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Nuclear Instruments and Methods in Physics Research A 515 (2003) 665–670

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Superior radiation tolerance of thin epitaxial silicon detectors☆

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Received 4 July 2003; received in revised form 18 July 2003; accepted 22 July 2003

Abstract

For the LHC upgrade (fluences up to 10^{16} p/cm^2) epi-Si devices are shown to be a viable solution. No type inversion was measured up to 1.3×10^{15} 24 GeV/c protons/cm^2 and the charge collection efficiency (CCE) remained close to 100%. For reactor neutrons CCE was measured to be 60% at 8×10^{15} n/cm^2. Annealing measurements have shown that only moderate cooling during beam off periods would be necessary. As a tentative explanation for the superior quality of these devices, we assume that radiation-induced donor generation leads to compensation effects of deep acceptors. In the future, we will extend the experiments to fluences up to 10^{16} p/cm^2 and use also different variants of the epi-Si material and device geometry.

PACS: 85.30.De; 29.40.Wk; 29.40.Gx

Keywords: Silicon detectors; Charge collection efficiency; LHC upgrade

A possible upgrade of the Large Hadron Collider (SLHC) will demand the inner most layers of the vertex detector to sustain fluences of about 10^{16} charged hadrons/cm^2 [1]. Due to the high multiplicity of tracks and the required spatial resolution small-area pixel detectors are the logical choice. Although silicon detectors are a proven technology and can survive the LHC fluences (up to 10^{15}/cm^2) using oxygen-rich material [2], it was not shown so far that they can operate at an order of magnitude higher fluence and still retain particle detection capability. The results presented in this work show that devices based on the use of thin epitaxial silicon layers grown on low-resistivity Czochralski substrates are a viable solution for this challenge.

The considerable reduction of the pixel area, essential for the inner layers of a vertex detector at the SLHC (cell size $\sim 50 \times 50$ μm^2), allows correspondingly a smaller detector thickness while

☆Work performed in the framework of the CERN-RD50 collaboration.

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doi:10.1016/j.nima.2003.07.021

maintaining the same input capacitance and hence its influence to electronic noise. Also the shot noise due to the leakage current should not exceed that at LHC as the shorter shaping times of electronics ($\sim$12 ns) and smaller cell volumes compensate an order of magnitude larger current densities. Thin detectors would certainly reduce the needed operational voltage. In addition, the dopant concentration $N_{eff,0}$ of the silicon bulk could be considerably larger such that radiation-induced donor removal and generation of deep acceptors would have smaller effects than in standard LHC detectors with a thickness of 300 μm processed on 2–5 kΩ cm silicon.

In order to prove this basic idea simple pad detectors (diodes) with a 50 μm-thick n-type epi-Si layer grown on low-resistivity Cz-substrates and with an active area of 0.5×0.5 cm^2 were studied. The wafers were produced by ITME[1] and detector processing done by CiS.[2] Their initial resistivity was $\sim$50 Ω cm resulting in full depletion voltages (V_{dep}) around 120 V. Irradiations were performed with 24 GeV/c protons at CERN-PS and reactor neutrons at the Josef Stefan Institute in Ljubljana. The particle fluences were scaled to 1 MeV neutron NIEL equivalent fluence by using $\Phi_{eq} = \kappa \Phi$ with hardness factor $\kappa = 0.62$ [2] for protons and $\kappa = 0.91$ [3] for reactor neutrons.

Diodes subjected to different fluences were studied during elevated temperature annealing at 60°C and 80°C after irradiation. In addition, one diode was investigated during consecutive irradiation steps with PS-protons and 4 min annealing at 80°C in between (CERN scenario). Standard C–V (10 kHz) and I–V measurements were done at 20°C to determine the full depletion voltage and standardized leakage current I.

