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Gamma non-ionizing energy loss: Comparison with the damage factor in silicon devices

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The concept of non-ionizing energy loss (NIEL) has been demonstrated to be a successful approach to describe the displacement damage effects in silicon materials and devices. However, some discrepancies exist in the literature between experimental damage factors and theoretical NIELs. ^{60}Co gamma rays having a low NIEL are an interesting particle source that can be used to validate the NIEL scaling approach. This paper presents different ^{60}Co gamma ray NIEL values for silicon targets. They are compared with the radiation-induced increase in the thermal generation rate of carriers per unit fluence. The differences between the different models, including one using molecular dynamics, are discussed. *Published by AIP Publishing.* https://doi.org/10.1063/1.5013211

I. INTRODUCTION

In matter, incident energetic particles (i.e., charged and uncharged particles) lose their energy through a variety of interactions, which result in two main processes. Particles can lose their energy by ionization that is the consequence of the collision between the energetic particle and atomic electrons leading to excitation or ionization (i.e., emission of atomic electrons). The second process is the consequence of the interactions with nuclei that result in atomic displacement or displacement damage (i.e., displace a target atom from its normal lattice position). This type of interaction is quantified by the NIEL (Non Ionizing Energy Loss). Generally, the part of the total energy loss of an incident particle by non-ionizing processes is very small compared to the energy loss by ionization. However, in certain cases, the displacement damage could be the main contributor to the degradation of some electrical properties in electronic devices. The radiation, by means of atomic displacement, introduces new stable defect levels in the bandgap of semiconductor that affect the transport of carrier in the semiconductor materials.[1] In many cases, the degradation related to these defects is demonstrated to be proportional to the NIEL.

The parameters of bulk material and devices (e.g., diodes and solar cells) that are most sensitive to displacement damage effects are the minority carrier lifetime, diffusion length, mobility, and carrier concentration. The changes in these parameters, most of time proportional to the particle fluence, allow one to extract a damage factor (K_d) that depends mainly on the type and energy of the incident particle. The measured degradation could also be affected by the material type (n or p), impurity type, concentration, fabrication technique, irradiation temperature, temperature, and time at which the measurements are made (i.e., effect of annealing, which leads to recovery of defects generated by radiation),[2] and the effects of non-uniform radiation damage.[3] This increases the difficulty of using theoretical calculations to predict accurately the radiation effects on different materials and devices.

Numerous investigations have been made on the correlation of displacement damage produced by various particle types and energies in silicon.[1,4–9] The results of these studies demonstrate that experimental damage factors can be estimated reasonably well by using the theoretical calculations of the NIEL, which describes the fraction of the total incident particle energy that is imparted to a material to produce displacement damage.[6,10,11] However, in some cases, the NIEL will fail to reproduce the experimental data.[1,6–12] Some discrepancies between NIEL and measured damage factors have been observed in different materials. In the case of silicon material, a linear correlation between the measured K_d and NIEL is found for heavy particles (heavy ions, protons) and neutrons.[1,5–9] But, in the case of electrons and gamma rays, a significant deviation from linearity of K_d with the NIEL calculations is observed.[1,6–9] Because of the greater availability of electron accelerators and gamma sources for laboratory testing and simulation of radiation environments and effects, some efforts focused on developing the NIEL prediction for both electrons and gamma rays[13–18] have been performed. Inguimbert *et al.*[13] proposed a new approach that includes molecular dynamic results, which could explain the quadratic dependence of the damage factor found in silicon following electron irradiation.[9] The US Naval Research Laboratory (NRL) group[14–16] addresses this issue by introducing a power factor n (i.e., the fitting parameter) to the NIEL. The value of n is experimentally determined and varies from one device to another and depends on the type of measured electrical parameter; its values range between 0.5 and 3.[16]

The primary goal of this paper is to present the gamma ray NIEL calculations for silicon. These calculations can be used for predicting the displacement damage effects, due to ^{60}Co gamma ray irradiation in silicon devices, without the

