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Charge collection efficiencies of planar silicon detectors after reactor neutron and proton doses up to $1.6 \times 10^{16}\,\mathrm{n_{eq}\,cm^{-2}}$ ☆

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ABSTRACT

The planned luminosity upgrade of the large hadron collider at CERN (Super-LHC) will provide a challenging environment for the tracking and vertexing detector systems. The innermost devices at a radius about 4 cm from the interaction region will have to be able to withstand a combined charged and neutron hadron dose in the order of 10^{16} 1 MeV neutron equivalent particles ($\mathrm{n_{eq}}$) per square centimeter over the anticipated 5 year lifespan of the SLHC experiments. Planar, segmented silicon detectors with n-strip readout are one of the many radiation tolerant technologies under consideration for use for the Super-LHC tracking detectors in either pixel or strip geometries.

This paper details charge collection efficiency measurements made with silicon sensors that have been irradiated to doses as high as $1.5 \times 10^{16}\,\mathrm{n_{eq}\,cm^{-2}}$ with reactor neutrons and as high as $1.6 \times 10^{16}\,\mathrm{n_{eq}\,cm^{-2}}$ with 26 MeV protons and 24 GeV protons. In this study, $\mathrm{n^+}$ segmented strip readout in either n-bulk (n-in-n) or p-bulk (n-in-p) substrates are considered. Both diode configurations were processed in substrates grown with float zone (FZ) and magnetic Czochralski (MCz) techniques. For the fluences studied, all the $\mathrm{n^+}$ strip readout technologies are still viable assuming that adequate bias voltage and cooling can be supplied and low noise, low threshold readout electronics can be designed.

1. Introduction

The proposed 10-fold luminosity upgrade to the present LHC machine, the Super-LHC (SLHC) [1], presents significant challenges for all of the experiments' tracking systems with respect to radiation tolerance, as the detectors will be exposed to nearly an order of magnitude more radiation than the current detectors. For the present ATLAS upgrade detector layout [2], a total fluence of $1.3 \times 10^{16}\mathrm{n_{eq}\,cm^{-2}}$ [3] is expected during 5 year SLHC operation at the innermost layer of the detector ($r = 3.7$ cm). These challenges were foreseen with the RD48 [4] and RD50 [5] collaborations both being formed to study the radiation hardening of silicon sensors through device geometry choice and controlled defect introduction. Studies so far [6,7] have shown that n-strip readout has a significant radiation tolerance enhancement relative to the standard p-strip readout.

The purpose of the measurements presented here is to determine the radiation tolerance of n-strip readout devices produced with n-bulk and p-bulk silicon substrates grown with different techniques to neutron and proton irradiations up to SLHC fluences. Devices produced with high purity float zone (FZ) n-type and p-type silicon substrates have been studied. Newly available high resistivity (1−2 kΩ cm) magnetic Czochralski [8] method substrates of both n-type and p-type have also been used to make devices.

2. Experimental methods and results

Miniature, ~300 μm thick ($1 \times 1\,\mathrm{cm^2}$) AC coupled sensors with a 80 μm strip pitch have been designed within the framework of the CERN-RD50 collaboration [5] and produced by Micron Semiconductor, Ltd.[1] on 6 in. diameter silicon wafers. Float zone (FZ) and magnetic Czochralski (MCz) substrates were used to produce sensors in n-in-n and n-in-p sensor geometries using the same mask sets. High purity float zone materials have been chosen with resistivities of 14 and 20 kΩ cm for the p-bulk and n-bulk silicon, respectively. High purity MCz materials have also been used with resistivities of 1.5 and 2 kΩ cm for the p-bulk and n-bulk silicon, respectively. Strip isolation was guaranteed through the use of a blanket p-spray [9] on the segmented detector side. Due to component scarcity, additional n-in-n FZ miniature ($1 \times 1\,\mathrm{cm^2}$) micro-strip detectors from the LHCb vertex

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locator (VELO) [10] silicon production were used to finish this study. These miniatures (denoted n-in-n FZ VELO for the rest of this paper) have resistivities of $5\,\mathrm{k\Omega\,cm}$. The n-in-n FZ devices produced within the RD50 framework are denoted n-in-n FZ RD50 for the rest of the paper.

