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Development of radiation tolerant semiconductor detectors for the Super-LHC

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RD50 Collaboration

Abstract

The envisaged upgrade of the Large Hadron Collider (LHC) at CERN towards the Super-LHC (SLHC) with a 10 times increased luminosity of $10^{35}\,\mathrm{cm^{-2}\,s^{-1}}$ will present severe challenges for the tracking detectors of the SLHC experiments. Unprecedented high radiation levels and track densities and a reduced bunch crossing time in the order of 10 ns as well as the need for cost effective detectors have called for an intensive R&D program. The CERN RD50 collaboration “Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders” is working on the development of semiconductor sensors matching the requirements of the SLHC. Sensors based on defect engineered silicon like Czochralski, epitaxial and oxygen enriched silicon have been developed. With 3D, Semi-3D and thin detectors new detector concepts have been evaluated and a study on the use of standard and oxygen enriched p-type silicon detectors revealed a promising approach for radiation tolerant cost effective devices. These and other most recent advancements of the RD50 collaboration are presented.

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Keywords: Radiation damage; Semiconductor detectors; Silicon particle detectors; Defect engineering; SLHC; Super-LHC

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1. Introduction

The Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN) in Geneva, Switzerland is scheduled to be operational in 2007. Although the LHC is not yet in function, studies on the physics potential and the experimental challenges for an upgrade of the LHC to a 10 times higher luminosity of $10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (Super-LHC or SLHC) have been performed for the accelerator [1] and the experiments [2]. A clear gain in physics potential has been identified but also the urgent need for setting up as soon as possible an intensive R&D program for both, the accelerator and the detectors, in order to match the more stringent and very challenging requirements of SLHC.

Particularly severe problems on the detector side are the increase of track density and radiation level, and the expected reduced bunch crossing time of the order of 10 ns. The inner tracking detectors will face fluences of fast hadrons up to $1.6\times10^{16}\,\mathrm{cm}^{-2}$ assuming a 5 years of operation accumulating $2500\,\mathrm{fb}^{-1}$. This is a 10 times higher radiation level than predicted for the LHC detectors and it is more than doubtful that the present detector technology can survive in this radiation environment. The increased track density calls for higher granularity detectors at all radii which, together with the required radiation tolerance, will make the cost of the detectors and electronics a major issue. The reduced bunch crossing time will ask for faster electronics and detectors that deliver their signal within 10 ns.

In 2004 ATLAS and CMS, the two biggest LHC experiments, have held their first workshops focusing on the required hardware upgrades for SLHC and the necessary detector R&D [3,4]. The CERN RD50 collaboration "Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders"[5], which was formed in 2002 with the aim to develop semiconductor sensors matching the requirements for SLHC tracking detectors, is deeply involved in these developments. Presently the RD50 collaboration consists of 52 institutes with about 270 members. Special emphasis is put on the development of radiation tolerant defect engineered silicon and new semiconductor materials like Czochralski (Cz), epitaxial (EPI) and oxygen enriched (DOFZ) silicon, SiC and GaN. New detector concepts like 3D and Semi-3D detectors as well as thin detectors are evaluated and cost effective radiation tolerant devices are under development. Furthermore, the collaboration is working successfully on the identification and understanding of the microscopic radiation-induced defects that lead to the macroscopic degradation of detector properties.

Like in previous RD50 conference articles [6–9], only some specific topics of the RD50 scientific program will be described while more detailed information can be found in Refs. [5,10] and literature cited there. This article will focus on the development of defect-engineered silicon and new silicon-based detector concepts.

2. Defect-engineered silicon

The term "defect engineering" stands for the deliberate incorporation of impurities or defects into the silicon bulk before, during or after the processing of the detector. The aim is to suppress the formation of microscopic defects with a detrimental effect on the macroscopic detector parameters during or after irradiation. In this sense defect engineering is coping with the radiation damage problem at its very root.

