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Restriction on the gain in collected charge due to carrier avalanche multiplication in heavily irradiated Si strip detectors

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ABSTRACT

Recent experiments on silicon detectors developed by the CERN-RD50 collaboration for very high luminosity colliders showed a significant enhancement of the collected charge Q_c in Si detectors irradiated to the fluence of 10^{15}–10^{16} n_{eq}/cm^2 if the devices were operated at high bias voltage. The enhancement arises from carrier avalanche multiplication in high electric field of the junction. However, calculated and experimental results indicated that a maximum Q_c enhancement is much lower than the signal gain in avalanche photodiodes. The study of the collected charge in Si n-on-p strip detectors described here is focused on the restriction of the internal gain in irradiated Si strip detectors. It is demonstrated that (1) the gain in the collected charge due to avalanche multiplication is strongly restricted by the negative feedback arisen from a space charge limited current (SCLC negative feedback), which is an inherent property of heavily irradiated Si detectors with high concentration of radiation-induced defects; (2) the dependence of the gain on fluence is nonmonotonous due to competition between enhanced carrier trapping at high fluence and avalanche multiplication, which correlates with recent experimental results; (3) SCLC negative feedback makes the internal gain practically insensitive to the design of the detector region with high electric field. The results of this study show that the avalanche multiplication effect can be efficient in improving the radiation performance of Si detectors developed for the sLHC in a limited fluence range, which luckily covers the range expected in the upgraded LHC experiments.

1. Introduction

Radiation degradation in Si detectors used in the LHC experiments is a challenge for their successful long-term operation. Investigations of the CERN-RD50 collaboration [1] whose goal is the development of radiation hard semiconductor devices for very high luminosity colliders (sLHC) have clearly demonstrated that one of the possible ways to enhance the collected charge Q_c in heavily irradiated Si detectors is to operate them at very high bias voltages V [2–7]. This enhancement was first observed in Si n-on-p strip detectors irradiated to the fluence F up to 2.2×10^{16} n_{eq}/cm^2 operated at the bias voltage close to, or exceeding 1 kV and at lower T (−20 °C to −50 °C). The same was observed later in Si detectors of different configurations: pad, 3D (whose operational bias is lower due to a reduced distance between contacts), the so-called "spaghetti" diodes, and different types of Si [8–14]. Recently the RD50 collaboration showed that "spaghetti" detectors are still capable of collecting charge, when irradiated to 8×10^{16} n_{eq}/cm^2 [13].

Several mechanisms were considered to find what underlies this observation [15]. One might be the electric field in the base region; it increases under irradiation up to tens of kilovolt per centimeter and stimulates the carrier drift through the entire detector thickness. This mechanism, however, accounts only for ~30% Q_c enhancement in strip detectors, which does not agree with the experimental data. The contribution of the Poole–Frenkel effect, which predicts reduction of the cross-section of trapping centers in high electric field, does not seem to be significant.

Finally, in the Ioffe Physical-Technical Institute (PTI) the model was built based on carrier avalanche multiplication in high electric field of the n^+–p junction of n-on-p strip detector to explain the observed Q_c enhancement [16–18]. This model combined the effects of avalanche multiplication in the space charge region (SCR) near the n^+ contact, the hole injection from this region towards the p^+ contact, and hole trapping to the radiation induced deep level (DL) defects. It unveiled a new phenomenon referred to as space charge limited current (SCLC) negative feedback in the

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semiconductor devices utilizing the avalanche multiplication and having a high concentration of DLs [18]. The model predicted that this effect will prevent breakdown by stabilizing the detector performance at high voltage, and, nevertheless, at high F the avalanche multiplication efficiency will undergo reduction.

An internal amplification of the collected charge due to impact ionization is widely exploited in avalanche photodiodes (APDs). The latter are usually produced as the Read structures with a high doped thin region near the junction, or as structures with a deep diffused junction, and operate at several hundreds of volts up to kilovolts. The electric field in the ionization region is ranging within hundreds of kV/cm, this results in a superlinear gain vs. voltage dependences and the internal gain equal to 200 [19] and even more, which even qualitatively disagrees with irradiated detector characteristics. Although $Q_c(V)$ dependences for heavily irradiated Si detectors show different behavior, almost linear rise [7], or more pronounced rise as in 3D detectors [10,11], or a slight tendency to saturation [2,4,13], in a majority of cases enhancement of the collected charge compared with the charge generated by minimum ionizing particles (MIPs) does not exceed a factor of two (see e.g. [7]). It is only in pad Epi-Si p-on-n detectors that the Q_c enhancement rises up to 6–9 [8,9]. This value, however, is obtained when the collected charge is measured using laser or alpha-particle generation of nonequilibrium carriers near the detector surface, whereas MIPs generate carriers in the entire detector volume.

