Compact Modeling of Radiation Effects in Thin-Layer SOI-MOSFETs

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***Abstract*— Radiation can generate huge amounts of carriers in thin-layer SOI-MOSFETs, which change the device-internal potential distribution, known as an origin for of malfunction of circuits. 2D-numerical device-simulation analysis shows that the radiation-generated electrons initially flow-out from the SOI layer to both source and drain electrodes, which moderates the radiation-effect magnitude on device currents in this beginning stage. Subsequent enhancement of the current flow is due to accumulated holes caused by the potential barrier at source/channel junction. Compact modeling of the carrier movements during the initial radiation stage and of the hole-accumulation dynamics is based on the dynamically generated carrier densities. The developed compact model has been implemented into SPICE and model evaluation has been done by comparison to 2D-numerical device-simulation results. Under the off-state, it is shown that circuits can be easily switched to operation condition. Under the on-state, it is demonstrated that circuits can easily malfunction by operating differently from the designed circuit function. Though the radiation itself happens only for a short time, the radiation-induced effects continue for a rather time long, which causes serious effects in the circuits and is explained by the capacitor features of the SOI-MOSFET**

Keywords—radiation effect, ETSOI, SOTB, compact model, HiSIM, circuit simulation, malfunction

I. Introduction

SOI-MOSFET technology is often used to improve device reliability under radiation, thus suppressing malfunction of circuits in radiative environments [1, 2]. The key for predicting radiation-induced circuitry instabilities is an accurate compact model, which includes the microscopic radiation effects on the device, such as the potential redistribution within the device. Previously, phenomenological modeling has been done with existing models without explicit carrier-generation modeling due to the deficit of a fundamental modeling technique. Here, our focus is given on the carrier-generation modeling based on the radiation features and characterized by physical quantities. The dynamics of the generated carriers are modeled in conjunction with the potential redistribution by developing two key model components. One is the movement of carriers caused by the radiation, which changes the MOSFET reaction to the operating condition. The second is the carrier-accumulation delay, which causes a long-term radiation effect. The developed radiation-effect model is implemented in the compact model HiSIM_SOI series [3] for the SOI MOSFET.

II. Modeling and Implementation of Radiation Effect

A. Single MOSFET Operation

Transient characteristics of a single nMOS under radiation are investigated with 2D numerical device simulation (2D-Sim) [4]. A thin SOI-MOSFET device is studied, which represents one of the important devices utilized in space activities [5, 6]. The investigation condition with a radiation event is depicted in Fig. 1. The body-potential node V_{body} is introduced to monitor the substrate condition and no current flow is possible, because the gate voltage V_{gs} is set to zero so that the device is in the off-state. The radiation particle is assumed to hit through the device middle with a diameter of 0.1μm and a linear energy transfer of 25MeV-cm^2/mg. The generation rate is assumed to have a Gaussian profile with a characteristic time of 10ps. Fig. 2 shows the potential distribution from 2D-Sim along the channel at different time points after the radiation event. A short time of 5ps after the radiation impact, the potential in the drain contact has already reduced to zero and then recovers gradually to the initial value of 1.2V after 30ps. This behavior is explained by the huge flow of generated electrons to the drain contact, where they disappear.

2D-Sim results of the immediate separation of generated electrons and holes and their flow-out from the channel are depicted in Fig. 3. Nodes of all observed current flows are additionally depicted in Fig. 1. Most of the time, the drain current I_{drain} (electron flow) and the source current I_{source} (hole flow) are identical with opposite signs. However, it can be seen that electrons flow out from both electrodes during the initial stage (see Fig. 3b), which is due to the extremely high electron/hole densities induced within the SOI layer. Since the gate is biased to zero, such huge carrier amounts cannot be sustained within the SOI layer. Therefore, electrons flow out immediately to the drain as well as to the source. However, the electron flow to the source is diminished shortly after the radiation event. Since the induced source-channel field due to the built-in potential prevents holes from flowing out, they are accumulated within the SOI layer for a relatively long time, as can be seen in Fig. 4. The resulting positively-charged SOI layer reduces the built-in potential and thus causes the hole flow-out through the source [7].

