Recent results from RD50

D. Bortoletto

Available online at www.sciencedirect.com
ScienceDirect
Nuclear Instruments and Methods in Physics Research A 569 (2006) 69–72
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
www.elsevier.com/locate/nima

Recent results from RD50

Daniela Bortoletto

Physics Department, Purdue University, West Lafayette, IN 47906, USA[1]

Abstract

The luminosity upgrade of the large hadron collider (SLHC) at CERN will require the innermost layers of the vertex detectors to achieve excellent performances up to fluences of about 10^{16} hadrons cm^{-2}. New solid state detectors are currently being developed by the CERN RD50 collaboration. In this paper recent results on magnetic Czochralski, epitaxial, and oxygen-enriched silicon will be presented. The development of novel 3D and semi-3D devices will also be discussed.

PACS: 29.40.Wk; 29.40.Gx; 61.82.Fk

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

1. Introduction

Currently available silicon detector technology will not be able to cope with the extreme requirements at the proposed upgrade of the large hadron collider (LHC) called super-LHC or SLHC [1]. The upgrade is expected to increase the luminosity of this proton–proton collider from 10^{34} to $10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. In this scenario the innermost vertex detectors will have to sustain fast hadron fluences of about $10^{16}\,\mathrm{cm}^{-2}$ after five years operation accumulating an integrated luminosity of $2500\,\mathrm{fb}^{-1}$. This is a 10 times increase with respect to the radiation expected for the vertex detectors which will operate at the LHC. Moreover, the physics goals require that the SLHC detectors will achieve the same performance of the one under construction for the LHC. Due to the required high-rate capability, the excellent spatial resolution, and the needed radiation hardness, new detector concepts and possibly new sensor materials will be needed.

The CERN RD50[2] research program [2] was started in 2002 with the aim to develop semiconductor sensors for the SLHC tracking detectors. The focus of the RD50 effort is divided into: *material engineering* which includes the enrichment of silicon with oxygen or other impurities; *investigation of new materials* such as SiC, amorphous silicon, GaN, and other compound semiconductors; *device engineering* to modify the sensor configuration and therefore improve the performance of planar detector structures; and the investigations of the *optimum detector operational conditions*.

In this paper I will emphasize studies of magnetic Czochralski (MCz) silicon and epitaxial (EPI) silicon. I will also discuss new sensor concepts like 3D and semi-3D. More complete and detailed information about the RD50 activities can be found in Ref. [3].

2. Defect engineering and new materials

Defect engineering aims at suppressing the formation of microscopic defects due to irradiation by introducing impurities into the silicon bulk during the growth of the ingot or the processing of the detector. The interest in oxygen-enriched silicon started in 1998 when the RD48 (ROSE) collaboration demonstrated that oxygen-enriched float zone (denoted as DOFZ) silicon is more resistant against charged hadron and γ-ray irradiation than (standard) FZ silicon [4]. In DOFZ detectors oxygen is diffused from the SiO_2–Si interface during a prolonged tempering after oxidation for up to 72 h at 1150 °C performed before processing of the detector [5]. An average

---

E-mail address: daniela@physics.purdue.edu.

[1] Representing the RD50 collaboration.

[2] The complete RD50 author list can be found at http://www.cern.ch/rd50.

0168-9002/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2006.09.015

oxygen concentration of about $1 \times 10^{17}\,\mathrm{cm}^{-3}$ is reached which is almost one order of magnitude higher than in standard FZ silicon. ATLAS, CMS, and LHCb have chosen to produce some of their sensors with DOFZ.

