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Strip Detectors Processed on High-resistivity 6-inch Diameter Magnetic Czochralski Silicon (MCz-Si) Substrates

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***Abstract*—Tracking detectors for future high-luminosity particle physics experiments have to be simultaneously radiation hard and cost efficient. This paper describes processing and characterization of $p^+/n^-/n^+$ (n-type silicon bulk) detectors made of high-resistivity Magnetic Czochralski silicon (MCz-Si) substrates with 6-inch wafer diameter. The processing was carried out on a line used for large-scale production of sensors using standard fabrication methods, such as implanting polysilicon resistors to bias individual sensor strips. Special care was taken to avoid the creation of Thermal Donors (TD) during processing. The sensors have a full depletion voltage of 120 V and this is uniform over the investigated sensors. All of the leakage current densities were below 25 nA/cm² at 200 V bias voltage. A strip sensor with 768 channels was attached to readout electronics and tested in particle beam with a data acquisition (DAQ) similar to the system used by the CMS experiment at the CERN LHC. The test beam results show a signal-to-noise ratio greater than 40 for the test beam sensor.**

***Index Terms*—High energy physics, radiation hardness, silicon radiation sensors, strip detector**

I. Introduction

The performance of the CERN Large Hadron Collider (LHC) is gradually improving, enabling new particle physics discoveries. A major accelerator upgrade, boosting the luminosity by an order of magnitude, is planned to take place after about ten years of operation [1]. The concept known as high-luminosity LHC (HL-LHC) would result in an integrated fast hadron fluence of 1.5×10^{15} neq/cm² (1 MeV neutron equivalent fluence) for the innermost strip layers and about 1×10^{16} neq/cm² for the pixel layers in the silicon tracking systems [2,3]. The most important measure of the detector radiation hardness is the Charge Collection Efficiency (CCE), which is affected by the electric field distribution in the irradiated silicon, and the charge trapping by radiation-induced centers. At the expected maximum fluence of the strip sensor layers, the required full depletion voltage (V_{fd}) would be on the scale of thousand volts for a 300 µm thick oxygen-lean Float Zone silicon (Fz-Si) [4-6]. Moreover, when heavily irradiated the Fz-Si undergoes Space Charge Sign Inversion (SCSI) in which the maximum electric field shifts from the segmented front side towards the back plane of the $p^+/n^-/n^+$ (p on n, or n-type sensor) structured sensor. Thus, SCSI together with significant trapping makes traditional n-type Fz-Si strip sensors unusable in the high-luminosity environment [7].

Improving the radiation hardness of silicon detectors has been of interest in the scientific community for the past couple of decades. The CERN RD48 Collaboration reported diffusion oxygenation of Fz-Si to result in a lower increase of V_{fd} compared with the oxygen-free silicon materials when irradiated with charged particle. Very little or no effect of oxygenation had been observed when irradiated with neutrons [8]. RD48 developments were followed by the RD50 proposals for using naturally oxygen-rich high-resistivity Czochralski silicon (Cz-Si or MCz-Si if grown in a magnetic field) [9, 10] and device engineering in terms of $n^+/p^-/p^+$ (n on p, or p-type sensor) structure [11-13]. P-type detectors do not suffer from SCSI and thus the electric field maximum remains on the segmented side of the sensor. CCE is further enhanced by the Weighting Field (WF) effect [14, 15], which is based on the electrostatic coupling between the drifting charge and the sensing electrode. Thus, if the electric field E(x) is present at the segmented side of a position sensitive silicon detector, E(x) and thus CCE are largely increased.

The drawback of p-type devices is the more complex fabrication technology. This is due to the positive oxide charge of the dielectric layers on the detector. There are basically two methods to suppress the electron accumulation

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near the surface: p-spray and p-stop techniques. The p-spray method utilizes boron field implantation, which provides additional negative space charge near the surface and thus compensates the electron accumulation. The p-stop method involves a localized p^+ implant that terminates the surface inversion. Both methods, however, involve increased process complexity and, in addition, might lead to localized high electric fields, which increase the likelihood of early breakdowns [16].

