VII

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Test beam results of a proton irradiated Czochralski silicon strip detector

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Abstract

We report on test beam results obtained with a 32.5 cm^2 microstrip detector processed on an n-type 380 μm thick magnetic Czochralski (MCZ) grown silicon substrate with 1200 Ωcm effective resistivity. The full depletion voltage of the as-processed detector was 420 V with a leakage current of 2 μA. The AC coupled detector had 1024 p$^+$ strips, 10 μm by width and 6.154 cm by length with a pitch of 50 μm. The detector was irradiated with 10 MeV protons to 1.6×10^{14} 1 MeV neutron equivalent fluence and annealed for 345 days at room temperature. The post-irradiation full depletion voltage of the detector was 225 V. The leakage current at the full depletion measured at −10 °C was 261 μA. The beam tests were carried out at the CERN H$_2$ area using a Silicon Beam Telescope, which consists of pairs of horizontal and vertical position sensitive silicon detectors. This telescope determines the tracks of incoming particles and hence provides a reference measurement for the detector characterization. In the beam test an average signal to noise ratio of 3 with a spatial resolution of 20 μm and a particle detection efficiency of 36% were measured. These results show that the MCZ device detected particles, which encourages further investigations of MCZ silicon as a detector material. The poor performance of the MCZ detector may be explained by the problems observed in the reference telescope.

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Keywords: Si particle detectors; Radiation hardness; Material engineering

1. Introduction

In high-energy physics (HEP) silicon strip detectors have been used in particle tracking applications since the 1980s, but the Large Hadron Collider (LHC) experiments are the first ones, where these detectors are used on a large scale and under severe radiation conditions [1,2]. Silicon strip detectors provide excellent spatial resolution while being cost-effective due to well-established manufacturing technology.

Particle radiation causes crystallographic defects in the silicon material that deteriorate the detector performance by inducing generation-recombination centers that result in increased detector leakage current [3]. Additionally, crystallographic defects compensate the initial space charge of silicon [4], finally changing the sign of the space charge [5].

Experiments have shown that the radiation tolerance of particle detectors is improved if the oxygen concentration in the silicon crystal exceeds the concentration typically met in silicon wafers grown with the float zone (FZ) method [6,7]. Recent developments in crystal growth technology of Czochralski silicon (Cz–Si) have enabled production of high oxygen concentration Cz–Si wafers with sufficiently high resistivity for detector applications [8]. Since the Cz–Si is a basic raw material in the microelectronics industry, it is abundantly available even as large wafers. Thus it is a promising material candidate for future large-scale HEP experiments.

We tested the detection performance of a proton-irradiated strip detector processed on a silicon wafer grown by the magnetic Czochralski (MCZ) method

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[9,10]. The MCZ method has several advantages, e.g., extending the controllable concentration range of oxygen dissolving from the silica crucible during the crystal growth. In the MCZ method the ingot is grown in a magnetic field, which is used to dampen the oscillations in the silicon melt [11]. The applied field creates an electric current distribution and an induced magnetic field in the electrically conducting silicon melt. This produces a Lorentz force that influences the flow and reduces the amplitude of the melt fluctuations [10].

2. Detector processing, irradiation and annealing

The detector was fabricated using a simple four mask level process at the Microelectronics Centre of the Helsinki University of Technology. The starting material for the detector was a 4″ single-side-polished 380 μm-thick ⟨1 0 0⟩ Cz–Si wafer grown with the MCZ method by Okmetic Ltd, Finland. The nominal wafer resistivity prior to processing was 900 Ωcm and the oxygen concentration was less than 10 ppma. The detector fabrication process contained two thermal oxidations, two ion implantations, and three sputter depositions. A detailed process description is presented in Ref. [12].

In the strip detector design, the width of one p^+-strip was 10 μm, the strip length was 6.159 cm, and the strip pitch was 50 μm. The number of strips was 1024, resulting in a total detector area of 32.5 cm^2. A 200 nm thick SiO_2 dielectric insulator between the p^+-implant and the strip metallization was made by dry oxidation. In order to reversely bias the p^+-strips and to deplete the n-type bulk from charge carriers, a tungsten nitride (WN_x) thin-film resistor (900 kΩ ± 5%) was processed between each strip and the common bias line. In addition, a structure of five guard rings surrounded the active detector area.