2.1. Cz and MCz

Cz and MCz silicon are especially interesting since due to the growth technology they have an oxygen concentration of about $10^{18}\,\mathrm{cm}^{-3}$. High-resistivity Cz and MCz material needed for the processing of standard 300-μm thick detectors has become recently available. The RD50 collaboration has investigated Cz silicon from Sumitomo-Sitix, Japan (600 Ω cm, n-type, ⟨1 0 0⟩, $[\mathrm{O}] = 8 \times 10^{17}\,\mathrm{cm}^{-3}$) and MCz silicon from Okmetic Ltd., Finland (900 Ω cm n-type and 2 kΩ cm p-type, ⟨1 0 0⟩, $[\mathrm{O}] = 5 \times 10^{17}\,\mathrm{cm}^{-3}$). Cz silicon was processed at CiS (Germany) and MCz at Helsinki University of Technology (Finland) and more recently at BNL (USA), IRST (Italy), and SINTEF (Norway). The samples were irradiated with reactor neutrons, high-energy (23 GeV) and low-energy (10, 20, 30 MeV) protons, 190 MeV pions, 900 MeV electrons and ^{60}Co γ-rays. Preliminary results reveal advantages of MCz and Cz with respect to FZ and DOFZ silicon. MCz silicon has a lower depletion voltage than DOFZ silicon after irradiation at high fluences. The variation of the depletion voltage of Cz silicon as a function of the fluence is small and it might provide more stable conditions during detector operation [6].

Systematic measurements comparing FZ and MCz silicon were recently conducted within the SMART project funded by the Instituto Nazionale Fisica Nucleare (INFN) in the framework of RD50 [7]. The wafer layout included 66 test structures and 10 microstrip sensors of different geometries. Processing of the wafers was performed by ITC-IRST (Trento, Italy) first on n-type (RUN-I) and then on p-type (RUN-II) materials. The isolation between n^+ implants was achieved with p-spray doped to $3 \times 10^{12}\,\mathrm{cm}^{-2}$ (low-dose p-spray) and $5 \times 10^{12}\,\mathrm{cm}^{-2}$ (high-dose p-spray). Pre-irradiation measurements of the n-type devices (FZ,MCz) showed uniform wafer resistivity, good current density, and breakdown performance for all sensor designs. Local variations in the depletion voltage were observed in MCz p-type wafers possibly due to thermal donor creation. Low breakdown voltages in both FZ and MCz material with high-dose p-spray were observed. The p-type detector performance improved significantly after irradiation. The breakdown voltages of the low-dose p-spray detectors increased to 600 V after irradiation. The high-dose p-spray detector performance improved only after irradiation to 6×10^{14} 1-MeV $n_{\mathrm{eq}}\,\mathrm{cm}^{-2}$. The depletion voltage is shown in Fig. 1 for both FZ and MCz n-type and p-type diodes irradiated with 26 MeV protons to 5.39×10^{14} 1-MeV $n_{\mathrm{eq}}\,\mathrm{cm}^{-2}$. The depletion voltage of MCz Si (both n- and p-type) changes very slowly after 200 min at 80 °C, while V_{dep} for FZ materials is rapidly increasing. The drop in depletion voltage observed in n-type MCz silicon after an annealing time of about 200 min has been observed by other groups [8]. The reduced reverse annealing of MCz silicon is very promising since it could simplify the operation of the SLHC detectors.

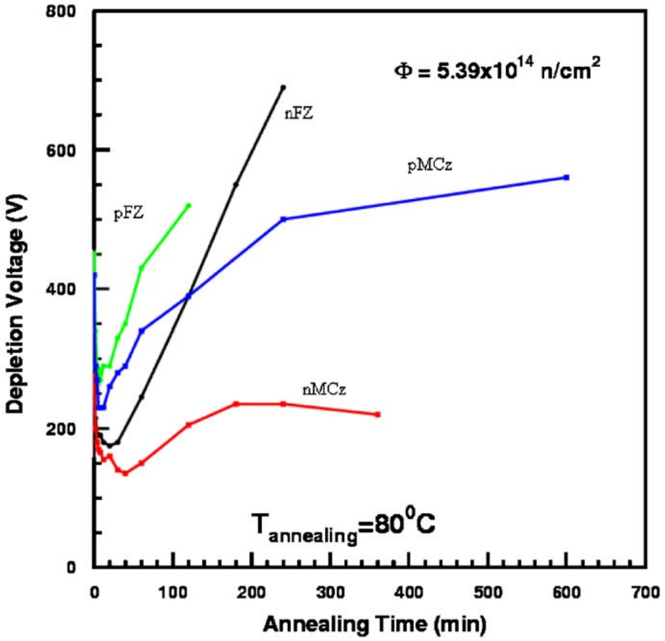

Fig. 1. Comparison of FZ and MCz detectors after irradiation and annealing at 80 °C.

