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Radiation-hard detectors for very high luminosity colliders

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Abstract

Recent results from the CERN RD50 Collaboration for the development of radiation-hard detectors for the LHC upgrade (Super-LHC) and in general for very high luminosity colliders are reported and discussed. Particularly, the attention is focused on Czochralski and Magnetic Czochralski silicon, thin detectors and p-type substrate devices.

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1. Introduction

The future upgrade of the CERN Large Hadron Collider (LHC), called Super-LHC, will bring to a possible increase of the luminosity from 10^{14} to $10^{15}\,\mathrm{cm^{-2}\,s^{-1}}$ [1]. Decreasing fast hadron fluences in the range 16–$2.3\times10^{15}\,\mathrm{cm^{-2}}$ are expected at a radius distance 4–11 cm from the beam interaction point, typically corresponding to the inner part of the silicon tracker, i.e. the pixel detector. Detectors considered for CMS [2] and ATLAS [3] experiments at LHC and manufactured with state of the art radiation-hard technology, i.e. n^+–n–p^+ pixel sensors on Diffusion Oxygenated Float Zone (DOFZ) silicon (Si), are expected to survive up to the fast hadron fluence of $\approx10^{15}\,\mathrm{cm^{-2}}$, which is one order of magnitude lower than the values anticipated for the Super-LHC. The CERN RD50 Collaboration [4], formed in 2001, is extensively investigating how to develop ultra-radiation hard semiconductor detectors for the luminosity upgrade of LHC. Actually six different research lines are under investigation: (1) Defect/Material Characterization; (2) Defect Engineering; (3) New Materials; (4) Pad Detector Characterization; (5) New Structures; and (6) Full Detector Systems. This paper will summarize some important results for the emerging technologies to be considered for the silicon tracker upgrade at Super-LHC focusing the attention on Czochralski and Magnetic Czochralski silicon, thin detectors and p-type substrate devices. A deeper discussion for the six different research lines can be found in Ref. [5].

2. FZ, DOFZ, CZ and MCZ silicon

The oxygen concentration is $[\mathrm{O}]\approx4\times10^{16}\,\mathrm{cm^{-3}}$ in Float Zone (FZ) silicon. The CERN RD48 Collaboration investigated how [O] can be increased up to $\approx10^{17}\,\mathrm{cm^{-3}}$ by oxygen diffusion at high temperature (1100–1200 °C), obtaining the so-called Diffusion Oxygenated Float Zone (DOFZ) silicon [6]. High [O] in n-type silicon substrates improves the radiation hardness for what concerns the depletion voltage (V_{dep}) variations after irradiation: the acceptor introduction rate and the amplitude of the reverse annealing for charged hadron (proton and pion) irradiation are lower for DOFZ than FZ Si [7]. This effect has been observed also for devices irradiated by Li ions [8], but not with neutrons [7].

Recently Czochralski (CZ) and Magnetic Czochralski (MCZ) silicon wafers from Sumitomo Mitsubishi Silicon Corporation (Tokyo, Japan) and Okmetic Oyj (Vantaa, Finland), respectively, have been available with resistivities (ρ) suitable for detector production: $\rho_{\mathrm{CZ}}=0.6\,\mathrm{k\Omega\,cm}$ and

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$\rho_{MCZ} = 0.9\,k\Omega\,cm$. CZ and MCZ ingots are grown in a quartz (SiO_2) crucible and oxygen concentrations ($[O] \approx 10^{17}$–$10^{18}\,cm^{-3}$) higher than in DOFZ silicon are intrinsically present at the end of the crystal growth, without the extra process for the oxygen diffusion at high temperature. In particular $[O]_{MCZ} \approx 5 \times 10^{17}\,cm^{-3}$ and $[O]_{CZ} \approx 8 \times 10^{17}\,cm^{-3}$ for the previously considered materials, suggesting that an improved radiation hardness is expected for what concerns the V_{dep} variations after charged hadron irradiation.

As an example for MCZ silicon, Fig. 1 [9] shows the depletion voltage for diodes processed on n-type FZ, DOFZ and MCZ wafers irradiated by low energy (10–30 MeV) protons. The space charge sign inversion (SCSI) occurs in FZ, DOFZ and MCZ Si, i.e. the effective substrate doping concentration ($|N_{eff}| = 2\varepsilon V_{dep}/(qW^2)$, where ε is the absolute silicon dielectric constant, q is the electron charge and W is the detector thickness) decrease from positive to negative values due to radiation induced deep acceptors [5], but MCZ detectors present a lower V_{dep} increase rate after SCSI than FZ and DOFZ devices.

Other results [10] concerning irradiation with ^{60}Co γ-rays, which generates mainly point defects, have shown that SCSI occurs in FZ Si, due to deep acceptor generation, but not in DOFZ and MCZ Si where, on the contrary, $N_{eff} > 0$ increases with the ionizing dose due to donor activation during irradiation. The N_{eff} increase rate linearly depends on the substrate oxygen concentration, being higher in MCZ than DOFZ samples. On the other hand, the positive effect of high [O] on N_{eff} and V_{dep} is strongly reduced when MCZ detectors are irradiated by fast neutrons [10], which generate mainly high defect density regions called clusters, as already observed for DOFZ Si [7].