An irradiation-induced increase of the bias voltage, needed for efficient operation, limits the use of standard (STFZ) and also diffusion oxygenated float zone silicon detectors (DOFZ) at larger fluences [2]. Under irradiation, such detectors undergo type inversion and thereafter the effective dopant concentration N_{eff} increases linearly with fluence. No such effect was observed for epi-Si detectors irradiated up to $\Phi_{eq} = 8.1 \times 10^{14}$ cm^{-2} as shown in Fig. 1. Instead, V_{dep} and consequently N_{eff} initially decrease and then exhibit a moderate increase.

A clearer picture for the dependence of N_{eff} on fluence is obtained by comparing different stages of annealing (Fig. 2a). If measured after 1 min annealing at 80°C, N_{eff} shows a decrease with fluence which would eventually lead to type inversion as depicted in Fig. 2b. On the other hand, detectors would never invert after 8 min annealing at 80°C, but rather exhibit an increase of N_{eff} (Fig. 2b). If so, donors must be generated over-compensating acceptors. At larger annealing times (40 min) this effect is reduced. Therefore, a proper maintenance scenario can always be found resulting in only moderate changes of N_{eff} during the entire LHC resp. SLHC operation. This can be achieved by keeping the detector even at close to room temperatures. This is the most important feature of epi-Si diodes, even exceeding the expectation resulting from the larger initial dopant concentration and the smaller value of the donor removal constant [4]. A tentative explanation for the donor generation is based on the evidence that oxygen dimers and, subsequently, the "earlier" thermal donors (TDD1, TDD2) are formed during irradiation in oxygen-rich material [5]. These

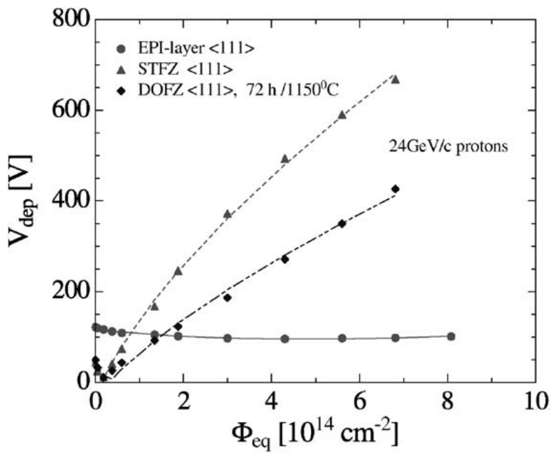

Fig. 1. Dependence of full depletion voltage on fluence. Measurements according to CERN scenario.

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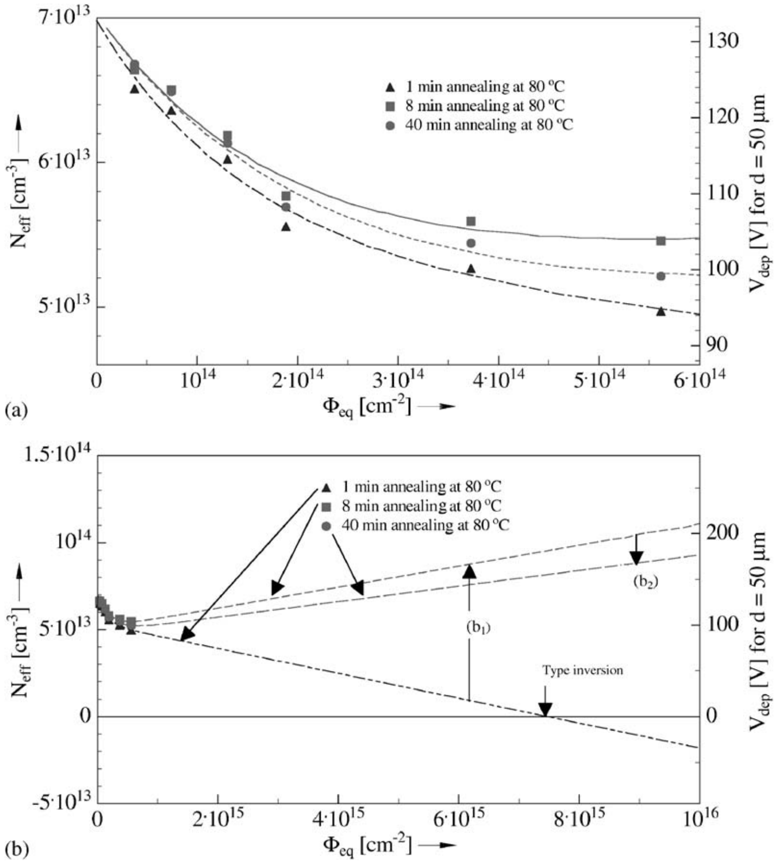

