Czochralski Silicon as a Detector Material for S-LHC Tracker Volumes

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Abstract

With an expected ten-fold increase in luminosity in S-LHC, the radiation environment in the tracker volumes will be considerably harsher for silicon-based detectors than the already harsh LHC environment. Since 2006, a group of CMS institutes, using a modified CMS DAQ system, has been exploring the use of Magnetic Czochralski silicon as a detector element for the strip tracker layers in S-LHC experiments. Both p+/n-/n+ and n+/p-/p+ sensors have been characterized, irradiated with proton and neutron sources, assembled into modules, and tested in a CERN beamline. There have been three beam studies to date and results from these suggest that both p+/n-/n+ and n+/p-/p+ Magnetic Czochralski silicon are sufficiently radiation hard for the $R > 25$ cm regions of S-LHC tracker volumes. The group has also explored the use of forward biasing for heavily irradiated detectors, and although this mode requires sensor temperatures less than -50 °C, the charge collection efficiency appears to be promising.

Key words: Magnetic Czochralski silicon, Current Injected Detector, SiBT

1. Introduction

Although the time-scale for Large Hadron Collider (LHC) luminosity upgrades has recently slipped, the ultimate goal of increasing the design LHC design luminosity by a factor of ten remains unchanged. This increase means that trackers planned for S-LHC experiments will require sensor materials in the innermost layers with an order of magnitude improvement in radiation hardness over what is presently in use. For pixel systems, which typically extend from just outside the beam pipe to a radius of about 25 cm, the sensor material should be able to survive fluences in excess of $1{\times}10^{16}$ 1 MeV neutron equivalents per square centimeter.[1] However, pixel detectors are relatively small in total sensor area, so that expensive semiconductor materials, such as diamond, are not out of the question. Pixel systems with their close proximity to the beam pipe also offer the possibility of a periodic replacement strategy.

In the strip tracker regions, which start at around $R = 25$ cm, the maximum fluences are significantly reduced, to about 1×10^{15} n_{eq}/cm^2 . However, LHC strip trackers tend to have large sensor areas—some 200 m^2 in the case of CMS—and do not provide the option of easy replacement. It is also assumed that for ease of construction and operation, experiments will want to use a single technology for the strip sensors.

Since 2006 a group of CMS institutes (SiBT group [1]) has been studying, based on the use of a modified CMS DAQ system, the use of Magnetic Czochralski (MCz) silicon as a potential replacement for the Float Zone (FZ) silicon that is presently used in the CMS strip tracker. The Czochralski process utilizes a quartz crucible for containing the molten silicon, which facilitates the production of large area wafers but at the same time is a source of contaminants. However, it has been shown that one of contaminants, oxygen, actually improves the radiation hardness of the silicon [2, 3]. By carrying out the Czochralski process in the presence of of a magnetic field the concentration of oxygen can be precisely controlled.

2. Beam Telescope

The beam telescope used by the SiBT group has been previously documented [4]. It is based on the cold box developed by the Vienna HEP group for long-term testing of CMS silicon strip modules during the construction period. CMS DAQ components and software are used for the readout of modules containing CMS front-end hybrids. Figure 1 shows a schematic of the 10-slot Vienna box and its orientation relative to the CERN SPS H2 beam (225 GeV/c muons or pions). There is a 4 cm spacing between slots and the box has an internal clearance height of 17 cm and a depth of about 44 cm. The box is capable of achieving an inside temperature of -25 °C with detectors under power in all 10 slots; was run as close to this as possible

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[1] For brevity the fluence unit is abbreviated as n_{eq}/cm^2 in this note.

when irradiated detectors were present so as to limit the leakage currents.

