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Evaluation of gamma dose effect on PIN photodiode using analytical model

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ABSTRACT

The PIN silicon photodiodes are widely used in the applications which may be found in radiation environment such as space mission, medical imaging and non-destructive testing. Radiation-induced damage in these devices causes to degrade the photodiode parameters. In this work, we have used new approach to evaluate gamma dose effects on a commercial PIN photodiode (BPX65) based on an analytical model. In this approach, the NIEL parameter has been calculated for gamma rays from a ^{60}Co source by GEANT4. The radiation damage mechanisms have been considered by solving numerically the Poisson and continuity equations with the appropriate boundary conditions, parameters and physical models. Defects caused by radiation in silicon have been formulated in terms of the damage coefficient for the minority carriers' lifetime. The gamma induced degradation parameters of the silicon PIN photodiode have been analyzed in detail and the results were compared with experimental measurements and as well as the results of ATLAS semiconductor simulator to verify and parameterize the analytical model calculations. The results showed reasonable agreement between them for BPX65 silicon photodiode irradiated by ^{60}Co gamma source at total doses up to 5 kGy under different reverse voltages.

1. Introduction

Photodiode is one of the optoelectronic semiconductor device which are widely used in the environments with high level of ionizing radiation such as space, accelerators, medical imaging systems and nuclear power plants (McLean, 1987; Hopkinson, 1994; Moscatelli et al., 2013). A silicon p-i-n photodiode (PIN) is similar to the ubiquitous p-n diode, except a nearly intrinsic region exists between the two highly doped terminals (Bell, 2009). Radiation damage in the PIN photodiodes can occurs when there is energy deposition in a sensitive volume of these device mainly in the form of ionization and/or atomic displacement (Lutz, 1999; Onoda et al., 2001; McPherson et al., 1997).

Ionization generates electron–hole pairs along the path of incident ionizing radiations. Carriers created either recombine or move away from the point of generation by diffusion or drift. Then those either undergo recombination, or become trapped or are collected at a semiconductor electrode (Messenger and Ash, 1986). Displacement damages are related to the dislocation of atoms from their initial lattice position resulting from non-ionizing energy transfer which are termed 'non-ionizing energy losses' (NIEL). This is produced by the impact of energetic particles to generate point defects (i.e. vacancies and interstitials). These defects cause alterations in the periodicity of the lattice, originating energy levels located in the forbidden band of the semiconductor. As consequence of this, atomic displacement damages, which produce a decrease in the carriers' lifetime, will affect semiconductor electrical properties (Srour et al., 2003).

The main characteristic of the silicon photodiodes, which is expected to be changed after irradiation, is the effective dark current. Although in gamma irradiations, the densities of the primary defects (PKAs) are small compared to the densities that occur in neutron and protons irradiations, produced electrons can generate considerable divacancies and vacancy complexes in silicon bulk (Moll et al., 1997; Gökçen et al., 2008).

Knowledge of the behavior of the different electronic devices exposed to spatial radiation is a challenge for designers of radiation-hardened systems. Therefore, as a mandatory step to assess the applicability of silicon PIN photodiode devices in a radiation environment, radiation tests must be performed to evaluate their response to radiation damage (McPherson et al., 1997; Kalma and Hardwick, 1978). The most practical approach requires expensive and time-consuming experiments. For this reason, there is an increasing interest in the development of accurate modeling and simulation techniques to predict device response under different conditions such as radiation dose rate, particle energy and bias. These modelling of electronic devices are achieved with the development of the computer codes, which involve equations representing their physical behavior (Chumakov et al., 1999; Barnaby et al., 2009; Eladl, 2009).

In recent years, several of the present authors have studied the

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behavior of a PIN photodiode under different light intensities and different proton fluences (Cappelletti et al., 2006). Previous results have shown that the model developed reproduces the experimental results with high precision (Yag¨uez et al., 2004). In this work, we have used new approach to evaluate gamma irradiation effects on a commercial PIN photodiode (BPX65) based on an analytical model. In this approach, the NIEL parameter has been calculated for gamma rays from a ^{60}Co source, as an irradiation standard, by the Monte Carlo transport code of GEANT4. The radiation damage mechanisms as well as the formation of deep traps at silicon band gap due to the primary knock on silicon atoms have been considered by solving numerically the Poisson and continuity equations with the appropriate boundary conditions, parameters and physical models. Defects caused by radiation in silicon have been formulated in terms of the damage coefficient for the minority carriers' lifetime. The gamma induced degradation parameters of the silicon PIN photodiode have been analyzed in detail and the results were compared with experimental data and as well as the results of ATLAS semiconductor simulator.