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use of a power factor n. There are certain types of radiation-induced displacement damage to semiconductors that cannot be reproduced by either gamma radiation or non-relativistic electrons. These include loose and tight cluster defects, from end-point energies of protons and heavy ions, respectively,[12] and linear paths of displacement defects, from intense ionization produced by highly ionized cosmic rays or energetic knock-on lattice ions.[19,20] They are generally not a significant source of total device degradation in most radiation environments; however, they do occur and, if significant, they must be addressed separately. Nevertheless, the modification to the NIEL calculation suggested here may be a practical step in resolving some issues with the model.

II. THE CALCULATION METHOD OF NIEL FOR ^{60}CO GAMMA RAYS

The passage of gamma rays through matter and devices causes ionization and the production of energetic secondary electrons via the photoelectric effect, Compton scattering, and pair production processes. The observed degradation in some materials and devices following ^{60}Co gamma ray irradiation is due primarily to displacement damage from the secondary electrons generated by gamma rays. For instance, gamma rays produced from a ^{60}Co source having an average energy of 1.25 MeV can generate a secondary electron spectrum ranging up to 1.2 MeV in the shielding material that surrounds the test device. These secondary electrons are slowed down by shielding before they leave to produce displacement damage in the active region of the device. In order to calculate the NIEL of ^{60}Co gamma rays (^{60}Co NIEL$_\gamma$), we have to integrate the slowed down spectrum of secondary electrons with the amount of atomic displacements produced by these secondary electrons (i.e., the electrons NIEL), and the gamma NIEL is expressed as[18]

$$NIEL_\gamma = \int_0^{E_{max}} \frac{dS_c}{dE}(E).NIEL_e(E).dE, \qquad (1)$$

where dS_c/dE is the slowed down spectrum of secondary electrons (Fig. 1) and $NIEL_e(E)$ is the electrons NIEL (Fig. 2) at a given secondary energy E.

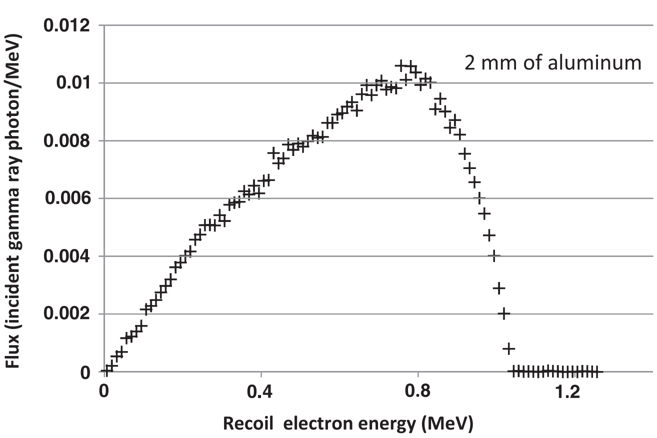

FIG. 1. Slowed down spectrum of secondary electrons generated by gamma rays (1.25 MeV) in the aluminum shielding with a thickness of 2 mm. The spectrum is normalized per incident photon.

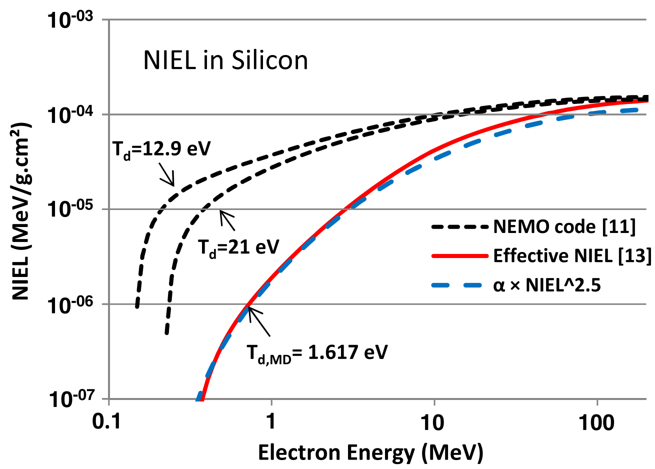

FIG. 2. Different electron NIEL curves from classical NIEL[11] and effective NIEL calculations[13] that will be used to calculate the $^{60}Co\ NIEL_\gamma$. The long-dashed curve corresponding to the classical NIEL to the 2.5 power is also plotted, where α is the proportionality constant.