The reference planes, which normally occupy slots 1-4 and 7-10, are based on 4×10 cm^2 Hamamatsu [5] sensors provided by the D0 collaboration and leftover CMS outer barrel hybrids. Although the reference detectors have a 60 μm pitch, they also contain intermediate strips so that the resolution of planes is more consistent with that of a 30 μm pitch detector (and in fact has been measured to be as small as 6.5 μm). Within the Vienna box the reference planes are mounted either in +45° or −45° orientations as shown in Fig. 2. With this geometry the uncertainty in beam track positions in slots 5 and 6, as determined by the four "+" reference planes, is around 3.3 μm. Details on the calibration and alignment of reference planes can be found in Ref. [6].

Figure 1 also shows a second, single-detector cold enclosure, which was installed immediately downstream of the Vienna box. This Cold Finger used a three-stage Peltier element for cooling, but with a smaller volume and tighter insulation was able to achieve an internal temperature as low as -53 °C. Detectors installed in this box had a "+" orientation and were operated in both reverse and forward bias modes.

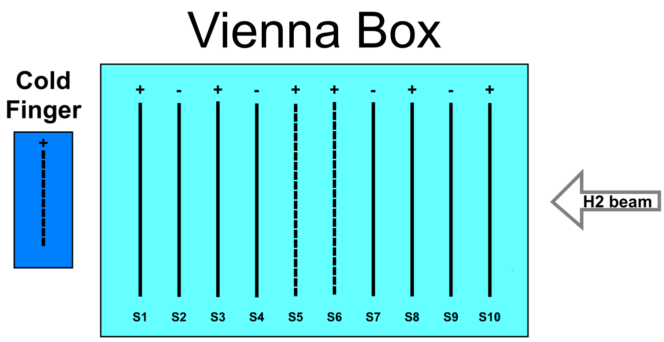

Figure 1: Beam telescope used for MCz studies.

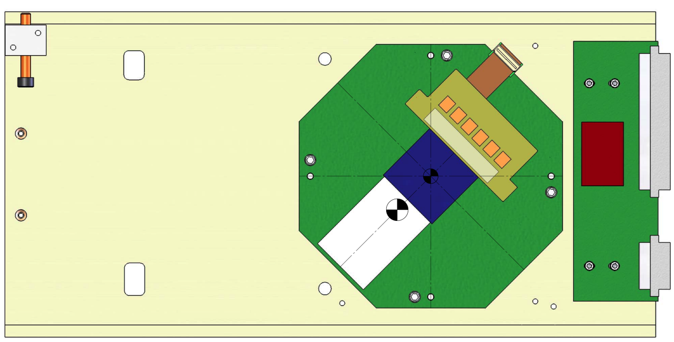

Figure 2: Vienna box insertion plate illustrating the +45° orientation for a reference module (long, white sensor) or a DUT (short, blue sensor).

3. Detectors Under Test

The SiBT group has studied a number of MCz detectors starting with the initial beam study in the summer of 2007. Table 1 lists those detectors that are the subject of this note. In the table and subsequent sections "n(-type)" refers to p+/n-/n+ sensors and "p(-type)" to n+/p-/p+ sensors. Within the Vienna box the detectors under test (DUT) were installed in slots 5 or 6 given the minimized beam track uncertainty in these locations as described in the previous section.

The MCz sensors used in the DUT modules were processed at the Helsinki University of Technology Centre for Micro and Nanotechnology (Micronova) facility. The raw material was provided by Okmetic [7] in the form of 4 inch wafers with a thickness of 300 μm and a nominal resistivity of 900 Ωcm. Details on the processing can be found in Ref. [8]. With an area of 4.1×4.1 cm^2 the MCz sensors are considerably shorter than the reference sensors, as is illustrated in Fig. 2. All of the sensors had a strip pitch of 50 μm and a strip width of 10 μm.

Similarly, sensors were also fabricated from Topsil [9] FZ wafers, obtained from an RD50 [10] common order, using the same masks from the MCz production. The Topsil wafers had a thickness of 285 μm.