In order to interpret in terms of physics what underlies the restriction on Q_c enhancement in heavily irradiated Si detectors, we carried out the analysis of the electric field profiles and Q_c vs. V and F dependences. It will be shown that the SCLC negative feedback described in [20], in addition to stabilizing the irradiated Si detector characteristics, imposes a strong restriction on the internal gain, which leads to relatively low Q_c enhancement and even to its saturation. Thus, the signal reduction due to trapping cannot be compensated by the internal gain even at very high bias. This study considers only Si strip n-on-p detectors, as intensively developed in the framework of the RD50 collaboration program. Applicability of the model to the other detector configurations will be discussed.

2. Physics of Q_c enhancement modeling in irradiated Si detectors

The PTI model of enhancement of the signal from MIPs in heavily irradiated Si strip n–on–p detectors is based on the carrier avalanche multiplication phenomenon in the reverse biased abrupt n–p junction. The avalanche multiplication is taken to be the mechanism responsible for the formation of a steady-state electric field in SCR of irradiated detector and the enhancement of the collected charge. The major feature of the model, as compared with standard physics of the avalanche photodiode, is that it is built for a silicon diode with high concentration of radiation-induced DL defects. This makes the space charge density sensitive to the current flow through the detector bulk and leads to formation of the double peak electric field distribution in SCR of irradiated detectors [21].

The PTI model is based on parameterization of the radiation related changes in microscopic parameters of Si, which were ascribed to the introduction of two effective radiation-induced DLs: deep acceptors (DAs) and deep donors (DDs), located at E_c−0.53 eV and E_v+0.48 eV, respectively. This minimized set of DLs was applied earlier in numerous simulations of irradiated detector characteristics [21]. The model uses a linear approximation vs. fluence for microscopic parameters (DL concentrations with constant introduction rates, K_{DD} and K_{DA}, and the trapping time constant of electrons and holes,$\tau_{e,h}$), which correlates with the observations in Si detectors irradiated up to medium fluences ($\sim 2 \times 10^{14}$ n$_{eq}$/cm^2). Unlike the Hamburg model, where a linear dependence of the effective space charge concentration N_{eff} on F is used [22], in this study N_{eff} is calculated from the Poisson and continuity equations with trapping/detrapping statistics for deep level occupancy by the charge carriers (rate equations).

In the model two aspects of the carrier avalanche multiplication, which affect detector performance, are taken into account. These are multiplication of carriers from a steady-state thermally generated bulk current responsible for the electric field distribution via carrier trapping on DLs before multiplication, and multiplication of nonequilibrium carriers generated by MIPs, which is too small, even after multiplication, to affect the electric field distribution in the detector bulk. We consider impact ionization here only in the case of electrons, as the probability of the avalanche multiplication of holes is significantly lower. Consequently, multiplication occurs near the n$^+$ contact of n-on-p detectors and the extra holes increase the steady-state bulk generated current. We used a one-dimensional approach for the detector geometry, i.e. the electric field E is $E(x)$ where x is the distance from the p$^+$ contact in the direction normal to the detector back side.

In the model the following three processes are involved:

- Formation of a steady-state $E(x)$ distribution via trapping of equilibrium carriers from the steady-state thermally and avalanche generated current flows in the bulk, which give rise to the SCLC negative feedback.
- Trapping of MIP generated nonequilibrium carriers on DLs.
- Signal induction on the detector contacts by the “primary” nonequilibrium electrons and holes generated by particles and by the “secondary” nonequilibrium holes generated by avalanche multiplication during their drift from the n$^+$ contact into the detector bulk with a calculated $E(x)$ profile.

The model exploits several parameters whose values are derived from the experiment. The density of the bulk generated current I_b is parameterized as

$$I_b = e\sigma v_{th} n_i M F d \times \exp(-E_a/kT) \qquad (1)$$

where e is the elementary charge, σ the carrier cross-section, v_{th} the thermal velocity, n_i the intrinsic concentration, M the introduction rate of current generation centers, d the detector thickness, E_a the activation energy of the bulk generated current, k the Boltzmann constant and T the temperature. The trapping time constants of the electrons and holes, $\tau_{e,h}$, depend on the radiation fluence as

$$1/\tau_{e,h} = \beta_{e,h} F_{eq} \qquad (2)$$

where $\beta_{e,h}$ is the proportionality constant for electrons and holes.

The parameters used in the calculation are listed in Table 1. The introduction rates for DAs and DDs were used as defined in [18]. In n-on-p strip detectors there is the additional increase of the electric field at the n$^+$ side due to the focusing of the electric field

Table 1
Parameters used in the calculation of the $E(x)$ profile and $Q_c(V, F)$ dependences.

Parameter	Unit	Value	Reference
β_e	cm^2 s^{-1}	3.2×10^{-7}	[3]
β_h	cm^2 s^{-1}	3.5×10^{-7}	[3]
M	cm^{-1}	1	[23]
E_a	eV	0.65	[23]
K_{DD}	cm^{-1}	0.07	[18]
K_{DA}	cm^{-1}	2	[18]