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Influence of a 3D Electric Field Enhancement Model on the Monte Carlo Calculation of the Dark Current in Pixel Arrays

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A new three-dimensional electric field enhanced generation model has been developed to describe the electric field effects on the thermal electron-hole pair generation rate. The originality of this model lies on the full three-dimensional description of the synergetic mechanism between the Poole-Frenkel barrier lowering and the Phonon-Assisted Tunneling mechanism. To do this, a classical 1D model has been integrated over all possible directions of emission of the carriers. The 3D model has been implemented in a Monte Carlo tool devoted to the simulation of the dark current increase induced by radiations in image sensors. Our three-dimensional simulation has been compared to one-dimensional electric field effects simulations and experimental data found in the literature in the context of gold contamination. The consequence of using a three-dimensional electric field enhanced generation (EFEG) model is the reduction of the dispersive effect on the dark current distribution of the electric field: hence each dark current peak is narrower and shows higher peak's amplitude. The three-dimensional model needs to slightly change the cross section parameters used for a 1D EFEG case to keep a realistic description of each dark current peak of the histogram. In the rest of the paper, we extended our work on constraints relative to space applications. The histograms of the simulated dark current taking into account one and three dimensional electric field enhancement effects have been estimated and compared to experimental data acquired after a proton irradiation at room temperature. The use of a three-dimensional model tends to give a more realistic prediction of the dark current non uniformity in an irradiated pixel array.

I. INTRODUCTION

Thanks to their low manufacturing cost and good performance¹, the CMOS (Complementary Metal-Oxide Semiconductor) technology is widely used in diverse domains of engineering and science, like medical imagery, automotive and Earth observation. Silicon based technologies are most used for applications in the visible domain. During the manufacturing of the CMOS, some impurities can be introduced (carbon, oxygen, metals...). If the defect introduced in the crystal lattice by the impurity is electrically active, it introduces an intermediate level in the semiconductor band gap, leading to pixels that present a higher parasitic signal, the so-called dark current. This natural intrinsic current is due to the fact that, in a semiconductor, some electrons gain enough energy thanks to thermal agitation and can go from the valence band to the conduction band. Hence these electrons participate to the electrical current. In the presence of a crystal defect, also called a trap level, the charge carriers cross more easily the band gap of the semiconductor, resulting in a higher dark current. As a consequence, an intrinsic dark current peak is observed. If the same defect is present in the pixel numerous times, a series of dark current peaks corresponding to their electrical signature can be observed. Because each pixel does not contain the same number of defects, a matrix of pixels shows a non-uniformity of the dark current.

During space missions, the image sensors suffer from high energy particles bombardment (protons, electrons, heavy ions)². The high energy deposited in the material leads to atomic displacements: the atom is ejected from its lattice position and a pair of an interstitial and a vacancy (unoccupied lattice site) is created. A pair of an interstitial and a vacancy is called a Frenkel pair. If the displaced atom, the Primary Knock-on Atom (PKA), has a sufficient energy, it can also displace the atoms located on its recoil trajectory, also called Secondary-Knock-on Atoms (SKA) and create a damage cascade. A short time after irradiation, a large part of the Frenkel pairs recombine, that means that the interstitial finds a vacancy to retrieve a lattice position and the crystal returns to a normal structure³. However the remaining part of the defects forms electrically active deep trap levels which enhance the dark current. Due to the non-uniformity of the irradiation, a statistical distribution is observed on the dark current increase in the image sensor. Indeed, a pixel can contain a large number of defects and so be¹ highly degraded, while its neighbor could be far less damaged. The resulting distribution is known as the Dark Current Non Uniformity (DCNU).

According to the charge state, the orientation in the crystal cell and the nature of the primary defects which composed the crystalline defect⁴, the defect does not have the same energy level in the semiconductor band gap as well as electron and hole capture cross sections. These properties are important to describe the SRH (Shockley-Read-Hall) generation

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mechanism⁵. Depending on these properties, the number of charge carriers emitted by the defect is different and as a consequence the dark current is directly impacted.

In addition, the electric field existing in the center of the pixel interacts with the deep trap levels induced by manufacturing or irradiation⁶. In the presence of a significant electric field, the deep trap level emits more charge carriers, so its generation rate increases. The influence of the electric field in the vicinity of a deep trap level has been described for the first time by *J. Frenkel*⁷ and the electric field enhanced generation (EFEG) phenomena are often cited to explain high dark current events in image sensors^{2,6,8-13}. To our knowledge, except the paper from *Bogaerts et al.*¹⁰ which proposed a combination between a 1D and 3D EFEG model, the EFEG mechanisms are often described with a one dimensional approach^{6,9,14} in the literature. That means that only one direction of charge carrier emission is considered, but this assumption is known to overestimate the impact of the EFEG on the charge carrier thermal generation rate^{14,15}.

The contributions of high displacement damages, EFEG effects or both lead to the appearance of pixels with a high dark current value, the so-called hot pixels. The dark current increase is clearly undesirable since it reduces the useful dynamic of an image sensor, and can lead to misleading interpretations of the data acquired by the device. The need of more realistic simulations of the damages caused in a harsh environment is therefore important.

In this paper, an original three dimensional EFEG analytical model is presented. It aims at giving a more realistic description of the thermal generation enhancement. As a first part, the main equations describing the 1D EFEG model are reminded, and then the 3D EFEG model is presented. In a second time, the results of the 3D EFEG model are compared with 1D EFEG simulations found in the literature¹⁶ in the context of metal contamination. Then a parametric study of the 3D EFEG model according to the trap parameters is shown, in order to highlight the importance of these parameters on the electron-hole pair thermal generation rate influenced by an electric field. In order to experiment the 3D EFEG model to a representative case of space applications, this model has been implemented in our Monte Carlo tool dedicated (named *DAAN*) to the calculation of the dark current increase after a particle irradiation similar to space environment¹⁷⁻²¹. From particle fluence as well as type and pixel geometry, the statistic of the number of interactions in a pixel is computed. Through a *GEANT4*²² application the number of atomic displacements is added for each nuclear interaction that occurs in the depleted region of the pixel. The number of atomic displacements is then converted into electrical current. Hence the dark current non uniformity is estimated over the whole pixel array. Monte Carlo based simulations, taking into account EFEG effects, are compared with experimental data coming from proton irradiations of image sensors with energies and fluences corresponding to space applications.

II. THE ELECTRIC FIELD ENHANCEMENT MODEL

The carrier thermal generation rate can be enhanced by electric field through two mechanisms: the Poole-Frenkel Barrier Lowering (PFBL) phenomenon and the Phonon-Assisted Tunneling (PAT)²³. These effects are known to enhance carrier generation in the depletion region of a PN junction and raise the so-called dark current. These mechanisms do not affect the generation of charges in the same way depending on involved trap properties. If the trap is neutral when it is occupied by a charge, and charged after the emission of this charge, the trap is called a coulombic center. In the other hand, if the trap is neutral after the emission of a charge carrier, this trap is called a Dirac center^{6,24}. In this paper, we only make a reminder of the one-dimensional main equations, in order to understand which equations are impacted by the three-dimensional formalism proposed in section II.B.

