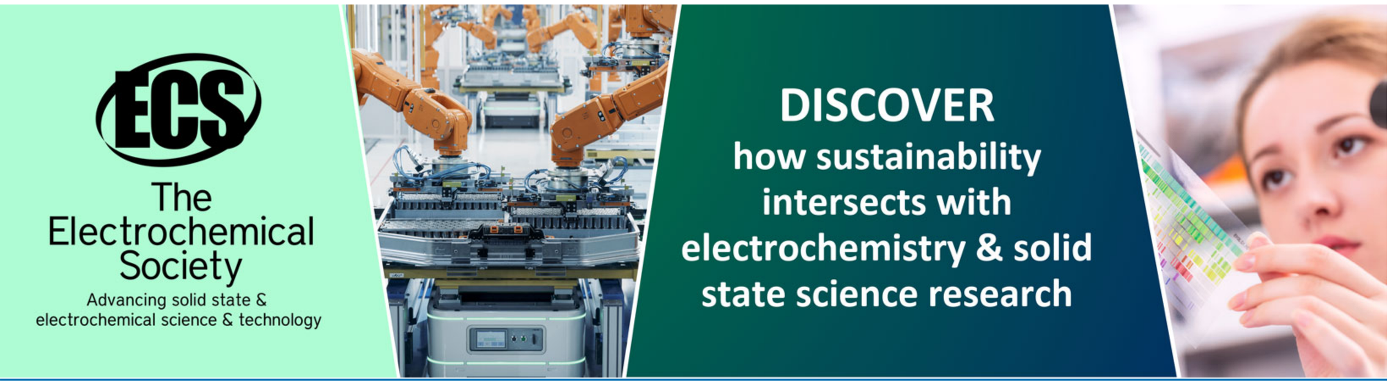
Journal of Instrumentation

Development of radiation tolerant silicon sensors

To cite this article: R Eber 2014 *JINST* **9** C02024



PUBLISHED BY IOP PUBLISHING FOR SISSA MEDIALAB

RECEIVED: *December 13, 2013*
ACCEPTED: *January 13, 2014*
PUBLISHED: *February 21, 2014*

13th TOPICAL SEMINAR ON INNOVATIVE PARTICLE AND RADIATION DETECTORS
7–10 OCTOBER 2013
SIENA, ITALY

Development of radiation tolerant silicon sensors

R. Eber[1]

Karlsruhe Institute of Technology,
Kaiserstr. 12, Karlsruhe, Germany

E-mail: eber@kit.edu

ABSTRACT: Within the CERN RD50 Collaboration, a massive R&D programme is underway across experimental boundaries to develop silicon sensors with sufficient radiation tolerance. One research topic is to gain a deeper understanding of the connection between the macroscopic sensor properties such as radiation-induced increase of leakage current, doping concentration and trapping, and the microscopic properties at the defect level. RD50 also studies sensors made from p-type silicon bulk, which have a superior radiation hardness as they collect electrons instead of holes, exploiting the lower trapping probability of the electrons due to their higher mobility. Simulations have become important to predict the performance of silicon sensors at high fluences. They can be a useful tool to explore the large parameter space of strip sensor geometries and help to explain the charge multiplication effect occuring in sensors at high radiation levels. Charge multiplication plays an important role in sensors irradiated to high fluences and is investigated in RD50. Several studies are ongoing to exploit the effect for future silicon sensors. The latest results of the microscopic studies, the simulation activities, the performance of heavily irradiated strip sensors and the investigations on charge multiplication are presented.

KEYWORDS: Si microstrip and pad detectors; Radiation-hard detectors; Charge transport and multiplication in solid media; Avalanche-induced secondary effects

[1] On behalf of the RD50 collaboration. A complete author list can be found at: http://cern.ch/rd50.

doi:10.1088/1748-0221/9/02/C02024

Contents

1 Introduction

The RD50 Collaboration is a CERN-based organization, which consists of 48 institutes with over 270 international members. Its mission is to develop radiation hard semiconductor devices for very high luminosity colliders. The upgrade of the LHC to the High Luminosity LHC (HL-LHC) is foreseen after 2022. Current silicon sensor technologies (planar n-bulk Float Zone) in the general purpose experiments ATLAS [1] and CMS [2] are not able to work effectively at the HL-LHC. An integrated luminosity of 3000 fb^{-1} during the operation of the HL-LHC implicates high radiation levels for the silicon sensors. Simulations foresee, that the innermost detectors have to withstand radiation damage of more than $10^{16}\,\mathrm{cm}^{-2}$ neutral and charged hadrons. The development of silicon sensors to operate at such high radiation levels is the challenge the RD50 collaboration is facing.

