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Characterization of Interface States & Radiation Damage Effects in Duo-lateral PSDs - Using Scanning Electron Microscopy and UV Beam Profiling Techniques

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Photo credit: Xerviar/Xerviar Photography.
Cover description: A semiconductor engineer in a cleanroom inspecting photolithographic patterns of electron/UV detectors on a double side polished Silicon wafer.

**Characterization of Interface States & Radiation Damage Effects in Duo-lateral PSDs - Using Scanning Electron Microscopy and UV Beam Profiling Techniques**

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Abstract

There has been an increase in the use of duo-lateral position sensitive detectors in practically every radiation and beam detection application. These devices unlike other light detection systems utilize the effect of the lateral division of the generated photocurrent to measure the position of the integral focus of an incoming light signal. The performance of a PSD is impaired or strengthened by a number of events caused by parameters such as interface states and recombination introduced during the fabrication of the detector and/or its absorption of ionizing particles. This thesis show the results from the successful implementation of alternative characterization methods of these effects and parameters using scanning electron microscopy and UV beam profiling techniques on duo-lateral position sensitive detectors (LPDs).

To help create the groundwork for the research content of this thesis, different technical reviews of previous studies on interface states, surface recombination velocity and radiation damage due to continuous absorption of ionizing irradiation on detectors are investigated. The thesis also examines published theoretical and measurement techniques used to characterize these surface/interface phenomena.

The PSDs used in this research were developed using silicon technology and the various methodologies put into the fabrication of the detectors (p-n and p-i-n structures) were fashioned after the simulated models. The various steps associated with the cleanroom fabrication and the prior simulation steps are highlighted in the content of the thesis. Also discussed are the measurement techniques used in characterizing the fixed oxide charge, surface recombination and the position deviation error of the LPDs in a high vacuum environment of a scanning electron microscope SEM chamber. Using this method, the effects of interface states and surface recombination velocity on the responsivity of differently doped LPDs were investigated. By lithographically patterning grid-like structures used as scale on p-i-n doped LPD and using sweeping electrons from the SEM microscope, a very high linearity over the two-dimensions of the LPD total active area was observed. An improved responsibility for low energetic electrons was also achieved by the introduced p-i-n structure. The lithographically patterned grids helped eliminate further external measurement errors and uncertainties from the use of other typical movable measurement devices such as actuators and two-
dimensional adjusters which would normally be difficult to install in a remote vacuum chamber.

In a similar vein, field plate and field rings were patterned around an array of the PSDs used as pixel detector(s). By studying the interpixel resistance and breakdown characteristics, the most effective structural arrangement of the field plate and field rings used to curb induced inversion channel between the $p^+$ doped regions of the pixel-detector is observed.

By using UV beam profiling after the irradiation of UV (193 nm or 253 nm) beam on $p^p$ and $p^+n$ doped PSDs, the degree of radiation damage was also investigated. The results obtained help to illustrate how prolonged UV radiation can impact on the linearity and the position deviation/error of UV detectors.

The results in this thesis are most relevant in spectroscopic and microscopic applications where low energy electrons and medium UV (MUV) radiation are used.
Sammanfattning

Duo - laterals positionskänsliga detektorer (LPSD) har fått en ökad användning inom ett stort antal olika strålningsapplikationer där bestämnings av strålningsposition är en viktig parameter. Duo - laterals positionskänsliga detektorer utnyttjar en lägesberoende lateral delning av fotoströmmen för att bestämma positionen. Egenskaperna hos en LPSD kan degraderas samt i vissa fall förbättras, då interface laddnings tillstånd och rekombination tillstånd uppstår under tillverkning av detektorn och/eller vid joniserande bestrålning. Denna avhandling visar resultaten från ett framgångsrikt genomförande av alternativa metoder för karakterisering av dessa effekter med svepelektromikroskop och profilering med hjälp av fokuserad UV- strålning på LPSD.

Avhandlingen innehåller en resumé för bestämnings av interface tillstånd, ytrekombination och strålningsskador på grund av absorption av joniserande bestrålning i detektor. Avhandlingen berör även i litteraturen beskriven teoretiska och experimentella metoder som används för att karakterisera dessa gränssnittsphenomen.

De LPSDs som används i denna forskning har utvecklats med hjälp kisellekologi och de olika val av metoder som används i tillverkningsprocessen av detektorena ($n^p$ och $p^n$ strukturer) baseras på resultat av använda simuleringsmodeller. Dessutom diskuteras de måtmetoder som används vid karakterisering av fixerade oxid laddningar, ytrekombination samt de resulterande positionsavvikelse som detta medför för LPSD. Med hjälp av dessa metoder, har effekterna av interface tillståndens och ytrekombinationens inverkan på elektronresponsivitet på olika typer av LPSDs undersöckts. Med hjälp av litografisk mönster som positionsbestämning på $n^p$ -dopad LPSD och använda den svepande elektron strålen från SEM-mikroskopet, visade sig en mycket hög linjäritet erhållas i 2 dimensioner, vidare erhölls en förbättrad responsivitet för lägnergetiska elektroder med införandet av $n^p$ struktur.

Till skillnad från $p^n$ strukturer har $n^p$ strukturer den nackdelen att de ger en ledande kanal av elektroner under kiseldioxidlager. Detta lager av elektroner induceras av de i oxid existerande fasta positiva laddningarna, vilket kan leda till höga läckströmmar. Detta förhindras med att ett kanalstopp införs. Detta kan vara i form av en p-dopning eller en på oxidens spänning satt fältring. Denna form av spänning satt fältring visade sig vara ett effektivsätt att isolera en struktur så att
hög genombrottspänning och låg läckström erhålls samt i förekommande fall (pixelerade strukturer) överhöning undertrycks.

Slutligen, med hjälp av UV- profilering efter bestrålning av UV (193 nm eller 253 nm) på p+n och p-n LP3D strukturer, undersöktes graden av strålningsskador också. De erhållna resultaten bidrar till att illustrera hur långvarig UV-strålning kan påverka linjäritet och positionsavvikelse i UV-LPSD.
Dedication

... to the memory of my late maternal grandpa, to every single teacher that has inspired me & to everyone who at one time thought they could never make it
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List of Publications

This thesis is mainly based on the following papers, herein referred to by their Roman numerals:

Paper I:
High Resolution, Low Energy Electron Detectors
O X Esebam, D Krapohl, G Thungström and H-E Nilsson
2011, 1748-0221 6 P01001 doi:10.1088/1748-0221/6/01/P01001

Paper II:
Surface State Effects on n+p Doped Electron Detector
O X Esebam, K Hammarling, G Thungström and H-E Nilsson
2011, 1748-0221 6 C12019 doi:10.1088/1748-0221/6/12/C12019

Paper III:
A Different Approach for Determining the Responsivity of n+p Detectors Using Scanning Electron Microscopy
Omeime Xerviar Esebamen, Göran Thungström and Hans-Erik Nilsson
2012, 1674-4926 33 074002 doi:10.1088/1674-4926/33/7/074002

Paper IV:
n+p Photodetector Characterization Using the Quasi-steady State Photoconductance Decay Method
Omeime Xerviar Esebamen
2012, 1674-4926 33 123002 doi:10.1088/1674-4926/33/12/123002

Paper V:
Simulation and Measurement of Short Infrared Pulses on Silicon Position Sensitive Device
D Krapohl, O X Esebamen, H E Nilsson and G Thungström
2011, 1748-0221 6 C01036 doi:10.1088/1748-0221/6/01/C01036
Paper VI:
Gridded Duo-lateral Position Sensitivity Detector with High Linearity to Low Energetic Electrons in Vacuum Environment
O. X. Esebamen, G. Thungström, H.-E. Nilsson and A. Lundgren
Accepted for publication, IEEE (TheIET) Optoelectronics Journal, April 2014

Paper VII:
Fabrication, Characterization and Simulation of Channel Stop for n in p-substrate Pixel Detectors
Accepted for publication, April 2014, Journal of Instrumentation (JINST)

Paper VIII:
Comparative Study of UV Radiation Hardness of n*p and p*n Duo-lateral Position Sensitive Detectors
O. X. Esebamen, G. Thungström, H.-E. Nilsson and A. Lundgren
Under Peer Review

Related paper(s) not included in the thesis

1 Spectral Performance of Photon Counting Pixel Detector Using Attenuation Spectra for Test Samples
Omeime Xerviar Esebamen, Börje Norlin, and Göran Thungström
Introduction

In nuclear engineering, experimental, applied particle and nuclear physics, a particle detector also known as a radiation detector, is a device used to detect track, and/or identify high-energy particles, such as those produced by nuclear decay, cosmic radiation, or reactions in a particle accelerator. Nuclear radiation, charge particles and x-rays are ionizing radiation and they can be detected from the ionizing events they produce with the use of special radiation detectors. Modern detectors are also used as calorimeters to measure the energy of the detected radiation. They may also be used to measure other attributes such as momentum, spin, charge etc. of the particles.

If their main purpose is radiation measurement, they are called radiation detectors, but as photons are also (massless) particles, the term particle detector still applies.

The term counter is often used instead of detector, when the device counts the particles but does not resolve its energy or ionization. Particle detectors can also track ionizing radiation (high energy photons or even visible light). These types of detectors can be accomplished by stretching a wire inside a gas-filled cylinder and raising the wire to a high positive voltage. The total charge produced by the passage of an ionizing particle through the active volume can be collected and measured.
Neutron detection is the effective detection of neutron particles entering a well-positioned detector while micro-channel plate detectors are planar components used for the detection of particles in the form of electrons or ions as well as impinging ultraviolet (UV) and X-rays radiation. To detect the presence of ionizing particles (even in radiation protection applications), gaseous ionization detectors are used. They use the ionizing effect of radiation upon a gas-filled sensor. If a particle has sufficient energy to ionize a gas atom or molecule, the resulting electrons and ions cause a current flow which can be measured. When the energy of particles is the subject of interest, experimental apparatus called calorimeters are generally used. A pictorial overview of different types of radiation detectors can be seen in Figure 1.

Figure 1. A summary of different types of radiation detectors
The most commonly used detectors are semiconductor detectors. These are devices that use a semiconductor (silicon or germanium are the commonest) as its main structure to detect traversing charged particles or the absorption of photons. In the use of semiconductors as radiation detectors, radiation is measured by means of the number of charge carriers set free in the detector, which is arranged between two electrodes. Ionizing radiation produces free electrons and holes to form electron-hole pairs. The quantity of electron-hole pairs produced is proportional to the energy transmitted by the radiation to the semiconductor. This implies that for the process to take place a number of electrons are transferred through the energy gap from the valence band to the conduction band and an equal number of holes are created in the valence band. Under the influence of an electric field, electrons and holes are swept to the electrodes, where there is a resultant pulse that can be measured in an outer circuit through the electrodes (see Figure 2).

From the above overview, radiation detectors in general have been employed in a wide spectrum of areas. This thesis concentrates on detectors employed under the irradiation of UV and electrons as electron/UV -detectors and -lateral position sensitive detectors (LPSDs). In other words, they were primarily designed for the capture and detection of electrons and UV photons. The detectors were fabricated on silicon wafers as their primary materials and are generally similar to the usual p-n junction photodiodes [1].

1.1 Examples of Low Energy Electron- and UV- Detectors

Electron detectors are primarily designed for the capture and detection of electrons - however, they can sometimes be effective in the detection of other charge particles. A number of electron detectors come in various forms and with different sensitivity. The most common are those designed to be best used for
electrons with energies up to 20 keV. The device can be optimized for the measurements of backscattering inside Scanning Electron Microscopes (SEMs), with added features making them non-magnetic - i.e. with no external effect on electron beam trajectories inside the SEM microscope.

One way which an electron detector can be applied is as an Electron Capture Detector (ECD). It is a device applied in the detection of atoms and molecules in gas to detect trace amounts of chemical compounds in a sample. This is conducted in the form of atoms drawing electrons towards itself - e.g. compounds containing halogen elements in gas mixtures [2]. The ECD operates such that the electrons discharged from the electron emitter collide with the molecules of the makeup gas emitting free electrons which are attracted to the anode. This leads to the generation of current proportional to the degree of electron capture and concentration of chemical compounds to be detected.

There are also electron detectors that can also be used as ‘Secondary Electron Detectors’¹ which are the primary means of viewing images in the scanning electron microscopes. This form of detector is important in electron beam lithography, optimum beam calibration and for mark recognition.

Backscattered Electron Detector (BSEd) is another type of electron detector designed for the simultaneous collection of backscattered electrons² in different directions. It is usually integrated into either a SEM or an electron probe micro-analyzer (EPMA) instrument. The quantity of backscattered electrons collected by a BSE detector usually corresponds to the mean atomic number of the sample under investigation. This detector can also be used to determine the structure detail of a sample.

BSEd which are usually made of scintillator or semiconductor have the advantage of serving as sample maps for locating spot analyses and the images

¹ Secondary electrons are electrons generated as ionization products and are known as 'secondary electrons' because they are generated as a by-product from/by other radiation known as the 'primary' radiation. This radiation can be in the form of ions, electrons, or photons with sufficiently high energy, i.e. exceeding the ionization potential

² Backscattered electrons are made up of high-energy electrons emanating from the electron beam that are reflected or backscattered out of the sample interaction volume by elastic scattering interactions with the sample atoms
generated can be acquired almost instantly at any magnification within the instrument range although this is dependent on the scan rate used as well as serve as sample maps for locating spot analyses [3].

There exist variable wavelength UV detectors with the designed to implement spectroscopic scanning and specific absorbance readings at different wavelengths. One of such is (photo)diode array detector (PDA or DAD) which is largely the most common detector for liquid chromatography. It has the merit of permitting the best wavelength(s) to be selected for actual analysis and it also permits the use of absorbance rationing at several wavelengths in deciding whether the peak represents a single compound or a composite peak. PDA can also be employed as UV-vis dispersive spectrophotometer and in applications where the light level is relatively high. This is because the photon saturation charge of a DAD is much greater than detectors like charge-coupled devices CCDs [4]-[6]. Another popular UV detector is the photoionization detector (PID) which is a type of gas detector used to measure volatile organic compounds and used as monitoring solutions varying from ammonia detection, industrial hygiene and safety to indoor air quality control.