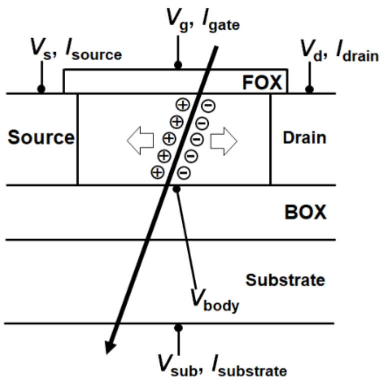

Figure 1: Schematic of studied radiation event in the SOI-MSOFET, where V_{body} is introduced to monitor the charging condition in the SOI layer.

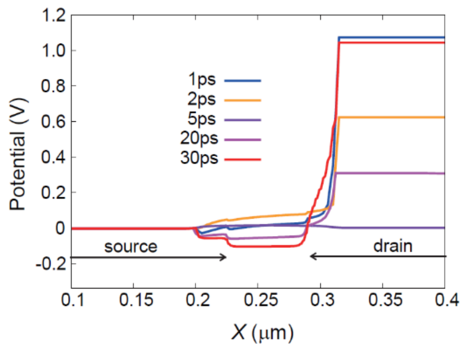

Figure 2: 2D device simulation results of the potential distribution along the device (X) at different time steps during radiation. The gate voltage V_{gs} is set to zero and the drain voltage V_{ds} to 1.2V. t=0 refers to the radiation starting and t=5ps is the end (see SEU in Fig. 4).

Consequently, the main modeling tasks are accurate descriptions of generated charge G and remaining accumulated hole charge Q_h in the SOI layer [8]. Since G is simultaneously induced during the radiation event, the model includes several parameters (see Table 1), which are extracted from measurable currents [8]. Q_h is obtained by integrating G over time, as shown in Fig. 5. Here, the generation occurs multiplicatively and takes time until completion. Therefore, Q_h is the integrated G including a delay. Additionally, holes also flow out from the SOI layer continuously through the diffusion mechanism after the generation is over. The relationship between the current and the generated carriers is modeled consistently with the basic device equations (see Table 2). Since the linear energy transfer of the radiation is extremely high and their crossing track is very thin, the energy attenuation can be neglected.

