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An Analytical Model for Deposited Charge of Single Event Transient (SET) in FinFET

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Abstract
With feature size scaling down, the effect of single event transient (SET) on the reliability of circuits is necessary to be considered. The bipolar amplification effect plays a key role in the charge collection of SET of nano-meter FinFET devices. It is important taking into account the bipolar amplification to calculate deposited charge, which is always obtained by a linear model dependency on linear energy transfer (LET) and silicon film thickness. Based on radiation-induced generation rate model and genetic arithmetic, an accurate analytical for the deposited charge of SET in FinFET is proposed. The effects of LET, volume of particle hit, characteristic radius and decay time of Gaussian function on the deposited charge are analyzed by the proposed model. The dependence of the device structure on the deposited charge is also discussed by the model. The results indicate that the presented model agrees with TCAD well. Compared with TCAD, the proposed model has an average relative error 0.002% while the linear model has an average relative error 50.5% for LET ranging from 3 to 110 MeV·cm^2/mg. Due to large sensitive volume of the particle hit in source and drain areas, the deposited charge has two maxima in source and drain areas and a minimum round the gate-drain junction of fin. The deposited charge increases with the characteristic radius and decay time decrease and the relative error between TCAD and the proposed model represent a reduction trend.

Keywords Deposited charge · Bipolar amplification · FinFET · Single event transient

1 Introductions

With technology node shrinking, traditional planar CMOS transistors are vulnerable to undesirable short channel effects (SCEs), which present the most important constraints to MOSFET scaling rules [23]. However, owing to high density, high speed, high scalability, and lower power, fin-type field-effect-transistor (FinFET), one of non-planar and multi-gate devices, has been drawn much for one of the most promising candidates to continue CMOS scaling [8, 18, 23].

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It has been shown that single event transient (SET), induced by an energetic particle hitting the sensitive area of devices, has become one of the most important issues with FinFET at radiation environment [23]. Due to the reduced critical charge causing a soft error, it is significant to reduce the charge collection in FinFET devices. As in planar devices, parasitic bipolar amplification, which is the ratio between the collection charge and the deposited charge, can also play a key role in the charge collection of bulk and SOI FinFETs [9, 11, 23]. The most popular used model for evaluating the deposited charges is the linear model of silicon film thickness and linear energy transfer (LET) [12, 13]. However, the deposited charge is the function dependence on not only LET, but also the radial and temporal distributions of the radiation induced pairs [13]. With nano-scaled thin FinFET, the electron-hole pairs generation volume will also impact the deposited charge. Therefore, the linear model of the deposited charge is not suitable to FinFET due to large errors.

In the present work we analyze the effect of the spatial radius and temporal time of ion strike on SET by TCAD. An accurate analytical model of the deposited charge of SET in 14 nm SOI FinFET is proposed. Then the model is optimized by genetic arithmetic (GA). The rest of this paper is organized as follows. In Section 2, the effects of spatial radius and temporal time of ion strike on SET are analyzed. The model of the deposited charge in 14 nm SOI FinFET is proposed in Section 3. The validation and analysis of the presented model is performed in Section 4. Finally, the paper is concluded in Section 5.

2 TCAD Simulation of SET

Technology computer aided design (TCAD) tool is one of the most important methods to study single event effects of FinFET. Based on TCAD [19], some calibrated FinFET devices were built. The physics model of the radiation effects is necessary to simulate SET. In the single event transient simulation model, the distribution of the ion cross-section amplitude obeys to the Gaussian distribution. The characteristic radius (r_c) is defined as the distance from the center of the track to the point where its amplitude is down to 1/e of the maximum and the responding time is defined as the decay time (t_c). They are the important parameters in the simulation. Here, the statistical analysis of the used two parameters at different technology nodes in the papers [1–3, 5, 6, 10, 11, 13–17, 20, 23, 24] are performed, shown in Fig. 1.

It can be found that with technology node scaled down, both of the characteristic radius and decay time for single event effects simulation model present the reducing trend. For example, when technology node is scaled down from 100 nm to 14/16 nm, the two parameters are set from 50 nm and 2ps [3] to 10 nm and 0.5ps [1]. It has been validated that TCAD simulations with 10 nm radius and 0.5ps decay time for 14/16 nm FinFET agreed very well with the radiation experimental data [1]. Here the effects of the characteristic radius and decay time on SET current and the collected charge are analyzed, shown in Fig. 2. A calibrated TCAD model of high k (HfO_2)/metal gate stacked SOI FinFET at 14 nm technology node is used. The LET is 5 MeV·cm^2/mg. The ion hit location is the middle of fin between drain and gate. The collected charge is obtained by integrating the drain current over the transient duration [7]. From Fig. 2, it can be noticed that the reductions of radius (r) and decay time (t_c) will lead to the increase of peak current and narrowed pulse width. Full width at half maximum (FWHM) of SET current is reduced from 5.5ps to 2ps when t_c reduces from 2ps to 0.5ps. Although the collected rate of the charge increases with the decay time decrease, the maximum of the collected charge increases with the characteristic radius decrease. Due to different peak and width of the transient current with different radius and decay time, the deposited charge is different. In Fig. 2, the deposited charge with $r = 10$ nm and $t_c = 0.5$ps is the maximum value 0.343fC while one with $r = 20$ nm and $t_c = 2$ps is the minimum value 0.216fC. However, as mentioned in the paper [12, 13], the deposited charge is the linear model of silicon film thickness and LET. This fact disagrees with the linear model shown in [12, 13]. Therefore, an accurate analytical model of the deposited charge is very necessary.

