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Low-temperature TCT characterization of heavily proton irradiated p-type magnetic Czochralski silicon detectors

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Abstract

$n^+/p^-/p^+$ pad detectors processed at the Microelectronics Center of Helsinki University of Technology on boron-doped p-type high-resistivity magnetic Czochralski (MCz-Si) silicon substrates have been investigated by the transient current technique (TCT) measurements between 100 and 240 K. The detectors were irradiated by 9 MeV protons at the Accelerator Laboratory of University of Helsinki up to 1 MeV neutron equivalent fluence of $2 \times 10^{15}\,\mathrm{n/cm^2}$. In some of the detectors the thermal donors (TD) were introduced by intentional heat treatment at 430 °C. Hole trapping time constants and full depletion voltage values were extracted from the TCT data. We observed that hole trapping times in the order of 10 ns were found in heavily (above $1 \times 10^{15}\,\mathrm{n_{eq}/cm^2}$) irradiated samples. These detectors could be fully depleted below 500 V in the temperature range of 140–180 K.

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Keywords: Si particle detectors; Thermal donors; TCT; Cryogenic operation

1. Introduction

The proposed upgrade scenario of LHC (Super-LHC, S-LHC) to a luminosity of $10^{35}\,\mathrm{cm^{-2}/s}$, corresponding to expected total fluences of fast hadrons above $10^{16}\,\mathrm{cm^{-2}}$ and reduced bunch-crossing interval of about 10 ns, sets a tremendous challenge for the radiation hardness of silicon particle detectors [1].

Particle radiation causes irreversible crystallographic defects in silicon material deteriorating the detector performance [2,3]. First, the donor doping concentration of silicon is compensated by acceptor-type defects and further reduced by phosphorous removal process. This may cause space charge sign inversion (SCSI) in n-type silicon material. After the SCSI, the full depletion voltage (V_{fd}) increases monotonically with respect to fluence. However, the detectors used in particle tracking systems should be efficient at reasonably low operating voltages. A practical limit of the operating voltage is 500 V.

Second, the leakage current of the detector (I_{leak}) increases linearly as a function of the accumulated radiation fluence. The high leakage current is a severe challenge for the cooling and mechanical design of a large tracker system of about 200 m^2 of silicon sensors. Every 10 μA/cm^2 would result in 1 kW of heat dissipation when biasing the tracker with 500 V. It is, therefore, obvious that cooling is needed and −20 °C, which is commonly adopted design criteria in LHC experiments silicon trackers, will not be sufficient in S-LHC [4].

Third, overall charge collection efficiency (CCE) degrades. The deterioration of the CCE due to the trapping of charge carriers will be the most severe obstacle for the use of silicon sensors in the future very high luminosity colliders with extremely harsh radiation environment. For example, in high-resistivity magnetic Czocharalski silicon

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(Cz-Si) detectors the effective doping concentration (N_{eff}) increases up to $3–5\times10^{13}\,\mathrm{cm}^{-3}$ after $10^{16}\,\mathrm{n_{eq}/cm^2}$ ($\mathrm{n_{eq}}$: 1 MeV neutron equivalent) when irradiated with charged hadrons [5,6]. A 200 μm thick Cz-Si detector could still be fully depleted below 1 kV operating voltages. Due to the saturation of thermal velocity at about 10^7 cm/s value, the trapping time constant would, however, limit the collection of charge carriers within 20–30 μm depth in the bulk, thus 80–90% of the segmented pad detector volume would represent dead space [7].

The methods used to overcome the radiation hardness challenge are defect engineering of silicon [2,8,9], device engineering of sensors, e.g., thin sensors and low temperature (below 230 K) operation of tracking sensors [10]. Each of these approaches has its drawbacks. The defect engineering stands mainly for deliberate introduction of oxygen into the silicon lattice. This can be done during the crystal growth or by high-temperature long-time oxygenation process. The oxygen-rich silicon is clearly, according to investigations performed within the framework of CERN RD50 and RD48 Collaborations, more radiation hard in terms of V_{fd} increase in proton irradiations, but provides no or very little improvement in neutron irradiation. Also, no significant improvement in effective trapping times and leakage current has been observed when compared to traditional Fz-Si devices [2].

