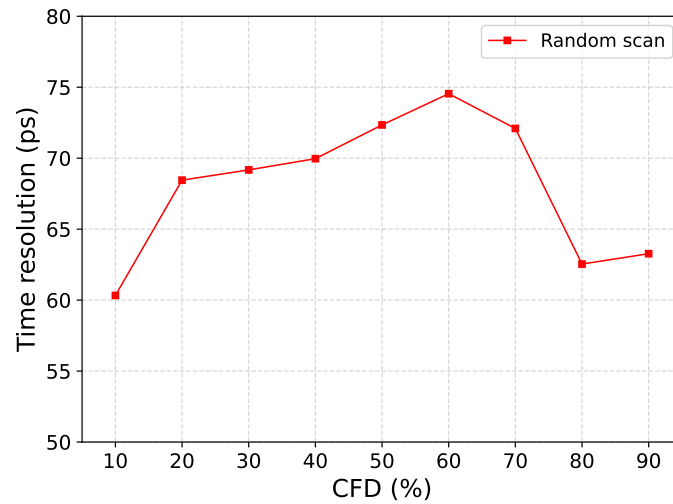


Fig. 6.18 Simulated time resolution as a function of the applied CFD threshold with MIPs impinging randomly using a square source with a side length of $100\ \mu\text{m}$ and centered on the pixel.

The ToA information on the particle impact position was investigated as it was described in Section 5.1.2 and the results are shown in Figure 6.19. In these simulation studies, the delay of arrival times between the center of the sensor and its edge has been significantly reduced. This provides further evidence that the electric field depression has disappeared, and that the small delay between arrival times is mostly

related only to the non-uniformity of the electric field and the weighting potential configuration.

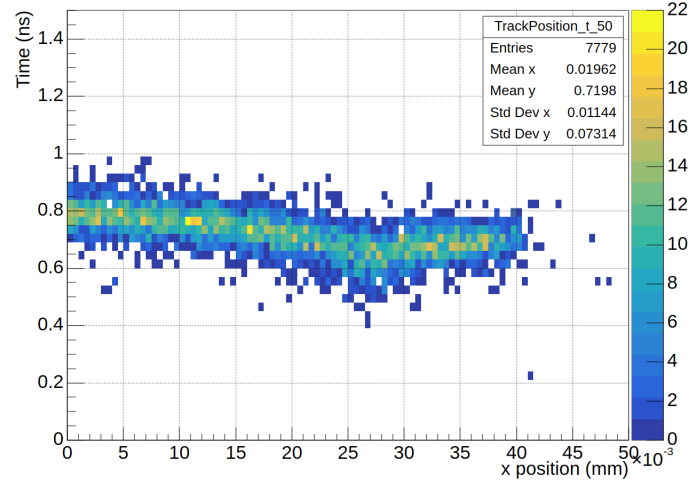


Fig. 6.19 ToA as a function of the particle impact position for the random-position simulation, taken at 50% of CFD. The delay in arrival times between the sensor center and its edge was significantly reduced. This confirms that the electric field depression has been reduced and that the residual timing differences are primarily attributed to non-uniformity in the electric field and weighting potential configuration.

6.5 Characterization of run 3.2 MADPix devices

As described in Chapter 5, the full characterization of the monolithic device is performed through electrical characterization and in-beam measurements. The characterization of the sensor belonging to the short-loop run 3.2 is described in detail in the following subsections.

6.5.1 I-V measurements

Since the same production masks were exploited to fabricate the new short-loop, it was not possible to make changes to the sensor structures and, thus, it was necessary to proceed with the connection of the floating guard ring using the FIB technique. Once this operation was completed, electrical characterizations through I-V measurements were performed on the different devices with an A2 layout and belonging to different dose splittings. Figure 6.20 shows the backside current on the left and

the top current on the right, as a function of the reverse bias voltage applied at the backside electrode and of the topside bias voltage, respectively.

In Figure 6.20a, the back current gives the possibility to identify the onset of punch-through approximately at -27 V, with slight differences from one split to another. In Figure 6.20b, the top current as a function of the same electrode's voltage allows studying the breakdown phenomenon. The breakdown effect is observed in the voltage range of approximately 65–70 V, where the device enters a regime of uncontrolled carrier multiplication, resulting in a significant increase in leakage current. As expected, the breakdown voltage for the +3.3% gain dose split is reached at a lower voltage due to the higher gain. For the CMOS sensors without gain, the breakdown occurs earlier.

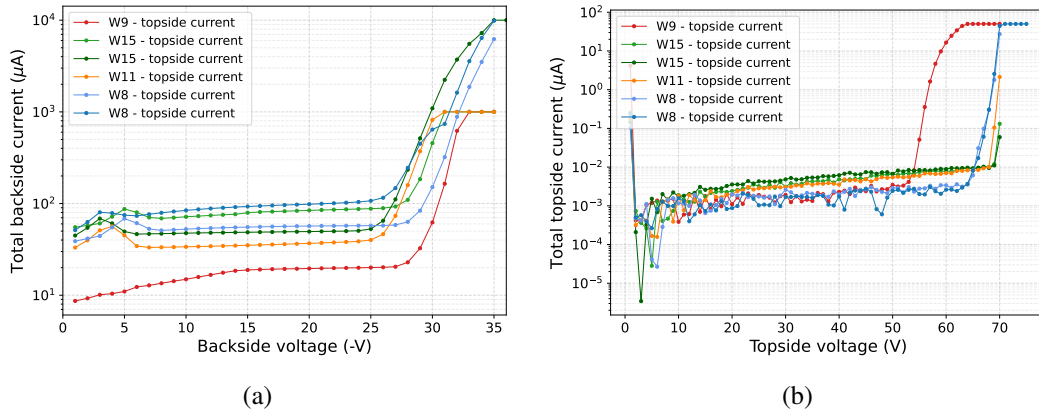


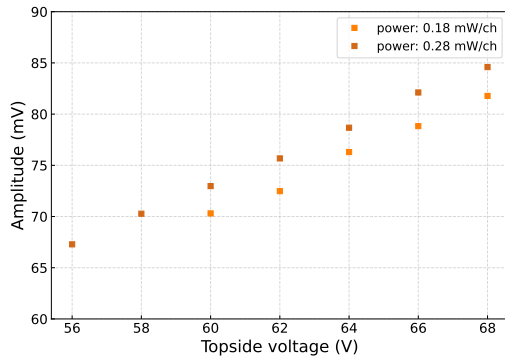
Fig. 6.20 (a) Backside current as a function of the reverse bias voltage applied on the back electrode for A2 termination layouts. The collection electrode voltage was biased at 45 V, while the guard ring was at 9 V. (b) Topside current as a function of the top bias voltage. The backside electrode was left at a fixed voltage of -25 V while the guard ring was at 9 V.

6.5.2 Measurements with particle beams and results on time resolution

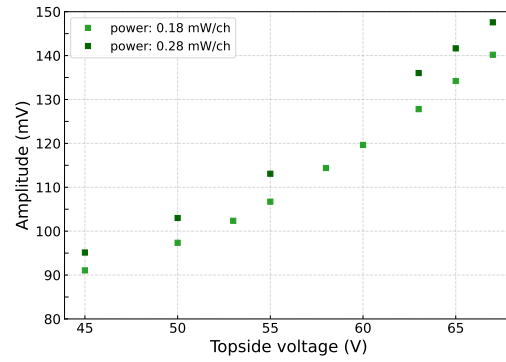
As for the run 3 sensor production, once the FIB process was performed on these devices, they were tested at the T10 beamline of the CERN PS using a hadron beam primarily consisting of protons and pions with a momentum of 10 GeV/c. The adopted analysis method was the one already explained in the previous chapter. The results achieved for the sensors of the run 3.2 are reported in the following.

Sampling the entire analog waveform, the maximum amplitude of each signal was

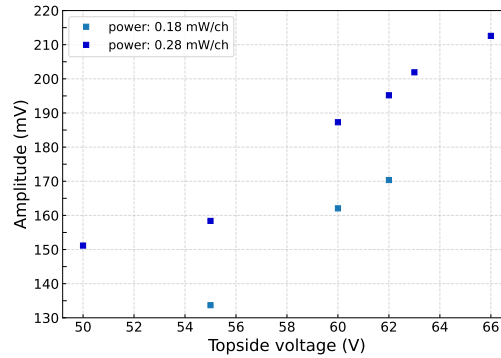
extracted and recorded in a histogram. The amplitude distribution was calculated for all the tested sensors and voltage configurations, and it was then fitted using a Landau–Gaussian convolution. Figure 6.21 reports the MPVs of the amplitude distributions as a function of the top collection electrode voltage and for three different devices: the one with -3.3% of dose (W11, orange), the one with reference dose (W15, green), and the one with +3.3% of dose (W8, blue).



(a) MADPix sensor with dose split of -3.3%



(b) MADPix sensor with dose split of +0%



(c) MADPix sensor with dose split of +3.3%

Fig. 6.21 MPVs of the maximum amplitude distributions measured for the A2 structures of run 3.2 and for three different MADPix devices as a function of the topside voltage. For each plot, the standard (0.18 mW/ch) and boosted (0.28 mW/ch) electronics configuration is reported. The backside electrode was set to a fixed voltage of -25 V while the guard ring at 9 V.

