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Section A
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Recent advancements in the development of radiation hard semiconductor detectors for S-LHC

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The CERN-RD50 collaboration

Abstract

The proposed luminosity upgrade of the Large Hadron Collider (S-LHC) at CERN will demand the innermost layers of the vertex detectors to sustain fluences of about 10^{16} hadrons/cm^2. Due to the high multiplicity of tracks, the required spatial resolution and the extremely harsh radiation field new detector concepts and semiconductor materials have to be explored for a possible solution of this challenge. The CERN 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 S-LHC. Different strategies are followed by RD50 to improve the radiation tolerance. These include the development of defect engineered silicon like Czochralski, epitaxial and oxygen-enriched silicon and of other semiconductor materials like SiC and GaN as well as extensive studies of the microscopic defects responsible for the degradation of irradiated sensors. Further, with 3D, Semi-3D and thin devices new detector concepts have been evaluated. These and other recent advancements of the RD50 collaboration are presented and discussed.

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

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1. Introduction

For the luminosity upgrade of the Large Hadron Collider (LHC) at CERN to $10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ (Super-LHC or SLHC) [1] the presently available silicon detector technology cannot match the extreme requirements with respect to the necessary radiation tolerance. The innermost vertex detectors have to face fluences above $10^{16}\,\mathrm{cm}^{-2}$ of fast hadrons after five years operation accumulating an integrated luminosity of $2500\,\mathrm{fb}^{-1}$. This is a ten times higher radiation level than expected for the vertex detectors of the LHC experiments. Due to the required very high rate capability and spatial resolution together with the demand for a significantly improved radiation hardness new detector concepts and possibly new sensor materials have to be explored and developed. The CERN RD50 research program "Development of Radiation Hard Semiconductor Devices for Very High Luminosity Colliders" [2] started in 2002 with the aim to develop semiconductor sensors matching the requirements for SLHC tracking detectors. Special emphasis is put on the development of more radiation tolerant silicon like high resistivity Czochralski (Cz) or Magnetic Czochralski (MCz) silicon, epitaxial (epi) silicon layers or other defect engineered silicon. In addition, the compound semiconductor materials SiC and GaN are explored regarding their possible ability to sustain such extremely high radiation levels. On the other hand, new device concepts like 3D and semi-3D as well as thin sensors are under development and investigation. A further research field of the collaboration is the characterization and identification of radiation-induced defects and the study of the reaction kinetics in order to understand their impact on the degradation of the detector properties. Only this way a deliberate defect engineering of the material for an improved radiation hardness could be successfully achieved. Only specific topics of the overall RD50 research program and recent results are presented and discussed in this paper. More detailed information can be found in Refs. [3,4].

2. Material engineering

2.1. Defect engineering in silicon

The aim of defect engineering is to influence the formation of microscopic defects in such a way that their detrimental effect on the macroscopic device properties by radiation is reduced or suppressed. This can be achieved by an incorporation of impurities or gettering sites into the silicon bulk before, during or after the processing of the detector.

2.2. Oxygen in silicon

A successful example for defect engineered silicon is the oxygen enrichment of high resistivity FZ (DOFZ) silicon by diffusion of oxygen into the bulk material from the oxide surface layer at high temperatures of about 1100–1200 °C for a prolonged period. At 1150 °C and a diffusion time of 72 h the oxygen content can be increased to a level of $10^{17}\,\mathrm{cm}^{-3}$ which is almost one order of magnitude higher than in standard FZ silicon [5]. This method was introduced by the RD48 (ROSE) collaboration in 1998 and it was demonstrated that the build-up of negative space charge in a reverse biased detector after irradiation with high energetic charged hadrons is strongly suppressed [6,7]. This beneficial effect was recently found to be even more pronounced after gamma irradiation [8,9]. Here, the effective space charge of oxygen-enriched silicon remains positive and gets even more positive with increasing dose in contrast to standard FZ silicon which shows a strong built-up of negative space charge. The underlying microscopic reasons for these macroscopic effects could be mainly clarified [10–12].

The limitation in the oxygen concentration by the DOFZ technique can only be overcome by the use of Cz or MCz silicon which contains due to their specific growth technology a much higher amount of oxygen in the order of about $4–10\times10^{17}\,\mathrm{cm}^{-3}$ [5,13]. But only recently high resistivity material became available needed for the processing of standard 300 μm thick detectors.