2.1. Oxygen-rich silicon

The up-to-date most successful example of defect-engineered sensor material is oxygen-enriched silicon. In 1998 the RD48 (ROSE) Collaboration demonstrated that oxygen enriched FZ silicon is more resistant against charged hadron and γ-ray irradiation than oxygen lean (standard) FZ silicon [11,12]. This so-called DOFZ[3] silicon is enriched with oxygen by a long lasting oxidation step (e.g. 72 h at 1150 °C) performed before processing of the detector. It contains an average oxygen concentration in the order of $\approx 1\times10^{17}\,\mathrm{cm}^{-3}$ which is almost one order of

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[3] Diffusion Oxygenated Float Zone, which is sometimes also referred to as High Temperature Long Time oxygenated silicon.

magnitude higher than in standard FZ silicon. Due to the improved radiation tolerance and the relatively simple manufacturing process, the ATLAS and CMS pixel collaborations as well as the LHCb Velo group decided to produce their LHC sensors out of this material. While RD50 is still working intensively on a comprehensive characterization of DOFZ silicon, CZ and Magnetic Czochralski (MCZ) silicon are coming into focus. These types of silicon are produced in quartz crucibles and contain, due to the solution of the quartz (SiO_2) crucible into the silicon melt, an even higher oxygen concentration ranging from ≈ 4 to $10 \times 10^{17}\,\mathrm{cm}^{-3}$ depending on the specific CZ or MCZ growth technique. Only recently, CZ and MCZ silicon became available with a high enough resistivity to serve as detector material.

In the framework of the RD50 project CZ silicon from Sumitomo-Sitix, Japan ($600\,\Omega\,\mathrm{cm}$, n-type, $\langle 1\,0\,0 \rangle$, $[\mathrm{O}] = 8 \times 10^{17}\,\mathrm{cm}^{-3}$) and MCZ silicon from Okmetic Ltd., Finland ($900\,\Omega\,\mathrm{cm}$ n-type and $2\,\mathrm{k}\Omega\,\mathrm{cm}$ p-type, $\langle 1\,0\,0 \rangle$, $[\mathrm{O}] = 5 \times 10^{17}\,\mathrm{cm}^{-3}$) has been investigated. The CZ was processed at CiS (Germany) and the MCZ at the Helsinki University of Technology (Finland) and more recently at BNL (USA) and IRST (Italy). Irradiation experiments were performed with reactor neutrons [16], high energy (23 GeV [13]) and low energy (10, 20, 30 MeV [14]) protons, 190 MeV pions[13], 900 MeV electrons [15] and Co^{60} γ-rays [16] revealing clear advantages of MCZ and especially CZ silicon against FZ and DOFZ silicon.

An example of an irradiation[4] experiment performed with 23 GeV protons is shown in Fig. 1 [13]. Comparing the results for FZ and DOFZ detectors a strongly reduced depletion voltage is observed for the oxygen-enriched material. The use of CZ silicon seems not to improve the radiation tolerance further and (the lower resistivity) MCZ silicon even inhibits a higher depletion voltage than DOFZ silicon at all fluences. The only visible amelioration is the fact that the overall variation of the depletion voltage during irradiation is less in the CZ materials giving thus more stable conditions during detector operation. The huge advantage of the CZ and MCZ is only displayed in more subtle experiments that probe the electric field inside the irradiated devices and measure the signal (charge) delivered by the device. With Transient Charge Technique (TCT) measurements it has been shown that both materials do not undergo type inversion up to the highest fluence investigated here while the effective trapping times are very similar to the ones of standard and DOFZ silicon [13]. If these results can be confirmed in further experiments CZ silicon will become the ideal detector material for single sided radiation tolerant p-in-n detectors[5]. The high electric field will stay on the structured side of the device even after high fluences.

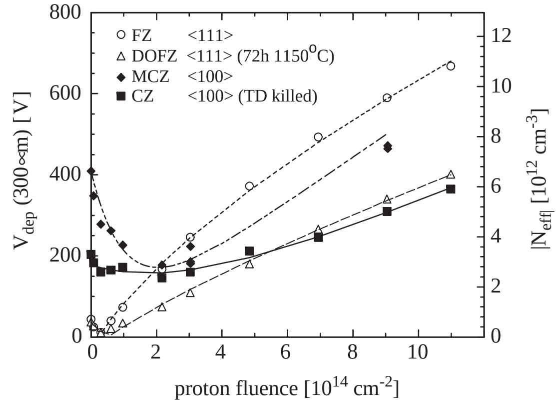

Fig. 1. Comparison of standard (FZ) and oxygenated (DOFZ) Float Zone silicon with Czochralski (CZ) and Magnetic Czochralski (MCZ) silicon detectors in a CERN irradiation scenario with 23 GeV protons [13].