The interstrip capacitance C_{I} was also measured by the SMART collaboration to evaluate the expected noise. Before irradiation C_{I} reaches a minimum value between 0.5 and $1.2\,\mathrm{pF\,cm}^{-1}$, depending on the device geometry, once the sensors are overdepleted. The MCz and the FZ microstrip detectors have comparable C_{I} after irradiation. In n-type sensors, C_{I} did not change significantly with the fluence. On the contrary, in p-type detectors C_{I} decreased with the fluence and reached the n-type values in sensors irradiated to $4 \times 10^{14}\,n_{\mathrm{eq}}\,\mathrm{cm}^{-2}$.

Few unirradiated SMART microstrip sensors were connected to the front-end readout chip and the DAQ system used by the CMS tracker. Electrons from a ^{106}Ru source were used to measure the charge collected by n-type FZ and MCz sensors. The results show that MCz and FZ n-type detectors have a similar performance. Both MCz and FZ detectors have an average value of the charge collected of about 18.8 ± 0.3 ADC channels and a signal-to-noise (S/N) ratio of 19 for a 50-μm-pitch detector.

Many RD50 groups are studying the performance of MCz silicon. Wafers were fabricated by SINTEF matching the CMS n-on-n pixel layout. The characterization of these wafers showed excellent breakdown properties. These wafers are now being bump-bonded to custom made PSI46 readout chips [9]. After dicing the sensors, they will be irradiated and their performance will be evaluated in a beam test at Fermilab [10].

In summary, the improved performance in terms of depletion voltage of MCz and Cz sensors with respect to

FZ is very promising but it needs to be complemented by further studies of S/N ratio and the charge collection efficiency (CCE) after irradiation in order to fully establish Cz and MCz detectors as ideal material for the trackers at the SLHC.

2.2. Epitaxial detectors

After irradiation with $10^{16}\,\mathrm{cm}^{-2}$ fast hadrons the effective drift length of charge carriers is reduced by trapping and the collected charge 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 ($\approx 2000e$) as pixels with $d = 25\,\mu\mathrm{m}$ [11]. Thin detectors have several advantages such as lower leakage current and lower depletion voltage. The increase in capacitance and noise can be minimized by smaller cell sizes. The smaller initial signal puts stringent requirements on the readout electronics. The activity in thin sensors and the availability of 25-, 50-, and 75-μm epitaxial silicon grown on low-resistivity ($<0.02\,\Omega\,\mathrm{cm}$) Cz silicon substrates is increasing interest in EPI detectors. Short microstrip sensors were irradiated with 23 GeV protons and 58 MeV lithium ions. Measurements reported in Refs. [12,13] show that the EPI layers have different properties than thin detectors made from FZ material. In Fig. 2, N_{eff} as function of the 23 GeV proton fluence is shown for 25-, 50-, and 75-μm thick detectors. The depletion voltage rises with increasing fluence for both EPI and FZ detectors. The major difference between EPI and FZ material appears in the annealing studies shown in Fig. 3. For Standard FZ silicon V_{dep} increases with time while for EPI silicon a decrease of depletion voltage with time is visible. This is a very promising development for high-energy physics experiments since it indicates that EPI detectors would not be degraded by reverse annealing. Moreover, EPI detectors could be kept at room temperature during shutdown periods which will significantly simplify their operation and maintenance. Studies of the CCE have been initiated. The CCE of EPI microstrip sensors exposed to beta particle emitted by an ^{90}Sr source was measured with LHC electronics with a shaping time of 25 ns [14]. After 8×10^{15} (6×10^{15}) neutrons (protons) the most probable signal with 50-μm thick EPI sensors is 2300 (2400) electrons. This charge is below the threshold currently used to operate pixel sensors at the LHC. EPI layer of 150 μm is now available within the RD50 effort and it will be studied shortly.

