LETTER

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Collection of charge in NMOS from single event effect

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Abstract: In aerospace environment, single event effect (SEE) will occur and single event transient (SET) current pulse will be induced in drain/source region of Metal Oxide Semiconductor Field Effect Transistor (MOSFET) when high energy ion strikes semiconductor devices. The typical double exponential transient current model proposed for traditional technology is not suitable for ultra deep sub-micron technology devices. In this paper, a novel multi-dimensional double exponential transient current model is proposed based on our new understanding of ultra deep sub-micron radiation mechanism, which has been validated using Technology Computer Aided Design (TCAD) simulation. This model can be important basis for the searching of SEE at circuit level and can be transparently applied to evaluate the effectiveness and performance of hardening technique, thus shortening the developing cycle of integrated circuit intended to operate within aerospace environment.

Keywords: single event effect, ultra deep sub-micron, double exponential transient current model, multi-dimensional

Classification: Electron devices, circuits, and systems

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1 Introduction

SET is caused by collecting of charge generated from high energy ion striking the semiconductor devices. With the progress of semiconductor technology, the device feature size and distance between adjacent devices has been methodically reduced, which increases the probability of SET in ultra-deep sub-micron technologies. Simulations of SET have been crucial to developing an understanding of the mechanisms behind SEE and seeking hardening design technology. Thus, characterizing the SET current is of great importance in the radiation-hardened design for aerospace application.

In this paper, a novel multi-dimensional double exponential transient current model for 65 nm bulk silicon MOSFETs semiconductor physics simulation. This model has compact form and can be easily integrated into Spice transistor model to study the details of SEE (SEU, SET etc.) and SEE-hardened design at multi-device circuit level.

2 Single event transient current model

When a high energy ion strikes MOSFET, the shell electrons in an atom can obtain potential energy and escape from the fettering of atomic nucleus to become free electrons under the action of Coulomb force [1, 2, 3]. The high energy ion frees electron-hole pairs (EHPs) along its path as it loses energy. The built-in or applied electric fields in the reverse biased PN junction can very efficiently collect the particle-induced charge through drift processes, leading to a transient current at the junction contact. Strikes near a depletion region can also result in significant transient current as carriers concentration gradients in the device exist and carriers diffuse into the vicinity of the depletion region field where they can be efficiently collected. The transient current has been modeled using double exponential function expressed as equation (1) in reference [1]. However for ultra deep sub-micron technologies, the traditional double exponential model proposed for early technologies cannot exactly describe the transient current in ultra deep sub-micron MOS transistors any more [4]. Based on theory analysis and TCAD semiconductor physics simulation, this paper develops a novel multi-dimensional double exponential transient current model for 65 nm bulk silicon MOSFETs with varying sizes at varying LET values.

$$I(t) = I_0[\exp(-\alpha t) - \exp(-\beta t)] \tag{1}$$

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2.1 Ion tracks

Basic governing equation set for the electron hole pairs in the ion track is

$$\left.\begin{aligned} &\frac{dp}{dt} = G_p - U_p - \frac{1}{q}\nabla \cdot J_p \\ &J_p = qu_p pE - qD_p \nabla p \\ &\frac{dn}{dt} = G_n - U_n - \frac{1}{q}\nabla \cdot J_n \\ &J_n = qu_n nE - qD_n \nabla n \end{aligned}\right\} \tag{2}$$

Poisson's equation is

$$\nabla^2 \mathrm{V} = -\frac{\rho}{k\varepsilon_0} \tag{3}$$

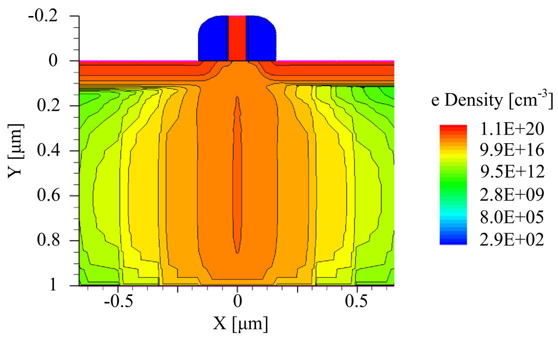

Fig. 1. Contours of constant electron density in NMOSFET with channel length L = 0.24 µm, 1 ps after an ion striking

