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Recent results from the CERN RD39 Collaboration on super-radiation hard cryogenic silicon detectors for LHC and LHC upgrade

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Abstract

The CERN RD39 Collaboration is developing super-radiation hard cryogenic Si detectors for applications in experiments of the LHC and the future LHC Upgrade. Radiation hardness up to the fluence of $10^{16}\,n_{eq}/cm^2$ is required in the future experiments. Significant improvement in the radiation hardness of silicon sensors has taken place during the past years. However, $10^{16}\,n_{eq}/cm^2$ is well beyond the radiation tolerance of even the most advanced semiconductor detectors made by commonly adopted technologies. Furthermore, at this radiation load the carrier trapping will limit the charge collection depth to the range of 20–30 μm regardless of the depletion depth. The key of our approach is freezing the trapping that affects Charge Collection Efficiency (CCE).

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Keywords: Si particle detectors; Radiation hardness; Material engineering

1. Introduction

The CERN RD39 Collaboration has made significant advances in obtaining super-radiation hard cryogenic silicon (Si) detectors for applications in experiments for LHC and future LHC Upgrade. Our approach differs from the traditional methods for improvement, which are based on the modification of the properties of Si by doping with impurities or lattice defects [1]. The best results were achieved for silicon doped with oxygen, e.g., Czochralski silicon [2] or doping by long-term oxidation [3]. The maximum improvement of radiation hardness is by a factor of 2–3 for protons, but little improvement is revealed for neutrons [4,5]. Detailed modeling of the Lazarus effect [6] has shown that the electric field in irradiated Si detectors can be manipulated by the filling status of two deep defect levels at cryogenic temperatures. The key of our approach is to freeze the trapping that affects charge collection efficiency (CCE).

2. Charge collection in heavily irradiated silicon

The deterioration of CCE due to the trapping of charge carriers is a severe obstacle for the use of silicon sensors in future having very high luminosity colliders with extremely harsh radiation environment [7]. The particle radiation induces trapping centers that eventually leads to the reduction in the signal height, produced by mip's (minimum ionising particles).

The detector CCE can be considered to be a product of two factors [8].

$$\mathrm{CCE} = \mathrm{CCE_{GF}}\mathrm{CCE_t} = \frac{w}{d}\,\mathrm{e}^{-t_{\mathrm{dr}}/\tau_{\mathrm{t}}} \tag{1}$$

where w is depletion depth, d detector thickness, τ_t trapping time constant, and t_{dr} carrier drift time. In Eq. (1), $\mathrm{CCE_{GF}}$ is a geometrical factor that is affected by the detector full deletion voltage V_{fd} (or effective doping concentration N_{eff}) via the relations:

$$w = \sqrt{\frac{2\varepsilon\varepsilon_0 V}{\mathrm{e}N_{\mathrm{eff}}}}\ \text{and}\ \frac{w}{d} = \sqrt{\frac{V}{V_{\mathrm{fd}}}} \tag{2}$$

where e and ε have their usual meanings. The second term $\mathrm{CCE_t}$ in Eq. (1) is the trapping factor that is related to the trapping of carriers by defects.

The trapping (τ_t) and detrapping (τ_d) time constants for a trap level can be defined by

$$\tau_{\mathrm{t}} = \frac{1}{\boldsymbol{\sigma} v_{\mathrm{th}} N_{\mathrm{t}}}$$
$$\tau_{\mathrm{d}} = \frac{1}{\boldsymbol{\sigma} v_{\mathrm{th}} N_{\mathrm{C}} \mathrm{e}^{-E_{\mathrm{t}}/kT}} \tag{3}$$

where σ is capture cross-section of the trap, v_{th} is the thermal velocity of charge carriers, N_{T} is the concentration of traps, N_{C} the electric state density in conduction band, and E_{t} the trap energy level in the band gap.

The trapping time constant is nearly independent of temperature (or the dependence is weak). However, it depends strongly on the radiation fluence Φ_n. The elevated depletion voltage of heavily irradiated silicon detectors is due to various radiation-induced defects. Two deep levels, however, are recognized to be the most responsible for an increase in effective doping concentration and are adopted as basis of the modeling of radiation effects [9–12]. These experimentally observed levels are a deep donor (DD) 0.48 eV above the valence band and a deep acceptor (DA) 0.527 eV below the conduction band. The capture cross-section of both levels is approximately $10^{-15}\,\mathrm{cm}^2$. Presumably because of the introduction of these DD and DA levels, hadron irradiation of Super-LHC like fluence would give rise to very high N_{eff}. For example, in recently developed, very high oxygen concentration, high resistivity magnetic Czocharalski silicon (Cz–Si) detectors, the N_{eff} increases up to $3-5\times10^{13}\,\mathrm{cm}^{-3}$ after a fluence of $10^{16}\,\mathrm{n_{eq}/cm^2}$ [13]. A 200 μm thick Cz–Si detector could still be fully depleted below 1 kV operating voltages. Due to the saturation of the drift velocity at about $10^7\,\mathrm{cm/s}$, the trapping time constant [14] would, however, limit the collection of charge carriers within the depth of 20–30 μm in the bulk, thus about 80–90% of the detector volume would represent dead space.

