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Studies of charge collection efficiencies of planar silicon detectors after doses up to $10^{15}\,n_{eq}\,cm^{-2}$ and the effect of varying diode configurations and substrate types ☆

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ABSTRACT

Planar, segmented silicon sensors are used for the tracker and vertex detectors of high energy physics experiments at the Large Hadron Collider (LHC) because of their unsurpassed performance in terms of granularity, resolution and speed while offering relatively low mass. The planned luminosity upgrade of the LHC at CERN (Super-LHC, SLHC) will provide a difficult environment for these silicon tracking and vertexing detector systems. For the regions where silicon micro-strip detectors are envisaged in the SLHC ATLAS experimental upgrade, the expected particle fluence at the innermost micro-strip layer is up to 1×10^{15} 1 MeV neutron equivalent particles (n_{eq}) per square centimeter over the anticipated 5 year lifespan of the experiment, making the radiation hardening of the silicon detectors more important than ever.

We present studies of the charge collection efficiencies of various diode configurations (p^+-strip in n-bulk, n^+-strip in n-bulk, and n^+-strip in p-bulk) as well as substrate types (float zone, FZ or magnetic Czochralski, MCz) after neutron irradiation up to $1\times10^{15}\,n_{eq}\,cm^{-2}$. The charge collection efficiency measurements have been carried out using 128 channel analogue, high-speed (40 MHz) electronics and a strontium electron source. These measurements indicate that p-in-n sensors are not radiation tolerant enough for use at the SLHC for micro-strip detectors. Both n-in-n and n-in-p geometries in both FZ and MCz substrates have shown sufficient charge collection for use in these regions, with n-in-p FZ chosen as the baseline technology choice for the ATLAS upgrade.

1. Introduction

The proposed 10-fold luminosity upgrade to the Large Hadron Collider (LHC), the Super-LHC (SLHC) [1] will provide a significant challenge to the tracking systems at all four LHC experiments (ALICE, ATLAS, CMS, LHCb). Silicon detectors will be the likely technology choice for the upgraded detectors as they can provide the needed speed, spacial resolution, and granularity with relatively low mass. The current large-scale tracking systems of ATLAS and CMS [2,3] use segmented p^+-strip readout on n-bulk silicon (p-in-n geometry). This geometry requires single-sided processing, which has the advantage of being widely available at relatively affordable cost. One limitation of this technology may be the charge collection performance of the silicon after the extremely high radiation exposures predicted in the tracker volume of the experiments during the SLHC [4]. In order to address this issue, the RD48 [5] and RD50 [6] Collaborations were formed to study the radiation hardening of silicon sensors both in terms of device geometry as well as the improved radiation tolerance of the silicon crystal through controlled defect introduction.

Studies [7–10] have already shown that detectors with n-side readout are considerable more radiation tolerant than the p-in-n geometry. The increased radiation tolerance of n-strip readout is due to many factors: electrons, the dominant charge carrier for n-strip readout signals, have longer trapping times and higher mobilities relative to holes, the dominant charge carrier for p-strip readout signals; during annealing [11–13] trapping times increases for electrons and decrease for holes; and after irradiation, the dominant junction with the largest depletion region and strongest electric fields originates from the n^+ implant. The smaller, inner vertexing systems at the LHC (LHCb VELO micro-strip [14] and ATLAS and CMS pixels [2,3]) use segmented n^+ readout on n-doped substrate (n-in-n). This geometry requires double-sided processing and additional strip isolation steps [15], which increases cost and reduces the number of foundries with this process available. Newly available n^+ readout on p-type

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substrate technology (n-in-p) still requires additional strip isolation steps but only requires the cheaper single-sided processing, which decreases costs and increasing the number of foundries available relative to n-in-n.

Studies [5,6] have also shown that the intentional introduction of oxygen to high resistivity float zone (FZ) silicon through the means of high temperature diffusion decreased the rate of the change of the full depletion voltage (V_{fd}) with increasing proton irradiation, although no improvement is seen with the degradation rate of V_{fd} during neutron irradiations. A relatively low concentration of oxygen ($\sim 10^{16}\,\mathrm{cm}^{-3}$) can be obtained in high purity FZ materials used for detectors. Detector-grade, silicon wafers with higher oxygen concentrations ($4-5\times10^{17}\,\mathrm{cm}^{-3}$) are available from industry [16] grown using the magnetic Czochralski (MCz) method. Due to its higher oxygen concentration, it is being proposed [17] as a more radiation tolerant substrate material for silicon detectors.

The measurements presented here establish the charge collection efficiency of these different detector geometries and substrate types with particular focus on suitability for use in the regions of SLHC upgrade detectors [18] currently envisioned to consist of micro-strip detectors with sensitive element lengths from 2.5 to 9 cm long. These detector systems will occupy the region between 40 and 100 cm in radius from the LHC beams, which is predicted to see fluences of $2-10\times10^{14}\,n_{eq}\,\mathrm{cm}^{-2}$ during SLHC operation, including a 2× safety factor. These large detector systems will have sensor areas in excess of $100\,\mathrm{m}^2$, making cost and production capacity issues as well.

