

SIGNAL FORMATION AND ACTIVE EDGE STUDIES OF 3D SILICON DETECTOR TECHNOLOGY

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To my wonderful parents & my godfather, Richard

Abstract

3D detectors and devices with an ‘active edge’ were fabricated at the Stanford Nanofabrication Facility. Characteristics such as time response and edge sensitivity were studied. The induced signals from a 3D detector were studied using a fast, low-noise transimpedance amplifier. The rise time of the output signal obtained for a minimum ionising particle was faster than 4 ns at room temperature and 2 ns at 130 K. This is in agreement with earlier calculations of 3D detectors that predicted the charge collection time to be between one to two ns. The first understanding of signal formation in a 3D detector was achieved by comparing measurements with a full system simulation. The differences in collection behaviour between electrons and holes were also understood and verified by measurement. Edge sensitivity was measured at the CERN SPS, using a high energy muon beam and a silicon telescope. The detector was measured to be efficient up to less than $4\mu\text{m}$ from its physical edge. This confirmed that active edge technology can be used in the proton detectors for the TOTEM experiment, which requires the detectors to have a dead region of less than $50\mu\text{m}$. Results in this thesis also confirm the suitability of this design for possible future upgrades of the Large Hadron Collider, where the integrated fluence is expected to increase by a factor of 10.

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Chapter 1

Introduction

Near-term and future experiments in high energy physics and molecular biology will require radiation hard and fast detectors without insensitive border regions (edgeless) to cope with increasingly stringent research requirements. The unique geometry of 3-D detectors, schematically sketched in Figure 1.1, covers many of these requirements and presents several advantages over conventional planar silicon detectors.

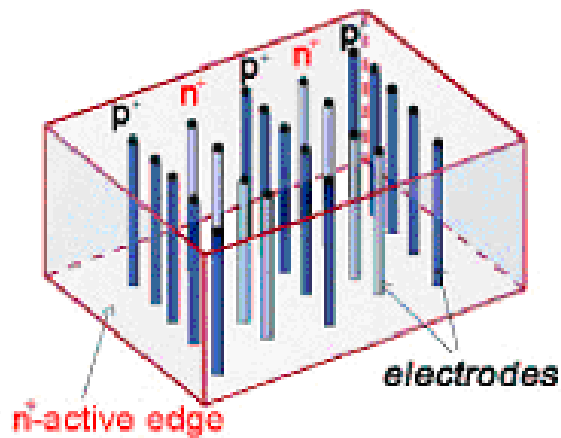


Figure 1.1: Structure of a 3D detector with electrodes penetrating through the entire substrate with a surrounding n+ electrode, allowing edgeless capability.

In particular, radiation hardness and fast time response have become increasingly important for possible future upgrades of the Large Hadron Collider (LHC) at CERN [1]. A luminosity upgrade (SLHC) of a factor 10, foreseen after 2012, is meant to improve the accuracy of the Standard Model and the new parameters, which are predicted to be discovered at the initial phase of the LHC experiments. The necessary increased statistics will be obtained not only by increasing the luminosity but also by reducing the bunch crossing to possibly half of the current one. In this new scenario, the radiation levels will increase by a factor of 10, exposing the innermost layers of the tracker to an integrated fluence equivalent of 10^{16} 1 MeV neutrons/cm² in 10 years of operation. Besides the SLHC, there is also motivation for further studies on topics such as supersymmetry and measurements that may be unravelled by the LHC. These studies and measurements necessitate e^+e^- colliders of energy up to at least 3 TeV, such as the CERN Linear Collider (CLIC) [2], where the corresponding bunch crossing might subsequently be reduced to 1.2 ns. The full pulse width of a typical signal induced from a conventional 300 μ m thick planar silicon device from a minimum ionising particle is typically 25 ns. New technology must therefore be developed. In molecular biology, protein crystallography is used to identify protein structure using X-ray diffraction at synchrotron light sources. The X-ray diffraction pattern produced by low energy X-rays (13 keV), scattered by the protein crystal is recorded by a high spatial resolution detector. Phosphor screens with fibre optic demagnification to CCD sensors have been successfully used for this type of research, but alternatives are required to improve time, sensitivity, linearity and large area coverage at a limited cost. Standard planar silicon detectors have been considered, but they suffer from intrinsic limitations for this application. One limitation is the typical dead border surrounding the sensor's active area of about 100 mm² (which might increase to 500-1000 mm² in some cases). This insensitive area is required because of the need for guard rings to control the surface leakage current by keeping the electric field uniform and intercepting the current before the first signal electrode [31]. This dead area leaves behind important information of the diffraction pattern. In a 3D detector, where electrodes penetrate through the entire bulk, the edge is normally made into an electrode. Moreover, as the inter-electrode distance is normally much smaller than the bulk thickness, the maximum collection path and depletion voltage can be made much smaller for a comparable signal to noise ratio to that achieved of a planar detector [3] [4].

3D detectors have advantages that fulfil the requirements for these future applications. It

is therefore important to study their advantages and to understand their characteristics in detail if 3D detectors are to be considered as potential candidates. Some preliminary results of tested 3D detectors can be found in earlier publications [3] [4] [5] [6]. In this thesis, the emphasis is on studying the signal formation and edgeless capability. The signal formation study was made by using a high speed transimpedance amplifier [7]. With this amplifier, the fast charge collection time was verified. It also allowed observations of the induced signal shape from a 3D detector. The results will be described in Chapter 3. The measurement alone was insufficient to give a full understanding of the system. In particular the output signal shape was dominated by the amplifier shaping time. Simulation provided a theoretical model that can give a better understanding of the detector and the full system and by a comparison of the measured and simulated results. The understanding derived from the theoretical model was verified. This will be discussed in Chapter 4. The edgeless capability of a 3D detector was studied using a high energy muon beam at CERN SPS. The beam track position was predicted by a silicon telescope [70]. All details are described in Chapter 5. This test was dedicated for the TOTEM experiment, in which the silicon detectors are required to have a dead region of less than $50\text{ }\mu\text{m}$. The TOTEM experiment will be discussed in Section 1.3.1. In addition, the precise prediction of the beam track by the silicon telescope allowed the measurement of the detector efficiency and how this behaves at both the n- and p-electrodes in a 3D device.

This chapter describe the motivation for this thesis by giving a brief discussion of existing technology and 3D detectors. The three advantages of 3D detectors and their foreseen applications will be given in further detail. Chapter 2 will give a brief description of semiconductor detectors which is important background theory required to understand the work in this thesis. In Chapters 3, 4 and 5, the measurement methods, the simulation model and active edge measurement and results are described. The key results from the test will then be summarised in the final chapter.

1.1 A Historic Review of Semiconductor Detectors

Solids can be used as the material for radiation detectors. Their radiation detection mechanism is similar to that in gaseous detectors. Gaseous detectors are limited by the spreading of liberated electron clouds. Solids have a larger stopping power and

therefore have some advantages over gaseous detectors such as being smaller in size and potentially higher spatial resolution [11].

The very first useable semiconductor nuclear detector was made in Utrecht, around 1943 in the form of an AgCl crystal [10]. Since then, silicon has been one of the most popular materials because its band gap of 1.1 eV; low enough to create a large number of charge carriers, liberated for a given incident radiation event, but at the same time high enough to avoid large dark current. In the 1980s, the planar process for manufacturing silicon integrated circuits was developed to a fine art [13], leading to further development of silicon detectors in a vast range of scientific experiments with potentially the most important applications in medical imaging. These applications include cancer diagnosis, identification of new viruses and protein structures [13], which result in more efficient and effective treatments and examinations. In high energy physics, silicon detectors have been used to discover some of the smallest and shortest-lived particles. These discoveries give a better understanding of what the constituents of this universe are and how they are structured.

In order to identify particles with lifetimes in the order of 10^{-13} s, the very first position-sensitive silicon detector was developed [8]. The standard planar process was first used to fabricate silicon microstrip detector in 1980 and they were used in the NA11 and NA32 experiments at CERN [12].

There were then motivations to develop two-dimensional readout, and this began in 1982 when C. Damerell et al at Rutherford Laboratory used Charge Coupled Devices (CCD) to develop the first CCD detector [14], that had a spatial resolution of 4.3-6.1 μm and an efficiency of 98%.

The development of Very Large Scale Integration (VLSI) around 1985 allowed the integration of silicon detectors with the readout electronics. This compact design allowed silicon detectors to be used as vertex detectors in collider experiments. The first silicon microstrip detectors with VLSI electronics were installed at Mark II at SLAC and also at LEP, CERN. They will also be used in several inner trackers for experiments at the LHC that will be operational in 2007.

The first silicon pixel detectors for high energy physics were built from CCD chips. Two new technologies are; monolithic active pixel sensors and hybrid active pixel sensors. Pixel devices can survive in extreme radiation levels due to their thin active layer and

lower operating voltages [17].

Monolithic Active Pixel Detectors have readout circuitry integrated with the detector on the same silicon substrate [18]. They operate by recording the amount of ionisation charge freed by the interaction radiation in a reverse biased p-i-n diode. The first prototype monolithic pixel detector was fabricated in 1988 by W. Snoeys et al. and is described in ref. [19]. Monolithic pixel detectors have found wide application in high rate imaging sensors for biological and medical imaging [20].

Another type of pixel detector is the hybrid active pixel sensor, where the detector and the readout chips are separated. Each pixel is bump bonded to a readout channel. The limitation in this design is often the size of the readout circuit. This type of detector is again widely used in medical imaging with MEDIPIX [22] being one of the current leading research and development projects. Hybrid active pixel sensors have been successfully used in tracking detectors and imaging devices in radiography, autoradiography, protein crystallography and in X-ray astronomy. Pixel detector technology is also starting to be transferred to be more commercial uses in order to increase the potential of off-the-shelf availability. Recent trends are described in [23] and a review of all recent designs is given in [24]. 3D detectors are amongst one of these recent trends, that give potential for faster readout rate, higher radiation tolerance and a more compact design due to its edgeless capability.

1.2 Advantages of 3D Detectors

3D detectors were proposed by S.I. Parker and C.J. Kenney in 1994 [3]. Fabrication of 3D detectors was made possible on high-resistivity silicon through the combined use of VLSI and micro-machining technologies. Methods to fabricate narrow electrodes that penetrate through the silicon wafer have been developed and tested [4]. Narrow holes and trenches are etched through silicon wafers and then back filled with conductive polysilicon (n and p doped).

The geometry of 3D detectors decouples the charge depletion from the electric field that collects the charge. The electrode spacing can be made to be as short as $50\text{ }\mu\text{m}$. This allows a short depletion distance and fast charge collection. These two properties make 3D detectors both fast and highly radiation tolerant. In addition, the new etching

technology allows 3D detectors to be edgeless with no dead region. The technology also gave rise to a new design - planar-3D detector, this is a planar silicon detector with a 3D electrode around its entire perimeter, illustrated in Figure 1.2.

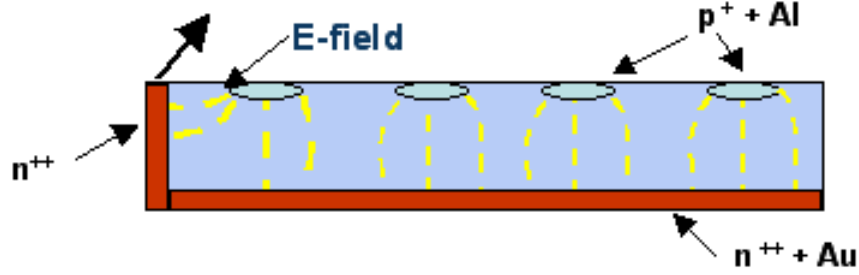


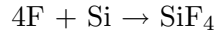
Figure 1.2: A planar silicon detector with a 3D edge electrode all around. The edge is etched and doped with n+dopant.

The advantages of 3D detectors are therefore; fast charge collection, radiation hardness and active edges. These will be explained and discussed briefly in this Section but further details can be found in earlier publications [3] [4] [26] [6] [5] [27].

1.2.1 Fabrication

3D detectors were processed at the Stanford Nanofabrication Facility (SNF) [29]. The processing is briefly described in this section. A detailed description can be found in ref. [4] and [30]. Recent technologies in silicon fabrication made the manufacture of 3D detectors possible, with the most critical steps being the etching of the holes and the processing of the electrodes.

Etching of such fine holes is a great challenge but has been made possible using an inductively coupled plasma etching machine, which became commercially available in 1997 [35] and was manufactured by Surface Technology Systems [28]. The machine has an etch rate of 1-5 $\mu\text{m}/\text{minute}$. During the etching process, the etchant species in the gas phase is first generated by dissociation of SF_6 by collision with plasma electrons. The etchant species (F^-) then diffuse and are absorbed into the surface of the silicon wafer and the following reaction occurs;



In order to ensure conformity of the etched hole from top to bottom, the etching process is alternated with a passivation process using C_4F_8 (perfluorocyclobutane) every few seconds. The C_4F_8 then forms a TeflonTM coating on all surfaces including the holes, preventing any unreacted fluorine ion from etching the side walls. The fabrication process of etching and coating alternates every few seconds until the hole is fully etched to the bottom of the wafer. Figure 1.3 shows a profile from scanning electron microscope (SEM) of a $14\text{ }\mu\text{m}$ diameter holes etched to a depth of $525\text{ }\mu\text{m}$ [4], with an aspect ratio of 15:1.

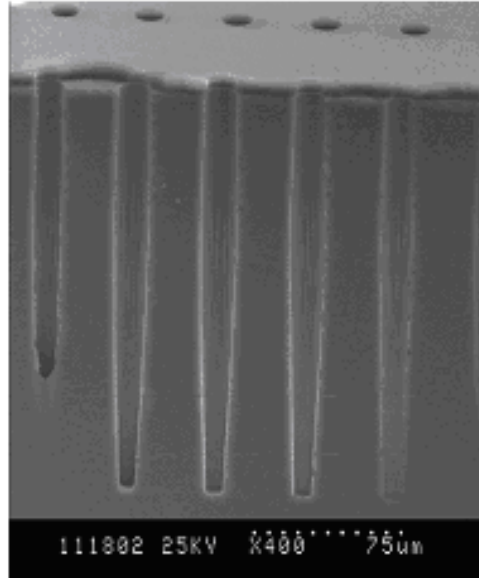


Figure 1.3: SEM profile of $14\text{ }\mu\text{m}$ diameter etched holes of an aspect ratio of 15:1. [4]

When the holes are etched, the electrodes are made by filling the holes with polysilicon that is doped to form the n- or p- electrode. Several microns of polysilicon are first deposited into the hole, which is then doped via diffusion by the addition of dopant gases such as phosphine P_2O_5 and diborane B_2O_5 . This process continues until the etched

hole is fully filled and doped. Once the n- and p- electrodes are formed, annealing drives in the dopants into the single crystal in the bulk of the detector. The dopant makes the polysilicon and the silicon around it into a highly conductive electrode, forming the main structures of 3D detectors. The interconnections are formed by metal deposition connecting the electrodes. The pattern of the the metal deposition is determined by the chosen readout method. So far both strip and pixel detectors have been fabricated, but the detectors evaluated in this thesis are strip detectors. A 3D detector in a strip arrangement is shown in Figure 1.4. The arrangement is formed by joining like-type electrodes by aluminium strips.

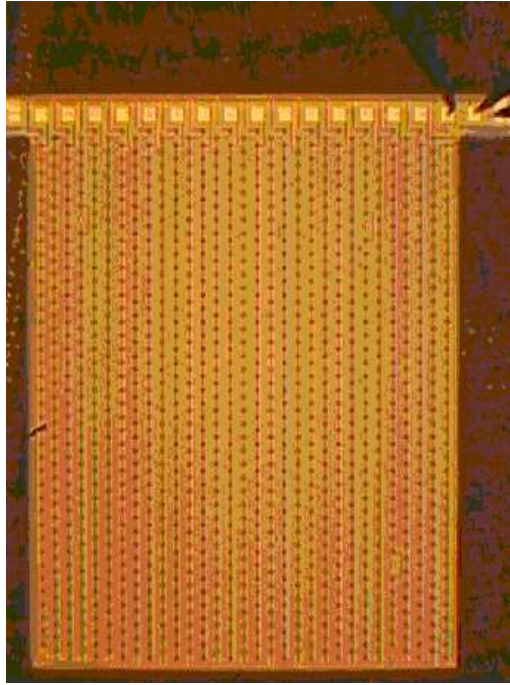


Figure 1.4: A 3D detector. The p+ electrodes are connected using 16 aluminium strips to make a 3D strip detector, giving a $200\,\mu\text{m}$ pitch.

1.2.2 Fast Charge Collection

In 3D detectors, the inter-electrode distance can be smaller than the wafer thickness resulting in shorter average collection lengths. By the Shockley-Ramo Theorem, [56] the signal current from the detector arises because of the motion of charge carriers after

they are formed by incident radiation. An ionising particle generates charge carriers along its path as it traverses the silicon bulk. In a planar detector, each charge along the ionisation path is at a different distance from the collecting electrode, and for each charge, the signal has a different time structure. In contrary, the ionisation path in a 3D detector is parallel to the collecting electrodes, as shown in Figure 1.5.

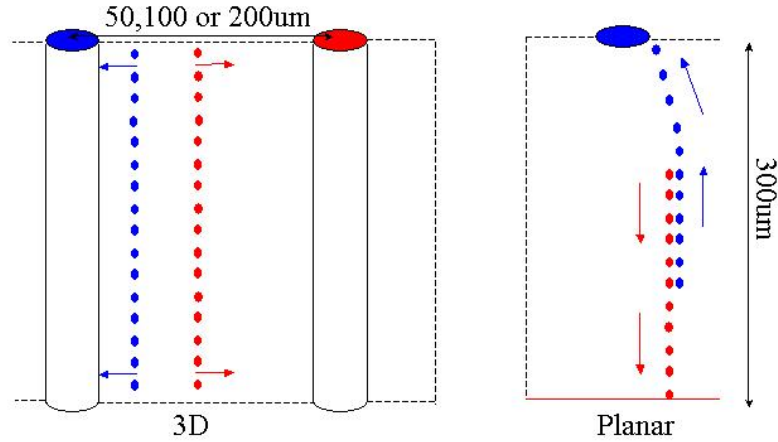


Figure 1.5: Collecting electrodes of 3D detector (left) are almost parallel to the particle track and all charges generated from the track have similar collection times whilst induced signal is spread out in time for a planar device.

All the charges along the path are at almost the same distance from the collecting electrodes. Ignoring the spreading due to diffusion, the arrival of all the charges is simultaneous, inducing a signal with a faster rise time compared to a planar silicon detector. Moreover, the cylindrical shape of 3D detector electrodes forces the electric field lines to terminate on a cylinder rather than a single pad. This results in a higher average field for any given maximum field in the drift path of all charges. As a consequence, the drift velocity increases. These differences allow 3D detectors to be very fast. In addition, another feature, which takes advantage of the innovative 3D design, is the possibility for drift time corrections to improve the accuracy of signal timing by reading

out simultaneously from both n+ and p+ electrodes, since both types of electrodes can be accessed from the top surface of the detector. This will further improve the timing accuracy.

Initial calculations were performed to study the effects of induced charges from a minimum ionising particle in 3D detectors [3] with a $50\text{ }\mu\text{m}$ pitch. These simulations showed a signal peaking time of 0.5 ns with a return to baseline at 1.5 ns . This is over a factor of 10 faster than a signal obtained from a planar silicon detector with 2D electrodes, which takes about 25 ns to return to the baseline, neglecting any amplifier delays [57]. The comparison of the calculated induced signals from the two detectors is given in Figure 1.6.

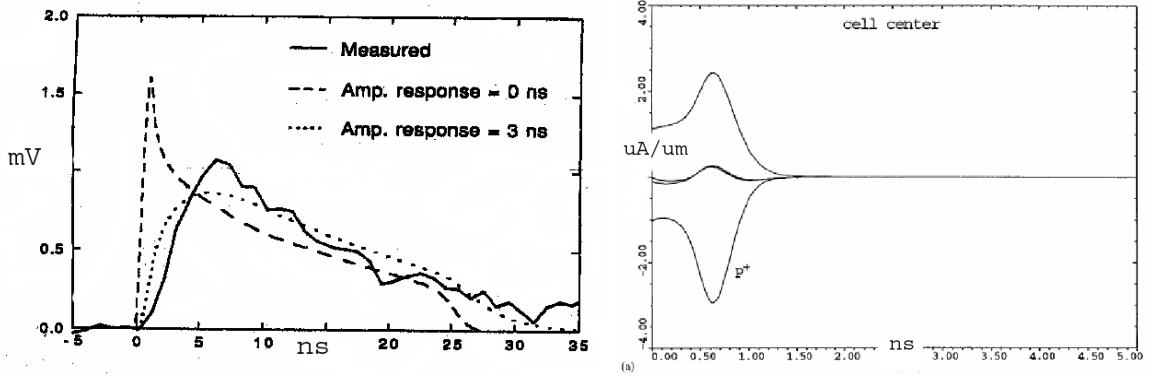


Figure 1.6: Left: Signals induced from a planar silicon detector (extracted from [57]) both from simulation and measurement have a return to baseline of 25 ns more than 10 times of the charge collection time calculated for a 3D detector shown on the right (extracted from [3]).

1.2.3 Radiation Hardness

The radiation hardness of planar silicon detectors remains a challenge if the LHC is to be upgraded. New silicon detectors are yet to be developed in order to meet this extreme radiation environment. Defects are formed in the silicon lattice due to radiation damage [32]. As a result, several macroscopic effects occur. In [59], it is shown by calculation that after irradiation with a fluence of 10^{15} n/cm^2 , the effective drift lengths of electrons and holes become $150\text{ }\mu\text{m}$ and $50\text{ }\mu\text{m}$ respectively at -20°C . This is shown in Figure 1.7. Both are significantly short when compared to the electrode distance of a conventional

planar silicon detector that is $300\,\mu\text{m}$ thick. The charge collection efficiency is reduced tremendously. Several different approaches have been studied to provide a solution to fulfil the future requirements [59]. The inter-electrode spacing of a 3D detector can at present be made to be as short as $50\,\mu\text{m}$. This is comparable to the reduced calculated effective drift lengths, but at the same time the wafer thickness remains as 250 to $300\,\mu\text{m}$ to maintain a good signal-to-noise ratio, making a 3D detector radiation hard. Moreover, as compared to a planar detector, the voltage required to maintain full depletion remains lower because of the shorter inter-electrode distance. Some 3D detectors were irradiated with a fluence that is equivalent to the lattice damage expected after 10 years of operation at the innermost B layer of the ATLAS detector (1×10^{15} 55 MeV protons/cm²) [4]. Performance studies were made and the depletion voltage was found to be around 105 V for a detector with a cell size of $(100 \times 134)\,\mu\text{m}^2$. This is at least a factor of 7 lower than that of a $300\,\mu\text{m}$ thick planar oxygenated [32] detector irradiated with the same fluence. This property of 3D detectors make them very attractive to be the detectors for many future particle colliders where the fluences are predicted to be far higher than the LHC.

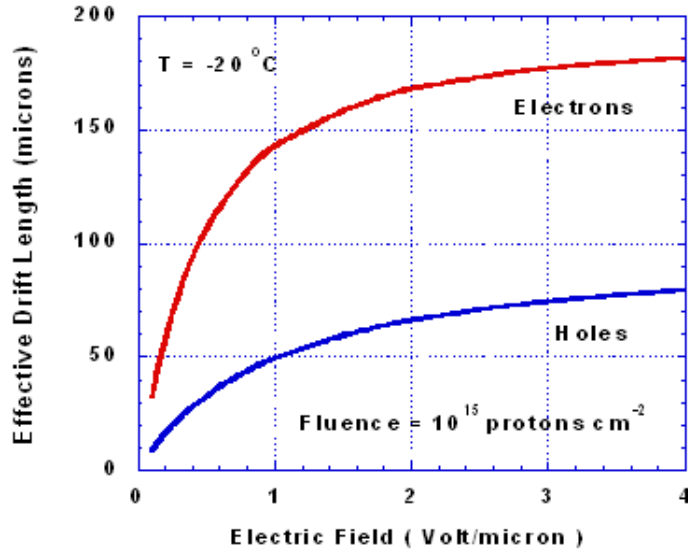


Figure 1.7: Effective drift lengths were calculated for both electrons and holes after being irradiated with a fluence of 10^{15} protons/cm² at -20°C [59].

1.2.4 Active Edge

Conventional silicon detectors are separated from the wafer by dicing. Sawcuts around the edge result and these leave behind many dangling bonds at the detector's physical edge, increasing the detector's leakage current as well as creating an uneven electric field close to the edge. Guard rings are required to sink this large leakage current and to maintain a more uniform electric field distribution. The guard rings usually cover a dead region from about $100\text{ }\mu\text{m}$ to 1 mm .

3D active edge and planar-3D detectors were proposed by C. Kenney in 1997. An active edge detector is surrounded by n+ or p+ implant (depending on the bulk type and electrode) acting as an electrode and extending the electric field right to its physical edge. As shown on the left of Figure 1.8, a trench is etched around the detector, it is then doped and filled with polysilicon. This terminates the electric field all around the detector physical edge. After the detector processing is completed, the material surrounding the detector is etched away and no sawing is needed. The elimination of guardring was made possible by extending the electric field right up to its physical edge and by replacing sawcut with etching when separating the detectors from the wafer. The right of Figure 1.8 shows a corner of a 3D active edge detector. The doped trench around the detector edge is shown.

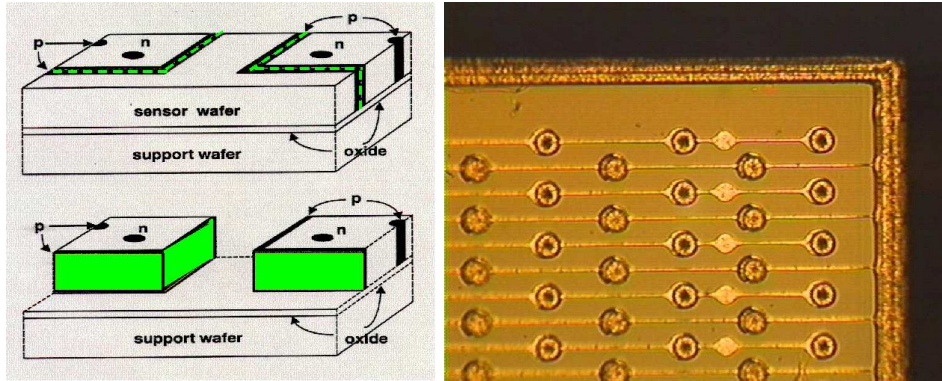


Figure 1.8: Left: This shows the processing of 3D active edge detector. A trench is etched and doped to form an electrode all around the detector. The remaining material is etched away instead of using sawcuts. Right: A corner of a 3D active edge detector, showing the trench electrode all around its physical edge.

Figure 1.9 [27] shows a comparison of the three different detectors: 3D detector, planar-3D and conventional planar detector.

All three detectors have the same thickness but a shorter collection path for electrons and holes is clearly seen in the 3D detector. Figure 1.9 shows the particle track is not seen by the planar detector due to its inactive region caused by the guardrings and both the 3D detector and planar-3D detector solves this problem.

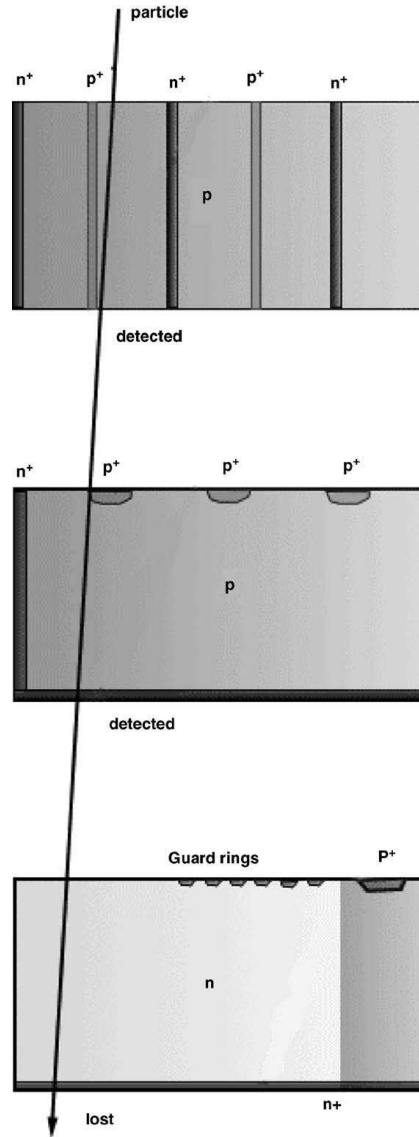


Figure 1.9: Schematics of a 3D detector (top), planar 3D detector (middle), and planar detector (bottom). The scale has been kept the same in each. The detectors are 300 μm thick.

Detailed fabrication steps for the active edge are described in [4] and [26]. In 2003, active edge detectors were successfully fabricated and were tested using an X-ray micro-beam at the Advanced Light Source (ALS) at Lawrence Berkeley Laboratory and the insensitive edge was measured to be less than $5\mu\text{m}$ [66]. Active edge detectors were proposed for the TOTEM experiment and were tested in 2003 with a high energy muon beam and this is described in Chapter 5.

1.3 Future Applications

3D and planar-3D detectors are foreseen to be used in future high energy physics and molecular biology experiments. The work presented in this thesis was carried out closely by collaborating with the CERN microelectronics group and the TOTEM experiment. The foreseen applications discussed here will therefore concentrate mainly on high energy physics experiments at CERN, but a short description of molecular biology will be given at the end of this section.

The Large Hadron Collider (LHC) at CERN, Geneva is scheduled to be operational in 2007 [36]. Figure 1.10 [37] shows the location of the LHC, 27 km in circumference, near the city of Geneva. The LHC creates proton-proton collisions at an energy of 14 TeV. The schematic of the LHC arrangement and its four general purpose detectors: ALICE [39], ATLAS [38], CMS [46], LHCb [40] are shown in Figure 1.11. TOTEM is considered as a sub-detector of CMS and will be discussed in further detail. Each experiment is dedicated to understanding the Standard Models and beyond and their details can be found on the CERN website [36].



Figure 1.10: The Large Hadron Collider with a circumference of 27 km is scheduled to be operational in 2007. This instrument will be running underground, crossing the border between France and Switzerland, in the city of Geneva.

The upgrade towards the so-called Super-LHC will include an increase in luminosity to $10^{35} \text{ cm}^{-2}\text{s}^{-1}$, a factor of 10 larger than the maximum luminosity at the LHC. The bunch crossing may also be reduced to less than 10 ns [1]. A task force was set up at CERN in July 2001 to study the feasibility of the Super-LHC [42]. This upgrade creates two main concerns for detector physicists, one being the increase in radiation level and the other is the reduction in bunch crossing time. This implies that silicon detectors are required to have a higher radiation tolerance and a faster time response if the LHC is to be upgraded. Many radiation hardness issues were studied by the ROSE collaboration [32] and the study is in continuation by many other groups [43]. The unique geometry of 3D detectors allows them to be potential candidates to fulfil these future requirements in high energy physics, mainly because of their radiation hardness and fast charge collection time.

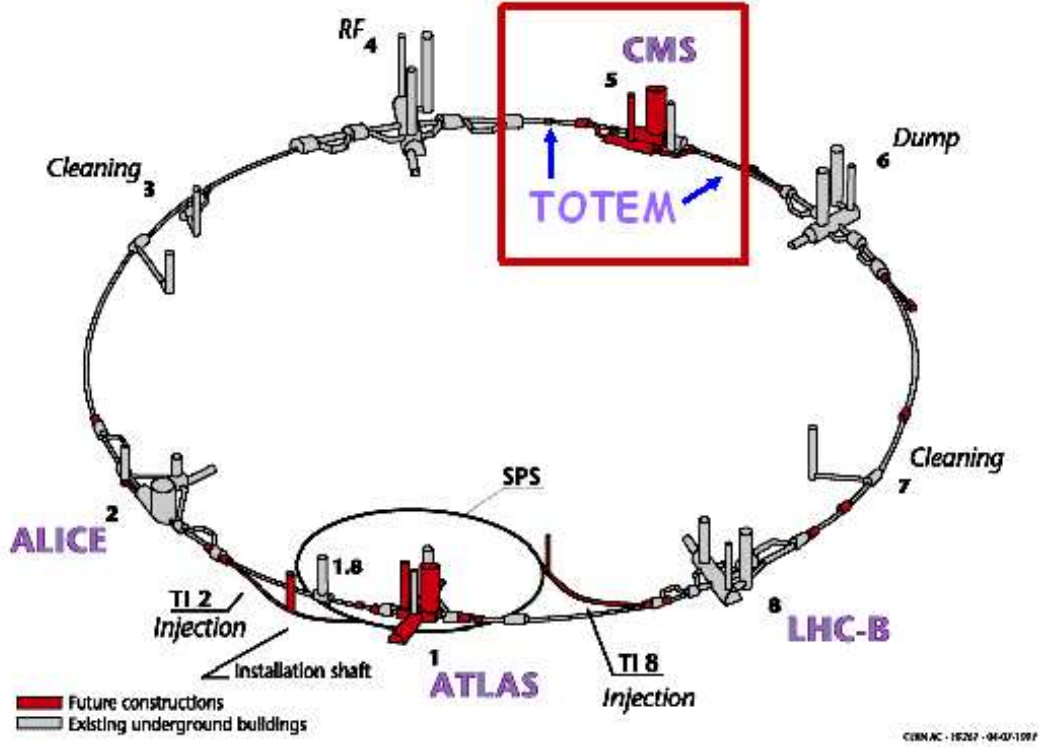


Figure 1.11: The physical ring of the LHC have several general purpose detectors: ALICE, ATLAS, CMS, LHCb and TOTEM. Each is dedicated for their purposes. Extracted from [37]

After the Super-LHC, there is also interest in understanding physics beyond many theories that will be discovered by the LHC. Linear colliders such as CLIC - the CERN Linear Collider, would allow the discovery of physics beyond the Standard Model [41]. It will provide the possibility to make precise measurements of particles detected at the LHC or by other linear e^+e^- colliders of lower energy. The initial planning of CLIC indicates that the bunch crossing could be as low as 1.2 ns, this is far beyond the time response that is provided by current planar technology.

These future experiments provide great challenges to current silicon detector technology; radiation hardness and faster charge collection are two major issues. When building a large experiment, many other issues have to be considered and one must make a compromise by considering the performance, cost and manufacturing feasibility. The characteristics of all potential detector candidates should therefore be studied in detail.

Besides being potential candidates for the Super-LHC and CLIC, the unique property of 3D detectors its sensitive area right up to their physical edge, which is desirable for the TOTEM experiment and molecular biology applications. These applications are discussed in the following sections.

1.3.1 TOTEM

TOTEM was proposed in 1997 as an experiment at the LHC to measure the total proton-proton cross section and to study elastic scattering and diffractive dissociation [44]. A Technical Proposal [45] was prepared in 1999, in which CMS was identified to be the optimal host experiment for TOTEM. A technical design report was submitted in January 2004 and has now been approved by the LHCC Committee.

CMS is a general-purpose detector at the LHC, which is also scheduled to be operational in 2007. The TOTEM experiment will place its detectors in the forward region of CMS, which consists of a strong solenoidal magnetic field that will provide a high momentum resolution for charged particles. A schematic view of the CMS detector is shown in Figure 1.12. The main constituents of the CMS detector are the inner tracker, an electromagnetic calorimeter, a hadron calorimeter and a muon chamber [46].

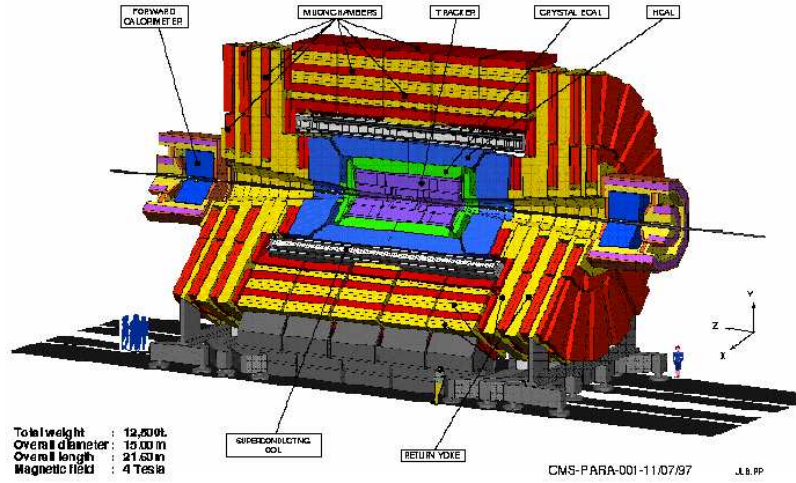


Figure 1.12: A schematic view of the CMS detector [46].

TOTEM will place two forward tracking telescope (T1 and T2) inside the CMS detector and a system of 2 Roman Pot Stations will be situated at 147 m, and 220 m from the CMS interaction point (IP5) [47]. The arrangement is summarised in Figure 1.13.

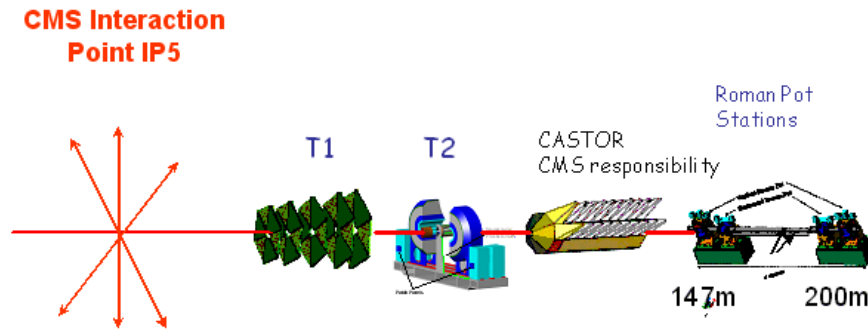


Figure 1.13: This figure shows the arrangement of the TOTEM experiment away from the CMS interaction point. CASTOR is under CMS responsibility. A symmetrical arrangement will be placed on the other side of the interaction point.

Figure 1.13 shows T1 and T2 are close to the interaction point with CASTOR a detector system that is under the responsibility of CMS. A symmetrical arrangement will be placed on the other side of the interaction point, as indicated by Figure 1.14, showing where the two sets of telescopes T1 and T2 are situated inside the CMS tracker.

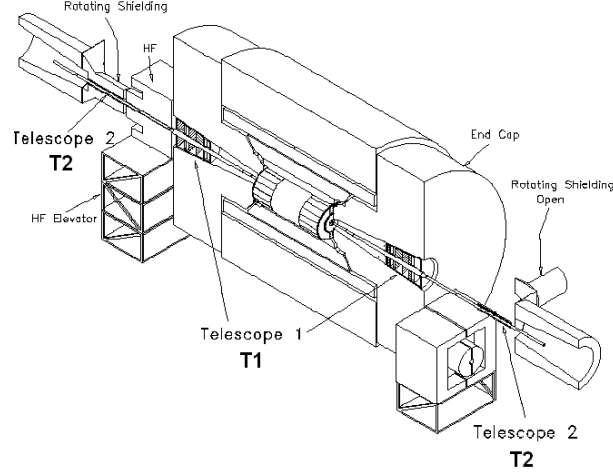


Figure 1.14: Two tracker telescopes T1 and T2 are placed on each side from the CMS interaction point (IP5). They will measure the inelastic interaction rate, that will allow measurement of the total cross-section.

In any colliding beam experiment, the collision rate is an important parameter. The interactions of protons can be elastic or inelastic. In the TOTEM experiment, these are related to the integrated luminosity of the machine by the following equation [48].

$$L\sigma_{tot} = N_{el} + N_{inel} \quad (1.1)$$

σ_{tot} is the total cross sectional area, L is the luminosity, N_{el} and N_{inel} are the numbers of elastic and inelastic interaction rates respectively. Using the optical theorem, this allows one to determine the total cross-section σ_{tot} and the luminosity. As a result of this measurement, the TOTEM experiment will provide an absolute calibration of the machine luminosity. N_{inel} will be measured by the tracking telescopes T1 and T2 and N_{el} will be measured by the Roman Pot stations.

The precise determination of the total cross-section also requires that the TOTEM experiment must measure the elastic proton-proton scattering down to a four-momentum transfer of $-t \approx 10^{-3} \text{ GeV}^2$. This requirement plus the fact that the total cross-section reduces exponentially with the scattering angle means that for an accurate measurement, the detectors in the Roman Pot must reach the 10σ envelope of the beam profile. At the LHC, this 10σ envelope will only be about 1 mm. The Roman Pot system is optimised to measure the scattering angles down to a few μrad in accordance with this requirement. The silicon detectors inside the Roman pots are therefore required to have a good spatial resolution and a dead zone as small as possible. Figure 1.15 shows a sketch of a Roman Pot station and its interior design. On the right of Figure 1.15 the individual pot shows where the silicon detector will be mounted. The size of the detector will be approximately $3 \times 4 \text{ cm}^2$.

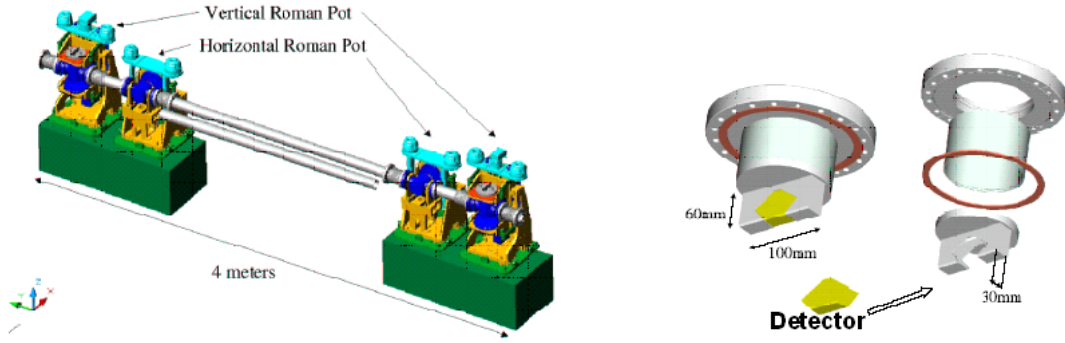


Figure 1.15: Left: A roman pot station. Right: An individual pot inserted showing where the silicon detector will be located.

Both 3D active edge and planar 3D detectors are good candidates as the Roman Pot detectors as they have edgeless capability; the necessity of guardrings is eliminated in this design as explained in Section 1.2.4. In August 2003, 3D active edge detectors were fabricated at the Stanford Nanofabrication Facility and shipped to CERN for the TOTEM test beam. The active edge was measured using a silicon telescope. The test will be described in Chapter 5 and the results will show that 3D active edge detector is sensitive to within $4\mu\text{m}$ from its physical edge. Full size planar-3D detectors together with the first Roman Pot prototype were installed for testing in October 2004 at CERN SPS. The final analysis of this detector is still undergoing.

1.3.2 Macromolecular Biology

Proteins observed in nature have evolved to perform specific functions, which depend upon their three-dimensional structure. The primary structure of a protein's polypeptide chain is an amino acid sequence. These sequences fold to generate structures from simple linear chains to compact domains with specific three-dimensional shape. These include virus particles and muscle fibres. It is desirable to predict the three-dimensional structure from the amino acid sequence in order to understand the biological function of these proteins. Unlike the simple structure of DNA, protein folding is very complex. This is because there are 20 different amino acids that can be combined into many more different proteins than there are atoms in the known universe [50]. The three-dimensional structure must therefore be determined by other methods. X-ray crystallography has been used for this purpose and has contributed in many areas of molecular biology today. These experiments are carried out at synchrotron radiation beamlines with a compatible detector system to measure the X-ray scattering by the protein under study.

Charged Coupled Device detector systems have been the most successful system developed for X-ray scattering experiments. However, they have inherent drawbacks [51] and further improvements can clearly be made. 3D detectors have the potential that could improve the performance of the detector system due to their fast time response and edgeless capability. This would allow a detector system with no dead area except the electrodes. A discussion of performance that can be improved by using 3D detectors in such a system instead of CCDs can be found in ref. [51]. It is a proposal submitted to the National Institute of Health by Dr E. Westbrook - Director of the Molecular Biology Consortium to develop an X-ray detector system using 3D detectors. This high rate, fast read-out system can discriminate individual X-ray photons even at room temperature. The detector will sense individual X-ray photons at counting rates in each pixel between $0-400,000\text{ s}^{-1}$, observing more than 80 % of the incident X-rays with a time resolution of $100\text{ }\mu\text{s}$. The use of 3D detectors allows the required time response and a cheaper solution than CCD modular systems, that are now used at the synchrotron beamlines. [51].

A schematic of the proposed design of the detector system is shown in Figure 1.16. The tilting of the arranged 3D detectors in a so-called 'shingle' system, allows diffracted X-ray photons to enter the surface at 90° , to cover a largest area of the diffraction pattern

possible without any dead regions. The pixels of the detectors will be bump bonded to the readout electronics. Details of the design can be found in [51].

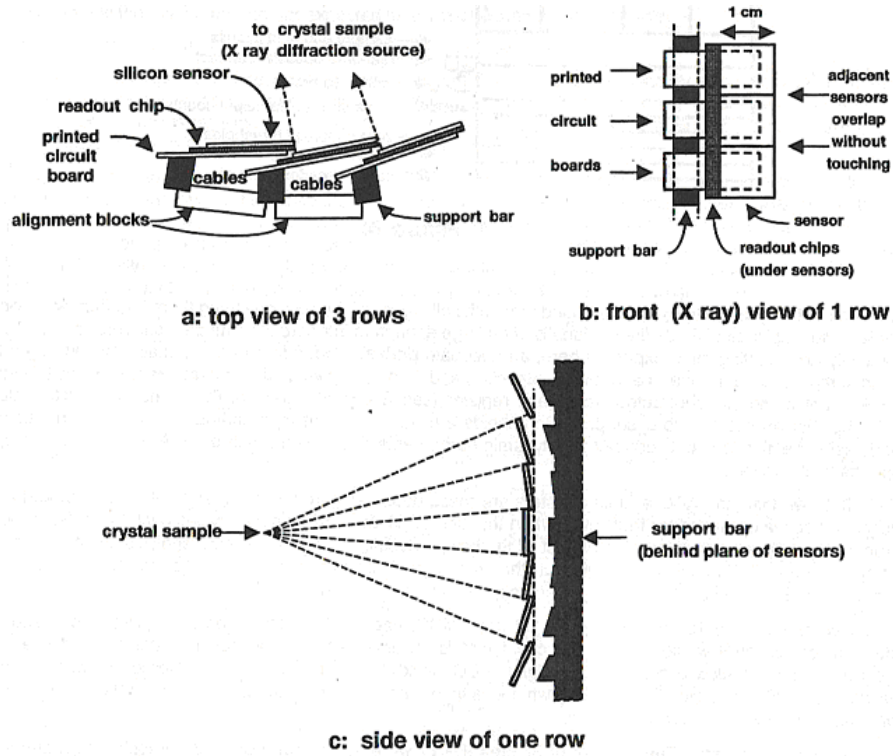


Figure 1.16: Schematic design for full scale protein detector (a) front view, looking in the direction of the X-ray motion (b) front view of the connection of the sensors to the readout chips of one bar (c) side view of one bar and its sensors. Extracted from [51].

1.4 Summary

3D detectors have the potential to fulfil many stringent requirements of future experiments in both high energy physics and molecular biology as well as to improve the performance of current technology. This has generated a keen interest to better understand such detectors, forming the motivation of this thesis to understand the signal formation, time response, edgeless capability and electrode behaviour of 3D detectors. In this chapter, the advantages of 3D detectors over conventional planar silicon detectors

have been explained, which have led to their potential as future detectors for many different experiments. In the next chapter, some basic semiconductor physics and radiation detector systems will be given, which is the background theory required to understand the work that will be described in Chapters 3, 4 and 5.

Chapter 2

Semiconductor Radiation Detectors

The basic principle of any radiation detector is to collect the charge generated by the deposited energy from an incident radiation. In a semiconductor detector, the energy deposited by the radiation particle or photon is converted to an electrical signal. This energy deposition produces mobile charge carriers. They are then swept to the electrodes by the applied electric field, inducing an electrical current [52]. The number of generated electron-hole pairs is proportional to the deposited energy, thus allowing the identification of the absorbed energy by integrating the induced signal. This is very small and an electronic preamplifier is needed in most semiconductor detector systems. The preamplifier is designed carefully in order to minimise the electronic noise and to ensure good stability of the system. In many systems, the preamplifier stage is followed by a pulse shaper to improve the signal-to-noise ratio. A similar system used in the testing of 3D detectors is described in Chapter 3. This consists of a 3D detector and a fast current preamplifier. In this chapter, particle interactions with matter are explained, followed by a description of some basic semiconductor properties and performance characteristics.

2.1 Particle Interactions with Matters

Depending on the radioactive isotopes, radiation particles can have different masses, different charge units and kinetic energy once emitted from their isotopes. Interactions

with matter and thus the energy deposition mechanism are different. In nuclear physics, radiation is generally divided into two major categories; charged particles and particles with no charge. Examples of charged particles are alpha and beta particles. Alpha particles are heavy and ionising. They can be stopped within a short distance. An alpha particle consists of two protons and two neutrons, carrying two positive charge units. It is often not a useful radiation source in detector testing due to its low penetration depth. Beta particles are fast electrons carrying one negative charge unit. Both particles are emitted from decays of radioactive nuclei. These charged particles ionise the absorber when traversing through the material, producing electron-hole pairs along their paths. Minimum ionising particles are charged particles that have minimum energy deposition and all tracking systems in particle physics are designed to detect this minimum energy. Its definition will be explained in the next section. X-rays and gammas are high-frequency photons and have neutral electrical charge and their energy deposition mechanism are therefore different to charged particles.

2.1.1 X-ray Interactions

X-rays are electromagnetic photons emitted by excited atoms and have quantum energies between 1 to 100 keV. X-ray photons do not interact with materials by the Coulomb force since they are neutral and can travel a long distance without any significant interactions. Some can even pass through the material without any interactions but when it does interact it usually loses all its energy in one single interaction. The photon can either be absorbed or scattered and loses its energy by three main processes; photoelectric effect, Compton effect and pair production. [53].

2.1.1.1 Photoelectric Effect

When an X-ray photon has an energy greater than the binding energy of the electron in an atom, an electron is ejected at high velocity. This is called the photoelectric effect. When an X-ray photon interacts by the photoelectric effect, the photon energy is completely absorbed by the absorbing material. The velocity of the ejected electron depends on its kinetic energy and this is the difference between the energy of the individual X-ray photon and the binding energy of the electron to the atom, defined by Eqn.2.1 [53].

$$E_{ke} = E_{\gamma} - E_B \quad (2.1)$$

The photoelectric effect is a complete conversion of the photon energy into the kinetic energy of the ejected electrons. The ejected electron can interact with neighbouring atoms by Coulomb interactions and eject further electrons from their atoms. In a semiconductor detector, the resulting electron-hole pairs drift to the electrodes to give an induced signal at the electrode. As mentioned earlier, the photons can travel a long way in the material without any interaction and the probability for an interaction to occur is related to the cross section, which depends on the photon energy as shown in Figure 2.1. The figure shows that the cross section decreases with increasing photon energy, but a prominent peak is observed when the energy approaches the binding energy of the K-shell and it then drops drastically as the K-electrons are no longer available for the photoelectric effect [53] .

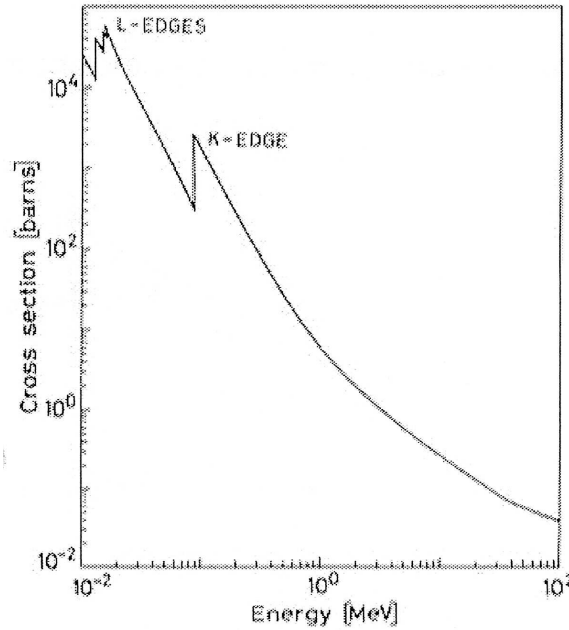


Figure 2.1: The cross section plotted as a function of incident photon energy for photoelectric effect. A peak is observed when the photon energy matches the K-shell and L-shell energy [53]

2.1.1.2 Compton Effect

Compton scattering was first observed by Arthur Compton in 1923 [54]. It occurs when the incident X-ray photon scatters off an atomic electron, transferring some of its energy to the scattered electron. Consequently, the scattered photon has a lower energy than the incident photon. If the incident photon energy is large enough, the electron can be ejected from its atom. Relativistic energy and momentum are conserved in this process and the scattered X-ray photon has less energy and therefore a longer wavelength than the incident photon, this scattering effect is demonstrated in Figure 2.2.

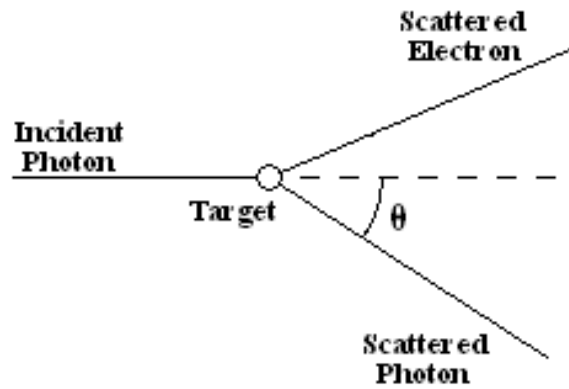


Figure 2.2: Compton scattering process. An incoming photon interacts with a free electron, producing a scattered photon and a recoiled electron.

Using the conservation of linear momentum, conservation of energy, special relativity and basic trigonometry, the Compton scattering equation is given by [54];

$$\Delta\lambda = \frac{h}{m_0c}(1 - \cos\theta) \quad (2.2)$$

m_0 is the electron mass, h/m_0c is known as the ‘Compton wavelength’ and θ is the angle by which the incident photon scatters.

Compton scattering occurs when X-ray (or gamma ray) photons with energies of around 0.5 MeV to 3.5 MeV interact with electrons in a material although this is material dependent.

2.1.1.3 Pair Production

Pair production refers to the creation of an electron and its anti-particle, the positron. This occurs when a high-energy photon interacts in the electromagnetic field of the atomic nucleus so that the energy and momentum are conserved. Due to energy conservation, the photon must have a total energy that is twice the electron mass (i.e. 1.02 MeV) for pair production to occur. If the photon energy exceeds this value, the remaining energy will appear as the kinetic energy of the electron and the positron. A positron is positively charged with a mass of an electron. Once the pair is produced they both travel until all their energy is deposited. The positron will annihilate with a normal electron from the absorbing material at the end of its path. Two photons result from the annihilation each with an energy of 511 keV. These can penetrate a large distance in the absorbing material without any interactions [53].

2.1.2 Minimum Ionising Particles

The energy deposition mechanism of charged particles is different to X-ray photons. The primary interactions of charged particles with the atoms in the absorber materials are due to Coulomb interactions and this causes ionisation in the absorber.

As a charged particle passes near an electron in the material, it transfers a small fraction of its momentum to the electron. As a result, the charged particle slows down slightly, and the electron gains kinetic energy from the charged particle. At a given time, the charged particle interacts with many electrons. The particle slows down continuously and is eventually brought to a halt, producing electron-hole pairs along its path. The distance it traverses is known as the ‘range’ [11]. Many primary ionisation electrons are energetic enough to produce further free charge carriers. The primary electron loses energy through this ionisation process and comes to a stop once it loses all its kinetic energy.

The energy loss of heavy particles (particles heavier than electrons) in matter by inelastic collisions is described by the Bethe-Bloch Formula - Eqn.2.3.

$$\frac{dE}{dx} = -\frac{z^2NZ}{v^2} \cdot \frac{q^4}{4\pi\epsilon_0^2m_0} \left[\ln \frac{2m_0v^2}{I} - \ln \left(1 - \frac{v^2}{c^2}\right) - \frac{v^2}{c^2} \right] \quad (2.3)$$

z is the atomic number of the incident particle, N and Z are the density and the atomic number of the absorbing material respectively. In the second term, q is the electron charge, ϵ_0 is the permittivity of free space and m_0 is the electron rest mass. v is the velocity of the incident particle and I is a constant related to the absorbing material.

Eqn.2.3 shows the energy loss or the stopping power of a particle depends on several factors; the charge and the velocity of the incident particle and the properties of the absorbing materials. There are also other energy losses but they are not critical for heavy charged particles. One example is bremsstrahlung radiation which is not included in this formula. Bremsstrahlung radiation can be significant for electrons and this model is therefore not valid in this case.

Electrons are much lighter than heavy charged particles but they too interact with electrons in the absorber material via the Coulomb force. There are three main differences between electrons and heavy charged particles; electrons can travel further for an equivalent initial energy, they can easily be deflected along this path and can radiate energy known as bremsstrahlung radiation. Bremsstrahlung radiation is an emitted photon due to the interaction of charged particle with the Coulomb field of the absorber material. The total energy loss of electrons is therefore the combined energy loss of collision with the atoms in the absorber and the Bremsstrahlung energy loss, as given by [55];

$$\left(\frac{dE}{dx}\right)_{total} = \left(\frac{dE}{dx}\right)_{bremsstrahlung} + \left(\frac{dE}{dx}\right)_{interactions} \quad (2.4)$$

The Bremsstrahlung energy loss is given by;

$$\left(\frac{dE}{dx}\right) \simeq \frac{ENZ^2}{m^2} \quad (2.5)$$

m is the mass of the incoming particle, N and Z are the density and atomic number of the absorbing material. Bremsstrahlung energy loss is in fact rather insignificant for electron energies below 10 MeV [53]. Besides the difference between electrons and heavy charged particles, the Bethe-Bloch formula also shows differences in energy loss with different charged particles. The characteristics of this formula are that the energy loss rapidly decreases with the incident particle energy and then reaches a minimum when the energy is above several hundred MeV. This is illustrated in Figure 2.3 when the specific energy loss is plotted as a function of particle energy.

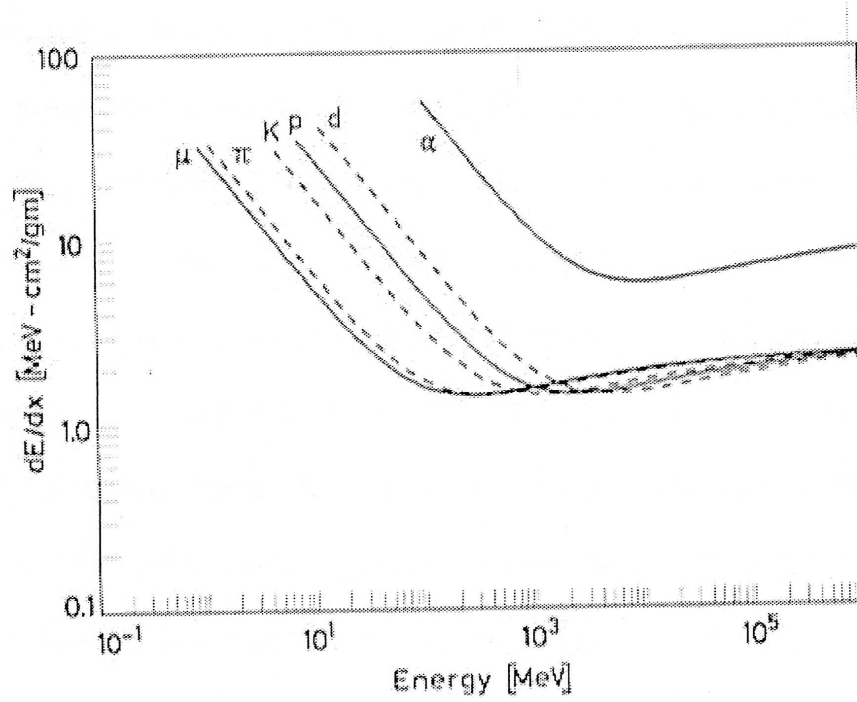


Figure 2.3: The mean energy loss for different particles as a function of energy. The plots show the energy loss reaches a minimum.

The energy loss behaviour is almost identical once the energy of the charged particles are beyond several hundred MeV and the energy loss reaches a minimum for all types of particles. This forms the definition of a minimum ionising particle.

The Bethe-Bloch formula gives the mean total energy loss but fluctuations in energy loss can be very large due to a low number of high energy ionisations. A typical energy loss distribution due to a minimum ionising particle is therefore not symmetrical. Instead it follows a Landau distribution [53], that has a long tail towards the high energy region, which is a result of large fluctuations from the high energy ionisations (δ -rays).

2.2 Basic Semiconductor Properties

Intrinsic semiconductors are materials whose conductivity goes to zero as they are cooled. The conductivity increases as the temperature rises. Their electrical conductivity can be altered drastically if suitable impurity atoms are used to ‘dope’ the material. In this section, energy band diagrams for n and p-type materials and the behaviour of a p-n junction are described.