During the past ten years, detectors made of high-resistivity Cz-Si and MCz-Si materials have been subjected to many studies [17], including electric field distribution analysis with the Transient Current Technique (TCT) method [18-21] and test beam measurements of full-size strip detectors [22]. Test beam measurements performed with CMS front-end electronics and data acquisition (DAQ) on MCz-Si detector irradiated to 1.1×10^{15} neq/cm^2 fluence revealed a 50% CCE and a signal-to-noise (SNR) ratio of more than ten. The finding was supported by TCT measurements, which showed a double-peak for the electric field distribution E(x) in MCz-Si sensors, suggesting that the electric field on the segmented side remaining strong even after heavy irradiation [23-25].

In this context, we report processing and characterization of MCz-Si detectors from 150 mm diameter wafers and manufactured on a fully automated, cassette-to-cassette process line capable of annual production of thousands of wafers.

II. Processing of MCz-Si detector

The 150 mm diameter n-type MCz silicon wafers with crystal orientation of <100> were provided by Okmetic Ltd. The nominal thickness of the single-sided polished wafers is 330 µm and the average resistivity mapped with four-point probing was about 2000 Ohm·cm. The interstitial oxygen concentration was measured, using the Fourier Transform Infrared Spectroscopy method defined in the standard ASTM F1188-93a [26], to be homogeneously $2.9\text{-}3.0\times10^{17}$ cm^{-3}.

The charge carrier recombination lifetime in the silicon substrates was studied by using µPCD (Microwave detected Photoconductive Decay) method [27, 28]. The lifetimes were mapped by Semilab WT85 scanning tool with a 2 mm × 2 mm raster, resulting in about 1800 data points. The measurements were carried out at high injection level, i.e. laser pulse excitation is much larger than the free carrier concentration caused by the doping. The measured wafers were passivated by thermally oxidized dry silicon dioxide. The histogram of lifetime data points is shown in Fig. 1.

The average value of lifetime is 3070 µs and it can be seen that after about 3300 µs the numbers of entries falls off and there are no entries above 3400 µs. This is because the measured lifetime, often called as effective lifetime, is a complex combination of surface recombination velocity and carrier recombination lifetime in the silicon bulk. In this case, with the given wafer thickness and surface recombination, it is impossible to measure effective lifetimes higher than 3400 µs due to the surface contribution.

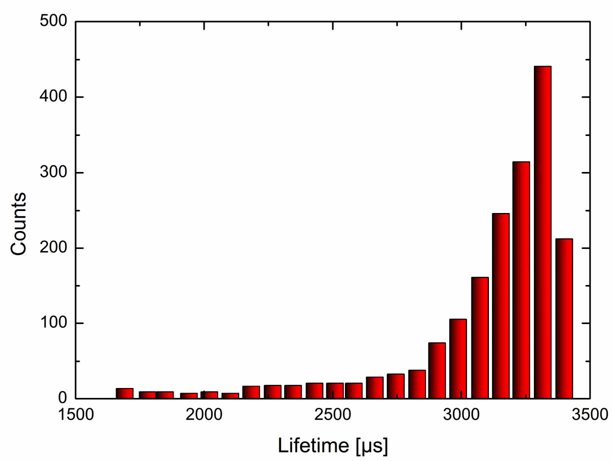

Fig. 1. Histogram of about 1800 lifetime measurement data points mapped over a thermally dry oxidized process monitor wafer.

The layouts used for the 6-inch wafer process were provided by the Helsinki Institute of Physics. The wafer contains four 3.87 × 3.76 cm^2 AC-coupled strip detectors, thirty-two 1 × 1 cm^2 AC-coupled mini-strip detectors and twenty-eight 0.5 × 0.5 cm^2 diodes. Figure 2 shows the 6-inch wafer layout and design details of the AC-coupled strip detector.

