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$p^+/n^-/n^+$ Cz-Si Detectors Processed on p-Type Boron-Doped Substrates With Thermal Donor Induced Space Charge Sign Inversion

J. Härkönen, E. Tuovinen, P. Luukka, E. Tuominen, and Z. Li

***Abstract*—We have processed pad detectors on high-resistivity p-type Cz-Si wafers. The resistivity of the boron-doped silicon is approximately 1.8 kΩ cm after the crystal growth. The detector processing was carried out using the common procedure for standard n-type wafers, to produce $p^+/p/p^-/n^+$ detector structures. During the last process step, i.e., sintering of aluminum electrode, the p-type bulk was turned to n-type through generation of thermal donors (TD). This way, high oxygen concentration $p^+/n^-/n^+$ Cz-Si detectors were realized with low temperature process. The full depletion voltage of detectors could be tailored between wide range from 30 V up to close 1000 V by changing heat treatment at 400 °C–450 °C duration from 20 to 80 min. The space charge sign inversion (SCSI) in the TD generated devices (from $p^+/p^-/n^+$ to $p^+/n^-(\text{inverted})/n^+$) has been verified by transient current technique measurements. The detectors show very small increase of full depletion voltage after irradiations with 24 GeV/c protons up to $5 \star 10^{14}$ p/cm^2.**

***Index Terms*—Czochralski silicon, particle detector, thermal donor.**

I. Introduction

The Silicon detectors in high-energy physics (HEP) experiments are exposed to very hostile radiation environments. High particle fluences result in irreversible deterioration of the detectors, leading to crystallographic defects which, in turn, induce generation-recombination centers in the silicon material. These lead to increased leakage currents and elevated depletion voltages. Deliberate introduction of oxygen into the silicon material has been experimentally proven to alter the formation of electrically active radiation induced defect centers and, thus, improves the electrical properties of silicon detectors used in harsh radiation environments [1]–[3].

The sensors used in particle tracking systems must be fully depleted at reasonably low operating voltages, typically less than 100 V. Therefore, the silicon sensors have traditionally been fabricated on wafers made by the float zone (Fz-Si) crystal growth technique. The Fz-Si technique ensures high-purity and sufficiently defect-free silicon crystals that are the basic requirements for producing high-resistivity silicon substrates for detector applications [4]. On the other hand, Fz-Si characteristically has a low oxygen concentration because of the contact-less, crucible-free crystal growth technique. Low oxygen concentration in Fz-Si is, however, a drawback for radiation hardness.

The Czochralski (Cz-Si) crystal growth method enables the production of silicon wafers with sufficiently high resistivity and with well-controlled oxygen concentration. Although Cz-Si is the basic raw material for microelectronics industry, high-resistivity (> 1 kΩcm) Cz-Si wafers suitable for detector fabrication have become available only recently. Particle detectors made of phosphorous-doped n-type Cz-Si having resistivity of 1 kΩcm have been fabricated [5] and tested as part of various irradiation campaigns within the framework of CERN RD50 collaboration [6], [7]. The n-type Cz-Si devices require about 300 V reverse bias for full depletion. An interesting feature of Cz-Si is the formation of thermal donors (TDs) at certain temperatures. When the TDs are generated in boron-doped Cz-Si, the p-type bulk will be compensated and eventually turn to n-type. With this method, it is possible to fabricate, with low cost and low thermal budget process, high oxygen concentration detectors that can be depleted with voltages less than 100 V. Furthermore, there are clues that the charge collection efficiency in very heavily irradiated detectors might be better in p-type detectors than in n-type [8]. Possibly, the better charge collection efficiency is related to a difference in defect kinetics in p-type material, although the authors of [8] and others would argue that the primary difference comes from collecting electrons rather than holes on the finely segmented read-out side. However, this does give a reason to study material where the only donors are oxygen related complexes.