2.2.1 Doping

The conductivity of a semiconductor can be significantly altered by introducing impurities into the intrinsic material. An increase in conductivity can be provided by increasing either the electron or hole concentration, which results in n-type or p-type material respectively. In both cases, a silicon atom is replaced by an atom from a different element. In n-type doping, an atom with five valence electrons replaces the silicon atom as illustrated in Figure 2.4. Four valence electrons form a covalent bond with the silicon atom, leaving an unbonded free electron, this impurity is known as a ‘donor’. A common element used in silicon doping as a donor is phosphorus.

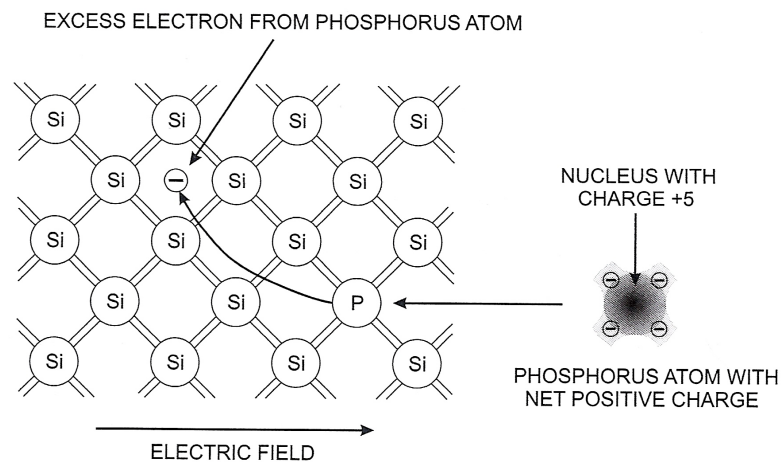


Figure 2.4: Introducing a group 5 impurity (eg. P or As) introduces a lightly bound electron that can move freely under the influence of an electric field [52].

Shown in Figure 2.5 is the band diagram for an n-type material. It shows the energy level due to the donor atom. The bound level of these lightly held electrons is 0.01 eV below the conduction band and at room temperature they are energetic enough to be introduced into the conduction band, as a result increasing the conductivity of the intrinsic material.

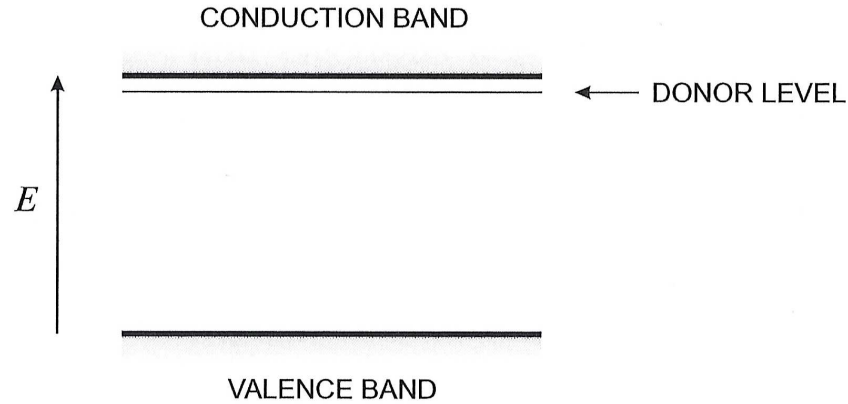


Figure 2.5: The donor electron is lightly bounded by the impurity atom. This bound level lies in the forbidden band gap just below the conduction band and at room temperature the thermal energy is enough to introduce the donor electron into the conduction band [52].

In contrary, in a p-type material a silicon atom is replaced by an atom with three valence electrons, leaving one electron of the impurity atom without a partner. This is illustrated in Figure 2.6 [52]. This type of dopant is called an ‘acceptor’.

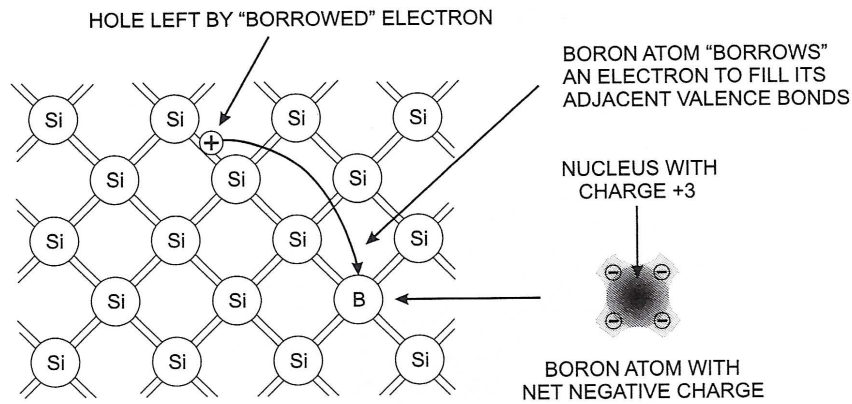


Figure 2.6: Introducing a group 3 impurity leaves an unpaired silicon bond, which can attract a neighbouring electron. As other electrons are borrowed to fill the unpaired bond, the resulting vacancy, a hole moves through the lattice [52].

The band diagram for a p-type material shows that an acceptor level is introduced above the valence band as shown in Figure 2.7.

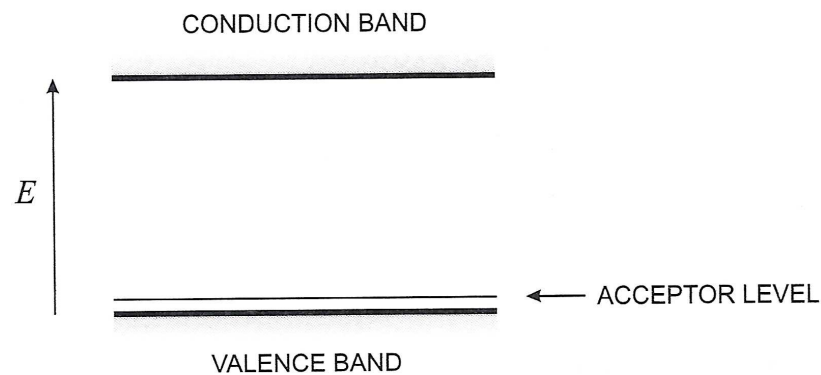


Figure 2.7: The acceptor level lies in the forbidden gap just above the valence band. [52].

At room temperature, the electrons in the valence band have enough energy to be excited

to fill some of the states in the acceptor level. This leaves behind positive mobile charges in the valence band, called - ‘holes’. Holes are unfilled electron states that behave like positive carriers.

2.2.2 pn-junction Diode Detector

A simple pn-junction diode is formed by doping a material differently in two different regions. This results in two different doping areas; a donor and an acceptor region. Initially, both regions are neutral, but thermal diffusion will drive holes and electrons across the junction. The electrons in the n-region diffuse to the p-region leaving behind a net positive charge. Similarly, the holes in the p-region diffuse to the n-region leaving behind a net negative charge. When the potential caused by this space charge region is too large for thermal diffusion to occur, there will be no more diffusion, leaving a fixed space charge region that has a fixed potential. This is called the ‘built-in’ potential (V_{bi}). This region is free of mobile charges and is known as the depletion region.

The built-in potential (V_{bi}) depends on the acceptor and donor concentrations as well as the intrinsic carrier concentration,

$$V_{bi} = \frac{kT}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right) \quad (2.6)$$

N_a and N_d are the acceptor and donor concentrations and n_i is the intrinsic carrier concentration [60]. The built-in potential is also related to the Fermi levels of the two regions. The Fermi level is the energy at which the probability of occupation by an electron is exactly one half at zero kelvin. For an intrinsic silicon material, the Fermi level is in the middle of the forbidden band gap between the valence band and the conduction band. The Fermi level however changes once impurities are introduced. It is shifted closer to the conduction band for n-type doping and the valence band for p-type doping.

At the pn-junction, the Fermi levels of the p- and n-regions are different, but in thermal equilibrium the Fermi level must be constant throughout the device. The bands are therefore offset to allow a gradual transition between the p- and the n-regions. The band diagram of a pn-junction is shown in Figure 2.8. The gradual change in potential between the p and n-regions is also caused by the space charge region.

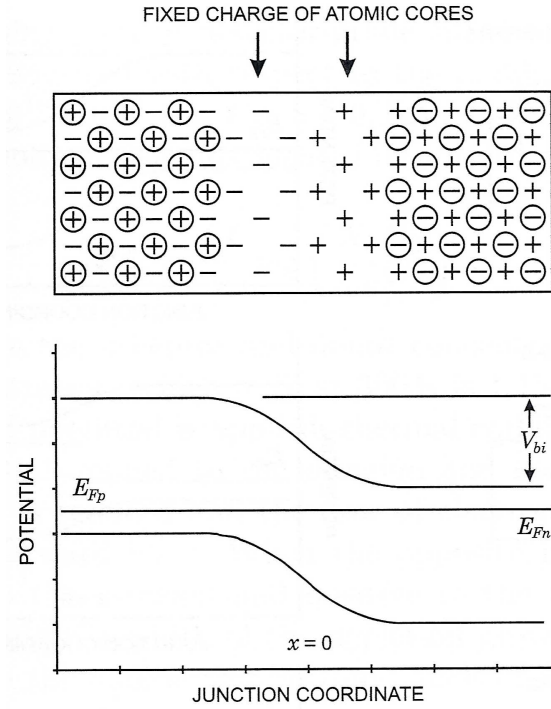


Figure 2.8: Diffusion of electrons and holes across the junction forms depletion zone with a resulting potential between the p- and n-regions [52].

The potential difference between the p- and n-regions is therefore the built-in potential. This equilibrium can be altered by applying an external electric field. The effect of an external electric field can increase the "built-in" potential and also the width of the space charge region. A basic semiconductor detector is a reverse biased pn-junction diode. Reverse biasing increases the width of the depletion region. The reverse bias voltage required to fully deplete the device is called the 'depletion voltage'. At full depletion, the entire detector is free of mobile charge carriers. The diode then acts as an ionisation chamber, that will sweep any additional mobile charge carriers to the electrodes and an electric current is induced and allows particle detection.. The depletion width depends on the bias voltage, the donor and acceptor levels in both the p and n-regions, [52].

$$w = \sqrt{\frac{2\epsilon V_b}{e} \frac{N_a + N_d}{N_a N_d}} \quad (2.7)$$

w is the depletion width, ϵ is the permittivity, N_a and N_d are the concentrations of acceptor and donor respectively. As mentioned in Chapter 1, there are different structures of electrodes and geometry of semiconductor detectors, but they are all simply ionisation chambers once fully depleted. The required reverse bias voltage depends on the dimension of the detector and the doping concentrations. In the next section, it will be shown how the depletion width affects the capacitance of the detector, which is an important design parameter for the readout electronics in a semiconductor detector system.

2.3 Detector Performance Characteristics

A semiconductor detector alone is not sufficient to fulfil the requirements for a detector system. Signals induced in a semiconductor are usually small and therefore need to be amplified and sometimes processed. All semiconductor detector systems consist of the same basic building blocks; semiconductor detector, preamplifier and a pulse shaper. The preamplifier and pulse shaper are used mainly for amplification and easier data processing. This will be discussed in the next section and can affect the overall system performance. However, the detector is the key component that determines the system performance and several factors are discussed in this section.

2.3.1 Detector Capacitance

The depletion region of a pn-junction is a region without any mobile charge carriers, acting as a dielectric sandwiched between the p and n electrodes, forming a capacitor. This capacitance depends on the dielectric of the depletion region and the bias voltage of the detector. Once the detector is fully depleted the dielectric is fixed and the capacitance remains constant with increasing bias voltage. The capacitance as a function of bias voltage is given by Eqn.2.8 and is valid until the detector is fully depleted [65]. The capacitance is then just given by a parallel plate capacitor formed around a material with dielectric constant $\epsilon\epsilon_0$.

$$C(V) = \sqrt{\frac{\epsilon\epsilon_0 q_0 N_D}{2V}} \quad (2.8)$$

Eqn.2.8 shows the capacitance decreases with increasing reverse bias voltage until it is fully depleted. and is Figure 2.9 illustrates the capacitance vs bias voltage relationship of a diode.

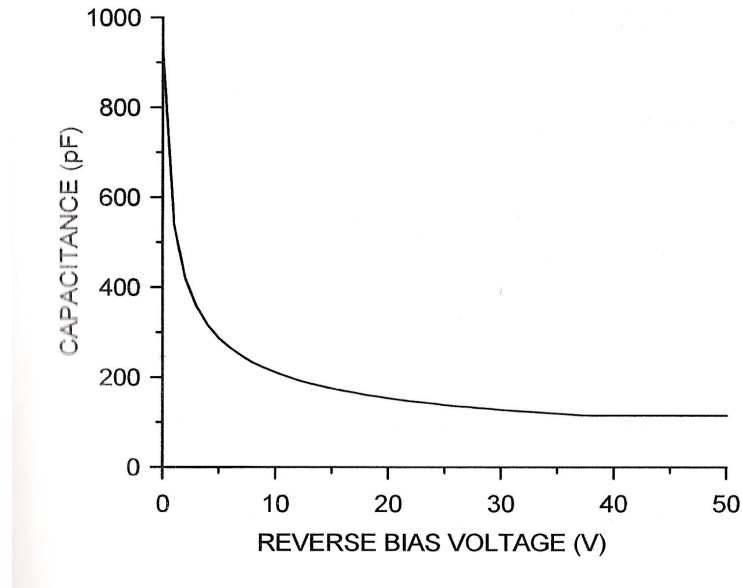


Figure 2.9: The diode capacitance decreases as the reverse bias voltage increases until the diode is fully depleted [52].

Capacitance is an important parameter for the preamplifier stage. This can affect the output response and the noise level of the preamplifier, a low input capacitance is desirable to achieve the minimum noise level possible.

2.3.2 Charge Collection

There are two mechanisms of charge transport in a semiconductor detector; diffusion and drift. Diffusion is a random process mainly caused by thermal energy. It is however also driven by the concentration gradient, and carriers will diffuse to the higher concentration area. A localised charge concentration therefore spreads out over time.

In the presence of an electric field, the charge carriers move parallel to it and the drift velocity is a function of the electric field, given by Eqn. 2.9.

$$v = \mu E \quad (2.9)$$

v is the drift velocity, E is the electric field and μ is the mobility. The mobility is related to the temperature and the diffusion constant of the material through the Einstein relation in Eqn.2.10. The mobility of electrons and holes are different. Electrons have a higher mobility [60] and can therefore arrive at the electrode in a shorter time. Eqn.2.9 is valid until the charge carriers reach velocity saturation [60] and for silicon, the drift velocity saturates at an electric field of 10^7 cm/s.

$$\mu = \frac{e}{kT} D \quad (2.10)$$

Incident radiation when absorbed by the detector material generates electrons and holes. These are swept across to the electrodes by the electric field. Although the electrons and holes have opposite charge, they contribute the same polarity of the signal at the electrode because they travel in opposite directions. The time required for the charge carriers to arrive at the electrodes is called the ‘collection time’. This depends on the applied electric field and the mobility. The collection time of mobile charge carriers in a 3D detector is predicted to be very short. In Chapter 3, signals induced in a 3D detector were observed with a rise time of about 3-4 ns at room temperature.

The charge collection times can be estimated as follows. Assume the position at which a charge originates from is $x = x_0$, the electric field can be found using the Poisson’s Equation [65]. This can be expressed in terms of the depletion width of the detector. This together with Eqn.2.9 can be expressed as

$$v(x) = \mu E(x) = -\mu \frac{eN_D}{\epsilon} (w - x) \quad (2.11)$$

w is the depletion width and N_D is the dopant concentration. The charge collection time of charge carriers can be found by the charge position and the electric field, by the following relation:

$$t(x) = \int_{x_0}^x \frac{1}{v(x)} dx \quad (2.12)$$

x_0 is the position at which the charge carrier originates from and x is usually the distance of the electrode from the charge original position. Using Eqn.2.12 and the electrode position, for a hole drifting towards the p-electrode with $x=0$, the collection time can be expressed as

$$t(x) = \int_{x_0}^x \frac{1}{v(x)} dx = \frac{\epsilon}{\mu e N_D} \ln \frac{(w-x)}{w-x_0} \quad (2.13)$$

From this, a characteristic collection time is defined as

$$\tau_p = \frac{\epsilon}{\mu e N_D} \quad (2.14)$$

The characteristic collection time τ_p is independent of the bias voltage. It depends only on the doping concentration and the mobility. This is related to the resistivity, and thus the resistivity of a material can give an approximation of the collection time. The collection time of electrons cannot be found using Eqn.2.13. It can however be rewritten to yield the position as a function of time:

$$x(t) = w(1 - e^{-t/\tau_n}) \quad (2.15)$$

τ_n is defined in the same way as τ_p .

In any semiconductor detector, the bias voltage plays a major role in the charge collection time. The collection time can be greatly reduced by increasing the bias voltage and hence the electric field. The collection times with respect to the bias voltage for both electrons and holes are given in Eqns.2.16 and 2.17 respectively. The full derivation of these expressions can be found in [52].

$$t_{cn} = \frac{d^2}{2\mu_n V_{di}} \ln \left(\frac{V_b + V_{di}}{V_b - V_{di}} \right) \quad (2.16)$$

$$t_{cp} = \frac{d^2}{2\mu_p V_{di}} \ln \left(\frac{V_b + V_{di}}{V_b - V_{di}} \right) \quad (2.17)$$

$V_{di} = V_d + V_{bi}$, where V_{bi} is the bias voltage and V_d is the depletion voltage. V_b is the built-in voltage. For a 300 μm n-type silicon, the depletion voltage is about 30 V. From

Eqn.2.16 and 2.17, when biased at 60 V the collection time for electrons and holes are 12 ns and 36 ns respectively. In a 3D detector, the depletion width (d) and the depletion voltage V_d are much smaller. The charge collection time is expected to be much shorter and this will be shown in Chapter 3.

2.3.3 Signal Formation - Ramo's Theorem

During the collection time of mobile charge carriers generated by an incident radiation particle, the moving charge carriers give rise to a signal current at both collecting electrodes. The current flow begins instantaneously as soon as the charge carriers begin to move and it can be modelled as a current source.

The induced current is the result of the change in induced charge at the signal electrode during the collection of the mobile charges. The induced charges cannot be observed directly, but can be inferred indirectly by integrating the induced current. Ramo's theorem [56] gives an elegant formulation for calculating the induced current and applies to all structures that register the effect of charges moving towards a set of electrodes. In this elegant method, the instantaneous current can be expressed in terms of the weighting field, the total charge and the charge velocity, as shown in Eqn.2.18. A derivation of Eqn.2.18 can be found in [56].

$$i = -qvE_Q \quad (2.18)$$

i is the instantaneous current, q is the charge, v is the velocity and E_Q is the weighing field.

The weighting field describes the coupling of a charge at any position to the signal electrode and depends only on the electrode geometry [52]. The weighting field is determined by solving the Laplace Equation by setting a unit potential at the measurement electrode and zero potential at all other electrodes. Note that the weighting field is distinctly different to the electric field.

2.3.4 Energy Resolution and the Fano Factor

An important performance characteristic for a radiation detector is to have a good energy resolution. This is determined by the magnitude of the induced signal and also the fluctuations of the signal for a given absorbed energy [52]. The fluctuations of the absorbed energy is measured by the so-called ‘Fano Factor’. The ‘Fano Factor’ is introduced as a function of all the various fundamental processes, which can lead to an energy transfer in the detector. This is mainly deduced by considering the energy fluctuations in ionisation and excitation energy. Excitation energy is the energy absorbed by phonon production or lattice vibration. The total deposited energy from the incident radiation is the sum of the excitation and ionisation energy, summarised in Eqn.2.19 [52].

$$E_0 = E_{ion}N_{ion} + E_xN_x \quad (2.19)$$

E_{ion} is the band gap in silicon and N_{ion} is the number of ionisation interactions. E_x is the excitation energy and N_x is the number of excitations. For a given event, if more energy goes into charge formation, less energy will be available for excitation. The standard deviation in the two types of energy absorption will be equal after many events, and the following (Eqn.2.20) holds.

$$E_{ion}\sigma_{ion} = E_x\sigma_x \quad (2.20)$$

The standard deviation in the number of excitations follows a Gaussian function and $\sigma_x = \sqrt{N_x}$. Substituting this into Eqn.2.20 and using Eqn.2.19, the standard deviation in ionisation processes can be deduced,

$$\sigma_{ion} = \frac{E_x}{E_{ion}} \sqrt{\frac{E_0}{E_x} - \frac{E_{ion}}{E_x} N_{ion}} \quad (2.21)$$

The number of ionisations equals the number of charge pairs formed. This equals the total deposited energy divided by the average energy required to produce a charge pair E_i . This gives the standard deviation in ionisation processes written in Eqn.2.22

$$\sigma_{ion} = \sqrt{\frac{E_x}{E_{ion}}} \sqrt{\frac{E_x}{E_{ion}} - \left(\frac{E_i}{E_{ion}} - 1\right)} \quad (2.22)$$

The second term in Eqn.2.22 is called the Fano factor, F . Since the standard deviation in ionisation is proportional to the standard deviation in signal charge σ_Q , Eqn.2.24 can be rewritten as

$$\sigma_Q = \sqrt{FN_Q} \quad (2.23)$$

In silicon, the measured Fano Factor is in fact 0.1 but is 0.08 from the above expression. A correction factor is added and the standard deviation in signal charge is approximately equal to $0.3\sqrt{N_Q}$.

The energy resolution of a detector is usually referred to as the full width half maximum (FWHM) of the observed energy spectra. For an X-ray monoenergetic photon energy, the FWHM is related to the standard deviation of the distribution by $FWHM=2.35\sigma$ for a Gaussian distribution.

Including the Fano factor correction, the energy resolution (ΔE) FWHM is

$$\Delta E = 2.35.E_i\sqrt{FN_Q} \quad (2.24)$$

The standard deviation of the detector signal charge is a significant contribution to the system noise because the electronic noise is often about 100 eV. Figure 2.10 shows that the intrinsic energy resolution of a detector is in the same order of magnitude if not larger.

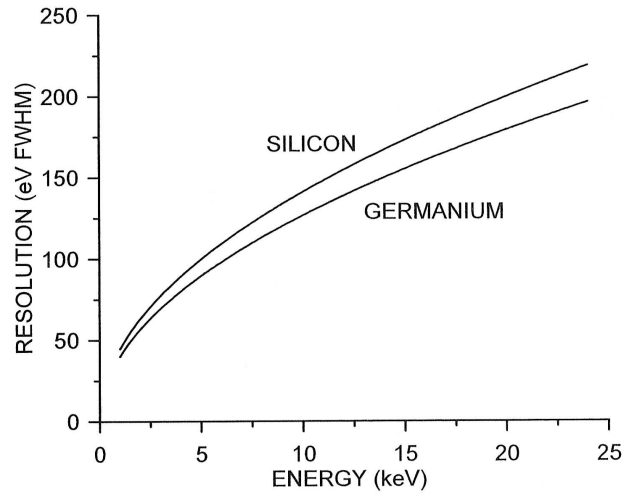


Figure 2.10: Intrinsic resolution of silicon and germanium detectors vs energy [52].

The Fano factor indicates the ultimate limit in energy resolution. Another factor that can limit the the energy resolution is electronic noise.

2.4 Signal Acquisition - Readout Amplifier

Induced signals from a silicon detector are small and need to be amplified. The amplifier response provides some pulse shaping effect. There are several types of amplifier in common use: voltage sensitive amplifier, current sensitive amplifier and charge sensitive amplifier. In the work described in this thesis, two types of amplifiers were used; a current amplifier and a charge amplifier. The general operation principles of the two are described here.

2.4.1 Current Sensitive Amplifier

This is a simple configuration with the detector induced signal modelled as a current source as shown in Figure 2.11. This configuration can also result in a voltage sensitive

amplifier. The determination of whether it is in current or voltage mode depends on the input time constant. The time constant is a product of the detector capacitance and the input resistance of the amplifier ($R_{in}C_{det}$). If this is short compared to the charge collection time of the detector, the output pulse shape of the amplifier follows the detector induced current, hence a current amplifier. On the other hand, if the time constant is long compared to the charge collection time, the detector capacitance discharges very slowly. The induced current is integrated over the detector capacitance and discharges slowly through the amplifier input resistance. The output voltage of the amplifier therefore depends on the voltage developed across the detector due to the charging effects. In this case, the amplifier is in a voltage mode. The design of the amplifier, in other words the input resistance and other design parameters must be carefully chosen to select the desired operating mode. In both cases, the amplifier provides a voltage gain so that the output signal voltage is directly proportional to the input voltage. The only difference is that the output pulse shape follows the instantaneous current in a current amplifier and the integrated current in a voltage amplifier. A feedback component is usually added to this simple configuration (Figure 2.11) to control the gain and the amplifier input resistance. The feedback component can also perform special functions, for example, in a charge sensitive amplifier, a feedback capacitor is used.

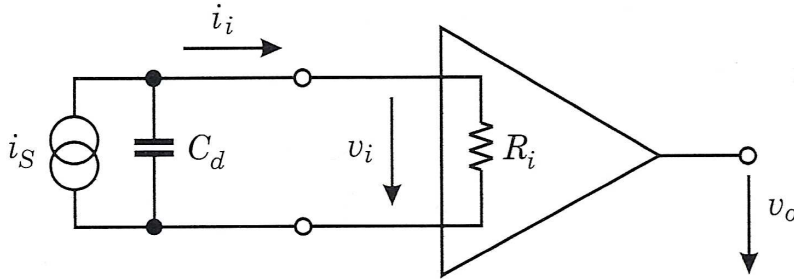


Figure 2.11: A simple configuration of a current amplifier. The detector induced current is modelled as a current source and a capacitance. This simple configuration has no feedback component.

In the work described in Chapter 3 and 4, a fast current amplifier was used. This was because we were interested in the signal formation in a 3D detector. It is therefore

desirable to have an amplifier that follows the induced current rather than the voltage developed across the detector due to the induced current.

2.4.2 Charge Sensitive Amplifier

Charge sensitive amplifiers are widely used in detector systems. The circuit design for a charge sensitive amplifier is given in Figure 2.11. It is an inverting amplifier with a feedback capacitor.

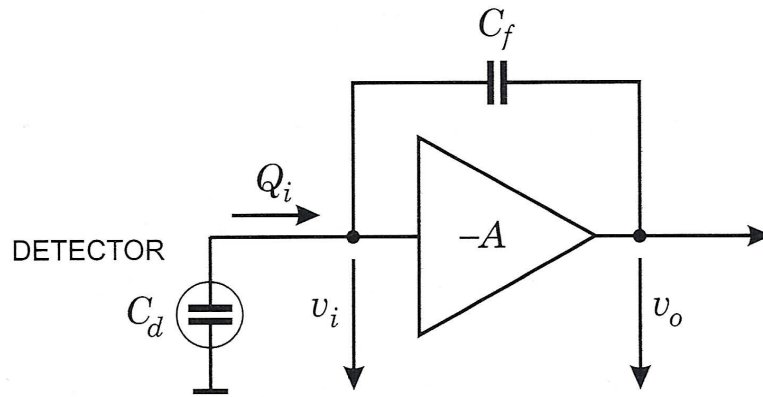


Figure 2.12: A simple configuration of a charge amplifier with a feedback capacitor to perform integration over the input current.

The feedback path also provides a reduction in input impedance. In this configuration the output voltage level is proportional to the input charge. The output voltage per unit charge is determined by a well defined component - the feedback capacitor and the gain is simply given by Eqn.2.25.

$$\frac{V_o}{Q_i} = \frac{1}{C_f} \quad (2.25)$$

V_o is the output voltage, Q_i is the input charge and C_f is the feedback capacitance. The input-output relationship allows easy charge calibration. Since the amount of charge carriers generated in a semiconductor detector is proportional to the energy of the

incident radiation, the output voltage in a charge sensitive amplifier easily identifies the energy spectra of a specific type of radiation. The drawback of charge sensitive amplifiers is that it responds more slowly than the time duration of the current pulse from the detector. Although all input charges are stored in the input capacitance, the pulse shape is nevertheless affected by the time response of the amplifier. Current amplifiers without any capacitive components allow a faster time response and are used when time response is of primary concern. This also explains why a current amplifier was used in the measurement described in Chapter 3.

The time response of an amplifier is related to the frequency response which is determined by the poles of the amplifier. A typical amplifier consists of a transistor with a low pass response. The cut-off frequency limits the high frequency components observed at the amplifier output, making some fast components of the input unobservable. The current-amplifier described earlier is a fictitious model without any parasitic or any design parameters. In reality, there are parasitic and input/output impedances in the circuit design. These will determine the frequency response of the amplifier and thus the time response. This was studied for the fast transimpedance amplifier that was used to study the signal formation of 3D detector see Chapter 3.

2.5 Summary

The basic operating principles and properties of semiconductor detectors have been described in this chapter. It is a research area that involves many areas of knowledge, including nuclear physics, microelectronics and material properties. It is out of the scope of this thesis to provide a full understanding of semiconductor radiation detectors. The focus of this thesis concentrates on signal formation and some advantages of 3D detectors such as edgeless capability. This chapter therefore has provided information on these subjects that are required to understand key properties of 3D detectors. Interested readers can find further information on semiconductor detectors in the list of references, in particular [11] [52] [55] [53].

Chapter 3

Time Response Measurement

Chapter 1 explains that 3D detectors were predicted to have a fast charge collection time and initial calculations were made in reference [3], in which the effects of the induced signals from a minimum ionising particle were calculated using Ramo's Theorem [56]. The main emphasis of this thesis is to investigate the time response behaviour of signals induced in a 3D detector. In this chapter, the time response of a 3D detector is studied from measurements using a fast transimpedance amplifier. The aims of this measurement are as follows:

1. to study the induced signals from a 3D detector
2. to identify the time response of the induced signals and their dependence with bias voltage
3. to identify the minimum charge collection time of a 3D detector

A readout amplifier that has a time response faster or at least close to the 3D detector charge collection time is required to achieve these aims. Electronic amplifiers that are currently used in high energy physics experiments, at the Large Hadron Collider, have a typical shaping time of 25 ns. This is more than 10 times slower than the predicted charge collection time of a 3D detector.

A high-speed low-noise transimpedance amplifier was recently designed by the micro-electronics group (G. Anelli et al) at CERN in Geneva. It was designed using $0.25\ \mu\text{m}$

CMOS technology [7]. In ref. [7], the amplifier was shown to have a rise time of 3 ns at room temperature. This is comparable to the predicted time response of 3D detectors. Moreover, it was also designed to operate at 130 K and the corresponding rise time was measured to be 1.5 ns. The amplifier was therefore suitable to verify the short collection time in a 3D detector and to provide some insight into its signal formation.

This amplifier is newly designed and many characteristics were required to be understood, in particular those that are closely related to the detector behaviour. Studies of these characteristics were made for the amplifier. The results and how they affect the overall testing of the detector are explained in this chapter. Once these were understood, signals obtained from the detection of both X-rays and betas were recorded.

This chapter will explain the set up and results in the following manner:

1. Description of the 3D detector under test and its specifications
2. Measurement set up
3. Amplifier characterisation
4. Results from X-rays and Betas

The results described in this chapter will be compared with a full system simulation in Chapter 5. This will provide a better understanding of the measured signals. As a consequence, a deeper understanding of a 3D detector will be achieved.

3.1 Detectors Under Test

Preliminary test results such as I/V characteristics and depletion voltage of the detector used in this test can be found in earlier publications ([4] [6]). In this preliminary design, the detector has no ‘active edge’ with a simple electrode arrangement, similar to a strip detector. The electrode arrangement is described in Figure.3.1 and specified in Table.3.1. In this test, the readout channels were formed by arrays of p-electrodes and the n-channels were connected to a high voltage power supply to provide the detector biasing.

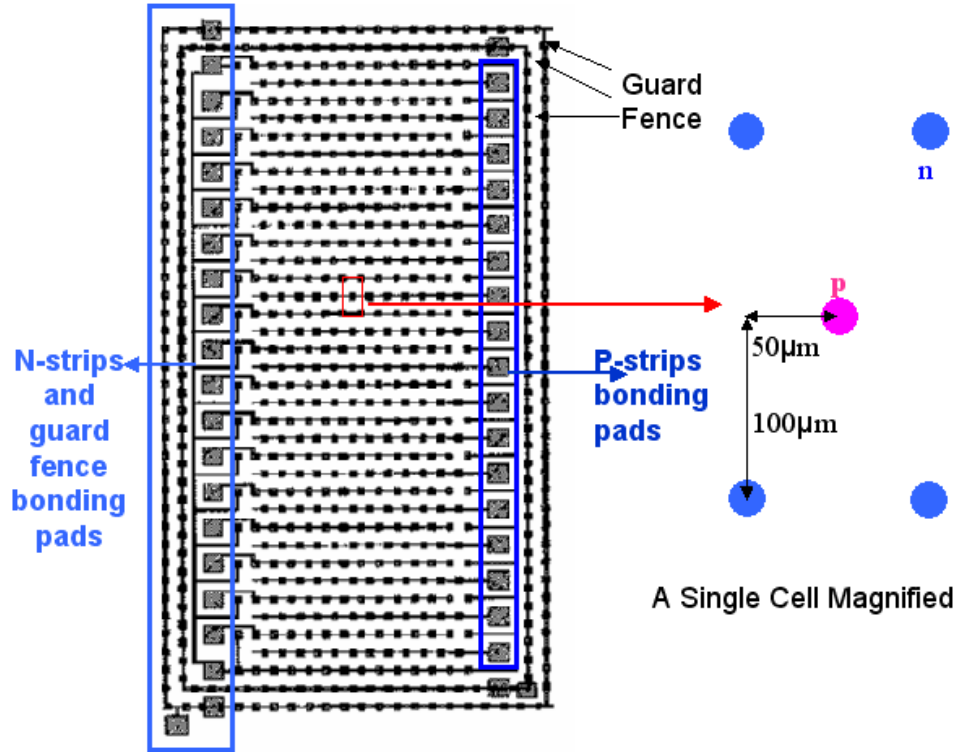


Figure 3.1: The layout of the tested detector with $200\text{ }\mu\text{m}$ pitch and alternate arrays of p and n electrodes. Strips were formed by arrays of p-electrodes that are $200\text{ }\mu\text{m}$ apart. The single cell arrangement is also shown by extracting the arrangement of the cell situated at the detector centre.

Dimension	$0.0121 \times 0.36 \times 0.195\text{cm}^3$
Electrode spacing	$100\text{ }\mu\text{m}$
Pitch (p to p)	$200\text{ }\mu\text{m}$
Thickness	$121\text{ }\mu\text{m}$

Table 3.1: Specifications of the 3D detector tested in this thesis.

3.1.1 Current-Voltage (I/V) Characteristics

The I/V characteristic of the detector was measured after it was mounted on a printed circuit board (PCB) and wire-bonded to the input of the amplifier. The full mounting structure and PCB layout are described in the next section. This mounting structure affected how the I/V characteristics were measured and it was not possible to measure the I/V characteristics of each individual strip.

Electrodes of the same type (p or n) were joined together by a 2 mm long aluminium strip on the front side of the wafer, as can be seen in Figure 3.1. In this design, there is no active edge. A ‘guard fence’ consists of n-electrodes around the edge of the device, which was used to sink the current from cracks and chips around the edge which can be very large. When measuring the current, the detector was reversed biased by applying a positive voltage to the n-electrodes. The biasing scheme is shown in Figure 3.2. All the n-electrodes (including the guard fence) were connected to one single metal contact. This was then connected to the biasing components - the resistor and the capacitor. The p-electrodes were set to ground by the input of the amplifier. As a consequence, all the n-strips were connected and the current through each strip could not be separated. The measured I/V curve is shown in Figure 3.3. The leakage current was very large as expected, in the order of a few μA since the n-electrodes were not separated and this includes the large edge current. This current measurement gives little information of the leakage current in the central strips away from the edge. However, it nevertheless shows the full depletion voltage to be around 15 V.

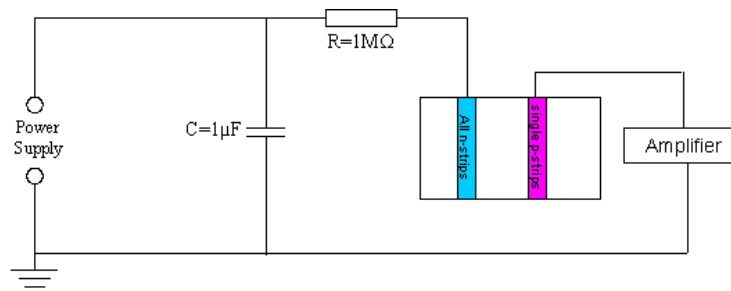


Figure 3.2: Biasing scheme of the detector, including the current limiting resistor and decoupling capacitor. All n-strips were connected together to the power supply, including the ‘guard fence’. Each p-strip was connected to an input channel of the amplifier.

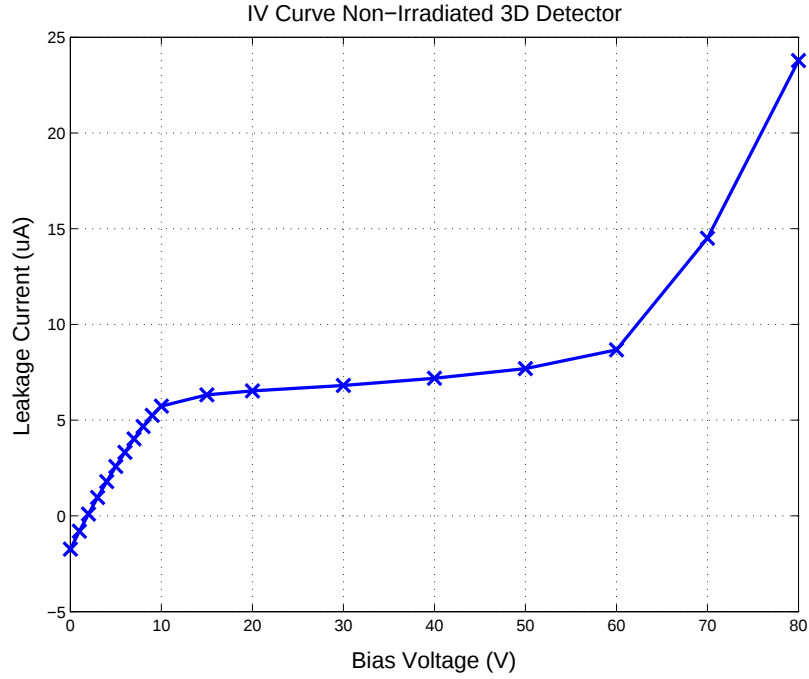


Figure 3.3: I/V characteristics was measured for the entire detector. All the n-strips were connected, including the guard fence around the edge. The leakage current is therefore very large.

Despite the large leakage current mostly caused by the large edge current, this should not affect the performance of strips far away from the edge where the electric field is more uniformly distributed. In Section 3.3.6, the amplifier was used to verify that the leakage current per strip was less than 25 nA.

3.2 Measurement Method

In this section, the measurement set up is described, this includes the mounting procedure of the detector, the data acquisition chain and the cryogenic equipment used for low temperature measurement.

3.2.1 Mounting of Printed Circuit Board(PCB)

A PCB was designed for the testing and mounting of both the detector and the amplifier. Figure 3.4 shows the 3D detector (right) glued onto a gold plate situated approximately at the center of the PCB. Each bonding pad of the p-strips was wire-bonded to an input channel of the amplifier (left). All the n-strips were bonded to the gold plate, which was connected to a high-voltage power supply via the RC components explained in Section 3.1. The details of the mounting are explained more clearly in Figure 3.5.

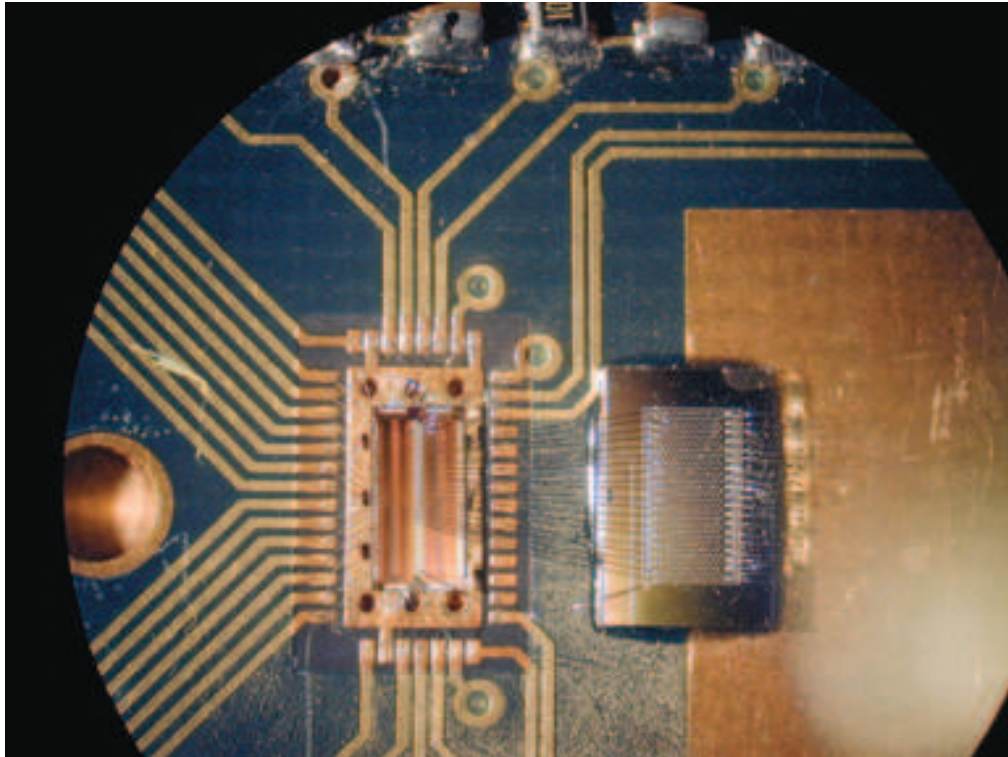


Figure 3.4: Part of the PCB used in the measurement with the detector (right) glued on the gold plate and wire bonded to the input channels of the amplifier (left).

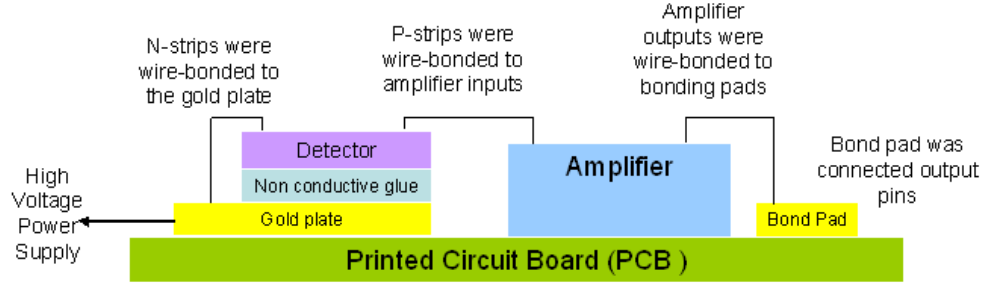


Figure 3.5: A side view that shows the detector glued on the gold plate situated on the PCB with non-conductive glue. It also shows how the detector was biased and readout.

The electrodes in a 3D detector penetrate through the silicon bulk and to prevent shortage between the two types of electrodes, a non-conductive glue was used to glue the detector onto the gold plate as shown in Figure 3.5. Each p-strip was wire-bonded to the amplifier input channel. The corresponding output channel was then connected to some output pins. A jumper was used to select the channel which was read out and only one channel could be read at a time.

A test channel was also available for amplifier testing, which allowed characterisation of the amplifier by injecting a test charge at the input of this test channel. This characterisation was made before testing the detector and the results are described in Section 3.3.

3.2.2 Data Acquisition

Signals from the selected output were recorded through a decoupling capacitor on a $50\ \Omega$ cable, using a fast digital oscilloscope (Agilent 54516C [58]). The oscilloscope had a sampling rate of 2 Gsamples/s and a bandwidth of 500 MHz. The data acquisition was controlled by a Labview program via a GPIB interface. The program first set the oscilloscope to stand-by, ready to record an output signal when a trigger arrived. The

trigger level was set well above the noise level but was also as low as possible to obtain the full spectrum of incident particles. Once the trigger was received, the output signal was recorded and sent to the computer. When the data was written to an output file, the Labview program sent a signal to reset the oscilloscope, so that it was ready for the next trigger.

3.2.3 Vacuum Cryocooler for Low Temperature Measurement

The detector and the amplifier perform differently at cryogenic temperature so it is of interest to perform the same test at 130 K . The change in performance is due to the fact that the charge transport in silicon depends on the mobility of charge carriers which is inversely proportional to temperature. The faster charge transport at low temperature should give a faster time response. The amplifier used in this measurement was optimally designed to operate at 130 K as stated in ref. [7] and has a rise time of 1.5 ns . Low temperature measurement should therefore give interesting insights on the detector time response behavior.

Low temperature was achieved using a vacuum cryocooler shown in Figure 3.6. The picture shows how the PCB was placed on a copper plate situated inside the cooler. The back of the PCB was plated with gold, giving a good thermal contact in order to remove the heat effectively. The major heat source was from the electronics - both the detector and amplifier. Accurate temperature monitoring was provided by a sensor placed underneath the copper plate.



Figure 3.6: PCB with both the detector and the amplifier mounted was placed inside the cryocooler for low temperature measurement. Room temperature measurement was taken using the same set up with the cryocooler switched off.

This full set up allowed testing of both the amplifier and the detector. The amplifier was tested with a test charge before the detector was tested. The next section will describe the measured characteristics of the amplifier.

3.3 Readout Amplifier Characterisation

The test channel mentioned earlier was used to test the amplifier. A test charge of 1.6 fC was injected at the input, which was equivalent to the total amount of charge generated by a minimum ionising particle in a $121 \mu\text{m}$ thick silicon. This is the same as the 3D detector tested in this measurement.

The amplifier can have different operating conditions and each set of conditions has a different output shaping time and gain. The output characteristics are therefore

adjustable by selecting the appropriate operating conditions dependent on the preferred application. This section explains how the operating condition was chosen for this test. Once the optimal operating condition was chosen, the output response of the amplifier was studied by varying the following parameters:

1. The input capacitance
2. The input rise time (10 % to 90 %)
3. The input charge
4. The current in the feedback path transistor

These parameters were chosen for various reasons. The input capacitance was determined by the detector and this varied with bias voltage. If one wishes to understand the output signal dependence with bias voltage, the effects on the output signals due to the input capacitance must be studied. The amplifier minimum time response was identified by varying the input rise time. The charge collection time of a 3D detector with $50\text{ }\mu\text{m}$ pitch was calculated to be a couple of ns. This is of the same order of magnitude as the amplifier and its minimum time response must not be mistaken as the detector minimum time response. By varying the amount of input charge, the amplifier gain linearity can be checked. Although the amplifier used is a current amplifier, if the input charge is faster than the output response, the output signal should be proportional to the input charge. The last parameter is unique for this particular amplifier. Due to its design, its feedback path is an NMOS or PMOS transistor, which has a transconductance that depends on its biasing current. Any changes in this current can change its output response. The details will be explained in the following sections.

3.3.1 Amplifier Operating Conditions

The current amplifier used in this test consists of NMOS and PMOS devices with no passive component. Its basic configuration is shown in Figure 3.7. The feedback resistor in a traditional current amplifier was replaced by an NMOS or PMOS device (T_F). In this specific amplifier used in these tests, the feedback was a PMOS transistor. The amplifier response is therefore controlled by the transconductance - T_F rather than a fixed resistance. The transconductance (T_F) depends on its biasing conditions and

must therefore be selected carefully. This also implies that the amplifier is sensitive to the detector leakage current. When the detector was connected to the amplifier, the leakage current passed through the feedback transistor, which caused a change in its transconductance and thus the system response. The effect of the detector leakage current is studied in Section 3.3.6.

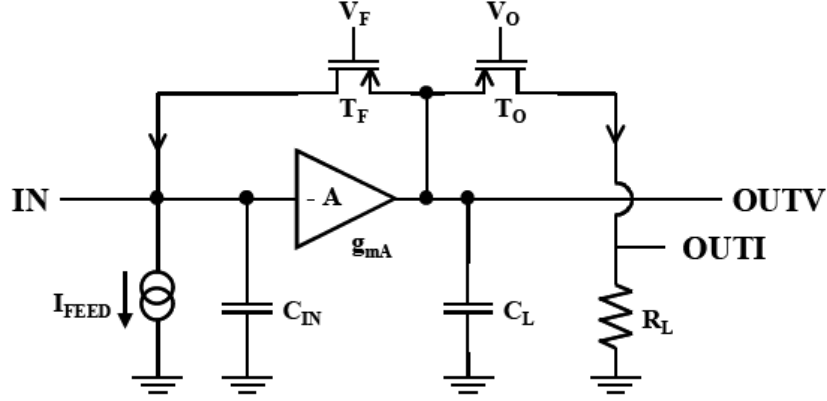


Figure 3.7: The simplified diagram of the amplifier used in the measurement, showing its active components in its feedback path.

The derivation of the system transfer function will not be discussed in this thesis, but it was used to identify several factors that can affect the amplifier performance and the understanding of the results. The transfer function of the amplifier is [7];

$$G(s) = -\frac{1}{g_{T_o}} \cdot \frac{1}{s^2 \frac{C_{in} C_L}{g_A g_{T_F}} + s \frac{C_{in}}{g_{m_A}} \cdot \frac{1}{k} + 1} \quad (3.1)$$

g_{T_o} is the transconductance of transistor T_o , g_{T_F} is the transconductance of the feedback transistor T_F , C_{in} and C_L are the input and load capacitances respectively, g_{m_A} is the transconductance of the main amplifier and k is defined by Eqn 3.2;

$$k = \frac{g_{T_F}}{g_{T_F} + g_{T_o}} \quad (3.2)$$

From the transfer function in Eqn. 3.1, several factors that affect the amplifier performance were identified. The system is a two-pole system, in which one pole depends on the input capacitance and the other depends on the transconductance of the feedback transistor (T_F). The transconductance is determined by its biasing conditions and was chosen to be a compromise in gain, time response, noise and stability. This compromise was chosen by inspecting the outputs when different operating conditions were applied. The amplifier was tested alone to identify the optimal conditions. In initial testing of the amplifier, the optimal biasing conditions stated in ref. [7] were used as a guideline but were redetermined once the 3D detector was connected because it caused a change in the input capacitance due to a difference in parasitics from wire-bonding, transmission lines on the PCB as well as the detector capacitance.

3.3.2 Test Charge Injection

The amplifier was tested by injecting a charge of 1.6 fC with a rise time of 1 ns. The test charge was injected by applying a step voltage via a 1 nF capacitor, illustrated in Figure 4.14. The step voltage took 0.5 ns to reach from zero to 1.6 μ V and the current was simply the derivative of the step voltage multiplied by the capacitance given by Eqn.3.3.

$$i(t) = C \times \frac{dV}{dt} \quad (3.3)$$

The resulting current impulse was 0.5 ns in duration with an amplitude of 3.2 μ A. This is only an impulse approximation but the current duration of 0.5 ns was short when compared to the amplifier rise time of 3-4 ns and could therefore be considered as an impulse function.

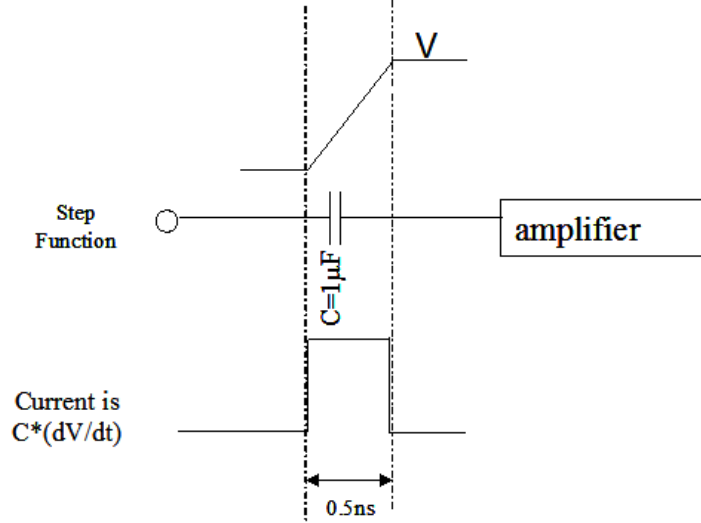


Figure 3.8: A step voltage that applied to a 1 nF capacitor. This resulted in a current generated at the input of the amplifier with a duration of 0.5 ns, which approximated an impulse.

Different output signals were inspected to fine tune the operating conditions. The operating condition that gave an output signal that had the best gain and time response was chosen.

The output signals shown in Figure 3.9 were obtained from both HSPICE [61] simulation and measurement with the chosen operating condition. As shown in Figure 3.9, the gain of the signal was 2.38 mV/fC. The rise time and fall time were 4 ns and 10 ns respectively. This operating condition was kept for all measurements to allow fair comparisons in all measured data. The impulse response observed at the amplifier output was used to test various performance characteristics of the amplifier.

3.3.3 Effects of Input Capacitance

The transfer function in Eqn.3.1 shows that the dominant pole of the amplifier depends strongly on the input capacitance. The input capacitance therefore plays an important role in the frequency response. This affects the shaping time and the gain of the amplifier. The higher the input capacitance, the lower its cutoff frequency and slower the output response. It is therefore important to study how the input capacitance affects the

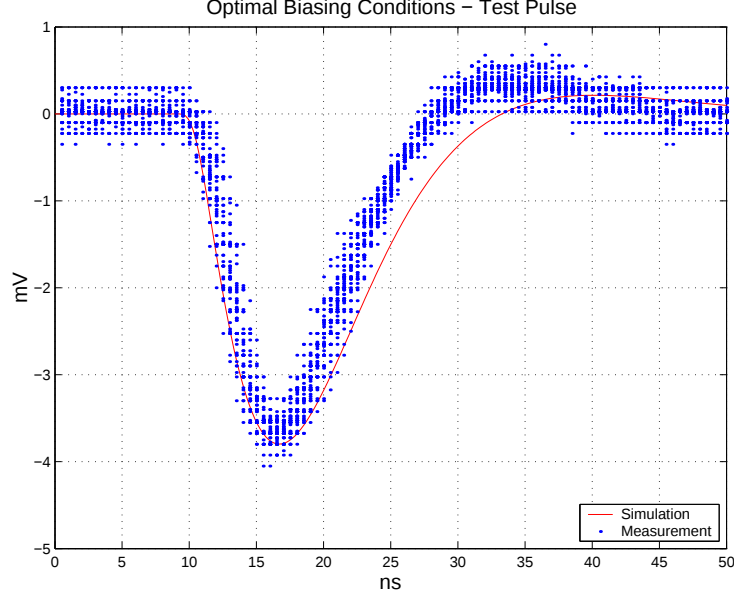


Figure 3.9: Both simulated and measured output signals were obtained by injecting a test charge of 1.6 fC. The operating conditions of the amplifier were chosen to be optimal in terms of stability, gain and time response.

amplifier behaviour. This is particularly important when studying the detector signal dependence with its bias voltage because the detector capacitance also varies when changing the bias voltage.

The capacitance of one single electrode in a 3D detector was measured in ref. [5] to be 0.2 pF. Each channel consists of 12 p-electrodes joined by an aluminum strip and connected to the amplifier input. Assuming that the electrodes are all in parallel with each other, the capacitance of one strip would be 2.4 pF. To study the effect of input capacitance on the output signal, an HSPICE simulation was performed to calculate the output signals when different input capacitances were applied. The resulting output signals for several capacitances are shown in Figure 3.10. These are compared to a typical signal obtained from a ^{90}Sr source at full depletion voltage.

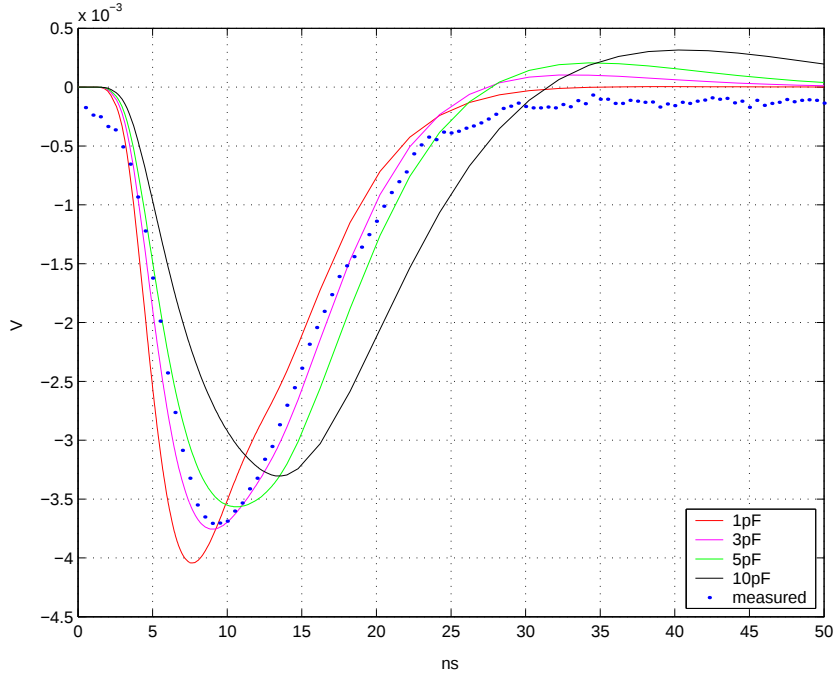


Figure 3.10: Simulated amplifier outputs resulted from different input capacitances are compared to a typical signal from a ^{90}Sr source at full depletion voltage.

Results in Figure 3.10 show that the time response increases with input capacitance. It also indicated that the detector capacitance at full depletion is approximately 3 pF. This is because the best agreement is seen between the recorded signal from a ^{90}Sr source and the predicted output signal when the input capacitance was 3 pF. The approximation of 2.4 pF per strip was therefore reasonable, although smaller than 3 pF. This can be explained by other capacitances that were not included in the simulation, such as the parasitic capacitance in the bonding wires, bonding pads and the transmission lines on the Printed Circuit Board PCB).

The time response parameters of each output signal were calculated and they are defined as:

1. Pulse height
2. Rise Time - 10 % to 90 %

3. Fall Time - 90 % to 10 %
4. Full Width Half Maximum - 50 % to 50 %

The results are given in Table.3.2 and plotted in Figure 3.11

Input Capacitance (pF)	Rise Time (ns)	Fall Time (ns)	FWHM (ns)
1	3.09	12.77	10.80
3	3.78	11.22	12.02
5	4.48	10.43	13.30
10	8.03	12.07	15.53

Table 3.2: HSPICE simulation showing the variations in the rise time and fall time with different capacitances. The input test charge was 1 fC.

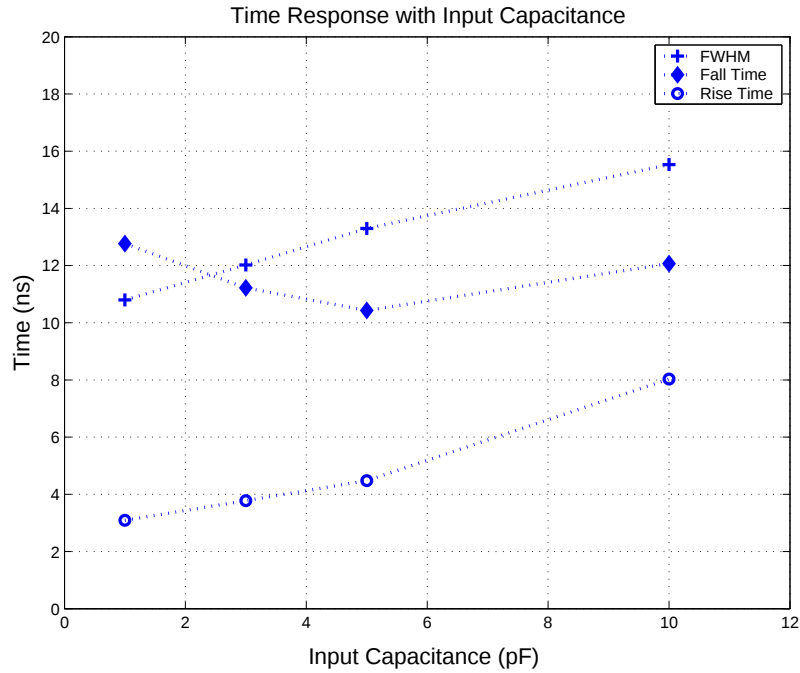


Figure 3.11: Output signals were simulated with different input capacitances using HSPICE. The time response parameters were calculated. This shows how the time response changes with different input capacitances.

The rise time in Figure 3.11 decreases with input capacitance. In contrast, the fall time initially decreases when the capacitance increases. This is because the signal height also

reduces with increasing input capacitance, reducing the time difference between the 10 % and 90 % points. The change in rise time was about 2 ns when the input capacitance changed from 1 to 5 pF. Similarly, the change in fall time was also about 2 ns. The results show that if the change in the detector capacitance is smaller than 5 pF, the effect in the output signal due to the change in capacitance would be negligible. It is therefore important to understand how the detector capacitance varies with bias voltage.