In the literature, it is common to express the dark current I_{dark} as an Arrhenius law²⁵:

$$I_{dark} = I_0 e^{-E_A/k_B T}, \quad (1)$$

with T the temperature (K), k_B the Boltzmann's constant (eV/K), I_0 the dark current prefactor and E_A the activation energy (eV). Experimentally, it is possible to deduce the activation energy of the pixel dark current by making the ratio of the measurement of the same pixel at two different temperatures.

FIG. 1. Field-induced mechanisms: Poole-Frenkel effect corresponds to a potential lowering barrier ΔE_i . The Phonon-Assisted Tunneling is a two-step mechanism, first a thermal transition occurs and after the charge carrier crosses the potential barrier. This scheme represents EFEG for a coulombic center (applies either for electrons or holes, depending on the trap charge state).

The activation energy gives useful information about the nature of the dark current: high activation energy corresponds to a diffusion current²⁶, an activation energy close from 0.62 eV corresponds to a generation current²⁷, a reduction of the activation energy can be interpreted as an enhancement effect due to the presence of a significant electric field. The lowering of the dark current activation energy can be observed when plotting the distribution of the activation energy versus the dark current^{10,28}.

A. Reminders of the one-dimensional electric field enhancement model

The Poole-Frenkel Barrier Lowering (PFBL) is a mechanism consisting in the generation of a thermally generated carrier assisted by the lowering of the potential barrier due to the presence of an electric field⁷. Hence, the PFBL induces a lowering of the potential barrier ΔE_i as illustrated in FIG. 1. It results from the coulombic interaction between the emitted charge carrier and the trap, so it depends on the trap charge state. The Poole-Frenkel barrier lowering is only dependent on material type and electric field.

The phonon-assisted tunneling consists in the tunneling of a thermally generated carrier. More precisely, this mechanism can be decomposed in two steps: the thermal transition to a level under the top of the barrier and the tunneling through the potential barrier^{23,29}. The probability for a charge carrier to reach an energy band through phonon-assisted tunneling is the product of the probability of a charge carrier to be thermally emitted to a virtual level by the probability of crossing the potential barrier. For a Dirac center, there is no Poole-Frenkel effect, and only the PAT applies. In the case of a coulombic center, the PFBL and PAT both apply. Moreover, it is possible to consider a hyperbolic potential barrier. Vincent *et al.*⁶ have approximated the expression of charge carrier emission with a semi empirical method, from which is deduced the expression of the electric field enhancement factor for electrons and holes, $\lambda_{n,PF\&PAT}$ and $\lambda_{p,PF\&PAT}$ respectively:

$$\lambda_{n,PF\&PAT} = \exp\left(\frac{\Delta E_i}{k_B T}\right) + \int_{\Delta E_i/k_B T}^{(E_C - E_t)/k_B T} \exp\left(z - z^{3/2} \left(\frac{4(2m^*)^{1/2}(k_B T)^{3/2}}{q\hbar F}\right) \left(1 - \left(\frac{\Delta E_i}{zk_B T}\right)^{5/3}\right)\right) dz, \quad (2)$$

$$\lambda_{p,PF\&PAT} = \exp\left(\frac{\Delta E_i}{k_B T}\right) + \int_{\Delta E_i/k_B T}^{E_t/k_B T} \exp\left(z - z^{3/2} \left(\frac{4(2m^*)^{1/2}(k_B T)^{3/2}}{q\hbar F}\right) \left(1 - \left(\frac{\Delta E_i}{zk_B T}\right)^{5/3}\right)\right) dz. \quad (3)$$

with z a possible energy transition normalized by thermal energy $k_B T$, m^* the effective mass (kg) of the charge carrier, E_C the energy level of the bottom of conduction band, F the electric field (V/m), q the elementary charge (C) and E_t the energy trap level (eV). The first term represents the pure Poole-Frenkel enhancement factor, while the second term takes into consideration the combination of the phonon-assisted tunneling enhancement factor with the Poole-Frenkel barrier lowering. These equations must be solved numerically since they have not simple solution. In order to simplify the notation in the following, we consider that λ_n is the electric field enhancement factor for trap electron emission, and λ_p the electric field enhancement factor for trap hole emission when Poole-Frenkel and phonon-assisted tunneling both apply.

The trap electron-hole generation rate enhanced by the electric field can be expressed as function of λ_n and λ_p :

$$g' = \frac{\lambda_n \lambda_p \sigma_n \sigma_p v_{th,n} v_{th,p} n_i}{\lambda_n \sigma_n v_{th,n} \exp\left(\frac{E_t - E_i}{k_B T}\right) + \lambda_p \sigma_p v_{th,p} \exp\left(\frac{E_i - E_t}{k_B T}\right)}, \quad (4)$$

with $\sigma_{n,p}$ the capture cross section (m^2) of electrons and holes respectively, $v_{th,n,p}$ the thermal velocity ($m.s^{-1}$) of electrons and holes respectively, T the lattice temperature (K), n_i the intrinsic carrier density (m^{-3}) and E_i the ionization energy (eV) which is the energy between the conduction band and the deep trap energy level. The expression (4) is valid under the hypothesis of a fully depleted space charge region. That means that in any place in the pixel space charge region we suppose that the free carrier's densities are completely negligible compared to the intrinsic carrier density (i.e $n_i^2 \gg np$, where n and p are free electron and hole densities respectively).

By definition the electron-hole pair generation rate enhancement factor λ_g (or more simply the EFEG factor) is the ratio between the trap electron-hole pair generation rate enhanced by the electric field and the electron-hole pair generation rate without electric field effects:

$$\lambda_g = \frac{g'}{g} = \frac{\lambda_n \lambda_p (e_n + e_p)}{\lambda_n e_n + \lambda_p e_p}. \quad (5)$$

The terms e_n and e_p designate the electron and hole emission rate respectively³⁰. The EFEG factor λ_g depends on energy trap level, cross sections, electric field intensity and temperature. The factor λ_g is a key parameter in our simulation tool because it determines how much is amplified the dark current produced by each interaction that occurs in the pixel. *Jonscher*¹⁵ and *Martin et al.*¹⁴ mentioned that the one-dimensional Poole-Frenkel effect overestimates the enhancement of carrier generation because it is only calculated at its maximum value, reached for an angle $\theta = 0$ where θ represents the angle between the direction of charge carrier emission and the direction of the electric field¹⁵.