Monte Carlo simulations are broadly used to simulate the passage of incident particles through matter, because of its flexibility and accuracy. In this work, the Monte Carlo transport code GEANT4[21] is applied to compute the slowed down spectrum of secondary electrons generated by ^{60}Co gamma rays in aluminum. This code provides a good description of the interactions that can occur between the primary gamma source and target, using the Electromagnetic Standard Physics model. Usually, in gamma ray irradiation experiments, the samples must be shielded during irradiation by the proper material to achieve a secondary charged-particle equilibrium. It is recommended that the shielding thickness be equal to the practical range of the maximum energy of secondary electrons, which can be calculated from the method described in Ref. 22. For example, the maximum secondary electron energy produced by ^{60}Co gamma rays is approximately 1.2 MeV. To ensure equilibrium, the samples can be surrounded by 2 mm of aluminum shielding. Therefore, the principle of the calculation is to send a unidirectional beam of monoenergetic gamma rays (1.25 MeV) into aluminum shielding with a thickness of 2 mm, and then the energy spectrum of secondary electrons exiting the shielding is determined (i.e., the slowed down spectrum that irradiates the active region) as shown in Fig. 1. This slowed down spectrum can vary, if a device or tested material is surrounded by heavy materials, and also depends on the thickness of such materials. It has been reported that the difference in equilibrium spectra between lighter materials and heavy materials could be up to 40%.[18]

Figure 2 shows different NIEL for electrons in silicon that will be used to estimate the $^{60}Co\ NIEL_\gamma$. Some classical NIEL values, based on the Binary Cascade Approximation (BCA), are shown using two different threshold displacement energies ($T_d = 12.9$ eV and $T_d = 21$ eV). These calculations have been performed using the NEMO code.[11] There are other electron NIEL calculations for silicon using the BCA approach,[6,10,23,24] and they are in agreement with those calculated by the NEMO code. The "effective" NIEL based on some molecular dynamic simulation results is also plotted

TABLE I. NIEL values for ^{60}Co gamma rays in silicon.

References	The threshold displacement energies	$^{60}Co\ NIEL_\gamma$ (MeV cm^2/g)
This study	$T_{d,MD} = 1.617$ eV	5.00×10^{-09}
This study	$T_d = 12.9$ eV	1.79×10^{-07}
This study	$T_d = 21$ eV	1.11×10^{-07}
Summers[6]	$T_d = 21$ eV	1.30×10^{-05}
Akkerman[10]	$T_d = 21$ eV	1.07×10^{-07}
Shatalov[25]	$T_d = 21$ eV	1.83×10^{-07}

in this figure.[13] The effective NIEL is demonstrated to follow, as a function of the energy, the classical NIEL to the 2.5 power (Fig. 2). This effective NIEL has been shown to be well correlated with some damage factors at low electron energies.[9]