II. High Resistivity Cz-Si as Detector Material

During the crystal growth of high-resistivity Cz-Si, oxygen is dissolved into silicon from the quartz crucible. A major part of the oxygen is dissolved as silicon monoxide and is flushed away by argon gas. Furthermore, the resulting oxygen concentration depends on the velocity of the silicon melt flow as well as on the rate of oxygen evaporation from the surface of the melt. All these parameters can be influenced in order to achieve the desired oxygen concentration in the silicon ingot. Application of a magnetic field is particularly effective way to moderate and control the melt flow since the silicon melt is an electrically

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J. Härkönen, E. Tuovinen, P. Luukka, and E. Tuominen are with the Helsinki University, Helsinki Institute of Physics, FIN-00014 Helsinki, Finland (e-mail: jaakko.haerkoenen@cern.ch).

Z. Li is with the Brookhaven National Laboratory, Upton, NY 11973-5000 USA (e-mail: zhengl@bnl.gov).

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conductive liquid. For processing detectors, we have used silicon wafers grown by the magnetic Czochralski (MCz) method. The MCz method has the advantage extending the controllable range of oxygen being dissolved from the silica crucible during the crystal growth. A magnetic field can be applied in the crystal growth system in order to dampen the oscillations in the melt. The applied field creates an electric current distribution and an induced magnetic field in the electrically conducting melt. This produces a Lorentz force that influences the flow and reduces the amplitude of the melt fluctuations [9].

In order to grow n-type silicon ingots, phosphorous dopant is added to the silicon melt in order to create desired donor concentrations in the silicon. However, boron is a common element in nature and exists also e.g., in the quartz material. At temperatures above the melting point of silicon, the boron can drift from quartz crucible to silicon melt during the crystal growth. Since boron forms acceptor state in silicon, the amount of unwanted boron is an important limitation to the achievable resistivity in n-type silicon.

High-resistivity Cz-Si substrates can basically be processed to make segmented or pad detectors in the same manner as traditionally used Fz-Si substrates. The process sequence is described in detail in [5]. The essential difference between Cz-Si and Fz-Si is the oxygen concentration. It is well known that the aggregation of oxygen atoms will lead to formation of electrically active defects, i.e., TDs [10]–[12]. The TDs are shallow donor levels, within 0.01 eV–0.2 eV the conduction band [13]. The formation of TDs is strongly depended on temperature and oxygen concentration in the silicon material. Heat treatment between 400 °C–600 °C lead to TD formation. In relatively short time, e.g., 30 min, a donor concentration comparable with the background doping can be achieved. When processing phosphorous-doped n-type Cz-Si this can result in elevated full depletion voltages. It has also been found that the presence of hydrogen in the detector fabrication process can enhance the TD generation [14].

III. Thermal Donor Generation

Possible sources of hydrogen in detector manufacturing are CVD (Chemical Vapor Deposition) process steps using silane (Si_3H_4) gas. CVD is frequently used e.g., for the polysilicon bias resistor formation for strip detectors and deposition of passivation insulators films (Si_3N_4 or/and SiO_2) on the patterned metal electrodes. In our detector process, we have used the Plasma Enhanced Chemical Vapor Deposition (PECVD) method for silicon nitride (Si_3N_4) deposition on patterned aluminum. A set of detectors without PECVD Si_3N_4 was also fabricated for comparison. The V_{fd} values of $p^+/n^-/n^+$ pad detectors made of phosphorous-doped Cz-Si wafers are summarized in Fig. 1. The full depletion voltage (V_{fd}) values of pad detectors were determined from CV measurements performed at 10 kHz frequency.

As seen in Fig. 1, the deviation of V_{fd} possibly caused by hydrogen enhanced TD generation, is small or even negligible in n-type detectors. The aluminum sintering temperature of these devices was less than 400 °C. It was also observed that there is no influence on V_{fd} whether the PECVD deposition was carried out before or after the aluminum sintering below 400 °C.

