

Geant4-based spatially resolved electron-hole pair correction in silicon photonic waveguides

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ABSTRACT

Silicon photonic platforms, including silicon-on-insulator (SOI) and silicon nitride (SiN), have demonstrated high tolerance to total ionizing dose (TID) in space-relevant irradiation experiments, particularly for passive waveguides. However, the physical origin of this radiation tolerance remains difficult to quantify because existing radiation-aware models often rely on simplified or empirically scaled estimates of the initial radiation-induced charge. In particular, the effects of non-equilibrium energy deposition in sub-micrometer photonic structures and the subsequent prompt recombination of electron-hole pairs (EHPs) are not generally accounted for. In this work, a physics-based methodology is developed combining Geant4 Monte Carlo simulations of spatially resolved energy deposition with geminate-recombination models to estimate the EHP population available for subsequent transport and trapping in representative SOI and SiN waveguides under Co-60 irradiation. The results show that the absence of transient charged particle equilibrium in sub-micrometer structures substantially reduces the generated EHP density compared with bulk-material predictions. More importantly, at zero applied electric field, representative passive SOI waveguides preserve between 0.5% and 2.4% of the initially generated EHPs, while SiN waveguides retain approximately 5% to 25% depending on the assumed thermalization distance. These results demonstrate that prompt geminate recombination, together with spatially resolved energy deposition, can produce a substantial correction to the charge available for subsequent trapping. The proposed approach provides a physics-based initial condition for charge-transport, trapping, and electro-optical models and offers a framework for interpreting the experimentally observed radiation tolerance of integrated photonic devices.

Keywords: Photonics, Total Ionizing Dose, Photonic integrated circuit

1. INTRODUCTION

Silicon photonics (SiPh) platforms, particularly silicon-on-insulator (SOI) and silicon nitride (SiN), have demonstrated high tolerance to total ionizing dose (TID) levels relevant to space applications, with minimal degradation reported in several experimental studies, particularly for passive waveguide structures.¹⁻³ This observed radiation tolerance is not straightforward to infer from the amount of ionizing energy deposited in the device alone. Radiation-induced electron-hole pairs (EHPs) are generated in the dielectric materials surrounding the optical waveguides, but only a fraction of these carriers survives the ultrafast recombination processes following ionization and subsequently contributes to carrier transport and charge trapping. Consequently, understanding the relationship between radiation-induced energy deposition and the carrier population ultimately available for trapping is essential for interpreting the experimentally observed radiation response in photonic integrated circuits (PICs).

Several modeling approaches have been proposed to explain the radiation response of PICs, including models based on radiation-induced carrier generation, carrier transport and trapping, refractive-index modification, and the resulting optical response.³⁻⁵ These approaches provide useful descriptions of the later stages of the radiation-response chain, but their predictions depend critically on the initial radiation-induced charge population

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used as input. In particular, the generation and prompt-recombination stages are often represented using bulk-material dose relationships, empirical scaling factors, or assumed trapped-charge distributions, without explicitly accounting for the spatially non-equilibrium energy deposition that occurs in sub-micrometer photonic structures.

Despite its importance, the estimation of radiation-induced charge in silicon photonics remains highly inconsistent across the literature. In SOI technologies, reported studies employ different assumptions regarding trapped charge densities, including fixed interface charge concentrations, empirical dose-dependent expressions, and arbitrarily scaled charge distributions intended to account for unresolved physical mechanisms or computational constraints.^{3–6} As a result, the predicted charge densities may differ by several orders of magnitude, complicating direct comparison between studies and obscuring the physical interpretation of the simulated radiation response.

For SiN photonic platforms, the situation is even less mature. To the author’s knowledge, no physically based models describing charge generation or charge yield in SiN waveguides have been reported in the integrated photonics literature. Existing approaches are mainly inherited from SONOS memories and nitride-based transistor technologies, where radiation-induced charge generation in Si₃N₄ is often approximated through empirical scaling factors applied to SiO₂ models.^{7–9} While empirical charge-yield parameterizations are well established for SiO₂,^{10,11} physically based geminate recombination models offer a more general framework based on material properties and irradiation conditions, potentially enabling charge-yield estimation in materials lacking dedicated experimental parameterizations.