The change in capacitance with bias voltage can be estimated. Chapter 3 in ref. [65] explains how the capacitance of a diode varies with its bias voltage. The capacitance can be calculated easily using Eqn.3.4 [65] and is valid until the detector is fully depleted. Eqn.3.4 shows that the capacitance is inversely proportional to the square of the applied voltage until it is fully depleted.

$$C(V) = \sqrt{\frac{\epsilon\epsilon_0q_0N_D}{2V}} \quad (3.4)$$

Using this together with the estimated strip capacitance of a 3D detector channel - 2.4 pF and the full depletion voltage of 15 V, the C/V relationship per channel was estimated. This is plotted in Figure 3.12.

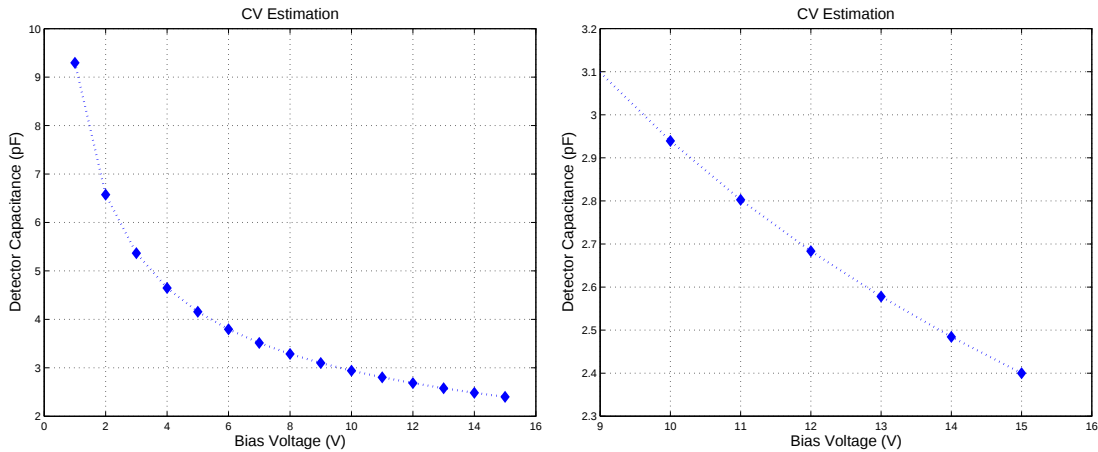


Figure 3.12: The estimated capacitance per strip at full depletion was 2.4 pF. This was used in Eqn.3.4 to estimate the C/V relationship of a 3D detector channel. Left: Shows the estimation from 1 V to 15 V. Right: Zoom in for a better identification of capacitance change due to the change in bias voltage used in the measurement.

In the measurement, the minimum applied bias voltage was 10 V. This is because the signal pulse height was too small with bias voltages below 10 V and most signals were hidden by the system noise. We are therefore only interested in the capacitance change when the bias voltage changes from 10 V to full depletion - 15 V. The right of Figure 3.12 magnifies this region of interest, showing that the detector capacitance changes by just over 1 pF between 10 to 15 V. Applying this to the results in Figure 3.10, the corresponding change in time response is less than 1 ns, if the input capacitance changes from 2.5 to 3.5 pF. In conclusion, the input capacitance does not play a significant contribution in the time response studies.

Another method to determine whether the change in input capacitance is significant, is by looking at how the amplifier noise varies with the detector bias voltage. If the change in the detector capacitance is significant, there will be a change in the amplifier noise as the bias voltage changes. The RMS noise was therefore measured at different bias voltages. The results are shown in Figure 3.13 with a total change in RMS of only 0.017 mV. Taking the average noise to be 0.175 mV, as indicated in Figure 3.13, the change in noise over this range of bias voltages is less than 10 %. This is very small, suggesting that the change in capacitance was insignificant. Moreover, the detector capacitance decreases with increasing bias voltage but this is not true in Figure 3.13, so the change in the RMS noise was caused by other factors such as the change in the detector leakage current. This further confirms that the effect of the change in capacitance on the amplifier performance is insignificant.

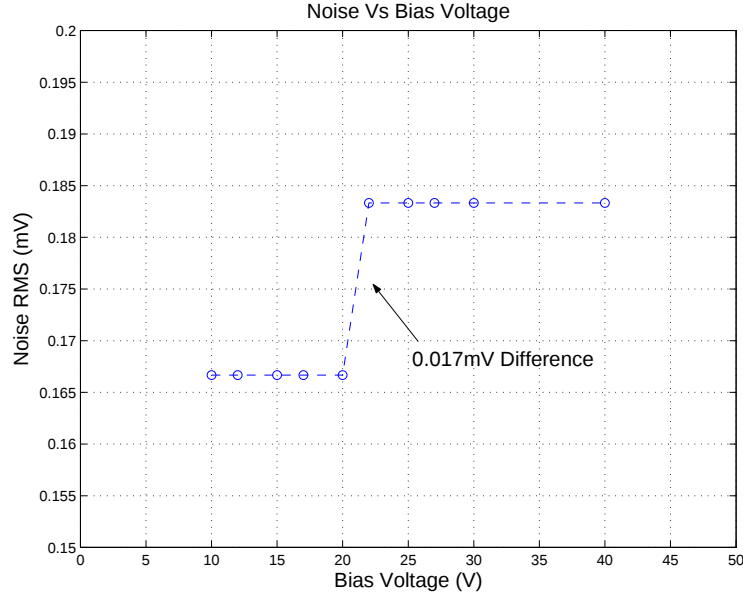


Figure 3.13: The noise was plotted as a function of detector bias voltage. The change in noise was only 0.017 mV.

3.3.4 Amplifier Signal Height Variations

The readout amplifier used in this measurement was a current amplifier. The output signal pulse height was therefore determined by the total input charge and the charge collection time.

The gain was tested by applying test charges varying between 0.8 fC to 3 fC to the input of the amplifier and the corresponding output signal heights were measured. The results could be used to give an estimate of the expected pulse height from particles of different energies. The energy deposited in the detector differed dependent on the types of radiation. The result of output signal heights with different input charge are shown in Figure 3.14 and was fitted with a linear equation given by Equation.3.5.

$$P(mV) = 2.02 \times Q(fC) + 0.805 \quad (3.5)$$

P is the output pulse height in mV and Q is the input charge in fC. Eqn.3.5 shows how

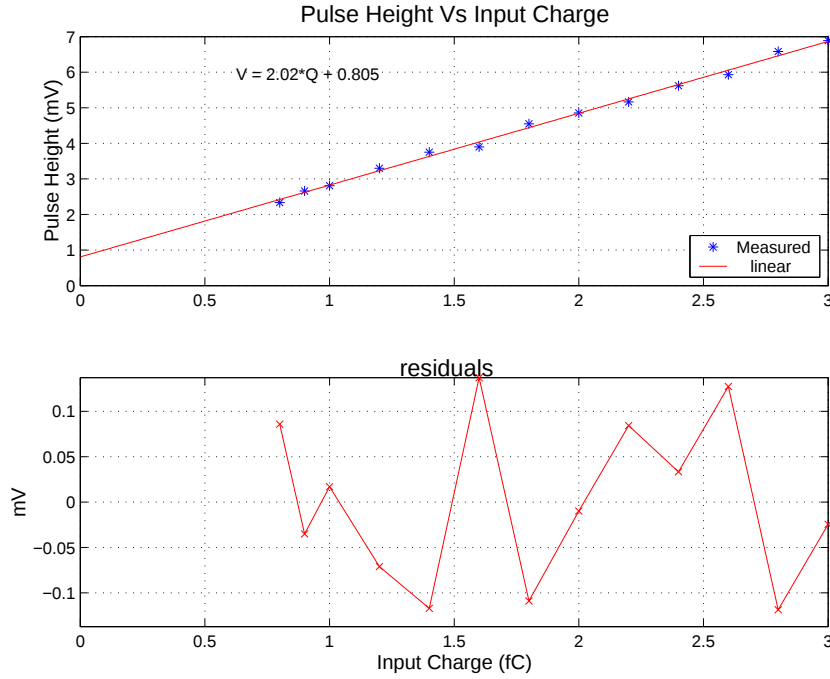


Figure 3.14: Top: The amplifier gain linearity was investigated to ensure that the calibration of different radiation energy can be correctly determined by the output pulse height. Bottom: The residual shows a random pattern indicated a good fit to the measured data.

the output pulse height varies with input charge provided the charge collection time is fast enough ie. for an impulse response. If the input is not fast enough, the output signal simply follows the input signal shape and its integral will be an indication of the total collected charge.

3.3.5 Time Response Limitation

The amplifier minimum time response must be identified, so that it would not be mistaken as the 3D detector limitation. This was identified by applying test charges with different rise times in the HSPICE simulation model and recording the output rise times. As shown in Figure 3.15, the output rise time decreases and reaches a minimum at 4 ns. It then remains as 4 ns regardless of how fast the input rise time was. Thus, the detector induced signal that has a rise time less than 4 ns would always be observed as an output signal with a rise time of 4 ns.

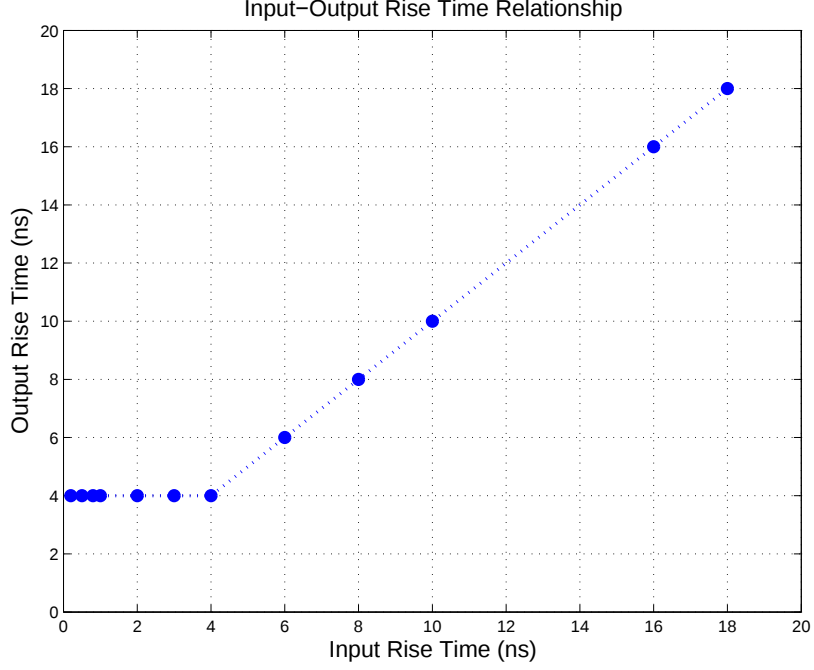


Figure 3.15: The rise time behaviour of the output signal was studied using HSPICE by injecting test inputs with different rise times.

The charge collection time for a $50\text{ }\mu\text{m}$ pitch 3D detector was calculated to be 1-2 ns in ref. [3]. The detector in the set up has a pitch of $200\text{ }\mu\text{m}$, and the estimated charge collection time should not be longer than 10 ns. The amplifier time response was of the same order of magnitude and should give a good insight into the detector time response behaviour. However, the 4 ns limitation of the amplifier rise time should not be forgotten.

3.3.6 Effects of Detector Leakage Current

As mentioned in Section 3.3.1, the current through the feedback transistor controls its transconductance. It therefore determines the amplifier frequency response and thus its shaping time and its gain. The p-strips of the detector channels were connected to the amplifier via wire bonds. In Figure 3.7, the simplified circuit diagram of the amplifier shows the input node is in parallel with its feedback path. Since the amplifier input

impedance is very large, the detector leakage current will enter the feedback transistor and if significant can affect the amplifier performance.

The amplifier output signals were studied when different currents were applied to the feedback transistor. This quantifies the change in current through the transistor that could give a significant change in the output signal. This was again studied using the HSPICE simulation. The gain was measured for each output signal and its relationship with different currents through the feedback transistor is plotted in Figure 3.16. The feedback current chosen for the optimal biasing condition was $0.82 \mu\text{A}$. In this region of Figure 3.16, the amplifier gain varies by 0.2 mV/fC if the feedback current changes by about $0.25 \mu\text{A}$. This suggests that if the detector leakage current is no more than a fifth of a μA , it should not affect the amplifier response significantly.

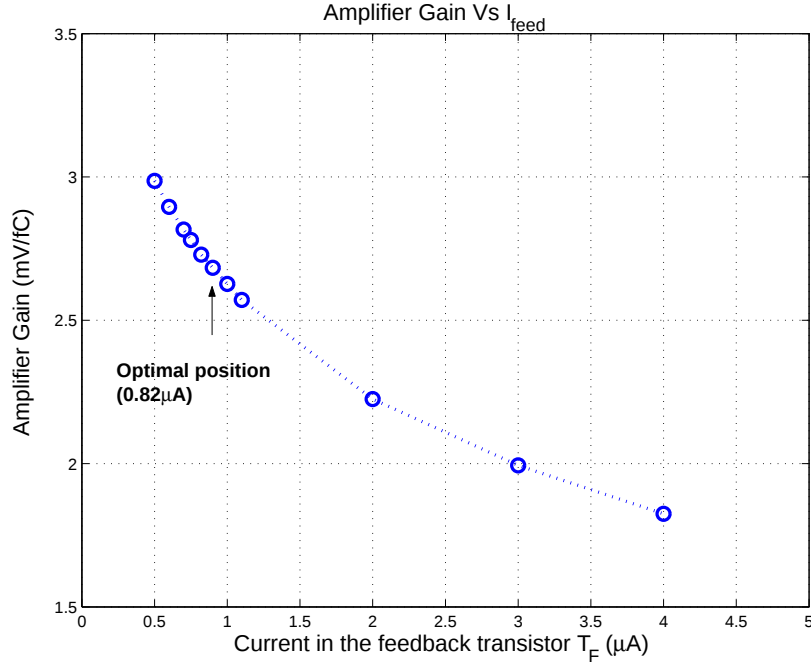


Figure 3.16: Amplifier gain as a function of the current in the feedback transistor, with a test charge of 1.6 fC .

Section 3.1.1 shows that the leakage current of the entire detector including the edge current was a few μA , but was mainly from the detector edge. In order to identify how this affects the amplifier response, the detector leakage current per strip must be

identified. An alternative method to measure the effects of the leakage current, was by looking at the DC offset at the amplifier output. The DC offset is indirectly related to the leakage current since it is determined by the amplifier operating conditions, which is affected by the current through the feedback transistor including the detector leakage current.

The test channel was used to provide a reference DC offset when the detector leakage current was zero. Any differences in other channels from this reference is due to detector leakage current. The DC offset at the test channel was measured as a function of feedback current and is shown in Figure 3.17. Referring to Figure 3.17, the DC offset only changes by 7 mV or 0.007 V if the feedback current changes by $0.18 \mu\text{A}$. This implies that if the feedback current changes by about $0.025 \mu\text{A}$ or 25 nA, the output DC offset would change by 1 mV. A DC voltage meter can normally measure this value up to one mV. Therefore, if no changes is observed in the DC offset of a particular channel, the detector leakage current of that particular strip must be less than 25 nA.

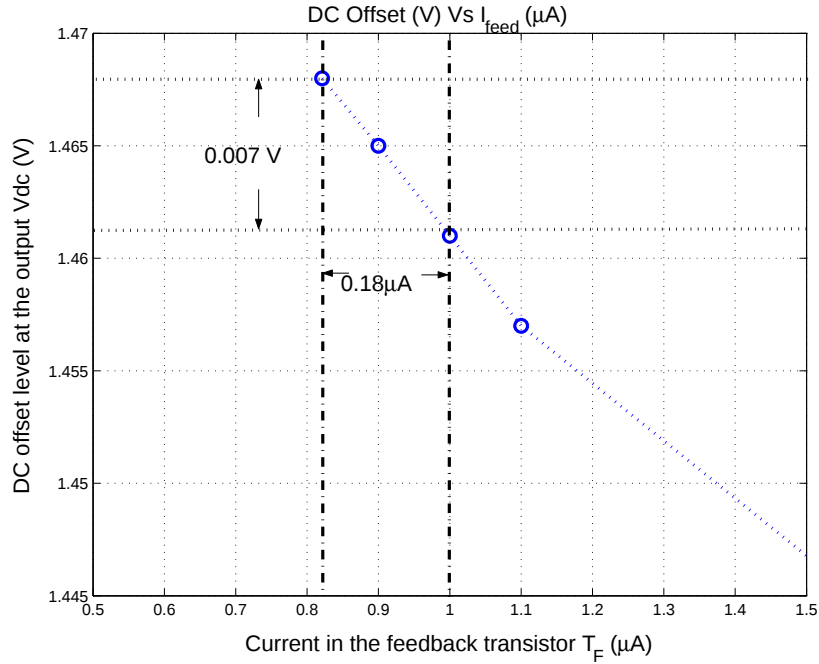


Figure 3.17: The output DC offset was measured when different currents were applied to the feedback transistor. This plot shows how the DC offset varies with the the feedback current.

The DC offset of all the channels were measured and the results as shown in Table.3.3 and in Figure 3.18.

Amplifier Output Channels	DC Operating Level (V)
1 (Test Channel)	1.464
2 (Guard Fence)	1.360
3 (Guard Fence)	1.312
4	1.432
5	1.458
6	1.461
7	1.464
8 (Middle Strip)	1.464
9	1.462
10	1.458
11	1.440
12 (Guard Fence)	1.36

Table 3.3: DC operating level measured for all channels at the output of the amplifier. The value measured at the test channel was used a reference when the detector leakage current was zero and was measured to be 1.464 V.

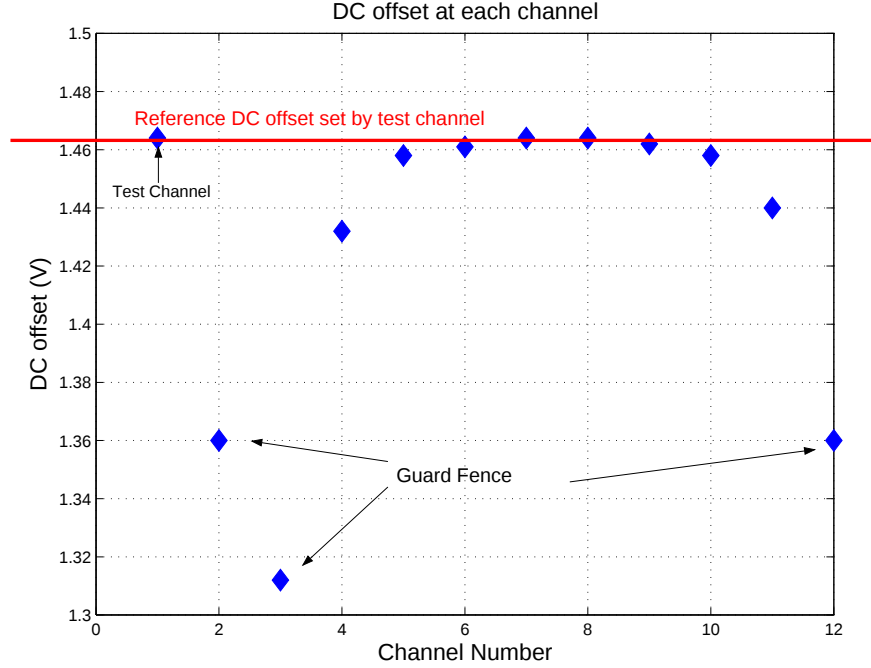


Figure 3.18: The DC offset of each connected channel was measured. With the chosen operating conditions, the test channel (channel 1) had a DC offset of 1.464 V. The guard fence had a value much smaller than the test channel. Channel 7 and 8 are the same as the test channel.

Channels 7 and 8 had a DC offset that is the same as the test channel of 1.464 V, indicated by the line in Figure 3.18. A large difference from the test channel value was seen in channels 2, 3 and 12. This implies that the leakage current is large in these channels. They are also located around the edge, confirming the measured current in Section 3.1.1 is mainly due to the edge current.

Because channels 7 and 8 and the test channel had the same DC offset, this indicates that the leakage current in these two channels were less than 25 nA, referring to Figure 3.17. This confirms that the leakage current measured in Section 3.1.1 was mostly caused by the large edge current that was taken away by the ‘guard fence’. This study also shows that channels 7 and 8 are best for data taking.

3.4 Detections of X-ray and Beta Particles

Studies of the amplifier provided key information for the detector testing. The operating condition was chosen for the optimal output response. Channel 8 was chosen for signal recording since it had the smallest leakage current. Once this was prepared and set up, induced signals from a 3D detector were recorded using two radioactive sources - ^{90}Sr and ^{109}Cd .

Figure 3.19 shows how the source was situated in the measurement set up. The radioactive source was placed 3.2mm above the surface of the Printed Circuit Board. Each induced signal was recorded by the digital oscilloscope as explained in Section 3.2. Several thousands of signal traces were recorded for each set of data with different sources and bias voltage. In this section, induced signals from each radioactive source are shown and described. Their time response, pulse heights and their dependence with bias voltage are also studied. These results will be compared with further simulation in Chapter 4. Some measurements were also taken at low temperature and will be shown in Section 3.4.3.

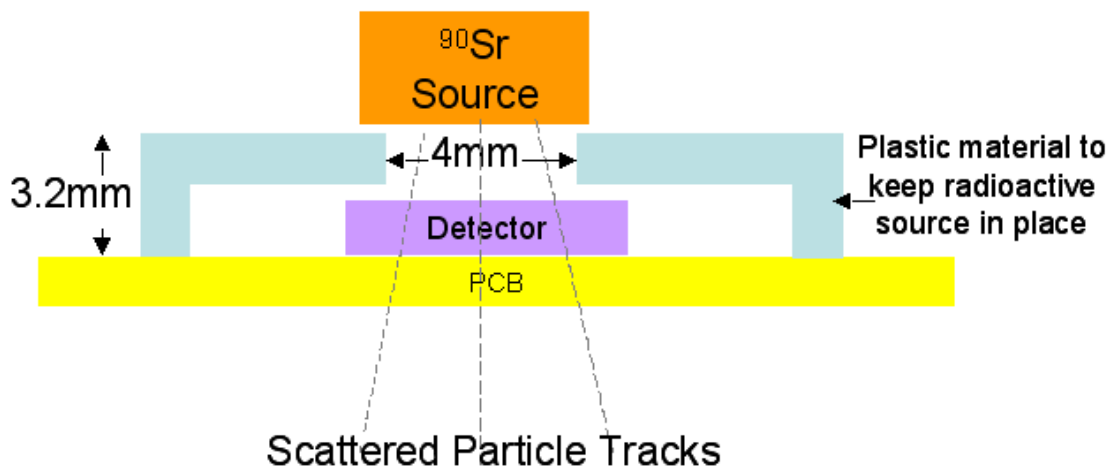


Figure 3.19: During measurement taking, the radioactive source was placed on top of the detector and held in place by a holder made of a perspex material. It was placed 3.2mm away from the surface of the PCB. Not to scale.

Measured signals show clear detection of X-rays and betas. Figure 3.20 shows two recorded signals when the detector was fully depleted. One resulted from an X-ray photon (^{109}Cd) and the other from a beta electron (^{90}Sr). Both signals have a rise time of 4 ns and a fall time of 10.5 ns, the fast charge collection time of 3D detectors was thus demonstrated. For a full statistical analysis, many traces were recorded.

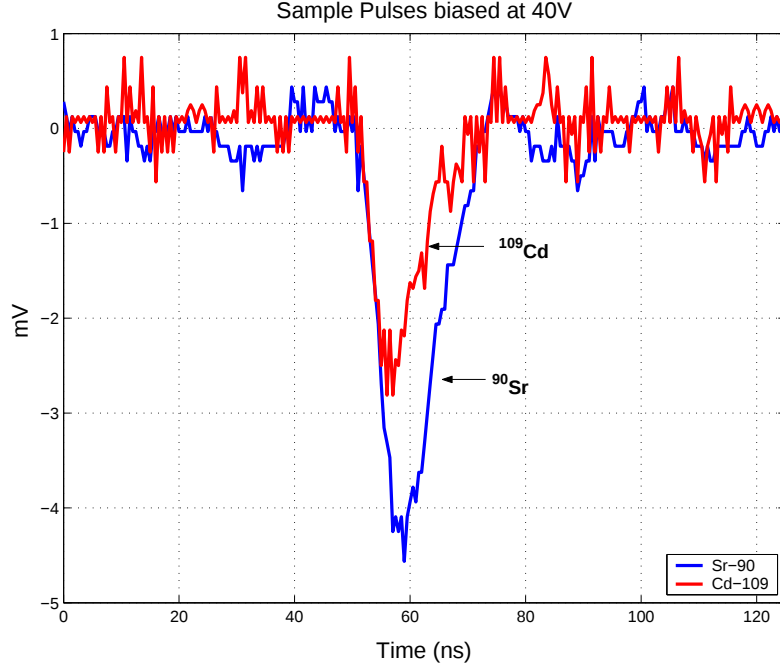


Figure 3.20: Example of recorded signals obtained from an X-ray photon - ^{109}Cd source (red) and a minimum ionizing electron - ^{90}Sr (blue). The detector was biased at 40 V

An analysis program was written in MATLAB in order to study the signal behaviour and its dependence with bias voltage. This involved the calculation of statistical parameters for every set of data collected. The program was also used to minimise fluctuations in the recorded signals. Due to the wide bandwidth of the readout amplifier, reducing the system noise was an ongoing challenge throughout data taking. The minimum noise of the system was measured to be 750e^- . This is higher than the noise quoted in ref. [7] and can be explained by the extra input capacitance due to the detector, the wire bonds and extra transmission lines, when compared to the set up described in ref. [7] with the amplifier alone.

The effect of the noise made it difficult to determine the time response parameters accurately. It also caused problems in getting a full pulse height spectrum. This is because signals with low pulse heights were hidden by the noise, in particular at low bias voltage. In later sections, it will be shown that the data taken from the X-ray source was not reliable because of the noise.

The first purpose of the analysis program was to reduce these fluctuations in the recorded signals. It first measured the RMS value of the noise by looking at the baseline of each recorded signal. It then identified the signal pulse height and consequently the 10 %, 50 % and 90 % points of each signal trace. Data points that were within plus and minus one RMS noise from these points were extracted and were fitted by a linear equation to provide some smoothing of the data, illustrated in Figure 3.21. From the fitted equations, the 10 %, 50 % and 90 % points were redetermined, allowing measurement of the following parameters for each recorded signal:

1. Pulse height
2. Rise Time - 10 % to 90 %
3. Fall Time - 90 % to 10 %
4. Full Width Half Maximum - 50 % to 50 %

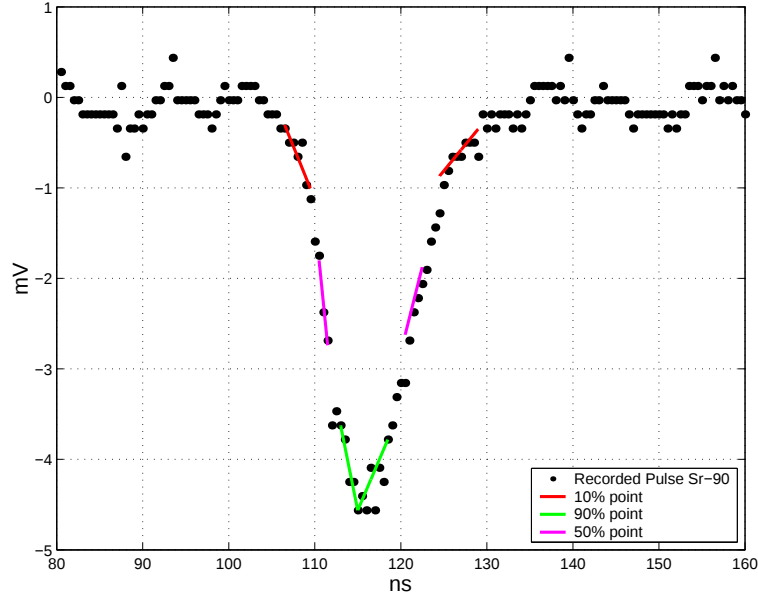


Figure 3.21: A typical output signal due to a beta particle with the detector biased at 40 V. The data that were within plus and minus one rms noise value at the 10 %, 50 % and 90 % points were fitted to a straight line. The points were determined from the fitted equation. These gave a better estimation for the time response parameters.

3.4.1 Pulse Height Distribution

From the analysis program described in the last section, the pulse height of each induced signal was measured. This resulted in the pulse height spectrum for a given radiation. The system was calibrated by finding the mean of the pulse height distribution obtained by the 3D detector at full depletion using a ^{109}Cd source. ^{109}Cd was used as it provides a discrete X-ray energy line at 22 keV and in principle the distribution of the pulse height should follow a Gaussian distribution.

The mean pulse height can be predicted using Eqn.3.5 if the deposited energy is known for the incident particle. The average energy required to generate an electron-hole pair in silicon is 3.6 eV. A 22 keV X-ray photon should therefore generate approximately 6111 electrons in a silicon detector, corresponding to an input charge of 1 fC. Using Eqn.3.5 in Section 3.3.4 and assuming the charge collection time is fast enough, the pulse height of an induced signal resulted from an X-ray photon at 22 keV is 2.8 mV.

Similarly, the most probable pulse height of an induced signal from a beta particle emitted from a ^{90}Sr was also predicted. A minimum ionising particle typically generates 80 electron-hole pairs in one μm thick silicon. In the 3D detector under test which was $121\ \mu\text{m}$ thick, 9860 electrons should result from a beta particle, this is equivalent to a charge of 1.6 fC. Using Eqn.3.5 in Section 3.3.4, the most probable pulse height for a beta particle would be 4.48 mV.

Figure 3.22 shows the pulse height distributions obtained from a ^{109}Cd source at different bias voltages. The distributions show a bad signal to noise especially at low bias voltage. One reason was due to the low statistics and a lot of the recorded signals were noise with large amplitude that were difficult to be separated from the valid signals. This is particularly true at low bias voltage. In order to identify a solution, a detailed observation of each recorded signal was made. It was found that at low bias voltages, many noise signals had very large amplitudes, most are as large as the valid X-ray signals. An example of this large noise signal is shown in Figure 3.23.

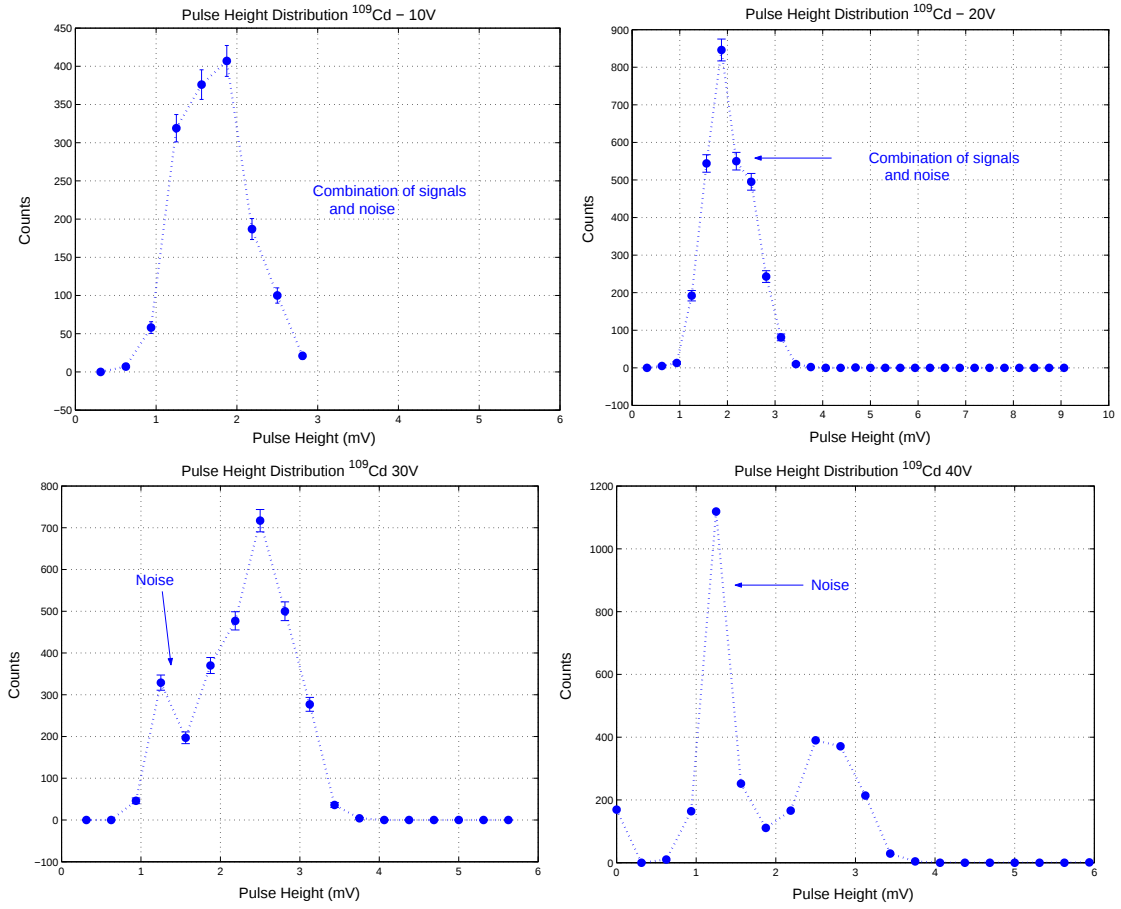


Figure 3.22: The pulse height distributions were obtained at different voltages. The signals were obtained using an X-ray source - ^{109}Cd .

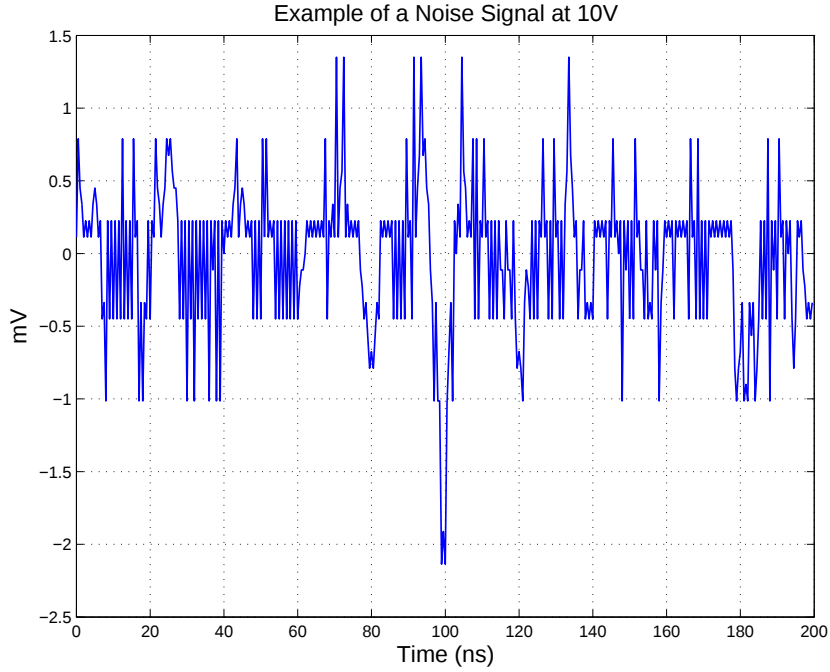


Figure 3.23: These noise pulses are very large and occurred at regular intervals. The intervals are long. This made them difficult to be recorded when the oscilloscope was busy recording the X-ray signals at high bias voltages. They were therefore only recorded at low bias voltages.

These noise signals at low bias voltages occurred at long regular intervals. At high bias voltage, the detector count rate was high and the oscilloscope was busy recording valid X-ray signals at all times. The noise signals were therefore rarely recorded at high bias voltages. Their amplitudes were large and applying a threshold in amplitude could not eliminate them. Moreover, the low signal-to-noise of less than 10 at low bias voltage also made the X-ray data at low bias voltage very difficult to analyse accurately. The analysis from here onwards therefore uses the data obtained from the beta source - ^{90}Sr , for which the signal-to-noise at full depletion was about 14.

The pulse height distributions from the beta source are shown in Figure 3.24. At 40 V, the distribution follows a Landau distribution, although the lower end of the expected distribution was hidden by noise. The distribution at 40 V was fitted with a Landau approximation (Eqn.3.6) [62].

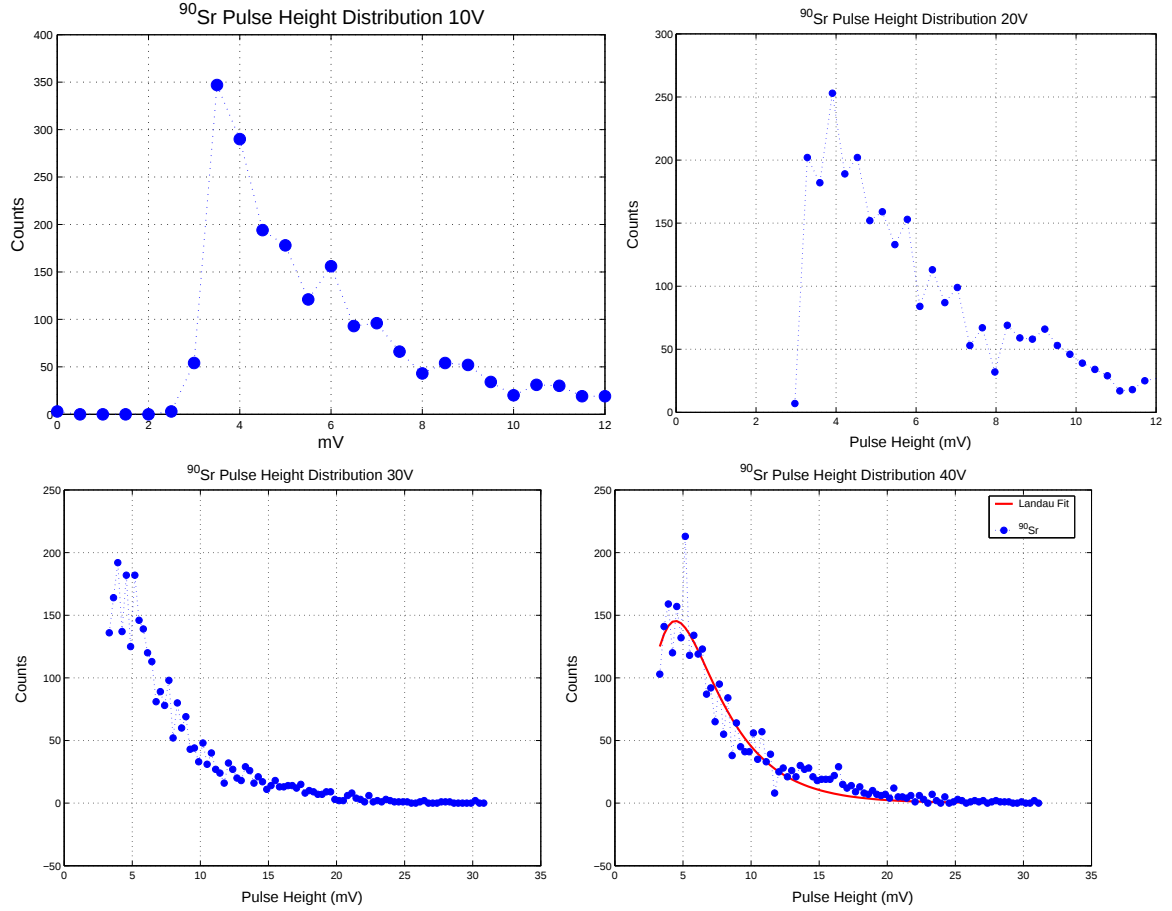


Figure 3.24: The pulse height distributions were obtained at different voltages. The signals were obtained using an β -source - ^{90}Sr .

$$\Phi(\Lambda) = \sqrt{\frac{e^{-\Lambda} + e^{-\Lambda}}{2\pi}} \quad (3.6)$$

The most probable value obtained from the fit was 4.49 mV. This is in very good agreement with the predicted value of 4.48 mV using the amplifier gain characteristics. As already mentioned, these distributions cannot be used to deduce the true energy spectra accurately because it is a current amplifier, in which the output pulse height is proportional to the charge collection time as well as the total charge collected. It is however, of interest to understand how the pulse height of the output signals behave and their dependence with bias voltage. This was studied by obtaining the mode for each pulse

height distribution which are plotted as a function of bias voltage in Figure 3.25. The data from betas and X-rays have similar trends.

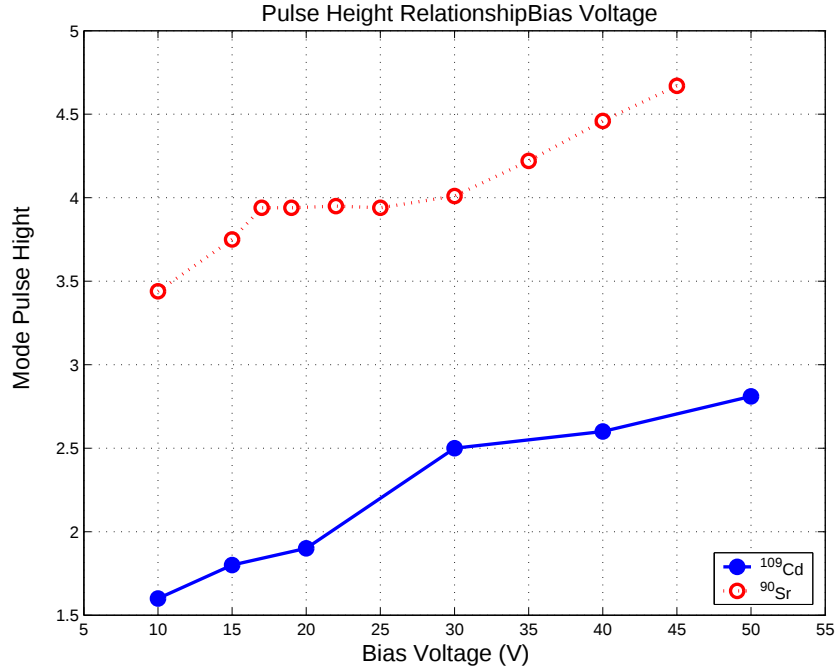


Figure 3.25: Measured pulse heights (modes) at different bias voltages for signal induced from minimum ionising particle ^{90}Sr and ^{109}Cd .

The data obtained from a ^{90}Cd source was scaled to be equivalent to that of the beta source and are compared in Figure 3.26. This plot clearly shows that the data from the two sources have the same trends. This continuous increase in the pulse height with bias voltage is understood because a current amplifier was used. The output pulse height increases with the drift velocity of the charge even beyond its depletion voltage.

3.4.2 Time Response Studies

The time response parameters were measured for each recorded signal. Variations at a specific voltage were studied by calculating the statistical parameters, but the raw distributions were first inspected.

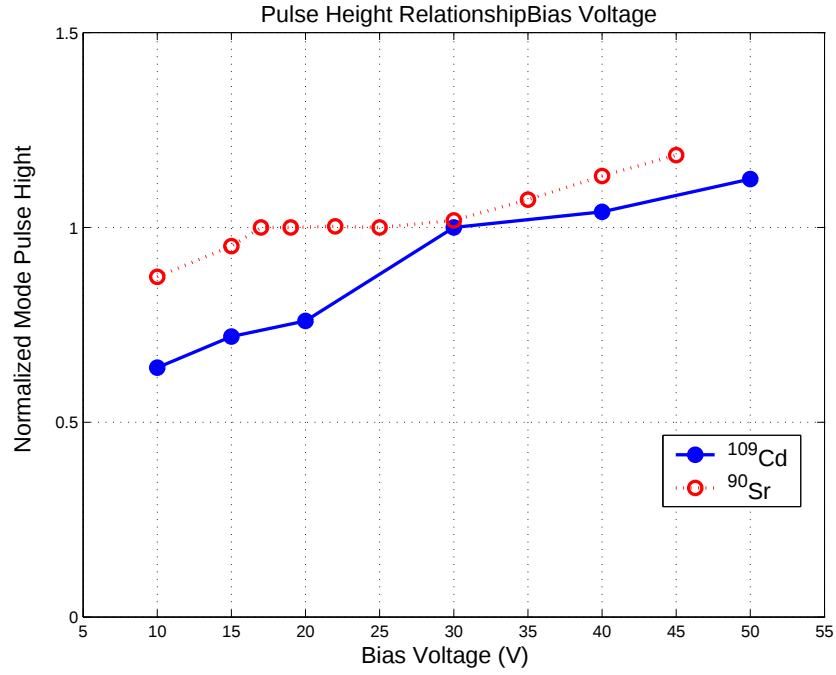


Figure 3.26: Measured pulse heights at different bias voltages for signal induced from minimum ionizing particle ^{90}Sr and ^{109}Cd .

3.4.2.1 Time Response Distributions

The rise time distributions are shown in Figure 3.27 and they all show a skewness towards the right. Each distribution was fitted with a lognormal distribution.

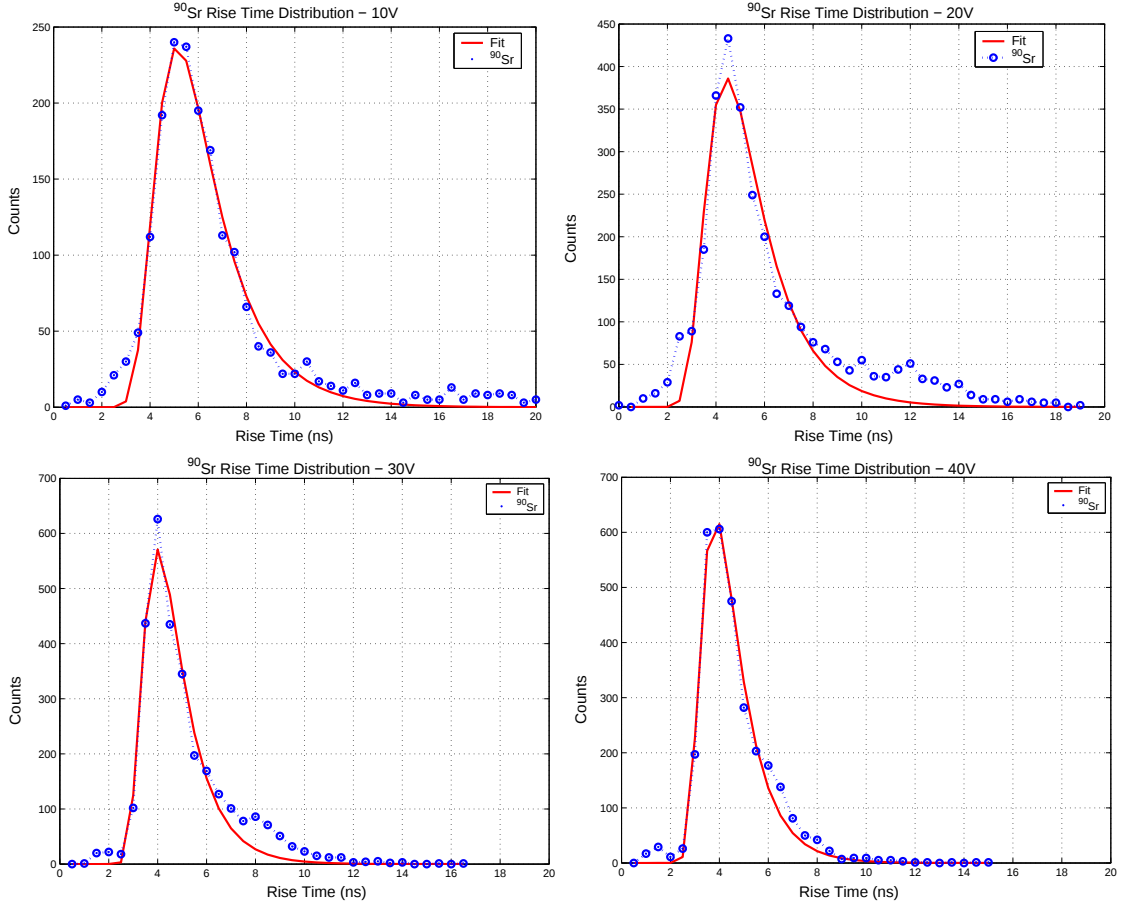


Figure 3.27: The rise time distributions were obtained at different voltages. The signals were obtained using an beta source - ^{90}Sr .

Similarly, the fall time distributions at different voltages are shown in Figure 3.28. Unlike the rise time, the differences in the four distributions are very distinct, in particular at 10 V where the spread is very large. The spread of each distribution then reduces with bias voltage. This implies that there is a more uniform behaviour across the detector once it is fully depleted. The symmetry of the distributions also changes with the bias voltage, this will be studied in Section 3.7 by calculating the skewness factor. The distributions were fitted with a lognormal distributions except for the one obtained at 40 V. At 40 V, the distribution became very symmetrical and was therefore fitted with a Gaussian Distribution.

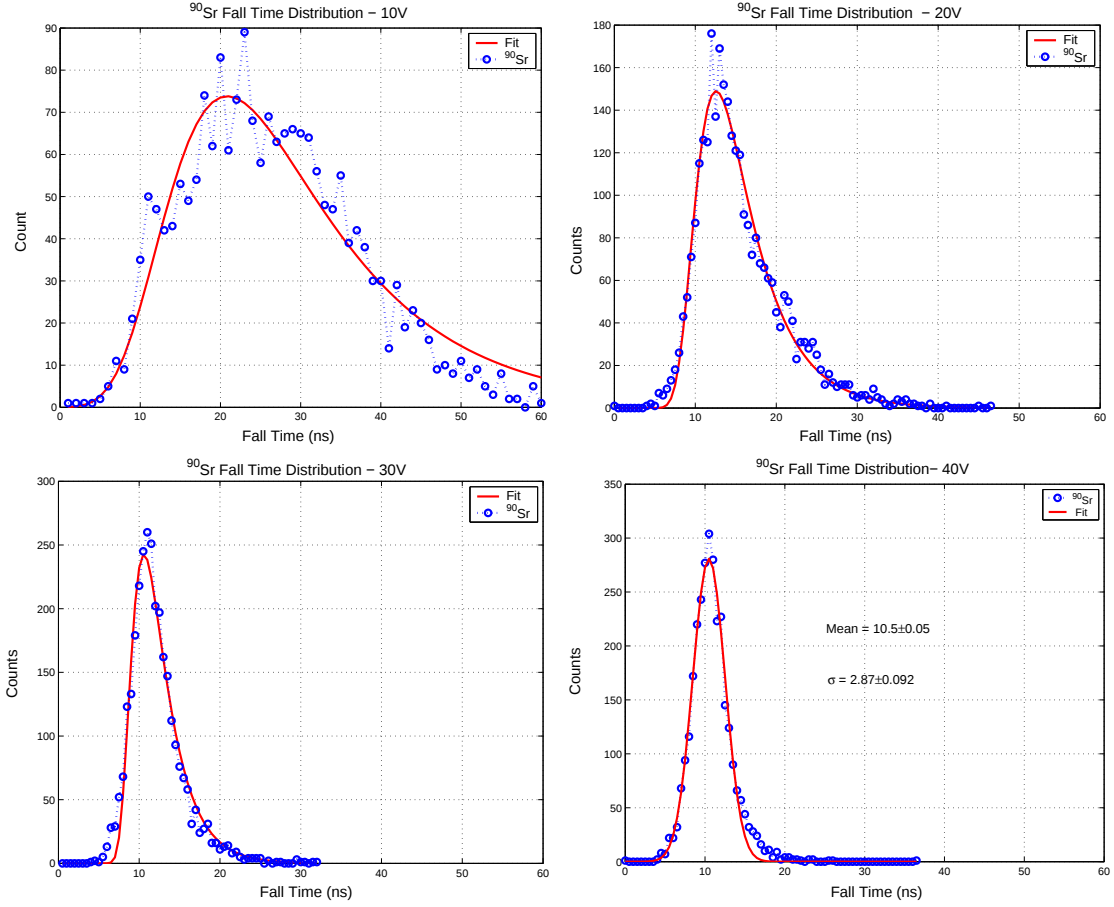


Figure 3.28: The fall time distributions were obtained at different voltages. The signals were obtained using a beta source - ^{90}Sr .

The distributions of the signal full-width-half-maximum (FWHM) at various voltages are shown in Figure 3.32, very similar the fall time distributions. The signal FWHM as observed from these distributions, appeared to give little extra information when compared to the rise and the fall time. The analysis from here onwards will exclude this parameter. Similar to the other time response parameters, the distributions were fitted to a lognormal distribution except for the one obtained at 40 V. At 40 V, this was fitted with a Gaussian distribution when the distribution became symmetrical.

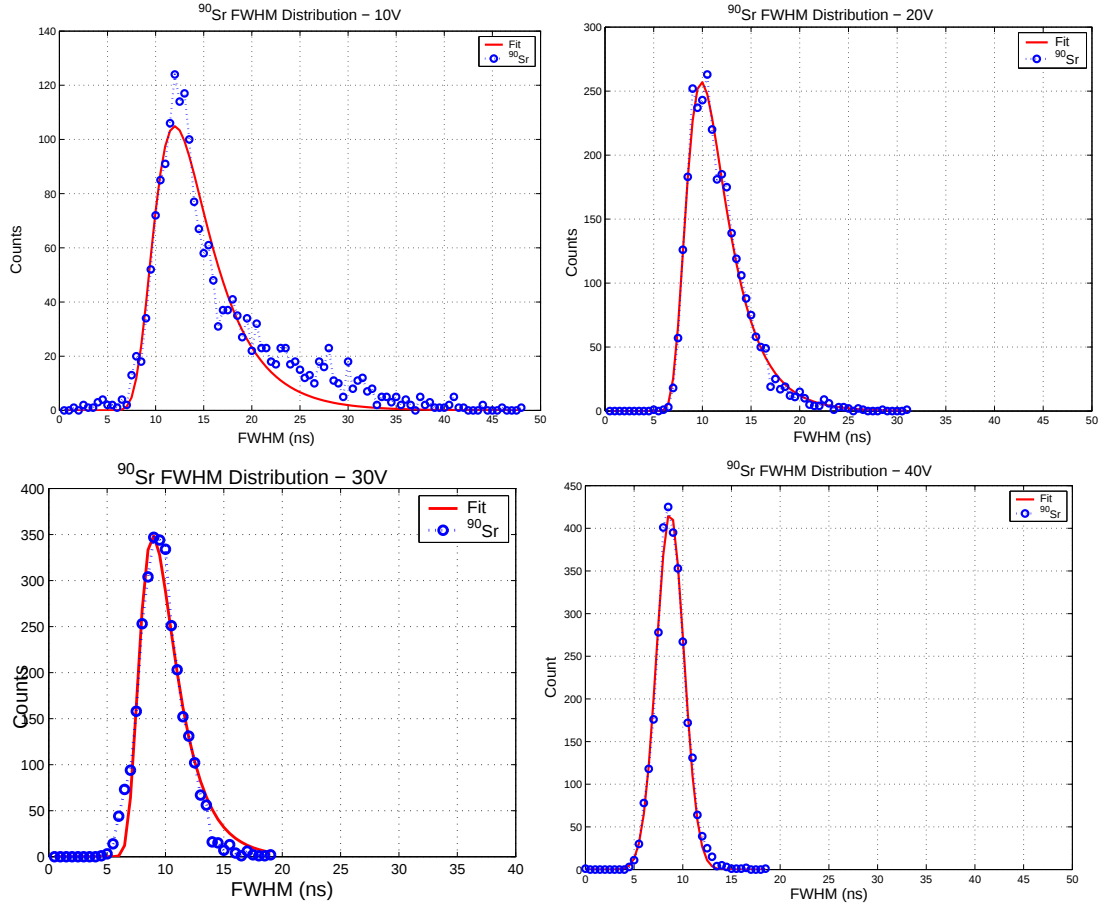


Figure 3.29: The signal full-width-half-maximum distributions were obtained at different voltages. The signals were obtained using an beta source - ^{90}Sr .

3.4.2.2 The Average Time Response Behaviour - Mean

The means of each time response parameter were obtained by fitting the raw distributions to the equations as described earlier. The results are plotted as a function of bias voltage in Figure 3.30.

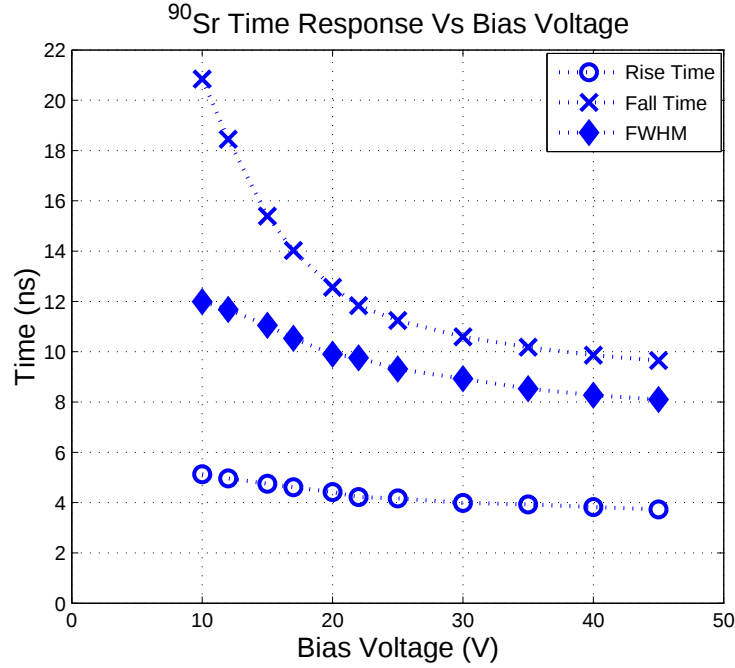


Figure 3.30: Various time parameters were measured to identify speed variations at different bias voltages. The rise time, fall time and FWHM (full-width-half-maximum) were measured for data taken with biasing from 10 V to 45 V.

In Figure 3.30, it is clear that the time response decreases with bias voltage. It also reaches a minimum at around 30 to 40 V. The minimum rise and fall time was 4 ns and 10 ns respectively. The minimum time response however was limited by the amplifier. This is confirmed by Figure 3.15 when the amplifier output rise time did not decrease with decreasing input rise time. The minimum found here is also 4 ns, the same as the minimum of the amplifier. In order to further identify the minimum time response of the detector, one must use an amplifier that has a faster time response. Some studies are currently being performed using a faster amplifier designed in $0.13\ \mu\text{m}$ technology, which has a rise time of 1.5 ns at room temperature.

In order to understand the variance in the output signals and their dependence with bias voltage, the following parameters were calculated besides the fitted means; the standard deviation, full-width-half-maximum and the skewness factor.

3.4.2.3 Time Response Variations - Standard Deviation

The standard deviation and the full-width-half-maximum of each distribution can show how the measured time responses vary from its mean. They were calculated for each bias voltage. Figure 3.31 shows the standard deviation decreases at higher bias. This means that the variations across the cell reduce at higher voltages and the time response behaviour becomes more uniform. When the detector was not fully depleted at low bias voltage, the particles arrived in the un-depleted region, travel more slowly than those traversing the depleted region. This explains the large variations when the detector was partially depleted at low bias voltage. At 30 to 40 V, the detector was fully depleted except for the highly doped electrodes. A more uniform behaviour was therefore expected and as a consequence a lower standard deviation is recorded. The behaviour of the electrodes are very different to the bulk and this is studied in Chapter 5. A similar trend is shown in Figure 3.32 for the distribution full-width-half-maximum. This further confirms a more uniform behaviour across the detector at high bias voltage. Notice in both Figure 3.31 and Figure 3.32, that the change in the fall time is more prominent than the rise time. Chapter 4 will describe a system simulation that will explain this observation.

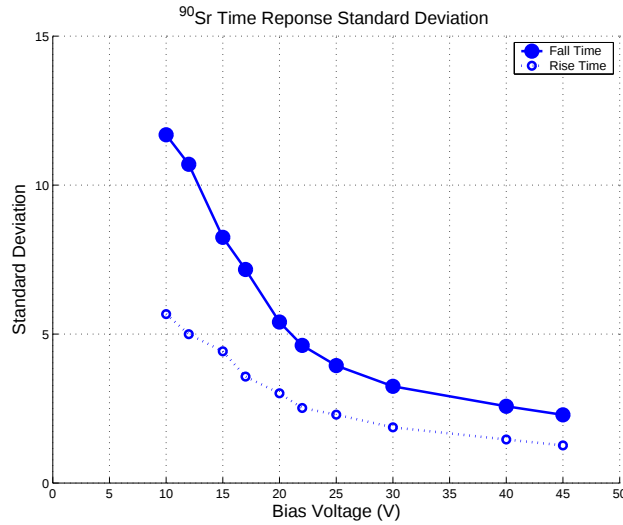


Figure 3.31: The spread of the data for each voltage is measured by calculating the standard deviation. The variations decrease with bias voltage.