For reference purposes, test diodes were fabricated with essentially the same process parameters. However, the process steps required for bias resistors formation were not performed to the test diode wafers. The p^+ implanted area of the diodes was 6/6 mm. Two guard rings surrounded the active area.

After processing, the detector and the test diodes were characterized by means of current–voltage (*I–V*) and capacitance–voltage (*C–V*) measurements. The *I–V* and *C–V* measurements were carried out up to 1000 V without observing electrical breakdown. The MCZ detector was depleted at 420 V prior to irradiation. The leakage current at full depletion, measured at room temperature (22 °C ± 5%), was 2.3 μA, which is compatible with the requirements of most HEP experiments, e.g. CMS [1].

The detector and the reference diodes were irradiated with 10 MeV protons at the Jyväskylä University Accelerator Laboratory. The test diodes were glued with photoresist to ceramic supports, and for the detector, a customized sample holder was designed and constructed in order to ensure homogenous irradiation. The samples were placed inside a vacuum chamber at the end of the Radiation Effects Facility (RADEF) beam line [13], where the temperature was maintained at −10 ± 1 °C during the irradiation.

The detector was irradiated with 3.8×10^{13} protons/cm^2 corresponding to a 1.6×10^{14} 1 MeV neutrons/cm^2 equivalent dose that was calculated using a hardness factor of 4.32 for 10 MeV protons [14,15]. The test diodes were irradiated to several different doses.

The *I–V* and *C–V* measurements of the irradiated strip detector and reference diodes were performed at the University of Karlsruhe, Germany, using a probe station equipped with a vacuum cold chuck [16]. The measurement temperature was −10 ± 1 °C and the frequency of the capacitance measurement was 10 kHz. During the characterization, the outermost guard ring of the strip detector multi-guard ring structure was grounded, while this guard ring was left floating during the test diode measurements.

The depletion voltage was measured to be 225 V with a leakage current of 261 μA [17]. Because the IV measurements were performed at different temperatures, the leakage current values were made comparable by using the temperature conversion equation [6,18]

$$I(T) = I(T_{\mathrm{m}})\left(\frac{T}{T_{\mathrm{m}}}\right)^{2} \mathrm{e}^{-E_{\mathrm{g}}/2k_{\mathrm{B}}\left(1/T-1/T_{\mathrm{m}}\right)}, \tag{1}$$

where T is the comparison temperature, T_{m} is the measurement temperature, E_{g} is the bandgap of silicon (1.12 eV) and k_{B} is Boltzmann's constant. Using Eq. (1), the leakage current of the irradiated detector at room temperature (22 °C) was calculated to be 4.8 mA. It is worth observing that the depletion voltage of the MCZ detector after the irradiation was approximately half of the pre-irradiation value. This is comparable to the results obtained in Ref. [19], which indicate that Cz–Si pin-diodes are less sensitive to changes in depletion voltage than standard FZ silicon or diffusion oxygenated FZ silicon pin-diodes. Even after a 5×10^{14} 1-MeV neutrons/cm^2 equivalent dose the full depletion voltage did not exceed its initial value.

After the *C–V*- and *I–V*-characterization, the MCZ detector was stored 345 days at room temperature. According to the Arrhenius relation, this corresponds to a period of 60–70 min at 80 °C [6]. The standard parameterization of the full depletion voltage as a function of irradiation dose, annealing time, and temperature, might not be valid for the MCZ material. Hence, an irradiated diode (1.6×10^{14} 1 MeV neutrons/cm^2 equivalent dose) was used to verify the annealing behavior. Fig. 1 shows the evolution of the effective doping concentration as a function of annealing time at 80 °C. According to this measurement, the effective doping concentration exhibits a minimum after 60–80 min of annealing at 80 °C. Beyond 80 min, the beneficial annealing turns into reverse annealing. This means that the MCZ detector had approximately reached the limit of reverse annealing after being stored for a year at room temperature. It also means that the

