Single Event Transient in bulk MOSFETs: original modelling for SPICE application

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***Abstract*—Single Event Transient (SET) is an important issue concerning reliability of MOS devices. Lots of experimental and simulation works have already been done [1- 4] but few of them are dealing with compact modelling. In this paper, we develop a physical model which describes the transient current pulse which appears at the electrodes of a Bulk MOSFET after the striking of an ionizing particle in the device. The validation of the model has been done by some confrontations with TCAD simulations. It turned out that the developed model has an innovative aspect for implementation into SPICE simulator.**

***Keywords*— SET, Radiation, heavy ion, TCAD, SPICE, Bulk transistor.**

I. INTRODUCTION

During the last decades, according to Moore's law, size of MOSFETs has decreased so that sensitivity of transistor to ionizing particles increased [1, 2]. The nature and energy of particles cover a wide range: from cosmic particles (highly energetic neutrons, muons, protons ...) to α particles due to inherent radioactivity of Uranium/Thorium contamination [1]. Such events lead to some damages and errors in integrated circuits (IC's). In this paper, we focus on Single Event Transient (SET) which is parasitic transient current following the ionizing particle striking. In SRAM cell, it could involve a memory shift called Single Event Upset (SEU) [1]. In bulk MOSFET case, these currents will appear at each electrode (Source, Drain and Bulk). Some works concerning the compact modelling of SETs have already been done [3, 5, 6, 7] and two models have been considered so far: the double exponential model and the diffusion/collection model. The former model is currently used in SPICE simulators but is based on calibration parameters which have not clear physical meaning. The second model refines the physical description of SETs but does not take P/N junctions effects into account.

In this paper, based on deep understanding of TCAD simulation [8], we develop a new modelling approach for calculation of transient current pulse taking P/N junctions electric field into account, considering it as a boundary condition. Moreover, it turned out that this model can be implemented in SPICE simulators because it can be converted into an equivalent circuit. The paper is organized as follow: in Section I, we perform some TCAD analysis which allow us to investigate the physical phenomena and define the approach for the modelling of the parasitic transient current pulses. In Section II, we focus on modelling aspect first in the basic case of an infinite material and then in the realistic case of the bulk NMOSFET. Finally, in Section III, we describe the portability of the physical model as an equivalent circuit for implementation into SPICE simulators.

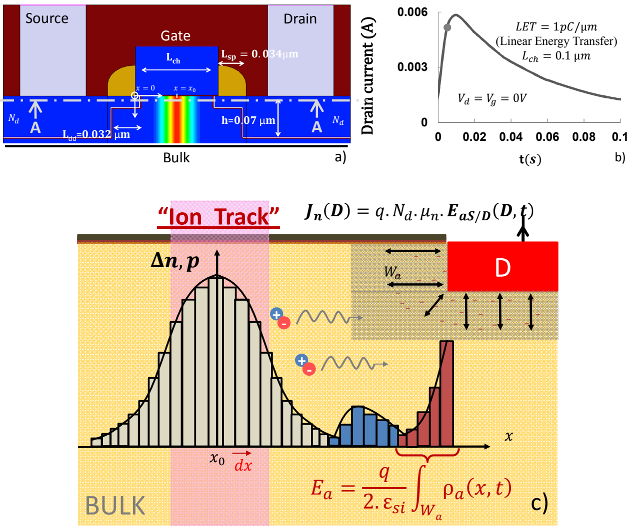

Fig. 1: a) NMOS Bulk structure and definition of main geometrical & electrical parameters. The generation rate $G(\mathbf{r}, t)$ is plotted. b) drain current vs time. c) physical mechanisms involved in SETs: from electron/hole pairs generation to transient current pulse induced by the resulting transient electric field. We focused on the drain current.

