Tanja Grönlund

DEVELOPMENT OF ADVANCED SILICON RADIATION DETECTORS FOR HARSH RADIATION ENVIRONMENT

Thesis for the degree of Doctor of Science (Technology) to be presented with due permission for public examination and criticism in the Auditorium 1382 at Lappeenranta University of Technology, Lappeenranta, Finland on the 9th of January, 2008, at noon.

Acta Universitatis
Lappeenrantaensis
297
Supervisor
Professor Tuure Tuuva
Department of Electrical Engineering
Lappeenranta University of Technology
Finland

Reviewers
Professor Pekka Kuivalainen
Electron Physics Laboratory
Helsinki University of Technology
Finland

PhD Risto Punkkinen
Department of Information Technology
University of Turku
Finland

Opponent
Professor Pekka Kuivalainen
Electron Physics Laboratory
Helsinki University of Technology
Finland
Abstract

Tanja Grönlund

Development of advanced silicon radiation detectors for harsh radiation environment

Lappeenranta 2007

80 p.

Acta Universitatis Lappeenrantaensis 297

Diss. Lappeenranta University of Technology


This thesis describes the development of advanced silicon radiation detectors and their characterization by simulations, used in the work for searching elementary particles in the European Organization for Nuclear Research, CERN. Silicon particle detectors will face extremely harsh radiation in the proposed upgrade of the Large Hadron Collider, the future high-energy physics experiment Super-LHC. The increase in the maximal fluence and the beam luminosity up to $10^{16}$ n$_{eq}$/cm$^2$ and $10^{35}$ cm$^{-2}$s$^{-1}$ will require detectors with a dramatic improvement in radiation hardness, when such a fluence will be far beyond the operational limits of the present silicon detectors. The main goals of detector development concentrate on minimizing the radiation degradation. This study contributes mainly to the device engineering technology for developing more radiation hard particle detectors with better characteristics. Also the defect engineering technology is discussed.

In the nearest region of the beam in Super-LHC, the only detector choice is 3D detectors, or alternatively replacing other types of detectors every two years. The interest in the 3D silicon detectors is continuously growing because of their many advantages as compared to conventional planar detectors: the devices can be fully depleted at low bias voltages, the speed of the charge collection is high, and the collection distances are about one order of magnitude less than those of planar technology strip and pixel detectors with electrodes limited to the detector surface. Also the 3D detectors exhibit high radiation tolerance, and thus the ability of the silicon detectors to operate after irradiation is increased.

Two parameters, full depletion voltage and electric field distribution, is discussed in more detail in this study. The full depletion of the detector is important because the only depleted area in the detector is active for the particle tracking. Similarly, the high electric field in the detector makes the detector volume sensitive, while low-field areas are non-sensitive to particles. This study shows the simulation results of full depletion voltage and the electric field distribution for the various types of 3D detectors. First, the 3D detector with the n-type substrate and partial-penetrating p-type electrodes are researched. A detector of this type has a low electric field on the pixel side and it suffers from type inversion. Next, the substrate is changed to p-type and the detectors having electrodes with one doping type and the dual doping type are examined. The electric field profile in a dual-column 3D Si detector is more uniform than that in the single-type column 3D detector. The dual-column detectors are the best in radiation hardness because of their low depletion voltages and short drift distances.

Keywords: high-energy physics, silicon radiation detector, 3D detector, TCAD simulation, characterization, electric field distribution

UDC 539.1.074 : 546.28 : 621.382 : 539.1.076
Acknowledgements

The research work for this thesis was carried out at Lappeenranta University of Technology in the Laboratory of Microelectronics during the years 2003–2007. I would like to express my gratitude to my supervisor, Professor Tuure Tuova who suggested this idea for a thesis and introduced an exciting world of the radiation detectors and high-energy physics. I thank the reviewers, Professor Pekka Kuivalainen and PhD Risto Punkkinnen for a number of important comments and corrections, which significantly helped me to improve the thesis.

A great number of researchers were involved in this work. I would like to thank Helsinki Institute of Physics group, Dr. Jaakko Härkönen, Dr. Eija Tuominen, Dr. Panja Luukka and M.Sc. Esa Tuovinen for collaboration during these years. Especially, I would like to express my appreciation to Dr. Zheng Li from Brookhaven National Laboratory in New York, where I worked as a visitor researcher for two months in the spring 2007. His precious advices and the great experience from the field helped me in an invaluable way to finish this project. Also I would like thank Dr. Li’s group members at BNL, Dr. Gabriella Carini and Dr. Wei Chen for helping me blend in the local life. I wish to thank Dr. Simo Eräinen from VTT Technical Research Center of Finland for providing the samples of n-type 3D detectors.

I express my thanks to the microelectronics group at LUT. Dr. Kari Leinonen taught me the measurement techniques of the detectors. He was also the one who introduced the scanning electrode microscopy method to measure the electric field distribution inside the detector. At this point, I would also like to thank M.Sc. Jyri Roihuvuo from North Karelia Polytechnic for providing the facilities of the SEM.

M.Sc. Miia Koski was the bubbliest colleague I have ever had. No wonder, we were called “the giggling assistants”. I would like to thank her for help at the beginning of this project. I warmly thank M.Sc. Arja Korpela for sharing the challenges that were brought to us as employees of the microelectronics laboratory.

There are plenty of people to thank who have supported my work somehow. I would like to thank M.Sc. Antti Puisto for maintaining the simulation software. Many thanks belong to Ph.D. Hanna Niemelä for carefully reviewing the language of this manuscript. Especially I am grateful to our department’s marvelous secretaries, Piipa Virki and Tarja Sipiäinen, for helping me out to solve many practical problems and making the traveling around the world such a joy.

The financial support by the Research Foundation of Lappeenranta University of Technology (Lappeenrannan teknillisen yliopiston tukisäätiö), the Foundation of Technology (Tekniikan edistämissäätiö), the Finnish Cultural Foundation (Suomen Kulttuurirahasto), Walter Ahlström Foundation and Magnus Ehrnrooth Foundation is greatly appreciated.

For my family, I want to express my deepest thanks; I also owe my thanks to my friends, who have been spurred me along the way. I warmly wish to thank my husband Joonas for his support during this process.

Lappeenranta, December 2007

Tanja Grönlund
List of Publications

**Publication I**  

**Publication II**  

**Publication III**  

**Publication IV**  

**Publication V**  

**Publication VI**  
Z. Li, T. Grönlund, 3D Simulation Studies of Irradiated BNL One-Sided Dual-column 3D Silicon Detector up to 1E16 n/cm², *will be submitted for publication: Nuclear Instruments and Methods in Physics Research* **A** (2008).

Author’s Contribution

The research has been carried out at Lappeenranta University of Technology within the Department of Electrical Engineering, the Laboratory of Microelectronics group and in the framework of CERN RD50 collaboration during the years 2003–2007. A part of the research work was performed at the Brookhaven National Laboratory in the USA in the spring 2007, where the author worked as a visitor researcher. The author has participated actively in the modeling and the electrical characterization of radiation silicon detectors presented in this thesis. The publications in this thesis are a result of group effort. The author is the main writer in Publications II, IV and V and has contributed to the publications I, III, VI. The results have also been presented at international conferences. In this dissertation, these publications are referred to as Publication I, Publication II, Publication III, Publication IV, Publication V and Publication VI.
Summary of Publications

Publication I presents the proposed new structure, a silicon semi 3D detector, developed by VTT Technical Research Center of Finland. In this case, only the vertical p-type doping pillars are employed for the n-type substrate. The vertical depth of the doping profiles is left as a variable. The paper describes the fabrication and the first results on the behavior of the semi 3D silicon radiation detector structure. The semi 3D detectors are processed on both Float Zone (FZ) and Czochralski (Cz) material. The measured electrical characteristics include leakage current and capacitance-voltage measurement. These were measured by a CV-IV measurement setup. The results show that the semi 3D pixel structures have low leakage currents and low pixel capacitances. On the FZ silicon, the leakage current is smaller than on the Cz silicon and the breakdown occurs at higher voltages.

Publication II continues the work done for Publication I. In this paper, the simulation method and measurements using a scanning electron microscope are added to the study of the silicon semi 3D radiation detector structure in order to investigate the potential distribution inside the detector. There is a correspondence between the simulation results and SEM measurements, in other words, they show the same phenomenon: the semi 3D detector structure is fully depleted at low voltages, and with the high bias, the electric field is mainly formed between the end of the pillars and the backside.

In Publication III, the voltage measurement system with a scanning electron microscope was applied to 10 MeV proton irradiated Float Zone silicon radiation pad detectors. The results were compared with those acquired with other methods. The same semiconductor type inversion of n-bulk and a double-junction behavior were observed in this study with a better accuracy.

Publication IV describes the proposed p’/n/n’ pad detector structure with n’ guard ring placed at the edge of the detector. In this structure, the guard ring has the same doping type as the substrate and the n’ electrode at the bottom of the structure. Now, a full depletion region (active region) can be extended also sideways, when it is normally formed vertically from anode to cathode. This guard ring technique has evolved to minimize the dead space at the edge of the detectors and thereby to enhance the efficiency of the detector.

In Publication V, the simulation results of two single-sided 3D detector designs, one with single-type (n-type) columns and the other with dual-type columns (n- and p-type) on the p-type substrates are presented. The detectors are developed by Brookhaven National Laboratory (BNL). The full 3D simulations of different detector types show that it is possible to achieve similar electric field profile between a BNL dual-column 3D detector and other dual-column 3D detectors developed by other institutes with the benefit of the true one-sided process. In the case of the BNL single-type column detector, the simulations show that the high electric field is on the pixel side, which is the sensing area. Also the 3D simulations of weighting field profiles for different 3D detector structures were reported in this publication.

Publication VI presents the results of the 3D simulations that have been performed to study the effect of the irradiation on the dual-column 3D Si detectors. BNL dual-column 3D detectors have been simulated in detail with a variety of fluences. First, the full depletion voltage and then the electric field for a dual-column 3D detector are studied by simulations under the irradiations. Also it has been suggested that for future development, to achieve full depletion in a dual-column 3D detector at 1E16 n_{eq}/cm^2 with a reasonable bias (≤ 200 V), the column spacing should be reduced.
Contents

Abstract
Acknowledgements
List of Publications
Author’s Contribution
Summary of Publications
Contents
Symbols and Abbreviations

1 Introduction .................................................................................................................... 13
  1.1 Scientific aspects of the semiconductor radiation-hard detectors .................................... 13
  1.2 CERN RD50 collaboration ............................................................................................. 19

2 Radiation silicon detector properties ........................................................................... 21
  2.1 PN junction ..................................................................................................................... 21
  2.2 Thermal equilibrium ...................................................................................................... 22
  2.3 Full depletion ................................................................................................................ 24
  2.4 Effective doping concentration $N_{eff}$ ...................................................................... 25
  2.5 Radiation ...................................................................................................................... 29
  2.6 Operation of a silicon radiation detector ..................................................................... 31
  2.7 Advantages of radiation silicon detectors .................................................................... 33

3 Characterization of advanced radiation detectors by simulations .............................. 34
  3.1 Simulation program ...................................................................................................... 34
  3.2 Silicon 3D radiation detector ...................................................................................... 36
  3.3 The operation of standard 3D detectors .................................................................... 37
  3.4 Semi 3D detector structure on the n-type material ...................................................... 37
  3.5 3D detectors for p-type material ................................................................................. 42
  3.6 Irradiated 3D detectors ............................................................................................... 53
  3.7 Comparison of n- and p-type 3D detectors ................................................................ 56
  3.8 Active edge of the detector ......................................................................................... 56

4 Discussion .................................................................................................................... 59

5 Conclusions .................................................................................................................. 62

Appendix A ....................................................................................................................... 64
Appendix B ........................................................................................................................ 71

References ........................................................................................................................ 76

Appended publications I-VI
Symbols and Abbreviations

b  bottom quark
b  acceptor introduction rate
c  charm quark
c  donor removal coefficient
$D_n$ diffusion coefficient for electrons
$D_p$ diffusion coefficient for holes
d  down quark
d  thickness
d_t  trapping distance
$E, E$ electric field
$E(x)$ electric field distribution
$E_0$ weighting field
$E_C$ conduction band
$E_a$ activation energy on conduction band
$E_F$ Fermi level
$E^*_{F0}$ Fermi level on n-side
$E^*_{F0}$ Fermi level on p-side
$E_i$ intrinsic level
$E_m$ maximum electric field
$E_V$ valence band
$E_v$ activation energy on valence band
e  electron
e^+  positron
g  average introduction rate
$G_n$ electron generation rate
$G_p$ hole generation rate
$G_{th}$ thermal equilibrium generation rate
h  hole
$I_{leak}$ leakage current
i  current
$J_n$ electron current density
$J_p$ hole current density
k  Boltzmann constant, $1.38 \cdot 10^{-23}$ J / K
$kT$ thermal energy
$L_p$ column spacing
$N_A$ acceptor impurity density or short-term annealing component
$N_B$ acceptor or donor impurity density
$N_C$ stable damage part
$N_D$ donor impurity density
$N_{D,0}$ donor concentration before irradiation
$N_{eff}$ effective carrier / doping concentration
$N_Y$ reverse annealing component
n  neutron
n  n-type semiconductor material
n  electron concentration
$n_0$ equilibrium electron concentration
$n_i$ intrinsic carrier density, $1.45 \cdot 10^{10}$ cm$^{-3}$ (Si, 300K)
$n^*$ heavily doped n-type material
$n^-$ low-doped n-type material
$P$ pitch width
$p$ proton
$p$ p-type semiconductor material
$p$ hole concentration
$p_0$ equilibrium hole concentration
$p^*$ heavily doped p-type material
$q$ elementary charge, $1.6021 \times 10^{-19}$ As
$R$ recombination rate
$R_n$ electron recombination rate
$R_p$ hole recombination rate
$R_{th}$ thermal equilibrium recombination rate
$s$ strange quark
$T$ temperature
$t$ top quark
$t$ time
$t$ electrode length
$U$ excess recombination rate
$U_{dep}$ depletion voltage
$V$ potential, external voltage
$V_{bi}$ built-in potential
$V_{dep}$ depletion voltage
$V_{fd}$ full depletion voltage
$V_{SEI}$ voltage applied to a secondary electron detector of SEM
$v$ up quark
$v_d$ drift velocity
$W$ diode thickness
$W_N$ device depth
$W$ boson
$x$ x-direction
$x_d$ depletion region length
$x_n$ depletion region length on n-side
$x_p$ depletion region length on p-side
$Z$ boson

**Greek letters**

$\beta$ recombination factor
$\varepsilon_0$ permittivity of vacuum, $8.854 \times 10^{-12}$ F/m
$\varepsilon_{Si}$ permittivity of silicon, $11.7 \times \varepsilon_0$
$\mu$ muon
$\mu_n$ electron mobility
$\mu_p$ hole mobility
$\nu_e$ electron-neutrino
$\nu_\mu$ muon-neutrino
$\nu_\tau$ tau-neutrino
$\pi^+$ pion
$\rho$ charge density
$\tau$ tau (lepton)
$\tau$ lifetime
$\tau_g$ generation lifetime
$\tau_r$ recombination lifetime
\( \tau_{n} \)  recombination lifetime for n-type semiconductor
\( \tau_{p} \)  recombination lifetime for p-type semiconductor
\( \tau_{\text{trap}} \)  trapping time
\( \Phi_{\text{eq}}, \phi_{\text{eq}} \)  radiation fluence

**Acronyms**

AC  Alternating current
ADC  Analog to digital converter
ALICE  A Large Ion Collider Experiment
ATLAS  A Toroidal Lhc ApparatuS
BNL  Brookhaven National Laboratory
CCE  Charge collection efficiency
CERN  Centre Européen pour la Recherche Nucléaire
CMS  Compact Muon Solenoid
ClOi  Donor defect complex
CV  Capacitance (C) vs. Voltage (V)
Cz  Czochralski silicon
DA  Deep acceptor
DC  Direct current
DD  Deep donor
DOFZ  Diffusion Oxygenated Float Zone
DP  Double peak
FZ  Float Zone
IV  Current (I) vs. Voltage (V)
LCR  Inductance, capacitance, resistance
LEP  Large Electron Positron Collider
LHC  Large Hadron Collider
LHCb  B mesons experiment in LHC
LUT  Lappeenranta University of Technology
MCz  Magnetic Czochralski silicon
MIP  Minimum ionizing particle
OBIC  Optical beam induced current
PC  Personal computer
RD  Research and development
RF  Radio-frequency
SCSI  Space charge sign inversion
SEI  Secondary electron image
SEM  Scanning electron microscope
SLHC  Super Large Hadron Collider
SMU  Source measure unit
SPS  Super Proton Synchotron
STC  Single type of column
TCAD  Technology Computer Aided Design
TCT  Transient current technique
TOTEM  TOTal cross-section and Elastic scattering Measurement experiment
V2  Di-vacancy defect
V3  Tri-vacancy complex defect
VO  Vacancy-oxygen
VTT  Technical Research Center of Finland
Chapter 1

Introduction

Silicon detectors have been chosen as central tracking detectors for the next generation of high-energy physics experiments such as the Large Hadron Collider (LHC) at CERN\(^1\). For this purpose, silicon detectors, both pixel and strip, are the most precise electronic tracking detectors for charged particles. In high-energy physics experimental stations at the LHC, the silicon detectors are located as close as a couple of centimeters from the beam line, meaning operation in a very harsh radiation environment.

In the proposed upgrade of the LHC (Super-LHC, SLHC), the increase in the maximal fluence and the beam luminosity up to \(10^{16}\) n\(_{eq}\)/cm\(^2\) and \(10^{35}\) cm\(^2\)s\(^{-1}\) will require detectors with a dramatic improvement in radiation hardness. Therefore, the main goals of detector development for the SLHC concentrate on the technologies that minimize the radiation degradation. Several technologies have been extensively studied by CERN RD\(^2\) collaborations during the last ten years:

- defect and material engineering (RD48, RD50)
- device engineering (RD50)
- operational mode engineering (RD39)
- applications of materials other than silicon (Si), such as diamond (RD42)

This work contributes to the first and the second topic. The goal of this work is to research and develop new detector structures such as 3D detectors and study the radiation damage effects inside the detector. The main emphasis is on the simulation methods, which can be used to simulate the processing and the electrical characteristics of the device. This work is part of the CERN RD50 research activity.

This dissertation is composed of the summarizing part and the appended original publications. The content of the summarizing part is organized in five chapters. In the following chapter, an overview of radiation silicon detector properties will be given. The basic radiation damage mechanisms and the radiation-induced defects in silicon bulk are reviewed. Chapter 3 describes the simulation methods of detectors and shows the results of characterization of various detector structures. Chapter 4 presents the discussion on the raised matters while completing this study. Finally, conclusions with suggestions for future research are given in Chapter 5.

1.1 Scientific aspects of the semiconductor radiation-hard detectors

In general, there are numerous fields of industry where radiation-hard detectors are used. Radiation-hard detectors are needed for example in medical, telecommunication, security and high-energy physics applications. This thesis concentrates on one detector type, semiconductor detectors. The main objective is the research of semiconductor detectors processed on the silicon (Si) and their use in a harsh radiation environment. The silicon detectors are particularly suitable for the detection of ionizing radiation such as protons, neutrons, pions and heavy ions.

In 1949, Louis de Broglie proposed setting up The European Organization for Nuclear Research (CERN). It was founded in 1954 in Geneva, Switzerland to research the basic structure of matter, particles. We know today that all matter in the Universe is built from nearly a hundred different types

\(^1\) CERN - The European Organization for Nuclear Research, Geneva, Switzerland
\(^2\) Research and Development
of atoms, each one made up of electrons with negative electric charge circulating a positively charged nucleus. The nucleus itself further consists of nucleons: positive protons and neutral neutrons. The electron seems to have no internal structure. Protons and neutrons are composite particles, each containing three quarks. Similarly as the electron, the quarks appear to have no structure. Only two types of quark, called "up" and "down", are needed to build the proton and neutron (Fig. 1.1).

The generic names for particles in Figure 1.1 are often defined as follows (Coughlan 2006)

- **nucleons**: neutrons and protons
- **hadrons**: all particles affected by the strong nuclear force
- **baryons**: hadrons, which are fermions (half-integral spin particles) such as the nucleons
- **mesons**: hadrons, which are bosons (integral spin particles) such as the pion
- **leptons**: all particles not affected by the strong nuclear force, such as the electron and the muon.

In fact, there are less "ordinary" forms of matter that exist which we cannot see: cosmic matter coming from the space, high-energy collision matter and the "mirror image" of all of it, antimatter. To include them in the picture, we need a more general description and more particles. Based on the theories and discoveries in the physics research, the Standard Model of Particles and Forces has been created. The achievement is comparable to the unification of the electric and the magnetic forces into a single electromagnetic theory by J.C. Maxwell in the 19th century (CERN website – Particle Physics Today: The Standard Model).

Next, the theory behind the Standard Model of Particle Physics is described in brief. For further information, the reader is referred to textbooks (Coughlan 2006, Cottingham 2001). The Standard Model requires 12 matter particles and 4 force carrier particles to summarize all that we currently know about the most fundamental constituents of matter and their interactions. Figure 1.1 shows two matter particle "families" – the quarks and the leptons – both point-like and without internal structure. There are six quarks, which are usually grouped in three pairs based on their mass and charge properties: up/down (v and d), charm/strange (c and s), and top/bottom (t and b).
Further, there are six leptons, three with a charge and a mass – electron (e), muon (μ) and tau (τ) – and three neutral and with very little mass – electron-neutrino (νe), muon-neutrino (νμ) and tau-neutrino (ντ). Again, as their name openly implies, they are grouped to form three pairs (because of some distinctive behavior during the creation or decay processes). The (e/νe) and (up/down) have the lightest mass and are all that is needed to build up the stable matter and what is called the first generation of matter. However, high-energy processes produce a large variety of short-lived particles, which require the existence of "heavier" pairs, or heavier "generations" of matter. We have then (μ/νμ) and (charm/strange), which make up the second generation, while (τ/ντ) and (top/bottom) constitute the third generation. All second- and third-generation particles are unstable and quickly decay into stable first-generation particles; the second- and third-generation quarks can only be observed in high-energy physics experiments.

The standard model includes three types of forces acting among particles: strong, weak and electromagnetic. Gravity is not yet part of the framework. Forces are communicated between particles by the exchange of special "force-carrying particles" called bosons, which carry discrete amounts of energy from one particle to another. Each force has its own characteristic bosons: the gluon (strong force), the photon (electromagnetic force), the W and Z bosons (weak force).

Particles have a wide range of masses. Photons and gluons are completely massless, while the W and Z particles each weigh as much as 80 to 90 protons or as much as a reasonably sized nucleus. The most massive fundamental particle found so far, the top quark, is twice as heavy as the W and Z particles, and weighs about as much as a nucleus of gold. Why there is such a range of masses is one of the remaining questions of particle physics. Indeed, how particles get a mass at all is not yet properly understood (CERN website – Particle Physics Today: The Standard Model).

In the Standard Model, particles gain a mass through the Higgs mechanism (named after theorist Peter Higgs). According to this theory, both matter particles and force carriers interact with a new particle, the Higgs boson. It is the strength of this interaction that gives rise to what we call mass: the stronger the interaction, the greater the mass. Experiments have yet to show whether this theory is correct. The search for the Higgs boson has already begun at the LEP collider at CERN, and this work will continue with CERN's next machine, the Large Hadron Collider. In the LHC, very high-energy protons will collide against protons, and heavy ions such as the nuclei of lead will be smashed against heavy ions. The LHC experiment is used to find a proof of the existence of the Higgs boson (Fig. 1.2).
The LHC is a particle accelerator, which will collide beams of protons at an energy of 14 TeV. In the accelerator, the beam travels inside a chamber, which is a metal pipe, where air is permanently pumped out to make sure that the residual pressure is as low as possible. Inside the pipe, particles are accelerated by electric fields. Powerful amplifiers provide intense radio waves that are fed into resonating structures, the radio-frequency (RF) cavities. Each time the particles traverse an RF cavity, some of the energy of the radio wave is transferred to them and the particles are accelerated. To make a more effective use of the limited number of RF cavities, the particle beam can be forced to go through them many times, by curving its trajectory into a closed loop (CERN website – How does an accelerator work?).

Curving the beam's path is usually achieved by the magnetic field of dipole magnets. This is because the magnetic force exerted on charged particles is always perpendicular to their velocity. The higher the energy of a particle, the stronger is the field that is needed to bend it. In addition to just curving the beam, it is also necessary to focus it. Focusing the beam allows its width and height to be constrained so that it stays inside the vacuum chamber. This is achieved by quadrupole magnets, which act on the beam of charged particles. The maximum magnetic field is limited to some 2 Tesla for conventional magnets and some 10 Tesla for superconducting ones. This explains why the machines used in this kind of research are so large. The more powerful a machine is, the larger it needs to be. The whole accelerator system requires also several more objects such as: other magnets to perform "fine tuning" of the trajectory or the focusing, injection/ejection elements to put the beam into the accelerator or to take it out, measurement devices to give the operators information on the behavior of the beam, and of course, the safety elements (CERN website – How does an accelerator work?).

