Charge-collection Modeling for SER Simulation in FinFETs

Udit Monga, Jaehee Choi, Jongwook Jeon, Uihui Kwon,
Keun-Ho Lee
CAE, Semiconductor R&D Centre
Samsung Electronics Co., Ltd , Hwaseong Campus
Gyeonggi-do, Korea
udit.monga@samsung.com

Seungjin Choo, Taiki Uemura, Soonyoung Lee ,
Sangwoo Pae
TQR, System LSI
Samsung Electronics Co., Ltd , Giheung Campus
Gyeonggi-do, Korea

***Abstract*— Soft-errors are one of the most important reliability issues in logic and memory circuits. Proper estimation of soft-error-rate (SER) is important for error mitigation and SER robust circuit design. This paper presents a physical charge collection model for accurate simulation/prediction of SER in FinFETs. The modeling is scalable and includes the effect of variation of FinFET process and layout parameters.**

Keywords—radiation-effect; soft-errors; reliability; FinFET

I. INTRODUCTION

Soft-errors are basically temporary errors in stored or transmitted data in a device/circuit due to ionization caused by charged particles emitted from the radioactive traces in the BEOL/packaging or Cosmic rays [1-5]. Although ionization is only possible by the charged particles, neutrons (from cosmic rays) also cause SER as they induce the nuclear reactions which generate the secondary charged particles [6-7] .The ionization produces a cylindrical track of electron-hole pairs [8], these *e-h* pairs are absorbed by the junctions by drift-diffusion process [9]. Charge-carriers near to the junction are affected by drift process, while the ones far away from junction diffuse slowly before getting recombined. The corresponding ionization current at a sensitive node charges or discharges the node capacitance, thus affecting the node voltage. Fig.1 depicts the ionization due to particle-strike.

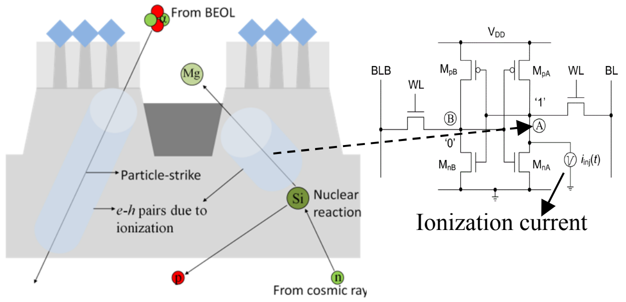

Fig. 1 Ionization and soft-error due to particle strike

One of the main criterions of SER is that the ionization charge collected by a sensitive node (Q_{col}) is higher than the charge required for changing the state of that node; also known as critical charge (Q_{crit}) [10]; the collected and critical charges are basically given as:

$$Q_{col} = \int_{0}^{\infty} i(t)dt \tag{1}$$

$$Q_{crit} = C_{node}\Delta V + \int i_d(t)dt \tag{2}$$

where $i(t)$ is the ionization current, $i_d(t)$ is the drain current, C_{node} is the node capacitance, and ΔV is minimum voltage change required to change the state of the node. The total number of errors in a circuit with m sensitive node and n particle strikes can be given as:

$$e = \sum_{j=1}^{m}\sum_{i=1}^{n} H\left(Q_{collji} - Q_{critj}\right) \tag{3}$$

where H denotes the Heaviside step function, Q_{critj} is the critical charge of jth node and Q_{colji} is charge collected by the jth node at ith strike.

The critical charge is calculated using SPICE simulations. The collected charge is estimated using extensive TCAD simulations [11]. However, particle-strike TCAD simulations are computationally very expensive, and it's not feasible to run these simulations for all the scenarios. In this paper we present a physical model of charge collection (Q_{col}) by a sensitive node in FinFET based circuits. The model captures the effect of variation of device dimension and particle strike location on collected charge; and it eliminates the need of computationally expensive TCAD simulations to predict SER in FinFETs

II. CHARGE COLLECTION MODLEING

3D TCAD simulations were performed to understand the charge collection process in FinFETs. Fig.2 shows the simulated TCAD device along with different components of ionization current. The simulations show that in FinFETs majority of collected charge comes from the ionization in the Fin/active region. The ionized charge in the well region diffuses away and only negligible portion is collected by the device – far less to cause any upset. However, in bulk devices the charge ionized in the well region is collected through slow diffusion process [12]. Fig.3 depicts the charge collection difference in FinFETs and bulk devices.