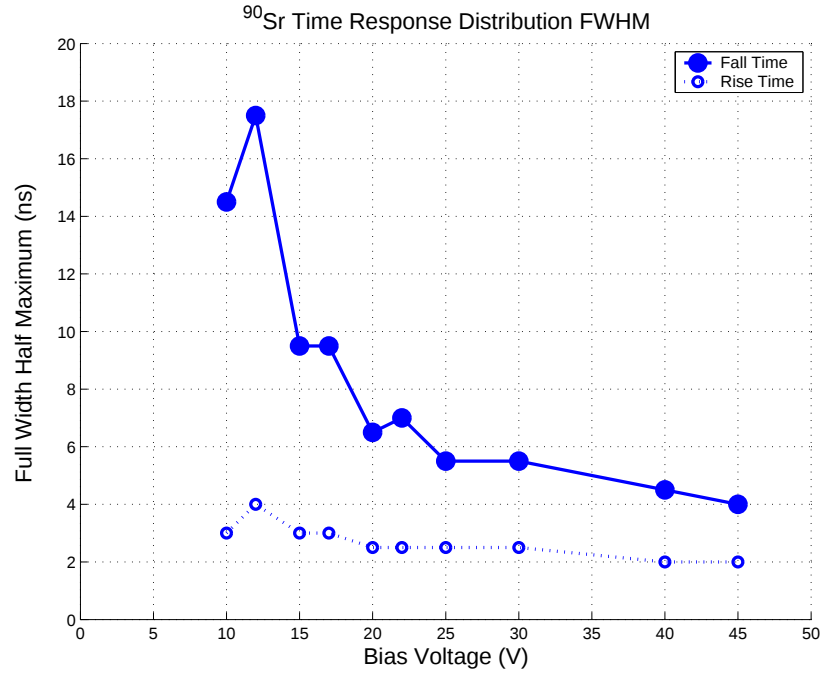


Figure 3.32: The spread of the data for each voltage is measured by calculating the full-width-half-maximum of the distribution.

3.4.2.4 Symmetry of the Time Response Distributions

The time response distributions were shown to be unsymmetrical in particular at low bias voltage. The magnitude of the symmetry was measured by calculating the skewness factor using Eqn.3.7. This is a well known statistical parameter [63].

$$Skewness = \frac{(Y_i - \bar{Y})^3}{(N - 1)\sigma^3} \quad (3.7)$$

$\bar{Y}$ is the mean, σ is the standard deviation and N is the number of samples taken. The skewness for a normal distribution is zero and symmetrical data should have a skewness factor close to zero. This was investigated by plotted the skewness factor with respect to the bias voltage as shown in Figure 3.33.

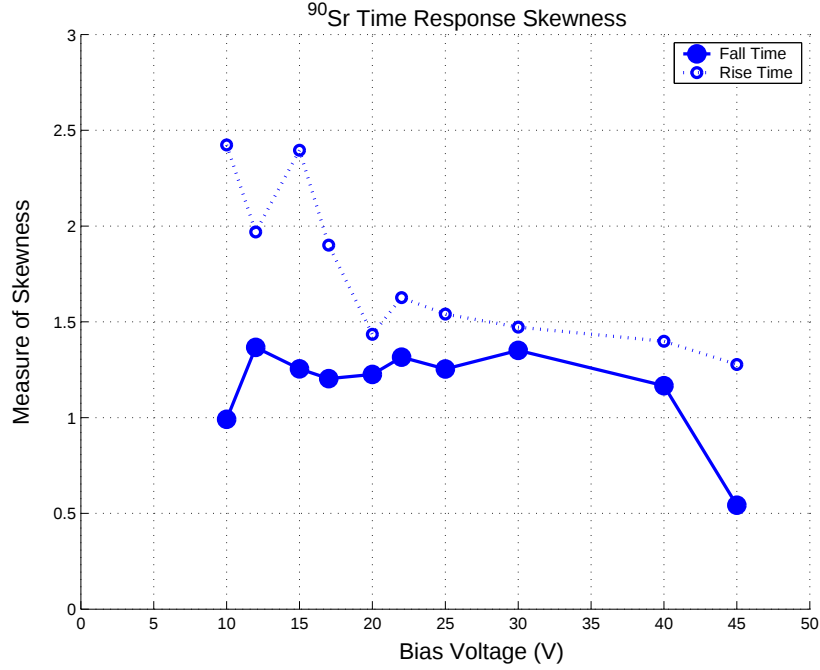


Figure 3.33: The skewness factors were calculated for each distribution. It decreases with increasing bias voltage. This suggests a more symmetrical distribution at high bias voltage. This also implies the reduction of the long tail with increasing bias voltage.

Figure 3.33 shows the skewness factor decreases with increasing bias voltage, which can be seen by inspecting the raw distributions. The long tails observed in both the rise time and the fall time distributions (Figure 3.27 and Figure 3.28) became shorter at high bias voltage. Once fully depleted, the induced signal in the 3D detector is faster than the amplifier. The observed output signals had a variance that are dominated by noise only. This observation is therefore expected. However, the trends between 10 to 20 V are not clear in the two cases studied here: variance and symmetry. This was not understood at this stage of the analysis. In Chapter 4, the full system simulation will give a better understanding of this behaviour.

3.4.3 Low Temperature Measurement

Charge carriers have a higher mobility at 130 K. This implies that both the detector and the amplifier have a faster time response at low temperature. The current amplifier used was designed to operate at cryogenic temperature and was shown to have a rise time of 1.5 ns at 130 K. The amplifier would therefore provide a good readout tool to test the charge collection time in a 3D detector at cryogenic temperature. This temperature was achieved by using a vacuum cryocooler shown in Figure 3.6 discussed in Section 3.4.3. A hermetically sealed ^{90}Sr source was placed inside the vacuum chamber.

One recorded signal is shown in Figure 3.34 with the detector biased at 40 V. The signal has a rise time of 1.5 ns and a fall time of 4 ns. From the baseline of the trace, it is clear that the signals suffered from some oscillations. The amplifier was at its stability limit with the same operating condition that was chosen at room temperature. Attempts were made to retake the data with improved conditions, but this was difficult if one wishes to have a compromise in both gain and the time response at the output signals. Due to this oscillation, the analysis program that was previously used at room temperature was not able to identify the time response parameters accurately.

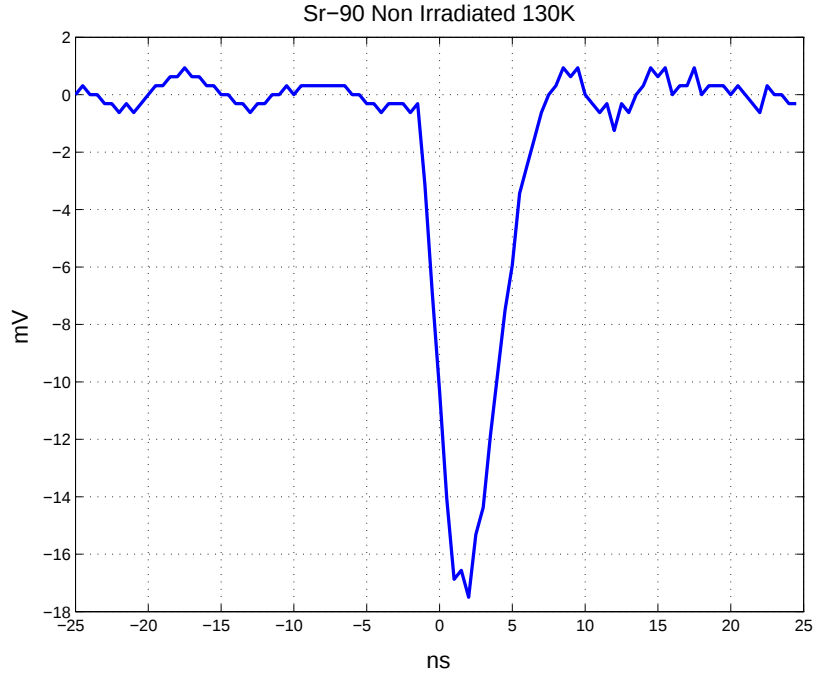


Figure 3.34: An output signal recorded at 130 K using a ^{90}Sr source with the detector biased at 40 V.

An alternative method was used to analyse this set of data. Each output signal was inspected carefully. Figure 3.35 shows a set of recorded signals when the detector was biased at 10 V, the signal shapes between them were shown to be very similar, except for fluctuations that were caused by noise and the amplifier oscillation. The only main difference was the pulse height of the signals. This is expected because of Landau fluctuations of the minimum ionising particles. Since the signal shape does not vary by a large amount at a given voltage, an average signal should give a good approximation of the time response. However, the variance could not be studied with this approximation.

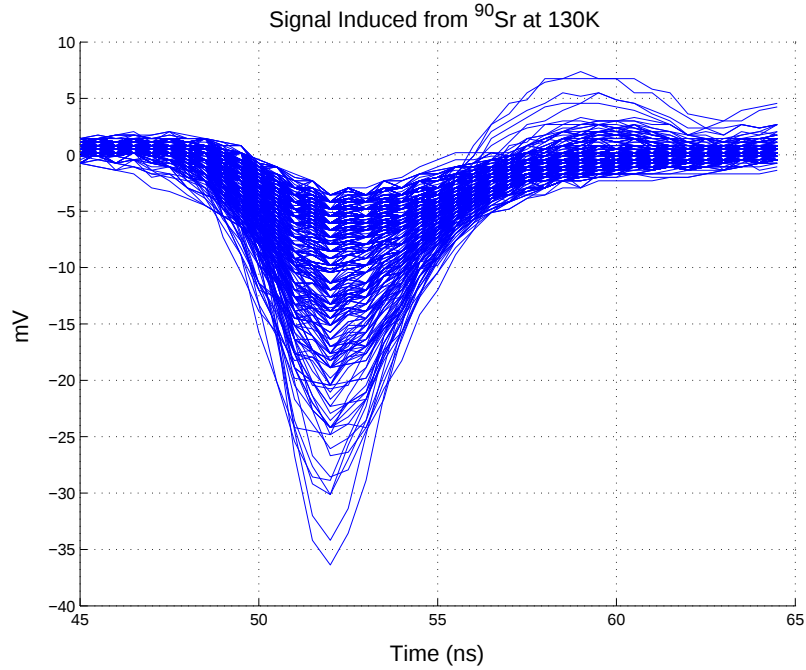


Figure 3.35: Inspection of many signals recorded at 130 K with the detector biased at 40 V using a ^{90}Sr radioactive source. Results show that small differences in shaping and time response.

The average signal was obtained by averaging all signals at a particular voltage after aligning them at their peak value to avoid any time jitter effects. The resulting average signals are shown in Figure 3.36. These were used to study the time response dependence with bias voltage, by measuring the fall time, the rise time and the full-width-half-maximum for each average signal. These are plotted as a function of bias voltage in

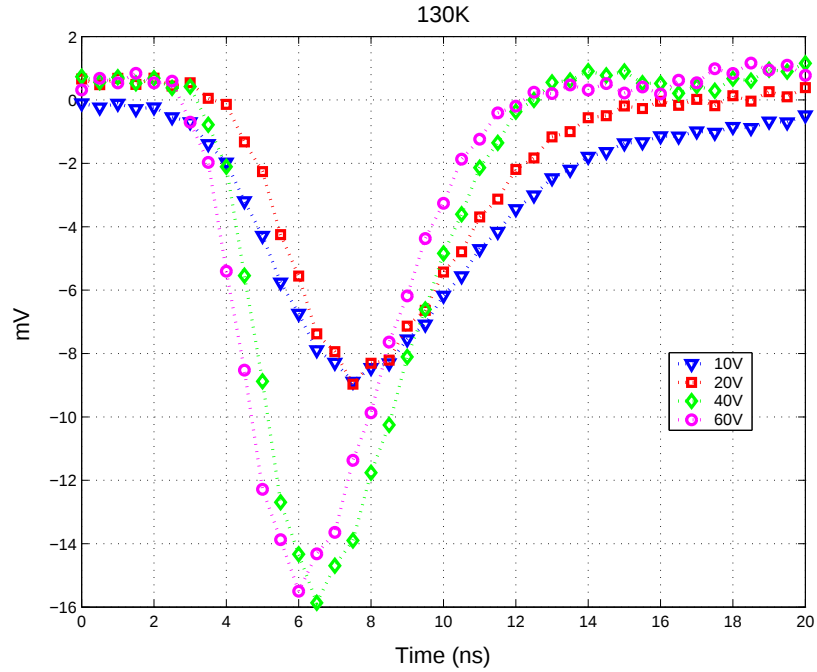


Figure 3.36: An average signal was obtained by averaging all signals recorded at a specific voltage. These were used to give study of the time response dependence with bias voltage.

Figure 3.37. The results show a similar trend to the one seen at room temperature (Figure 3.30), the time response decreases with increasing bias voltage and eventually reaches a minimum.

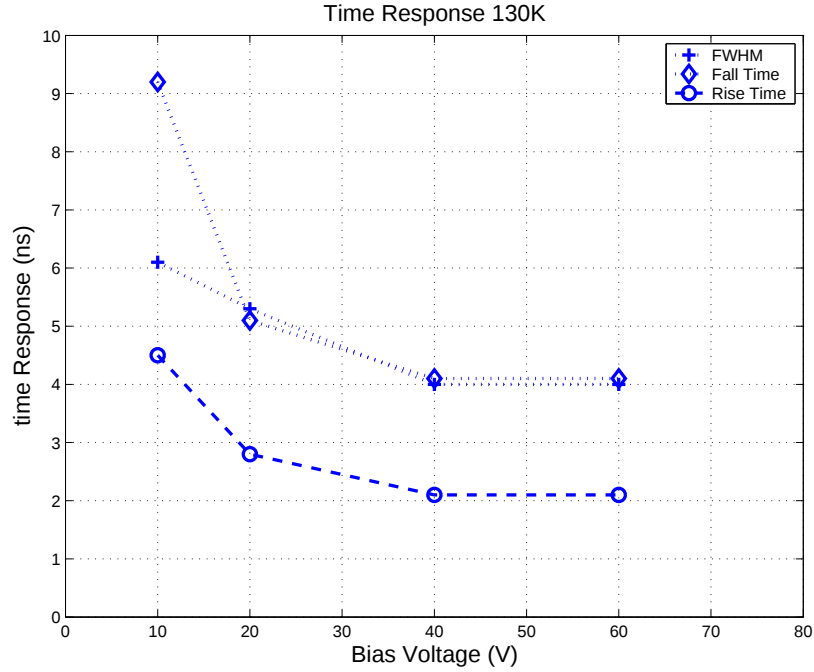


Figure 3.37: Relationship of time response parameters with detector bias voltages at 130K, showing an inverse proportionality, until it reaches the minimum time response of the amplifier.

In order to ensure that this simple analysis is valid, the same method was applied to the data taken at room temperature. The average pulses obtained using the same method are shown in Figure 3.38. The corresponding time response was measured and its dependence with bias voltage is shown on the left of Figure 3.39.

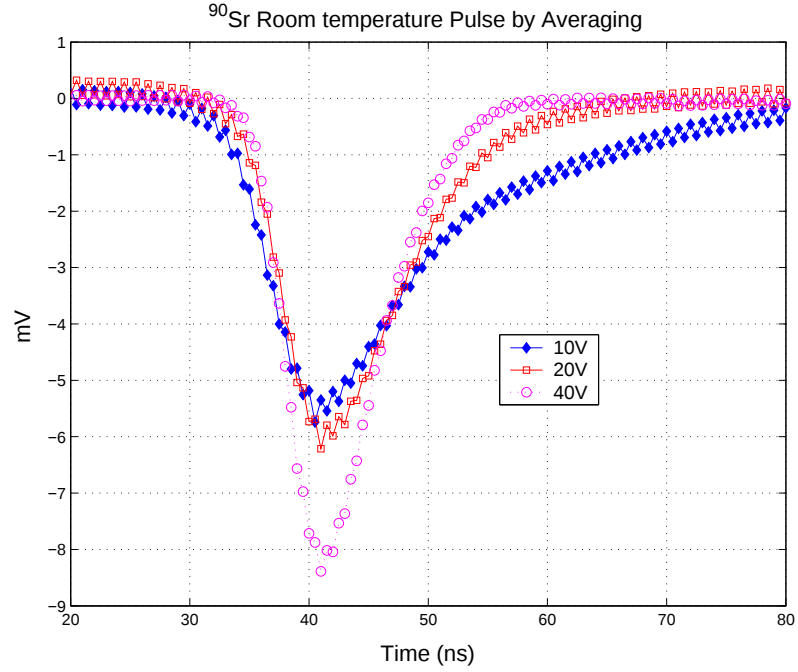


Figure 3.38: Average signal was obtained at different bias voltage after aligning the peak values of all recorded signals. These signals were obtained at room temperature. This was performed to check if this method gave similar results to the previous analysis.

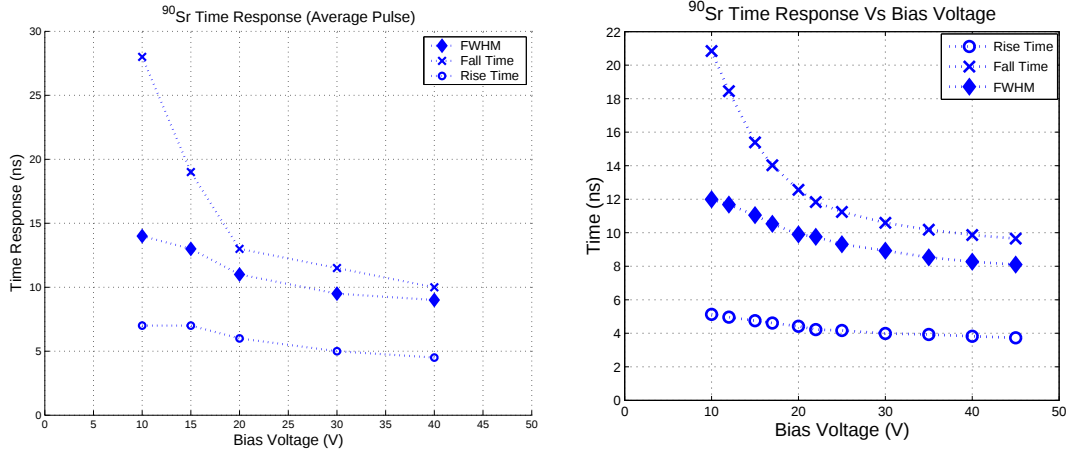


Figure 3.39: Left: The time response parameters were measured for the average signals shown in Figure 3.38. Right: the time response dependence with bias voltage obtained by using the fitted means to all signals. This is compared to the results shown on the left to check if the method by averaging the signals give a reasonable approximation for the data at 130 K. Results are almost identical.

The results are almost identical to the ones shown on the right of Figure 3.39 obtained from the full analysis program. For a better comparison, the fall time and rise times are extracted from the two plots and are compared directly in Figure 3.40. A lesser agreement is observed in the rise time. However, the agreement between the two methods shows that this simple analysis by averaging all the signals was valid. Although it does not give full details, it has successfully derived the relationship between the time response and bias voltage at 130°K for a 3D detector.

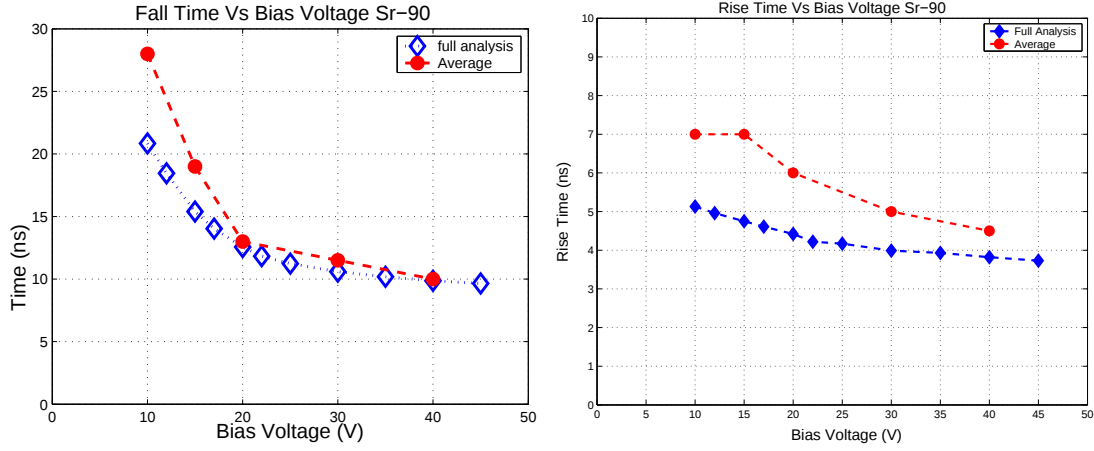


Figure 3.40: Left: Fall times obtained using two different analysis are compared as functions of bias voltage Right: Rise times obtained using two different analysis are compared as functions of bias voltage.

This study of measured signals from the 3D detector gave an understanding at both room temperature and $130^\circ K$. Signals with a rise time of 4 ns were observed at room temperature when the detector was fully depleted. At $130^\circ K$, the rise time was 2 ns at full depletion. 3D detectors are verified to be many times faster than a planar silicon detector. However, many details in the signal behaviour are yet to be understood and a full understanding can only be understood by simulation. The first attempted simulation was performed by Julie Segal using MEDICI and this was fed into the HSPICE model of the amplifier to predict the output signal.

3.4.4 Simulation Using HSPICE

A preliminary simulation was performed to compare the predicted results to the measured pulse shape from a minimum ionising particle. 3D detector calculations were made by Julie Segal using MEDICI [64] to give predictions of induced signals. An example of the calculated signal at a p-electrode for a $121 \mu\text{m}$ thick detector is shown in Figure 3.41, where the detector was biased at 40 V. Two peaks are seen in Figure 3.41, one is formed by the hole and the other is formed by the electron.

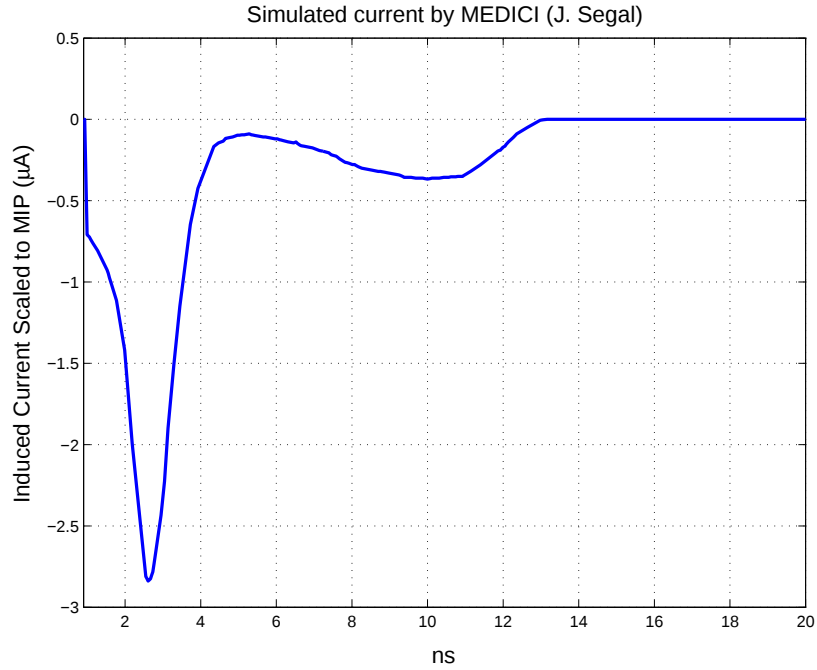


Figure 3.41: A calculated induced current pulse at a p-electrode by a minimum ionizing particle using MEDICI in a 3D detector.

The fast amplifier used in the measurement was simulated thoroughly before production using HSPICE, this model was a useful tool in many studies. Here, it was used to predict the output signal due to an induced current from a 3D detector. The simulated output signal is compared with a typical signal recorded from a minimum ionising particle is shown Figure 3.42, showing a good agreement between them. Further simulation studies are described in Chapter 4.

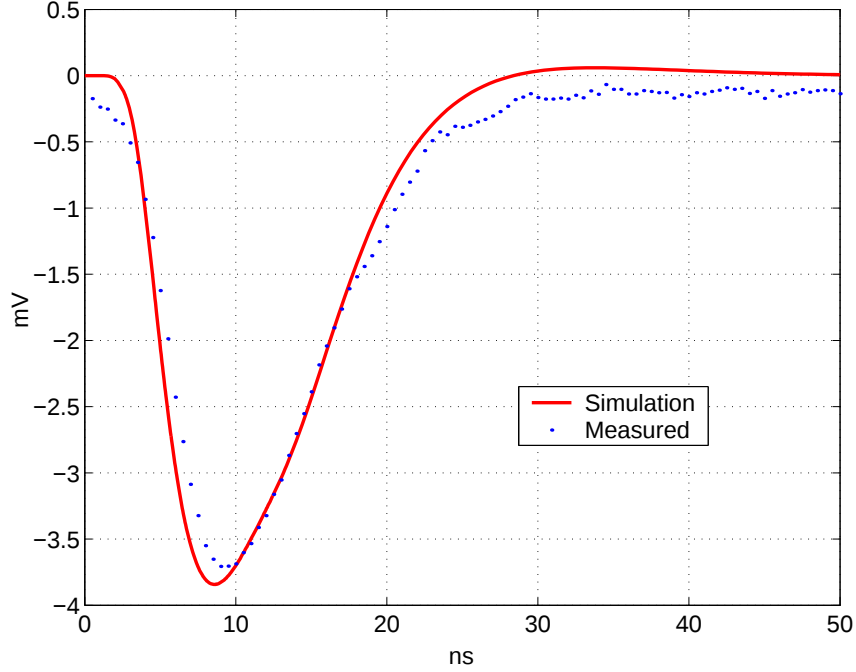


Figure 3.42: Current pulse simulated shown in Figure 3.41 was used as an input to the amplifier’s simulation model. The simulated output response is compared with the measured signal pulse

3.5 Summary

This chapter explains the setup used to measure the time response of a 3D detector using a fast readout amplifier at both room temperature and 130 K. Signals due to X-ray photons and minimum ionising particle were studied and the short collection time of 3D detectors was verified. The minimum rise time was measured to be 4 ns and 2 ns at room temperature and 130 K respectively. This is the limit set by the amplifier. The pulse shape of the output signal is highly dependent on the amplifier response once the detector is fully depleted; the induced signal from the detector is faster than the amplifier response. The detector used in this test has a pitch of $200\text{ }\mu\text{m}$. The time response is expected to be even faster with a newer version of 3D detector that has a pitch of $50\text{ }\mu\text{m}$. In this scenario, a even faster amplifier would be required.

A comparison between measured and predicted signals were made for a minimum ionising particle using the HSPICE model of the amplifier, which a good prediction for the output signal. In Chapter 4, a detailed full system simulation will be described.

Chapter 4

Simulation of Time Response Studies

Measured signals resulting from betas and X-rays were studied and analysed in Chapter 3. The main emphasis was to study the dependence of the output signals with bias voltage. The aim of the simulation is to model the system and to produce comparable results in order to give a better understanding of the measured signals from a 3D detector. In the measurement, the hit position of the particles were unknown and it is important in order to understand the signal behaviour across a 3D detector. This is therefore investigated by the full system simulation, including both the detector and the amplifier. The system model and the simulated results are described in this chapter.

4.1 Full System Simulation

The full measurement set up described in Chapter 4 was split into three main subsystems. Each was modelled separately as described in Figure 4.1 and they are:

1. Detector Model
2. Induced Signal Formation Model
3. Amplifier Model

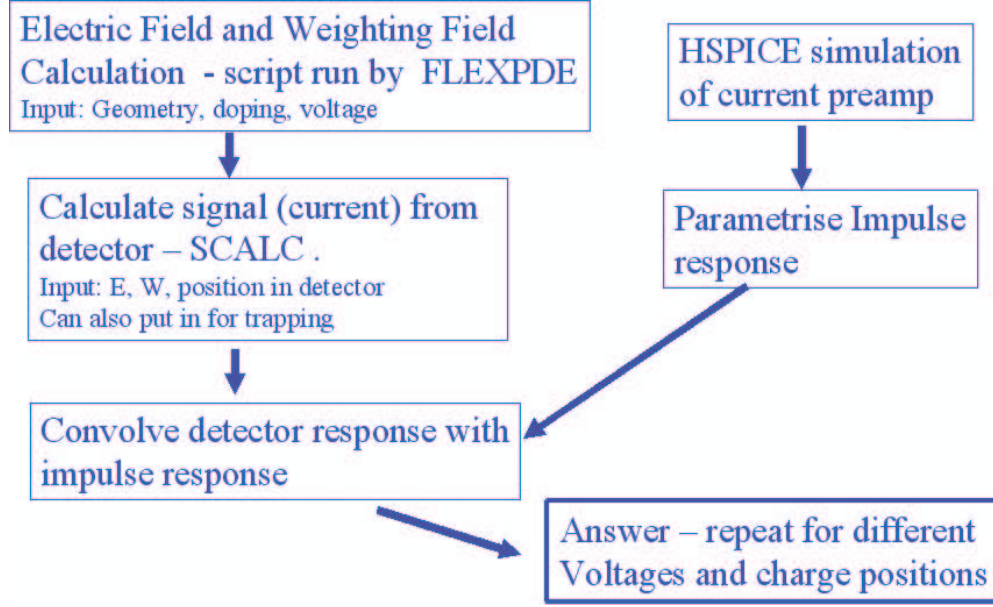


Figure 4.1: Simple block diagram showing the main subsystems in the simulation model to obtain results to compare with measurements.

The first subsystem was the detector. A software package called FlexPDE was used to calculate the weighting fields and the electric fields across the detector after details of the detector geometry and doping details were given. The mathematical detail and results obtained are described in Section 4.1.1.

The weighting field and the electric field calculated from FlexPDE [68] were used to calculate the induced current using Ramo's Theorem. A program was written to perform this calculation called SCALC. The program started with the injection of an electron-hole pair at a specified position. Using the calculated weighting field and electric field, together with a given charge position, it calculated the induced signal using Ramo's Theorem.

A model of the fast amplifier was essential to complete the simulation chain and was modelled by its impulse response. A current impulse was injected into the HSPICE simulation model and the corresponding impulse response was fitted by a chosen mathematical formula. By convolving the calculated induced currents with the resulting amplifier model, output signals due to a single electron-hole pair were calculated. The

parametrisation process for the amplifier model is described in Section 4.1.3.

The combination of the three subsystems formed the simulation model for the entire measurement system. The full calculation process was repeated for different charge positions at various voltages, forming sets of predicted signals that were compared to the measured data. More information and detailed results of each individual model are described in the following subsections.

4.1.1 Detector Model - Carrier Collection Simulation

This requires that one calculates the electric field and weighting field for a specified device. One first requires a geometric model of the device which also defines the doping (n-type or p-type) in various regions. 3D technology requires a 3D model, although in some cases this reduces to a 2D solution due to symmetry. Devices manufactured using this technology often involve electrode geometries with circular structures arranged on a rectangular grid. This mix of circular and rectangular geometry is a challenge to many device simulators. Initially the EVEREST [67], 3D simulator was tried. It could not generate the required geometrical structures. Subsequently, a general purpose partial differential equation (PDE) solver was investigated which has an excellent script language which describes the geometry, the PDE's and the boundary conditions. This PDE solver is called FlexPDE [68]. This solver is currently in version 5. Version 4 was used for the work described here. Version 5 allows moving meshes. This may prove a useful feature for future work. FlexPDE4 has no difficulty generating complex geometries. The problem is now to properly describe the PDEs for the system and the boundary conditions. Semiconductor device simulation requires one to solve several coupled PDEs, namely the Poisson equation and continuity equations for electrons and holes. This is non-trivial. However, for the situation in which reverse bias is used across a junction, and when leakage currents are negligible, one can use the non-linear Poisson equation only. This simplifies the problem considerably and allows one to solve for the potential distribution very quickly on a high-end PC.

Poisson's Equation is;

$$\nabla^2 \bullet \phi = -\frac{q}{\epsilon} \rho \quad (4.1)$$

where ϕ is the potential, q is the charge on the electron, ϵ is the dielectric constant of the medium and ρ is the charge density.

$$\rho = (N_D - N_A + p - n) \quad (4.2)$$

where N_D is the fixed donor density, N_A is the fixed acceptor density and p, n are the mobile hole and electron densities respectively.

These equations are always valid. The problem is how to define the mobile charge densities. This is solved by using the fermi-level and relating it to the local potential. This is described in ref. [69]. Referring to Figure 4.2, this results in the following equation for the charge density in an np junction, where the dependence on region, R , has been shown explicitly. The dependence of the potential on x and y is also indicated.

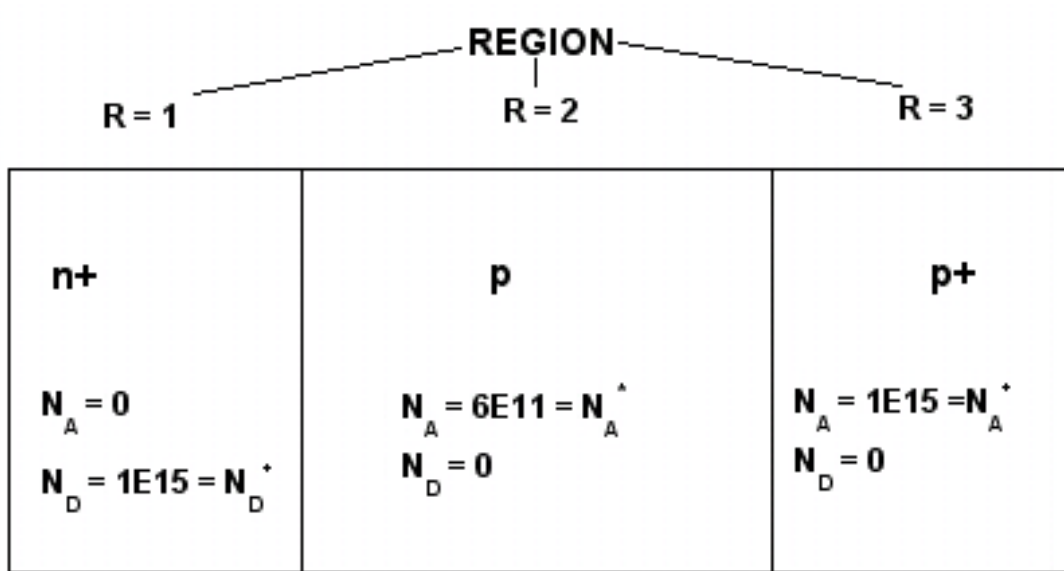


Figure 4.2: Schematic of a n^+p^+ diode defining the doping parameters for various regions. The units of N_A and N_D are cm^{-3} . The main doping parameters for the n^+ , bulk p and p^+ are labelled N_D^+ , N_A^* respectively.

$$\rho = N_D(R) - N_A(R) \exp\left[\frac{(\phi(x,y) - V_L)}{V_{th}}\right] + N_A(R) \exp\left[\frac{(V_R(R) - \phi(x,y))}{V_{th}}\right] \quad (4.3)$$

where $V_L=0$, the reference potential on the n^+ junction, $V_R=-V_{BuiltIn}-V_{Applied}$ which varies with region. $V_{Applied}$ is the applied bias on the p^+ junction. The thermal voltage, V_{th} , is 0.026 V at 300 K. All simulations were performed at this temperature.

The built in voltage, $V_{BuiltIn}$,

is zero in the n^+ junction region ($R=1$),

is $V_{th} \ln\left(\frac{N_A^* N_D^+}{n_i^2}\right)$ in the p bulk ($R=2$),

is $V_{th} \ln\left(\frac{N_A^* N_D^+}{n_i^2}\right) + V_{th} \ln\left(\frac{N_A^+}{N_A^*}\right)$ in the p^+ electrode ($R=2$)

The last term in the above expression represents the built-in potential between the p bulk and p^+ electrode, about 0.2 V. This was not included in the solution shown in this section, but has now been added. It makes little change to the solution.

FlexPDE was also used to solve for the weighting potential. The geometry was identical to that used for the electric potential. The Laplace equation was solved for the weighting potential, namely,

$$\nabla^2 \bullet \phi_w = 0 \quad (4.4)$$

where ϕ_w is the weighting potential. The boundary conditions were, $\phi_w=1$ on the collection electrode (central p_+) and zero on all other electrodes. The weighting field E_w is $\Delta\phi_w$.

Figure 4.3 shows the geometry and finite element mesh used for the 3D detector. The mesh is generated by FlexPDE and is automatically refined if required. It has an inter-electrode spacing of $100 \mu\text{m}$. Figure 4.4 and 4.5 show the development of the electric potential as the external bias was increased. Full depletion occurs at around 20 V. Doping concentrations were as for the 1D device given in Figure 4.2.

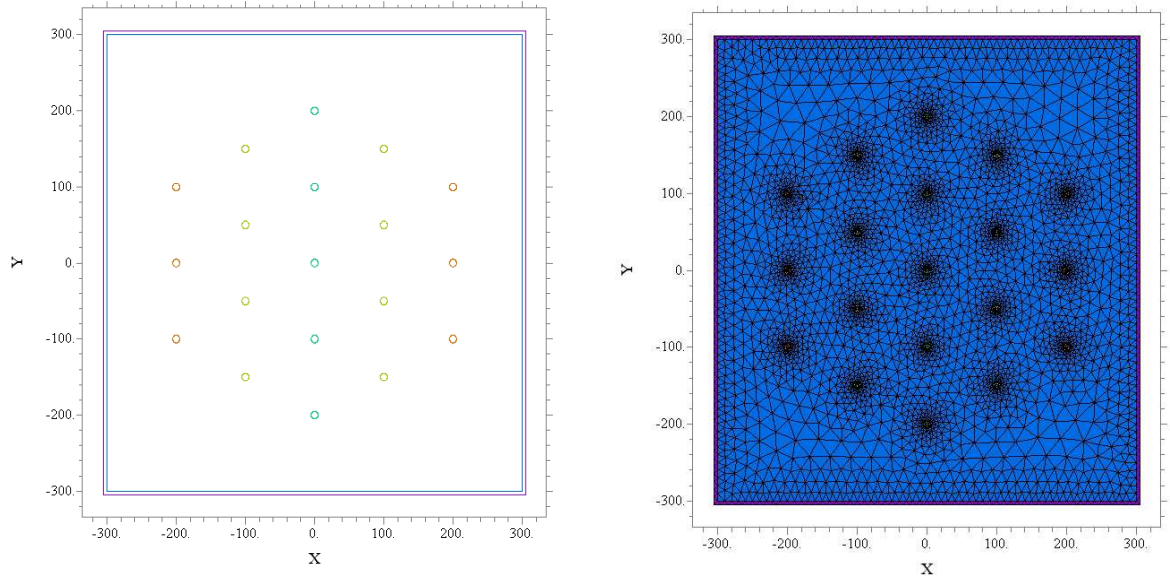


Figure 4.3: Left: The geometry used to model the 3D detector. The p^+ electrodes are at $x=-200$, 0 and $+200$. The n^+ electrodes are at $x=-100$ and $+100$. The dimensions x and y have units of microns. There is a n^+ electrode around the perimeter of the device. The bulk material was p-type. Right: The initial mesh generated by FlexPDE.

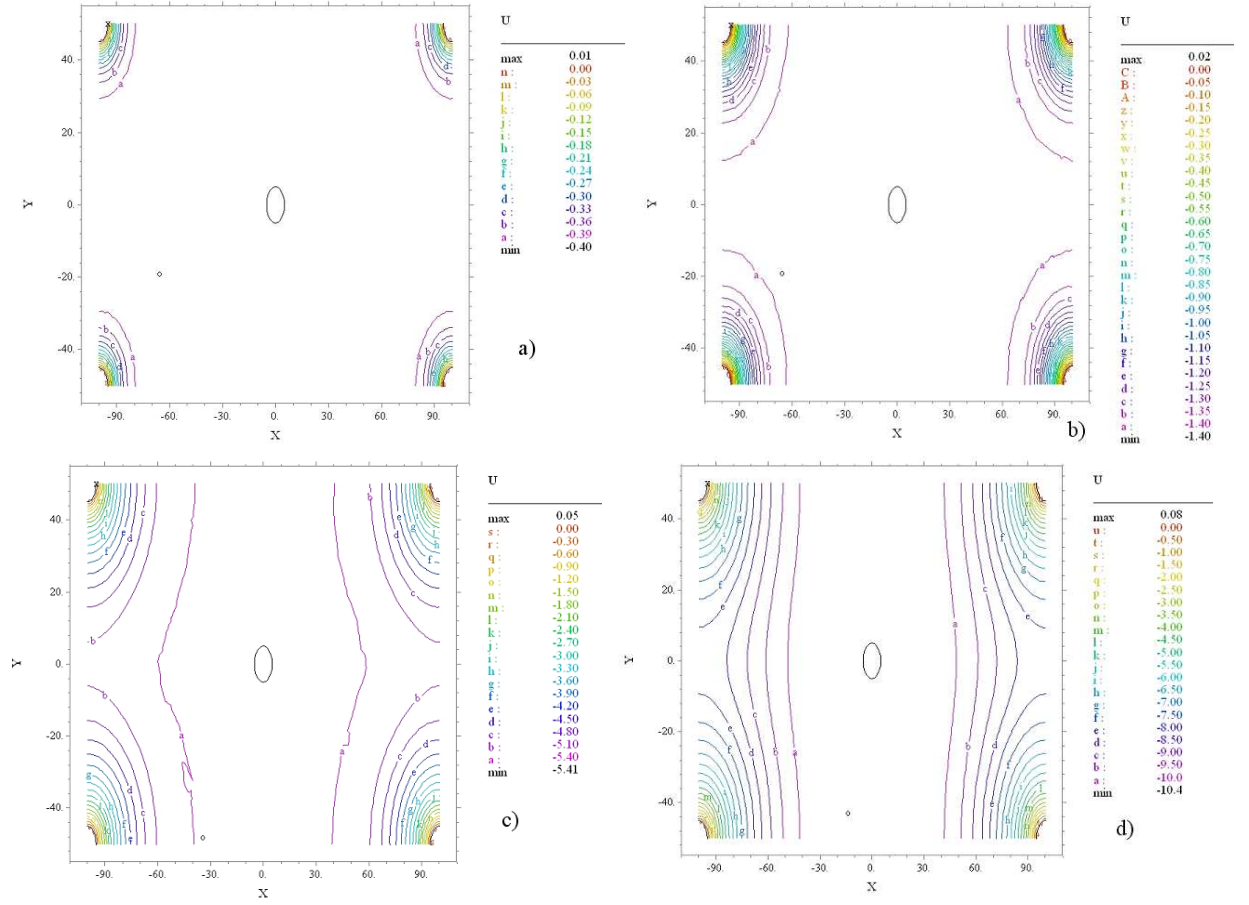


Figure 4.4: Contour plots for different applied potentials for the central region a) 0 V b) 1 V c) 5 V d) 20 V. Dimensions are in μm

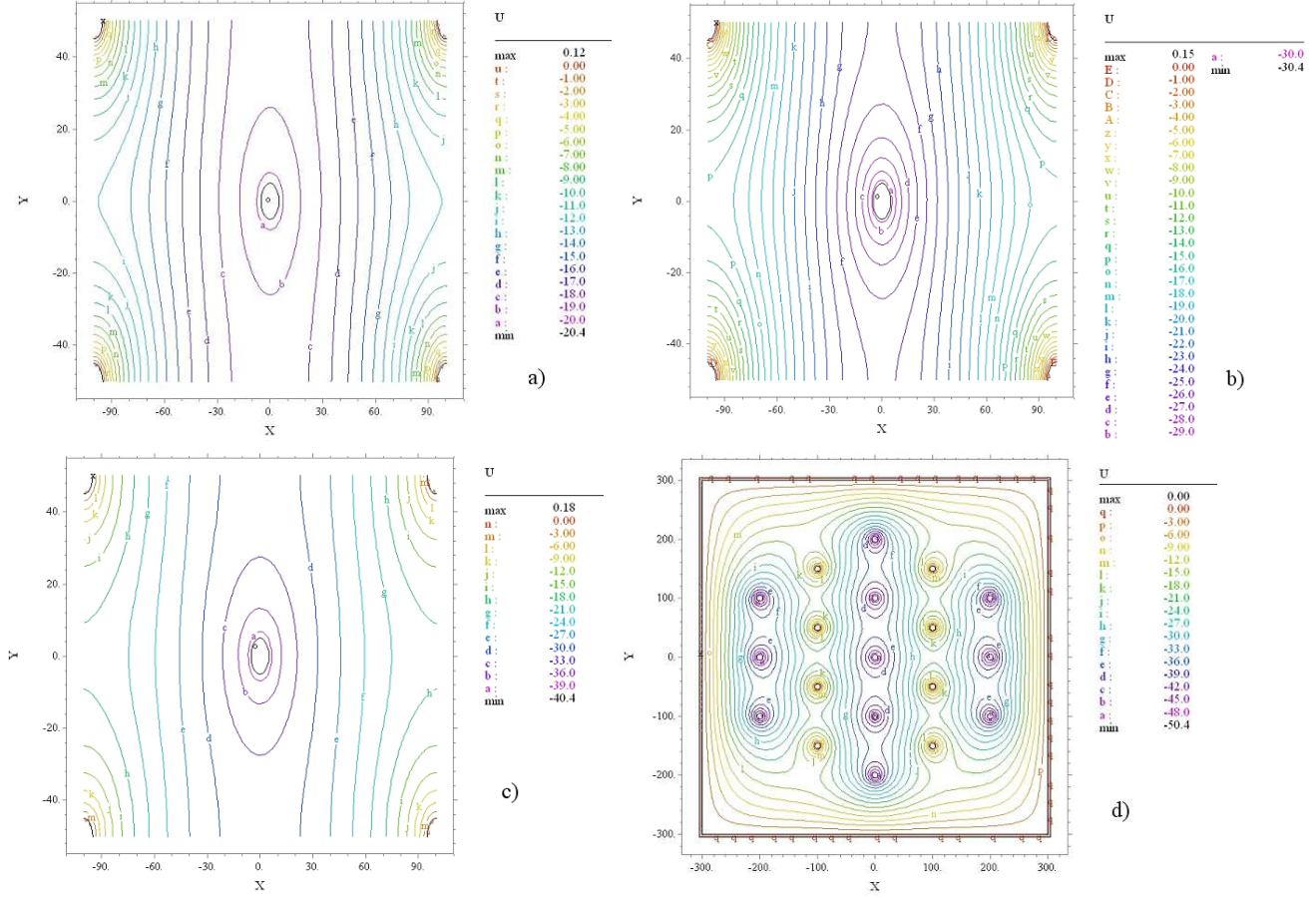


Figure 4.5: Contour plots for different applied potentials for the central region a) 20 V b) 30 V c) 40 V d) is for the whole device. Dimensions are in μm

Figure 4.6 shows the weighting potential for the 3D detector being simulated. Data files for the potential, electric field, and weighting potential were written to disk by the FlexPDE program. These were then used by a specially written program, SCALC, to calculate the current pulse for an electron-hole pair starting at a given point in the device. The results of this calculation are described further in Section 4.1.2.

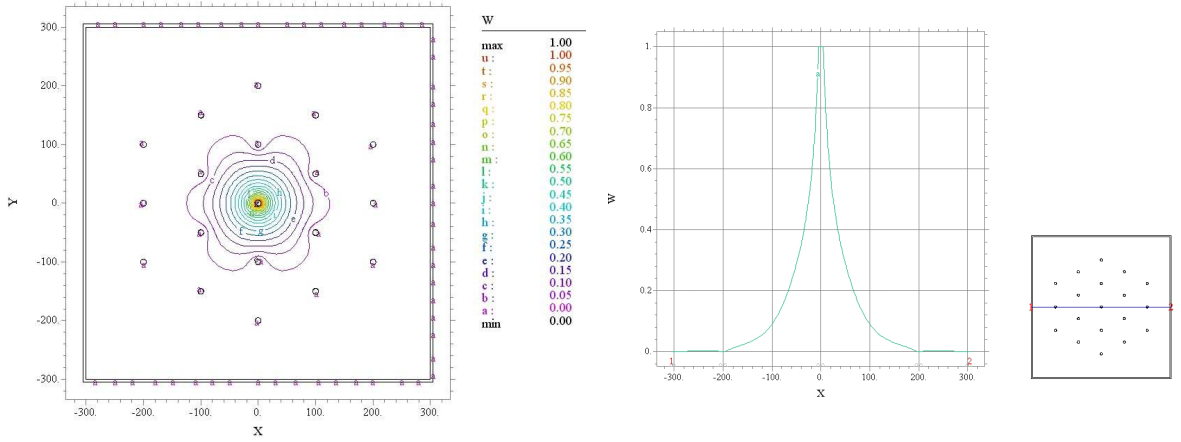


Figure 4.6: Left: Contour plot for the weighting potential, W . Right: A slice across the device, indicated by the smaller inset picture, showing the weighting potential as a function of x . Dimensions x and y are in μm .

4.1.2 Induced Signal Formation Model

Figure 4.7 shows the studied cell that was divided into 400 rectangles by a 20×20 grid. Each rectangle was $10 \times 5 \mu\text{m}^2$ in size and the studied cell was $200 \times 100 \mu\text{m}^2$, which is the same as the cell size in the tested detector described in Chapter 4. The grid provided a coordinate system that had an origin at the centre of the collecting p-electrode. An electron-hole pair was injected at the centre of each rectangle that had a coordinate of (x_i, y_i) . The corresponding induced current was calculated using Ramo's theorem by the SCALC program according to the charge position and the calculated weighting field and electric field. As a result, a total of 400 induced currents at the defined locations in Figure 4.7 were generated. This was repeated for voltages varying between 10 V and 50 V, producing a set of simulations that could be compared with the measured signals. In this section, the induced signal from two different positions are studied at different bias voltages. This provides an understanding of the variations in the output signals and how their behaviour vary with bias voltage. Examples of induced signals are studied in this section. Two charge positions are shown and they are $(-80, -25)$ and $(-50, 0)$ according to the coordinate system in Figure 4.7. This section first shows the collection path of both the electron and hole for each charge position.

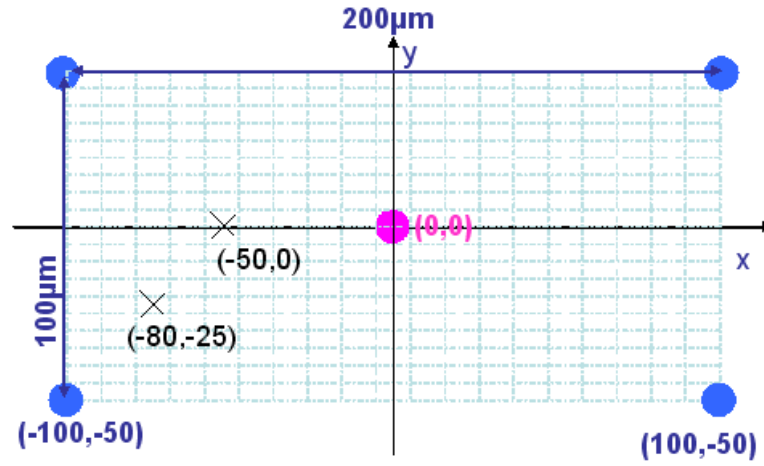


Figure 4.7: The central cell of the detector far away from the edge was divided into 400 rectangles by the defined grid. Charge was injected at the centre of each rectangle. This gave an induced current at the collecting p-electrode according to the calculated weighting field, electric field and charge position using Ramo's Theorem.

When a 3D detector is reversed biased, the holes are collected by the p-electrode and the electrons are collected by the n-electrode. Figure 4.8 shows the collection paths of both the electron and the hole from the point of charge injection to the corresponding collecting electrodes. The detector was biased at 40 V. The total charge collection times were different for the two different positions, as shown in the overall induced currents for the two positions in Figure 4.9.

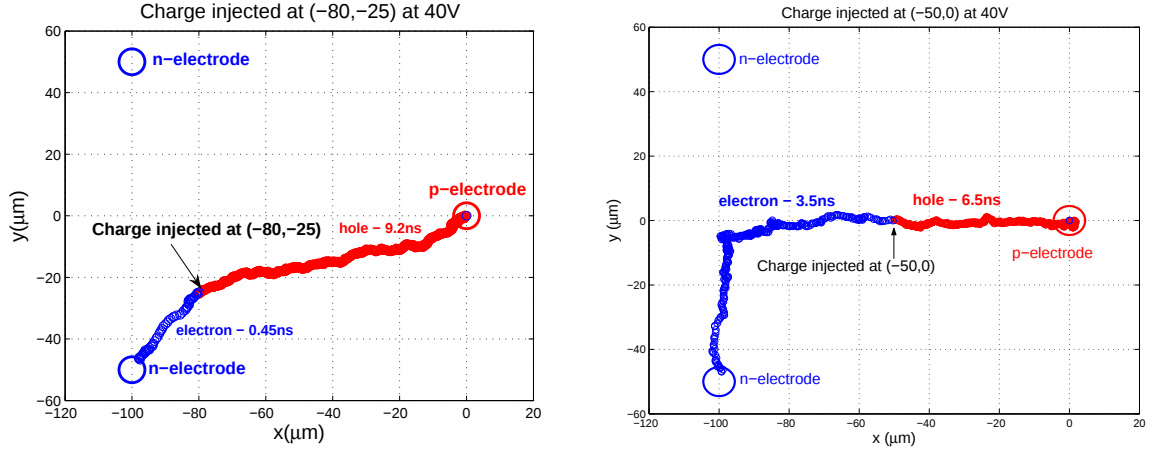


Figure 4.8: The collection paths of both the electron and hole at 40 V. Left: Charge injected at (-80,25). Right: Charge injected at (0,50).

Figure 4.9 shows an induced current that was scaled to a minimum ionising particle at full depletion, biased at 40 V with an electron-hole pair injected at (-80,-25) and (0,50). The position was in accordance with the coordinate system defined by the grid in Figure 4.7. The induced currents are different from the two different positions. The induced signal due to charge injected at (-80,-25), as shown on the left of Figure 4.9, indicates that the electron and the hole were collected within 8 ns with two separate peaks. Electrons are collected faster because they have a higher mobility compared to holes. The first peak at about 0.5 ns was formed by the electron and the peak at 5 ns corresponds to the hole. The next example will show that the two peaks in the induced signals would be indistinguishable if the hole travels a shorter distance than the electron. The collection times vary with charge injected at different positions. An induced current calculated for a charge position at (-50,0), fully depleted at 40 V is shown on the right of Figure 4.9. In this case, the electron had to travel further to reach the collecting electrode than the hole. With a higher mobility, the time it took the electron to reach the electrode is similar to that of the hole at this particular position. The single peak observed in the induced current is therefore a combination of the signal induced from both the hole and the electron. The total charge collection time is about 5-6 ns, shorter than at (-85,-25). This observation suggests that the time response varies across the cell even at full depletion. The details of the behaviour across the cell is studied in Section

4.3.

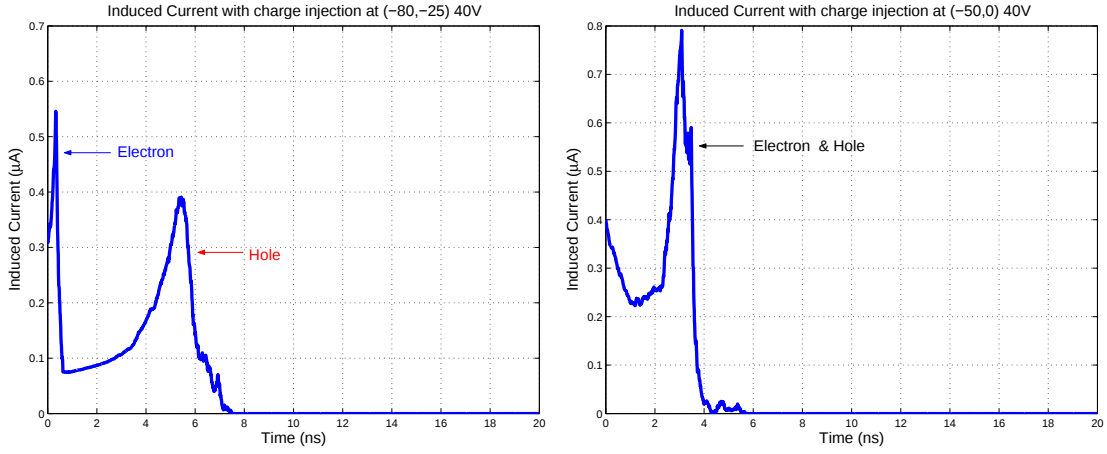


Figure 4.9: Calculated induced current resulting from the collection of both the electron and the hole shown in Figure 4.8. Both currents are scaled to a minimum ionising particle in a $121\text{ }\mu\text{m}$ thick silicon. The detector was biased at 10 V. Left: Charge injected at $(-80,-25)$. Right: Charge injected at $(0,50)$.

The induced signals are also different at different bias voltage. The left of Figure 4.10 shows the induced current calculated for an electrode-hole pair injected at $(-80,-25)$ at 10 V. Only a single peak was observed, while at the same charge position at 40 V, two separate peaks are produced. At 10 V, this induced current never returned to zero in the time window that was simulated. This is because the hole was collected very slowly by diffusion. Similarly, a long tail is also observed with the charge position at $(-50,0)$, shown on the right of Figure 4.10. This qualitatively explains the long fall time observed in the measured signals described in Chapter 4 at low bias voltage.

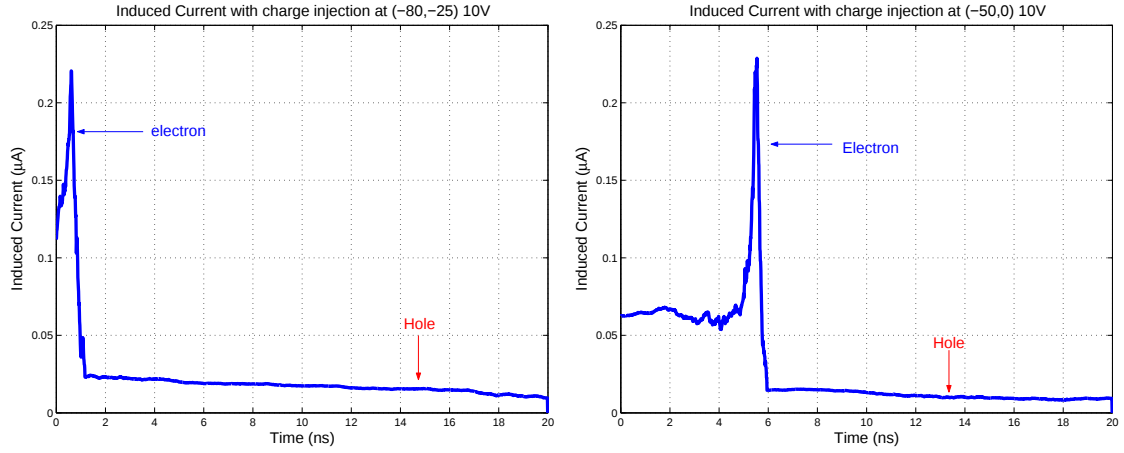


Figure 4.10: Calculated induced currents resulting from the collection of both the electron and the hole shown in Figure 4.11. Both currents are scaled to a minimum ionising particle in a $121\mu\text{m}$ thick silicon. The detector was biased at 10 V. Left(a): Charge injected at $(-80,-25)$. Right(b): Charge injected at $(0,50)$.

The long tail can be explained by the charge collection path diagram in Figure 4.11. Figure 4.11 shows that the hole was never collected at this voltage, within the simulated time window which was 40 ns. The slow collection of hole did not give a peak in the overall signal but gave a small background signal throughout this time window. These are more clearly demonstrated when the hole and electron currents were plotted separately.

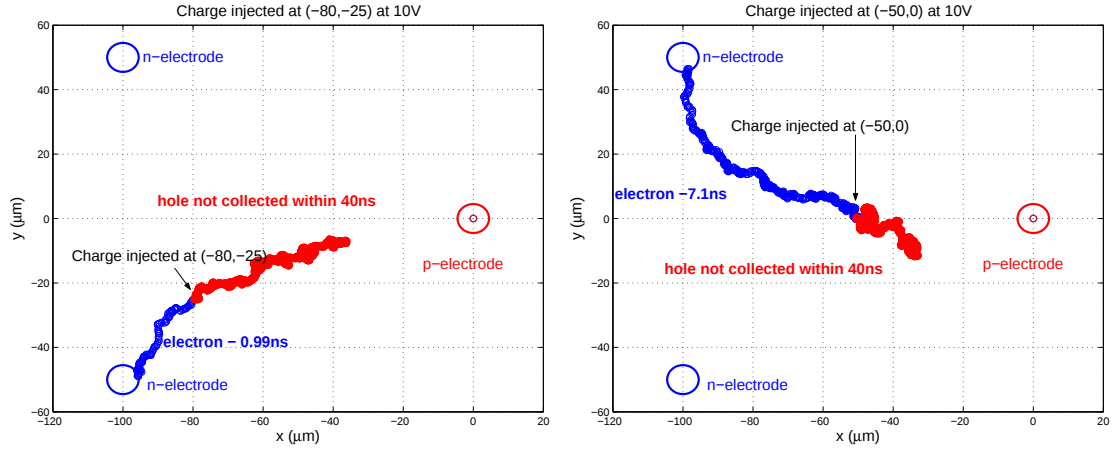


Figure 4.11: The collection paths of both the electron and hole at 10 V. Left: Charge injected at (-80,25). Right: Charge injected at (0,50).

Signals observed at the collecting p-electrode were the summation of the currents due to both the electron and the hole could easily be separated in the overall induced current when the charge was injected at (-85,-25) - Figure 4.10. This is more clearly shown in Figure 4.12 by plotting the two currents separately. The progression of the induced current behaviour from 10 V to 40 V is also clearly shown.

