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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).

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

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

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

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).

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

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).

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

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

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

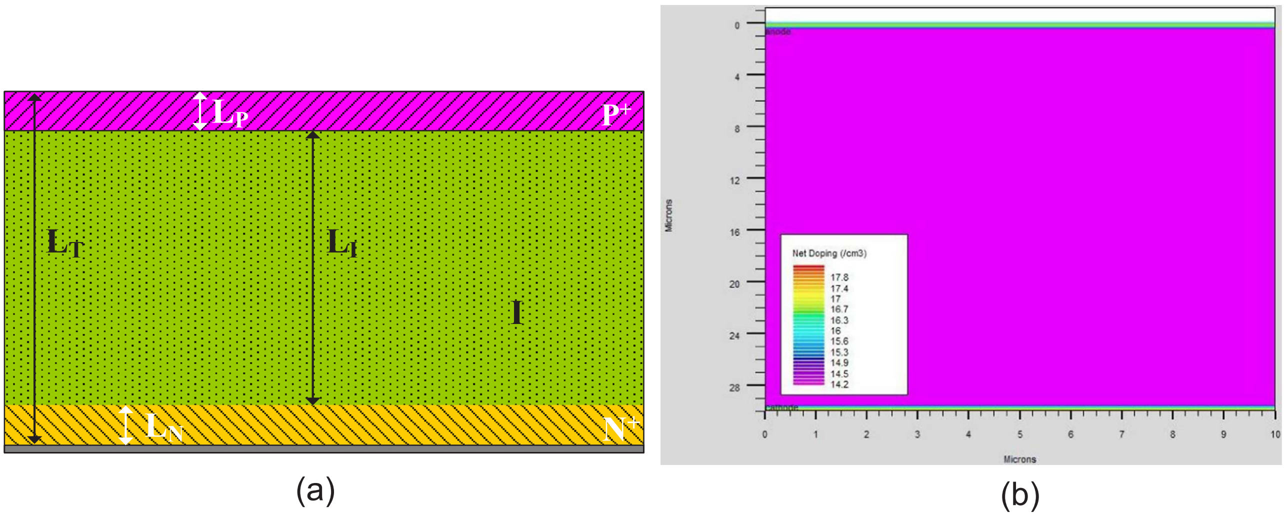

Fig. 1. (a) The schematic structure of PIN photodiode (b) The simulated structure of BPX65 in ATLAS.

use of the NIEL parameter since it allows to measure K_τ only for one particle (at one specified energy) from which the values for all particles (and energies) are easily estimated. Therefore, we use Eq. (13) to find the lifetime damage-coefficient for Co-60 ($K_{\tau\gamma}$).

$$\frac{NIEL_\gamma}{NIEL_n} = \frac{K_{\tau\gamma}}{K_{\tau n}} \tag{13}$$

Here, we considered $K_{\tau n} = 10^{-7}$ cm^2/s for 1 MeV neutrons with the $NIEL_n$ value of 2.04×10^{-3} MeV cm^2/g in silicon which were obtained by Akkerman et al. (2001). Therefore, we needed to calculate the $NIEL_\gamma$ for predicting the carrier lifetimes degradation of silicon photodiode device due to the Co-60 irradiation.

Generally, it is difficult to obtain the NIEL (gamma) directly from the experiment for the displacement damage caused by nuclear particle and gamma ray induced secondaries, because of the short range of the recoils. The main approach is thus to use theoretical calculations (Messenger et al., 1999). Since the evaluation of the NIEL (gamma) should involve proper treatment of each interaction physics, a charged particle Monte Carlo code with complete cross-section library can be used. Geant4 is a Monte Carlo code for transport radiation through the matters (Agostinelliae et al., 2003). This code has been developed in C++ language and has been applied frequently in space radiation study, microdosimetry, medical application etc. It includes different physics models to calculate particle interaction in a wide range of energy. Therefore, Geant4 has been used to calculate the electron fluence and NIEL (gamma) produced by gamma irradiation in sensitive volume of silicon PIN photodiode.