This includes the work on the several subjects, the collaboration is divided into: defect and material characterization, the characterization of irradiated detectors, the development of new structures and measurements with full detectors systems. Significant progress has been made in understanding radiation induced defects on a microscopic level and defects have been identified responsible for the annealing behaviour. The development of a simulation defect model describing the macroscopic performance of irradiated sensors has become an important topic. Commercial software (TCAD) or custom made software assume effective deep levels responsible for the increase in leakage current, the change in the effective doping concentration and charge trapping. It is possible to reproduce characteristic double peak shapes of TCT (Transient Current Technique [3]) signals, the dependence of charge collection efficiency on fluence and bias voltage and impact ionization phenomena.

The choice of a possible future material is of particular importance within the RD50 collaboration. Silicon materials from different fabrication techniques are being tested: Float Zone (FZ), Magnetic Czochralski (MCz) and epitaxial Silicon (Epi). Generally, detectors made of p-bulk silicon with n-side readout have shown a higher charge collection efficiency after high fluences ($10^{15}\,n_{\mathrm{eq}}\,\mathrm{cm}^{-2}$) than silicon made of n-bulk silicon with p-side readout. N-in-n sensors, which also collect electrons, also show a good charge collection efficiency but are more expensive due to the double sided processing. Hence p-type silicon, which has been brought forward by the RD50 collaboration, is now considered the baseline option for the ATLAS and CMS Strip Tracker upgrade.

Detailed studies have been performed and are ongoing on the charge multiplication effect occuring in heavily irradiated sensors. A dedicated R&D project has been launched to understand the underlying mechanism, to simulate the effect and to optimze the charge collection efficiency to possibly produce reliable high-signal sensors.

Not all results from a large active collaboration can be covered here. The impact of defects on the sensors, the simulation of the macroscopic observations and the performance of heavily irradiated strip sensors is enlightened in more detail. More on the results and a complete description of the research can be found at http://rd50.web.cern.ch.

2 Defect characterization

The defect characterization project within RD50 aims to identify the defects induced by radiation, which are responsible for the degradation of the devices. The microscopic study can then lead to a possible mitigation of radiation damage by defect engineering. The outcome of the microscopic measurements are valuable input for the simulations to predict the sensor performance under various conditions. The measurement of defects responsible for the annealing of leakage current and space charge are identified using the Thermally Stimulated Current (TSC) technique as well as the Deep Level Transient Spectroscopy (DLTS).

2.1 Impact on leakage current

The leakage current of silicon material is found to scale mainly with the non-ionizing energy loss (NIEL) independent of the silicon material. This is true for hadrons but not for gamma irradiation. During the annealing process, all investigated samples show a decrease of the leakage current with time and temperature. The defects responsible for the build-up of the leakage current and for the annealing of leakage current are the E4 and E5 defect contributing with about 60% and the E205a contributing with about 30% [4, 5]. The E4/E5 defect can be possibly assigned to a tri-vacancy defect (V_3) [4]. Its properties can also be found in [4]. The E4/E5 already anneals at 60°C whereas the E205a anneals at 200°C. Correspondingly, the leakage current decreases about the same percentage as the concentration of these defects anneals.

2.2 Impact on effective space charge

In several oxygen rich silicon materials, neutron irradiation leads to the build-up of an overall negative space charge. This leads to the so-called type-inversion in n-bulk silicon sensors. In contrast, irradiation with charged hadrons leads to a net positive space charge. This is a clear violation of the NIEL hypothesis [6].

The negative space charge is mainly introduced by the H(116K), H(140K) and H(151K) defects and the concentration of these defects scales with NIEL for the irradiation with both types of particles. The three defects are a group of deep acceptors with given ionisation temperature. They have been discovered and described by [6]. However, in the samples irradiated with charged hadrons, the E(30K) defect appears more pronounced and basically dominates the space charge directly after irradiation [4].This very shallow donor always contributes to the space charge at room temperature.