A major part of the research has been conducted on the response of electron/UV detectors and on different methods of characterizing the responses and behaviors of the detectors [7]-[12]. Thus, the means by which these electron devices generally respond to a range of electron energy is not a new phenomenon. However, what has been lacking from these areas of the research field is the reason or effect of interface states and other surface parameters, such as surface recombination, on the responsivity of these detectors. Surface parameters have been widely known to have different effects on the performances of radiation devices in general [13]-[16] but studies on such effects on electron detectors in particular are few and far between. As a result, a better understanding of how they affect electron detectors will significantly assist in providing solutions with regards to ways to improve their responsivity and sensitivity to a wide range of electron/UV energy.

In researching these detectors as electron/UV detectors, the research focus was streamlined in relation to discovering answers to some research questions dealing with the effect of interface states and surface recombination on the performance of the detector.
1.2 Research Contributions

The main purpose of this thesis is to develop an alternative characterization method(s) for the study of interface states and traps (with particular focus on fixed oxide charge, $Q_f$), surface recombination velocity, radiation hardness in a duo-lateral position detectors PSD. The techniques of interest were broadly focused on scanning electron microscopy SEM, and ultra-violet UV beam profiling.

Using SEM microscopy, the following objectives were investigated:

- Comparing the effect of fixed oxide charge interface states and surface recombination velocity on the responsivity of a $p^n$ and an $n^p$ detector.

- The varying performance in terms of the responsivity of an electron detector when the doping profile is altered in relation to the interface states of the detector.

- The significance of the effect of the minority carriers transport velocity and interface states on the responsivity of detectors with different donor impurities.

- Characterizing the linearity and position detection error of both the $x$- and $y$-axes of a duo-lateral PSD in a remote high vacuum environment.

Characterizing or using a PSD in a high vacuum environment to track the position of a beam on the detector without the use of other devices such as actuators or translation stages can be expensive and challenging. Part of this thesis is dedicated to the design and fabrication of a duo-lateral position sensitive detector incorporated with some simple lithographic surface features. These features were made to assist in locating the precise location of the beam as it strikes on the detector.

With radiation damage in mind, the following studies were carried out:

- The electrical properties of common pixel detectors are generally undermined by the inversion layers created in the substrates and induced by the interface states. As a result, the effect of interface states induced inversion layer on the performance of $p$-type substrate pixel detectors was
investigated. To subdue the formation of the problematic induced inversion layer, an investigation was conducted in relation to the efficacy of using simplified field plates, or field rings by characterizing the resultant interpixel leakage current or breakdown voltage of the detectors. This becomes necessary in order to achieve better detection with low leakage current and radiation hard structure.

- Comparative research of the radiation hardness of UV irradiated duo-lateral PSDs as well as formulating a 3-dimensional mapping system of the degraded portions of the PSD active area. The motivation behind this was based on the fact that as ionizing radiation continuously irradiate on a detector, it (the detector) starts to experience some malfunction or loss of its efficiency. As a result, investigation was carried out on the rate at which different $n^p$ and $p^m$ doped detectors lose their radiation hardness when irradiated with ionizing UV photons.

In addition, one challenge often encountered during the use of radiation detectors or PSDs used under heavy radiation is the determination of the particular part of the active area of the detector that has lost its sensitivity due to continuous irradiation. As such the research was to enable one effectively determine the degraded section and the resultant change in linearity of the detector active area and the resultant.

1.3 Methodology

Different methods were employed in conducting this research. One method was the use of simulation tools before the processing and fabrication of the detectors in the cleanroom. Two methods of simulations were typically used - Monte Carlo simulation using Geant4/CASINO and Finite Element simulation involving the use of Taurus TSuprem4 and Medici. Geant4 and CASINO were used to track and visualize the passage of the bombarding electron particles through the detector taking into account possible interactions and decay processes.

To simulate the distribution of impurities, model various detector processing steps as well as calculations with regards to the response of the simulated detectors, finite element simulation was used.

Another method was the use of device fabrication in the cleanroom which involves a multiple-step sequence of the photolithographic and chemical
processing steps created on the wafer made of pure semiconducting material of choice. Various compound semiconductors are used for specialized applications but in the case of this thesis, Silicon was used because of its wide availability, low cost and its excellent absorption coefficient with regards to the charge particles/light beam used.

Electrical and optical characterization by laboratory measurements was also carried out. An overview of the methodology utilized in this thesis is shown in Figure 3.

<table>
<thead>
<tr>
<th>- Monte Carlo Simulation</th>
<th>Geant4 simulation toolkit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purpose:</td>
<td>CASINO v2.42</td>
</tr>
<tr>
<td></td>
<td>Investigation of low electron beam interaction in the device(s)</td>
</tr>
<tr>
<td></td>
<td>Tracking irradiated electrons as they travel through the device(s)</td>
</tr>
<tr>
<td></td>
<td>Visualization of the electrons trajectories and calculate energy losses</td>
</tr>
</tbody>
</table>

| - Finite Element Simulation   | Taurus TSuprem4/Medici     |
|                               | Purpose:                  |
|                               | Simulating the distribution of impurities |
|                               | Modelling various processing steps |
|                               | Calculation of induced current and observation of the response of the simulated devices |

| - Fabrication                 | Cleanroom fabrication processing (implantation, diffusion, etching etc) |
|                               |                                                                       |

| - Measurement                 | Use of scanning electron microscopy, UV Laser-driven light source, beam profiler, data acquisition apparatus, transimpedance circuits and remote control translation stages |

Figure 3. A synopsis of the methodology employed in the thesis
1.4 Chapters Review

An insight into the content of subsequent chapters of this thesis highlighted below.

Chapter 2:
This chapter deals with technical reviews of previous studies on semiconductor interface states. It also deals with several research results and conclusions on the characteristics, and the effect of interface traps, oxide charges and surface recombination velocity on the performance of detectors.

Chapter 3:
Chapter 3 is on substantive findings, as well as theoretical and methodological contributions to the topic of radiation damage such as lattice displacement effect, ionization effect, Frenkel effect and single event effects in radiation detectors. It also reviews previous studies on different techniques for radiation damage characterization and control.

Chapter 4:
This part outlines the methodology used in this research. It describes in detail, the simulation and fabrication processes used in the design and creation of the electron- and UV-position sensitive detectors.

Chapter 5:
The content of this section represents the different analytical techniques and procedures used to characterize the detector(s). It also draws a summary of the results obtained from the measurements.

Chapter 6:
Chapter 6 is an overview or summary of the content of the thesis.

Chapter 7:
This chapter contains a summary of the authors’ publications.
Chapter 8:
This chapter is a bibliography of list of the references used in this thesis

The results obtained from conducting this research offer a significant improvement in radiation spectroscopy and PSD technology and applications where sensitivity and position detection is imperative. The wide use of particle detectors in various optical applications as diverse as telecommunication, biomedical and data storage signifies that qualitative results that can improve the use of such detectors are highly welcomed.
2

Semiconductor Interface States

Surface states can be introduced into semiconductor devices during the fabrication processes or induced by radiation damage from the absorption of ionizing charge particles. Because the focus of this thesis is predominantly on the effect of interface states and radiation damage (described in chapter 3), this chapter is focused on the description, the technical reviews of interface states/traps (with special attention on fixed oxide charge Q), and recombination of e-h pairs in semiconductors.

The later part of this chapter contains reviews of various researched characterization techniques for measuring these parameters and their effects on semiconductor devices.

2.1 Introduction

At the surface of materials, there exist electronic states which are referred to as interface states. These states are produced as a result of the steep transition from a solid material that terminates with a surface and are located only at the atom layers closest to the surface. The termination of a material with a surface leads to a change of the electronic band structure and in the case of a semiconductor, interface states are as a result of incomplete covalent bonds at the surface of the semiconductor of which the nearly free electron approximation can be employed to deduce the basic characteristics of interface states for narrow gap semiconductors.

---

3 Nearly-free electron model (otherwise known as NFE model) is a quantum theory model of physical characteristics of electrons that can migrate almost freely through the crystal lattice of a solid. The model which is closely related to the more conceptual Empty Lattice Approximation LEA enables the understanding and calculation of the electronic band structure of materials.
Interface states also known as surface or fast states generally result in electron energy levels within the energy bandgap and are also known as Tamm-Shockley states. The density of such bonds at a silicon surface is about \(10^{15} \text{ cm}^{-2}\), a rather large number considering that the density of donors in a 0.1 mm depletion region in a material with a doping density of \(10^{17} \text{ cm}^{-3}\) is only \(10^{12} \text{ cm}^{-2}\). Depending on whether or not they are neutral when occupied, they can be referred to as either in the donor state or acceptor state.

Interface states can be said to be intrinsic in a situation where interface states arise from clean and well ordered surfaces. This case also involves states arising from reconstructed surfaces, where the two-dimensional translational symmetry gives rise to the band structure in the \(k\) space of the surface. It is the other way around when it is in the 'Extrinsic' surface state. That is, the states do not originate from a clean and well ordered surface and they cannot easily be described in terms of their chemical, physical or structural properties. Examples of such cases are surfaces with defects caused by irradiation of charge particles, implantation of doping elements and from impurities such as oxygen etc. It also arises in cases where the translational symmetry of the surface is broken, or at interfaces between two materials such as a semiconductor-oxide, semiconductor-metal interfaces or the interfaces between solid and liquid phases.

### 2.2 Interface Traps in Si-SiO\(_2\) Interface

Interface states are generally of almost negligible importance in the case of thicker gate oxides but as the oxide thickness is reduced, interface trapped charges become gradually more significant [17]. As a result, the requirement for very thin oxide in present day or new generation devices has made it important to pay special attention to the study of interface traps and other interface states.

The fundamental designation of interface states and charges are as seen in Figure 4 and as listed below

- **Interface traps of density \(D_e\)** – They are the density of traps per unit area per unit energy and are situated at the Si-SiO\(_2\) interface with energy states within the forbidden bandgap of silicon. They are known to exchange charges with silicon in a short time and can be as high as \(10^{5} \text{atoms/cm}^2\) [18]. Dangling-orbital silicon interface defects (also known as trivalent silicon defect or \(V_s\) centers) at the Si-SiO\(_2\) interface has been considered the
dominant source of these interface traps [19] and their density depends on the orientation the silicon wafer. Using capacitance-voltage C-V measurement on oxides grown on n- and p-type Si at 1000 °C (2 hrs) in 1 atm O2/H2O ambient reveals that Dv(111) > Dv(110) > Dv(100) [20].

- Trapped charges Qt – As it the case for Do, they are also located at the Si-SiO2 interface with energy states within the forbidden bandgap of silicon. They arise from structural defects, oxidation/irradiation induced defects, metal impurities and/or other bond breaking processes and are as a result of carriers trapped at the Si-SiO2 interface [21][22]. Qt is also determined by the occupancy or the Fermi level so its amount is bias dependent. These traps can also possibly be produced by P3 centers, broken Si-H bonds, and excess oxygen [18].

- Fixed oxide charges Qf – occupy near the vicinity of the Si-SiO2 interface and are immobile under an applied electric field [18]. They can be generated by irradiation and are a significant cause of instability and decrease in responsivity in radiation detectors [23][24][25]. More on fixed oxide charges Qf is discussed in detail in later part of this thesis.

![Diagram of charges](image)

**Figure 4.** Terminology for charges associated with thermally oxidized silicon. After: [26]

- Oxide trapped charges Qt – These Traps can be introduced from x-ray radiation exposure or hot-electron injection. They are as a result of
radiation generated electron-hole (e-h) pairs and are predominately positive charged because the electrons are more mobile than holes, many of which are trapped in oxide defects such as oxygen vacancies [27]. Q$_e$ shifts the flatband voltage at both the front and back interfaces but not the threshold voltage [28], [29]. Low temperature (< 500°C) treatment and/or tunneling are known to eliminate oxide trapped charges [18][30].

- Mobile ionic charges Q$_m$ – can be introduced into oxide from ionic impurities such as Li$^+$, Na$^+$, K$^+$ and possibly H$^+$ and are mobile within the oxide under bias-temperature stress conditions [18][31]. It is highly advisable not to touch the devices with bare hands especially during processing because of the presence of sodium in human sweat. These charges have been known to be very problematic especially when the devices are used at elevated temperatures or high electric field operations [32]. The fast mobility of these charges can stimulate unwanted instability and distortions in the electrical characteristics of devices. The use of a small percentage of Hydrochloric acid (HCL) or Chlorine to the oxidizing atmosphere significantly improves the electrical stability of SiO$_2$ films grown in the presence of dry oxygen [33]. Aside from the traditional C-V measurement technique, charge-pumping technique [33], the Triangular Voltage Sweep (TVS) method [34], and the Thermally Stimulated Ionic Current (TSIC) method [35] have also been used to measure the density of Q$_m$.

### 2.3 Technical Reviews on Fixed Oxide Charge Q$_f$

As earlier stated, surface charge density is constituted by among other charges, fixed oxide charge Q$_f$ which is usually positive and dependent on oxidation and annealing conditions on silicon orientation but not the gate bias. This charge, otherwise regarded as charge sheet, is located at approximately 3nm of the Si-SiO$_2$ interface and associated with defects in SiO$_2$. It is also fixed and very challenging to charge or discharge. Typical Q$_f$ for a well prepared Si-SiO$_2$ interface is approximately 10$^9$cm$^{-2}$ for a <100> silicon surface and about 5x10$^9$cm$^{-2}$ for a <111> silicon surface [36].

Fixed oxide charge Q$_f$ has a strong dependence on oxidation temperature and as such, the higher the temperature, the lower the Q$_f$. Due to the fact that there is a
limitation regarding how high a temperature oxidation can be carried out; it is possible to reduce $Q_t$ by annealing an oxidized wafer (done at any sensible temperature) in a nitrogen or argon ambient.

This method invented by Deal et al shows the reversible relations between $Q_t$ and the oxidation and anneal [37]. The resulting value of $Q_t$ being associated with the final temperature and any $Q_t$ value resulting from previous oxidation can be reduced to a constant value as shown in the Deal triangle [38].

Various methods can be used to grow silicon oxide for passivation of which one is the Plasma-Enhanced Chemical Vapor Deposition (PECVD) method. The use of this method in itself presents the problem of fixed oxide charge [39][40]. In studying the effects of surface-passivation methods on the performance of 4H-SiC bipolar junction transistor (BJTs) it was recorded that the method of passivation has a huge influence on the breakdown voltage and current gain directly attributed to the different $Q_t$ resulting from the passivation technique used [40].