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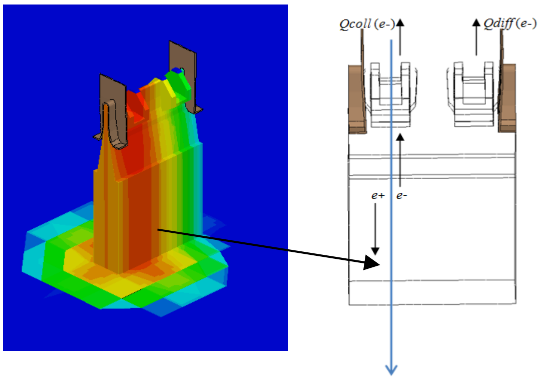

Fig. 2 Simulated TCAD device and ionization current components

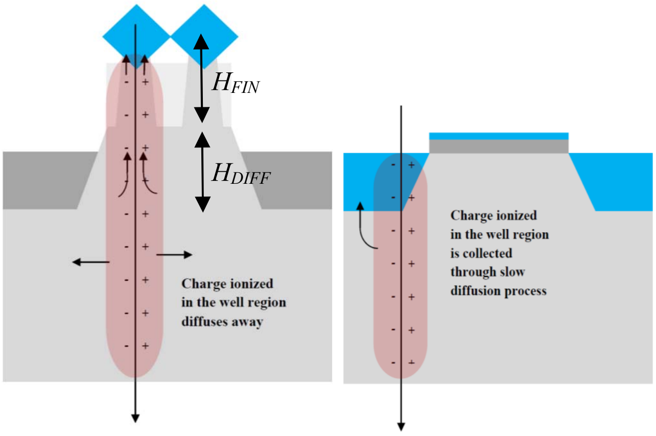

Fig. 3 Charge collection process

To model the charge-collection by a sensitive node, we consider a generic FinFET device with channel length=L, source/drain extension length=L_{SD}, Fin thickness=T_{FIN}, Fin height=H_{FIN}, Under-Fin diffusion height=H_{DIFF}, Fin pitch=F_p, number of fingers=N_F, and number of Fins=N_{FIN}. The particle strike is assumed to be at distance (d_x, d_y, d_z) away from the sensitive node (see Fig.4). Here d_x is along the device channel length, d_y is along Fin thickness, and d_z is along Fin height. The particle strike is assumed to be normal to the FinFET plane (θ=0), however the modeling methodology can be extended to cases of $\theta \neq 0$. For the model derivation, we assume a Gaussian radial distribution of ionized charge. The charge density in this case is given as:

$$n(x,y,z)=\frac{1}{\pi R^2 E_p} LET(z)\exp\left(-\frac{x^2+y^2}{R^2}\right) \tag{4}$$

where R is the characteristic radius of the distribution, and $LET(z)$ is the linear energy transfer of the ion. The total charge deposited in the Fin/Active region is given as:

$$Q_{dep}=\frac{q}{\pi R^2 E_p}\int_0^{z_o} LET(z)dz \int_{FIN}\int_{L}\exp\left(-\frac{x^2+y^2}{R^2}\right)dxdy \tag{5}$$

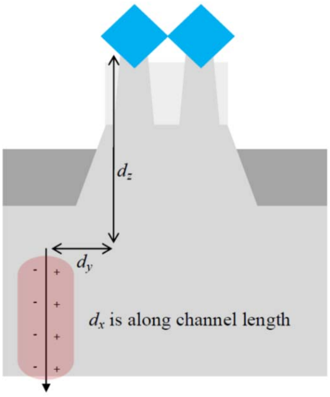

Fig. 4 Particle strike in the device

where z_o (total distance travelled by particle in the Fin region) $\leq H_{FIN}+H_{DIF}$, and E_p is the energy required to create one electron-hole pair=3.6eV. Since z_o is much smaller than the average range of a particle, LET can be assumed as constant over z, and Q_{dep} is simplified as:

$$Q_{dep}=\frac{qLETz_1}{4E_p}F_1F_2+\frac{qLETz_2}{4E_p}F_1F_3 \tag{6}$$

where z_1, z_2 are the distances travelled in the Fin and active regions. For a particle strike at distance d_z below the sensitive node, z_1 and z_2 are given as:

$$\begin{aligned} z_1 &= (H_{FIN}-d_z)H(H_{FIN}-d_z) \\ z_2 &= (H_{FIN}-d_z)H(d_z-H_{FIN})+H_{diff} \end{aligned} \tag{7}$$

and F_1, F_2, F_3 are given as:

$$\begin{aligned} F_1 &= Erf\left[\frac{N_F(L+2L_{SD})-d_x}{R}\right]+Erf\left(\frac{d_x}{R}\right) \\ F_2 &= \sum_{i=0}^{NFIN-1} Erf\left(\frac{iF_P-d_y}{R}\right)-Erf\left(\frac{iF_P-T_{FIN}-d_y}{R}\right) \\ F_3 &= Erf\left(\frac{N_{FIN}F_P}{R}\right) \end{aligned} \tag{8}$$