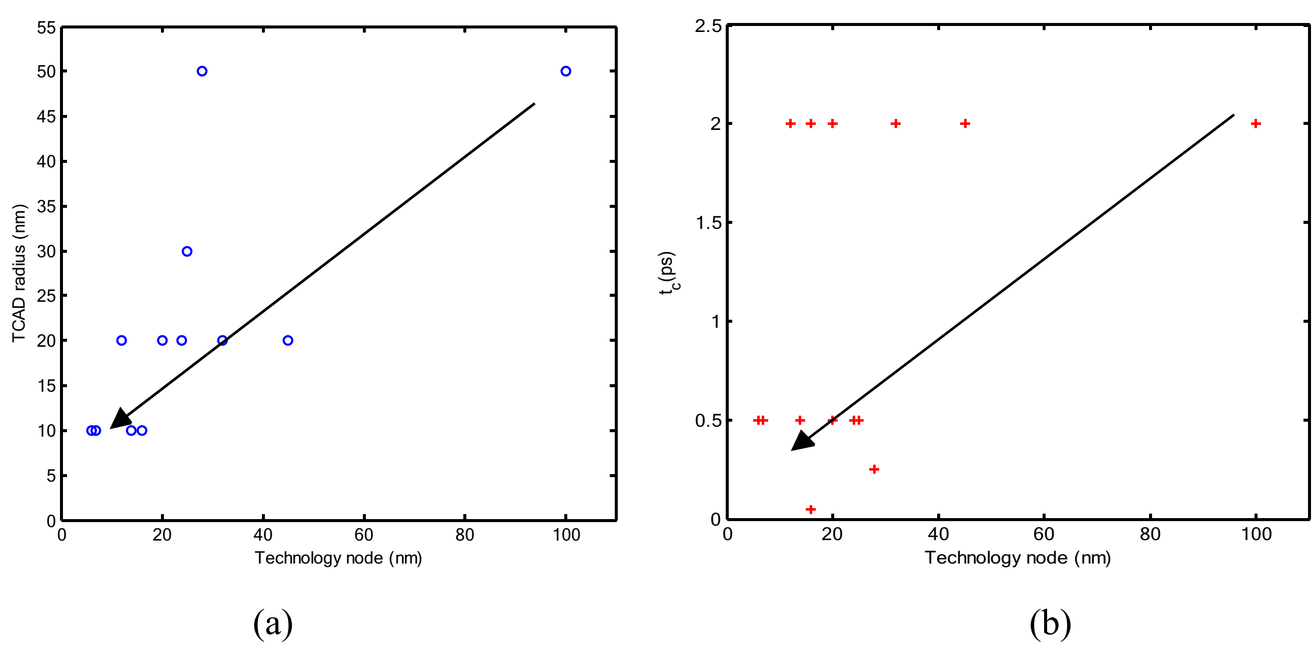


Fig. 1 Statistical analysis of parameters of TCAD at different technology nodes: **a** characteristic radius; **b** characteristic decay time

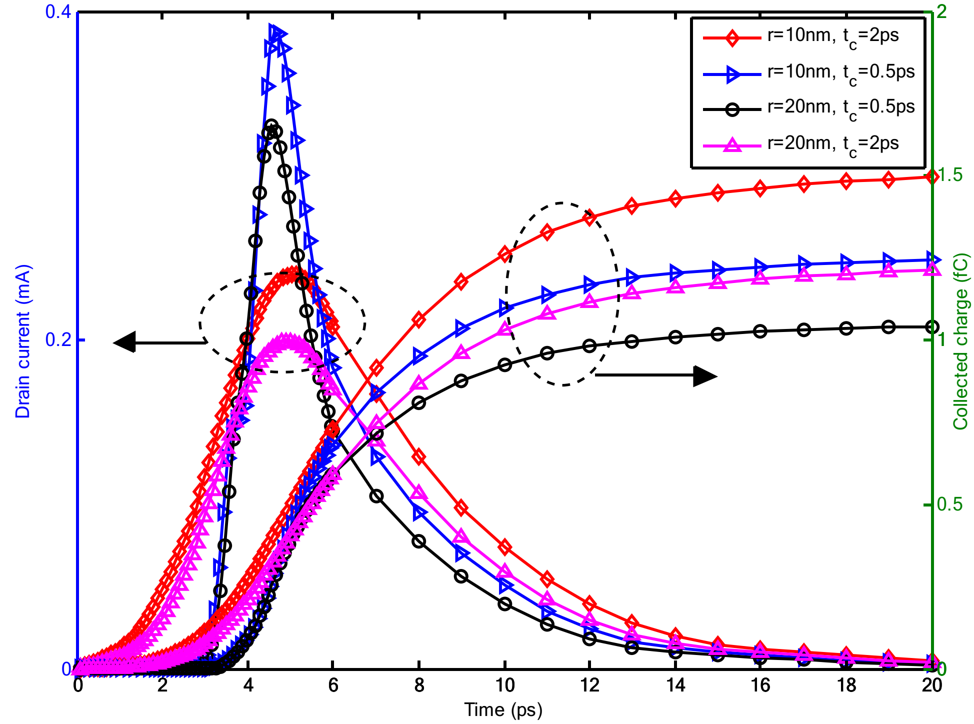


Fig. 2 SET transient currents and collected charges with different radiuses and decay times in 14 nm SOI FinFET