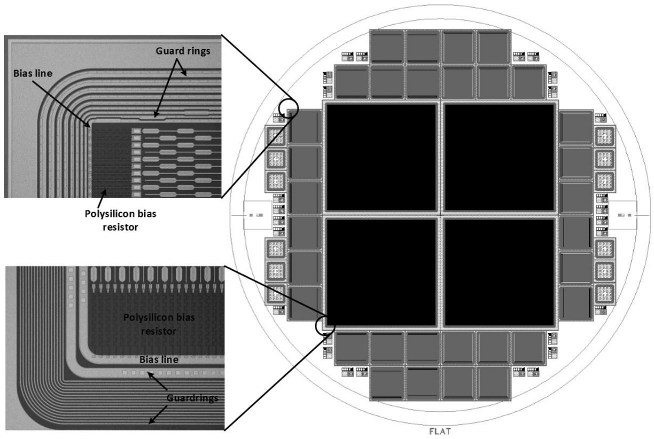

Fig. 2. The layout of the 6-inch wafer. The two insets on the left show the corners of AC-coupled strip detectors. All strips have 10 µm width but strip pitch varies from 50µm to 80 µm in different sensors. Strip electrodes are connected to a common bias ring through serpentine-layout polysilicon resistors. In the mini-strip sensors, the active areas are embraced by 6 guard rings with stepup pitches, while in the full-size strip sensors, 16 isometric narrow guard rings and one wide guard ring are implemented.

The wafer processing was performed at the Microelectronic Center of VTT (Technical Research Center of Finland). VTT has all equipment necessary for 150 mm wafer fabrication. Totally six MCz-Si wafers and two monitoring Fz-Si wafers were processed. A brief description of the process is graphically represented in Fig. 3. Frequently repeated routine steps such as wafer cleaning, photoresist depositions and strippings are excluded.