In order to measure the collected charge of an irradiated device, the sensor is bonded to a SCT128A [11] analogue readout ASIC clocked at SLHC speeds (40 MHz). Signals in the sensors are induced by fast electrons from a ^{90}Sr source and are triggered by two scintillators in coincidence. The scintillators are shielded by a 2 mm thick plastic sheet in order to remove low energy betas and better mimic the ionization spectrum of minimum ionizing particles in silicon. Through the use of multiple pitch adapters between the SCT128A ASIC and the silicon sensor under test, the same chip can be re-used multiple times which removes calibration uncertainties. New SCT128A ASICs are calibrated with a reference non-irradiated $300\,\mu\mathrm{m}$ thick detector with a most probable charge deposition of $23\,000\,\mathrm{e}^-$. The charge collection efficiency as a function of bias voltage, reported in kilo-electrons (ke^-), is measured at $-25\,^{\circ}\mathrm{C}$ to reduce the reverse current and prevent thermal runaway during the measurements. The errors on the charge collection measurements are given by the estimated error on the calibration of the system added in quadrature to the estimated error on the fit of the signal spectrum.

2.1. *Charge collection efficiencies after up to* $1.5\times10^{16}\,\mathrm{n\,cm^{-2}}$ *reactor neutrons*

In the ATLAS straw-man design [2], the b-layer at a radius of 3.7 cm is expected to see a total fluence of $1.3\times10^{16}\,\mathrm{n_{eq}\,cm^{-2}}$ during SLHC operation. In order to study the radiation tolerance of different n-strip readout technology, a series of miniature sensors were irradiated with neutrons at the J. Stephan University's Triga research nuclear reactor [12] in Ljubljana, Slovenia. These irradiations extend upon our previous studies [13,14] of the radiation hardness of the different n-strip readout technologies to unprecedented fluences consistent with the expected doses for the innermost layers of the SLHC experimental upgrades. The neutron flux is tunable with a maximum rate of about $5\times10^{12}\,\mathrm{n\,cm^{-2}\,s^{-1}}$, which results in irradiation times of less than an hour for the highest fluences studied. The estimated error in the dosimetry of the irradiation is 10%. After irradiation, the sensors were shipped in a cold package and stored at $-20\,^{\circ}\mathrm{C}$ to prevent annealing processes. No additional annealing steps were performed prior to the charge collection efficiency measurements.

Fig. 1 shows the collected charge as a function of bias voltage for n-in-p FZ and n-in-p MCz devices. At the lowest fluences studied ($1\times10^{14}\,\mathrm{n_{eq}\,cm^{-2}}$), the n-in-p FZ device shows a better charge collection at low bias voltage due to the higher initial resistivity of the float zone silicon relative to the magnetic Czochralski silicon used. As the dose is increased, the collected charge for the n-in-p FZ and n-in-p MCz sensors become more consistent with each other, with identical charge collection efficiency measured for the highest common fluence measured in this study ($3\times10^{15}\,\mathrm{n_{eq}\,cm^{-2}}$).

In all of the samples measured, the collected charge increases with the applied bias voltage until either the maximum voltage of this study (1100 V) is achieved or the full charge prior to irradiation is collected. This trend indicates that charge trapping is not yet limiting the collected charge for neutron irradiations, which has been confirmed by Ref. [15] to much higher bias voltages.

Finally, an appreciable collected charge of $6.6\,\mathrm{ke}^-$ at 800 V bias was measured after a fluence of $1.5\times10^{16}\,\mathrm{n_{eq}\,cm^{-2}}$, which is a larger dose than that expected for the b-layer of the SLHC ATLAS upgrade. As charged hadrons will be the dominant source of radiation damage for detectors at this radii at the SLHC, further studies after charge hadron irradiation is needed in order to determine if the technology is radiation tolerant enough to be used at the inner radii of the SLHC experiments.