High resistivity n-type Cz silicon from Sumitomo (Japan) and n- and p-type MCz material from

Okmetic Ltd. (Finland) has been investigated. In the detector processing various institutions are involved: CiS (Germany), Helsinki University of Technology (Finland), BNL (USA), IRST (Italy) and CNM (Spain). Numerous irradiation experiments have been performed with high energy (23 GeV [13,14]) and low energy (10, 20, 30, 50 MeV [15]) protons, reactor neutrons [16], ^{60}Co gamma rays [16] and 900 MeV electrons [17,18]. The results from these experiments clearly reveal advantages of MCz and Cz silicon against standard and oxygen-enriched FZ material with respect to the development of the effective doping concentration N_{eff} with increasing fluence or dose. As an example, Fig. 1 shows the change of N_{eff} after 900 MeV electron irradiation for n-type Cz and n- and p-type MCz devices. The 1 MeV neutron equivalent fluence values in Fig. 1 are derived by scaling the electron fluence with a hardness factor of $\kappa = 0.023$ [17].

Both n-type materials behave very similar showing after an initial decrease of N_{eff} up to $4 \times 10^{15}\,\mathrm{e/cm^2}$ a very small increase in the higher fluence range. In contrast, p-type MCz silicon shows a decreasing trend of N_{eff} up to the highest fluence value, but with a much lower rate above $1 \times 10^{15}\,\mathrm{cm^{-2}}$ ($\beta = 1.5 \times 10^{-3}\,\mathrm{cm^{-1}}$) compared to the n-type material [18]. Further, after 23 GeV proton irradiation it has been shown by probing the electric field distribution inside the irradiated devices via the Transient Current Technique (TCT) that both n-type materials do not undergo type inversion up to the highest fluence investigated [14,19]. This effect can only be explained by a formation of donors, which at high fluences overcompensate the introduction of deep acceptors. As will be shown later, the formation of donors was proven by microscopic defect studies. It should also be mentioned that the annealing behavior of irradiated Cz and MCz devices is quite different from that observed for standard FZ or DOFZ detectors. E.g. the overall change of the depletion voltage with annealing time at 80 °C up to about 33 h is substantially smaller compared to FZ silicon, i.e. Cz devices are much more stable with respect to the full depletion voltage against prolonged storage at room temperature [13]. This is a beneficial effect for the operation of such devices under S-LHC conditions during beam off periods.

More recently the role of thermal donors (TD) in contributing to the effective doping concentration was studied for a possible radiation hardening method [4,20]. It is well known that thermal donors can be activated and deactivated by appropriate heat treatments [21]. The creation of TD offers the possibility to tailor the starting resistivity of the material to a specific value. This way initially p-type material can be converted into n-type silicon. Fig. 2 presents the evolution of the space charge concentration for a set of samples

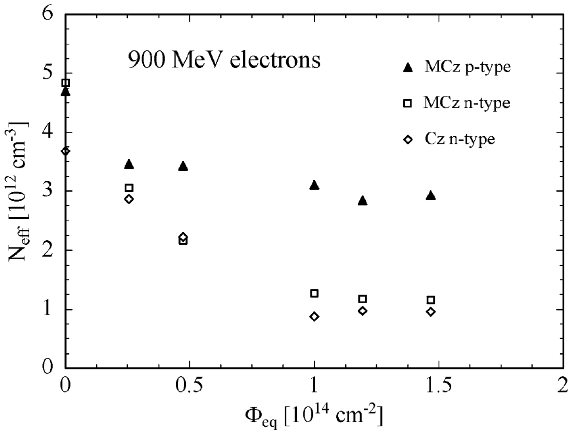

Fig. 1. Development of effective doping concentration as function of fluence for Cz and MCz silicon devices after irradiation with 900 MeV electrons.

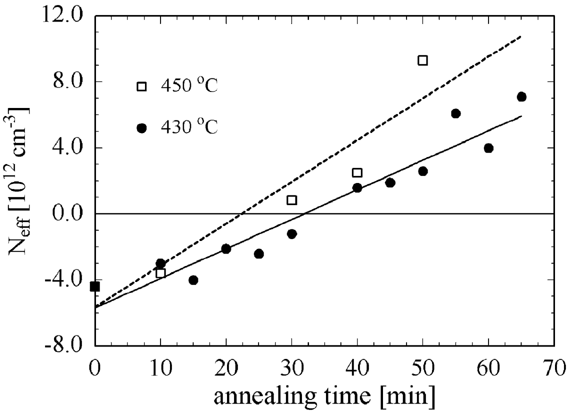

Fig. 2. Effective doping concentration in MCz silicon as function of heating time at 430 and 450 °C.

with annealing time at the peak temperatures 430 and 450 °C [20].

