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Characterization of 150 μm thick epitaxial silicon detectors from different producers after proton irradiation

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Abstract

Epitaxial (EPI) silicon has recently been investigated for the development of radiation tolerant detectors for future high-luminosity HEP experiments. A study of 150 μm thick EPI silicon diodes irradiated with 24 GeV/c protons up to a fluence of 3×10^{15} p/cm^2 has been performed by means of Charge Collection Efficiency (CCE) measurements, investigations with the Transient Current Technique (TCT) and standard CV/IV characterizations. The aim of the work was to investigate the impact of radiation damage as well as the influence of the wafer processing on the material performance by comparing diodes from different manufacturers. The changes of CCE, full depletion voltage and leakage current as a function of fluence are reported. While the generation of leakage current due to irradiation is similar in all investigated series of detectors, a difference in the effective doping concentration can be observed after irradiation. In the CCE measurements an anomalous drop in performance was found even for diodes exposed to very low fluences (5×10^{13} p/cm^2) in all measured series. This result was confirmed for one series of diodes in TCT measurements with an infrared laser. TCT measurements with a red laser showed no type inversion up to fluences of 3×10^{15} p/cm^2 for n-type devices whereas p-type diodes undergo type inversion from p- to n-type for fluences higher than $\approx 2\times10^{14}$ p/cm^2.

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1. Introduction

Silicon detectors for use in future experiments at high luminosity colliders such as an upgraded LHC or the SLHC with design luminosities exceeding $10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$ demand the development of detectors which can perform in extremely harsh radiation levels. The radiation damage suffered by the silicon results in an increase of leakage current, a change of full depletion voltage and an increased trapping of the drifting holes and electrons created by traversing charged particles. These three effects reduce the Charge Collection Efficiency (CCE), and the signal-to-noise ratio (S/N) of the detector. Recently epitaxial silicon grown on low resistivity CZ substrates has been investigated (see Refs. [1–4]) as a possible candidate for radiation hard silicon detectors, as it exhibits improved properties after particle irradiation compared to standard float zone (FZ) silicon, which is used in most of the current HEP detectors. The CCE of EPI diodes was reported to be superior to standard material [4] after neutron and proton irradiation. Furthermore, a build up of positive space charge after irradiation is found in EPI detectors, which means that n-type EPI material does not undergo type inversion contrary to the case of FZ material [2]. This would allow for scenarios in which the change in effective doping concentration (N_{eff}) during detector operation can be counteracted by the reverse annealing effect during shut down periods [2].

In this work 150 μm thick EPI silicon diodes irradiated with 24 GeV/c protons up to a fluence of 3×10^{15} p/cm^2

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were characterized in CCE evaluations, TCT measurements and by means of standard CV/IV measurements. The main aim of the work was to investigate the influence of the wafer processing on the material performance by comparing diodes from different manufacturers. The following section describes the investigated material and gives details about the irradiation. Section 3 describes the experimental facilities and outlines the measurement procedures. In Sections 1–6 detailed results are given for the behavior of leakage current, effective doping concentration and CCE following the irradiation. The results of the TCT measurements are given in Section 7.

2. Investigated material

The material investigated in the course of this study was 150 μm thick EPI silicon produced by ITME (Institute of Electronic Materials Technology, Warzawa, Poland) grown on highly doped Cz-silicon substrates. Further processing of the raw material was performed by three different silicon manufacturing facilities:

- IMB-CNM CSIC Centro Nacional de Microelectronica, Barcelona, Spain (CNM-xx and RD50-xx detectors, four different series, see Ref. [5]).
- HIP Helsinki Institute of Physics, Helsinki, Finland (HIP-004-B detectors, see Ref. [6]).
- ITC-IRST Microsystems Division, Povo, Trento, Italy (W-11 detectors, see Ref. [7]).

Both pad detector and strip detector processes[1] were used. Six different series of diodes were used as specified in Table 1. The detectors from the series RD50-16 (p type) could not be analyzed due to very high leakage currents already at low bias voltages.

2.1. Irradiation

The detectors were irradiated with 24 GeV/c protons at the CERN PS [8] with fluences up to 3×10^{15} p/cm^2. The fluence received was measured with an accuracy of ±15% through spectroscopy of aluminum foil placed with the detectors in the PS beam during irradiation [8]. The 1 MeV equivalent neutron fluence Φ_{eq} cited below was calculated from the proton fluence using a hardness factor of 0.62 [9]. Table 2 lists the applied proton fluences including the relative error and the equivalent fluence. For each fluence, one diode from each of the five different detector series was irradiated. After the irradiations the detectors were annealed for 4 min at 80 °C. At all other times the detectors were stored at −24 °C to minimize further annealing.

[1] Strip detector fabrication involves additional processing steps, e.g. the deposition of polysilicon for the strip detector resistors. For details see Refs. [5–7].

Table 1
Investigated material

Producer	Series name	Processing	Type	size (mm^2)
CNM	CNM-22	Pad detector	p	5 × 5
CNM	CNM-11	Pad detector	n	5 × 5
CNM	RD50-23	Strip detector	n	5 × 5
CNM	RD50-16	Strip detector	p	5 × 5
ITC-IRST	ITC-W-11	Strip detector	n	3.7 × 3.7
HIP	HIP-004-B	Pad detector	n	5 × 5

Table 2
Applied fluences and corresponding equivalent fluences Φ_{eq} for the proton irradiations

Fluence p$^+$ (cm^{-2})	Φ_{eq} n^0 (cm^{-2})
$4.78\times10^{13}\pm14.4\%$	2.96×10^{13}
$1.32\times10^{14}\pm14.4\%$	8.18×10^{13}
$2.27\times10^{14}\pm11.0\%$	1.41×10^{14}
$5.10\times10^{14}\pm13.3\%$	3.16×10^{14}
$1.30\times10^{15}\pm12.9\%$	8.06×10^{14}
$2.64\times10^{15}\pm14.1\%$	1.64×10^{15}
$3.06\times10^{15}\pm13.4\%$	1.90×10^{15}

3. Experimental setup and procedures

3.1. β-MIP CCE setup

The CCE measurements were performed by means of a system obtained from NIKHEF [10]. Electrons originating from a collimated ^{90}Sr source are used to create charge in the investigated diode and a scintillator–photomultiplier combination provides the trigger for the readout electronics (combination of Amptek A250 integrating amplifier and two A275 shaper hybrids, signal shaping time: 2.5 μs, electronic noise of $567e^- + 4.26e^-/pF$). The diode is mounted on a sample PCB with the detector frontside and guard ring contacted by means of wire bonds and can be biased up to ±1000 V. The measurement temperature can be adjusted with an integrated peltier element and the whole setup can be flushed with nitrogen and operated inside a small freezer to achieve temperatures as low as −25 °C. All measurements presented in this paper were carried out at -22 ± 1 °C. The measurements are controlled by labview software which collects a predefined number of events for a series of bias voltages and stores the signal values in a data file. Subsequently a labview analysis program is used to create a histogram, fit a Landau distribution to the data and deconvolute the electronic noise from the signal. The most probable value of the deconvoluted Landau distribution used for the CCE(V) or CCE(ϕ, V) plots. In repeated measurements of an irradiated detector carried out during several days and involving repeated installation in the setup and cooldown to −10 °C the most probable value of the Landau