On the other hand, the increase in dark current (I_{DC}) is related to the minority carrier lifetime of the photodiode as Eq. (14) if the generation-recombination is dominated by mid-band levels caused by defects (Schroder, 1982):

$$I_{DC} = \frac{qwAn_{\mathrm{int}}}{2\tau} \tag{14}$$

where, w is depletion depth of photodiode and A is the active area. Therefore, the variation in the dark current induced by incident particle fluence, Φ, is obtained by substituting the carrier lifetime with that in the Eq. (12). The difference between the dark current before and after irradiation is represented by ΔI_{DC} as Eq. (15).

$$\Delta I_{DC} = K_R \Phi \tag{15}$$

The device parameters can be involved into the constant by defining a new damage-coefficient (K_R). In general, this damage-coefficient in semiconductors depend on the parameters such as type and energy of the incident particle, kind of material, resistivity, types and concentration of impurities, injection level, temperature and elapsed time after irradiation (McPherson et al., 1997; Srour and Lo, 2000).

A finite-difference approach has been used to solve the Eqs. (1)–(3) in one dimension with the appropriate boundary conditions. Then, the potential and free carrier densities have been calculated at each node, which subdivide the solution domain, by means of the Scharfetter-Gummel method (an iterative numeric method) (Gummel, 1964). Knowing of these quantities allows calculating the dark current with the purpose of evaluating the radiation-induced traps on the analyzed devices. The calculation process was repeated until the relative error at each grid-point fell below a predetermined level (1×10^{-10}).

In addition, Radiation-induced degradation can be calculated numerically using semiconductor device simulators. ATLAS is one of the physically-based commonly device simulators, which can predict the electrical characteristics associated with specified physical structures and bias conditions (ATLAS User's Manual, 2012). Steady state, transient, AC-small signal and optical device simulation can be performed with this simulator.

Due to the lack of a precise description of the real PIN photodiode (BPX65), we used approximated values for our simulations. However, the approaches that we used for the model allow us to obtain a quite real description of the effects of the radiation on the devices. Fig. 1 shows the schematic diagram of simulated PIN photodiode. L_P, L_I and L_N are the thicknesses of P+, intrinsic and N+ regions, respectively. Actually, the intrinsic layer is not a pure silicon region but a slightly n-type doped one (Sze and Ng, 2006). The parameters of the various implants for BPX65 photodiode are detailed in Table 1.

It has been assumed that gamma penetrates the devices through all directions. As described, reasonable layer dimensions and doping profiles (with Gaussian distribution) have been adopted for device simulation purposes, with L_T = 30 µm, L_I = 27.75 µm, $L_P = L_N$ = 2.25 µm and active area of 1 mm^2. Uniform densities were considered both, for shallow impurities and traps. The most likely candidate for the deep acceptor level related damage after Co-60 irradiation detectable with the DLTS method is the VO_i complex which is situated 0.17 eV below the conduction band (E_C − 0.17 eV) (Corbett et al., 1961). The main

Table 1
The specification of implants for simulated BPX65 photodiode structure.

Implant	Concentration [cm^{-3}]	Depth [µm]
P+	Peak level 1×10^{18}	2.25
N+	Peak level 1×10^{18}	2.25
I	Uniform 1.5×10^{14}	27.75

Table 2
Main parameters used in ^{60}Co-gamma-irradiated samples.

Parameter	Values
Electrons capture cross section (σ_n)	1.48×10^{-14} cm^2
Holes capture cross section (σ_p)	1.48×10^{-14} cm^2

parameters used in ^{60}Co gamma irradiated samples are given in Table 2.

3. Experimental details

The radiation damage analysis was performed on a structure based on the silicon PIN photodiodes of BPX65. This photodiode is a family of semiconductor detectors feature Centronic's 1mm^2 cross-sectional area, high speed, high sensitivity chip, which has already been successful in a wide variety of applications (BPX65 Silicon p-i-n Photodiode Datasheet). The dark current of these photodiodes was measured employing a Keithley 485 picoammeter. During the measurements, the photodiode was isolated in a dark box to avoid stray light which effects the measurements. The reverse voltage was set by the Hameg HMP4030 Programmable power supply.

The devices under test were irradiated by a Co-60 gamma source, with the energies of 1.33 and 1.17 MeV and dose rate of 2.71 Gy/s (in Si). The photodiodes were exposed to irradiation dose up to 5000 Gy (in Si). The components were irradiated in the air at a temperature of 21 °C. The results were obtained by averaging the parameters which were measured for five photodiodes in each dose level.

