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TCT and test beam results of irradiated magnetic Czochralski silicon (MCz-Si) detectors

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ABSTRACT

Pad and strip detectors processed on high resistivity n-type magnetic Czochralski silicon (MCz-Si) were irradiated to several different fluences with protons. The pad detectors were characterized with the transient current technique (TCT) and the full-size strip detectors with a reference beam telescope and a 225 GeV muon beam. The TCT measurements indicate a double junction structure and space charge sign inversion in MCz-Si detectors after 6×10^{14} 1 MeV n_{eq}/cm^2 fluence. In the beam test a signal-to-noise (S/N) ratio of 50 was measured for a non-irradiated MCz-Si sensor, and a S/N ratio of 20 for the sensors irradiated to the fluences of 1×10^{14} 1 and 5×10^{14} 1 MeV n_{eq}/cm^2.

1. Introduction

There is a strong physics case for eventually increasing the LHC luminosity by an order of magnitude. The planned LHC upgrade scenario, the super-LHC (SLHC) entails a factor of ten increase in the integrated luminosity, which would correspond to the expected total fluences of fast hadrons above $1\times10^{16}\,cm^{-2}$. This is well beyond the radiation tolerance of any standard p-on-n float zone silicon (Fz-Si) devices used in the current large scale experiments such as CMS and ATLAS trackers. Furthermore, with the higher luminosity, also the detector occupancy will increase correspondingly. This means that the new SLHC tracker systems should be more radiation hard and provide higher resolution than the current tracker systems to address the increased occupancy.

Oxygen enrichment of silicon bulk has widely been acknowledged to improve the radiation tolerance of silicon detectors [1–3]. For example ATLAS experiment decided to use diffusion oxygenated Fz-Si (DOFz-Si) in their pixel detectors that will receive the highest fluence during the 10 years of LHC operation. However, in DOFz-Si the oxygen is introduced into the silicon material by high-temperature long-term diffusion, which increases the risk of contaminating the silicon wafers. However, Czochralski silicon (Cz-Si) contains intrinsically a high concentration of oxygen ($>5\times10^{17}\,cm^{-3}$) and developments in the Cz-Si crystal growth technology have enabled the production of Cz-Si wafers, for example by magnetic Czochralski (MCz) method, with sufficiently high resistivity and with well-controlled, high concentration of oxygen. Furthermore, since Cz-Si is commonly used semiconductor material in the microelectronics industry, it is available in large quantities and many commercial foundries are familiar with its processing. These aspects are important when constructing large tracking systems, which can consist of hundreds of square meters of silicon sensors.

The MCz-Si material has been studied extensively in the RD50 and RD39 collaborations [4,5] and it has been found to be more radiation hard against protons than traditional Fz-Si or DOFz-Si in terms of the depletion voltage behavior. In large scale systems the power consumption of the tracking system is an important factor, and thus a lower full depletion voltage can be an asset, when choosing the material for the SLHC detector applications. However, most of the radiation hardness studies have been done on pad detectors. Yet, in order to prove that the MCz-Si material is suitable for any large-scale tracking system like the SLHC CMS tracker, it is necessary to perform extensive tests on full-size segmented devices in addition to pad detector characterization.

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For example, the charge collection efficiency (CCE) is partly determined by the electric field distribution in silicon. In irradiated silicon, the electric field distribution is complicated and contains, for example, the so-called double junction (DJ) structure [6]. Moreover, the electric field distribution is very different in a pad detector compared to a segmented device. This affects the detector weighting field, i.e. the electrostatic coupling between the drifting charge and the sensing electrode. In a simple diode the weighting field is inversely proportional to the thickness of the device and hence the induced charge that has been generated by a traversing particle is proportional to the length of the drift. However, in a segmented device due to the different electric field shape, the moving charge induces most charge in the electrode, when it is close to it and not through the entire device thickness [7]. Furthermore, the space charge sign inversion (SCSI) of the detector bulk affects the CCE. Despite extensive research, the SCSI phenomenon is poorly understood in the potentially radiation hard silicon materials such as MCz-Si. However, it is assumed that in a segmented detector the SCSI will manifest itself as a degraded cluster resolution after the type inversion fluence.

In this experiment we tested the performance of several proton irradiated silicon sensors processed on magnetic Cz-Si wafers. The pad detectors were characterized with transient current technique (TCT) and the full-size strip detectors with a reference telescope in a 225 GeV muon beam.

