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SEE rate estimation based on diffusion approximation of charge collection

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ABSTRACT

The integral rectangular parallelepiped (IRPP) method remains the main approach to single event rate (SER) prediction for aerospace systems, despite the growing number of issues impairing method's validity when applied to scaled technology nodes. One of such issues is uncertainty in parameters extraction in the IRPP method, which can lead to a spread of several orders of magnitude in the subsequently calculated SER.

The paper presents an alternative approach to SER estimation based on diffusion approximation of the charge collection by an IC element and geometrical interpretation of SEE cross-section. In contrast to the IRPP method, the proposed model includes only two parameters which are uniquely determined from the experimental data for normal incidence irradiation at an ion accelerator. This approach eliminates the necessity of arbitrary decisions during parameter extraction and, thus, greatly simplifies calculation procedure and increases the robustness of the forecast.

1. Introduction

Today, the most common approach to estimation of single-event-effect (SEE) rate (SER) uses the concept of total charge collection within a limited sensitive volume [1,2]. The sensitive volume is typically modeled as a rectangular parallelepiped (RPP) or, less frequently, as a thin layer with a certain cutoff angle. To estimate SER, in addition to sensitive volume dimensions, we also need to know the dependence of SEE cross-section on linear transfer energy (LET). Usually, it is obtained at normal ion incidence for several LET values and approximated by the Weibull function.

Under this approximation, SER in the isotropic ion field with constant LET is dependent only on change of the chord length (ion path) within the sensitive volume. The experientially observed gradual increase of the cross-section with increasing LET was explained by variation in the energy needed for SEE. In our opinion, such a concept is in total contradiction with SEE physical nature. In reality, the SEE threshold energy stays nearly the same (within process variation limits), but charge collection efficiency changes across the sensitive volume. It is obvious that for SEE to occur a low-LET ion should hit close to the charge collection node, but a high-LET ion may hit further away from the node. This very consideration, rather than the spread of sensitivity parameters, actually accounts for the shape of the cross-sectional curve.

Such physical approach enables an entirely different method of SER estimation. First, we build a model to describe SEE cross section vs. LET based on physically valid assumptions. Then we have to account for angular dependence to correlate the cross-section $\sigma_{is}(LET)$ in the isotropic field, with the experiment.

In this case, SER can be estimated using a fairly simple equation:

$$R_{SEE} = \int \sigma_{is}(LET) \cdot \phi_z(LET) \cdot dLET \qquad (1)$$

where $\phi_z(LET)$ is the differential omnidirectional particle flux as a function of LET, $\sigma_{is}(LET)$ is the SEE cross-section in the isotropic field.

Therefore, the main task is to obtain SEE cross-section dependence on LET under the isotropic ion field $\sigma_{is}(LET)$ from the experimental results at normal ion incidence.

2. Proposed method

2.1. Charge collection model

For single event upset (SEU), cross-section dependence on LET in the isotropic radiation field can be obtained in diffusion approximation neglecting drift collection processes [3–5]. This approximation holds reasonably well at relatively high LET values, but the drift processes may affect cross-sections at near-threshold LET values.

As the first step, we have to obtain the value of ionization response of a separate sensitive element for different locations of charged particle track. This problem was solved for the structure shown in Fig. 1 [3]. For this model geometry, processes of charge collection by

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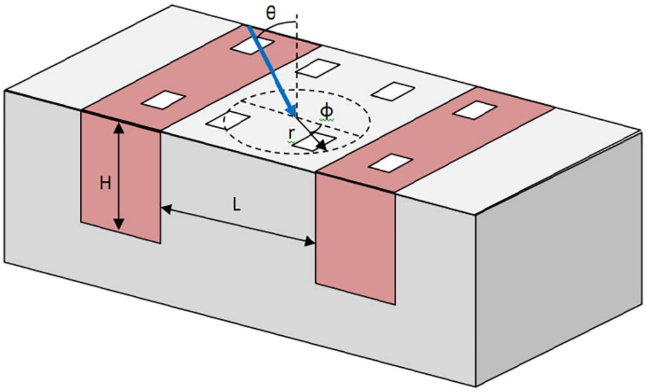

Fig. 1. Problem illustration: the structure with multiple sensitive p-n junctions and an ion incident at a point between two well borders. The "critical" area is shown by the dashed line.

relatively deep well-substrate junctions play a crucial role. The proposed ionization current model is based on the diffusion equation solved under linear approximation with account for the well borders effect.

The approximate equation for the diffusion current of the separate junction with a center at $\mathbf{r} = (x,y,0)$ created by the point charge source at $\mathbf{r_0} = (x_0,y_0,z_0)$ can be presented in the form (Appendix A):

$$i(\mathbf{r},\mathbf{r_0},t) \approx \mathrm{qD_m}\frac{R}{\pi^{3/2}\sqrt{Dt}\,(Dt+R^2/2)}\times\left(1+\frac{2\sqrt{4\pi Dt}}{L}\right)\cdot \exp\left(-\frac{|\mathbf{r}-\mathbf{r_0}|^2}{4Dt}-\frac{\pi^2}{L^2}Dt\right) \tag{2}$$

where R is the p-n junction radius, D is the ambipolar diffusion coefficient, D_m is the diffusion coefficient of minority carriers, q is the elementary charge.