Such converted devices were irradiated with 23 GeV protons with fluences between 5×10^{12} and $5 \times 10^{14}\,\mathrm{cm}^{-2}$ and it was shown that the ratio of the full depletion voltage after irradiation with respect to the value before irradiation varies between 0.5 and 1.6 only [20].

2.3. Oxygen dimers in silicon

A possibly more elaborate defect engineering approach could be the enrichment of oxygen dimers (O_2) in silicon instead of interstitial Oxygen (O_i). In such a material radiation-induced vacancies are gettered not only by the formation of A-centers via $V + O_i \rightarrow VO$ but also by the creation of VO_2 centers via $V + O_2 \rightarrow VO_2$, a defect which is electrically not active. Further, the formation of the V_2O complex, which is believed to be responsible for a part of the radiation-induced degradation of the detector properties, can only be formed via a second-order process ($V + VO \rightarrow V_2O$) and would also be strongly suppressed in O_2-rich material. On the other hand, the generation of V_2O_2 via $V + VO_2 \rightarrow V_2O_2$ becomes possible, a defect which might not be as harmful as V_2O. In a first attempt Cz material with different O_i concentration, DOFZ and standard FZ material were chosen for a so-called dimerization process [22]. In this process these materials as well as detectors were irradiated with 2.5 MeV electrons at 350 °C to a high dose ($1 \times 10^{18}\,\mathrm{cm}^{-2}$) to form dimers [23]. However, the maximal achieved ratio between $[O_2]$ and $[O_i]$ was only about 3% (see Fig. 3) and in particular the resistivity of the material was changed to such high levels (most probably by the formation of thermal donors) that a detector operation became impossible. Nevertheless, these activities will continue since the process might be improved to a reduced creation of thermal donors.

It is interesting to note that oxygen dimers in small concentrations can play an essential role in the performance of silicon devices after irradiation with charged hadrons. This was studied by Thermally Stimulated Current (TSC) measurements on detectors processed on Cz and thin epi-layers grown on Cz substrates [24]. As an example in Fig. 4 TSC spectra are shown for a Cz- and an epi-sample after irradiation with 23 GeV protons to a 1 MeV neutron equivalent fluence of $1.8 \times 10^{14}\,\mathrm{cm}^{-2}$. Here, the presence of O_2 could be monitored by the formation of the interstial-oxygen-dimer (IO_2) defect complex. The relative O_2 concentration could be determined from the introduction rate of IO_2 for both materials. In the epi-device it was found to be about 37% of that

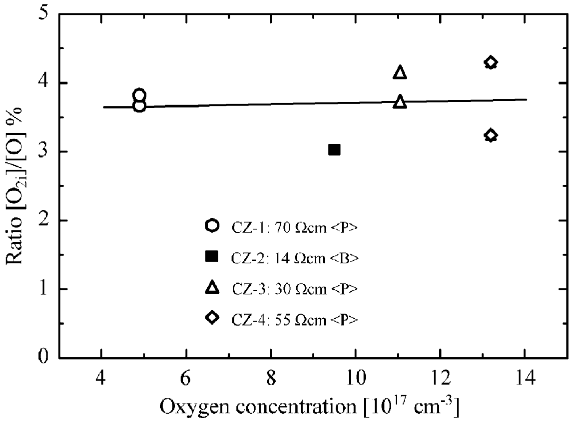

Fig. 3. Ratio of oxygen dimers to oxygen after a dimerization process ($T = 330-340\,°\mathrm{C}$, $\Phi = 1 \times 10^{18}\,\mathrm{cm}^{-2}$) of CZ samples with different initial oxygen content.

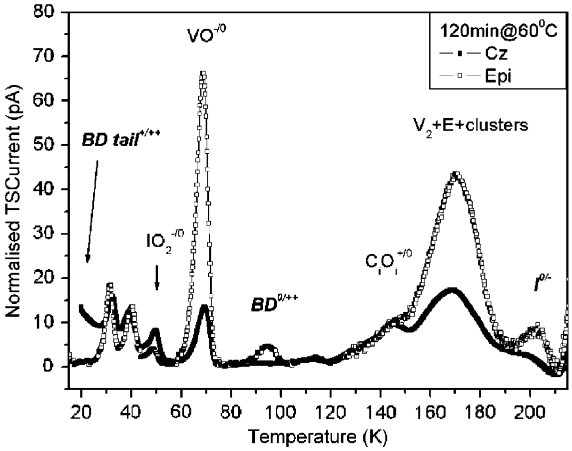

Fig. 4. TSC spectra after irradiation with 23 GeV protons with an equivalent fluence of $1.84 \times 10^{14}\,\mathrm{cm}^{-2}$ recorded on Cz and epi-material after annealing at 60 °C for 120 min.