3 Model of Deposited Charge

In TCAD, the effect of a particle hit is taken into account as an external generation source of carriers [12, 19]. The electron-hole pair generation induced by the particle strike is included in the continuity equations via an additional generation rate [12]. The generation rate as the number of electron-hole pairs along the track via the following radiation-induced generation rate [12, 19]:

$$G(r,l,t) = \frac{\mathrm{d}N_{\mathrm{ehp}}}{\mathrm{d}l}(l) \bullet R(r) \bullet T(t) \tag{1}$$

where, r is the radial distance from the center of the track to the point, l is the distance along the track and t is the time. N_{ehp} is the number of electron-hole pairs created by the particle strike. $R(r)$ and $T(t)$ are the functions of radial and temporal distributions of the radiation induced pairs, respectively. They can be expressed by the following,

$$\frac{\mathrm{d}N_{\mathrm{ehp}}}{\mathrm{d}l} = \frac{1}{E_{\mathrm{ehp}}}\frac{\mathrm{d}E}{\mathrm{d}l} \tag{2}$$

$$R(r) = \frac{\mathrm{e}^{-(r/r_{\mathrm{C}})^2}}{\pi r_{\mathrm{C}}^2} \tag{3}$$

$$T(t) = \frac{\mathrm{e}^{-(t/t_{\mathrm{C}})^2}}{t_{\mathrm{C}}\sqrt{\pi}} \tag{4}$$

where, E_{ehp} is the mean energy necessary to create an electron-hole pair, such as, 3.6 eV for silicon. LET is defined as energy lost by unit of length $-\mathrm{d}E/\mathrm{d}l$. r_{c} and t_{c} are the characteristic radius and time of the most used Gaussian function which allows one to adjust the ion track width and the pulse duration, respectively.

The deposited charge can be obtained by integrating the function $G(r,l,t)$. Therefore, the deposited charge is the function dependence on LET, volume, r_{c} and t_{c}. In order to independently analyze the relationship between these four parameters and the deposited charge, several TCAD simulations of SET of 14 nm SOI FinFET, which only one parameter is varied, while the others are kept unaltered, are performed. The unaltered parameters are set as following. The ion hit location is the middle of fin between drain and gate. LET of the ion is 5 MeV•cm^2/mg. The characteristic radius (r_{c}) and time (t_{c}) for the radiation model in TCAD are 10 nm and 0.5ps, respectively. By the curve fitting tool, the functions between every parameter and the deposited charge are achieved, shown in Fig. 3.

In Fig. 3, the following relationships between the four parameters and the deposited charge are obtained,

$$Q_{\mathrm{d}} \propto \mathrm{e}^{-\frac{(t_{\mathrm{C}}-a_1)^2}{b_1^2}}, Q_{\mathrm{d}} \propto \mathrm{e}^{-k_1 r_{\mathrm{C}}}, Q_{\mathrm{d}} \propto LET, Q_{\mathrm{d}} \propto V \tag{5}$$

where, a_1, b_1 and k_1 are the fitting constants, V is the volume of the particle hit area, which depends on r and l. We assume the following hypothesis: the four parameters are independent. Therefore, the deposited charge is proposed the following model:

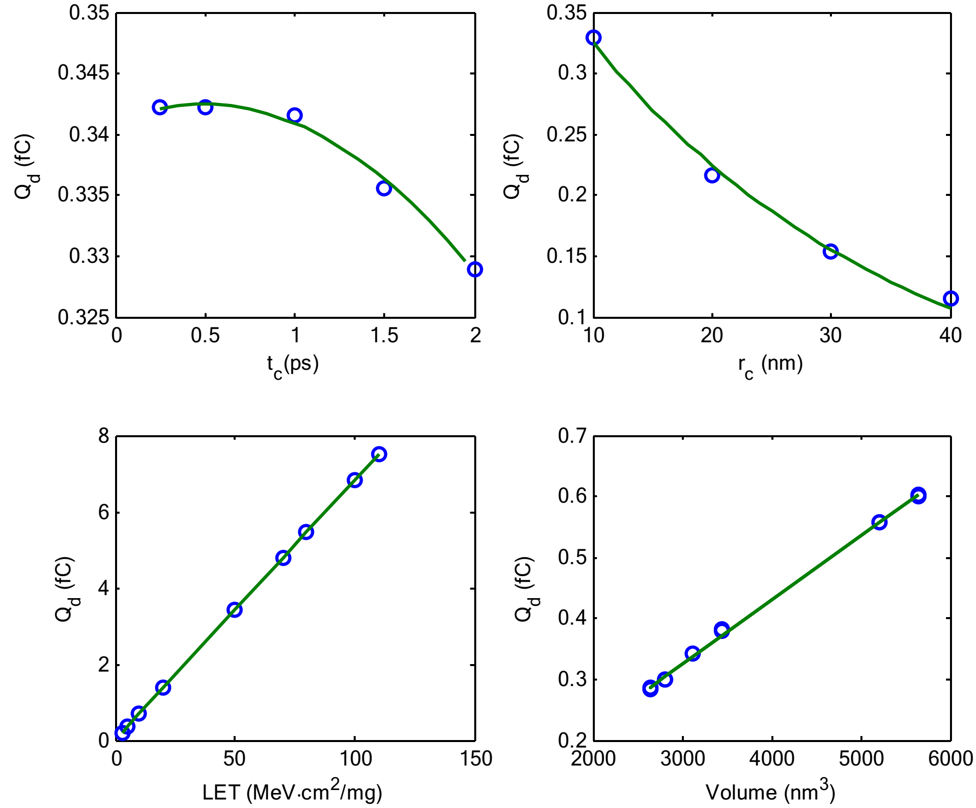


Fig. 3 Deposited charge dependency of four parameters: "O" marker denotes TCAD result, line denotes the curve fitting function

$$Q_{\mathrm{d}} = k_2 \bullet LET \bullet V \bullet \mathrm{e}^{-k_1 r_{\mathrm{C}}} \bullet \mathrm{e}^{-\frac{(t_{\mathrm{C}}-a_1)^2}{b_1^2}} \tag{6}$$

where, a_1, b_1, k_1 and k_2 are the fitting constants.

