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Operation of heavily irradiated silicon detectors in non-depletion mode

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Abstract

The non-depletion detector operation mode has generally been disregarded as an option in high-energy physics experiments. In this paper, the non-depletion operation is examined by detailed analysis of the electric field distribution and the current pulse response of heavily irradiated silicon (Si) detectors. The previously reported model of double junction in heavily irradiated Si detector is further developed and a simulation of the current pulse response has been performed. It is shown that detectors can operate in a non-depletion mode due to the fact that the value of the electric field in a non-depleted region is high enough for efficient carrier drift. This electric field originates from the current flow through the detector and a consequent drop of the potential across high-resistivity bulk of a non-depleted region. It is anticipated that the electric field in a non-depleted region, which is still electrically neutral, increases with fluence that improves the non-depleted detector operation. Consideration of the electric field in a non-depleted region allows the explanation of the recorded double-peak current pulse shape of heavily irradiated Si detectors and definition of the requirements for the detector operational conditions. Detailed reconstruction of the electric field distribution gives new information on radiation effects in Si detectors.

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1. Introduction

Application of Si detectors in high-energy physics (HEP) experiments is based on particular advantages of this semiconductor in well-controlled modification of material properties such as type of conductivity, resistivity and concentration of the impurities such as oxygen and carbon. Another benefit of Si is the well-developed manufacturing technology of devices with variable design and dimensions. Being installed into a semiconductor tracker of ATLAS or CMS experiments at the Large Hadron Collider (LHC), Si detectors will be exposed to the intensive radiation of high-energy charged particles. Radiation damage results in the introduction of defects. Most of them have deep energy levels that affect the detector operation negatively [1–3]. The deterioration of the detector operational characteristics has three aspects [3,4]:

(1) increase of reverse current,
(2) increase of detector operational bias voltage required for full depletion and
(3) reduction of the charge collection efficiency (CCE).

CCE reduction is related to two effects. First, deep levels (DLs) of radiation-induced defects act as trapping centers for non-equilibrium carriers. The second effect is a reduction of the detector signal due to ballistic deficit, which becomes significant at a short shaping time required by experiments (25 ns for ATLAS). These aspects of CCE reduction become more crucial with the consideration of the proposed luminosity upgrade of the LHC when the radiation fluence will be as high as $10^{16}\,\mathrm{cm}^{-2}$ and the shaping time will be reduced. The increase of full depletion voltage (V_{fd}) and ballistic deficit cannot be overcome under

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real experimental conditions of detector operation at a fixed bias voltage. Therefore, the detector operation inevitably changes from the full depletion mode to the non-depletion one. Hence, the non-depletion mode of Si detector operation should be studied and considered as an alternative of the full depletion mode.

Electric field distribution $E(x)$ in the detector bulk is an important characteristic of irradiated Si detectors due to its influence on both charge trapping and ballistic deficit. Earlier studies have shown that Si detectors irradiated beyond space charge sign inversion (SCSI) have a structure with two junctions, i.e., two depleted regions adjacent to the p^+ and n^+ contacts [5,6]. Depending on reverse bias, there is an electrically neutral base between these two junctions. A qualitative explanation of the electric field distribution with two maxima at the p^+ and n^+ contacts was first suggested in Ref. [7] and related to trapping of free carriers into DLs of radiation-induced defects. The detailed model of this Double Peak (DP) $E(x)$ distribution considered the trapping of free carriers created by the bulk generation current into the midgap energy levels of deep donors (MGDs) and deep acceptors (MGAs) with activation energies of $E_v + 0.48\,\text{eV}$ and $E_c - 0.52\,\text{eV}$, respectively [8,9]. Trapping of holes to the MGD levels occurs near the p^+ contact that creates a depleted region with positive space charge, while electrons are captured by MGAs near the n^+ contact and a depleted region with negative space charge arises. The charged fractions of DLs contribute to the space charge concentration N_{eff}. Direct experimental evidence of the DP electric field profile was obtained by comparing the measurements of optical beam-induced current and surface potential in detectors irradiated by 25 MeV protons with an 1 MeV neutron equivalent fluence of $2 \times 10^{14}\,\text{n}_{\text{eq}}/\text{cm}^2$ [10]. The measurements showed the existence of two depletion layers adjacent to the contacts that are separated by a layer inverted to p-type Si with a resistivity being close to intrinsic.

The pulse response of heavily irradiated Si detector also shows specific DP shape [6–9,11–13]. The first observation of this shape was obtained for detectors irradiated by neutrons and operated in the temperature range 305–240 K [7]. The physics of detector operation with DP $E(x)$ distribution was investigated in the frame of RD48, RD39 and RD50 CERN Collaboration programs and was considered in two aspects. First, the qualitative explanation of DP response shape was based on its correlation to the DP $E(x)$ profile which arises from trapping of free carriers to the midgap energy levels specified above [8,9]. The trapping is sensitive to the temperature and thus the distribution of $E(x)$ varies with T resulting in the changes of the pulse response shape. Secondly, a simplified approach for the evaluation of the effect of DP $E(x)$ distribution on the detector response was presented in Ref. [6]. The detector model included the depleted regions adjacent to the p^+ and n^+ contacts and the base region *in between*. The base region was considered as a neutral region inside the detector, i.e., without an electric field in steady-state conditions. During the charge collection, the charge moving in any depleted region induces a transient electric field in the base, which in turn stimulates a transient current in it. This current provides transfer of injected carriers through the base region that generates a slow component of the detector response or the second peak. In this model, the influence of the base region on the detector response was considered as a relaxation process with a time constant of Maxwell (or dielectric) relaxation time. This model explains correctly the trends in the influence of the neutral base; however, the model could not quantitatively explain the full detector response. Additionally, the influence of the low carrier lifetime in irradiated detectors was disregarded, which creates a problem with the interpretation of the experimental results.

The new approach for characterization of heavily irradiated Si detectors presented in this paper is based on the detector model in which significantly high electric field in the non-depleted electrically neutral base region arises. This electric field stimulates drift of the collected carriers through the base region and the detector response can be simulated as a result of the carrier drift through the entire detector thickness. This new approach allows the development of a formal method for the electric field reconstruction from the detector current pulse response. This provides an additional "experimental tool" for the investigation of heavily irradiated detectors. The examples of the reconstructed $E(x)$ profiles in heavily irradiated Si detectors processed from various materials and with different technologies illustrate the soundness of the developed model. These examples also show the effect of the neutral base on the detector response and give a clear understanding that heavily irradiated Si detector can operate at a bias voltage below full depletion voltage as a "virtual" fully depleted detector.

2. Experimental observation of DP response shape in irradiated Si detectors

In heavily irradiated detectors, the electric field distribution $E(x)$ arises from the filling of the DLs of radiation-induced defects by trapping of free carriers. The free carriers are electrons and holes created by the bulk generation current. The charged fractions of midgap DLs contribute to N_{eff}, which defines the electric field distribution and collection time t_{coll} for electrons/holes and thus the shape of the detector pulse response [14,15]. Since the concentration of any of radiation-induced defect correlates to radiation fluence F, the shape of the current pulse response varies with F.

In the measurement of transient current shapes, a pulse laser with a wavelength of 670 nm and pulse duration of 1 ns was used for non-equilibrium carrier generation. Beneficial annealing of the detectors was carried out before the measurements. The current pulse shapes were recorded at room temperature.