Figure 1.2: a) CERN accelerator complex. The LHC ring is 27 km long (CERN website). b) The map of the accelerator area (CERN – Web Communications Copyright used with permission). c) In the photo of the CERN site, the LHC and SPS rings are presented as visible structures, but actually the accelerator is placed under the ground (CERN website).
The basic layout of the LHC follows the LEP tunnel geometry and is depicted in Fig.1.3 a. The LHC has eight arcs and straight sections. Each straight section is approximately 528 m long and can serve as an experimental or utility insertion. The two high-luminosity experimental insertions are located at diametrically opposite straight sections: the ATLAS experiment is located at octant 1 and the CMS experiment at octant 5. Two more experimental insertions are located at octant 2 and octant 8, which also contain the injection systems for Beam 1 and Beam 2, respectively. The injection kick occurs in the vertical plane with the two beams arriving at the LHC from below the LHC reference plane. The beams only cross from one magnet bore to the other at these four locations. The remaining four straight sections do not have beam crossings. Insertions 3 and 7 each contain two collimation systems. Insertion 4 contains two RF systems: one independent system for each LHC beam. The straight section at octant 6 contains the beam dump insertion, where the two beams are vertically extracted from the machine using a combination of horizontally deflecting fast-pulsed “kicker” magnets and vertically-deflecting double steel septum magnets. Each beam features an independent abort system (LHC Design Report).

Figure 1.3: a) Schematic layout of the LHC. Beam 1 circulates clockwise and Beam 2 counter-clockwise (LHC Design Report). b) LHC hall (http://atlas.ch/atlas_photos/lhc/lhc.html).

Five experiments have been approved for the LHC accelerator: ATLAS, CMS, ALICE, LHCb and TOTEM. These experiments, TOTEM excluded, are actually massive detectors used to track the particles formed after collision. ATLAS (A Toroidal Lhc ApparatuS) and CMS (Compact Muon Solenoid) are general-purpose detectors at the LHC. They are used to record proton-proton collisions. ALICE (A Large Ion Collider Experiment) will also study proton-proton collisions, but it is mainly looking for the formation of a new phase of matter, the quark-gluon plasma, which is expected to happen with strongly interacting matter at extreme energy densities. The LHCb experiment is a specialized detector only for studying B mesons. TOTEM (TOTal and Elastic Measurement) experiment is positioned to the same place with CMS. Its purpose is actually to study the quality of the beam. TOTEM will measure the total proton-proton cross-section and study elastic scattering and diffractive dissociation at the LHC.
If we look, for example, the CMS experiment in more detail, we can see that the detector actually consists of many different pieces of equipment and detector types, each one able to recognize and measure a special set of particle properties such as charge, mass and energy.

Figure 1.4: a) CMS experiment and b) particle interactions in detectors (CERN website).

Figure 1.4 shows that the CMS detector is divided into the silicon tracker, electromagnetic and hadron calorimeters, and muon chambers. The reason why detectors are divided into so many components is that each component tests for a special set of particle properties. These components are stacked so that all particles will go through the different layers sequentially. The tracking chambers make the path of the particle visible. It is not possible to see the particle itself, but the track of the particle can give a lot of useful information. A particle will not be evident until it either interacts with the detector in a measurable fashion, or decays into detectable particles.

Figure 1.5: Interaction of various particles with the different components of a detector (http://atlas.ch/etours_exper/etours_exper07.html).

Charged particles, such as electrons (e\(^-\)), positrons (e\(^+\)), protons (p) and charged mesons (pions \(\pi^\pm\)) are detected both in the tracking chamber and the electromagnetic calorimeter, protons and pions also in the hadron calorimeter. Neutral particles, such as neutrons (n) and photons, are not detectable in the tracking chamber; they are only evident when they interact with the detector. Photons are detected by the electromagnetic calorimeter, while neutrons are evidenced by the energy they deposit in the hadron calorimeter. If a particle is only detected in the electromagnetic calorimeter, then it is fairly certainly a photon. Muons and neutrinos are often the only particles capable of escaping the calorimeter. Muons can hardly be stopped, but they leave a track and can be identified. Muon chambers are located outside
the calorimeter, and only muons can emerge and leave a track there. Neutrinos are not shown in Figure 1.5 because they rarely interact with matter, and can only be detected by missing matter and energy.

Silicon detectors are the major type of particle detectors in inner tracks of high-energy physics experiments. The objective of these semiconductor detectors is to make the particle track visible for other detector components. Silicon detectors can be used either in the pixel or the strip tracker. The sensors closest to the collision point are the pixel trackers. These devices consist of thin layers of silicon subdivided into tiny rectangular regions, pixels. Each time a charged particle traverses such a layer, a signal is produced that identifies which pixel has been traversed, and thereby gives a precise measure of the particle position. Indeed, this position is precise enough to determine whether the particle originated at the proton-proton collision point, or a few millimeters from it as a decay product of another particle. To provide additional position measurements somewhat further from the collision point, in the silicon strip tracker, layers of silicon subdivided into narrow strips are used to provide accurate information of the particle position. When a charged particle passes through the strip detector, signals identify which strip has been traversed. These strips provide precise 3-dimensional position measurement of particle trajectories. Strip detectors are used because the pixel detectors are too expensive for larger areas.

1.2 CERN RD50 collaboration

The CERN Research & Development RD50 collaboration “Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders” has started in 2002 an R&D program for the development of detector technologies that will fulfill the requirements of the future high-energy physics colliders such as the possible upgrade of the LHC at CERN towards the Super-LHC. CERN RD50 collaboration offers an excellent forum to work with international partners. It consists of 51 institutes and 262 scientists (June 2007). Its objective is to support the activity in basic silicon research and to develop feasible detector solutions for the future high-energy physics experiments, where the irradiation field will be an order of magnitude higher than in the actual experiments. RD50 is a relatively large consortium, and therefore, it is organizationally divided into six research lines; the participating institutes concentrate on the research topics that best correspond to their expertise.

The main research objective of the RD50 collaboration is to develop radiation hard semiconductor detectors that can operate beyond the limits of present devices (R&D Prop. 2002). These devices should withstand fast hadron fluences as expected for example for a luminosity upgrade of the LHC. For the Super-LHC experiments, the luminosity is upgraded to $10^{35}$ cm$^{-2}$s$^{-1}$ and the innermost tracking detectors have to face fluencies above $10^{16}$ cm$^{-2}$ of fast hadrons after five years operation accumulating an integrated luminosity of 2500 fb$^{-1}$ (Fretwurst 2005). This is a ten times higher radiation level than expected for the tracking detectors of the LHC experiments. Under these conditions, detector performance may be limited by a large number of defects introduced into the device.

A luminosity upgrade is intended to improve the accuracy of the Standard Model and the new parameters, which are predicted to be discovered at the initial phase of the LHC experiments. Super-LHC experiment is predicted to run in 2017. Comparing the LHC environment to the assumed Super-LHC conditions, the intensity of the spectra increases one order of magnitude corresponding to the order of magnitude increase of luminosity. The beam energy is increased with a factor of two, and the average energy of the spectra is shifted to higher energy with 50 MeV (RD50 2004).

The presently available silicon detector technology cannot match the extreme requirements with respect to the necessary radiation tolerance. Several different research fields are under development and investigation to overcome problems of detectors caused by a super harsh radiation environment. Semiconductor sensors can be further developed for this purpose either by developing a more
radiation-tolerant detector material such as high-resistivity Czochralski (Cz) silicon both n- and p-type (material engineering) or investigating new device concepts such as 3D and edgeless detectors (device engineering). These advancements among others can set scene for radiation-tolerant cost-effective devices. Developing the suitable device for detecting the particles requires very cost-effective technologies and the optimum material, device structure and operational conditions for detectors.

At the fluencies up to \(10^{15}\ \text{cm}^{-2}\) (outer layers of a Super-LHC detector), the change of the depletion voltage and the large area to be covered by the detectors are the major problems. At the fluencies of \(10^{16}\ \text{cm}^{-2}\) (the innermost layer of a Super-LHC detector), the active thickness of any silicon material is significantly reduced because of trapping.

Table 1.1: Detector requirements for regions close to the beam in Super-LHC (Li 2007).

<table>
<thead>
<tr>
<th>Region (cm)</th>
<th>25-50</th>
<th>15-25</th>
<th>7-15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiation level ((n_{eq}/\text{cm}^2))</td>
<td>(10^{14}-10^{15})</td>
<td>(~10^{15})</td>
<td>(~10^{16})</td>
</tr>
<tr>
<td>Occupancy requirement</td>
<td>(80\ \mu\text{m} \times 2-3\ \text{cm})</td>
<td>(50\ \mu\text{m} \times 400\ \mu\text{m})</td>
<td>(50\ \mu\text{m} \times 300\ \mu\text{m})</td>
</tr>
<tr>
<td>Detector type</td>
<td>Strip</td>
<td>Pixel</td>
<td>Pixel</td>
</tr>
<tr>
<td>Radiation hardness requirement</td>
<td>Strip</td>
<td>Pixel</td>
<td>3D pixel or replacing every 2 years</td>
</tr>
<tr>
<td>Overall detector type</td>
<td>Strip</td>
<td>Pixel</td>
<td>3D pixel or replacing every 2 years</td>
</tr>
</tbody>
</table>

Table 1.1 lists the requirements for silicon detectors to be used in various regions in Super-LHC at or near room temperature. Due to the combined requirement of occupancy and radiation hardness, the only options for the most inner region (7–15 cm) seem to be the 3D pixel detectors or replacing the detectors every two years. For the outer regions, however, more detector choices can be made.
Chapter 2

Radiation silicon detector properties

In silicon detectors, the basic structure to make a particle track visible is based on a pn diode junction working under reverse bias. Next, the basic operation of the radiation silicon detector is described.

2.1 PN junction

In order to explain the operation of a pn diode junction, one may first imagine the opposite sides of the junction originally isolated (Fig. 2.1a). Then, these extrinsic semiconductors of an opposite doping type are brought together and a pn junction is formed. Actually, a single crystal of the semiconductor is doped with acceptors on one side and with donors on the other side. The structure is originally electrically neutral, that is, the number of holes is the same as the number of acceptor ions, and the number of free electrons is the same as the number of donor ions. Once the regions are brought into contact, the electrons originating from the donor atoms will diffuse into the p region and the holes from the acceptor atoms into the n region. An electron and a hole that meet at the junction will recombine, and thus they both will disappear. This will lead the acceptors and the donors in the neighborhood of the junction to lose their mobile electrons and holes. Since this region is depleted from mobile charges, it is called the depletion region (Fig. 2.1b).

![Figure 2.1: Schematic representation of a pn junction in thermal equilibrium a) with its parts separated and b) with its parts brought together. The negative acceptor ions are indicated by minus signs and the positive donor ions by plus signs. The free electrons are indicated by small filled circles and the holes by small unfilled circles. Fermi level $E_F$ in the p-type region is shifted towards the valence band $E_v$ and in the n-type region towards the conduction band $E_c$. When the regions are brought into contact, diffusion of electrons and holes results a static negative and positive electric charge in the p and n regions respectively. The conduction band energy and the valence band energy are continuous, and in thermal equilibrium the Fermi level is the same throughout the whole pn junction.](image-url)
Considering this kind of an abrupt junction in thermal equilibrium conditions, where there is no applied voltage or current flow, a charge distribution is formed over the depletion region because of the uncovered fixed donor and acceptor ions. The depletion region is hence also called the space charge region. The thickness of the depletion region depends on the doping of the two sides of the junction. If both sides are heavily doped, then only a very thin depletion region needs to be uncovered to produce the necessary charges. If both sides are lightly doped, a significant depletion region needs to be uncovered to support the built-in potential. If one side of the junction is more lightly doped than the other one, the depletion region will extend further into the lightly doped side.

2.2 Thermal equilibrium

The electrically unneutralized ions in the neighborhood of the junction result in a space charge density \( \rho \) (Fig. 2.2a). The charge density is expressed by acceptor and donor concentrations. In thermal equilibrium, the total negative charge per unit area in the p-side must be equal to the total positive charge per unit area in the n-side

\[
N_A x_p = N_D x_n
\]

(2.1)

where \( N_A \) and \( N_D \) are the acceptor and donor impurity densities and \( x_p \) and \( x_n \) are the depletion region length on the p-side and n-side of the junction.

Because the n-side of the depletion region is positive and the p-side negative, there is an electric field across the depletion region (Fig. 2.2b). The electric field \( E \) is determined by the charge distribution through Poisson’s equation

\[
\frac{\partial^2 V}{\partial x^2} = \frac{\partial E}{\partial x} = \frac{\rho}{\varepsilon_s \varepsilon_0}
\]

(2.2)

where \( V \) is the potential, \( E \) is the electric field, \( x \) is the x-direction, \( \rho \) is the charge density, \( \varepsilon_s \) is the dielectric constant of silicon (11.7) and \( \varepsilon_0 \) is the permittivity of vacuum (8.85*10\(^{-14}\) F/cm).

Because of the electric field, a potential difference or a voltage is developed across the depletion region without any external voltage connected to the structure (Fig. 2.2c). This voltage across the depletion region is known as the built-in potential \( V_{bi} \). It can be calculated from

\[
V_{bi} = \frac{kT}{q} \ln \left( \frac{N_A N_D}{n_i^2} \right)
\]

(2.3)

where \( N_A \) and \( N_D \) are the acceptor and donor impurity densities, \( n_i \) the intrinsic carrier density (for silicon \( n_i = 1.45*10^{10} \) cm\(^{-3}\) at 300 K), \( k \) is the Boltzmann constant (1.38*10\(^{-23}\) J/K), \( T \) is the temperature (together, \( kT \) is the thermal energy [eV]) and \( q \) is the charge (1.60*10\(^{-19}\) C).
The length in the x-direction of the depletion region can be calculated using Poisson’s equation together with the value of the built-in potential. The built-in potential makes the pn junction reverse biased, which means that the depletion region exists. The total depletion region width is calculated from

$$x_d = x_p + x_n = \sqrt{\frac{2\varepsilon_0 \varepsilon_r}{q} \left( \frac{N_A + N_D}{N_A N_D} \right) V_B}$$ \hspace{1cm} (2.4)$$

and the depletion region widths on the p- and n-sides are calculated from the total depletion region width

$$x_p = \frac{N_D}{N_A + N_D} x_d$$ \hspace{1cm} (2.5)$$

$$x_n = \frac{N_A}{N_A + N_D} x_d.$$ \hspace{1cm} (2.6)$$
2.3 Full depletion

The proper operation of silicon detectors is strongly limited by the requirement for the detectors to be fully depleted. The full depletion of the detector is necessary for a maximum detector signal and detector resolution. Only that part of the detector is active, which is fully depleted. In particle detector applications, an external reverse bias is added to this built-in potential causing the depletion region to become longer. Now, the total depletion region width is

\[
x_d = \sqrt{\frac{2\varepsilon_0 \varepsilon_r}{q} \left( \frac{N_A + N_D}{N_A N_D} \right) V_b - V}
\]

(2.7)

where \(V\) is the external voltage applied. Equation 2.7 is for a two-sided abrupt junction; for a one-sided abrupt junction, the equation reduces to

\[
x_d = \sqrt{\frac{2\varepsilon_0 \varepsilon_r}{qN_B} (V_b - V)}
\]

(2.8)

where \(N_B = N_D\) or \(N_A\) depending on whether \(N_A >> N_D\) or vice versa.

It is easier to achieve full depletion for the non-irradiated detectors processed on high-resistivity silicon than it is for irradiated detectors. This is because the full depletion bias voltage changes with the irradiation fluence due to a change in the effective doping concentration \(N_{eff}\). For a planar detector, the depletion voltage \(V_{fd}\) needed to fully deplete the detector varies with the doping concentration and the substrate thickness by (Sze 1981)

\[
V_{fd} = \frac{N_{eff} d^2 q}{2\varepsilon_0 \varepsilon_r} V_b.
\]

(2.9)

The built-in voltage \(V_{bi}\) is often neglected since in most cases the depletion voltage is more than one order of magnitude higher. In Equation 2.9, \(d\) is the diode thickness.

For example, a diode made of the n-type material \((N_D = 10^{13} \text{ cm}^{-3})\), which has the p-contact on the upper surface of the detector, is fully depleted by applying a high enough negative potential to the p-contact (Fig. 2.3). The n-type back contact is connected to the ground (0 V potential).
Figure 2.3: Spreading of the depletion region due to an external reverse bias. In the first quarter, the -1 V is applied; next, -5 V, -10 V and finally -25 V are applied. The last quarter shows that the structure is basically fully depleted. The electron concentration is presented in logarithm scale in legends. The source code of this simulation run is found in Appendix A.6.

In the simulations, the depleted area in the n-type bulk can be seen from the electron concentration, and in the p-type bulk from the hole concentration. The original doping concentration ($10^{13}$ cm$^{-3}$) is indicated in Figure 2.3 with yellow color. The electron concentration values under the original concentration value are depleted (blue). The calculated full depletion voltage from Equation 2.9 for these impurities and for a 50 µm distance was -19 V. The simulated value (Fig. 2.3, the last quarter) is -25 V.

### 2.4 Effective doping concentration $N_{\text{eff}}$

As shown above in Equation 2.9, the depletion voltage is proportional to the absolute value of the effective doping concentration $N_{\text{eff}}$. An increase in the doping concentration leads to higher negative voltage values needed to deplete the valid distance. Because the reach of the full depletion is very crucial parameter in radiation detector applications, to ensure that the whole volume of the detector is active, the silicon is originally lightly doped (high resistivity). The detector material should have a high resistivity to facilitate the depletion of a deep volume with a reasonable voltage, and also because a shallow pn junction then has a higher breakdown voltage.

However, the irradiation causes an increase in the effective doping concentration. The change in the effective doping concentration is caused by the defects generated by radiation in the substrate. The depletion voltage as a function of absorbed fluence of silicon detectors is shown in Fig. 2.4.
Type inversion. The effective doping concentration \( N_{\text{eff}} \) undergoes further changes at the end of the irradiation, because the defects in the bulk can also migrate and combine among themselves. The effect of negative fraction of \( N_{\text{eff}} \) that increases with the fluence is related to two factors: the first mechanism is the shallow donor removal and the second is the increase in deep acceptor generation (Eremin 2002a). The first period, which the devices experience and where \( N_{\text{eff}} \) is reduced, is called annealing. For the starting n-type material at lower fluences, the \( N_{\text{eff}} \) is reduced by a donor removal. Also acceptor-like states are generated leading finally to the inversion of the sign of the space charge from positive to negative. This leads to the inversion of the type of the material. In irradiation, by increasing the particle fluence, the initially positive substrate doping concentration decreases up to the type inversion of the semiconductor bulk and becomes negative. The negative \( N_{\text{eff}} \) means that the high-resistivity n-type bulk material inverts to p-type. For standard planar detectors with p-type electrodes on the n-type substrate, after high irradiation, the region with a high electric field moves towards the backplane of the detector, to the ohmic n’ contact, and the device, which was originally p’-n -n’ will turn to a p’-p -n’ structure. After the type inversion, a further increase of \( N_{\text{eff}} \) is called reverse annealing, and it can cause a very high bias needed to fully deplete highly irradiated silicon detectors.

Publication III shows the capacitance-voltage (CV) and the scanning electron microscope measurement (SEM) results of proton-irradiated n-type FZ silicon detectors. Both measurement setups are presented in Appendix B. The n-bulk detector samples were irradiated with 10 MeV protons in the Accelerator Laboratory at the University of Jyväskylä. After the irradiations, the full depletion voltages \( V_{\text{fd}} \) and the effective doping concentrations \( N_{\text{eff}} \) were resolved by CV measurements at 10 kHz in parallel mode. The results are presented in Figure 2.5.
In Figure 2.5 we can see that increasing the amount of radiation fluence leads to the decreasing $N_{\text{eff}}$ values towards the kink of the solid curve. It is assumed that at the kink the n-type bulk is fully compensated, and after the deep acceptor generation turns the bulk into p-type.

**Double-peak electric field distribution.** Defects generated by radiation in the substrate cause the variation of $N_{\text{eff}}$, which leads to two effects in silicon detectors: an increase in the full depletion voltage $V_{\text{fd}}$ and the space charge sign inversion (SCSI). Due to the space charge sign inversion, heavily irradiated detectors stay on both sides sensitive to the short-range particles causing a double-peak (DP) effect in the electric field distribution (Eremin 2002b), which is also called a double-junction effect.

In the study in *Publication III*, three different n-type detectors were selected for further investigation of electric field distribution; one with no irradiation, the second one with a radiation fluence of $2.53 \times 10^{15}$ p/cm$^2$ and the third one with a radiation fluence of $1.50 \times 10^{14}$ p/cm$^2$. The latter two samples correspond to 1 MeV equivalent neutron fluence of $1.09 \times 10^{14}$ and $6.45 \times 10^{14}$ cm$^{-2}$. These samples were cut and the cross-sections of the detectors were investigated with a SEM to study the electric field distribution inside the detector from the front surface to the back.

In the first detector, which has not been irradiated, it is expected to find a normal pn junction near the front surface and then near the p$^+$ pad of the detector. Figure 2.6 shows the SEM measurement results of the non-irradiated detector sample. The electric field distribution is shown along the detector thickness. The peak in the electric field and the place of the junction is found near the front surface of the detector as expected with all eight bias voltage values.
The second detector with intermediate fluence has the $N_{\text{eff}}$ value close to the kink in Figure 2.5. With low bias voltages under 60 V, the electric field distribution behaves similarly as in the non-irradiated sample in Figure 2.6, whereas with higher bias voltages, another peak can be seen in the electric field distribution close to the backside of the detector in Figure 2.7. This indicates a pn junction at this depth.

The third detector with the highest fluence is supposed to have its pn junction near the n-type backside of the detector because the fluence is clearly above the kink of the solid curve in Figure 2.5. The n-type bulk is expected to be inverted to p-type, and the pn junction is expected to reside near the backside of the detector. Figure 2.8 shows that the largest electric field appears near the backside at a distance of 15–20 µm from the back surface indicating that the pn junction has moved to the backside of the detector, and the bulk has reversed its type from n to p.
However, there is a smaller peak of the electric field near the front surface in Figure 2.8. The field curves indicate that the bulk is not yet fully depleted at the highest measurement voltage 100 V and therefore there is also a pn junction near the front surface.

2.5 Radiation

The fluence dependence of the effective doping concentration assuming an absence of acceptor removal and donor creation is expressed as

$$N_{\text{eff}}(\phi) = N_{D,0}e^{-c\phi} - b\phi$$

(2.10)

where $N_{D,0}$ is the donor concentration before irradiation, $c$ the donor removal coefficient and $b$ the acceptor introduction rate.

The irradiation-induced change in the effective doping concentration $\Delta N_{\text{eff}}$ can be divided into three components, namely $N_A$, $N_C$ and $N_Y$ (Moll 1999). $N_A$ is a short-term annealing component, whereas $N_C$ does not depend on annealing and is therefore called the stable damage part, which consists of an incomplete donor removal; finally, $N_Y$ is the reverse annealing component, as its behavior is opposite to the beneficial annealing.

After irradiation, for type-inverted detectors, the depletion voltage decreases (beneficial annealing), while for not-type-inverted detectors, the depletion voltage increases. In both cases, the $N_{\text{eff}}$ is increasing, because for type-inverted detectors, $N_{\text{eff}}$ is negative and becoming less negative, while for not-type-inverted detectors, $N_{\text{eff}}$ is positive and becoming more positive. Usually, this behavior is attributed to the annealing of acceptors (Moll 1999). Because only the longest decay time constant is relevant to the operation of silicon detectors in high-energy physics experiments, the fluence dependence of $N_A$ can be represented by

$$N_A = g_a\phi N_{\text{yr}}.$$  

(2.11)

The average introduction rate $g_a$ is given by $g_a = (1.81 \pm 0.14) \times 10^{-2}$ cm$^{-1}$ (Moll 1999). The introduction rate for different types of silicon materials has been defined by measurements in Li (2004). There introduction rate for Czochralski and Float Zone silicon in neutron radiation is defined.
as 0.017 and 0.022, respectively. Also for proton radiation, the introduction rate for Czochralski silicon is defined as 0.0045. This relation between the fluence and \(N_{\text{eff}}\) is used in the simulations presented later in this study. The value 0.02 for introduction rate has been used.

With radiation detectors, it is the radiation itself that is desired to be detected; its drawback is however that it may also cause damage to the detectors. Electrically active defects are responsible for changes in the main macroscopic properties of the particle detector.

The radiation-induced damage can be classified in two categories of bulk and surface defects. The most fundamental type of bulk radiation damage is a defect, produced by the displacement of an atom of the semiconductor material from its normal lattice. Defects are formed in the silicon lattice owing to the radiation damage, and several macroscopic effects occur including increase in the leakage current and the depletion voltage. The defects affect the detector properties such as carrier densities, mobility, generation lifetime, recombination lifetime and trapping probability. All defects will decrease the mobility. The generation and recombination lifetime will most strongly be reduced by the defects with energy levels close to the band gap center. For trapping, the capture and delayed release of charge carriers by the defects with medium-depth energy levels are dominant (Lutz 1999).

The radiation-generated defect complexes have complicated electrical properties: they act both as recombination-generation centers and as trapping centers, and they can also change the charge density in the space-charge region. The defect as a recombination-generation center is able to capture and emit electrons and holes, which leads to an increase in the reverse-bias current. In trapping centers, electrons and holes are captured and re-emitted with some time delay. This may lead to the reduction of the signal. When defects change the charge density, the increased bias voltage is needed to make the detector fully sensitive (fully depleted).

The vacancy left behind, together with the original atom at an interstitial position, constitutes a trapping site for normal charge carriers. The traps, which can be deep impurities, can capture a hole or an electron and keep it immobilized for a relatively long period of time. Two dominant trapping centers are the vacancy-oxygen (VO) and di-vacancy (V2) defects (Da Via 2003a). Although the trapping center ultimately may release the carrier back to the band from which it came, the time delay is often sufficiently long to prevent that carrier from contributing to the measured pulse. After an irradiation up to \(10^{16} \text{ cm}^{-2}\) fast hadrons, the trapping drastically reduces the effective drift length of charge carriers and, therefore, the produced signal does no longer depend linearly on the detector thickness or the electrode distance.