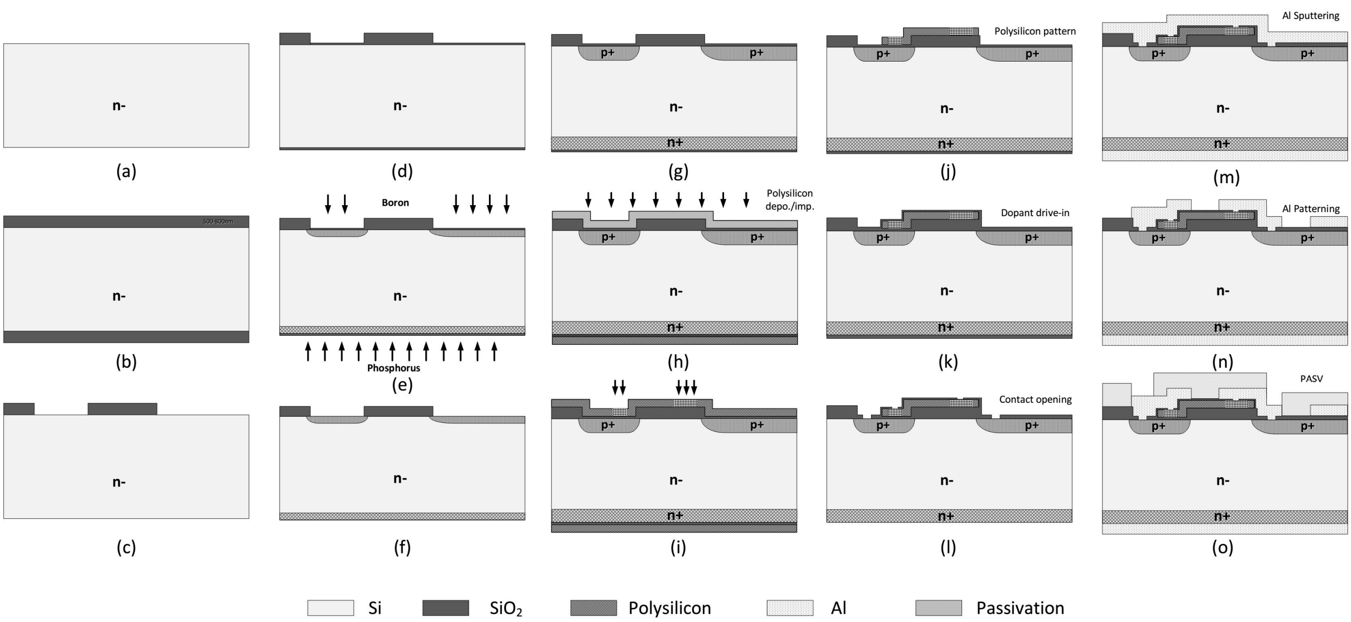

Fig. 3. Process sequence illustration of MCz-Si detectors.

The starting wafers (a) were thermally wet oxidized at 950 °C (b). Implantation windows were opened in the masking field oxide layer (c) and followed by the growth of a 70 nm screen oxide layer at 950 °C (d). Blank boron and phosphorous implantations were made on two sides of the wafer respectively through the screen oxide layer (e). After removing the damaged screen oxide layer (f), a 100 nm silicon dioxide layer was grown at 1050 °C as the strip coupling insulator (g). The implanted ions were simultaneously activated. A 500 nm polysilicon layer was deposited by LPCVD (Low Pressure Chemical Vapor Deposition) technology. The polysilicon layer was implanted with boron ions to adjust the target resistivity (h). An extra implantation with the high dose was then given to defined regions of polysilicon to achieve the low contact resistance between polysilicon and strip implants (i). After the reactive ion etching of polysilicon (j), the implanted ions in polysilicon were activated during a subsequent dry oxidation at 950 °C resulting in simultaneously designed strip insulator thickness of 150 nm (k). Contact windows were opened on polysilicon resistors and on desired regions on p^+ implants (l). Aluminum layers of 1 µm were sputtered on both sides of the wafer (m). The front side metal was patterned (n). The processing was ended with the plasma-enhanced chemical vapor deposition of the SiO_2 passivation at 300 °C followed by a furnace annealing at 350 °C in the forming gas ambient (o).

It is well known that the aggregation of oxygen atoms leads to a formation of electrically active defects, commonly referred to as the thermal donors (TDs). When processing n-type (p^+ segmentation on phosphorous doped bulk) MCz-Si detectors, the TD formation is generally harmful. TDs result in additional donor doping of the bulk and thus elevated the V_{fd}. The formation of TDs starts approximately at an annealing temperature of 400 °C and annihilation will take place at temperatures above 600 °C [29-34]. Thus, temperatures in the range of 400-600 °C were avoided after the last high temperature process step.

III. Electrical Characterization

Electrical characterization was performed on the large 3.87 × 3.76 cm^2 strip sensors, 1 × 1 cm^2 mini-sensors, and 0.5 × 0.5 cm^2 diodes using a probe station in a dark chamber. The dimensions refer to active areas enclosed by the guard rings, which are grounded during the measurements. The Capacitance-Voltage (C-V) measurement was performed with an Agilent 4263B LCR meter with a 10 kHz 500 mV signal superimposed on a DC level. Previous measurements of the open loop capacitance, including the capacitance induced by the AC-coupling of the high voltage bias, were subtracted from the measurement data. Figure 4 shows C-V curves of mini-sensors. Totally three processed MCz-Si wafers were investigated and the data points and error bars were constructed from 20 C-V measurements on each wafer. The y-axis error bars are standard deviations of the average values.