Non-irradiated MCz sensors fully deplete at around 350 volts and non-irradiated Topsil FZ sensors at around 10 volts.

The MCz and FZ sensors were irradiated, prior to module assembly, with 25 MeV protons at the Universität Karlsruhe and, in a limited number of cases, also with 3-45 MeV neutrons at the Université Catholique de Louvain. Irradiation levels for the detectors covered in this note are listed in Table 1. As described in Section 2 the Vienna box was operated close to the coldest setting for the irradiated detectors. Actual sensor temperature were somewhat higher, though, given the power consumption of the CMS hybrids and the leakage currents.

Table 1: Detectors Under Test

year	fluence	proton %	sensor	box	bias
2007	non-irrad.		nMCz	Vienna	rev
2008	non-irrad.		nFZ	Vienna	rev
2009	1.0×10^{14}	100	nFZ	Vienna	rev
2008	2.2×10^{14}	100	nFZ	Vienna	rev
2009	3.0×10^{14}	100	nFZ	Vienna	rev
2008	6.1×10^{14}	84	nMCz	Vienna	rev
2008	1.1×10^{15}	91	nMCz	Vienna	rev
2008	1.6×10^{15}	94	nMCz	Vienna	rev
2009	2.0×10^{15}	100	pMCz	CF	rev/for
2008	2.8×10^{15}	100	nMCz	CF	rev/for
2009	3.1×10^{15}	100	nMCz	Vienna	rev/for
2009	4.9×10^{15}	100	nMCz	CF	rev/for

4. Charge Collection Efficiency

Charge clusters in the DUTs are determined in a standard way: seed strips are identified based on the requirement that the signal to noise ratio (S/N) exceeds 2.5. Neighboring strips are then added to the seed if their S/N exceeds 2.0 and the final cluster must have a S/N greater than 2.75. The total charge associated with a cluster is then taken to be the sum of the charges of the two largest adjacent strips within the cluster. As the DUTs are normal to the beam, the DUT clusters tend to be dominated by single-strip clusters. In these cases the cluster charge is simply the charge of the single strips. Clusters are classified as either "on-track" or "off-track" depending on their proximity to the beam track.

In some cases where strip and cluster charges are likely to be below threshold a *non-clustering* algorithm [11] has been used. In this approach the cluster charge is taken to be the sum of charges for the two strips that are closest to the intersection of the beam track, as determined by the reference planes, and the DUT.

The signal associated with a particular bias voltage is taken to be the most probable value of a Landau function convoluted with a Gaussian function that has been fit to the on-track data. Figure 3 shows the distribution of cluster charges for four of the n-type MCz detectors. A MPV of about 40 ADC counts for the non-irradiated MCz sensor is in agreement with the level seen in the reference detectors. As can be seen in the figure, increasing fluence levels result in correspondingly lower charge collection efficiencies. It should be pointed out that 600 V was the maximum bias voltage[2] that was applied during the studies. At 600 V the 6.1×10^{14} n_{eq}/cm^2 is just below full depletion whereas the 1.1×10^{15} n_{eq}/cm^2 and 3.1×10^{15} n_{eq}/cm^2 detectors are well below their full depletion values. However, the 1.1×10^{15} n_{eq}/cm^2 detector does exhibit a MPV of about 20 ADC at this voltage, corresponding to a charge collection efficiency of 50%. Coupled with a noise measurement of 2 ADC counts [12] this leads to a predicted S/N>10 at the end of S-LHC running.

One p-type MCz detector, irradiated to a fluence of 2.0×10^{15} n_{eq}/cm^2 , was operated in reverse bias mode in the Cold Finger in 2009. Figure 4 compares the signal versus voltage for the p-type detector with that of the 1.1×10^{15} n_{eq}/cm^2 n-type detector. Despite the different fluence levels the two detectors have approximately the same charge collection efficiency, at least up to the maximum 600 V applied to the n-type detector. Also shown on the figure is the result of a transport model for the p-type detector that has been tuned to roughly fit the data (by adjusting trapping time constants for holes and electrons within reasonable ranges).