observed for the Cz sample. This ratio is surprisingly large considering the fact that the concentration of O_2 is expected to be proportional to the square of the O_i concentration and that the O_i concentration in the Cz material is about a factor 10 higher compared to that in the epi-layer [25]. These observations lead to the presumption that the high O_2 content in the thin epi-layer might be caused by an out-diffusion of O_2 from the Cz substrate into the epi-layer during thermal treatments involved in the device processing. Further, it should be emphasized that for the radiation tolerance of both materials it is of major importance that shallow donors are created by irradiation which were detected in the TSC spectra and labeled "*BD tail*$^{+/++}$" and "*BD*$^{0/++}$". The consequence of the donor generation is that both materials do not undergo type inversion after exposure to charged hadrons or electrons [18,26,27].

2.4. Hydrogen in silicon

A further defect engineering approach is the enrichment of silicon with hydrogen. It is well-known that hydrogen can easily penetrate into silicon crystals at various stages of detector processing [28]. It is expected that an enrichment with hydrogen will lead to more radiation-tolerant devices due to hydrogen passivation of radiation-induced defects [28,29], and acceleration of oxygen diffusion by promoting the formation of oxygen dimmers O_2 [30–32]. In a first experiment standard FZ devices were hydrogenated in a plasma at 300 °C for 2 h, irradiated with 3.5 MeV electrons to a dose of $3 \times 10^{12}\,cm^{-2}$ followed by an isochronal annealing for 30 min up to 350 °C in steps of 50 °C [33]. After each annealing step DLTS spectra and depth profiles of the carrier concentration $n(x)$ were recorded. The depth profiles were derived from $C-V$ characteristics measured at a frequency of 1 MHz.

In Fig. 5 depth profiles before and after hydrogenation and after irradiation and three annealing steps are shown. The effect of hydrogenation is an increase of the carrier concentration due to a formation of hydrogen-related thermal donors. After irradiation and annealing at temperatures higher than 250 °C a redistribution of $n(x)$ is observed with an increasing tendency of $n(x)$ towards the p^+-contact which can be correlated with a redistribution of hydrogen from the n^+ contact region to the p^+ contact. From the measured DLTS spectra after irradiation and annealing (see Fig. 6) one observes a decrease of the well-known peaks E1 ($VO + C_iC_s$), E2 ($V_2^{(=/-)}$) and E4 ($V_2^{(-/0)}$) and an increase of the signal E5

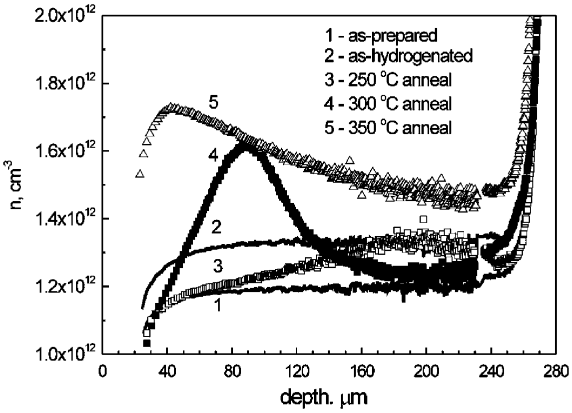

Fig. 5. Carrier depth profile for a standard FZ sample: (1) before, (2) after hydrogenation and after irradiation and annealing for 30 min at (3) 250 °C, (4) 300 °C and (5) 350 °C.

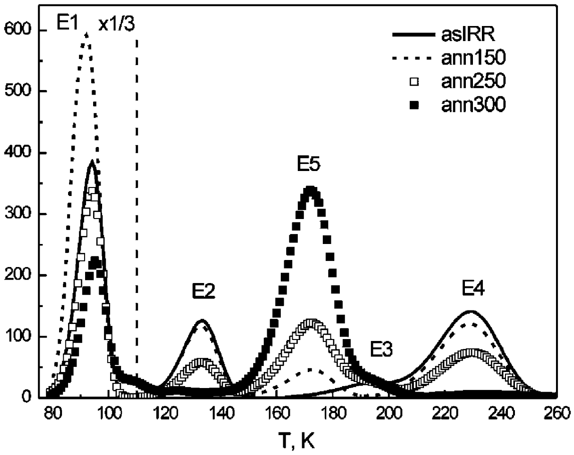

Fig. 6. Development of DLTS spectra for a hydrogenated standard FZ sample after electron irradiation and 30 min isochronal annealing with increments of 50 °C.

which is attributed to the hydrogen-related VOH complex. Similar measurements on oxygen-enriched and hydrogenated FZ samples had been performed by Monakov et al. [34], revealing the same annealing behavior as shown in Fig. 6.