The effect of reverse annealing appearing at long annealing times describes the non-beneficial change of macroscopic sensor properties. During the annealing process, the concentration of defects introducing negative space charge increases. Mainly responsible for this increase are the mentioned three hole traps. The increase of negative space charge cannot be compensated by the positive charge, mainly given the E(30K). Summing up the contribution from the donors and acceptors to the space charge, the negative space charge dominates and leads to an overall increase of the effective space charge und thus of the full depletion voltage [4, 5, 7].

3 Simulation of silicon sensors

The simulation of irradiated silicon sensors has become an important topic with respect to performance simulations of silicon sensors in the high luminosity LHC radiation environment. A dedicated RD50 simulation working group has been set up and is progressing towards reproducing experimental results on leakage current, space charge, electric field and trapping. Different custom made and commercial tools are used for the simulation of irradiated silicon devices.

A model describing all important observations with only one parameter set has been tuned for the commercial TCAD software Synopsys Sentaurus [8]. The effective two-defect model is based on the model by Eremin [9] and uses only one deep acceptor and one deep donor to effectively parametrize the radiation induced defects. The parameters of the two defects, electron cross section, hole cross section and defect concentration, have been tuned according to leakage current, depletion voltage and the signal shape of TCT signals. The latter enables the precise tuning of the cross sections for a correct description of trapping effects.

TCT signals in irradiated silicon show two peaks, which appear due to a high electric field in the sensors near the surfaces arising from a high space charge of opposite sign in the regions near the front or the back. In the bulk, the space charge changes sign. Near the zero space charge transition in the bulk, the electric field is very low.

Two radiation damage models have been derived to describe the different results of diodes and sensors irradiated with 1 MeV neutrons and 23 MeV protons. The increase in depletion voltage with fluence is higher for samples irradiated with neutrons than for samples irradiated with protons. The concentration of the two defects is given as a linear function of the fluence. The models are only valid for fluences higher than $10^{14}\,n_{\mathrm{eq}}\,\mathrm{cm}^{-2}$. The parameters for the models according the particle type are listed in table 1 and 2 [10].

In figure 1, the measured and simulated TCT signals of a Float Zone diode with 320 μm thickness irradiated with protons to $F = 1 \times 10^{15}\,n_{\mathrm{eq}}\,\mathrm{cm}^{-2}$ are shown. The agreement between measurement and simulation is very good, though reflections appear in the measured signal at 3 ns.

The electric field, which is responsible for the appearance of the two peaks in the TCT signal can be extracted from the simulation (see figure 2). The field is high at the front side and at the back side of the diode. In the bulk, the electric field reaches a minimum and the charge carriers

Table 1. Defect Model for Neutron Irradiation.
The energy level of the defects is given as the energy from the conductance band edge E_C or valence band edge E_V. The fluence F is given in $n_{eq}\,cm^{-2}$.

Type of defect	Level (eV)	σ_e (cm^2)	σ_h (cm^2)	Concentration (cm^{-3})
Deep acceptor	$E_C - 0.525$	1.2×10^{-14}	1.2×10^{-14}	$1.55\,\mathrm{cm}^{-1} \times F$
Deep donor	$E_V + 0.48$	1.2×10^{-14}	1.2×10^{-14}	$1.395\,\mathrm{cm}^{-1} \times F$

Table 2. Defect Model for Proton Irradiation.
The energy level of the defects is given as the energy from the conductance band edge E_C or valence band edge E_V. The fluence F is given in $n_{eq}\,cm^{-2}$.

Type of defect	Level (eV)	σ_e (cm^2)	σ_h (cm^2)	Concentration (cm^{-3})
Deep acceptor	$E_C - 0.525$	1.0×10^{-14}	1.0×10^{-14}	$1.189\,\mathrm{cm}^{-1} \times F + 0.65 \times 10^{14}\,\mathrm{cm}^{-3}$
Deep donor	$E_V + 0.48$	1.0×10^{-14}	1.0×10^{-14}	$5.589\,\mathrm{cm}^{-1} \times F - 3.96 \times 10^{14}\,\mathrm{cm}^{-3}$