A further difficulty arises from the dimensions of integrated photonic structures. Conventional dose-based approaches generally rely on conditions associated with transient charged particle equilibrium (TCPE), under which absorbed dose provides a direct measure of local energy deposition. However, the characteristic dimensions of photonic waveguides are typically hundreds of nanometers, whereas the secondary electrons generated by MeV gamma irradiation can travel over micrometer-scale distances. Consequently, the local energy deposition and EHP generation in a waveguide may differ substantially from bulk-material estimates.²

In this work, Geant4 simulations are used to calculate the spatial distribution of radiation-induced energy deposition in representative SOI and SiN waveguide structures under Co-60 irradiation. The deposited energy is converted into an initial EHP density using material-dependent EHP creation energies. Several geminate-recombination models are then used to estimate the fraction of carriers that survives prompt recombination. The resulting surviving-carrier distributions provide a physics-based input for subsequent charge-trapping and electro-optical simulations. Particular emphasis is placed on the differences between bulk-material dose estimates and spatially resolved carrier generation in sub-micrometer photonic structures.

2. CHARGE ESTIMATION METHODOLOGY

2.1 Electron-hole pair estimation

Under TID irradiation, incident gamma photons interact with dielectric and semiconductor materials primarily through Compton scattering at Co-60 energies, producing energetic secondary electrons. These electrons lose energy by ionization along their trajectories, generating EHPs. The resulting EHP density, N_{EHP} , is determined from the deposited energy according to

$$N_{\text{EHP}} = \frac{E_{\text{dep}}}{WV}, \quad (1)$$

where E_{dep} is the deposited energy in the material, V is the volume of the material, and W is the average energy required to generate one EHP. The absorbed dose is related to the deposited energy through

$$D = \frac{E_{\text{dep}}}{\rho V}, \quad (2)$$

where ρ is the density of the irradiated material. For bulk materials, the deposited energy corresponding to a reference absorbed dose (e.g., 1 krad), can be converted into the generated EHP density using the previous

expression. This quantity is commonly expressed through the electron-hole pair generation constant g_0 , which represents the number of EHPs generated per unit absorbed dose as

$$N_{\text{EHP}} = g_0 D. \quad (3)$$

For bulk reference materials, under TCPE conditions, the absorbed dose in other materials corresponding to a specified reference dose in Si can be estimated as:

$$\frac{D_{\text{mat}}}{D_{\text{Si}}} = \frac{(\mu_{\text{en}}/\rho)_{\text{mat}}}{(\mu_{\text{en}}/\rho)_{\text{Si}}} \quad (4)$$

where D_{mat} and D_{Si} denote the absorbed doses in the material of interest and in silicon, respectively, and (μ_{en}/ρ) is the corresponding mass energy-absorption coefficient. For elemental materials, tabulated values were employed whenever available. For compound materials, such as SiO_2 and Si_3N_4 , the coefficients were estimated from the elemental constituents using the corresponding weight fractions w_{mat} :¹²

$$(\mu_{\text{en}}/\rho)_{\text{mat}} = \sum_i w_i (\mu_{\text{en}}/\rho)_i \quad (5)$$

This formulation assumes conditions consistent with TCPE, under which the energy transported into a volume by secondary electrons is balanced by the energy transported out. Therefore, the absorbed dose provides an accurate representation of the local deposited energy and can be directly related to the generated EHP density. This assumption is generally valid for bulk materials whose dimensions are much larger than the range of radiation-induced secondary electrons.¹³ However, in sub-micrometer photonic waveguides, the characteristic dimensions of the structure are on the order of hundreds of nanometers, whereas secondary electrons can travel over distances of several to tens of micrometers, preventing the establishment of TCPE.¹⁴ Under these conditions, the deposited energy distribution may differ from that predicted by conventional bulk dose formulations, leading to inaccuracies in the estimation of EHP generation. To overcome this limitation, the deposited energy was calculated directly using Geant4 Monte Carlo simulations,^{15–17} taking into account the actual material composition and device geometry. The photon and secondary-particle transport was performed using the electromagnetic physics processes implemented in Geant4, with the interaction probabilities determined by the corresponding physics models and material properties. The material composition and density were explicitly defined for each region, allowing the transport of primary photons and secondary electrons and the local accumulation of their deposited energy to be simulated. For each interaction, the local deposited energy was accumulated within the simulated volume, and the generated EHP density was obtained from

$$N_{\text{EHP}}(\mathbf{r}) = \frac{U_{\text{dep}}(\mathbf{r})}{W}, \quad (6)$$

where $U_{\text{dep}}(\mathbf{r})$ is the spatially resolved deposited energy in the material $E_{\text{dep}}(\mathbf{r})$ obtained from Geant4 simulations per unit volume.