B. The three-dimensional electric field enhancement model

Hartke et al. and *Jonscher* proposed an expression of the 3D Poole-Frenkel Barrier Lowering^{15,31}. In 3D the electric field carrier generation enhancement depends on the angle θ . This assumption introduces a dependency on θ of the expression of the potential barrier lowering:

$$\Delta E_i(\theta) = \left(\frac{q^3 F \cos \theta}{\pi \epsilon} \right)^{1/2}, \quad (6)$$

with θ dependence for $0 \leq \theta \leq \pi/2$. Following the assumption made by *Hartke*³¹ and *Martin et al.*¹⁴, the emission of a charge carrier is supposed to be field independent for the hemisphere $\pi/2 \leq \theta \leq \pi$. In order to calculate the enhanced charge carrier emission, the enhancement factor shall be averaged among all possible directions of emission characterized by θ and ϕ . Assuming an isotropic emission of the charge carrier, that leads after integration to:

$$\lambda_{PF} = \frac{1}{2} + \frac{1 + \left(\frac{\Delta E_i}{k_B T} - 1 \right) \exp\left(\frac{\Delta E_i}{k_B T}\right)}{\left(\frac{\Delta E_i}{k_B T} \right)^2}, \quad (7)$$

with ΔE_i the simplified expression of the barrier lowering:

$$\Delta E_i = \left(\frac{q^3 F}{\pi \epsilon} \right)^{1/2}. \quad (8)$$

However a full description of the electron-hole pair thermal generation rate enhancement must include the PAT. *Bogaerts et al.*¹⁰ have added a 1D PAT mechanism on the EFEG factor. We propose here to add a 3D PAT EFEG expression that also includes itself the lowering of the barrier induced by the Poole-Frenkel mechanism. To achieve this, the spatial dependence of $\Delta E_i(\theta)$ must be considered simultaneously in the bottom limit of the integral and within the exponent of the PAT expression. Hence for each step during the integration, a new bottom limit is calculated according to the value of θ as well as a new $\Delta E_i(\theta)$ within the exponent. That leads to an analytical formalism that describes the combination of the Poole-Frenkel and the PAT effects ((9) and (10)):

$$\lambda_n = \lambda_{PF} + \frac{1}{4\pi} \int_0^{2\pi} d\phi \int_0^{\pi/2} \left[\int_{\Delta E_i(\theta)/k_B T}^{(E_C - E_t)/k_B T} \exp\left(z - z^{3/2} \left(\frac{4(2m^*)^{1/2} (k_B T)^{3/2}}{3 q \hbar F} \right) \left(1 - \left(\frac{\Delta E_i(\theta)}{z k_B T} \right)^{5/3} \right) \right) dz \right] \sin \theta d\theta, \quad (9)$$

$$\lambda_p = \lambda_{PF} + \frac{1}{4\pi} \int_0^{2\pi} d\phi \int_0^{\pi/2} \left[\int_{\Delta E_i(\theta)/k_B T}^{E_t/k_B T} \exp\left(z - z^{3/2} \left(\frac{4(2m^*)^{1/2}(k_B T)^{3/2}}{q\hbar F} \right) \left(1 - \left(\frac{\Delta E_i(\theta)}{zk_B T} \right)^{5/3} \right) \right) dz \right] \sin\theta d\theta. \quad (10)$$

Equations (9) and (10) show the electric field enhancement factor for electrons and holes in its integral form by considering a Poole-Frenkel Barrier Lowering and its contribution to the PAT. Depending on the trap type (acceptor or donor), the Poole-Frenkel barrier lowering applies only on λ_n (donor trap) or on λ_p (acceptor trap). As with equations (2) and (3), no simple solution can be found for these equations and have to be solved numerically, with a special care on the value of ΔE_i according to θ for each step during the integration.

III. APPLICATION OF THE 3D ELECTRIC FIELD ENHANCEMENT MODEL TO GOLD CONTAMINATION

In their paper, *Domengie et al.*¹⁶ used a Monte Carlo method to describe the dark current increase observed after a gold contamination during the manufacturing process of the CMOS image sensor, similar to the one used in our work for space applications^{17–21}. A Poisson distribution rules the number of gold atoms introduced in each process. Their simulation is equivalent to a spectroscopy experiment: from the position of each dark current peak, they can deduce if the pixel contains one, two or more gold atoms. They assumed that the distribution tail of each dark current peak comes from the contribution of EFEG effects. As a consequence, they used the equations presented in section II.A to take into account a 1D EFEG model in their simulation. They show that taking such model into account gives reasonable agreement with their experimental data, but conclude that a 3D EFEG model could give a more realistic description. An extensive work has been made to compare their 1D EFEG simulation results with our 3D EFEG simulation results. In order to keep the same simulation conditions, we have used the same probability distribution of EFEG factor as used by *Domengie et al.* ($\sigma_n = 2 \times 10^{-20} \text{ m}^2$ and $\sigma_p = 7.6 \times 10^{-19} \text{ m}^2$), the same energy level and cross sections for the gold atom, and we have set the fluence to keep the same mean number of gold atoms per pixel for the Poisson distribution. Since the same equations are used to compute the 1D EFEG effects on the generation current in our work and the one of *Domengie et al.*, similar results are expected. For the purpose of making a proper comparison between the work of *Domengie et al.* and our work, each curve has been normalized by its integral. This way, the Y axis shows a relative unit, corresponding to an event frequency. Finally, the work of *Domengie et al.* and our work both normalized the counts (frequency events) per unit of dark current (per aA).

FIG. 2. Comparison between the model of *Domengie et al.* (dotted line) and our simulation of gold contamination (solid line). The model of *Bogaerts et al.* (3D PF + 1D PAT EFEG) is also plotted, in order to compare the previous state of the art with a full 3D EFEG model. The slight shift along the x-axis is due to the difference between the physical parameters used in both simulations which are not exactly the same. Because of the decreasing dispersive effect of EFEG for a 3D EFEG, the dark current peaks are narrower and have higher amplitude.

Some points of the FIG. 11 of the paper of *Domengie et al.* have been extracted, and then compared with our 1D and 3D simulation results on FIG. 2. The first peak on the left corresponds to the source of intrinsic dark current level common to each pixel, modeled by a Gaussian distribution centered on 4.5 aA with a standard deviation of 1.2 aA. This peak contains the electrical contribution of all residual defects and classical band-to-band generation contribution. The following peak on the right corresponds to one gold atom level, the next one corresponds to two gold atom levels and so on. The slight shift observed along the x-axis is due to the physical parameters used to compute the thermal electron-hole pair generation rate, which are not exactly identical (a little difference of electron and hole velocity value could explain this slight difference for example). It causes a little shift of each peak, and the difference propagates a little more on each dark current peak. Our 1D gold contamination simulation is in good agreement with the work of *Domengie et al.*. The 3D EFEG model used for our simulation is the one presented in section II.B with the same simulation conditions cited previously. The impact of a three-dimensional computation instead of a one-dimensional one is clearly visible on FIG. 2: the 3D EFEG model reduces the intensity of the EFEG factor for any electric field value, so the dispersive effect of the electric field on the generation current is reduced for the same electric field distribution in the pixel. Each dark current peak is narrower and consequently each amplitude peak is higher. Also, the center of dark current peaks containing more than one gold atom are slightly shifted to lower dark current values, because the mean amplification factor for pixels containing a given number of gold atoms is lower. For the purpose of comparing the previous state of the art with our work, the equations of λ_n and λ_p given by *Bogaerts et al.* are used to compute the EFEG factor λ_g , since these equations are a mix of 3D PF and 1D PAT. From the FIG. 2, it is important to note that the work proposed by *Bogaerts et al.* corresponds to a transition between the full 1D EFE

model and the full 3D EFEG model studied in this paper. This conclusion was expected since the Poole-Frenkel barrier lowering is considered in 3D, so the EFEG factor is reduced if we compare with the one dimensional Poole-Frenkel effect. However, the PAT is still considered with a 1D approach, so the EFEG factor is higher the one considered for the 3D approach for the PAT mechanism. By doing so, our work proposes a full 3D EFEG that reduces the amplitude of the EFEG factor in comparison with the previous state of art.

The simulations of gold contamination taking into account the 3D EFEG model according to different parameters are compared on FIG. 3 with the experimental data extracted from the work of *Domengie et al.*.