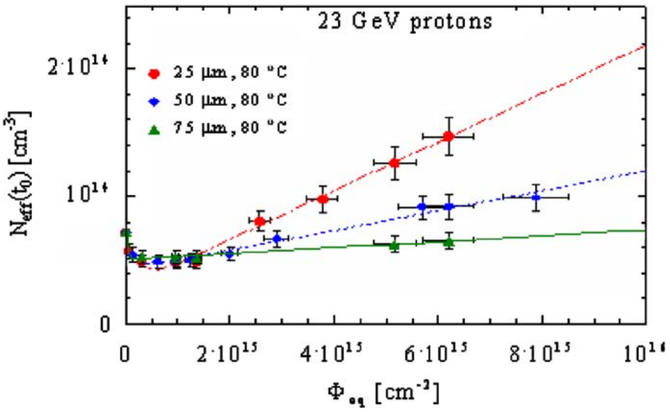

Fig. 2. N_{eff} for 25, 50, and 75-μm thick EPI detectors after irradiation with 23 GeV protons.

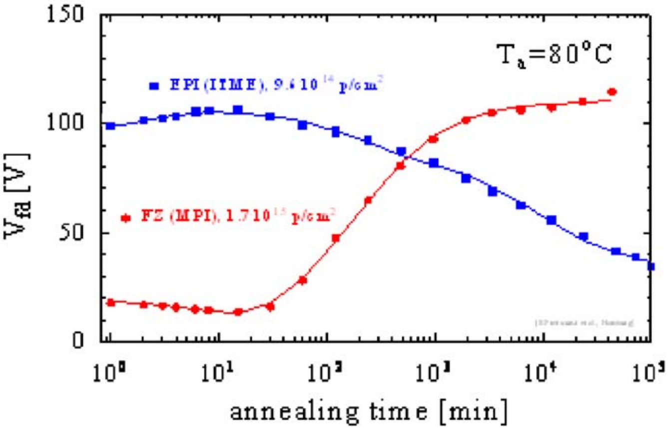

Fig. 3. Comparison of 50-μm thick FZ and EPI detectors after irradiation with 23 GeV protons and annealing of 8 min at 80 °C.

3. The 3D and semi-3D detectors

RD50 is also investigating 3D [15] and "semi-3D" [16] detectors. In 3D detectors the electrodes are arrays of vertical columns drilled or etched in the bulk of the detector. Therefore, the fabrication of these detectors requires the combination of micromachining with standard techniques used in the production of planar detectors.

The standard designs of 3D detectors proposed by Parker et al. [15] uses vertical electrodes of both doping types arranged in adjacent cells. The small distances between the electrodes (50–100 μm) result in low full depletion voltages and short collection times. Therefore, this technology is a candidate for the layers closer to the interaction region where doses of about 10^{16} particles cm^{-2} are expected. The main drawbacks with these devices are dead regions due to the implants and the "zero-field" regions between same type electrodes. The latter causes a delay in the collection of carriers which could be reduced with overbiasing the devices.

Recently the group of ITC-IRST (Trento, Italy) has developed a new 3D detector architecture which aims at simplifying the manufacturing process [17]. The proposed devices feature electrodes of one doping type only such as n^+ columns in a p-type substrate. The main advantage is that the column etching and doping has to be performed only once. The columns may extend deep into the bulk or all the way through it. The first option leads to a further process simplification, since the initial wafer bonding and

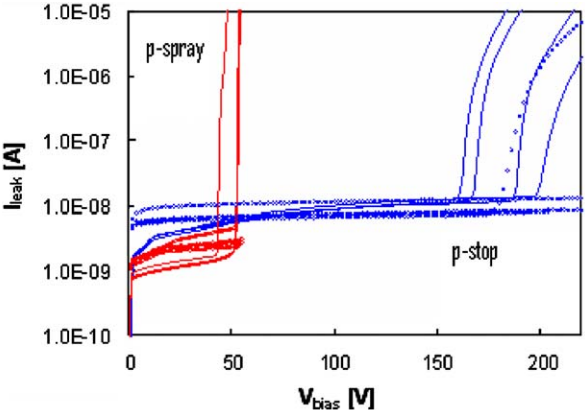

Fig. 4. Leakage current versus bias voltage for 3D strip detectors.

the final removal of the support wafer is not required [17]. The electric field configuration of these detectors forces the electrons generated in the substrate to move laterally to the closest n^+ electrode, whereas the holes drift towards the region between the electrodes and then move slowly to the p^+ rear side. The drawback of this novel architecture is larger low-field regions. The fabrication of the first prototypes has been completed at ITC-IRST in collaboration with CNM (Barcelona, Spain) for the hole etching process.