![Figure 5. Deal triangle showing the reversibility of heat treatment effect on fixed oxide charge. After: [37]](image)

It is known that the rate of trapings induced by (prolong) radiation is due to oxygen vacancy defect but in a study designed to research radiation-induced oxide charge in low- and high hydrogen ambients, it was interesting to discover that hole trapping dominates for typical hydrogen densities. But as the density of ambient
hydrogen increases, the rate at which $Q_i$ increase is attributed to protons free from charged oxygen vacancies [41].

Results have confirmed that the properties of SiO$_2$ devices based on steam grown oxides are more heavily affected by radiation than devices based on dry oxides. The study also showed that a dependence of fixed oxide charge $Q_i$ on radiation dose is estimated by a first-order reaction equation and that there is a distinct linear correlation between the degradation of low field mobility of Metal-Oxide Semiconductor (MOS) transistors and the logarithm of positive oxide charge incorporation during irradiation for only wet-oxide samples [42].

![Figure 6. A simulation result on the influence of fixed oxide charge, $Q_i$ on the responsivity of an electron detector. Source: [43]](image)

To study the effect of a fixed oxide charge on an electron detector, an oxidation-induced fixed oxide charge was introduced at the interface between the silicon bulk and a 10nm Silicon-Oxide through an oxidation process [43], [44]. An overview of the charge effect on the measure of the input–output gain of an $n\pi p$ electron detector is shown in Figure 6. The study was conducted using fixed oxide charge values ranging from $5\times10^8$C/cm$^2$ to $3\times10^9$C/cm$^2$.

While retaining other interface properties at their constant values and sweeping the accelerating electron energy from 0.5keV to 20keV, the finding shows that the responsivity of the electron detector tends to increase as the fixed oxide charge increases, with the increase being more predominant at the lower electron energy.
2.4 Recombination in Semiconductors

The well established physics in semiconductors is that processes exist whereby mobile charge carriers in the form of electrons and electron holes are either created or destroyed. These processes are respectively known as generation and recombination. They are as a result of interactions between electrons and other carriers, either with the lattice of the material, or with irradiated optical photons. Energy may be transferred or gained depending on the movement of electrons from one energy band to another. The gained or transferred energy takes other forms that are used to differentiate between the various types of generation and recombination processes that have taken place. The formation of electron–holes pairs or e-h pairs is the fundamental unit of generation and recombination. An electron–hole pair depicts an electron transitioning between the valence band and the conduction band of the semiconductor material energy band.

![Diagram of Auger process and Photon emission](image)

**Figure 7.** Basic diagram showing the process of (a) Band-to-band recombination whereby energy is exchanged to a radiative or Auger process (b) non-radiative recombination. After [18].

Recombination in a semiconductor exists to recondition the system back to equilibrium when the thermal-equilibrium condition of the semiconductor is disturbed [18]. This process can occur in various forms – radiative or Auger process. The former, otherwise known as photon emission recombination, occurs when the energy of an electron transiting from the conduction band to the valence band is stored by the discharge of a photon. The photon emitted has a wavelength proportional to the energy released and this forms the basis of LED’s operation. The direct opposite of this is the direct optical absorption process – in which
absorption is the active process that occurs in solar cells, photodiodes and other photodetectors. See Figure 7 for a summary of these recombination processes.

On the other hand, the Auger process occurs when a transiting electron passes its energy to free another electron or hole. This process is a three-particle interaction and only becomes significant when the carrier density is very high and the condition is not in a state of equilibrium. This type of recombination is similar to the Auger effect, which is a physical phenomenon in which the transition of an electron in an atom filling in an inner-shell vacancy causes the emission of another electron known as an Auger electron.

In commonly used semiconductors such as the silicon Si and germanium Ge, the dominant transitions are usually an indirect recombination via single-level traps in the bulk material, and the energy present in the bandgap. The recombination process through the single level traps can be described by electron capture and hole captures processes and the net rate of transition is defined by Shockley-Read-Hall SRH statistic

$$U = U_n = U_p = U_{SRH} + U_{Auger}$$

where $U_{SRH}$ and $U_{Auger}$ are the Shockley-Read-Hall recombination and the Auger recombination respectively; and $U_n$ and $U_p$ are respectively the electron and holes recombination [45].

2.5 Surface Recombination Velocity

Surface Recombination Velocity occurs at the surface or interface of two semiconductors and its resultant effect can be of significant importance with regards to the behavior of the semiconductor device/s. The reason for this is because semiconductor surfaces and interfaces come with a huge number of centers for recombination to take place because of the sudden termination of the semiconductor lattice structure, which results in so many electrically active states [46]. These recombination centers lie at an energy level defined as the equilibrium electron and hole concentrations in a sample whose Fermi level coincides with the position of the recombination centers [47]. This signifies that any defect or impurity around the confines of the surface of the semiconductor will assist in the propagation of recombination.

In a solar cell, for example, high recombination rates at the surface or interfaces result in adverse effects on the short-circuit current as well as the open-circuit voltage. This is because the highest generation regions of mobile carriers are
located at these interfaces and surfaces. Thus, because the surface of the solar cell
depicts a massive disruption of the crystal lattice, it becomes an attractive region
for high recombination. The defects at a semiconductor surface are caused by the
interruption to the periodicity of the crystal lattice, which causes dangling bonds at
the semiconductor surface [48].

To compensate for a region where there is a low concentration of carriers, the
carriers in a region of higher concentration flow or diffuse towards that region with
the surface recombination rate only being restricted by the rate at which minority
carriers move towards the surface. The rate at which these carriers can migrate to
recombine at the surface is regarded as the surface recombination velocity \( v_s \) in units
of cm/sec.

In a case where the movement of carriers towards the surface or interface of the
semiconductor is zero, this signifies that the surface or interface has no
recombination activity present or the surface recombination velocity is zero and
vice versa. High surface recombination velocity \( v_s \) of up to \( 10^7 \) cm/sec can be
recorded for most semiconductors. The net recombination rate due to trap-assisted
recombination is similar to that of Shockley-Read-Hall recombination - SRH -
except that the recombination is due to a two-dimensional density of traps that
only exist at the surface or interface.

### 2.5.1 Surface Recombination Velocity in Relation to Trap-Assisted
Recombination Lifetime

At every defined point on the discrete mesh of a simulated Si-SiO\(_2\) interface, a
simple model can be used for which an effective SRH recombination lifetime for
each carrier \( \tau_{\text{eff}} \) relates to the recombination velocities of electrons \( v_e \) and it is
given as [45]

\[
\frac{1}{\tau_{\text{eff}}(i)} = \frac{v_e d_i}{A_i} + \frac{1}{\tau_{n,p}(i)}
\]

where \( \tau_{n,p}(i) \) is the SRH lifetimes (of hole or electron) that are concentration
dependent trap-assisted recombination lifetimes; \( A_i \) the semiconductor area
associated with the node; and \( d_i \) the length of the interface associated with the
node.\(^4\)

\(^4\) Every region of the device structure is divided into a mesh of non-overlapping
triangular elements. Solution values during simulations are computed at the mesh
In the case of a metal acting as a Schottky contact with a semiconductor, finite surface recombination velocities can be determined with the assumption that the electron and hole quasi-Fermi potential (\(\Phi_n\) and \(\Phi_p\)) are not equal to but, are rather, defined by the current boundary conditions at the surface \([49]\). The current boundary conditions are defined as

\[
\begin{align*}
J_n &= q \nu_n n_s - n e_q \\
J_p &= q \nu_p p_s - p e_q
\end{align*}
\]

where \(J_n\) and \(J_p\) are the electron and hole current densities at the contact; \(n_s\) and \(p_s\) are the actual surface electron and hole concentrations; \(n_0\) and \(p_0\) are the equilibrium electron and hole concentrations, assuming infinite surface recombination velocities.

### 2.5.2 Surface Passivation with respect to Surface Recombination Velocity

The significance of surface recombination velocity in semiconductor devices in general has made it an area of research interest and efforts are been made by researchers to fully fathom this phenomenon. Passivating the bulk substrate with a thin film is the most common way of suppressing the effect of surface recombination velocity. It can range from passivation using germanium oxide (GeOx) on germanium substrate \([50]\), aluminum oxide (Al\(_2\)O\(_3\)) \([51]\) or SiO\(_2\) on Silicon \([51]\), \([52]\).

A number of research projects have shown that, in solar cells, the surface recombination velocity has a diverse effect on the open circuit voltage \(V_o\) and the short-circuit current \(I_{sc}\). To minimize its effect a thin SiO\(_2\) layer is thermally grown on the front surface of both \(n\)-doped and \(p\)-doped regions of the device \([53]\). The thin SiO\(_2\) layer acts as a ‘passivation’ to reduce the surface recombination of electron and hole carriers. In other words, the solution to the reduction of the quantity which is the root cause of recombination (dangling bonds) and invariably, the recombination, lies in placing a layer of material on top of the semiconductor surface, which has the capability of terminating some of these dangling bonds.
As an alternative to thermal oxidation (i.e. thermally growing a thin layer of silicon oxide on the surface of a wafer), low-temperature passivation techniques have become increasingly popularly. One such technique is the plasma-enhanced chemical vapor deposition (PECVD) - a process used to deposit thin films (of oxide) from a vapor state to a solid state on the area to be passivated. For SiO₂ to be deposited using PECVD, a blend of silicon and oxygen precursor gases are used at pressures ranging from a few millitorr to a few torr (where 1 Torr is estimated as equal to 1mm of mercury).

2.5.3 Review of Characterization Techniques for Measuring Interface States, Traps and Surface Recombination Velocity and Their Effects on Semiconductor Devices.

One of the classic methods used to measure interface states and oxide charges in semiconductors is the use of capacitance-voltage C-V or frequency-capacitance measurement [18], [54]. By observing the shift in flat-band, increase in capacitance and/or the stretching of the C-V curve in the voltage direction as a result of the extra charge required to fill the traps during the measurement, the surface state effects can be approximated. Another standard method is the use of low-frequency differential capacitance measurements to estimate the energy distribution of interface states at Si-SiO₂ interface of a MOS structures [55]. By using this method, it is potentially feasible to resolve the silicon surface potential as a function of MOS voltage directly without the need for the doping profile in the silicon structure.

Researchers have devised different characterization techniques to study the effect of surface state trappings, interface charges and surface recombination velocity on specific semiconductor devices. One of such is the use of the semi-numerical model to study the effect of interface states on the electrical and optical characteristics of Indium Phosphide Metal-Insulator-Semiconductor (InP MIS) capacitor [56]. By studying the deviation of the surface potential with the applied voltage and the surface potential with incident photon flux density for three different values of surface state, the author showed that the capability of InP MIS devices for use as a voltage controller and/or optically controlled capacitor is significantly constrained by the number of interface states at the interface.

Similarly, by way of a two-dimensional transient simulation, the surface state effect on gate lag phenomena in GaAs MESFET was researched. The authors' results showed that the slow transient phenomenon exhibited at the ungated
access region of the transistor is as a result of charge exchanges in the surface state present [57]. A similar study and approach incorporated with pulsed, transient, and small-signal measurements, was used to investigate surface-related drain current dispersion effects on Aluminium Gallium Nitride – Gallium Nitride High-Electron-Mobility Transistor (AlGaN–GaN HEMTs) [58]. The conclusion drawn from the investigation was that surface traps behave as hole traps interacting with holes attracted at the AlGaN surface by the negative polarization charges and by the associated upward band bending. It also concluded that gate turn-on transients are connected to hole capture by surface traps, whereas drain turn-on and gate turn-off transients are as a result of hole emission by surface traps.

To determine surface space-charge capacitance, a technique known as surface photovoltage measured capacitance (SPMC) was implemented [59]. In using this method, the intrinsic surface photovoltage induced by low-intensity-high-frequency chopped light was measured and the result showed that the intrinsic surface photovoltage has a strong correlation to the inverse surface space-charge capacitance present in the Gallium Arsenide semiconductor used. The author also used the method with a three-electrode electrochemical cell, to successfully measure the energy of interface states, the doping concentration and the flat band in the semiconductor.

Different spectroscopic and microscopic techniques have also been used to estimate surface state densities and energy. Examples are (a) the use of four-point probes, piezoactuators and electrons from a SEM microscope to measure the surface-state conductivity of the device under test [60]; (b) electrochemical photocapacitance spectroscopy (EPS) on p-type Zinc Phosphide Zn:P, n- and p-type GaAs [61]; and (c) the use of low-temperature Scanning Tunneling Spectroscopy to measure lifetime effects on Shockley surface-state electrons from Ag(111) sample [62]. The results obtained from [62] although lesser than results from angle-resolved photoemission, were higher than theoretical predictions.

It is well established that the typical interface state for a well prepared Si-SiO₂ interface is about \(10^{10}\) cm\(^{-2}\) for a \(<100>\) silicon surface and \(5\times10^{10}\) cm\(^{-2}\) for a \(<111>\) silicon surface [36]. A research by J. N. Shenoy et al estimated the fixed charge densities to be as low as \(9 \times 10^{11}\) cm\(^{-2}\) and interface state densities as low as \(1.5\times10^{13}\) cm\(^{-2}\) eV\(^{-1}\) for oxides grown on a p-type 6H-SiC at 1150°C in wet O₂ followed by a 30 min in-situ argon anneal. These results were obtained using the popular C-V measurement and the ac conductance technique at temperatures well above 300K.
so that all states can follow changes in DC bias. They also suggested that to correctly obtain interface state density at room temperature, the application of photoexcitation is necessary in order to revamp the interface state population [63].

Spectroscopic methods such as Electron paramagnetic resonance spectroscopy (EPRS) and constant-capacitance deep-level transient spectroscopy (DLTS) have also been used to accurately determine the interface states centers in silicon wafers. The prospect of using these methods in other interface states characterization within the boundaries of their limitation is promising [64], [65]. The result from the DLTS method was obtained through the analysis of electronic defect-levels measurements at the Si–SiO₂ interface and the method showed a minimum signal distortion at high defect densities, high energy resolution, and the determination of dynamic properties.

The utilisation of simple parametric inputs like current-voltage I-V characteristics, and substrate doping concentration such as metal Silicide–Silicon Schottky barrier as well as ac-admittance measurements for Au/GaAs Schottky contacts have also been used to measure the interface-state density of Schottky barriers [66], [67].

The interface state density measured as $2 \times 10^{10}/\text{cm}^2\cdot\text{eV}$ was deduced from the characterization of the 1/f noise of MOS transistor equivalent noise voltage and current [68]. An outcome drawn from the study is that the experimental values of the equivalent noise voltage and the equivalent noise in the saturated operation is inversely proportional to the gate input capacitance but proportional to the effective gate voltage, and the interface state density. It was also confirmed that a proper heat treatment not only reduces the number of states but also removes the near band-edge peaks, which usually appear in the trap distribution function.