In order to improve the accuracy of the presented model, the curve fitting methods combined with genetic arithmetic (GA) optimized method are used to obtain the constants in Eq. (6). The parameters of GA are set as the following, population size is 40, crossover fraction is 0.8, mutation rate is 0.05, stop generations is 5000. The flowchart for the methodology and the result of GA are shown in Figs. 4 and 5.

Finally, the optimized deposited charge in 14 nm SOI FinFET is achieved as,

$$Q_{\mathrm{d}}(\mathrm{fC}) = 3.2081 \times 10^{-5} LET \bullet V \bullet \mathrm{e}^{-0.0368 r_{\mathrm{C}}} \bullet \mathrm{e}^{-\frac{(t_{\mathrm{C}}-0.9209)^2}{4.0765^2}} \tag{7}$$

where, LET is in MeV•cm^2/mg, V in nm^3, r_c in nm, and t_c in ps.

4 Validation and Analysis

In order to validate the proposed model, a 3D simulation model for SOI FinFET at 14 nm technology node has been built by using TCAD [7]. It fits well the experiment data. The gate length is 14 nm and the equivalent gate oxide thickness is 0.5 nm. The length of the extent source/drain region is 33 nm. The width (W_{fin}), height (H_{fin}) of fin is 10 nm, 18 nm, respectively. High k/metal gate stacked (HfO_2/TiN) structure was also included. The particle hit location is the middle of fin between gate and drain areas. The transient current is collected at the drain area. LET is 5 MeV•cm^2/mg. The characteristic radius and time for the radiation model in TCAD are 10 nm and 0.5ps, respectively. The supply voltage is 0.8 V. The linear model of the deposited charge is shown in the following [12, 13, 22],

$$Q_{\mathrm{dep}} = \frac{LET \times t_{\mathrm{Si}} \times \rho_{\mathrm{Si}} \times q}{E_{\mathrm{eh}}} \tag{8}$$

where Q_{dep} is the deposited charge in unit of fC, t_{Si} is the silicon film thickness in unit of μm, q is the charge of an electron, ρ_{Si} is the density of silicon and E_{eh} is the electron-hole pair creation energy (3.6 eV for silicon) [12, 22]. The range of LET is from 3 to 110 MeV•cm^2/mg. The deposited charges, predicted from the proposed model and the linear model, are compared with the results from TCAD at 14 nm SOI FinFET. The result is shown in Fig. 6.

It can be found that the deposited charge of the proposed model agrees very well with one of TCAD while the error of the deposited charge between the linear model and TCAD

