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Study of radiation damage induced by 24 GeV/*c* and 26 MeV protons on heavily irradiated MCz and FZ silicon detectors

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Abstract

The aim of this work is the development of radiation hard detectors for very high luminosity colliders. A growing interest has been recently focused on Czochralski silicon as a potentially radiation-hard material. We report on the processing and characterization of micro-strip sensors and pad detectors produced by ITC-IRST on n- and p-type magnetic Czochralski and float zone silicon. Part of the samples has been irradiated using 24 GeV/*c* protons (CERN-Geneva), while another part has been irradiated with 26 MeV protons (FZK-Karlsruhe) up to a fluence of 5×10^{15} 1 MeV-neutron-equivalent/cm^2. All the samples have been completely characterized before and after irradiation. Their radiation hardness as a function of the irradiation fluence has been established in terms of breakdown voltage, leakage current and evaluating the more relevant mini-sensor parameter variation. Moreover, the time evolution of depletion voltage, leakage current and inter-strip capacitance has been monitored in order to study their annealing behavior and space charge sign inversion effects.

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Keywords: Silicon detectors; Radiation damage; Micro-strip detectors

1. Introduction

ATLAS and CMS, two multipurpose high energy physics experiments, are under construction at the Large Hadron Collider (LHC) at CERN. LHC is a large p–p accelerator with a beam energy of 7 TeV and a designed peak luminosity of 10^{34} cm^{-2} s^{-1} [1]. The tracker detectors of both experiments have been designed to work in a very hostile radiation environment with a fast hadron fluence of 3×10^{15} 1 MeV-neutron-equivalent/cm^2 (n_{eq}/cm^2) expected at the minimum instrumented distance from the collision point (~4 cm). Detector technology has been developed to ensure the survival of these systems to an integrated luminosity of 500 fb^{-1}, corresponding to 10 years of LHC operation [2].

A planned upgrade of the LHC collider (SLHC project [3]) will increase both the luminosity up to a final value of 10^{35} cm^{-2} s^{-1} and the beam energy up to 12.5 TeV. Tracker detectors of SLHC experiments should maintain their performance up to the maximum expected fast hadron fluence: 1.6×10^{16} n_{eq}/cm^2 at 4 cm from the beam line and 8×10^{14} n_{eq}/cm^2 at an intermediate distance of 22 cm. Silicon detectors and in particular micro-strip sensors can still be considered a viable solution in the intermediate and outer tracker regions, provided that an improvement of their radiation hardness to fluences of the order of 10^{15} n_{eq}/cm^2 can be achieved. For this purpose the

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activity of the SMART project, a collaboration of Italian research institutes funded by the INFN, has been focused on the development of radiation hard silicon position sensitive detectors for SLHC in the framework of CERN-RD50 collaboration [4].

Previous studies highlighted the beneficial effect in terms of radiation hardness of FZ silicon material enriched with oxygen atoms (DOFZ—diffusion oxygenated FZ silicon) [5]. Nowadays, with the magnetic Czochralski (MCz) growth technology it is possible to produce Si devices with an intrinsically high oxygen content and with a resistivity suitable for particle detector applications [6].

Furthermore, silicon detectors built on p-type substrates (n+ micro-strip implants on p substrate, i.e., n+ on p) is a possible radiation harder solution compared to the more common p+-on-n technique, mainly for two reasons: first the p substrate, at any dose after irradiation, does not show type inversion, preserving the highest electrical field on the strip side, and second the n+ implants on p substrate collect electrons which have, with respect to holes, an higher mobility and a lower trapping probability, thus improving charge collection efficiency.

In this paper we report on the results achieved with test structures and micro-strip detectors processed on MCz and FZ substrates (n and p type) heavily irradiated with protons of two different energies.