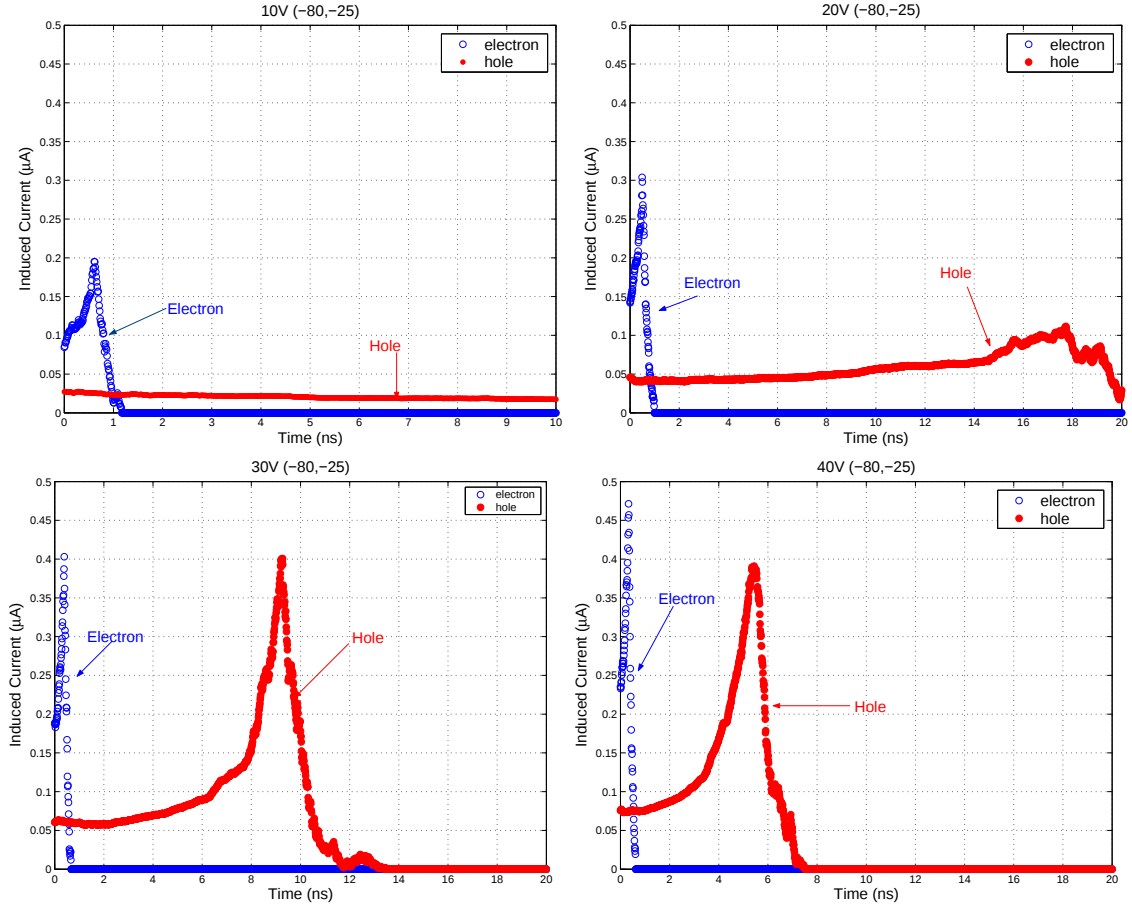


Figure 4.12: The overall calculated induced signal is a summation of the hole current and the electron current. The separation in this figure shows their individual contribution in the overall signal at various bias voltage. Currents plotted in this figure correspond to a charge injection at $(-85, -25)$. The coordinate system was defined in Figure 4.7

The signal peaks at low voltages are significantly lower and increase with bias voltage. The signal height were almost the same at 30 V and 40 V, showing a signal saturation after full depletion.

The hole current was more affected at low bias voltage. No peak due to the hole was observed at 10 V. The collection of holes was by diffusion at this voltage because the electric field across the detector was not strong enough for hole collection at 10 V. Diffusion is a slow collection mechanism, this formed a long tail in the induced current without a prominent peak. The time location of the peak is also an indication of the

collection time. At 40 V, the hole had a peak at 5 ns, compared to a peak at 9 ns at 30 V. This implies that the collection time has not reached saturation at 30 V. The total collection time of an electron was less than 1 ns in all cases as expected due to its higher mobility.

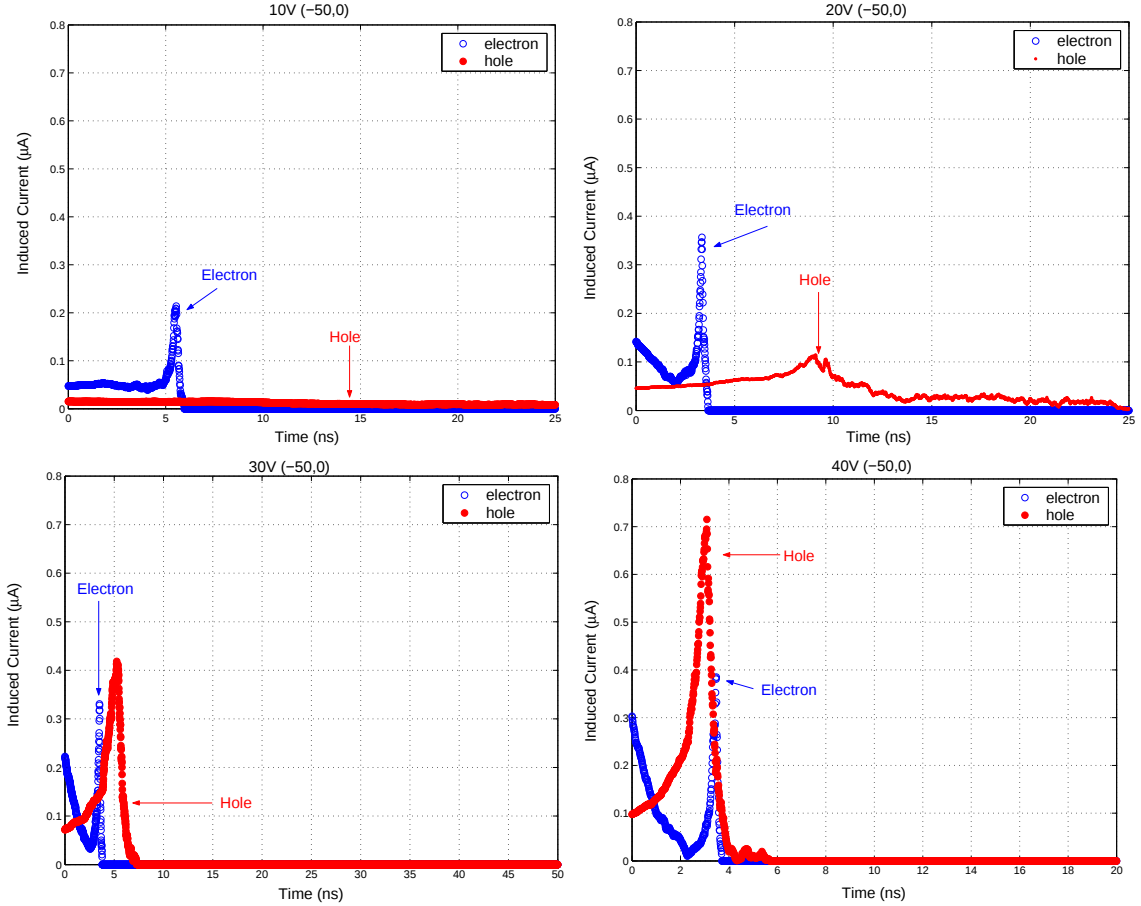


Figure 4.13: The overall calculated induced signal is a summation of the hole current and the electron current. The separation in this figure shows their individual contribution in the overall signal at various bias voltage. Currents plotted in this figure correspond to a charge injection at (-50,0). The coordinate system was as defined in Figure 4.7

Similar studies were made for a different position with charge injected at (-50,0) with voltages varying from 10 V to 40 V. Previously, it was shown that at this position, the peaks due to the electron and the hole merged together at 40 V. This was verified by plotting the hole and the electron current separately in Figure 4.13.

The positions of the injected charge play a key role in the induced current behaviour. The signal behaviour across a single cell in a 3D detector is therefore not homogeneous in particular at low voltage. However, the amplifier time response in the measurement set up described in Chapter 4 had a signal width of about 5-10 ns. These differences due to different charge positions would not be identified in the measurements once the detector is fully depleted. This is because the total collection time at 40 V was less than 10 ns, faster than the amplifier. Any difference in this time window would not be observed in the measurement. The simulated output signals observed across a single cell are described in Section 4.3.

4.1.3 Amplifier - Impulse Response Approximation

In Section 3.4.4, the HSPICE amplifier model predicted the output signal due to an induced current from a 3D detector. HSPICE is an accurate electronic circuit simulator. It calculates the amplifier response at different operating conditions. In our measurement, one set of operating conditions was used all the time. It was therefore more convenient to use a single mathematical model, which could easily be integrated into the full system simulation model.

The impulse response observed at the amplifier output when biased at the chosen operating condition was used to model the amplifier. It was obtained by injecting an impulse current that had a total charge of 1.6 fC, equivalent to the amount of charge generated by a minimum ionising particle in 121 μm thick silicon. This was injected by applying a step voltage via a 1 nF capacitor, illustrated in Figure 4.14. The step voltage took 0.5 ns to reach from zero to 1.6 μV and the current was simply the derivative of the step voltage multiplied by the capacitance given by Eqn.4.5.

$$i(t) = C \times \frac{dV}{dt} \quad (4.5)$$

The resulting current impulse was 0.5 ns in duration with an amplitude of 3.2 μA . This is only an impulse approximation but the current duration of 0.5 ns was short compared to the amplifier rise time of 3-4 ns and could therefore be considered as an impulse function.

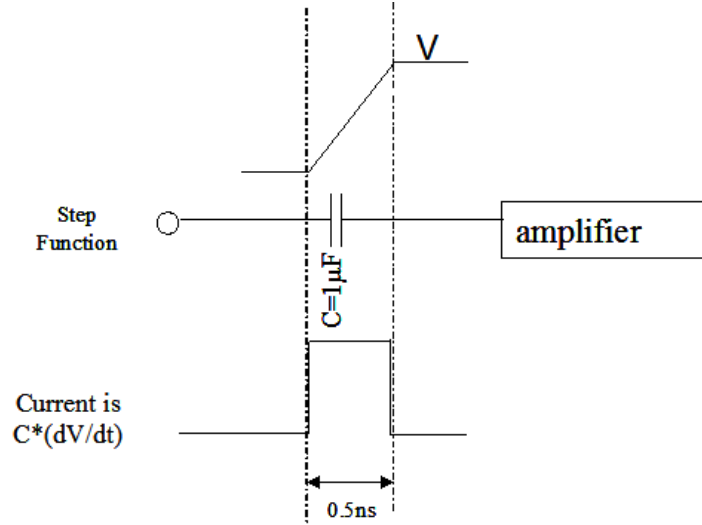


Figure 4.14: A step voltage that applied to a 1 nF capacitor. This resulted in a current generated at the input of the amplifier with a duration of 0.5 ns, that was approximated to be an impulse function.

The approximated impulse current was injected into the HSPICE model, resulting in the amplifier system response at the output. The output response was fitted to an Extreme Value Distribution given by Eqn.4.6. The fitting algorithm was a Least Square Minimisation and MATLAB was used.

$$V(t) = \frac{1}{A} e^{\frac{t-m}{B}} e^{-\frac{t-m}{B}} \quad (4.6)$$

$V(t)$ is the output response, t is time. A , B and m are constants obtained from the fitting routine

The fitted parameters resulting from the fitting routine are given in Table.4.1. This model allowed a simple calculation that could be run repeatedly with different induced signals from the detector that resulted from different bias voltages and charge positions. The mathematical formula was chosen without any theoretical reasons, but was found to be the most reasonable fit to the impulse response.

Fit Parameters	Values obtained from fit
A	0.007
B	4.0
m	13.9

Table 4.1: Parameters obtained from fitting the impulse response of the amplifier using Eqn.4.6. These parameters together with Eqn.4.6 gave a mathematical model for the amplifier.

The fitted voltage is plotted in Figure 4.15 together with the impulse response simulated from the HSPICE model. The residual between the fit and the HSPICE simulation shows some discrepancies and further modification could improve the accuracy of the model. Table.4.2 shows the comparison of the fall time and rise time obtained from the two different simulations. The fall times are in very good agreement, but there is a 1 ns difference in the rise time. This difference in the rise time will be corrected in later analysis as this is sufficient enough to give a full understanding of the detector behaviour.

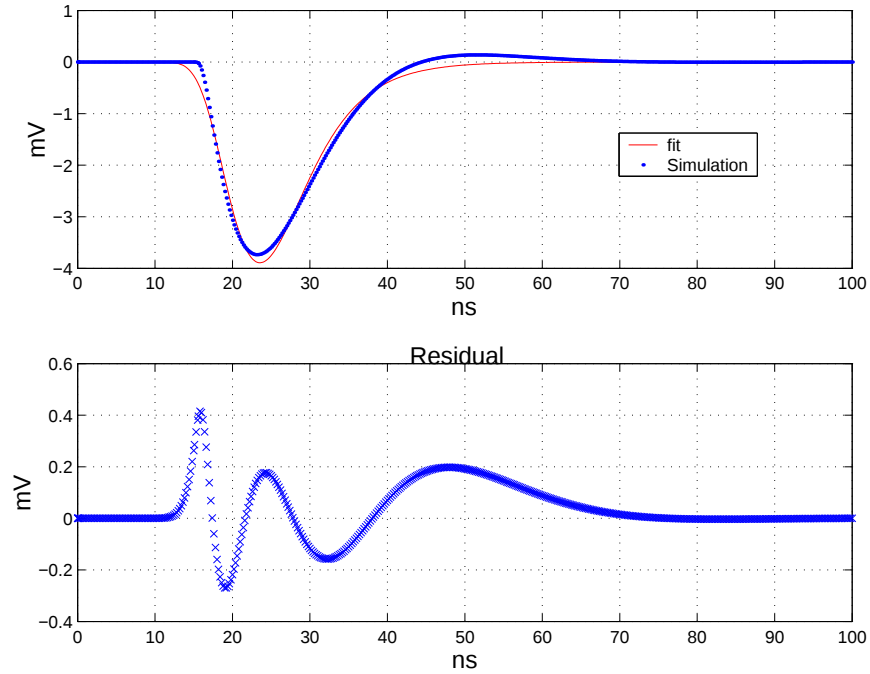


Figure 4.15: The output response simulated when injected an impulse 0.5 ns rise time. The output was fitted with the equation given in Eqn.4.6. The residual between the fit and the data shows some discrepancies between the impulse approximation and the HSPICE model.

	HSPICE Simulation	Impulse Approximation	Difference
Rise Time (ns)	3.7	4.9	+1.2
Fall Time (ns)	9.8	10.2	+0.4

Table 4.2: Parameters obtained from fitting the impulse response of the amplifier using Eqn.4.6. These parameters together with Eqn.4.6 gave a mathematical model for the amplifier.

The resulting model was tested via convolution with a test impulse. The convolved signal was compared with the signals obtained from X-rays and betas with a detector at full depletion. This ensured the biasing conditions of the amplifier used in the impulse approximation were the same as that used during data taking. At full depletion, the induced signals obtained from a radioactive source are equivalent to the amplifier impulse

response. This is because the induced current is faster than the amplifier. The impulse approximation and the measured signals can therefore be compared to ensure the impulse approximation is accurate. Figure 4.16 and Figure 4.17 show good agreement between the recorded signals and the convolved signal. The rise time of the measured signal is clearly faster than the approximated output signal.

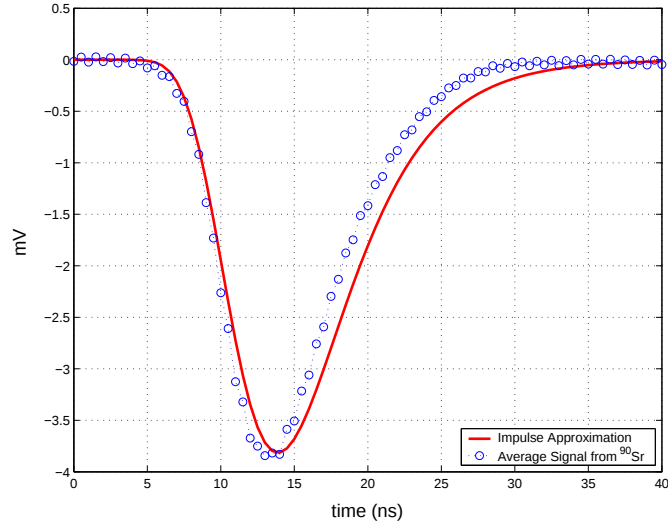


Figure 4.16: A signal simulated at the amplifier's output using the impulse approximation by applying an impulse input that had the same amount of charge generated by a minimum ionizing particle in a $121\text{ }\mu\text{m}$ thick silicon. This was compared to the average signal obtained using ^{90}Sr .

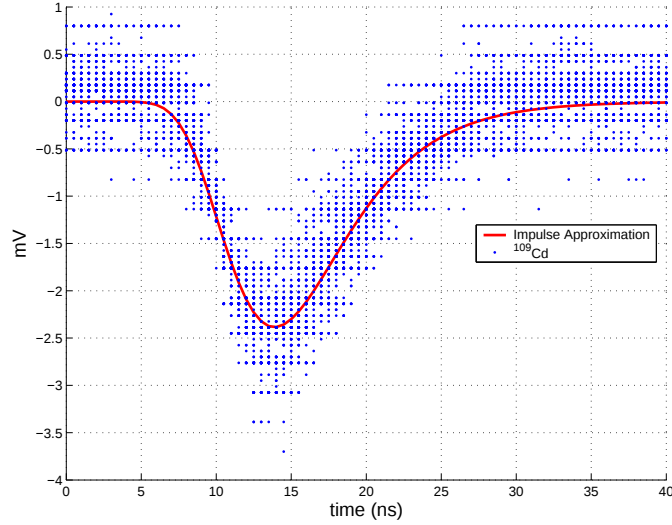


Figure 4.17: A signal simulated at the amplifier’s output using the impulse approximation by applying an impulse input has the same charge generated by a 22 keV X-ray photon using a ^{109}Cd source. This is compared to several signal traces obtained.

The agreement between the test signal and measured signals from the two different sources in Figure 4.16 and Figure 4.17 confirms that the impulse approximation model for the amplifier is sufficient enough to give a good prediction for the measured signals. However, careful inspection shows that the model is slightly slower than the measurement. The impulse response of the amplifier was difficult to be modelled perfectly by any known mathematical formula. Given that the model is sufficient to give a better understanding of the measurement, no further improvements in the model were made at this time.

4.2 Full System Simulation

The three separate models described were used to produce simulated output signals. The induced currents described in Section 4.1.2 were convolved with the amplifier impulse model to give predictions of the measured signals. An example of the predicted output is shown at the top of Figure 4.18. The corresponding induced current before convolution is given below the output signal. In this case, the electron-hole pair was injected at

(-85,-25) in accordance with the coordinate system defined in Section 4.1.2.

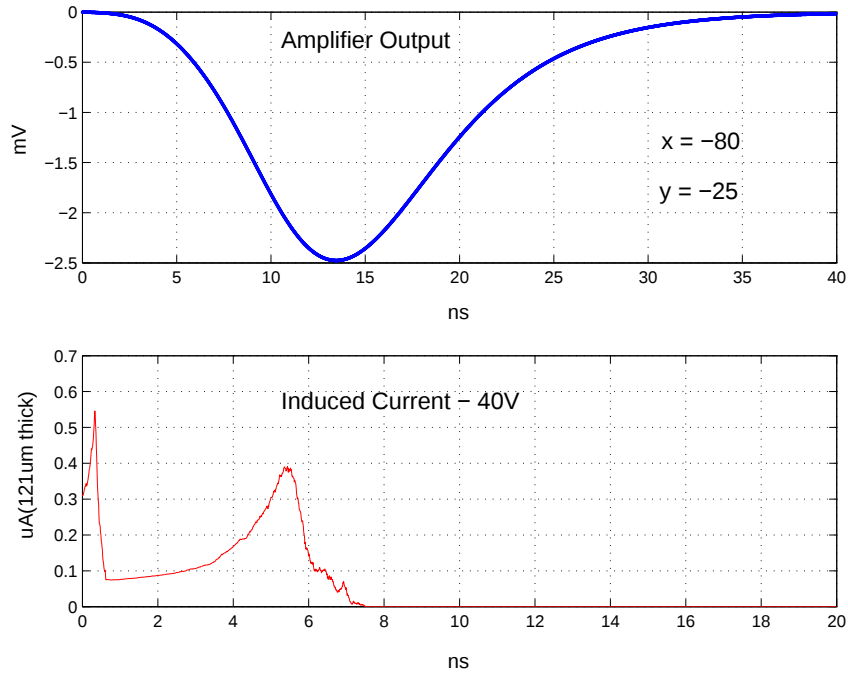


Figure 4.18: Top: Output signal simulated using the full system model with the detector biased at 40 V at (-80,-25). Bottom: The corresponding induced current resulted from an injection at (-80,-25) before convolution.

The two distinct peaks in the induced current were not observed at the amplifier's output. This is because the difference in the collection time between the hole and the electron was too fast for the amplifier to respond. The output shape was therefore dominated by the amplifier at this bias voltage. This was confirmed by a similar output signal shown in Figure 4.19. The induced current was injected at (-50,0). The induced currents from the two different positions, (-80,-25) and (-50,0) were clearly different, but the resulting convolved output signals were similar with the only difference being the pulse height.

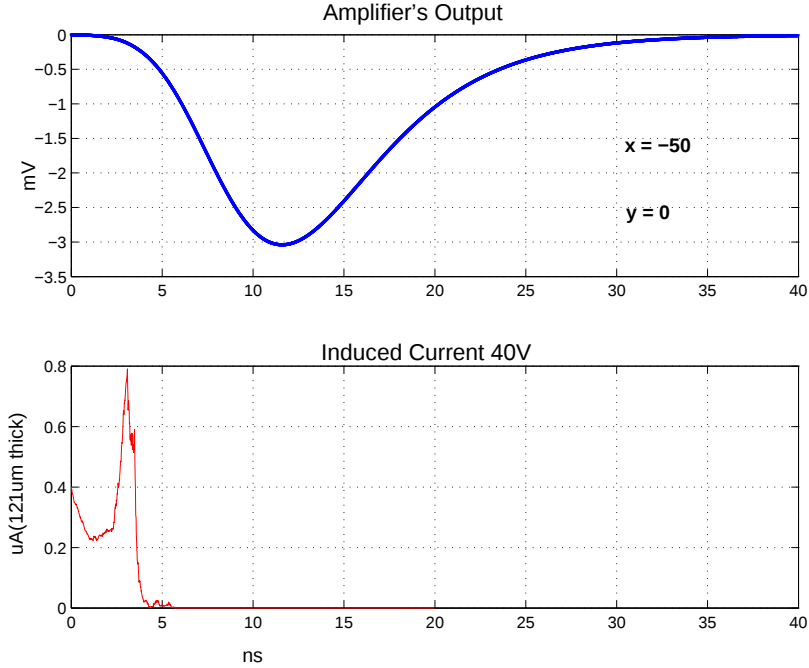


Figure 4.19: Top: Output signal simulated using the full system model with the detector biased at 40 V at $(-50,0)$. Bottom: The corresponding induced current resulted from an injection at $(-50,0)$ before convolution.

Since the amplifier was a current amplifier the pulse heights could be different even when the total collected charge is the same. The faster the charge was collected, the larger the amplitude of the input current and thus the larger the output signal. This suggests that the pulse height distribution of the measurements is not a simple energy spectrum and therefore not reliable to give information of the total charge collected. In contrast, the time response at full depletion does not show any difference between the two positions. Both signals have a rise time of 4 ns and a fall time of 10 ns, which are the minimum of the amplifier.

At a lower bias voltage of 10 V, the induced current from the detector was slower than at high voltage. As shown in Figure 4.20 and Figure 4.21, the fall times are very long and are over 20 ns in both cases. The slow charge collection, particularly for the hole, was also observed at the output of the amplifier. Figure 4.20 even shows an irregular shape in the output signal, while Figure 4.21 shows a more conventional shape. Both

figures clearly show there are large variations in time response across the cell at low voltages. This in fact was already observed in the measurements described in Chapter 4 when the standard deviations were calculated at different voltages. The statistical parameters will be studied in Section 4.5 to quantify the spread and variations in the simulated results. They are then compared with the measured results for verification of the understanding.

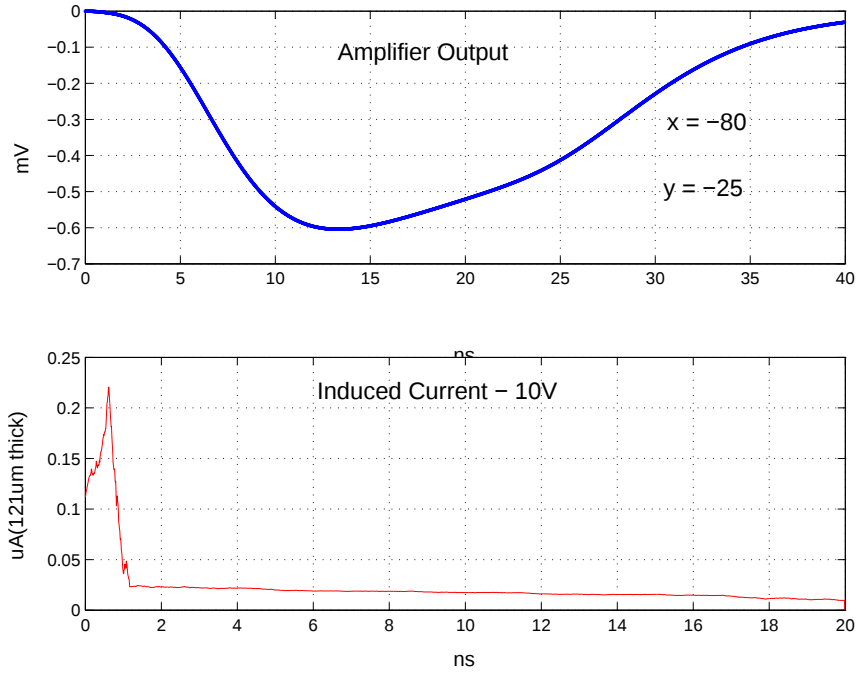


Figure 4.20: Top: Output signal simulated using the full system model with the detector biased at 10 V at (-80,-25). Bottom: The corresponding induced current resulted from an injection at (-80,-25) before convolution.

The two output signals calculated at 10 V have a low pulse height both below 1 mV. These signals would be hidden by the noise level. Minimum ionizing particles follow a Landau distribution in terms of energy deposition. The long tail of the Landau distribution contains particles that deposit a large amount of energy. Due to the high level of noise in the system, signals recorded at this voltage in the measurement set up, are most likely due to particles at the end of the Landau distribution. These signals will have a much larger pulse height than the simulation, since the simulation was scaled to the most probable values. This suggests that the measured results are selective and

may not be an objective study of the 3D detector at low bias voltage, in terms of pulse height.

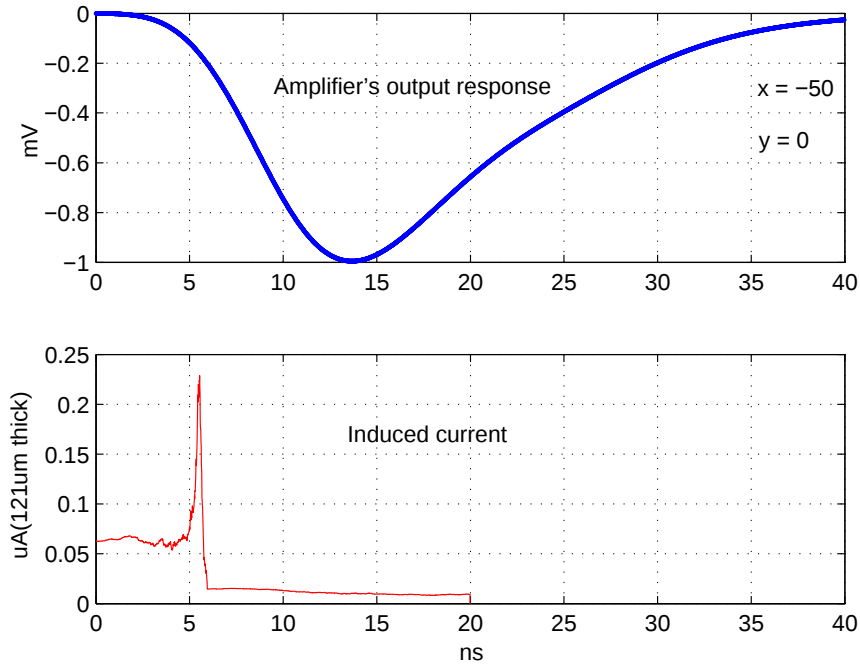


Figure 4.21: Top: Calculated induced current with injection of an electron-hole pair at $(-50,0)$ was convolved with the impulse response of the amplifier. Bottom: The induced current calculated with the detector biased at 10 V.

The above examples gave an insight into the variations in the output signals at different charge positions and voltages. In order to have a more quantitative study and understanding, characteristics were measured for each convolved output signal at a specific voltage. Studies were made in four categories as follows:

1. Signal behaviour across a single cell
2. Time response - rise and fall time
3. Pulse height
4. Comparison with measurement

These are discussed in the following sections. The behaviour across a single cell is first studied, followed by the overall performance and its comparison with the measured results.

4.3 Uniformity of A Single Cell

In the measurement set up, the particle hit positions on the detector were unknown. Understanding the output signals resulting from charge injected at different positions across a single cell was achieved by full system modelling. The simulated cell was defined by Figure 4.7 in Section 4.1.2. The cell was divided into 400 rectangles and an electron-hole pair was injected at the centre of each rectangle. The induced current at the collecting p-electrode was then calculated by Ramo's Theorem. Each was fed into the amplifier model and the output signal was obtained. Characteristics of each simulated signal were studied by measuring the following parameters:

1. Rise time (10 % to 90 %)
2. Fall time (90 % to 10 %)
3. Full-width-half-maximum FWHM (50 % to 50 %)
4. Pulse Height

Each set of parameters corresponds to a hit position at the centre of the $5 \times 10 \mu\text{m}^2$ rectangle. In the next section, the time response across the cell is first discussed, followed by a study of the pulse height across the cell.

4.3.1 Time Response Across a Single Cell

The time response parameters were measured with respect to the hit position for a range of voltages. The cell studied is defined in Figure 4.22. This section will start the discussion at 10 V when the detector was only partially depleted. Its behaviour with increasing voltage will follow after. The time response parameters across a single cell at 10 V are shown in Figure 4.23, 4.24 and 4.25 for the rise time, fall time and FWHM respectively. The behaviour across the cell depends on the bias voltage.

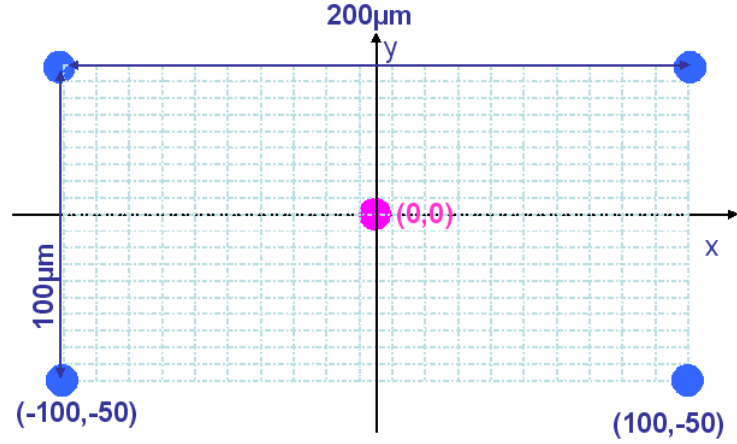


Figure 4.22: Time response with respect to the hit position was studied using the cell defined in this figure. The p-electrode is at the centre and four n-electrodes at each corner. The time response was calculated for an output signal calculated by injecting an electron-hole pair at the centre of each rectangle defined by the grid.

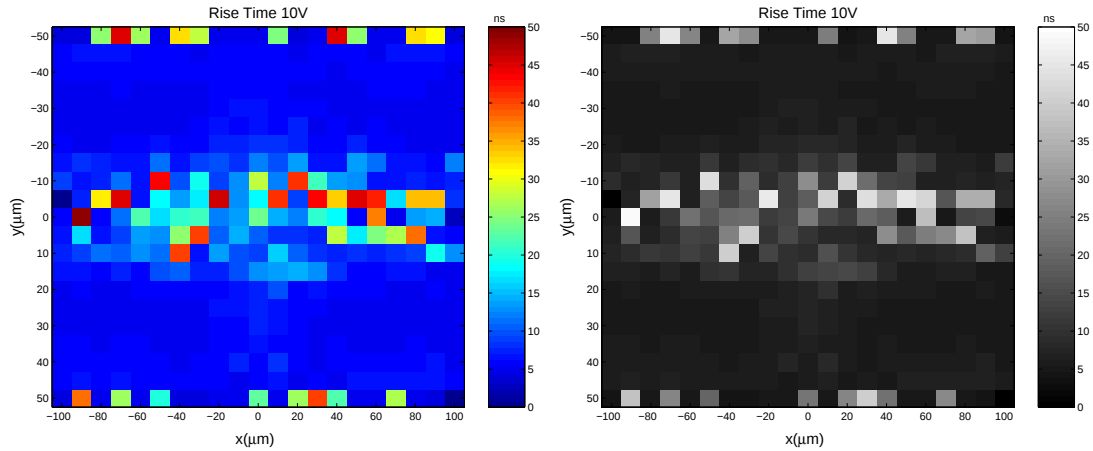


Figure 4.23: The rise time for each simulated output signal was measured with the detector biased at 10 V. The calculated rise time across the cell are indicated by the colour code (left) and the shading in black and white (right).

The rise time was not affected significantly by the slow charge collection at low bias voltage. At 10 V, Figure 4.23 shows the rise times were less than 10 ns throughout the

cell, except for the middle band along the x-axis with $y=0$ and around the cell edge. This region is an area that the electrons have to travel a long distance to the collecting n-electrode. The long rise times are therefore caused by the slow electron collection at 10 V. One would suspect that the slow time response should be caused by the hole due to its lower mobility. However, as shown earlier in Section 4.1.2, the hole does not contribute a peak to the overall signal at this voltage, except for a small background, and therefore does not affect the rise time. Long rise times are also observed around the cell edge due to a weak electric field in these regions.

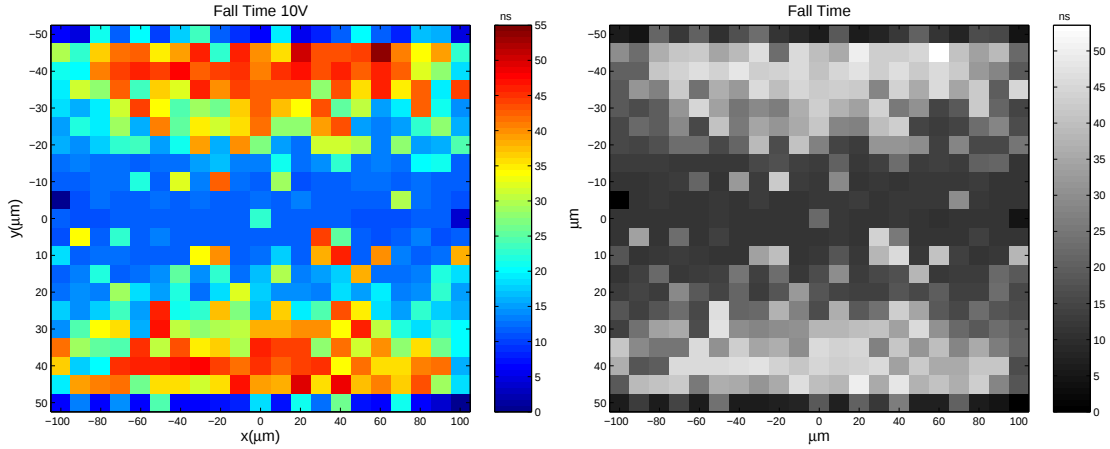


Figure 4.24: The fall time for each simulated output signal was measured with the detector biased at 10 V. The calculated fall times across the cell are indicated by the colour code (left) and the shading in black and white (right).

The fall time behaviour at 10 V is also studied. Figure 4.24 shows the fall times are long across the entire cell. The maximum fall time was over 50 ns. As described in Section 4.1.2, the hole diffused slowly to the p-electrode at this low voltage. The motion of hole never formed a peak in the signal but formed a background signal that did not affect the rise time. This created a long tail in the induced current and thus a long fall time in the output signals. The fall times are shorter along the x-axis with $y=0$, as shown in Figure 4.25. This is because the hole in this region travelled a shorter distance to the p-electrode. This further shows that the fall time was determined by the hole.

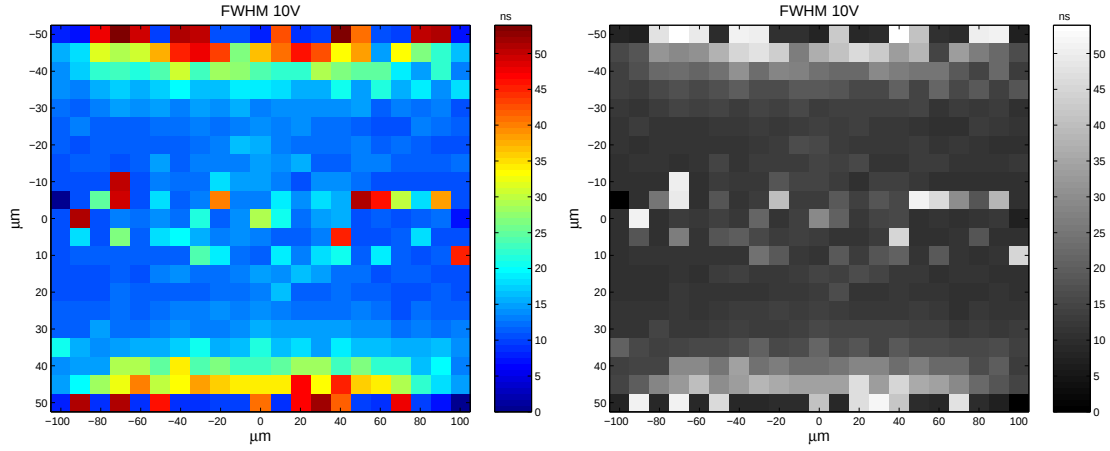


Figure 4.25: The FWHM for each simulated output signal was measured with the detector biased at 10 V. The calculated FWHM across the cell are indicated by the colour code (left) and the shading in black and white (right).

The behaviour of the full-width-half-maximum across the cell is shown in Figure 4.25. Its behaviour is similar to the fall times across the cell. FWHM is related to both the rise time and the fall time but is more affected by the fall time since it is significantly longer than the rise time at this voltage. This explains the similar trends between them across the cell. It is therefore unnecessary to investigate its behaviour further. The analysis will concentrate on the rise time and the fall time from this point onwards. The cell behaviour with increasing bias voltage are given in Figure 4.26 and Figure 4.28 for the rise time and the fall time respectively.

The inhomogeneous behaviour in the time response at 10 V is clearly shown at 10 V in both the rise time and fall time. The behaviour becomes more homogeneous with increasing bias voltage. At 40 V both Figure 4.26 and Figure 4.28 show a single colour across the cell, showing its homogeneity at full depletion.

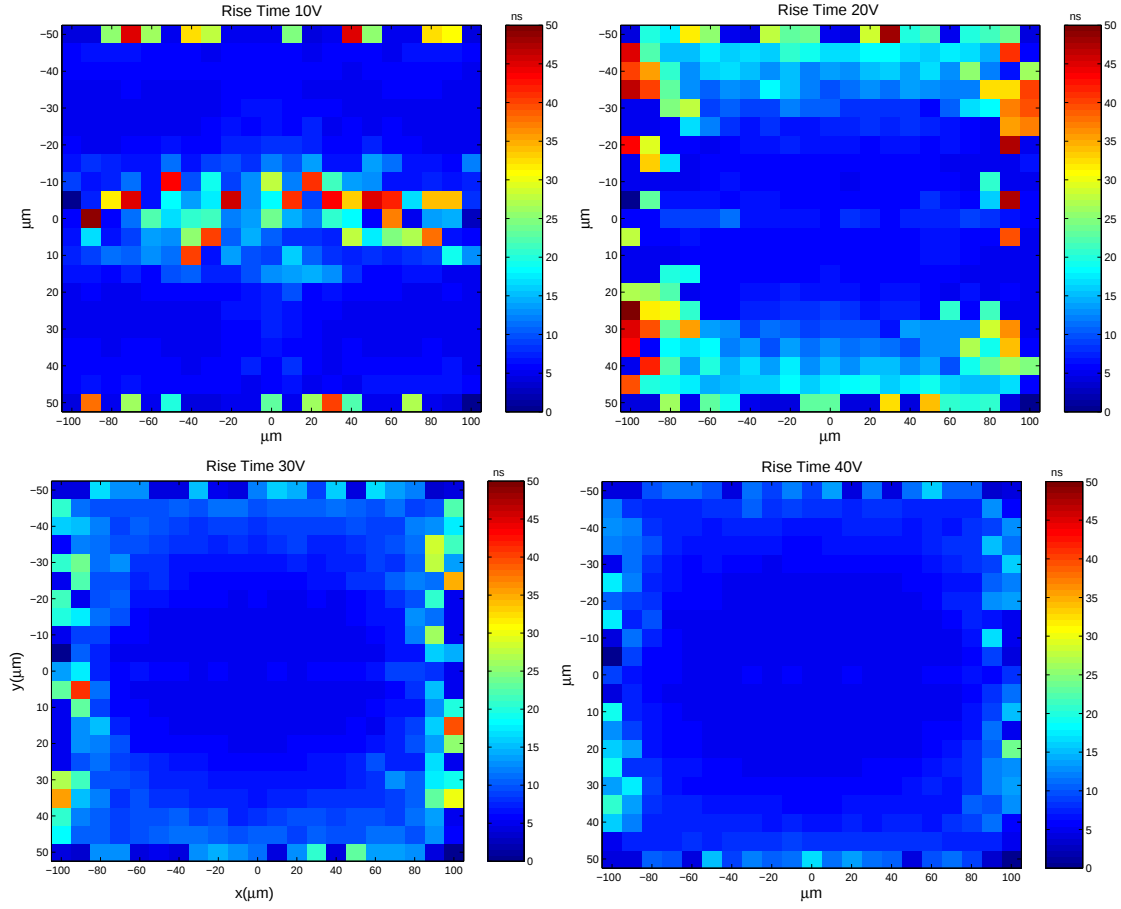


Figure 4.26: The rise time behaviour across the single cell at various bias voltages. This shows how the behaviour changes as the bias voltages increases from 10 V to 40 V.

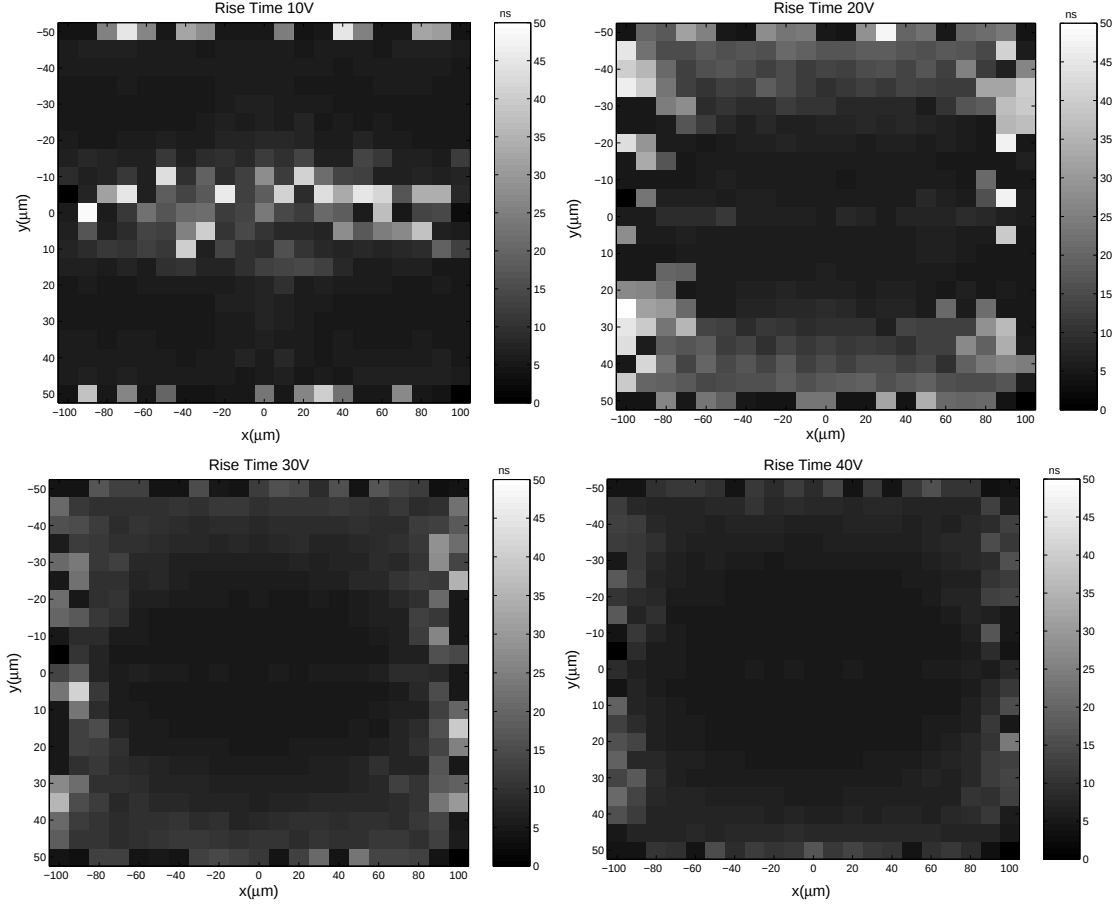


Figure 4.27: Same plot as Figure 4.26, plotted in black and white only.

As previously explained the rise time was short even at 10 V except for the region along the x-axis with ($y=0$). An interesting feature is shown in Figure 4.26. The rise time is longer across the cell at 20 V than at 10 V. Recalling the induced currents reported in Section 4.1.2, the hole was never collected at 10 V. At 20 V, the collection of the hole was slow, but it nevertheless created a peak in the overall induced current. This peak due to the slow collection of hole prolonged the rise time, while at 10 V, the hole contribution was too small to give a peak in the output signal. It therefore does not affect the rise time. The electron is collected faster at 10 V than the hole at 20 V. This explains why the rise times are generally longer at 20 V. The hole contribution also increase the rise time variations across the cell at 20 V. This is clearly shown in Figure 4.26 and 4.27. As the bias voltage increases, the cell starts to reach full depletion and the rise time

then became more homogeneous across the cell. At 40 V, the entire cell in the plot is in one single colour, showing its homogeneity across the cell. However, it is important to note that the homogeneity was due to the limitation of the amplifier response not the detector alone. The fall time behaviour across the cell with increasing bias voltage is shown in Figure 4.28 and Figure 4.29 in black and white only. The fall time behaviour between 10 V and 20 V is not the same as the rise time at these voltages. This suggests that the fall time is affected by a different charge collection behaviour.

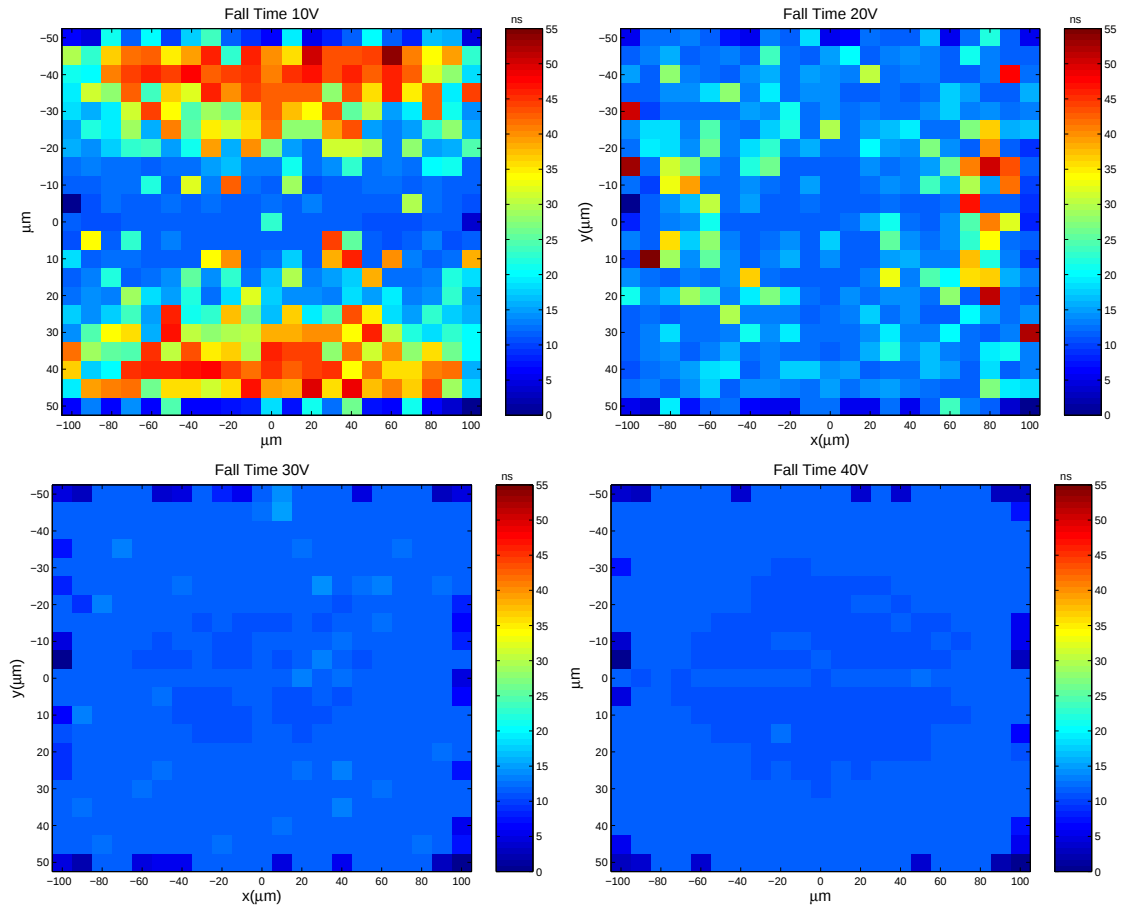


Figure 4.28: The fall time behaviour across the single cell at various bias voltages. This shows how the behaviour changes as the bias voltages increases from 10 V to 40 V.

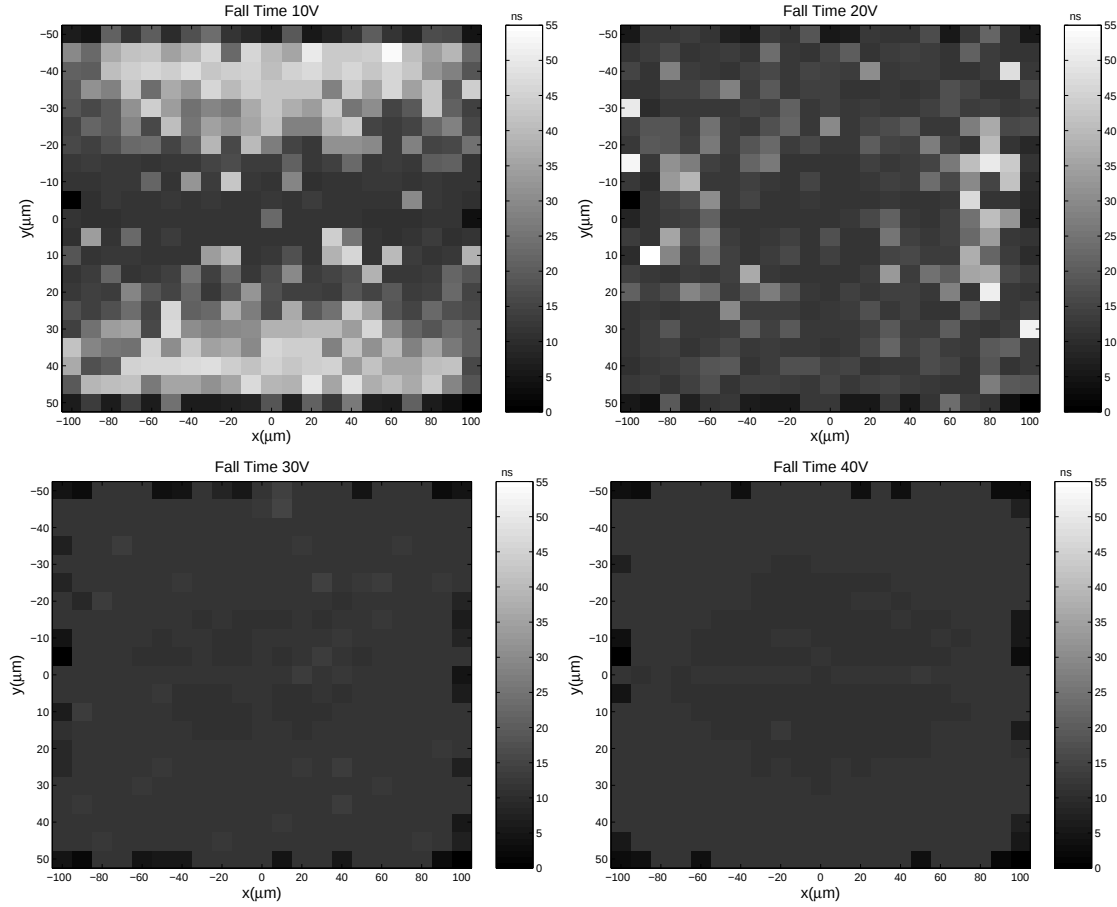


Figure 4.29: The fall time behaviour across the single cell at various bias voltages. This show how the behaviour changes as the bias voltages increases from 10 V to 40 V.

As shown earlier, the electron was collected faster than the hole due to its higher mobility. The electron was collected within a few ns even at low bias voltage and the rise time of the amplifier is 3-4 ns. The collection time of the electron therefore only affects the rise time but not the fall time. In contrary, the collection time of holes can be up to a several ns even when the bias voltage is as high as 40 V. The fall time is therefore determined by the hole collection. Figure 4.28 and Figure 4.29 (in black and white) shows how the fall time behaviour changed across the cell with increasing bias voltage. The overall fall time progressively become shorter and reached a minimum of about 10 ns at 40 V. The homogeneous behaviour at 40 V is indicated by a single colour throughout the cell. Similar to the rise time results, the output signal behaviour at full depletion

was dominated by the amplifier response. This therefore does not represent an absolute homogeneous behaviour of the detector, but a homogeneous behaviour across the cell for the entire system.

In summary, the output signals have a homogeneous behaviour across a single cell once fully depleted. At 10 V, the rise time and the fall time are affected by the electron and the hole respectively. Longer rise times are observed at 20 V when compared to 10 V. This was because the peak of the signal at 10 V was contributed by the electron only. Electrons have a shorter collection time due to a higher mobility when compared to the holes. At higher voltages, the total collection time became very short and this was too fast for the amplifier to respond. This resulted in a homogeneous behaviour across the cell when the detector was fully depleted. The overall behaviour and variations are studied in Section 4.4. Statistical parameters such as the standard deviation are calculated, and provide further information on how the bias voltage affects the overall behaviour in the full measured system.

4.3.2 Signal Height Across a Single Cell

The pulse height was measured for each simulated output signal which was scaled to a minimum ionizing particle in 121 μm thick silicon. As mentioned earlier, the amplifier was a current amplifier and was sensitive to the velocity of charge. This suggests that pulse height is very sensitive to the electric field distribution across the cell. The measured distribution is therefore not a simple energy spectrum. This is particularly true at low bias voltage when the electric field variation is large across the cell. A very non-uniform behaviour across the cell was therefore expected, this is clearly shown in Figure 4.30.

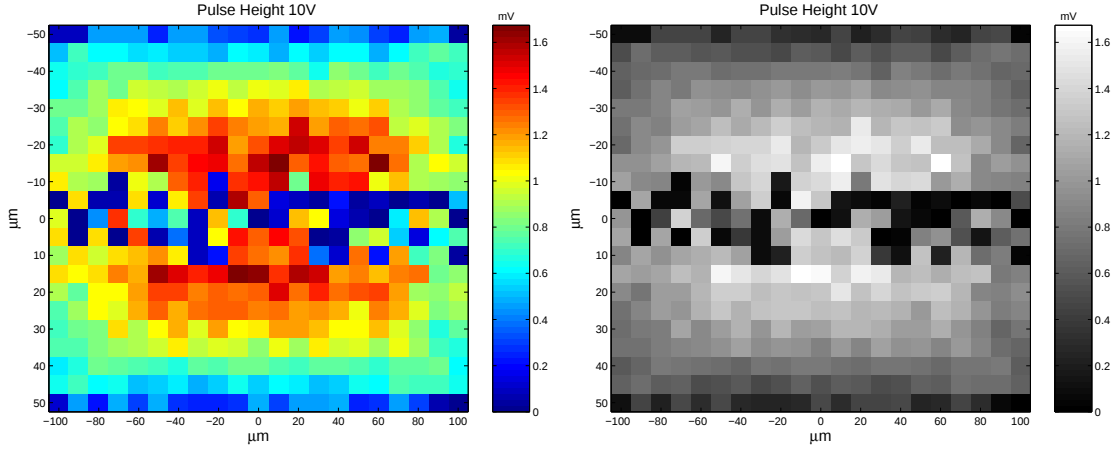


Figure 4.30: The pulse height for each simulated output signal was measured with the detector biased at 10 V. The calculated pulse height across the cell is indicated by the colour code (left) and the shading in black and white (right).

The signal height varied across the cell at 10 V. This can be explained by the undepleted regions at this bias voltage. Signals along the x-axis with $y=0$ contain signals with particularly low pulse heights. This is because the electrons are far from the n-electrodes and the signal contribution by the hole is insignificant. One feature that was not modelled in this simulation is the electrode behaviour. No significant drop in the pulse height is observed at the electrodes in Figure 4.30. The behaviour at the electrodes are studied in other tests. A similar detector was tested with a muon beam and is described in Chapter 6. A silicon telescope that provided precise beam positions was used and the studies of the electrode behaviour are described in Chapter 6, and it will be shown that there is a difference in behaviour between the p and n electrodes. This is not fully understood but some reasons are suggested. These include differences in doping concentration, doping profile, diameter and fabrication steps. Results from the muon beam test described in Chapter 6, showed a higher signal height was observed at the n-electrodes when compared to the p-electrodes. This is because of the same uncertainties that made the understanding in the differences in the two types of electrodes difficult. The electrodes are modelled as crystalline silicon. In reality, they are polysilicon, which has different properties to crystalline silicone. This is an area for future development for the simulation software. The modelling however gave a good understanding of the

detector and the measured results described in Chapter 4.

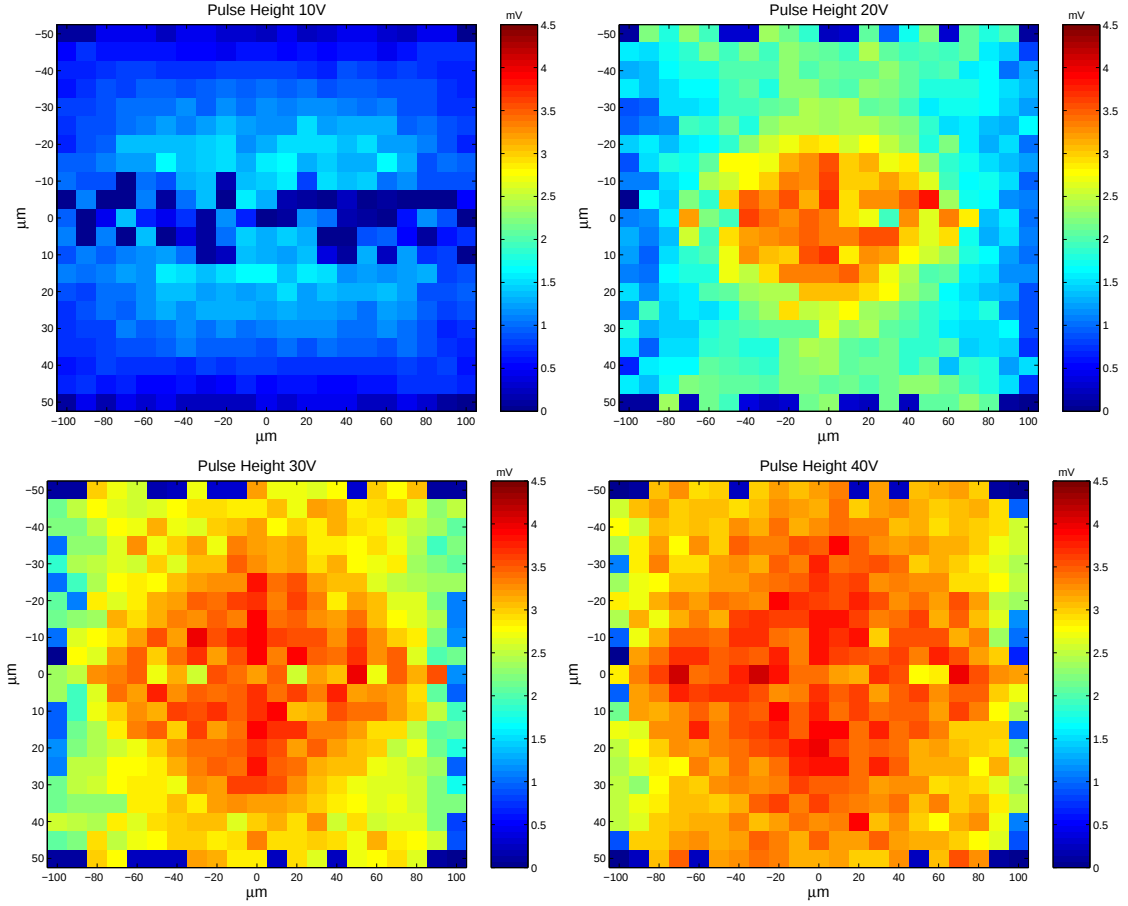


Figure 4.31: The pulse height was measured for each simulated output signal with the corresponding injected position of the charge at various voltages. The pulse height increases with bias voltages and the cell behaviour becomes more uniform at high bias voltage.