FIG. 3. Comparison of 3D EFEG simulations and experimental data (dotted line) for gold contamination. Two different hypotheses are tested here: two couples of cross section parameters (named “Default” and “Adjusted”) and two different intrinsic dark current distributions : a Gaussian distribution (solid lines) and a gamma distribution (dashed lines) for the intrinsic distribution. The inset is focused on the two first dark current peaks, in order to highlight the contribution of a gamma distribution in comparison with the Gaussian one.

If the cross sections selected by *Domengie et al.* are used with a 3D EFEG model, the simulation results are not optimal compared to the experimental data. However if another couple of cross sections is used (“adjusted” curves on FIG. 3), a better fit of the experimental data is obtained. In this case, $\sigma_n = 2.4 \times 10^{-20} \text{ m}^2$ and $\sigma_p = 3 \times 10^{-19} \text{ m}^2$, these cross section values are within the experimental range found in the literature^{32–36}. In addition to the 3D EFEG model, a second hypothesis has been tested in this paper: the use of a gamma distribution to model the intrinsic dark current level instead of the Gaussian distribution chosen by *Domengie et al.*. The choice is supported by the fact that historically, gamma distributions were used to model the DCNU³⁷, and the intrinsic dark current peak shows an asymmetric profile as the one observed for the gamma distribution. The main contribution of a gamma distribution compared to a Gaussian one (for the shape and scale parameters considered) is the reduction of the amplitude of the first dark current peak (0 gold atom), because the distribution of dark currents is enlarged. As a consequence, the distribution tail is more extended on larger dark current values, and reproduces more realistically the asymmetric shape of the first dark current peak (see the inset on FIG. 3). Moreover, the use of a gamma distribution avoids the simulation of negative dark currents.

Combining the 3D EFEG model with a gamma distribution leads to a good fit of the experimental data. The influence of the gamma distribution is only noticeable for low dark current peak, typically the first three dark current peaks (0, 1 and 2 gold atoms). It is interesting to note that the amplitude and the shape of the intrinsic and the first gold level dark current peaks are well simulated in the case of the 3D EFEG model with adjusted parameters coupled to a gamma distribution, excepted for the inter-peak region. The wider standard deviation of the gamma distribution used (the shape parameter is equal to 4.5 aA, the scale parameter to 1) compared to the Gaussian one leads to slight wider dark current peaks. This case study shows that the cross section parameters and the choice of the intrinsic dark current distribution are not negligible parameters.

The consideration of the 3D EFEG model results to a good agreement with the experimental data shown in the paper of *Domengie et al.*¹⁶. However the 3D EFEG model does not improve the inter-peak transition zone. This slight discrepancy of the simulations from the experimental data could be explained by the fact that in both works, a 1D electric field map has been used which can be a source of error. Indeed, the 3D electric field map is not a three-dimensional projection of the one-dimensional electric field map. It could lead to an underestimation of the number of defects that could be located in high electric field regions for example. A second hypothesis could be also the choice of the distribution type and its parameters to model the intrinsic dark current level, which could be not optimal in this case. Finally, the electron and hole cross section parameters could explain some discrepancies observed between experimental data and simulations.

In order to highlight the EFEG contribution in our dark current simulations, the simulation of the dark current without EFEG contribution and with the 3D EFEG model have been superimposed with the experimental data on FIG. 4. This plot shows that in the context of this work, taking into account EFEG effects is clearly necessary to compute a realistic simulation of the gold contamination.

FIG. 4. Comparison of 3D EFEG (solid line) and no EFEG simulations (dashed line) with experimental data (dotted line) for gold contamination. The “Default” parameters (see FIG. 3) and gamma distribution are used to simulate the dark current.

Each dark current peak for the zero field case is much higher than the 3D EFEG case because there is a very little dispersion of the dark current. For the zero field case, the scattering of each peak comes only from the intrinsic dark current level distribution. Without this intrinsic distribution, we would observe a series of Dirac current peaks.

In this scope it is interesting to investigate the impact of including 3D EFEG mechanisms in the modeling of the DCNU induced in image sensors by radiations of the space environment. This analysis is described in the following section, after a parametric study focused on the importance of the choice of the defect parameters in such kind of analysis.

IV. APPLICATION OF THE 3D ELECTRIC FIELD ENHANCEMENT MODEL TO SPACE ENVIRONMENT

A. Parametric Studies of Electric Field Enhancement Factor

As mentioned by Domengie *et al.*¹⁶ and as was done in this paper, using capture and emission cross section values that are different from the usual values, like fitting parameters, can help to better fit the experimental data. In order to understand the influence of the cross sections and energy trap level on the electric field enhancement factor, a parametric study has been performed. In this paper we are interested in the variability of the thermal electron-hole pair generation rate λ_g due to the EFEG with energy level and cross section parameters, whereas in the literature^{10,14} the authors are often interested in the EFEG of the thermal emission rate of a charge carrier (λ_n or λ_p), which is not exactly equivalent. λ_g is the enhancement of the emission of an electron-hole pair, i.e the enhancement of a simultaneous exchange between the conduction and the valence bands, which takes into account the capture cross section $\sigma_{n,p}$ (equivalent to a probability of exchange between a charge carrier and a band)³⁰. However $\lambda_{n,p}$ are the enhancements of the emission of electron or hole towards the conduction band or the valence band respectively. The factors $\lambda_{n,p}$ do not take into account the cross section parameter, so that it is not adequate to directly link $\lambda_{n,p}$ to the enhancement of the reverse bias current. Moreover, in the literature the factors $\lambda_{n,p}$ are often calculated for an energy level located at the midgap^{10,14}.

Firstly, the variation of λ_g (computed with the 3D EFEG model) according to the energy trap level has been plotted (FIG. 5). A large electric field range is spanned in order to cover electric fields encountered in CMOS image sensors (CIS) and in SPAD (Single-Photon Avalanche Diode) image sensors, which presents higher maximum electric field than in CIS and precisely some authors showed their interest to electric field influence in such irradiated devices¹³.

FIG. 5. Evolution of the 3D EFEG factor λ_g with the electric field for different energy levels eT considered as acceptor traps. A great part of the silicon band gap (1.12 eV) is screened by step of 0.2 eV from 0.1 eV to 0.9 eV. Until 2×10^8 V/m, for these capture cross section parameters and temperature, we observe two distinct regimes. Above this electric field value, we observe several decades of discrepancy.

The capture cross sections are equals to 5×10^{-19} m², and the temperature is fixed to 294.15 K.

Note that the parametric study is only focused on an acceptor trap because the evolution of λ_g of an acceptor trap is expected to be very similar to a donor trap when they are located at the same absolute distance from the midgap (i.e mirrored position, an acceptor +0.1 eV up to the midgap, a donor -0.1 eV under the midgap for example), and if they have the same capture cross sections for a given temperature and electric field.

FIG. 5 shows that λ_g follows two distinct regimes according to the energy level from low electric fields to approximately $2 \times 10^8 \text{ V/m}$.