There is no evidence for avalanche or charge multiplication effects in any of the SiBT data although 5×10^{15} n_{eq}/cm^2 and 1000 V is the largest combination of fluence level and bias voltage that has been studied to date.

Figure 5 shows the charge collection efficiency for four n-type MCz detectors, one p-type MCz detector, and three n-type FZ detectors as a function of fluence. The last three points were measured at 600 V, which is well below the expected full depletion voltages.

[2] 600 V is the approximate safe operating limit for high voltage cables presently installed in CMS; it is unlikely that these cables will be changed for S-LHC.

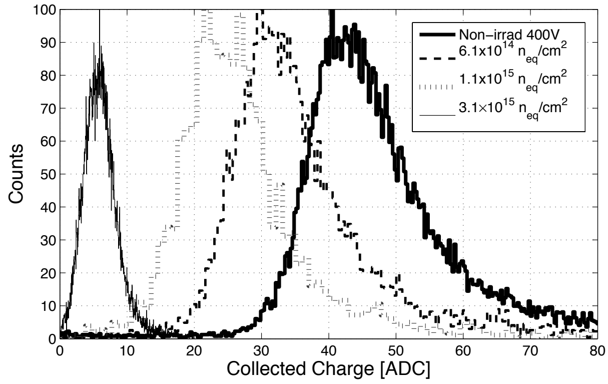

Figure 3: Superimposed cluster charge distributions for four of the n-type MCz detectors. The distributions have been scaled so that there are 100 counts in the highest bin and they are all based on the non-clustering method described in the text. Bias voltage of 600 V and 420 V were applied for the 1.1×10^{15} n_{eq}/cm^2 and 3.1×10^{15} n_{eq}/cm^2 detectors, respectively, and these are well bellow the full depletion values.

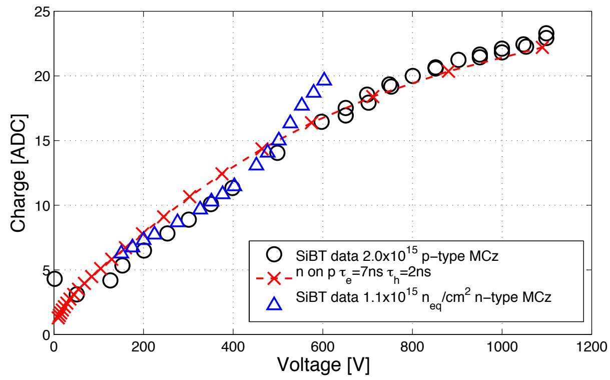

Figure 4: Comparison of n-type and p-type MCz charge collection efficiency. The dashed line represents a transport model prediction that has been tuned to fit the p-type data. A non-clustering approach was used for the the p-type data.

5. Current Injection

For heavily irradiated detectors there exists the possibility of filling trapping sites under forward bias with either holes or electrons and, assuming the trapping can be continually balanced by detrapping, establishing a stable electric field throughout the entire bulk [13, 14]. The field, which increases toward the backplane of the detectors as the square-root of the distance from the injecting junction, is relatively insensitive to the applied voltage and fluence level. Since detrapping time constants depend exponentially on temperature, creating a steady-state condition requires a sensor temperature that is considerably lower than the optimal -10 °C for irradiated detectors under reverse bias.