For each plot, the MPV values are evaluated both in the standard and boosted configuration of the electronics, see Section 5.4.7. The values are slightly better for the boosted configuration since there is an increase in the dynamic range, and consequently, of the electronics gain. Raising the topside voltage leads to higher

output amplitudes in both operating conditions, indicating increased device gain at higher bias. The values of the amplitude vary for the three sensors with different dose splitting, indicating that the internal gain is also different.

In addition to these sensors, a device without internal gain was also measured to have a reference for the gain evaluation. Therefore, a more precise sensor gain G , compared to the one estimated in Section 6.1.1, was evaluated as the ratio of the MPV values of the maximum amplitude distributions measured in a sensor with gain layer ($MPV_{w/ gain}$) and in another one without internal gain ($MPV_{w/o gain}$):

$$G = \frac{MPV_{w/ gain}}{MPV_{w/o gain}} \quad (6.2)$$

Figure 6.22 shows the gain as a function of the top bias voltage in the standard configuration for the three sensors described before. As expected, when the topside voltage increases, the electric field and, thus, the gain enhance. Moreover, it can also be noted that for each device the values measured for the gain are similar to those estimated exploiting the IR measurements on the passive structures (see Figure 6.5).

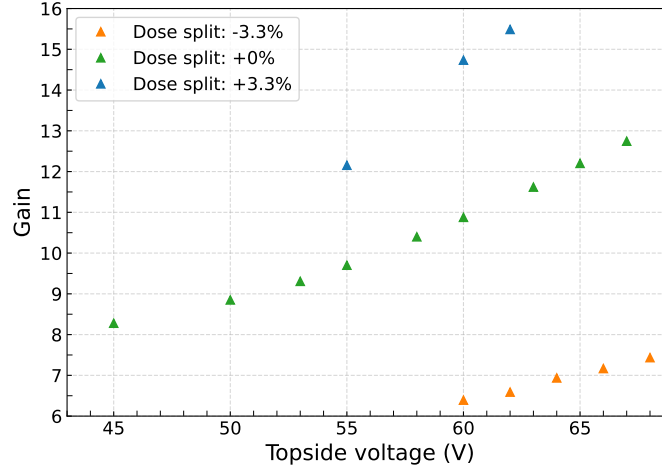


Fig. 6.22 Gain as a function of the topside voltage measured for three different sensors. The backside electrode was biased at -25 V and the guard ring at 9 V.

In this analysis, the reported gain refers to the behavior of a single pixel, whereas for the IR measurements shown in Figure 6.5 the extracted current corresponds to the entire passive structure, which includes 10 individual pixels. This means that the IR current represents an average contribution over all pixels. In addition, when

illuminating the device with an IR LED, the light cannot be focused exclusively on the central region of the active area. As a consequence, the peripheral regions of the sensor, which exhibit a lower gain, are also illuminated. This results in an effectively reduced gain compared to that obtained with a MIP. On the other hand, in tests with beams, a slight reduction of the effective gain may also occur due to space-charge effects. The high local charge density generated along the particle track can partially screen the electric field in the multiplication region, leading to a possible gain suppression compared to the case of unfocused optical illumination. The IR measurements provide an order-of-magnitude for the estimated gain of the devices, as they also include the current contribution generated by charge carriers collected at the sensor edges. For a more accurate determination of the gain, test-beam measurements are necessary, as they allow for a selection based on the collected charge, enabling the isolation of the response of the central region.

The in-beam measurements were carried out to evaluate the time resolution and to compare the sensor performances with that of previously studied devices. The measurements were performed using the same experimental setup and data analysis procedure described in the previous chapter, ensuring a consistent estimation of the resolution. Also in this case, the fixed threshold algorithm was employed together with the time walk correction. Figure 6.23 shows the time resolution of a single pixel as a function of the top (Figure 6.23a) and back (Figure 6.23b) bias voltages for a sensor, belonging to the production run 3.2, with reference dose split (+0%). The estimated time resolution σ_t is reported for the two electronics configurations: the standard one, in which the in-pixel front-end dissipates 0.18 mW per channel (lighter markers), and the boosted configuration, characterized by a power consumption of 0.28 mW per pixel (darker markers). The timing performance of the single pixel was obtained using the LE method applied over a range of fixed threshold values. For each V_{top} value, the minimum σ_t achieved within the selected threshold range is reported.

The experimental results show that the new short-loop sensors are characterized by a better time resolution with respect to that measured in the previous production after the FIB operation and with increased top voltage (see Figure 5.42). This demonstrates that a higher gain helps to improve the timing performance. In addition, the dependence of σ_t on both the top and back bias voltages follows the expected trend: by increasing the topside polarization, the electric field becomes higher and, as a

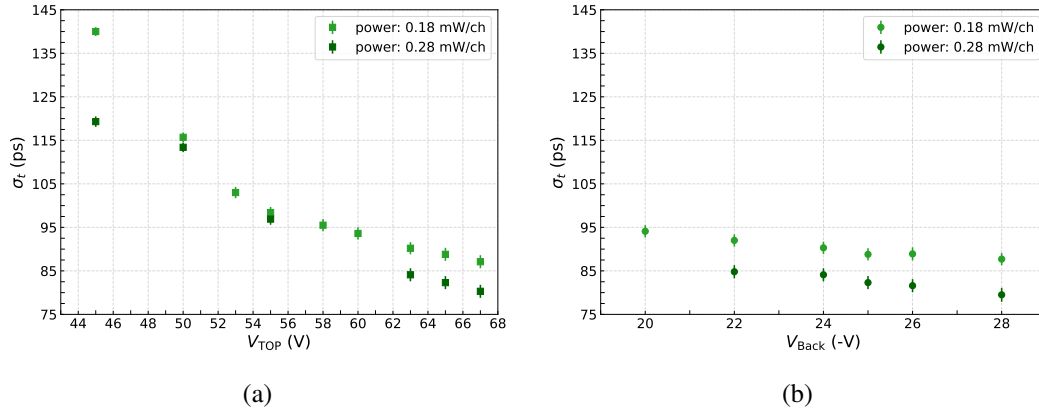


Fig. 6.23 Time resolution as a function of the top and back voltage for a MADPix device with A2 termination layout and reference split dose (+0%) obtained using the LE method. (a) σ_t versus V_{top} scan for two electronics configuration. The backside bias polarization was fixed at -25 V, just before the punch-through onset, as shown in Figure 6.20a. (b) σ_t versus V_{back} scan for the same electronics configuration reported in (a). The collection electrode voltage was biased at 65 V, before that the breakdown occurs (see Figure 6.20b).

consequence, the gain increases leading to a better time resolution. At the same time, the sensor depletion and the electric field also increase, allowing the carriers to almost reach their saturation velocities and leading to a decrease in σ_t , which eventually reaches a plateau.

Figure 6.24 reports the time resolution versus top bias voltage evaluated for two additional dose splittings: -3.3% in 6.24a, and +3.3% 6.24b. Also for these devices, the behavior of the timing performance is the expected one. By reducing the dose split, a slight degradation of the timing resolution is observed. This behavior can be attributed to an increase in the jitter term, arising from the lower internal gain and the consequently reduced signal slope at the threshold crossing for a given noise level. Conversely, no significant variation is evident between the timing performance obtained with the reference doping and that corresponding to a +3.3% of gain dose, indicating that, within this range, the signal-to-noise ratio and the resulting jitter contribution remain essentially unchanged. The increase in timing resolution for a topside of 66 V, which is visible in Figure 6.24b, is consistent with the sensor operating point close to breakdown. In this regime, enhanced multiplication and increased noise levels, together with possible local field instabilities, are expected to deteriorate the time resolution. Furthermore, the need to adjust the oscilloscope

vertical scale to properly record the waveforms further supports this interpretation. Despite these non-ideal operating conditions, this bias point was deliberately included to obtain additional information on the sensor behavior near breakdown and to assess the limits of its timing performance.

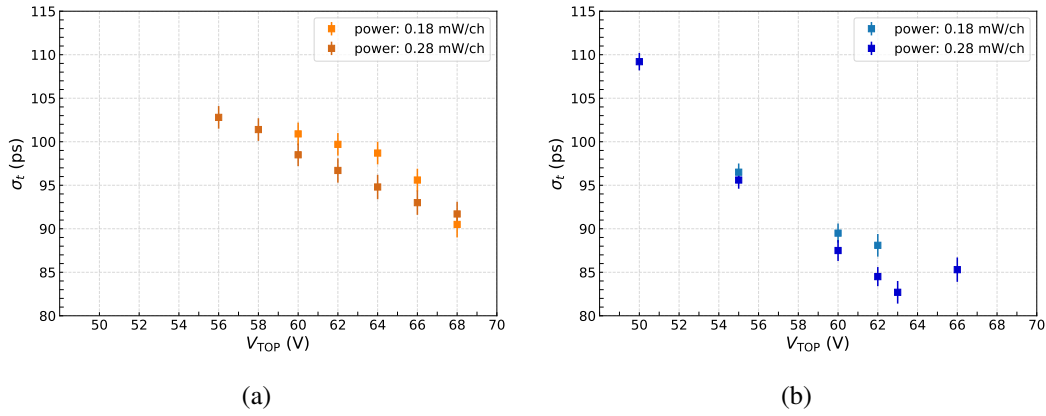


Fig. 6.24 Time resolution as a function of the top voltage for two MADPix devices with A2 termination layout obtained using the LE method. (a) σ_t versus V_{top} for the sensor with split dose (-3.3%) and with two electronics configuration. (b) σ_t versus V_{top} for the sensor with split dose (+3.3%) and with two electronics configuration. In both studies, the backside bias polarization was fixed at -25 V. The uncertainties associated to σ_t are the statistic errors evaluated from the q-Gaussian fit applied on the corrected time difference distribution.