According to Eq. (1), the results represented in Figs. 1 and 2 are used to calculate the $^{60}Co\ NIEL_\gamma$ in silicon, with three different values of threshold displacement energies ($T_d = 12.9$ eV, $T_d = 21$ eV, and $T_{d,MD} = 1.617$ eV), where T_d is the minimum energy of the primary knock-on atom (PKA) required to displace the target atom from its lattice position; the conventionally used T_d value for silicon is 21 eV,[26] but the $T_d = 12.9$ eV is sometimes cited as an appropriate value for silicon.[27] The definition of $T_{d,MD}$ is different from T_d. Some molecular dynamic simulations have shown that a defect can be produced even if the energy transferred to the PKA is lower than the threshold displacement energy T_d.[13] A defect can result from the recrystallization of a disordered region before it can return to its normal state. $T_{d,MD}$ represents the minimum energy that must be imparted to all the atoms of this damaged region. Our calculations and values given by other authors for the $^{60}Co\ NIEL_\gamma$ in silicon are listed in Table I. When the same threshold displacement energy ($T_d = 21$ eV) is used, our NIEL value is very close to the value calculated by Akkerman *et al.*[10] (4% difference), and it is a little different from the value presented by Shatalov *et al.*[25] (35% difference). It differs by a factor of about 100 with the $^{60}Co\ NIEL_\gamma$ value given by Summers *et al.*[6] that represents the NIEL for the average electron energy in the slowed down spectrum of secondary electrons produced by incident ^{60}Co gamma rays. By looking at Table I, one observes that the gamma ray NIEL is strongly dependent on the T_d value; it increases when the T_d value goes from 21 eV to 12.9 eV. In addition, our $^{60}Co\ NIEL_\gamma$ values calculated using the classical NIEL curves ($T_d = 12.9$ eV and $T_d = 21$ eV) are found to be a factor of 22 and 36 greater than that calculated using the effective NIEL curve ($T_{d,MD} = 1.617$ eV), respectively. Based on the foregoing, to use the NIEL in estimating the effect of gamma rays on materials and devices, it is necessary to take into account three parameters; the nature and the thickness of shielding surrounding the test material as well as the threshold displacement energy.

III. COMPARISON OF NIEL WITH DAMAGE FACTOR

The NIEL presented in Sec. II has been compared with some experimental measurements. Srour and Lo[7] present a large set of experimentally measured damage factors for various particle types and energies. They found for protons, neutrons, and heavy ions a linear behavior of the damage factor as a function of the NIEL. They deduced from this analysis the value of an universal dark-current damage factor (K_{dark}) valid for a variety of silicon devices. It represents the increase in thermal generation rate (ΔG) of carriers per unit deposited displacement damage dose (DDD = NIEL × fluence).[7] This damage factor is independent of the type of incident particles, except for electrons and gamma rays, and it is dependent on the irradiation temperature and time after irradiation. The K_{dark} value proposed was 1.9×10^5 carriers/cm^3 s/(MeV/g) at 300 K and 1 week after irradiation, and this value applies only for heavy particles (heavy ions, protons) and neutrons of all energies.[7] As can be seen in Fig. 3, the ΔG per unit fluence scales linearly with NIEL for heavy particles and neutrons; but, it follows a quadratic dependence on the NIEL for both electrons and gamma rays. To the contrary, when the ΔG per unit fluence is plotted as a function of the effective NIEL for electrons and our $^{60}Co\ NIEL_\gamma$ value, evaluated using the effective NIEL curve ($T_{d,MD} = 1.617$ eV), the quadratic scaling becomes linear. This suggests that there is a reasonable agreement between experimental measurements and NIEL. However, Fig. 3 shows a quadratic dependence of the ΔG per unit fluence on our $^{60}Co\ NIEL_\gamma$ values calculated using the classical NIEL curves ($T_d = 12.9$ eV and $T_d = 21$ eV).

It is also noteworthy that the damage-factor values for ^{60}Co gamma-ray radiations in the work of Srour[7] were converted to an equivalent electron damage factor by using a $^{60}Co\ NIEL_\gamma$ value taken from Summers *et al.*[6] and this $^{60}Co\ NIEL_\gamma$ value is obtained by combining the slowed-down secondary electron spectrum with the electron NIEL based on the BCA approach. In the present work, we used our $^{60}Co\ NIEL_\gamma$ value ($T_{d,MD} = 1.617$ eV) that provides a best fit to the experimental data. This $^{60}Co\ NIEL_\gamma$ value is obtained by integrating the slowed-down secondary electron spectrum (Fig. 1) with the electron NIEL based on MD simulations.[13] In both