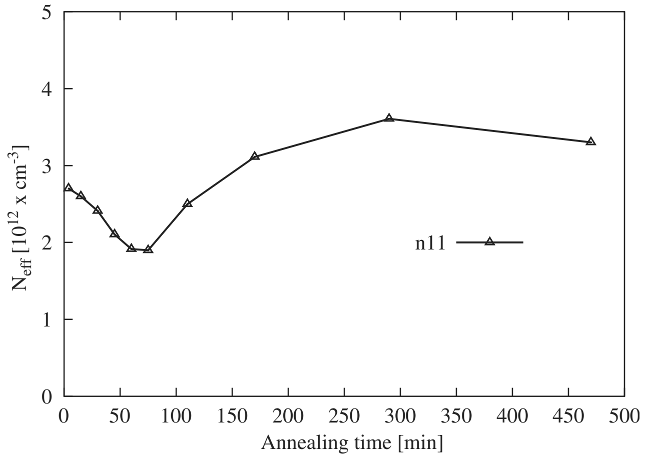

Fig. 1. Annealing curve of a reference test diode irradiated to 1.6×10^{14} 1 MeV neutrons/cm^2 equivalent fluence as measured by CV.

depletion voltage and the leakage current of the device were at their minimum at the time of the beam test.

3. Experimental setup and data analysis

The MCZ detector was characterized in a test beam experiment at the CERN H2 experimental area using 225 GeV muons. A Silicon Beam Telescope [20] that determines the tracks of the incoming particles was used to provide a reference measurement. The telescope consisted of six single-sided FZ silicon detectors bonded to a hybrid containing eight 128-channel VA1 readout chips (Ideas ASA, Norway) [21]. The detectors were installed as three pairs orthogonal to the beam axis. Each pair consisted of one detector with strips positioned vertically and one with strips positioned horizontally. The middle horizontal reference plane was of the same design as the MCZ detector. The other reference planes were as described in Ref. [20] with a strip pitch of 55 μm and a strip width of 14 μm resulting in a total detector area of $5.6\times5.6\,\mathrm{cm}^2$. The system trigger was provided by two standard plastic scintillators attached to photo-multiplier tubes mounted before the first and after the last detector along the beam. The MCZ detector was installed as a vertical plane after the first pair of reference detectors and it had the same readout electronics as the reference planes. The detector was kept at −17 °C with the relative humidity being less than 30%. The bias voltage of the detector was set to 350 V to clearly exceed the 225 V full depletion voltage measured prior to annealing. The readout of all detectors was realized with a commercially available 8-channel VME ADC module (SIS3300, Struck Innovative Systeme GmbH, Germany) [22] and a PC Linux-based Data Acquisition System (DAQ) realized with C++-code using object-oriented techniques [23].

The clustering was done in two phases; first in the DAQ software and then in the offline analysis. The following notations are used: R = raw data of a strip, P = pedestal, i.e., long-term average of R, N = noise, i.e., long-term standard deviation of R, $S = R - P$ = signal of a strip. For each strip, the long-term average P was modeled online and the N was calculated between each particle spill [23]. Since common mode noise was assumed to be small, it was left out from the N calculation.

In the online clustering, the strip was declared a 'central strip' if it satisfied the central strip condition: $S > N\times$ constant. If the consecutive strip also satisfied the condition, it was added to the cluster and this process continued until the central strip condition no longer was satisfied. Then one strip adjacent to the cluster on each side of it was added to the cluster. The constant value was determined experimentally for all planes. For the MCZ detector it was 2.1. This value was chosen in order not to cut any signal, while still ensuring proper clustering. Only the cluster information was saved, i.e., the position, the signal, the noise and the pedestal for every strip participating in the cluster. If a noisy or dead strip [23] was part of the cluster, the cluster was discarded. In addition, only clusters containing no more than 10 strips were saved. In the offline analysis the cluster candidate was built from the clusters in the data file and a cluster size cut was made. Clusters wider than seven strips were rejected and each reference detector was allowed to have at most 20 clusters in order to reconstruct a track.

The exact position of the hit corresponding to the cluster was calculated by applying the η-algorithm [24] to the pair of adjacent strips with the largest sum of charge. The track reconstruction was carried out as a sum-of-least-squares fit in three dimensions, and a hit from all six reference detectors was required. The applied χ^2 cut for two degrees of freedom was set to 15 in order not to reject real tracks.

The digital resolution value, $\mathrm{pitch}/\sqrt{12} = 55/\sqrt{12} = 16\,\mu\mathrm{m}$, was used for all reference detectors. The system was aligned by introducing corrections manually for one translational and one rotational degree of freedom until the residual plots were qualitatively similar.

For the MCZ detector, the hit residuals were calculated with tracks interpolated to the front surface of the detector. A sum of a constant and a Gaussian was fitted to the residual distribution to obtain the sigma of the residuals.