These results demonstrate that the higher gain values implanted in the new run 3.2 improve the timing performance and allow to achieve a time resolution at the level of approximately 80 ps, depending on the biasing conditions, p-gain dose splittings, and the electronics configuration.

6.6 Radiation damage in silicon sensors

The radiation damages in a silicon sensors may be divided into two categories: surface-related and bulk-related damages. In both cases, the effect of the generated damage depends on the nature and energy of the incident particles. Concerning the surface damages, the irradiation causes the formation of a significant concentration of trapped positive charges at the interfaces between Si and SiO₂. In the second case, instead, hadrons or high-energy leptons cause mainly the displacement of a primary knock-on atom from its lattice position, leading to the formation of a silicon

interstitial (Si_i) and an associated residual vacancy, known as a Frenkel pair [99]. A portion of these pairs recombines, resulting in non-permanent damage, whereas the remaining interstitials and vacancies diffuse through the crystal lattice and interact with other impurities present in the bulk, thereby generating point defects. Atomic displacement takes place when the energy transferred by the incident particle exceeds the displacement threshold energy E_d (approximately 25 eV). In certain cases, the recoiling atom may acquire an energy greater than 25 eV, leading to additional ionization events and further atomic displacements. At the end, a resulting dense agglomeration of defects, commonly referred to as clusters, is formed.

Charged hadrons interact with silicon mainly through Coulomb interactions at low energies. Consequently, a substantial fraction of the particle energy is dissipated via ionization of lattice atoms. Neutrons, instead, interact exclusively with atomic nuclei, and the dominant processes are elastic scatterings. The portion of energy deposition that does not contribute to ionization is referred to as Non-Ionizing Energy Loss (NIEL). Part of this energy leads to lattice excitations, whereas the remaining fraction is responsible for bulk damage. To enable a comparison of the effects produced by particles of different types or energies, the assumption that radiation damage scales with their respective NIEL values was formulated, commonly known as the NIEL scaling hypothesis. The standard reference NIEL value is conventionally defined as that corresponding to 1 MeV neutrons. Accordingly, irradiation levels are frequently expressed in terms of the number of 1 MeV n_{eq}/cm^2 . Figure 6.25 illustrates the NIEL factors in silicon for neutrons, protons, pions, and electrons, normalized to the NIEL value corresponding to 1 MeV neutrons.

6.6.1 Impact of radiation damages on silicon sensor properties

The impact of the defects caused by radiation damages on the silicon sensors properties are reported in the following.

- **Leakage current (I_{bulk}):** defects near the center of the band gap act as generation centers for electron-hole pairs and thus cause an increase in the leakage current of the substrate (I_{bulk}). This current is proportional to the depleted volume V_d , the electron charge q_0 , the intrinsic carrier concentration n_i , and

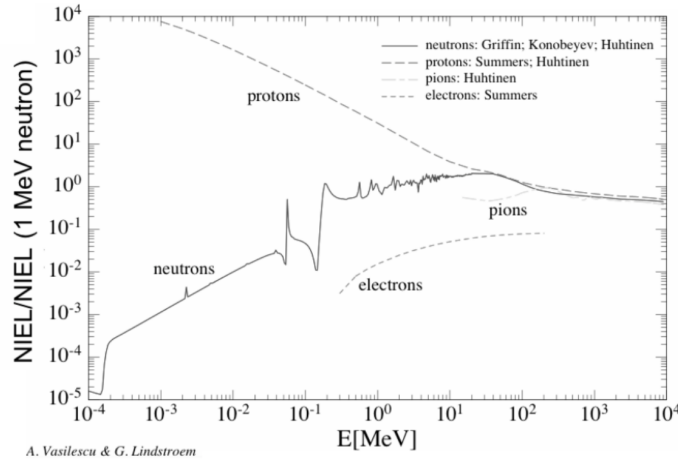


Fig. 6.25 The relative NIEL factors in silicon for neutrons, protons, pions, and electrons, normalized to the NIEL value corresponding to 1 MeV neutrons, as a function of the particle energy. Low-energy protons induce significantly greater displacement damage than neutrons. For energies exceeding 50 MeV, the NIEL values for neutrons and protons converge and become nearly identical. Figure taken from [40]

the reciprocal of the generation lifetime τ_g :

$$I_{bulk} = V_d q_0 \frac{n_i}{\tau_g} \quad (6.3)$$

- **Charge Collection Efficiency (CCE):** electrons and holes generated by a crossing particle are driven toward the electrodes under the influence of the applied electric field. During the drift process, a fraction of the charge carriers may be captured, or trapped, by deep-level defects. This phenomenon, referred to as trapping, results in a charge collection deficiency. The trapping probability of electrons by a given type of defect is proportional to the drift duration rather than to the drift distance; consequently, higher drift velocities result in increased collected charge. The current signal $i(t)$ in an irradiated sensor follows an exponential decrease as a function of time:

$$i(t) = i(t)_{\Phi_{eq}=0} \cdot e^{-\frac{t}{\tau_{eff}}} \quad (6.4)$$

In particular, $\Phi_{eq}=0$ is the 1-MeV equivalent fluence, while the time constant τ_{eff} is given by:

$$\frac{1}{\tau_{eff}} = \Phi_{eq} \beta_{e/h} \quad (6.5)$$

where $\beta_{e/h}$ are proportionality factors known as effective trapping damage constants. The effective trapping time decreases with increasing irradiation fluence and with the magnitude of the $\beta_{e/h}$ parameter.

- **Decreased carriers mobility:** the mobilities of electrons and holes decrease with increasing fluence as the density of scattering centers enhances. Reduced mobility results in lower kinetic energy for the charge carriers, preventing the controlled multiplication.
- **Doping densities:** three mechanisms contribute to modify the doping concentration: donor removal, acceptor removal, and acceptor generation. These effects are summarized in Eq. 6.6:

$$N_{eff} = N_{D0} e^{-c_D \Phi_{eq}} - N_{A0} e^{-c_A \Phi_{eq}} - g_{eff} \Phi_{eq} \quad (6.6)$$

where N_{eff} denotes the effective dopant concentration. The first term corresponds to donor removal, the second to acceptor removal, and the third to acceptor creation. $N_{D0/A0}$ represents the initial donor and acceptor concentrations, $c_{d/A}$ are the respective donor and acceptor removal coefficients, and $g_{eff} = 0.02 \text{ cm}^{-1}$ is the proportionality constant relating the fluence to the density of new acceptor-like defects.

6.6.2 Impact of radiation damages on LGAD sensors

The impact of defects on sensor properties will be discussed, with particular attention devoted to the effects most relevant for LGAD sensors.

- **Leakage current:** in sensors featuring internal gain, the leakage current originating in the bulk is amplified by the gain factor G , leading to an increase both in current and in power consumption. However, by cooling the sensor, it is possible to reduce the power consumption and, thus, the leakage current since it exhibits a dependence on temperature:

$$i(T) \propto T^2 e^{\frac{1.2 \text{ eV}}{2k_B T}} \quad (6.7)$$

where T is in Kelvin. A variation of 7 °C corresponds to a variation by a factor of two in current.

- **Shot noise:** a second effect, which is also related to the increase in the leakage current, is the increase in the shot noise. This is linked to the electrons flow across the pn junction generating current fluctuations. In silicon sensors with low gain (10-30), the shot noise has a lower contribution compared to electronic noise; but, after irradiation, the leakage current increases substantially, and shot noise may become a dominant component of the total noise. Therefore, operating irradiated sensors with low gain and at low temperature is essential to keep the shot noise low and below the level of electronic noise.
- **Variation in doping densities:** Eq. 6.6 shows that the irradiation causes a modification of the doping concentration which depends on the fluence. The process of **acceptor removal** involves the gradual reduction in the number of active acceptor atoms. This effect is particularly important in LGADs, as it deactivates the acceptor-doped implant, the gain layer. An important point to note is that Secondary Ion Mass Spectrometry (SIMS) measurements [40] have shown that boron atoms are not removed, but rather become electrically inactive when this phenomenon occurs. A potential explanation for the acceptor removal mechanism involves the formation of ion-acceptor complexes due to irradiation [100]. Irradiation displaces silicon atoms from their lattice positions, creating silicon interstitials and vacancies. Both vacancies and interstitials exhibit mobility at temperature values close to the room temperature and can interact with impurities. In particular, Si_i reacts with elements such as boron (B_s), oxygen (O_i), and carbon (C_s). Through a process known as the Watkins replacement mechanism [101], an interstitial can occupy a lattice site by interacting with a boron or carbon atom already positioned at a lattice site. In this reaction, for example:



the boron or carbon atoms are transformed into interstitials, which then migrate through the lattice. These new B_i can further interact with other impurities, such as O_i , and potentially generating additional defect complexes:



The effect of this process is an overall deactivation and loss of acceptor atoms, resulting in a decrease of the internal gain. Figure 6.26 illustrates the acceptor removal mechanism in a boron-based gain layer.