From more detailed studies including investigations of non-hydrogenated devices it can be concluded, that hydrogen in silicon is not only present as atomic hydrogen but also as hydrogen molecules whose diffusivity is much smaller compared to atomic hydrogen. Further, hydrogen promotes the annealing of A-centers (VO) and of divacancies (V_2) and accelerates the formation of shallow donors. Studies on the influence of hydrogen on hadron damage in silicon are in preparation.

2.5. New materials

In the frame of the RD50 project silicon carbide (SiC) and gallium nitride (GaN) are under investigation in comparison to silicon. Some characteristic properties of SiC and GaN in comparison to silicon are listed in Table 1. The large band gap of both materials compared to silicon leads to very low dark currents, which would allow an operation of such devices at room temperature. In particular, the displacement threshold of 25 eV for 4H-SiC indicates a potentially higher radiation tolerance than silicon (13–20 eV). However, it has to be kept in mind that SiC and GaN are compound semiconductors and more reaction channels for creation of harmful defects might result in a stronger degradation of the device properties than in monoatomic silicon. Within this project the developments and research activities are focused on 4H-SiC and GaN epi-layers.

Table 1
Properties of GaN, 4H-SiC and Si crystals at 300 K

Property	GaN	4H-SiC	Si
Bandgap (eV)	3.39	3.27	1.12
Electron mobility ($cm^2 Vs^{-1}$)	1000	800	1500
Hole mobility ($cm^2 Vs^{-1}$)	30	115	450
e–h energy (eV)	~8–10	8.4	3.6
Displacement energy (eV)	~10–20	25	13–20

Epitaxial 4H-SiC layers grown by Cree Research Inc. (USA) and IKZ (Berlin, Germany) with very high crystal quality were recently investigated with respect to their radiation hardness [35]. For Schottky-diodes a 100% charge collection efficiency for β-particles of a ^{90}Sr-source was obtained before irradiation. Irradiation experiments have been performed with 23 GeV protons up to $1.4 \times 10^{16}\,cm^{-2}$ at the PS (CERN). After this high fluence the material becomes intrinsic and a charge collection efficiency in the order of 30% was measured at 800 V. Further, various samples with thicknesses between 40 and 50 μm were irradiated with reactor neutrons up to $7 \times 10^{15}/cm^2$ in Ljubljana. In this case the charge collection efficiency was studied with α-particles and at $7 \times 10^{15}\,n/cm^2$ an efficiency of 20% could be attained at 700 V (see Fig. 7). These measurements, carried out by the Florence group, have been performed using a low-noise read-out electronic system with 2 μs shaping time [35].

These results, showing a limited radiation hardness of epitaxial 4H-SiC to fast hadrons, have to be confirmed by a more systematic work on the same material, which is presently under way. Further developments on the processing of p^+–n–n^+ devices and first results can be found in Ref. [4].

The R&D of GaN-based detectors within RD50 is carried out mainly by three groups (University of Glasgow, Surrey and Vilnius). A main part of the activities is concentrated on the material

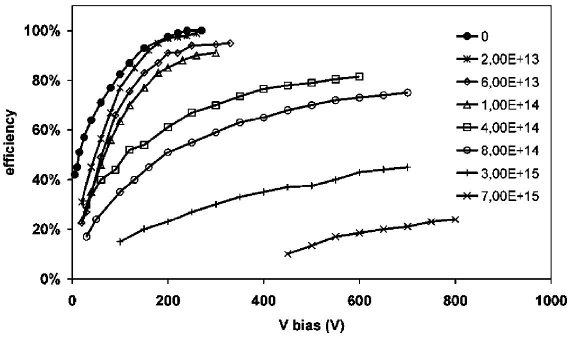

Fig. 7. Charge collection efficiency as function of bias voltage after neutron irradiation, measured with α-particles on 4H-SiC epi-devices.