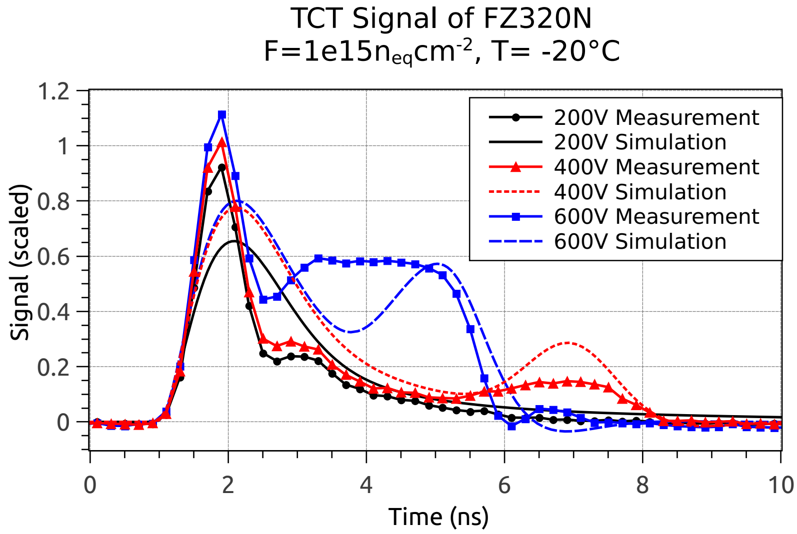


Figure 1. Measurement and simulation of the TCT signal in a 320 μm thick n-bulk FZ silicon diode irradiated with 23 MeV protons to $10^{15}\,n_{eq}\,\mathrm{cm}^{-2}$.

drift slowly in this region. They are accelerated again after this region, which leads to the second peak in the signal. The electric field shows a type-inverted behaviour: an increase in bias voltage leads to a higher electric field at the back side of the diode, the negative space charge introduced by the acceptors dominates. The trapping of the charge carriers during the drift from the front to the back is expressed in the second peak of the TCT signal, which is lower than the first peak, although the electric field is higher.

After the validation of the model with available data, it has been used to simulate charge collection efficiency of irradiated diodes [11] and sensors. The extrapolation to strip sensors has been shown to be quite successful. The proton model can predict the collected charge of sensors in the testbeam within 10% at fluences from $10^{14}\,n_{eq}\,\mathrm{cm}^{-2}$ to a few $10^{15}\,n_{eq}\,\mathrm{cm}^{-2}$ [12].

2014 JINST 9 C02024

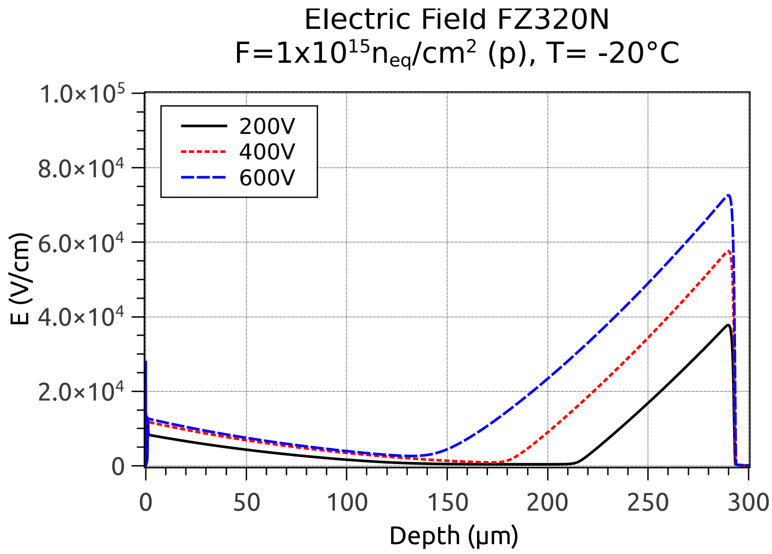


Figure 2. Simulated electric field in a 320 μm thick n-bulk FZ silicon diode irradiated with 23 MeV protons to $10^{15}\, n_{\mathrm{eq}}\, \mathrm{cm}^{-2}$.

4 Performance of heavily irradiated sensors

The key for future tracking detectors are radiation hard silicon sensors. Silicon sensors come in either p-bulk or n-bulk. The natural readout for single side processed sensors thus is on the p^+ strips for n-bulk, collecting holes, and on the n^+ strips for p-bulk sensors, collecting electrons. N-bulk sensors have shown type-inversion after irradiation, which swaps the high electric field from the segmented front side to the back side. In combination with hole collection, this is a serious disadvantage for n-bulk sensors. In p-bulk sensors, the electric field is high at the segmented side after irradiation and coincides with the weighting field for sensors [13]. Collecting electrons, which are not trapped as easily as holes, the p-bulk sensors have proven to be very radiation hard [14] and type-inversion has not been observed.

