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Comparison of charge collection efficiency of segmented silicon detectors made with FZ and MCz p-type silicon substrates

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Abstract

High-resistivity p-type silicon has emerged as one of the most promising materials for the finely segmented detectors to be used in particle physics experiments where high levels of radiation damage are expected. Beside the standard high-purity float-zone (FZ) silicon, relatively high-resistivity magnetic Czocharlski (MCz) is now available from industry. This material has been proposed as possibly more radiation hard than the standard FZ. This work shows a comparison of these substrate materials in terms of charge collection efficiency measurements performed with 40 MHz analogue electronics, before and after irradiation.

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Keywords: Silicon microstrip; Radiation hardness; SLHC; Charge collection efficiency

1. Introduction

Plans for a staged upgrade of the LHC to a factor of ~10 higher luminosity are well advanced (the super LHC, SLHC) [1]. Silicon detectors are the strongest candidate for the tracker upgrade of the SLHC experiments due to their low mass and high position resolution. The increased luminosity leads to a tremendous level of irradiation in the detector volume, due to the particles emerging from the interaction region and due to backscattered albedo neutrons [2]. The irradiation dose that the tracker detectors will suffer depends on the radial distance to the interaction region. The sensors need to be qualified to the dose they will receive at the end of the physics program. Charge collection efficiency (CCE) measurements of the signal generated by minimum ionizing particles are the most direct method for qualifying the performances of the detectors before and after irradiation. Recent CCE results show that sufficient signal can be obtained using high-resistivity float-zone (FZ) p-type silicon substrate devices with n-side segmented electrodes after irradiation to the predicted doses of the innermost microstrip layer of the preliminary layout of the upgraded ATLAS detector at the SLHC [3].

An alternative substrate to the high-grade FZ is magnetic Czocharlski (MCz) silicon. This technology is a refinement of the standard Czocharlski (Cz) method for growing silicon single crystal with resistivity higher than the original method. Higher resistivity silicon is required to keep the initial full depletion voltage sufficient to ensure maximal charge collection at an achievable bias voltage, given system constraints. For example, the largest applicable bias voltage in ATLAS is anticipated to be 500 V for microstrip detectors. This requires p-type substrates with a minimum resistivity of 2 kΩ for a depletion voltage of 450 V in 300 μm thick sensors before irradiation. It has been suggested that the higher oxygen content of the MCz

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crystals could lead to better radiation hardness with respect to FZ silicon [4]. A comparison of irradiated FZ and MCz detectors is required to determine the most suitable substrate for applications where severe radiation damage is a limiting factor.

2. Experimental method

The radiation damage in the tracker volume of the upgraded ATLAS detector will be caused by both charged particles emerging from the interaction region and by albedo neutrons.

Simulations [2] show that the two contributions are equal at a radial distance of about 20 cm from the beam axis. The silicon microstrip detectors for the barrel tracker are planned to be at a radii between ~25 and 100 cm [5] from the beam axis. At these radii, the neutron contribution to the radiation damage ranges between ~53% and 87%. The neutron damage is therefore more relevant to the microstrip detectors for the ATLAS upgrade. The dose expected for the innermost layer, corresponding to $3000\,\text{fb}^{-1}$ of integrated luminosity, is $5\times10^{14}\,\text{cm}^{-2}$ 1 MeV neutron equivalent.

Two sets of MCz and FZ p-type silicon detectors were irradiated with neutrons to this final dose in order to evaluate the radiation resistance of the substrates. The detectors, fabricated by Hamamatsu Photonics, were $1\times1\,\text{cm}^2$, with 128 AC coupled strips with ~75 μm pitch. The strips are electrically isolated by dedicated isolation structures. Fig. 1 shows the different fabricated structures studied ranging between no isolation structures to various types of implanted p-stops. All the prototypes with isolation implants had interstrip resistance in excess of 1 GΩ.