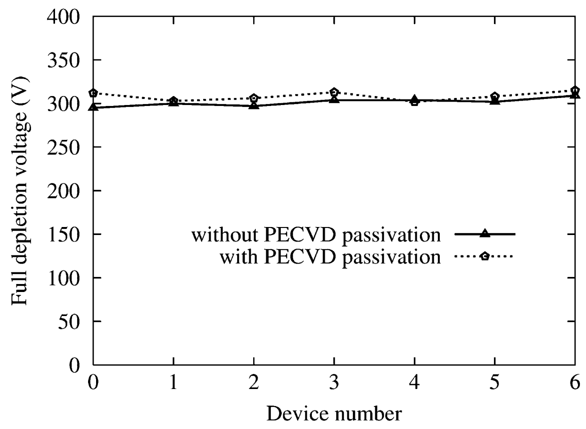

Fig. 1. V_{fd} values for n-type Cz-Si detectors made (a) without and (b) with PECVD Si_3N_4 passivation. The average values of V_{fd} are 302 V and 307 V for (a) and (b), respectively.

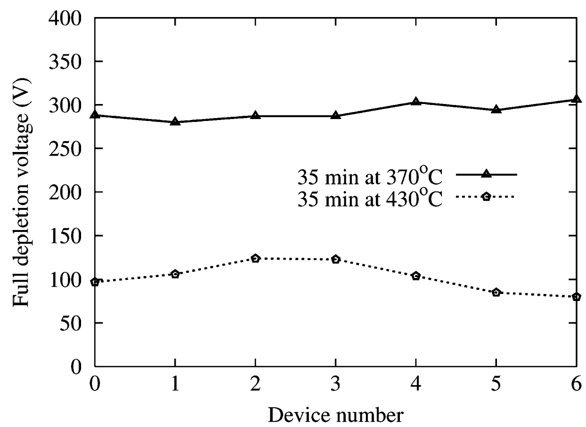

Fig. 2. V_{fd} values for p-type Cz-Si detectors made (a) without TD generation and (b) with TD generation heat treatment. The average values of V_{fd} are 292 V and 104 V for (a) and (b), respectively.

When processing $p^+/n^-/n^+$ pin-diode detectors on phosphorous-doped n-type Cz-Si substrates, the TDs increase V_{fd}. On the other hand, if the starting material is boron-doped p-type high-resistivity Cz-Si substrate, the TD generation compensates the acceptor doping. With compensation doping it is possible to achieve very low depletion voltages compared with devices doped only with boron acceptors. Full depletion voltage comparison of compensated and noncompensated diodes made of p-type Cz-Si is shown in Fig. 2.

The depletion of as-processed p-type devices took place at 300 V, which corresponds to a resistivity of approximately 3000 Ωcm, which differs from the 1800 Ωcm value provided by the wafer manufacturer. It is, therefore, obvious that boron doping has been to some extent compensated during the detector processing.

The TD generation rate depends exponentially on the oxygen concentration in the silicon material [15]. The influence of oxygen concentration variation along the wafer's diameter on the V_{fd} was studied by mapping diced diodes. The V_{fd} as function of distance from wafer center is presented in Fig. 3.

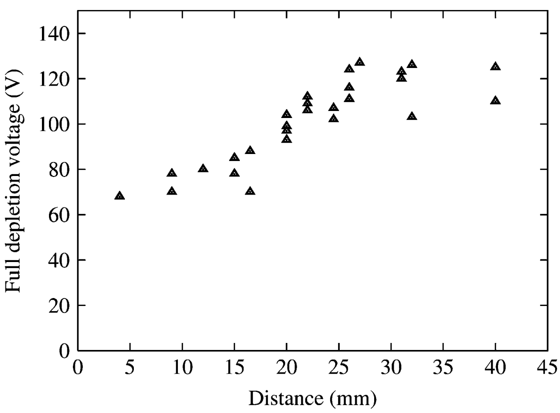

Fig. 3. Full depletion voltage versus distance from wafer center.

IV. Transient Current Technique (TCT) Measurements

The TD induced space charge sign inversion (SCSI) was further studied by the transient current technique (TCT) method [16]. In the TCT measurement, the pin-diode is illuminated with a red (660 nm) laser that has an absorption depth of only a few micrometers in silicon at room temperature. The diode is reverse biased during the measurement and current transients due to the illumination are recorded by the oscilloscope. The detector can be illuminated from either front or rear surfaces. For this purpose, a circular opening for the front side aluminum metallization has been etched and the backside metallization has been mesh patterned. Until the TDs have not compensated the boron doping, the silicon bulk is p-type and, thus, the collecting junction is on the rear side of the detector. Assuming the bulk to still be p-type, only one type of charge carriers will drift across the detector: holes when the laser illuminates the backside (n^+-side) or electrons when the laser illuminates the front side (p^+-side). Fig. 4 shows a TCT transient of hole current of a detector that has been heat treated 35 min at 430 °C.