As the initial radius of ion track is usually greater than the channel length of ultra deep sub-micron MOS transistors, part of the ion track can extend to the heavy doped drain\source region. The diffusion of excess carriers can directly determine the shape of ion track. According to the different electron diffusion coefficient in N+ drain/source region (D_1) and P-substrate (D_2), we divide ion track into two parts (two connected cylindrical tracks, as shown in Fig. 1), which assumes that the generation rate is constant along the path. After a high energy ion strike sat the channel region of MOSFET, the generated excess electron concentration can be expressed as

$$\delta n(x, y, t) = \frac{N}{4\pi Dt} \exp\left(-\frac{(x - \mu E_x)^2 + (y - \mu E_y)^2}{4Dt} - \frac{t}{\tau}\right). \tag{4}$$

Here E_x and E_y represents the component of electric field along the X-axis and Y-axis respectively, z is the distance from device surface into the substrate along Y-axis, X_j is the drain/source junction depth, $N = \mathrm{LET} \cdot \rho / 3.6\,\mathrm{eV}$, D_1 and D_2 represents the electron diffusion coefficient in drain/source region and silicon substrate respectively as following:

$$D = \begin{cases} D_1, & z \le X_j \\ D_2, & z \ge X_j \end{cases}. \tag{5}$$

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2.2 Motion of carriers in depletion region

The initial density of EHPs generated due to an ion-strike in the ion track is much higher than the intrinsic doping density in the junction. However, when the carriers concentration become comparable to the intrinsic doping concentration in the junction [5], diffusion parallel to the track is negligible, $(-qD_n\nabla n) \approx 0$ and excess carrier continuity equation becomes

$$\mu \cdot \delta n \cdot \nabla E - \frac{\delta n}{\tau_n} = \frac{d\delta n}{dt} \tag{6}$$

Integrating,

$$\delta n = \frac{N}{4\pi Dt} \cdot \exp\left(\bar{\mu} t \nabla E - \frac{t}{\tau_n}\right) \tag{7}$$

where $N/4\pi Dt$ is the excess electron density in the track.

There is θ degree angle between the device surface and the elliptical section over which the current flows. This leads to $S = S_{cylindrical}/\cos\theta$, where $S_{cylindrical} = 4\pi Dt$, $\cos\theta = E_y/E$. Thus the drift component of electron current density in depletion region is

$$I_{drift}(t) = q\bar{\mu}\frac{LET}{3.6\,\text{eV}}E_y \cdot \exp\left(\bar{\mu} \cdot \nabla E - \frac{1}{\tau_n}\right)t. \tag{8}$$

Noting that excess electrons diffuse into the depletion region field due to concentration gradient resulting in diffusion current, which is positively correlated to electron diffusion coefficient and in the opposite direction on drift current. Correcting the transient current in equation (8) with diffusion current, the electron current in depletion region can now be obtained,

$$I(t) = q\bar{\mu}\frac{LET}{3.6\,\text{eV}} \cdot W \cdot E_y \cdot \left[\exp\left(\bar{\mu} \cdot \nabla E - \frac{1}{\tau_n}\right)t - \exp(D_n \nabla n)t\right]. \tag{9}$$

The total charge collected can be obtained by integrating equation (9) over time from 0 to ∞, that is $\int_0^\infty I(t)dt = -q\frac{\rho}{3.6\,\text{eV}} \cdot W \cdot LET \cdot X$, X is the ion track length.