The thin detectors have drawback in collected absolute charge. The reduction of the thickness is, therefore, a compromise between the full depletion requirement and the number of electron hole pairs generated in silicon. The new device structures, e.g. 3D detectors, suffer from complex manufacturability and thus high costs per unit area. The main drawback of the low temperature operation of tracking sensors is the very difficult implementation of a large-scale cryogenic tracker system.

Recently, intensively investigated approach to improve the radiation hardness of silicon particle detectors is to use $\mathrm{n^+/p^-/p^+}$ structures instead of conventional $\mathrm{p^+/n^-/n^+}$ detectors [9,11]. The essential advantage is that no SCSI occurs in p-type bulk, resulting in the main junction to remain on the segmented side of the detector. In addition, the signal comes dominantly from electrons having three times higher mobility than that of holes and, consequently, the amount of trapped charge carriers during their drift (determined by the amount of particle radiation) is reduced. This allows higher charge collection in $\mathrm{n^+/p^-/p^+}$ devices than in conventional detectors [11]. Furthermore, if p-type Czochralski silicon is used as detector starting material, it is possible to tailor the full depletion voltage of the device by deliberate introduction of thermal donors (TD) [12–14]. TDs are complexes consisting of four or more oxygen atoms. Their formation takes place during the annealing of silicon wafers at 400–600 °C [15], i.e. at temperatures that are frequently used during the detector processing. The drawback of $\mathrm{n^+/p^-/p^+}$ devices is the more complex fabrication technology. Conventional, AC coupled, poly-Si biased, detectors can be processed with 6–7 lithography mask levels while $\mathrm{n^+/p^-/p^+}$ devices require two more lithography steps and additional ion implantations.

In this paper, we report the results of the transient current technique (TCT) characterization of heavily proton irradiated $\mathrm{n^+/p^-/p^+}$ diodes made on p-type magnetic Czochralski silicon (MCz-Si). Two sets of samples, one compensated by TDs and one without TDs, were measured by TCT in the temperature range of 100–240 K.

2. Samples and irradiation

The samples used in this study were pad detectors that were processed on p-type MCz-Si wafers [16]. The starting material of the detectors was 4 in. diameter double-side-polished 300 ± 2 μm thick ⟨1 0 0⟩ Cz-Si wafers. The nominal resistivity, measured by the four-point probe method, of the boron-doped wafers was 1800 Ω cm, which corresponds to a boron concentration of $4.38\times10^{12}\,\mathrm{cm}^{-3}$. The processing and layout are discussed in detail in Ref. [17]. Two types of diodes were chosen for this study. First, diodes originating from a wafer that was sintered at 370 °C for 30 min (wafer ID p261). Second, set with intentional TD introduction at 430 °C for 45 min (wafer ID p047). The full depletion voltages of the diodes were measured by the capacitance–voltage (CV) method and were 300 ± 10 and 80 ± 10 V, respectively [13]. The pad leakage currents of all $0.25\,\mathrm{cm}^2$ active area diodes were in the range of 1–2 nA. The surface current isolation of $\mathrm{n^+/p^-/p^+}$ devices was realized by p-stop implants.

The proton irradiation was carried out at the Accelerator Laboratory of University of Helsinki. The proton energy was 9 MeV. The irradiation was performed in the vacuum chamber at the 250 K temperature. The beam current was monitored by a Faraday-cup. The five proton fluencies were 5, 8, 10, 25 and $50\pm10^{13}\,\mathrm{p/cm^{-2}}$. The highest fluence was achieved after about 5 h of irradiation. After the irradiation the samples were stored at −20 °C except during the 1-day period of transportation at the room temperature. Before the measurements, all samples were annealed at 80 °C for 4 min. The TD-treated sample irradiated with highest fluence, $5\times10^{14}\,\mathrm{p/cm^{-2}}$ was additionally annealed at 80 °C for 90 min.