A decreasing induced current with time can be seen in Fig. 4, thus indicating holes drift from the high electric field (n^+-side) to the low field (p^+-side). The junction, as expected, is on the backside (n^+-side).

After sufficient TD generation, the bulk is compensated, and even inverted to n-type, switching the junction to the front side (p^+-side). In this case, SCSI occurs in the detector, although a true type inversion has taken place in the detector material due to the shallowness of the TD levels. Consequently, the shapes of the electron and hole currents are reversed compared to those before the SCSI. Thus, the conduction type of the bulk can be deduced from the shape of the drift current, or the shape of the electric field, in the detector. Fig. 5 shows a TCT transient of hole current of a similar detector as in Fig. 4 that has been heat treated 75 min at 430 °C.

It is clear that the hole current shapes shown in Fig. 5 are drastically different from those shown in Fig. 4: the hole current transients increase with time, indicating holes drifting from low electric field (n^+-side) to high electric field (p^+-side). Now the junction is switched from the backside (n^+-side) to front side (p^+-side). The SCSI has taken place from negative to positive, and the bulk is type-inverted to n^- type. The device structure

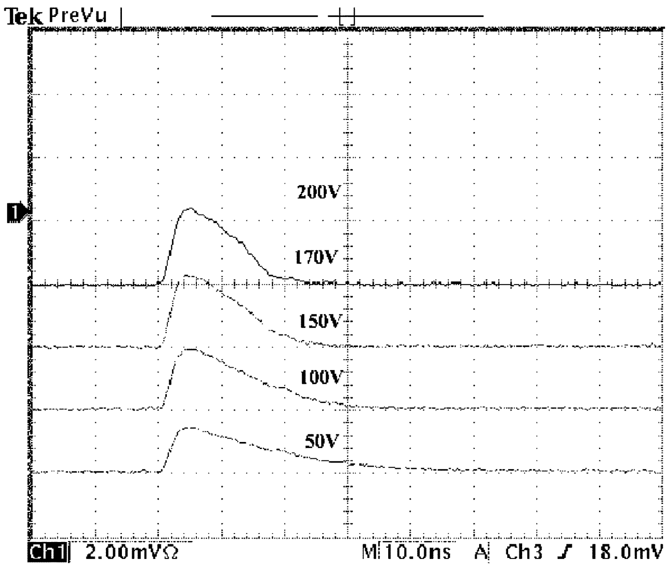

Fig. 4. Current transients with different reverse bias voltages of p+/p/n+ detector. In this sample TDs have been generated at 430 °C for 35 min. The detector has been illuminated from the backside (n^+-side).

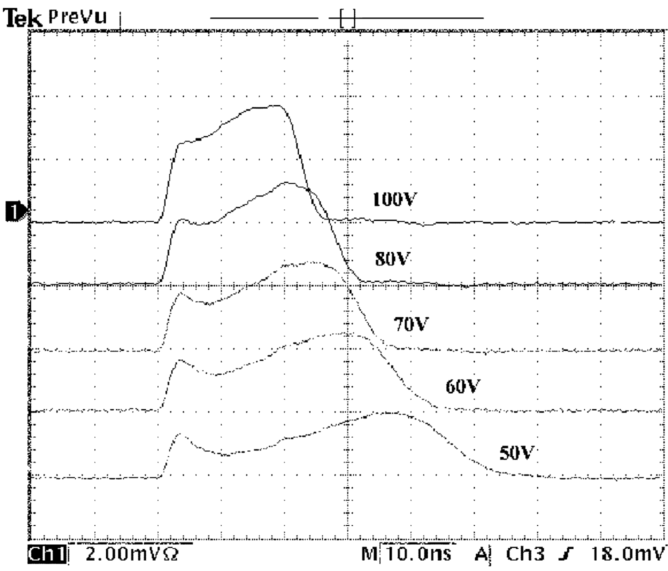

Fig. 5. Current transients with different reverse bias voltages of p+/p/n+ detector. In this sample TDs have been generated at 430 °C for 75 min. The detector has been illuminated from the backside (n^+-side).

is, therefore, transformed from the original $p^+/p^-/n^+$ to the intended $p^+/n^-/n^+$.