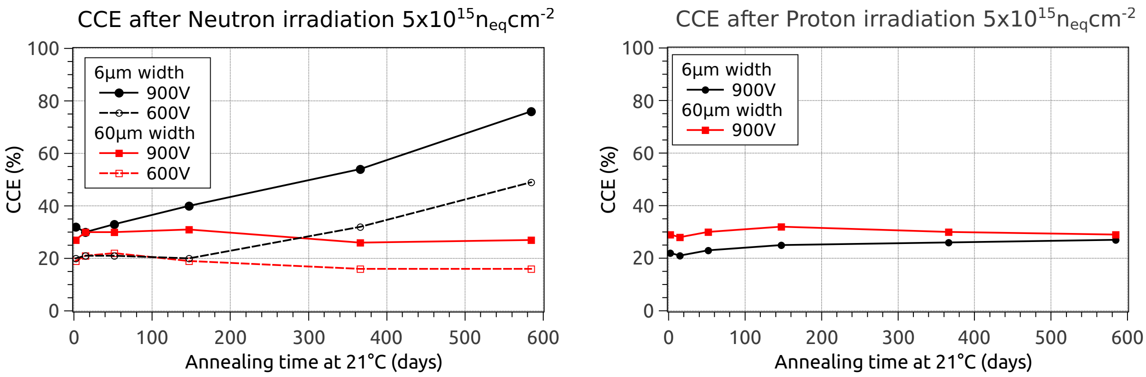
At a fluence of $10^{16}\, n_{\mathrm{eq}}\, \mathrm{cm}^{-2}$, 300 μm thick FZ n-in-p sensors still showed a charge collection efficiency of 30% at 900 V [14]. Additionally, p-bulk Float Zone detectors irradiated to fluences of a few times $10^{15}\, n_{\mathrm{eq}}\, \mathrm{cm}^{-2}$ did not show a significant reverse annealing effect of charge collection efficiency [15].

Another irradiation study of different silicon materials for the CMS tracker upgrade showed, that 300 μm thick sensors collect more charge at 900 V for fluences up to $10^{15}\, n_{\mathrm{eq}}\, \mathrm{cm}^{-2}$. At higher fluences, 200 μm thick sensors collect about the same amount of electrons. At $5 \times 10^{15}\, n_{\mathrm{eq}}\, \mathrm{cm}^{-2}$, the thicker bulk cannot be fully depleted any more and the volume is lost for signal generation [16].

5 Charge multiplication

Charge multiplication has been observed in several silicon sensors at high fluences and bias voltages [17–20]. The effect is well-established and occurs due to a very high electric field near the pn-junction. The effect occurs in p-bulk sensors because electrons have a higher multiplication factor. The electric field configuration at the surface can be designed to create a high electric field

2014 JINST 9 C02024



(a) 1 MeV neutrons

(b) 23 MeV protons

Figure 3. Charge collection efficiency of sensors irradiated to $5 \times 10^{15}\, n_{\text{eq}}\,\text{cm}^{-2}$ with 1 MeV neutrons or 23 MeV protons. The strip pitch is 80 μm, the strip width is 60 μm or 6 μm.

near the collecting electrode. Thus, charge multiplication can be influenced by the geometry of the strips on the silicon sensor.

Dedicated sensors have been fabricated and distributed within the RD50 collaboration to investigate the geometrical effects influencing the charge multiplication [21]. The effect of charge multiplication is strongly dependent on the implant strip width, the irradiation particle type and the annealing time. The depth of the doping of the strip also has an influence on the effect.

Figure 3 shows the charge collection efficiency of 300 μm thick FZ n-in-p sensors, which have been irradiated to a fluence of $5 \times 10^{15}\, n_{\text{eq}}\,\text{cm}^{-2}$ with either reactor neutrons or 23 MeV protons. The pitch of all sensors is 80 μm, the strip width has been varied between 60 μm and 6 μm. Only the sensor with a small strip width irradiated with neutrons shows a sizable charge multiplication effect, the charge collection efficiency increases with larger annealing time and is significantly higher than expected for this fluence [22].

Due to the ionising dose deposited in the sensors by irradiation with charged hadrons, the silicon dioxide of the sensor gets charged up positively and compensates part of the high electric field in the bulk responsible for charge multiplication. This is confirmed by the simulations (see figure 4) using the model from table 2 in combination with a fixed interface charge concentration of $10^{12}\,\text{cm}^{-2}$ at the Si-SiO_2 interface [10, 22].

