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Carrier generation in irradiated Si detectors and its impact on the electric field profile

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ABSTRACT

The reverse current of irradiated Si detectors was analyzed in terms of carrier generation via defects with the energy levels in the Si bandgap. The data for detectors irradiated by 23 GeV protons and 1 MeV neutrons were obtained in the temperature (T) range of 200–300 K. Two models of the bulk generation current were developed to allow fitting and simulation of the reverse current vs. T data. These are a model of carrier generation via a single effective energy level for the direct estimation of detector performance, and a model of two generation centers with the effective energy levels originating from radiation-induced deep levels adjacent to the midgap. The influence of the bandgap temperature dependence ($E_g(T)$) on the parameters of the current generation centers was estimated. The first model gives the effective level energy of $E_v+0.65$ eV and a linear dependence of the effective defect concentration on fluence. The second model involves contribution from deep donors and deep acceptors positioned at $E_v+0.48$ eV and $E_c-0.52$ eV, respectively, and is adapted for simultaneous calculation of the reverse current and the electric field distribution in irradiated detectors. The results of the study show that: (a) both models fit well to the experimental data; (b) contribution of the $E_g(T)$ dependence to E_t does not exceed 5%; (c) taking into consideration the bulk generation current gives the correct electric field distribution, which is a key reference for other characteristics of irradiated Si detectors; and (d) the generation lifetime is significantly larger than the carrier trapping time constant pointing to additional levels taking part in trapping of the drifting charge.

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1. Introduction

The increase of the reverse current (I) is one of the main damage effects in irradiated Si detectors used in the experiments at the Large Hadron Collider (LHC). It is caused by radiation-induced defects in the semiconductor bulk. Point defects in the crystal lattice have energy levels in the bandgap, which lead to the increase of the bulk generation current of p–n junction detectors and reduction of the signal-to-noise ratio. This effect can be reduced by a proper choice of the signal shaping time θ_{sh}. Another negative consequence is that the Joule heat dissipation requires reduction of the maximum operational bias voltage V limited by its thermal runaway if cooling is not powerful enough. In case this voltage is below the full depletion voltage (V_{fd}), the detector will be partially depleted, which enhances degradation of the charge collection efficiency (CCE). To minimize such negative effects, in the ongoing LHC experiments the detector operational temperature T is as low as -20 °C. In the experimental study of heavily irradiated Si detectors developed by the CERN RD50 collaboration for high luminosity collider the temperatures can be still lower (down to -50 °C) [1].

One of the approaches used in the development of radiation-hard Si detectors is defect/material engineering, and different Si grades were tested in detector processing. Nevertheless, as was shown in numerous studies, the dependence of the bulk generation current (I_{bgen}) on radiation fluence was rescaled to 1 MeV neutron equivalent, Φ_{eq} (n_{eq}/cm^2), represents a unified linear curve independent of the particle type and Si grade

$$I_{bgen}/Vol = \alpha\Phi_{eq} \quad (1)$$

where Vol is the detector sensitive volume at full depletion voltage and α the current related damage rate (4×10^{-17} cm^{-1} at 20 °C and 80 min annealing at 60 °C [2–4]). Eq. (1) gives a strong argument for assigning the increase of the reverse current to the concentration of radiation-induced defects acting as generation centers with their concentration increasing linearly with Φ_{eq}.

The present study is focused on the analysis of the bulk generation current in Si detectors irradiated by neutrons and protons. Simulation of reverse current vs. T dependence is carried out taking into account the Shockley–Read–Hall theory describing

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carrier generation via the defect energy levels in the silicon bandgap [5]. Two models are used in the simulation/fit of the $I(T)$ curves: carrier generation via a single effective generation center (SL model, macroscopic approach), which correlates with Eq. (1), and generation via two effective radiation-induced deep level (DL) defects (TL model, microscopic approach). The argument for the microscopic approach is that the two-level model has been shown to allow calculation of the double peak (DP) electric field profile [6] in irradiated Si detectors, which agrees with the experimental results [6,7]. In our study this aspect is extended and the impact of generation current on characteristics of irradiated Si detectors is analyzed.

2. Model of reverse current calculation

2.1. Basic equations for generation current

In this study the reverse current of irradiated Si detectors is considered to be a bulk generation current determined as

$$I_{bgen} = en_iAw/\tau_{gen} \tag{2}$$

where e is the elementary charge, n_i the intrinsic carrier concentration, A the p–n junction area, w the depth of space charge region and τ_{gen} the carrier generation lifetime. The bulk generation current arises from generation of electron–hole pairs in SCR as a result of a sequential transition of electrons from the valence band (generation of holes) to the conductance band (generation of electrons). According to the Shockley–Read–Hall theory, the bulk generation current is determined by the parameters of generation-recombination centers originated from deep levels characterized by the activation energy E_t and carrier capture cross-sections of electrons (σ_e) and holes (σ_h). The carrier exchange between the energy bands is described by the probabilities of carrier capture c_e, c_h on DLs and emission e_e, e_h from DLs to the bands. Thus, there are four coefficients corresponding to the process:

$$c_e = v_{th}^e\sigma_e; \quad c_h = v_{th}^h\sigma_h \tag{3a}$$

$$e_e = v_{th}^e\sigma_e \exp\left(-\frac{E_c-E_t}{kT}\right); \quad e_h = v_{th}^h\sigma_h \exp\left(-\frac{E_t-E_v}{kT}\right) \tag{3b}$$