V. Proton Irradiation of Thermal Donor Treated Samples

The irradiation with 24 GeV/c high-energy protons was performed at CERN Irrad1 facility operating by PS accelerator [17]. During the irradiation the samples were not cooled or biased. After the irradiation, the samples were stored at the temperature below -10 °C and before the measurements they were annealed at 80 °C for 4min. The irradiated diodes were taken from a wafer, which was subjected to a TD heat treatment at 430 °C for 45 min. The pre-irradiation $V_{\rm fd}$ values are shown in Fig. 3. The proton fluencies were between $6 \star 10^{12}$ p/cm ^{2} and

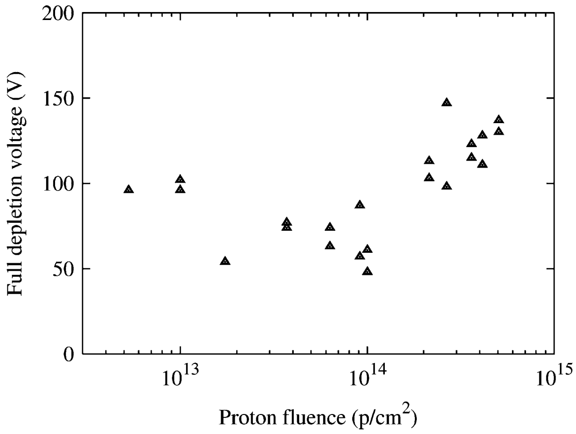

Fig. 6. Full depletion voltage versus 24 GeV/c proton irradiation fluence.

$5 \star 10^{14}$ p/cm ^{2}. The evolution of $V_{\rm fd}$ as function of proton fluence is presented in Fig. 6.

It can be seen in Fig. 6 that the evolution of $V_{\rm fd}$ with proton fluence is significantly less pronounced than for phosphorous-doped n-type Cz-Si (as, for example, presented in [7]). With fluencies less than $1\star10^{14}$ p/cm ^{2}, the $V_{\rm fd}$ remained practically unchanged compared with the pre-irradiation value. Only a small increase of $V_{\rm fd}$ was observed in samples irradiated with higher than $1\star10^{14}$ p/cm ^{2} fluencies.

VI. Conclusion

It is possible to fabricate $\rm p^+/n^-/n^+$ detectors on boron-doped Cz-Si wafers by compensating the acceptor doping by TDs. In this way, a high oxygen concentration detector can be processed with low thermal budget, i.e., high-temperature long time (HTLT) diffusion oxygenation process [1]–[3] is not needed. It is remarkable that the pre-irradiation $V_{\rm fd}$ of TD compensated $\rm p^+/n^-/n^+$detectors is well below the 300 V typical for 300 μm thick n-type Cz-Si detectors [5], [7].

When processing $\rm p^+/n/n^+$ pin-diode detectors on n-type phosphorous-doped Cz-Si substrates, the TD formation decreases the effective bulk resistivity and consequently increases the $V_{\rm fd}$. However, we have shown that with correct processing, the harmful TD generation can effectively be suppressed. Thus, n and p-type Cz-Si detectors can be manufactured on large diameter substrates in large quantities. The mass production of silicon sensors with reasonable costs might be necessary for future large HEP experiments.

The results of 24 GeV/c proton irradiation up to 5×10^{14} p/cm^2 show a very small increase of full depletion voltage. Therefore, the TD compensated $\rm p^+/n^-/n^+$ detectors made of high oxygen concentration Cz-Si can be considered to be suitable for very harsh radiation environments, such as that found at the LHC experiments.

Acknowledgment

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