Fig. 2. (a) Dependence of N_{eff} on fluence. The diodes were irradiated with fixed fluences and then annealed at 80°C. (b) Extrapolation of measurements from (a) to SLHC end fluences using the Hamburg model described in Ref. [4]. (b_1): large increase of positive space charge in early stage of annealing, (b_2): reduction of this effect at later stages.

donors can also be formed in our case as the fast diffusing oxygen dimers [6] may migrate from the Cz-substrate to the epi-Si bulk.

The evolution of irradiation-induced defects as given by $\Delta N_{eff}(t) = N_{eff,0} - N_{eff}(t)$ [4] during annealing is shown in Fig. 3a. It can be well described by a first-order process for beneficial annealing, constant damage and two different components of reverse annealing (build-up of negative space charge). While the initial phase of reverse annealing is described by a first-order process, the later stage is due to a second-order effect, as confirmed by the respective fits. In Fig. 3b, the annealing curves are shown for two different temperatures. The deduced time constants governing the initial reverse annealing coincide with results from standard FZ-Si material, described by an activation energy of 1.31 eV (see Ref. [4]). This value was, therefore, used to transform the elevated temperature scale to the equivalent one for 20°C (top scale in Fig. 3a). From Fig. 3a, it is clearly seen that the second reverse annealing stage would become visible only beyond 20 years at room temperature and thus does not have any effect for practical LHC resp. SLHC applications. The generation rate of defects leading to the first component of reverse annealing is smaller than observed in FZ-Si materials. The fact that the minimum in ΔN_{eff} is reached at approximately 8 min at 80°C points to the conclusion that beneficial annealing may be the same as in FZ-Si material [2]. The main difference between epi-Si

