Unified SPICE Model for Transient Ionizing Radiation Response of SOI MOSFET

Neil Rostand
CEA,DAM,DIF
Arpajon, France
neil.rostand@cea.fr

Damien Lambert
CEA,DAM,DIF
Arpajon, France
damien.lambert@cea.fr

***Abstract*— Transient Ionizing Radiation Response (TIRR) of Metal Oxide Semi-Conductor Field Effect Transistors (MOSFET) is a transient parasitic current induced by ionizing radiations. These radiations might have various both spatial and temporal profiles depending on the considered application. In recent work, we have developed Single Event Transient (SET) compact model for MOSFET, which is the parasitic current pulse induced by an individual ionizing particle. This model has been implemented in Verilog-A, as an equivalent electrical circuit made of many RC circuits. In this work, we extend this model to any kind of TIRR of SOI MOSFET, keeping the same compact modeling approach. Cross-comparisons with realistic 3D TCAD simulations of SOI MOSFET are then made.**

Keywords— ***compact model, ionizing radiations, SET, SOI MOSFET, SPICE, TCAD***

I. INTRODUCTION

Radiation effects on electronics is a major issue for reliability of modern systems, these effects being more significant as microelectronics technologies are getting more and more integrated [1]. Transient Ionizing Radiation Responses (TIRR) is a range of effects consisting in transient parasitic currents due to excess electron/hole (e/h) pairs generated by any kind of ionizing radiation (heavy ions, low energy protons, γ/X rays, …) in any operational environment (nuclear experimentations, laser, space environment). Developing compact models for these effects is a mandatory step for multi scale simulation purpose [2,3] as compact models allow making the link between particle-matter interaction codes and circuit-level SPICE simulation.

Single Event Transient (SET) is one specific TIRR and consists in a parasitic current pulse induced by an individual particle. Various SET models have been exposed through the last decades, with different approaches and applications [4-6]. In [7-9], we proposed a SET compact model for MOSFET, designed in a way to fit well with suitable Verilog-A implementation methods [10,11]. The approach was to describe SET as the sum of current generators which were controlled by RC circuits submitted to an impulsional voltage stimulus at the impact time of the particle, as the e/h pairs generation was supposed to be instantaneous. In this paper, we propose an extension of this approach to any kind of TIRR with arbitrary generation rate dynamics and space distribution, for the case of Silicon-On-Insulator (SOI) Metal-Oxyde-Semiconductor Field Effect Transistor (MOSFET). Cross-comparisons are made with TCAD simulations [12] of such a device submitted to laser irradiation with different dynamics to illustrate how the model is able to catch results of numerical methods calculations.

II. COMPACT MODELING OF TIRR

A. Model assumptions

In the former work [9], we have developed a SET compact model in the case of many punctual e/h pair generations in the SOI transistor body. We have chosen a 1D approach meaning that each generation point located in (x, y, z) (see Fig.1.a for notations) was converted into a generation plane orthogonal to the x direction. This generation was assumed to be instantaneous at the impact time of the particle. Compact modeling of TIRR is based on the assumption that any TIRR can be seen as the time integral of SET-like currents induced by elementary generated e/h pair densities:

$$\delta n_{gen}(x, t_i) = G(x, t_i).dt_i \quad (1)$$

In (1), $G(x, t_i)$ is the generation rate in $m^{-3}.s^{-1}$ and $\delta n_{gen}(x, t_i)$ is the elementary e/h pair density in m^{-3}, generated between times t_i and $t_i + dt_i$ at location x. The actual underlying assumption is the independence between transport laws related to each local $\delta n_{gen}(x, t_i)$ along time. We also assume that the space distribution of $\delta n_{gen}(x, t_i)$ is the same $\forall t_i$ allowing us to separate time and space variables as usually done:

$$G(x, t_i) = \frac{G_x(x)}{W.T_{si}}.G_t(t_i) \quad (2)$$

Note that such an assumption is valid as long as the variability along time of the 3D profile of the radiation induced deposited energy can be neglected. In (2), W is the transistor width, T_{si} the SOI film thickness, while functions $G_x(x)$ and $G_t(t_i)$ are respectively expressed in m^{-1} and s^{-1}. These functions are chosen so that:

$$\int_{\Delta t_{sim}} G_t(t_i).dt_i = 1 \quad (3.a)$$

$$\int_0^{L_{ch}} G_x(x).dx = N_{eh} \quad (3.b)$$

In (3.a&b) N_{eh} is the number of e/h pairs generated inside the body volume, L_{ch} is the channel length and Δt_{simu} is the simulation time window. All these considerations are depicted in Fig.1.