II. TCAD ANALYSIS OF SETS

A. Description of the system and simulation set up

The device considered is a bulk MOSFET as shown on **Fig.1.a**. The transistor is crossed by an ionizing particle which generates electron/hole pairs along its track following a Gaussian spatial distribution. This phenomena results in transient current pulses (illustrated on **Fig.1.b**). To get clues for modelling of those effects, we developed a bulk NMOSFET TCAD transient simulation methodology; including Drift Diffusion transport model, doping dependence mobility and Shockley - Read - Hall (SRH) recombination. The device is struck by the ionizing particle at t=0s and we track the evolution with time of carriers. In this paper, we only consider vertical tracks of the particle, centered in the bulk at x_0, for $V_g = 0V$. As

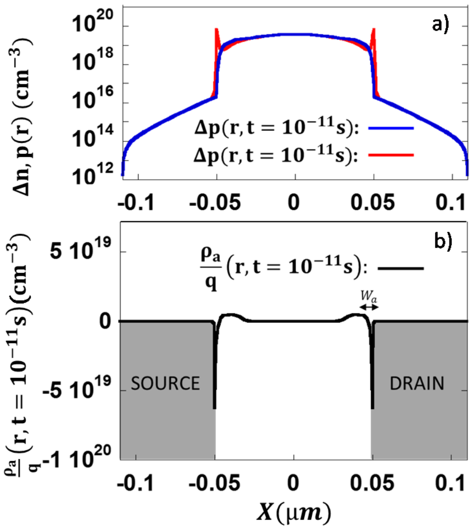

Fig. 2: For $LET = 1pC.\mu m^{-1}$and $L_{ch} = 0.1\mu m$ in the AA cutline vs position. a) $\Delta n, p(\boldsymbol{r}, t = 10^{-11}s)$; we notice $\Delta n(\boldsymbol{r}, t = 10^{-11}s) = \Delta p(\boldsymbol{r}, t = 10^{-11}s)$ far from the jonctions. b) $\rho_a(\boldsymbol{r}, t = 10^{-11}s)/q$; we observe the formation of $\rho_a(\boldsymbol{r}, t = 10^{-11}s)/q$ at the P/N junctions.

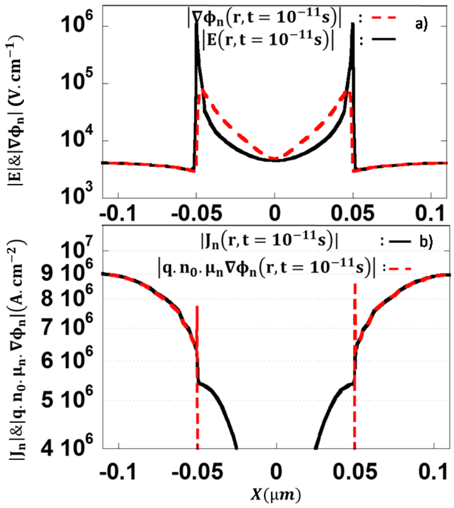

Fig.3: For $LET = 1pC.\mu m^{-1}$and $L_{ch} = 0.1\mu m$ in the AA cutline vs position. a) Comparison of $|\nabla\phi_n(\boldsymbol{r}, t = 10^{-11}s)|$ and $|E(\boldsymbol{r}, t = 10^{-11}s)|$; we observe that drift is the dominant mechanism for electrons in N++ regions. b) Comparison of $|J_n(\boldsymbol{r}, t = 10^{-11}s)|$ and $q.n_0.\mu_n.|\nabla\phi_n(\boldsymbol{r}, t = 10^{-11}s)|$; we observe that high electron current density in N++ regions is dominated by n_0 transport.

a result, we are in depletion regime and we only observe the current due to the ionizing particle. Note that we consider 2D simulations because it is less time consuming and are sufficient to understand the main physical aspects.