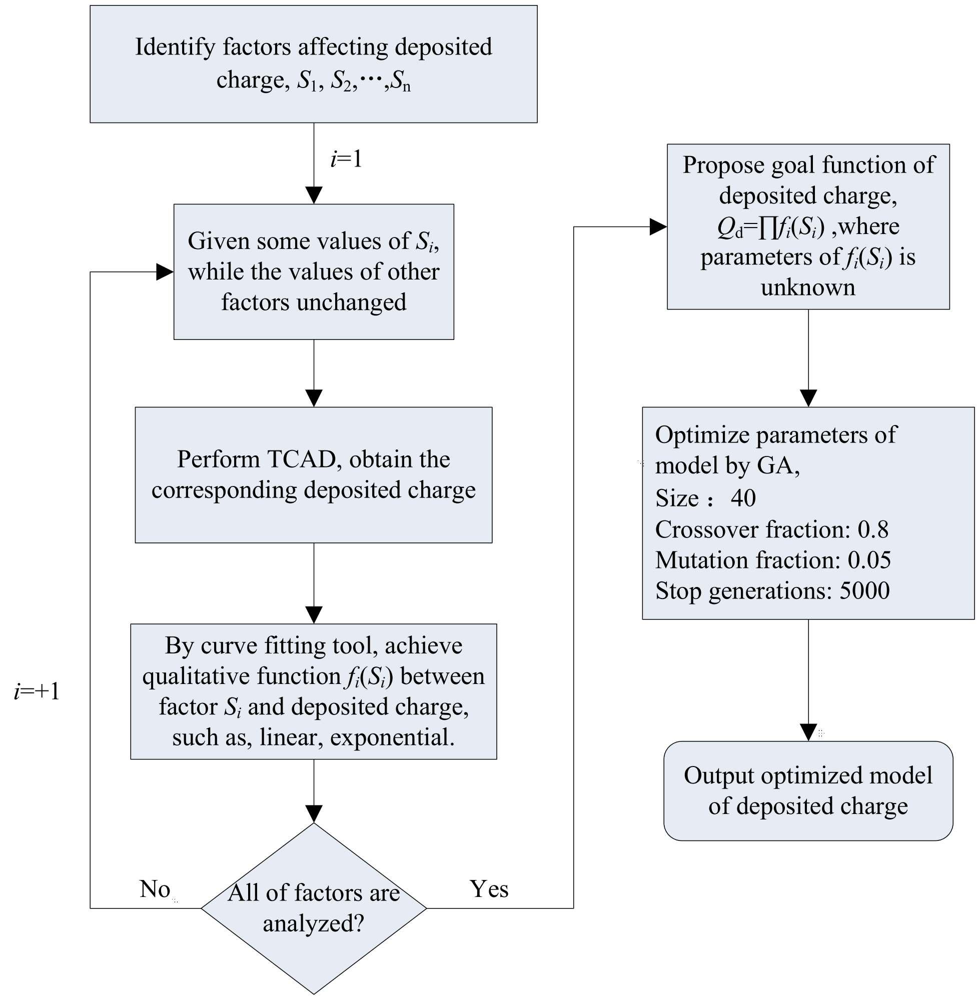


Fig. 4 Flowchart for the deposited charge model

is serious, especially at high LET. Compared with TCAD, the relative average errors of the deposited charges for the proposed model and the linear model are 0.002% and 50.5%, respectively. The result indicates that the presented model is more accurate to achieve the deposited charge of nano FinFET than the linear model.

The effect of the volume of the particle strike area on the deposited charge is analyzed. Due to fixed thickness of fin, the volume of the particle hit area only depends on the strike location. The result is shown in Fig. 7. It indicates that due to larger volumes at the source and drain area, the deposited charge has a valley-shaped profile with a minimum around the gate-drain junction of fin and two maxima at the source and drain areas. The proposed model agrees well with TCAD with an average relative error 1.40% and max relative error 2.72%, respectively.

The deposited charges at several r_c and t_c of the radiation model are obtained by TCAD and the proposed model, respectively, shown in Fig. 8. Compared with TCAD, the max relative error of the deposited charge of the proposed model is 6.90%. As r_c reduces, the relative error between the presented model and TCAD represents the reduction trend. For example, the max error is only 2.0% at $r_c = 10$ nm with several t_c. The reason of this fact may be that the deposited charge becomes small as the radius r_c and time t_c increase. The relative error is the inverse proportion to the deposited charge of TCAD. Therefore, when the deposited charge is smaller, the relative error may be larger even if the difference between the model and TCAD is small.

Several different structures of FinFET are used to validate the proposed model, shown in Fig. 9. Their names are BUL, TRI, STEP, SEMCY and ROUD, respectively. They are deduced from the rectangle FinFET. The section of BUL consists of a semicircle and a trapezoid. The section of TRI is a triangle. The section of STEP is a step.