The first regime is attributed to the energy levels located under the midgap, i.e. $eT < 0.56 \text{ eV}$ (the most visible curve is the 0.50 eV one, the others are superimposed), and the second regime is attributed to the energy levels located beyond the midgap, i.e. $eT > 0.56 \text{ eV}$ (the most visible curve is the 0.90 eV one, the others are superimposed). As the electric field rises, λ_g becomes more and more different with respect to the energy level. Moreover, the closer the energy level is to the middle of the gap, the lower λ_g is. This means that if a trap has an energy level close to the midgap, the electric field will not enhance a lot the thermal generation rate, but the absolute thermal generation rate itself will be higher than a trap energy level which is far from the middle of the band gap.

In a second time, the variation of λ_g with capture cross sections of electrons and holes has been studied. The cross section parameter is screened on a large range (from 10^{-21} m^2 to 10^{-18} m^2) because experimental measurements present a discrepancy from a study to another^{4,38-41}. This underlines the importance of cross section choice in simulations. The curves for one and three dimensional models are plotted on the same graph, in order to highlight the contribution of the three dimensional model compared to the one dimensional one. The EFEG factor on electron-hole pair thermal generation rate has also been computed using the equations given by *Bogaerts et al.* in order to analyze the contribution of the full 3D EFEG model presented in this work compared to the previous state of the art. One defect has been chosen to make this study: the divacancy defect in its one negative state charge $V_2^{-/0}$, which is positioned at approximately 0.71 eV above the valence band in the silicon bandgap^{4,38}. This choice has been supported by the fact that this defect is well-known and characterized, stable at ambient temperature. This defect is electrically active with a significant charge generation rate so it is a non-negligible contributor of the dark current. The temperature is fixed to 294.15 K and a large range of electric field (from 10^6 V/m to 10^8 V/m) has been screened. For the divacancy level, σ_n is screened on 4 orders of magnitude and σ_p is set to an arbitrary value of $1 \times 10^{-17} \text{ m}^2$. In this case, σ_n is at least 10 times higher than σ_p , so $\sigma_n \gg \sigma_p$. On FIG. 6a, each curve is attributed to a couple of capture cross sections; the dashed line corresponds to the 1D model and the solid line to the 3D model.

FIG. 6. Evolution of the EFEG factor λ_g with the electric field for different couple of cross sections σ_n/σ_p for an acceptor trap located at 0.71 eV . The 1D (dashed lines) and 3D (solid lines) are presented on the same graph to capture the relevance of using a 3D EFEG model (a). On the bottom graph, the “hybrid” model inspired by the work of *Bogaerts et al.* is also reported (cross lines) for one couple of capture cross sections. The electric field range is more restricted to highlight the transition region between the 1D and 3D model.

For the acceptor trap located at 0.71 eV from the valence band, a diminution of the EFEG factor from the 1D model to the 3D model by a factor between 2 to approximately 8 is observed, depending on the cross sections considered. *Bogaerts et al.*¹⁰ have a ratio of less than 3 for an electric field of 10^7 V/m and a trap at the midgap when they compared their 1D and 3D EFEG ($\lambda_{n,p}$) models. Thus, we observe a ratio of similar magnitude in our model. Finally, by using the equations given by *Bogaerts et al.*, the EFEG factor on electron-hole pair thermal generation rate λ_g (and not $\lambda_{n,p}$) is

computed, and named as “hybrid” model because it mixes 3D PF and 1D PAT. Hence, the contribution of a full 3D approach in comparison with the hybrid model, inspired from the work of *Bogaerts et al.*. For the parameters considered to plot FIG. 6b, in comparison with their work, our model reduces the amplitude of λ_g . As an example, from the FIG. 6b at an electric field value of 10^7 V/m for $\sigma_n = 10^{-21} \text{ m}^2$ and $\sigma_p = 10^{-17} \text{ m}^2$, the amplitude of λ_g predicted by the full 3D EFEG model is 1.4 times lower than the one predicted by the previous state of the art. FIG. 6b clearly shows that the work proposed by *Bogaerts et al.* is the transition between a full 1D EFEG model and a full 3D EFEG model. Indeed, from 10^6 V/m to $5 \times 10^6 \text{ V/m}$, their “hybrid” model fits very well with the full 3D EFEG model, since the Poole-Frenkel Barrier Lowering dominates in this electric field range, and this phenomenon is computed with a 3D approach in both cases. However, as the electric field increases, the hybrid model tends to the full 1D EFEG model. It is explained by the fact that the PAT mechanism becomes the main contribution of EFEG when the electric field rises. Since the hybrid model considered a 1D PAT EFEG, it converges to the full 1D EFEG model, contrary to the full 3D EFEG model.

Note that the diminution of λ_g from 1D to 3D EFEG model is not homogenous along all the studied electric field range. A similar discrepancy has been observed during our parametric study on the energy trap level (shown in FIG. 5) but it is not plotted here for clarity reason. *Martin et al.*¹⁴ have observed a similar behavior than the one shown on FIG. 5 when varying the ionization energy in the PAT equation.

Thus, the larger the electron capture cross section is, the larger the EFEG factor is. For two orders of magnitude between two couples of cross section parameters, a factor of 2 to 10 is observed and much higher for excessive electric field values (above 10^8 V/m , not plotted here). For the low range of electric field (under 10^6 V/m), not so much differences are observed between each set of parameters, because the electric field value is not so high to show great differences.

The variations of λ_g would not be so large if a lower value of σ_p would have been chosen. To clarify this point, the expression of λ_g (5) must be reminded. For a trap above the midgap, like the divacancy level, if $\sigma_n \gg \sigma_p$ it is always true that $e_n \gg e_p$, and so λ_g tends to λ_p . However, if $\sigma_p \gg \sigma_n$, e_n can be of the same order of magnitude as e_p , hence λ_g is a combination of the variation of e_n and e_p with σ_n and σ_p . It is the opposite case for an energy trap level located under the middle of the band gap⁴². Following this rule, the variation of λ_g can be anticipated: if the energy level is above the midgap and $\sigma_n \gg \sigma_p$, λ_g will tend to a constant for a given electric field and it is also true for an energy level under the midgap with $\sigma_p \gg \sigma_n$. That is why we only looked at a fixed σ_p for a range of σ_n in the case of the divacancy defect. These observations are independent from 1D or 3D models.

According to this study, even for low electric fields (under 10^6 V/m) which are not represented here in our plots, the EFEG is not negligible. For example, λ_g is almost equal to 1.6 for the divacancy level for an electric field of 10^6 V/m , and 1.15 if an electric field of 10^4 V/m is applied. Thus the dark current density is amplified by a non-negligible factor even for a low electric field range. Of course this conclusion depends on the nature of the studied defect. For a given electric field, these values will vary depending on the trap parameters.

The sensitivity of the EFEG factor λ_g to energy level and cross section parameter has been shown. As a consequence it is necessary to be careful about this sensitivity when using or interpreting electric field enhancement calculations. This sensitivity is especially observed for high electric field (approximately above 10^6 V/m) and as a consequence it can influence the extreme dark current event prediction like hot pixels. Moreover, if the electrical properties of studied defects are quite different, the parametric sensitivity of λ_g should be taken into account. Also, these parametric studies showed how the transition from 1D to 3D EFEG model and the variation of the trap parameters can affect the calculation of the dark current increase.