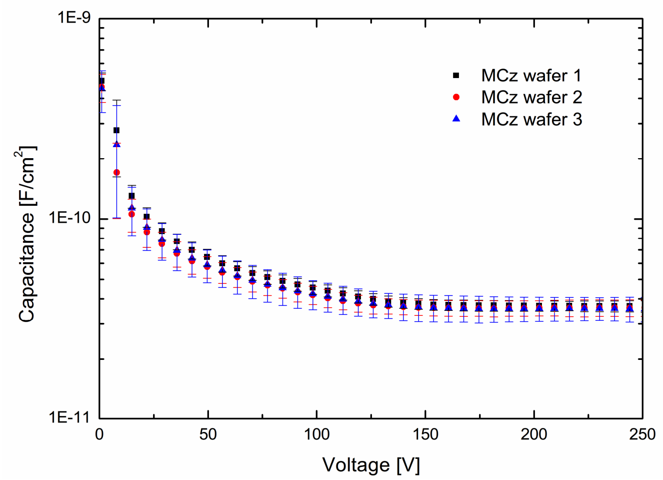

Fig 4. C-V curves of 1 cm^2 mini-sensors. The measurement was performed on three wafers and 20 mini-sensors were measured on each wafer. The V_{fd} is determined from the point where the saturation of capacitance is reached.

The specific capacitance at 250 V for the investigated mini-sensors on the three wafers are 37.2+/-0.9, 36.7+/-2.6 and 37.9+/-1.3 pF/cm^2 respectively. Figure 4 shows that all detectors reach the capacitance saturation and V_{fd} to be about 140-150 V.

During the Current-Voltage (I-V) measurement, the bias voltage was fed from the backside of the chip and current was read from the common bias line while the innermost guard ring was kept at the ground potential. A summary of the leakage current measurements is given in Fig. 5.

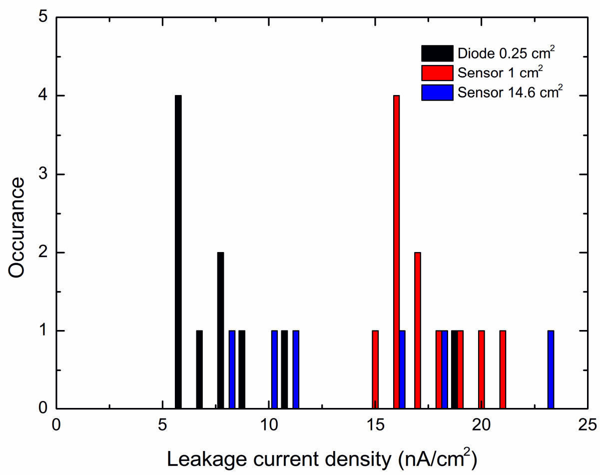

Fig. 5. Histogram of leakage current density at 200 V reverse bias. The measurement was performed at the room temperature.

The polysilicon resistance was monitored during the process and in the characterization phase. The process monitor wafers were oxidized blank wafers with 500 nm of polysilicon on top of the oxide layer. Wafers were sent for implantation with various doses at a constant energy of 30 keV. The polysilicon sheet resistance was measured using a four-probe method and the results, shown in Fig. 6(a), can be used to find the proper implantation parameters in the process. Figure 6(b) shows the values of polysilicon resistors on all process wafers. Most of the resistances fall in the 350 to 500 kOhm range. The wafers MCz1 and MCz5 were not passivated when the measurement was performed, which might explain why they have a larger variation than the others.

IV. Test Beam Results

One 3.87 × 3.76 cm^2 sensor with 50 µm strip pitch and 768 channels was selected for a test beam measurement. The full depletion voltage for this sensor was about 120 V and the leakage current from the guard ring limited area was 120 nA at V_{fd} and 290 nA at 300 V. The capacitance for the area delimited by the guard ring was 470 pF at 120 V. The sensor was first glued on a supporting PCB and then wire bonded to a CMS APV25 read-out board [35] using a pitch adapter (aluminum traces on a glass substrate) fabricated at the Micronova Centre. After the module assembly, the leakage current was measured from the bias rails of the supporting PCB resulting in 220 nA at 120 V and 300 nA at 300 V. The physical thickness of the sensor was measured with a micrometer to be 330 µm. C-V measurements made on diodes with 0.5 cm × 0.5 cm area, limited by a grounded guard ring, resulted in capacitances of 8.2 pF, which corresponds to the effective sensor thickness (fraction of silicon thickness where electric field enables charge drift transportation) of about 315 µm.

