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Radiation hardness of silicon detectors based on pre-irradiated silicon

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Abstract

Radiation hardness of planar detectors processed from pre-irradiated and thermo-annealed n-type FZ silicon substrates, and standard FZ as a reference, was studied. The high purity n-Si wafers with carrier concentration $4.8 \times 10^{11}\,\mathrm{cm}^{-3}$ were pre-irradiated in Kiev's nuclear research reactor by fast neutrons to fluence of about 10^{16} neutrons/cm^2 and thermo-annealed at a temperature of about 850 °C. Silicon diodes were fabricated from standard and pre-irradiated silicon substrates by IRST (Italy). All diodes were subsequently irradiated by fast neutrons at Kiev and Ljubljana nuclear reactors. The dependence of the effective doping concentration as a function of fluence ($N_{\mathrm{eff}} = f(\Phi)$) was measured for reference and pre-irradiated diodes. Pre-irradiation of silicon improves the radiation hardness by decreasing the acceptor introduction rate (β), thus mitigating the depletion voltage (V_{dep}) increase. In particular, β in reference samples is about $0.017\,\mathrm{cm}^{-1}$, and for pre-irradiated samples is about $0.008\,\mathrm{cm}^{-1}$. Therefore, the method of preliminary irradiation can be useful to increase the radiation hardness of silicon devices to be used as sensors or detectors in harsh radiation environments.

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

1. Introduction

The attention towards the increase of radiation hardness of semiconductor devices is growing due to their possible long-term operation in high radiation environments as, for instance, in the experiments foreseen at the LHC at CERN. The RD50 CERN collaboration [1] has the purpose of investigating the potentiality of new materials defect engineering and novel designs for future detectors [2], which have to operate up to 10^{16} 1 MeV equivalent neutrons/cm^2. In this framework, the INFN in Padova, the Institute of Nuclear Research (KINR) in Kiev and IRST have investigated radiation hardening by preliminary neutron irradiation of silicon, which is expected to create gettering sites in the silicon bulk. Pre-irradiation of silicon by fast neutrons and the subsequent annealing lead to the formation of sinks for primary radiation defects. These sinks are complexes of radiation-induced defects with neutral impurities, such as C and O, always present in

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the silicon wafers. Preliminary irradiation can increase the radiation hardness of silicon [3,5] the best effect being achieved in each particular case by optimizing the sink concentration.

In this study we have investigated the hardness to reactor fast neutron irradiation of diodes manufactured by IRST from standard, as a reference, and from silicon pre-irradiated float zone silicon (FZ).

2. Description of experiment

2.1. Tested devices

The starting material for tested diodes was n-type float zone silicon wafers from a single batch produced by Topsil [4] with the following characteristics: $\langle 111 \rangle$, carrier concentration $4.8 \times 10^{11}\,\mathrm{cm}^{-3}$ and life time of minority carriers (τ) about 300 μs. Tested devices are p^+-n silicon diodes processed by IRST on both standard high purity n-Si and pre-irradiated silicon wafers. The diodes have various layouts. The active area of each diode is surrounded on the junction side by a single- or multi-guard-ring. Pre-irradiations [5] were performed at the WWR-10 M KINR's nuclear research reactor by fast neurons up to a fluence of about 10^{16} neutrons/cm^2; thermal neutrons were shielded using a Cd container. After preliminary irradiation, wafers were thermally annealed for 2 h at 850 °C in order to anneal all the electrically active radiation defects and achieve material with similar electrical characteristics as before the pre-irradiation process [6]. The annealing temperature (850 °C) was experimentally obtained by the authors. We found that in pre-irradiated silicon after annealing at a temperature of 850 °C creation of complexes of radiation-induced defects with neutral impurities, such as C and O (so called "sinks") is finished, and these complexes are electrically inactive. On the contrary, at 1000 °C we have seen changes in resistivity and life-time of minority carriers. Therefore, before processing, pre-irradiated silicon wafers have to be annealed at 850 °C in order to avoid negative changes caused during oxidation process at 1000 °C. Effective substrate doping concentrations are $4.8 \times 10^{11}\,\mathrm{cm}^{-3}$ for standard and $5 \times 10^{11}\,\mathrm{cm}^{-3}$ for pre-irradiated silicon. After such pre-irradiation and annealing procedures changes in the electrical characteristics with respect to not pre-irradiated wafers are negligibly small.