B. Monte Carlo Simulations

During space missions and depending on the satellite orbits, the embedded image sensors are exposed to various particles from low to high fluences. This results in the introduction of defects of various natures in different concentration in the pixel volume. As a consequence, it is difficult to identify and predict which defects will dominate the generation of the dark current on a whole pixel array. To solve this, *Srouf et al.*²⁷ have extracted from a great number of experimental data a coefficient that allows to convert Displacement Damage Dose (DDD) into an electrical current. This coefficient is called the Universal Damage Factor (UDF) because it can be used for any silicon devices at any fluence and particle energy. UDF hence describes a mean degradation occurring in the silicon device due to the DDD. Through our Monte Carlo tool¹⁷⁻²¹, the statistical degradation on a whole pixel array is computed according to the energy and the fluence of the considered particle as well as the pixel geometry. The number of atomic displacements is computed with *GEANT4*²² for elastic and inelastic nuclear reactions while analytical expressions are used for the Colombian interactions¹⁷⁻²¹. The UDF is used to convert the number of atomic displacements calculated to an electrical current. The EFEG effects are taken into account as a dispersive contribution of the UDF. It means that for each nuclear interaction occurring in the depleted region of the pixel, the number of atomic displacements created during this interaction is multiplied by the UDF and by the EFEG factor normalized by the mean EFEG factor of the simulation. The computation of the dark current for each nuclear reaction occurring in a pixel is expressed as follow:

$$\Delta I_i \propto N_{d,i} \times K_{dark} \times \left(\frac{\lambda_{g,i}}{\langle \lambda_g \rangle} \right), \quad (11)$$

where ΔI_i is the dark current increase induced by one nuclear interaction, $N_{d,i}$ the number of atomic displacements created during one nuclear interaction, K_{dark} the UDF computed for a given temperature and time after irradiation, $\lambda_{g,i}/\langle\lambda_g\rangle$ the ratio of the random EFEG factor with the mean EFEG factor of our simulation. By doing so, the electric field effect in our simulation maintains the definition of a mean dark current provided by the UDF. Indeed, the UDF is a mean degradation parameter representative of experimental observations on a large set of devices²⁷ that shall be kept unchanged in order to remain within the same assumptions. This way, the scattering effect induced by the EFEG mechanisms is added to the simulation. This allows also adding a dispersive contribution to the DCNU tail. This approach can be compared to the one followed by *Bogaerts et al.*¹⁰, who normalized their EFEG factor to fit their experimental data. Here no fitting procedure is applied, the EFEG factor is just normalized to its calculated average.

Finally, we want to highlight the fact that the normalization of the EFEG factor does not imply implicitly an electric field contribution in the UDF, and this operation seems necessary to be in compliance with the SRH theory. Indeed according to FIG. 5, $\lambda_g(0.50 \text{ eV}) < \lambda_g(0.90 \text{ eV})$ for identical electron and hole capture cross sections at any electric field value. According to SRH statistics and these trap parameters, the electron-hole pair thermal generation rate is higher for the 0.50 eV level than for the 0.90 eV one (i.e $g(0.50 \text{ eV}) > g(0.90 \text{ eV})$), since the first is close to the midgap. Because the study stands in the framework of the UDF, only the EFEG factor is used and not the thermal generation rate as opposed to the gold contamination study. Not normalizing the EFEG factor would be equivalent to consider that the 0.90 eV level generates more charge carriers than the 0.50 eV one, and by extension considering that the 0.90 eV level is responsible of a higher dark current increase than the 0.50 eV level. Because this is not in compliance with SRH statistics and not experimentally observed, it seems to be important to normalize the EFEG factor in the UDF framework.

C. Comparison with experimental data

To run our Monte Carlo simulations, the divacancy level is kept as the reference value, and the capture cross sections of electrons and holes are fixed to $5 \times 10^{-19} \text{ m}^2$. The choice of energy level and cross sections is quite difficult, because the values of these parameters come from different experimental results. This can lead to a difference of several different orders of magnitude between experimental studies, especially for cross section measurements. We opted for the most representative parameters from many defect studies in the literature^{4,39,43,44}. Concerning the UDF, as indicated by *Srouf et al.*²⁷, time and temperature corrections have been applied to be in accordance with the experimental conditions. Thus, the UDF has been computed for 1 month after irradiation at the sensor measurement temperature.

In this section the results of DCNU simulations with one dimension and three dimensions EFEG modeling are compared to new experimental data (SAPPHIRE image sensor) and experimental data used in the work of *Ursule et al.*²¹ (JADE image sensor). The SAPPHIRE and JADE image sensors are products of Teledyne E2V⁴⁵. SAPPHIRE image sensor has been irradiated at Synergy Health facilities (Harwell, UK) for a 6.5 MeV proton energy at a fluence of $3.89 \times 10^9 \text{ p+}/\text{cm}^2$, and the JADE image sensor has been irradiated at Kernfysisch Versneller Instituut (KVI) facilities in Netherlands for a 60 MeV proton energy at a fluence of $7.28 \times 10^{10} \text{ p+}/\text{cm}^2$. The SAPPHIRE dark current measurements have been done at 294.15 K (accuracy of $\pm 0.2^\circ\text{C}$, thermal stability of $\pm 0.01^\circ\text{C}$), and those for the JADE at 296.15 K (accuracy of $\pm 0.3^\circ\text{C}$, thermal stability of $\pm 0.1^\circ\text{C}$). Both components were irradiated at room temperature. The experimental measurements were made one month after irradiation. The electric field ranges of JADE and SAPPHIRE components are both between approximately $2 \times 10^3 \text{ V/m}$ and $3 \times 10^7 \text{ V/m}$.

The DCNU are presented in FIG. 7 for one and three-dimensional models as well as the experimental data for SAPPHIRE and JADE components. The figures are shown in logarithmic scale for both X and Y axis to highlight the tail of the DCNU. The DCNU plotted on FIG. 7 are differential distributions: it means that the number of events for a given dark current interval is normalized according to the total number of events of the distribution and to the interval width. Hence each distribution can be strictly compared. The distribution of electric field along the depth in the pixel is given by Teledyne E2V and the electric field is determined randomly from this electric field map for each nuclear interaction in our simulations.

FIG. 7. Distributions of the dark current density (DCNU) for one and three-dimensional models and experimental data for SAPHIRE (a) and JADE (b) components. SAPHIRE experimental data come from 6.5 MeV one month after proton irradiation at a fluence 3.89×10^9 p+/cm² at 294.15 K, and JADE experimental data come from 60 MeV one month after proton irradiation at a fluence of 7.28×10^{10} p+/cm² at 296.15 K.

As expected from the conclusion of the section IV.A and as can be seen in FIG. 7, the three-dimensional model decreases the intensity of highest dark current densities by a factor from 2 to 3 in comparison with the one-dimensional model. For the chosen trap properties and the given electric field map, the mean EFEG factor is approximately equal to 7 for the one-dimensional model and about 2.25 for the three-dimensional model.