978-1-6654-0685-7/21/$31.00 ©2021 IEEE

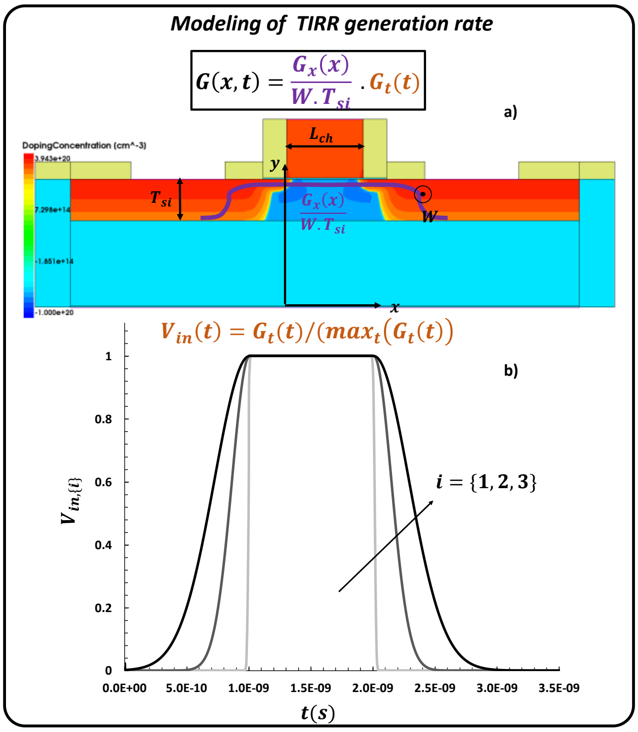

Fig.1: Approach for the generation rate, as a separate variable function. a): Illustration of an arbitrary space variable function $\frac{G_x(x)}{W.T_{si}}$ b): Illustration for some time variable functions $G_t(t)$ considered in this paper.

B. Model derivation

The theoretical form of the transient current pulse induced by $\delta n_{gen}(x,t_i)$ at one given electrode can be expressed as in (4.a-d):

$$\delta I_{tirr,j}(t,t_i) = \sum_{k=1}^{\infty} i_{k,j}.S_k.G_t(t_i).e^{-\frac{t-t_i}{\tau_{M_k}}}.H(t-t_i).dt_i \quad (4.a)$$

$$S_k = \int_0^{L_{ch}} G_x(x).\sin\left(\frac{k.\pi}{L_{ch}}.x\right).e^{-\frac{v_x x}{2.D}}.dx \quad (4.b)$$

$$\{i_{k,j=drain}, i_{k,j=source}\} = \left\{\frac{2.q.D_n.(-1)^k.k.\pi.e^{\frac{v_x.L_{ch}}{2.D}}}{L_{ch}^2}, \frac{2.q.D_n.k.\pi}{L_{ch}^2}\right\} \quad (4.c)$$

$$\tau_{M_k} = \left(\frac{1}{\tau} + \frac{k^2.\pi^2.D}{L_{ch}^2} + \frac{v_x^2}{4.D}\right)^{-1} \quad (4.d)$$

In (4.a-d), H is the Heaviside function, v_x the ambipolar drift velocity in the body in $m.s^{-1}$, D the ambipolar diffusivity in the body in $m^2.s^{-1}$, q the elementary charge in C, D_n the electron diffusivity in the body in $m^2.s^{-1}$, and τ the recombination time in the body in s. This formalism stems from an extension of the excess carrier model exposed in [7] to the case of an arbitrary space distribution of $G(x,t_i)$ and spreading out the instantaneous "initial" e/h pair density generated at time t_i over the time interval $[t_i, t_i+dt_i]$, see (4.a). The current calculation method consists then in integrating electron diffusion current density at the considered p/n junction. The TIRR current is then obtained by integration, resulting in (5.a-b):