Charge multiplication in sensors appears only at very high fluences and increases with annealing time. At the LHC and HL-LHC, charged hadrons contribute a lot to the radiation damage and also to the ionising dose the sensors experience, the effect of charge multiplication is unlikely to build up in an experiment.

Hence, quite some effort is dedicated to the design of special charge multiplication structures, which provoke charge multiplication by special geometries. Strip detectors with a deep polysilicon trench have shown a sizeable effect. Depending on the depth of the trench, the sensors irradiated to $5 \times 10^{15}\, n_{\text{eq}}\,\text{cm}^{-2}$ neutrons show a significantly higher charge collection efficiency than strip detectors without the trench [23]. Yet a drawback is the increased interstrip capacitance, which leads to a higher noise. The reverse current is much larger on the sensors with trench due to the engineered junction.

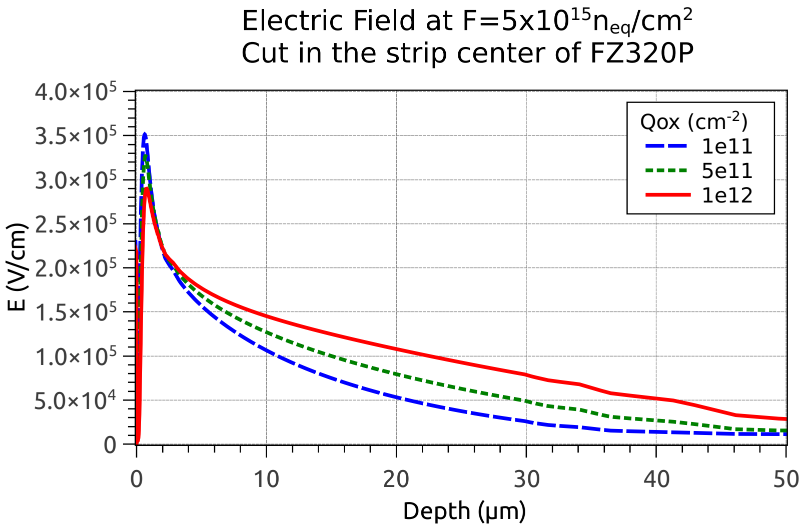


Figure 4. Simulation of the electric field in a p-bulk sensor with pitch 80 μm and strip width 6 μm along the depth of the sensor cut in the center of the strip implant.

Low gain avalanche detectors (LGAD) on the other hand try to establish a high electric field near the electrode, which creates charge multiplication already before irradiation [24]. The high electric field is achieved by an additional doping layer beneath the implant of the electrode. The multiplication of the signal is about a factor of ten, yet it is decreasing with increasing fluence so far [24].

6 Summary

Significant progress in developing and understanding radiation hard silicon sensors has been made by the RD50 collaboration. Microscopic defects responsible for the change of detector performance have been identified. The change of defects during the annealing is a valuable input to the sensor simulation. Simulations using effective damage models have progressed towards the description of many sensor properties simultaneously at high irradiation levels at certain annealing times. RD50 has significantly contributed to the choice of future materials for HL-LHC tracking detectors, clearly preferring n-in-p bulk sensors at very high fluences. New structures like 3D sensors show encouraging results and could be an option for HL-LHC pixel detectors. The effect of charge multiplication is clearly observable at high fluences and studies are ongoing to understand and exploit the effect for the use in future silicon particle detectors.

References

[1] ATLAS collaboration, *The ATLAS experiment at the CERN Large Hadron Collider*, 2008 *JINST* **3** S08003.

[2] CMS collaboration, *The CMS experiment at the CERN LHC*, 2008 *JINST* **3** S08004.

2014 JINST 9 C02024

[3] H.W. Kraner, Z. Li and E. Fretwurst, *The use of the signal current pulse shape to study the internal electric field profile and trapping effects in neutron damaged silicon detectors*, Nucl. Instrum. Meth. **A 326** (1993) 350.

[4] A. Junkes, *Influence of radiation induced defect clusters on silicon particle detectors*, Ph.D. Thesis, Hamburg University, Germany (2011).

[5] A. Junkes, *Status of defect investigations*, in Proceedings of the *20th Anniversary International Workshop on Vertex Detectors (Vertex 2010)*, Rust Austria, 19–24 Jun 2011 [PoS(Vertex 2011)035].