To measure surface recombination velocity in semiconductors, a number of techniques have been suggested. Some of these techniques have been advocated in conjunction with specialized fabrication/process steps in order to minimise the resultant surface recombination velocities. An example of this is by E. Yablonovitch et al who suggested that a systematic fabrication process of a <111> silicon wafer followed by a Hydrofluoric acid HF etch resulted in a surface recombination velocity of about 0.25 cm/sec. To measure this value, a multiple-internal-reflection infrared spectroscopic technique was used and the results revealed a wafer surface covered by covalent Si-H bonds and no surface dangling bonds to act as recombination centers [69].
Figure 8. A simulation result on the influence of interface recombination velocity of minority carriers on the responsivity of a) arsenic doped $n\!p$ detector. Source: [43]

Other common methods of measuring surface recombination velocity involve the use of photoconductivity decays [70][71]; diffraction from picosecond transient free-carrier gratings [14]; Electrochemical characterization, performed through impedance measurements and intensity modulated photovoltage spectroscopy (IMVS), [72]; and through the use of scanning electron microscopy to determine the effect of surface recombination velocity on the responsivity of an $n\!p$ electron detector [43]. The latter ([43]) was performed by retaining other interface properties at the Si-SiO$_2$ interface constant and sweeping electrons with acceleration energies ranging from 0.4keV to 8keV – see Figure 8. The fixed oxide charge was also maintained at a constant value$^5$ of $5\times10^{10}$ cm$^{-2}$.

The result, as seen in the figure above, shows that the surface recombination velocity has a strong effect on the responsivity of a detector especially at low electron energy. It is seen that at 0.5keV, the responsivity of the detector increases by about 40% when the surface recombination velocity of the minority carrier at 10cm/s is reduced by a factor of 10.

$^5$ This value of $Q_i$ was chosen because typical values for $Q_i$ are of the order of $10^{10}$ to $10^{11}$ charges per cm$^{-2}$, depending on the process conditions [36]. Though some research has determined that for some interfaces, the magnitude of the fixed charge can be higher especially under interface bond strain and bias voltage applied to the detector oxide [145][146].
3

Radiation Damage in Semiconductors

As a detector or part of a detector is continuously irradiated by high-energy electromagnetic radiation particles, it becomes more susceptible to damage or malfunctions caused by the absorption of the ionizing radiation. As a result, studies are continuously been carried out on the main components of radiation detectors in particular, and electronic parts and equipment in general, in ways to make them less sensitive to radiation damage. The act or process of a radiation detector losing its hardness is known as degradation and the process of making them more resistant to radiation damage is known as radiation hardening.

There are generally two types of damage mechanism that can occur with respect to radiation damage on devices. They are namely,

- Lattice displacement effect
- Ionization effect

The occurrence of these effects in electronic devices depends on a variety of factors which include the nature and type of radiation the device is exposed to, the total dose and radiation flux irradiated, combination of types of radiation, as well as the kind of device load (i.e. operating frequency, voltage, actual state - on/off - during the instant it is struck by the radiation particles).

Lattice displacement effect is as a result of cumulative long-term non-ionizing damage induced by ionizing radiations including neutrons, protons, alpha particles, heavy ions, and very high energy gamma photons. The resultant damage is a product of nuclear interactions and customarily scattering. As the particles penetrate into the device structure, they collide with the atoms in the atom lattice. The collisions alter the arrangement of the atoms in the crystal lattice, and in the
process can raise the number of recombination centers and/or create lasting damage. The collision also can result in the reduction of the minority carriers, aggravate the analog properties of the affected semiconductor junctions as well as speed up the degradation of energy resolution of the detector brought about by the fluctuations in the amount of charge lost [73]. Irradiating a material such as silicon and silicon oxide by photon and neutron particles can generally result in primary and secondary effects which have been summarized in the figure below.

<table>
<thead>
<tr>
<th>Radiation Type</th>
<th>Energy range</th>
<th>Main type of interaction</th>
<th>Primary effects in Si and SiO₂</th>
<th>Secondary effects in Si and SiO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons</td>
<td>Low energy</td>
<td>Photoelectric effect</td>
<td>Ionizing phenomena</td>
<td>Displacement damage</td>
</tr>
<tr>
<td></td>
<td>Medium energy</td>
<td>Compton effect</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>High energy</td>
<td>Pair production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutrons</td>
<td>Low energy</td>
<td>Capture &amp; Nuclear reaction</td>
<td>Displacement damage</td>
<td>Ionizing phenomena</td>
</tr>
<tr>
<td></td>
<td>High energy</td>
<td>Elastic scattering</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 9.** The effect of photon and neutron ions irradiated on Silicon and Silicon oxide materials. Sources [74]-[76]

A number of defects in the form of vacancies, interstitials, Frenkel pairs, and dislocations can arise from a series of collisions caused by a single high energy particle. Frenkel pairs from the Frenkel defect is known as the most crucial type of bulk radiation damage in semiconductor materials. This defect, also known as point defect occurs when a trapping site for normal charge carriers is formed by the vacancy created from an atom being knocked off, in conjunction with the original atom now at an interstitial position [73].

For point defect to occur, gamma rays and electrons⁶ (and even beta rays) with energy of no less than a few thousand electron volts (eV) is required whereas heavier charged particles of the same energy will result in more devastating

---

⁶ Studies have shown that little damage can only be done with electrons with energy less than 250keV [147].
damages known as the *Cluster effect* which formed along the track of a primary "knock-on" atom [73]. Frenkel defects as a result of radiation damage causing a carbon atom in graphite to be knocked off from either an α and a β lattice site in the host crystals.

In semiconductor devices such as MOSFETs (Metal-Oxide-Silicon Field Effect Transistor), the resultant consequence of this effect is that it brings about a decrease in transconductance (ratio of the output current change to the input voltage change), drain-source breakdown voltage and surface mobility. Other consequences include the increase in the leakage current and other noise parameters, increase in surface recombination velocities of minority carriers as well as a shift in threshold voltage [75][76][77].

For charge particles with energies not sufficient to induce lattice effects, ionization effects take place. This effect in itself is transient i.e. may not be able to cause permanent or heavy damage in semiconductor devices as can point/Frenkel effects. But instead, its effect can advance into a more serious device error if they set off other damage mechanisms such as a circuit latchup7. Ionization effects from ultraviolet UV and x-ray radiation is usually associated with surface effects created within silicon oxide and its trappings at the interfaces [78][79][80].

When a detector is operated under a high intensity UV environment, radiation induced damage can occur as in the case with charge particles. The nature or severity of the ionization damage effects depends on the wavelength of the beam and the material/semiconductor on which the device is fabricated. With the presence of SiO₂ and/or Silicon nitride (SiN) in devices such as MOSFETs and CCDs (Charge-Coupled Devices), they are susceptible to UV radiation damage. This is because, as UV photons are absorbed, oxide trapped charges and interface states are generated which create a shift in signal or response in the devices. Research has shown that at low dose, the creation of oxide charge is the principal component cause for radiation-induced shifts in device performance, whereas the creation of (other) interface state is the reason for such shift at medium doses [81].

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7 This is the unintentional creation of a low-impedance path between the power supply rails of a MOSFET circuit, generating a parasitic structure that makes the device work in a fashion that it was not designed to [148]. This short circuit error usually arises from appropriately designed circuits which can cause irreversible damage from excessive current.
Irradiating a MOS device with a UV beam with energy greater than 9eV (the bandgap of SiO2), causes absorption of the UV photons in the oxide layer that result in the creation of electron-holes pairs and charge centers. The oxide absorption characteristic is significantly reliant on the density of pre-existing defects in the layers [82] and the continuous absorption of UV photons can introduce further changes in the oxide properties. These changes according to research include UV-induced absorption due to color center formation; change in the optical index of refraction due to the formation of Silicon-hydroxyl (SiOH), resulting from variations in the chemical composition; a change in density of the material brought about by structural rearrangement and alteration of its chemical composition, which result in stress-induced birefringence and surface deformation [83].

3.1 Type of Damage(s) From Single Particle Event

The study of the destructive and non-destructive effects of the radiation of a single, energetic particle through an active region of a semiconductor device is important and has also been of research interest [84]–[88].

The effect caused by such phenomena is referred to as single event effect (SEE). It is defined by National Aeronautics and Space Administration (NASA) Thesaurus as "radiation-induced errors in microelectronic circuits caused when charged particles (usually from the radiation belts or from cosmic rays) lose energy by ionizing the medium through which they pass, leaving behind a wake of electron-hole pairs." The various types of SEE can be seen in Figure 10 and are defined as such

- **Single event latchup (SEL)** - temperature dependent event which causes loss of device functionality from short circuiting and may be reversible with power off-on reset or power strobing of the device [89]–[91].

- **Single-event burnout (SEB)** – determined by device avalanche characteristics and occurs in MOSFETs when biased in its off state which then induces a turn-on thereby causing high current and local overheating [92], [93]. Simulation results of single-event burnout according to [92], suggest that the ion pulse creates very high drain current from highly accelerated charge carriers that sufficiently cause a breakdown twice depending on the
applied drain voltage. As reported by the authors of the study, it is a combination high current density and a drain bias in excess of 650V that will switch the off-state transistor on.

![Diagram of Single-event Effects]

**Figure 10. Types of single event effects (SEE)**

- **Single-event gate rupture (SEGR)** – occurs at the gate oxide of a MOSFET under applied high gate voltage creating a conduction path. This results in a breakdown and high leakage current in the device [94][95].

- **Single-event snapback** – occurs when an ion hits near the drain junction of a MOSFET causing it to open through a massive generation of electron-hole pairs due to impact ionization in the depleted region of the charge carriers (a process otherwise known as avalanche multiplication) [96], [97].
• **Single-event transient (SET)** - happens when the charge aggregated from an ionization event releases in the form of a pseudo signal that transverses through the circuit. This occurrence is in practice, the effect of an electrostatic discharge.

• **Single-event upsets (SEU)** – is a soft-destruct also known as the transient radiation effect which manifests itself as the change in state of memory or register bits caused by a single ion interacting with the chip.

### 3.2 Review of Techniques for Characterizing Radiation Damage

Different methods have over the years, been explored to examine UV radiation damage in semiconductors. Two of such are researches conducted to study the effects of high energy laser radiation on the characteristics of photon detectors [82][98]. The authors of [82] examined the effects of 157 nm laser radiation on the characteristics and the mechanisms responsible for UV laser damage on a CCD image sensor with thinned oxide overlayers on the photodiode-based pixels. Their results revealed significant bond structure modifications in the CCDs as a result of ionization damage effects. They also showed that the overlying oxide thickness and the quality of Si-SiO₂ interface have a massive effect on the sensitivity and stability of the CCDs as it relates to UV radiation. In other words, the thinner the SiO₂ layer and the better the integrity of the Si-SiO₂ interface, the higher the quantum efficiency and stability of the CCD device.

Using a setup consisting of a laser-generated plasma extreme UV beam (13.5 nm) from a pulsed gaseous Xenon jet, the authors of [98] were able to show the morphology of the observed surface and crater damage of UV ionization on silicon. The results show that the probability of UV induced damage happening to silicon at 13.5 nm occurred at threshold fluences of 4.1 J/cm² for surface damage and 5 J/cm² for crater damage whereas surface and crater damage occurs in Calcium fluoride crystals at 1.1 J/cm² and 2.2 J/cm² respectively.

The effect of UV or charge particle radiation on other semiconductor materials has also been investigated, In a study using Zinc Oxide (ZnO) microtube crystals fabricated by microwave growth techniques, the researchers observed that the crystals exhibited highly selective UV light response with a cut-off wavelength at approximately 370 nm. They also observed that the photoresponse property of the ZnO microtubes to the UV beam was strongly dependent on the ambient
atmosphere in which the irradiation occurred – about three times higher in argon
ambient than in pure oxygen [99]. This is because the pure oxygen atmosphere
provides much more oxygen adsorption on the ZnO surface, which produces
deeper low conductivity depletion layer than that in pure nitrogen or argon
atmosphere.

By applying the Electron Paramagnetic Resonance (EPR) technique, radiation
damage effect on silicon wafer (10¹⁶/cm³ aluminum doped) was first proposed by
Watkins in 1969 [100]. To carry out the study, the device under test (DUT) was
irradiated with 1.5 MeV electrons of flux 10⁷ e/Cm² under a liquid hydrogen
temperature – 20.4±K. The study was performed by placing the DUT in a magnetic
field and then inducing microwave transitions which split the spectral lines (using
Zeeman Effect) to observe the defects caused by the irradiated electrons.
Interesting experimental results were recorded in the form of defects in the isolated
lattice vacancies and interstitial aluminum atoms as a result of the electron beam.

By using Dopant Driven Lithography the effects of electron beam irradiation
on Cu:TiSe₂ crystals heated (60-100°C) in a vacuum oven after the addition of
various amounts of iodine in the proximity of the expose area of the sample was
studied [101]. The results show that the size and density of the reaction (Copper
Iodide CuI crystallites) are inversely proportional to the amount of electron
radiation exposure.

Alpha particle radiation damage (flux=2.8x10⁹ α/cm² s) was also studied in a
number of room-temperature semiconductor radiation detectors with primary
components from Cadmium Zinc Telluride (CZT), Cadmium Telluride (CT) and
Mercuric Iodide (HgI₂) [102]. The methodology of the research was from survey
data obtained from a literature search using computer databases INSPEC and
CALPLUS together with DoE (United States Department of Energy) archives. The
outcome showed that energy resolution losses of varying proportions were
exhibited by the various detectors except that of Mercuric iodide where no
radiation damage was reported under the irradiation conditions used in the study.
The detector (HgI₂) was unaffected by proton and neutron-induced radiation
damage while the CZT detector exhibited degradation in the resolution from 200
MeV protons beginning in the region of 10⁹ p/cm² as well as a negative shift in
peak channel commensurate to the proton fluence.

By employing low-temperature photoluminescence spectra and studying the
acceptor density as a function of electron-irradiation energy, a experiment was
conducted on the radiation induced damages on Zinc Oxide (ZnO), Gallium Nitride (GaN), and Gallium Arsenide (GaAs) detectors [103]. Using high-energy electrons of $4 \times 10^{16} \text{ cm}^2$, ZnO was recorded to be most resistant to the particle radiation. In a similar vein, by employing low temperature photoluminescence spectroscopy measurements, studies were performed on the radiation damage on GaN and GaAs films by a 2 MeV proton radiation. The test recorded radiation induced damage constant of $1.4 \times 10^{13} \text{ cm}^2$ in the GaN film occurring at 3,474 eV in contrast to 1,492 eV in GaAs with a constant of $4 \times 10^{13} \text{ cm}^2$. For photonic applications, the authors concluded that GaN is more robust than GaAs because of its lower displacement damage [104].