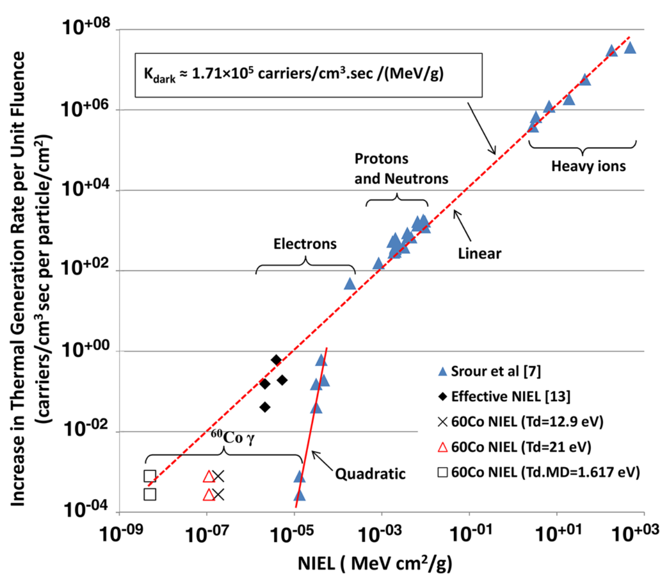

FIG. 3. Radiation-induced increase in the thermal generation rate per unit fluence (=K_{dark} × NIEL) as a function of corresponding NIEL values.

works, it is considered that the displacement damage produced by ^{60}Co gamma-rays is due to energetic secondary electrons. The value of K_{dark} calculated with this set of data derived from Ref. 7 and references cited therein is 1.71×10^5 carriers/cm^3 s/(MeV/g), which is close to the one given by Srour[7] [1.9×10^5 carriers/cm^3 s/(MeV/g)].

IV. DISCUSSION

Two main sources of the error can limit the scope of the NIEL scaling approach:

(i) The experimental conditions.
(ii) The threshold displacement energies used in the NIEL calculation.

Sufficient details of the test conditions for gamma irradiation unfortunately are often not mentioned in the literature. For example, is an equilibrium material placed in front of the test device or not during irradiation and, if so, what is the nature and the thickness of this equilibrium material? This is critical because the spectrum of secondary electrons that degrades the tested device strongly depends on the nature and the thickness of the materials which surround this device.[18] The lack of such detailed information introduces uncertainties into the determination of the $^{60}Co\ NIEL_\gamma$.

In the case of light particles such as electrons and gamma rays, the dependence of the NIEL on the threshold displacement energy is an important source of uncertainty. From Fig. 2 and Table I, the NIEL is demonstrated to be strongly dependent on the value of T_d, and this parameter is poorly estimated for many materials. In fact, there is ambiguity about the meaning of T_d. The T_d value is obtained by comparing the experimental defect introduction rate as a function of the incident particle energy with the calculated defect introduction rate for different T_d values. But the data obtained have a large scatter. For instance, values of $T_d = 12.9$ eV and $T_d = 21$ eV are found for silicon.[26,27] Both choices are considered because of the mathematical description used to fit experimental results.

The best agreement between the ΔG per unit fluence, evaluated at 300 K and 1 week after irradiation and predicted NIEL, was obtained with our $^{60}Co\ NIEL_\gamma$ value calculated using the effective NIEL curve ($T_{d,MD} = 1.617$ eV). Therefore, if the damage factor is known for silicon device irradiated with a particular incident particle, the linearity obtained in Fig. 3 makes it possible to estimate the dark-current damage factor of other particles in different energies. However, this result can be controversial because it is not clear whether the universal value of K_{dark} that applies for heavy particles and neutrons will also apply for low-energy electrons and ^{60}Co gamma rays.