4. Results and discussions

The dark current versus reverse bias characteristic for BPX65 PIN silicon photodiode before irradiation is shown in Fig. 2. As illustrated, the results associated with analytical model, experimental data and ATLAS simulations have been compared.

As depicted in Fig. 2, the dark current of the desired photodiode increases with reverse voltage at the time before gamma irradiation. The dark current was 0.882 nA under reverse voltage of 30 V before irradiation. There is an acceptable agreement between model results and ATLAS simulations and experimental data which has been used for extracting simulation parameters of BPX65 photodiode. The ATLAS simulation results reveal approximately 15% relative difference with experimental while the model displays approximately 6% with experimental result.

The described silicon photodiodes were irradiated with total dose levels up to 5000 Gy by Co-60 gamma source. As illustrated, Compton electrons generated by incident photons, are responsible for displacement of the lattice atoms in this structure. The distribution of primary electron fluence was calculated using GEANT4 in silicon structure of desired photodiodes. The energy distribution of primary electrons fluence from Co-60 gamma irradiation per source particle in simulated photodiode structure is shown in Fig. 3 as well as the NIEL (gamma) distribution of produced electron in silicon photodiode. This distribution has been obtained based on computing the Coulomb interactions on nuclei which has been carried out by an online validated calculator for more verification (SR-NIEL and Nuclear Stopping Power Calculators for Elements and Compounds). In addition, The Displacement Threshold Energy in Silicon has been considered 21 eV. In the present treatment, screening effects are factorized in the expression for the differential cross section (Boschini et al., 2011). However, it has to be remarked - as derived by Zeitler and Olsen (Zeitler and Olsen, 1964) - that for electron energies above 200 keV the overlap of spin and screening effects is small for all elements and for all energies.

Therefore according to the Eq. (13), the calculation of NIEL (gamma) using the values in Fig. 3 gives $K_\tau = 4.9 \times 10^{-12}$ cm^2/s. In addition, the values of damage-coefficient K_R, which were obtained by Geant4 calculation of NIEL (gamma) and measured variation in dark current before and after irradiation (Eq. (15)) for different reverse voltages are depicted in Fig. 4. It can be clearly seen that the damage in silicon PIN is greatly dependent on the photodiode reverse voltage.

As illustrated, the minority carrier lifetime of device decreases with increasing primary electron fluence in silicon photodiode structure from Co-60 gamma source. The variation of BPX65 photodiode dark current versus total dose under reverse voltage of 20 V is shown in Fig. 5 which was given for comparison the analytical model results with the experimental data and ATLAS simulation results.

It can be seen that the dark current increases with total dose linearity. The dark current of BPX65 photodiode under reverse voltage of 20 V is calculated 1.01 nA at total dose of 5000 Gy which was about 2 times greater than its value before irradiation. The maximum relative difference between experimental and model calculation results is 6.2%. Moreover, it is 1% between ATLAS results and model calculation. Fig. 6 shows the dark current results of BPX65 photodiode under several reverse voltages as function of total dose.

It can be noticed that the difference of photodiode dark current between before and after irradiation increases with the increase in the reverse voltage. Thus, the differences between dark currents before and after 5000 Gy total dose irradiation were 9.01×10^{-3}, 3.66×10^{-1} and 1.15 nA at reverse voltages of 1 V, 15 V and 35 V respectively. The