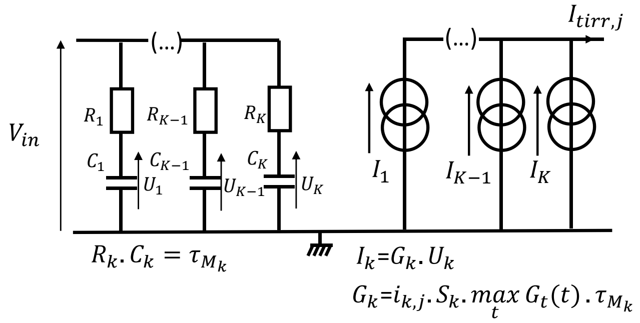

Fig.2: Equivalent electrical circuit for TIRR, truncating the series (5.a) at the order K.

$$I_{tirr,j}(t) = \int_{\delta I_{tirr,j}(t,0)}^{\delta I_{tirr,j}(t,t)} \delta I_{tirr,j}(t,t_i)$$
$$= \sum_{k=1}^{\infty} i_{k,j}.S_k.\max_t G_t(t).\tau_{M_k}.F_k(t) \quad (5.a)$$

$$F_k(t) = \frac{1}{\max_t G_t(t).\tau_{M_k}} \int_0^t G_t(t_i).e^{-\frac{t-t_i}{\tau_{M_k}}}.H(t-t_i).dt_i \quad (5.b)$$

As evidenced by (5.a-b), the TIRR is the superposition of an infinite number of modes, related to the temporal responses $F_k(t), k \in \mathbb{N}^*$. We can show that $F_k(t)$ is a solution of the ordinary differential equation (6), whatever the form of $G_t(t)$:

$$\tau_{M_k}.\frac{dF_k}{dt} + F_k = \frac{G_t(t)}{\max_t G_t(t)} = V_{in}(t) \quad (6)$$

This equation can been seen as the behavioral equation of a capacitance voltage F_k of a RC circuit with the time constant $R_k.C_k = \tau_{M_k}$, submitted to the input voltage stimulus $V_{in}(t)$. Then, we can see $I_{tirr,j}(t)$ as the sum of an infinite number of current generators, each of them controlled by a voltage $U_k = F_k, k \in \mathbb{N}^*$. A truncation method for the series of (5.a) needs then to be chosen according to TIRR type (see [8] for the specific case of SET). Finally, we obtain the equivalent electrical circuit depicted in Fig. 2, which is implemented in Verilog-A. Such a circuit is the general version of the one we obtained in [7] in the particular case of SET, considering input voltage stimulus $\delta(t-t_i)$, δ being the Dirac distribution (properly implemented in SPICE). This generalization strongly relies on assumptions exposed in II.A. Note that we normalized $V_{in}(t)$ by dividing by $\max_t G_t(t)$ to avoid convergence issues during the solving. With such a choice, we can show that $|U_k|$ magnitudes are limited to $|U_k| < 1V \ \ \forall k \in \mathbb{N}^*$.

III. CROSS COMPARISONS WITH TCAD SIMULATION

Cross-comparisons between TIRR compact model and TCAD are performed. The TCAD structure describes a N type SOI MOSFET (including the presence of body contact to reduce bipolar amplification magnitude [13,14]). We consider a structure without substrate as depicted in Fig.1.a, allowing us to align the TCAD structure with the one related to our TIRR compact model. Electrical transient simulations