Fig. 2 shows similar charge collection measurements for n-in-n FZ and n-in-n MCz sensors after neutron irradiations; the fluences measured for n-in-n MCz sensors were limited by part ability at the time of the irradiations and will be extended once further parts are produced by Micron Semiconductor. For the fluences studied, n-in-n MCZ sensors show much more collected charge at lower bias voltages. The n-in-n FZ detectors display trends similar to the n-in-p FZ, with no sign of charge collection saturation below full charge collection for any fluence. For the common dose studied ($5\times10^{14}\,\mathrm{n_{eq}\,cm^{-2}}$) for two different resistivity n-in-n FZ devices used, the collected charge versus depletion voltage is consistent; this similarity indicates that the induced defects after this neutron fluence dominate the charge collection performance of these devices. After the maximum fluence studied for the n-in-n FZ detectors ($1\times10^{16}\,\mathrm{n_{eq}\,cm^{-2}}$), $5.7\,\mathrm{ke}^-$ is collected at a bias voltage of 600 V.

A summary of the charge collection performance as a fluence of neutron irradiation dose is shown in Fig. 3 and in Fig. 4 for bias voltages of 500 and 900 V, respectively. For both bias voltages, the basic trends are the same; at lower fluences ($<10^{15}\,\mathrm{n_{eq}\,cm^{-2}}$) there is a difference in collected charge for the difference substrate types and growth techniques studied. As the fluence is

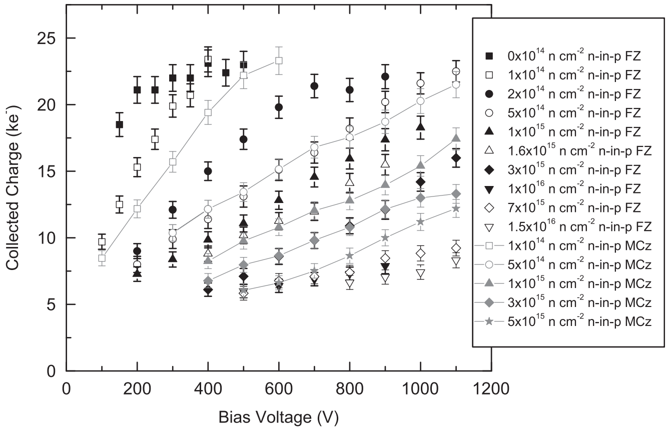

Fig. 1. Collected charge as a function of bias for n-in-p FZ and n-in-p MCz sensors irradiated with reactor neutrons up to $1.5\times10^{16}\,\mathrm{cm^{-2}}$.

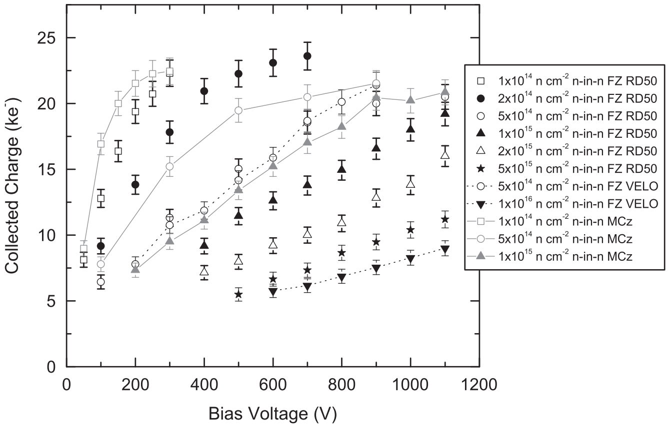

Fig. 2. Collected charge as a function of bias for n-in-n FZ and n-in-n MCz sensors irradiated with reactor neutrons up to $1.0\times10^{16}\,\mathrm{cm^{-2}}$.