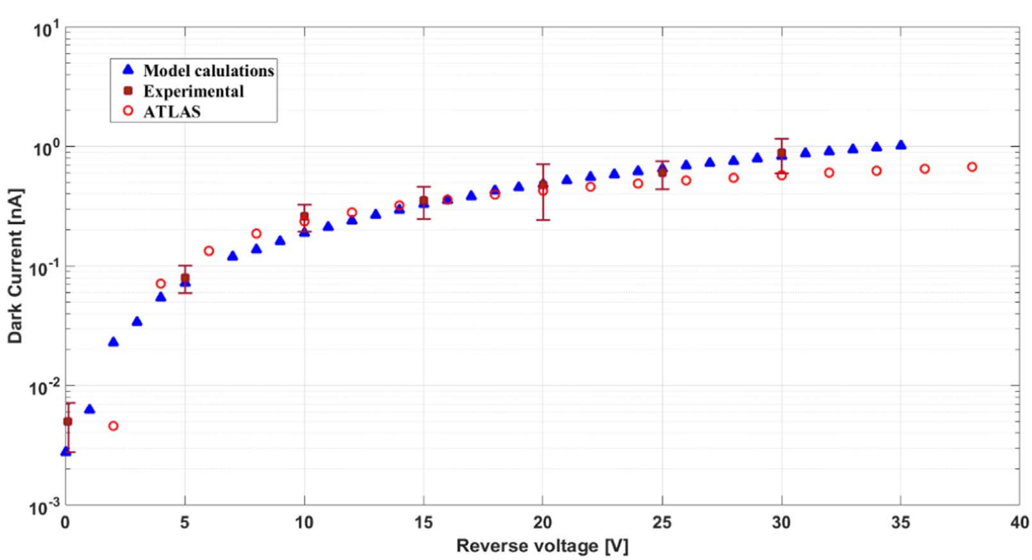

Fig. 2. Dark current as function of reverse voltage for BPX65 PIN silicon photodiode.

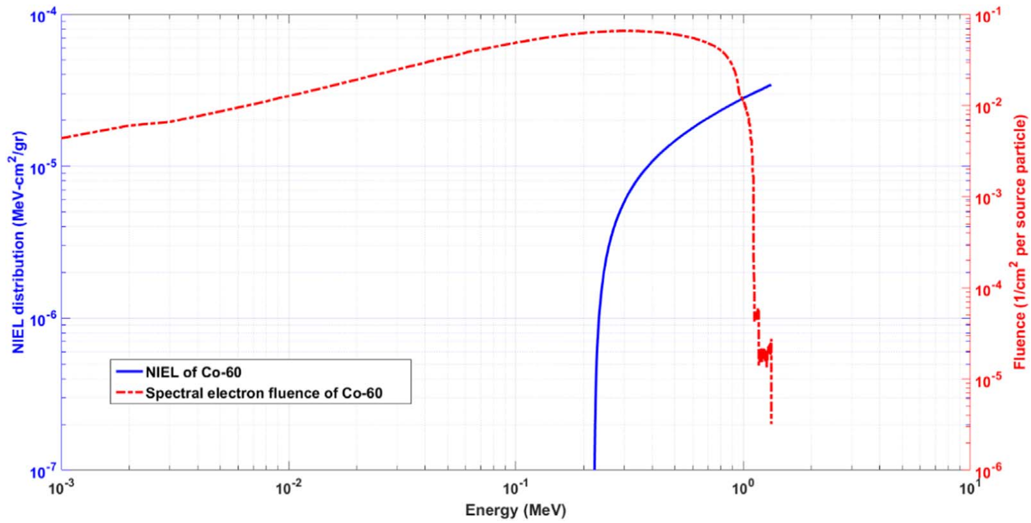

Fig. 3. The energy distribution of primary electrons fluence and its NIEL distribution from Co-60 gamma irradiation in simulated structure of BPX65 silicon photodiode.

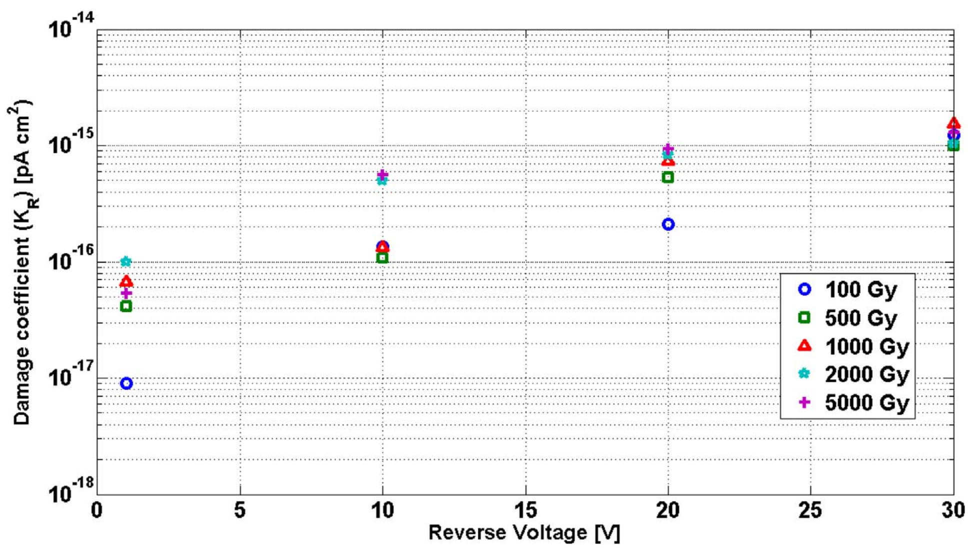

Fig. 4. The damage coefficients of silicon PIN photodiodes at different reverse voltages for Co-60 gamma source.