properties (carrier life times, photoelectric properties, defects, etc.) which are summarized in Ref. [4]. First studies on detector properties in particular on charge collection and its degradation by irradiation were performed on thin semi-insulating GaN films (2.5 μm) deposited on sapphire with a buffer layer of 2 μm n^+ GaN [36]. Due to the small thickness of the epi-layer, the contact potential was able to deplete the diode fully at 0 V bias. Before irradiation a maximum CCE of 97% for α-particles was obtained at 15 V using a read-out electronics with a 1 μs shaping time. Neutron irradiations were performed at the reactor in Ljubljana (Slovenia) with fluences between 5×10^{14} and $1 \times 10^{16}\,\mathrm{n/cm^2}$. The irradiated samples showed a decrease in CCE with fluence reaching a value of about 5% at $10^{16}\,\mathrm{n/cm^2}$. One GaN diode was also irradiated up to $1 \times 10^{16}\,\mathrm{cm^{-2}}$ 23 GeV protons and an efficiency of about 13% was observed. More investigations are foreseen especially on new and thicker epi-layers with an improved process technology for the Schottky contacts.

3. Device engineering

After an irradiation up to $10^{16}\,\mathrm{cm^{-2}}$ fast hadrons the effective drift length of charge carriers is drastically reduced by trapping and, therefore, the produced signal does no longer depend linearly on the detector thickness or the electrode distance. In order to improve the charge collection properties different detector geometries are under development and investigation in the frame of RD50, which are described in Sections 3.1 and 3.2.

3.1. Thin silicon detectors

A considerable reduction of the pixel area, essential for the inner layers of a vertex detector at S-LHC, allows correspondingly a smaller detector thickness while maintaining the same input capacitance and hence its influence to the electronic noise. Thin active layers will certainly reduce the voltage for total depletion. This allows to establish a high electric field strength throughout the sensitive sensor volume and the degradation of the charge collection efficiency due to trapping can be partly compensated.

For the development of thin detectors different technological approaches are possible and under investigation in the framework of RD50. These are thin epi-layers grown on highly doped Cz substrates [26], thinning of high resistivity FZ devices by chemical etching [37] and processing of thin high resistivity FZ devices using the so-called wafer bonding technology [38].

Epi-Si detectors grown on Cz substrates were found to exhibit a superior radiation hardness in terms of the effective doping concentration [26]. Several wafers of different epi-layer thicknesses (25, 50 and 75 μm) and a resistivity of 50 Ωcm were grown by ITME (Warsaw, Poland) and processed by CiS. The epi-Si diodes were irradiated up to $\Phi_{\mathrm{eq}} = 10^{16}\,\mathrm{cm^{-2}}$ and show (Fig. 8) no space charge sign inversion after proton and also neutron irradiation when the full depletion voltage V_{fd} is measured after 8–30 min annealing at 80 °C [39]. In particular, the full depletion voltage of neutron-irradiated samples does not exceed the value before irradiation. In standard FZ detectors charged acceptors generated during the reverse annealing add to the effective acceptor concentration representing the stable damage. This leads to a significant increase of full depletion voltage if the devices are not kept at low temperatures. On the other hand, the reverse annealing is beneficial for epi-Si detectors as the generated acceptors

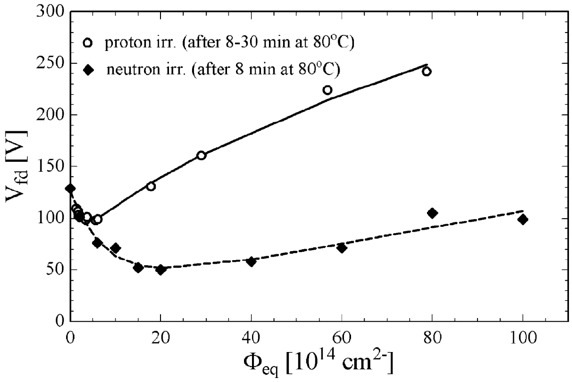

Fig. 8. Full depletion voltage as function of equivalent fluence for 50 μm epi-Si detectors (open symbols: 23 GeV protons, filled symbols: reactor neutrons).

compensate the stable positive space charge. The difference in the annealing behavior between FZ and epi-Si devices irradiated to similar fluences can be seen in Fig. 9. Although the full depletion voltage of the high resistivity FZ detector is very small after irradiation it increases with time and after few hundred minutes at 80°C reaches the same value of the epi-Si detector.