The above equation models the total charge collected by the Fin region. However, a part of this charge is absorbed by the source; depending upon the location of strike, ion-track radius and drain bias (V_{dd}). For SER calculation, only the charge collected by the drain node is important. This is modeled by subtracting the charge ionized at the source junction from (6). The charge absorbed by the source junction is modeled by calculating F_1 for the source side; given as:

$$F_{1s}=Erf\left[\frac{N_F(L+L_{SD}-dx)}{R}\right]-Erf\left[\frac{N_F(L-dx)}{R}\right] \tag{9}$$

The final equation for charge collected by drain, including drain bias dependency is given as:

$$Q_{coll}=\left[\frac{qLETz_1}{2E_p}(F_1-F_{1s})F_2+\frac{qLETz_2}{2E_p}(F_1-F_{1s})F_3\right]\times$$
$$[1-0.5\exp(-\beta V_{dd})] \qquad (10)$$

where β is an empirical parameter extracted from TCAD.

III. RESULTS AND DISCUSSIONS

Fig. 5 shows the comparison of model and 3D TCAD (Sentaurus-device) simulations for the collected charge variation with the ion-track radius. For large ion-track radius, most of the ionized charge is deposited outside the Fin region and thus the collected charge reduces substantially. Figures 6 and 7 show the comparison of model and TCAD simulations for the variation of collected charge with the location of strike, along the channel length (d_x), and the Fin thickness (d_y),. As evident from the figures, the collected charge due to particle strike significantly drops once the strike is outside the Fin region

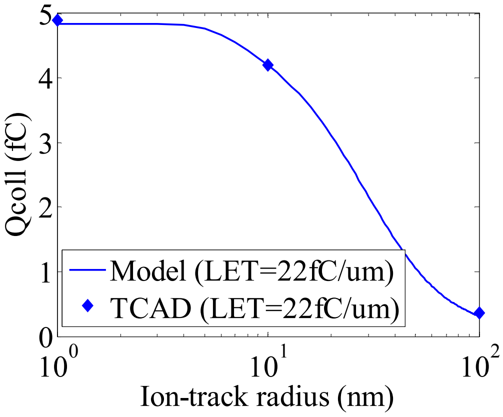

Fig. 5. Variation of collected charge with ion-track radius

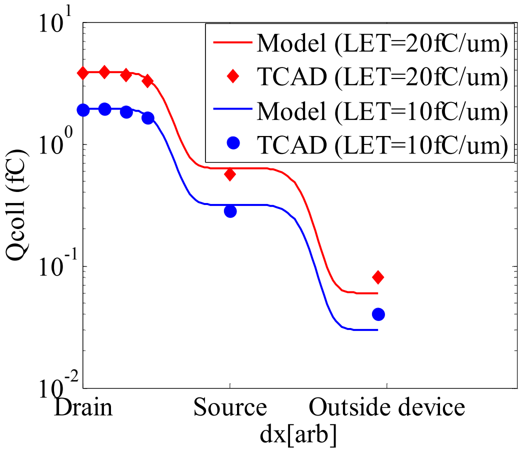

Fig. 6. Comparison of model and TCAD simulations for variation of charge along the channel length direction

The above analysis does not include the bipolar effect [13-14]. The bipolar effect is basically amplification in the collected charge due to increase in channel potential (barrier lowering) caused by temporary charge storage in the channel [15].

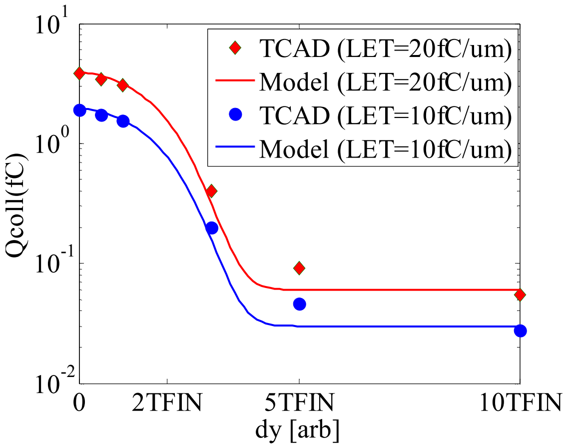

Fig. 7. Comparison of model and TCAD simulations for variation of charge along Fin thickness direction

The barrier lowering results in additional charge flow from the source to drain and thus increases the total collected charge by the drain node. Bipolar effect is more pronounced in case of heavy-ion strikes. The barrier lowering can be modeled by solving the Poisson's equation, given as:

$$\frac{\partial^2\varphi(y)}{\partial x^2}=-\frac{q}{\varepsilon}\left[N_{dep}(y)+n_o e^{\frac{\varphi(y)}{V_{th}}}\right] \qquad (11)$$

where first term in RHS represents the ionized charge-carrier density and second term represents additional charge-carrier density due to band bending. Complete analytical solution of (11) is rather involved, but a simplified solution of potential and corresponding charge density by neglecting the second term (assuming small potential change) and constant N_{dep} is given as:

$$\varphi(y)=\frac{qN_{dep}}{2\varepsilon}\left(yT_{FIN}-y^2\right)$$
$$n_s=\int_0^{T_{FIN}} n_o e^{\frac{\varphi(y)}{V_{th}}}\,dy \qquad (12)$$