The wafers processed at ITC-IRST contain long and short strip sensors, planar, and 3D test structures. They were fabricated on standard FZ and Cz material. The strip detectors have between 12,000–15,000 columns and an intercolumn pitch between 80 and 100 μm. The hole diameter is between 6–10 μm. The n-columns are isolated with p-stops and p-sprays. First measurements, shown in Fig. 4, indicate that the deep reactive ion etching does not degrade the device performance. Early breakdown was measured on p-spray sensors similar to what was found on planar sensors. Irradiation studies will follow.

Semi-3D detectors are single-sided planar devices that have alternating n^+ and p^+ strips on the front side while the rear side has a uniform n^+ implant [16]. According to simulations, the advantage of this electrode configuration is the reduction of the full depletion voltage by a factor of about 2 compared to standard planar strip detectors, since the depletion develops both from the n^+ strips on the front side and the n^+ back plane towards the p^+ readout electrodes. First prototypes of these structures have been produced at BNL (USA). Several samples were irradiated at CERN with 23 GeV protons and at IUCF (USA) with a 200 MeV proton beam. First measurements after irradiation to a fluence of $\phi_{eq} = 5 \times 10^{14}\,\mathrm{cm}^{-2}$ confirm that semi-3D detectors deplete at about half the expected voltage of standard planar strip devices [16].

4. Conclusions

The RD50 collaboration has already produced impressive results in defect-engineered silicon and new detector concepts. It was demonstrated that oxygen-enriched silicon and, especially, MCz and EPI silicon offer promising radiation tolerance and could provide cost-effective p-in-n detectors. Novel 3D and the semi-3D detectors were realized and are presently under intense tests.

References

[1] F. Giannotti, et al., April 2002, ⟨hep-ph02004087⟩.
[2] RD50 Proposal, LHCC 2002-003/P6, CERN, 15 February 2002.
[3] RD50 Status Report 2002/2003, CERN-LHCC-2003-058 and RD50 Status Report 2004, CERN-LHCC-2004-031.
[4] G. Lindström, et al., Nucl. Instr. and Meth. A 465 (2001) 60; G. Lindström, et al., Nucl. Instr. and Meth. A 466 (2001) 308.
[5] G. Lindström, et al., Nucl. Instr. and Meth. A 512 (2003) 30.
[6] E. Fretwurst, et al., Nucl. Instr. and Meth. A 552 (2005) 124.
[7] V. Radicci, et al., Study of radiation damage induced by 24 GeV/c and 26 MeV protons on heavily irradiated magnetic Czochralski and float zone silicon detectors, Presented at the Seventh International Conference on Large Scale Applications and Radiation Hardness of Semiconductor Detectors, 5–7 October 2005, Florence, Italy.
[8] J. Härkönen, Private communication.
[9] H. Chr. Kästli, et al., Nucl. Instr. and Meth. A 565 (2006) 188.
[10] D. Bortoletto, et al., Measurements of MCz sensors, Presented at the Sixth RD50 Collaboration Meeting, 2–5 June 2005, Helsinki, Finland.
[11] G. Kramberger, D. Contarato, Nucl. Instr. and Meth. A 511 (2003) 82.
[12] G. Lindström, et al., Nucl. Instr. and Meth. A 556 (2006) 451.
[13] G. Lindström, et al., Epitaxial silicon detectors for particle tracking applications—overview on radiation tolerance in extreme intensity hadron fields, Presented at the 10th RD50 European Symposium on Semiconductor Detectors, 12–16 June 2005, Wildbad Keuth, Germany.
[14] G. Kramberger, et al., Nucl. Instr. and Meth. A 554 (2006) 212.
[15] S. Parker, et al., Nucl. Instr. and Meth. A 395 (1997) 328.
[16] Z. Li, et al., Nucl. Instr. and Meth. A 478 (2002) 303; A. Roy, et al., Nucl. Instr. and Meth. A 552 (2005) 112.
[17] A. Pozza, et al., First electrical characterization of 3D detectors with electrodes of the same doping type, in: Seventh International Conference on Large Scale Applications and Radiation Hardness of Semiconductor Detectors, 5–7 October 2005, Florence, Italy.