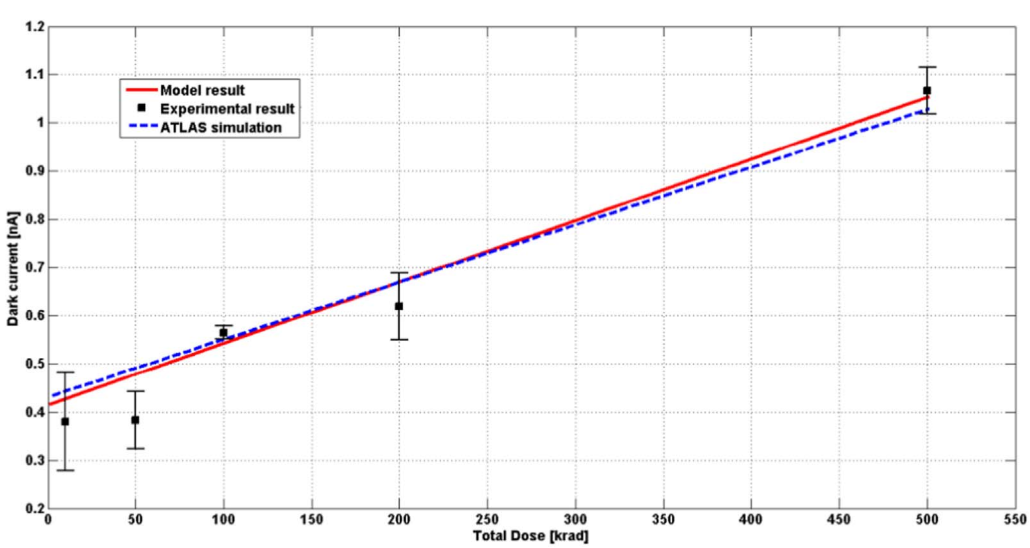

Fig. 5. The dark current of BPX65 photodiode as function total dose under reverse voltage of 20 V.

normalized photocurrent spectrums of PIN photodiode, which have been obtained by ATLAS simulation, are shown in Fig. 7 for the various total doses. These spectrums have been fitted by a Gaussian function which their main parameters are summarized in Table 3.

It is clear that the maximum sensitivity of simulated structure of desired photodiode was obtained at wavelength about 870 nm. As

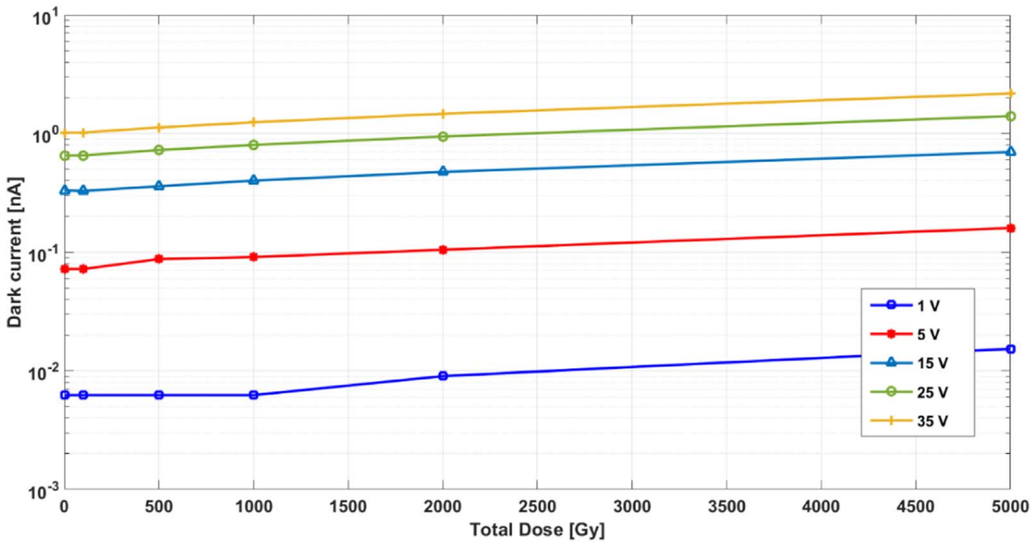

Fig. 6. The dark current of BPX65 photodiode as function of total dose under several reverse voltages.