3. TCT setup and measurements

The TCT measurement is based on the detection of the dominant type of charge carrier, electron or hole, which drifts across the whole detector thickness after being excited by a photon. This is achieved by illuminating the front ($\mathrm{n^+}$ implant) or back ($\mathrm{p^+}$ implant) side of the detector with a laser of wavelength smaller than 800 nm, whose light creates electron–hole pairs close to the device surface. When the front side of the detector is illuminated, the electrons are collected to the $\mathrm{n^+}$-electrode so fast that the signal is damped by the rise time of the data acquisition electronics; and therefore the measured induced current is mainly coming from the holes that travel a longer distance through the silicon bulk. Correspondingly, when a $p^+/n^-/n^+$ detectors front side is illuminated, mainly the induced current by electrons is measured [18,19].

Depending on the space charge of the bulk, the electric field i.e. the collecting junction is either on the front side or the backside of the detector. When the induced current is measured at the n^+ side, a descending hole transient current is measured, if the main junction is also at n^+ side. If the junction is on the p^+ side, i.e. the bulk has inverted, an ascending hole transient current is measured. When analyzing the electric field of an irradiated detector, one has to take into consideration that the measured signal is affected by the trapping of the charge carriers into the radiation-induced defects. The influence of the trapping can be deducted by applying so-called trapping correction method (CCM) [20,21], which is a mathematical manipulation of the measured raw data. The charge correction used in this work was performed by a Matlab program where the user-defined input parameters are V_{fd} and the integration time of the recorded TCT signal. The full depletion voltage can be determined from the TCT measurement either by visual inspection of the shape of the transient or by, more analytical method, integrating the charge with respect of bias voltage and extracting the voltage at which the saturation of the induced charge starts (QV method). In this study, the V_{fd} values were determined by the QV method.

Our TCT setup consists of Tektronix TDS 784C 1 GHz bandwidth oscilloscope, Keithley 6487 source meter unit capable to source up to 500 V, vacuum chamber, cold finger, Leybold helium stirling cooler, temperature and vacuum control units, LabView-based data acquisition system and laser emitting 678 nm light. The laser and its driver are supplied by the Advanced Laser Diode Systems A.L.S. GmbH. The width of the laser pulse is about 30 ps (FWHM) and the maximum optical power is 250 mW. The laser can be tuned ranging 0–100%. The trigger rate can be adjusted from 1 MHz to single shots. The biasing circuit, i.e., so-called T-bias, of the setup consists of 100 kΩ resistor and 10 nF capacitor. The signal is amplified between the T-bias and the 50 Ω oscilloscope input by Phillips Scientific 6954 wide bandwidth amplifier having a gain of approximately 50.

During the measurements, the laser was operated typically at 10 Hz repetition rate while tuned to 10% of relative power. This is practical minimum level of optical excitation in our system taking into consideration the reasonable S/N ratio. The low injection is preferred in order to minimize the polarization [22] effects at the cryogenic temperatures. Due to the mechanical design of the copper made cold finger, the diodes could only be illuminated on the front side. Thus, the current transients of the investigated $n^+/p^-/p^+$ diodes presented in this content are dominantly hole current.

The diodes were taped by double-sided conductive carbon adhesive tabs on patterned gold plated ceramics. The ceramics have opening in the middle and a gold needle is soldered into the opening. The back contact that provides the high voltage is achieved by inserting the gold needle into a female coaxial connector in the cold finger. The pad contact and guard ring contact of the diodes were wire bonded into the gold metallization of the ceramics. Prior the measurements, the thermal contact between the ceramic and the cold finger are enforced by copper springs. Before the cold finger was cooled down, the vacuum chamber was pumped to 5×10^{-4} mbar pressure. Cooling down the cold finger to 60 K took typically 1 h. Every measurement took place only after the cold finger temperature saturated within 1 K of the set point. The temperature stabilization took typically about 5 min. The detectors leakage current was monitored during the temperature stabilization in order to ensure sufficiently small thermal gradient between the sample and the cold finger.