The Geant4 simulation geometry used to obtain the spatial distribution of deposited energy is shown in Figure 1. The device under test (DUT) was positioned 2 cm from the Co-60 source. Primary photons were generated with energies randomly sampled from the two main gamma-ray energies of Co-60 (1.17 and 1.33 MeV). Their initial directions were uniformly sampled within a conical solid angle θ centered on the z-axis and oriented toward the DUT, reducing the computational cost compared with an isotropic source while maintaining irradiation coverage. The same number of primary photons was simulated for all configurations under the same irradiation conditions. The resulting energy deposition was normalized to the number of primary photons.

Bulk materials of 1 cm^3 , sufficiently large compared with the relevant secondary-electron transport distances, and representative SOI and SiN waveguides with different core widths and thicknesses were simulated to quantify the influence of device dimensions on the generated EHP density. Figure 2 illustrates the cross-sectional geometries of the SOI and SiN strip and rib waveguides considered in this work. The SOI platform consists of a silicon core separated from the silicon substrate by a $1 \mu\text{m}$ BOX and covered by a $1 \mu\text{m}$ thick deposited SiO_2 layer. The SiN platform comprises a silicon nitride core embedded within SiO_2 claddings of the same thickness. The SOI

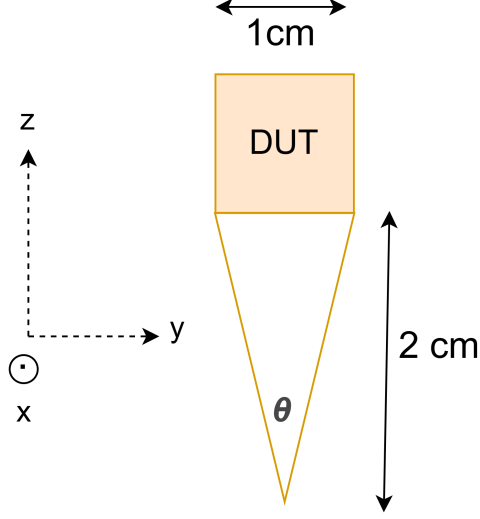


Figure 1. Irradiation geometry used in the Geant4 simulations.

strip waveguide comprises a 220-nm-thick silicon core ($h_{\text{Si,Strip}}$) with a width of 600 nm ($w_{\text{Si,Strip}}$). The SOI rib waveguide consists of a 120-nm-high rib $h_{\text{Si,Rib}}$ formed on a 100-nm-thick silicon slab $h_{\text{Si,Slab}}$ with a rib width of 600 nm ($w_{\text{Si,Rib}}$). The SiN strip waveguide employs a 300-nm-thick silicon nitride core ($h_{\text{SiN,Strip}}$) with a width of 800 nm ($w_{\text{SiN,Strip}}$), while the SiN rib waveguide consists of a 200-nm-high rib $h_{\text{SiN,Rib}}$ on a 100-nm-thick silicon nitride slab $h_{\text{SiN,Slab}}$ with a rib width of 800 nm ($w_{\text{SiN,Rib}}$). For both rib geometries, the slab width was set to 5 μm , representative of typical fabricated devices and sufficiently large to avoid edge effects. The different core dimensions reflect the distinct refractive index contrast of the two platforms. Owing to the higher refractive index contrast of SOI, optical confinement can be achieved with smaller waveguide cross-sections, whereas SiN waveguides require larger core dimensions to provide comparable optical confinement. For all simulations, the waveguide structures were centered laterally on a representative 1 cm $\times$ 1 cm silicon substrate section with a thickness of 500 μm .