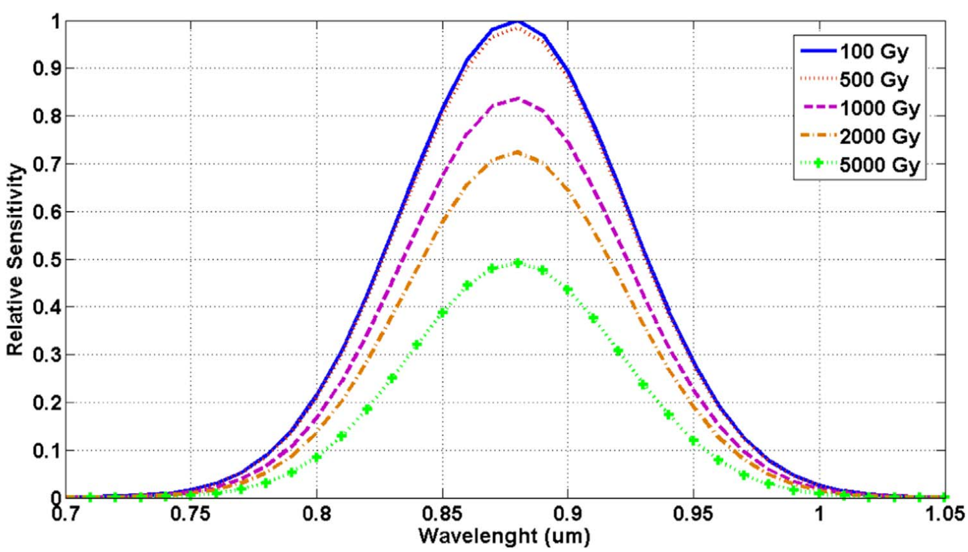

Fig. 7. Estimated relative spectral sensitivity of BPX65 photodiode at several dose levels.

Table 3
The main parameters of fitting Gaussian in spectral sensitivity of BPX65 photodiode at several dose levels.

Total dose (Gy)	Value of peak	FWHM (μm)
100	1.00	0.1055
500	0.98	0.1052
1000	0.83	0.1033
2000	0.72	0.1019
5000	0.49	0.0993

depicted, the photocurrent is attenuated with an increasing total dose. Hence, the photocurrent for a total dose of 5000 Gy becomes 2 times less than before irradiation. In addition, increasing the total dose reduces the full with at half maximum (FWHM) of sensitivity spectrum.

5. Conclusion

The main PIN silicon photodiode parameters can be degraded by gamma-induced damage. Therefore, a comprehensive modeling must be considered to analyze the increase of trap density at silicon band gap and variation of carrier lifetime. In the present study, the variations of a commercial PIN silicon photodiode (BPX65) characteristic arising from gamma irradiation dose were obtained by analytical model based on solving numerically the Poisson and continuity equations.

The results of analytical solved model were compared with the results of ATLAS semiconductor simulator and experimental data in order to validate the calculation of Co-60 gamma induced degradation parameters of a silicon PIN photodiode in several total doses under different reverse voltages. Additionally, GEANT4 calculations were carried out to obtain the damage coefficient from primary electron fluence and the NIEL(gamma) distribution of produced electron in silicon photodiode which was about 4.9×10^{-12} cm^2/s.

In this regard, the dark current increased from 0.651 nA before irradiation to 1.40 nA at total dose of 5000 Gy under reverse voltage of 25 V. Furthermore, the photocurrent was attenuated by a factor of 2 after irradiation at total dose of 5000 Gy in the maximum sensitivity of simulated photodiode structure at wavelength of 870 nm. A good agreement was found between the analytical results and measured data for irradiated BPX65 silicon photodiode by Co-60 gamma source in several total doses and different reverse voltages. Generally, because of the predictive nature of these devices, a proper parameterization of the model allows extrapolating the calculations to higher doses for high level dose applications.

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