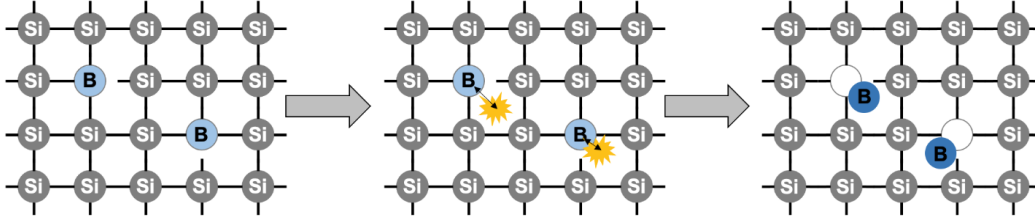


Fig. 6.26 Schematic representation of the acceptor removal mechanism in the boron-based gain layer, resulting in a reduction of the effective acceptor concentration.

Two opposite and simultaneous contributions occur: initial acceptor removal and acceptor generation. Both processes influence both the gain implant and the bulk region of the sensor. For high fluences ($\Phi > 1 \cdot 10^{16} \text{ n}_{eq}/\text{cm}^2$), the acceptor concentration in the gain implant becomes comparable to that of the bulk, resulting in a complete removal of the gain layer. Different solutions are under investigation to mitigate the deactivation of the gain layer, such as the implantation of carbon atoms in the p -gain implant to reduce the concentration of Si_i defects.

The reduction in gain is due to a decrease in the electric field within the gain layer, caused by the inactivation of the gain implant. As a consequence, the free path λ increases; however, it can be reduced by increasing the bias voltage, thereby partially restoring the gain. When the bias voltage is further increased, the multiplication process also occurs within the bulk. This phenomenon, known as bulk gain, exhibits a very sharp onset and rapidly drives the device toward breakdown conditions.

6.7 Irradiation campaign for run 3.2 sensors

The results obtained after an irradiation campaign carried out on MADPix are presented in this section. The purpose of studying irradiated devices is to understand how their performance and behavior change when radiation damage occurs. The

campaign was conducted using the neutron facility available at the TRIGA research reactor of the Jožef Stefan Institute (JSI) in Ljubljana. This facility is widely used by numerous research groups for radiation hardness studies, as its neutron flux and energy spectrum are well characterized [102]. The irradiation fluence is reported in terms of $1 \text{ MeV } n_{eq}/\text{cm}^2$. For this first test campaign, 5 fluences ranging from $5 \cdot 10^{12} - 10^{15} \text{ 1 MeV } n_{eq}/\text{cm}^2$ were selected.

6.7.1 Defect annealing

In a high energy physics experiment such as ALICE 3, detectors are exposed to radiation over several years, in contrast to short-term irradiation campaigns where the dose is delivered within days or hours. As a result, partial annealing of radiation-induced defects can occur in real detectors, whereas such recovery mechanisms are largely suppressed in sensors exposed to rapid irradiation procedures. This difference can be mitigated by annealing the devices. After the irradiation process, the effective doping concentration N_{eff} changes due to radiation damages. The behavior of these defects is time- and temperature-dependent, which makes annealing a key aspect of the sensor characterization. Figure 6.27 shows the variation in effective doping concentration ΔN_{eff} due to the irradiation. The trend of ΔN_{eff} can be divided into three components: the short-term annealing component N_A , the stable damage part N_C , which does not depend on annealing, and the reverse annealing N_Y .

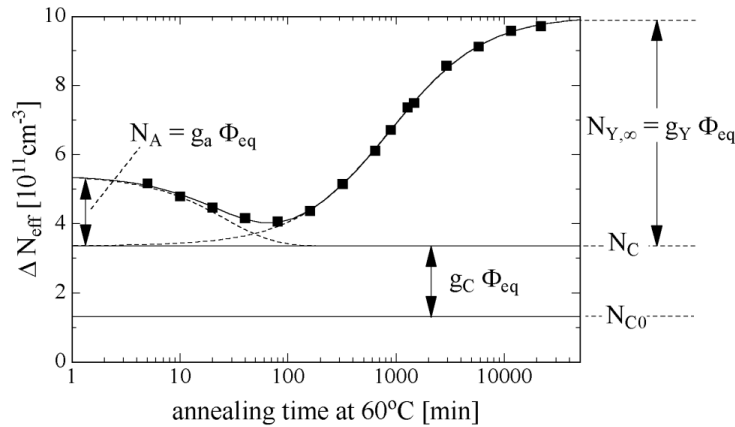


Fig. 6.27 Annealing characteristics of the radiation-induced variation in effective doping concentration (ΔN_{eff}) at 60°C . Figure taken from [103]

The short-term annealing is also called beneficial annealing because it is responsible for an increase in the effective doping concentration N_{eff} . N_A is due to the annealing of microscopic defects through a single jump (either dissociation or reorientation) rather than via long-range migration. Beneficial annealing occurs at relatively short annealing times and moderate temperatures. During this phase, many of the metastable defects, created by irradiation, recombine or transform into electrically less active configurations. As a consequence, the leakage current decreases, charge trapping is reduced, and the effective doping concentration tends to move toward a more stable value. Beneficial annealing, therefore, improves sensor performance. On the other hand, for longer annealing times or at higher temperatures, reverse annealing becomes dominant. In this regime, more stable defect complexes are formed, which increase the effective space charge density in the silicon bulk. This leads to a rise in the depletion voltage and can significantly degrade the operational performance of the sensor. Reverse annealing is particularly critical for long-term operation, as it continues even at relatively low temperatures and can only be slowed down by cooling the detector.

Once the irradiation campaign was completed, the sensors were annealed in a thermal chamber before starting their characterization. A typical annealing procedure lasts 80 minutes and is performed at a temperature of 60 °C. This duration was chosen because it approximately corresponds to the time required to anneal short-term radiation-induced defects, as shown in Figure 6.27. After annealing, the devices were stored in a freezer at a temperature of approximately -20 °C. All irradiated MADPix sensors underwent the annealing cycle described above.

6.7.2 Electrical characterization of irradiated sensors

After the thermal annealing cycle, both active and passive structures were tested by performing I-V measurements. Electrical characterization after irradiation is essential to assess the impact of radiation-induced damage on the sensor performance. In particular, I-V measurements allow the evaluation of leakage current increase, changes in breakdown voltage, and the degradation of the effective doping concentration, providing crucial information on the operational stability and radiation tolerance of the devices.

Irradiated passive structures: I-V measurement and first gain estimation

Twenty five irradiated passive structures with an A2 termination layout and different p-gain split doses were measured in a probe station. For each value of the 5 fluences chosen for the irradiation, multiple devices were tested. Figure 6.28 shows the current collected by the p-well, while its bias was fixed at 0 V, as a function of the reverse bias voltage of the backside electrode. Thanks to this I-V characteristic, the punch-through phenomenon is visible, and it is highlighted by the dips in the curve associated with the change of the current sign. In this figure, the p-well current is reported for sensors with +3.3% of p-gain dose and irradiated at different fluences ($5 \cdot 10^{12}$, $1 \cdot 10^{13}$, $5 \cdot 10^{13}$, $1 \cdot 10^{14}$, and $1 \cdot 10^{15} \text{ n}_{eq}/\text{cm}^2$). Three devices were tested for each value of fluence. The absolute current level and the voltage at which the punch-through onset occurs are strongly dependent on the irradiation fluence. Sensors irradiated at lower fluences (e.g. $5 \cdot 10^{12}$ and $10^{13} \text{ n}_{eq}/\text{cm}^2$) exhibit lower leakage currents and a delayed onset, while higher fluences cause a significant increase in leakage and an earlier transition to the high-current regime.

Irradiation affects the punch-through behavior by modifying the effective doping concentration of the bulk. Radiation-induced acceptor removal leads to an expansion of the depletion region, causing the punch-through phenomenon to occur at lower bias voltages. In addition, the increased density of generation centers enhances the leakage current once punch-through is reached, resulting in a more pronounced current increase compared to non-irradiated devices.

Once the working point in terms of back voltage has been defined and fixed to a value below the onset of the punch-through, the top current is measured as a function of the topside electrode for the same devices. The results are shown in Figure 6.29. These I-V characteristics allow defining the breakdown onset point and studying the damage-induced effect on it. Irradiation significantly affects the breakdown behavior by modifying both the effective doping concentration and the internal electric field distribution.

As explained in Section 6.6.1, radiation-induced defects produce an increase of the leakage current. This is clearly visible in Figure 6.29, where it is possible to note that the increase of the fluence determines an increase in the top current. Moreover, the acceptor removal mechanism in the gain layer occurs, reducing the local electric field and delaying the onset of avalanche multiplication. This effect causes a shift of the breakdown voltage towards higher values.