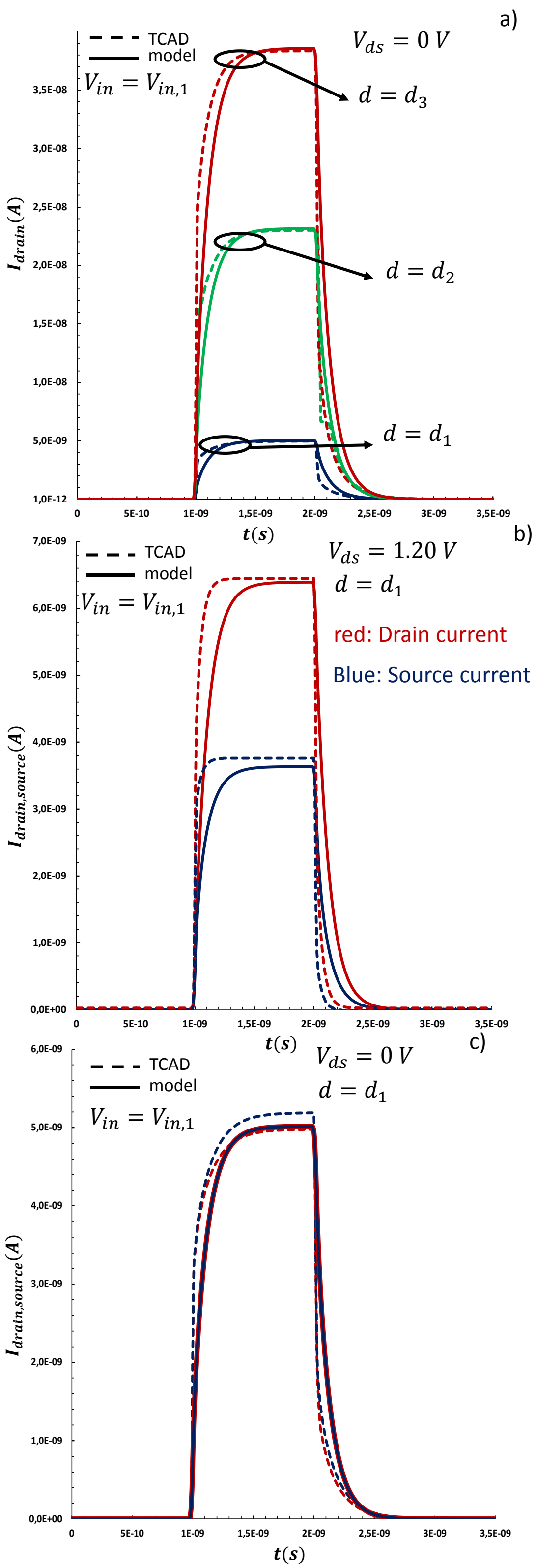

Fig.3: Calibration procedure of TIRR model versus TCAD. a): for $V_{ds} = 0V$ and 3 dose levels, comparisons between TIRR model and TCAD. b) &c): for $d = d_1$, comparisons of V_{ds} behaviour for TIRR model and TCAD. For all these comparisons, the model parameters values obtained are $D = D_n = 1.6.10^{-5}\, m^2.s^{-1}$, $v_x = 167.V_{ds}$, $\theta = 6.2$, $\tau = 10\, ns$.

include a drift-diffusion transport model, a Fermi distribution, Shockley-Read-Hall (SRH) and Auger recombination, a doping dependent mobility, and the γ radiation built-in module in Silicon (used for simulating laser irradiation). This module allows some freedom on $V_{in}(t)$ choice (3 profiles are chosen ($V_{in,\{1,2,3\}}(t)$, see Fig.1.b)) to validate our TIRR model in the case of uniform energy deposition per unit of Silicon mass i.e. the dose d (in Gy, with $1\, Gy = 100\, rad$). The dose is related to $G_x(x)$ through:

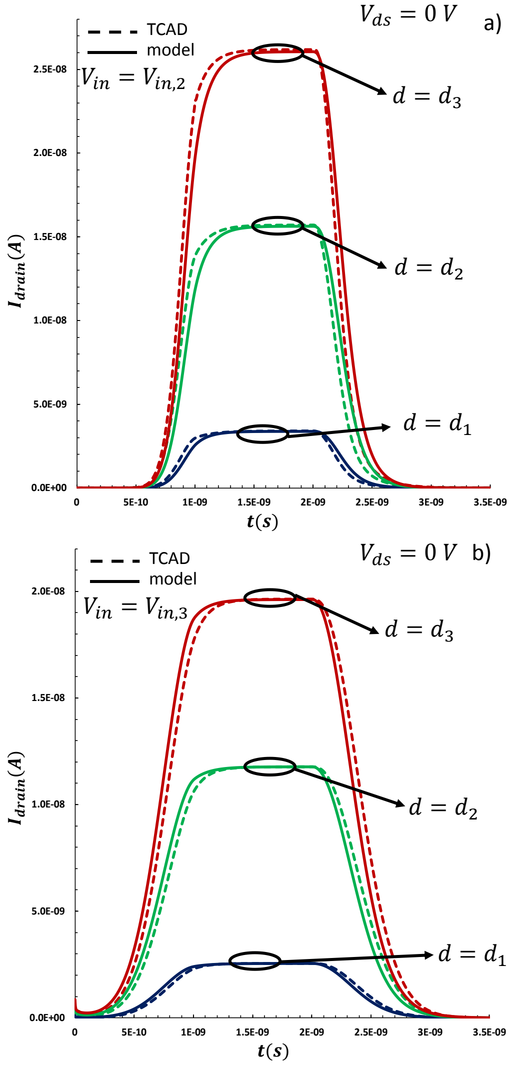

Fig.4: Calibration procedure of TIRR model versus TCAD, for $V_{ds} = 0V$, 3 different dose levels, and separately for : a): $V_{in}(t) = V_{in,2}(t)$ b): $V_{in}(t) = V_{in,3}(t)$.Values of θ were respectively $\theta = 5.64$ and $\theta = 5.36$, while values for other parameters were the same as for Fig.3.