The radiation effects in silicon detectors are: first, the change in the effective doping concentration of the space charge region \(N_{\text{eff}}\) alters the operating voltage needed for full depletion; second, the fluence-proportional increase in the leakage current is caused by the creation of generation/recombination centers, and third, the deterioration of charge collection efficiency is due to the charge carrier trapping and incomplete depletion leading to a reduction of the effective drift length for both electrons and holes. These effects also influence the electronic noise (signal-to-noise ratio \(S/N\)), they increase the power dissipation and deteriorate the spatial resolution (R&D Prop. 2002). As a conclusion, the main effects of radiation damage on macroscopic silicon sensor properties are (Wunstorf 1997):

1. An increase in the leakage current \(I_{\text{leak}}\); can be reduced by cooling.
2. An increase in the effective doping concentration \(N_{\text{eff}}\) in depleted silicon; may lead to the type-inversion.
3. An increase in \(N_{\text{eff}}\) increases the bias voltage needed to achieve a given active thickness.
4. A decrease in the charge drift lifetime \(\tau\), which reduces the charge collection efficiency (CCE) from the depleted region.
The effects caused by \( N_{\text{eff}} \) can be moderated by using silicon growth techniques other than the commonly known Float Zone (FZ) and Czochralski (Cz) silicon methods such as oxygen-rich silicon substrates like Diffusion Oxygenated Float Zone (DOFZ) or magnetic Czochralski (MCz) method. The resistance to radiation can be improved with a high oxygen concentration in the silicon. In the FZ wafers, the originally low oxygen concentration can be moderated higher with the crystal growth or thermal diffusion from \( \text{SiO}_2 \) layers on polished wafers. With MCz method, the concentration and distribution of the oxygen can be better controlled than in the standard Cz method. Also the device engineering, together with material engineering, can lead to a better radiation hardness. The reduction of depletion voltage will increase the ability of silicon detectors to operate in the presence of a severe bulk radiation damage expected at high-intensity colliders. This is the case with the 3D detectors discussed later in this study. The voltage required to maintain a full depletion remains lower because of the shorter electrode distance.

2.6 Operation of a silicon radiation detector

Detecting particles is possible only when they interact with matter. In the case of silicon detectors, this happens when a charged particle travels through the silicon and generates electron-hole pairs, which are then separated by the electric field and drawn to opposite electrodes. The result of the radiation interaction in the semiconductor detectors is the appearance of a given amount of electric charge within the detector active volume. This charge must be collected to form a basic electrical signal. When a charged particle hits a semiconductor, an electron-hole pairs are created in the semiconductor. The collection of charge is accomplished through the imposition of an electric field within the detector, which causes the positive and negative charges (holes and electrons) created by the radiation to flow in opposite directions (Fig. 2.9). These are collected at the electrodes, which gives a measurable signal. The electrodes are DC or AC coupled to the readout electronics. In DC coupling, the signal readout electronics are connected directly to the electrodes. A problem in DC coupling is that also the leakage current is connected to the readout. In AC-coupled detectors, this is prevented by using a simple high-pass filter, where the resistor conduct the leakage current to the common bias line and the signal current is measured through the capacitor. Sometimes, the term detector is used to define the sensor and its readout electronics. From here onwards, the term refers to the sensor itself.

![Figure 2.9: Schematic diagram of the operation of an n-type planar (2D) pad silicon detector. p⁺ electrode at the top collects the positive charges (holes, which are indicated by small unfilled circles) and n⁺ electrode at the bottom of the structure collects the negative charges (electrons, which are indicated by small filled circles).](image-url)
The single-pad detector is a simple planar pn junction structure. The junction consists of a highly doped shallow p⁺ region on a very low-doped n substrate and a backsides of a highly doped shallow n⁺ layer. The p⁺ pad is directly connected to its metallic contact, aluminum on top of the pad, and to the readout electronics. Typical dimensions of the pad detector surface are 1 × 1 cm² and the thickness is a few hundreds of micrometers.

The pad detector is not very suitable for tracking the precise particle position. For that purpose microstrip detectors were developed. In microstrip detector geometry, the planar p⁺ implantation of a pad detector is subdivided into a number of independent narrow parallel strips. The strips widths are typically of the order of a few tens of micrometers. The pitch is defined as the distance between the center of two adjacent strips, which typically varies from a couple of tens micrometers to less than one hundred micrometers. For position sensing, each of these strips is connected to the signal readout electronics. However, the position sensitivity is only in one dimension in this kind of structure. For a second dimension, the n-strips perpendicular to the p-strips are added on the detector backside, thereby forming the double-sided microstrip detector structure. This is very effective on position resolution, because both electrons and holes are included in the signal; yet a drawback is very difficult processing. The fabrication of a large-area double-sided wafer is extremely challenging. That is the reason why planar silicon detectors are usually designed such that only one side is patterned.

Usually, the detector has a sensitive area and a cut edges feature one or more guard rings. In the case of traditional planar silicon detectors, the depleted (operational) region when reverse biased, must be kept away from the physical edge since the dangling bonds there and on the chips and cracks can short the electrodes (Kok 2006). Allowing extra dead space between the active electrode and the physical edge solves this problem but a portion of the detector volume is lost to be dedicated generally to protective structures, which control the stability of the working performance. Also the area at the detector edges must be allocated for guard ring electrodes that control the voltage drop and sinks the surface leakage current generated at the edge of the device. The methods of reducing the leakage current are an important consideration in the design of semiconductor detectors, because otherwise the leakage current obscures the small signal current and is a significant source of noise in many situations. The thermal generation of electrons and holes in the bulk gives rise to the leakage current. The leakage current decreases exponentially with inverse temperature and increases proportional to the number of active defects in the bulk. Some configurations use guard rings to help suppress surface leakage current. Guard rings minimize the surface leakage current by confining the electric field on the surface. The corner of RD50 pad detector with the protective guard ring structures surrounding the detector active area is shown in Figure 2.10 (RD50 2003).

![Figure 2.10: Top view of a corner of RD50 pad detector with multi-guard ring structure. Sixteen narrow 16 µm width guard rings and one 100 µm wide guard ring surrounds the active area of the detector. The distance between the active area implant and the first guard ring is 10 µm (RD50 2003).](image-url)
A drawback of a standard planar silicon detector is the typical dead border surrounding the sensor’s active area. This insensitive area is required because of the need for guard rings required to control the surface leakage current by keeping the electric field uniform and intercepting the current before the first signal electrode (Kok 2006). This dead area leaves behind important information. The dead space reduces the efficiency and the tracking accuracy of a detector. This is because the charge signal gets lower when the track is moved from the sensitive area towards the cut edge, becoming practically zero at the first guard ring. Minimizing the dead space or even totally edgeless detectors are discussed in the next chapter.

For a semiconductor diode detector, the collection time of charges is in the range of a few nanoseconds (Knoll 2000). These times reflect both the mobility of the charge carriers within the detector active volume and the average distance that must be traveled before arrival at the collection electrodes. When the bias voltage exceeds the full depletion voltage, the thicker sensor collects a larger signal, but the advantage of the additional active thickness is limited by charge trapping.

2.7 Advantages of radiation silicon detectors

Advantages of silicon detectors can be described by comparing them with the most widely used radiation detectors that are based on ionization in gas (Lutz 1999). The most common advantages are a compact size, relatively fast timing characteristics (due to the mobility of electrons and holes) and an effective thickness that can be varied to match the requirements of a certain application. The small band gap of the silicon (1.12 eV) leads to a large number of charges per energy loss unit to be detected, meaning excellent energy resolution. Furthermore, in silicon the average energy for creating an electron-hole pair is 3.6 eV, which is an order of magnitude smaller than the ionization energy of gases (approximately 30 eV). The high density of silicon compared with gas counters leads to a high efficiency and makes it possible to build thin detectors. One of the main advantages with semiconductor detectors compared with other types of detectors is the possibility of creating fixed space charges by doping. This allows creating different field configurations and detector structures with new properties. Also the integration of the detector and electronics into a single device is possible if they are built out of silicon. On the other hand, disadvantages of semiconductor detectors are their limitation to small sizes, sensitivity to radiation and expensive manufacturing. Further, the development of more radiation-hard silicon detectors is discussed.
Chapter 3

Characterization of advanced radiation detectors by simulations

Standard planar silicon detectors have been considered for high-energy physics applications, but they suffer from limitations of speed, sensitivity, linearity and large-area coverage at a limited cost. To solve these problems, a 3D detector structure has been developed. Using p-type material instead of n-type gives a benefit to avoid type inversion and makes detectors more radiation hard. To improve the efficiency of the detector, the active area of the detector has to be maximized. This can be achieved by designs known as active-edge detectors or edgeless detectors. In these structures, the non-sensitive area is minimized. These applications are studied in this chapter, and the characterization of more advanced radiation detector structures has been made using a semiconductor simulation program by Silvaco Data Systems Inc. With this Silvaco program, the device characterization can be made.

3.1 Simulation program

Computer simulations of detectors are important to find understanding on the device physics and to predict the detector performance in the actual applications such as in the collider physics experiments. The simulation results achieved with commercial software packages help understanding the limitation of irradiated silicon devices. At their best, the computer simulations can cover the whole process of radiation damage in semiconductor detectors. The primary interactions of the damaging particles with the semiconductor lattice, the formation of defects, the structural and electrical properties of these defects, the impact of these defects on the macroscopic detector properties, and finally, the macroscopic device in the presence of defects can be simulated. In this chapter, the main interest is in the impact of the defects on detector performance by investigating electrical properties of the detector. Device simulations on a variety of radiation detector structures are presented later in this chapter.

For TCAD simulations in this study, the software package ATLAS by Silvaco is used as a device simulation tool. ATLAS can be used on its own by defining the structure under the investigation or with the ATHENA process simulator. ATHENA predicts the physical structures that result from the processing steps. The resulting physical structures are used as an input by ATLAS, which then predicts the electrical characteristics associated with the specified bias conditions. The combination of ATHENA and ATLAS makes it possible to determine the impact of process parameters on device characteristics. Besides simulators, there are other interactive tools in Silvaco Virtual Wafer Fab framework needed for producing the simulation results: DeckBuild provides an interactive run-time environment, TonyPlot supplies data visualization capabilities and DevEdit is an interactive tool for structure and mesh specification and refinement. A brief description of the Silvaco and its parts is given in Appendix A.

ATLAS is a physically based device simulator, which predicts the electrical characteristics associated with specified physical structures and bias conditions by using the basic equations for semiconductor-device operation. These equations describe the static and dynamic behaviour of carriers in semiconductors under the influence of external fields that cause deviation from the thermal-equilibrium conditions. The basic equations can be classified in three groups: Maxwell’s equations, current-density equations and continuity equations (Sze 1981).

In Atlas, first, the structure to be simulated has to be defined including a two- or three-dimensional grid consisting of a number of grid points. By applying a set of differential equations, derived from Maxwell’s laws and consisting of Poisson’s Equation 2.2, the continuity equation and the current-density equations to the defined grid, the electrical performance of a device can be modelled. The
continuity and the current-density equations describe the way that the electron and hole densities evolve as a result of transport processes, generation processes, and recombination processes.

Current-density equations. The electron current density $J_n$ and the hole current density $J_p$ consist of the drift component caused by the field and the diffusion component caused by the carrier concentration gradient. The current-density equations are the base for analyzing the current-voltage curves in the semiconductor.

$$J_n = q\mu_n E + qD_n \nabla n$$

$$J_p = q\mu_p E - qD_p \nabla p$$

where $\mu_n$ and $\mu_p$ are the electron and hole mobilities. The carrier diffusion constant $D_n$ and $D_p$ and the mobilities are related by the Einstein relationship $D = (kT/q)\mu$.

Continuity equations. In the above current-density equations, the charge generation and recombination has been treated separately from the charge transfer phenomena, that is drift and diffusion. The continuity equation states that the increase in the number of charge carriers per time of a given type in an arbitrary part of the semiconductor is given by the difference of generation and recombination in the volume and the inward flux through the surface.

$$\frac{\partial n}{\partial t} = -\frac{1}{q} \nabla \cdot J_n + G_n - R_n$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q} \nabla \cdot J_p + G_p - R_p$$

where $G_n$ and $G_p$ are the electron and hole generation rate and $R_n$ and $R_p$ the electron and hole recombination rate. Electron-hole pair generation occurs by emission of an electron and a hole in sequence, whereas recombination is an inverse process, in other words, an electron and a hole are captured in sequence.

A very important parameter of a detector material is the charge-carrier lifetime, and there needs to be a distinction between the recombination and generation lifetimes, $\tau_r$ and $\tau_g$ respectively. These terms describe the transient behavior from a nonequilibrium charge distribution obtained either by injection of additional carriers or by their removal. Knowing electron and hole capture cross-sections, emission probabilities and the initial value of the electron and hole densities, one can find the time development of the charge-carrier densities and thus their lifetime (Lutz 1999). In thermal equilibrium, the rates of capture and emission have to be equal, separately for both electrons and for holes. In the stationary nonequilibrium case, the net recombination rate can be calculated either for electrons or for holes by taking the difference between capture and emission rates. One expects the same answer for electrons and holes because the average occupation rate of the defects has to be constant. The excess recombination rate $U$ is defined with the recombination rate $R$ and the same rate in thermal equilibrium $R_0$ (Lutz 1999).

$$U = R - R_0 = \beta \left( np - n_i^2 \right)$$

From this the carrier concentration dependent recombination factor $\beta$, the recombination lifetime and the generation lifetime can be derived. Lifetimes $\tau_r$ and $\tau_g$ are inversely proportional to the net rate $U$. 

In thermal equilibrium, the generation rate $G_{th}$ equals the recombination rate $R_{th}$. The generation lifetime $\tau_g$ is closely related to the current generated in space-charge region of the detector.

The radiation fluence causes the increase in the leakage current resulting from the creation of generation/recombination centers. The leakage current associated with a reverse-biased semiconductor junction has three components: diffusion, thermal generation and surface leakage. For silicon detectors operated at room temperature (300 K) and below, the diffusion component is so small that it can be ignored. The surface leakage current depends strongly on the fabrication process and often a guard ring structure is used to reduce the surface leakage current. The main contribution to the leakage current in a good silicon detector should come from thermal generation in the depleted silicon volume. To minimize the leakage current, the generation lifetime must be maximized.

For modelling carrier generation-recombination, ATLAS includes several different physical models (ATLAS 2007). Shockley-Read-Hall recombination model (Shockley 1952, Hall 1952) is one to be used for phonon transitions. Phonon transitions occur in the presence of a trap or a defect within the forbidden gap of the semiconductor. After defining the grid, device and the necessary mathematical methods and models, finally, the bias conditions are defined.

### 3.2 Silicon 3D radiation detector

When the detector suffers high radiation damage, full depletion cannot be achieved anymore and charge trapping reduces the amount of collected charge drifting for longer distances. A novel type of solid-state radiation detectors using a three-dimensional array of electrodes of both doping types penetrating into the detector bulk were proposed by Parker et al. in the mid 90s (Parker 1997). These 3D silicon detectors were introduced to reduce the electrode distance and therefore, to increase the amount of charge collected after heavy irradiation, while keeping the same detector thickness. The benefit of the 3D detectors is their capability to control the depletion mechanism by acting on the design of the electrodes rather than via material engineering.

Because of the geometry of the 3D detectors, the distances between the electrodes are small, which results in a very low full depletion voltage and very short collection time compared with the conventional single-sided planar detector. Advantageous with the 3D detectors are the collection distances, which are about one order of magnitude less than those of planar technology strip and pixel detectors with electrodes limited to the detector surface. The 3D detector devices exhibit high radiation tolerance, because the needed full depletion bias is smaller than in planar detectors and the drift distance is also reduced resulting in a fast signal, thereby increasing the ability of the silicon detectors to operate after irradiation.
3.3 The operation of standard 3D detectors

The standard design of 3D detectors presents the columnar electrodes of both doping types arranged in an adjacent cell and penetrated through the silicon substrate. The charge collection distance is notably shorter in 3D detectors than it is in planar detectors because of the columnar electrodes and their placement distance.

Figure 3.1: Schematic diagram of the operation of a standard 3D silicon detector. p+ electrode collects the positive charges (holes, which are indicated by small unfilled circles) and n+ electrode collects the negative charges (electrons, which are indicated by small filled circles).

The manufacturing process of the standard 3D detector is rather complicated because the columnar electrodes penetrate through the whole wafer. To make 3D detectors easier to process, a transitional form between the standard 3D and planar detector technology has been developed, called a semi 3D detector. Because of single-sided processing, the semi 3D detectors are easier to process than standard 3D detectors. In these designs, the columnar electrodes do not extend all the way through the wafer.

3.4 Semi 3D detector structure on the n-type material

Semi 3D or partially penetrating 3D electrode devices have been proposed (Li 2002) as a means to maximize signal response to incident radiation, to minimize sensitivity to defects arising from radiation damage and to reduce the $V_{fd}$ value after irradiation. Silicon semi 3D detectors have vertical columnar electrodes, where the depth of the doping profiles is left as a variable. This makes the manufacturing process of the semi 3D detectors simpler than the manufacturing process of the standard 3D detectors because the column etching and the doping has to be performed only once (Fretwurst 2005). Semi 3D detector can have electrodes of both doping types, or just one, opposite to the bulk material.

Publication 1 presents the basic unit cell of the semi 3D detector shown in Figure 3.2. Semi 3D detectors are single-sided devices that have strips of one doping type on the front side while the backside has a uniform implant. In Figure 3.2 the unit cell has one p-type vertical columnar electrode on the n-type substrate. The depth of the p-type pillar depends on the diameter of the pillar. In addition to the p-type doping pillar, the front side of the detector has a p-type implantation around the pillar. There is also a square contact window in each pixel, the smallest unit cell of the detector. The pixels are connected as strips with the aluminium lines. The backside of the structure is a uniform
implantation similar to the planar detectors, and it is an n-type electrode. The semi 3D detector structure studied here is 300 µm thick.

Figure 3.2: Unit cell of the semi 3D detector (Eränen 2004).

The full depletion of the detector volume has a high importance for the operation of the detector to be used in the high-energy physics experiments. To study the active area of the detector, the potential distribution inside the detector has to be investigated. In Publication II, the detector simulation results and also scanning electron microscope (SEM) measurement results have been presented. The SEM measurement setup is described in Appendix B.

First, the full depletion voltage of the semi 3D detector is studied by simulations. In the simulations, three p-type pillars penetrate 150 µm into the 300 µm deep detector bulk. The diameter of the p-type pillar is 10 µm. In addition to the p-type doping pillar, the front side of the detector has a p-type implantation around the pillar. For the 100 µm pitch, the width of this square implant is 90 µm, and from the edge of the pillar the width of which is then 40 µm towards the next pillar in the same contact line. P-type pillars constitute the anodes, and the cathode is placed on the backside of the detector as n⁺ layer. The n-type substrate doping concentration was $1 \times 10^{12}$ cm$^{-3}$. The negative bias voltage is applied to the anode while the cathode remains at zero.

The simulations show that the semi 3D detector structure is fully depleted at low voltages. Figure 3.3 shows the electron concentration at 20 V bias.
Figure 3.3: Electron concentration of the semi 3D detector structure at 20 V of bias. The original substrate doping concentration is $1 \times 10^{12}$ cm$^{-3}$ (light green color). Lower concentrations (light blue) are the depleted volume of the detector. It can be seen that at 20 V bias, the detector volume is already almost fully depleted. There are only shallow areas between the p-type pillars and at the bottom of the structure, which are not totally depleted.

The full depletion is not the only critical parameter for the proper operation of the detector. The detector volume should also have a high electric field. The low field area in the detector is insensitive to the particles and almost a dead space. Particles travelling through the low electric field area of the detector cannot be recognized. The potential and electric field distributions can be studied by simulations or SEM measurements. A benefit of SEM measurements is that they directly describe the potential distribution inside the detector.

The electric field can be modified higher by overdepleting the detector. That is the reason why simulations and SEM measurements were carried out with 0 V, 10 V, 40 V and 80 V bias voltages, where 40 V and 80 V bias are over the full depletion bias, which is approximately 20 V. Negative voltages were used because the p-type anodes were biased in the study.

The color scheme describes the potential distribution inside the detector structure. In the simulation figures, the color scheme is a rainbow spectrum divided into 30 colors, while the color scheme in the SEM measurements is a continuous rainbow spectrum. In the rainbow spectrum, the most positive voltage is presented as red and the most negative voltage is presented as bright magenta (voltage applied to the p-type anodes). There is a correspondence between the simulation results and the SEM measurements, in other words, they show the same phenomenon: with the high bias voltage the electric field is mainly formed between the end of the pillars and the backside. Because of the structure of the semi 3D detector, the charge-collecting field is only below the pillars where the electric field has formed. This can be seen from the potential figures with varied voltages of the silicon semi 3D
radiation detector structure (Fig. 3.4-3.7) generated in the simulations and the SEM measurements. The SEM photographs are taken from the cross-section of the split silicon semi 3D detector. The detector cross-section is in a slightly oblique angle compared with the array of the semi 3D detector. Therefore, four to five p-type pillars with varying lengths are shown in the photographs.

Figure 3.4: Potential distribution of the semi 3D detector structure at 0 V of bias a) simulation result and b) SEM measurement.

Figure 3.5: Potential distribution of the semi 3D detector structure at -10 V of bias a) simulation result and b) SEM measurement.
In Figure 3.4 there is no voltage connected. The potential differences are only seen between p-type pillars in the structure. When there is 10 V connected in Figure 3.5, the potential differences begin to show between the end of the pillars and the backside of the structure. The potential spreads downwards. When 40 V is connected, also the potential of the front side starts to spread between p-type pillars (Fig. 3.6). Finally, in Figure 3.7, where 80 V is applied, the space between the pillars is almost at the same potential.

When the simulation results and the SEM measurements are compared, it can be seen that there is a good correspondence between these two. Both results show the properties of the n-type semi 3D detector. Due to the structure of the semi 3D detector, the charge-collecting field is only below the pillars where the electric field is formed. With the high bias, the electric field is mainly formed between the end of the pillars and the backside. This can be seen even better from the simulated electric field in Figure 3.8.
There are also factors, which may cause differences between the simulation results and the SEM measurements. First of all, the simulation results are ideal and do not take into account the oxide charge or surface states, which affect the depleted region. However, the surface states do not have a significant influence when studying the depletion inside the detector bulk. Second, the SEM photographs differ from the simulation results because the relation between contrast and voltage is not linear. With small voltages below -20 V, the relation between contrast and voltage is close to linear, whereas with higher voltages, the change of the potential does not affect the change of the contrast linearly (Leinonen 2005b).

Drawbacks of this n-type semi 3D silicon radiation detector are its non-uniform electric field and the fact that it is formed on the backside of the detector. Moreover, it suffers from the type inversion of the bulk material. This can be reduced by changing the n-type substrate material to the p-type. The p-type material does not suffer from the type inversion, and the mobility of collected charges, now electrons, is higher than for the n-type material producing a larger signal.

### 3.5 3D detectors for p-type material

The most commonly used detector type is p-on-n, where the detector has an n-type bulk and a p-type structured front electrode. The bulk radiation damage results in a change in the doping concentration. A progressive irradiation of the initial n-type silicon leads to the inversion of its type of conductivity, turning into p-type silicon. The type inversion of a p-on-n detector poses a problem since the high electric field is switching from the structured readout side to the backside of the detector (RD50 2003). Further, if the detector is not operated with voltages well above the depletion voltage, the charge collection efficiency is reduced (Moll 2005).
The p-type silicon does not suffer from type inversion after irradiation. The n-on-p detectors do not type invert because their bulk is already of p-type, and the structured read-out side will be the one with the high electric field before and after irradiation. When the read-out side is in contact with a high electric field, the charge collection efficiency is improved because the n-side does not suffer from the space charge sign inversion (SCSI). Consequently, it presents higher charge collection efficiency (CCE) than p-on-n detectors beyond the SCSI point (Casse 2002). Moreover, n-on-p detectors collect electrons, which have three times higher mobility than that of holes, collected in p-on-n detectors. Therefore, the trapping of charge carriers is reduced (Bruzzi 2006). It is preferable to process n-type electrodes on the p-type substrate especially in the cases of close-to-beam applications, where highly non-uniform irradiation is present.

The n-on-p detectors are expected to be more radiation hard than standard p-on-n detectors. These detectors are more complex as they need an extra surface insulation. This insulation is achieved by a blank surface implant, named p-spray, or by p-type junctions, named p-stops. P-spray is a lightly doped layer over the wafer surface, and p-stops are heavily doped guard rings between the n-type guard rings in the case of a planar detector. In 3D detectors, p-stops can surround the n-type column electrodes at the front surface of the electrode.

In Publication V, the simulation results of two single-sided 3D detector designs, one with the single-type (n-type) of the columns (Fig. 3.9) and the other one with the dual-type of the columns (n- and p-type) (Fig. 3.10) on the p-type substrates are presented. Detectors were developed by Brookhaven National Laboratory (BNL) (Li 2007).