As demonstrated by the previous RD39 results [15], $\mathrm{CCE_{GF}}$ can be increased close to 1 by manipulating the electric field in the detector via current and/or charge injection at temperatures from 130 to 150 K. Since for a fluence less than $10^{15}\,\mathrm{n/cm^2}$ the trapping term $\mathrm{CCE_t}$ is insignificant, CCE can be significantly improved by improving $\mathrm{CCE_{GF}}$ at temperatures from 130 to 150 K. This is the original "Lazarus" effect. However, for extremely high fluence ($10^{16}\,\mathrm{n/cm^2}$) in the environment of LHC upgrade, the trapping term can greatly affect CCE. The approach of RD39 to overcome the fundamental trapping problem at very high fluencies is to modify $\mathrm{CCE_t}$ at low temperatures. Temperatures lower than 80 K may be needed here.

As can be seen in Eq. (3), the detrapping time constant depends very strongly on temperature. This dependence makes it possible to freeze trapping centers at low temperatures. If a trap level is filled (e.g. by current or charge injection) and then frozen (very long detrapping time, see Eq.(3)) at cryogenic temperatures, this trap level will no longer be able to trap free carriers again, and it becomes electrically inactive. In this case, CCE_t can be improved to a value close to 1, and therefore CCE improves significantly. Since some trap levels are shallow, cryogenic temperatures are needed to freeze them. In addition to deep DA and DD, a well-known, shallow radiation-induced trapping center in Si is the so called A-center (O–V) at $E_{\mathrm{c}}-0.18\,\mathrm{eV}$ with a capture cross-section of $10^{-15}\,\mathrm{cm}^2$. For the A-center, detrapping time constants at various temperatures are listed in Table 1.

The A-center is freezing already for 10's of seconds at 60 K. At 45 K, the A-center will be frozen for 15 days after filling, and at 40 K for 13 years. So, if one fills the A-center at 40 K, it will not be active as trapping center for the next 13 years! Even at higher temperatures, say at 45 K, one may need to fill the A-center every 15 days, which can easily be done.

3. Space charge manipulation with temperature

Significant improvement of the CCE of irradiated detectors was observed below 150 K and named as the Lazarus effect [16]. The recovery of CCE was then studied [17] and modeled [18] by the RD39 Collaboration. This model suggests that CCE recovery is due to the reduction of the charged fraction of radiation induced deep donors and acceptors. This reduction increases the depth of the space charge region and therefore improves the CCE. As an example, temperature dependences of, N_{eff} are presented in Fig. 1 for two detectors made of standard Si and oxygenated Si and irradiated to extremely high doses, ~1.7 grad γ-rays.

Table 1
Detrapping time constant for the A-center

T(K)	300	150	100	77	60	55	50	45	40
τ_d	10 ps	10 ns	10 µs	6 ms	12 s	5 min	3.6 h	15 d	13 a

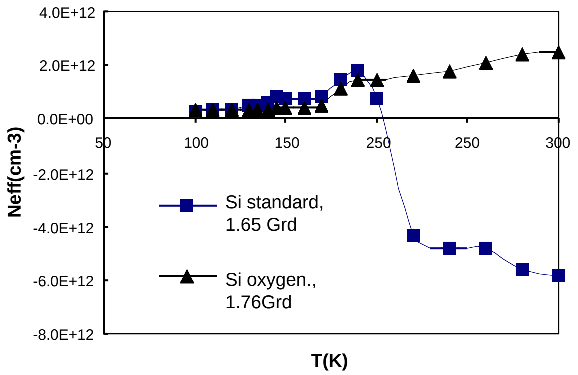

Fig. 1. $N_{eff}(T)$ for detectors made of standard Si and oxygenated Si and irradiated by ultra-high dose of γ-rays.