The radiation hardness improvement for CZ Si is shown in Fig. 2 [11]: again SCSI occurs for FZ and DOFZ detectors irradiated by high energy (24 GeV) protons due to deep acceptor generation, but no SCSI is observed for

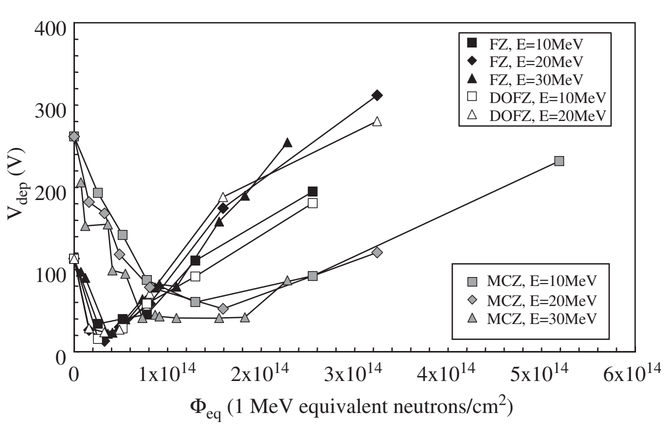

Fig. 1. Depletion voltage (V_{dep}) as a function of the proton fluence scaled to 1 MeV equivalent neutrons (Φ_{eq}) for 300 μm thick diodes manufactured on FZ (closed symbols), DOFZ (open symbols) and MCZ (dashed symbols) silicon and irradiated with 10 MeV (squares), 20 MeV (diamonds) and 30 MeV (triangles) protons.

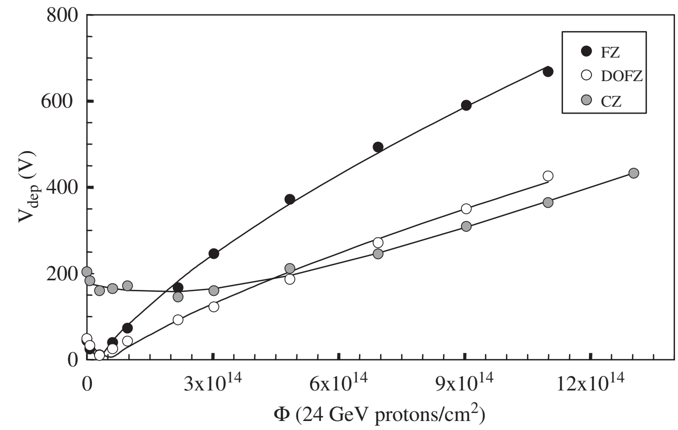

Fig. 2. Depletion voltage (V_{dep}) as a function of the 24 GeV proton fluence after 4 min of annealing at 80 °C for diodes manufactured on 300 μm thick FZ (close circles), DOFZ (open circles) and CZ (dashed circles) substrates.

CZ Si. The V_{dep} increase of the CZ devices at high fluences is due to predominant donor generation during irradiation as a consequence of high [O] in the substrate. The V_{dep} increase rate is lower for CZ than for FZ and DOFZ Si.

From a microscopic point of view, oxygen in the silicon substrate combines with vacancies (V), so forming the vacancy–oxygen (VO) complex, which is neutral at room temperature (RT). Depending on [O] competitive processes to VO formation occurs: vacancies can combine among them so generating V_2 related defects or with VO complexes giving rise to divacany-oxygen (V_2O) defects. Both V_2 related defects and V_2O are deep acceptors at RT. These processes generating deep acceptors depend on the local oxygen [O] and vacancy [V] concentrations, being enhanced for "low oxygen concentrations" (i.e., [O] < [V]) and mitigated for "high oxygen concentrations" (i.e., [O] > [V]). Moreover, high [O] values cause donor activation during irradiation.

These considerations are in agreement with the results previously discussed for FZ, DOFZ, MCZ and CZ Si. On one hand, neutrons generate mainly high defect density regions called clusters where [O] < [V] for FZ, DOFZ, MCZ and CZ Si, and consequently deep acceptor generation predominates, SCSI occurs and the oxygen positive effect for mitigating the V_{dep} increase rate after SCSI is not observed. On the other hand, ^{60}Co γ-rays generate mainly point defects, i.e. vacancies and interstitials: [O] < [V] for FZ Si where deep acceptor generation predominates and SCSI occurs, but [O] > [V] for DOFZ and MCZ silicon where SCSI is not observed and donor activation during irradiation predominates. Protons generate both point defects and cluster, i.e. they are at an intermediate condition also depending on the particle energy. In FZ and DOFZ silicon, SCSI occurs independently on the proton energy, even if the V_{dep} increase rate after SCSI is mitigated in DOFZ sensors ([O] > [V]) and this effects is enhanced by increasing the proton energy [12]. At low proton energies (10–30 MeV) SCSI occurs also in MCZ Si