Studies have been performed on the influence of radiation induced defects on minority carrier lifetime and the threshold at which radiation damage starts to occur in semiconductors [105]. The test was performed using a simple experiment setup made up of a Van de Graaff electron generator, thermocouple and potentiometer to measure the photovoltaic short circuit current (and invariably the minority carrier lifetime from their established correlation) induced from electron bombardment. The analysis showed the minority carrier lifetime, $\tau$, in semiconductors is more sensitive, by a factor of $10^6$ to radiation-induced defects than the conductivity. In addition, the minimum energy required to produce a point defect in Germanium and Silicon was found to be about 14.5 and 12.9 eV respectively. The results also confirm previous studies that the degradation of minority carrier lifetime is commensurate with neutron fluence up to levels of at least $2.5 \times 10^6 \text{ n/cm}^2$[106].

The threshold for electron radiation damage in Zinc Selenide (ZnSe) at 240 keV is also well established [107] as the displacement of ZnSe atom from the lattice by electron particles has been observed. It was proved that at the irradiated energy, about 8.2 eV was transferred to the selenium atom and 10 eV to the zinc atom. The displacement, which was observed by the production at 85°C of a broad fluorescence band was resolvable into two overlapping bands with peaks at 5460 Å and 5850 Å and reversible by annealing in a temperature of 160 °K.

By applying Electron Spin Resonance ESR, - a technique used in chemical spectroscopy to identify unpaired electrons and free radicals - on MOS capacitors fabricated on <111> silicon-substrates, Lenahan et al. were able to propagate Pb centers by ionizing radiation. Their results showed that the generated Pb centers (Figure 11) are the dominant radiation induced interface state and have the same
annealing behavior radiation with induced interface states[108][109]. Pₓ centers, a
term first used by Y. Nishi et al. in 1972 to describe the point defect (a trivalent
silicon defect) near the Si/SiO₂ interface in MOS capacitor, strongly corresponds
with variations in interface state density induced by a variety of high temperature
processing steps.

![Diagram](image)

**Figure 11.** A schematic showing the formation of the Pb interface trap from the reaction
between a proton and an interfacial Si-H bond (a) Protons reach the interface from a Si-H
bond (b) H⁺-H-Si “bridge” is generated. (c) The dimeric hydrogen and a charged defect D⁺
is created. (c) This defect then may react further with electrons from the silicon. Sources
[110][111]

While studying structures and effects of radiation damage in cuprate
superconductors (i.e., containing copper anions) irradiated with several hundred-
MeV heavy ions, it was observed that the extent to which a detector can be
damaged by (heavy ions) radiation depends on a number of factors [112]. They
include “the rate at which ions lose their energy in the target; the crystallographic
orientations with respect to the incident ion beam, thermal conductivity and chemical of the
sample”. The study which was carried out by irradiating 300-MeV Au²⁺ and 276-
MeV Ag²⁺ ions on Bi₂Sr₂CaCu₂O₈, oxygen-reduced and ozone-treated YBa₂Cu₃O₇-δ
materials also concluded that the severity of massive disks-like defects induced by
the irradiated ion trajectories or tracks is proportional to not just the orientation of
the crystal and its concentration of \( \text{O}_2 \) but also to previously present defects in the crystal prior to irradiation.

Several papers have also been written on radiation damage in other popular semiconductors such as Gallium Nitride (GaN)-based materials and devices. An example is the study of the effect of irradiation on GaN light emitting diodes (LEDs) bombarded with high energy electrons of about 300-1400 keV at room temperature [113]; radiation damage in GaN and InGaN by 400 keV Au implantation [114]; the effects of proton, neutron, \( \gamma \)-ray, and electron irradiation on the same material [115]; and radiation damage formation from low temperature ion implantation and neutron irradiation [116].

The introduction of transitions in the near infrared part of the light spectrum when irradiated with 2 MeV protons was observed by paper [113] in comparison with a previous study which also found the same effect from irradiating 2.5 MeV electrons using photoluminescence (PL) (although the damage caused by 2 MeV protons was recorded to be more than 10,000 times more severe than from 2.5 MeV electrons), The study [113] found a threshold energy of 440 keV correlating to a gallium atom displacement energy (approx. 19eV) which is similar to that of silicon carbide, larger than that of GaAs but smaller than that of diamond. Due to the good probability of a nitrogen sub-lattice self-repairing through annealing, no threshold energy was recorded for the nitrogen atom.

The difference in the types of defect caused from irradiating different charge particles revealed that disordered regions in the GaN detector were predominantly created by neutron irradiation while point defects occurred from irradiating, electron, proton and \( \gamma \)-ray particles [115]. One common denominator was the major degradation of the efficiency of the devices at high doses and the conspicuous formation of carrier traps which subsequently lowers the mobility and conductivity of charged carriers in the defected region of the devices. Also noted in the report was that the radiation hardness exhibited by the GaN based devices was several magnitude higher than GaAs based devices of the same doping concentration irrespective of the radiation particle (proton, neutron, \( \gamma \)-ray, or electron irradiation) they were bombarded with. But with regards to the GaAs device, carrier lifetimes were recorded to be lower with an increasing implantation dose of protons at low implantation levels whereas beyond the “amorphization dose” a saturation at 500 ns was observed as a result of a peak in the defect density.
when measured with time-resolved reflectivity and photoconductivity method [117].

Solar cells have not been left out in the research quest to understand radiation damage in semiconductor devices. The effect of 1 MeV electron radiation on a number of solar cells made from molecular beam epitaxy-grown Aluminum Gallium Arsenide (AlGaAs), Copper Indium Selenide (CuInSe) and Indium Gallium Arsenide (InGaAs) materials in comparison to Indium Phosphide (InP) and GaAs have been looked into [118]. The researchers reached their conclusion by studying the damage constants, bandgap energies and optical absorption coefficients. They concluded that CuInSe, and InP-based solar cells are the most radiation-resistant of all the materials studied as a result of higher optical absorption coefficient of CuInSe and InP lower damage constants or defect introduction rates.

3.3 Method of Radiation Induced Damage Control

For future applications involving very hostile radiation environments, semiconductor devices can be fabricated to withstand such conditions if technological improvements are actualized [119]. One such proposition is that the radiation detectors be operated and if possible, stored in an environment of about -10 °C even when not in use. Other suggestions include the use of diffusion oxygenation Float Zone silicon wafers with <100> orientation, and Czochralski silicon if surface radiation degradation is to be reduced [38][39][121].

The control of radiation damage in high energy electron environment has been studied [122]. Some methods suggested by the author/s include operating the device in liquid-nitrogen temperature and coating both front and back sides of the device in evaporated thin film carbon which can reduce the radiation damage induced by a factor of 10.

In order to make a hexagonal Boron Nitride BN film less prone to electron beam radiation damage than graphene, a research synthesized the BN film by flakes produced by liquid-phase chemical exfoliation of the film in N-methyl-2-pyrrolidone [123]. The research revealed that after 80 keV electrons irradiation, the monolayer hexagonal BN did not amorphize or form vacancy defects during the

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9 It is important to note that for full amorphization to take place (that is the complete conversion of a crystalline material into an amorphous one), the sum of the interstitial
extended electron beam irradiation because a higher energy is required to displace the nitride atoms from the BN molecular structure than carbon from graphene.

Similarly, radiation hardness was also activated in field effect transistors fabricated with exfoliated single layers of Molybdenum disulfide - MoS2 and graphene, respectively. The radiation hardness of the transistors was tested using three different fluences of 1.14GeV U29+ ions. At the highest fluence of $4 \times 10^{13}$ ions/cm$^2$, the graphene based transistor was discovered to be more radiation hard than the MoS2 transistor after characterization using Atomic Force Microscopy and Raman spectroscopy.

Another interesting approach is the use of substrate bias during irradiation to improve radiation hardness [124], [125]. The former [124] reported that the use of reverse bias on nMOS transistors during and after ('post-irradiation test') irradiation of $^{60}$Co $\gamma$-ray diminishes and enhances the radiation hardness respectively. The latter [125] reported that degradation in AlGaAs and GaInAsP light emitting diodes as a result of $\gamma$-ray irradiation of 108 rad(Si) is improved by applying forward-bias on the devices during irradiation.

Other materials that have been researched and suggestions proposed in relation to improving the radiation hardness characteristics of devices include zero-bias Titanium Oxide - TiO2 to 45 Mrad(Si) of ~1-MeV gamma radiation and 23 Mrad(Si) of 941-MeV Bi-ions [126]; using 1.20 - 1.80 MW/cm$^2$-pulsed Nd:YAG laser radiation as Cd$_{16}$Zn$_{34}$Te crystal is irradiated with $\gamma$-ray [127]; by simply tweaking the inner structures or peripheral of the substrate [128][129]; or incorporating epoxy resin at the front end to strengthen the radiation hardness of Multi Pixel Photon Counter (MPPC) to 150 MeV protons by a factor of 8 [130].

The method applied in the penultimate work [128] is fascinating because of its use of doped interconnect-like electrodes created in the form of columns or rods through the top to bottom of the device to form a 3-dimensional detector. The results showed that these detectors are more radiation hard than usual planar detectors because it decouples the charge drift length from the ionization path, reduces the charge collection time, charge defects and the drift length (limited to concentration $p_i$ and the vacancy concentration $p_v$ in an irradiated area should be greater than an assumed amorphization threshold level $p_a$. Where the sum of $p_i$ and $p_v$ is less than $p_a$, the structure is (still) crystalline [149].
the \( p^- \) and \( n^- \)-doped inter-column spacing) [131]. The demerit with the 3-d detector is that it showed a higher inter-electrode capacitance (with higher electronics noise), non-sensitive regions in the columns and the dependence of the signal size on the hit position. A somewhat similar 3-d approach was also employed on Super-Luminescent Diodes SLD in the form of InGaAsP/InP MQW\(^9\) structures to increase neutron radiation hardness [132]. Fluence of \( 6 \times 10^{13} - 1 \times 10^{14} \) n/cm\(^2\) 1 MeV neutron irradiation was used in test.

\(^9\) Indium-Gallium-Arsenide-Phosphide/Indium-Phosphide multi quantum wells.
4

Research Methodology

This chapter outlines the methodology used in this research. It describes in detail, the simulation and fabrication processes used in the design and creation of the duo-lateral position sensitive detectors that were measured using the techniques described in the next chapter.

The two methods of simulations are

- Monte Carlo simulation using Geant4/CASINO, These were used to track and visualize the passage of the bombarding electron particles through the detector taking into account possible interactions and decay processes.

- Finite element simulation using Taurus TSuprem4 and Medici. These were used to mimic real life device fabrication processes (e.g. ion implantation, diffusion, oxidation, etching, deposition and dopant activation). It was also used to simulate the distribution and diffusion of impurities, as well as calculating the electrical response of the simulated detectors.

Later described in this chapter are the device fabrication processes which came after the simulation stage. These processes conducted in the cleanroom involve a multiple-step sequence of photolithographic, chemical etch and cleaning processing steps created on the silicon wafer.
4.1 Simulation Process

To understand how the detector will perform in reality under the irradiation of electrons, it was necessary to carry out simulations with estimated real-life parameters. The simulations were good avenues to model the two-dimensional distributions of potential and carrier concentrations in the anticipated real-life/fabricated electron detector. Simulation was also helpful in forecasting the typical electrical features of the device under different arbitrary bias circumstances.

A great deal of consideration was involved with regards to opting for the proper simulation tools that could help simulate and replicate the results that will be obtained in reality from the processing steps (doping, implantation and diffusion etc) used in the manufacture of silicon integrated circuits and other discrete devices. It was imperative for the device simulation tools to also have the necessary physical equations that will be able to describe the semiconductor device as well as having the capability to include energy balance equations, self-consistent within the system of device equations behavior.

4.1.1 Stage I: Device Simulating With Geant4

By simulating the passage of electron particles through a simple silicon wafer, it was possible to
- Track the particles and the resultant electromagnetic fields through the silicon material.
- Visualize the particle trajectories in the detector (see Figure 12) as well as observe the response of the constituent sensitive detector components.

To perform the above routines, a simulation tool known as Geant4 was used [10][133]. The tool was used based on the fact that it is an open source program that offers a number of alternatives for visualization, provision for recording the silicon detector response as the electron particles pass through the volume detector, and

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10 Geant4 is a free software package made up of tools for "both full and fast Monte Carlo simulation of detectors in different Energy Physics using Object oriented programming in C++. It is composed of facilities for handling geometry, tracking, detector response, run management, visualization and user interface.
also provides approximations with regards to how a real detector would respond (with good consideration of possible interactions and decay processes).

As an ionizing impinges and travels through a target, it covers an average distance known as the mean free path between ensuing collisions which alters its direction, energy or other particle properties [134]. The mean distance covered by the irradiated electron particles between successive collisions for the decay electron particle in flight through the simulated thin silicon wafer was calculated using [135]

![Image](image_url)

**Figure 12.** x-z plane simulation trajectories of electron at 8 kV accelerating voltage in a silicon detector (Number of electron trajectories simulated = 100, 000)

\[ \lambda = \gamma \beta t_c \]  \hspace{1cm} (5)

where \( \tau \) is the lifetime of the particle and \( \beta \) is used to calculate the decay length

\[ \gamma = \frac{1}{\sqrt{1 - \beta^2}} \]  \hspace{1cm} (6)

For a homogeneous silicon wafer, the number of mean free paths that an electron particle travels is defined as

\[ n_{\lambda} = \int_{x_1}^{x_2} \frac{\partial x}{\lambda(x)} \]  \hspace{1cm} (7)

The travelling electrons go through a series of free mean paths before they arrive at an interaction point between the electrons and the silicon detector and the
total number of mean free paths reaching this point, \( n_\lambda \) is sampled at the beginning of the trajectory by

\[
n_\lambda = -\log (\eta)
\]

(8)

where \( \eta \) is a random number uniformly distributed in the range \((0, 1)\). \( n_\lambda \) is updated after each step \( \Delta x \) according the formula

\[
n'_\lambda = n_\lambda \frac{V_x}{\lambda(x)}
\]

(9)

until the step originating from \( s(x) = n_\lambda \cdot \lambda(x) \) is the shortest [135].