![Figure 3.9: Schematic of the single-type of column (STC) 3D detector structure used in the device simulations. Device parameters in the simulations: \( d = 300 \, \mu m, t = 270 \, \mu m, P = 60 \, \mu m \) (Li 2007).](image)

![Figure 3.10: Schematic of the dual-type of column 3D detector structure used in the device simulations. Device parameters in the simulations: \( d = 300 \, \mu m, t = 270 \, \mu m, P = 60 \, \mu m \) (Li 2007).](image)
Single-type of column 3D detectors. A minimum cell of the BNL single-column detector used in simulations is shown in Figure 3.11. Here, the columnar electrodes are all of the same type, n-type, which are of the type opposite to the p-type substrate. They extend to 270 µm into the 300-µm-deep bulk. The ohmic contacts are achieved by placing two ion-implanted p-type electrodes on the front surface, in the other two corners in a simulation cell as shown in Fig. 3.11b. The backside is covered by a uniform silicon oxide layer and there is no implantation; thus the process is single-sided. The n-type column electrodes and p-type electrodes are covered with aluminum layers on the detector surface. The rest of the detector front side is covered with silicon oxide. The cell is simulated with two n-type columns on the opposite corners and two p-implants (0.5 µm deep) in the other corners. N-columns are surrounded by p-stops.

P-stops are used for surface insulation. The isolation is necessary since the positive charge in the SiO₂ induces the creation of an electron accumulation layer at the oxide-silicon interface. Otherwise, the interelectrode capacitance increases and shorts the electrodes together. The positive oxide charge increases with the irradiation, but it is present even in non-irradiated oxides and saturates when all traps are occupied by holes in the oxide layer.

Figure 3.11: Simulated BNL 3D detector featuring columnar electrodes of one doping type, a) detector simulation cell and b) top view.

A sketch of the BNL dual-column detector used in the simulations is shown in Figure 3.12. In this structure, there are two n-type and two p-type doped columns on a p-type substrate. Same types of doped columns are placed to the opposite corners in the simulation cell. All the columns are placed on the front side of the detector, and they extend 270 µm into the 300-µm-thick p-type bulk. N-type columns are surrounded by p-stops. The backside is covered by a uniform silicon oxide layer and is never processed; hence, the process is again single-sided.
Figure 3.12: Simulated BNL 3D detector featuring columnar electrodes of n- and p- doping type, a) detector simulation cell and b) top view.

The full 3D simulations on 3D Si detectors were performed using the DEVICE3D package of ATLAS by Silvaco (ATLAS 2007). The aim of the numerical simulations was to investigate the electric field profiles in various 3D detectors. The strength of the electric field with the applied voltage, when the full depletion is reached, expresses the high- and low-field areas in the detector and its sensitivity to particles. The full 3D simulations of different detector types show that one can achieve a similar electric field profile between a BNL dual-column 3D detector and other dual-column 3D detectors developed by other institutes with the benefit of the true one-sided process. In the case of the BNL single-type column detector, the simulations show that the high electric field is on the pixel side. It is an advantage that the particle sensitive area is on the front side of the detector.

The sensitive region of a detector can be seen from the simulated electric field profile in the detector. BNL single-column detectors have the high electric field region on the pixel side (front side) of the detector and along the n-type columns, as shown in Figure 3.13 for single cell, similarly as in Figure 3.11. The bias voltage here is 100 volts on the n-type electrodes with respect to 0 volts on the p-type electrodes. It is clear that the electric field is highly non-uniform, and is the lowest in the volume directly under the p-type electrodes, which are only implants on the front surface.
To see the electric field inside the detector in more detail, a 2D cut plane is plotted along the two n-type columns in Figure 3.14. We may observe that for the BNL single-type of column 3D detectors biased at 100 volts 1) the front side (or pixel side) is with the highest field, and it extends about 30 µm into the detector; 2) there is a high field along the n+ columns all the way through the detector with a volume of about 2/5 of that between the n+ columns; 3) the medium field between the n+ columns also occupies about 2/5 of the volume; 4) the lowest field is near the middle of the two n+ columns, which occupies about 1/5 of the volume; and 5) there are some medium to low fields in the volume under the n+ columns, which also make this volume with some sensitivity to particles – it may not be entirely dead. Point 5) also raises the possibility that the volumes directly under the n+ columns may serve as a way to recover some sensitivities from the supposed dead volumes of the n+ columns themselves.
Figure 3.14: 2D cut plane of the simulated electric field in a BNL single-type of column 3D detector at 100 V bias.

It is interesting to note here that the simulated full depletion voltage for the BNL single-type of column 3D detectors is far smaller (5-10 volts) than that of planar detectors (80 volts) with the same thickness and resistivity. In this aspect, this type of 3D Si detector may be more radiation tolerant than the 2D planar Si detectors, especially after modest fluence (>1x10^{14} \text{n}_{eq}/\text{cm}^2) when the \( N_{eff} \) becomes higher and the electric field becomes better. This latter point was first systematically simulated at Trento for their single doping type column 3D Si detector (Piemonte 2005), where detectors built on a lower initial resistivity material have shown better electric field profiles. However, a voltage higher than the full depletion voltage should be used to obtain a high field near the back of the detector. Also, the longest drift length for a particle-generated free carrier (holes here) is still the whole detector thickness that can be notably larger than the column spacing, one may lose the contribution to CCE of one type of carrier (holes here) at very high radiation fluences (>2x10^{15} \text{n}_{eq}/\text{cm}^2).

To see the bias voltage effect on this type of 3D detectors, we plot a 2D cut plane for the same detector as shown in Figures 3.13 and 3.14; this time the bias is increased to 200 volts (Fig. 3.15). As we can see, the main change here is in point 1) listed above: the high field region near the front surface is extended to about 80 \( \mu \text{m} \) into the detector bulk as compared to 30 \( \mu \text{m} \) in the case of 100 volts. Points 2–5 are almost the same as those for the 100 volts case.
Figure 3.15: 2D cut plane of the simulated electric field in a BNL single-type of column 3D detector at 200 V bias.

It is interesting to compare the field profiles between the BNL single-column 3D detector and the Trento one proposed early by ITC-irst in Trento (Piemonte 2005, Fleta 2007). In a Trento single-type of column 3D detector, n-type columns are placed in every corner in one unit cell (Fig. 3.16), that is, $n^+$ columns in places where $p^+$ implants are located (Fig. 3.11) for the BNL single-type of column 3D detector. The $p^+$ ohmic contact is a uniform $p^+$ ion implant on the backside.

Figure 3.16: Sketch of a 3D detector featuring columnar electrodes of one doping type proposed by ITC-irst (Piemonte 2005).

Figure 3.17 shows the 2D electric field profiles of the two types of single type of column (STC) 3D detectors at 100 volts along a cut plane between the two $n^+$ columns. Field profile differences are clearly shown: 1) instead of a high field on the pixel side (BNL), the high field in a Trento detector is near the backside; 2) instead of some high field developed along the $n^+$ columns all through the
column length (BNL), half of the n' columns length near the pixel side has a low field in a Trento detector; and 3) in fact, most of the volume under the pixel (about 40% of the detector volume) has a low field in a Trento detector. The BNL single-type of column 3D detector provides better field distribution, and may therefore give better charge collection performance.

Figure 3.17: Comparison of electric field profiles between two types of single-column 3D detectors operated at 100 V bias. The 2D cut plane is along the two n' columns.

**Dual-column 3D detectors.** The 3D electric field profile of a BNL dual-column 3D detector operated at 40 volts is shown in Figure 3.18. It is clear that a high field is distributed all along the n' and p' columns, and throughout the detector. Again, similar to the BNL single-column 3D detector, there is a field developed under the columns near the backside, which could provide an extra sensitive region for the detector. The electric field profile in a dual-column 3D Si detector is more uniform than that in a single-type column 3D Si detector: the non-uniformity is minimum along the detector thickness, especially 20–30 µm away from either surfaces. The dual-column 3D Si detector is easier to deplete at lower bias voltages than the single-column 3D detector.

Figure 3.18: Electric field profiles of a BNL dual-column 3D detector operated at 40 V bias: a) 3D profile; b) 2D profile in a cut plane in the middle.
However, the field profile is still highly non-uniform as shown in a 2D cut plane in the middle of the detector at half of the detector thickness, 150 µm. The low field is near the center between the four electrode columns in a simulation cell, and the field is zero right at the center point (saddle point). This low-field region is common for all dual-column 3D detectors as we will show next, which is due to the symmetry in the detector unit cell.

The BNL dual-column 3D detector is compared with other dual-column 3D detectors: the standard one developed by Parker (Parker 1997), and the one developed by IMB-CN (Barcelona), where p-type and n-type columns are placed to the opposite surfaces as shown in Figure 3.19 (Fleta 2007).

Comparing different dual-column 3D detector structures, the electric field profiles are extremely similar in the vast bulk of the detectors; only minor differences are found on the surface of the detector at 100 V bias, as shown in Figure 3.20.
Figure 3.20: Comparison of the electric field profiles between three types of dual-column 3D detectors operated at 100 V bias. The 2D cut plane is along the two n^+ columns.

In fact, one of the main differences among various types of dual-column 3D detectors is the processing. The processing of a BNL dual-column 3D detector is true one-sided process, both in terms of detector processing and detector access. It is clear that one-sided processing is far simpler and cheaper than double-sided one. Single-side access can also be simple, but in some cases, double-sided access may be desirable due to the fact that different voltage levels may be separated by the entire thickness of the detector. In the case of one-sided processing, the electrodes do not go all the way through the wafer, which makes these devices mechanically stronger than standard 3D detectors – no support wafer and therefore wafer bonding is necessary.

The main advantages for dual-column 3D Si detectors as compared to 2D planar detectors are: 1) much smaller full depletion bias (depletion between the columns, which can be made in the order of <70 µm, and is independent of detector thickness); 2) the drift distance is also significantly reduced in this way, which results in a fast signal, and much improved radiation hardness in terms of CCE if the column spacing is made in the same order of magnitude of that of the trapping distance \(d_t\) at the SLHC fluence, and \(d_t\) can be in the order of 10’s of µm. These are in fact the main reasons that 3D Si detector is one of the detector options for SLHC. The main disadvantages of dual-column 3D detectors as compared to 2D planar ones are the non-uniform electric field profiles including low fields and difficulties in detector processing.

**Weighting field.** The 3D simulations of weighting field profiles for different 3D detector structures were reported in Publication V. The induction of signals in the electrodes of the detectors is generally based on the Shockley-Ramo theorem (Shockley 1938, Ramo 1939, Cavalleri 1971). The theorem states that the instantaneous current induced on a given electrode is equal to the products of the charge of the carrier, its drift velocity \(v_d\) (which is proportional to the electric field as simulated before) and the weighting field \(E_0\) (Knoll 2000):

\[
i = qv_d \cdot E_0
\]

(3.9)

For efficient charge collection, it is required that the maximum electric field arisen from the applied bias should be located in the position of the weighting field maximum. The weighting field is
simulated with the following boundary conditions: potential 1 V to the electrode of interest and 0 V to all others. Figure 3.21 illustrates the simulated weighting field for the BNL single-column detector, whilst Figure 3.22 presents the weighting fields for BNL dual-column detector and another dual-column detector by CNM.

**Figure 3.21:** Weighting field of the BNL single-column detector.

**Figure 3.22:** Weighting fields of the dual-column detectors a) the BNL dual-column detector and b) the dual-column detector developed by CNM.

It is clear that the high-weighting field region is mainly concentrated along the collecting $n^+$ column, here on the bottom left corner, extending across the simulation cell. The details of the weighting field distribution are more clearly indicated in the 2D cut plane of the detector. In Figure 3.23, the BNL single- and dual-column detectors have been cut at 150 µm in the middle of the detector thickness. As shown in Figure 3.23b for a BNL dual-column 3D Si detector, the high-weighting field exists within 30 µm from the collecting column, which is more than 60% of the cell length. Two low-weighting field regions are present between the opposite $n^+$ column and the $p^+$ columns. This weighting field profile is similar for other types of dual-column 3D Si detectors except near the surfaces.
Figure 3.23: Weighting field cuts at 150 µm for a) BNL single-column detector and b) BNL dual-column detector.

As for the BNL single-column 3D Si detector, the high-weighting fields are concentrated near the two \( n^+ \) columns, extending 25 µm away from the columns. Two low-weighting field regions exist directly under the \( p^+ \) implants.

3.6 Irradiated 3D Detectors

As shown in section 2.4, there is a relation between the effective doping concentration and the fluence. The challenge of simulating the radiation damage is the generation of electrically active defects and the donor removal within the device simulator. The effect of bulk damage caused by hadron environment in the Si detectors can be simplified simply by simulating the effect on the doping concentration and varying it. This simulation method gives an insight into the device behavior after radiation damage.

The simulations for dual-column 3D detectors were carried out with a variety of fluences. The simulated full depletion voltage \( V_{fd} \) for a dual-column 3D detector shows to be about 1.4 times higher than that of for calculated full depletion voltage of a 2D pad detector with a thickness \( d \), which is the same as the column spacing \( L_p \) in the 3D detector. The results are shown in Table 3.1.

Table 3.1: Full depletion voltage, calculated for a 2D detector and simulated for the 3D detector with a thickness \( d \), which is the same as the column spacing \( L_p \) in the 3D detector.

<table>
<thead>
<tr>
<th>Fluence ( \Phi_{eq} ) [cm(^{-2})]</th>
<th>Doping concentration ( N_{eff} ) [cm(^{-3})]</th>
<th>2d pad detector (d=50µm) Calculated ( V_{fd} ) [V]</th>
<th>Dual-column 3D detectors (L_p=50µm) Simulated ( V_{fd} ) [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.00x10^{14}</td>
<td>1.00x10^{13}</td>
<td>19</td>
<td>30</td>
</tr>
<tr>
<td>1.00x10^{15}</td>
<td>2.00x10^{13}</td>
<td>38</td>
<td>60</td>
</tr>
<tr>
<td>2.00x10^{15}</td>
<td>4.00x10^{13}</td>
<td>76</td>
<td>110</td>
</tr>
<tr>
<td>3.00x10^{15}</td>
<td>6.00x10^{13}</td>
<td>114</td>
<td>160</td>
</tr>
<tr>
<td>4.00x10^{15}</td>
<td>8.00x10^{13}</td>
<td>152</td>
<td>210</td>
</tr>
<tr>
<td>5.00x10^{15}</td>
<td>1.00x10^{14}</td>
<td>190</td>
<td>250</td>
</tr>
<tr>
<td>6.00x10^{15}</td>
<td>1.20x10^{14}</td>
<td>228</td>
<td>300</td>
</tr>
<tr>
<td>7.00x10^{15}</td>
<td>1.40x10^{14}</td>
<td>266</td>
<td>350</td>
</tr>
<tr>
<td>8.00x10^{15}</td>
<td>1.60x10^{14}</td>
<td>304</td>
<td>400</td>
</tr>
<tr>
<td>9.00x10^{15}</td>
<td>1.80x10^{14}</td>
<td>342</td>
<td>450</td>
</tr>
<tr>
<td>1.00x10^{16}</td>
<td>2.00x10^{14}</td>
<td>380</td>
<td>500</td>
</tr>
</tbody>
</table>
Compared with thin planar detectors, 3D detectors need a higher full depletion voltage. Usually the planar detectors used in high-energy physics experiments are 300 µm thick. In that case, the full depletion voltage of 3D detectors is lower with 50 µm column spacing, which is an advantage against planar detectors.

Simulations show that the highest E-field is near the n+ column in dual-column 3D detector (Figure 3.24). The high E-field mainly distributes between the n+ and p+ columns. The low E-field is between the two p+ columns (Figure 3.25a), and the lowest E-field is in the center of the simulation cell with two p+ columns and two n+ columns (Figure 3.25b).

**Figure 3.24:** Electric field, $\phi_{eq} = 4 \times 10^{15} \text{n}_e \text{ cm}^{-2}, V = 200 \text{ V}$.

**Figure 3.25:** Electric field. Fluence $\phi_{eq} = 9 \times 10^{15} \text{n}_e \text{ cm}^{-2}$ and the applied voltage is a) $V = 200 \text{ V}$ and b) 450 V.

Figure 3.25a shows that when detector is under the full depletion voltage (200 V), the low-electric-field area is between p-type electrodes. When reaching full depletion in Figure 3.25b, almost the all detector space has a high electric field, only in the middle of the structure is a spot of low-electric-field area.

In the future, high-energy physics experiments require very high fluences up to $1 \times 10^{16} \text{n}_e \text{ cm}^{-2}$. In order to fully deplete a dual-column 3D detector at $1 \times 10^{16} \text{n}_e \text{ cm}^{-2}$ with a reasonable bias ($\approx 200 \text{ V}$), the column spacing $L_p$ should be reduced to 30 µm (Fig. 3.26).
Figure 3.26: Electric field, \( \phi_{eq} = 1 \times 10^{16} n_{eq} / \text{cm}^2 \), \( V = 200 \text{ V} \), \( L_p \) varies from 10 µm to 50 µm.

The volume under the columns (10% of the total volume) can be depleted with a modest bias (\( \leq 200 \text{ V} \)), and this volume under the columns is not dead volume (Fig.3.27).

Figure 3.27: Depletion in 3D detector with \( L_p = 30 \mu \text{m} \) at 200 V and \( \phi_{eq} = 1 \times 10^{16} n_{eq} / \text{cm}^2 \).

In Figure 3.27, the depletion volume can provide some detection sensitivity directly under the columns, which may reduce the effective dead volume in 3D detectors.
3.7 Comparison of n- and p-type 3D detectors

Comparing various 3D detector structures, simulation results show that the dual-column detectors are at best in the radiation-hard environments, but single-column detectors are easier to process. The electric field profile (active area of the detector) is the best in the dual-column detectors including the standard 3D detector. The single-column detectors suffer from the non-uniform electric field, although in BNL single-column 3D detectors, some high field can be developed along the junction column. The n-type 3D detectors are not very suitable for high-energy physics experiments because of the large low-field area and the type inversion of the detector type. The advantages and disadvantages are summarized in Table 3.2.

Table 3.2: Summarizing comparison of the properties of different 3D detector structures.

<table>
<thead>
<tr>
<th>Structure</th>
<th>E-field profile</th>
<th>Rad-hard</th>
<th>Mechanical integrity</th>
<th>Processing</th>
<th>Accessibility</th>
<th>Sensitivity under the column</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-TYPE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Std 3D (UH)</td>
<td>Good</td>
<td>Super</td>
<td>Good with supporting wafer</td>
<td>Difficult, wafer bonding needed</td>
<td>One-side</td>
<td>Some reported (Da Via 2006)</td>
</tr>
<tr>
<td>BNL dual-C</td>
<td>Good</td>
<td>Super</td>
<td>Good</td>
<td>True one-sided</td>
<td>One-side</td>
<td>Some</td>
</tr>
<tr>
<td>CNM dual-C</td>
<td>Good</td>
<td>Super</td>
<td>Good</td>
<td>Double-sided</td>
<td>Two-side</td>
<td>Some</td>
</tr>
<tr>
<td>BNL single-C</td>
<td>Low field on the back side</td>
<td>Good</td>
<td>Good</td>
<td>True one-sided</td>
<td>One-side</td>
<td>Some</td>
</tr>
<tr>
<td>Trento single-C</td>
<td>Low field on the front and center</td>
<td>Good</td>
<td>Good</td>
<td>One-sided (backside uniform ion implant and metallization)</td>
<td>Two-side</td>
<td>Some</td>
</tr>
<tr>
<td>N-TYPE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Semi 3D</td>
<td>Low field on the front</td>
<td>Suffers from SCSI</td>
<td>Good</td>
<td>One-sided</td>
<td>Two-side</td>
<td>Some</td>
</tr>
</tbody>
</table>

Also the 3D simulations of weighting field profiles for different p-type 3D detector structures verify that the high-weighting field has been found to exist in more than half of the volume in the detector unit cells, which should be a significant advantage for 3D detectors.

3.8 Active edge of the detector

In general, planar silicon detectors have a wide insensitive border region around the sensitive area. This insensitive area is occupied by a sequence of guard rings, which control the potential distribution between the sensitive area of the detectors and the die cut to minimize the electric field and the surface leakage current (Fig. 3.28). The need for this area can be avoided if the detector is designed to be edgeless or a trench around the detector bulk is made into an active-edge electrode. In this way, the electric field can extend to within a few microns of the physical edge of the detector when a bias voltage is applied.
Figure 3.28: Schematic cross-section view of a standard detector edge showing some reasons for an insensitive region there: a) space is needed for guard rings, b) the saw-cut edges are conducting, and c) chips or small cracks must remain clear of d) the bulge of the electric field in the depleted region (Kenney 1999).

Edgeless position sensitive detectors are of interest in imaging applications using non-penetrating radiation such as soft X-rays or vacuum ultraviolet, and in applications where the sensor must be positioned as close as possible to a beam or to a wall. In the first case, the edge sensitivity permits contiguous imaging with overlapped sensors, while in the latter category, particles can be tracked very close to a high-intensity beam (Perea Solano 2006).

Minimizing the dead space is an additional advantage as it enhances the efficiency of a detector (Ranjan 2004). The guard ring technique has evolved to minimize the dead space at the edge of detectors. Also the guard ring structure is used to improve the breakdown performance of silicon detectors. Detectors collect charge from the depletion region. It is therefore important to minimize the dead space, from where it is not possible to collect charge. Usually, depletion is formed vertically from anode to cathode, but *Publication IV* describes a proposed new $p^+/n^+/n^+$ pad detector structure with $n^+$ guard ring placed at the edge of the detector (Fig. 3.29), where the depletion region also extends sideways. This phenomenon is due to the cathode and the guard ring being of the same doping type. The remaining dead space is only directly under the guard ring.

![Figure 3.29: Schematic cross-section view of a detector edge with n+ guard ring placed at the edge of the detector (Publication IV).](image)

The same processing procedure performed to fabricate the electrodes in standard 3D detectors can be used to create a trench all around the detector bulk, making it into an active-edge electrode (Kenney 2001). Figure 3.30 shows a sketch of a 3D detector, where the $p^+$ and $n^+$ electrodes are processed inside the silicon bulk. The edge is a trench electrode making the active volume sensitive to a few $\mu$m from the physical edge when a bias voltage is applied.
Kenney (2006) gives the basic architecture of active-edge planar radiation sensors. Planar/3D-active edge devices have planar microstrips and a three-dimensional edge (Fig. 3.31). The diode junction can be formed either at the edges and bottom or at the top-side electrodes by interchanging n and p. When the diode junction appears at the top-side electrodes, a drawback of the planar/3D design is that the bottom edge corner is very difficult to fully deplete with similarly low bias voltages. Also the disadvantages compared with pure 3D devices are the loss of speed and radiation tolerance.

Other methods to reduce the dead edge volume of planar detectors are a cut-through edge operated at cryogenic temperature and a current terminating structure. The latter case is investigated by the TOTEM experiment group, motivated mainly by the need for the measurement of very forward elastic scattering at the CERN LHC near room temperature and preferring production based on the standard planar fabrication technology. These kinds of edgeless detectors are explained in more detail in Ruggiero (2005), Noschis (2006) and Pellegrini (2006).
Chapter 4

Discussion

The interest in the 3D silicon detectors is continuously growing because of their many advantages as compared to conventional planar detectors: the devices can be fully depleted at low bias voltages, the speed of the charge collection is high, and the collection distances are about one order of magnitude less than those of planar technology strip and pixel detectors with electrodes limited to the detector surface. Also the 3D detectors exhibit high radiation tolerance, and hence the ability of the silicon detectors to operate after irradiation is increased. The properties of 3D and planar detectors are compared in Table 4.1.

Table 4.1: 3D versus planar detector design parameters for a 300 µm thick silicon substrate. The depletion voltage quoted is for a detector prior to irradiation (Da Via 2003b).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>3D</th>
<th>Planar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depletion voltage</td>
<td>&lt; 10 V</td>
<td>70 V</td>
</tr>
<tr>
<td>Collection length</td>
<td>~ 50 µm</td>
<td>300 µm</td>
</tr>
<tr>
<td>Charge collection time</td>
<td>1-2 ns</td>
<td>10-20 ns</td>
</tr>
<tr>
<td>Edge sensitivity</td>
<td>&lt; 10 µm</td>
<td>~ 300 µm</td>
</tr>
</tbody>
</table>

To achieve some of the prime goals of high-energy physics experiments – for example the discovery and possible study of Higgs particles – the silicon detectors have to operate in an extreme harsh radiation environment. To achieve the properties of silicon detectors needed for such applications, the radiation degradation has to be minimized. This is done by device and defect engineering. Defect analysis and 3D detectors are the hottest topics in the future in the area of detecting particles in high-energy physics experiments.

In this study, the radiation detectors have been researched. The effect of radiation to the detectors has been characterized by simulations. The simulations on the radiation damage are done by varying the effective carrier concentration $N_{cb}$. This simulation method gives an insight into the device behavior after radiation damage. It is clear that radiation will cause irreversible damage in the detector bulk material. The radiation-induced changes in the macroscopic silicon detector properties such as leakage current, depletion voltage and charge collection efficiency are caused by radiation-induced electrically active microscopic defects. The challenge of simulating the radiation damage is the generation of electrically active defects and the donor removal within the device simulator.

Highly energetic ionizing particles, while crossing the detector, interact with the silicon layer resulting in the generation of electron-hole pairs along their path. Electron-hole pairs can be collected at the electrodes of an inversely biased junctions, but if the energy of the highly energetic ionizing particles is high enough, a lattice atom can be displaced from its original position and two defects are generated in the silicon lattice (Passeri 2001, Petasecca 2005a), namely an interstitial atom and a vacancy. Most of the generated interstitials and vacancies quickly recombine because of their very high mobility, but a significant proportion of them can interact with impurities to produce electrically active defects, whose energy is located within the forbidden band. These defects behave as recombination-generation centers in the band gap and act as traps for carriers (Petasecca 2005a, Petasecca 2005b).