2. Samples and irradiation campaigns

The wafer processing has been performed by ITC-IRST (Trento, Italy) in two successive runs, using both MCz and FZ 4 inch. silicon wafers for comparison. In the first run (RUN-I) wafers from n-type material have been processed while on the second one (RUN-II) p-type substrates have been manufactured; on both cases the same mask set has been used. For RUN-II the p-spray technique (uniform implantation) [7] is used to obtain isolation between n+ implants with two different implantation doses, namely $3\times10^{12}\,\mathrm{cm}^{-2}$ (low p-spray) and $5\times10^{12}\,\mathrm{cm}^{-2}$ (high p-spray). The wafers produced for RUN-I (p on n) on MCz substrates have a resistivity $\rho \gtrsim 500\,\Omega\,\mathrm{cm}$, a thickness of 300 μm and $\langle 1\,0\,0 \rangle$ crystal orientation, while the ones produced on FZ materials are of type $\langle 1\,1\,1 \rangle$, have a resistivity of around 6 kΩ cm and a thickness of 300 μm. For RUN-II (n on p) all the wafers are of $\langle 1\,0\,0 \rangle$ type and have a substrate resistivity $\geqslant 2\,\mathrm{k}\Omega\,\mathrm{cm}$; the thickness is 300 μm for MCz substrates and 200 μm for FZ silicon.

Each wafer hosts various test structures and ten mini-sensors with equal active area ($\sim 0.5\times5\,\mathrm{cm}^2$) but with different geometry, to investigate the dependence of the detector performance on the design parameters (see Table 1). Further details can be found in Refs. [8–10].

The irradiation of the devices was performed with protons of different energies in order to compare the different radiation damages. The first campaign was carried out at the CERN-SPS facility with 24 GeV/c protons and at fluences up to $3\times10^{15}\,\mathrm{n_{eq}/cm^2}$, the second one was performed at the Compact Cyclotron of the Forshungszentrum in Karlsruhe (Germany) with 26 MeV protons at fluences up to $2\times10^{15}\,\mathrm{n_{eq}/cm^2}$.

Table 1
Strip parameters of the ten mini-sensors in the wafer

μ-strip #	Pitch	Implant width	Poly-width	Al width
S1	50	15	10	23
S2	50	20	15	28
S3	50	25	20	33
S4	50	15	10	19
S5	50	15	10	27
S6	100	15	10	23
S7	100	25	20	33
S8	100	35	30	43
S9	100	25	20	37
S10	100	25	20	41

All the dimensions are in μm. The devices are AC coupled and microstrips are biased through 600 kΩ poly-silicon resistors.

3. Pre-irradiation characterization

All the devices were completely characterized before and after irradiation, following the standard procedures defined within the RD50 Collaboration. The leakage current I_{leak} and the back-plane capacitance C_{back} measurements were performed both on diodes and on micro-strip sensors in order to evaluate the breakdown performance and the depletion voltage. The strip isolation was checked by means of the inter-strip capacitance C_{int} and the inter-strip resistance R_{int} measurements.

Pre irradiation measurements show that all n-type devices (FZ and MCz) show high breakdown voltages ($V_{\mathrm{bd}} > 600\,\mathrm{V}$) and in average all the sensors have a leakage current density around $J\sim1.4\,\mathrm{nA/mm^3}$ at 400 V, well beyond their depletion voltage.

Different performance has been observed for p-type sensors that show a low breakdown voltage, in particular for sensors processed with high p-spray dose. Moreover, in detectors with larger pitch (100 μm) the breakdown is even lower than 70 V (big dot curves in Fig. 1). A simulation of these devices [11] has identified as responsible for the avalanche breakdown at low bias voltage the high values of the electric field, localized between the n+ implant and the p-spray layer.

A local variation of the depletion voltage V_{dep} in the MCz material is also measured, especially for p-type wafers, due to the nonuniform oxygen distribution that leads to a spread in the thermal donor activation in the wafer after the processing 10.

For n-type micro-strip sensors a typical behavior of C_{int} as a function of the bias voltage is observed, with a saturation value in over-depletion condition ranging from 0.5 to 1.2 pF/cm, in agreement with the different device geometries.