Fig. 1. illustrates the hole current transients measured by our setup of irradiated and non-irradiated diodes.

It can be seen that in the signal there is an apparent pick-up at around 15 ns. This is presumably due to the electrical reflection in the bias circuit.

4. Results

The V_{fd} values, obtained by the QV method as function of temperature, are shown in Fig. 2.

As can be seen from Fig. 2, in all three data point sets the V_{fd} reaches its minimum between 140 and 180 K. The V_{fd} increases sharply when the temperature approaches 100 K and also above 200 K. The exception is the $5\times10^{14}\,n_{eq}/cm^2$ irradiated TD treated sample that could be fully depleted below 500 V at 285 K. The minimum of the V_{fd} of the non-TD treated samples are about 80 and 180 V for 2.5×10^{14} and $5\times10^{14}\,n_{eq}/cm^2$ irradiated samples, respectively.

The extracted hole trapping time constant values as function of temperature are shown in Fig. 3.

Appositively to Fig. 2, the effective hole trapping time constant in all samples peaks between 140 and 180 K. The τ_h values vary from 2 to 15 ns within the order of magnitude of the irradiation fluence. Also, the temperature dependence is strong. For example, in $5\times10^{14}\,n_{eq}/cm^2$ irradiated sample the τ_h is 8 ns at 145 K and 2 ns at 175 K.

Fig. 4 shows the measured and CCM corrected TCT transients of $2.5\times10^{14}\,n_{eq}/cm^2$ irradiated non-TD treated sample at 120, 150 and 180 K. According to Fig. 2, the V_{fd} minimum of this sample is at 140 K.

At 120 K, the both transients, measured and corrected, show ascending hole transient current. Thus, the region with high electric field is on the backside of the detector, i.e. the bulk of the silicon is n-type. At 150 K, the measured signal is descending and corrected signal is quite flat or slightly descending. At 180 K, measured and corrected signals both are clearly ascending indicating p-type bulk. This temperature induced SCSI was observed in all samples regardless of the TD treatment or irradiation fluence.