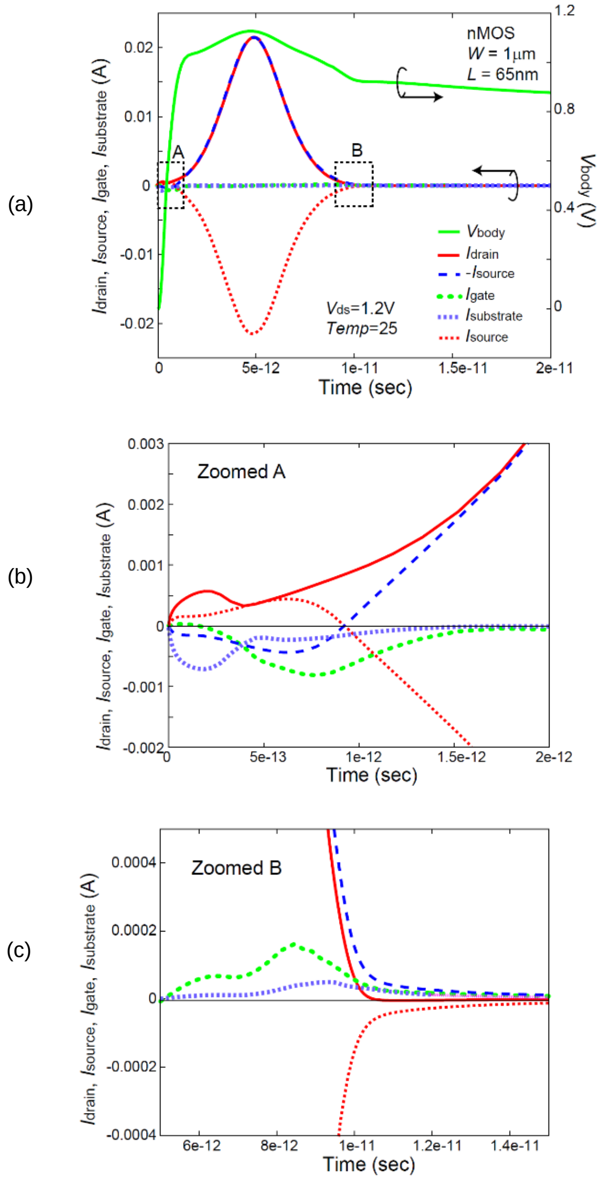

Figure 3: (a) 2D device simulation currents flowing to different electrodes during radiation event. The potential value at the bottom of the SOI layer in the channel middle V_{body} is depicted together. Zoomed features of (b) the A square and (c) the B square are also shown together. The radiation starts at t=0 and ends at t=5ps (see Fig. 4).

B. Implementation into SPICE

Circuit simulation is performed with a SPICE simulator, where the developed compact radiation model is implemented, using the industry standard compact model HiSIM_SOI [3] as its platform. The radiation model is implemented with consideration of two important characteristics. One is the generated electron flow-out from both electrodes until the MOSFET is turned on, namely, until Q_h becomes large enough so that more current can flow due to the increased substrate potential. The other is the Q_h inclusion in the Poisson equation to obtain self-consistent potential distributions. By solving the Poisson equation simultaneously, the carrier dynamics according to the device reaction is automatically modeled in a correct way.

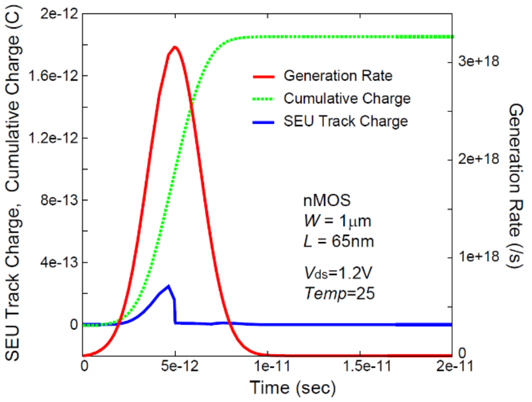

Figure 4: 2D-simulated generation rate and cumulated hole charge Q_h, which refers to the integration of the generated charge G over time. The applied radiation is also depicted in the graph. The SEU (Single Event Upset) particle streak ends at t=5ps.

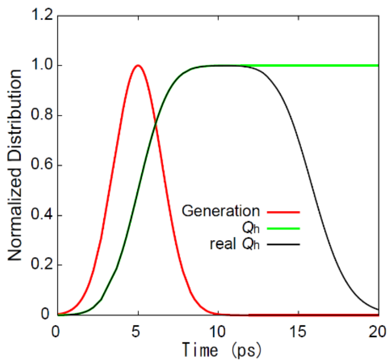

Figure 5: Normalized G and Q_h of model-calculation results, where the gradual hole flow-out is also considered in the quantity "real Q_h". Model parameters are depicted in Table 1.

Table 1. Model parameters and their notations.

Model Parameters	
Generation current delay:	RADIPDA0
Q_h charging delay:	RADQHA0
Q_h release delay:	RADQHDLY
Characteristic time for G:	RADPSIG

Table 2. Important device equations.