The additional leakage current can be approximated as:

$$I_d(t)=-q\mu H_{FIN}n_s\frac{dV}{dx}T(t) \qquad (13)$$

where T(t) is the time dependent Gaussian function [8]. The additional charge due to bipolar effect is approximated as:

$$Q_b=\int I_d(t)dt=\lambda_2\frac{\sqrt{\pi}e^{\frac{\lambda_1 T_{FIN}{}^2}{4}}}{\sqrt{\lambda_1}}Erf(0.5\lambda_1 T_{FIN})\left(1-e^{-\frac{V_{dd}}{V_{th}}}\right) \qquad (14)$$

where the parameter, $\lambda_1 = qN_{dep}/2\varepsilon$, and parameter, λ_2 depends upon device dimensions and Temporal function $T(t)$ – it can be estimated from TCAD simulations. As (14) indicates, the additional bipolar charge is function of N_{dep} (and thus LET), T_{FIN}, and V_{dd}. Heavy ions – with higher LET – result in higher bipolar effect. Also, this effect is more pronounced in thick-Fin devices compared to thin-Fin devices.

IV. CONCLUSION

We have developed an accurate, physical, charge-collection model for SER prediction in FinFETs. The model includes the effect of variation of device dimensions and particle-strike location. The model shows good agreement with 3D TCAD simulations from Sentaurus device simulator.

REFERENCES

[1] P. Shivakumar, et. al, “Modeling the effect of technology trends on the soft error rate of combinational logic ,” Proc. IDSN., pp. 389-398, 2002.

[2] Shubhendu S. Mukherjee, et.al, “The Soft Error Problem: An Architectural Perspective,” Proc. 11th Int’l SHPCA, pp. 243-247, 2005

[3] G.R. Srinivasan, et.al., “Accurate, Predictive Modeling of soft-error Rate due to Cosmic rays and Chip Alpha Radiation,” Proc. IRPS, pp. 12-16, 2004

[4] G.A. Sai-Halasz, et.al., Alpha-particle-induced soft error rate in VLSI circuits,” IEEE Trans. Elec. Dev., vol. 29, no. 4, 1982.

[5] N. Cohen, “Soft error considerations for deep-submicron CMOS circuit applications,” Proc. IEDM, pp. 315-318, 1999

[6] J. F. Ziegler et.al., “Accelerated testing for cosmic soft-error rate,” IBM Journal of Research and Development, vol. 40, no.1, pp. 51-72, 1996

[7] Peter Hazucha and Christer Svensson, “Impact of CMOS Technology Scaling on the Atmospheric Neutron Soft Error Rate, ” IEEE Trans. Nucl. Sci, vol. 47, no. 6, 2000

[8] G. C. Messenger, “Collection of Charge on Junction Nodes from Ion Tracks,” IEEE Trans. Nucl. Sci, vol. 29, no. 6, 1982

[9] Fan Wang and Vishwani D. Agrawal, “Single Event Upset: An Embedded Tutorial,” Proc. 21st International conference VLSI design, pp. 429-434, 2008

[10] TC May, “Alpha-particle-induced soft errors in dynamic memories,” IEEE Trans. Elec. Dev., vol. 26, no. 1, 1972

[11] J. Noh, “Study of Neutron Soft Error Rate (SER) Sensitivity: Investigation of Upset Mechanisms by Comparative,” IEEE Trans. Nuc. Sci., vol. 62, no. 4, 2015

[12] R.C. Baumann, “Radiation-induced soft errors in advanced semiconductor technologies, ” IEEE Trans. Dev and Mat. Reliability, vol.5 no. 3, 2005

[13] B. D. Olson, D. R. Ball, K. M. Warren et al., “Simultaneous single event charge sharing and parasitic bipolar conduction in a highly-scaled SRAM design,” IEEE Trans. Nucl. Sci., vol. 52, no. 6, no. 2135-2136, Dec. 2005

[14] K Osada, “Cosmic-ray multi-error immunity for SRAM, based on analysis of the parasitic bipolar effect,” Proc. Symposium VLSI circuits, 2004

[15] Huichu Liu, Matthew Cotter, Suman Datta, Vijaykrishnan Narayanan, “Soft-Error Performance Evaluation on Emerging Low Power Devices,” IEEE Trans. Dev and Mat. Reliability, vol.14 no. 2, 2014