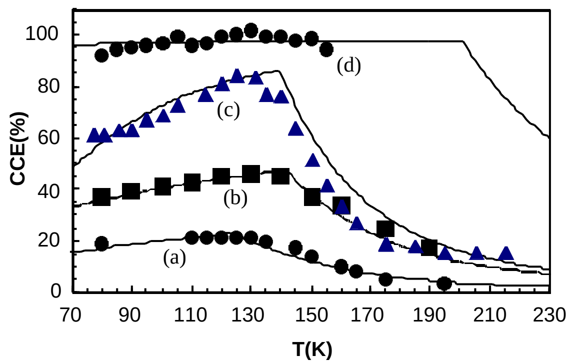

Fig. 2. Experimental CCE vs. T for MIPs for detectors irradiated by neutrons. Points—experimental data; solid lines—simulated curves. Neutron fluences (cm^{-2}): (a) 10^{15}; (b) 5×10^{14} (c) and (d) 10^{14}. Reverse bias potential: (a–c) 250 V and (d) 100 V.

For oxygenated Si, N_{eff} is positive at any T and at $T < 190$ K. For standard Si, $N_{eff}(T)$ shows non-monotonic behavior with space charge sign inversion, which is quite unique for irradiated detectors and is related with the temperature dependence of the deep level filling. The slight increase in N_{eff} from its initial value of $-6 \times 10^{12}\,cm^{-3}$, occuring from RT to 220 K, is followed by a sharp increase up to about zero and space charge sign inversion at 200 K. The maximum positive N_{eff} of $2 \times 10^{12}\,cm^{-3}$ is achieved at $T \approx 190$ K after which N_{eff} goes down monotonically to saturated value of $\sim 3 \times 10^{11}\,cm^{-3}$. Below 200 K N_{eff} has the same positive value in both types of Si detectors, thus indicating that the same deep levels contribute to N_{eff}.

The model of Lazarus effect allows the investigation of deep defects in detectors irradiated by very high fluences. The calculation of the charged fractions for mid-gap DD ($E_v + 0.48$ eV) and DA ($E_c - 0.53$ eV) was performed, by taking into account the density of free electrons and holes that are thermally generated in the space charge region. The results of these calculations with respect to experimental data are shown in Fig. 2.

The calculation showed that at temperatures below 140 K the concentration of space charge decreases, which leads to full depletion even at low bias voltages.

4. Conclusions

In super-LHC the tracking sensors close to the interaction point will be subjected to maximum fluence as high as $10^{16}\,n_{eq}/cm^2$ in 10 years. Cryogenic operation of Si detectors offers some obvious advantages, e.g., no detector leakage current (low electrical power from HV supply), fast charge transit (higher mobilities) and faster readout electronics with less noise.

Studies are now under way for developing ultra-radiation-hard cryogenic Si detectors for LHC upgrade. We are convinced that our approach to freeze detrimental trapping centers and to control their electrical activity via charge injection is feasible for the applications infuture for very high luminosity colliders.

References

[1] G. Lindstrom, et al., Nucl. Instr. and Meth. A 426 (1999) 87.
[2] J. Härkönen, et al., Nucl. Instr. and Meth. A 514 (2003) 173.
[3] Z. Li, et al., IEEE Trans. Nucl. Sci. NS- 39 (6) (1992) 1736.
[4] E. Tuominen, et al., IEEE Trans. Nucl. Sci. NS- 50 (2003) 1942.
[5] Z.Li, et al., IEEE Trans. Nucl. Sci., submitted for publication.
[6] B. Dezillie, V. Eremin, Z. Li, E. Verbitskaya, Nucl. Instr. and Meth. A 452 (2000) 440.
[7] F. Gianotti, et al., hep-ph/0204087: April 2002.
[8] E. Verbitskaya, et al., Nucl. Instr. and Meth. A 514 (2003) 47.
[9] V. Eremin, Z. Li, E. Verbitskaya, Nucl. Instr. and Meth. A 476 (2002) 556.
[10] Z. Li, et al., Nucl. Instr. and Meth. A 388 (1997) 297.
[11] M. Moll, Ph.D. Thesis, University of Hamburg, 1999.
[12] E. Fretwurst, et al., Nucl. Instr. and Meth. A 388 (1997) 356.
[13] E. Tuovinen, et al., Czochralski silicon detectors irradiated with high and low energy protons, IEEE Nuclear and Space Radiation Effects Conference, 2004, submitted for publication.
[14] G. Kramberger, et al., Nucl. Instr. and Meth. A 481 (2002) 297.
[15] RD39 Status Report, CERN-LHCC-2003-060, 2003.
[16] V.G. Palmieri, et al., Nucl. Instr. and Meth. A 413 (1998) 475.
[17] K. Borer, et al., Nucl. Instr. and Meth. A 440 (2000) 5.
[18] V. Eremin, E. Verbitskaya, I. Ilyashenko, Z. Li, T. O. Niinikoski, G. Ruggiero, Temperature dependence of charge collection efficiency in heavily irradiated silicon detectors: the Lazarus effect model, Nucl. Instr. and Meth. A, submitted.