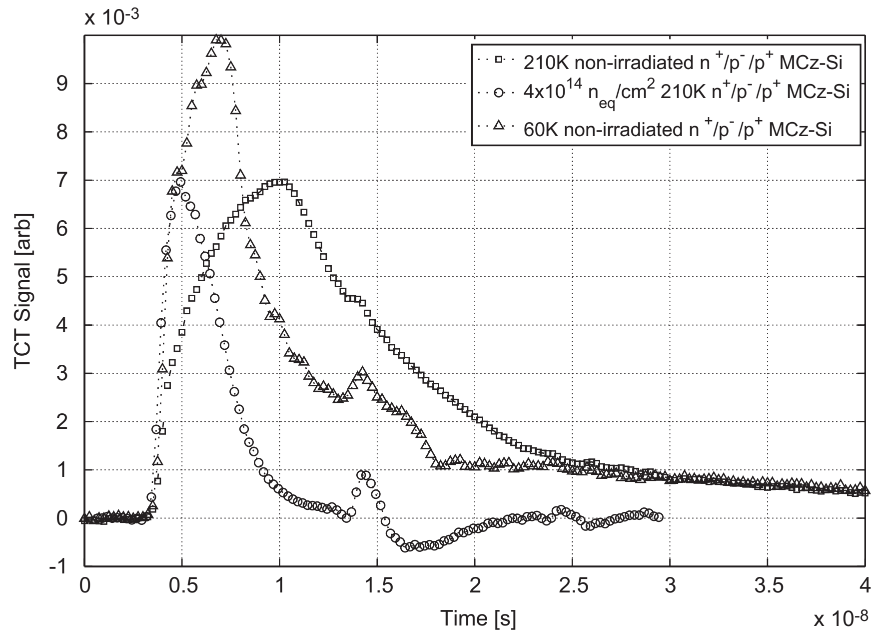

Fig. 1. Hole current transients on non-irradiated $n^+/p^-/p^+$ TD-treated detector at 60 K (Δ) and 210 K (□), and proton irradiated $4\times10^{14}\,n_{eq}/cm^{-2}$ (○) diodes. The bias voltage is 150 V for non-irradiated diode and 500 V for the irradiated sample.

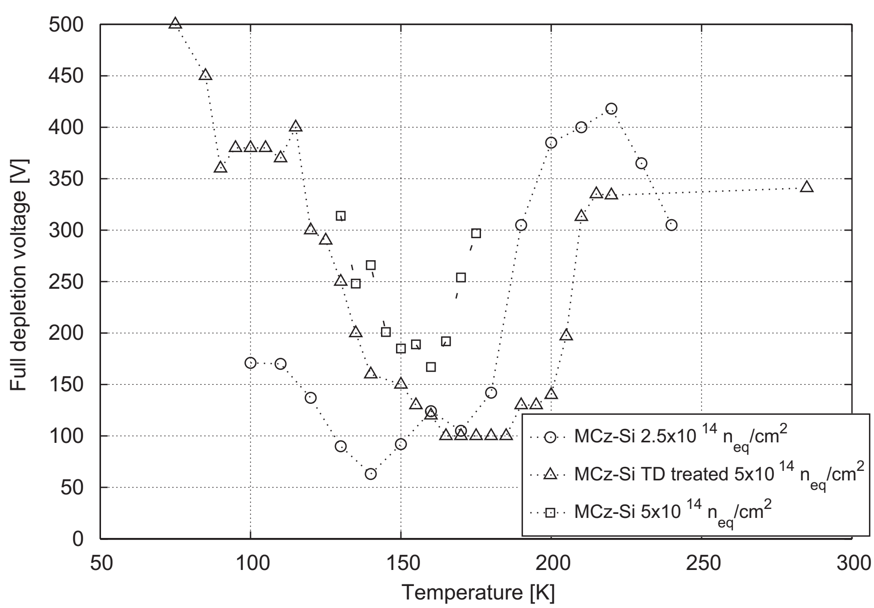

Fig. 2. V_{fd} values as function of temperature.

Fig. 5 shows the collected charge measured by the QV method with respect to temperature in the TD-treated sample irradiated with $2.5\times10^{14}\,n_{eq}/cm^2$.

As can be seen from Fig. 5, at 90 K there is a very sharp increase of the collected hole current. This kind of behavior is typical when the collecting junction is on the opposite side of the illumination. Thus, this is a further proof of temperature induced SCSI in irradiated p-type MCz-Si detectors [21,23].

5. Conclusions

$n^+/p^-/p^+$ diodes were irradiated by 9 MeV protons up to 1 MeV neutron equivalent fluence of $2.5\times10^{15}\,n_{eq}/cm^2$. Only diodes irradiated to the smallest fluence could be fully depleted below 500 V at temperatures above 240 K. The depletion voltages were 270 V at room temperature for the TD treated sample irradiated to $2.5\times10^{14}\,n_{eq}/cm^2$ depleted at about 270 V at room temperature, 340 V for the