The spatial resolution of the MCZ detector σ_{MCZ} was obtained according to the method described in Ref. [25] by subtracting the uncertainty of the impact point from the sigma of the residuals. This uncertainty was calculated to be 12.9 μm at the installation point of the MCZ detector.

The detection efficiency of the MCZ detector was calculated as follows: the number of tracks, for which a cluster with a residual smaller than $\pm2\sigma_{\mathrm{MCZ}} = 40\,\mu\mathrm{m}$ was observed, was divided by the total number of tracks. Inoperative chips in the reference detectors caused an inhomogeneous track profile. To correct for this, the detection efficiency was calculated for bins of the same width as the MCZ detector pitch. These bins were averaged after background subtraction. The background was calculated for each bin as follows: in one-track events all the hits in each bin were summed and this value was divided by the total number of events recorded in this bin. The result was the average number of clusters in each bin.

To define the signal-to-noise ratio (S/N) of the MCZ detector, clusters with residuals smaller than $\pm 2\sigma_{\mathrm{MCZ}} = 40\,\mu\mathrm{m}$ were considered. The signal was obtained by summing signals from all strips in the cluster, whereas the noise was obtained as the quadratic average noise of these strips.

4. Results and discussion

A spatial resolution of 19 μm was measured for the reference detectors, while the spatial resolution of the MCZ detector σ_{MCZ} was 20 μm. These values are worse than the expected resolutions (pitch/$\sqrt{12}$) 14 μm for 50 μm pitch and 16 μm for 55 μm pitch. The resolution degradation of the MCZ detector was possibly due to radiation-induced surface and dielectric damage that increase the charge division between neighboring strips. The measured noise correlation was 20.4% for adjacent strips and 18.2% for next-to-adjacent strips. In addition, the z-coordinate (along the beam axis) of the reference detectors contained an uncertainty on the order of one mm that might have an effect of a few microns on the resolution values.

An average particle detection efficiency of 36.0% for all reconstructed tracks was measured for the MCZ detector. The detection efficiency varied with position (Fig. 2). In some large areas in the center of the detector, the particle detection efficiency was 20–30%, whereas in the edge regions values higher than 50% were frequent. The low efficiency might be partly explained by the clustering algorithm. It was required that a strip belongs to a cluster only if it meets the criteria of $2.1 * N$. Therefore, with a S/N close to the cut level, all of the clusters were rejected. In addition, all of the clusters with a noisy or a dead strip were rejected. The shape of the η-distribution also supports the assumption that there was a large bias in the cluster selection.

The numerical ratio of signal clusters to background clusters whose residuals were smaller than $\pm 2\sigma_{\mathrm{MCZ}}$ was 12.7. It was found that 92.5% of the clusters consisted of three strips (the signal strip and its two neighboring strips), 4.7% of four strips, and 2.7% of five or more strips. The average S/N of the MCZ detector was 3. The S/N varied as a function of hit position being mostly between 2 and 5 (Fig. 3).

For comparison, the S/N values for the reference planes are presented in Table 1. Especially reference plane number three is interesting, since its design was the same as that of the MCZ detector.

The high noise in the telescope partially explains the low S/N values. In addition, most of the reference tracks hit the MCZ detector in regions with low efficiency. The S/N and resolution values were not corrected for this inhomogeneous track profile. Therefore the reported values are probably underestimated. Furthermore, the shaping time of the readout chip VA1 (1 μs) is considerably longer than that in the LHC-like readout ASICs (25 ns). As presented in Refs. [26,27] the shaping time affects the shot noise (a long shaping time increases the shot noise). Especially for the irradiated detectors, this can be detrimental, since the