Current Injected Detectors (CID) are based on the concept of trapping and detrapping in forward bias and the SiBT group has explored this operating mode in parallel with the standard MCz studies [15]. As described in the Beam Telescope section, the Cold Finger was used for these studies. With an operating temperature as low as -53 °C the enclosure was capable of

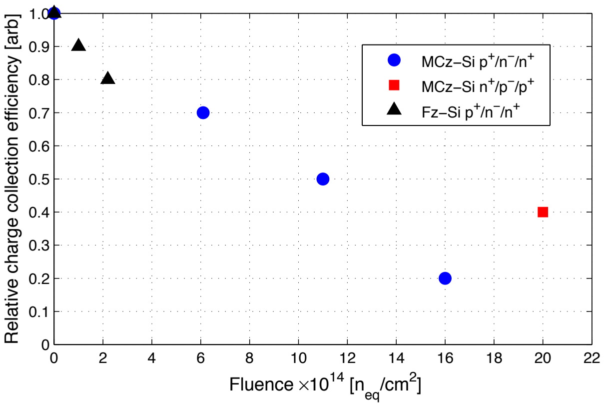

Figure 5: Charge collection efficiencies for n-type MCz, p-type MCz, and (n-type) FZ detectors as a function of fluence. The MCz detectors have been normalized to the non-irradiated MCz detector and the FZ detectors to the non-irradiated FZ detector. The last three points were taken at 600 V, which is well below the estimated full depletion voltages.

providing the required short detrapping times.

Figure 6 shows the signal versus bias voltage for two n-type MCz detectors that have been irradiated to fluences of 2.8×10^{15} n_{eq}/cm^2 and 4.9×10^{15} n_{eq}/cm^2 respectively. Both detectors were operated in the Cold Finger at the lowest temperature setting. The 2.8×10^{15} n_{eq}/cm^2 detector has a noise value around 2 ADC counts at 600 V, which would imply a S/N around 8. Although this level is probably at the margin of acceptability, the current injection mode might provide a means for extending the lifetime of the innermost layers in S-LHC strip trackers. However, engineering a cooling system capable of providing sensor temperature less than -50 °C would be a formidable challenge.

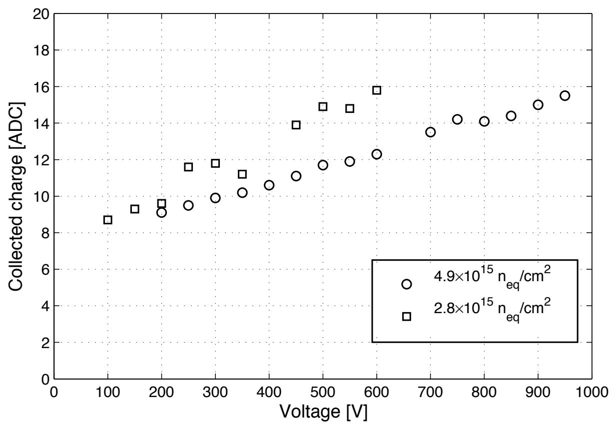

Figure 6: Signal versus bias voltage for two heavily irradiated detectors under forward bias (current injection mode).

6. Conclusions and Future Plans

The beam studies of irradiated MCz detectors suggest that both n-type and p-type sensors will survive S-LHC integrated fluence in strip tracker volumes of planned detectors. The p-type detector does have a higher charge collection than the n-type, which is not unexpected given the known advantages in collecting electrons over holes. However, given the extra processing required to isolate the n+ implants in p-type sensors, this may weigh in favor of n-type sensors for the very large silicon surface areas in the planned strip trackers.

The CMS Collaboration has recently contracted with Hamamatsu for over one hundred 6 inch wafers including the following substrates and thicknesses: MCz 200 μm, FZ 200 μm, FZ 100 μm, epi 100 μm, and epi 75 μm. These will include both n-type and p-type and for the p-type detectors both p-spray and p-stop isolation methods are specified. Detector geometries include pixel, long pixel, and strips. Once the sensors have been delivered and probed, a large fraction will be irradiated with proton, neutron, and mixed proton and neutron sources. A number of the irradiated strip-geometry sensors will be assembled into modules using CMS hybrids, and the SiBT group expects to test many of these in a beam study planned for the fall of 2010.

7. Acknowledgments

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