$$G_x(x) = \frac{N_{eh}}{L_{ch}} = \left(\frac{\rho}{E_b}.Y.\theta.W.T_{si}\right).d \qquad (7)$$

In (7), $\rho = 2.33\, g.cm^{-3}$ is the Silicon density, Y the field factor [15] equal to 1 in these simulations, and $E_b = 3.6\, eV$ the mean energy required to create an e/h pair in Silicon. We also introduce the fitting parameter $\theta \geq 1$ as the ratio between both the sensitive volume, which is the part of the Silicon active volume where generated e/h pairs are able to contribute to the current, and the body volume. Such a use of θ in (7) means that we choose to bring back all of these e/h pairs inside the body volume to ease the modeling approach. Note that for the considered radiation event, simply truncating the series (5.a) at order $K = 14$ is sufficient to reach convergence with relative error below 4% (simply compensated during the calibration procedure through the parameter θ). The shorter the input stimulus, the more necessary it is to truncate at higher order. Fig.3.a illustrates the drain current vs time obtained for different dose levels $d = \{d_1, d_2, d_3\}$ with $d_1 < d_2 < d_3$, and the shortest stimulus ($V_{in,1}(t)$), at $V_{ds} = V_{gs} = 0V$. We see the model is able to reproduce TCAD after a realistic calibration of the model parameters, even if the description of the dynamics is not perfect. Then, keeping these calibration results, the drain and source currents versus time for $V_{ds} = \{0\ V, 1.20\ V\}$, and $d = d_1$ are displayed in Fig.3.b. It can be seen that the model is able to reproduce V_{ds} dependence of TIRR, which is higher at the drain compared to the source for $V_{ds} = 1.20V$. This is due to the enhanced generated electron collection at the drain, and it is directly caught through the ambipolar drift velocity parameter v_x if an empirical relationship with respect to V_{ds} is chosen. If we assume a uniform applied electric field along x, v_x can be expressed as:

$$v_x = \frac{\mu}{L_{ch}}.V_{ds} = \alpha.V_{ds} \tag{8}$$

In (8), $\alpha = \mu/L_{ch}$ (μ being the ambipolar mobility in $m^2.s^{-1}.V^{-1}$) is a fitting parameter equal to $167\ m.s^{-1}.V^{-1}$. Such a value is hardly grasped due to the high uncertainty in what would be a consistent value for the ambipolar mobility, as μ is in reality not uniform and neither static and its value spans from 0 in high injection condition to the minority carrier (electrons for NMOS) mobility value in low injection. Note that at $V_{ds} = 0V$, TCAD predicts that collection is not totally symmetrical between the source and the drain, conversely to the model, but the induced error remains low compared to the magnitude of both currents. Fig.4.a-b shows the comparison between TCAD and model drain currents for slower input stimuli $V_{in,\{2,3\}}(t)$, each case being separately calibrated. Very good agreement is obtained for each dose level once we allow some freedom on θ parameter value (values for other parameters remaining the same as in Fig.3.a-c). Overall, the slower the input stimulus $V_{in}(t)$ is, the better the dynamics of the TIRR is described and fits the one of $V_{in}(t)$. It is due to the progressive change in the limiting process (i.e. the slower process, governing the dynamics), from the drift/diffusion transport, relying on several strong assumptions and approximations, to the e/h pairs generation which is perfectly known as being an input of the TIRR model. Note that adjusting θ value conveys both uncertainty on the sensitive volume value (being somewhere in between the body volume and the total SOI film volume) and the simplification in our modeling approach consisting in not solving the problem in the whole SOI film (including highly doped areas). Note also that generation of e/h pairs in the substrate might impact TIRR shape for low dose due to capacitive coupling through the buried oxide. The next version of the TIRR model should include both the resolution in highly doped areas and the effect of e/h pairs generated in the substrate.