As the electrons travel through the detector, electromagnetic interactions between the charged electron arising from their electric and magnetic fields take place and the electrons particle begins to lose some of its energy along the way. Determining the energy loss process was performed calculating the continuous and discrete energy loss in the silicon material with reference to a set energy threshold. Below the threshold, the loss was regarded as continuous and above it the energy loss was simulated by the explicit production of secondary electrons [135].

The mean rate of the electron energy loss with a set threshold \( T_{\text{cut}} \) as the electron travel through the detector was determined by [135]

\[
\frac{dE_{\text{abs}}(E,T_{\text{cut}})}{dx} = n_{at} \cdot \int_0^{T_{\text{cut}}} \frac{d\sigma(Z,E,T)}{dT} \cdot T \cdot dt
\]

(10)

where \( n_{at} \) is the number of atoms/volume in the silicon. The term \( \frac{d\sigma(Z,E,T)}{dT} \) is regarded as the differential cross-section per atom (atomic number \( Z \)) for the ejection of a secondary particle with kinetic energy \( T \) by an incident particle of total energy \( E \) moving in the material of density \( \rho \).

With the physical models, the total absorbed energy in the sample as shown in Figure 12, Figure 13 and Figure 14 were simulated for different energies. The simulated absorbed energies were of assistance in calculating the Linear Energy Transfer (LET) which was used for later simulations. The LET is basically a measure of the energy transferred to the silicon target material as an ionizing particle travels through it.
4.1.2 Stage II: Simulating with Medici/Tsprem4

For accurate process simulation results, an appropriate grid structure had to be defined by systematically specifying the locations and spacing of grid lines which are adjusted automatically as various process steps were simulated. The structure was divided into different meshes as solution values are calculated at the mesh nodes. The total number of nodes in the structure was computed by summing the number of mesh points (consisting of non-overlapping triangular elements) in each material of the simulated detector, and the number of mesh points along exposed boundaries. The mesh were made as fine as possible in order to optimize results while at the same time bearing in mind the simulation resource time.

During the simulation of ion implantation, adaptive mesh refinement (adding mesh points) was used to obtain optimized simulation results while adaptive mesh unrefinement (removing mesh points) was used during diffusion and oxidation simulation [136].

Figure 13. A simulated measure of the absorbed energy for 10keV, 15keV and 20keV through a silicon wafer
Figure 14. A two-dimensional cross-section view (a) x-z plane (b) x-y plane (top-down view) of absorbed energy in a silicon wafer substrate simulated with 8 kV accelerating voltage (Number of electron trajectories simulated = 100,000)
The crystalline orientation of the silicon substrates simulated for this research was <111> (in paper 1-8, except in paper 7 where <100> was used), and the initial concentration are shown in the table 1 below (in paper 1)

Table 1

<table>
<thead>
<tr>
<th></th>
<th>Concentration</th>
<th>Dopant</th>
</tr>
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<tbody>
<tr>
<td>( p^n ) detector</td>
<td>( 10^{15} \text{ cm}^{-3} )</td>
<td>Phosphorus</td>
</tr>
<tr>
<td>( n^p ) detector</td>
<td>( 10^{15} \text{ cm}^{-3} )</td>
<td>Boron</td>
</tr>
</tbody>
</table>

Preparation for impurity implantation was performed by anisotropically depositing a thin layer of silicon oxide of about 55nm on the front side of the wafer. Anisotropic deposition is, in this case, defined as a ratio of the layer thickness on top of the flat surface to the thickness of the layer deposited on a vertical wall. It is through the 55nm oxide that the impurity doping was implanted.

The implanted impurity dose for the simulated \( p^n \) detector (paper 1) and the \( n^p \) detectors (paper 2) are shown in Table 2 below

<table>
<thead>
<tr>
<th></th>
<th>Dose</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p^n ) detector</td>
<td>( 10^{15} \text{ ions/cm}^2 )</td>
<td>30 keV</td>
</tr>
<tr>
<td>( n^p ) detector</td>
<td>Profile 1 = ( 0.4 \times 10^{15} \text{ ions/cm}^2 ); Profile 2 = ( 8 \times 10^{15} \text{ ions/cm}^2 )</td>
<td>56 keV</td>
</tr>
</tbody>
</table>

To take care of backscattering during the implantation, the part of the distribution above the top of the simulation structure was assumed to be backscattered at the surface and the portion of the distribution below the bottom of the simulation region was assumed to have been implanted into the structure. The energetic displacement cascades of the implanted ions cause some damage or structural change to the silicon lattice structure. A simple implant damage model was used to evaluate the silicon atoms knocked out of lattice sites and for interstitials produced when silicon atoms are displaced by implanted ions. The consequence of amorphization was considered and the need for an analytical model of point defect recombination was included to catalyze subsequent diffusion processes to remedy the damages caused.
As already stated, each dopant atom implanted into the silicon prompts some local lattice distortion in the silicon lattice as local microscopic deformities that reveal themselves as very tiny strains. When the dopants enter the silicon lattice as substitutional atoms, the resultant strain can be approximated from the atomic radius mismatch which induces a mismatch stress. During normal impurity implantation, some of the induced point defects combine with dopants or other defects to form pairs or clusters. These point defects are removed from the population of free point defects to ensure that the total number of added defects (free or otherwise) is given by the cumulative damage model. The 3-stream diffusion model used aggregates the damage caused by successive implants and simulates defect recombination and amorphous regrowth at the beginning of the first diffusion step immediately after the implantation. It simulates the total damage at any point in the structure from all implants since the last high temperature processing step [136].

To remedy the aforementioned defects caused by the energetic displacement cascade, the diffusion process was modeled on the already implanted silicon under oxidizing for a certain period of time specified in minutes and temperature (in degree Celsius - °C). The diffusion was conducted at a stable temperature or by linearly varying the temperature over the required steps or at a certain rate. With the temperature rate specified, the temperature varies as

\[ T_d = T_i + \text{Temperature Rate} \times T \]  

(11)

where \( T \) is the time since the start of the step, \( T_d \) is the diffusion temperature (in °C) at time \( T \) and \( T_i \) is the initial temperature of the step.

In a situation where the final temperature \( T_f \) is specified, the temperature varies as:

\[ T_d = T_i + \frac{T_f - T_i}{\text{Time}} \]  

(12)

The temperature becomes constant if neither the temperature rate nor the final temperature \( T_f \) is specified. The same analogy can be applied in the formulae above for the diffusion pressure with the values chosen to yield positive, nonzero pressures throughout the step.
4.1.3 Ambient Condition

For all the detectors simulated for this thesis, the diffusion process was performed at 900°C in nitrogen ambient for a period of 30 minutes and at an ambient pressure of 1 atmosphere just after implantation. For other diffusion steps depending on the case (e.g. growing thin passivation oxide or growing thick oxide as mask etc), the ambients used were either dry oxygen DryO₂ or wet oxygen WetO₂ steam or inert gas.

These ambients are defined as thus:

- **DryO₂**: The dry oxygen ambient contains 100% oxygen O₂.
- **WetO₂**: The wet oxygen ambient contains 92% water H₂O and 8% nitrogen N₂. This depicts the condition where wet O₂ bubbled through H₂O at 95°C is the same as pyrogenic steam with O₂ and H₂ flow rates of 1.175 and 2.0 liters/minute, respectively [137]. (The actual ambient contains 8% O₂ but because the TCAD programme used is unable to model simultaneous oxidation by H₂O and O₂ N₂ is replaced for the oxygen in the simulation.)
- **Steam**: The steam ambient contains 100% H₂O. This depicts the formation of H₂O by a complete pyrogenic reaction of O₂ and H₂ without excess O₂ or H₂.
- **Inert gas**: This contains 100% N₂ or other inert gases Nᵢ.
The result obtained after the simulated annealing of implanted dopants shown in table 2 can be seen in Figure 15.

4.1.4 Simulating Thin Oxide film passivation and metallization

To simulate a thermally grown thin passivating oxide layer of thickness $x$, (in this case, the 10nm thick oxide as shown in Figure 16), a gradual growth derived from a model used and it is given as

$$\frac{\delta x}{\delta t} = \frac{B}{2x+A} + Ce^{-\frac{x}{L}}$$

(13)

where $B$ and $A$ are the oxidation rate coefficients, $C$ and $L$ are the empirical constants. [136].

![Figure 16](image)

**Figure 16.** A simple schematic of the simulated $p^n$ detectors (the figure is not drawn to scale)

The final step in the simulation of the fabrication process was the deposition and patterning of the detector ohmic contacts. Aluminum was chosen as the contact material and it was specified that the interfaces between the contact material and silicon be converted to electrical contacts points. The ohmic contacts were executed as basic Dirichlet boundary conditions, where the surface potential $\psi_s$ and electron and hole concentrations are fixed (set at a value consistent with zero space charge). Also the carrier quasi-Fermi potentials (both minority and majority) are at equilibrium and are fixed to the applied bias of that electrode.
4.1.1. Recombination and Mobility Models Used in Simulation of Electrical Characteristics

During the modelling and the analysis of electrical properties of the device operation, the total recombination \( U \) in the device was simulated using the sum of the optical/band-to-band, Auger and Shockley Read Hole - SRH – recombination. This is mathematically expressed as

\[
U = (C_d * np - n_e^2) + U_{\text{Auger}} + U_{\text{SRH}}
\]  

(14)

where:

\[
U_{\text{SRH}} = \frac{pn - n_e^2}{\tau_n [n + n_e \exp \left(\frac{E_r}{kT}\right)] + \tau_p [p + n_e \exp \left(\frac{-E_r}{kT}\right)]}
\]  

(15)

\[
U_{\text{Auger}} = [n A_n \left(\frac{T}{300}\right)^{\text{Auger,N}} + p A_p \left(\frac{T}{300}\right)^{\text{Auger,P}}] * (pn - n_e^2)
\]  

(16)

\( E_r \) trap level (\( E_l - E_i \)) is used for determining the Shockley-Read-Hall recombination rate; \( n_e \) is the effective intrinsic concentration; \( \tau_n \) and \( \tau_p \) are the electron and hole lifetimes; \( C_d \) is the band-to-band recombination coefficient. \( A_n \) and \( A_p \) are the Auger coefficients for electrons and holes, respectively; \( \text{Auger,N} \) and \( \text{Auger,P} \) represent the exponents of temperature for the Auger coefficient for electrons and holes, respectively; \( p \) and \( n \) are the net hole and electron concentration, respectively. The bracketed term in eqt(14) is the optical/band-to-band recombination.

It is also important to state that, for each device electrical analysis, explicit model statement(s) specifying model flags were used to indicate the inclusion of various physical mechanisms. For simulations involving optical parameters, specific models mobility that affect the diffusion of carriers were used. These are

- Mobility tables used to model the dependence of carrier mobility on impurity concentration. The mobility tables are tables of values used to describe the dependence of electron and hole mobility on impurity concentrations for Silicon and Silicon-oxide,
• carrier-carrier scattering model that includes the dependence of mobility on doping

• Field dependent mobility model using the parallel electric field component. This was important where the device was reverse biased and/or as a result of presence of high electric fields in the depletion region,

• Shockley-Read-Hall recombination with concentration dependent lifetimes and

• Auger recombination.

4.2 Fabrication Process

The electron/UV detectors simulated in the previous section were fabricated using a number of sequential processing steps in a very controlled environment. The processes were analogous to the simulation processes in which layers of materials are deposited on substrates, doped with impurities, and patterned using photolithography etc. to finally arrive at the finished product. Figure 17 shows the interrelationship between the major processing steps used in the fabrication of the electron detectors used in this thesis.

One difference between the simulation process of the detectors and the ‘real life’ fabrication was the time involved. While most parts of the simulation steps could be achieved in a relatively shorter time, the physical fabrication involved sometimes several months of work to complete. As a result, caution was taken at every step because a single mistake at any stage was capable of ruining the detector in particular and several months of processing in general.
The $n^p$ electron detector and position sensitive detector PSD were fabricated at the Mid Sweden University cleanroom while some $p^n$ detectors were fabricated and provided by Sitek Electro Optics AB, Sweden.

**Figure 17.** Flow chart for generic detector process sequence

![Flow chart for generic detector process sequence](image)

**Figure 18.** Axial resistivity of the starting wafer used measured by the 2 and 4-point method. Source: Topsil Semiconductors, Denmark (topsil.com)
4.2.1 Starting Wafer Properties

The starting wafers used for processing the detectors were Float Zone - High Purity Silicon wafer (FZ silicon – HPS wafers) from Topsil Semiconductor, Denmark.

Each was a single side polished wafer with a primary flat of 32.5 ± 2.5 mm; Orientation: (1-10) +/- 1deg and a thickness of 400μm. It has a bulk lifetime measured by the photo conductive decay method as 1180μsec, <1-1-1> orientation (see Figure 18) and a diameter of 103mm with resistivity measured by two and four point probes at the seed and tail sections of the ingot. (In paper 7, <100> Silicon was used)

4.2.2 Sample Preparation

Cleanrooms usually provide passive cleanliness but it is general practice for the wafers to be actively cleaned before every critical step. As such, though the cleanroom at the Mid Sweden University - where a number of the detectors used for this report were fabricated - is of low level of environmental pollutants and of very controlled level of contamination, the wafers were still subjected to the usual SC 1-3 (Standard Clean) procedures.

In processing the detectors, it was necessary to pattern the wafer/film into specific features or to create openings on the wafer. Photolithography (or "optical lithography") was used, using UV light to transfer the desired pattern from a photomask to photoresist or resist on the bulk substrate.

Post-exposure bake - PEB was performed before developing to assist in minimizing the minimize standing wave phenomena brought about as a result of the destructive and constructive interference patterns of the incident UV light [138]. The resulting wafer was then oven-baked for another 20minutes in a 120°C oven. This was to solidify the remaining photoresist in order to make a more durable protecting layer in future ion implantation, wet chemical etching, or plasma etching.

4.2.3 Implantation of Impurities

For the 4\textsuperscript{th} detector/PSD detector, a boron concentration of 10\textsuperscript{18}/cm\textsuperscript{3} was diffused into the initial wafer structure at a temperature of 950°C for 60mins, Analogous to the simulation process, preparation for impurity implantation was conducted by thermally growing a thin layer of SiO\textsubscript{2} of about 55nm on the front
side through which the impurity doping was implanted. A dose of 0.4x10^{15} ions/cm² As was implanted to create the blocking contacts using an implantation activation step at an acceleration energy of the ion implant beam of 30keV. The implantation was made at a 7° tilt angle of the wafer, measured in a clockwise direction from the horizontal in the plane of the implantation.