2. Experimental methods and results

Miniature, ~300 μm thick ($1\times1\,\mathrm{cm}^2$) AC coupled sensors with a 80 μm strip pitch have been designed within the framework of the CERN-RD50 Collaboration [6] and produced by Micron Semiconductor, Ltd.[1] The small size of the sensors allows for easier handling and improved uniformity during the irradiation process and also maximizes the number of samples produced per wafer allowing for a greater number of different irradiation doses to be studied. FZ and MCz substrates were used to produce sensors in p-in-n, n-in-n, and n-in-p sensor geometries. 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. Newly available, high purity MCz materials have been used with resistivities of 1.5 and 2 kΩ cm for the p-bulk and n-bulk silicon, respectively. The same mask set has been used to process all geometries. An additional step was required by the n-in-n and n-in-p geometries to add the necessary p-spray inter-strip isolation [15].

To measure the charge collection of the irradiated sensors, the pieces are bonded to a SCT128A [19] 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 a scintillator 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. The analogue data were digitized by a 40 MHz Sirocco ADC. The readout system was calibrated with a reference non-irradiated 300 μm thick detector with a most probable charge deposition of 23 000 e^-. The charge collection efficiency as a function of bias voltage, reported in kilo-electrons (ke^-), is measured at $-25\,^\circ$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 charge collection spectrum.

2.1. Charge collection efficiencies after up to $1\times10^{15}\,n\,\mathrm{cm}^{-2}$ reactor neutrons

In the ATLAS straw-man design [18], micro-strip detectors of differing length are foreseen between the radii of 38 and 95 cm. During SLHC operation, this region is predicted to see a total fluence of $2-10\times10^{14}\,n_{eq}\,\mathrm{cm}^{-2}$ including a 2× safety factor. Neutrons are predicted to be dominant source of radiation damage contributing about 50–90% of the total damage for the inner and outer radii of these regions. In order to study the radiation tolerance of the various sensor geometry and substrate choices, a series of detectors has been irradiated with neutrons at the J. Stephan University's Triga Research nuclear reactor [20] at Ljubljana, Slovenia. The neutron flux during the irradiation is $1.9\times10^{12}\,n\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, allowing for a relatively short irradiation times (between 52 seconds and 9 minutes for the fluences under study). The estimated error in the dosimetry of the irradiation is 10%. After irradiation, the sensors were shipped in a cold package and stored at $-20\,^\circ$C to prevent annealing processes. No additional annealing steps were performed prior to the charge collection efficiency measurements.

Fig. 1 shows the charge collected as a function of bias voltage for the four detector irradiated to $1\times10^{14}\,n\,\mathrm{cm}^{-2}$. As expected from V_{fd} measurements [21] of pad diodes obtained from the same wafers, the n-in-n MCz detectors show the best charge collection efficiency at low voltages, with the n-in-n FZ device showing slightly worse performance. The n-in-p FZ and n-in-p MCz devices require even larger bias voltages (200 and 300 V more than the n-in-n MCz device, respectively) to fully collect the deposited charge. All four detectors show full charge collection at the maximum rating of the current ATLAS's high-voltage system (500 V).

The next set of devices were irradiated to $2\times10^{14}\,n\,\mathrm{cm}^{-2}$. As shown in Fig. 2, the current standard large-scale detector (p-in-n FZ) shows the worst charge collection performance, especially at lower bias voltages. The p-in-n MCz device shows similar performance to the n-in-n FZ device, which gives some indication that the MCz material is more radiation tolerant.

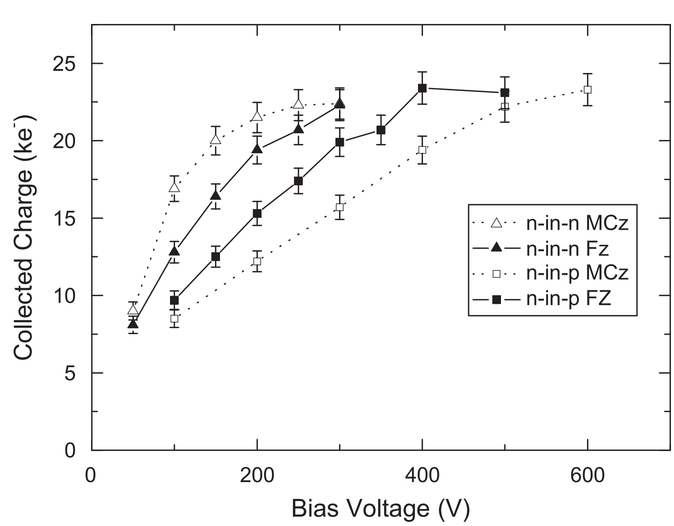

Fig. 1. Collected charge as a function of bias for four types of sensors irradiated with neutrons to $1\times10^{14}\,\mathrm{cm}^{-2}$.

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