IV. Conclusion

In this paper, we developed a TIRR compact model to be used for SPICE simulation of any kind of ionizing radiation. The implementation methodology relies on an equivalent electrical circuit described in Verilog-A and is a generalization of the former work [7]. The main underlying concept is to see any TIRR as the sum over time of SET-like currents induced by elementary generated e/h pair densities. Cross comparisons with TCAD simulations of SOI MOSFET submitted to laser radiations have been performed. We show that our TIRR compact model is able to catch results of numerical methods calculations. This model can be improved to obtain a simplified and more realistic calibration procedure solving the problem inside the whole SOI film. It might also be important to account for e/h pairs generated in the substrate as it can influence TIRR temporal shape.

References

[1] J.L. Autran Soft errors: from particle to circuit. CRC press Taylor & Francis book 2015.

[2] G. Hubert, S. Duzellier, C. Inguimbert, C. Boatella-Polo, F. Bezerra and R. Ecoffet, "Operational SER Calculations on the SAC-C Orbit Using the Multi-Scales Single Event Phenomena Predictive Platform (MUSCA ${\rm SEP}^{3}$)," in IEEE Transactions on Nuclear Science, vol. 56, no. 6, pp. 3032-3042, Dec. 2009, doi: 10.1109/TNS.2009.2034148.

[3] Uznanski, S. 2011. Monte-Carlo simulation and contribution to understanding of single event upset (SEU) mechanisms in CMOS technologies down to 20 nm technological node. PhD Thesis, Aix-Marseille University, Marseille, France.

[4] G. C. Messenger, "Collection of Charge on Junction Nodes from Ion Tracks," in IEEE Transactions on Nuclear Science, vol. 29, no. 6, pp. 2024-2031, Dec. 1982.

[5] L. Artola et al., "SEU Prediction From SET Modeling Using Multi-Node Collection in Bulk Transistors and SRAMs Down to the 65 nm Technology Node," in IEEE Transactions on Nuclear Science, vol. 58, no. 3, pp. 1338-1346, June 2011.

[6] J. S. Kauppila et al., "Geometry-Aware Single-Event Enabled Compact Models for Sub-50 nm Partially Depleted Silicon-on-Insulator Technologies," in IEEE Transactions on Nuclear Science, vol. 62, no. 4, pp. 1589-1598, Aug. 2015.

[7] N. Rostand, S. Martinie, J. Lacord, O. Rozeau, J. Barbe and G. Hubert, "Single event transient in bulk MOSFETs: Original modelling for SPICE application," 2017 International Conference on Simulation of Semiconductor Processes and Devices (SISPAD), Kamakura, 2017, pp. 89-92.

[8] N. Rostand et al., "Compact Modelling of Single Event Transient in Bulk MOSFET for SPICE: Application to Elementary Circuit," 2018 International Conference on Simulation of Semiconductor Processes and Devices (SISPAD), Austin, TX, 2018, pp. 364-368.

[9] N. Rostand, S. Martinie, J. Lacord, O. Rozeau, T. Poiroux and G. Hubert, "Single Event Transient Compact Model for FDSOI MOSFETs Taking Bipolar Amplification and Circuit Level Arbitrary Generation Into Account," 2019 International Conference on Simulation of Semiconductor Processes and Devices (SISPAD), 2019, pp. 1-4, doi: 10.1109/SISPAD.2019.8870520C.

[10] C. McAndrew et al., "Best Practices for Compact Modeling in Verilog-A," in IEEE Journal of the Electron Devices Society, vol. 3, no. 5, pp. 383-396, Sept. 2015.

[11] T. Wang and J. Roychowdhury. Guidelines for Writing NEE DS-compatible Verilog-A Compact Models. https://nanohub .org/resources/18621,Jun 2013.

[12] TCAD Sentaurus, Synopsys, Inc.: Q-2019.

[13] V. Ferlet-Cavrois et al., "Large SET Duration Broadening in a Fully-Depleted SOI Technology—Mitigation With Body Contacts," in IEEE Transactions on Nuclear Science, vol. 57, no. 4, pp. 1811-1819, Aug. 2010, doi: 10.1109/TNS.2010.2048927V.

[14] V. Ferlet-Cavrois et al., "Characterization of the parasitic bipolar amplification in SOI technologies submitted to transient irradiation," in IEEE Transactions on Nuclear Science, vol. 49, no. 3, pp. 1456-1461, June 2002, doi: 10.1109/TNS.2002.1039683.

[15] J.L. Leray, short course NSREC 1999.