![Graph](image.png)

**Figure 19.** The doping profile of the simulated p/n detectors and that of the fabricated detector measured with Secondary ion mass spectrometry (SIMS)

### 4.2.4 Annealing/Diffusion Steps

The wafer was annealed at 900°C in nitrogen ambient for a period of 30 minutes to help remedy the tiny strains and point defects from the ion-implantation. Annealing which is a high-temperature furnace operation helps to abate the stress in the wafer, mobilize the ion-implanted dopants, decreases the structural defects and stress in the lattice, as well as reducing the density of the interface charge at the Si-SiO₂ interface [139]. The resultant doping profile or concentration of the measured impurity after the implantation and annealing process of a p/n LPSD can be seen in Figure 19.
To measure the doping profile of the fabricated detector, Secondary ion mass spectrometry (SIMS) profiling was performed at the Laboratory of Solid State Electronics (LSE) of KTH University, Sweden – see Figure 19. SIMS is basically a technique to examine the structural content of solid surfaces and thin films by sputtering the surface of the material under test with a focused primary ion beam.

During the process, secondary ions are given up that are collected and analyzed with a mass spectrometer to determine the composition of the material which may include the elemental, isotopic, or molecular composition of the surface. The technique can be described as the most sensitive surface analysis technique which is able to detect elements present in the parts per billion range. Physical vapour deposition technique (PVD) was used to deposit a 0.5μm thick aluminum as the front and reverse contacts that were orthogonal to each other.

The final processing step was the forming gas annealing which was used to reduce the interface states located at the Si-SiO₂ interface. This process is no different from nitrogen annealing except that the forming gas annealing was performed in a mixed gas of 95% Nitrogen and 5% Hydrogen. An image of the finished n+p PSD is shown in Figure 20.
Figure 21. An optical microscope image of grids patterned on the surface of the PSD using photoresist

Figure 22. An XZ plane projection of energy by position image of electrons absorbed in a photoresist toped PSD. The simulation was performed at 15keV acceleration energy, 1,000,000 electrons particles and electron beam radius of 10nm [140].
4.2.5 Grid Formation on the \( n^p \) Position Sensitive Detector

The grid patterning was done using photoresist with optical lithography processes to form a resist layer of 1\( \mu \)m thickness and exposed to a pattern of intense UV light for 10 seconds to imprint the mask patterns on it. A round of post-exposure bake was also performed before standard practice lithographic development to solidify the photoresist. An optical microscope image of the photoresist patterned surface of the PSD is shown in Figure 21.

Photoresist was used to create the grids because it involved a cheaper, simpler and faster process of pouring/spinning rather than sputtering/deposition of metal. Another reason is because of its low surface reflection and backscattering of irradiated electrons. Simulation using CASINO – a Monte Carlo simulation tool for electron trajectory was performed to accurately determine the exposure parameters and the thickness of photoresist required. The result can be seen in Figure 22. The photoresist is labelled as PMMA in the figure.

The simulation result showed that a minimum thickness of 1.5 \( \mu \)m was required to successfully absorb the 10 keV electrons in the elevated region of the grids. See Figure 22. A schematic showing the lithographically patterned grids on the fabricated position sensitive detector is shown in Figure 23.

4.2.6 Metallization

The deposition of the ohmic contacts/electrodes for the detectors used in this research was made with aluminium by electron beam evaporation. Field rings and field plates were also deposited by electron beam evaporation around an array of the \( oh \)-lateral PSDs to be used as a pixel detector. The 0.3 \( \mu \)m thick field-plates channel stops (Figure 24) deposited on the 220 \( \mu \)m pixel pitch detector and researched in paper 7 were also made with Aluminium. It was the metal of choice because of its

- excellent adhesion on Silicon and oxide
- excellent contacting with gold/aluminium wire bonds and epoxies
- excellent ohmic contacts with \( n \)-type semiconductors
- low electrical resistance of approximately 3 \( \mu \Omega \cdot \text{cm} \)
- very low cost compared to silver, gold and copper
- considerably good electrical toughness and resistance against corrosion.
For the detector in Figure 24, the patterning of the Aluminium metal film deposited on the top layer was performed using the ‘lift-off’ technique [142]. This process as a patterning technique was used because
- direct etching of the deposited aluminium may have undesirable effects on the layer
- possibility of having sloped side walls resulting in good step coverage
- it is a relatively simple process without the use of chemical etchants.

**Figure 23.** A schematic of the fabricated detector featured with photoresist grids

**Figure 24.** Mask set showing the dimensions of one of the three different structures of field rings and field plates created on an $n^+$ in $p$-wafer pixel position sensitive detectors [141]. The other two dimensions can be found in paper 7. All dimensions are in $\mu$m.
Measurement and Results

The results contained in this thesis were obtained from three measurement procedures. The first stage involved using scanning electron microscopy to extract the surface state characteristics of the detectors. Using the same technique and some novel but inexpensive surface features lithographically patterned on the top layer of a duo-lateral electron-PSD, the position of electron particles and the linearity of the detector were evaluated in the second stage. The final stage involved using high intensity UV photons to examine the radiation hardness of duo-lateral PSDs with different doping characteristics. By also using a simple method, the resultant radiation damage on the active area of the PSDs was mapped.

5.1 Measuring Surface Recombination Velocity and Fixed Oxide Charge

An experimental setup that involved the use of a Scanning Electron Microscope (SEM) was used as shown in Figure 25. The SEM is a kind of electron microscope that images a sample by scanning it with a high-energy beam of electrons in a raster scan fashion. The emitted electrons interact with the atoms of the sample to induce photogenerated carriers. These photogeneration signals are converted to e.g. current to retrieve information about the sample’s surface topography, composition, and other properties such as electrical conductivity.

To generate the electrons, a Stereoscan 360 SEM was used and electron energies ranging from 500 eV to 20 keV were generated at an electron beam current of 1nA. The electron beam current was measured with the use of a Faraday cup
(Figure 26) which was first irradiated with an electron beam of energy resulting in a measurable current that was used to determine the quantity of electrons hitting the cup.

The number of electrons impinging the detector can be mathematically defined as [143]

\[ n_o = \frac{I_{o, pd} t}{q} = \frac{I_{o, pd} F \cdot 10^6}{q} \]  

(17)

where \( t \) = time (seconds); \( F \) = frame scan time (seconds); \( q = 1.6 \times 10^{19} \)

![Image of the Stereoscan 360 Scanning Electron Microscope used for this research](image)

The actual number of electrons \( n \) detected by the detector depends on the beam-specimen interaction and the efficiency of the detector. This can be described as \( n = \eta n_o \) where \( \eta \) represents the product of the detector’s efficiency (approx 1) and the electron yield (approx 0.1 - 0.2) for secondary electrons.

To measure the detector current \( I_{pd} \), a pico-Ampere multimeter was used and the detector was operated in photovoltaic mode to reduce the noise factor of the signal output. With the measured currents, the responsivity which represents the ratio of generated detector current to incident electron energy was calculated using

\[ R_m = \frac{(I_{pd} - I_d) \mu A}{I_o V_o} \]  

(18)

where \( I_{pd} = \) measured detector current; \( I_d = \) measured detector leakage current; \( I_o = \) incident beam current; \( V_o = \) electron acceleration voltage
Figure 26. Schematic showing the experimental setup with a scanning electron microscope (b) setup to measure electron beam current.

Responsivity measures the input–output gain of the detector system and is proportional to the number of electron hole pairs generated as the irradiated electrons are absorbed in the active layer of the detectors. As the electron-hole pairs which can also be referred to as carriers are created, an electric field is also created. The electric field at the junction of the different doping regions (i.e. p-n junction) split the charges and drives the current in the external circuit. With the energy needed to create an electron-hole in silicon found to be 3.6 eV, the ideal responsivity $R$ in an electron/UV detector free from any form of energy loss can be expressed in Amp/Watt (A/W) as [144]

$$ R = \frac{1}{3.6} \approx 0.28 \text{ C/J} \approx 0.28 \text{ A/W} $$  \hspace{1cm} (19)

While there is a unique responsivity for a detector that responds linearly to its input, a nonlinear detector has a responsivity that is derivative or slope-like as the energy of the photon or irradiated particle increases. The surface recombination velocity and fixed oxide charge of the detector were deduced by extrapolation by comparing the measured responsivity from a series of simulated responsivity-vs-energy plots at different surface recombination velocities and fixed oxide charges.

The responsivity of a measured n-p and p-n-doped PSDs are plotted in Figure 27. It is seen from the figure that the p-substrate detector is more linear that the n-substrate detector. The gradient of the former is less inclined and the level of predictability of the detector’s response is higher than that of the p-n detector.
Figure 27. (a) A comparison of the responsivity of a p'n and an n'p detector (b) the leakage current measurement of an n'p detector

The maximum responsivity obtained from the n'p is slightly less than the theoretical value of 0.27A/W as a result of energy losses from processes such as backscattering, secondary electron formation etc. An estimation of the loss from backscattered electrons was calculated by simulation which shows a 0.5% loss can occur from backscattered electrons as a result of beaming 20000 electron particles at 10 keV. See Figure 28a
Figure 28. The energy of backscattered electrons escaping the surface of the sample obtained from irradiating a simulated detector with an accelerating voltage of 13keV. Number of electron trajectories simulated = 200,000. The y-axis (Hits) is on the scale of 10^4. (b) Net recombination in number per cubic centimeter per second plotted against distance along the specified line through the device from the point of impact of both arsenic and phosphorus doped n-p detectors. Results with S_n and Q were obtained where S_n = 10^5 cm/s and Q = 5x10^3 C/cm^2.

The net rate of recombination U of an n-p detector was examined under non-equilibrium conditions. The net rate of recombination is the difference between the total generation of carriers and the total recombination which includes the recombination at the surface of the detector.

To investigate the net recombination rate U of a detector, an imaginary slice along a specified line was drawn down through the device from the point of
electron impact at 90°. The electron enters through the top SiO$_2$ film and impacts at the upper right corner perpendicular to the x-axis = 1.5μm, and the y-axis = 0 on the contour plots (Figure 29). With $U_e$ and $U_h$ representing the net electron and hole recombination rates, respectively, the net recombination rate $U$ was simply calculated from the sum of Shockley-Read-Hall, and Auger around the vicinity of the Si-SiO$_2$ interface and the result can be seen in Figure 28b.

![Figure 29](image_url)

**Figure 29.** (a) Contours of constant net recombination for an $n^+p$ detector where there are no surface recombination velocity and fixed oxide charge i.e. $S_{np} Q = 0$ (b) Contours of constant net recombination for an $n^+p$ detector with the presence of surface recombination velocity and fixed oxide charge. Where $S_{np} = 10^{1} cm/s ; Q = 5x10^9 cm^2$
The figure also shows that when interface recombination velocity \( S_i \) and fixed oxide charge \( Q_f \) exist in the detector, there is a spike in the net recombination near the Si-SiO\(_2\) interface. This is because the sum of the Shockley-Read-Hall and Auger Recombination present at the Si-SiO\(_2\) interface is significantly increased with the presence of \( S_i \). The net recombination can also be visualized in Figure 29 where it is seen that due to the electron particle absorption and the presence of oxide charge and surface recombination, there is a larger area or effect of net recombination rate than in the case where there is an absence these interface states.

With the high leakage current as seen in Figure 27b, using the fabricated \( n\!p \) detector in a high reverse bias application can be tricky. The high leakage current can become problematic when a small increase in voltage bias results in a sharp decrease in the signal-to-noise ratio. Using an array of such detector as a pixel sensor can also be problematic because of the formation of the inversion layer of electrons (induced by positive oxide charges) connecting the \( n \)-doped region. To remedy this, three different structures (labeled as S1 to S3) field plates and field rings terminated around each individual pixel were fabricated (patterns as shown in Figure 24). The structures (S1, S2 and S3) have different area sizes in relation to the \( n \)-doped region, guard rings spacing and widths. By using the field plates and rings, it is expected that the \( p \)-substrate pixel will be more resistant to radiation damage and the effect of the unwanted induced inversion layers. The structural dimensions and other details can be found in See paper 7. Using a measurement setup which included an Agilent/HP 4142B Modular DC Source/Monitor, the interpixel leakage current and breakdown voltage of the pixel detector with different structural dimensions were measured.

The result (Figure 30) obtained from the measurement showed that the detector with the smallest \( n \)-doped area, S1 (with biased field plates), showed a large breakdown voltage and a property similar to that of a constant current generator. The results from all three different structures can be seen in paper 7.
Figure 30 (a) Measured interpixel leakage current for the structure S1 (120x120 μm n-doped region), with biased aluminium field plates. (b) Measured breakdown voltage for the same structures.

5.2 Electron Particle Position and PSD Linearity Measurement

The positions of electron particles from a Stereoscan 360 SEM on the PSD were determined using the lithographical patterned grid placed on the top surface of the PSD (Figure 31). By using the formula below, the x and y coordinates of the
electrons as they hit the PSD were determined from the voltage signal recorded from transimpedance amplifiers designed at each electrode of the PSD device.

The measured position \((x; y)\) coordinates is calculated using

\[
x = 0.5L_x \frac{V_{x2} - V_{x1}}{V_{x2} + V_{x1}}, \quad y = 0.5L_y \frac{V_{y2} - V_{y1}}{V_{y2} + V_{y1}}
\]

where \(V_{x1}\) and \(V_{x2}\) are the recorded voltages from two respective contacts perpendicular to the direction along which the beam is traveling and \(L_x\) is the length of the active area. \(V_{y1}\) and \(V_{y2}\) are the voltages from the corresponding two contacts orthogonal to the beam direction and the contacts used to calculate the aforementioned \(x\) coordinate. \(L_y\) is the width of the active area.

The difference between the measured electron beam position and the actual position, which is determined using the grids on the PSD is used to characterize the position detection error of the measured PSD.

**Figure 31.** (a) An electron microscope image of the \(p^n\) detector under test (Scale bar=2.5 mm) (b) a portion of the \(n^p\) detector/PSD showing the patterned grids. The detectors are irradiated with electrons energy of 15keV, beam current = 1nA.