The behaviour of the pulse height across the cell with increasing bias voltages from 10 V to 40 V is shown in Figure 4.31. Figure 4.32 shows the same plot in black and white only. The pulse height was low at 10 V as discussed earlier. Most signals were below 1 mV. In the measurement set up, these would be hidden by noise. Further comparisons are given in Section 4.5. The signal heights follow the electric field distribution at the corresponding voltage. The plots show the behaviour became more uniform at 40 V. It is, however, not completely homogeneous. Many variations can exist due to the variations in the charge transport velocity since the electric field is not uniform.

However, the variations remain within a mV from the most probable value across the cell. This indicates that the measured pulse height distribution can still be used to give information on the energy spectrum. In Chapter 4, a Gaussian distribution and a Landau Distribution were observed for ^{109}Cd and ^{90}Sr sources respectively when the detector was fully depleted.

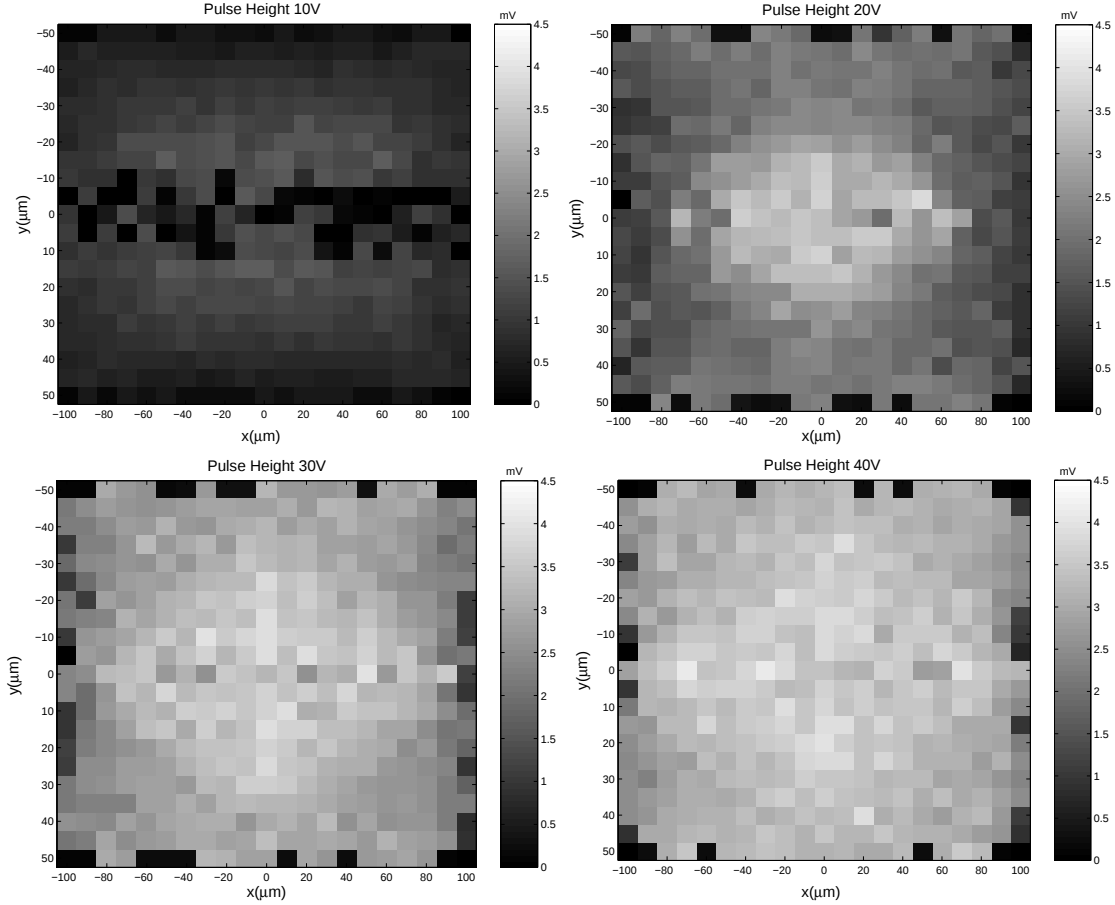


Figure 4.32: The pulse height was measured for each simulated output signal with the corresponding injected position of the charge at various voltages. The pulse height increases with bias voltages and the cell behaviour became more uniform at high bias voltage.

4.4 Overall Cell Performance

In the last section, several parameters were calculated for each simulated output signal with respect to the charge position, to study the behaviour across a single cell. The average performance in a single cell will be studied in this section by histogramming each parameter at each bias voltage for a single cell. Statistical parameters will be calculated for each resulting histogram. The mean, standard deviations and their dependence with bias voltage will be calculated and studied.

4.4.1 Time Response Studies

Three different time response parameters were calculated: the rise time, fall time and full-width-half-maximum (FWHM).

The rise time distributions at 10 V are shown in Figure 4.33. The variation in rise time at 10 V is small as shown by its narrow distribution. As explained previously, the rise time at 10 V depends on the electron only. This behaviour slowly changes with increasing bias voltage when the detector slowly reaches depletion.

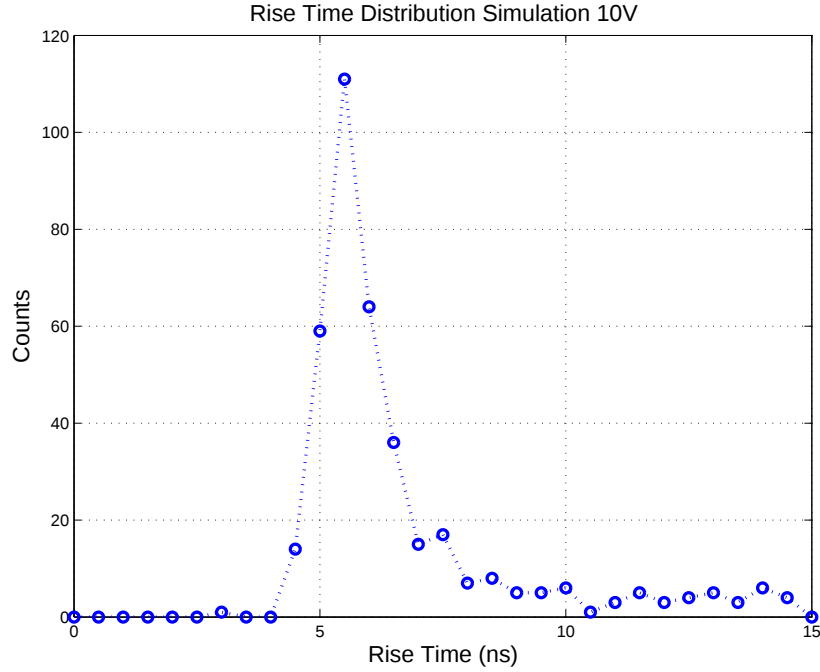


Figure 4.33: The rise time of each simulated output signal in the single cell. The detector was biased at 10 V.

Figure 4.34 shows how the rise time distribution progresses when the bias voltage changes from 10 to 40 V. The widest distribution was observed at 20 V. Again, due to the slow collection of holes, which do not contribute to a peak in the signal at 10 V. The rise time is only dependent on one type of charge carrier at this voltage, namely the electron. This implies that the variation is also smaller when compared to 20 V. Increasing the bias voltage to 30 V and 40 V, the number of signals with minimum rise time of 5 ns increases. The width of the distribution also reduces. These will be further quantified by calculating the mean and standard deviation at each bias voltage. Notice a second peak at 6-7 ns at 40 V.

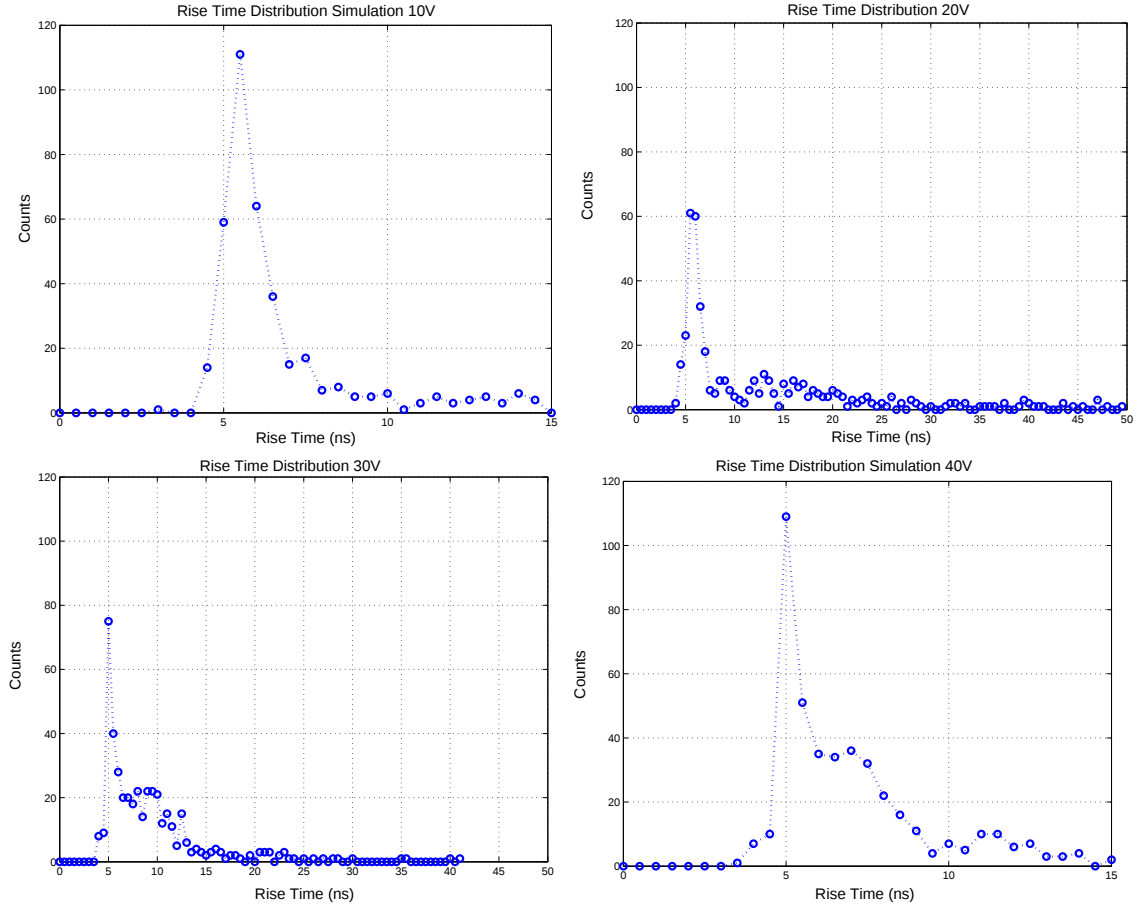


Figure 4.34: The rise time distribution changes with bias voltages. This shows how it progresses when the bias voltage increases from 10 V to 40 V.

The fall time was also studied and its distribution at 10 V is shown Figure 4.35. The distribution is wide with a maximum fall time of over 50 ns. At 10 V, the hole diffused slowly to the p-electrode. As explained in the last section, the motion of hole is slow and it takes a very long time for the hole to arrive at the p-electrode. The hole at this voltage never formed a peak in the overall induced signal, but gave a background signal of long duration at the p-electrode. This explains the long fall time observed at the measured output described in Chapter 3.

Figure 4.36 shows how the fall time distribution gradually progresses from a wide spread

distribution to a narrow peak. The distribution becomes narrower as the voltage increases. It eventually reduces to a single peak at 40 V. The peak fall time is dominated by the amplifier, which is a minimum of 10.5 ns. This is longer than the total charge collection times for both examples given in Section 4.1.2 when biased at 40 V. This further confirmed the limitation in time response of the amplifier once the detector is fully depleted. It is therefore not a surprise that the fall time distribution at 40 V is a single peak. This is because any variations in the induced current will not be observed at the amplifier output.

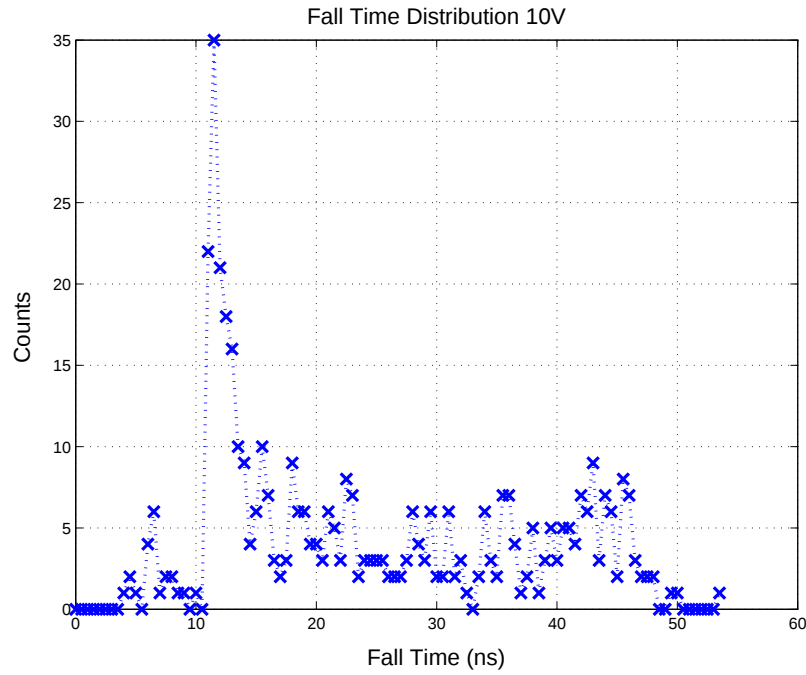


Figure 4.35: The fall time distribution of all simulated output signals in the single cell. The detector was biased at 10 V.

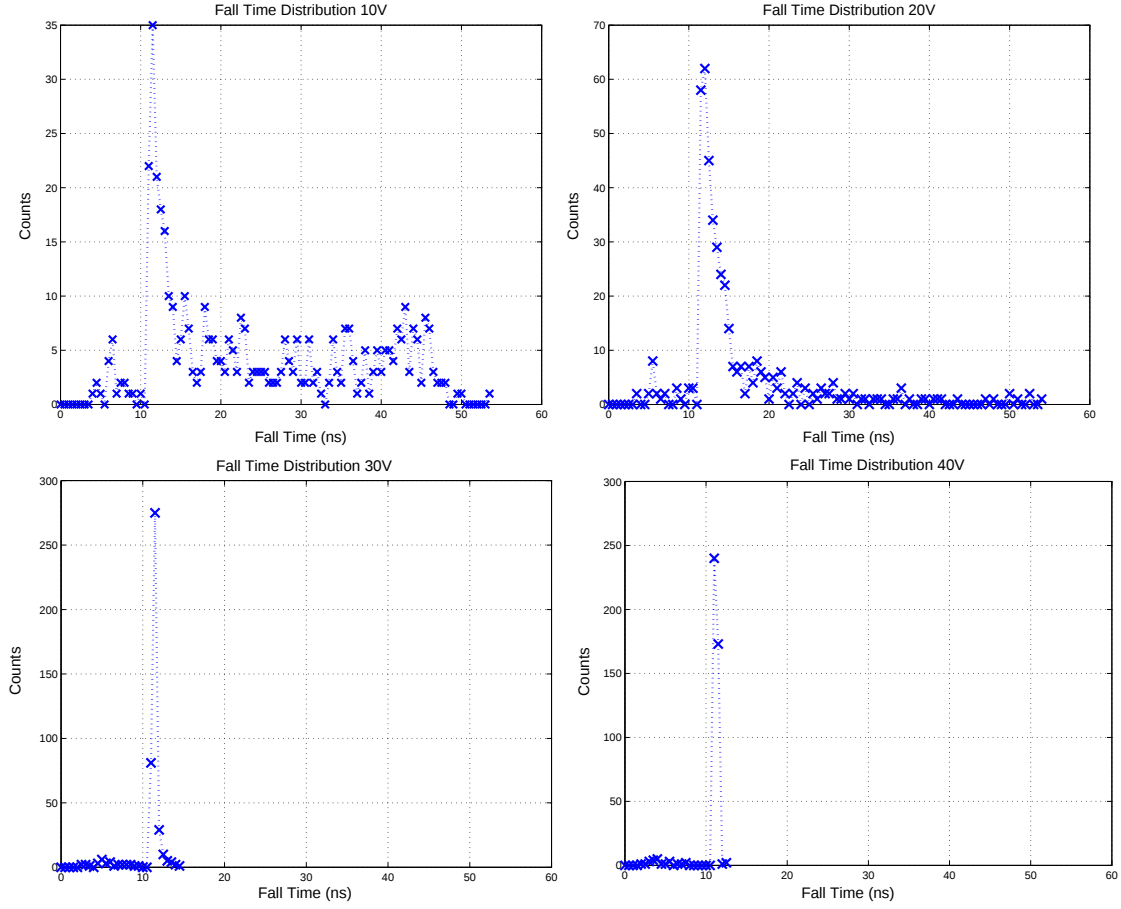


Figure 4.36: Fall time distribution as a function of bias voltage. The bias voltage increases from 10 V to 40 V.

The main emphasis in this study was to derive the dependence of the time response with bias voltage. The homogeneity across the cell and the overall performance with bias voltage has already been discussed. A more quantitative analysis with the bias voltage is performed by calculating the mean and the standard deviation. Their dependence with bias voltage are plotted in Figure s.4.37 and 4.38.

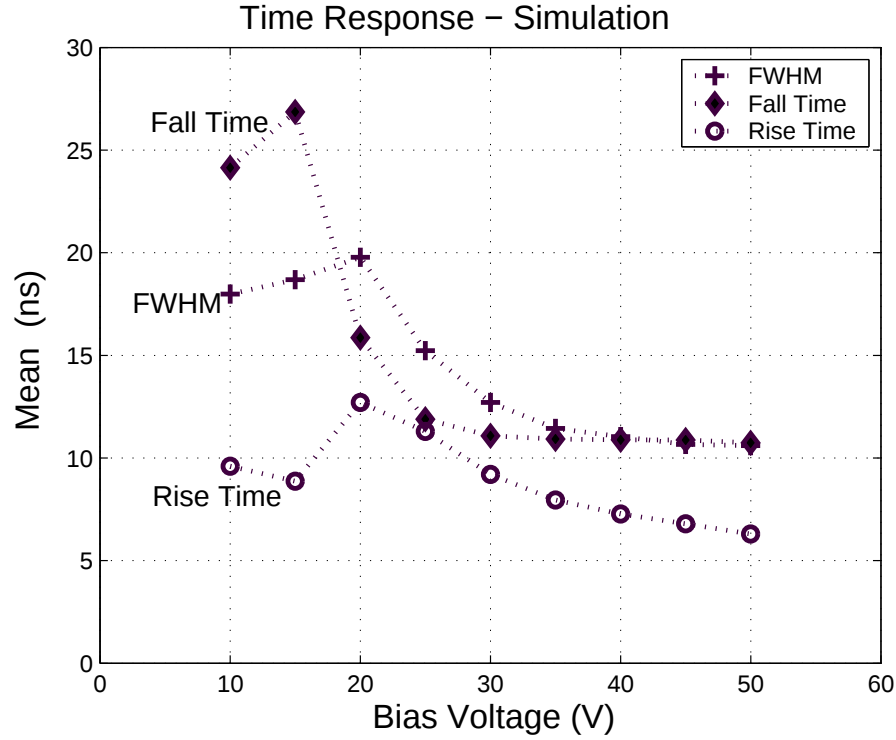


Figure 4.37: The time response parameters: rise time, fall time and full-width-half-maximum (FWHM) were measured and the means were calculated at each voltage. This shows the time response dependence with bias voltage.

The time response decreases with increasing voltages above 20 V as shown in Figure 4.37. From the results in Section 4.1.2 and the individual distributions, it was already concluded that the time response parameters at 10 V are faster than at 20 V. This was because the signal contribution was due to the electron only below 20 V. The hole then started to contribute to the induced signal significantly when the voltage increases to 20 V, but the collection time is still very slow when compared to the electron collection time at 10 V, and thus a slower time response is resulted. From 20 V onwards, all three parameters decrease with bias voltage and reached a minimum. The minimum fall time and FWHM are 10.5 ns and the minimum rise time is about 5.5 ns. The minimum is limited by the amplifier.

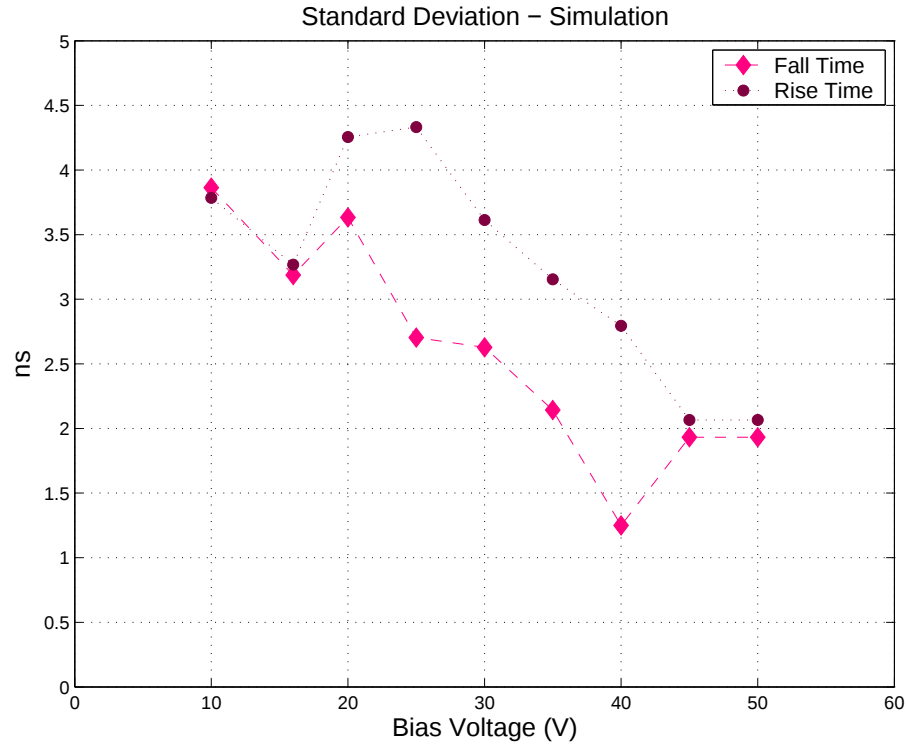


Figure 4.38: The standard deviation was calculated for each set of signal predicted at the output of the amplifier. This plot shows its relationship with increasing bias voltage.

The standard deviation is a measure of how much a set of data varies. The variation with bias voltage is studied by calculating the standard deviation at each bias voltage, the results are in Figure 4.38. Section 4.3 already showed that the variation across the cell reduces with bias voltage and the output signal behaviour became uniform across the single cell once fully depleted. A decrease in standard deviation with bias voltage was therefore expected. This is verified by the plot in Figure 4.38. In the plot, the standard deviation reduces to a minimum of 2 ns for both the fall time and the rise time. There is also a small dip between 10 and 20 V due to the contribution in signals by electrons only at low voltages, giving a smaller variation and thus a smaller standard deviation.

The simulated results will now be compared with the measured data described in Chapter 3.

4.4.2 Pulse Height Studies

The last section described the time response resulting from charge injection at different positions in the single cell. The pulse height was also calculated and the pulse height distribution at different bias voltages are shown in Figure 4.39. The pulse height was scaled to a minimum ionising particle.

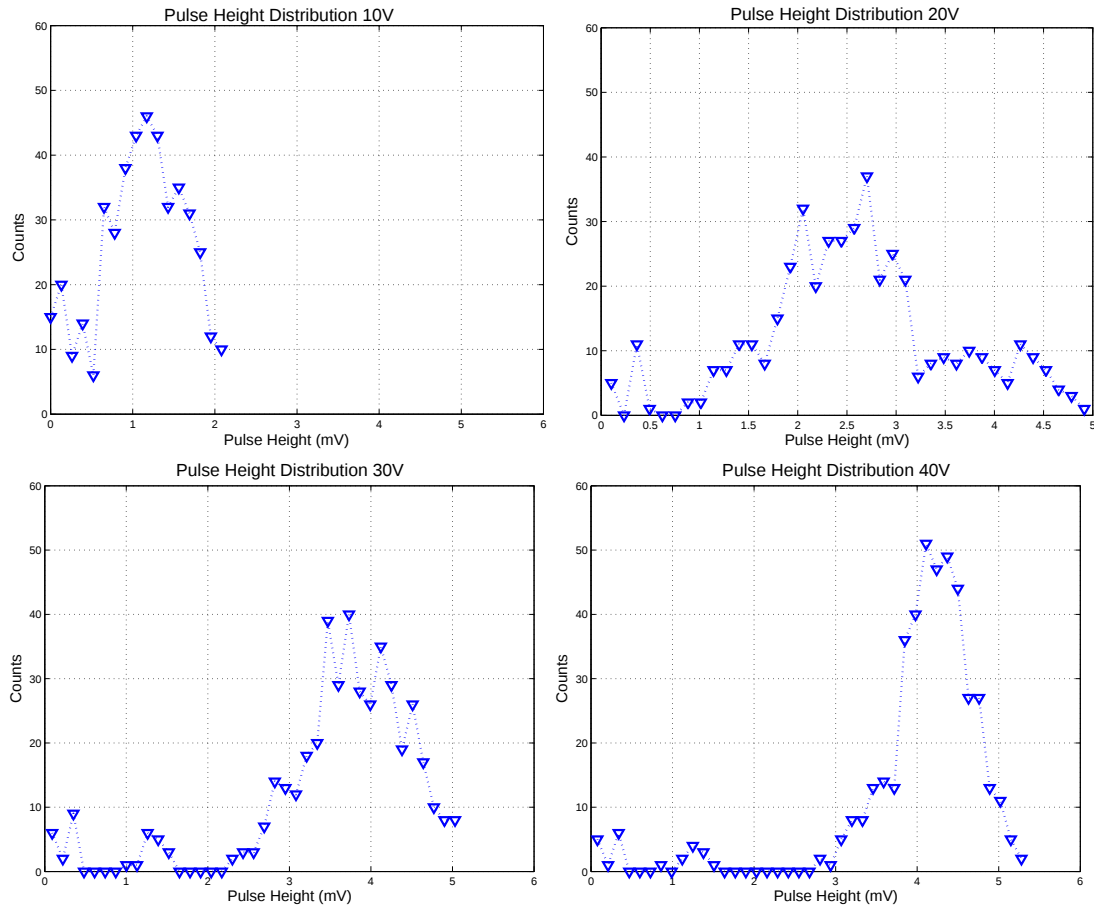


Figure 4.39: The pulse height distribution Vs bias voltage. The bias voltage increases from 10 V to 40 V.

Figure 4.39 shows an increase in pulse height with bias voltage. The most probable bin is about 1 mV at 10 V and 3.25 mV at 40 V. The spread of the distribution at 10 V is smaller when compared to 20 V, but it then reduces with increasing voltage. The variation across the cell is small at 10 V since the overall signal was contributed by

electrons only. The hole started to contribute to the signal at 20 V, and this increased the variation. As the detector approaches full depletion, the amount of variation reduces. The narrowest is seen at 40 V when fully depleted.

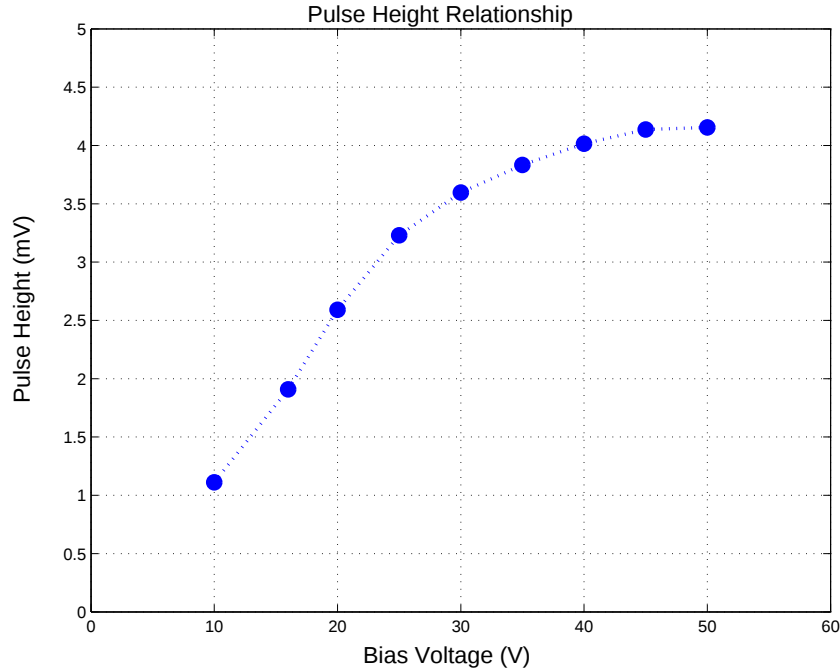


Figure 4.40: The mean pulse height was calculated at each bias voltage. The mean increases with bias voltage and reaches a plateau when the drift velocities saturate.

The mean of each distribution was calculated. Its relationship with the bias voltage is plotted in Figure 4.40. The mean pulse height increases with bias voltage and reaches a plateau once fully depleted. This was already predicted by brief inspections of the raw distributions. The means calculated between 10 and 20 V are very low, implying that most induced signals would be hidden by the system noise. For measured signals, the threshold applied to the signals will bias the pulse height with the applied voltage.

All simulated results are compared with the measured signals in the next section.

4.5 Comparison of Simulation and Measurement

The simulated induced current in the 3D detector under study was obtained by injecting a single electron-hole pair at a specific position. For a fair comparison between measurement and simulation, the measured signals must also come from a point source. Data taken using an X-ray source should be more point-like due to the nature of energy deposition. However, as explained in Chapter 4, the quality of the X-ray data was unfortunately too low to allow detailed study. The poor quality of the data resulted in a low signal to noise ratio, which implies that the recorded signals were highly selective because some are hidden by the noise. The data from the Sr^{90} are therefore used instead of the X-ray data in this study. However, for a fair comparison, it must be ensured that the particle tracks through that detector could be approximated as a point source. This is investigated by the following analysis.

4.5.1 Point Source Approximation

A particle track through a detector consists of two vector components. One is perpendicular to the detector surface and the other parallel. The simulation was performed in a 2-dimensional slice of the single cell.

In the parallel direction, the spread of the particle track depends on the angle at which the particle enters the surface of the detector. The larger the angle, the larger the spread. This can easily be calculated using simple trigonometry. If the average length of this spread is small enough, the particle track in a 2-dimensional slice can be approximated as a single point. A fair comparison between simulation and measurement can then be made. This study generated a series of scattering angles across a single cell. It then calculated the spread corresponding to each angle. The average spread was then estimated to determine whether a point-source approximation is reasonable for the data obtained from a Sr^{90} source.

The definition of this spread - the line segment, is illustrated in Figure 4.41. The right of the figure shows the particle track with respect to the p and n electrodes from a side view. The diagram also shows how the length of the line segment depends on the point at which the particle enters (x_E, y_E) and leaves (x_L, y_L) the detector. The coordinates were defined for easy calculation. The length of line segment is simply the scalar difference

between the two sets of coordinates (x_E, y_E) and (x_L, y_L) and can be calculated using Eqn.4.7

$$\text{Line Segment Length}(L) = \sqrt{(x_E - x_L)^2 + (y_E - y_L)^2} \quad (4.7)$$

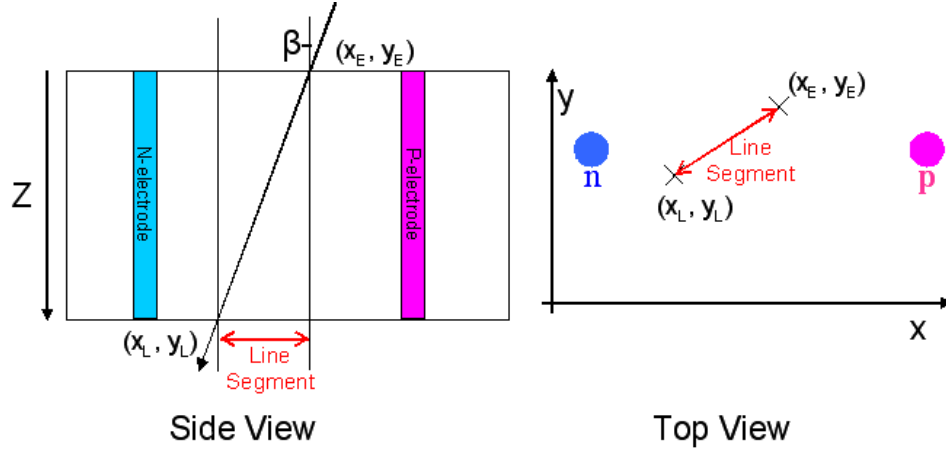


Figure 4.41: The track of a minimum ionizing particle from the ^{90}Sr source needs to be as point like as possible for a fair comparison with the simulation results. The side view indicates the particle track and how the angle of the track define the line segment in the 2-dimensional slice shown on the left.

The geometry of the measurement set up and how the source was placed must first be identified in order to calculate the line segment. Figure 4.42 shows how the source was placed with respect to the detector. It was 3.2 mm away from the surface of the detector. Using this geometry, the coordinates at which the particle entered (x_E, y_E) and left the detector (x_L, y_L) were identified. The corresponding line segment for each angle of incidence was therefore calculated.

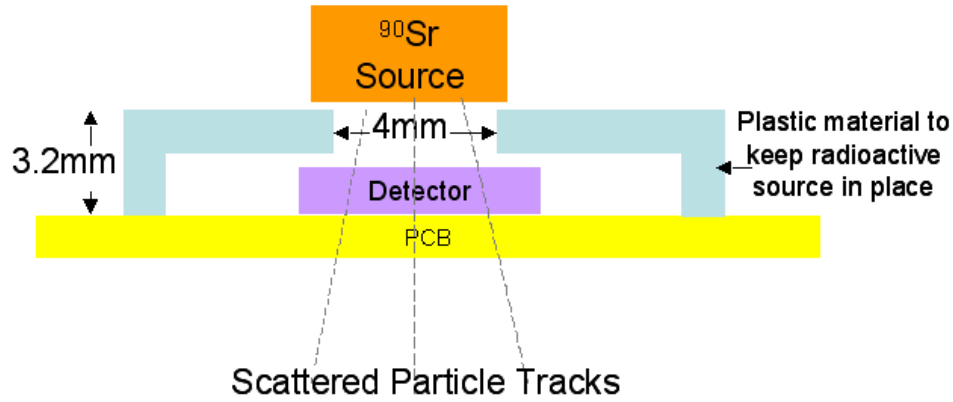


Figure 4.42: The source was placed on top of the detector and held in place by a plastic stand around the detector. The source is 3.2mm away from the surface of the PCB.

A program was written in MATLAB to generate a series of particle tracks. Each corresponding line segment was then calculated according to Eqn.4.7.

Figure 4.43 shows the two sets of angles that were considered in the program. The central axis was defined by the centre of the source. The two angles are θ_v and θ_h . θ_v is the vertical angle away from the central axis and θ_h is the rotational angle around the axis. The program first identified a series of angles for both θ_v and θ_h varying between 0 to 90° equally spaced. It then produced all possible combinations of the two angles that will produce particle hits that are evenly distributed across a quadrant of a single cell. The four quadrants were symmetrical and studying one quadrant was sufficient.

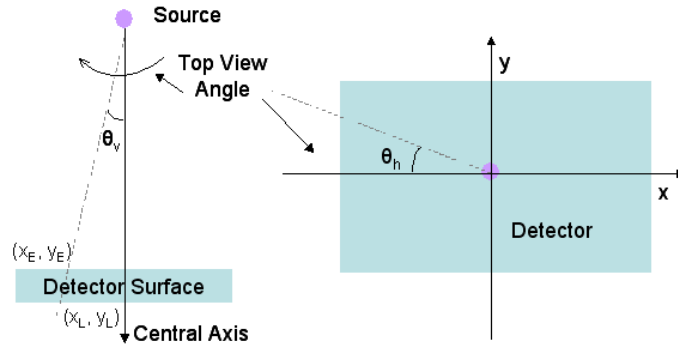


Figure 4.43: A program was written to generate particle traverse through the detector at different angle in two different directions: perpendicular(left) and parallel(right) to the detector's surface with respect to the center of the radioactive source. The length of the corresponding line segment was then calculated.

In the measurement, only one strip was read out at a time. Each strip covered an area of $2 \times 0.2 \text{ mm}^2$. Assuming the source was placed at the center of the strip, hits that were calculated to be in this region were selected to calculate the average line segment. Figure 4.44 shows hits generated in a quadrant using the combinations of θ_v and θ_h in a single quadrant. The positions at which the particle left the detector are indicated by red and yellow, while the blue and green show the positions at which the particles entered the detector. The green and yellow region was covered by the strip and was selected to calculate the average line segment.

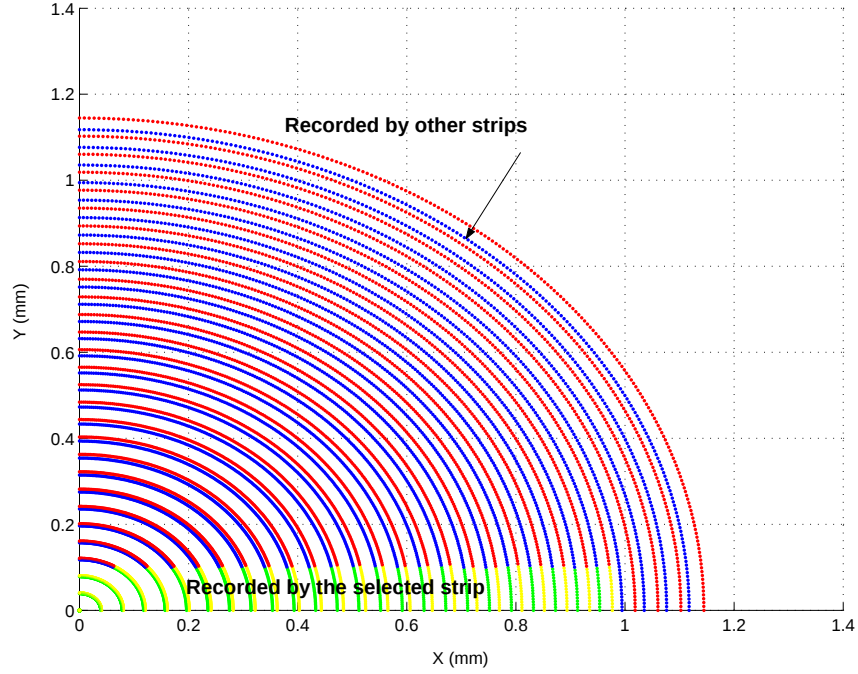


Figure 4.44: A quadrant of the scattering angles was selected. The corresponding line segment for each combination of θ_v and θ_h were calculated. Hits that were within a quadrant of the strip, indicated by the green and yellow, were read out were selected to calculate the average length of the line segment.

The length of line segment of each hit selected in the green and yellow region shown in Figure 4.44 was calculated. The overall distribution in the quadrant of a single strip is shown in Figure 4.45

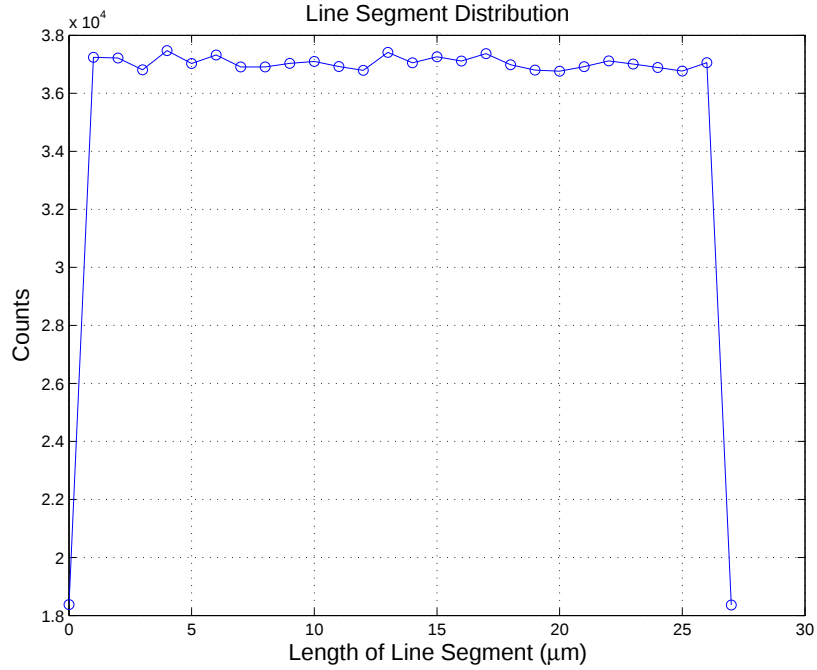


Figure 4.45: The selected line segments from Figure 4.44 are plotted above. The distribution is box-like and almost uniform.

The distribution is almost uniform as expected since the probabilities of all angles occurring were equal. The maximum line segment length is $27\mu\text{m}$. The mean and the standard deviation of the distribution are 13.8 and $7.5\mu\text{m}$ respectively. Recalling Figure 4.28 and Figure 4.26 in Section 4.3, where the time response across a single cell were shown. The time response does not vary by more than 2 ns within a distance of $10\text{--}20\mu\text{m}$. A particle track that spreads parallel to the detector surface with a mean of $13.8\mu\text{m}$ could therefore be approximated to be a point source. Similarly, the pulse height do not vary by more than 0.5 mV within this same distance.

This analysis confirms that the point-like assumption in the simulation is reasonable for the ^{90}Sr measurements. Future work will be needed to properly track the beta particles and effects such as multiple scattering and Landau fluctuations need to be included.

4.5.2 Time Response Comparison

The simulated and measured time response are compared in this section. Statistical parameters are calculated in order to give a comparison in the spread, the average and the shape of the distributions. Their dependence with bias voltage are also compared.

The rise time is first studied. Figure 4.46 shows the comparison of the distributions at 10 V and 40 V. The simulated distributions are shown on the left with the measured distributions shown on the right.

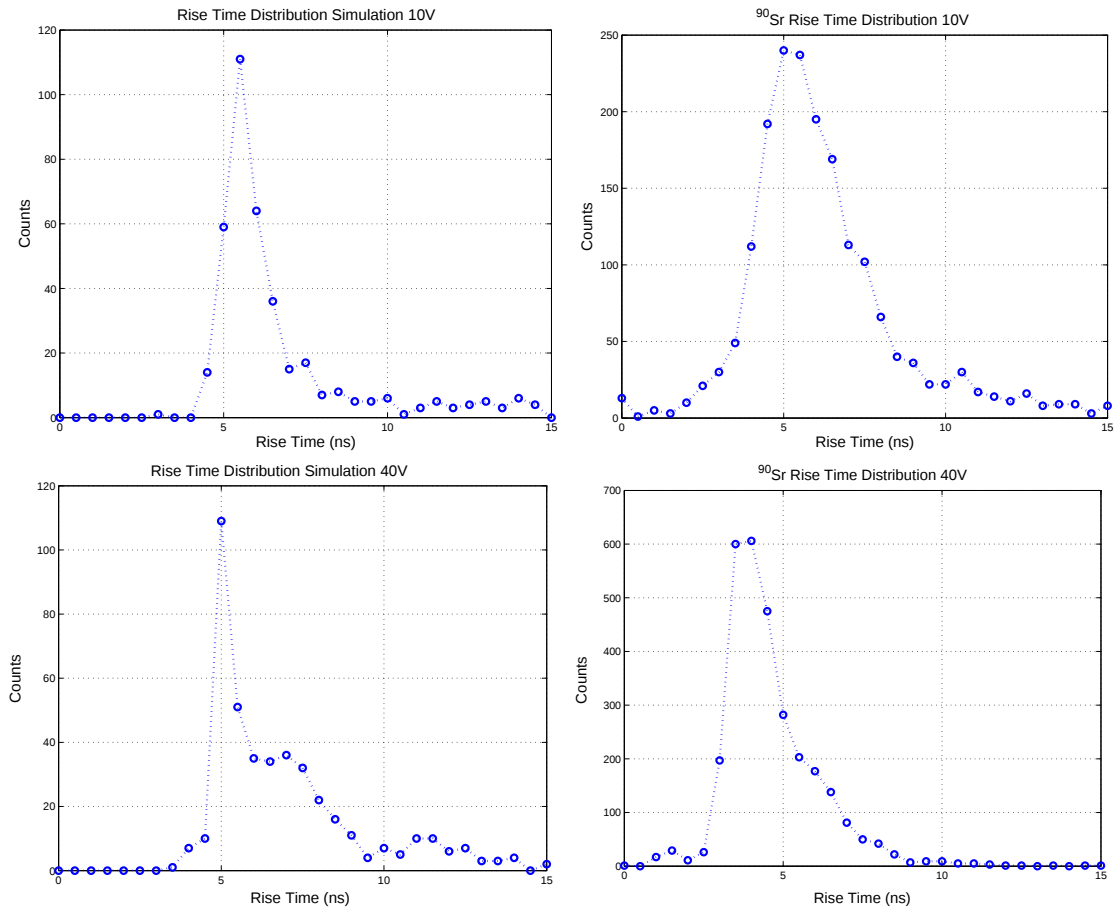


Figure 4.46: The rise time distributions obtained at 10 V and 40 V. Left: Simulation, Right: Data using a ^{90}Sr source

As shown in Figure 4.46, the simulated and measured distributions are similar at the

same bias voltage but the measured distributions are generally wider. This is particularly true at low bias voltages when the noise is higher due to a higher detector capacitance. A measured distribution is therefore expected to be wider. Another spreading effect in the measurement is caused by the spreading due to the tracks of minimum ionising particles as discussed in Section 4.5.1.

Another source of inaccuracy is the simulated rise time of the amplifier. In Section 4.1.3, the impulse approximation of the amplifier response was shown to have a longer rise time than the actual impulse response. The model was however kept in the simulation because it was sufficient enough to give the understanding of the measured signals if it was taken into account when comparing between the simulation and the measurement. The simulated rise time is about 1-1.5 ns longer than the measurement due to this inaccuracy.

Despite the faster rise time observed in the measurement, the shape of the two distributions at 40 V are extremely similar. Figure 4.47 shows a direct comparison between the simulated and measured distributions at 40 V. The simulated distribution was shifted by 1.5 ns to compensate for the inaccuracy from the amplifier model. An excellent agreement is shown, in which both the simulated and the measured distributions have a peak at around 3-4 ns and a second peak at about 6 ns.

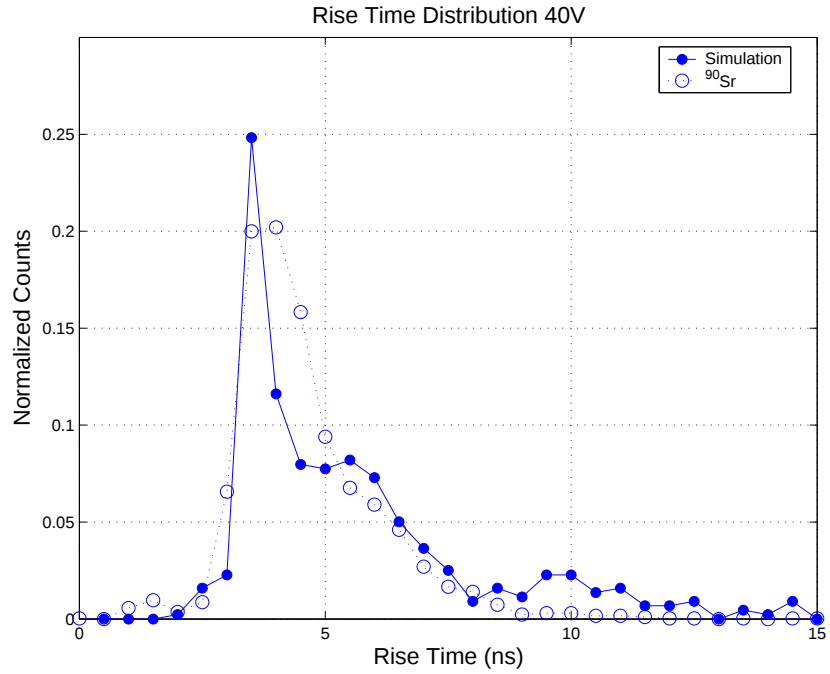


Figure 4.47: The simulated and measured rise time distributions were normalized and compared. The comparison shows an excellent agreement with a wider spread observed in the measured distribution.

The mean rise time at each bias voltage was calculated and is given as a function of voltage in Figure 4.48.

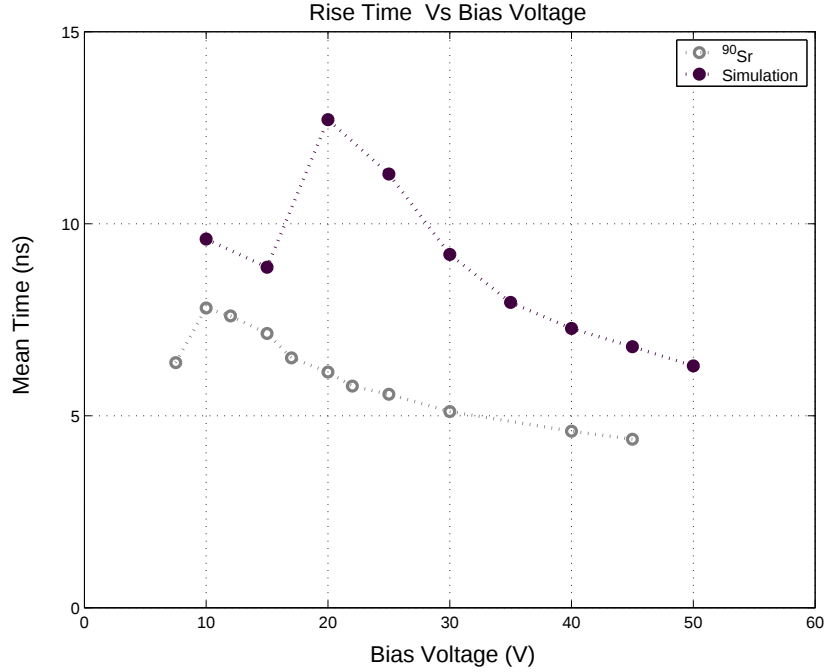


Figure 4.48: The rise time measured from both simulation and measurements using a ^{90}Sr source. The minimum rise time do not agree due to the inaccuracy of the amplifier model. There is also discrepancy in the trends between the simulation and the measurement at low bias voltage below 30 V.

Both the simulation and measurement follow a similar trend, with the mean rise time decreasing with the bias voltage once it is above 20 V. However, the overall results are very different quantitatively. Considering the inaccuracy of the longer simulated rise time as explained by the amplifier model, the differences in the two plots are still not explained. Moreover, the trend at low bias voltages are distinctively different between them. This suggests that the doping concentration in the simulation model is inaccurate and other effects are still yet to be understood. This unresolved understanding in the rise time behaviour encouraged us to inspect the individual distributions more carefully. By taking the log of a distribution, any distinct features can be identified more easily. These are shown in Figure 4.49, in which the simulation and measurement are compared.

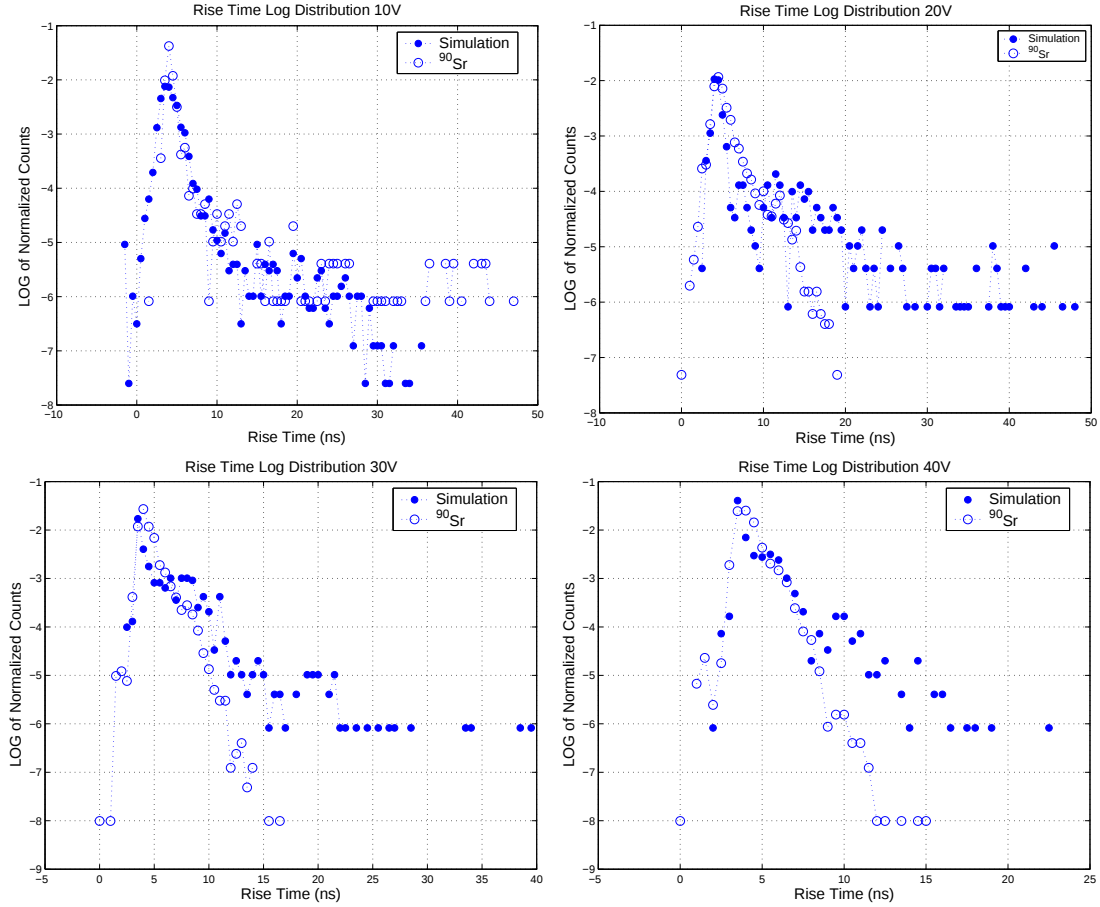


Figure 4.49: The log of the rise time distributions from both simulation and measurement are compared. These distributions are obtained for a set of various voltages. The peak was shifted to compensate for the inaccuracy from the impulse approximation model of the amplifier.

An excellent agreement is found at 10 V, with both the measurement and simulation have a long tail of similar magnitudes. Above this voltage, longer tails observed in the simulated distributions are not seen in the measured ones. For a further understanding, the positions of the injected charge and the corresponding signal pulse heights were identified for those signals that contributed to the long tails of the distribution. This was done by comparing the rise time and the pulse height behaviour across the simulated cell, as shown in Figure 4.50 at 40 V.

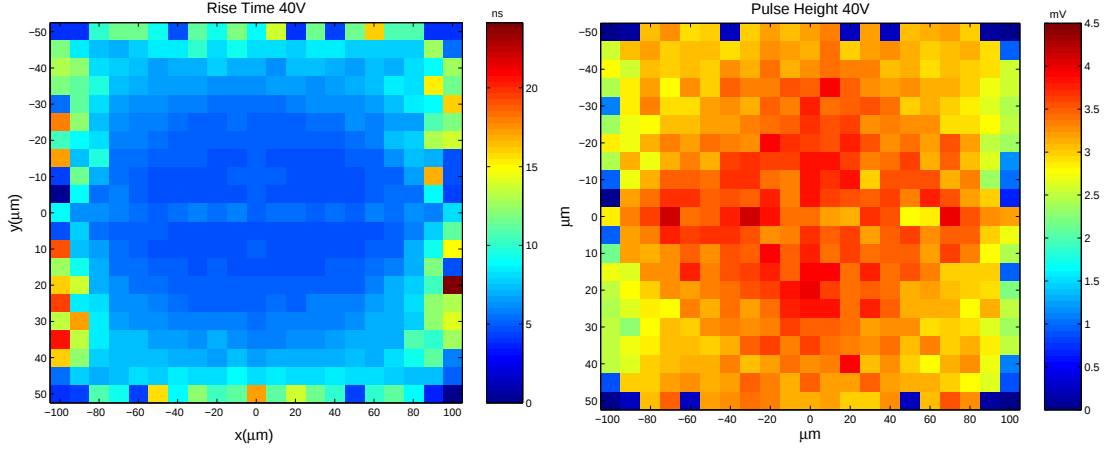


Figure 4.50: A comparison of rise time and pulse height across the cell to identify any correlation between the slow rise time and low pulse height when the detector was biased at 40 V. Left: Rise time. Right: Pulse height

As shown on the left of Figure 4.50, signals with long rise time are found around the four edges of the cell. On the right of Figure 4.50, the pulse heights around the four edges are lower and are typically between 1-1.5 mV. In the measured system, these would most likely be hidden by the system noise. As a consequence, signals with long rise times would not be observed, explaining the difference between the simulation and the measurement. Another contribution to the disagreement is the point charge approximation of the minimum ionising particle track. In the measurement, a minimum ionising particle spreads across a line segment as described in Section 4.5.1. Around the edge of the detector, part of the generated charge would be shared by adjacent cell. The resulting signal at the measured p-electrode would therefore have a lower pulse height than predicted due to the charge sharing with adjacent cell. These signals would also have a higher probability to be hidden by the system noise, again reducing the probability to observe these long rise time signals in the measurement.

The clear differences between the simulation model and the measured system suggests that the signals with long rise times should not be compared. If these are eliminated from the distributions, one would expect a better agreement between the simulated and the measured results. This was done by plotting the mode as a function of voltage instead of the mean as shown in Figure 4.51.

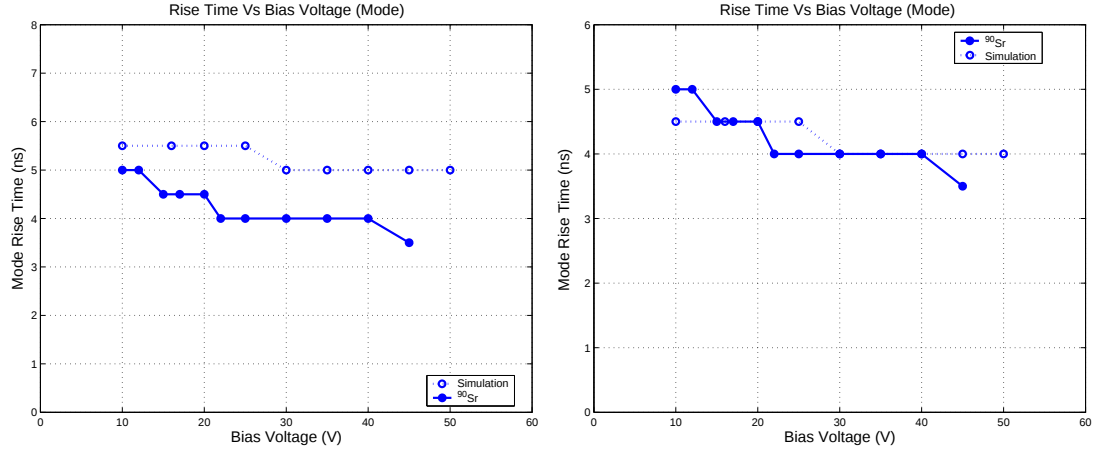


Figure 4.51: Left: The modes of the rise time distributions as a function of bias voltage. Right: The shifted modes as a function of bias voltage to compensate the inaccuracy of the amplifier model.

The left of Figure 4.51 shows a good qualitative agreement, but the measured minimum rise time is lower. This was already explained by the inaccuracy of the predicted rise time by the amplifier model. To compensate for this inaccuracy, the simulation was shifted by 1 ns as shown on the right of Figure 4.51. Once shifted, an excellent agreement is seen between the simulation and the measurement.