3. Results

Pre-irradiation measurements were performed to evaluate the capacitance–voltage, reverse current, and interstrip capacitance characteristics of the FZ and MCz samples. The CV curves presented in Fig. 2 display a much higher full depletion voltage (V_{FD}) for the MCz sensors (~400 V) compared to the FZ ones (~190 V), due to the lower initial resistivity of the MCz wafers. As shown in Fig. 3, the

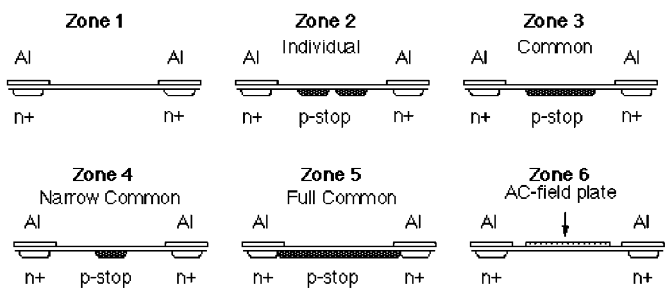

Fig. 1. Schematic showing the difference between strip isolation structures studied.

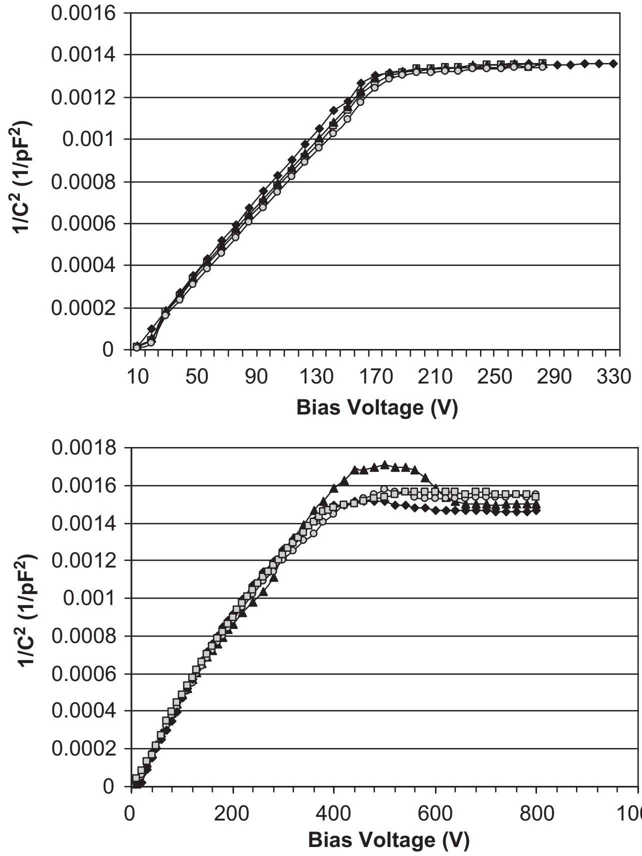

Fig. 2. Capacitance–voltage (CV) characteristics of FZ (above) and MCz (below) detectors before irradiation.

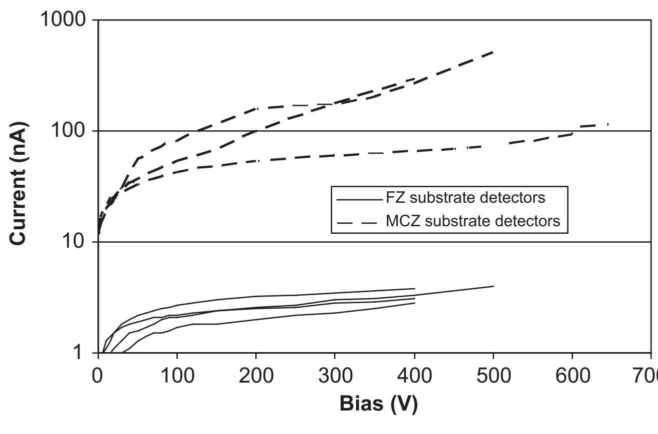

Fig. 3. Reverse current for FZ and MCz detectors before irradiation.

reverse current of the MCz detectors is also systematically higher than the FZ ones, due to the higher concentration of impurities in the MCz silicon crystal. The measured interstrip capacitances (shown in Fig. 4) were about the same for both FZ and MCz sensors. Fig. 5 shows the measured CCE of non-irradiated FZ and MCz detectors. The lower initial resistivity of the MCz crystals results in lower CCE for lower bias voltages (below V_{FD}).