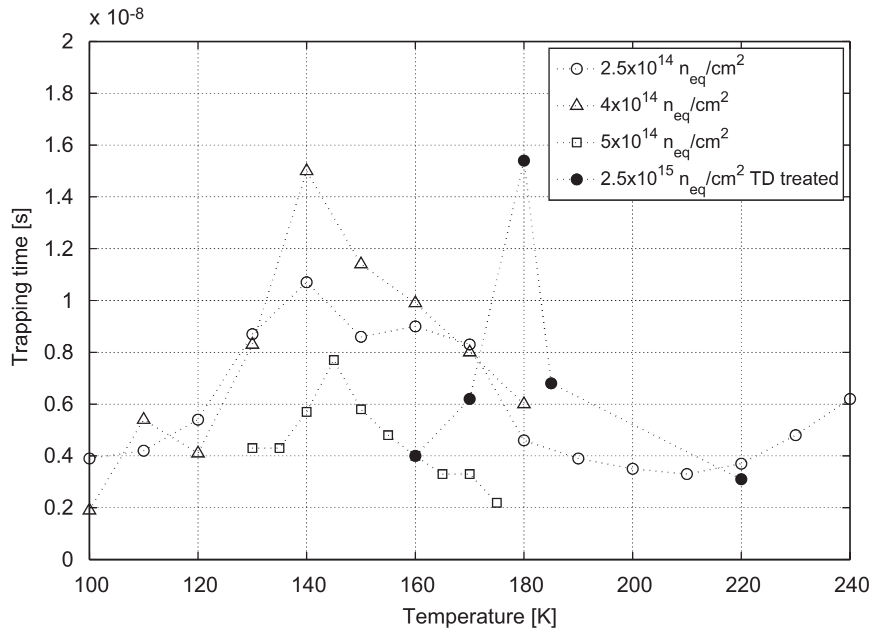

Fig. 3. Effective hole trapping time constant (τ_h) values as function of temperature.

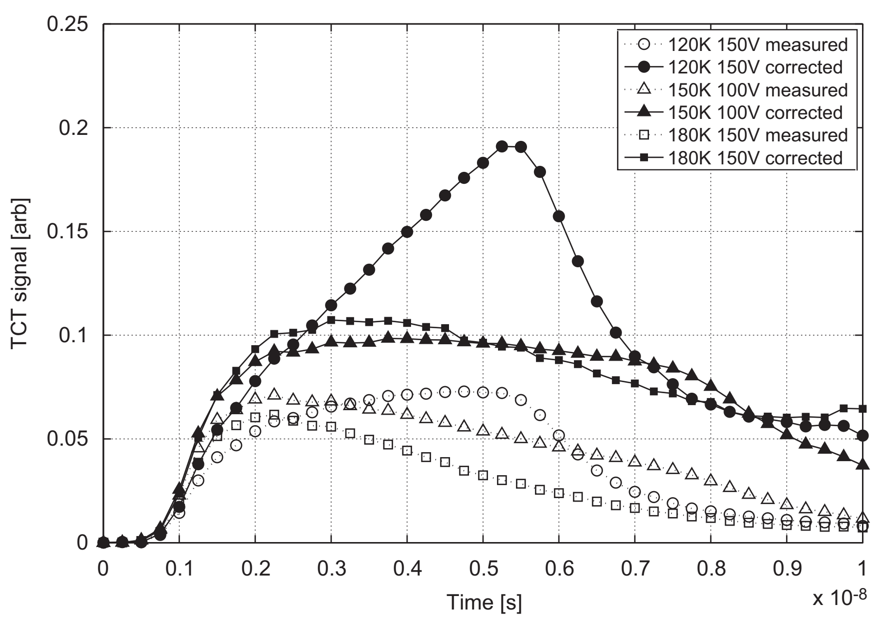

Fig. 4. Measured and CCM corrected TCT transients at 120, 150 and 180 K of $2.5\times10^{14}\,n_{eq}/cm^2$ irradiated non-TD-treated MCz-Si diode.