It has been shown elsewhere (Passeri 2001, Petasecca 2005a, Petasecca 2005b, Petasecca 2006) that the radiation damage effects can be described with a three-level radiation damage model (known as the Perugia trap model) to be used in simulations. The model is based on the progressive introduction of radiation-induced defects. Two main defects in the silicon bulk are related to the divacancy and to...
the carbon-oxygen complex. The presence of these defects causes the radiation-induced changes in the electrical properties of the detector. For n-type silicon, the three-level model is defined with two acceptor levels located at $E_c - 0.42$ eV ($V_2$) and $E_c - 0.55$ eV ($V_2O$), and a donor level located at $E_v + 0.36$ eV ($C_iO_i$) (Ahmed 2001, Petasecca 2005b). In proportion, the three-level model for p-type silicon has a divacancy defect level located at $E_c - 0.42$ eV ($V_2$), a tri-vacancy complex defect (Ahmed 2001) located at $E_c - 0.46$ eV ($V_3$) and a donor defect $C_iO_i$ complex located at $E_v + 0.36$ eV (Petasecca 2006).

There is only incomplete knowledge on the defect properties, and therefore, it is very difficult to determine the concentrations of impurities. The damage modeling in Silvaco simulation program also require information about activation energies, the cross sections for majority and minority carriers and the trap concentrations of main defects. All this information is difficult to find for the specific defect level. Moreover, it has been shown that trapping times of the Perugia model do not match with the experimental trapping times (Pennicard 2007).

In Silvaco, the command trap activates bulk traps at discrete energy levels within the bandgap of the semiconductor and sets their parameter values. For example, the three-level radiation damage model can be defined in the Silvaco program as follows:

```
#..... Three-level damage model for p-type
trap acceptor e.level=0.42 sigp=2e-6 sign=5.4e-9 density=7.5e11 degen=1
trap acceptor e.level=0.46 sigp=7e-15 sign=3.2e-12 density=5e11 degen=1
trap donor e.level=0.36 sigp=1.2e-10 sign=5.1e-23 density=1e12 degen=1
```

The type of the trap level is defined as acceptor or donor. $e.level$ sets the energy of the discrete trap level. For acceptors, it is relative to the conduction band edge. For donors, it depends on the valence band edge. $sigp$ and $sign$ specifies the capture cross section of the trap for holes and for electrons. The average capture time increases exponentially with depth and is inversely proportional to the capture cross-section (Lutz 2001). Instead of capture cross-sections, the electron and hole lifetimes can be specified. $Density$ sets the maximum density of states of the trap level and $degen$ specifies the degeneracy factor of the trap level used to calculate the density (ATLAS 2007).

Some values for the capture cross-section of the trap for holes and for electrons and also for the density of traps are reported in the literature (Hallen 1996, Bleichner 1996). The problem is that all the necessary information is not very well known for specific traps, and more information is needed to complete radiation-induced defect simulations with the Silvaco program.

Also it has been reported that the concept of double-peak electric field distribution in irradiated Si detectors can be expressed with a trap model (Verbitskaya 2007). The model of this DP electric field profile $E(x)$ distribution is based on trapping of equilibrium carriers to the midgap energy levels of radiation-induced defects that leads to a non-uniform distribution of space charge concentration with positively and negatively charged regions adjacent to the $p^+$ and $n^+$ contacts, respectively. The model takes into account the trapping of free carriers from the bulk generation current to the midgap energy levels of radiation-induced defects: a deep donor (DD) and a deep acceptor (DA) with the activation energies of $E_v + 0.48$ eV and $E_c - 0.52$ eV, respectively. From this point of view, when the traps are known better, the simulation of the double-peak electric field profile distribution is possible in the future.

The signal formation in 3D detectors is very important research field for understanding the properties of 3D detectors in terms of speed and charge collection efficiency. One way to study the signal is the calculation of electric and weighting fields as shown earlier. The second method is to simulate a certain amount of charge injected along a straight line or locally in the detector and analyze the time domain response. This kind of simulation can be done in Silvaco with single-event upset command. It enables to specify the radial, length, and time dependence of the generated charge along tracks. There
can be a single particle strike or multiple strikes. Figure 4.1 shows the first result of the transient simulations of the BNL dual-column detector. The charge collection was studied by introducing a minimum ionizing particle (MIP) that penetrates through the whole detector in the middle of the structure with the bias of 50 V. The voltage has been chosen to be higher than full depletion voltage, because it increases the electric field and thereby speeds up the charge collection. About 24 000 electron-hole pairs is created uniformly along the path in the silicon.

**Figure 4.1:** Charge collection time dependence of the BNL dual-column detector at 50 V bias and the charge traveling through the whole detector in the middle of the structure.

Figure 4.1 shows the dual-column 3D detector current response pulse from the center of the simulation cell shown in Figure 3.12. It can be seen that there is a delay, when a current pulse is returning back to the zero level causing a pulse tail. This is caused by the uniform surface charge at the silicon/oxide interface. The surface recombination causes some of the charge carriers to recombine, and thus, diffusion is caused toward the oxide, and the charge collection time increases. More research is needed to study the charge collection properties of 3D detectors in the future.
Chapter 5  

Conclusions

In this study, the various radiation detector structures were simulated and characterized to find an applicable silicon detector, which can operate in extremely harsh radiation environments such as in the experiments of the future Super-LHC. In the nearest region of the beam in Super-LHC, 3D-detectors are almost the only detector choice because of their radiation hardness. The full depletion voltage and the electric field distribution of 3D detectors were under investigation in this study. As expected, the full depletion voltage is lower in 3D detectors than in common planar detectors, because the charge collection distance is notably shorter, consisting only of the distance between the columnar electrodes. The drawback in 3D detectors is the non-uniform electric field, which reduces the sensitivity volume of the detector. That is why electric field distributions in various detector structures were studied. The optimization of the electric field distribution can ensure fast and efficient detector operation. Therefore, the knowledge of the electric field distribution is important for the prediction of detector operation in harsh radiation environments.

The key contributions of this study include the following:

- This study shows that the main reasons why 3D Si detector is one of the detector options for SLHC are: 1) far smaller full depletion bias voltage, because the needed depletion volume is between the columns, which can be made in the order of <70 µm, and is independent of the detector thickness; 2) this way the drift distance is also notably reduced, which results in a fast signal, and substantially improved radiation hardness in terms of CCE if the column spacing is made in the same order of magnitude of that of the trapping distance \(d_{tr}\). At SLHC fluence, \(d_{tr}\) can be in the order of 10’ s of µm.

- The study of the electric field distribution in n-type 3D detectors with partial-penetrating electrodes. Both the simulation results and the SEM measurement results show that the charge-collecting field (electric field) is formed only below the electrode pillars. With the high bias voltage, the electric field is mainly formed between the end of the pillars and the backside. The front side of the detector suffers from the low electric field, and consequently, the charge collection efficiency is reduced.

- The simulation study of the electric field distribution in p-type 3D detectors with single-type of the columns. The electric field distribution in the studied single-column p-type 3D detector structure shows to have many advantages compared with other types of single-column 3D detectors: 1) the high electric field shows to be on the sensing electrode side; and 2) some high electric field can be developed along the junction column as the bias voltage increases. However, the single-column detectors suffer from a more complicated, non-uniform electric field profile than dual-column detectors as shown in the simulation results. Single-column p-type 3D detectors are more radiation hard than the planar detectors because of their lower depletion voltages.

- The simulation study of the electric field distribution in p-type 3D detectors with dual-type of the columns. The electric field profile in a dual-column 3D Si detector is more uniform than that in the single-type column 3D Si detector: the non-uniformity is minimal along the detector thickness. The field profiles for all types of the studied dual-column 3D detectors are similar with just some minor differences on the front and back surfaces. The dual-column detectors are the best in radiation hardness because of their low depletion voltages and short drift distances.

- The simulations show that the volume under the columns where it is supposed to constitute the dead space (about 10%) can be depleted at high biases with a modest electric field, leading to the possibility of recovering some sensitivity from this region. This region can also provide some sensitivity to particle tracks directly through the columns.
• Dual-column p-type substrate 3D detectors were simulated with a variety of fluences to study the effect of the irradiation on the detector performance. The simulated full depletion voltage $V_{fd}$ for a dual-column 3D detector shows to be about 1.4 times higher than that of a 2D pad detector with a thickness $d$, which is the same as the column spacing $L_p$ in the 3D detector. Simulations also show that in order to fully deplete a dual-column 3D detector at $1 \times 10^{16}$ $n_{eq}/cm^2$ with a reasonable bias ($\leq 200$ V), the column spacing $L_p$ should be reduced to 30 $\mu$m.

Suggestions for future work. The study shows that in the future, defects and charge collection in the detectors studied here should be taken under further investigation as suggested in Discussion. More information is needed about the charge trapping: what are the effective traps and their parameters in the radiated silicon detector? Ab initio calculations can provide reliable estimates for the defect electrical levels, together with information about the defect concentrations and the migration energies. These data can then be used as input for the Silvaco program, thereby connecting the nanoscale with device-scale engineering.

Electrically active defects are responsible for the changes in the operation of the particle detectors. This causes the degradation of the overall charge collection efficiency. The deterioration of CCE caused by the trapping of charge carriers will be the most severe obstacle for the use of silicon detectors in the future very high-luminosity colliders with extremely harsh radiation environments. The main effect of the radiation damage on the macroscopic silicon detector properties is the decrease in the charge drift lifetime, which reduces the CCE from the depleted region. In addition to the trapping of free carriers causing the reduction in the CCE amplitude, the detector has to be fully depleted for achieving the maximal signal amplitude. Also, the high concentration of the radiation-induced deep traps leads to the electric field distortion, where there is the double-peak electric field distribution. The CCE depends on both the charge trapping and the electric field, and it is the most crucial parameter in the radiation detector research. It can be studied with the following methods listed in Table 5.1, which also shows the quantities that can be defined.

<table>
<thead>
<tr>
<th>Measurement setup</th>
<th>$E(x)$</th>
<th>$\tau_{trap}$</th>
<th>$V_{fd}$</th>
<th>CCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TCT</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SEM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CCE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TCAD simulation</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>

Charge collection can be simulated introducing a certain amount of charge traveling through the detector. The first results were presented in Figure 4.1; however, it is necessary to study the charge collection in various detector structures further. Also for future studies and simulations, the integration of the electric field and the weighting field is highly important; one can calculate the actual induced current in 3D Si detectors under various radiation fluences, and then analyze the CCE of the detector.
Appendix A

Silvaco TCAD software

Silvaco TCAD software allows the creation, fabrication and simulation of semiconductor devices and their electrical performances. In this study Silvaco TCAD was run under the Linux environment, yet it also can be run under Windows. The software is divided into several different programs, which all have a purpose of their own in the whole simulation chain (Fig. A.1). DeckBuild is the program, which runs the files under the simulation. With the ATHENA program, the semiconductor manufacturing process can be simulated and the semiconductor device can be created. The semiconductor device can also be described by the DevEdit/DevEdit3D program, but mostly it is used to edit the mesh or grid of the device to optimize it for the simulation run and the most interesting points of the device. With DevEdit3D, the three-dimensional structures can be created. ATLAS is the device simulation program, which is needed in every case for simulation of the electrical characteristics of the semiconductor devices. Also this program can be used to describe semiconductor devices by inserting the doping profiles. Finally, after the simulation run, the TonyPlot or TonyPlot3D is used to visualize the semiconductor device and its electrical characteristics.

![Diagram showing programs and information flow in Silvaco TCAD](image)

Figure A.1: Programs and information flow in Silvaco TCAD (ATLAS 2007). DevEdit, DeckBuild and TonyPlot form a Silvaco Virtual Wafer Fab (VWF) environment. ATHENA and ATLAS are the process and device simulation softwares. The input files of ATLAS are the command file from DeckBuild, which performs the simulation run and the structure file from either DevEdit or ATHENA or from both. In this file, the studied device structure is defined.

A.1 DeckBuild

DeckBuild is the surface between different simulation programs. In DeckBuild, the code for simulation is run; there it is possible to move freely from one simulation program to other, for example from ATHENA to DevEdit and finally to ATLAS. It provides an interactive run-time environment. DeckBuild can be used to create or edit input decks, or just load the ready input deck for the simulation run. Instead of using DeckBuild, the input code can be built in any text editor program and saved as an input file type. After that, these files can be loaded in DeckBuild and run.
The DeckBuild base window consists of two subwindows; an upper one for building, editing and showing the input decks and a lower one for running the simulation (Fig. A.2). This window shows the simulation steps and possible error messages. ATHENA is the default simulation program, when starting DeckBuild.

A.2 ATHENA

ATHENA is a simulator that provides general capabilities for numerical, physically based, two-dimensional simulation of semiconductor processing. Physically based process simulators predict the structures that result from specified process sequences. This is done by solving systems of equations that describe the physics and chemistry of semiconductor processes. A detailed analysis of various aspects of process simulation can be found in Plummer (2000).

An ATHENA simulation program has a modular architecture and several different tools. The ATHENA tool performs structure initialization and manipulation and also provides basic deposition and etch facilities. The SSUPREM4 tool is used in the design, analysis, and optimization of silicon semiconductor structures. It simulates silicon processing steps such as ion implantation, diffusion and oxidation. The simulation is done by first defining the problem. In ATHENA, the problem is specified by defining the initial geometry of the structure and the sequence of process steps (e.g. oxidation, implantation, etching, diffusion) that are to be simulated. The example of an ATHENA simulation is given in Appendix A.6.

ATHENA predicts the physical structures that result from processing. These physical structures are used as input by ATLAS, which then predicts the electrical characteristics associated with specified bias conditions. Using ATHENA and ATLAS makes it possible to determine the impact of process parameters on device characteristics.

A.3 ATLAS

ATLAS is a physically based two- and three-dimensional device simulator, which predicts the electrical characteristics that are associated with specified physical structures and bias conditions. This is achieved by approximating the operation of a device onto a two- or three-dimensional grid.
consisting of a number of grid points called nodes. By applying a set of differential equations, derived from Maxwell’s laws, onto this grid the transport of carriers through a structure can be simulated. The electrical performance of a device can be modeled in DC, AC or transient modes of operation.

In ATLAS, the problem to be simulated is specified by defining the physical structure, the physical models and the bias conditions for which electrical characteristics are to be simulated. The order in which statements occur in an ATLAS input file is important. There are five groups of statements (Table A.1) that must occur in correct order. The order of statements within the mesh definition, structural definition, and solution groups is also of importance. Otherwise, it may cause incorrect operation or termination of the program. For further information of statements, the reader is referred to ATLAS 2007 manual. The example of an ATLAS simulation code is given in Appendix A.6.

Table A.1: The Atlas commands.

<table>
<thead>
<tr>
<th>Group</th>
<th>Statements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure specification</td>
<td>mesh, region, electrode, doping</td>
</tr>
<tr>
<td>Material models specification</td>
<td>material, interface, model, contact</td>
</tr>
<tr>
<td>Numerical method selection</td>
<td>method</td>
</tr>
<tr>
<td>Solution specification</td>
<td>log, solve, save, load</td>
</tr>
<tr>
<td>Result analysis</td>
<td>extract, tonyplot</td>
</tr>
</tbody>
</table>

S-PISCES is a two-dimensional device modeling program that simulates the electrical characteristics of silicon-based semiconductor devices. It calculates the internal distributions of physical parameters and predicts the electrical behavior of devices under either steady-state, transient, or small signal AC conditions. This is performed by solving Poisson’s equation and the electron and hole carrier continuity equations in two dimensions. S-PISCES solves basic semiconductor equations on non-uniform triangular grids. Doping profiles and the structure of the device may be obtained from analytical functions, experimentally measured data, or from process modeling programs SSUPREM4 and ATHENA. DEVICE3D provides the semiconductor device in three-dimensional mode. It uses the same analog as the S-PISCES in the two-dimensional simulations.

### A.4 DevEdit

DevEdit is a device structure editor (Fig. A.3). It can be used to generate a new mesh on an existing structure or to create or modify a device. These devices can then be used by Silvaco 2-D and 3-D simulators. DevEdit can perform the following operations: definition of a device for subsequent device simulations, and remeshing a device structure between or during a process and device test simulations, when the process simulator does not create a good grid for the device simulator or when the mesh is no longer adequate for the next simulation step.
Defining the mesh is very critical in Silvaco simulations. First, the number of nodes in two-dimensional simulations is limited to 20,000, which is not much considering wide and high-radiation detector structure simulations. Because quite high voltages are applied in these applications, placing the nodes to the right places is also very important. Otherwise, the convergence problem during simulation run is reported and simulation is not finished correctly.

A.5 TonyPlot

TonyPlot is a graphical post processing tool for use with all Silvaco simulators, and it is an integral part of the Virtual Wafer Fab. Similarly, TonyPlot3D is a three-dimensional graphics viewer, capable of displaying data generated from the 3D process and device simulators (Fig. A.4).

A.6 SIMULATION SOURCE CODE

Next, an example of simulation source code is given. The simple diode structure is simulated to show the operation of pn junction under the reverse bias. First, ATHENA is started for the process simulation. All command lines in the program start with #.
The x- and y-dimensions of the structure are given with the space of grid.

# Mesh definition
#
line x loc=0.0 spac=5
line x loc=5.0 spac=5
line x loc=10.0 spac=1
line x loc=15.0 spac=2
line x loc=35.0 spac=1
line x loc=40.0 spac=3
line x loc=45.0 spac=5
line x loc=50.0 spac=5
#
line y loc=0.0 spac=0.5
line y loc=1.0 spac=1
line y loc=3.0 spac=1
line y loc=5.0 spac=2
line y loc=10.0 spac=3
line y loc=20.0 spac=5
line y loc=30.0 spac=5
line y loc=40.0 spac=5
line y loc=50.0 spac=5
#

The doping of silicon is given.

#
# Initial silicon structure
#
# n (1E13 cm-3)
init silicon c.phosphorus=1e13 orientation=111

The first processing step is to deposit oxide and aluminum on top of the structure and then etch them for the p-type pad implantation.

# =============== Oxide Cut for Boron implant ===============
# ================ Implantation Mask for Boron ================
#
deposit oxide thick=0.50 divisions=10
#
etch oxide start x=10 y=-0.5
etch cont x=10 y=0
etch done x=40 y=-0.5

deposit alumun thick=1.0 divisions=10

etch alumun start x=10 y=-1.5
etch cont x=10 y=0
etch cont x=40 y=0
etch done x=40 y=-1.5

Processing of the p-type pad is carried out by implanting boron. Then contacts are made by depositing aluminum both on the front side and backside.

# ================ Implantation ================
#implanting p+ with energy 25keV and dose 1e15cm-2
#
implant boron dose=1e15 energy=25 pearson tilt=7 rotation=0 crystal
#
# Etch aluminum (implantation mask)
etch aluminum all
# Aluminum Contact
# Front side
# deposit alumin thick=1.0 divisions=25
etch alumin start x=0 y=-2
etch cont x=0 y=0
etch cont x=10 y=0
etch done x=10 y=-2
etch alumin start x=40 y=-2
etch cont x=40 y=0
etch cont x=50 y=0
etch done x=50 y=-2

# Backside
# struct flip.y
deposit alumin thick=0.30
struct flip.y

Electrodes are named and the structure created is saved for device simulation.

# Name and the place of the electrode
electrode name=anode x=25 y=-0.1
electrode name=cathode x=25 y=30.1

# Saving the created structure
struct outfile=/u/home/tanjap/Simulation/pn_junction.str

# Plotting the structure
tonyplot

The device simulation starts by using ATLAS. First, necessary parameters are given and simulation models and methods are defined.

# Device simulation - ATLAS
go atlas

# Load mesh file created during process simulation
mesh inf=/u/home/tanjap/Simulation/pn_junction.str

# Adding work function to the electrodes
# SiO2 - Si surface charge
interface qf=4e11

# Simulation models
models bipolar numcarr=2
impact selb

# Simulation methods
method newton trap itlimit=20 maxtraps=10

Solving the device with a variety of bias voltages starts.

# Solving the initial solution
solve init

# Saving the voltages and currents
log outf=pm_junction.log

# Defining output type
output e.field
output flowlines

# Bias voltages applied
# anode = -0.5V...-30V (1) electrode #
solve vstep=-0.1 nsteps=5 elec=1
save outf=/u/home/tanjap/Simulation/pn_junction-p(-0.5V).std master
load inf=/u/home/tanjap/Simulation/pn_junction-p(-0.5V).std master
solve vstep=-0.1 nsteps=5 elec=1
save outf=/u/home/tanjap/Simulation/pn_junction-p(-1.0V).std master
load inf=/u/home/tanjap/Simulation/pn_junction-p(-1.0V).std master
solve vstep=-0.1 nsteps=5 elec=1
save outf=/u/home/tanjap/Simulation/pn_junction-p(-1.5V).std master
load inf=/u/home/tanjap/Simulation/pn_junction-p(-1.5V).std master
solve vstep=-0.1 nsteps=5 elec=1
save outf=/u/home/tanjap/Simulation/pn_junction-p(-2.0V).std master
load inf=/u/home/tanjap/Simulation/pn_junction-p(-2.0V).std master
solve vstep=-0.1 nsteps=30 elec=1
save outf=/u/home/tanjap/Simulation/pn_junction-p(-5.0V).std master
load inf=/u/home/tanjap/Simulation/pn_junction-p(-5.0V).std master
solve vstep=-0.1 nsteps=50 elec=1
save outf=/u/home/tanjap/Simulation/pn_junction-p(-10.0V).std master
load inf=/u/home/tanjap/Simulation/pn_junction-p(-10.0V).std master
solve vstep=-0.1 nsteps=100 elec=1
save outf=/u/home/tanjap/Simulation/pn_junction-p(-20.0V).std master
load inf=/u/home/tanjap/Simulation/pn_junction-p(-20.0V).std master
solve vstep=-0.1 nsteps=50 elec=1
save outf=/u/home/tanjap/Simulation/pn_junction-p(-25.0V).std master
load inf=/u/home/tanjap/Simulation/pn_junction-p(-25.0V).std master
solve vstep=-0.1 nsteps=50 elec=1
save outf=/u/home/tanjap/Simulation/pn_junction-p(-30.0V).std master
load inf=/u/home/tanjap/Simulation/pn_junction-p(-30.0V).std master

Finally, the simulation results are plotted. The results of this simulation run are presented in Figure 2.3 in Chapter 2. After the plotting, simulation stops.

tonyplot
tonyplot pn_junction.log -set diode.set
quit
Appendix B

Measurement setups

B.1 CV/IV measurement setup

Capacitance-voltage (CV) measurements yield the depletion voltage and the effective doping concentration. Also, the semiconductor behavior studied by the CV measurements will give information of the behavior of the resistivity, that is, the required depletion voltage as a function of the radiation dose. LUT has measuring equipment for CV measurements, and measurements can be made to high voltages (up to 1100 V). The characterization of the detectors is performed with the CV measurement equipment consisting of a probe station, semiconductor parameter analyzer, LCR meter and separate voltage sources (Fig. B.1).

Figure B.1: CV measurement station. On the left, there is the probe station; in the middle, the HP 4155A semiconductor parameter analyzer, and on the right, the HP 4284A LCR meter and the Keithley 2410 voltage sources.

For measuring the capacitance of the detector as a function of voltage, an HP 4284A LCR meter is applied. The voltage range of the LCR meter is 40 volts at maximum. Should a higher voltage be needed, a separate voltage source has to be used. The Keithley 2410 voltage sources can produce high voltages up to 1100 volts. Measuring the current of the detector as a function of voltage, an HP 4155A semiconductor parameter analyzer can be used up to 100 volts. The Keithley 2410 voltage source also includes a current meter, and thus, when higher voltages are required, the current measurements can also be made with the Keithley 2410.
The voltage source and the LCR meter are connected to the probe station and the probe needles by a self-made electronic circuit (Fig. B.2). This electronic circuit is used to isolate the LCR meter from the high voltage by a transformer.

Figure B.2: a) Circuit diagram of the connector between voltage sources, the LCR meter and the probe needles and b) the photo. With this electronic circuit, both IV and CV curves can be measured simultaneously. Keithley no. 1 is used as a voltage source, Keithley no. 2 measures the current and the LCR meter measures the capacitance.
B.2 SEM measurement setup

The type inversion and the double-junction effect have been investigated with several indirect methods: capacitance-voltage (CV) measurements, transient current technique (TCT), optical beam induced current (OBIC), and by measuring the surface potential with a mechanical probe from a cleaved sample (Leinonen 2006). The CV measurements reveal the full depletion voltage, where the effective doping concentration can be calculated. The TCT method is based on the electric field transformation caused by trapping of laser injected carriers. The TCT gives information about the position of the electric field maximum inside the detector through observing the shape and the delay of a current pulse after generating carriers near one surface of the detector with a short laser pulse (Eremin 1994, Eremin 1996). The OBIC technique induces the creation of electron-hole pairs in the sample through the laser signal injection.

Similarly as CV or TCT methods, the above are macroscopic and secondary by nature. The voltage-contrast effect in the scanning electron microscope (SEM) provides a more direct way to measure the desired quantities, that is, the potential distribution and electric field inside the detector structure. This is done by cleaving the detector; now, the examined surface is the cross-section of detector. This way, the potential distribution and the electric field can be measured more directly from the inside of the detector sample. The SEM method provides an accurate microscopic means of imaging and measuring the desired quantities more directly from the sample as a function of position. A drawback is that the device must be split before examination.