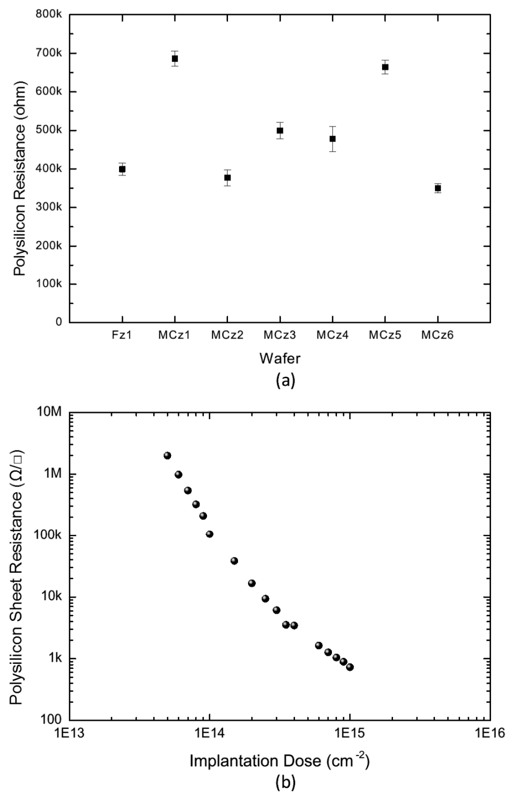

Fig. 6. The poly-silicon resistance monitored on (a) the monitor wafers and (b) the process wafers

The test beam experiment was carried out in May 2012 at the CERN H2 beam line utilizing a 220 GeV muon beam from the SPS accelerator. A beam telescope, consisting of 8 reference detectors inside a Peltier cooled box [36, 37], was used to track particles passing through the DUTs. The reference detector modules are made of Fz-Si sensors produced by Hamamatsu Photonics K.K (HPK) for the D0 experiment at Fermi National Accelerator Laboratory (FNAL). The full depletion voltage of the reference detectors is about 100 V extracted from C-V measurements. The capacitance measured from the sensor active area (9.8 cm × 3.8 cm) is 1.38 nF corresponding to the effective thickness of about 290 µm. The physical thickness of the reference detectors is 320 µm ± 20 µm as reported with other technical details in [38]. During the data taking the reference detectors were biased with 150 V.

The data acquisition (DAQ) and off-line analysis of the telescope are based on the CMS experiment software and analysis framework [39]. The output of the DAQ is expressed in analog to digital converter (ADC) counts. For the conversion from ADC units to electric charge we assume that the non-irradiated reference planes operate with 100% relative CCE and the most probable value of the collected charge is on average 40+/-0.8 ADC counts. Thus, taking into account minimum ionizing particle ionization in silicon (80 electron/hole pairs per micron), one ADC count corresponds to about 600 e-/0.1 fF charge. Figure 7 shows signal distributions of MCz-Si (DUT) and one reference plane, showing highest signal among the eight planes. The data was recorded during the same data taking session and both sensors were biased with 150 V. The temperature of the cold box during the data taking was set to -20 °C.

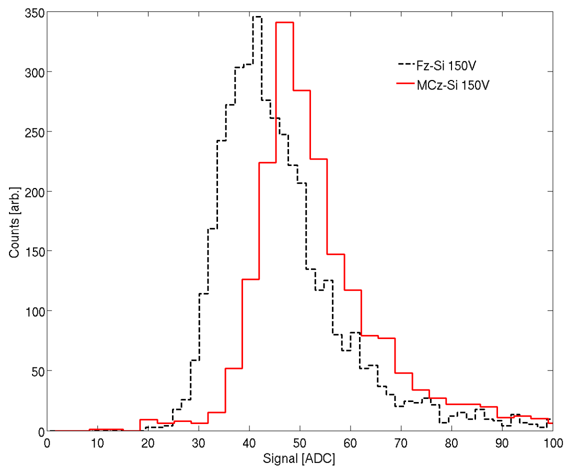

Fig. 7. Signal distributions of MCz-Si sensor under the investigation (blue) and one of the telescope reference planes (red). The distributions consist of about 2000 reconstructed events (data run 4926) seen by all planes of the telescope. One ADC count corresponds to about 600 e⁻/0.1 fF charge.