TD-treated sample irradiated to $5\times10^{15}\,n_{eq}/cm^2$ at 285 K and 400 V for non-TD-treated sample at $2.5\times10^{14}\,n_{eq}/cm^2$ at room temperature. This is obvious since we know from our previous studies [5,6] and from the work done RD50 Collaboration that low-energy proton irradiation of $2.5\times10^{14}\,n_{eq}/cm^2$ induces negative space charge in the order of $2\times10^{12}\,cm^{-3}$ into MCz-Si, which would result in V_{fd} above about 500 V if the pre-irradiation V_{fd} is in the order of 300 V. The main restriction to determine V_{fd} by the QV method was 500 V bias voltage limitation, further reduced by the voltage drop across 100 kΩ resistor in the bias circuit due to the high leakage current.

At the low temperatures (<200 K), it is apparent that SCSI occurs at certain temperature. This is due to the fact that the effective space charge is balanced by the trapping and detrapping. Trapping has no strong temperature dependence and it is inversely proportional to the concentration of trapping centers, while detrapping is exponentially dependent on the temperature. In other words, when a trap has absorbed an electron or a hole, it becomes neutral and does not contribute anymore to the

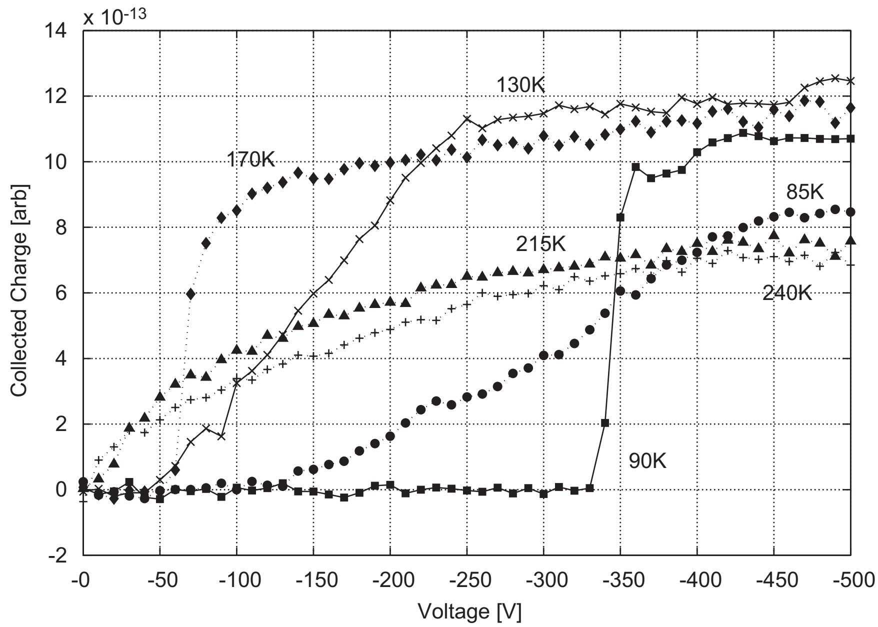

Fig. 5. Collected charge of a $2.5\times10^{14}\,\mathrm{n_{eq}/cm^2}$ irradiated TD-treated MCz-Si diode at different temperatures.

N_{eff}. This finding is very similar to the results obtained by signal measurements of the minimum ionizing particle (MIP) done by the RD39 Collaboration and often denoted as "Lazarus effect" [24,25]. With the TCT it is, however, possible to extract effective trapping times and the effective polarity of the space charge. The increase of the V_{fd} and consequent decrease of the τ_{h} can be explained by the polarization, i.e., rapid decrease of the electric field by free carriers when the traps are filled and remain filled within the signal integration time. The MIP measurements are not that sensitive on polarization because of much lower event rate compared to the TCT measurements. Thus, high CCE values below 100 K were reported in Refs. [24,25].

The hole trapping times in the order of 10 ns were found in heavily irradiated (above $1\times10^{15}\,\mathrm{n_{eq}/cm^2}$) samples at temperatures below 190 K. In the literature, hole trapping times in MCz-Si materials of about 10 ns are recorded for the samples irradiated by order of magnitude lower fluencies [26]. Above 220 K, no trapping time data exists simply because of too high V_{fd} and leakage current that prevent TCT measurements.

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