Charge collection efficiency measurements in epi-Si detectors have been performed with minimum ionizing electrons from a collimated ^{90}Sr source on several samples irradiated with protons and neutrons up to $\Phi_{\mathrm{eq}} = 10^{16}\,\mathrm{cm}^{-2}$. The read-out system includes a charge-sensitive preamplifier and a shaping amplifier with a peaking time of 25 ns [39]. The mean and the most probable values of the collected charge as function of fluence are presented in Fig. 10. To evaluate the effect of trapping, the measured data were compared with simulations. Below $\Phi_{\mathrm{eq}} = 2 \times 10^{15}\,\mathrm{cm}^{-2}$ the simulation agrees nicely with the experimental values for both 50 and 75 μm diodes while at larger fluences underestimates the collected charge. This latter effect indicates that the effective trapping probability at very high fluences might be lower than extrapolated from data presented in the literature [14,40,41].

Detectors with a thickness of 50 and 100 μm had been processed by IRST on high resistivity n-type FZ silicon [37,42]. First radiation damage tests were performed with 58 MeV Li ions at the SIRAD Irradiation Facility of the INFN National Laboratory of Legnaro (Italy) up to fluence values of $1 \times 10^{14}\,\mathrm{Li/cm}^2$. It was demonstrated that devices made from thinned substrates exhibit a very low depletion voltage even after the highest fluence, in particular, V_{fd} does not exceed 60 V for the 50 μm thick detectors. Also charge collection efficiency measurements have been carried out with a ^{90}Sr β-source showing that an efficiency of 100% could be achieved after irradiation up to $1 \times 10^{14}\,\mathrm{Li/cm}^2$ if the devices were sufficiently over-biased (200 V for 50 μm devices) [4,42].

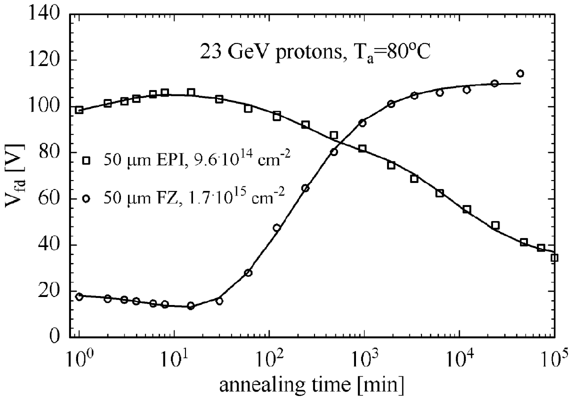

Fig. 9. Difference in annealing evolution of full depletion voltage between 50 μm thick high resistivity FZ and epi-detector.

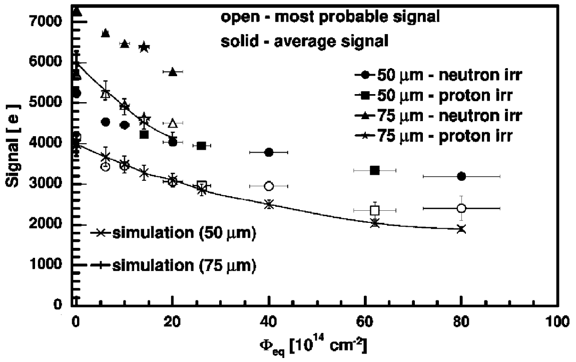

Fig. 10. Collected charge as function of fluence for different epi-Si samples and comparison with simulation (lines).

The third approach for manufacturing thin silicon particle detectors is the so-called wafer bonding technology introduced by the MPI Semiconductor Laboratory (Munich, Germany) in cooperation with the MPI for Microstructure Physics (Halle, Germany) [38]. The main advantage of this technology is the possibility to perform a fully double-sided process on very thin silicon layers as e.g. needed for the production of n-in-n pixel sensors or DEPFET pixel arrays. Irradiation experiments of 50 μm thick pad detectors with 23 GeV protons revealed a similar behavior with respect to their macroscopic properties (effective doping concentration, leakage current) as observed for oxygen-enriched FZ Si detectors if one scales the values to the same detector thickness. Charge collection efficiency measurements with 5.8 MeV α-particles have shown that at fluences of $10^{16}\,\mathrm{p/cm}^2$ CCE values of about 66% could be achieved, which is in the same order as derived for 50 μm thick epi-layers with ^{90}Sr β-particles [43].