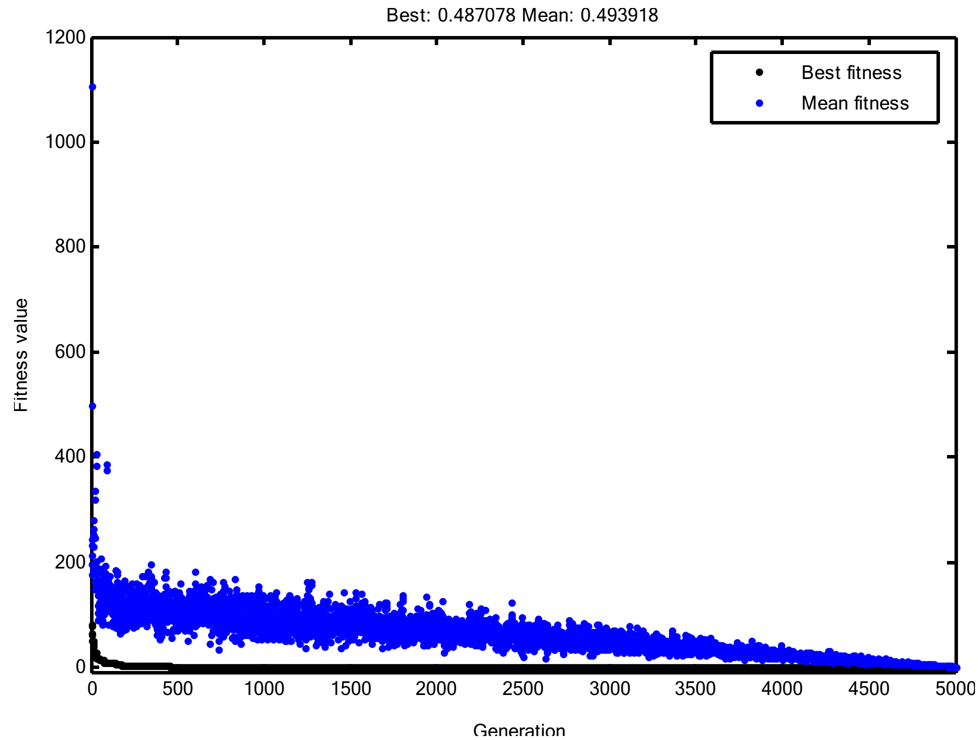


Fig. 5 Result of optimized model by GA

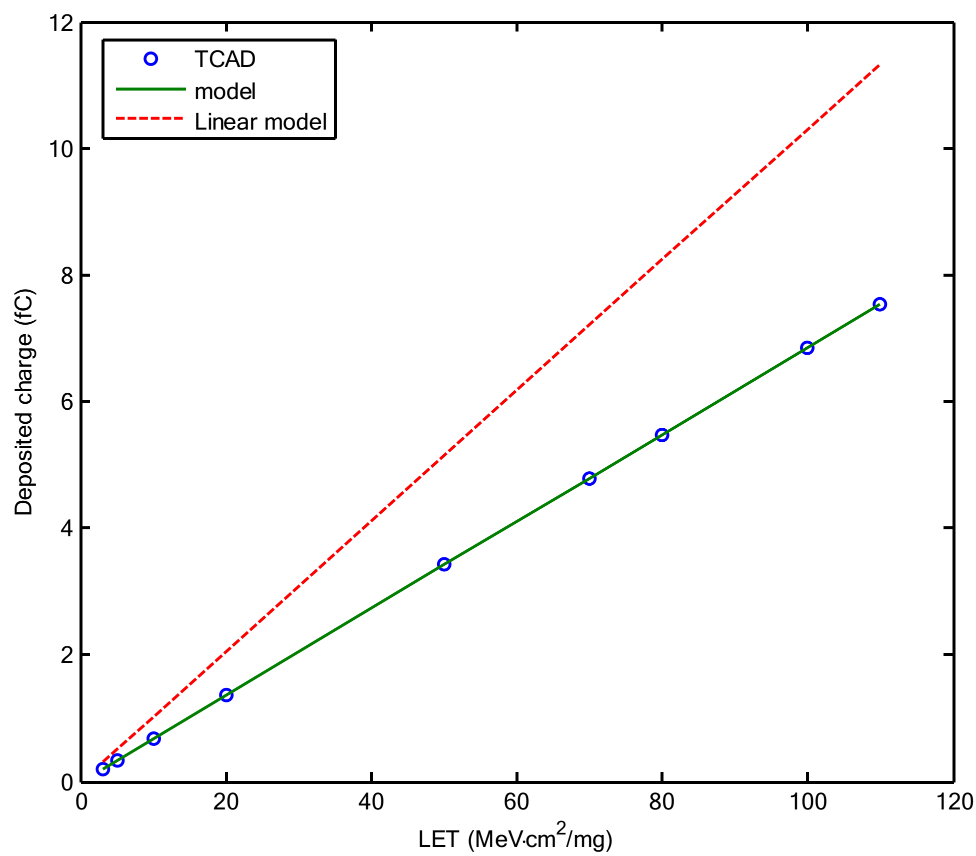


Fig. 6 Deposited charge at different LET

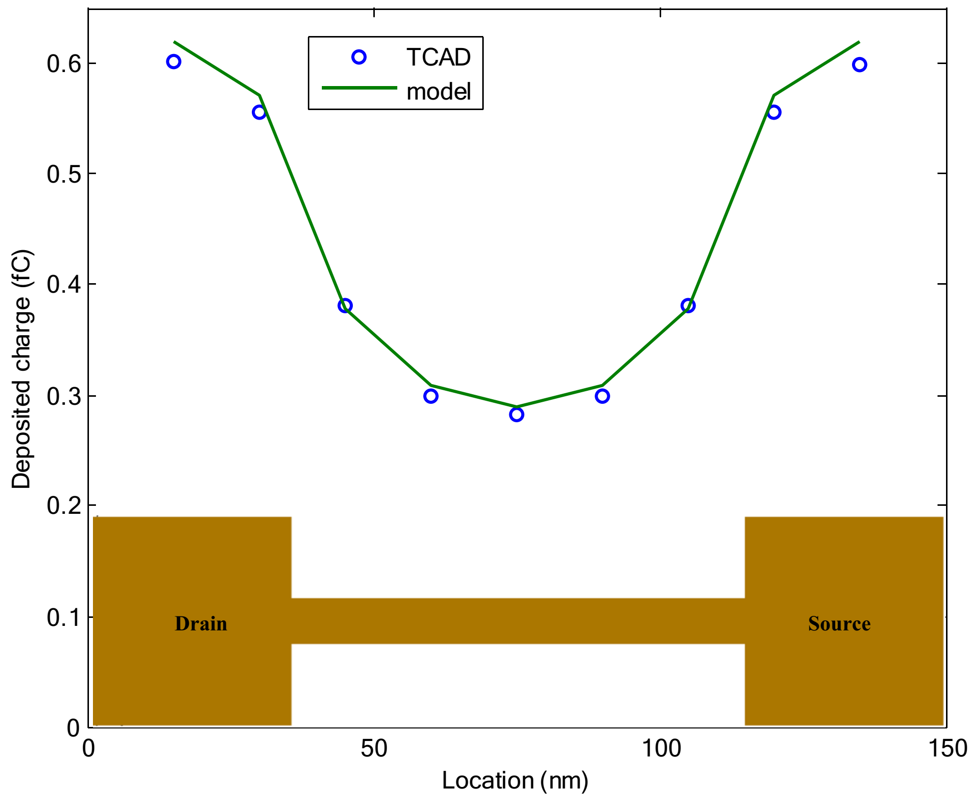


Fig. 7 Deposited charges at different hit locations

The section of SEMCY consists of a semicircle and a rectangle. The bottom ends of the rectangle are rounded into the section of ROUD. The parameters are set as the following. The width of the device (W_{Fin}) is 10 nm, the height H_{bul}, H_{tri}, H_{Fin} is 20.7 nm, 36 nm, 18 nm, respectively. The parameter R_{bul}, W_{step}, W_{R}, H_{R} is 6 nm, 2 nm, 4 nm, 4 nm, respectively. The hit location and LET of the ion are the same as the above mentioned. Their deposited charges are obtained from TCAD and the proposed model, shown in Fig. 10. Compared with TCAD, the relative error of the predicted deposited charge from the presented model for these structures is 1.51%, 2.60%, 3.10%, 1.83% and 1.42%, respectively. It is also concluded that the proposed model presents a good agreement with TCAD for different structures with the average relative error 2.09%. The proposed model is also very efficient. The CPU time for the above mentioned cases is less than 30 μs on a 3.4 GHz Inter(R) Core(TM) i5-7500 machine, while the time of TCAD simulation is more than 3 h. The presented model can achieve 8-9 orders of magnitude speedup over TCAD simulation.