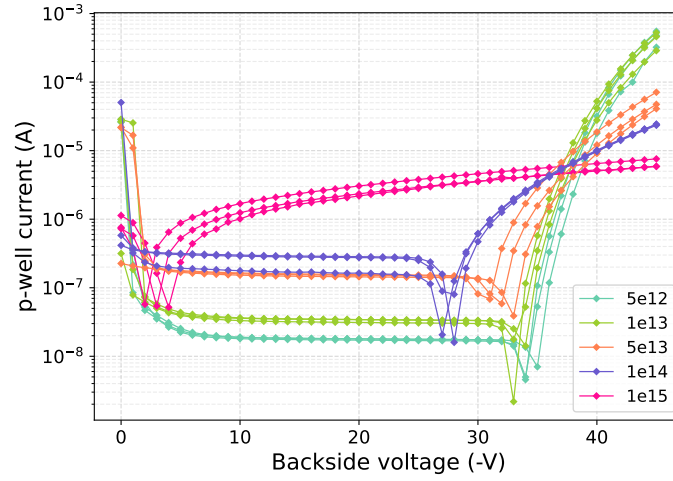


Fig. 6.28 p-well current as a function of the backside voltage for sensors with +3.3% of p-gain doping. The current is reported for the 5 different fluences used for the sensor irradiation. The top electrode was biased at 45 V while the guard ring was at 9 V.

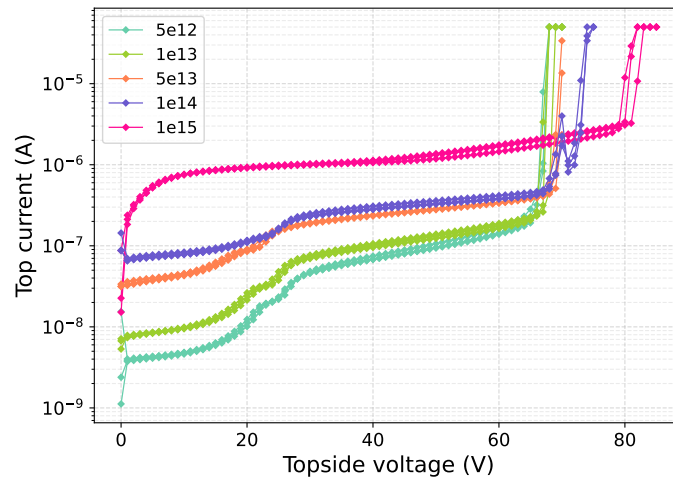


Fig. 6.29 Top current as a function of the topside voltage for sensors with +3.3% of p-gain doping. The current is reported for the 5 different fluences used for the sensor irradiation. The guard ring implant was fixed at 9 V, while the back electrode bias voltage is set to a value below the onset of the punch-through phenomenon.

As done for the passive structures before irradiation (Section 6.1.1), I-V measurements of the topside current as a function of the same top electrode were performed in a probe station by illuminating the devices with a uniform and continuous IR LED light source. This technique relies on the comparison of the top electrode current between a sensor with a gain layer and a reference device without internal gain. This

comparison allows the evaluation of the sensor gain G as expressed in Eq. 6.1. Figure 6.30 illustrates the gain measured for the sensor with a split dose of +3.3% as a function of the topside voltage for different irradiation fluences. The estimated gain increases with the applied top voltage for all irradiation levels, reflecting the progressive enhancement of the impact ionization mechanism when the electric field increases. For low fluences, a steep gain curve is observed, indicating an efficient charge multiplication mechanism. As the irradiation fluence is higher, a systematic reduction of the gain is evident over the entire voltage range. This is due to the acceptor removal mechanism in the gain layer, leading to a decrease in the effective doping concentration and consequently to a lower electric field. As a consequence, the maximum gain is significantly suppressed at high irradiation levels.

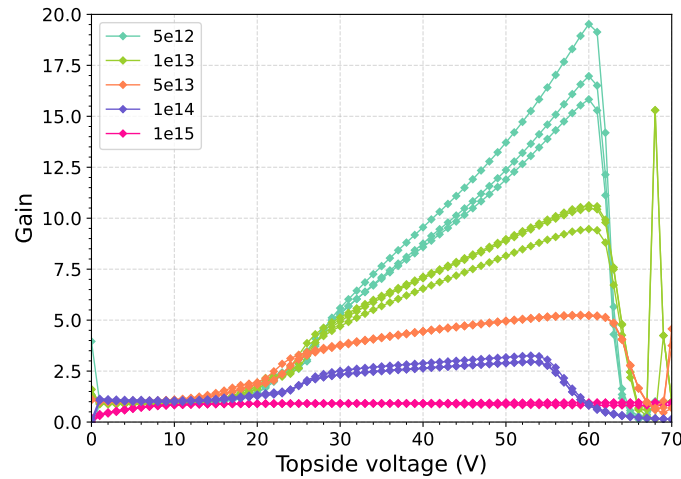


Fig. 6.30 Gain measured as a function of the top voltage using a continuous IR illumination for sensors with +3.3% of p-gain doping. The gain is shown for the 5 different fluences. The guard ring implant was biased at 9 V, while the back electrode bias voltage depends on the device fluence and it is set to a value below the onset of the punch-through phenomenon.

Irradiated MADPix devices: I-V measurement

The irradiated monolithic structures were also electrically characterized after performing the FIB process to connect the floating guard ring. This operation was performed only on MADPix devices irradiated with a fluence lower than $1 \cdot 10^{14} \text{ n}_{eq}/\text{cm}^2$. This choice was made based on measurements on passive structures, which showed that the gain is almost completely suppressed for fluences higher than this value. Moreover, one of the main goals of the test beam, described in the following, was to study

the sensor performance at a fluence of $1 \cdot 10^{13} \text{ n}_{eq}/\text{cm}^2$, which corresponds to the maximum expected fluence in the forward disks of the ALICE 3 Time Of Flight detector (see Table 2.1).

Figure 6.31 shows the I-V measurements performed on several devices belonging to the split dose of +3.3% for different fluences. In particular, the total backside current as a function of the reverse bias voltage applied at the backside electrode is shown in Figure 6.31a, while Figure 6.31b reports the topside current as a function of the topside bias voltage. For both measurements, sensors with the A2 termination layout were tested.

The back current allows the identification of the onset of punch-through at approximately -25 V, which is not significantly different from that of the pre-irradiation sensor. However, at an irradiation level of $1 \cdot 10^{14} \text{ n}_{eq}/\text{cm}^2$, the onset seems to occur earlier.

The dependence of the top current on the top voltage allows the investigation of the breakdown phenomenon. As for the passive structures, sensors irradiated at higher fluences systematically exhibit larger currents over the entire voltage range, reflecting the effect of radiation-induced damage.

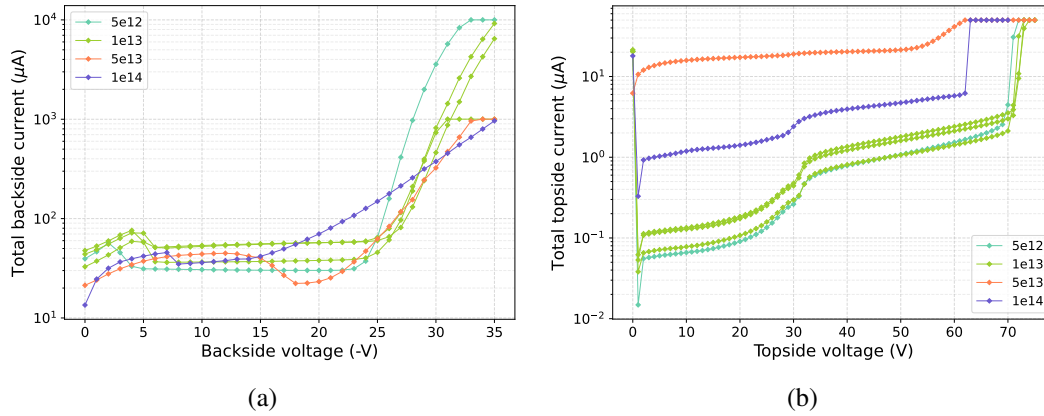
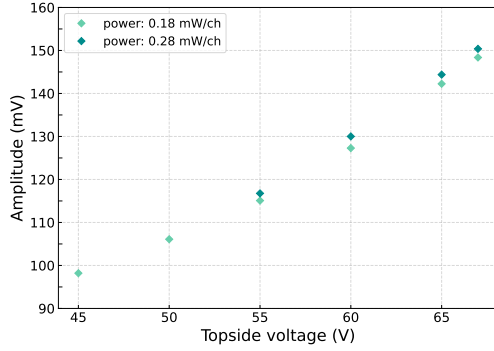


Fig. 6.31 (a) Backside current as a function of the reverse bias voltage applied on the back electrode for A2 termination layouts of irradiated sensors. The collection electrode voltage was biased at 45 V, while the guard ring was at 9 V. (b) Topside current as a function of the top bias voltage for irradiated MADPix devices. The guard ring implant was biased at 9 V, while the back bias voltage depends on the device fluence and it is set to a value below the onset of the punch-through phenomenon.