The next time response parameter studied was the fall time. Figure 4.52 shows both the simulated and measured fall time distributions. Both distributions show a wide spread at 10 V with a hint of an excess at 12 ns.

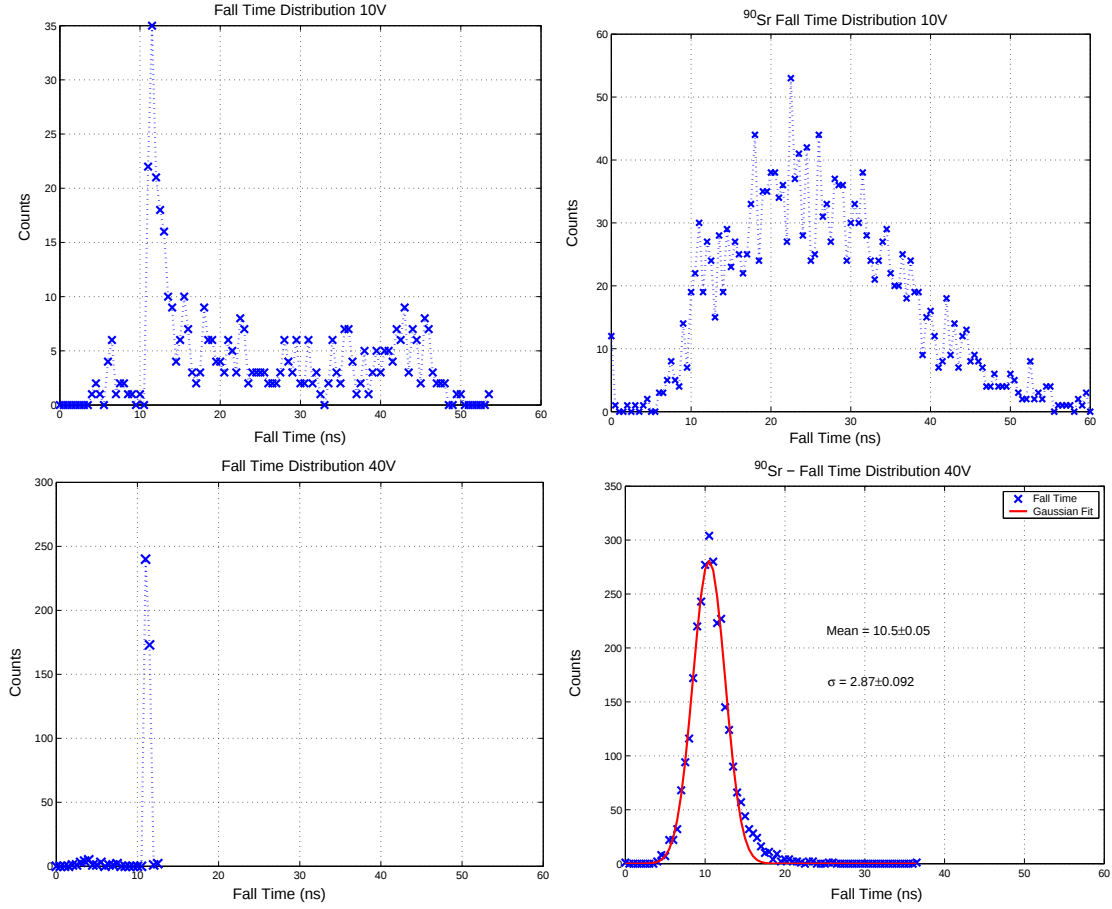


Figure 4.52: The fall time distributions obtained at 10 V and 40 V. Left: Simulation, Right: Obtained using a ^{90}Sr source

At 40 V, the measured distribution was very close to a Gaussian distribution as shown in Figure 4.52. It was therefore fitted with a Gaussian distribution, which gave a mean of 10.5 ns and a standard deviation of 2.87 ns. The simulated mean is also 10.5 ns, which is in good agreement with the measured data. For a clearer comparison, the measured and simulated distributions are plotted together in Figure 4.53 and Figure 4.54 for 10 V and 40 V respectively.

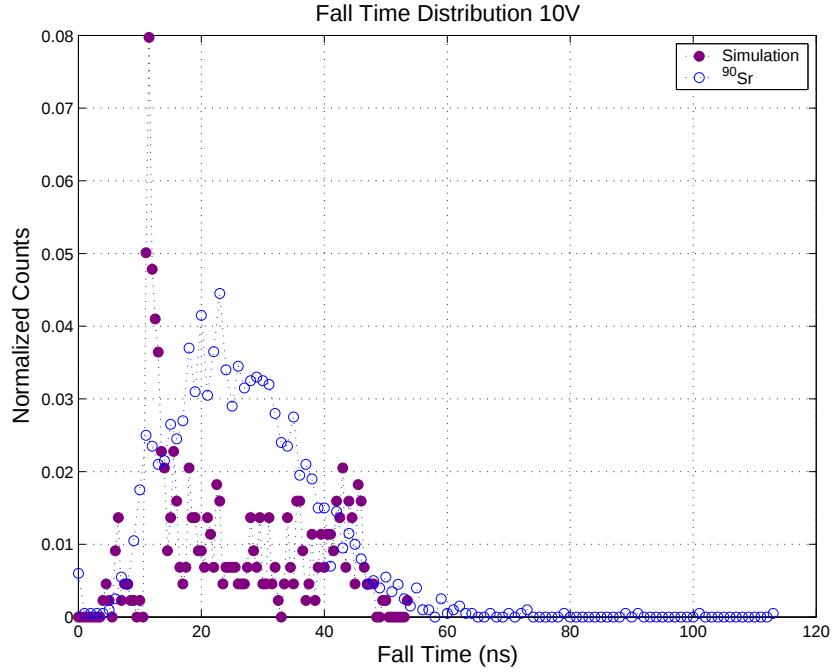


Figure 4.53: The fall time distributions from both simulation and measurement obtained using ^{90}Sr at 10 V are compared. The distribution shape do not agree but both have a spread from 0 to 50 ns.

The shape of the two distributions at 10 V are fairly different but they both spread from 0 to about 60 ns. The hint of excess at 12 ns in the simulation is completely smeared out in the measured distribution. The smearing factor is unclear, but one possibility is caused by a minimum ionising particle track. Assuming the peak at 12 ns existed in the measured distribution, it would be most likely smeared out by the spreading of the particle track. This together with other charge spreading factors such as noise and Landau fluctuations, it is not surprising that the peak at 12 ns in the simulation is not seen in the measurement. The fact that they both show the same amount of spread from 5 ns to about 60 ns, shows that the simulation gave a good prediction, but for an accurate understanding a better simulation model must be introduced.

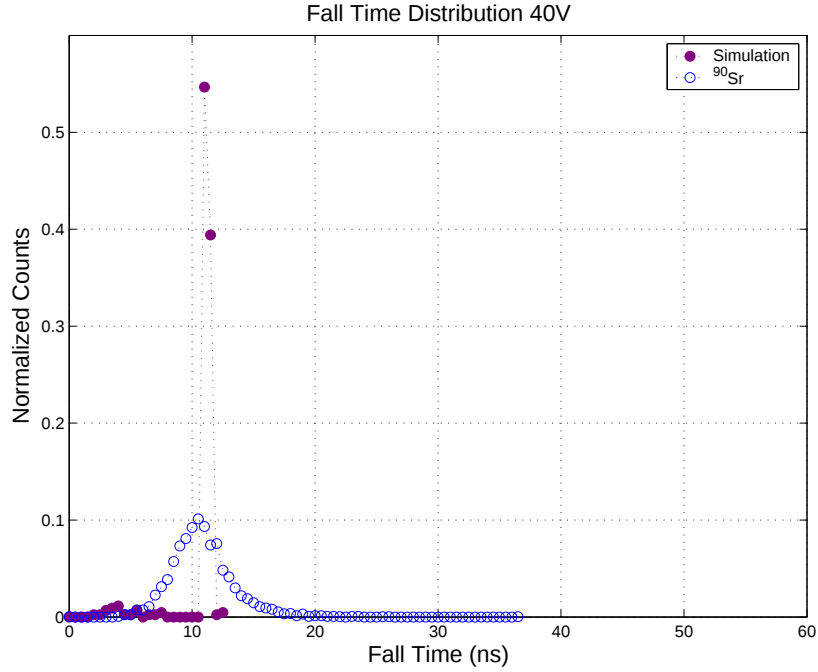


Figure 4.54: The fall time distributions from both simulation and measurement obtained using ^{90}Sr at 40 V are compared. The distribution shape do not agree but both have a peak at 10.5 ns.

Similarly, the distributions at 40 V are compared in Figure 4.54. The resulting peak from the simulation at 40 V is again smeared out in the measurement. As already mentioned, many factors are responsible for this smearing. Section 4.3 shows the fall time behaviour is homogeneous across the cell at 40 V, thus this single peak in the simulated distribution was expected. The spread of the measured distribution confirms the conclusion that important factors were not included in the simulation model. The Landau fluctuations, the point-source approximation and the noise should all be considered if one wishes to have a better prediction. The spreading at low bias voltages is more pronounced because of the undepleted region and a higher level of noise. All the effects are very well understood in the fall time studies, giving an excellent insight into the time response behaviour of 3D detectors.

The mean fall time was calculated at each bias voltage and is plotted as a function of voltage as shown in Figure 4.55.

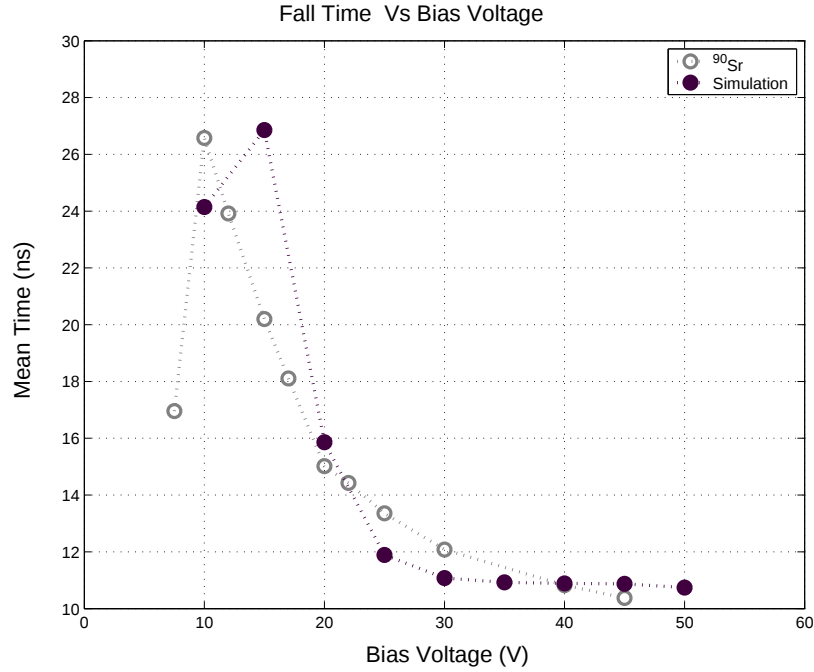


Figure 4.55: The fall time measured from both simulation and measurement obtained using ^{90}Sr are compared. A good very good agreement is observed.

Figure 4.55 shows an excellent agreement between the simulation and the measurement. The fall time decreases with increasing voltage above 16 V. The drop at low bias voltage was already explained in the simulation by the fact that the holes do not contribute a peak in the overall signal at low bias voltage. This is now verified by the measurement, although the turning point at which the hole started to contribute significantly to the overall signal are different. This suggests that the simulation model did not give an accurate prediction of the depletion voltage and is most likely caused by an inaccurate doping concentration. The studies show that the time response increases initially as the detector is being depleted. Once it reaches full depletion, the time response decreases with bias voltage. It then reaches a minimum that is limited by the minimum time response of the amplifier.

The time response across the single cell became more uniform with increasing bias voltage described in Section 4.4. This was also observed in the measured data by looking at the relationship between the standard deviation and bias voltage. Figure 4.56 shows

a comparison of the standard deviations of both the rise and the fall time between the measurement and the simulation. A good qualitative agreement is observed. However, the standard deviations of the measured results are higher due to the system noise.

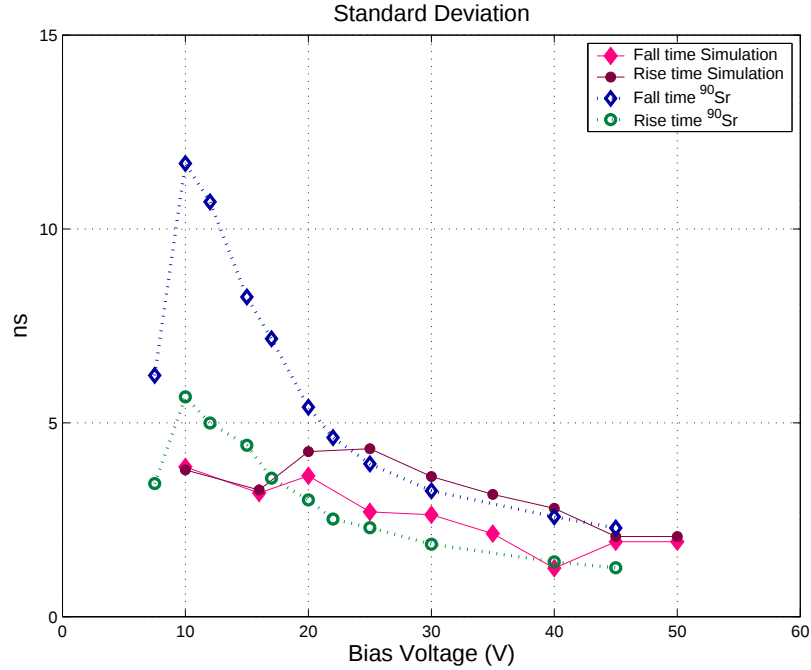


Figure 4.56: Standard Deviations as a function of bias voltage. The simulation and the measurement are compared.

4.5.3 Pulse Height Comparison

Simulated and measured pulse height distributions are compared in this section. The mean pulse height in the measurement is sensitive to many factors. It is affected by the thresholding effect required for discriminating the noise of the system from real signals. This is even more critical at low bias voltage when the noise was higher and the pulse height was lower. Moreover, the mean pulse height is also affected by the Landau fluctuations and both of these factors were not included in the simulation. Some disagreement between the simulation and the measurement are therefore expected. The mean signal pulse height is given as a function of bias voltage as shown in Figure 4.57 .

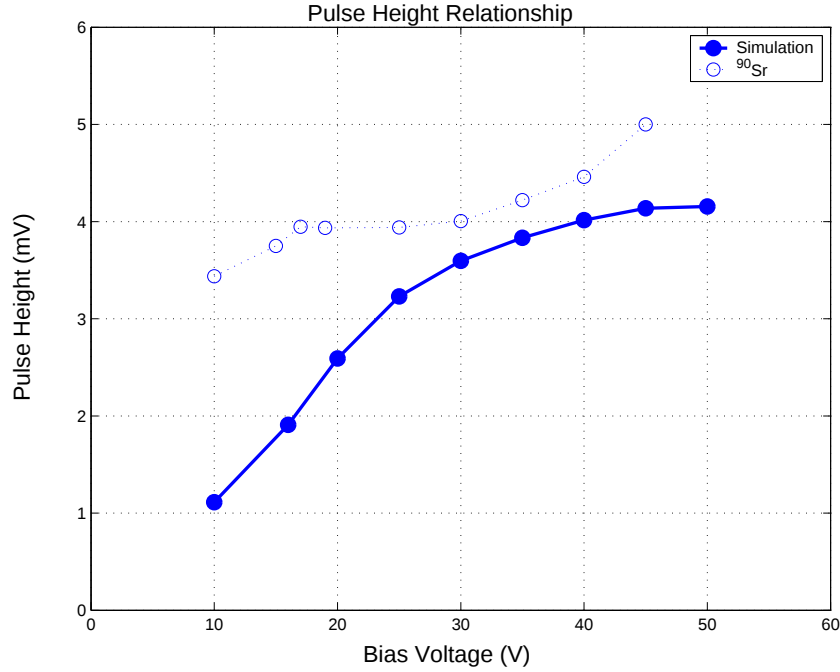


Figure 4.57: The relationship between pulse height and bias voltage are plotted for both simulation and measurement taken using ^{90}Sr .

As expected, Figure 4.57 shows disagreement between the measurement and the simulation. At low voltage, the simulated mean pulse height is very low. This suggests that signals with the most probable pulse heights were not recorded in the measurements. The recorded signals were from the end tail of the Landau Distribution. The comparison shown in Figure 4.57 shows a large difference between the simulation and measurement. The measured pulse height seems to reach a plateau and then keep on increasing beyond about 35 V. This was not seen in the simulation. The plot, however, shows a reasonable magnitude for a minimum ionizing particle traversing through the detector. For a better understanding, the Landau fluctuation must be included in the simulation model.

4.6 Summary

The full system simulation model is described in this chapter. The simulation gave predictions of the measured signals and the individual contributions from the electrons

and the holes are understood. Signals from charge injected at different positions were simulated. This gave an overview of the signal behaviour across a single cell. The output signal dependence with bias voltage was also simulated and these were compared with the measured signals. Several key results were identified.

The contribution of hole and electron in the overall signal varies with different bias voltage. At voltages around 10 V, the hole did not contribute a peak in the induced current as observed in the simulation. This resulted in a faster fall time at 10 V compared to 20 V when the hole started to contribute significantly in the induced current. This explanation was verified in the measurement although the exact voltage at which the hole started to contribute did not agree. The disagreement was due to the inaccuracy in the doping concentration in the simulation model.

The simulation gave a good understanding of the measured signal behaviour. Particularly, the time response and its dependence with bias voltage. Many other factors were shown to be required if one wishes to improve the simulation model in order to have a more accurate and better understanding. The measured system used also made it difficult to have an accurate simulation model. A better experimental setup should be used to reduce the complexity of a simulation model. For example, the scattered beta source can be replaced by laser beam with precise positioning. In this case, the position of charge will be known and there will not be any Landau fluctuations and charge spreading by the 'line segment'. The simulation model will then be much more accurate and will also give further insights and understanding into the detector behaviour.

Chapter 5

Active Edge Measurement at CERN SPS

The time response and signal behaviour of a 3D detector have been studied in Chapters 3 and 4. 3D detectors were shown to have a charge collection time of a few ns. Another advantage of 3D detector technology is the active edge. This property was tested using a muon beam at the CERN SPS. The experiment and the analysis results are described in this chapter. In addition to the active edge measurement, other characteristics such as efficiency and the electrode behaviour were studied and are presented in this chapter.

A description of these detectors, including their fabrication process, advantages and intended applications is described in Chapter 1. In this chapter, the test beam was dedicated to the TOTEM experiment.

In 2003, 3D detectors with active edges, were fabricated at the Stanford Nanofabrication Facility (SNF), USA. One intended application was as a proton detector for the TOTEM experiment [44] as explained in Chapter 1. The requirement for a proton detector in the experiment is that it has a dead edge region of less than $50\text{ }\mu\text{m}$. The muon beam test was therefore designed to identify the suitable candidates, that satisfy this key requirement of the TOTEM experiment. This was done by testing the detectors and measuring their sensitive area with respect to their physical dimensions and consequently the width of their inactive region at the edge. Precision was important and a silicon telescope was used for this purpose in the test.

In this chapter, the measurement setup, results on active edge and the detector overall efficiency are described. In addition, the detector homogeneity was also studied by looking at the signal efficiencies of the p and n-electrodes.

5.1 Measurement Methods

3D active edge detectors fabricated at Stanford Nanofabrication Facility, were shipped to CERN, Geneva in August 2003 for the TOTEM test beam. In this section, the setup and the measurement methods are described.

5.1.1 Detectors and Readout Amplifier

Details of the 3D detector and active edges were briefly described in Chapter 1 and more details can be found in [3]. The bulk of each detector was high resistivity silicon. The physical edge around the detector was etched and doped by dopant diffusion to form an n+ electrode, surrounding the entire perimeter and this is called the 'active edge'.

A tested detector is shown in Figure 5.1. As can be seen from the figure, each device has 16 channels, each channel has 38 p-electrodes $100\mu\text{m}$ apart. The first and the last bonding pads were for biasing only. They were joined by an aluminium strip, forming a channel similar to that of a strip detector. Midway between the p-electrodes, there is a row of n-electrodes that are also $100\mu\text{m}$ apart from each other. This forms an individual cell of $100\mu\text{m}$ by $200\mu\text{m}$. This single cell arrangement with a p-electrode at the center and n-electrodes at the four corners of the cell is shown in Figure 5.16. Neglecting the area under the bonding pads, each detector had a dimension of 3.195mm (y) by 3.948mm (x) and is $181\mu\text{m}$ thick.

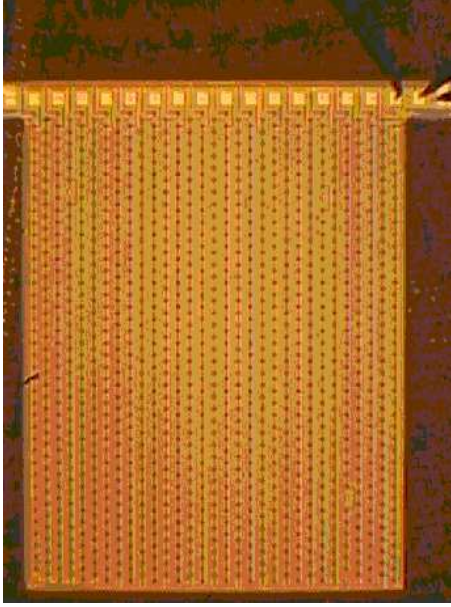


Figure 5.1: A 3D active edge detector fabricated in 2003 at the Stanford Nanofabrication Facility, California, USA. 38 p+ electrodes were connected together by a strip of aluminium to create a single channel.

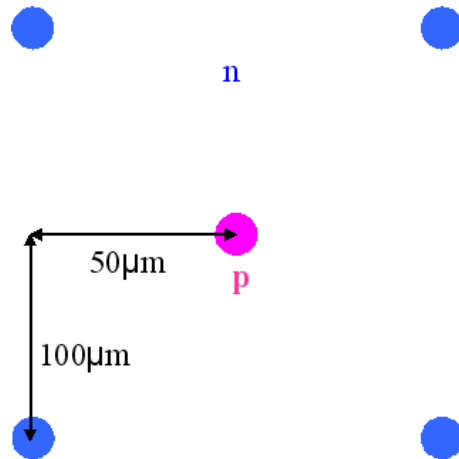


Figure 5.2: Definition and dimension of a cell in the 3D active edge detector. This definition was used in the cell efficiency studies.

Each strip of p-electrodes was wire-bonded to the input channel of an ATLAS SCTA128VG analogue readout chip [71]. This charge amplifier was originally developed for the ATLAS SCTA silicon tracker. Figure 5.3 shows the overall assembly with the SCTA chip shown on the left wire-bonded to the 3D detector shown on the right.

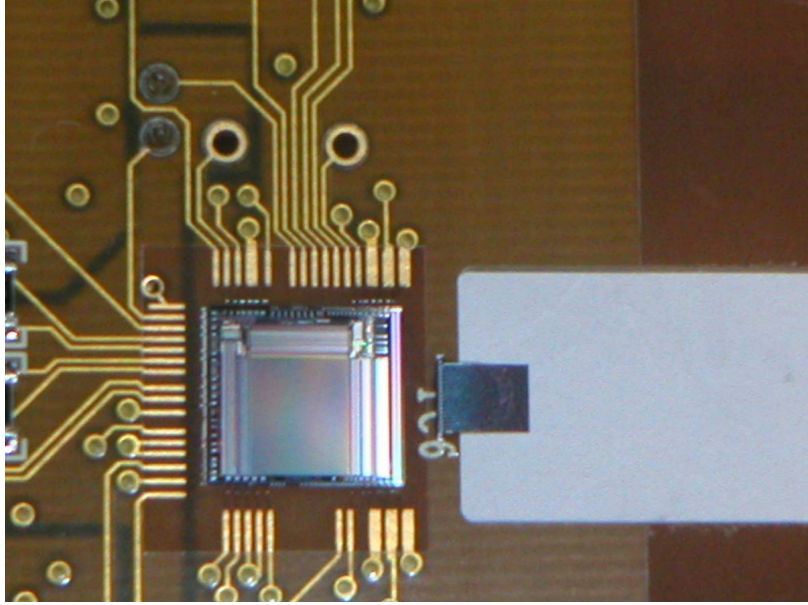


Figure 5.3: The hybrid board carrying the 3D detector (right) wire-bonded to the SCTA readout chip (left).

The SCTA chip has 128 input channels and only 16 channels were used in this test. Each channel consists of a front-end amplifier and a $128\text{-cell} \times 128\text{-channel}$ analogue pipeline that stores data from the amplifier. The front-end amplifier has an rms noise of $720 e^-$ and a peaking time of 20 ns. Output from each channel is multiplexed to give a single output. In its intended application as a strip detector readout for one of the LHC experiments, the instantaneous pulse height from each amplifier was stored in successive cells every 25 ns, which is the beam-crossing interval. The readout chip runs at 40 MHz, controlled by a clock, which was provided by a sequencer (SEQSI). The stored data was readout upon arrival of a trigger which was random with respect to the clock provided by the sequencer. Timing issues resulted due to the time delay between the clock and the trigger arrival. This affected the measurements in this test, especially the efficiency measurement. Further details are discussed in Section 5.1.4.

5.1.2 Mechanical Set up

The beamline setup was arranged such that the 3D detectors were located at the centre of the silicon telescope in order to achieve the best resolution of $4\text{ }\mu\text{m}$. The overall layout schematic is shown in Figure 5.4, Mechanical alignment and stability for the detector and the electronics were important for accurate measurement in this test. A mechanical device was designed to hold the hybrid boards and to keep them at the desired location - the centre of the telescope. The four detector planes (hybrid boards) were held by the device shown in Figure 5.5, it also provided a tool to align the detectors precisely before being fixed at the centre of the telescope.

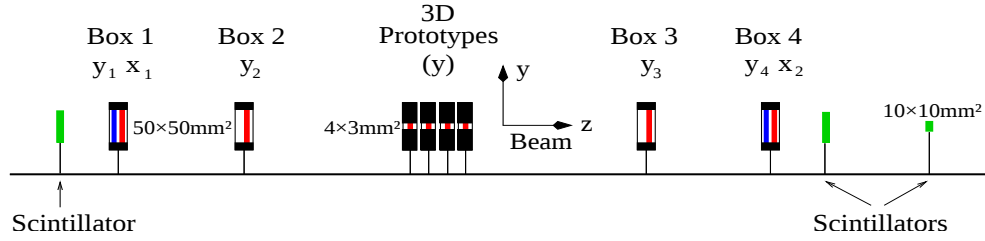


Figure 5.4: Schematic drawing of the X5 testbeam layout in August/September 2003. The boxes 1-4 constitute the silicon reference telescope ‘ODYSSEUS’ [70] with four detectors measuring the y-projection and two detectors measuring the x-projection. The 3D detectors were in the same orientation as the y-projection of the telescope planes.

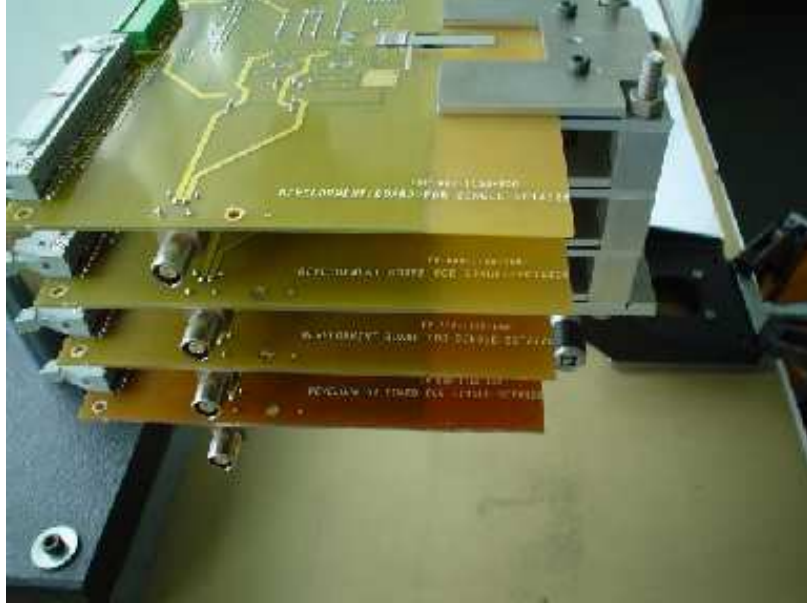


Figure 5.5: A mechanical device designed to hold four detector planes with the SCTA chip and detector mounted. It also provided a tool to align the detector planes with respect to each other.

The device with four hybrid boards was then placed at the center of the silicon telescope, which was placed on a bench in the test beam area (Figure 5.6). Alignment of the telescope and its specification are discussed in Section 5.2.1. A $5 \times 5 \text{ cm}^2$ scintillator was placed at each end of the telescope and the coincidence of the two formed the trigger for the data acquisition system.

In order to avoid radio frequency pick up, light induced noise and to provide a good grounding definition for the test system, an aluminium box was used to cover the entire mechanical device holding the 3D detectors.

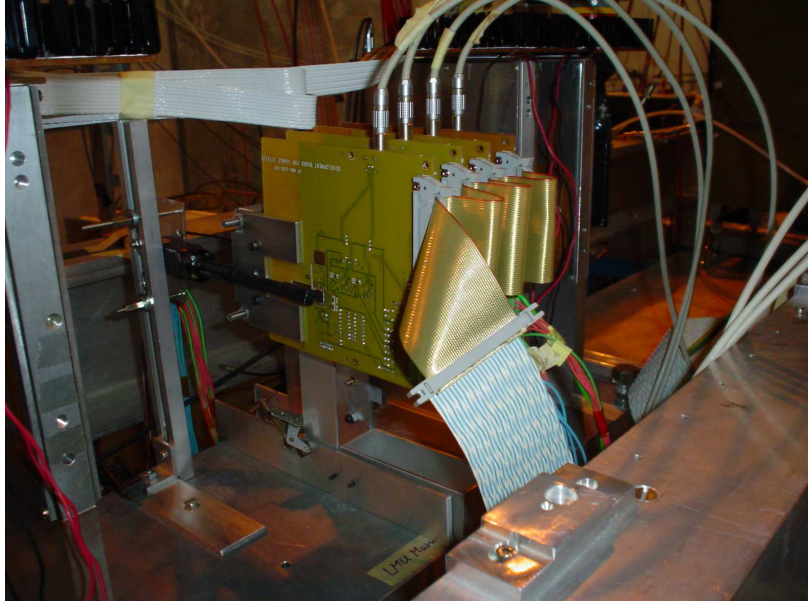


Figure 5.6: Four printed circuit boards mounted and wire bonded with 3D detectors and SCTA readout chip show in Figure 5.3 were aligned and held by a specially designed mechanical tool and was placed at the center of the silicon telescope with two y-planes and one x-plane on each side of the four detectors under test.

5.1.3 Silicon Telescope

The aim of this test was to identify the operation and edge response of 3D detectors. The position of the particle tracks must be known if one wishes to measure the dead region of the detector. For this purpose, a silicon telescope [70] was used. The telescope was originally developed for the ATLAS muon detectors in test beam experiments. As shown in Figure 5.8, it consists of six silicon microstrip detectors with a pitch of $50\text{ }\mu\text{m}$ and a typical hit cluster size between 2 and 3. This resulted in a resolution of about $8\text{ }\mu\text{m}$ per plane if charge sharing is taken advantage of. Four of the telescope focal planes had the same orientation as the 3D detectors. This direction in the measurement was labelled as the y-direction. Hence, the y-tracks through the 3D detector were measured with a resolution of $4\text{ }\mu\text{m}$. Specifications and how the resolution was derived for the telescope are described in [70]. The second coordinate (x-direction) of the tracks was measured by the two remaining telescope planes whose strips were orientated in the

x-direction.

The entire system was aligned mechanically as precisely as possible and fine adjustments were achieved by software. The software alignment procedures are discussed in Section 5.4.

5.1.4 Timing Issues for the Readout System

Section 5.1.1 described how the detector was connected to the SCTA readout chip and how the stored data in the analogue pipeline of SCTA was readout upon the arrival of a trigger. There existed a timing issue in the measurement as mentioned earlier. Particle hits and the arrival of the trigger were random with respect to the 40 MHz clock of the readout chip. This clock was provided by a sequencer module called SEQSI. There was a time delay between the trigger and when the data was recorded. This delay was measured by a time-to-digital converter (TDC).

The trigger signal was used to start the TDC. In the same way, a signal time-coherent with the readout clock, stopped the counting of the TDC, giving the time delay between data acquisition and the arrival of the trigger. The time window within which a trigger pulse had to arrive in order to coincide with the peak of the corresponding 3D detector pulse needed careful adjustment, which made the system susceptible to timing problems. The peak of the signal at the amplifier output was only readout if the TDC setting was optimal, which raised the probability to miss the peak of the signal from the 3D detectors. The content of pre-selected cell for each channel of the analogue pipeline was read out to a SIROCCO Flash-ADC [72]. If the adjustment was not made precisely, particle hits recorded by the 3D detector may be missed by the readout system.

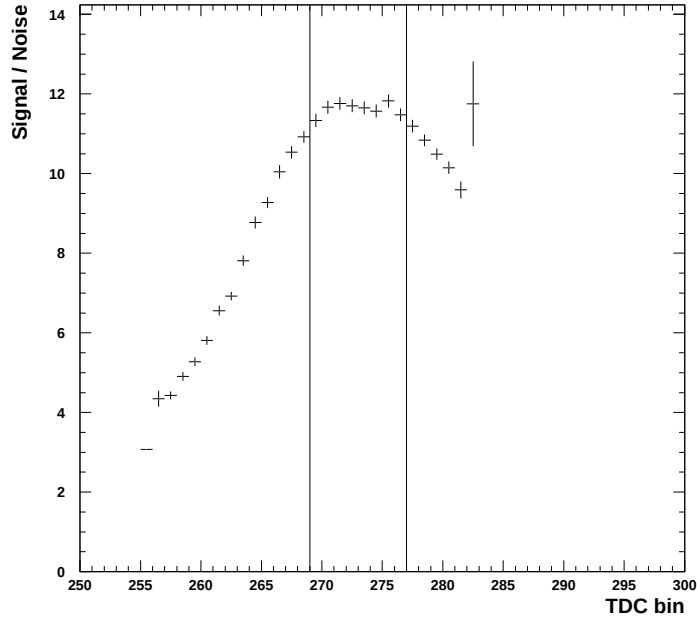


Figure 5.7: The signal height versus the time delay between trigger and data acquisition time. This shows the relationship between signal height and the time delay measured by the time digital converter (TDC). Each TDC bin corresponds to 1 ns.

Figure 5.7 shows the typical dependence of the signal-to-noise ratio (and hence the sampled pulse height) on the TDC timing. Only the events occurring between the two TDC cuts could be accepted for further analysis. The pulseheight-TDC relationship is statistical, some events could be missed or have a very low signal-to-noise ratio even within this selected time window. The timing issues became apparent when studying the detector efficiency and are described in Section 5.5. The full measurement set up described in this measurement was used to acquire data using the muon beam. The main aim was to test the active edge of the 3D detectors and to check whether it complies with the requirements of the TOTEM experiment. Once the data was collected, further software programs were used to align the telescope. These are described in the next section. Two of the installed detectors were fully tested, but one of the two contained a broken strip. Detailed analysis and results described are for the detector that was fully

operational and was numbered as plane 3 in the measurement set up.

5.2 Analysis and Results

5.2.1 Telescope Alignment and Software Analysis

In order to measure the active edge in a 3D detector, the position of particle tracks through the 3D detectors must be known. This was achieved by using a silicon telescope. After acquiring a large number of events, the entire detector was illuminated by the muon beam. The position of each track was predicted by the telescope, for which a measurement of the sensitive region of the 3D detectors was resulted. The sensitive area was then compared to its physical dimension measured from photolithography, giving the dead area of the detector. The actual measurement set up in the test beam area is shown in Figure 5.8.

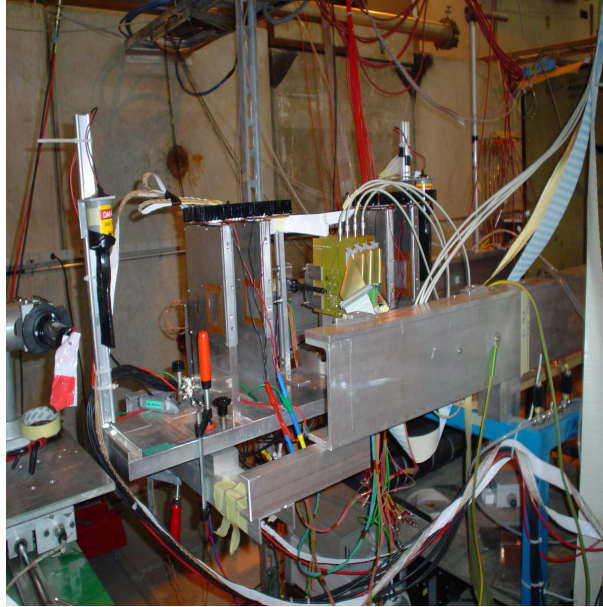


Figure 5.8: Test system with the 3D detector planes situated at the centre of the silicon telescope, installed at the muon beam test area at CERN SPS.

It is crucial to have good alignment of the telescope and the 3D detector, in order to

predict the track positions accurately. The six silicon strip detectors were aligned as precisely as possible mechanically, but fine alignments were made by software. The y-plane situated in Box 1 as shown in Figure 5.4 was used as the reference plane or treated as the absolute position. All other planes were aligned with this absolute position. Once the telescope was aligned, similar procedures were performed to align the 3D detectors with the silicon telescope. The alignment was included in all analysis.

In order to have a clean sample, strict requirements were placed on the telescope data. The requirements are as follow:-

1. Signals had to be greater than 3 times the RMS noise measured in the system
2. The two x-planes had the same hit position ie. the same strip number
3. At least one plane in the y-direction had a good cluster

If the data satisfied all the above, it was then fitted with a straight line using least mean square minimization to give a predicted track. The goodness of the track in the y-direction was then tested by a χ^2 hypothesis test. The fitted track predicted the hit positions of the beam in the 3D detectors under test. Although the main aim of the test beam was to measure the active edge, the data was also used to measure the following characteristics of 3D detectors:

1. Signal-to-noise-ratio
2. Tracking capability
3. Efficiency
4. Electrode behaviour

Each result is described in the following sections.

5.2.2 Signal-to-Noise Ratio

The signal-to-noise ratio distribution was measured for one of the fully operational 3D detectors (plane 3) as shown in Figure 5.9. A Landau distribution was observed

when a minimum ionising particle traverses the silicon detector. The most probable signal-to-noise-ratio was measured by fitting with a Landau distribution without the pedestal peak and was measured to be 12.62. For a $181\text{ }\mu\text{m}$ thick silicon detector, one would expect a higher signal-to-noise-ratio if the electronic noise is only $720\text{ }e^-$, given by the specification of the electronics [71]. However, this was quoted for an input capacitance of 0 pF and the noise was expected to be higher. The average number of electron-hole (e-h) pairs generated by a minimum ionising particle is $80\text{ e-h pairs per }\mu\text{m}$ in silicon. A total of 14480 e-h pairs are therefore expected to be generated in a detector that was $181\text{ }\mu\text{m}$ thick. The expected signal-to-noise-ratio should therefore be approximately 20. The capacitance of a 3D detector per electrode measured on a $121\text{ }\mu\text{m}$ thick substrate is 0.2 pF . Taking the number of electrodes, the strip geometry and the relative distance among neighbouring electrodes into account, the full capacitance should be approximately 10 pF/cm . The capacitance of each strip increased the input capacitance of the SCTA and increased the noise of the system. As a consequence, reducing the signal-to-noise. During the beam test, another source of noise was present. This was the heat generated inside the light tight box covering the 3D detector planes since no cooling system or ventilation was implemented. Heat inside the box was not removed during the test and the duration of the test lasted many hours. Although the temperature was not monitored, the heat generated certainly increased the noise level.

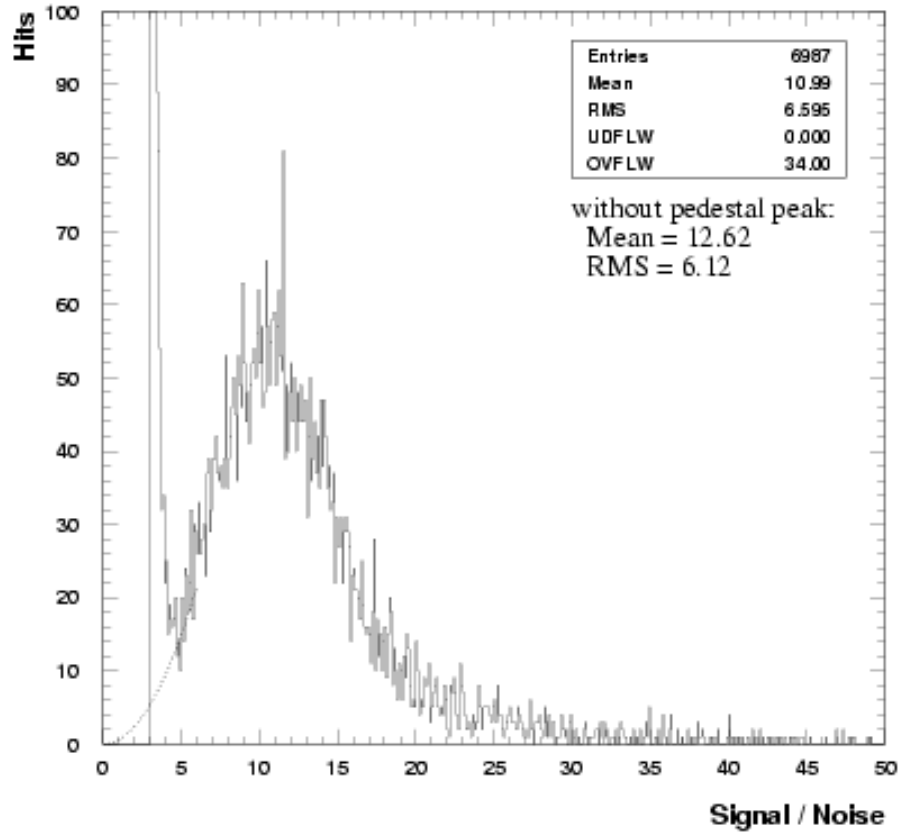


Figure 5.9: Signal to noise ratio distribution of a 3D detector obtained using a 120 GeV muon beam with the detector at full depletion. It is fitted with a Landau distribution without the pedestal or noise peak. The cut off threshold is at 3 sigma of the noise.

The signal-to-noise distribution measured here will be used to estimate the efficiency of 3D detectors. In addition, the efficiencies at the p and n-electrodes were also obtained using this distribution. These were compared with the results obtained at the Advanced Light Source at Lawrence Berkeley Laboratory [73]. This is described in Section 5.6. The Advanced Light Source provided an X-ray beam with a beam width of a few μm and was used to test both the active edge and electrode behaviour. The details of this test will be presented in a future publication.

5.3 Tracking Capability

Tracking capability is an important performance of any detector used in high energy physics experiment. When a trigger arrived, it indicated that a particle beam traversed through the silicon telescope. Particle tracks were reconstructed using the selection criteria, software alignment and fitting routine that were described in Section 5.2.1. The hit position on the 3D detector was predicted using these reconstructed tracks. The predicted hits in the 3D detector from the telescope was used as a 100 % count efficiency. Tracking in the y-direction by the 3D detector was compared with the telescope prediction. The correlation is shown in Figure 5.10. The hit positions recorded by the 3D detector in the y-direction were in agreement with the telescope predictions. This clearly verified the tracking capability of 3D detectors.

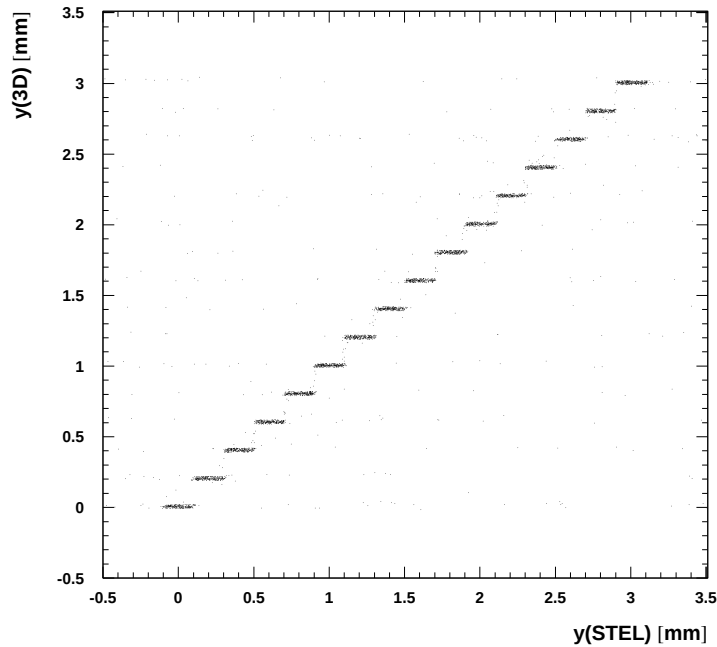


Figure 5.10: This is a correlation plot between the hit positions measured by the 3D detector - $y(3D)$ and the predicted position by the silicon telescope - $y(STEL)$. The quantisation shown in this plot is caused by the $200\mu m$ strip of the 3D detectors.

The resolution of the 3D detector was also measured by looking at the residual between the telescope prediction and the position recorded by a 3D detector ($y_{3D} - y_{STEL}$). The residual distribution in Figure 5.11 is a uniform distribution with a RMS value of $58.10 \mu\text{m}$. This is in agreement with the expected resolution for a detector that has a pitch of $200 \mu\text{m} - (200 \mu\text{m}/\sqrt{12})$.

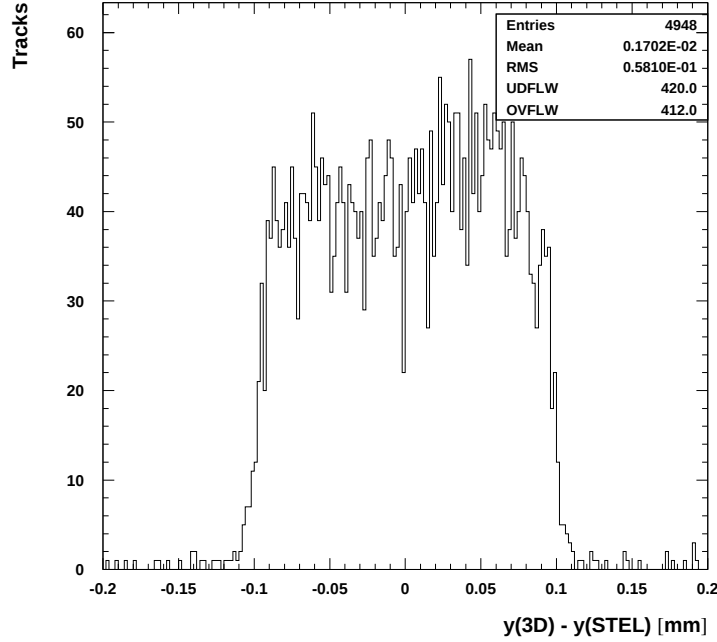


Figure 5.11: Residuals $y(3D) - y(STEL)$. The box distribution resolves well the $200 \mu\text{m}$ strip pitch of the 3D detector. As expected, the rms is close to $200 \mu\text{m}/\sqrt{12} = 57.7 \mu\text{m}$.

5.4 Active Edge Measurement

The TOTEM experiment is interested to have proton detectors that are sensitive within $50 \mu\text{m}$ from their physical edges. The ultimate aim of this beam test was therefore to measure the dead width of a 3D active edge detector. The sensitive area of the detector was measured by the silicon telescope. This was then compared with the physical dimension used by the photolithography. Figure 5.12 shows a two-dimensional image

of the 3D detector (plane 3). This was obtained by using the telescope predicted track positions providing that a hit was also recorded by the 3D detector. The two-dimensional map gave a qualitative image of the 3D detector's sensitive area to the muon beam. The image shows an inefficient band on the left vertical edge shown in Figure 5.12, caused by the bonding pads on the detector.

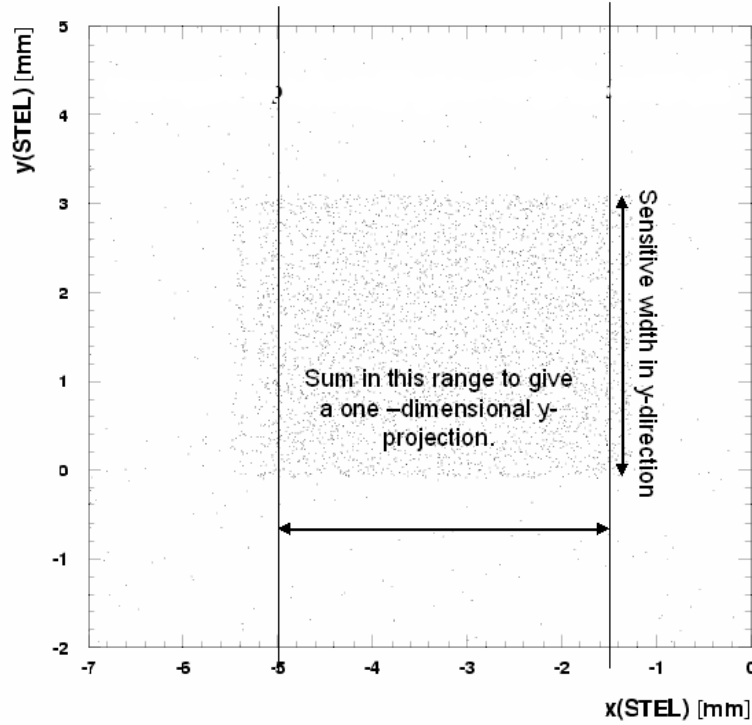


Figure 5.12: Two-dimensional efficiency map of the fully operational 3D detector. A point is plotted with respect to the position (x,y) predicted by the telescope as a valid track and a hit was recorded by a 3D detector. The efficient band near the lower x-edge was caused by the detector's bonding pads. The upper and lower y edges were used for active edge measurements

The dead edge for particle detection of the 3D detector from its physical edge was measured precisely by looking at the y-projection of the 2-dimensional efficiency map shown in Figure 5.12. The sensitive width in both x and y directions could be measured using the data shown in Figure 5.12. The data could be summed in both x and y directions. This produces a one-dimensional plot in both the x and y direction. The x-direction, however, was distorted due to the bonding pads and therefore was not used

in the width measurement. As indicated by Figure 5.12, the y-projection was obtained by summing the corresponding y-values in the x-range of (-5 mm - x - -1.5 mm).

The resulting y-projection is shown in Figure 5.13. This was fitted to Eqn. 5.1. The fitted equation is a combination of two error functions. Each fits the lower edge (y_l) and the upper edge (y_u) resulting from the y-projection shown in Figure 5.12. σ_l and σ_u define the steepness of the lower edge and the upper edge respectively. η_0 is the plateau of the y-projection (count efficiency) and b is the average of the background noise. The difference between the two edges (y_l) and (y_u) gave the active width of the 3D detector sensitive to the muon beam.

$$\eta(y) = b + \frac{1}{4}\eta_0 \left[1 + \operatorname{erf} \left(\frac{y - y_l}{\sigma_l \sqrt{2}} \right) \right] \left[1 + \operatorname{erf} \left(\frac{y_u - y}{\sigma_u \sqrt{2}} \right) \right] \quad (5.1)$$

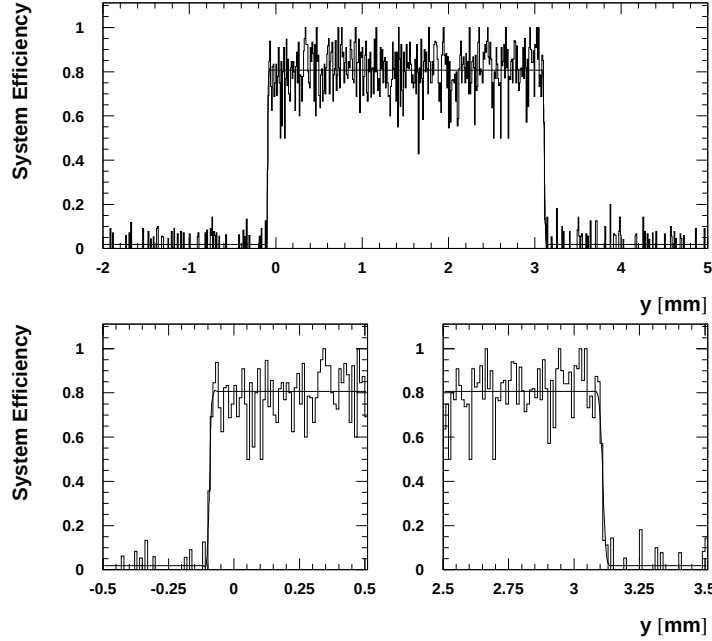


Figure 5.13: The y-projection of all the hits from the 2-dimensional hit map shown in Figure 5.12 was used to measure the sensitive width of the 3D detector by fitting with Eqn. 5.1

Table 5.1 lists all the parameters obtained from the fitting results. The width sensitive to the muon beam measured from the fit was compared to the actual physical edge measured by photolithography. The dead area was measured as the difference between the two and it shows that the detector was sensitive right up to its physical edge.

The mean width measured was 3.203 mm and was wider than that defined by the photolithography, which was 3.195 mm. However, this could be caused by any tilting between the telescope and the 3D detector, which would result in an overestimation of the sensitive edge.

Parameter	Fit result	Photolithography
Width $y_u - y_l$	$(3.203 \pm 0.004) \text{ mm}$	$(3.195 \pm 0.001) \text{ mm}$
Lower edge: σ_l	$(4.3 \pm 4.2) \mu\text{m}$	—
10 % – 90 % interval	$(11.0 \pm 10.8) \mu\text{m}$	—
Upper edge: σ_u	$(9.7 \pm 3.0) \mu\text{m}$	—
10 % – 90 % interval	$(25 \pm 8) \mu\text{m}$	—
Plateau η_0	$(80.8 \pm 0.6) \%$	—
Background b	$(1.8 \pm 0.1) \%$	—
χ^2/ndof	1183 / 994	—

Table 5.1: Results of the efficiency fit (Eqn. 5.1) shown in Figure 5.13.

Consequently, the measured width as a function of the tilt was determined. The minimum width occurred when the tilt between the telescope and the 3D detector was at a minimum. This relationship was used to identify the minimum tilt and sensitive width to exclude any overestimation. Figure 5.14 shows the relationship of measured width and the tilt angle between the telescope and 3D detector. The result was fitted with a quadratic equation (Eqn.5.2). The minimum point was $3.206 \pm 0.004 \mu\text{m}$, calculated by differentiating Eqn.5.2. This is even larger than the measured results from the original fitting y-width given in Table.5.1

$$y = 26.2 \alpha^2 - 1.622 \alpha + 3.206 \quad (5.2)$$

y is the measured width in μm and α is the tilt angle in radians.

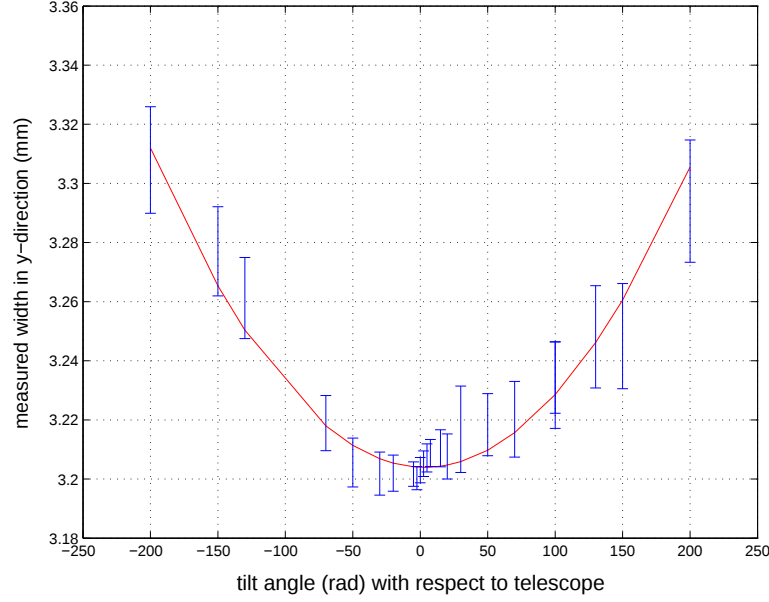


Figure 5.14: The y -widths were measured with a different tilt angle between the 3D detector and the telescope. The relationship shows the minimum width was measured with tilt angle between the telescope and the detector is at its minimum, confirming the original alignment was correct.

This study confirms that the active edge measurement was performed with the best alignment possible, indicating the width of the detector sensitive to the muon beam was not overestimated. The error in the photolithography was known to be small and should be less than $1\ \mu\text{m}$. The difference between the measured width and that expected from photolithography is $(8\ \mu\text{m} \pm 4\ \mu\text{m})$. This suggests that some other factor exists. As mentioned earlier, no cooling system was available in this set up. After many hours of data taking, the temperature of the electronics and the detector increased. The temperature was unknown but could be as high as 40°C . Photolithography was undertaken in a room with a well-controlled temperature, usually at 20°C . The difference between the two can be due to the thermal expansion of the detector in this set up. The thermal expansion coefficient of silicon is $3 \times 10^{-6}\ ^\circ\text{C}^{-1}$. This implies that a piece of silicon, which has a length of $3.195\ \text{mm}$ can expand by several μm when the temperature changes by 20°C . Moreover, the detector was glued to the PCB. This has a thermal expansion coefficient of $\sim 17 \times 10^{-6}$, even greater than silicon. With the set up dismantled, it is now difficult

to fully verify the width when operating. However, this simple calculation shows that thermal expansion is certainly significant to explain the wider width that was measured. The detector is therefore sensitive up to its physical edge within an error of $4\mu\text{m}$.

5.5 Efficiency Measurement

The number of tracks traversing through the 3D detectors predicted by the silicon telescope was used as an absolute 100 % count efficiency. The count efficiency at a specific position of the 3D detector was simply the count ratio between those recorded by the 3D detector and those predicted by the telescope.

In the active edge measurement (Section 5.4), the y-projection of the sensitive region has a fitted plateau of 81 %, as given in Table 5.1, and so the count efficiency was 81 %. The second 3D detector system (plane 1) also had a very similar efficiency of 78 %. This was surprisingly lower than expected. From the signal-to-noise distribution in Figure 5.9, a much higher efficiency was expected. The signal to noise distribution shows any signal that has a signal-to-noise-ratio below 5 would not be counted, and this constituted an inefficiency. The inefficiency was estimated by integrating the fitted Landau distribution extended down to zero without the pedestal peak. The percentage of counts estimated from this integration of the entire fitted Landau distribution gives an estimated efficiency of 97 % using Eqn. 5.3. The expected efficiency measured using the telescope should also be about 97 %.

$$\eta(\text{from } S/N) \approx \frac{\int_5^{50} \Lambda_{\text{meas}}(x) dx}{\int_5^{50} \Lambda_{\text{meas}}(x) dx + \int_0^5 \Lambda_{\text{cont}}(x) dx} \quad (5.3)$$

However, the efficiency measured using the telescope reference was much lower than 97 %. The first suggestion for the cause was inefficient electrodes. The electrodes were not depleted under normal biasing conditions. These results are explained and discussed in Section 5.6. The 3D detectors consist of rectangular cells, each with an area of $100 \times 200 \mu\text{m}^2$. This is demonstrated in Figure 5.16. The electrode diameter is between 10-15 μm , they therefore occupy about 1.8 % of the total cell area. Assuming that the electrode are totally insensitive and the particle tracks passed through the detector were perpendicular to its surface, an efficiency of 98.2% is expected. Adding the inefficiency

that was caused by the system noise, the overall expected efficiency should be approximately 95 %. The insensitive electrodes are therefore not sufficient enough to explain the low measured efficiency of 80 %.

The efficiency obtained as the plateau of the fit using Eqn. 5.1 was based on the assumption that the data acquisition for both silicon telescope and the 3D detectors were in absolute synchronization. The measured efficiency was not the efficiency of the detector alone but the efficiency of the entire system including the read-out electronics whose problematic timing with respect to the rest of the setup (in particular the telescope) was already mentioned. The readout for the two systems (3D detectors and silicon telescope) were independent and separate, synchronization was only achieved by using a common trigger. Efficiency correlations between the two tested 3D detectors (plane 1 and 3) were investigated to identify any timing problems and systematic effect in the data acquisition chain. If the timing problem does not exist in the data acquisition chain, hits predicted by the telescope that were not recorded in the two detectors should be independent and their combined hit probabilities factorize. In contrast, if a correlation exists in the recorded hits between the two 3D detector planes (plane 1 and 3), the probabilities would not factorize. The following analysis identifies correlations between the two planes using the properties of independent probabilities.