where v_{th}^e, v_{th}^h are the thermal velocities of electrons and holes, respectively; E_c-E_t and E_t-E_v the activation energies for carrier transition between DLs and conduction/valence band ($E_g=E_c-E_v$ is the energy bandgap), E_t the defect energy level measured from the top of the valance band, and k the Boltzmann constant. In steady-state conditions the excess carrier generation rate U is determined by the difference between generation and recombination rates G and R

$$\begin{aligned} &G_e = e_en_t; \qquad G_h = e_h(N_t-n_t)\\ &R_e = c_e(N_t-n_t)n; \qquad R_h = c_hn_tp\\ &U = G_e-R_e = G_h-R_h \end{aligned} \tag{4}$$

where n, p are the concentrations of free electrons and holes, respectively, N_t the deep level concentration, and n_t the concentration of electrons captured on DL.

In steady-state conditions and in the case of negligible concentrations of free carriers in the bands (n, $p \approx 0$, like in the SCR), Eqs. (3) and (4) give the carrier generation rate U [5]:

$$U = \frac{\sigma_e\sigma_hv_{th}n_iN_t}{\sigma_e\exp((E_t-E_i)/kT)+\sigma_h\exp((E_i-E_t)/kT)} = \frac{n_i}{\tau_{gen}} \tag{5}$$

where N_t is the concentration of the effective generation center and E_i the midgap energy. The thermal velocities of the electrons and holes in this equation are set to be the same as in a majority of reports referred to, e.g. [5]. This gives the bulk generation current as

$$I_{bgen} = \frac{e\sigma_e\sigma_hv_{th}n_iN_tAw}{\sigma_e\exp((E_t-E_i)/kT)+\sigma_h\exp((E_i-E_t)/kT)} \tag{6}$$

The values of n_i and E_i are defined as

$$n_i = (N_cN_v)^{0.5}\exp(-E_g/2kT) \tag{7}$$

$$E_i = \frac{E_g}{2}+\frac{kT}{2}\ln\left(\frac{N_v}{N_c}\right) \tag{8}$$

where N_c, N_v are the effective densities of states in the conduction/valence band, respectively.

The form of I_{bgen} in Eq. (6) does not reflect the real process of carrier generation, which, as mentioned above, is a sequential transition of electrons from the valence band to the generation center and from this center to the conductance band by the thermal activation mechanism. To make it evident, Eq. (6) is transformed by inserting in it Eq. (7) and assuming that $E_i \approx E_g/2$, the latter will be justified in Section 2.2. This gives

$$I_{bgen} = \frac{e\sigma_e\sigma_hv_{th}n_i^2N_tAw}{\sqrt{N_cN_v}[\sigma_e\exp(-(E_g-E_t)/kT)+\sigma_h\exp(-(E_t/kT))]} \tag{9}$$

where the exponential terms in the denominator come from the probabilities of a sequential electron transition from the valence band to the DL and from the DL to the conduction band.

Eqs. (5), (6) and (9) describe carrier generation via a single DL and are symmetrical with respect to the generation via the energy levels located symmetrically to the midgap. If the deep level is in the upper half of the bandgap ($E_t > E_i$), the exponential term exp $[-(E_g-E_t)/kT]$ is larger than the second exponential term, provided the abs(E_g-E_t) exceeds several kT, and vice versa. The physical meaning of this regularity is in that the process which governs the current is the carrier transition through a larger energy gap, i.e. for $E_t < E_i$ it will be a process of electron emission from DLs to the conductance band, and for $E_t > E_i$ it will be a hole emission from DLs to the valence band. Then Eq. (9) may be simplified for abs$(E_g-E_t) > kT$, converting to

$$I_{bgen} = \frac{e\sigma_hv_{th}\sqrt{N_cN_v}N_tAw}{\exp(E_t/kT)} \tag{10a}$$

for DLs in the upper half of bandgap, and to

$$I_{bgen} = \frac{e\sigma_ev_{th}\sqrt{N_cN_v}N_tAw}{\exp((E_g-E_t)/kT)} \tag{10b}$$

for DLs in the lower part. Both equations have a similar exponential term referring to the biggest gap between the valence or conductance band and the current generation DL. It should be noted that in Eq. (10a) E_t is, on the one hand, the energy of the effective deep level and, on the other, the activation energy of the generation current. Thus, from the formal point of view, it would be right for the current to be expressed in terms of the current activation energy plus the effective cross-section σ_{eff}, which is convenient in practice and does not contradict the physics of the current generation. In the case of multiple defects, such as in irradiated Si detectors, each defect level gives an independent contribution to the current, i.e. $U=\Sigma U_i$. Below we will follow this approach, using Eqs. (6), (9), (10a) and (10b), in the simulation/fit of experimental $I(T)$ data.

The logic of the bulk generation current simulation given above differs from that of generation current temperature scaling described by the exponential term exp$(-E_g/2kT)$ in [8]. As is known, in Eq. (9) the term E_g expresses a real forbidden bandgap, being a fundamental parameter for semiconductor material. Therefore the activation energy of the bulk generation current equal to $E_g/2$ can be revealed only in a semiconductor doped with the DLs positioned exactly at E_i, which is not the case for Si

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