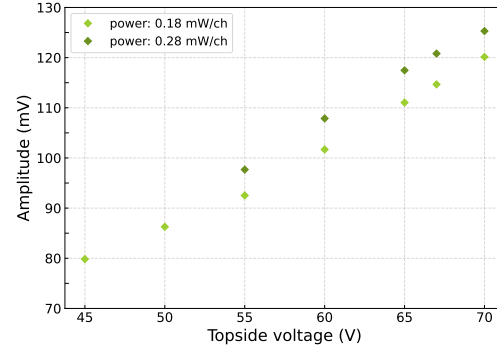
6.7.3 Measurements with particle beams and time resolution results for irradiated sensors

Once the electrical characterization was completed, the same test boards were tested with a particle beam at the T10 beamline of the CERN PS. In particular, TB1 was equipped with a sensor irradiated at fluence of $5 \cdot 10^{12} \text{ n}_{eq}/\text{cm}^2$, TB2 with a sensor irradiated at $1 \cdot 10^{13} \text{ n}_{eq}/\text{cm}^2$, TB3 with a sensor irradiated at $5 \cdot 10^{13} \text{ n}_{eq}/\text{cm}^2$, while TB5 with a sensor irradiated at $1 \cdot 10^{14} \text{ n}_{eq}/\text{cm}^2$. In this latest test beam, the data analysis was carried out following the method adopted in the previous tests, in order to obtain results that can be directly compared with those obtained in earlier measurements.

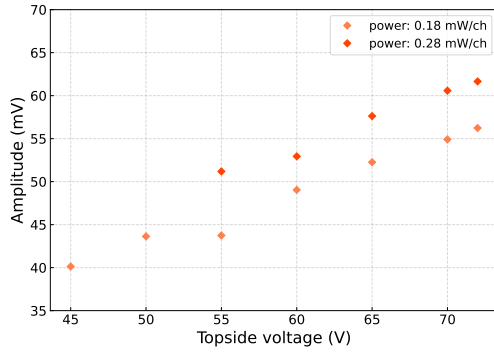
By sampling the full analog waveform, the resulting maximum amplitude distributions were obtained for all the test boards and bias voltage configurations, and subsequently fitted with a Landau–Gaussian convolution. Figure 6.32 shows the MPVs of the amplitude distributions versus the voltage applied to the topside electrode for the different irradiation fluences. For each sensor, the MPVs were evaluated both in the standard and in the boosted electronics configuration. In the latter case, the MPV values are higher, since the dynamic range of the readout electronics increases. For all the irradiation levels, an increase in the V_{top} leads to a rise in the output signal amplitude, indicating an enhancement of the internal gain. The evolution of the MPV for the different test boards shows a clear dependence on radiation damages. For a given topside voltage, the MPV progressively decreases as the fluence increases, indicating a reduction of the collected signal after irradiation. At low fluences, the MPVs trend exhibits a marked increase, reflecting an efficient charge collection and the presence of an internal gain. As the fluence increases, the slope of the trends becomes less steep, and the overall MPV values are reduced. At the highest irradiation levels, the MPV shows a much weaker dependence on the topside voltage, indicating a significant impact of the acceptor removal mechanism on the gain layer suppression, as already observed in Figure 6.30. Finally, comparing these results with the trend of the MPV extracted for the sensors before the irradiation procedure (see Figure 6.21c), one can see that a reduction in the signal amplitude is already present at low irradiation fluences.



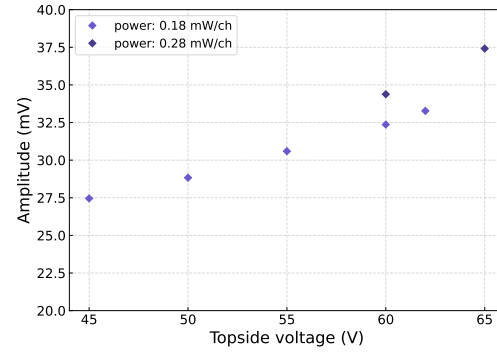
(a) TB1: MADPix sensor irradiated at fluence of $5 \cdot 10^{12} \text{ neq/cm}^2$



(b) TB2: MADPix sensor irradiated at fluence of $1 \cdot 10^{13} \text{ neq/cm}^2$



(c) TB3: MADPix sensor irradiated at fluence of $5 \cdot 10^{13} \text{ neq/cm}^2$



(d) TB5: MADPix sensor irradiated at fluence of $1 \cdot 10^{14} \text{ neq/cm}^2$

Fig. 6.32 MPVs of the maximum amplitude distributions measured for run 3.2 MADPix devices with a split dose of +3.3% and irradiated at different fluences. For each plot, the standard (0.18 mW/ch) and boosted (0.28 mW/ch) configuration of the electronics is reported. The backside electrode was biased at -25 V while the guard ring was at 9 V.

To quantify the loss of gain in irradiated sensors, the gain was evaluated as the ratio of the MPVs, as defined in Eq. 6.2. Figure 6.33 shows the gain as a function of the top bias voltage for the four irradiation levels. For all fluences, the gain increases with increasing top bias voltage, reflecting the enhancement of internal charge multiplication at higher electric fields. At the same time, the absolute gain decreases with increasing fluence, consistent with the behavior observed in the MPVs. This trend is attributed to the reduction of the electric field in the gain layer caused by the acceptor removal mechanism, which leads to a diminished multiplication effect. Finally, a comparison with the results for non-irradiated sensors (blue points

in Figure 6.22) confirms that a degradation of the gain is already present at low fluences.

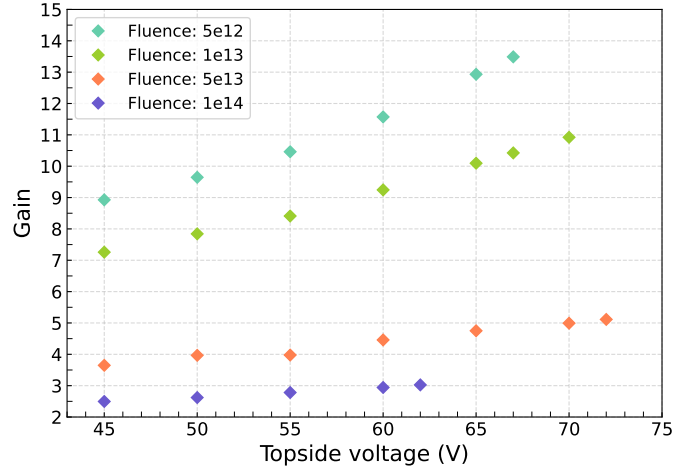


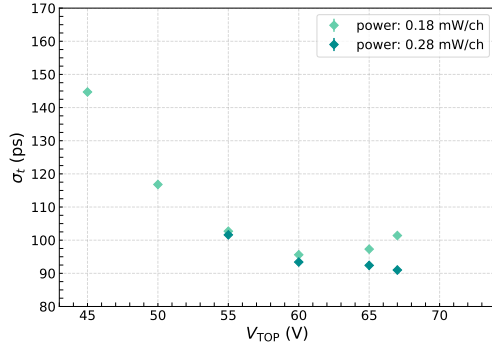
Fig. 6.33 Gain measured for sensors with +3.3% of p-gain doping and irradiated at different fluences. The backside electrode was biased at -25 V while the guard ring was at 9 V.

The results of the timing performance of the irradiated sensors are presented in the following, in order to compare them with the pre-irradiation measurements and to assess the impact of the irradiation on the time resolution.

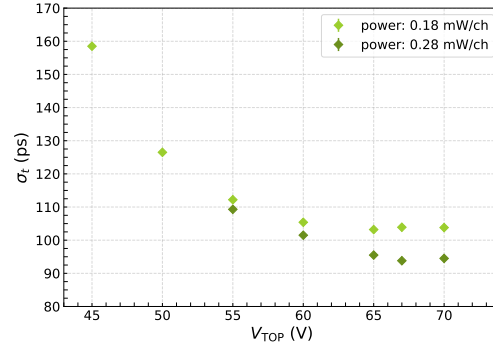
The measurements were carried out following the data analysis method outlined in a previous chapter (Section 5.4.5), thus guaranteeing a consistent evaluation of the time resolution. A fixed-threshold algorithm was applied in combination with a time-walk correction. Figure 6.34 reports the measurement of the time resolution for a single pixel of each test board with an initial p-gain dose of +3.3% and then irradiated at different fluences. Only the time resolution as a function of the top bias voltage is reported, since variations in the corresponding σ_t are more pronounced than those observed when changing the back bias voltage. This is due to the direct influence of the top voltage on the electric field, and consequently, on the gain. As for the previous test, the timing performance is evaluated for two readout electronics operating modes: the standard (light-colored markers) and the boosted configuration (dark-colored markers). For each V_{top} setting, the lowest σ_t obtained within the considered fixed LE threshold interval is reported.

The results confirm that irradiation has a significant impact on the time resolution due to radiation-induced damage in the gain layer. The development of the acceptor removal mechanism and the introduction of deep-level defects lead to a reduction in

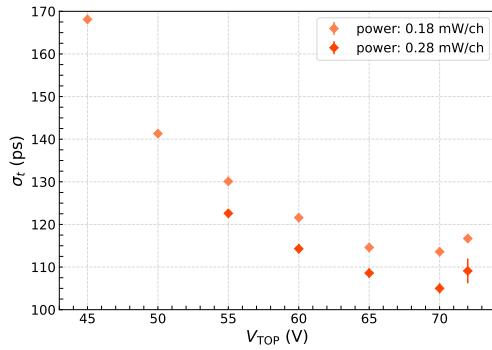
internal gain and an increase in carrier trapping, resulting in enhanced jitter. As a consequence, the time resolution degrades with increasing irradiation fluence. For all measurements shown in Figure 6.34, the increase in σ_t at high top bias voltages is related to the sensor operating point approaching breakdown. In this regime, the time resolution is expected to degrade.