3.2. 3D and semi-3D detectors

The so-called "3D" [44] and "semi-3D" detectors [45] offer a reduced full depletion voltage but still a 300 μm thick active layer provide the same charge as in standard planar devices. Prototype detectors of both variants have been produced in the framework of RD50.

The standard designs of 3D detectors as those proposed by Parker et al. [44] present vertical columnar electrodes of both doping types arranged in adjacent cells. The small distances between the electrodes (50–100 μm) result in very low full depletion voltage and very short collection time. Two main drawbacks characterize these devices: (a) columnar electrodes are dead-regions; (b) the regions located in the middle between electrodes of the same type present a "zero-field" region. This leads to a delay in the collection of carriers generated in such zones that slowly move by diffusion until they reach a region with a sufficient electric field. By over-biasing the device the low field region can be reduced.

The group at the University of Glasgow has pursued the fabrication of the full 3D detectors on n-type silicon substrates [46]. Two different techniques for the production of deep pores were investigated, deep reactive ion etching and electrochemical etching. Using the second method very deep holes of 10 μm diameter could be produced and an excellent aspect ratio of 30:1 was achieved. The first set of holes was p-type doped by boron diffusion, while the second set was metallized to form the electrical contacts. A first irradiation of close packed hexagonal pixel devices (85 μm pitch) with 23 GeV protons was performed. In Fig. 11 the development of the full depletion voltage as function of proton fluence is shown. The beneficial effect of 3D devices having very small full depletion voltages is obvious and the variation of V_{fd} with increasing fluence remains small up to the highest fluence of $4.5 \times 10^{14}\,\mathrm{p/cm^2}$.

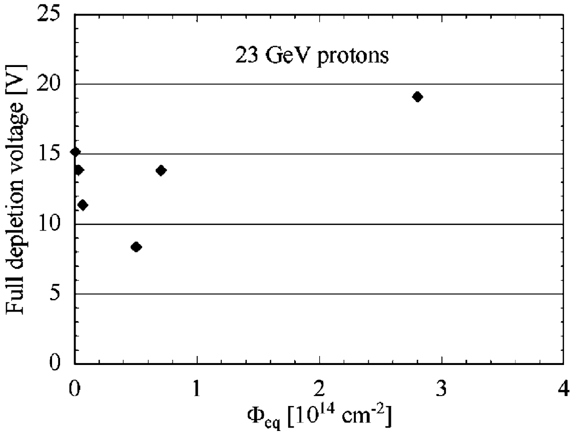

Fig. 11. Development of full depletion voltage versus fluence for a 3D pixel device.

The group of ITC-irst (Trento, Italy) has developed a new 3D detector architecture [47] with the aim to simplify the manufacturing process. In particular, the proposed device features electrodes of one doping type only, e.g. n^+ columns in a p-type substrate. The main advantage is that the column etching and doping has to be performed only once, a fact that provides a considerable simplification of the process. 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 the final removal of the support wafer is not required [47]. 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 main drawback of the proposed structure is that the low-field regions have a larger extension with respect to the standard 3D detector design and that these regions cannot be controlled by over-biasing. The fabrication of the first prototypes is underway at ITC-irst in collaboration with the group of CNM (Barcelona, Spain) for the hole etching process.

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 [45]. According to simulations, the advantage of this design should be observed after type inversion when the bulk of the detector is converted to p-type. In this situation a reduction of the full depletion voltage by a factor of about 2 is predicted 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 $\Phi_{\mathrm{eq}} = 5 \times 10^{14}\,\mathrm{cm}^{-2}$ confirm that semi-3D detectors deplete at about half the expected voltage of standard planar strip devices [48].

4. Conclusions

Recent developments and advancements of the RD50 collaboration related to defect engineered silicon, new semiconductor materials and new detector concepts have been presented. It is demonstrated, that especially Cz and epi-Si devices exhibit an unprecedented radiation tolerance. This is mainly due to the high concentration of oxygen as interstitial atoms (O_i) and as so-called oxygen dimers (O_2). Defect studies indicate that a high O_i concentration leads to a suppression of deep acceptors, while a high concentration of O_2 additionally promotes the formation of shallow donors resulting in a compensation of the radiation-induced negative space charge by deep acceptors. This results in an absence of type inversion opening new prospects in the production of cost effective radiation tolerant p-in-n devices. Recent efforts have been made in the development and production of 3D and semi-3D detectors and first irradiation tests have demonstrated their expected performance after irradiation. Further, the new materials SiC and GaN were a subject of extensive investigations and developments including first radiation damage studies in particular on their charge collection efficiency degradation by irradiation.

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