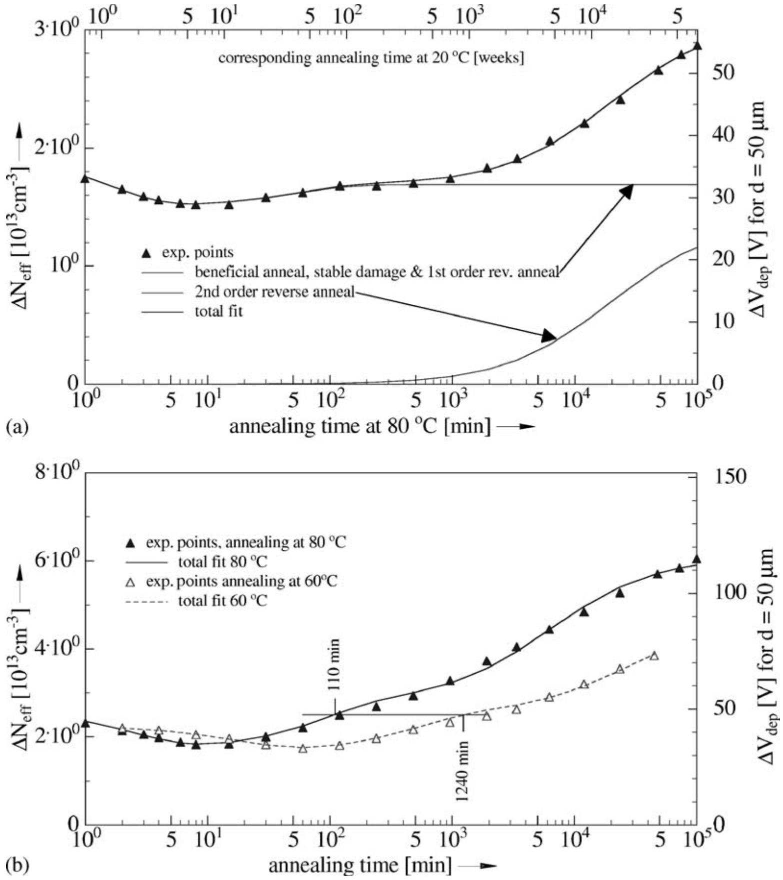

Fig. 3. Annealing of irradiation-induced changes in $N_{\rm eff}$ after the diodes received the proton fluence of $\Phi_{\rm eq} = 5.6 \times 10^{14}\ {\rm cm}^{-2}$. Solid lines refer to fit results (see inserts and text).

and FZ-Si material seems therefore to be related to the stable damage which is dominated by donors in epi-Si and acceptors in FZ-Si material. Clearly, much more measurements are needed to confirm the picture and enable more reliable predictions.

In contrast to proton-irradiated diodes, the neutron-irradiated ones do invert, however at a large fluence of a few times $10^{15}\ {\rm cm}^{-2}$ as shown in Fig. 4 (inset). Again the high initial dopant concentration and a small donor removal constant are clearly beneficial. Even at $8 \times 10^{15}\ {\rm cm}^{-2}$ the full depletion voltage was measured to be $V_{\rm dep} < 100$ V at the end of the beneficial annealing.

Good position resolution and high detection efficiency require the signal-to-noise ratio to be as large as possible. As envisioned here, the noise level will stay at or below the one at LHC. The loss of the drifting charge due to trapping is, therefore, the main problem. The charge collection properties of irradiated epi-Si detectors were measured using the Transient Current Technique (TCT), but instead of light pulses a collimated source of α particles (^{244}Cm) was used. The CCE was defined as the ratio of the measured induced charge in irradiated and non-irradiated diodes. As the α particle penetration depth is 23 μm both holes and electrons, though not equally, contribute to the induced charge. The results were compared with simulations (see Ref. [7] for details) using the trapping times measured in FZ-Si detectors [8]. Simulated and measured CCE values coincide for moderate proton fluences as shown in Fig. 5a. A slightly worse agreement was obtained for neutron-irradiated diodes (see Fig. 5b), but it should

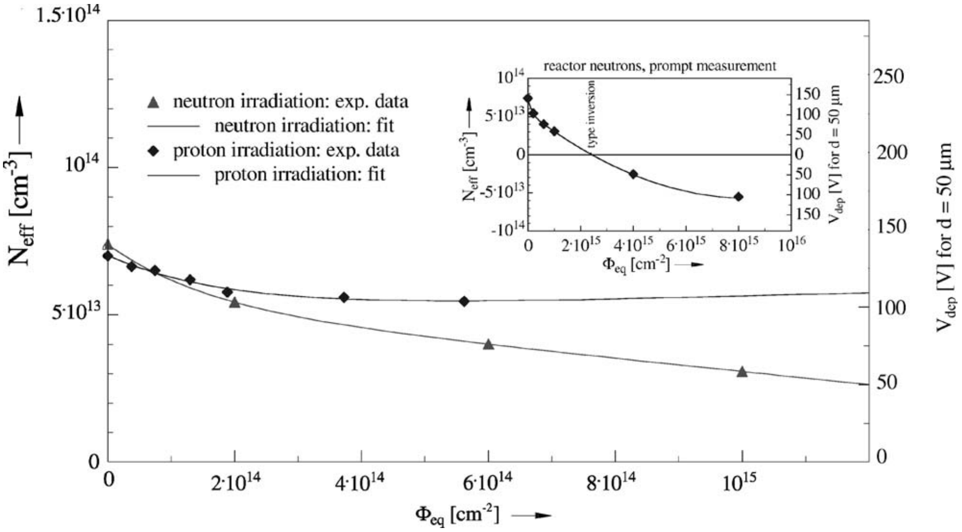

Fig. 4. Dependence of N_{eff} on fluence for proton- and neutron-irradiated diodes after 8 min annealing at 80°C.