2.3 Funnel phenomenon

Immediately after EHPs' generation the high conductivity of ion track gives rise to a collapse of the junction field resulting a distortion of the electrostatic potential in the depletion region and termed this the "filed funnel" [6, 7]. This funneling effect may increasing the charge collection at the hit transistor by extending the junction electric filed away from the junction and further deep into the substrate [8, 9]. The funneling phenomenon can be modeled by the voltage drop in the substrate [10], $V_A = V_J + R_S$. Applying this model to equation (9), a corrected multi-dimensional double exponential transient current model can be obtained as

$$I(t) = q\bar{\mu}\frac{LET}{3.6\,\text{eV}} \cdot W \cdot E_y \cdot \left(\frac{V_0}{V_0 - I_M R_S}\right)\left[\exp\left(\bar{\mu} \cdot \nabla E - \frac{1}{\tau_n}\right)t - \exp(D_n \nabla n)t\right] \tag{10}$$

Equation (10) can be simplified to

$$I(t) = I_0(L, W, LET)[\exp(-\alpha(L, LET)t) - \exp(-\beta(L, LET)t)] \tag{11}$$

where

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$$\alpha(L, LET) = -\bar{\mu} \cdot \nabla E + \frac{1}{\tau_n} \tag{12}$$

$$\alpha(L, LET) = -D_n \nabla n \tag{13}$$

$$I_0(L, W, LET) = W \cdot q\bar{\mu} \frac{LET}{3.6\,\text{eV}} E_y \cdot \left(\frac{V_0}{V_0 - I_M R_S} \right). \tag{14}$$

2.4 TCAD verification

A set of TCAD simulations were carried out to analyze electric field and carrier concentration for structures of different channel width and different channel width at varying LET values. Three different simulations were performed at varying channel length, L, three different simulations were performed at varying channel width, W, and three different simulations were performed at varying LET values. Fig. 2 and Fig. 3 show potential contours following passages of the ionizing particle of varying channel length and LET values respectively. As shown in two figures, both varying L and LET values can result different potential contours shapes, indicating that electric field E is a function of L and LET. Deriving from equation (12) function variable α is also a function (α (L, LET)) of L and LET. Similarly, as shown in Fig. 4 and Fig. 5, different L and LET values can also result different electron density contours, concluding that β is also a function (β (L, LET)) of L and LET according to equation (13). By equation (14), I_0 is a function of L, W and LET. The transient response for varying W, L and LET is shown in Fig. 6.

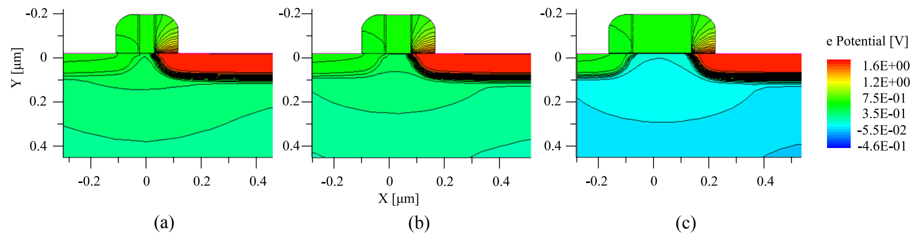

Fig. 2. Contours of constant potential for MOSFET of different L, 20 ps after an ion striking. (a) L = 0.06 µm (b) L = 0.1 µm, (c) L = 0.24 µm

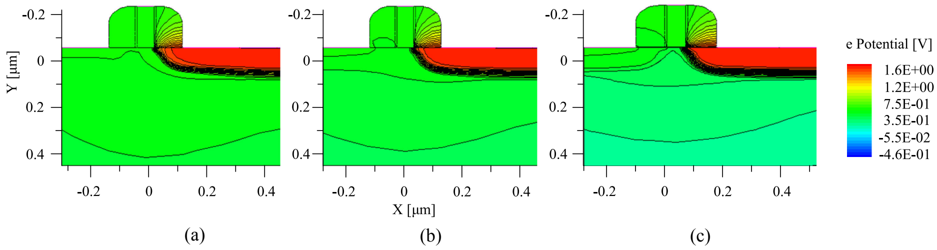

Fig. 3. Contours of constant potential for MOSFET of different LETs, 20 ps after an ion striking. (a) LET = 100 MeV·cm^2/mg. (b) LET = 50 MeV·cm^2/mg. (c) LET = 30 MeV·cm^2/mg.