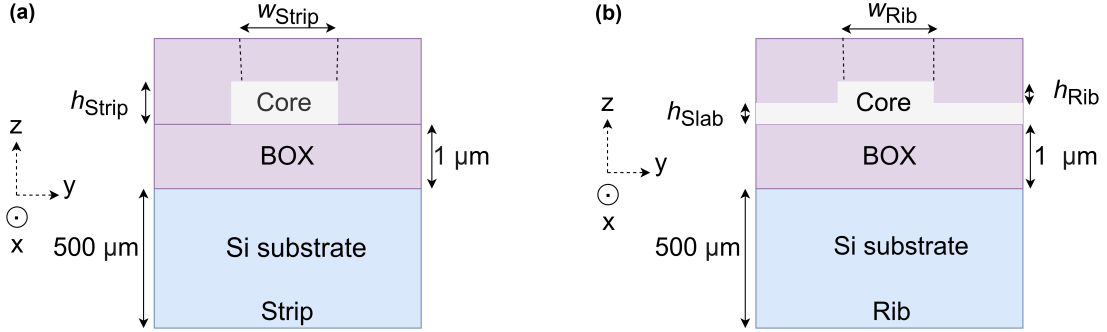


Figure 2. Waveguides cross-sectional geometries. (a) SOI / SiN strip waveguide. (b) SOI / SiN rib waveguide.

2.2 Surviving Carrier Fraction

The EHP generation described in the previous section represents the initial EHP population generated by the radiation. However, only a fraction of these carriers survives the fast recombination processes occurring immediately after ionization. This surviving fraction, commonly referred to as the charge yield, depends on the local radiation track structure, material properties, and the electric field within the dielectric. Charge-yield models can be broadly divided into two categories. The first comprises physics-based models that describe the competition between carrier separation and geminate recombination from first principles. The second consists of

empirical formulations derived from experimental TID measurements, which provide analytical expressions for engineering-oriented calculations.

Several physics-based models have been proposed to describe the survival of radiation-generated EHPs, including the Onsager theory,¹⁸ Jaffé's columnar recombination model,¹⁹ and the more recent Sano-Tachiya-Noolandi-Hong (STNH) formulation.²⁰ These models differ in their treatment of carrier recombination, radiation track structure, and electric-field dependence. Jaffé's columnar model assumes that charge carriers are generated along a continuous ionization column and has shown good agreement with experimental data for intermediate-energy electrons.²¹ However, studies have shown that for electron energies above approximately 5 keV the ionization track evolves into a collection of branching tracks composed of isolated spurs rather than a continuous column.²² Since Co-60 irradiation produces high-energy secondary electrons, the assumptions underlying the columnar model are no longer strictly valid. The STNH model provides a more detailed description of charge yield by incorporating additional physical mechanisms and a more sophisticated treatment of carrier transport and recombination.²⁰ Nevertheless, the increased complexity of the model introduces additional parameters and computational effort, while offering limited practical benefit for the objectives of the present work. Therefore, the Onsager approach was selected and adopted as the representative recombination model. It provides a physically grounded description of geminate recombination that is well suited to the isolated-spur regime relevant to Co-60 irradiation. To account for charge yield in amorphous SiO₂, the formulation is implemented following the approach proposed by Ausman.²³

$$f_{\text{Ons}}(r, E) = \langle P(r_{\text{th}}, E, \phi) \rangle = \frac{1}{\pi} \int_0^\pi d\phi \exp[-\beta r_{\text{th}}(1 + \cos \phi)] \times \int_{r_c/r_{\text{th}}}^\infty ds e^{-s} I_0 \left(2 [\beta r_{\text{th}}(1 + \cos \phi)s]^{1/2} \right), \quad (7)$$

where r_{th} is the electron-hole thermalization distance, ϕ is the angle between the electric field and the initial electron-hole separation vector, s is an integration variable, I_0 is the modified Bessel function of the first kind of order zero, E is the applied electric field and β is

$$\beta = \frac{eE}{2k_B T}, \quad (8)$$

where e is the elementary charge, k_B is the Boltzmann constant, T is the absolute temperature and r_c is the Onsager radius defined as

$$r_c = \frac{e^2}{4\pi\epsilon k_B T}, \quad (9)$$

where ϵ is the dielectric permittivity of the material.

The Onsager model has several limitations. In particular, it assumes isolated geminate recombination events and neglects the stochastic nature of charge transport and track evolution. Previous studies have also reported discrepancies at low electric fields, where Monte Carlo transport simulations may provide a more accurate description of carrier recombination.²⁴ Nevertheless, the model has shown good agreement with experimental observations under moderate and high electric-field conditions typically encountered in metal oxide semiconductor (MOS) irradiation studies. In contrast, empirical formulations do not explicitly model the underlying recombination physics, but instead reproduce experimentally observed charge-yield measurements through analytical expressions. The field-dependent model adopted in this work provides an analytical expression fitted to experimental measurements, is widely used for engineering-oriented TID analyses, is given by¹¹

$$f_y(E) = \left[\frac{|E| + E_1}{|E| + E_2} \right]^m \quad (10)$$

where E is the applied electric field, and E_1 , E_2 , and m are fitting parameters.