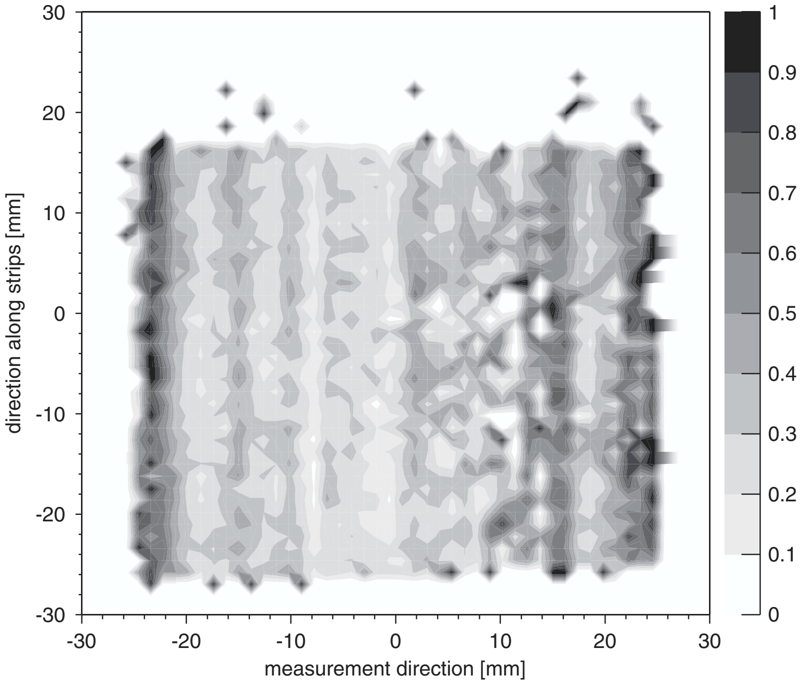

Fig. 2. The MCZ detector efficiency as a function of hit position.

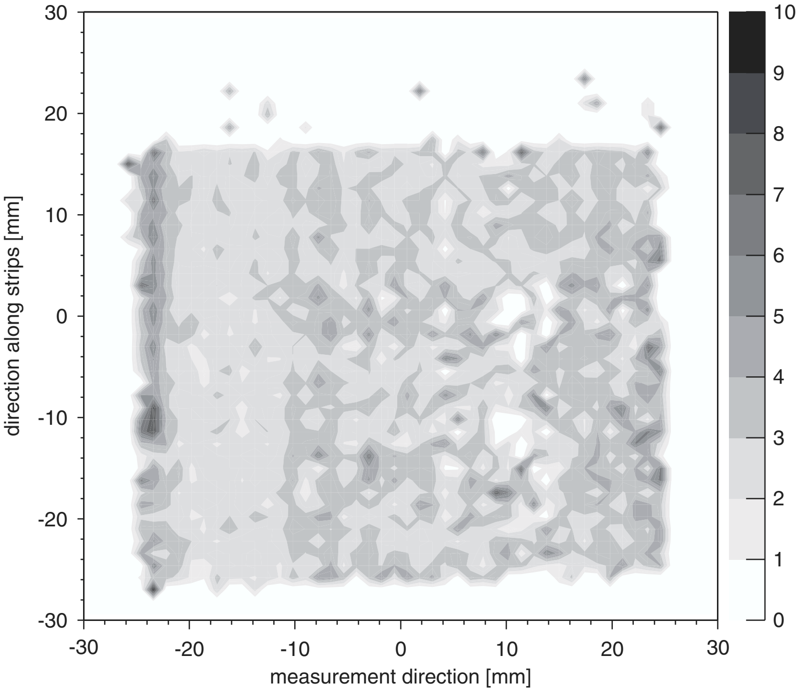

Fig. 3. S/N of the MCZ detector as a function of hit position.

Table 1
S/N values for the reference detector planes

Detector	Plane 1	Plane 2	Plane 3	Plane 4	Plane 5	Plane 6
S/N	7	10.6	7.5	2.9	14.2	24.9

reverse current shot noise is much higher than it is in non-irradiated detectors. Therefore, future work will concentrate on investigating the MCZ detector parameters with LHC-like fast shaping time electronics.

5. Conclusions

A 32.5 cm^2 large-area strip detector was processed on n-type MCZ silicon material. The detector was characterized using C–V- and I–V-methods before and after irradiation to 1.6×10^{14} 1 MeV neutron equivalent fluence. After the irradiation, the detector was annealed for 345 days at room temperature and characterized in a testbeam experiment using 225 GeV muons. In this beam test an average S/N of 3 with a spatial resolution of 20 μm and a particle detection efficiency of 36% were measured. This performance is much deteriorated compared to the results obtained in a previous beam test with a non-irradiated MCZ silicon strip detector with the same design [28], where a S/N of 10 and resolution of 10 μm were measured. However, the presented results show that the MCZ device detected particles, which encourages further investigations of MCZ silicon as a detector material. The poor performance of the MCZ detector may be explained by problems observed in the reference telescope.

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