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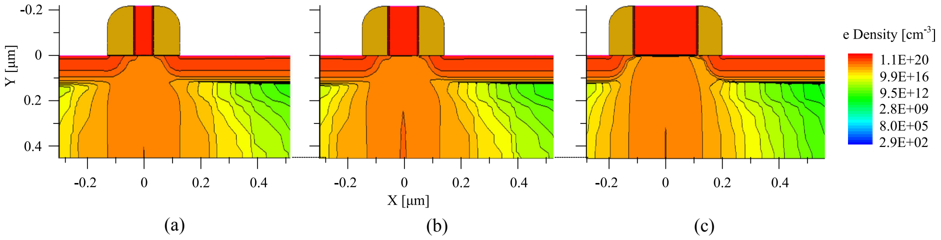

Fig. 4. Contours of constant electron density for MOSFET of different L, 1 ps after an ion striking. (a) L = 0.06 μm. (b) L = 0.1 μm. (c) L = 0.24 μm.

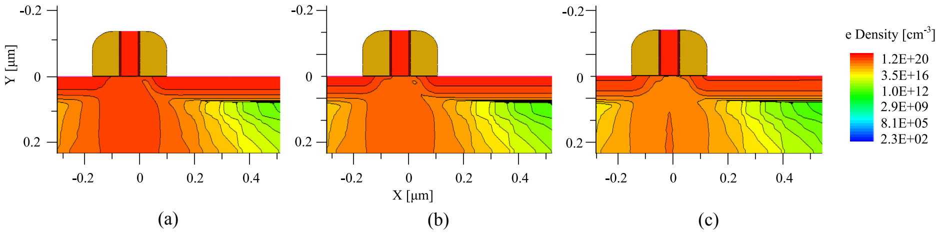

Fig. 5. Contours of constant electron density for MOSFET of different LETs, 1 ps after an ion striking. (a) LET = 100 MeV·cm^2/mg. (b) LET = 50 MeV·cm^2/mg. (c) LET = 30 MeV·cm^2/mg.

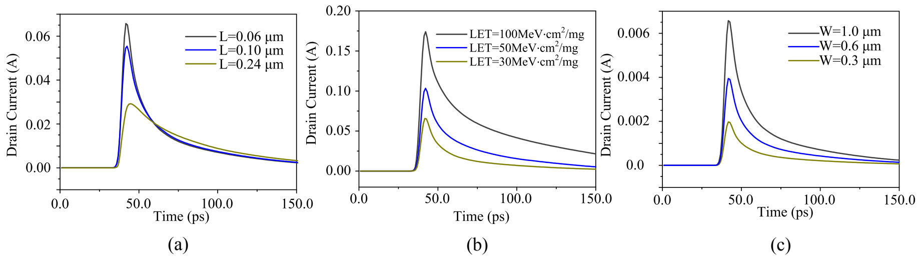

Fig. 6. Transient response for varying L, W and LET values: (a) W = 10 μm, LET = 30 MeV·cm^2/mg. (b) L = 0.06 μm, W = 10 μm. (c) L = 0.06 μm, LET = 30 MeV·cm^2/mg.MeV·cm^2/mg. (c) LET = 30 MeV·cm^2/mg.

2.5 Fitting of single effect transient current

In this paper, the semiconductor technology related parameters, I_0 (W, LET), a (LET), β (LET) in equation (11), were obtained through TCAD simulation, as they cannot be provided by foundry due to commercial confidentiality. Considering that the length of every MOSFET in standard cells (actually in almost all of digital design) that based on 65 nm bulk silicon technology is 0.06 μm, so L is fixed at 0.06 μm in TCAD simulations.