B. TCAD simulation of SET: deep understanding

We observe on **Fig.2.a** that generated carriers $\Delta n, p(\boldsymbol{r}, t)$ are transported in the whole device: far from the P/N junctions the transport mechanism is mainly ambipolar ($\Delta n(\boldsymbol{r}, t) \approx \Delta p(\boldsymbol{r}, t)$). The ambipolar transport is the common transport of generated holes and electrons because of their electrostatic attraction. But approaching the N++ regions, the built in electric field is strong enough to split the electron/hole pairs, electrons being injected toward the N++ region while holes are drifted back. Consequently, excess carriers induce a space charge $\rho_a(\boldsymbol{r}, t) = q.(\Delta p(\boldsymbol{r}, t) - \Delta n(\boldsymbol{r}, t))$ which spreads over a width W_a from the P/N junction (illustrated on **Fig.1.c** and **Fig.2.b**). It results in an electric field in the whole device, especially in N++ regions. The current density expression for electrons is:

$$\boldsymbol{J_n}(\boldsymbol{r}, t) = -q.\left(n_0(\boldsymbol{r}) + \Delta n(\boldsymbol{r}, t)\right).\mu_n.\boldsymbol{\nabla}\phi_n(\boldsymbol{r}, t) \qquad (1)$$

where q is the elementary charge in C, μ_n is the electron mobility in $m^2.s^{-1}.V^{-1}$, and $\boldsymbol{\nabla}\phi_n(\boldsymbol{r}, t) = -\boldsymbol{E}(\boldsymbol{r}, t) - u_t.\boldsymbol{\nabla}n/n$ ($\phi_n(\boldsymbol{r}, t)$ being the quasi-Fermi potential for electrons and u_t the thermal voltage). The first term leads to drift transport and the second one to diffusion transport. On **Fig.3.a** we note that $|\boldsymbol{\nabla}\phi_n(\boldsymbol{r}, t)|$ matches with $|\boldsymbol{E}(\boldsymbol{r}, t)|$ in N++ regions which means that drift transport dominates as a consequence of low injection level in Source/Drain ($n_0 \gg \Delta n(\boldsymbol{r}, t)$ with $n_0 = N_d$). It is important to notice that there is no initial field in $N++$ areas so the field in these regions is only due to excess carriers. Finally, the transient current pulse at Source/Drain is due to the excess charges induced electric field which acts on the initial electron density distribution $n_0 = N_d$ in N++ regions, as proved on **Fig.3.b** where the total electron current density J_n exactly matches $|q\mu_n n_0\ \boldsymbol{\nabla}\phi_n(\boldsymbol{r}, t)|$.

III. MODELLING OF SET INDUCED BY IONIZING PARTICLE: FROM INFINITE MATERIAL TO TRANSIENT CURRENT PULSES

A. Homogeneous and infinite material

As a first step, we consider an infinite P-type semi-conductor crossed by an ionizing particle. We can find analytical solution for $\Delta n, p_\infty(\boldsymbol{r}, t)$ in literature [3,5] for low and high injection regime, respectively $p_0 \gg \Delta n, p(\boldsymbol{r}, t)$ and $p_0 \ll \Delta n, p(\boldsymbol{r}, t)$ with $p_0 = N_a$ but with simple spatial dependence of the generation rate $G(\boldsymbol{r}, t)$ (spherical or cylindrical generation). It has been shown that for α particles or heavy ions the generation term $G(\boldsymbol{r}, t)$ can be expressed as a sum of Gaussian functions [1]. So, we develop a model for $\Delta n, p_\infty(\boldsymbol{r}, t)$ including a Gaussian generation rate which is a relevant first step. We make the following assumptions: ambipolar transport of carriers, no electric field as done in [1,5] and no recombination within the time scale we consider as evidenced by our TCAD simulations. We obtain the 2D ambipolar diffusion equation:

$$\frac{\partial \Delta n, p}{\partial t} = D.\left(\frac{\partial^2 \Delta n, p}{\partial x^2} + \frac{\partial^2 \Delta n, p}{\partial y^2}\right) + G(x, y, t) \qquad (2.a)$$