Since the model parameters are obtained from experimental calibration, their values depend on the irradiation conditions, oxide characteristics, and fabrication process. Consequently, different parameter sets may lead to different charge-yield estimations when extrapolated to other materials or device technologies. In this work, representative models from both categories are considered in order to evaluate the sensitivity of the estimated available charge to the selected yield formulation.

Finally, values from the charge-yield models and from $N_{\text{EHP}}(\mathbf{r})$ are combined to estimate the surviving carrier density available for subsequent trapping processes as

$$N_{\text{surviving}} = f(E, \text{parameters}) \cdot N_{\text{EHP}}(\mathbf{r}) \quad (11)$$

where $f(E, \text{parameters})$ is the charge-yield function obtained from either the Onsager or empirical models. The *parameters* correspond to ε and r_{th} in the Onsager model, or to empirical fitting parameters in the empirical model.

3. RESULTS AND DISCUSSION

3.1 Electron-hole generation

The following sections compare the carrier densities obtained using the conventional dose-based approach and the spatially resolved Geant4 simulations. Particular attention is given to the differences arising from the treatment of energy deposition in bulk materials and representative photonic waveguide geometries.

Table 1 summarizes the deposited energy and absorbed dose obtained from the Geant4 simulations, together with the corresponding N_{EHP} values in dielectric regions. The analysis focuses on radiation-induced charge generation in the dielectric regions, which are the regions considered in this work for the subsequent trapping analysis. Therefore, the corresponding silicon core values are not included in the table. These quantities are subsequently converted into EHP densities using the simulated energy-deposition. The average EHP creation energy was taken as $W_{\text{SiO}_2} = 17$ eV for SiO_2 , following the experimental determination reported by Benedetto et al.²⁵ and the density $\rho_{\text{SiO}_2} = 2.20$ g/cm³. For Si_3N_4 , a density of $\rho_{\text{Si}_3\text{N}_4} = 3.17$ g/cm³ was assumed. However, no widely accepted value has been reported for the electron-hole pair creation energy $W_{\text{Si}_3\text{N}_4}$. Literature has shown an empirical correlation between the W and the bandgap energy for semiconductors and a wide range of insulating materials^{26–28}. In particular, values of W are often found to be close to $3E_g$.²⁸ However, experimental measurements in wide-bandgap dielectrics such as SiO_2 ($E_g \approx 9$ eV) indicate values of approximately $2E_g$.²⁵ Since no widely accepted experimental value is available for Si_3N_4 , a sensitivity range of $W_{\text{Si}_3\text{N}_4} = 10\text{--}15$ eV was adopted to represent the uncertainty associated with the absence of an established experimental value. The uncertainty interval arises solely from the assumed $W_{\text{Si}_3\text{N}_4}$ range and does not include uncertainties in density, Geant4 transport, photon interaction data, or other model parameters.

Table 1. Simulation results for deposited energy, mass and dose

Region	Energy deposited [MeV]	Dose [rad]	N_{EHP} [cm ⁻³]
Bulk Si	1.45×10^8	1.000	N/A
Bulk Si_3N_4	2.02×10^8	1.020	1.347×10^{13} - 2.024×10^{13}
Bulk SiO_2	1.45×10^8	1.060	8.53×10^{12}
Rib waveguide (SOI) Si	3.29×10^{-1}	0.396	N/A
Rib waveguide (SOI) SiO_2	1.80×10^4	0.656	5.29×10^{12}
Strip waveguide (SOI) Si	9.00×10^{-2}	0.409	N/A
Strip waveguide (SOI) SiO_2	1.77×10^4	0.656	5.29×10^{12}
Rib waveguide (SiN) SiN	6.16×10^{-1}	0.472	6.220×10^{12} - 9.329×10^{12}
Rib waveguide (SiN) SiO_2	1.80×10^4	0.656	5.29×10^{12}
Strip waveguide (SiN) SiN	2.61×10^{-2}	0.549	7.236×10^{12} - 1.085×10^{13}
Strip waveguide (SiN) SiO_2	1.80×10^4	0.656	5.29×10^{12}