TCAD simulations were used to simulate single event effect for NMOSFET in 65 nm CMOS technology. Develop a transient current pulse model I(t) for NMOS in cut-off operation as an example. The circuit schematic for simulation is shown in Fig. 7, where the NMOS source, gate, substrate contact were tied to ground and the drain contact was tied to high level V_D.

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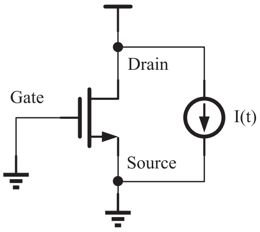

Fig. 7. Schematic of single event simulation for NMOSFET

Varying W and LET values were chosen for modeling (the L value was set 0.06 µm), that the W values are 0.3 µm, 0.6 µm, 1 µm, 10 µm. LET values are 30 MeV·cm^2/mg, 50 MeV·cm^2/mg, 75 MeV·cm^2/mg, 100 MeV·cm^2/mg. The drain transient current pulses in above cases are shown in Fig. 6.

Model parameters α and β can be obtained by fitting TCAD simulated current data verse time, and then fit parameter α, β, I_0 which is dependent on LET, W verse LET and W to obtain function express α (LET), β (LET) and I_0 (LET,W). As an example, the fitting result of transient pulse current for normal ion hit NMOS (L = 0.06 µm) in cut-off operation can be expressed as

$$\left.\begin{aligned}
&I(t) = I_0[\exp(-\alpha t) - \exp(-\beta t)] \\
&I_0 = (1.40E-7) \times LET + 0.0058 \times W + 0.00013 \times LET \times W - 6.95E-6 \\
&\alpha = (-1.86E-5) \times LET^3 + 0.0038 \times LET^2 - 0.24 \times LET + 8.16 \\
&\beta = (-6.19E-6) \times LET^3 + 0.0002 \times LET^2 - 0.16 \times LET + 13.58
\end{aligned}\right\} \quad (15)$$

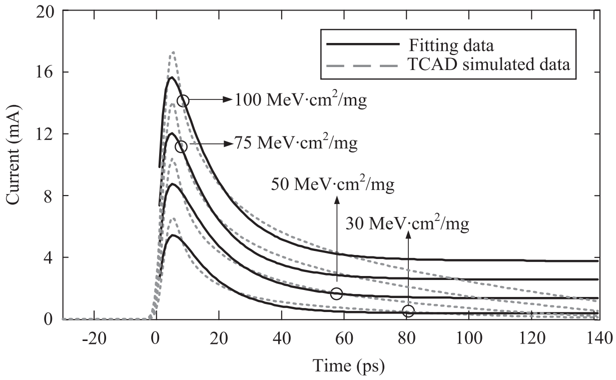

Fig. 8. The fitting results of NMOS transient current, For this fitting L = 0.06 µm

Fig. 8 shows the fitting results of transient current. Comparing the pulse Full-Width at Half-Maximum (FHPW) of the SET current and the TCAD simulation current, the error is less than 10%, which confirms the accuracy of the proposed current model.

3 Conclusion

Based on the intensive research of SEE mechanism, a multi-dimensional double exponential transient current model has been developed in this paper, which is capable of accurately describing the SET current for ultra deep sub-micron devices

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of varying size at varying LET values. Specifically, the model is capable of providing theoretical guidance to seek SEE-hardened design and evaluate the hardening performance for ultra deep sub-micron technology. Integrating this model inside the Spice transistor model, can study the details of SEE (SEU, SET etc.) and SEE-hardened design at multi-device circuit level (standard cell and IP). Simulations using the integrated single-event model enable us to evaluate the effectiveness and performance of hardening technique, thus shortening the developing cycle of integrated circuit operated in aerospace environment. The single event effect of NMOSFET is simulated using TCAD. By fitting the simulated current data and parameters extraction, the proposed multi-dimensional double exponential current model is validated. We will further study and explore the transient current model in ultra deep sub-micron technologies, make the progress of the integrated circuit radiation-hardened design and evaluation technology, and prolong service life of integrated circuit intended to operate within aerospace environment.

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