The SEM method is based on the voltage-contrast phenomenon. The contrast is converted mathematically to voltage. The simple mathematical equations used in the conversion are explained in detail in Leinonen (2005b). With this SEM measurement method, after splitting the detector, the potential distribution and the electric fields can be imaged and measured straight from the sample. These kinds of measurements are the benefit of the SEM. A drawback of this method is that with this measurement setup the voltage contrast starts to saturate at relatively small voltages. With this method, it is therefore impossible to characterize heavily irradiated detectors under full depletion conditions. With 40-60 V bias, however, a clear, non-saturated voltage-contrast can be seen. This is sufficient to see from which side of the detector the electric field starts to extend (Tuovinen 2006).

The SEM, JEOL JSM-25S III scanning electron microscope was used in this research. This SEM setup is shown in Fig. B.3. A detector is placed in the vacuum chamber of the SEM. The bias voltage is fed over the detector from the Agilent semiconductor parameter analyzer 4155C.
One source measure unit (SMU) is constituted by $V_{\text{SMU}}$ and its associated voltage and current meters in the semiconductor parameter analyzer. The bias voltage from the analyzer is connected through the sample holder, placed inside the vacuum chamber, to the detector (Fig. B.4).
In the vacuum chamber, a 5 keV electron beam is scanned over the examined surface of the biased detector at a speed of 2-5 µm/s (Leinonen 2005b). The primary 5 keV electron beam generates secondary electrons at most a few nanometers below the examined surface. These electrons are pulled to a secondary electron detector (SEI=Secondary Electron Image), placed on the inside wall of the vacuum chamber, by a positive voltage $V_{SEI}$ around this detector. The value of $V_{SEI}$ is fixed to 10 kV in this microscope. The secondary electron detector works as a scintillator. It absorbs the electrons, which the primary beam has generated to the examined surface. These secondary electrons form the signal. The energy of secondary electrons is small, less than 50 eV, and thus even a small positive voltage on the sample can decrease the number of electrons arriving to the secondary electron detector and thereby cause a phenomenon called voltage-contrast (Leinonen 2005b). Then in the setup, the secondary electron signal is amplified and converted from analog to digital mode. This signal plus the horizontal and vertical timing signals of the SEM are read to a PC. The PC is used to display the images and waveforms, and to calculate potential distributions and electric fields.
References


(Cavalleri 1971) G. Cavalleri et al., Extension of Ramo’s theorem as applied to induced charge in semiconductor detectors, Nuclear Instruments and Methods 92 (1971), pp. 137–140.


(Da Via 2006) C. Da Via, 3D active edge silicon sensor test results, presented at the Sixth International “Hiroshima” Symposium on the Development and Application of Semiconductor Tracking Detectors, Carmel, California, September 11-15, 2006.


Publication I

S. Eränen, T. Virolainen, I. Luusua, J. Kallipuska, K. Kurvinen, M. Eräluoto, J. Härkönen, K. Leinonen, T. Palviainen, M. Koski

“Silicon Semi 3D Radiation Detectors”

Abstract—The paper describes the first results on the behavior of semi three dimensional (3D) silicon radiation detectors. As compared to the normal 3D detectors with the n- and p-type vertical doping profiles, the present structure employs the p-type profiles, only. The report covers the proposed new structure, fabrication sequence, the electrical characteristics like the capacitance, leakage current, breakdown voltage, x-ray response for the Am-source. These results are reported for the high resistivity Cz and FZ starting material. The measured electrical characteristics are compared with the 3D simulation results obtained with the ISE TCAD software. In addition, the 3D mixed mode transient simulations are employed in order to learn about the signal charge collection capabilities of the new structure.

I. INTRODUCTION

Since the pioneering work of J. Kemmer at the beginning of eighties the planar silicon detectors have become real work horses in the field of the radiation detecting devices [1]. These devices have a wide range of applications including e.g. the instrumentation using devices, that are sensitive to light and/or soft x-rays, high energy physics, radiation and other safety aspects, non-destructive testing and inspection, space applications and imaging, where the various medical applications are currently becoming very important.

The success of the planar silicon detector technology is not very surprising, since it has been able to take the benefit of some parts the enormous growth and development of the silicon integrated circuit technology. This development is roadmaped in the ITRS [2] and it is believed to continue at least until the year 2018. In particular, several innovations for the rapidly growing digital market have been directly utilised for the silicon detector business, as well. This is especially true for the process equipment, chemical and process purity, material and process development and wafer handling systems. In addition, the silicon radiation detector community has been able to overcome the inherent weaknesses of the basic silicon material like the insensitivity to the gammas and hard x-rays. This has been accomplished with the ingenious radiation conversion methods like e.g. the scintillator technology.

In the mid nineties new architectures of silicon radiation detectors employing three dimensional (3D) arrays of electrodes, that penetrate into the detector bulk, were proposed [3,4]. The fabrication of these silicon structures heavily employ the methods of the silicon micromechanics. From the user point of view the interest in the 3D detectors comes from several facts: the devices can be fully depleted at low bias voltages, speed of charge collection is high, good spatial resolution can be obtained, the devices exhibit high radiation tolerance, the technology permits also the fabrication of detectors with narrow edge dead regions and, finally, the detectors can be fabricated on the large area CZ-silicon substrates.

This paper describes the fabrication and the first results on the semi 3D radiation detector structure fabricated on silicon. Usually, the 3D detectors have vertical p- and n-type vertical doping profiles or pillars through the wafer resulting in the vertical depletion of the structure. In the present case the vertical p-type doping pillars are employed, only, and the vertical depth of the doping profiles is left as a variable. The backside or the n-type contact of the structure is a blank implantation, similar to the normal planar strip or pixel silicon detectors. The electrical results include the leakage currents, breakdown voltages, reverse biased capacitance values and radiation measurement results with the Am-source. In addition, the comparison with the FZ and CZ wafer materials and the radiation hardness results will be presented. We also present the comparison between the measured leakage current and capacitance values with the true 3D simulation values, that were obtained using the ISE TCAD simulation tool. Finally, the same simulation program is employed in the transient mode including the external bias circuit (voltage source and resistor).
in order to predict signal charge collection performance of the proposed detector structure.

II. STRUCTURE AND FABRICATION

Fig. 1 describes the basic structure of the proposed semi 3D structure. The structure has the p-type vertical doping profiles, the diameter of which is ten or twenty microns. In the fabricated detectors the depth of the p-type is dependent on the diameter. For the twenty micron diameter the depth is 200 µm and for the ten microns diameter the corresponding value is 150 µm. The n-type electrode of the detector is a uniform n-type doping on the backside of the device. The pitch between the p-type electrode is a variable. In the current structure we had 100 and 200 µm. The present devices were not optimized for any particular application, but the work merely presents a technology demonstration. In addition to the p-type doping pillar the front side of the detector has a p-type implantation around the pillar in order to tune the electric field inside the device. For the 100 µm pitch the widths of these square implants were 40 and 90 µm, while for the 200 µm pitch the widths are 100 and 190 µm. Finally, each pixel of the detector had a square contact window with the width of 30 µm.

The semi 3D detectors were fabricated on the n-type high resistivity FZ-silicon wafers with the resistivity above 6 kΩcm. The wafer thickness is 300 microns and the crystal orientation <111>. For comparison a few CZ-silicon wafers with the resistivity of 1 kΩcm and <100> orientation were included in the process.

The fabrication starts with the growth of the field oxide for the passivation of the surface. This is followed by the first mask, that defines the hole positions of the vertical p-type doping pillars. The holes are first opened into the field oxide and then the deep ICP silicon etching is employed in order to define the vertical electrodes. In our case the silicon etching depth varied between 150 and 200 microns depending on the hole diameter. In the next step the holes were filled using the in-situ doped p-type LPCVD poly silicon. In order to fill the hole with the diameter of 20 microns the layer thickness of at least ten microns is required. After the hole filling the extra layer of polysilicon on the wafer surface must be removed either by etching or by the CMP planarization. The same technique of deep etching and filling can also be used for the formation of the so-called active edge structures. Further the oxide is opened for the p-type surface implant, the meaning of which is to reduce the effect of the oxide charge on the surface and ease the depletion of the total detector volume. The rest of process contains standard steps for the backside, contact windows and metal patterns.

III. RESULTS

A. Electrical results

Fig. 2a and Fig. 2b show the measured dark, reverse leakage currents for the selected structures from the zero bias up to 100 V at 25 °C on the FZ silicon wafers. The title on the figure denotes the selection of the layout parameters of the measured structure. Thus, in Fig. 2a the diameter of the vertical doping pillar is 20 µm, the pitch between the adjacent pixels 200 µm and the width of the surface implant 100 µm. Correspondingly, in Fig. 2b the diameter is 10 µm, the pitch 100 µm and the width of the surface implant 40 µm.

As mentioned above, the individual pixels are connected as strips for the electrical testing. Thus each curve in Figs. 2 represents the parallel connection of a number of pixels. The legend on the right explains the type of the test structure. For Fig. 2a 1M5 is a 100x100 matrix and 1M1 a 10x10 matrix. Thus, the upper curve is the result of one hundred pixels in parallel and the lower curve is the result of ten pixels in parallel. In the same fashion in Fig. 2b M16 and M12 are 100x100 matrices and thus the two upper curves display the result of one hundred pixels in parallel. M21 is a 10x10 matrix.

As a general behavior the 100 pixels strips seem give currents, that are about ten times larger than those of the ten pixels strips. At 100 V the leakage current per pixel is about a few pico amperes. There are variations from one layout structure to another, but variations also exist between similar structures.
further work is needed in order to make decisions about the recommended layout parameters.

In Fig. 2b, the curves display repeatable kinks at certain reverse voltages. The reasons for these are not understood at present (see simulations).

As to the CZ wafers one example of the leakage curves is shown in Fig. 3. Here M16 and M12 are the 100x100 matrixes and M21 is again the 10x10 matrix. At fixed voltages the leakage currents on the CZ wafers are larger than the currents on the FZ wafers. If we compare e.g. Figs. 2b and 3, where the results measured for the equivalent structures on the FZ and CZ wafers are shown, it is clear, that the leakage current on the FZ silicon is about seven times smaller than on the CZ silicon.

The other prominent feature in Fig.3. is the the clear avalanche breakdown, that takes place between 60 and 80 volts. On the FZ wafers the breakdown in general occurs above 140 V for the pixel strips. In some cases this value can even exceed 200 V, which was the test limit in these experiments. Further, on these wafers the the breakdown of the circular diodes (surface implant) occurs above 200 V without an exception. On the other hand for the CZ pixel strips the breakdown is always between 64 and 90 V, whereas the circular CZ diodes display the breakdown characteristics between 120 and 140 volts.

The reverse biased capacitance curves as a function of the bias voltage were measured on the 100 pixel strips using a 10 kHz probe signal with the amplitude of 50 mV. Some results are shown in Fig.4. for various structures with the pixel pitch of 100 micrometers on the FZ silicon. Here the level of the capacitance is dependent on the choice of the layout parameters, but the most prominent feature of Fig.4. is the saturation of the capacitance values for each curve above 30 V. This gives a hint, that the structures with the pixel pitch of 100 micrometers become fully depleted already at 30 volts. The same behavior is not seen with the pixel pitch of 200 micrometers on the FZ material or with any structure on the CZ silicon below 34 V, which was the bias test limit of the capacitance measurements. At the saturation the capacitance per pixel seems to vary between 40 and 90 fF/pixel. However, this value greatly overestimates the actual pixel capacitance, since the measured value also includes the parallel (over depleted) MOS capacitance, that is caused by the aluminum line, which connects the individual pixels within one strip. Separate measurement were done on the MOS test structures in...
order to ascertain, that the MOS capacitances also remain flat with the chosen probe parameters in the voltage region, where saturation of the total strip capacitance is observed.

For the radiation hardness testing four CZ and four FZ samples were prepared. Each sample had the area of 1 cm² and the layout parameters were pitch 100 µm, surface implant width 40 µm and hole diameter 10 µm. The samples were irradiated at Cern using 24 GeV/c protons at the fluences of 1.4e15, 4.0e15, 6.0e15 and 1.0e16 cm⁻². There was no cooling or bias during the irradiation.

**TABLE I**

<table>
<thead>
<tr>
<th>Dose</th>
<th>Depl. Voltage V_d (V)</th>
<th>Current @ V_d</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.4e15</td>
<td>60</td>
<td>26</td>
</tr>
<tr>
<td>4.0e15</td>
<td>87</td>
<td>29</td>
</tr>
<tr>
<td>6.0e15</td>
<td>95</td>
<td>75</td>
</tr>
<tr>
<td>1.0e16</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

**TABLE II**

<table>
<thead>
<tr>
<th>Dose</th>
<th>Depl. Voltage V_d (V)</th>
<th>Current @ V_d</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>30</td>
<td>0.0005</td>
</tr>
<tr>
<td>1.4e15</td>
<td>82</td>
<td>24</td>
</tr>
<tr>
<td>4.0e15</td>
<td>86</td>
<td>30</td>
</tr>
<tr>
<td>6.0e15</td>
<td>90</td>
<td>70</td>
</tr>
<tr>
<td>1.0e16</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

TABLE I and II summarize the depletion voltages and the leakage currents at the depletion voltages for the test samples as a function of the proton dose on the CZ and FZ material. Here the measurement setup was different from the one that was used for the leakage currents and capacitances reported earlier. The depletion voltages of the samples were not determined before the irradiation and the zero dose values of the FZ material have been taken from the different setup and samples. After the dose of 1e16 cm⁻² the samples were heavily damaged and no reliable data could be obtained. The essential point here is, that there is no essential difference between the FZ and CZ material. The depletion voltage of the detectors remain below 100 V even at the dose of 6e15 cm⁻². The leakage currents at the depletion voltage increase with the proton dose – but not linearly.

**B. Simulations**

The performance of the new semi 3D structure was simulated using a true 3D tool ISE TCAD. First of all the leakage current of one pixel was compared with measured data.

Fig. 4. Capacitance curves for selected structures with pixel pitch of 100 micrometers on FZ silicon (see text)

Fig. 5. Am-spectrum of 4 sqcm detector on FZ Si (see text)
for a chosen layout. The simulations can very well predict the magnitude of the leakage current, but cannot reproduce the kinks in Fig. 2b. This leads to the conclusion, that the kinks could be caused by the measurement setup, where one strip is biased, only.

The capacitance simulations give the result, that the pixel capacitance saturates already at very low voltages and the saturation capacitance per pixel is around 10 fF. This shows, that the measured values in Fig. 4 are dominated by the MOS contribution.

![Integral of signal caused by proton](image)

**Fig. 6.** Integral of signal caused by proton (see text)

The charge collection behavior of the semi 3D structures were studied using the transient mixed mode option of ISE TCAD. We studied the case, where a proton hits the center of a square cell formed by four p-type doping pillars with the pitch of 100 micrometers. Fig. 6 shows the integral of the signal current caused by the proton. In the time scale the hit takes place at 1 ns and the voltage source in the detector circuit has the output voltage of 40 V. In addition the circuit has a series resistor of 100 ohms. The center of the square cell is an area of low electrical fields and thus the simulation represents the worst case scenario for the proposed structure. The result in Fig. 6 shows, that the signal charge will be collected in less than 20 ns. It is well known, that the dependence of the charge collection time on the hit location in the 3D detector cell and on the bias voltage are general properties of the 3D structures. The charge collection at high bias and high field points can be very fast i.e. in the order of a few nanoseconds. On the other hand every 3D structure exhibit low field regions, where the charge collection time becomes much slower. The present simulation result indicate, that the charge collection capability of the the semi 3D structure is comparable to the other 3D detectors.

**IV. CONCLUSION**

A new 3D detector structure was proposed. The current structure employs one type (p-type) of vertical doping profiles, only. This feature makes the fabrication scheme of these devices much simpler than the corresponding process flows of the conventional 3D detectors. This simplification has led to an easy demonstration of large area pixel detectors. Moreover, the semi 3D detectors should be well compatible with the current packaging processes like the flip chip bonding.

The fabricated demonstrators were not optimized for any applications. However, these test structures indicate, that the semi 3D pixel structures have low leakage currents, low pixel capacitances and good radiation hardness. Moreover, these structures can also be fabricated on the CZ silicon as well as on the traditional FZ detector starting material.

The true 3D simulations can give a good insight into the detector physics resulting in e.g. the true pixel capacitance values. In addition, the transient simulation indicate, that the proposed semi 3D devices have charge collection properties, that are comparable to other 3D detector structures.

**V. REFERENCES**

Publication II

T. Palviainen, K. Leinonen, T. Tuuva, S. Eränen, J. Härkönen, P. Luukka, E. Tuovinen

“Investigation of voltages and electric fields in silicon semi 3D radiation detectors using Silvaco / ATLAS simulation tool and a scanning electron microscope”

Investigation of Voltages and Electric Fields in Silicon Semi 3D Radiation Detectors Using Silvaco / ATLAS Simulation Tool and a Scanning Electron Microscope

Tanjia Palviainen, Kari Leinonen, Tuure Tuuva, Simo Eränen, Jaakko Härkönen, Panja Luukka, and Esa Tuovinen

Abstract—The structure of silicon semi three-dimensional radiation detector is simulated on purpose to find out its electrical characteristics such as the depletion voltage and electric field. Two-dimensional simulation results are compared to voltage and electric field measurements done by a scanning electron microscope.

I. INTRODUCTION

The new architecture for solid-state radiation detectors using a three-dimensional array of electrodes that penetrate into the detector bulk were proposed by S.I. Parker, C.J. Kenney and J. Segal in the mid 90’s [1]. 3D detectors have many advantages: the devices can be fully depleted at low bias voltages, the speed of the charge collection is high, and the collection distances are about one order of magnitude less than those of planar technology strip and pixel detectors with electrodes limited to the detector surface. Also the 3D detector devices exhibit high radiation tolerance, so the ability of the silicon detectors to operate after irradiation is increased.

Silicon semi 3D detectors have vertical p-type doping profiles. The vertical depth of the doping profiles is left as a variable [2]. The objective of this article is to present simulation results of silicon semi 3D radiation detector structure done by Silvaco ATLAS device simulation software [3] and show electric field measurement results done by a scanning electron microscope (SEM).

II. SILICON SEMI 3D RADIATION DETECTORS

A. Structure

The basic semi 3D detector structure is shown in Fig. 1 [2]. The structure has the p-type vertical doping profile. The depth of the p-type pillar is dependent on the diameter of the pillar.

Simulations are done using following dimensions: the diameter of the p-type pillar is 10µm, the depth of the doping profile is 150µm and the pitch between the p-type electrodes is 100µm. In addition to the p-type doping pillar, the front side of the detector has a p-type implantation around the pillar. The dimensions of this implantation used in simulations are 40µm and 90µm. There is also a square contact window in each pixel of the detector and the pixels are connected as strips with the aluminum lines. The backside of the structure is a uniform implantation similar to the planar detectors. The backside of the device is the n-type electrode. The top of the layout is shown in Fig. 2.
B. Simulation Results

Simulations and SEM measurements are done using 0 V, -10 V, -40 V and -80 V. The potential figures with varied voltages of the silicon semi 3D radiation detector structure are shown in simulation results (Fig. 4-7). In the simulated figures there are shown three p-type pillars penetrating to the detector bulk. P-type pillars are anodes and the cathode is placed on the backside of the detector. The negative bias voltages are applied to the anode while the cathode remains at zero. The colour scheme describes the potential distribution inside the detector structure. The color scheme in simulation figures and SEM measurements is continues rainbow spectrum where the most positive voltage is red and the most negative voltage is bright magenta.

C. SEM Measurements

Scanning electron microscope is used to investigate the properties of the silicon semi 3D radiation detectors. Usually the main methods used for this are: capacitance-voltage (CV) measurements and transient current technique (TCT). Both of these methods are macroscopic and secondary. Instead, scanning electron microscope provides an accurate microscopic means of imaging and measuring the desired quantities more directly from the sample as a function of position. The scanning electron microscope method is probably the only way to measure and view the potential distribution inside a semiconductor device directly [4].

Fig. 8 shows the SEM measurement when there is no voltage connected. The potential differences are only seen between p-type pillars in the structure. When there is 10 V connected in Fig. 9, the potential differences begin to show between the end of the pillars and the backside of the structure. The potential spreads downwards. When 40 V is connected also the potential of the front side starts to spread between p-type pillars (Fig. 10). And in the Fig. 11 where is 80 V applied, the space between pillars is almost in the same potential. The simulation results show the same phenomenon.

When SEM measurements are compared to simulation results it can be seen that there is a correspondence. Both results show the properties of semi 3D detector: the semi 3D detector structure is fully depleted at low voltages, and with the high bias the electric field is mainly formed between the end of the pillars and the backside.

There are also facts, which may cause differences between simulation results and SEM measurements. First of all, the simulation results are ideal and in simulations there has not taken into account oxide charge or surface states, which affect to the depleted area. Second, the SEM photographs differ from simulation results because the relation between contrast and voltage is not linear all the time. With small voltages (under -20 V) the relation between contrast and voltage is close to linear but with bigger voltages the change of the potential does not affect to the change of the contrast linearly [4].

The SEM photographs of the silicon semi 3D radiation detector structure are shown in Fig. 8-11.
Fig. 4. Potential of semi 3D detector structure at 0V of bias.

Fig. 5. Potential of semi 3D detector structure at -10V of bias.

Fig. 6. Potential of semi 3D detector structure at -40V of bias.

Fig. 7. Potential of semi 3D detector structure at -80V of bias.

Fig. 8. SEM measurement of the semi 3D structure using 0V.

Fig. 9. SEM measurement of the semi 3D structure using -10V.

Fig. 10. SEM measurement of the semi 3D structure using -40V.

Fig. 11. SEM measurement of the semi 3D structure using -80V.
III. CONCLUSION

Bias voltage used in simulations varied between 0 V and -80 V. Potential figures show that the semi 3D detector structure is fully depleted at low voltages (between -10 V and -40 V in these simulations). Because of the structure of the semi 3D detector, the charge-collecting field is only below the pillars where the electric field has formed.

SEM measurements verify the simulation results. However, simulation results are ideal, for instance no oxide charge or surface states were included, which affects the spreading of the depletion layer.

REFERENCES

Publication III

K. Leinonen, T. Palviainen, T. Tuuva, E. Tuovinen, J. Härkönen and P. Luukka

“Investigation of type inversion of n-bulk in 10 MeV proton-irradiated FZ silicon detectors using a scanning electron microscope”

Investigation of type inversion of n-bulk in 10 MeV proton-irradiated FZ silicon detectors using a scanning electron microscope

Kari Leinonen\textsuperscript{a,\*,b}, Tanja Palviainen\textsuperscript{a}, Tuure Tuuva\textsuperscript{a}, Esa Tuovinen\textsuperscript{b}, Jaakko Härkönen\textsuperscript{b}, Panja Luukka\textsuperscript{b}

\textsuperscript{a}Lappeenranta University of Technology, P.O. Box 20, Lappeenranta, FIN-53851, Finland
\textsuperscript{b}Helsinki Institute of Physics, P.O. Box 64, Helsinki University, FIN-00014, Finland

Received 28 April 2005; accepted 5 July 2005
Available online 26 July 2005

Abstract

Based on the results of capacitance–voltage measurements and transient current technique, it was earlier deduced that the n-type bulk of float zone silicon radiation detectors changes type in heavy irradiation. This paper describes the results of measuring the voltages and electric fields with a scanning electron microscope using the voltage-contrast effect, inside radiation detectors that were irradiated with 10 MeV protons with several fluences. The results confirm the earlier observations and give more accuracy to the electric field measurements. © 2005 Elsevier B.V. All rights reserved.

PACS: 29.40; 29.40.W; 61.16.B; 84.37

Keywords: Radiation detector; Silicon; Radiation tolerance; Type inversion; Voltage; Electric field

1. Introduction

Silicon detectors used in high-energy physics experiments are exposed to a very hostile radiation environment. An upgrade of the CERN LHC (Large Hadron Collider) luminosity up to \(10^{35} \text{cm}^{-2} \text{s}^{-1}\) (Super-LHC) has been proposed. This would raise the fluences of fast hadrons up to \(10^{16} \text{cm}^{-2}\), well beyond the operational limits of present silicon detectors [1]. Particle radiation causes irreversible crystallographic defects in the silicon material. Defects generated by radiation cause, e.g., variation of the effective doping concentration \(N_{\text{eff}}\) and consequently of the full-depletion voltage \(V_{\text{dep}}\). The microscopic mechanisms related to the \(N_{\text{eff}}\) variation in n-type float zone (FZ) silicon are the donor removal and...
generation and the deep acceptor generation. By increasing the fluence, $N_{\text{eff}}$ decreases up to semiconductor-type inversion, i.e. the density of the radiation-induced deep acceptors causes $N_{\text{eff}}$ to become negative [2].

Type inversion has been investigated with a few methods: capacitance–voltage (CV) measurements which yield the depletion voltage and the effective doping concentration, transient current technique (TCT) which gives information about the position of the electric field maximum inside the detector through observing the shape and the delay of a current pulse after generating carriers near one surface of the detector with a short laser pulse [3,4], optical beam-induced current (OBIC) [5] and measuring the surface potential with a mechanical probe from a cleaved sample [5]. The electric field profile has also been calculated based on the material data got from various macroscopic measurements [6].

The voltage-contrast phenomenon of the scanning electron microscope can be used to measure electric potentials and fields in a biased radiation detector with an accurate non-touching microscopic probe [7]. In this paper, this method is applied to irradiated pad detectors to get more accurate information about semiconductor-type inversion.