2. Modeling approach

A simplified 1-D model has been used to introduce the photodiode behavior. However, surface effects and non-uniformities along the lateral direction are ignored. This model can represent the investigation of this semiconductor devices behavior under irradiation. The most significant effect of gamma irradiation is the change in the device characteristics along the path of the collected signal charge (Moll et al., 1997). The free carrier (electron and hole) concentration and electrostatic potential through the device were extracted from the model. Therefore, the model includes the three basic semiconductor equations of Poisson and continuity for electrons and holes as represented by Eqs. (1)–(3) respectively (Sze and Ng, 2006).

$$\frac{d^2\psi}{dx^2} = -\frac{q}{\varepsilon}\left[\Gamma + p - n - \sum N_T^A f(E_T) + \sum N_T^D (1 - f(E_T))\right] \tag{1}$$

$$\frac{\partial n}{\partial t} = \frac{1}{q}\frac{dJ_n}{dx} - R \tag{2}$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\frac{dJ_p}{dx} - R \tag{3}$$

where ψ is the electrostatic potential, ε is the dielectric permittivity of the material, q is the electron charge, n and p are the concentrations of electron and hole respectively, Γ is the net doping concentrations, J_n and J_p represent the current densities of electrons and holes respectively, and R is the net recombination–generation rate. Furthermore, N_T represents the density of filled trap levels introduced during irradiation. The density of filled acceptors as N_T^A and donors as N_T^D are given by the product of the density of available trap levels, and the electron occupation probability, $f(E_T)$ which is described more in details in the following. Current density expressions are also formulated on the basis of the drift-diffusion approach as represented by Eqs. (4) and (5) for electrons and holes, respectively (Sze and Ng, 2006).

$$J_n = qD_n\frac{dn}{dx} - q\mu_n n\frac{d\psi}{dx} \tag{4}$$

$$J_p = -qD_p\frac{dp}{dx} - q\mu_p p\frac{d\psi}{dx} \tag{5}$$

where $\mu_{n(p)}$ is the electron (hole) mobility; $D_{n(p)}$ is the electron (hole) diffusion coefficient. This quantity can be used to attain experimental observables such as dark current and photocurrent at given bias voltages.

Trap levels which were introduced during irradiation affecting carriers transport are considered by means of a mathematical model which takes into account the carriers' emission and capture rates for each trap, based on Shockley- Read-Hall (SRH) theory (Shockley and Read, 1952; Hall, 1952). The SRH approach considers the number, location and type of each trap level within the forbidden gap of the semiconductor. The recombination-generation rate for a donor or an acceptor level is given by Eq. (6).

$$R_{SRH} = \frac{n.\,p - n_{\mathrm{int}}^2}{\tau_n(p + p_1) + \tau_p(n + n_1)} \tag{6}$$

where n_{int} is the intrinsic carrier concentration; τ_n and τ_p are the minority carrier lifetimes of electrons and holes, respectively. Parameters n_1 and p_1, which depend on the energy level of traps, are expressed by Eqs. (7) and (8) (Lampert, 1956).

$$n_1 = n_{\mathrm{int}}\exp\left(\frac{E_T - E_I}{kT}\right) \tag{7}$$

$$p_1 = n_{\mathrm{int}}\exp\left(\frac{E_I - E_T}{kT}\right) \tag{8}$$

where E_T is the energy level of the trap, E_I is the intrinsic Fermi level, T is the lattice temperature and k is the Boltzmann constant.

The net recombination-generation term to be included in the carrier continuity equations is the sum of the rates for each trap level. The total charge caused by the presence of traps deep in the band gap is subtracted from the net charge term in the Poisson equation, resulting in Eq. (1). This term implements the inclusion of gamma irradiation damage to the silicon crystal by the introduction of acceptor and donor like states. The dynamic equilibrium case is assumed as a situation in which the occupation probability of each introduced trap states is supposed to be time-independent and the recombination rates for electrons and holes are equal. In such a case, the electron occupation function, where fraction of filled trap levels at energy E_T probability for each trap can be written as Eq. (9) (Lampert, 1956).

$$f(E_T) = \frac{\tau_p.\,n + \tau_n.\,p_1}{\tau_p(n + n_1) + \tau_n(p + p_1)} \tag{9}$$

where, the lifetimes of minority carrier for electrons and holes are given by the Eqs. (10) and (11) respectively.

$$\tau_n = \frac{1}{C_n.\,N_T} \tag{10}$$

$$\tau_p = \frac{1}{C_p.\,N_T} \tag{11}$$

where C_n and C_p are the capture rates for electrons and holes, defined as $C_{n(p)} = \sigma_{n(p)}.v_{n(p)}$, in which $\sigma_{n(p)}$ is the capture cross section for electrons (holes) and $v_{n(p)}$ as the carrier thermal velocities.

The dark current increases during gamma irradiation is due to the introduction of recombination centers with energy levels deep in the forbidden gap of the silicon photodiode. This process is introduced in the simulation by the modification of the minority carrier life time which controls the SRH thermal generation- recombination term in the continuity equations. The rate at which the electrical properties of the semiconductors are degraded in a radiation environment is usually formulated in terms of the damage coefficient (Messenger and Ash, 1986). The main effect is a variation in minority carrier life time as expressed by Eq. (12).

$$\frac{1}{\tau_r} = \frac{1}{\tau_{r0}} + K_\tau \Phi \tag{12}$$

where τ_{ro} and τ_r are the carrier lifetimes before and after irradiation respectively, Φ is the incident particle fluence, in silicon under equilibrium conditions. In addition, K_τ is the lifetime damage- coefficient which characterizes the detailed phenomenological information relating to the physical interactions between the semiconductor material and the incident particles. Many experimental investigations have proved that to first order one might consider a linear proportionality, independent of the particle, between the damage coefficient and the particle NIEL (Marshall and Marshall, 1999). This is the essence of the