Eq. (4) was used to estimate the absorbed dose in each material from a reference dose of 1 rad(Si). Using the mass energy-absorption coefficients reported by Hubbell for 1.25 MeV photons, corresponding to the mean energy of the two principal Co-60 gamma emissions, namely $(\mu_{\text{en}}/\rho)_{\text{Si}} = 0.02652$, $(\mu_{\text{en}}/\rho)_{\text{O}} = 0.02669$, and $(\mu_{\text{en}}/\rho)_{\text{N}} = 0.02669$ cm²/g,¹² the effective coefficients of the compound materials were calculated according to Eq. (5). The resulting values were $(\mu_{\text{en}}/\rho)_{\text{SiO}_2} = 0.02661$ cm²/g and $(\mu_{\text{en}}/\rho)_{\text{Si}_3\text{N}_4} = 0.02658$ cm²/g, differing only in the fourth decimal place. Therefore, using Eq. (4), the absorbed doses were calculated to be 1.0034 and 1.0023 for SiO_2 and Si_3N_4 , respectively. These conversion factors are in line with the Geant4 results, with differences of 5.4% for SiO_2 and 1.8% for Si_3N_4 . The close agreement between the Geant4 deposited energies for bulk Si and

SiO₂ is consistent with their similar mass energy-absorption coefficients and densities at the considered photon energy. Although the deposited energies are nearly identical, the corresponding absorbed doses are not exactly equal because dose is normalized by the material mass. For SiO₂, the calculated value is also consistent with previously mass energy-absorption coefficients,²⁹ further supporting the adopted dose-conversion methodology.

For bulk SiO₂, the calculated value of N_{EHP} for 1 rad is $8.53 \times 10^{12} \text{ cm}^{-3}$, in good agreement with the generation constant g_0 reported in the literature of $8.11 \times 10^{12} \text{ cm}^{-3}$.²⁵ The slight difference is attributed to the assumptions adopted in the calculation, including the EHP creation energy and material properties.

Bulk Si₃N₄ exhibits a carrier generation density between 1.347×10^{13} and $2.024 \times 10^{13} \text{ cm}^{-3}$. These values are about 0.5 to 2.5 times higher than those obtained for SiO₂. This increase is primarily attributed to the larger energy deposition in Si₃N₄, resulting from its higher photon interaction probability.

For the waveguide structures, the SiO₂ claddings exhibit nearly identical EHP densities of $5.29 \times 10^{12} \text{ cm}^{-3}$ with variations below 0.1% among all geometries. The similar EHP densities obtained for the SiO₂ claddings of the different waveguide geometries indicate that, within the geometries considered, the cladding energy deposition is relatively insensitive to the core configuration.

A significant reduction in carrier generation is observed in the Si₃N₄ waveguides compared with bulk Si₃N₄. The rib waveguide exhibits carrier generation densities in the range 6.220×10^{12} and $9.329 \times 10^{12} \text{ cm}^{-3}$, while the strip waveguide exhibits densities in the range 7.236×10^{12} and $1.085 \times 10^{13} \text{ cm}^{-3}$. Although the difference between both geometries is relatively small, their carrier generation densities are reduced by approximately one half compared with bulk Si₃N₄.

These results demonstrate that the conventional absorbed-dose formulation based on TCPE can differ substantially from the spatially resolved energy deposition in the sub-micrometer photonic structures. The local deposited energy, and therefore the generated EHP density, differs significantly from the bulk-material prediction.

3.2 Surviving carrier fraction

The EHP densities presented in the previous subsection correspond to the total number of generated carriers. In this section we evaluate the fraction of these carriers that survives the fast geminate recombination processes and remains available for subsequent trapping mechanisms.

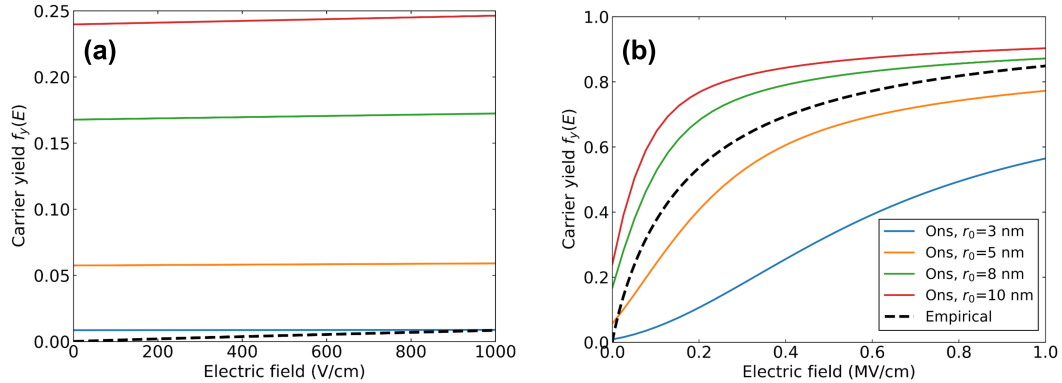


Figure 3. Onsager and empirical models charge yield comparison in SiO₂. (a) Zoom to the low field regime. (b) Total regime.