2. Sample preparation

One hundred millimeter diameter n-type 300 μm thick (100)-oriented FZ silicon wafers with a nominal resistivity of 1200 Ω cm, manufactured by Wacker, were used in this study. Using a very simple five-mask-level process, p$^+$/n$^-$/n$^-$ diodes were processed at the Microelectronics Center of Helsinki University of Technology. The p$^+$-implanted area of the diodes is 5 mm x 5 mm. One 100 μm wide guard ring surrounds the active area (the pad). This wide guard ring is surrounded by a multi-guard ring structure of 16 rings, each with a width of 16 μm. The detailed device structure is presented in Ref. [1]. The processing is described more in detail in Ref. [8]. The full-depletion voltage, extracted from capacitance–voltage measurements, is about 260 V. The leakage current at full-depletion was less than 5 nA for all diodes. Randomly selected diodes were measured above the full-depletion voltage, up to 1000 V, without observing breakdown [9].

The samples were irradiated with 10 MeV protons at the Jyväskylä University Accelerator Laboratory. Diodes were first glued with photore sist on ceramic supports so that four diodes were always placed on one support. Samples were placed inside a vacuum chamber at the end of RADiation Effects Facility (RADEF) beam line [10]. The intensity of the proton beam was typically 2 nA/cm$^2$. Samples were kept at −10 °C during the irradiation.

After the irradiations with 10 MeV protons, the samples were kept refrigerated below room temperature. Full-depletion voltages ($V_{\text{dep}}$) and effective doping concentrations ($N_{\text{eff}}$) were resolved by capacitance–voltage (CV) measurements at 10 kHz in parallel mode. The results are presented in Fig. 1. $V_{\text{dep}}$ values have been normalized to 300 μm thickness.

Three samples were selected for scanning electron microscope tests: radiation fluences 0 (no irradiation) and 2.53E13 and 1.50E14 p/cm$^2$. The latter two correspond to 1 MeV equivalent neutron fluence of 1.09E14 and 6.45E14 cm$^{-2}$. In the first detector, we expect to find a normal pn-junction near the front side (p$^+$-side) of the detector. The third detector is supposed to have
its pn-junction near the back side (n+)-side because the fluence is clearly above the kink of the solid curve in Fig. 1. It is assumed that at the kink the n-type bulk is fully compensated, i.e. intrinsic, and after that deep acceptor generation turns the bulk p-type. The second detector is a very interesting case because it is very near to the kink in Fig. 1.

For cross-section measurements, the sample chips were cut into two halves with an ordinary diamond pen and bending method: pressing half of the chip with a line ruler on paper towels and making a short scribe at the edge of the chip which makes the chip break along the (\(1\ 1\ 0\)) crystal plane. The chip breaks naturally along the (\(1\ 1\ 0\)) plane producing a clean surface that is exactly perpendicular to the wafer surface. The electric field will not bend near this perpendicular surface, which is essential for the correctness of the electric field measurement.

After cutting, the samples were usually placed into the SEM vacuum chamber within 10 min. A few hours in atmosphere did not influence the measurement, but a prolonged storage (weeks or months) in atmosphere at room temperature (and a thicker native oxide) can make the measurement impossible.

3. Electron microscopy

During voltage-contrast measurements in the SEM, the front side (p+) was at zero potential, and a positive voltage was applied to the back side (n+). The measurement system is explained in Ref. [7]. In this study, we spent 80 s to make one line scan of about 400 \(\mu\)m, which makes the scanning speed to be 5 \(\mu\)m s\(^{-1}\). The contrast \(C\) is converted to voltage \(V\) according to the equation

\[
V = -M \ln(1 + C/K)
\]

where the contrast scaling factor \(K\) and the voltage constant \(M\) are found by the procedure described in Ref. [7].

In heavily irradiated detectors, we expect most of the change in potential to take place near the back side of the detector. This could distort the voltage contrast in areas where the potential is near zero. In Ref. [7] we did not take such a proximity effect into account, but instead supposed that a high positive bias only lowers the contrast uniformly. This assumption was now tested by placing a thin insulator between the back side of the detector and the specimen holder and applying a positive voltage to the specimen holder back side while the specimen holder front side and the specimen itself (discarding built-in potentials) were at zero potential. The result is shown in Fig. 2 for zero bias and two high-bias voltages. The only proximity effect is seen surprisingly at zero bias. This is because the insulator was charged during image watching before the first line scan. After 25 min when making the scans with higher voltages, the insulator was discharged and no proximity effect is seen in detector thickness scale, and we can still use pure Eq. (1) to convert the contrast to voltage.

All SEM measurements were made at room temperature. The detector current was measured in situ during each voltage-contrast line scan.

4. Results

4.1. Non-irradiated sample

Fig. 3 displays the measured voltage as a function of distance from the front surface (p) in the non-irradiated sample at eight bias voltages.
The result is very near to the theoretical one except for the noise above 40 V. Assuming no voltage drop in the undepleted bulk, the bias voltages is across the depletion layer. Thus, we can see the spreading of the depletion layer as a function of bias voltage. Also, it is worth noting that the lowest curve, with zero bias, deviates from zero. This is not surprising, because with this method the built-in potential can also be seen.

The first derivative of the voltage yields the electric field

\[ E = -\frac{dV}{dx}. \]  

Differentiating the voltage data of Fig. 3 point-by-point produces the electric field as a function of position as displayed in Fig. 4. The electric field is negative according to standard axis definition; positive x-axis points to right, where the positive bias voltage is applied. The point-by-point differentiation again increases the noise above 40 V bias.

In theory, the negative peaks of the field curves should show the pn-junction depth and be at the same distance at every bias voltage. The processed junction depth is assumed to be 3 µm. The set of curves in Fig. 4 clearly overestimates this, specially at higher bias voltages. The reason for this is that the depth of the pn-junction is only a very small portion of the total inspected distance, the number of measurement points before the junction being less than 10 out of a total 800 points. The inevitable noise reduction by averaging also distorts the original signal near the surface. For this purpose it will do, and we have not increased the resolution, although it would be technically possible.

4.2. Highest fluence

In the sample irradiated with 6.45E14 n_{eq}/cm^2, we expect that the situation is almost reversed compared with the non-irradiated case. The n-type bulk is expected to be inverted to p-type, and the pn-junction is expected to reside near the back side of the detector.

Fig. 5 presents the results of measuring the potential distribution inside the detector irradiated with the highest fluence. Clearly, the detector starts to deplete from the back when increasing the bias voltage, which indicates that the pn-junction really has moved to the back side of the detector and the bulk has reversed its type from n to p.

After differentiating the voltage data of Fig. 5 we get the electric field curves as shown in Fig. 6. Specially at higher bias voltages, the curves in Figs. 5 and 6 have non-ideal features. The largest electric field appears near the back side at a distance of 15–20 µm from the back surface, which is the electrical pn-junction depth. There is, however, a smaller peak of the electric field near the front surface. The field curves indicate that the bulk is not yet fully depleted at the highest measurement voltage 100 V. These two imply that
there is a pn-junction also near the front surface. A small electric field exists throughout the bulk. The leakage current in the irradiated detectors is very high, maximum 50 μA, during this measurement. Using the resistivity of intrinsic silicon, 235 kΩ cm, bare leakage current is calculated to form a voltage difference of 3 V in the examined piece of silicon, which is not enough to explain all the bulk field.

4.3. Intermediate fluence

Fig. 7 displays the voltage as a function of distance from the front surface at eight bias voltages in the sample irradiated with 1 MeV neutron equivalent fluence of 6.45E14 cm⁻².

Fig. 7. Voltage as a function of distance from the front surface at eight bias voltages from 0 to 100 V in the sample irradiated with 1 MeV neutron equivalent fluence of 1.09E14 cm⁻².

4.3. Intermediate fluence

5. Discussion

From TCT measurements, the form of the electric field can be approximated. The overall
intensity of the field is very much determined by the applied bias voltage and detector thickness. The SEM measurements presented here provide a similar magnitude but a different shape. When studying an irradiated FZ detector, a simulation model used with TCT measurements yields a stepwise linearly changing electric field with two peaks located at the front and back contacts [11]. These SEM measurements show the same two peaks, but at some meaningful distance from the contacts. At the contacts, the electric field should be zero.

The calculation of the electric fields in Ref. [6] gives the same magnitude more accurately but a different shape compared with these SEM results. For irradiated detectors two peaks are present there, but they are located at the contacts just as in the TCT results.

OBIC measurements [5] result in very similar shapes of the electric field as found in this examination, the peaks being at some distance from the front and back contacts.

According to these SEM measurements, already a fluence of 1.09E14 neq/cm² inverts the lightly doped n-bulk to p-type at least partly, so that the detector starts to deplete from the back side with small bias voltages. When increasing the bias voltage, a separate electric field starts to form also near the front side of the detector. In lightly irradiated detectors, this front side pn-junction is finally found to be the principal one. In heavily irradiated detectors, the back side junction is the most important.

In principle, the number of pn-junctions should be odd in a structure like this. A third pn-junction between these two observed junctions is forward-biased and very gently graded in an almost intrinsic area and thus difficult to locate. It must be emphasized that small peaks of the electric field in the data of this examination are due to noise caused by point-by-point numerical differentiation and not due to a third junction.

6. Conclusion

In the cross-section of a non-irradiated silicon radiation detector, the voltage-contrast measurement with a scanning electron microscope yielded exactly the same electric potential and field curves which were predicted in theory.

In a heavily irradiated detector (1 MeV neutron equivalent fluence of 6.45E14 cm⁻²), the principal pn-junction and electric field were found near the back side. A secondary pn-junction existed very near the front side, probably at the site of the original manufactured junction. In a sample irradiated with an intermediate fluence of 1 MeV neutron equivalent fluence of 1.09E14 cm⁻² the depletion started from the pn-junction located at 25-40 µm from the back side. At larger bias voltages, the principal pn-junction was found at 45 µm from the front side and a smaller part of the total electric field lay near the back side of the detector.

Already small irradiation fluences compared to the requirements of the proposed Super-LHC fluence of fast hadrons up to 10¹⁶ cm⁻² change the electrical behaviour of FZ silicon radiation detectors dramatically.

The claim that the original p⁺/n-junction is always preserved even after heavy irradiation [12] is also found to be true in this investigation.

Acknowledgements

This work has been performed in the framework of CERN RD50 Collaboration.

References


Publication IV

T. Palviainen, T. Tuuva, K. Leinonen

“Minimizing guard ring dead space in the Si detector with n-guard ring at the edge of the detector”

Minimizing guard ring dead space in silicon detectors with an n-type guard ring at the edge of the detector

Tanja Palviainen*, Tuure Tuuva, Kari Leinonen
Lappeenranta University of Technology, P.O. Box 20, FIN-53851 Lappeenranta, Finland
Available online 28 November 2006

Abstract
Detectors with n-type silicon with an n+ type guard ring were investigated. In the present work, a new p+/n/n+ detector structure with an n+ guard ring is described. The guard ring is placed at the edge of the detector. The detector depletion region extends also sideways, allowing for signal collection very close to the n-guard ring. In this kind of detector structure, the dead space of the detector is minimized to be only below the guard ring. This is proved by simulations done using Silvaco/ATLAS software.

Keywords: Silicon-based detector; Simulation of detector; Detector characterization; Guard ring; Dead space

1. Introduction
Silicon detectors in high-energy physics experiments require a reliable performance under irradiation. Minimizing dead space is an additional advantage as it enhances the efficiency of a detector [1]. The guard ring technique has evolved to minimize dead space at the edge of detectors. Also the guard ring structure is used to improve the breakdown performance of silicon detectors.

Detectors collect charge from the depletion region. It is, therefore, important to minimize dead space, from where it is not possible to collect charge. Usually depletion forms vertically from anode to cathode, but in this application, where there is an n-type guard ring at the edge of the detector the depletion region also extends sideways. This phenomenon is due to the cathode and the guard ring being of the same doping type. The remaining dead space is only directly under the guard ring.

2. Structure
Fig. 1 describes the structure of the proposed new p+/n/n+ detector structure with the n+ guard ring. The guard ring is placed at the edge of the detector and the distance from the p+ anode to the guard ring is 200 μm. The depth of the pn-junction and the n-type guard ring is 3 μm. The width of the guard ring is 3 μm as well.

3. Simulation results
Simulations were done using Silvaco Virtual Wafer Fab (VWF) software, which is a simulation tool for electronic design. It includes different kinds of tools for device and process simulation [2]. ATLAS [2] software is meant for use in the design and development of all types of semiconductor devices. Silvaco is a physics-based simulator, which predicts electrical characteristics associated with specific physical structures and conditions [2].

Simulation results of the p+/n/n+ detector structure with n+ guard ring are presented below. The simulations were done using high resistivity silicon (ρ is ≈ 4 kΩ cm). The voltage required for the full depletion of the device has been calculated to be −70 V. In these simulations, −70 V is applied to the p-type anode (A in Fig. 2). The cathode (K in Fig. 2) covers the full backside of the detector. A bias voltage is applied to the anode and the cathode is connected to zero potential. The guard ring (g in Fig. 2) is connected to the cathode.
3.1. Potential

Fig. 2 shows the simulated potential of the detector. A voltage of \(-70\) V is applied to the anode. With that potential, the device is fully depleted.

3.2. Leakage current

Fig. 3 shows the simulated leakage current of the detector as a function of the anode bias up to \(-70\) V. The leakage current curve flattens towards \(-70\) V indicating full depletion of the structure.

3.3. Electric field

Fig. 4 shows the simulated electric field inside the detector. A strong electric field is formed at the end of the p-type anode.

4. Conclusions and future developments

In the detector structure described in this paper, the charge collection area is extended sideways towards the
n-type guard ring, hence minimizing the total dead space at the detector edge. We expect that by adding an extra electrode ring at the edge on the cathode side of the detector, we can further extend the charge collection area. Although this would require double-sided processing of the wafers, the lithographical requirements for the backside are less stringent than for the frontside of the detector. There is also a possibility to have n"-doping along the full edge of the detector to achieve full depletion up to the edge of the detector but this would require special processing.

References

Publication V

T. Grönlund, Z. Li, G. Carini, M. Li

“Full 3D simulations of BNL one-sided silicon 3D detectors and comparisons with other types of 3D detectors”

Full 3D simulations of BNL one-sided silicon 3D detectors and comparisons with other types of 3D detectors

Tanja Grönlund\textsuperscript{a,b*}, Zheng Li\textsuperscript{a}, Gabriella Carini\textsuperscript{a}, and Michael Li\textsuperscript{a, **}

\textsuperscript{a}Brookhaven National Laboratory, Upton, NY, USA
\textsuperscript{b}Lappeenranta University of Technology, Lappeenranta, Finland

Abstract

Full 3D simulations have been carried out on the BNL one-sided single-type column and dual-type column 3D Si detectors (p-type substrate). Due to the facts that columns are not etched all the way through, all electrodes are on the front side, and the backside was not supported nor processed at all, the BNL one-sided 3D detectors are true one-sided detectors. Simulations show that the volume under the columns where it is supposed to be dead space (about 10%) can be depleted at high biases with some modest electric field, leading to the possibility of recovering some sensitivity from this region. This region can also provide some sensitivity to particle tracks directly through the columns. The dual-type column detectors are the best in radiation hardness due to their low depletion voltages and short drift distances. Single-type column detectors are more radiation hard than the planar detectors due to their lower depletion voltages. Single-type column detectors are easier to process than dual-type column detectors, but have a more complicated, non-uniform electric field profile. The BNL one-sided 3D detectors were compared to various 3D detector structures developed by other institutes. The field profiles for all types of dual-type column 3D detectors are similar with just some minor differences on both surfaces.
(front and back). The BNL single-type column one-sided 3D detectors have some major difference from the Trento ones: 1) the high electric field is on the sensing electrode side (pixel or strip); and 2) it can develop some high electric field along the junction column as bias voltage increases.

PACS: 29.40

Keywords: silicon detectors, 3D sensors, 3D detectors, device simulation, electric field

*Corresponding author: Lappeenranta University of Technology, P.O. Box 20, FIN-53851 Lappeenranta, Finland, tel.: +358-5-6216764, fax: +358-5-6216799, email: tanja.gronlund@lut.fi.

**Permanent address: 30 Hancock Ct., S. Setauket, NY, 11973, USA

1. Introduction

To achieve some of the prime goals of high energy physic experiments – for example the discovery and possible study of Higgs-particles – silicon detectors have to operate in extremely harsh radiation environments. In the proposed upgrade of LHC (Super-LHC, SLHC), the increase of the maximal fluence and the beam luminosity up to $10^{16}$ n$_{eq}$/cm$^2$ and $10^{35}$ cm$^{-2}$s$^{-1}$, respectively, will require detectors with dramatic improvement in radiation hardness. Therefore, the main goals of detector development for the SLHC are concentrated on the technologies that minimize the radiation degradation and/or maximize the detector radiation tolerance. The interest for the 3D silicon detectors is continuously growing because of their many advantages as compared to
conventional planar detectors: the devices can be fully depleted at low bias voltages, the speed of
the charge collection is high, and the collection distances are about one order of magnitude less
than those of planar technology strip and pixel detectors with electrodes limited to the detector
surface. Also the 3D detectors exhibit high radiation tolerance, so the ability of the silicon
detectors to operate after irradiation is increased.

The architecture for solid-state radiation detectors using a three-dimensional array of
electrodes that penetrate into the detector bulk were proposed by S.I. Parker, C.J. Kenney and J.
Segal in the mid 90’s [1]. This standard design of 3D detectors present columnar electrodes of
both doping types arranged in adjacent cell and penetrated through the silicon substrate.
However, the fabrication process of standard 3D detectors is rather difficult. The difficulty in
processing for standard 3D Si detector we referred here is mainly the need for wafer bonding
(supporting wafer) for mechanical strength, especially for edge-sensitivity in standard 3D Si
detector, and possible double-sided processing. We have made the first prototype of single-type
column 3D Si detectors, where the n⁺ columns were etched by CNM using the well calibrated,
uniform etching rate to get 270 µm deep columns with a few percent in variations, which will
result in some difference in the depth of the volume under the columns [2]. However as we will
show late in simulations, since the volume under the columns may be largely depleted at high
enough biases, the variation in the dead volume under the column may be minimum. Better
control in etching rate can reduced this variation even more, which is one of the areas we are
trying to improve in the technology.

In this paper, we will present simulations for two single-sided 3D detector designs [2],
one with the single type (n-type) of the columns and the other one with dual type of the columns
(n and p-type) on the p-type substrates. With full 3D simulations of different detector types, we
will demonstrate that one can achieve similar electric field profile between BNL dual column 3D
detector and other dual column 3D detectors developed by other institutes with benefit of the true
one-sided process. In the case of the BNL single type column detector we will show that the high
electric field is on the pixel side, which is the sensing area.

2. Full 3D simulations and device description

Full 3D simulations on 3D Si detectors were performed using the DEVICE3D package of ATLAS Silvaco [3]. The numerical simulations were aimed to investigate the electric field profiles in various 3D detectors. The strength of the electric field with the applied voltage when the full depletion is reached, expresses the high and low field areas in the detector and its sensitivity for particles. A sketch of the BNL one-sided single-type column detector is shown in Fig. 1. The columnar electrodes are all of the same type (n-type here), which are of the type opposite to the substrate one (p-type here) and they extend to 270 µm into the 300 µm deep bulk. The ohmic contacts are achieved by placing two ion-implanted electrodes (p-type here) on the front surface, in the other two corners in a simulation cell as shown in Fig. 1b, where a minimum cell for simulation and a unit cell for the detector are also shown. The backside is covered by a uniform silicon oxide layer and is never processed, so the process is a true one-sided. The n⁺ electrodes (columns) and p⁺ electrodes (implants) are covered with aluminum layers on the detector surface. Other areas of the detector front side are covered with silicon oxide. One unit cell is simulated with two n-type columns on the opposite corners and two p-implants (0.5 µm deep) in the other corners. In our simulation here, n⁺ columns are surrounded by p-stops as marked in Fig. 1b. Note here that p-spray technology may not be used here since this will short
all the p⁺ electrodes together, and place them in contact with the n⁺ electrodes, which can easily cause breakdown along the surface.

Fig. 1. Sketch of a BNL one-sided single-type column 3D detector, a) a 3D cell in the simulation and b) top view of a minimum cell for simulation and a unit cell for the detector.

A sketch of the BNL dual-type column detector is shown in Fig. 2. In this structure there are two n-type and two p-type doped columns on p-type substrate. Same types of doped columns are placed to the opposite corners in the simulation cell. All the columns are placed on the front side of the detector and they extend 270 µm into the 300 µm thick p-type bulk. N-type columns
are surrounded by p-stops again similar to the previous case. The backside is covered by a uniform silicon oxide layer and is never processed, so the process is again true single-sided.

Fig. 2. Sketch of a one-sided dual-type column 3D detector, a) a 3D cell in the simulation and b) top view of a minimum cell for simulation. The unit cell for the detector is similar as one shown in Fig. 1b.

In the simulations the p-type substrate doping concentration was $1 \times 10^{12}$ cm$^{-3}$ in all cases. The edge of the cell is 70 µm, while the edge of the electrode is 10 µm. Then the distance between the electrodes is 50 µm.

For a planar detector, the depletion voltage $V_{fd}$ needed to fully deplete the detector varies with doping concentration and substrate thickness by [4]:

$$V_{fd} \propto \frac{1}{n^+} \frac{1}{x}$$
Very often the built-in voltage $V_{bi}$ is neglected since the depletion voltage is in most cases more than one order of magnitude higher.

In 3D detectors, the depletion grows laterally from the electrodes as the bias voltage is increased. For dual-type column 3D detectors, the substrate is fully depleted when the depletion region extends fully from the n-type column to the adjacent p-type column. For single-type column 3D detectors, the depletion region may have depth dependence (in thickness direction), but nevertheless, the full depletion can be reached when the depletion zones of two adjacent n-type columns (in our case) are joined near the bottom of the columns. We can estimate the full depletion voltage for a dual-column 3D detector as shown in Fig. 2 with $N_{eff} = 1 \times 10^{12}$ cm$^{-3}$ and column spacing of $t = 50$ µm: it is approximately 5 volts. It is clear that one of the main advantages for 3D detectors is its low full depletion voltage due to the dense placement of the electrodes; the depletion distance $t$ is independent of detector thickness $d$, and can be made much shorter than $d$. For example, the full depletion voltage of a 300 µm thick 3D detector with electrode placement distance of 50 µm is about 5 volts, as compared to 68 volts for the equivalent planar 300 µm thick 2D device. However, the actual simulated full depletion voltage, obtained from our 3D simulation, for a 3D detector can be slightly higher (about a factor of 1.4 higher) than that estimated using Eq. (1), due mainly to the small electrode effect.

3. Electric field simulation
The sensitive region of a detector can be seen from the simulated electric field profile in the detector. BNL one-sided single-type column detectors have the high electric field region on pixel side (front side) of the detector and along the n-type columns, as shown in Fig. 3 for a simulation cell shown in Fig. 1. The bias voltage here is 100 volts on the n-type electrodes with respect to 0 volts on the p-type electrodes. It is clear that the electric field is highly non-uniform, and is the lowest in the volume directly under the p-type electrodes which are only implants on the front surface.

Fig. 3. Simulated 3D electric field profile in a BNL one-sided single-type column 3D detector at 100 V bias.
Fig. 4. A 2D cut plane of the simulated electric field in a BNL one-side single-type column 3D detector at 100 V bias.

To see the electric field inside the detector in more details, we plot a 2D cut plane along the two n-type columns in Fig. 4. From the figure, we can observe that, for BNL one-sided single-type column 3D detectors biased at 100 volts: 1) the front side (or pixel side) is with the highest field, and it extends about 30 µm into the detector; 2) there are high field along the n⁺ columns.
columns all the way through the detector with a volume of about 2/5 of that between the n⁺ columns; 3) the medium field between the n⁺ columns also occupies about 2/5 of the volume; 4) the lowest field is near the middle of the two n⁺ columns, which occupies about 1/5 of the volume; and 5) there are some medium to low fields (on average of about 300-400 V/cm²) in the volume under the n⁺ columns (30 µm depth). So the volume under the columns may be depleted to a degree that can make this volume with some sensitivity to particles as well. In this volume, the largest drift distance for electrons is larger number of the depth of this region (30 µm) and the electrode spacing (50 µm), that is 50 µm in our case. It will take about 9 ns for electrons to drift to an n electrode column, which can be done even with the 25 ns shaping time for SLHC. So in this sense, the volume under the column may not be entirely dead. Point 5) also raised the possibility that the volumes directly under the n⁺ columns may serve as way to recover some sensitivities from the supposed dead volumes of the n⁺ columns themselves. It is interesting to note here that the simulated full depletion voltage for the BNL one-side single-type column 3D detectors shown in Fig. 1 is much smaller (5-10 volts) than that of planar detectors (80 volts) with the same thickness and resistivity. In this aspect, this type of 3D Si detector may be more radiation tolerant than the 2D planar Si detectors, especially after modest fluence (>1x10¹⁴ nₑq/cm²) when the Nₑq becomes higher and electric field becomes better. This last point was first systematically simulated by Trento for their single-type column 3D Si detector [5], where detectors built on lower initial resistivity initial material have shown better electric field profiles. However, higher voltage than the full depletion voltage should be used to get some high field near the back of the detector. Also, the longest drift length for a particle-generated free carrier (holes here) is still the whole detector thickness that can be much larger than the column spacing,
one may lose the contribution to CCE of one type of carrier (holes here) at very high radiation fluences (>2x10^{15} \text{neq/cm}^2).