$$G(x, y, t) = \frac{LET}{q.\sqrt{\pi}.L_t.d}.e^{-\frac{(x-x_0)^2}{L_t^2}}.\Pi_{0,l_y}(y).\delta(t) \qquad (2.b)$$

where D is the ambipolar diffusivity in $m^2.s^{-1}$, L_t is Full Width Half Maximum (FWHM) of the generation rate in m, LET is the Linear Energy Transfer in $C.m^{-1}$, x_0 the center of the Gaussian function in m, $\Pi_{0,l_y}(y)$ is the rectangular function centered in 0 and of l_y width and $\delta(t)$ is the Dirac function in 0. We decide to normalize $G(x, y, t)$ by introducing the length $d = 1\mu m$ as in our TCAD simulations. The resolution of (2.a) in the infinite material involves using Fourier transforms which leads to:

$$\Delta n, p_{\infty}(x,y,t) = \frac{LET}{4.q.d\sqrt{\pi.\left(D.t+\frac{L_t^2}{4}\right)}}.e^{-\frac{(x-x_0)^2}{4.\left(D.t+\frac{L_t^2}{4}\right)}}.\left(\operatorname{erf}\left(\frac{y+\frac{l_y}{2}}{2.\sqrt{D.t}}\right)-\operatorname{erf}\left(\frac{y-\frac{l_y}{2}}{2.\sqrt{D.t}}\right)\right) \quad (3)$$

This expression of $\Delta n, p_{\infty}(x,y,t)$ exhibits a shift L_t in the FWHM compared to solutions found in [5] and this parameter could be used to differentiate incoming particles. We found that both radial and longitudinal profiles (respectively **Fig. 4.a** and **Fig. 4.b**) predicted by (3) perfectly match with the same profiles extracted from TCAD for all considered instants.

B. Bulk NMOSFET

The previous approach is relevant when we consider devices composed of long and large homogeneous regions where we can consider infinite materials without any P/N junctions. Such an approach cannot be considered when we deal with advanced technologies because the volume of the active zone is too small and border effects, namely P/N junctions effects (built-in electric field, change in doping type...), become significant. So, we decide to model the transient current pulse at Source/Drain of a bulk NMOSFET considering Gaussian generation and absorption conditions [9] at P/N junctions for electrons. This boundary condition means that the junction built-in electric field value is so high that the P/N junction behaves as a sink for electrons from the P side which is an approximation. Indeed, TCAD simulations exhibit some accumulations of electrons at P/N junctions showing that absorption is not so efficient. Moreover, we virtually extended these P/N junctions in the vertical direction for modelling purpose. In the y direction, we chose reflective conditions [9] for electrons because electrons cannot flow through the bulk electrode and the Si/SiO_2 interface. These conditions can be written as:

$$\Delta n(x=\{0,L_{ch}\},y,t)=0\ ;\ \forall y,t \quad (4.a)$$

$$\frac{\partial \Delta n}{\partial y}(x,y=\{0,H\},t)=0\ ;\ \forall x,t \quad (4.b)$$

where H is the length in y direction. Taking the same assumptions as in Section III.A, we developed a model inspired from [9] which relies on the resolution of the ambipolar diffusion equation (2.a) by searching diffusion modes of the form $\Delta n_{ij}(x,y,t) = f_{i,x}(x).f_{j,y}(y).f_{i,j,t}(t)\ ,\ \{i,j\} \in \mathbb{N}^2$. Decomposing the solution over the diffusion modes, we notice that $f_{j,y}(y)$ has to be constant and we obtain the expression for the generated electrons density:

$$\Delta n(x,t) = \frac{2.LET}{q.\sqrt{\pi}.L_t.L_{ch}.d}.\sum_{i=1}^{K} A_i(x_0).\sin\left(\frac{i\pi}{L_{ch}}.x\right).e^{-\frac{i^2\pi^2 D}{L_{ch}^2}.t} \quad (5)$$