The equation for the diffusion current I can be derived from (2) by integrating along the ion track with account for the linear density of charge sources:

$$I(\mathbf{r},t) \approx q\frac{1}{\varepsilon_i}LET\frac{D_mR}{\pi(Dt+R^2/2)}\left(1+\frac{2\sqrt{4\pi Dt}}{L}\right) \times \exp\left(-\frac{r^2(1-b^2)}{4Dt}-\frac{\pi^2}{L^2}Dt\right)\left(1+erf\left(\frac{br}{2\sqrt{Dt}}\right)\right) \tag{3}$$

$$b = \sin(\theta)\cos(\varphi-\varphi_0)$$

where θ and φ are polar and azimuthal angles of the ion track, correspondingly (Fig. 1); φ_0 is the azimuthal angle of vector $\mathbf{r_0}$;ε_i is the mean energy required to create an electron–hole pair. Ionization current amplitude can be approximately described by the equation:

$$I_m(\mathbf{r}) \approx q\frac{1}{\varepsilon_i}LET\frac{D_mR}{a_0^2+\pi R^2/2}\left(1+\frac{4a_0}{L}\right) \times \exp\left(-\frac{\pi r\sqrt{1-b^2}}{L}\right)\left(1+erf\left(\frac{b}{\sqrt{2}(1-b^2)^{1/4}}\sqrt{\frac{\pi r}{L}}\right)\right) \tag{4}$$

$$a_0^2 = \frac{L}{2}r\sqrt{1-b^2}$$

where $r\sqrt{1-b^2}$ is the impact parameter. Estimation of the current amplitude (4) is obtained under the assumption that the maximum value of (3) depends primarily on the exponential term.

Eqs. (3) and (4) constitute the core of the proposed charge collection model and were used to derive the expression for estimation of the upset cross-section.

2.2. Cross-section calculation

The upset criterion plays an important role in determining the cross-section of the effect. It is usually assumed that the critical value of a quantity (current, voltage at the node or collected charge) has to be exceeded for an upset to occur. In [3,5], the amplitude of the signal on the internal RC circuit of the sensitive element is used as the criterion quantity. In this case, the upset criterion can be represented in the simplified form:

$$g(r,\theta,\varphi) = LET\exp\left(-\frac{\pi r\sqrt{1-b^2}}{L}\right)\times\left(1+erf\left(\frac{b}{\sqrt{2}(1-b^2)^{1/4}}\sqrt{\frac{\pi r}{L}}\right)\right) > LET_{th} \tag{5}$$

where LET_{th} is a threshold LET value. This is the LET that must be exceeded for a center ($r = 0$) hit to produce an upset.

Charge collected by the p-n junction is also often used as the criterion quantity [2]. In this case, an approximate expression for the charge collected by the separate junction with the center point at $\mathbf{r} = (x,y,0)$ created by the point charge source at $\mathbf{r_0} = (x_0,y_0,z_0)$ can be found from (2):

$$Q_0(\mathbf{r},\mathbf{r_0}) \approx q\frac{D_m}{D}\sqrt{\frac{2}{\pi}}\left(1+\sqrt{8|\mathbf{r}-\mathbf{r_0}|/L}\right)\exp\left(\frac{|\mathbf{r}-\mathbf{r_0}|^2}{2R^2}+\frac{\pi R^2}{2L^2}Dt\right) \times \mathrm{erfc}\left(\frac{|\mathbf{r}-\mathbf{r_0}|}{\sqrt{2}R}+\frac{\pi R}{\sqrt{2}L}Dt\right) \sim \exp\left(-\frac{\pi|\mathbf{r}-\mathbf{r_0}|}{L}\right) \tag{6}$$

The asymptotic form of Eq. (6), valid for $R \ll L$, is the main equation of the point-node model [6,7]. The upset criterion, in this case, has the form:

$$g(r,\theta,\varphi) = LET\int Q_0(\mathbf{r},\mathbf{s})d\mathbf{s}\Big/\int Q_0(0,\mathbf{s})d\mathbf{s} > LET_{th} \tag{7}$$

where integration is done along the ion track. It should be noted that the approximate nature of (5)–(7) (due to neglection of the term in front of the exponent) may lead to an additional error when determining the cross-section of the effect in the near-threshold region.

The proposed approach to upset cross-section evaluation is based on geometrical interpretation [3]. According to it, an upset occurs if the sensitive p-n junction is located in some region near the ion track (Fig. 1). The area of this region S depends on track parameters and the chosen upset criterion. Based on statistical theory [8], it can be assumed that for both regular and random placement of sensitive p-n junctions, mean cross-section per bit is equal to S. So the problem of cross-section estimation can be reduced to determining the area of the "critical" region where the cell upset criterion is met. This approach accounts for both SEUs (if $S < S0$, where $S0$ is a cell area) and MCUs (if $S > S0$). Using this approach, an equation for the cross-section can be obtained:

$$\sigma(LET,\theta) = \int_0^{2\pi}\int_0^{\infty}\Theta[g(r,\theta,\varphi)-LET_{th}]rdrd\varphi \tag{8}$$

where $\Theta(x)$ is the Heaviside step function, and $g(r,\theta,\varphi)$ is defined by (5) or (7).

Eq. (8) takes the simplest form in case of normal incidence ($I = 0$). For the first approach (5), the equation is:

$$\sqrt{\sigma(LET,0)} = L/\sqrt{\pi}\cdot\ln\left(\frac{LET}{LET_{th}}\right) \tag{9}$$

and for the point node model (7), it is approximately:

$$\sigma(LET,0) \approx L_t^2\left[\ln\left(\frac{LET}{LET_{th}}\right)\right]^{1.5} \tag{10}$$

Eqs. (8)–(10) contain only two unknown parameters (LET_{th} and L or L_t) which can be estimated based on the experimental data at normal incidence ($\theta = 0$). Also for the first approach, the cross-section curve defined by (9) becomes a straight line in a special linearizing coordinates $(\ln(LET),\sqrt{\sigma})$: this can serve as a criterion of model