[6] I. Pintilie, G. Lindström, A. Junkes and E. Fretwurst, *Radiation-induced point- and cluster-related defects with strong impact on damage properties of silicon detectors*, Nucl. Instrum. Meth. **A 611** (2009) 52 [arXiv:0907.3050].

[7] I. Pintilie, E. Fretwurst and G. Lindström, *Cluster related hole traps with enhanced-field-emission — the source for long term annealing in hadron irradiated Si diodes*, Appl. Phys. Lett. **92** (2008) 024101.

[8] Synopsys Inc., *Sentaurus Device. An advanced multidimensional (1D/2D/3D) device simulator*, Version G_2012.06-SP2 (2014), http://www.synopsys.com/Tools/TCAD/DeviceSimulation/Pages/SentaurusDevice.aspx.

[9] V. Eremin, E. Verbitskaya and Z. Li, *The origin of double peak electric field distribution in heavily irradiated silicon detectors*, Nucl. Instrum. Meth. **A 476** (2002) 556.

[10] R. Eber, *Investigations of new sensor designs and development of an effective radiation damage model for the simulation of highly irradiated silicon particle detectors*, Ph.D. Thesis, Karlsruhe Institute of Technology, Germany (2013), IEKP-KA/2013-27.

[11] R. Eber et al., *Simulation of CV, TCT and CCE with an effective 2-defect model*, presented at the *22nd RD50 Workshop*, University of New Mexico U.S.A., 3–5 Jun 2013.

[12] T. Peltola, *Simulations of edge-TCT and 2-defect model CCE*, presented at the *22nd RD50 Workshop*, University of New Mexico U.S.A., 3–5 Jun 2013.

[13] G. Kramberger, *"Why p-type is better than n-type" or electric field in heavily irradiated silicon detectors*, in Proceedings of the *21st Anniversary International Workshop on Vertex Detectors (Vertex 2012)*, Jeju Korea, 16–21 Sep 2012 [PoS(Vertex 2012)022].

[14] A. Affolder, P. Allport and G. Casse, *Collected charge of planar silicon detectors after pion and proton irradiations up to* $2.2\times10^{16}\,n_{\rm eq}\,cm^{-2}$, Nucl. Instrum. Meth. **A 623** (2010) 177.

[15] G. Casse, P.P. Allport and A. Watson, *Effects of accelerated annealing on p-type silicon micro-strip detectors after very high doses of proton irradiation*, Nucl. Instrum. Meth. **A 568** (2006) 46.

[16] J. Erfle, *Irradiation study of different silicon materials for the CMS tracker upgrade*, presented at the *22nd RD50 Workshop*, University of New Mexico U.S.A., 3–5 Jun 2013.

[17] J. Lange, J. Becker, E. Fretwurst, R. Klanner and G. Lindström, *Properties of a radiation-induced charge multiplication region in epitaxial silicon diodes*, Nucl. Instrum. Meth. **A 622** (2010) 49 [arXiv:1007.4735].

[18] G. Casse, A. Affolder, P.P. Allport, H. Brown and M. Wormald, *Enhanced efficiency of segmented silicon detectors of different thicknesses after proton irradiations up to* $1\times10^{16}\,n_{\rm eq}\,cm^{-2}$, Nucl. Instrum. Meth. **A 624** (2010) 401.

[19] A. Affolder et al., *Silicon detectors for the sLHC*, Nucl. Instrum. Meth. **A 658** (2011) 11.

[20] I. Mandic et al., *Accelerated annealing of n^+-p strip detectors irradiated with pions*, 2011 *JINST* **6** P11008.

[21] C. Betancourt et al., *A charge collection study with dedicated RD50 charge multiplication sensors*, *Nucl. Instrum. Meth.* **A 730** (2013) 62.

[22] L. Altan et al., *Investigation of charge multiplication in silicon strip detectors*, presented at the *22nd RD50 Workshop*, University of New Mexico U.S.A., 3–5 Jun 2013.

[23] G. Casse et al., *Charge multiplication in irradiated segmented silicon detectors with special strip processing*, *Nucl. Instrum. Meth.* **A 699** (2013) 9.

[24] S. Hidalgo, *Simulation and technology development of low gain avalanche detectors (LGAD) for high energy physics applications*, presented at the *22nd RD50 Workshop*, University of New Mexico U.S.A., 3–5 Jun 2013.

2014 JINST 9 C02024