where K is the approximation order ($K \rightarrow +\infty$ being the theoretical solution) and $A_i(x_0)$ is an explicit integral term which depends on the generation rate parameters. As noticed in part II, in order to model the transient current pulse due to the ionizing particle, we calculate the current density through:

$$\boldsymbol{J_{nS/D}}(t) = q.N_d.\mu_n.\boldsymbol{E_{aS/D}(t)} \quad (6)$$

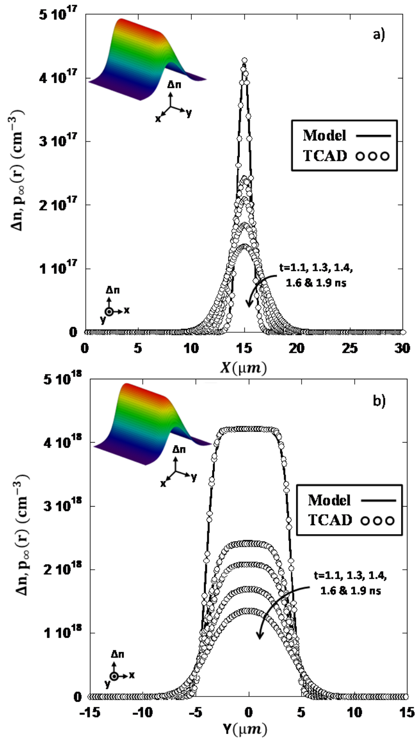

Fig. 4: $\Delta n(\boldsymbol{r},t)$ comparison between TCAD and model: a) $\Delta n(\boldsymbol{r})$ for given y b) and $\Delta n(\boldsymbol{r})$ for given x for different times and $LET = 1pC.\mu m^{-1}$. The ambipolar diffusivity is $D = 1.8.10^{-3} m^2.s^{-1}$. We notice very good agreement.

where the induced electric field $E_{aS/D}(t)$ is then calculated by considering infinite charged planes:

$$E_{aS/D}(t) = \frac{q}{2.\epsilon_{si}}\int_{L_{ch}} \rho_a(x,t).dx \quad (7.a)$$

$$\int_{L_{ch}} \rho_a(x,t)dx \approx -q.\int_{W_a} \Delta n(x,t)dx \quad (7.b)$$

where ϵ_{si} the Silicon permittivity. The outline of the **Fig 1.c** illustrates the physical approach explained previously from generation to transient current pulse. In fact, due to ambipolar transport in bulk, i.e $\Delta p \approx \Delta n$, generated holes density screens the contribution of electron density outside W_a which leads to equation (7.b).

Finally we get the considered electrode current using the formula (6-7) by using the corresponding model parameters: the ambipolar diffusivity D and the ambipolar space charge width W_a. By adjusting these two parameters to consistent values, we get a good matching between modelling and TCAD transient pulses, especially for $L_{ch} = 1\mu m$, see **Fig.5.a**. Still, the description of relaxation tails (falling part of the currents) has to be improved. For $L_{ch} = 0.1\mu m$ (**Fig.5.b**), short channel effect and smooth doping profile are not negligible anymore and we have to take it into account in order to improve accuracy of the model for short channel transistors without undervalue D.