Since the CZ material is not type inverting, the increase of the absolute effective doping concentration with fluence must be due to the formation of donors. Oxygen related thermal donors could be the explanation for the observed effect. In standard FZ silicon they are formed only in negligible concentration due to the low oxygen content. Therefore, negatively charged radiation-induced defects dominate. In DOFZ silicon some

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[4] After each irradiation step the devices are annealed for 4 min at 80 °C and then measured. The result is plotted against the cumulated fluence.

[5] A p-in-n detector has an n-type bulk and a p-type (structured) front electrode. This is the most commonly used detector type.

donors are formed compensating a part of the negatively charged defects leading to a reduced depletion voltage after type inversion. In CZ silicon the radiation-induced donors overcompensate the negatively charged defects leading to a net increase of the absolute effective doping concentration, this time with a positive space charge.

The formation of radiation-induced thermal donors can, however, only explain a part of the observed differences between oxygen-rich and oxygen-lean materials. It has for example been demonstrated that after γ-ray irradiation an oxygen related acceptor state, which tentatively was identified as the Divacancy-Oxygen (V_2O) defect, plays a major role [17]. Furthermore, in some experiments materials containing the same oxygen content showed different responses to radiation [6] leaving many open questions on the microscopic processes underlying the influence of oxygen on the detector radiation hardness. One clear hint comes from neutron irradiation experiments. A similar response of CZ, DOFZ and standard FZ silicon has been observed (all type inverting), indicating that the influence of the oxygen is to be searched in the formation of point defects rather than in the defect cluster production.

Finally, it should be mentioned that the potential threat of thermal donors forming during processing of CZ, MCZ and DOFZ detectors and leading to a lower resistivity can be overcome by a thermal donor-killing processes applied to the devices after processing. The formation of thermal donors offers, however, also the possibility to tailor the starting resistivity to a specific value. Like with neutron transmutation doping initially p-type CZ and MCZ silicon can be converted into n-type silicon by thermal donors. The radiation hardness of this kind of material is presently under study within RD50.

2.2. Oxygen dimer-enriched silicon

The maybe most elaborated defect engineering approach is the attempt to produce detectors which contain oxygen in the form of oxygen dimers (O_{2i}) instead of the usual interstitial oxygen (O_i). In such a material the Divacancy-Oxygen complex (V_2O), a defect which is believed to be responsible for a part of the detector radiation damage, could not be formed any more. Instead the V_2O_2 defect, which might not be as harmful, is generated.

In a so-called dimerization process detectors are exposed at $\sim$350 °C to a high fluence of MeV electrons (e.g. 2.5 MeV, $1\times10^{18}\,\mathrm{cm}^{-2}$) to form the oxygen dimers [18]. However, so far the maximal ratio between $[O_{2i}]$ and $[O_i]$ produced was $\approx$3%[19] which might not be enough to influence the radiation damage properties of detectors. The dimerization process is particularly difficult since O_{2i} is a precursor to thermal donors which alter the resistivity of the material. This happened during the first dimerization attempts of RD50. Thermal donors formed during the electron irradiation at high temperature and changed the resistivity of the investigated DOFZ and CZ detectors to values which make detector operation impossible.

Nevertheless, these activities are followed because the process still might be improved to produce less thermal donors. Furthermore, oxygen dimers might well be the precursors to the radiation-induced donors that render DOFZ and especially CZ and EPI silicon (see Sections 2.1 and 4) more radiation tolerant than standard FZ silicon. A support for this assumption is given by the recent discovery that the radiation-induced migration of oxygen dimers is the reason for the degradation of boron-doped CZ solar cells in space applications [20]. Therefore any study on a deeper understanding of this particular defect is essential for future defect engineering approaches.

2.3. Hydrogen enrichment and pre-irradiation

The enrichment of the Si bulk with Hydrogen is a further defect engineering approach. It is known that Hydrogen compensates shallow donors and acceptors [21] and has an influence on the annealing of divacancies [22]. Therefore, Hydrogen might as well compensate radiation-induced charged defects and accelerate the annealing of radiation-induced divacancy related defects. Presently first studies on hydrogen-enriched silicon detectors are performed [23].