The most probable values (MPV) of signal are 45 ADC and 41 ADC for DUT and reference sensors, respectively. The larger signal from the DUT is expected due to an approximately 10% higher effective thickness compared with the reference detector (315 µm vs. 290 µm). The strip noise distribution of DUT recorded during the same data taking run is presented in Fig. 8.

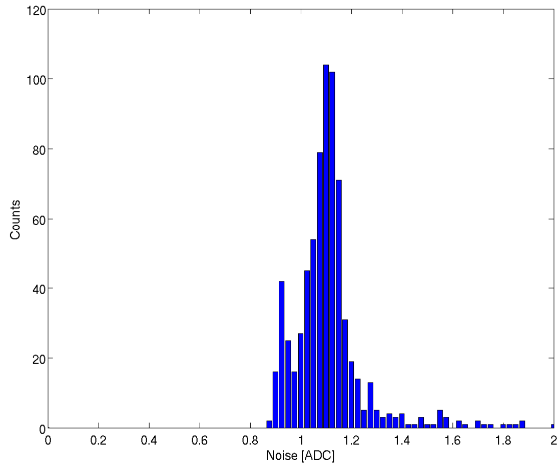

Fig. 8. The strip noise distribution for the MCz-Si detector used in the test beam. The data was recorded during run 4926.

The MPV of the noise distribution is 1.1 ADC counts, which would result in a signal-to-noise (SNR) ratio of about 41. Typical noise in reference planes is about 1.5 ADC. The noise seen in the MCz-Si DUT and the reference planes is, however, not comparable due to the different strip lengths. The resolution of the DUT was extracted from 35 data taking runs with different bias voltages 120-350 V. The sensor resolution is plotted in Fig. 9.

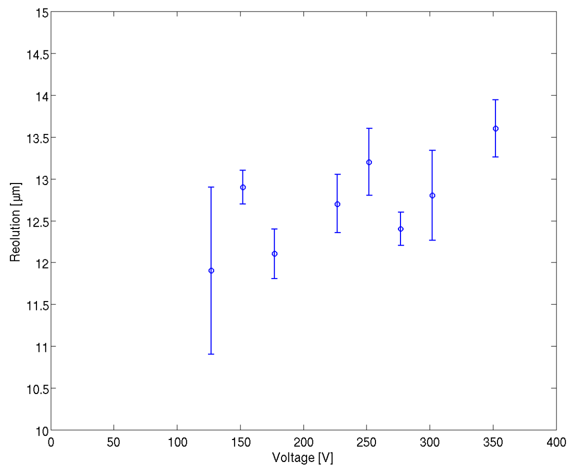

Fig. 9. Resolutions of DUT at different bias voltages.

As it can be seen in Fig. 9, the resolution of MCz-Si DUT is between 12 and 14 µm at 120-350 V. The digital resolution (all charge collected in a single strip) would be 50 µm/√12 = 14.4 µm for a 50 µm pitch sensor. This is slightly higher than what was observed in the test beam. In fact, the data analysis reveals that 92% of the signal in DUT is collected by the leading strip, while the same number is about 70% for the reference detectors. This is consistent with the sensor designs: The D0 reference sensors contain floating intermediate strips intended to improve the resolution by charge sharing between the channels.