Also, due to the inhomogeneous decrease of λ_g along all the electric field range, the 3D DCNU is not a simple shift from the 1D DCNU to the lower currents but it acts also on the shape of the DCNU by reducing the scattering effect of the EFEG model. The use of a 3D EFEG model to compute the DCNU seems to give a better fit of the experimental data, especially on the distribution of high dark current events. For both components, the 3D EFEG model leads to a better estimation of the dark current distribution tail. However, the 3D EFEG model seems to be more efficient on the global shape of the DCNU for the JADE simulation than for the SAPHIRE one. Indeed, the DCNU is better simulated for quite all the dark current range in the JADE case, whereas the DCNU is better estimated only for dark current values higher than 3-4 nA/cm² in the SAPHIRE case. Indeed, the dark currents simulated according to the 3D EFEG model are closer to the experimental data than the 1D case on the whole dark current range in the JADE case. As a consequence, the global shape of the DCNU is better estimated for this component. In the SAPHIRE case the low dark currents (10^{-3} to 10^{-1} nA/cm²) are less well estimated in the 3D case compared to the 1D one, but it is not that critical compared to hot pixels estimation.

Even if the 3D EFEG model tends to bring the dark current distribution tail (hot pixels distribution) closer to experimental distribution in both cases, the hot pixel dark currents and their frequency are still slightly overestimated for each tested component. We suspect that the trap parameters does not fit well with the real damage undergone by the components, as well as the hypothesis of a single level defect population may not be sufficient. Indeed, energetic radiations like in space environment induce the formation of many different complex defect species in the component (vacancy complexes, vacancy-impurity complexes, impurity complexes and more ^{2,4}), with their own electrical properties. As a consequence, these different species do not act the same way on the dark current increase. Finally, the fact that the same electric field is used to enhance the dark current induce by a damage cascade may overestimate the dark current calculations, since in reality a damage cascade can extend from several nanometers to microns.

V. DISCUSSION

The point we want to highlight in this discussion is what we could call a “cutoff electric field”. This concept is illustrated on the following figure.

FIG. 8. Dark current distributions for one gold atom level considering the same simulation conditions than in section III. For each distribution, the whole electric field distribution is divided by a coefficient a in order to reduce the electric field values. The abbreviation “EFE” means “Electric Field Enhancement”.

The idea of this concept is to study under which electric field value the EFEG contribution could be considered as negligible. The gold atom level (see section III) is considered with an electric field distribution used in section III. The whole electric field distribution is divided by a factor a in order to reduce at each point the electric field intensity taken from the

electric field map. In the work of *Domengie et al.*, the studied electric field range corresponds approximately to $[2 \times 10^5 - 3 \times 10^7 \text{ V/m}]$, so when $a = 100$, the electric field range becomes $[2 \times 10^3 - 3 \times 10^5 \text{ V/m}]$ for example. The FIG. 8 is a zoom of the dark current distribution for one gold atom level computed in the same simulation conditions as in the section III, and the reference gold atom dark current has been added to FIG. 8 (dark current without EFEG effects). The more the electric field magnitude is reduced, the more the dark distribution tends to the reference distribution (zero EFEG), but the distribution never centers on the reference one. That means that even for low electric field values, a little EFEG effect still exists, even if it is negligible when we consider only one atom (1 aA shift for gold atom level, equivalent to a value of 2% dark current increase in comparison with the reference value). The FIG. 8 highlights the dispersive effect of the electric field on the dark current distribution: the lower are the electric fields, the more the dark current distribution tends to the reference Gaussian distribution. 100% of the pixels present a dark current between 37 and 48 aA for the reference case. The number of pixels presenting a current in this range is estimated as a function of the electric field magnitude. From the FIG. 8, the dark current distribution tail shift induced by the electric field is clearly observed. Indeed, the dark current distribution spreads on higher dark current values than the reference one (zero field case) in the presence of an electric field. The consequence of the application of an electric field is a slight shift of the distribution peak and a wider distribution. However, as the electric field intensity decreases, the dark current distribution tends to the reference one. This behavior is studied through the variation of the electric field amplitude reduction factor a . When the true electric field distribution ("Full EFE" curve on FIG. 8, equivalent to $a = 1$) is considered, only 45% of the total events are in the interval. It means that 55% of the reference (zero field) population is put outside the reference dark current range (37 to 48 aA) when considering the true electric field distribution. As the electric field intensity decreases (i.e. as a increases), the number of pixels outside the reference dark current range decreases. As an example, for an electric field distribution reduction factor $a = 2$ there is 43.9% of the pixel population affected by the influence of the electric field, 14.8% for $a = 10$, 0.55% for $a = 100$. As a conclusion, even if the electric field distribution has been reduced by a factor of 100, a slight electric field effect remains on the dark current distribution.

The first way to improve the DCNU simulations could be using multilevel defect population. Indeed, the choice of a divacancy with parameters presented in section IV.C seems to be consistent with the experimental data, but the consideration of another dark current contributor trap like the interstitial carbon-interstitial oxygen complex C_iO_i ⁴⁶ for example, should help to improve our modeling of the DCNU. Indeed until now, we consider in our simulation tool that all the atomic displacements that have been created by one interaction in the pixel are used to create the same deep trap defect, with identical characteristics. In reality, even if the divacancy is a common defect, many more defects with different properties in different concentration are created in the irradiated sample, as explained at the end of the section IV.C. Advanced algorithms like Kinetic Monte Carlo algorithms⁴⁷ could help to determine the defect population after irradiation, in order to refine the DCNU simulations.

Many other ways could be explored to explain the discrepancy between the simulation and experimental data. As mentioned in section III, using a 3D electric field distribution could be a real benefit for simulation and easily achievable if the device's manufacturer can provide this information. Actually, the use of a 1D electric field distribution could underestimate or overestimate the electric field effects in some regions of the pixel. A deeper characterization of the intrinsic dark current level of the device could be a benefit to improve the modeling a low dark current level (using asymmetric distribution like log-normal or Weibull distributions for example). More complex ways could be the use of different defect potential well like presented *Martin et al.*¹⁴ (Yukawa, polarization and dipole potentials). Indeed, the authors showed that using different potential shape affects the computation of the EFEG factor.

VI. CONCLUSIONS

A new three-dimensional analytical electric field enhancement model has been proposed in this paper. This model takes explicitly into account the Poole-Frenkel barrier in the integration along all the possible charge carrier emission directions. A new barrier lowering is computed according to the direction of the charge carrier emission during each step of the integration. The results of this EFEG model has been compared to experimental and 1D EFEG simulations data found in the literature in the context of image sensor gold contamination. The 3D EFEG model needs the use of different capture cross sections in comparison with a 1D EFEG model to have a good fit of the experimental data. The remaining discrepancies between experimental and simulation results could be attributed to different reasons. The calculation neglects the 3D spatial electric field distribution. The importance of the choice of simulation parameters has been underlined through parametric studies on trap parameters. According to our model, the more the electric field increases, the more the difference between two sets of parameters increases. The variability of the EFEG factors has been highlighted.

The use of a three-dimensional approach reduces the scattering effects of the electric field compared to the one-dimensional case. Even if the EFEG effect is reduced by considering a three-dimensional modeling, the EFEG is not negligible even for low electric fields. For a device irradiated with energetic protons, a reduction by a factor from 2 to 3 is observed for the highest dark current. The shape of the DCNU is changed, and the number of hot pixels presenting the highest dark current values is reduced.

Finally comparisons with some experimental data obtained on the SAPPHIRE and JADE devices from Teledyne E2V show that the 3D enhancement model reduces the number of high dark current events and increases the number of intermediate dark current events, bringing the simulated DCNU closer to the experimental one. More studies on trap parameters and nature are needed to improve the estimation of the DCNU. The use of a 3D electric field distribution could also help to improve the simulation.