Figure 3 compares the charge yield predicted by the Onsager model for thermalization distances of 3, 5, 8, and 10 nm and a temperature of 300 K, together with the empirical calibrated model for SiO₂, using $E_1=0.1 \text{ V/cm}$, $E_2 = 2 \times 10^5 \text{ V/cm}$, and $m=0.9$ as a function of the applied electric field.¹¹ The selected thermalization distances span the range of values commonly reported in the literature for SiO₂.^{23,24} Both approaches predict the expected increase in charge yield with electric field. At high electric fields, the empirical model lies between the Onsager predictions obtained for thermalization distances of 5 and 8 nm, whereas at low electric fields it predicts a significantly lower charge yield. These differences arise from the different physical assumptions underlying the

two approaches, since the empirical model is a parameterization while the Onsager model explicitly describes geminate recombination. It should also be noted that the empirical model was parametrized for moderate and high electric fields and is not expected to accurately describe the low-field regime.³⁰ Consequently, the comparison suggests that thermalization distances of 5 and 8 nm provide good agreement with the empirical model over the electric-field range for which it was originally developed, while a value closer to 3 nm may be more appropriate at lower electric fields, consistent with previous Monte Carlo studies.²⁴

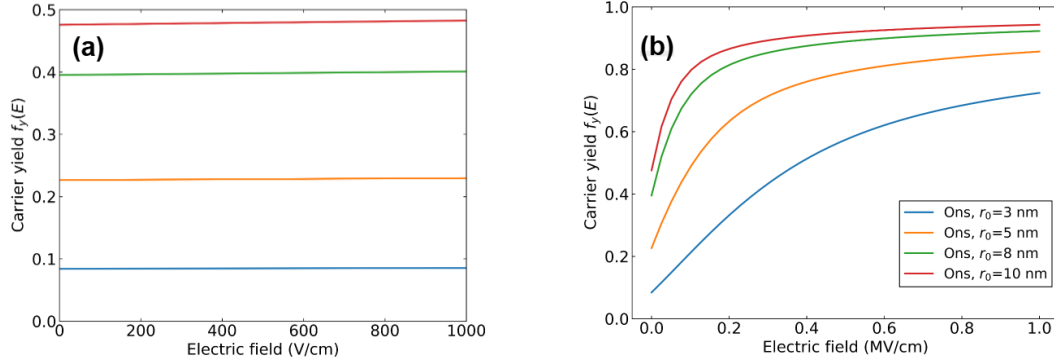


Figure 4. Onsager charge yield comparison in Si_3N_4 . (a) Zoom to the low field regime. (b) Total regime.

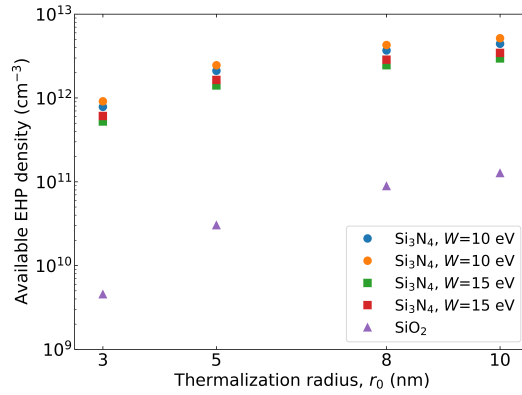


Figure 5. Available EHP density in SiO_2 and Si_3N_4 as a function of the Onsager thermalization radius for 1 rad(Si) of absorbed dose.