V. Conclusion

A set of strip sensors was made on 6-inch diameter high-resistivity MCz-Si wafers by using industrially feasible, largely automated and robust processing. The pre-processing material quality characterization shows very good homogeneity in terms of resistivity, oxygen concentration, and minority carrier lifetime. This is achieved by applying a magnetic field during the Czocharalski method crystal growth. Mechanical perturbations and oscillations in the molten silicon can be controlled by a magnetic field, which allows better tuning of the concentration of the oxygen and dopant impurities dissolving from the crucible. The full depletion voltage, extracted from C-V data, was found to be in range of 120-140 V in all devices produced in this batch. This corresponds to an effective resistivity of about 2.5-2.8 kOhm·cm of phosphorous doped n-type MCz-Si material. For comparison, in our earlier studies we have used MCz-Si material with resistivities ranging from 0.9-1.1 kOhm·cm with corresponding V_{fd} of about 300-350 V [9, 22, 25]. The leakage current density was less than 25 nA/cm^2 measured from different size sensors at 200 V bias, i.e., clearly above the full depletion voltage. This is due to the high minority carrier lifetime (>3 ms) that was maintained during the whole processing cycle.

The concentration of interstitial oxygen was found to be homogeneous and in the range of 2.9-3.0×10^{17} cm^{-3}, which is slightly less than 5.0×10^{17} cm^{-3}, reported earlier from MCz-Si material originating from different crystal [40]. It should be noted that MCz-Si materials used for particle detector applications have intentionally lower oxygen concentration than typically found in Czochralski method grown silicon used by microelectronics industry. During the processing, special care was taken to avoid the temperature range associated with the formation of thermal donors. The presence of hydrogen has earlier been speculated to enhance the TD formation [41]. Hydrogen was present in large quantity in our process during e.g. polysilicon deposition from silane (Si_3H_4), PECVD passivation layer deposition and during the sintering in forming gas. Nevertheless, our detector property measurements do not rule in or rule out the influence of hydrogen during the sensor processing.

The beam test results show that the MCz-Si sensor has performance comparable with commercially mass produced strip sensors delivered earlier for a large-scale particle physics experiment. The signal-to-noise ratio of MCz-Si sensors exceeds 40 when biased with 150 V, i.e., the same operating voltage that was applied to the Fz-Si reference sensors. The noise performance of MCz-Si DUT and reference sensors, with 2.5 times longer strips, are not directly comparable, because the noise in our test beam setup is largely dominated by strip capacitance. The design of the sensors is very robust, 3.8 cm long strips with 50 and 80 µm pitches surrounded by a simple guard-ring structure. The choice of these strip parameters is mainly due to the foreseen fivefold luminosity in the HL-LHC, which consequently results in undesirable channel occupancy. For instance, in the current CMS experiment the strip sensors with lowest granularity have strip length of 20 cm (two daisy chained large sensors) and 240 µm pitch [42]. The resolution of MCz-Si DUT sensor is very close to the digital/binary resolution of the given segmentation. In unirradiated sensors, more than 90% of the signal charge is collected by the channel closest to the impact point, i.e. the charge sharing between the channels is almost negligible. This results in a lower resolution when compared with the strip sensors having e.g. intermediate strips to enhance the charge sharing. In the high-luminosity environment, the resolution improvement by utilization of charge sharing between the channels is, however, largely limited because of the trapping by radiation defects. Taking into account the drift velocity saturation in the electric field, the effective charge collection distance will be in the order of strip pitch within given trapping time constant.

The Charge Collection Efficiency (CCE) is a complex product of the electric field distribution E(x) and trapping in the heavily irradiated silicon. According to the existing knowledge, the trapping is largely independent of the silicon material properties. Thus, the only way to improve the radiation-hardness is to optimize E(x), and elevating the oxygen concentration has been the only successfully demonstrated method to date. The essential difference between the MCz-Si and Fz-Si is the oxygen concentration. It is possible to enhance the oxygen concentration in Fz-Si by prolonged high temperature oxygen diffusion, which might last up to hundreds of hours. The compromise is, however, increased processing costs, limited number of qualified processing vendors as well as the risk of induced contamination. In summary, strip detectors made of 6-inch diameter high-resistivity MCz-Si wafers stand as mass production feasible and cost-effective candidate for future HEP experiments requiring ultimate radiation hardness.

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