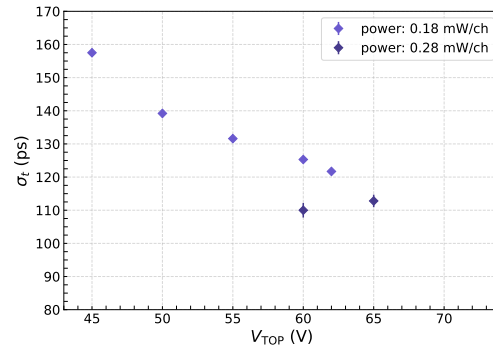
(a) TB1: MADPix sensor irradiated at fluence of $5 \cdot 10^{12} \text{ neq/cm}^2$



(b) TB2: MADPix sensor irradiated at fluence of $1 \cdot 10^{13} \text{ neq/cm}^2$



(c) TB3: MADPix sensor irradiated at fluence of $5 \cdot 10^{13} \text{ neq/cm}^2$



(d) TB5: MADPix sensor irradiated at fluence of $1 \cdot 10^{14} \text{ neq/cm}^2$

Fig. 6.34 Time resolution as a function of the top voltage measured for run 3.2 MADPix devices with a split dose of +3.3% and irradiated at different fluences. For each plot, the standard (0.18 mW/ch) and boosted (0.28 mW/ch) configuration is reported. The backside electrode was biased at -25 V while the guard ring was at 9 V. The uncertainties associated to σ_t are the statistic errors evaluated from the q-Gaussian fit applied on the corrected time difference distribution.

By comparing the time resolution measured before irradiation (Figure 6.24b) with that obtained at the maximum fluence foreseen for the ALICE 3 TOF detector (Figure 6.34b), it can be observed that the timing performance of the irradiated sensor

shows a moderate degradation. In particular, the minimum value of the time resolution worsens by approximately 10% with respect to the pre-irradiation case.

Moreover, for the TB2 test boards, the best time resolution is reached at slightly higher top bias voltages compared to the pre-irradiated case. This voltage shift indicates that increasing the applied bias partially compensates for radiation damage effects, mainly by enhancing the electric field and partially restoring the internal gain.

Figure 6.35 reports the time resolution as a function of fluence for the two different front-end electronics configurations. For both settings, a clear increase in the timing resolution is observed with increasing irradiation, indicating the impact of radiation-induced damage on the sensor response. For all fluence values, the time resolution σ_t is better for the higher power configuration (0.28 mW/ch). It should be noted that the bias voltage applied to the top electrode is not fixed but varies from sensor to sensor. For each irradiation level, the operating voltage was chosen to correspond to the best achievable temporal resolution, typically found at a value approximately 1–2 V below the breakdown voltage. This approach ensures that the reported results reflect the optimal timing performance achievable for each sensor, while preserving safe working conditions.

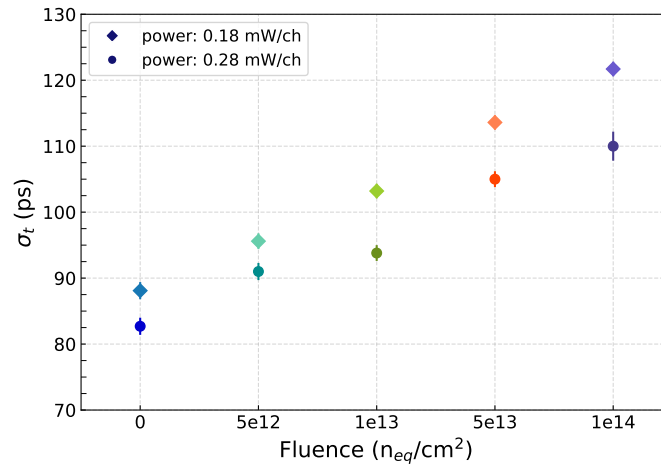


Fig. 6.35 Time resolution as a function of the different fluences. The values at $x=0$ correspond to the measurement performed with a non-irradiated sensor. The backside electrode was biased at -25 V while the guard ring was at 9 V.

All the results presented so far were obtained without cooling and under non-controlled temperature conditions. The operating temperature was approximately 40 °C and was monitored using a Pt100 resistance temperature detector (RTD) [104]. Therefore, the measured time resolution reflects the detector performance under relatively high-temperature operation, and a temperature optimization may represent a possible mitigation strategy for σ_t .

Lower temperatures are known to reduce leakage current and thermal noise, both of which increase as a result of irradiation. Consequently, cooling can partially compensate for radiation-induced effects, improving the signal-to-noise ratio and, in turn, the timing performance. However, no significant increase in thermal noise was observed at higher irradiation levels, likely because the selected fluences were not sufficiently high. As reported in the literature [105], due to the relatively low gain and the small hole impact ionization coefficient, the noise contribution to the temporal resolution remains negligible up to fluences of $2 \cdot 10^{15} \text{ n}_{eq}/\text{cm}^2$.

Another parameter that depends on temperature is the carrier mean free path. A decrease in temperature reduces phonon scattering, leading to an increase in carrier mobility and mean free path. As the carrier mean free path increases, charge carriers are able to gain sufficient kinetic energy over a single drift path to trigger the impact ionization process. Conversely, at higher temperatures, the increased phonon population enhances phonon scattering, which reduces the mean free path of the carriers. As a result, these carriers experience more frequent scattering events and can not accumulate enough energy between collisions to trigger impact ionization. Consequently, operating the detector at lower temperatures can improve the gain and partially mitigate the degradation in timing performance observed after irradiation.

This behavior is in agreement with the trend shown in Figure 6.36, where the measured gain G as a function of temperature for the different irradiation fluences is reported. The operating temperature was controlled using a cooling system based on a Peltier cells mounted on the back of the test board, a chiller to remove heat, and a Pt100 resistance temperature detector installed close to the DUT to have an online monitoring of the temperature. Nitrogen gas was continuously flushed inside the box to ensure a low-humidity environment to lower the dew point.

For all fluence levels, a clear increase in gain is observed when the temperature is reduced. As already outlined in the previous plot, the top bias voltage is not fixed but varies among the different test boards and temperature conditions. For each

point, the operating voltage was chosen to minimize the time resolution, ensuring consistency with the subsequent plot and coherence in the comparison of the results.

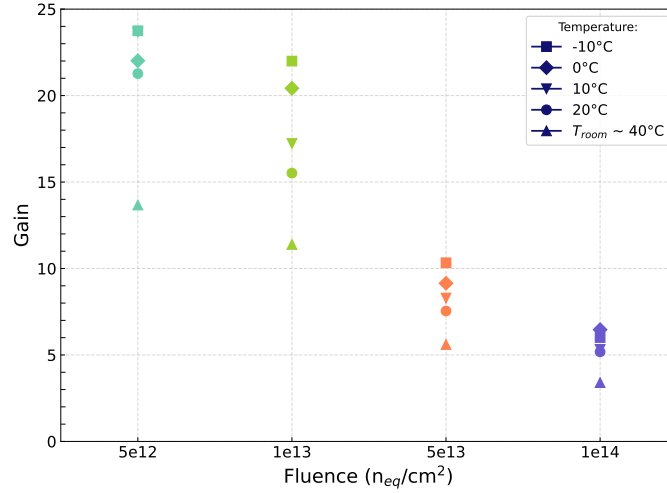


Fig. 6.36 Gain measured as a function of the different fluences operating at different temperatures. The backside electrode was biased at -25 V while the guard ring at 9 V.

The increase in gain at lower temperatures has a beneficial effect on the temporal resolution. Since a higher gain produces signals with larger amplitude, it improves the signal-to-noise ratio and reduces the jitter contribution.

In conclusion, the combined effects of reduced phonon scattering, longer carrier mean free path, and enhanced impact ionization at lower temperatures lead to an overall improvement in the timing performance of the detector. This trend, consistent with expectations, is confirmed by the results shown in Figure 6.37, where the best σ_t values as a function of temperature for different irradiation fluences are reported. A consistent improvement in resolution is observed across all fluences as the temperature decreases.

Figure 6.37 shows the expected degradation of the time resolution with increasing irradiation, as previously illustrated in Figure 6.35 at room temperature. However, the effect of the fluence on the time resolution is more pronounced at higher temperatures, where the increased phonon scattering further reduces the mean free path and gain. For each irradiation dose, the operating voltage was selected to achieve the best possible σ_t , which is typically found around 1–2 V below the breakdown voltage. This strategy guarantees that the reported results represent the optimal timing performance under the experimental conditions described before.

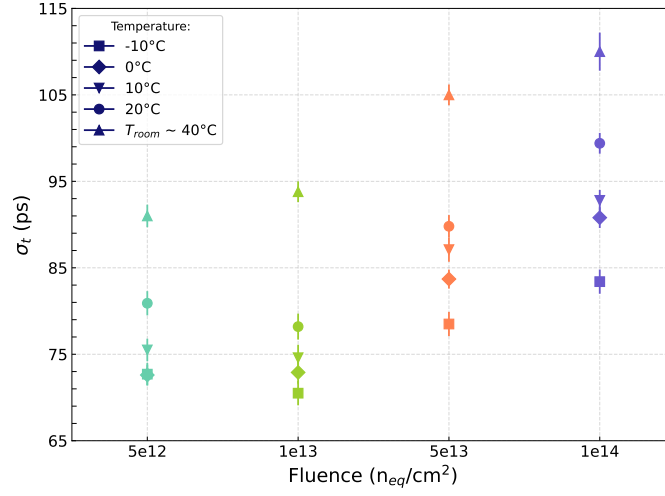


Fig. 6.37 Time resolution σ_t as a function of different fluences for different temperature conditions. The backside electrode was biased at -25 V while the guard ring at 9 V.