I_{RD}: generation current

$$I_{RD,nqs}(t) = I_{RD,nqs}(t-\Delta t) + \frac{\Delta t}{\tau_{ipd} + \Delta t}\left(I_{RD,qs}(t) - I_{RD,nqs}(t-\Delta t)\right)$$

$$I_{RD,qs}(t) = delay(RAD\_I_{RD}, \mathrm{RADIPDA0})$$

$$\tau_{ipd} = \mathrm{TAUFAC} \cdot \mathrm{RADPSIG}$$

Q_h: accumulated hole charge

$$Q_{h,nqs}(t) = Q_{h,nqs}(t-\Delta t) + \frac{\Delta t}{\tau_{qhi} + \Delta t}\left(Q_{h,qs}(t) - Q_{h,nqs}(t-\Delta t)\right)$$

$$Q_{h,qs}(t) = \mathrm{RADQHA0} \cdot \int_0^t Q_{RD}(t)\,dt$$

$$\tau_{qhi} = \mathrm{TAUFACQ} \cdot \mathrm{RADPSIG}$$

$$Q_{h\_out,nqs}(t) = Q_{h\_out,nqs}(t-\Delta t) + \frac{\Delta t}{\tau_{qh} + \Delta t}\left(Q_{h\_out,qs}(t) - Q_{h\_out,nqs}(t-\Delta t)\right)$$

$$Q_{h\_out,qs}(t) = delay\left(Q_{h\_in}, \mathrm{RADQHDLY}\right)$$

$$\tau_{qh} = \mathrm{TAUFACQO} \cdot \mathrm{RADPSIG}$$

G: generation rate

$$G(y,t) = \alpha e^{-\alpha y}\phi(t)$$

$$\phi(t) = \frac{\mathrm{RADETA} \cdot \mathrm{RADFLUX} \cdot \mathrm{RADLAMBDA}}{\left(hbar = 1.0546e^{-34}\right)\cdot\left(c = 3e^{8}\right)} \cdot P(t)$$

$$P(t) = e^{-\frac{(t - \mathrm{RADPTRI} - 3\cdot\mathrm{RADPSIG})^2}{2\cdot\mathrm{RADPSIG}^2}}$$

ϕ: photon flux
α: attenuation coefficient

III. Results and Verification

A. Inverter-Circuit Operation during Off-State

The radiation effects are investigated with an inverter circuit under V_{gs}=0 and V_{dd}=1.2V as depicted in Fig. 6a. Since V_{gs}=0, no current flow occurs and thus V_{out} is kept at 1.2V. A radiation is assumed to hit on the n-MOSFET at Time=0 so that electrons and holes are generated. The electrons start to flow out as observed in the electron current, and V_{out} is temporarily reduced to zero. The holes are accumulated within the substrate, which increases the substrate potential V_{body}. The calculated switching performance with the developed model is compared with 2D-Sim results in Fig. 6b. The calculated V_{body} is also depicted together. Fig. 6c compares model-simulation results for V_{out} with consideration of the initial electron flow and without. It can be seen that the initial current flow-out from both source- and drain contacts prevents the drastic change of the carrier distribution within the device and realizes smooth adjustment of the circuit reaction to the radiation event.

B. Inverter-Circuit Operation during On-State

Fig. 7 illustrates a malfunction event of the studied inverter circuit depicted in Fig. 6a. The simulation is performed under the assumption that the radiation event happens before the inverter's regular gate-controlled switching-off operation, which is scheduled to start at t=50ps and to completed at t=60ps. It can be seen, that an additional switching-off and switching-on glitch event occurs due to the radiation influence before the intentional gate-controlled switching-off. Because of the statistical nature of radiation events, precise prediction of a malfunction is not possible. However, it is shown here, that serious malfunction cases can be predicted with a certain statistical probability by using the developed compact model.