Using a relative permittivity ϵ of 7.5 in the Onsager model, Figure 4 shows the predicted charge yield in Si_3N_4 as a function of the applied electric field for thermalization distances and temperature identical to those assumed for SiO_2 . The results indicate that the charge yield increases with the electric field, similar to the trend observed in SiO_2 . Because no experimentally calibrated charge-yield parameterization for Si_3N_4 was identified, these results should be regarded as Onsager-based estimates rather than experimentally validated Si_3N_4 charge-yield values. The predicted charge yield in Si_3N_4 is substantially higher than that in SiO_2 at low electric fields, whereas at higher fields it approaches a similar saturation level. This difference can be related to the different dielectric permittivities of the two materials, which determine the Onsager radius and therefore the strength of the Coulombic interaction between the electron and hole. The Onsager radii calculated using Eq. (9) are 7.5 nm for Si_3N_4 and 14.3 nm for SiO_2 . The larger Onsager radius in SiO_2 indicates weaker dielectric screening of the Coulombic interaction, resulting in a larger spatial range over which the geminate EHP remains Coulombically bound. Consequently, at low electric fields, the probability of geminate recombination is expected to be higher in SiO_2 .

The surviving EHP population estimated in this work from Eq. (11) represents the carrier population available for transport and trapping processes. Figure 5 shows the surviving EHP density in SiO_2 and Si_3N_4 as a function of the Onsager thermalization radius for an absorbed dose of 1 rad(Si) in passive waveguide structures. For

SiO₂, the surviving EHP density corresponds to 0.53% of the initial EHP density in the bulk material at a thermalization distance of 3 nm. For Si₃N₄, the corresponding fractions are 3.88% for rib waveguides and 4.5% for strip waveguides. At a thermalization distance of 10 nm, these fractions increase to 2.4% for SiO₂, 21.9% for Si₃N₄ rib waveguides, and 25.5% for Si₃N₄ strip waveguides. The conversion of this charge into trapped charge depends on additional carrier transport and defect-trapping mechanisms, which can be modeled using established frameworks such as the McLean model.³¹ The resulting trapped-charge distributions can subsequently be incorporated into electro-optical simulations to evaluate TID-induced performance degradation in photonic devices.³⁻⁵

4. CONCLUSION

This work presented a physics-based methodology for estimating radiation-induced EHP generation and surviving carrier populations in representative SOI and SiN photonic waveguides. By combining Geant4 energy-deposition simulations with geminate-recombination models, the proposed methodology accounts for finite device geometry and secondary-electron transport, providing a more physically detailed estimate of the charge available for subsequent transport and trapping than conventional bulk dose-based approaches.

For the investigated sub-micrometer structures, the spatially resolved Geant4 simulations predicted substantially lower EHP densities than the corresponding bulk-material estimates. In the SiO₂ claddings, the EHP density was approximately 38% lower than the bulk SiO₂ value. In the SiN waveguides, the reduction was approximately 46-54%, depending on the assumed EHP creation energy $W_{\text{Si}_3\text{N}_4}$ =10-15 eV. These results demonstrate that finite waveguide dimensions and the associated departure from charged-particle equilibrium can significantly affect the local energy deposition and EHP generation in integrated photonic structures.

The charge-yield analysis further showed that the estimated surviving carrier fraction depends strongly on the applied electric field and the selected recombination model, with the largest differences occurring in the low-field regime. For SiO₂, Onsager predictions using thermalization distances of 5-8 nm showed good agreement with the calibrated empirical model over its applicable moderate- and high-field range. For Si₃N₄, the Onsager model predicted a higher charge yield at low electric fields, although these results should be regarded as physics-based estimates because experimentally established Si₃N₄ charge-yield and EHP-creation-energy parameters are not currently available.

When the spatially resolved EHP generation and geminate-recombination corrections are combined, the resulting population available for subsequent transport and trapping is substantially smaller than the initially generated EHP population. For the zero-field conditions representative of passive waveguides, the surviving EHP fraction was estimated to be approximately 0.5-2.4% in the SOI structures and 5-25% in the SiN structures, depending on the assumed Onsager thermalization distance. Thus, the initial EHP population available for subsequent radiation-induced charge transport and trapping can be reduced by approximately 98-99.5% in SOI and 75-95% in SiN. This correction highlights the importance of accounting for both non-equilibrium energy deposition and prompt geminate recombination when estimating the charge that can ultimately contribute to TID-induced degradation. The resulting spatially resolved surviving-carrier distributions provide a physically motivated input for subsequent carrier transport, charge-trapping, and electro-optical degradation analyses.

Future work should focus on experimentally constraining the EHP creation energy and charge-yield parameters of Si₃N₄, thereby reducing the uncertainty of the present Onsager-based estimates and improving radiation-aware modelling of SiN photonic devices.

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