In Figure 6.37, the temperature-controlled time resolutions of the irradiated sensor at $1 \cdot 10^{13} n_{eq}/cm^2$ appear to be lower than those of the sensor irradiated at $5 \cdot 10^{12} n_{eq}/cm^2$. However, this is only an apparent effect: a point-by-point comparison shows that the values are always compatible within the associated uncertainties.

In conclusion, no significant degradation of σ_t was observed for low fluences. Conversely, for irradiation doses above $1 \cdot 10^{13} n_{eq}/cm^2$, the timing performance deteriorates. The full characterization of the CMOS-LGAD sensors studied so far demonstrated the robustness of the detector under moderate irradiation levels. In particular, the time resolution measured in correspondence of the maximum fluence foreseen in the ALICE 3 TOF ($1 \cdot 10^{13} n_{eq}/cm^2$) shows a moderate degradation compared to the pre-irradiated case. The measurements performed at different temperatures show that this worsening can be mitigated by cooling the system, partially compensating for the radiation-induced loss of performance.

Chapter 7

Conclusions and outlooks

This thesis focuses on the design and full characterization of an innovative monolithic silicon sensor with internal gain for precise timing applications. The designed sensor is intended for the Time-of-Flight (TOF) detector of the future heavy-ion experiment proposed for the LHC Run 5, namely the ALICE 3 experiment. The main feature of the ALICE 3 TOF detector is its excellent time resolution of 20 ps.

After reviewing the physics motivations and the detector constraints, different candidate technologies were discussed: Low-Gain Avalanche Diodes, Fully Depleted Monolithic Active Pixel Sensor, and Single Photon Avalanche Diodes. The monolithic solution is the most attractive one in terms of well-established technology and cost-effectiveness, but at the same time, it requires an intensive R&D to meet the excellent time resolution required for the ALICE 3 TOF detector. Inspired by recent projects demonstrating the feasibility of achieving sub-100 picosecond timing with a monolithic approach, CMOS-based avalanche detectors, combining full depletion and an internal gain, were identified as the baseline for the *R&D* of the ALICE 3 TOF detector. CMOS-LGAD sensors may potentially offer competitive technology for excellent timing performance while enabling the development of a large-area demonstrator and reducing the system complexity. To this aim, a novel CMOS sensor architecture was developed, combining the LGAD concept with the advantages of monolithic devices. The starting technology is that of the ARCADIA Collaboration, which was further modified to achieve optimal timing resolution using a customized commercial LFoundry 110 nm CMOS process. The thesis focuses on the design, simulation, and full characterization of the first CMOS-LGAD prototypes based on this approach.

A solid and fully functional simulation chain, combining TCAD simulations and Monte Carlo studies, was developed to support the sensor design and optimization. In particular, TCAD simulations were employed to design and model sensor geometry and to study the electric field configuration, without requiring the fabrication and testing of a physical prototype. TCAD has the aim to describe the motion of electrical carriers and the generation of the electromagnetic field resulting from this motion. In addition, other phenomena that happen at the device level, such as charge carrier transport, the dopant concentration and temperature dependence, and the charge multiplication mechanism, are taken into account. Successively, the TCAD field maps are imported into the Allpix² Monte Carlo framework to model signal formation as realistically as possible and on a much faster timescale, while simultaneously incorporating stochastic phenomena. Monte Carlo simulations were finally used to evaluate the gain and the intrinsic timing resolution of the sensors. The combined use of these tools guided the sensor design and the interpretation of the experimental results. Moreover, optimization studies of the simulation parameters were essential not only to accurately capture the intrinsic device physics and ensure reliable results, but also because the tuned parameters offer valuable guidance for future productions, enabling predictive reliability in subsequent device generations.

The results obtained from the first engineering run demonstrated the feasibility of the proposed sensor concept. Electrical and dynamic characterizations of passive structures provided direct evidence of the internal gain and allowed the identification of implantation parameters that influence performance. Concerning the effect of the production parameters on the sensor performance, the device produced in run 3 showed a lower gain (approximately 2.5) compared to the one expected, which was in the range 10-25. Despite this inconvenience, the feasibility of implementing the LGAD concept in the 110 nm technology developed by LFoundry was successfully demonstrated, and the proper functioning of the produced devices was verified.

The first prototype of a Monolithic CMOS Avalanche Detector PIXelated (MADPix), featuring an internal gain and integrated readout electronics, was fabricated and successfully tested, both in the laboratory and with particle beams, to estimate its time resolution. In addition, the Focused Ion Beam (FIB) technique proved to be a valuable process to locally modify the sensor structures and, in particular, to access floating guard ring structures and to connect them to dedicated pads. This operation allowed reducing the substrate current and higher voltages. After optimizing the

sensor working points and performing the FIB technique, a first and encouraging time resolution of about 100 ps was achieved with the first production run.

A second short-loop run, also called run 3.2, allowed a refinement of the technology by increasing the internal gain, while the design and architecture of the chips remained unchanged. As for the previous production, both simulations and characterization were crucial to shape the device design and to fully characterize the sensors. Monte Carlo simulations with tuned doping profiles gave an accurate description of charge collection, gain, and timing performances. The characterization of this production batch was carried out by performing electrical measurements on both passive and monolithic devices. These measurements confirmed the gain values expected from the simulation, thus validating the fabrication process. Additional measurements with particle beams allowed a detailed evaluation of the time resolution of the run 3.2 devices, which is about 80 ps. Moreover, an irradiation campaign was performed to highlight the impact of radiation-induced defects on gain and timing performance. Although the loss of gain and the worsening of the time resolution for irradiated sensors are evident and increase for higher irradiation levels, it has been shown that temperature is a crucial factor in limiting damage. By cooling the system, thus partially compensating for the radiation-induced loss of performance, a good timing capability is still reachable at the maximum fluence foreseen in ALICE 3, which is $1 \cdot 10^{13} \text{ n}_{eq}/\text{cm}^2$.

In summary, the results presented in this thesis demonstrate that monolithic CMOS-LGAD detectors are a viable and competitive solution for future fast timing applications. Although further technological optimization is required, the achieved performance, together with the consistency between simulations and measurements, supports the suitability of this approach for the ALICE 3 Time-of-Flight system and for other experiments requiring precise time measurements.

The work presented in this thesis still leaves an open question on how the target time resolution of 20 ps for the ALICE 3 TOF detector can be achieved. Further technological optimizations are required, and in particular, the use of thinner substrates is expected to reduce the charge collection time while increasing the signal rise time, thus limiting the Landau noise term. In Figure 7.1, the time resolution of

a CMOS-LGAD sensor with 15 μm thickness is shown. These preliminary results highlight the benefit of reducing substrate thickness, achieving a time resolution slightly above 20 ps.

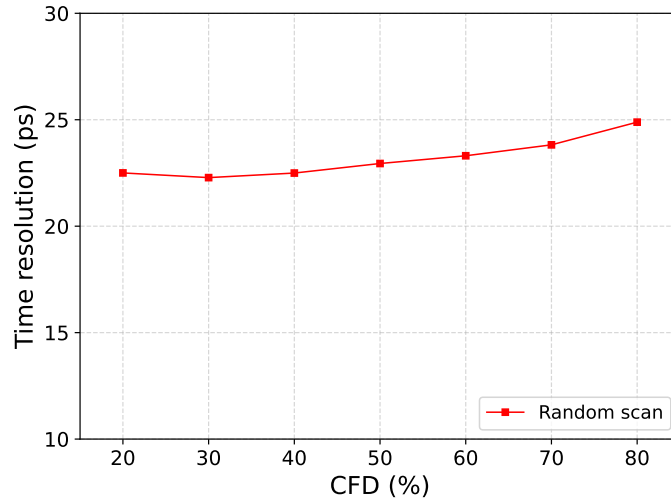


Fig. 7.1 Simulated time resolution as a function of the applied CFD threshold on a 15 μm -thick CMOS-LGAD sensor. MIPs impinged randomly on the sensor surface using a square source with a side length of 100 μm and centered on the pixel.

The choice of using sensors with a thickness of 50 μm was driven by the availability of wafers from the ARCADIA chip production. This strategic choice had the aim to demonstrate the feasibility of the proposed innovative sensor technology and to validate the sensor concept while keeping the cost under control. Recently, a new short-loop run has been submitted using thinner substrates, with the aim of achieving an improved timing performance.

Using thin sensors will not be sufficient to achieve the desired σ_t , therefore the design of a new pixel layout is crucial to reach a more uniform electric field across the device. To mitigate the distortion term and reduce position-dependent effects related to where the particle crosses the sensor, a new engineering run is necessary. Advanced TCAD studies concerning the effect of the electrode dimensions to produce smooth weighting fields are now ongoing.

The next generation of monolithic prototypes will benefit from improved readout architectures optimized for low jitter and reduced noise, as well as from larger and thinner sensors in order to finally achieve the ALICE 3 requirement. This innovative sensor is a promising solution in High Energy Physics fields, but it will also pave the way for new applications where an excellent time resolution is required.

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