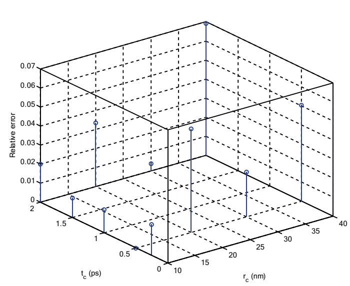


Fig. 8 Effects of radius and time on deposited charge

Considering the incidence of 30 MeV protons into the silicon and different energies laser induced charge deposition in 50 nm SOI nMOS transistor, the deposited charge from the proposed model is compared with the results of Ref [21] and Ref [4], shown in Fig. 11. The deposited charge is calculated by an electron-hole pair simulated energy (e.g. 3.6 eV) dividing into the deposited charge and then multiplying it by the electronic charge. The characteristic radius and the decay time of the model are 75.2 nm, 3.2ps, respectively. It can be found that the model presents a good agreement with the results of Ref [21] and Ref [4]. The average relative errors of the deposited charge from the model are 5.51%, 7.76% compared with Ref [21] and Ref [4], respectively.

Fig. 9 Cross-sections for different structures of FinFET

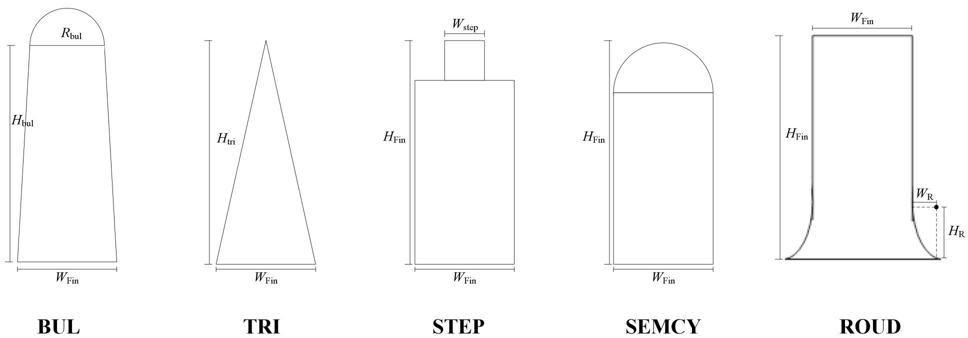


Fig. 10 Deposited charges for different structures

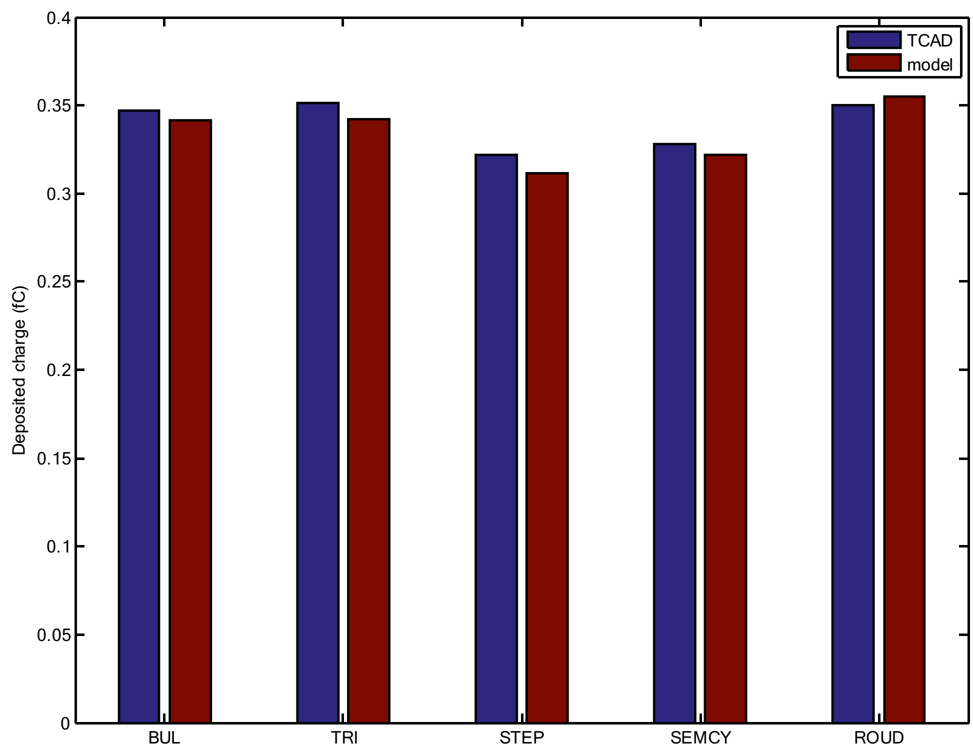
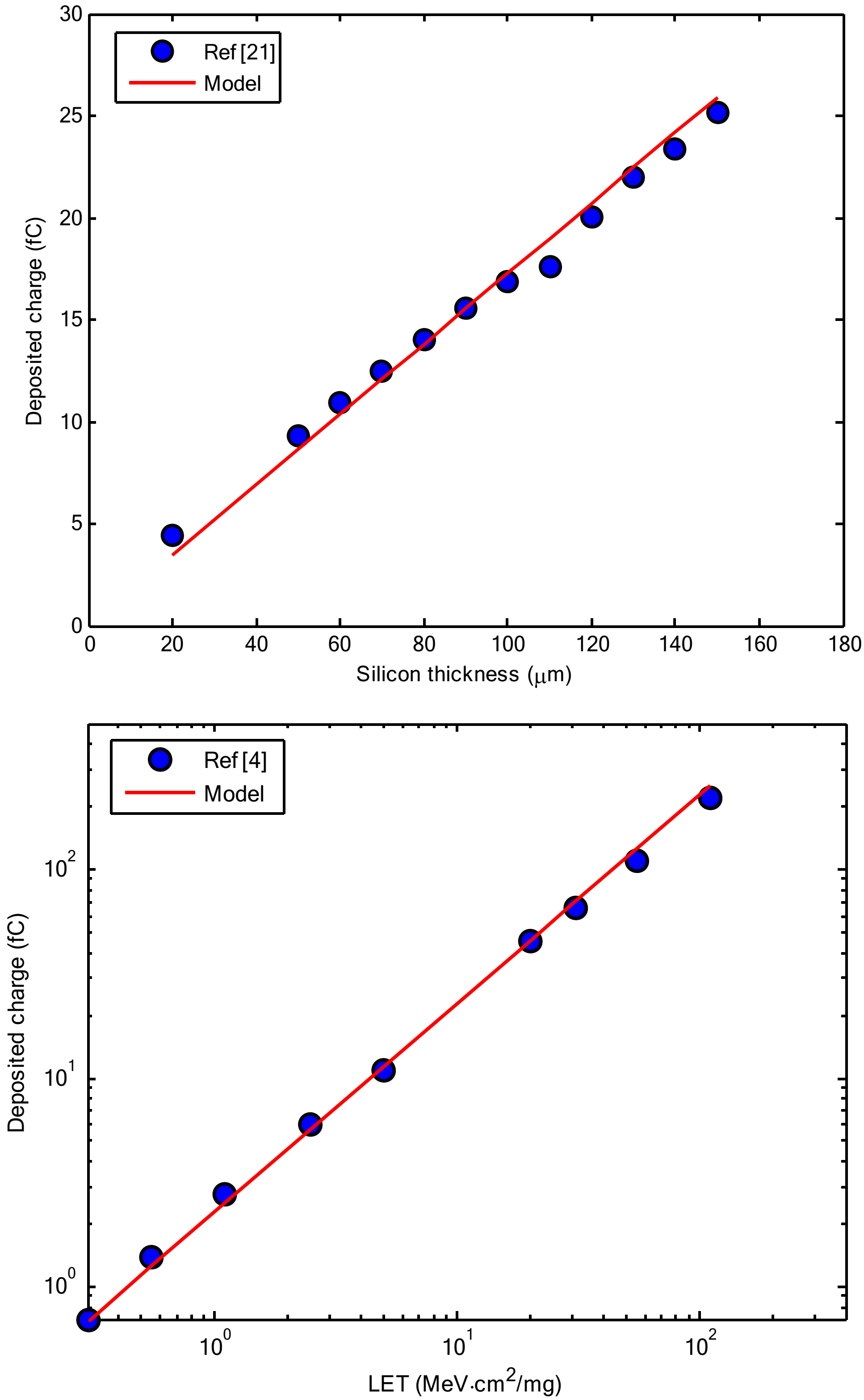


Fig. 11 Deposited charges of various thickness and LET



5 Conclusion

With device feature size scaled down, the size of the device and the sensitive volume of the particle strike reduce. It is very important taking into account the bipolar amplification to obtain an accurate deposited charge estimate. A linear dependency on LET of the particle and silicon film thickness has been always used to evaluate the deposited charge. However, it will bring large error when the deposited charge of nano-scaled FinFET is calculated by using the linear model. Actually, the deposited charge is affected by many factors, such as, LET, sensitive volume, and so on. The paper presents an accurate analytical model for the deposited charge in 14 nm SOI FinFET based on radiation-induced generation rate model. The deposited charge model depends on LET, volume of particle hit, characteristic radius and decay time of Gaussian function. The curve fitting tool and GA are performed to optimize the proposed model. The deposited charge dependence on LET, hit location, characteristic radius, decay time and structure is tested for the presented model. The results indicate that the proposed model presents a good agreement with TCAD. Compared with the linear model, the presented model has a significant accuracy with an average error 0.002% for LET ranging from 3 to 110 MeV•cm^2/mg. The effects of characteristic radius and time and sensitive volume on the deposited charge are also analyzed. For the sensitive volume, the model agrees well with TCAD with an average relative error 1.40% and max relative error 2.72%, respectively. As the characteristic radius and time reduce, the relative error between TCAD and the model presents the reduction trend. These results validate that the proposed model is efficient and accurate.

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Availability of Data and Material All data generated or analyzed during this study are included in this published article.

Declarations

Conflicts of Interest There is no conflict interest relevant to this manuscript, and manuscript is approved by all authors for publication in *Journal of Electronic Testing.*

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