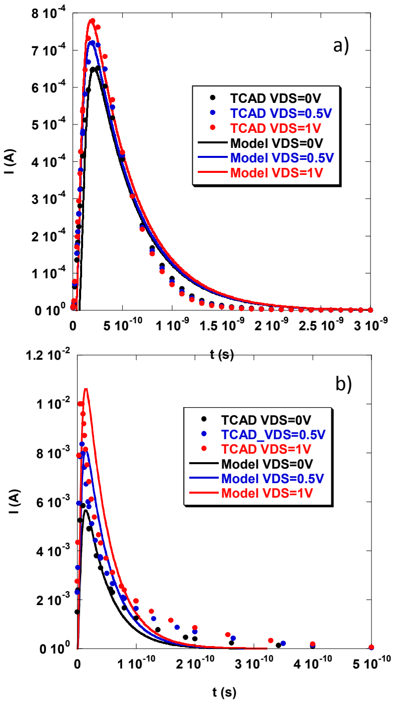

Fig. 5: Drain current comparison between TCAD and model for different V_d: a) $L_{ch} = 1\ \mu m$ and b) $L_{ch} = 0.1\ \mu m$ for $LET = 1 pC.\mu m^{-1}$. Model parameters are set to: a) $D=2.3.10^{-4}\ m^2.s^{-1}$ & $W_a(Vd)=1.1.10^{-9}.(V_d+V_{diff})^{0.14}$ and b) $D=2.5.10^{-5}\ m^2.s^{-1}$ and $W_a(Vd)=3.1.10^{-10}.(V_d+V_{diff})^{0.5}$. We notice good agreement. V_{diff} is the junction internal voltage and $W_a(Vd)$ is inspired from the expression of the space charge area width for P/N junction.

IV. FROM PHYSICAL MODELLING TO EQUIVALENT CIRCUIT: DISCUTION ON PORTABILITY IN SPICE

Currently in literature, the double exponential model is used to model the transient current pulse at the Source/Drain [6,7]. This model relies on calibration parameters which are not physical and does not take into account several aspects, like P/N junctions boundary conditions. Diffusion/Collection model is also used [3,5] and considers an equivalent transient current pulse related to parasitic flow of generated charges by introducing a collection speed which is not evidenced by our TCAD observations. The main pro for our proposed model is the temporal dependence of $\Delta n(\boldsymbol{r}, t)$ in terms of $exp(-i^2\,\pi^2 Dt/L_{ch}^2)$ which follows rigorous physical considerations and which was validated with TCAD simulation. These mathematical functions allow us to consider our phenomena as an equivalent circuit: one diffusion mode i contributing to the current is considered as a current generator controlled by a voltage U_i which is the temporal response of a $(RC)_i$ circuit to a voltage pulse due to particle strike; $(RC)_i$ being associated to time constant τ_i. Total current is obtained by simply summing over all individual current generators associated to each diffusion mode i. Total current is illustrated on **Fig.6.a & 6.b** and demonstrate that total current is almost converged by considering the 7th first modes.

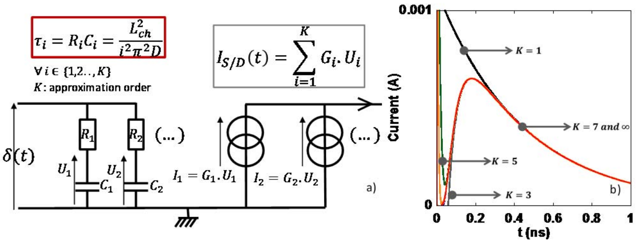

Fig. 6: a) equivalent electronical circuit. Each diffusion mode i is modelled as a current generator controlled by a voltage U_i. This voltage is the response of a RC circuit with a time constant τ_i to an impulsional voltage. The sum over each current generator linked to a diffusion mode i gives the total current induced by the ionizing particle. b) We see that the series quickly converges to the theoretical solution ($K \rightarrow \infty$) : we can stop the sum at K=7, so we consider 7 currents generators controlled by 7 RC circuits.

V. CONCLUSION

In this paper, we investigated a new approach for the SETs modelling. This modelling based on diffusion modes and which takes P/N junction effects into account should be useful when dealing with short channel transistors. Besides, this model exhibits interesting implementation aspects using an equivalent electronical model. We still have to provide some add-on to this model: include oblique incidence and particular case of incidence in source/drain areas.

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