2.2. Description of irradiation conditions and electrical characterizations

Diodes from reference and pre-irradiated wafers have been irradiated by neutrons up to a 1 MeV neutron equivalent fluence of 5×10^{14} neutrons/cm^2 at the Triga MARK III nuclear research facility [7] of the Jožef Stefan Institute (Ljubljana, Slovenia). Devices were packed in a small plastic cylindrical tube and inserted in the central reactor channel, where the neutron flux is isotropic and uniform within a few percent. The neutron energy spectrum of the nuclear reactor extends from thermal to fast (≈ 10 MeV) neutrons but only neutrons with energy above 100 keV have to be taken into account since below this energy their non-ionizing energy loss in silicon is orders of magnitude smaller than that of fast neutrons. Consequently, the fluences reported in the paper for the irradiations in the nuclear reactor refer only to the fast neutron component ($E \geqslant 100$ keV) plus a 1.5% correction accounting for the non-ionizing energy loss (NIEL) of the $E < 100$ keV neutron component [8]. The neutron fluences were determined by considering gold activation calibration measurements [8] performed previously under the same experimental conditions (geometry and reactor power). Devices were irradiated at room temperature in single steps, i.e., different devices were employed for each neutron fluence. After irradiation all samples were stored at room temperature for 20 days. This period corresponds to an annealing time of 4 min at 80 °C [9]. The diodes, as irradiated, were electrically characterized before and after irradiation by 100 kHz capacitance–voltage (C–V) measurements. The C–V measurements were performed by an HP4284A LCR meter and by an HP4142B DC source/monitor. During the electrical characterization, devices were contacted by standard microprobes and reverse biased by applying a positive voltage to the back side, while the p^+ junction was grounded. The p^+ guard-ring on the junction side was also separately grounded during the electrical characterization in order to prevent border effects on the C–V measurement. The diode depletion voltage (V_{dep}), i.e., the voltage at which the diode is fully depleted, has been determined by the intersection point of the two linear fits before and after the kink of the C–V curve on a log–log scale [10], as shown in Fig. 1.

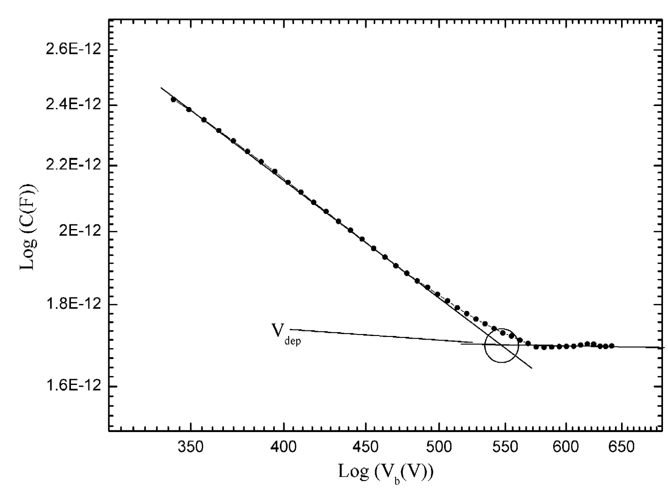

Fig. 1. An example of the typical curve of the diode capacitance as a function of the reverse bias voltage for a diode processed on pre-irradiated substrate irradiated by 5×10^{14} 1 MeV neutrons/cm^2. The diode depletion voltage (V_{dep}) is also shown. C–V curves similar in shape were observed for the other devices and irradiation fluences.