The RD50 pre-irradiation approach, which is similar to the Neutron Transmutation technique, is performed on the wafer level. Wafers are irradiated in a nuclear reactor to high fluences of fast neutrons ($\approx 10^{16}\,\mathrm{cm}^{-2}$). After the irradiation, the wafers are annealed at high temperatures ($\approx 900\,^{\circ}\mathrm{C}$) and then processed into detectors. It has been shown that a part of the defects produced during the first irradiation is even present in the material after high temperature annealing. These defects might well alter the response to irradiation of detectors, acting as getter centers for radiation-induced defects. First devices have been produced with this technique and are presently under study [24].

3. p-Type silicon detectors

The type inversion of p-in-n detector is posing a problem since the high electric field is switching from the structured readout side to the back side of the detector accompanied by a loss in spatial resolution and, if not operated with voltages well above the depletion voltage, by reduced charge collection efficiency. This is the reason why the more expensive n-in-n technology is used for pixel detectors in harsh radiation environments. After type inversion the high electric field will be on the structured side of the device and electrons rather than the three times slower holes will give the main contribution to the detector signal. Hence it is a promising approach to investigate n-in-p detectors which do not type invert (they are already p-type) and for which the structured readout side will be the one with the high electric field before and after irradiation.

Various sets of $1 \times 1\,\mathrm{cm}^2$ and $280\,\mu\mathrm{m}$ thick microstrip detectors have been produced on standard and oxygenated p-type FZ silicon [25]. The charge collected with LHC speed electronics after irradiation with 23 GeV protons is plotted in Fig. 2. The result is that even after a fluence of $7.5 \times 10^{15}\,\mathrm{cm}^{-2}$ about 6500 electrons are collected resulting in a signal over noise value of ~7.5 which is still a reasonable value for tracking. Following this promising result, further RD50 studies are presently under way to investigate the influence of the oxygen content in p-type silicon in more detail. Furthermore, the studies are presently extended to p-type CZ silicon.

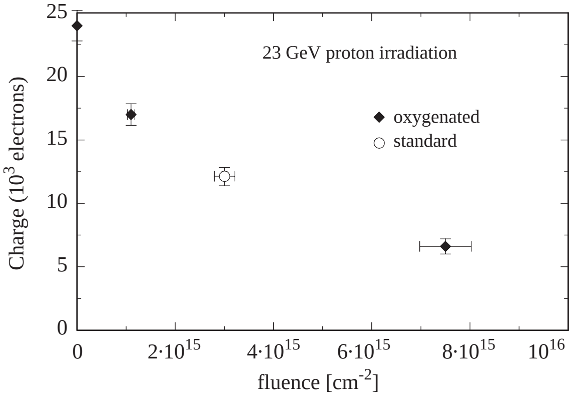

Fig. 2. Collected charge as a function of the 23 GeV proton fluence for standard and oxygenated n-in-p miniature microstrip detectors (source: Ru^{106}, chip: SCT128A–40 MHz, 800–900 V applied to irradiated devices, measured at $-20\,^{\circ}\mathrm{C}$) [25].

4. Thin and epitaxial silicon detectors

After an irradiation with $10^{16}\,\mathrm{cm}^{-2}$ fast hadrons the effective drift length of charge carriers is drastically reduced by trapping effects. Therefore, the produced signal does no longer depend linearly on the device thickness d. Simulations predict e.g. that pixels with $d = 100\,\mu\mathrm{m}$ will give only twice as much charge (~2000e) as pixels with $d = 25\,\mu\mathrm{m}$ [26]. Since thin detectors have the advantage of lower leakage current, lower depletion voltage and the feasibility to use lower resistivity silicon, RD50 started an investigation on this topic. The obvious drawbacks are the increase in capacitance which might be compensated by smaller cell sizes (as needed for the high track density at SLHC) and the smaller initial signal which puts more stringent requirements on the electronics. Two approaches have been followed, the thinning of processed silicon wafers (50, 60, $100\,\mu\mathrm{m}$) [27,28] and the growth of EPI layers (25, 50, and $75\,\mu\mathrm{m}$) on low resistivity ($<0.02\,\Omega\,\mathrm{cm}$) CZ silicon substrates [29,30].

Irradiation experiments performed with 23 GeV protons [29,30] and 58 MeV Lithium ions [31] clearly revealed that the EPI layers have very different properties from thin detectors made from standard material. In Fig. 3 the depletion voltage as function of the 23 GeV proton fluence is shown for 50 μm thick detectors. The depletion voltage rises with increasing fluence for both types of detectors.

