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Characterization of irradiation induced deep and shallow impurities

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ABSTRACT

Silicon Detectors close to the interaction point of the High Luminosity Large Hardron Collider (HL-LHC) have to withstand a harsh irradiation environment. In order to evaluate the behaviour of shallow and deep defects, induced by neutron irradiation, spreading resistance resistivity measurements and capacitance voltage measurements have been performed. These measurements, deliver information about the profile of shallow impurities after irradiation as well as indications of deep defects in the Space Charge Region (SCR) and the Electrical Neutral Bulk (ENB). By considering the theoretical background of the measurement both kinds of defects can be investigated independently from each other.

1. Introduction

Silicon detectors, which operate in recent and future High Energy Physics (HEP) experiments have to face a hostile radiation environment. The high flux of penetrating particles induces lattice defects and modifies the electrical properties of the material by generating a variety of additional energy levels inside the band gap. In the case of a depleted sensor most deep traps are activated inside the Space Charge Region (SCR) and act as generation and trapping centres. In contrast, these traps contribute only partially to the electrical properties of the Electrical Neutral Bulk (ENB). Dopant removal effects result in an increased resistivity ρ, concerning the homogeneously doped bulk as well as doping profiles. Such modifications of the doping profiles are only partially measurable with Capacitance Voltage (CV) methods. Four Point Probe (FPP) measurements and dedicated resistor test structures have been used [3] to investigate the bulk resistivity. Nevertheless profiles of electrically active dopants can only be characterized with high spatial resolution by using a Spreading Resistance Probe (SRP) technique, realizable with standard HEP equipment [1]. The results in turn only apply to the ENB and not to the biased sensor under operation. Especially after high irradiation fluences deep acceptor-like defects determine the behaviour of the biased sensor and the influence of shallow defects becomes negligible. Therefore CV measurements can be used to investigate deep traps inside the SCR. Due to the large time constant of these traps the measurements become strongly dependent on the measurement parameters. Therefore one has to be careful by extracting basic parameter as the full depletion voltage.

2. Theory

As almost all impurities are occupied inside the SCR the concentration of fixed charge N_{eff} is usually extracted from CV measurements. Irradiation induced defects, donors N_d as well as acceptors N_a, are of main interest and N_{eff} is calculated as a function of the 1 MeV neutron-equivalent fluence Φ_{eq}. The stable damage contribution N_C, which is not influenced by any subsequent temperature treatment equals [2]

$$N_C(\Phi_{eq}) = N_{C0} e^{-c\Phi_{eq}} + \beta\Phi_{eq} = N_d + N_a \tag{1}$$

Thereby the initial concentration N_{C0} and the removal constant c determine the exponential dopant removal process, covered by the first term of Eq. (1). The second term corresponds to the linear introduction of deep acceptor-like levels with the constant rate β. In the case of low fluences the exponential removal process determines N_{eff}, while the slowly rising amount of deep traps is negligible. N_{eff} adjusts with the concentration of deep traps after a large number of dopants have been removed from their regular lattice position. Both effects can be observed with measurements on the ENB and SCR.

The resistivity of the ENB is determined by shallow impurities only, which are occupied with respect to the Fermi occupancy function. Therefore simple resistivity measurements on the ENB deliver the possibility to investigate the concentration of electrically active dopants independent of the presence of deep defects. By using a SRP technique dopant removal effects can be studied with high spatial resolution and the characterization of doping

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profiles after irradiation and temperature treatment is possible. Due to the fact that not all impurities are occupied inside the ENB the relation between ρ and Φ_{eq} is non trivial. The resistivity of the ENB correlates to the free charge N, which equals the concentration of electrically active shallow impurities n.

$$\rho(x) = \frac{1}{qn(x)\mu(N(x))}; \qquad N(x) \cong n(x) \tag{2}$$

Different fluences affect ρ by their impact on $n(\Phi)$. The ENB is by definition in thermal equilibrium and the charge neutrality equation holds

$$n + N_a^+ = p + N_d^- \tag{3}$$

Eq. (3) can be used to calculate the Fermi level shift $E_F(\Phi_{eq})$ and therefore $n(E_F)$ as a function of the fluence. Thereby the partial ionization $N_{d/a}^{-/+}$ of radiation induced donor and acceptor traps $N_{d/a}$ (Eq. 1) has to be taken into account. By assuming proper trap energy levels E_d/a, $E_F(\Phi_{eq})$ can be numerically calculated [3]. A consequence of the modified Fermi level position is that inside the ENB almost no deep levels are occupied. Since the ENB becomes slowly intrinsic, E_F is shifted towards the mid gap energy and its distance to deep acceptor states, which are placed in the second half of the forbidden gap, increases [3]. Thus it has been suggested to attribute resistivity changes in the ENB to dopant removal effects only [4].