As shown in Fig. 6, the CCE measurements for FZ and MCz detectors were repeated after a $5\times10^{14}\,n_{eq}\,\text{cm}^{-2}$

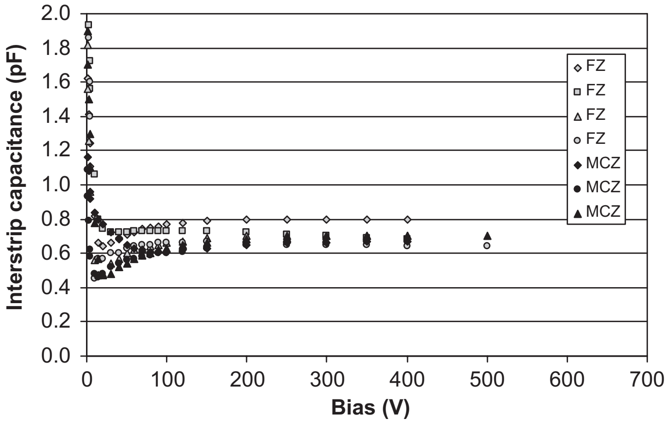

Fig. 4. Interstrip capacitance of FZ and MCz detectors before irradiation.

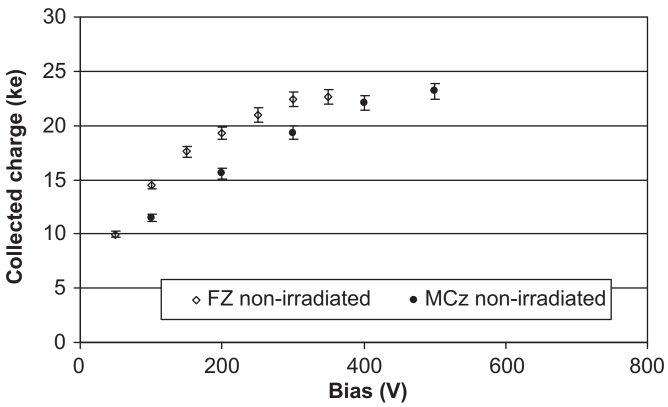

Fig. 5. Charge collection efficiency (CCE) of non-irradiated FZ and MCz detectors.

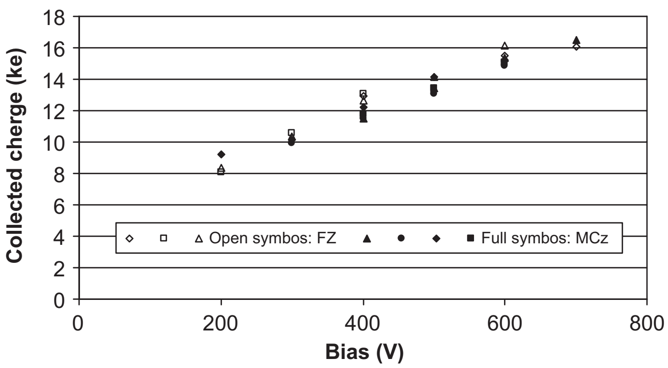

Fig. 6. Charge collection efficiency (CCE) of FZ and MCz detectors after $5\times10^{14}\,\mathrm{n\,cm^{-2}}$.

irradiation. The CCE curves are very similar, with a slightly higher efficiency of the FZ detectors between 400 and 600 V applied bias voltage.

4. Conclusions

The differences observed in the pre-irradiation characteristics between microstrip detectors made on FZ and MCz silicon are mainly due to the different values of the initial resistivity. For complete charge collection, much higher bias voltage is required for MCz detectors. In addition, higher reverse currents are measured for MCz devices. The higher initial currents are not a concern for applications where high radiation damage is expected, because after irradiation the reverse current will be dominated by the bulk generated current. After irradiation, the CCE curves are similar for both types of substrates, with slightly higher efficiency for the FZ substrates between 400 and 600 V. Before and after irradiation, the maximum collected charge at the highest bias voltage is similar for the FZ and MCz sensors. The maximum collected charge of $16\,\mathrm{Ke^-}$ after $5\times10^{14}\,\mathrm{n_{eq}\,cm^{-2}}$ is also consistent with previous measurements [6], but previously the saturation value was reached at a much lower voltage (about 350 V). The difference is thought to be due to the difference in the initial resistivity, in excess of $10\,\mathrm{k\Omega}$ for the results of Ref. [6], suggesting that higher values are advisable for silicon detectors that will be exposed to significant neutron damage.

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