The primary effect of displacement damage is the introduction of new energy levels in the Si bandgap. These defect levels can play an important role in changing the generation and recombination lifetimes. It was shown that those changes in electronic properties scale linearly with NIEL, especially for particles with relatively high NIEL values (i.e., $>2 \times 10^{-04}$ MeV cm^2/g) that primarily produce defect clusters in addition to isolated defects.[7,8] In that regime, K_{dark} is shown to be independent of material and impurity type and concentration, and the universal value of K_{dark} applies for various incident particles such as heavy ions, protons, and neutrons.[7] For particles with relatively low NIEL (i.e., 1-MeV electrons and ^{60}Co gamma rays), only isolated defects are produced.[1,8] In that regime, the situation is more complex because there is likely to be a dependence of K_{dark} on material and impurity type and concentration.[8] Hence, a universal damage factor, K_{dark}, is not formally demonstrated to apply in this regime. More generally, a single value of K_{dark} that can describe both high- and low-NIEL regimes needs confirmation. This hypothesis is largely based on the behavior of the recombination-lifetime damage factor (K_{rec}) for irradiated Si devices at relatively low NIEL, where the same behavior is assumed to occur for K_{dark}.[8] Systematic studies are required to confirm or deny this assumption. K_{rec} displays several dependences in the low-NIEL regime, such as material and impurity type, resistivity, oxygen concentration, and injection level.[8] For a high-NIEL regime, as discussed in Ref. 8, there are important similarities and differences between the behavior of K_{rec} and K_{dark}. For instance, the dependence of K_{rec} on dopant species, resistivity, and injection level is absent in the case of K_{dark}. Therefore, whether the behavior evident of K_{rec} at low-NIEL regime will also exist in the case of K_{dark} remains a very interesting open question.

To conclude, one cannot, at present, confirm or deny the potential dependence of K_{dark} on material and impurity type and concentration at low-NIEL values. Hence, our findings (Fig. 3) where the radiation-induced dark current in Si devices by means of increase in thermal generation in device depletion regions is described by a single value of K_{dark} for all kinds of particles (i.e., high- and low-NIEL regimes) may be reasonable given the existing possibilities. However, a systematic study is needed to understand and clarify the behavior of K_{dark} at low NIEL regime.

There is another approach developed by the NRL group,[14–16] which is an accepted method to eliminate the discrepancies observed between experimental data and predicted NIEL using a quality factor $Q(E)$ in Eq. (1). This is defined as

$$Q(E) = \left[\frac{NIEL(E)}{NIEL(E_{ref})}\right]^{n-1}, \tag{2}$$

where NIEL(E_{ref}) is the NIEL value for a reference particle with a reference energy (e.g., 1 MeV electrons), and the "n" factor is the fitting parameter used to make the experimental data agree with NIEL calculations. The value of n is experimentally determined, but it depends on the device type and parameter measured. Its value ranges between 0.5 and 3[16] and will also depend on the experimental conditions that could alter the secondary electron spectrum. This quality factor must be introduced into the calculation whenever the experimental degradation measurements do not scale linearly with NIEL. It is to be seen whether the method proposed in this present work holds for other damage parameters and is able to remove the need for a variable, n, in properly posed experiments.

V. CONCLUSION

The NIEL values for ^{60}Co gamma rays in silicon have been computed using the Monte Carlo radiation simulation code Geant4 to estimate the slowed down spectrum of secondary electrons. Different electron NIEL curves from classical NIEL and "effective" NIEL have also been used for the calculation. Sources of the error for the $^{60}Co\ NIEL_{\gamma}$ scaling approach were discussed, and it was demonstrated how the appropriate NIEL values can be used for predicting the ^{60}Co gamma ray-induced radiation damage in silicon devices without the use of a power factor n. It was found that the radiation-induced increase in the thermal generation rate of carriers per unit fluence, evaluated at 300 K and 1 week after irradiation, scales linearly with our $^{60}Co\ NIEL_{\gamma}$ value calculated using the effective NIEL curve. However, more work needs to be done to fully investigate the behavior of K_{dark} for irradiation with relatively low NIEL particles.

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