Dopant removal is explained by the shift of dopants like phosphor (P) from simple substitutional positions to interstitial ones. Primary displacement defects like vacancies (V) interact with dopants and create VP defects with a very high annealing temperature [4]. Defects, which are mobile at room temperature are postulated to migrate out of a primary damage clusters in more advanced models. After leaving the cluster region with a high concentration of lattice defects they may interact with dopants or vanish into other sinks [5]. This process is proportional to the amount of available dopants N_{C0} but also to the dopant removal constant c, which is indirect proportional to the initial donor concentration N_{C0} [2] (Eq. (1)).

If a bias voltage V is applied to the structure, band bending effects occur, which determine the occupancy of traps inside the depleted layer. For deep traps the difference of their energy levels to the levels of the band edges is large. As their time constant is also large deep defects will only be able to follow the test signal of a capacitance measurement if small frequencies are used. In contrast shallow defects contribute for all frequencies. The basic process can be explained by assuming n-type silicon, which contains the shallow donor concentration $N_d(x)$ at the energy level $E_D(x)$ and in addition one donor-like deep level of the concentration $N_t(x)$ at $E_T(x)$ (Fig. 1) [6]. Generally these concentrations may be non uniformly distributed along the depleted layer. If the concentration of free carriers inside the depleted layer is negligible the quasi-Fermi level will stay flat throughout the SCR. Thus the occupancy of a deep impurity level changes at the position where the quasi Fermi level crosses the energy level of the deep impurity.

The deep acceptor-like states N_T are assumed to finally lead to the sign inversion of the space charge from positive to negative. As this effect has been observed for different types of silicon material with different doping and impurity concentrations, specific defects are not sufficient to explain the process. Cluster related defects have been recently postulated to be responsible for type inversion process [7].

A comparison between measurements of the ENB and SCR is shown in Fig. 2 for n-type silicon. The influence of donor removal can be compared with the influence of acceptor-like deep impurities in n-type material. Therefore ρ is obtained from ENB measurements and N_{eff} extracted from CV measurements. An apparent resistivity has been calculated (Eq. (2)) by using the effective doping concentration inside the SCR N_{eff} instead of the free charge inside the ENB n [3]. As long as donor removal is dominant both methods deliver similar values while the difference increases with the influence of deep defects.

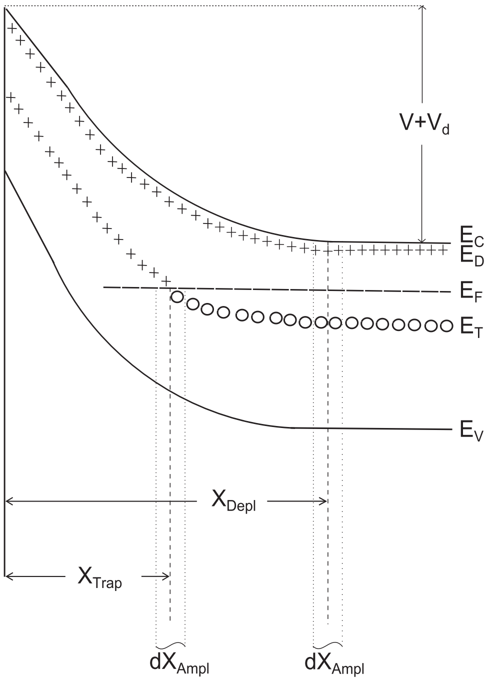

Fig. 1. The schematic energy band diagram of a n-type structure with an applied bias voltage V, a donor energy level E_d and a deep trap E_{dt} and a measurement amplitude dX_{Ampl} [6].

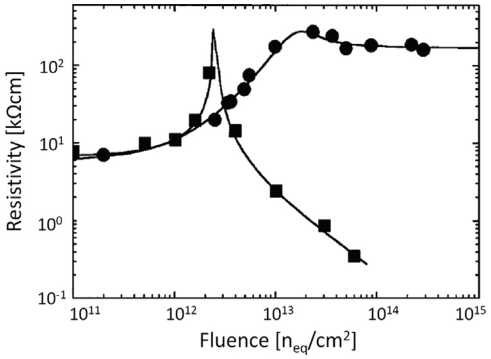

Fig. 2. The material resistivity (●) and the apparent resistivity value, calculated with the effective doping concentration (Eq. (2), ■) is shown as a function of the equivalent neutron fluence [3].

2.1. The measurement methods

Inside the ENB profiles of electrically active dopants can only be characterized by SRP. A SRP measurement is performed by contacting the beveled semiconductor surface with two closely aligned tungsten carbide probes, which measure the resistance at different position. If the probe tips are aligned close to each other, the measured resistance will be dominated by the spreading resistance R_{sp} (Fig. 3). The measurement of the spreading resistance with small probe tips with radius a provides the value of the material resistivity ρ according to

$$R_{sp} = 2a\rho \tag{4}$$