VII. DATA AVAILABILITY STATEMENT

Due to the nature of this research, participants of this study did not agree for their data to be shared publicly, so supporting data is not available. The only available data are the ones provided in this study.

VIII. BIBLIOGRAPHY

- ¹ E.R. Fossum, IEEE Trans. Electron Devices **44**, 1689 (1997).
- ² J.R. Srour, C.J. Marshall, and P.W. Marshall, IEEE Trans Nucl Sci **50**, (2003).
- ³ J.R. Srour and J.W. Palko, IEEE Trans. Nucl. Sci. **60**, 1740 (2013).
- ⁴ G.D. Watkins, Mater. Sci. Semicond. Process. **3**, 227 (2000).
- ⁵ W. Shockley and W.T. Read, Phys. Rev. **87**, 835 (1952).
- ⁶ G. Vincent, A. Chantre, and D. Bois, J. Appl. Phys. **50**, 5484 (1979).
- ⁷ J. Frenkel, Phys. Rev. **54**, 647 (1938).
- ⁸ M.J.J. Theunissen and F.J. List, Solid-State Electron. **28**, 417 (1985).
- ⁹ J.R. Srour and R.A. Hartmann, IEEE Trans. Nucl. Sci. **36**, 1825 (1989).
- ¹⁰ J. Bogaerts, B. Dierickx, and R. Mertens, IEEE Trans. Nucl. Sci. **49**, 1513 (2002).
- ¹¹ E. Martin, T. Nuns, J.-P. David, O. Gilard, J. Vaillant, P. Fereyre, V. Prevost, and M. Boutillier, IEEE Trans. Nucl. Sci. **61**, 636 (2014).
- ¹² C. Virmondois, V. Goiffon, M.S. Robbins, L. Tauziède, H. Geoffroy, M. Raine, S. Girard, O. Gilard, P. Magnan, and A. Bardoux, IEEE Trans. Nucl. Sci. **60**, 4323 (2013).
- ¹³ D. Fiore, M. Campajola, C. Nappi, E. Sarnelli, and F.D. Capua, in *2018 IEEE Nucl. Sci. Symp. Med. Imaging Conf. Proc. NSSMIC* (2018), pp. 1–4.
- ¹⁴ P.A. Martin, B.G. Streetman, and K. Hess, J. Appl. Phys. **52**, 7409 (1981).
- ¹⁵ A.K. Jonscher, Thin Solid Films **1**, 213 (1967).
- ¹⁶ F. Domengie, P. Morin, and D. Bauza, J. Appl. Phys. **118**, 024501 (2015).
- ¹⁷ C. Inguibert, T. Nuns, E. Martin, D. Falguère, and O. Gilard, in *2012 13th Eur. Conf. Radiat. Its Eff. Compon. Syst. RADECS* (Biarritz, France, 2012).
- ¹⁸ C. Inguibert, T. Nuns, M.C. Ursule, D. Falguère, D. Hervé, M. Beaumel, and M. Poizat, IEEE Trans. Nucl. Sci. **61**, 3323 (2014).
- ¹⁹ M.C. Ursule, C. Inguibert, and T. Nuns, IEEE Trans. Nucl. Sci. **63**, 2159 (2016).
- ²⁰ M.C. Ursule, C. Inguibert, T. Nuns, and J. Morio, IEEE Trans. Nucl. Sci. **65**, 1345 (2018).
- ²¹ M.C. Ursule, T. Nuns, C. Inguibert, H. Bugnet, F. Mayer, and J. Pratlong, in *2017 17th Eur. Conf. Radiat. Its Eff. Compon. Syst. RADECS* (Geneva, Switzerland, 2017), pp. 1–7.
- ²² (n.d.).
- ²³ L. Kleinman, Phys Rev **140** A637 (1965).
- ²⁴ O.K.B. Lui and P. Migliorato, Solid-State Electron. **41**, 575 (1997).
- ²⁵ J.C. Dunlap, M.M. Blouke, E. Bodegom, and R. Widenhorn, IEEE Trans. Electron Devices **63**, 26 (2016).
- ²⁶ R. Widenhorn, M.M. Blouke, A. Weber, A. Rest, and E. Bodegom, in *SPIE Proc.* (2002).
- ²⁷ J.R. Srour and D.H. Lo, IEEE Trans. Nucl. Sci. **47**, 2451 (2000).
- ²⁸ E. Martin, T. Nuns, C. Virmondois, J.-P. David, and O. Gilard, IEEE Trans. Nucl. Sci. **60**, 2503 (2013).
- ²⁹ D. Pons and S. Makram-Ebeid, J. Phys. **40**, 1161 (1979).
- ³⁰ S.M. Sze, *Physics of Semiconductor Devices*, 2nd ed (Wiley, New York, 1981).
- ³¹ J.L. Hartke, J. Appl. Phys. **39**, 4871 (1968).
- ³² G. Bemski, Phys. Rev. **111**, 1515 (1958).
- ³³ K. Graff, *Metal Impurities in Silicon-Device Fabrication*, 2nd ed. (Springer-Verlag, Berlin Heidelberg, 2000).
- ³⁴ V. Kalyanaraman and V. Kumar, Phys. Status Solidi A **70**, 317 (1982).
- ³⁵ A. Luis Santos Ferreira-Resende, An Ab Initio Study of Deep-Level Defects in Silicon, PhD Thesis, University of Exeter, 1999.
- ³⁶ E. Schibli and A.G. Milnes, Mater. Sci. Eng. **2**, 229 (1968).
- ³⁷ P.W. Marshall, C.J. Dale, and E.A. Burke, IEEE Trans. Nucl. Sci. **37**, 1776 (1990).
- ³⁸ J.C. Bourgoin and N. de Angelis, Sol. Energy Mater. Sol. Cells **66**, 467 (2001).
- ³⁹ A.O. Evwaraye and E. Sun, J. Appl. Phys. **47**, 3776 (1976).
- ⁴⁰ I. D. Konozenko, A. K. Semenyuk, and V. I. Khivrich, Phys. Status Solidi B-Basic Solid State Phys. - PHYS STATUS SOLIDI B-BASIC SO **35**, 1043 (1969).
- ⁴¹ M. Moll, H. Feick, E. Fretwurst, G. Lindström, and C. Schütze, Nucl. Instrum. Methods Phys. Res. Sect. Accel. Spectrometers Detect. Assoc. Equip. **388**, 335 (1997).
- ⁴² M.C. Ursule, Compréhension des mécanismes physiques à l'origine des dégradations électriques extrêmes des pixels dans les capteurs d'images irradiés, Toulouse, ISAE, 2017.
- ⁴³ C. Tivarus and W.C. McColgin, IEEE Trans. Nucl. Sci. **55**, 1719 (2008).
- ⁴⁴ G.D. Watkins and J.W. Corbett, Phys. Rev. **138**, A543 (1965).
- ⁴⁵ E2v (n.d.).
- ⁴⁶ J.M. Trombetta and G.D. Watkins, Appl. Phys. Lett. **51**, 1103 (1987).
- ⁴⁷ A. Jay, M. Raine, N. Richard, N. Mousseau, V. Goiffon, A. Hémercyck, and P. Magnan, IEEE Trans. Nucl. Sci. **64**, 141 (2017).