The concept is that as the beam travels along an axis and across the grids patterned on the PSD, a response in the form of a spike or a dip in the signal is recorded depending on the direction of the beam travel. See Figure 32. The number of grid spacings along the path of the beam line results in the same number of spikes/dips in the recorded signal. The merits of using the grids are that they act as a ‘path guide’, and as precise position indicators of the beam position. By recording the output signal in a time series (as shown in Figure 32), the grids become useful as beam ‘time stamps’ because it is possible to record the precise time and location at which the beam hits the detector. This method also helps to
detect the beam position at very high scan speed as well as assist in eliminating additional errors as a result of the absence of additional/stand-alone devices such as actuators and translation stages thereby also reducing measurement costs.

![Graph](image.png)

**Figure 32.** The response ($V_{1}$ and $V_{2}$) from the two bottom contacts of the PSD as 15keV of electron beam sweeps along the axis perpendicular to the contacts. The electron beam with 1.7nA of beam current causes an upward spike in voltage as it travels across the grids.

To increase the signal-to-noise ratio SNR during measurement, frame averaging which combines a fraction of the input live image with 1 minus that fraction of the stored image was used. The composite data was then stored and the displayed result was a noise reduced image. The amount of noise reduction was controlled by a $K$ factor and the noise reduced image is mathematically defined by

$$I_{\text{new}} = 0.5K \times I_{1} + (1 - 0.5K) \times I_{\text{old}}$$

(21)

where $I_{\text{new}}$ is the new image store content; $I_{\text{old}}$ is the old image store content; $I_{1}$ is the line image input; and $K$ is a factor between 0 and 8. To produce a more stable output voltage when the beam is on a grid, the SEM time constant $\tau$ was also significantly increased from 0 to 348 min and can be expressed as

$$\tau = \frac{t_{r}}{\ln(1 - 0.5K)}$$

(22)
where \( t_i \) is the frame interval.

Although signal averaging can impact upon the detection bandwidth, the \( K \)-factor parameter that allowed for a very good signal-to-noise ratio and reliability in a broad bandwidth application was consciously chosen. More results can be found in paper 6.

5.3 Radiation Hardness Measurement and Active Area Mapping

To study the radiation of the PSDs, a fabricated \( p\!n\!p \) and a commercially available \( p\!n\!n \) were exposed to UV light produced from an Energetiq EQ-1000 laser-driven light source that was part of the experimental setup shown in Figure 33.

The experiment was carried out in three stages. The first part involved mapping the entire active area and measuring the position deviation errors and non-linearity of the devices. The next stage was irradiating the detectors over a period of time to cause ionization damage and degradation on the PSDs under UV beam irradiation.

![Figure 33. The measurement set-up for the degradation, the 3-dimension mapping and the linearity measurement of the devices using a UV beam from an EQ1000 laser beam source. For the 3-dimension mapping and the linearity measurement, a 100 \( \mu \)m spot size fiber optic cable and a beam profiler were used in place of the 25 mm focal length lens and bandpass interference filter that were used during the degradation of the PSDs]
The third part involved repeating stage 1 in order to extract the induced radiation damage, position deviation errors and non-linearity of the devices brought about by the degradation. For stages 1 and 3, a similar transimpedance circuit configuration used in the previous section, a 100 μm spot size fibre optic cable and self-designed beam profiler in place of the 25 mm focal length lens and bandpass interference filter.

During the degradation of the devices in stage 2, they were operated in photodiode photovoltaic mode with the electrodes Ti,Ti connected as a common electrode and B,B_2 connected as another. For continuous data collection, a programmed Labview data acquisition system was used for stages 1 and 3 while a UDT 5370 optometer was used for stage 2.

It is important to note that placing the 45° laser line mirror and the plano-convex lens before the bandpass interference filter was inevitable even though it resulted in about a 15-20% loss in light intensity. A previous attempt to position the filter some distance directly after the laser source resulted in the damage shown in Figure 34.

![Burnt section of filter](image)

**Figure 34.** Burnt section of an interference filter caused by placing it directly after the laser source

By plotting the change in responsivity in relation to the intensity, the radiation hardness of the detector over a period of time at a specific irradiation energy/wavelength (253 nm in this case) can be known. Figure 35a, it shows that the PSD irradiated at 253nm (Figure 35b) with 1.4mW/mm² UV beam losses of about 60% of its responsivity after absorbing 3x10⁶ joules/cm² of UV. The resultant
effect of the radiation damage on its sensitivity can be seen in Figure 36a after a 3-
dimension mapping.

Figure 35. (a) Stability of a p’n detector diode exposed to 253 nm radiation. (b) The spectrum
of UV beam used for the degradation of the detector with peak at 253 nm measured with
Avantes AvaSpec-2048 spectrometer.

The result from the 3-dimension mapping is obtained by computing the sum of
the output signals at every measured coordinate of the beam position on the
PSD using eqn(20). The x- and y- coordinates on Figure 36a are the PSD width and
PSD length, respectively. By taking the output signals from the two top contacts in
the direction of ‘PSD Length’ (that is, as the beam travel along the y-plane in Figure
36a), the position detection error as a result of irradiation can be calculated. The
signals from the two contacts (similar to in Figure 36b) are used to calculate the
measured beam position along that axis and a difference between the measured
and the actual position of the beam gives the position error. The bump in Figure
36a and b is from the region of the beam focus on the PSD. More details and results
can be found in paper 8.
Figure 36. An active area map showing the exposed and unexposed region of the p’n p SD to 1.4mW/mm² irradiation of 253 nm UV photons, (b) The recorded output signal from two parallel contacts as the beam travel along the y-plane (PSD Length in Figure 36a).
Summary of Thesis

The thesis demonstrated results from the successful implementation of the scanning electron microscopy and UV beam profiling techniques for the characterization of position sensitive detectors.

It started by previewing different literature and technical reviews of previous studies on interface states and surface recombination velocity on detectors and as well as various measurement techniques (as in papers 4 and 5) used to research these semiconductor phenomena and how they affect the performance of semiconductor devices. The thesis also reviewed theoretical and methodological contributions to the topic of radiation damage in radiation detectors. This included researches from other authors covering effects including lattice displacement effect, ionization effect, Frenkel effect and single event effects in devices. It also reviews previous studies on different researched and published techniques such as dopant driven lithography, low-temperature photoluminescence spectra and Electron spin resonance for radiation damage characterization and control.

The thesis demonstrated the various methodologies involved in the fabrication of the $n\!p$ and $p\!n$ detectors which were fashioned after the simulated models. The various steps associated with the fabrication include the implantation, diffusion/annealing and the lithographic stages. Prior to the cleanroom fabrication process, some simulation tools were used. Geant4 and CASINO simulations were used to track the irradiated electrons, visualize the electron trajectories and depth profile of the absorbed energy per electron in the device(s). Taurus TSuprem4 was used to simulate the different doping profiles and their resultant electric- fields during irradiation. This was achieved by simulating the incorporation and redistribution of impurities into silicon wafers using, amongst others, the solutions of electron and hole energy balance equations. Using the transfer data (Linear
Energy Transfer file in picoCoul/micron) created using Geant4. Taurus Medic was used to calculate the net recombination rate, induced current and to observe the response of the TSuprem4-simulated detector.

This research explored an alternative method of characterizing a duo-lateral LPSD by means of scanning electron microscopy. One of such is the ability to use the responsivity to infer the interface recombination velocity and fixed oxide charge present in differently doped detectors. The duo-lateral PSDs (simulated and fabricated) were designed with similar parameters and the results gave rise to some interesting findings from which a number of conclusions were derived. The research, experimentally, showed that the $n\!p$ and the $p\!n$ detectors had a maximum responsivity of 0.25A/W, slightly less than the theoretical value of 0.27A/W due to energy losses.

The difference in performance with regards to the responsivity between differently doped electron PSDs with respect to doping concentration was also demonstrated by experimentation and simulation. It is concluded that the doping profile has an impact on the responsivity of an $n\!p$ detector with regards to the interface recombination velocity. This is because, at low energy, it was shown that the responsivity of the detector increases as the concentration of the impurity dopant increases. See paper 2. It can be concluded that the varying doping concentrations had no visible effect on the responsivity (wrt fixed oxide charge) of an $n\!p$ detector. This confirms previous research results that $Q_i$ depends on the oxidation/annealing conditions and the orientation of the silicon surface but its density is not influenced by the concentration of the dopants in the device [18]. The magnitude of the generated electric field in the interface of the detector is influenced by the doping concentration and the positive charge at the silicon oxide. For the $n\!p$ detector, an increase in the positive oxide charge assists in promoting the responsivity because these positive charges - from the fixed oxide charge - repel the holes somewhat deeper into the depletion region in the detector, thus preventing the recombination of electron and holes at the interface. See paper 1, 2 and 3.

Furthermore, an $n\!p$ duo-lateral LPSD with high sensitivity to low energetic electrons was fabricated. Using sweeping electrons from the SEM microscope, the linearity over the $x$- and $y$-axes of the PSD incorporated with patterned surface layer grids was researched. The evaluation showed a very high linearity over the two-dimensions of the PSD total active area. Using the SEM technique, it was
shown that a precise simple, inexpensive and effective method of position
detection measurement inside an ultra-high vacuum environment can be
successfully carried out. This is because the method used in this research assisted
in eliminating further external measurement errors and uncertainties from the use
of other typical movable measurement devices. By doing away with these devices
in beam position measurement, the total cost involved is reduced and the
measured accuracy is improved. See paper 6 for details.

Research has also been involved in the use of field plates/rings terminated
around the edges of $\eta$ in $p$-substrates to suppress the formation of unwanted
inversion layers in pixel devices. By simulation and measurements, the interpixel
leakage current and breakdown voltage of the pixel detector with different
structural dimensions were obtained. By using the field-rings, the leakage in $p$-
substrate pixel is reduced as well as the effect of the unwanted induced inversion
layers. See paper 7 for details.

The effect and extent of radiation damage on a in-house fabricated $\eta p$ LPDS
and commercially available $p\eta$ LPDS irradiated with 193 and 253 nm UV radiation
were researched. At both wavelengths, the degradation damage caused a much
more significant deterioration of responsivity in the $p\eta$ LPDS compared to the $\eta p$
LPDS. The morphological damage at the surface in 3-dimensions from UV damage
was investigated by using a simple novel mapping technique. With this, it was
possible to map the signal response of the entire active area and to image the part
that has suffered any loss in sensitivity and responsivity. By applying this method,
the effect of radiation damage on the linearity and position error of the detectors
was calculated. The result also shows that prolonged UV radiation has a significant
negative impact on the linearity and as such, increases the position deviation of the
detectors. The conclusion from the study is that the $\eta p$ LPDS is more UV radiation
hard than the $p\eta$ LPDS. See paper 8 for details.

Finally, the results in this thesis are most relevant in spectroscopic and
microscopic applications where low energy electrons and medium UV (MUV)
radiation are used. The electron detector with the duo-lateral position sensing
characteristics will be an ideal detector in traditional low energy space plasma
analyser instruments. The detector does not require high voltage to effectively
operate and its small size well fits to the small dimensions of some popular highly
miniaturised analyser heads. By incorporating grids on the active area, an LPDS
can be applied in any miniature remote high vacuum environment without the
need for other external devices thereby saving cost and reducing precision errors. The characterisation techniques used in thesis have also been shown to be simple and effective alternative/s to other known methods.
Summary of Publications

This thesis is mainly based on the following papers and a summary of their contents is briefly highlighted below:

Paper I: High Resolution, Low Energy Electron Detectors
This paper shows the simulation results of the responsivity of a $p_n$ and an $n_p$ detector. It also shows the fabrication steps taken in fabricating and measuring an $n_p$ detector and the results were compared to those obtained by simulation.

Paper II: Surface State Effects on $n_p$ Doped Electron Detector
This article describes how the performance of an electron detector varies in terms of its responsivity when the doping profile is altered in relation to the surface states of the detector. It presents the results obtained from the simulation of detectors with different doping profiles as well as the fabrication and measurement of a fabricated $n_p$ detector fashioned after one of the simulated detectors.

The simulation and measurement results presented in this paper use scanning electron microscopy to reflect the significance of the effect of the minority carriers' transport velocity and fixed oxide charge on the responsivity of detectors with different donor impurities.

Paper IV: $n_p$ Photodetector Characterization Using the Quasi-steady State Photoconductance Decay Method
Contained in this paper is the use of photoconductance (transient decay) method to characterise a fabricated $n_p$ photodetector in order to determine its linearity (photoresponse).
Paper V: Simulation and Measurement of Short Infrared Pulses on Silicon Position Sensitive Device
This paper investigated the responsiveness (rise and fall times) of a position sensitive device in a mixed mode simulation of a two dimensional full sized detector. It also involved measurements by way of quantifying the homogeneity of the PSD device by repositioning a spot of light from a pulsed infra-red laser diode on the surface area.

Paper VI: Gridded Duo-lateral Position Sensitivity Detector with High Linearity to Low Energetic Electrons in Vacuum Environment
Multiple grids were lithographically patterned on duo-lateral PSD. By sweeping electrons along two axes of the detector, the position detection error of both axes was determined from the signals recorded using a transimpedance amplification circuit. The results show a high linearity over the x- and y-axis of the PSD and that accurate beam monitoring for spectroscopic measurement without additional beam position monitoring devices is possible.

Paper VII: Fabrication, Characterization and Simulation of Channel Stop for n in p-substrate Pixel Detectors
Investigate in this article is the use of field plates to suppress the fixed positive charges and to prevent the formation of an inversion layer. The fabricated detector shows a high breakdown voltage and low interpixel leakage current for a structure using biased field plates with a width of 20 μm.

Paper VIII: Comparative Study of UV Radiation Hardness of n-p and p-n Duo-lateral Position Sensitive Detectors
This paper reports experimental results on the degree of radiation damage on the responsivity, linearity and position error in two LPDs to 193 nm and 253 nm UV beam. Also reported is a novel mapping technique, used to show how radiation damage impact on the linearity active area of the device. 

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Authors Contributions:
The tables below show the various contribution of the author and the co-authors of the above listed papers

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Contributions

M = Main author; simulation, processing, experiments and results
C¹ = Co-author; simulation
C² = Co-author; ideas, simulation, processing,
C³ = Co-author; ideas, suggestions and supervision
C⁴ = Co-author; SEM measurement
C⁵ = Co-author; ideas
C⁶ = Co-author; ideas, processing.
References


[40] R. Ghandi, B. Buona, M. Domeij, R. Esteve, A. Schoner, J. Han, S. Dimitrijev, S. A. Reshanov, C.-M. Zetterling, and M. Ostling, “Surface-Passivation Effects on the