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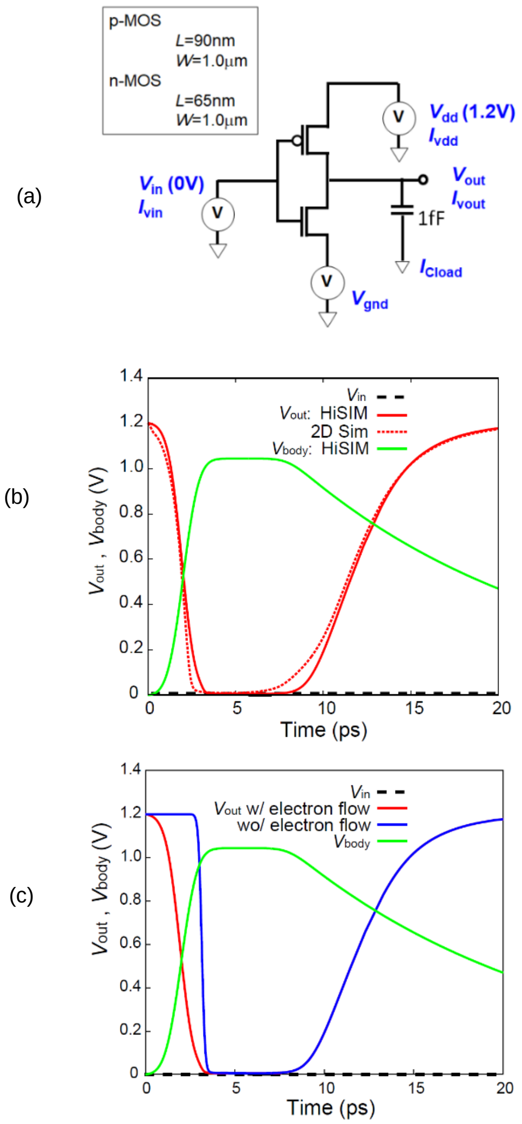

Figure 6: (a) Studied inverter circuit; (b) comparison of switching performance from model calculation results with those from 2D-Sim results under n-MOSFET off condition, and (c) switching performance with (red line) and without (blue line) consideration of the electron flow-out during the initial stage of the radiation.

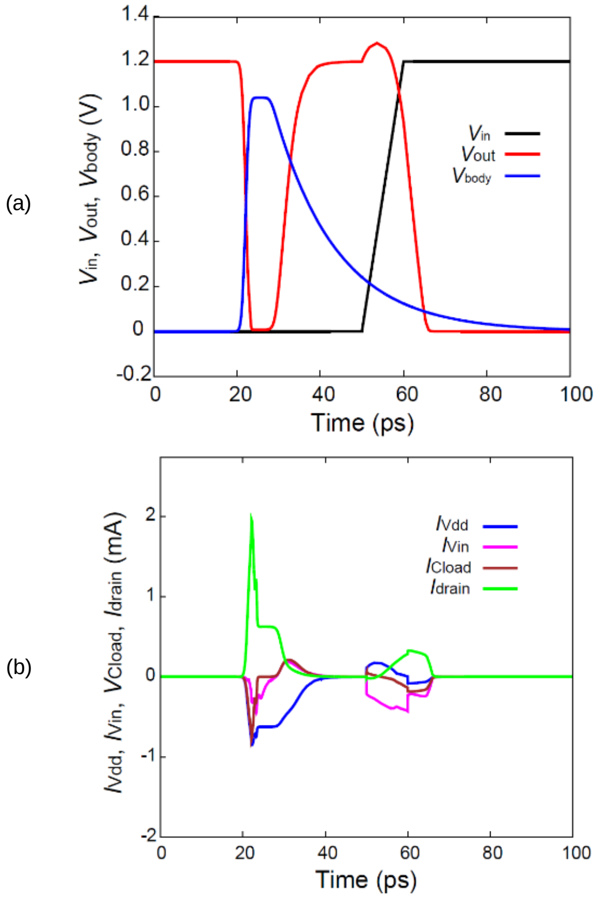

Figure 7: (a) Switching-performance malfunction of the studied inverter circuit (see Fig. 6a) due to a radiation event at the n-MOSFET before an intentional gate-controlled switching-on of the n-MOSFET. Without the radiation V_{out} stays 1.2V until switching-on starts at t=50ps. Due to the accumulated charge Q_h induced by the radiation V_{body} increases, which switches on the nMOSFET, causing the V_{out} inversion. (b) Transient current flows to different directions are summarized. I_{drain} is the current flowing between the nMOSFET and pMOSFET connection and V_{DD}, which is approximately equal to I_{Vdd}+I_{Cload}. It is seen that the first current flows between 20ps and 40ps by the radiation could be much larger than the expected ones.