Fig. 5. A 2D cut plane of the simulated electric field in a BNL one-sided single-type column 3D detector at 200 V bias.
To see the bias voltage effect on this type of 3D detectors, we plot a 2D cut plane for the same detector as shown in Fig. 3 and 4, this time the bias is increased to 200 volts. As it can be seen, the main change here is in the Point 1) as listed above: the high field region near the front surface is extended to about 80 µm into the detector bulk as compared to 30 µm in the case of 100 volts. Points 2-5 are almost the same as those for the 100 volts case.

It is interesting to compare the field profiles between the BNL one-sided single-type column 3D detector and the Trento single-type column 3D detector proposed early by ITC-IRST (Trento) [5-6]. In a Trento single-type column 3D detector, n-type columns are placed in every corner in one cell: i.e. n⁺ columns in places where p⁺ implants are located (Fig. 1) for the BNL one-sided single-type column 3D detector. The p⁺ ohmic contact is a uniform p⁺ ion implant on the backside. Fig. 6 shows the 2D electric field profiles of the two types of 3D detectors at 100 volts along a cut plane between the two n⁺ columns. Field profile differences are clearly shown: 1) instead of high field on the pixel side (BNL), the high field in a Trento detector is near the backside; 2) instead of some high field developed along the n⁺ columns all through the column length (BNL), half of the n⁺ columns length near the pixel side is with low field in a Trento detector; and 3) in fact, most volume under the pixel (about 40% of the detector volume) is with low field in a Trento detector. BNL one-sided single-type column 3D detector provides better field distribution, and may therefore give better charge collection performance.
Fig. 6. Comparison of electric field profiles between two types of single-type column 3D detectors operated at 100 V bias. The 2D cut plane is along the two n⁺ columns.

The 3D electric field profile of a BNL one-sided dual-type column 3D detector (Fig. 2) operated at 40 volts is shown in Fig. 7. It is clear that high field is distributed all along the n⁺ and p⁺ columns, and throughout the detector. Again, similar to the BNL one-sided single-type column 3D detector, there are some fields developed under the columns near the backside, which could provide extra sensitive regions for the detector. However, the field profile is still highly non-uniform as shown in a 2D cut plane in the middle of the detector (at half of the detector thickness, 150 µm). The low field is near the center between the four electrode columns in a cell, and the field is zero right at the center point (saddle point). This low filed region is common for all dual column 3D detectors, which is due to the symmetry in the detector cell. This is similar to the 2D multi-electrode, planar sensors where there exists a zero field line (point) parallel to the top surface midway between signal electrodes, also due to symmetry.
Fig. 7. Electric field profiles of a BNL one-sided dual-type column 3D detector operated at 40 V bias: a) 3D profile; b) 2D profile in a cut plane in the middle (Z = 150 µm).

The electric field profile in a dual-type column 3D Si detector is more uniform than that in a single-type column 3D Si detector: the non uniformity is minimum along the detector thickness, especially 20-30 µm away from either surfaces. The dual-type column 3D Si detector is easier to deplete at lower bias voltages than single-type column 3D detector. Comparing different dual-type column 3D detector structures: the standard one developed by Parker [1], the BNL one-sided one, and the double-sided one developed by CNM (Barcelona), where p-type and n-type columns are placed on the opposite surfaces [6], the electric field profiles are extremely similar in the vast bulk of the detectors, only minor differences are found on the surface of the detector at 100 V bias, as shown in Fig. 8.
Fig. 8. Comparison of electric field profiles between three types of dual-type column 3D detectors operated at 100 V bias. The 2D cut plane is along the two n+ columns.

In fact, one of the main differences among various types of dual-type column 3D detectors is the processing. BNL one-sided dual-type column 3D detector is true one-sided process: meaning both in terms of detector processing and detector access. It is clear that one-sided processing is much simpler and cheaper than double-sided one. Need to only access one side (front side in BNL case) for operation can also be simpler than that to access both sides, but in some cases, double-sided access may be desirable due to the fact that different type of voltages may be separated by the entire thickness of the detector. In the case of one-sided processing, the electrodes do not go all the way through the wafer, which makes the processing easier than the than standard 3D detectors – no support wafer and therefore wafer bonding are necessary. However a support wafer may be needed for the processing of an edgeless 3D detector (with edge sensitivity) to prevent detector chips from falling off in the deep reactive ion etcher.
The main advantages for dual-type column 3D Si detectors as compared to 2D planar detectors are: 1) much smaller full depletion bias (depletion between the columns, which can be made in the order of <70 µm, and is independent of detector thickness); 2) the drift distance is also much reduced in this way, which results in a fast signal, and much improved radiation hardness in terms of CCE if the column spacing is made in the same order of magnitude of that of the trapping distance $d_{tr}$ (or in a different term, charge collection distance $d_{CCE}$, at SLHC fluence, $d_{tr}$ can be in the order of 10’s of µm). These are in fact the main reasons that 3D Si detector is one of the detector options for the SLHC. The main disadvantages for dual-type column 3D detectors as compared to 2D planar ones are the field non-uniformity in the bulk (due to small electrodes in 3D detectors (10-20 µm diameter columns): the field is non-uniform in 2 dimensions (exclude the surfaces in standard 3D or the surface and the end of columns region in non-penetrating column 3D detectors) as compared to 1 dimension in 2D planar detectors; low or zero field region (the saddle point in the middle of the cell due to symmetry); and complexity in detector processing and possible lower yield. We note here that the field non-uniformity is even more, in 3 dimensions, in single-type column 3D detectors.

4. Weighting field simulation

The induction of signals in the electrodes of detectors is generally based on the Shockley-Ramo theorem [7-9]. The theorem states that the instantaneous current induced on a given electrode is equal to the products of the charge of the carrier, its drift velocity (which is proportional to the electric field as simulated before) and the weighting field $E_0$ [10]:

16
The weighting field can be simulated. Shown in Fig. 9 is the simulated weighting field for BNL one-sided single-type column detector and in Figure 10 are the weighting fields for BNL one-sided dual-type column detector and the double-sided dual-type column detector by CNM.

Fig. 9. The weighting field of BNL one-sided single-type column detector.
Fig. 10. The weighting fields of dual-type column detectors a) the BNL one-sided dual-type column detector and b) the double-sided dual-type column detector developed by CNM.

It is clear that the high weighting field region is mainly concentrated along the collecting column (n+ column here on the low left corner), extending all across the cell in the simulation. Details of the weighting field distribution can be seen more clearly from the 2D cut plane of the detector. In Figure 11 the BNL one-sided single and dual-type column detectors have been cut at 150 µm in the middle of the detector thickness. As shown in Fig. 11 b) for a BNL one-sided dual-type column 3D Si detector, the high weighting field exists within 30 µm from the collecting column, which is more than 60% of the cell length. Two low weighting field regions are present between the opposite n+ column and the p+ columns. This weighting field profile is similar for other types of dual-type column 3D Si detectors except near the surfaces.

As for the BNL one-sided single-type column 3D Si detector, the high weighting fields are concentrated near the two n+ columns, extending 25 µm away from the columns. Two low weighting field regions exist directly under the p+ implants.
Fig. 11. Weighting field cuts at 150 µm for a) BNL one-sided single-type column detector and b) BNL one-sided dual-type column detector.

For future studies and simulation, we plan to integrate the electric field and weighting field simulations such that one can calculate the actual induced current for various 3D Si detectors under various radiation fluences.

5. Conclusion

BNL one-sided single and dual-type column 3D Si detectors have been simulated in detail and compared to various other 3D detector structures. Dual-type column detectors are best in the radiation-hard, but single-type column detectors are easier to process since only one type of columns needs to be etched. Disadvantage of these single-type column detectors is the non-uniform electric field. In BNL one-sided single-type column 3D detectors, some high field can be
developed along the junction column. The advantages and disadvantages for various detector structures are concluded in Table 1.

In this paper we also reported on 3D simulations of weighting field profiles for different 3D detector structures. High weighting field has been found existing in more than half of the volume in a cell, which should be a good advantage for 3D detectors.

Acknowledgements

This research was supported by the U.S. Department of Energy: Contract No. DE-AC02-98CH10886.

References


Table 1
Summarizing comparison of the properties of different 3D detector structures.

<table>
<thead>
<tr>
<th>Structure</th>
<th>E-field profile</th>
<th>Rad-hardness</th>
<th>Mechanical integrity</th>
<th>Processing</th>
<th>Sides needed to access for operation</th>
<th>Sensitivity under the column</th>
</tr>
</thead>
<tbody>
<tr>
<td>Std 3d (UH)</td>
<td>Good</td>
<td>Super</td>
<td>Good with supporting wafer</td>
<td>Wafer bonding needed</td>
<td>Front side</td>
<td>Some reported [11]</td>
</tr>
<tr>
<td>BNL dual-C</td>
<td>Good</td>
<td>Added non-uniformity near the column tips</td>
<td>Good</td>
<td>True one-sided (backside not processed at all)</td>
<td>Front side</td>
<td>Some, the volume under the columns may be depleted</td>
</tr>
<tr>
<td>CNM dual-C</td>
<td>Good</td>
<td>Added non-uniformity near the column tips</td>
<td>Super</td>
<td>Double-sided</td>
<td>Front side and backside</td>
<td>Some, the volume under the columns may be depleted</td>
</tr>
<tr>
<td>BNL single-C</td>
<td>Low field on the back side, Higher degree of non-uniformity</td>
<td>Good</td>
<td>True one-sided (backside not processed at all)</td>
<td>Front side</td>
<td>Some, the volume under the columns may be depleted</td>
<td></td>
</tr>
<tr>
<td>Trento single-C</td>
<td>Low field on the front and center, Higher degree of non-uniformity</td>
<td>Good</td>
<td>One-sided (backside uniform ion implant and metallization)</td>
<td>Front side and backside</td>
<td>Some, the volume under the columns may be depleted</td>
<td></td>
</tr>
</tbody>
</table>
Figure captions

Fig. 1. Sketch of a BNL 3D detector featuring columnar electrodes of one doping type, a) detector unit cell and b) top view.

Fig. 2. Sketch of a BNL 3D detector featuring columnar electrodes of n- and p- doping type, a) detector unit cell and b) top view.

Fig. 3. Simulated 3D electric field profile in a BNL single type of column 3D detector at 100 V bias.

Fig. 4. A 2D cut plane of the simulated electric field in a BNL single type of column 3D detector at 100 V bias.

Fig. 5. A 2D cut plane of the simulated electric field in a BNL single type of column 3D detector at 200 V bias.

Fig. 6. Comparison of electric field profiles between two types of single column 3D detectors operated at 100 V bias. The 2D cut plane is along the two n⁺ columns.

Fig. 7. Electric field profiles of a BNL dual column 3D detector operated at 40 V bias: a) 3D profile; b) 2D profile in a cut plane in the middle.
Fig. 8. Comparison of electric field profiles between three types of dual column 3D detectors operated at 100 V bias. The 2D cut plane is along the two n⁺ columns.

Fig. 9. The weighting field of BNL single column detector.

Fig. 10. The weighting fields of dual column detectors a) the BNL dual column detector and b) the dual column detector developed by CNM.

Fig. 11. Weighting field cuts at 150 µm for a) BNL single column detector and b) BNL dual column detector.
Publication VI

Z. Li, T. Grönlund

“3D Simulation Studies of Irradiated BNL One-Sided Dual-column 3D Silicon Detector up to 1E16 n_{eq}/cm^2”
3D Simulation Studies of Irradiated BNL One-Sided Dual-column 3D Silicon Detector up to 1E16 neq/cm²

Zheng Li¹ and Tanja Grönlund¹,²
¹Brookhaven National Laboratory
²Lappeenranta University of Technology

Abstract

Full 3D simulations have been carried out on the BNL one-sided 2-column 3D Si detector (p-type substrate) at various irradiation levels up to 1E16 neq/cm². The n+ and p+ columns are not etched all the way through the wafer, leaving about 10% volume under the columns. The backside of the wafer is completed un-processed with a layer of SiO₂, and it is left floating during operation (true one-sided 3D detector). It has been shown that 1) simulated full depletion voltage $V_{fd}$ for a dual-column 3D detector is about 1.4 time higher than that of a 2D (planar) pad detector with a thickness $d$ the same as the column spacing $L_p$ in the 3D detector; 2) the highest E-field is near the n+ column, and high E-field mainly distributes between the n+ and p+ columns; 3) low E-field is between the two p+ columns, and the lowest E-field is in the center of the unit cell with two p+ columns and two n+ columns; 4) in order to fully deplete a dual-column 3D detector at 1E16 neq/cm² with a reasonable bias (≤ 200 V), the column spacing $L_p$ should be reduced to 30 µm; and 5) the volume under the columns (10% of the total volume) can be depleted with a modest bias (≤ 200 V), and this volume under the columns are not dead volume. In addition, this depletion volume can provide some detection sensitivity directly under the columns, which may reduce the effective dead volume in a 3D Si detector.

PACS:

Keywords: silicon detectors, 3D detectors, device simulation, irradiation, electric field, column spacing

Corresponding author: tel.; fax.; email: zhengl@bnl.gov.

1. Introduction

To achieve some of the high energy physics experiments prime goals – for example the discovery and possible study of Higgs-particles – the silicon detectors has to operate in extreme harsh radiation environment. In the proposed upgrade of LHC (Super-LHC, SLHC), the increase of the maximal fluence and the beam luminosity up to $10^{16}$ neq/cm² and $10^{35}$ cm⁻² s⁻¹ will require detectors with dramatic improvement in radiation hardness. Therefore, the main goals of detector development for the SLHC are concentrated on the technologies that minimize the radiation degradation. The interest for the 3D silicon detectors is continuously growing because of their many advantages against planar detectors: the devices can be fully depleted at low bias voltages, the speed of the charge collection is high, and the collection distances are about one order of magnitude less than those of planar technology strip and pixel detectors with electrodes limited to the detector surface. Also the 3D detectors exhibit high radiation tolerance, so the ability of the silicon detectors to operate after irradiation is increased.
The architecture for solid-state radiation detectors using a three-dimensional array of electrodes that penetrate into the detector bulk were proposed by S.I. Parker, C.J. Kenney and J. Segal in the mid 90’s [1]. This standard design of 3D detectors present columnar electrodes of both doping types arranged in adjacent cell and penetrated through the silicon substrate. In this paper, we present 3D detector design with dual type of the columns on the p-type substrates. The n+ and p+ columns are not etched all the way through the wafer, leaving about 10% volume under the columns. The backside of the wafer is completed un-processed with a layer of SiO₂, and it is left floating during operation so the process is true one-sided. With full 3D simulations, we present the dual column 3D detector properties under the irradiation and we show how to improve 3D detectors to face future high-energy physics demand of the beam luminosity up to $10^{16}$ neq/cm².

First, we compare the full depletion voltage between a planar 2D detector and a dual column 3D detector with a thickness $d$ the same as the column spacing $L_p$ in the 3D detector. As a result simulated full depletion voltage $V_{fd}$ for a dual-column 3D detector is about 1.4 time higher than that of a planar pad detector. Second, the electric field in the structure is studied. The highest electric field (E-field) is near the n+ column, and high E-field mainly distributes between the n+ and p+ columns. The low E-field is between the two p+ columns, and the lowest E-field is in the center of the unit cell with two p+ columns and two n+ columns as shown in simulations. For future development, achieve a fully depletion in a dual-column 3D detector at $1\times10^{16}$ neq/cm² with a reasonable bias ($\leq 200$ V), the column spacing $L_p$ should be reduced to 30 µm. Also, the volume under the columns (10% of the total volume) can be depleted with a modest bias ($\leq 200$ V), and this volume under the columns are not dead volume.

2. Full 3D simulations and device description

3D simulations were performed with ATLAS by Silvaco [2] and the DEVICE3D package of ATLAS was used to simulate 3D detectors. The numerical simulations were aimed to investigate the affect of the radiation introduced to the dual column 3D detector. A sketch of the BNL dual column detector is shown in Figure 1 [3-4]. In this structure there are two n-type and two p-type doped columns on p-type substrate. Same types of doped columns are placed to the opposite corners in the unit cell. All the columns are placed on the front side of the detector and they extend to 270 µm into the 300 µm deep p-type bulk. The ohmic contact is achieved by a uniform implant at the back surface of the wafer; the process is then single-sided.

Fig. 1. Sketch of a BNL 3D detector featuring columnar electrodes of n- and p- doping type.
A lot of studies have been done in the past to generate an empirical model for the evolution of the effective doping concentration \( N_{\text{eff}} \). Change in the depletion voltage with respect to the absolute effective doping concentration as measured immediately after irradiation is described in Ref. [5]. Detectors made to p-type substrate are not type inverted. Then, the depletion voltage increases because the effective doping concentration \( N_{\text{eff}} \) is increasing after irradiation. For not type inverted detectors \( N_{\text{eff}} \) is positive and becoming more positive and usually this behavior is attributed to an annealing of acceptors. That’s why \( N_{\text{eff}} \) can be divided in components with one component \( N_A \) as a short term annealing component. Because only the longest decay time constant is relevant for the operation of silicon detectors in high-energy physics experiments, the fluence dependence of \( N_A \) can be represented by [6]:

\[
N_A = g_a \Phi_{\text{eq}}
\]  

(1)

And the average introduction rate \( g_a \) is given by \( g_a = (1.81 \pm 0.14) \times 10^{-2} \text{ cm}^{-1} \) [6]. The doping concentration can be expressed as a function of fluence. In simulations the doping concentration varies and the affect of the radiation can be simulated.

3. Depletion voltage

Simulations for dual column 3D detectors were done with variety of fluences. The simulated full depletion voltage \( V_{\text{fd}} \) for a dual-column 3D detector show to be about 1.4 time higher than that of for calculated full depletion voltage of a 2D pad detector with a thickness \( d \) the same as the column spacing \( L_p \) in the 3D detector. The results are shown in Table 1.

Table 1. Full depletion voltage, calculated for a 2D detector and simulated for the 3D detector with a thickness \( d \) the same as the column spacing \( L_p \) in the 3D detector.

<table>
<thead>
<tr>
<th>Fluence</th>
<th>2d pad detector (d=50µm)</th>
<th>Dual columns 3D detectors (( L_p=50\mu m ))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculated ( V_{\text{fd}} )</td>
<td>Simulated ( V_{\text{fd}} )</td>
</tr>
<tr>
<td>5.00E+14</td>
<td>19</td>
<td>30</td>
</tr>
<tr>
<td>1.00E+15</td>
<td>38</td>
<td>60</td>
</tr>
<tr>
<td>2.00E+15</td>
<td>76</td>
<td>110</td>
</tr>
<tr>
<td>3.00E+15</td>
<td>114</td>
<td>160</td>
</tr>
<tr>
<td>4.00E+15</td>
<td>152</td>
<td>210</td>
</tr>
<tr>
<td>5.00E+15</td>
<td>190</td>
<td>250</td>
</tr>
<tr>
<td>6.00E+15</td>
<td>228</td>
<td>300</td>
</tr>
<tr>
<td>7.00E+15</td>
<td>266</td>
<td>350</td>
</tr>
<tr>
<td>8.00E+15</td>
<td>304</td>
<td>400</td>
</tr>
<tr>
<td>9.00E+15</td>
<td>342</td>
<td>450</td>
</tr>
<tr>
<td>1.00E+16</td>
<td>380</td>
<td>500</td>
</tr>
</tbody>
</table>
Comparing to thin planar detectors, 3D detectors need higher full depletion voltage. Usually the planar detectors used in high-energy physics experiments are 300 µm thick. In that case the 3D detectors full depletion voltage is lower (with 50 µm column spacing) and it is an advantage against planar detectors.

4. Electric field

Simulations show that the highest E-field is near the n+ column in Fig. 2.

Fig. 2. Electric field, $\phi_{eq} = 4 \times 10^{15} n_{eq} / \text{cm}^2$, $V = 200 \text{ V}$.

High E-field mainly distributes between the n+ and p+ columns. The low E-field is between the two p+ columns (Fig. 3a), and the lowest E-field is in the center of the unit cell with two p+ columns and two n+ columns (Fig. 3b).

Fig. 3. Electric field. Fluence $\phi_{eq} = 9 \times 10^{15} n_{eq} / \text{cm}^2$ and the applied voltage is a) $V = 200 \text{ V}$ and b) $450 \text{ V}$. 
From Figure 3a can be seen that when detector is under the full depletion voltage (200 V), the low electric field area is between p-type electrodes. When reaching full depletion in Figure 3b almost the all detector space has high electric field, only in the middle of the structure is a spot of low electric field area.

5. Radiation and column spacing

In the future high-energy physics experiments require really high fluences up to 1E16 neq/cm$^2$. In order to fully deplete a dual-column 3D detector at 1E16 neq/cm$^2$ with a reasonable bias ($\leq$ 200 V), the column spacing $L_p$ should be reduced to 30 µm (Fig. 4).

![Electric field density diagram](image)

Fig. 4. Electric field, $\phi_{eq} = 1 \times 10^{16}$ neq/cm$^2$, $V = 200$ V, $L_p$ varies from 10 µm to 50 µm.

The volume under the columns (10% of the total volume) can be depleted with a modest bias ($\leq$ 200 V), and this volume under the columns are not dead volume (Fig.5).
In the Figure 5 the depletion volume can provide some detection sensitivity directly under the columns, which may reduce the effective dead volume in 3D detectors.

6. Conclusion

In this paper we reported on TCAD simulations that have been performed to study the affect of the irradiation to the dual column 3D Si detectors. BNL dual column 3D detectors have been simulated in detail with variety of fluences. The simulated full depletion voltage \( V_{fd} \) for a dual-column 3D detector show to be about 1.4 time higher than that of for calculated full depletion voltage of a 2D pad detector with a thickness \( d \) the same as the column spacing \( L_p \) in the 3D detector. Simulations show that in this kind of detector structure the high electric field is near n-type electrode and the low electric field area is between the p-type electrodes. After reaching the full depletion there is still a low electric field spot in the middle of the structure. The future high-energy physics experiments demand the ability to face really high fluences up to \( 1 \times 10^{16} \text{ neq/cm}^2 \). In order to fully deplete a dual-column 3D detector at \( 1 \times 10^{16} \text{ neq/cm}^2 \) with a reasonable bias, the column spacing should be reduced.

Acknowledgements

This research was supported by the U.S. Department of Energy: Contract No. DE-AC02-98CH10886.

References


VEHVILÄINEN, JUHA. Procurement in project implementation. 2006. Diss.


RAUMA, KIMMO. FPGA-based control design for power electronic applications. 2006. Diss.

HIRVONEN, MARKUS. On the analysis and control of a linear synchronous servomotor with a flexible load. 2006. Diss.


LAITINEN, RISTO. Development of LC-MS and extraction methods for the analyses of AKD, ASA, and rosin sizes in paper products. 2006. Diss.

KUISMA, PETRI. Seinärakenteen infrapunakontrastin pienentäminen käyttäen ilmajäähdytystä ja säteilysuojausta. 2007. Diss.

ELLOMEN, HANNA-KAISA. Exploring the strategic impact of technological change – studies on the role of Internet in magazine publishing. 2007. Diss.

SOININEN, AURA. Patents in the information and communications technology sector – development trends, problem areas and pressures for change. 2007. Diss.

MATTILA, MERITA. Value processing in organizations – individual perceptions in three case companies. 2007. Diss.

VARTIAINEN, JARKKO. Measuring irregularities and surface defects from printed patterns. 2007. Diss.

SEKKI, ANTTI. Successful new venturing process implemented by the founding entrepreneur: A case of Finnish sawmill industry. 2007. Diss.

TURKAMA, PETRA. Maximizing benefits in information technology outsourcing. 2007. Diss.

BUTYLINA, SVETLANA. Effect of physico-chemical conditions and operating parameters on flux and retention of different components in ultrafiltration and nanofiltration fractionation of sweet whey. 2007. Diss.


QU, HAIYAN. Towards desired crystalline product properties: In-situ monitoring of batch crystallization. 2007. Diss.

JUSSILA, IIRO. Omistajuus asiakasomisteisissa osuuskunnissa. 2007. Diss.


275. SOUKKA, RISTO. Applying the principles of life cycle assessment and costing in process modeling to examine profit-making capability. 2007. Diss.


278. NEDEOOGLO, NATALIA. Investigation of interaction between native and impurity defects in ZnSe. 2007. Diss.

279. KÄRKKÄINEN, ANTTI. Dynamic simulations of rotors during drop on retainer bearings. 2007. Diss.


282. ILONEN, JARMO. Supervised local image feature detection. 2007. Diss.


286. PUNNONEN, PEKKA. Impingement jet cooling of end windings in a high-speed electric machine. 2007. Diss.


288. TUUPURA, ANNI. Market entry order and competitive advantage of the firm. 2007. Diss.


290. HUANG, JUN. Analysis of industrial granular flow applications by using advanced collision models. 2007. Diss.

291. SJÖMAN, ELINA. Purification and fractionation by nanofiltration in dairy and sugar and sweetener industry applications. 2007. Diss.

292. AHO, TUOMO. Electromagnetic design of a solid steel rotor motor for demanding operation environments. 2007. Diss.

293. PURHONEN, HEIKKI. Experimental thermal hydraulic studies on the enhancement of safety of LWRs. 2007. Diss.

294. KENGPOL, ATHAKORN. An evaluation of ICTs investment using decision support systems: Case applications from distributor’s and end user’s perspective group decision. 2007. Diss.


296. JASTRZEBSKI, RAFAL. Design and implementation of FPGA-based LQ control of active magnetic bearings. 2007. Diss.