The major difference is revealed in Fig. 4 where the annealing of the two materials is shown. While for the thin silicon the expected reverse annealing is observed for the EPI silicon a decrease of depletion voltage with time is visible. This coincides with TCT measurements proving that the EPI material is not type inverted while the standard silicon is type inverted. The built up of negative space charge due to the reverse annealing (and other effects) leads therefore in the EPI detectors to a decrease in depletion voltage with time. For the application in High Energy Physics experiments this constitutes a spectacular improvement, since these detectors would not suffer any more from the reverse annealing effect but rather profit from it. Detectors need not have to be kept cold any more during shutdown periods and the heating of detectors would decrease not only the leakage current but also the depletion voltage.

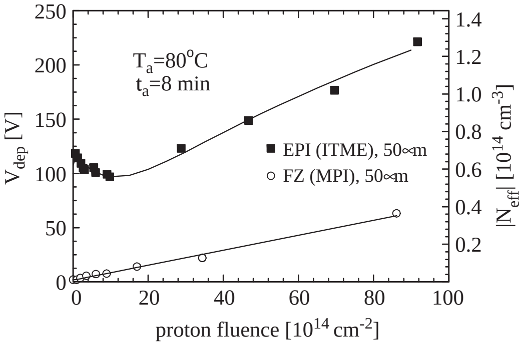

Fig. 3. Comparison of 50 μm thick FZ detectors and EPI detectors after irradiation with 23 GeV protons and an annealing of 8 min at 80 °C [30].

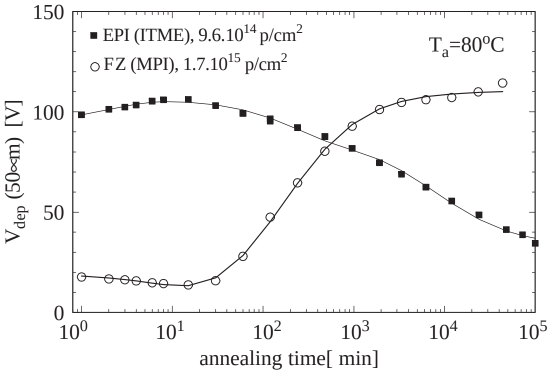

Fig. 4. Annealing at 80 °C of irradiated 50 μm thick standard and epitaxial detectors irradiated to the indicated fluences with 23 GeV protons [30].

5. 3D and semi-3D detectors

So-called "3D" [32] and "Semi-3D" [33] detectors offer a reduced depletion voltage but still a 300 μm thick ionization layer providing the same charge as in a standard planar detector. Both types of detectors have been produced in the framework of RD50.

In "3D detectors" the electrodes are an array of vertical columns penetrating the bulk of the detector. Techniques like dry etching, electrochemical etching or laser drilling have been used to produce holes with a ~5–15 μm diameter [34,35]. The holes are either filled alternating with n- and p-type doped material or are metallized to realize p–n junctions or Schottky contacts. The distance between the electrodes can be small, e.g. 30–100 μm, allowing for the lateral depletion with a very low depletion voltages. Since the drift length is reduced in comparison to standard devices, 3D detectors are especially fast. In the framework of RD50 3D detectors are presently fabricated at the Glasgow University [34] and by a collaboration of CNM in Barcelona and ITC-irst in Trento [35].

Semi-3D detectors are single-sided planar strip detectors that have on the front side alternating n- and p- strips while the back electrode is realized as a n-implant giving an ohmic contact [33]. The advantage, as predicted by simulations, should be observed after type inversion when the bulk of the detector is converted essentially to p-type. Compared to a standard planar detector the depletion voltage should be reduced by a factor of 2.5 since the electric field is developing from the n^+ front electrodes as well as from the n^+ back contact. First prototypes of these detectors have been fabricated at BNL, USA and are presently under investigation.

6. Conclusion

The goals and the developments of the CERN RD50 collaboration related to defect-engineered silicon and new detector concepts have been presented. It was demonstrated that oxygen-enriched silicon and especially Cz and EPI silicon offer an unprecedented radiation tolerance. The absence of type inversion opens new prospects in producing cost-effective radiation tolerant p-in-n detectors. The results presented on n-in-p devices also make p-type silicon now an interesting (non-type-inverting) option for SLHC detectors. With the production of 3D and the Semi-3D detectors RD50 has realized two new detector concepts which are presently under intense tests.

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