2. Detector processing and irradiation

The MCz-Si detectors used in this study were processed with a simple six mask level process at the Helsinki University of Technology Centre for Micro and Nanotechnology (Micronova) facility. The starting material was 4 in. n-type wafers with a thickness of $300 \pm 2\,\mu m$ and $\langle 1\,0\,0\rangle$ crystal orientation grown with the MCz method by Okmetic Ltd., Finland. A detailed process description can be found from Ref. [8].

The large area strip detectors had 768 channels and an area of $4.1 \times 4.1\,cm^2$. In the detector design the strip pitch was $50\,\mu m$, strip width $10\,\mu m$ and the strip length 3.9 cm. The pad detectors had $5 \times 5\,mm^2$ p^+ implanted area and a $2 \times 2\,mm^2$ opening in the front metallization for the TCT measurements.

Two full-size strip sensors were irradiated with 26 MeV protons (Universität Karlsruhe) to fluences of 1×10^{14} 1 and 5×10^{14} 1 MeV n_{eq}/cm^2, and one was used as a non-irradiated reference. The pad detectors were irradiated with 24 GeV protons (CERN PS) to several different neutron equivalent fluences. The devices were not annealed prior to their characterization with the beam telescope or the TCT setup.

3. Transient current technique measurements

In short, the TCT measurement is based on the detection of the dominant type of charge carrier, electron or hole, which drifts across the whole detector thickness after being excited by a photon. Detailed description of this method can be found from Refs. [9,10]. It is important to note that when the electric field of an irradiated detector is analyzed, the measured signal is affected by the charge trapping into the radiation-induced defects. The influence of the trapping can be deducted from the measured data by applying values obtained from the literature [11–13].

In this experiment the pad detectors were characterized with the RD39 Collaboration cryogenic TCT-setup, which is capable of operating below liquid nitrogen temperature. The TCT setup consists of a high bandwidth oscilloscope, a Keithley source meter unit capable of sourcing up to 500 V, a vacuum chamber, a cold finger, a Leybold helium stirling cooler, temperature and vacuum control units, a LabVIEW-based data acquisition system and two different lasers emitting at 670 and 1060 nm. A detailed description of the setup can be found from Ref. [14].

4. Beam test measurements

The detector measurements in the beam were done with a reference telescope and 225 GeV muon beam at the CERN H2 test

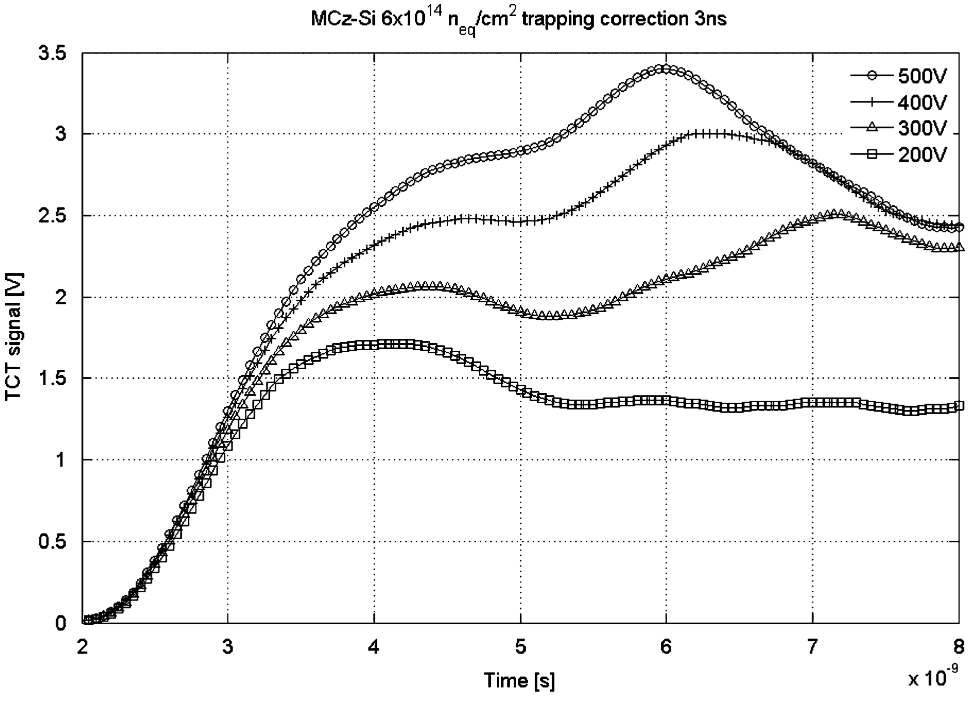

Fig. 1. Trapping corrected (3 ns) TCT measurement data from a sample irradiated with 24 GeV protons to the neutron equivalent fluence of 6×10^{14} 1 MeV n_{eq}/cm^2.