Assuming $P(1) = 78\%$ and $P(3) = 81\%$ determined by the algorithm discussed above, the true efficiencies for detectors 1 and 3 respectively, they are also the hit probabilities for detectors 1 and 3. Using these probabilities, four independent cases are distinguished to test the independence of the data recorded by the two detectors. For independent data, the following probability relationships for the four different cases are as follow:

1. No hit in both detectors: $P(\bar{1} \times \bar{3}) \stackrel{\text{indep}}{=} P(\bar{1}) \cdot P(\bar{3})$.
2. No hit in Detector 1 but a hit in Detector 3: $P(\bar{1} \times 3) \stackrel{\text{indep}}{=} P(\bar{1}) \cdot P(3)$.
3. A hit in Detector 1 but no hit in Detector 3: $P(1 \times \bar{3}) \stackrel{\text{indep}}{=} P(1) \cdot P(\bar{3})$.
4. Hits in both detectors: $P(1 \times 3) \stackrel{\text{indep}}{=} P(1) \cdot P(3)$.

The geometrical overlap between the two detectors was rather poor due to mechanical misalignment, limiting the statistics for this test to only 752, out of over 5000 tracks that were recorded for each detector individually. Figure 5.15 shows the calculated hit

statistics (dashed histogram) for the four cases listed above and was compared with the actual observations. Results are given in Table 5.2.

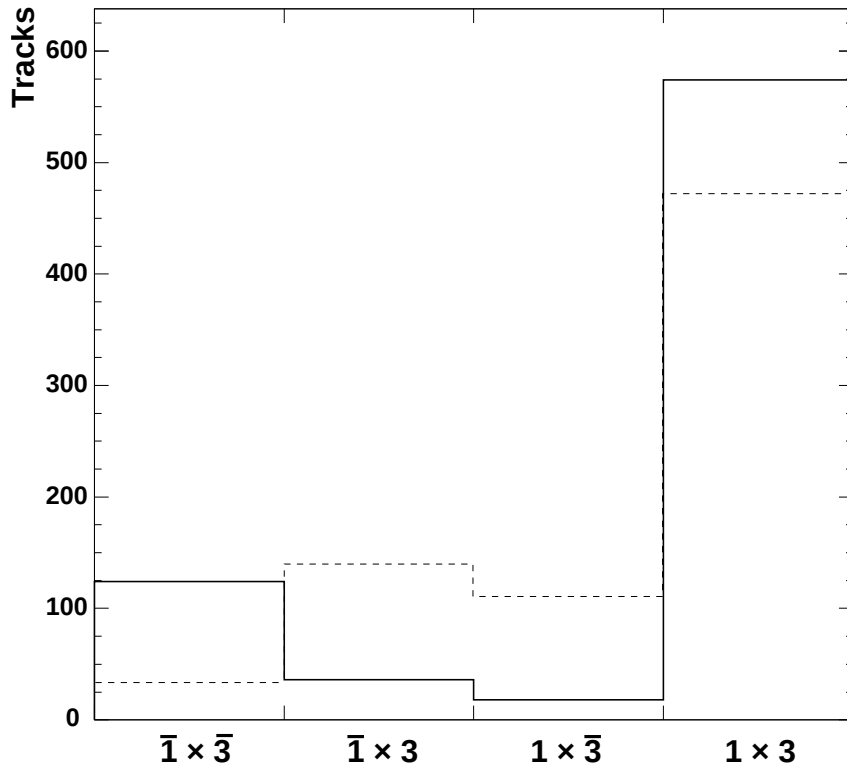


Figure 5.15: Hit correlations between 3D detector planes 1 and 3. The continuous histogram shows how often tracks (predicted by the telescope) passing through the sensitive areas of both detectors 1 and 3 created hits in neither plane, in only one plane or in both planes. The dashed histogram shows the hit statistics expected if the responses of the two planes are assumed to be independent and if the efficiencies 78 % (det. 1) and 81 % (det. 3) are used.

Combined Probability	Predicted assuming independence	Measured
$P(\bar{1} \times \bar{3})$	$(4.2 \pm 0.8) \%$	$(16.5 \pm 1.2) \%$
$P(\bar{1} \times 3)$	$(14.8 \pm 1.4) \%$	$(4.8 \pm 0.6) \%$
$P(1 \times \bar{3})$	$(18.2 \pm 1.6) \%$	$(2.4 \pm 0.4) \%$
$P(1 \times 3)$	$(62.8 \pm 2.9) \%$	$(76.3 \pm 3.2) \%$

Table 5.2: Combined hit probabilities as calculated from the observed system efficiencies and the values from direct observation from the beam tests.

A large discrepancy is evident between the beam test observation and the calculated results from the measured efficiencies. From the values shown in Table.5.2, one can infer that a missed hit in plane 3 entails a 87 % probability for missing a hit in plane 1. For independent systems, this probability would only be 19 %. Analogously, 78 % of the tracks missed by plane 1 are also missed by plane 3, in contrast to the prediction of 22 %. The large discrepancy between prediction and observation suggests that the two planes are not independent of each other and other systematic effects exist in the setup. In this case, the systematic effect is the sensitive timing problems of the data acquisition chain. Data from the readout system for the telescope is not always synchronized to the readout for the 3D detectors. Hits predicted by the telescope that passed through the 3D detectors could be missed if the timing was not set optimally. This made the measured efficiency for the 3D detectors lower than the predicted efficiency, which was estimated using the signal-to-noise and the insensitive electrodes.

The true efficiency can be estimated by introducing a common factor η_e into the observed system efficiencies that pertain to the read-out system of the 3D detectors. Using this model, the combined hit probabilities can be written as

$$P(\bar{1} \times \bar{3}) = P(\bar{1}) \cdot P(\bar{3}) \cdot \eta_e + (1 - \eta_e) \quad (5.4)$$

$$P(\bar{1} \times 3) = P(\bar{1}) \cdot P(3) \cdot \eta_e \quad (5.5)$$

$$P(1 \times \bar{3}) = P(1) \cdot P(\bar{3}) \cdot \eta_e \quad (5.6)$$

$$P(1 \times 3) = P(1) \cdot P(3) \cdot \eta_e \quad (5.7)$$

$$(5.8)$$

Resolving these equations, the bare efficiencies excluding missed hits caused by the data

acquisition system of the two 3D detectors are:

$$P(1) = 94\%, \quad P(3) = 97\%, \quad \eta_e = 84\% \quad (5.9)$$

Considering the error in these observations, the result agrees well with the expected efficiencies estimated from the signal to noise distribution where the inefficiencies are due to the noise level. The inefficiencies of the electrodes are negligible in comparison, and their behaviour in terms of count efficiency are studied and explained in the next section. The source of the timing problem is still not understood, despite the fact that it is a systematic and consistent error in the efficiency measurement.

5.6 Electrode Efficiency

In Section 5.5, the electrodes were identified as an inefficient or dead area for radiation detection. The electrodes are made of polysilicon with grain boundaries that allow many dangling bonds with free charge carriers. The electrodes are also highly doped, giving a high charge carrier concentration. They are therefore not depleted under normal biasing conditions and form insensitive areas for radiation detection.

The electrode diameter was approximately $10\,\mu\text{m}$. The actual dimension of the insensitive electrode could not easily be measured quantitatively with a small error since the best resolution provided by the telescope was $4\,\mu\text{m}$. This, however, as we shall see, allowed a good qualitative study of the electrodes.

The data had a rather low statistics because many events were rejected due to the timing problems. This left only leaving 10000 valid tracks for this study and made it difficult to identify the electrode inefficiency in Figure 5.12.

To increase the statistics of this study, all the cells away from the physical edge were superimposed in order to give a better understanding of the electrodes behaviour. The cell studied was defined as a rectangle, $100\,\mu\text{m} \times 200\,\mu\text{m}$ with the p-electrode at the centre and an n-electrode at each corner as shown in Figure 5.16. The detector edge was used as a reference for the alignment and the superposition.

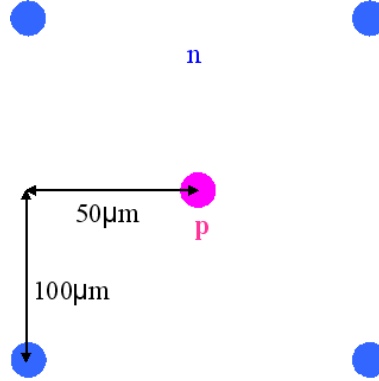


Figure 5.16: Definition and dimension of cell in the 3D active edge detector. This definition was used in the cell efficiency studies.

In addition, the superimposed cell from the two detectors (plane 1 and 3) were added to give higher statistics. Each cell was represented by a 10 by 20 grid with each square of $10 \times 10 \mu\text{m}^2$. This resolution was chosen to be a compromise for the finest resolution possible, otherwise the statistics in each square would not be adequate to give any useful information. The efficiency with respect to the hit position was measured and is shown in Figure 5.17. This efficiency includes the system inefficiency due to the timing issue explained in Section 5.1.4. It is clear in the plot that the central square, which corresponds to the p-electrode has a low count rate of about 35 %, while the efficiency in the rest of the cell is about 80 %. This was a surprise, because it had been expected that the electrodes will be completely inefficient.

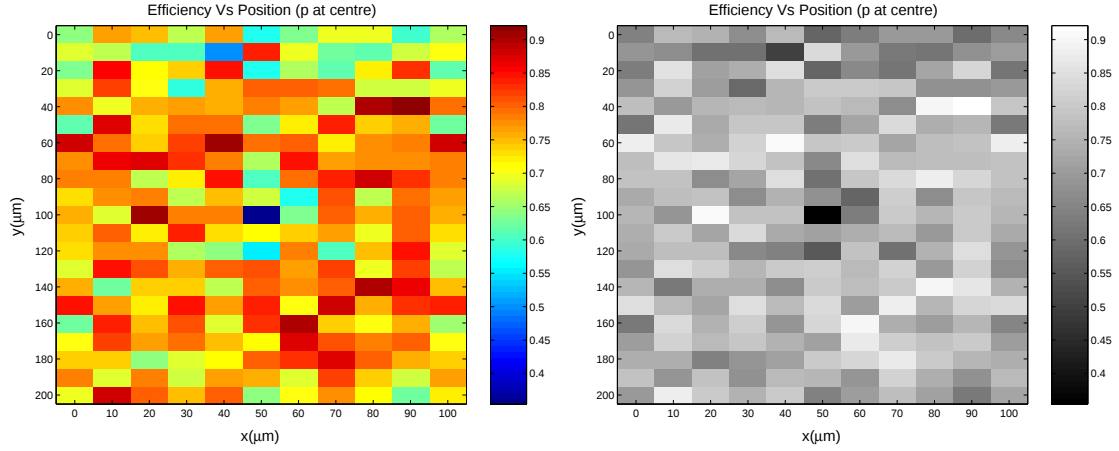


Figure 5.17: 2-dimensional efficiency map per $10 \times 10 \mu\text{m}$ square of the 3D detector under test. A significant drop in count efficiency from nominal of 80 % to 34.5 % at the p-electrode located in the center of the cell was observed using the silicon telescope as a reference system

A different cell arrangement was used to give a different visualization. This arrangement is the same as the one shown in Figure 5.16, but with the n-electrode at the centre and p-electrodes at the four corners of the cell. This was made a better visualisation to study the n-electrode. The cell efficiency map with this arrangement is given in Figure 5.18. The low count efficiency is still clearly visible at the p-electrode but not at the n-electrode.

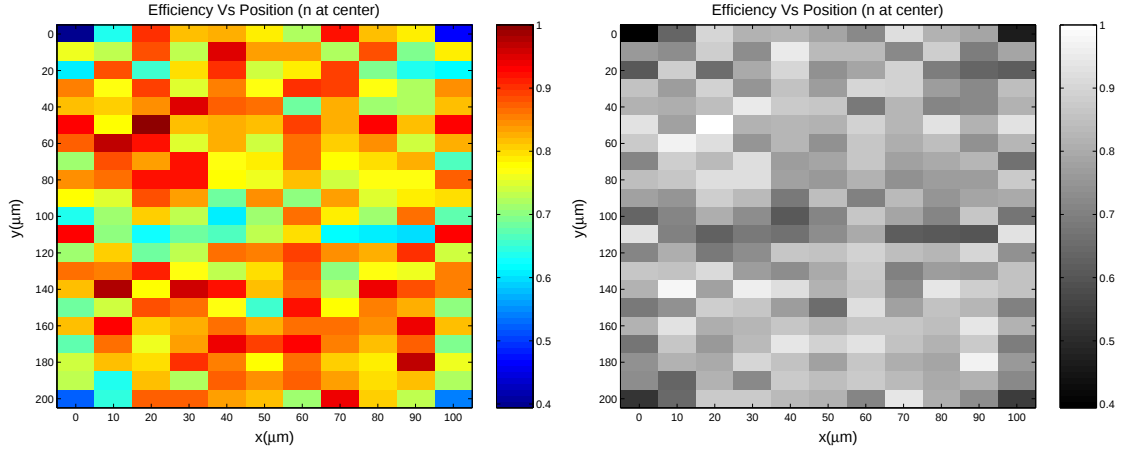


Figure 5.18: 2-dimensional efficiency map per $10 \times 10 \mu\text{m}$ square of the 3D detector under test. No significant drop in count efficiency at the n-electrode located in the center of the cell was observed using the silicon telescope as a reference system. Four corners of the cell have a drop in efficiency by the p-electrodes located at the four corners of the cell.

For a more quantitative understanding of both electrodes - p and n, the middle row (x) in Figures. 5.17 and 5.18 were extracted to give a clear one-dimensional view. On the left of Figure 5.19, the p-electrode is located at $x = 50 \mu\text{m}$. Similarly, an n-electrode is located at $x = 50 \mu\text{m}$ on the right of Figure 5.19. The measured efficiency shown at p-electrodes was $35.2\% \pm 10.2\%$ ($25.2\% - 45.6\%$). This is significantly lower than the count efficiency at other parts of the cell including the error bounds. This study confirms the inefficiency at the p-electrode. The count efficiency at the n-electrode is no different to other parts of the cell in this measurement. Both the p and n electrodes were predicted to be insensitive, the behaviour of the n-electrode in this measurement is still yet to be understood. The analysis in the next section explains why the inefficiency at the n-electrode was not observed in this measurement.

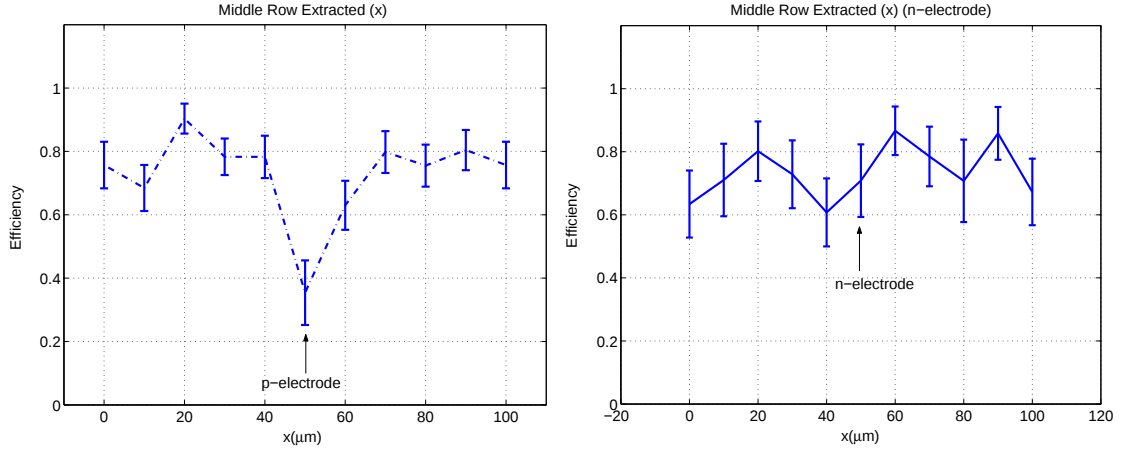


Figure 5.19: The central rows of a single cell of the detector containing the p-electrode and the n-electrode are plotted on the left and the right respectively. Considering the error in the measurement, the inefficiency at the n-electrode was not visible while the inefficiency in the p-electrode is clearly visible.

5.6.1 Comparison with ALS Test

A smaller 3D detector was tested at the Advanced Light Source (ALS) at Lawrence Berkeley Laboratory. The X-ray beam had a beam size of a few μm was used in this test. Details of this test can be found in [73]. In this test, the signal pulse height was measured with respect to the beam position. The test results showed that the signal pulse height at the p and the n-electrodes are 33 % and 66 % respectively, when compared to other regions of the cell.

In the muon beam test, the count efficiency was measured instead of signal pulse height and several criteria were used to select the valid events. In Section 5.2.2, the signal-to-noise distribution in Figure 5.9 shows any signal that has a signal-to-noise-ratio less than 5 was hidden by the pedestal peak and would be rejected as an invalid event. It also shows that the tested 3D detector had a most probable signal-to-noise ratio of 12.62. Assuming the signals at the n-electrodes follow the same distribution, but with a signal reduction of 66 % (suggested by the ALS test), the most probable signal-to-noise at the n-electrode would be about 8.32. This is well above 5 and most signals resulted in the n-electrode would most likely be considered as a valid event. In contrast, the

most probable signal-to-noise at the p-electrodes would only be about 4.16 (33 %). This implies that at least half of the events resulted in the p-electrodes would be rejected, giving a low count efficiency.

Assuming that the signals induced at electrodes follow the same Landau Distribution as in Figure 5.9 for the entire detector, the count efficiency at the two electrodes were calculated using Eqn.5.10. $\Lambda_{cont}(x)$ is the fitted Landau Distribution in Figure 5.9, which estimated the lower tail hidden by the pedestal peak. For the p-electrode, the most probable peak for $\Lambda_{cont}(x)$ was shifted to 4.16. Similarly, the peak was shifted to 8.33 for the n electrodes. These are illustrated graphically in Figure 5.20 and Figure 5.21 for the p and n electrode respectively.

$$\eta(from S/N) \approx \frac{\int_5^{50} \Lambda_{cont}(x) dx}{\int_5^{50} \Lambda_{cont}(x) dx + \int_0^5 \Lambda_{cont}(x) dx} \quad (5.10)$$

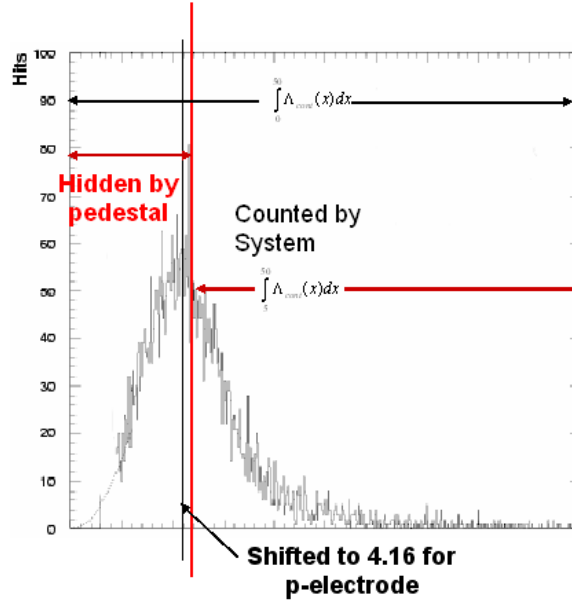


Figure 5.20: Signal-to-noise ratio shown in Figure 5.9 is shifted to have a most probable peak at 4.16 for an estimated Landau Distribution at the p-electrode.

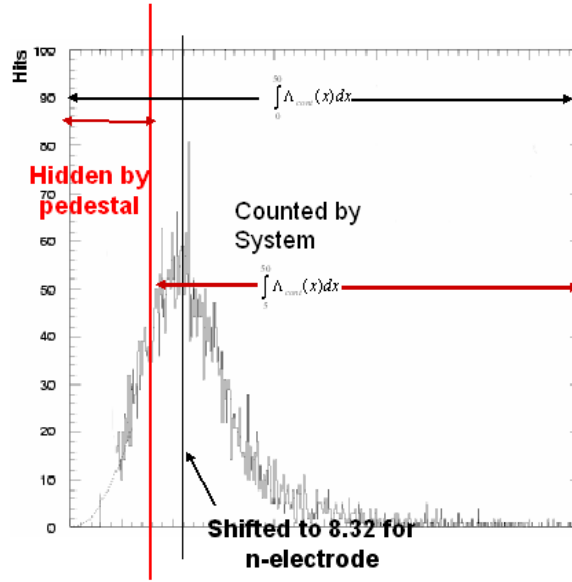


Figure 5.21: Signal-to-noise ratio shown in Figure 5.9 is shifted to have a most probable peak at 8.32 for an estimated Landau Distribution at the n-electrode.

Taking the system inefficiency due to the timing problem (84 %) measured in Section 5.5 into account, the corrected calculated count efficiencies for both p and n electrodes are given in Table 5.3. They are compared with the measured count efficiencies in the muon beam test. The comparison shows a quantitative agreement when considering the error bounds.

Electrode Type	Electrode Count Efficiency	
	Measured at SPS	Predicted using ALS Results)
p	$(35.4 \pm 10.2) \%$	44.0%
n	$(70.8 \pm 11.5) \%$	77.5%

Table 5.3: Comparison of count efficiencies measured with the silicon telescope as a reference and the predicted count efficiencies using the results obtained at ALS at Lawrence Berkeley Laboratory. The two studies agree within the error bounds from the measurement.

Cell efficiency studies from the test using a muon beam are in agreement with the test obtained at the Advanced Light Source at Lawrence Berkeley Laboratory. The two tests confirmed that the n-electrodes are more efficient with a pulse height reduction to 66 %. The pulse height at the p-electrodes reduced to 33 %. Consequently, the count efficiency at the p-electrodes reduced to 44 % for a minimum ionising particle in this set up. The pulse heights at the n-electrodes were large enough to have a count efficiency that were indistinguishable from the rest of the cell. However, the physical understanding for their differences are yet to be understood. Some explanations have been suggested.

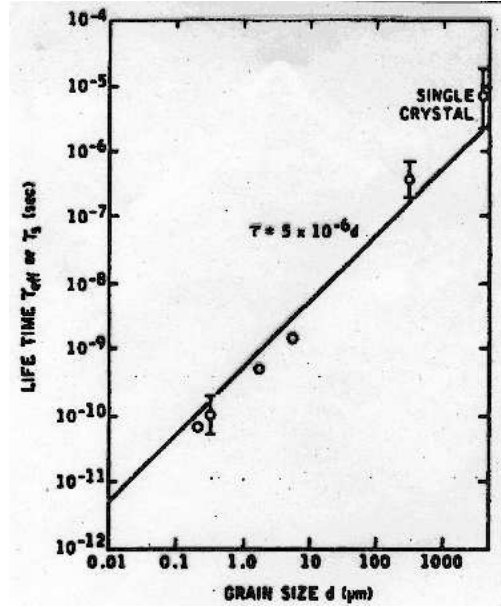


Figure 5.22: Extracted from [74] showing how electron lifetime varies with grain size in polysilicon. This shows that if there are differences in grain size, the charge collection time will be different.

The physical differences between the two electrodes are yet to be identified, but several suggestions have been made. The fraction of charge collected depends mostly on carriers, which escape from the poly into the bulk which is single crystal. The n and p electrodes collect electrons or holes respectively and they have different diffusion rate and lifetimes in polysilicon. During the fabrication of 3D active edge detectors, n-electrodes are doped before the p-electrodes. Any slight temperature differences during the process can cause differences in dopant diffusion distances, radius of built-in field and grain sizes in the electrodes. All of these differences make the amount of charge which escapes from the two types of electrodes to be different. Grain size is shown to have a direct linear

relationship with the carrier lifetimes [74], thus the charge collection efficiency will be different in the two electrodes if the grain sizes are different.

5.7 Summary

The edge sensitivity of 3D active edge detectors was measured using a high energy muon beam. The detector was found to be sensitive to within $4\mu\text{m}$ from its physical edge. The efficiency was measured to be 96 % when the systematic timing problem was excluded. The cause of this problem is still not understood. Using this setup, the efficiencies at the electrodes were also measured. The inefficiency due to the electrodes were shown to be insignificant when compared to the overall efficiency.

Chapter 6

Conclusions

3D detectors were successfully fabricated. Their advantages over conventional planar silicon detectors were discussed in Chapter 1. The motivation of this thesis was to test and to study their three main advantages; fast time response, edgeless capability and radiation hardness. The measurement set up and analysis was described in Chapter 3, 4 and 5. This final chapter summarises all key results, draws conclusions and suggests future work.

6.1 Time Response and Signal Formation

A key study was to understand the time response and the charge collection behaviour of a 3D detector. As explained in Chapter 3, a fast transimpedance amplifier was used to perform this study. Successful detection of an X-ray photon (22 keV) and a minimum ionising particle are shown in Figure 6.1.

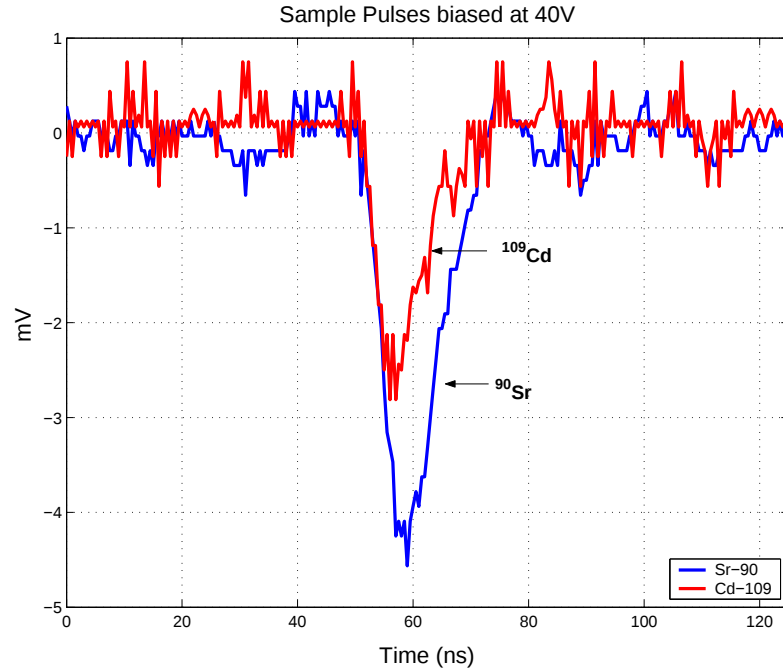


Figure 6.1: Example of recorded signals due to an X-ray photon - ^{109}Cd source (red) and a minimum ionising electron - ^{90}Sr (blue) at room temperature. The detector was biased at 40 V.

Using this set up, several aspects were studied, including the mean time response and its dependence with bias voltage at room temperature and 130 K.

The mean rise time of the output signals was 4 ns at room temperature, which was primarily limited by the readout amplifier. Identifying the minimum time response of a 3D detector will require faster electronics. A rise time of 2 ns was observed at 130 K. A signal due to a minimum ionising particle is shown in Figure 6.2.

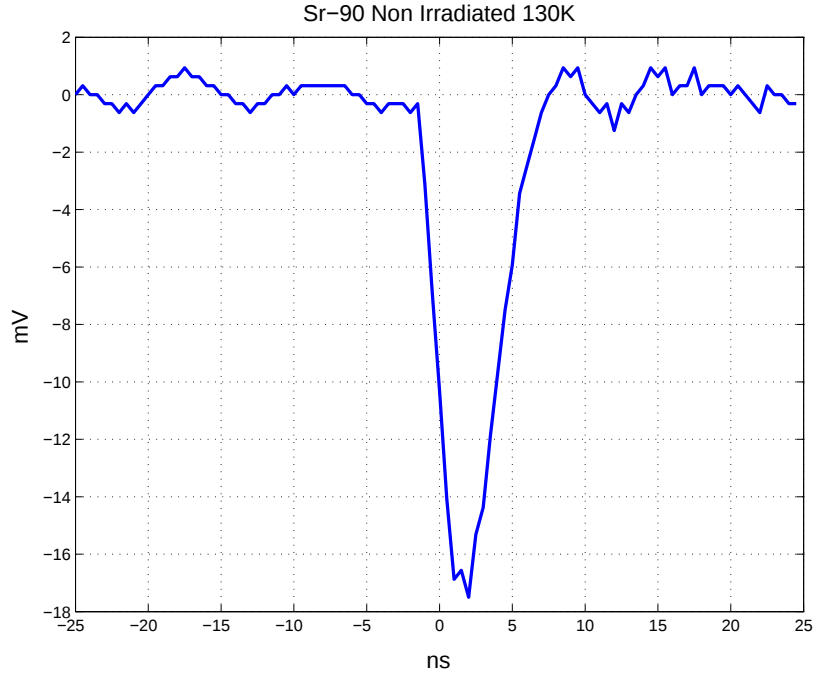


Figure 6.2: An output signal recorded at 130 K using a ^{90}Sr source with the detector biased at 40 V.

The dependence of the output signal with bias voltage was studied - Figure 6.3. The time response decreases with increasing bias voltage and eventually reaches a minimum. The same behaviour was observed at room temperature and at cryogenic temperature of 130 K - Figure 6.4.

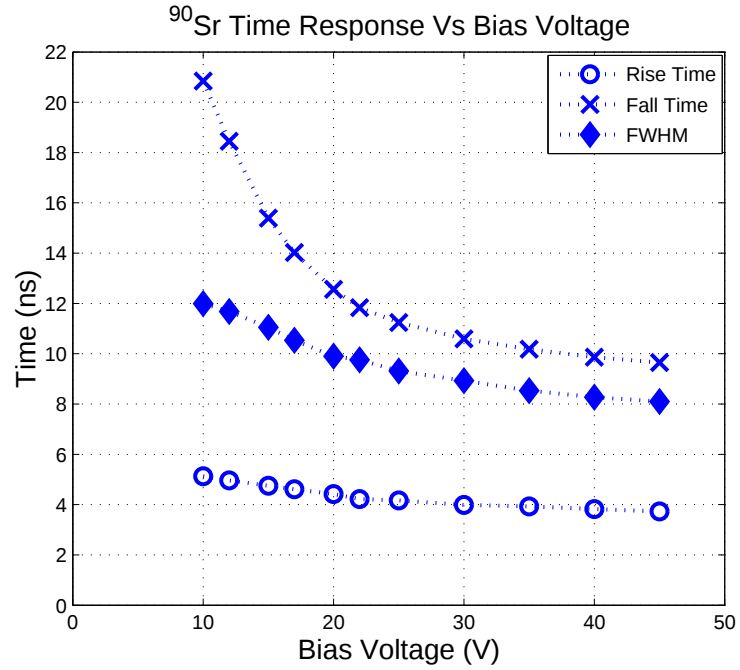


Figure 6.3: Various time parameters were measured to identify speed variations with different electric field applied to the detectors. The rise time, fall time and FWHM (full-width-half-maximum) were measured for data taken with detector bias from 10 V to 45 V at room temperature.

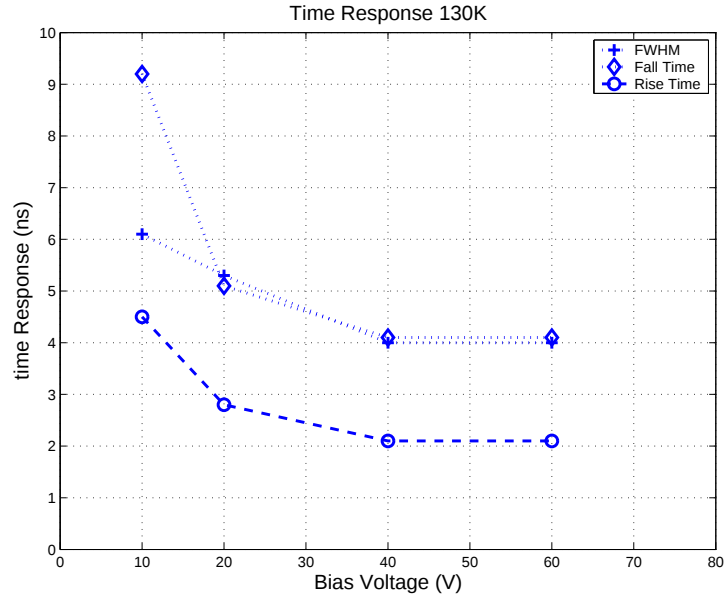


Figure 6.4: Relationship of time response parameters with detector bias voltages at 130K, showing an inverse proportionality, until it reaches the minimum time response of the amplifier.

The time response at the two different temperature - room temperature and 130K are compared in Figure 6.5. Both have the same trend but the minimum time response at room temperature is twice as that at 130 K.

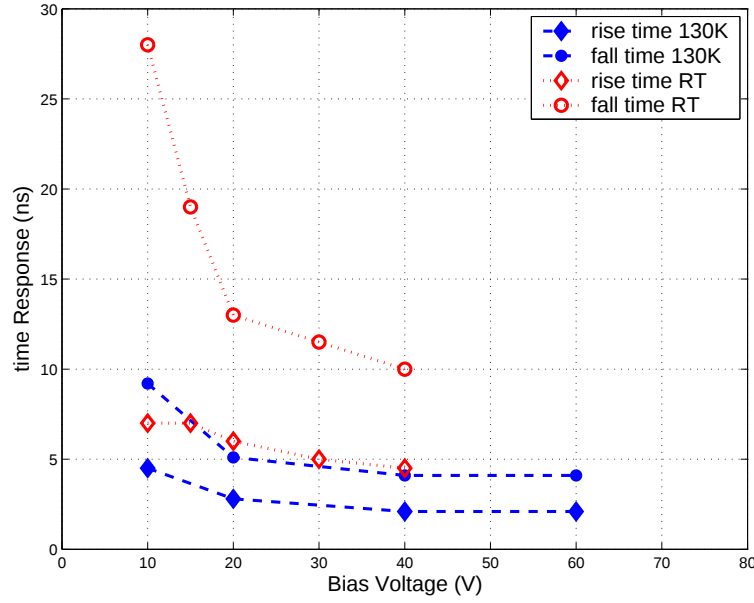


Figure 6.5: Relationship of time response parameters with detector bias voltages at 130K and room temperature are compared

A preliminary simulation using MEDICI and the amplifier HSPICE model gave an excellent prediction of the output signal. Further simulation was needed to fully understand the detector behaviour. In Chapter 4, the full measured system was simulated for a single cell geometry of the detector. The electric fields and weighting fields were calculated. Induced currents were calculated using Ramo's Theorem by injecting single point charges into the cell. The induced currents were then fed into the amplifier model to give a full system prediction. An example of a calculated induced signal in the detector and the final predicted output signal is shown in Figure 6.6.

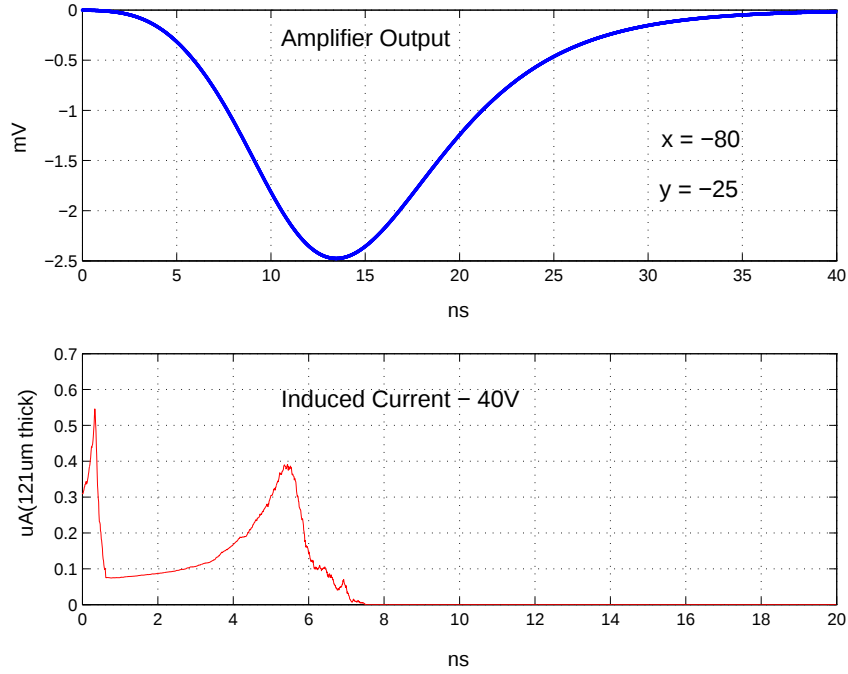


Figure 6.6: Top: Output signal simulated using the full system model with the detector biased at 40 V. Bottom: The corresponding induced current from the detector before convolution.

This simulation allowed a virtual scan across the cell to check the signal behaviour at different positions of the cell. Each resulting output signal had a different time response and the difference was most significant at low bias voltages such as 10V. Figure 6.7 shows an induced current at 10 V and its corresponding output that has a very long fall time.

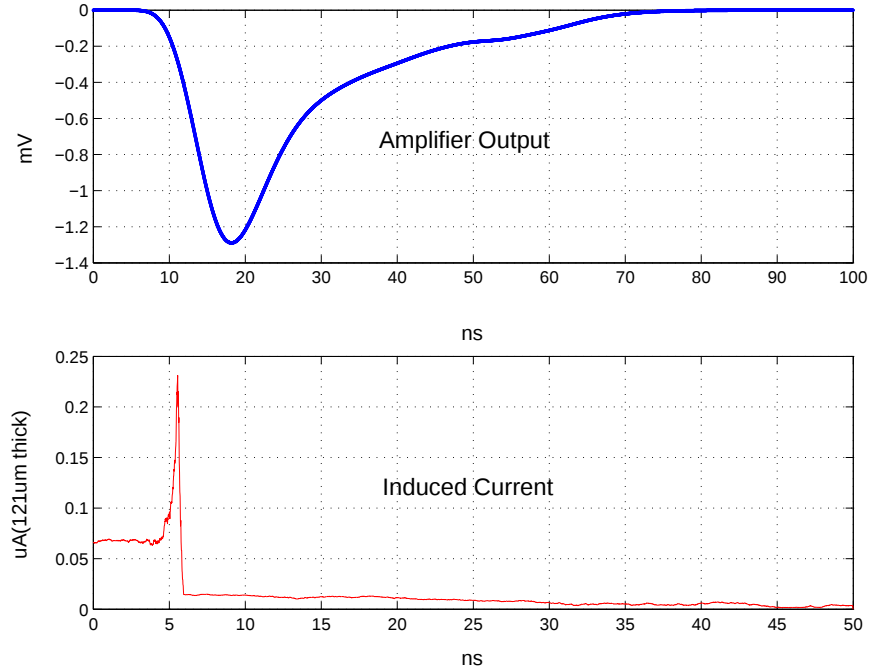


Figure 6.7: Top: Output signal simulated using the full system model with the detector biased at 10 V, showing a peculiar shape. Bottom: The corresponding induced current from the detector before convolution.

By injecting point charges at different positions, the time response across a single cell at different bias voltages were obtained as shown in Figure 6.8. The monochromatic colour at 40 V across the entire cell suggests that the variations in the fall time are negligible at full depletion, showing the detector has a more uniform behaviour at high bias voltage.

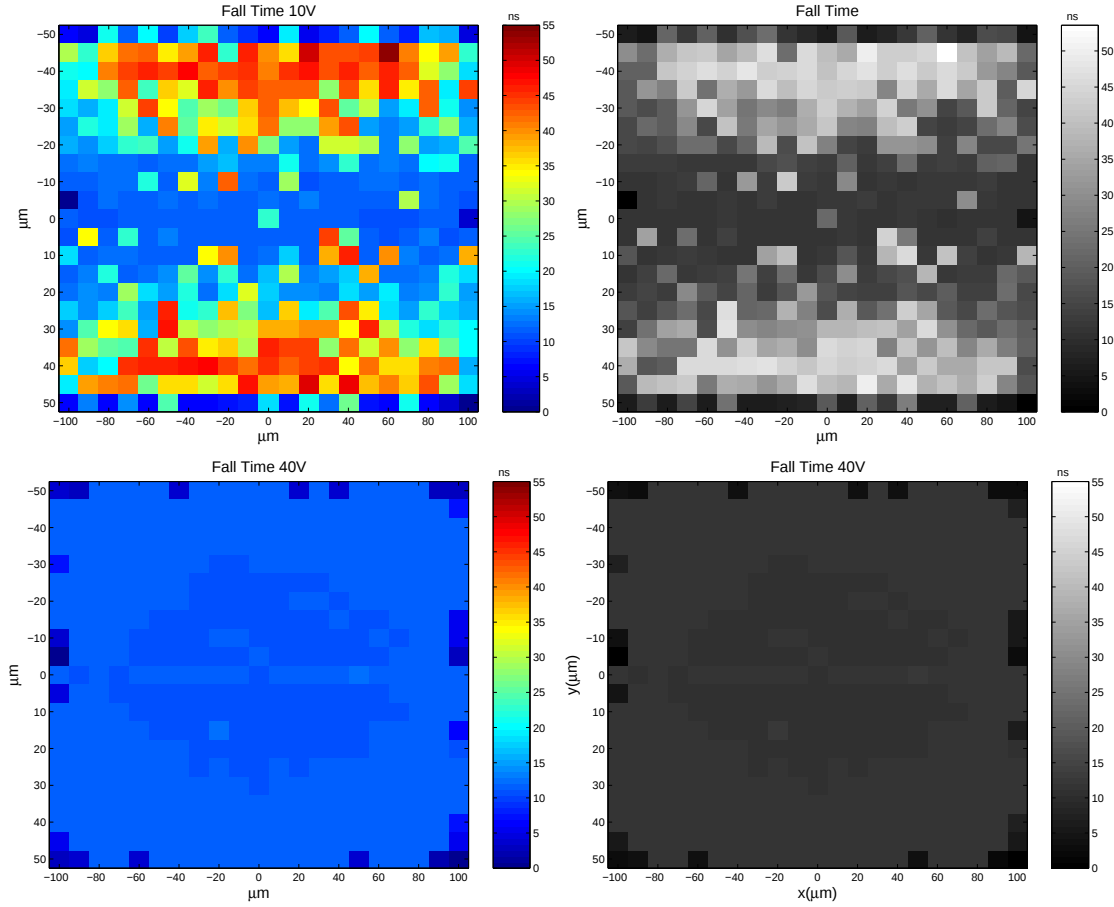


Figure 6.8: The fall time for each simulated output signal was measured. The calculated fall times across the cell are indicated by the colour code (left) and in black and white (right).

The mean time response was calculated at each bias voltage for different charge positions in the single cell. Excellent agreement was shown when compared to the measurement, in particular the fall time (Figure 6.9).

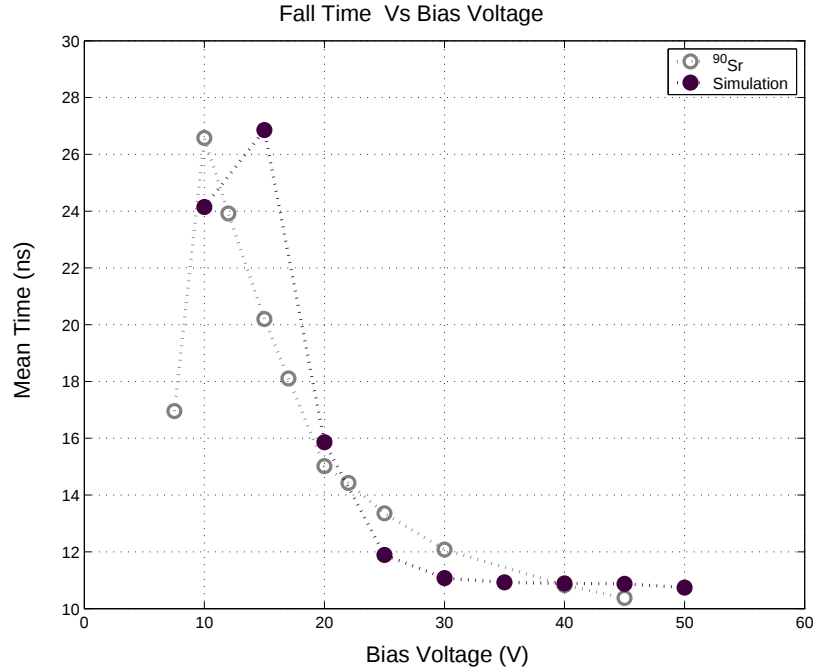


Figure 6.9: The fall time for both simulation and measurement using a ^{90}Sr are compared. Very good agreement is observed.

The simulated and measured rise time shows an agreement to a lesser extent. From the comparison of the log of the two distributions in Chapter 4 - Figure 6.10, it was found that this was caused by a long tail in the simulated rise time distributions that were not as pronounced in the measured distributions. This suggests inaccuracies existed in the simulation model and could be caused by the following:

1. The charge was injected as a point source and no Landau fluctuations were included in the simulation model.
2. The doping parameters in the detector model can also be improved to give a better prediction of the depletion voltage. This will improve the prediction of the peak shown in Figure 6.9.

More detailed understanding can also be achieved by a better experimental set up. This will be discussed in Section 6.4.

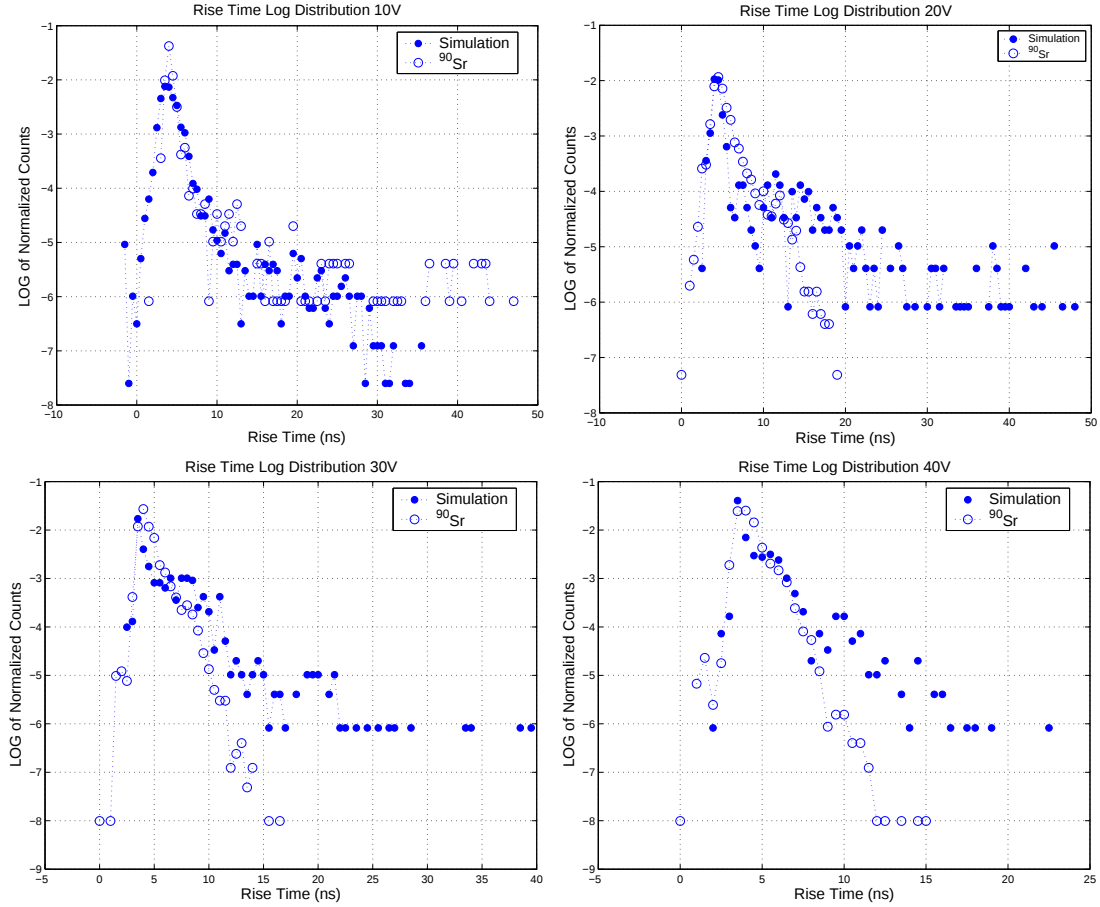


Figure 6.10: The log of the rise time distributions from both simulation and measurement are compared. These distributions are obtained for a set of various voltages. The peak was shifted to compensate for the inaccuracy of the amplifier impulse approximation model.

6.2 Active Edge

Testing of the edgeless capability of 3D detectors was very relevant to the TOTEM [44] experiment, which requires a proton detector with a dead edge of less than $50\text{ }\mu\text{m}$. The measurement set up used a high energy muon beam at the CERN SPS, with a silicon telescope to give precise positions of all particle tracks. The sensitive area of the detector was identified and a two-dimensional image was obtained - Figure 6.11.

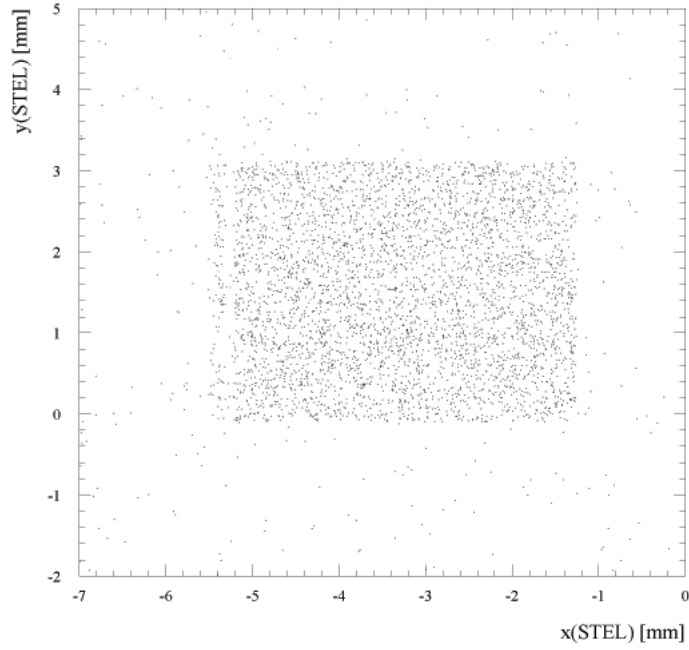


Figure 6.11: Two-dimensional efficiency map of a fully operational 3D detector. A point is plotted with respect to the position (x,y) predicted by the telescope as a valid track if a hit was recorded by the 3D detector.

The sensitive edge was measured quantitatively by projecting the y-direction of the two-dimensional image (Figure 6.11). The sensitive y-width was (3.203 ± 0.004) mm, compared to the width from photolithography of 3.195 mm. Given the measurement error, the detector is measured to be sensitive right up to its physical edge with an error of $4 \mu\text{m}$.

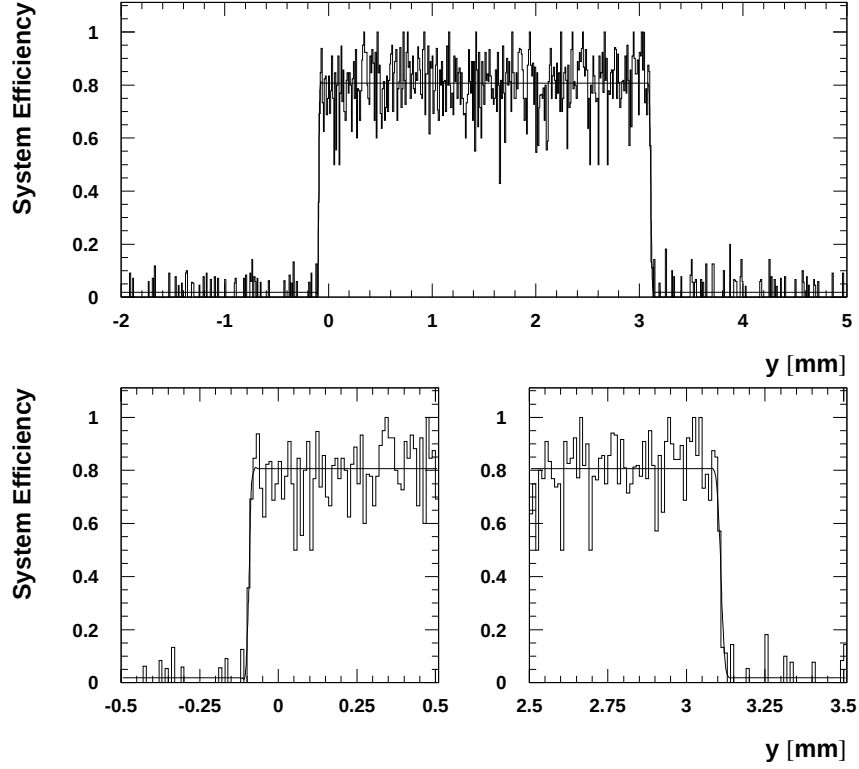


Figure 6.12: The y-projection of all the hits from the 2-dimensional hit map shown in Figure 6.11 was used to measure the sensitive width of the 3D detector.

The detector efficiency was also measured by using the telescope prediction as an absolute efficiency and is 96 % after correcting for the systematic timing problems. Another interesting study was the efficiency at the electrodes, which were thought to be insensitive. Studies in Chapter 5 - Figure 6.13, show that the n-electrode was not inefficient when compared to the main bulk of the detector within the error of the measurement error. In contrary, the p-electrode is shown to be 50 % less efficient. The count efficiencies at the p and n-electrodes were measured to be $42.1 \pm 10.2\%$ and $82.1 \pm 11.5\%$ respectively after correcting for the timing problem. The electrode behaviour is not yet understood, and will require further experimentation and modelling.

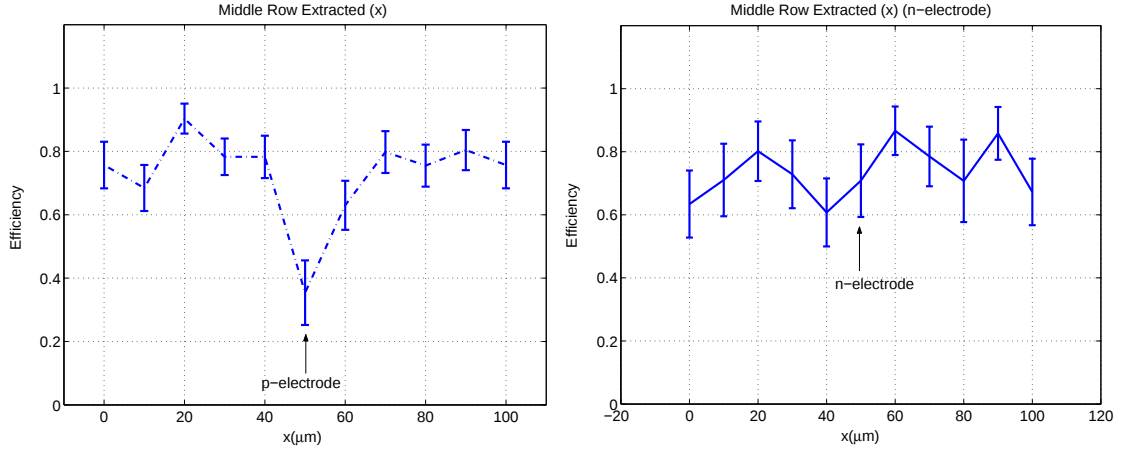


Figure 6.13: The central rows of a single cell of the detector containing the p-electrode and the n-electrode are plotted on the left and the right respectively. Considering the error in the measurement, the inefficiency at the n-electrode was not visible while the inefficiency in the p-electrode is clearly visible.

6.3 Radiation Hardness

Radiation hardness was not studied in this thesis. Previously, 3D detectors were irradiated with a fluence that is equivalent to the lattice damage expected after 10 years of operation at the innermost B layer of the ATLAS detector (1×10^{15} 55 MeV protons/cm²) [5]. Performance studies were made and the depletion voltage was found to be around 105 V for a detector with a cell size of (100 x 134) μm. This is at least a factor of 7 lower than that of a 300 μm planar oxygenated silicon detector irradiated with the same fluence [32].

A detector irradiated with the same fluence was tested using the same set up described in Chapter 3 to measure the time response. Successful detection of minimum ionising particles was still possible and a resulting signal is shown in Figure 6.14 with the detector biased at 40 V.

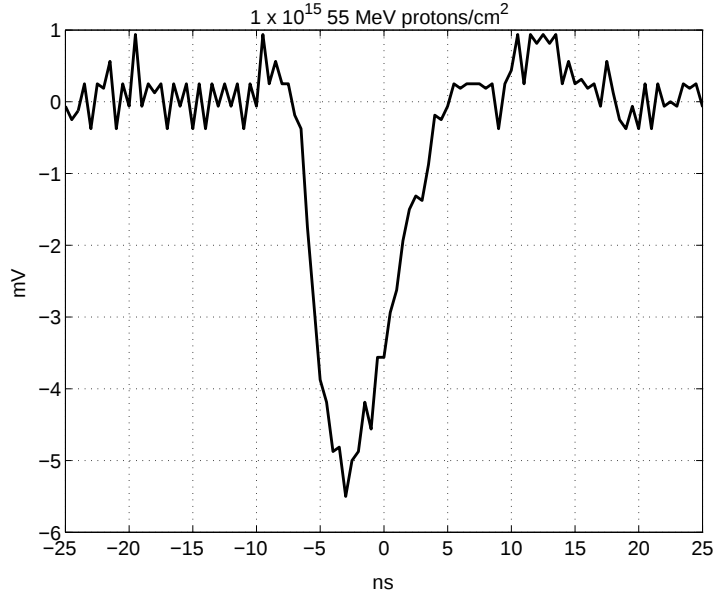


Figure 6.14: Oscilloscope trace of a signal pulse induced by a minimum ionizing particle obtained from a 3D detector after irradiation with a fluence of 1×10^{15} protons/cm². Rise time remains as 4 ns with a detector bias of 40 V.

Preliminary results show excellent radiation tolerance. However, the reduction of signal height after irradiation, the set up became susceptible to noise, making a full analysis extremely difficult. Work is still ongoing and detailed results are not yet available for publication.

6.4 Concluding Summary and Future Work

New results for 3D detectors have been shown in this thesis. 3D detectors are shown to be fast, edgeless and potentially radiation hard. The results are excellent showing a time response of a few ns and close to zero dead area. These are desirable characteristics for future high energy physics and macromolecular biology experiments.

The measurement set up also provided other interesting characteristics of 3D detectors. For example, the dependence of time response with detector bias voltage was derived. Measurements and a full system simulation allowed the contribution by electrons and

holes to the output signals to be understood, giving a clear understanding of signal formation in a 3D detector. Simulated results show good agreement with measurements, verifying the simulation model.

Using the muon beam test data, 3D detectors were measured to have a high efficiency of 96 %, with the efficiency at the electrodes of $41 \pm 10.2 \%$ and $82 \pm 11.5 \%$ at the p and n-electrodes respectively. Given the measurement error, the n-electrode appears to be fully efficient and the p-electrode is almost 50 % less efficient. However, the overall efficiency of a 3D detector is still excellent because the p-electrode with a 40 % efficiency only forms only about 1 % of the detector total area.

The results in this thesis suggest further work. Firstly, a faster readout amplifier would be desirable to identify the detector minimum time response as well as to study the shape of the induced signal more thoroughly. A new amplifier has recently been designed using $0.13 \mu\text{m}$ CMOS technology. It has a rise time of 1.5 ns at room temperature and measurements are currently underway. Secondly, the full simulation model can be improved by including the spatial charge deposition, Landau fluctuations and better electrode modelling. A more sophisticated experimental setup would also be desirable. Replacing the β -source with a laser beam would give precise beam positions to a few μm . Using such a setup, the behaviour of time response across the cell can be investigated experimentally. Another important parameter is the capacitance of a 3D detector for which a suitable model is required. This plays a major role in the electronics performance and compatibility. Some of the results described in this thesis have already been presented at several international conferences [76] [77] and journals - see publication list. The results are highly promising. All findings have shown 3D detectors to be an important addition to silicon detector technology.

Publication Lists

1. A.Kok et al, '3D Detectors - State of the Art', presented at the Vertex 2004, Como, Italy, October 2004 and accepted by Nucl Instr and Meth (A)
2. C. DaVia, G. Anelli, J. Hasi, P. Jarron, C. Kenney, A.Kok, S.Parker, E. Periozziello, S.J. Watts, 'Advances in Silicon Detectors for Particle Tracking in Extreme Radiation Environments', Presented for 4th International Workshop on Radiation Imaging Detectors (IWORID 2002), Amsterdam, The Netherlands, 8-12 Sep 2002. Nucl Instr and Meth A509 (2003) 86
3. C.DaVia', J.Hasi, C.Kenney, A.Kok, S.Parker, '3D Silicon Detectors Status and Applications', Nucl. Instr. And Meth A549 (2005) 122-125
4. TOTEM Collaboration, 'TOTEM: Technical Design Report (Addendum) Total Cross Section, Elastic Scattering and Diffraction Dissociation at the Large Hadron Collider at CERN', CERN-LHCC-2004-020, Jun 2004. 41pp
5. TOTEM Collaboration, 'The TOTEM Experiment', Presented at 4th International Symposium on LHC Physics and Detectors (LHC 2003), Batavia, Illinois, 1-3 May 2003. Published in European Physics Journal C34: S255-S268, 2004
6. TOTEM: Technical Design Report Total Cross Section, Elastic Scattering and Diffraction Dissociation at the Large Hadron Collider at CERN, CERN-LHCC-2004-002, Jan 2004. 218pp

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