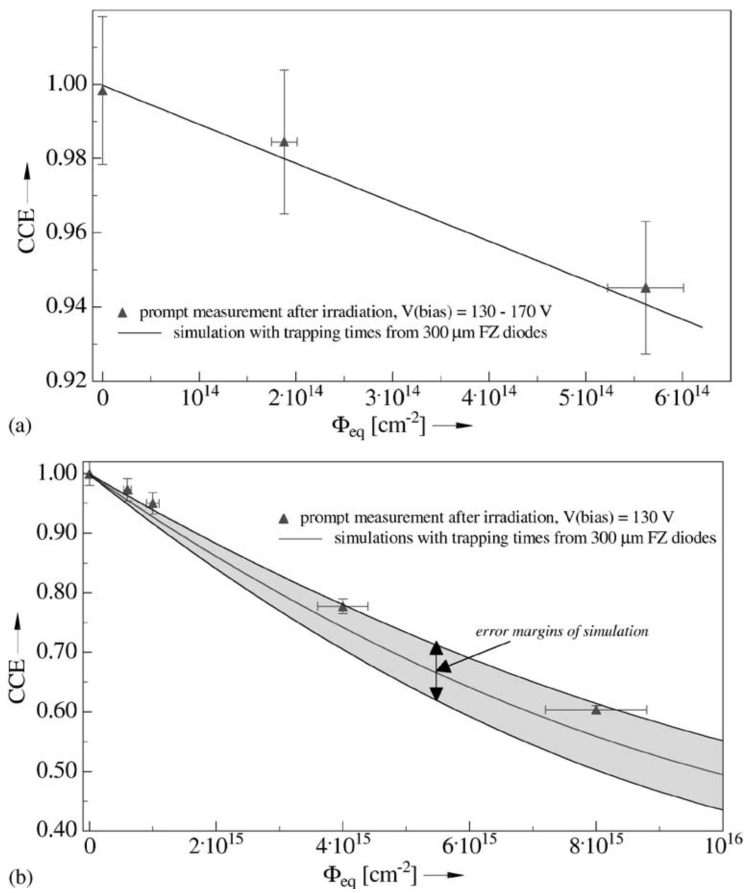

Fig. 5. CCE efficiency for proton-irradiated diodes (a) and neutron-irradiated diodes (b). Simulation prediction is depicted by the solid curve.

be mentioned that trapping times used in the simulation were extrapolated over more than one order of magnitude. This leads to the conclusion that, like the leakage current damage constant, the effective trapping times in irradiated epi-Si detectors are comparable with the ones in FZ-Si material. Of course detectors are supposed to detect minimum ionizing particles. Simulations performed at $\Phi_{eq} = 10^{16}\ \mathrm{cm}^{-2}$ charged hadrons and an average electric field strength of 25 kV/cm give CCE values of ~40%, roughly corresponding to a most probable signal of 1400 e. About the same amount of charge would be collected also in a pixel detector with a pitch/thickness ratio $\leqslant 1$ regardless of the collected carrier type [9]. Such signals should allow efficient operation by using state-of-the-art radiation hard electronics.

In conclusion, epi-Si detectors exhibit properties similar to FZ-Si detectors with the exception of donor-dominated stable damage. As a consequence, one can find a scenario to operate detectors at moderate voltages during the whole period of SLHC, in which the most exposed detectors will receive $\Phi_{eq} \approx 10^{16}\ \mathrm{cm}^{-2}$ of charged hadrons, and even beyond. The detectors proposed in this work represent also a cost-effective solution as low depletion voltages tolerate the use of a p^+–n device structure.

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