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Effective Radiation Damage Models for TCAD Simulation of Silicon Bipolar and MOS Transistor and Sensor Structures

Konstantin Petrosyants, Maxim Kozhukhov and Dmitry Popov
National Research University Higher School of Economics (Moscow Institute of Electronics and Mathematics), 34 Tallinskaya str., 123458, Moscow, Russia
E-mail: kpetrosyants@hse.ru

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Abstract: The special library of radiation damage models for physical parameters and electrical characteristics of bipolar and MOS transistor and sensor structures taking into account neutron, gamma and proton irradiation is developed and built-into Sentaurus Synopsys software tool. For different BJTs/HBTs, MOSFETs and radiation sensors the good agreement to simulated and experimental electrical characteristics is achieved. The RMS error is not more than 10-20 %.

Keywords: Bipolar and MOS transistors, Radiation sensors, Neutron, Gamma, Proton irradiation, Radiation induced device parameter degradation, Device modeling, TCAD software.

1. Introduction

The electronic devices employed in spacecraft, high-energy physics, RF and telecommunication, radiation measurement in technique and technology, diagnostics in medicine, military and other applications are subjected to different types of irradiation (neutrons, electrons, gamma rays, protons, heavy particles and others). However, the significant number of defects generated in semiconductor device structures after irradiation attracts the degradation of device parameters and increases the complexity of the design phase before the devices even have been fabricated.

To facilitate this problem the special strategy “radiation hardened by design” is used. It is realized at two levels: device scheme and modeling.

At the scheme level the hierarchy of bipolar and MOS components, circuits, systems on chip is introduced and built-into the device scheme. All these elements carry out the functions of sensing, measuring, control and monitoring of radiation influences and electrical regimes to provide the reliable operation range of electronic device under irradiation conditions.

At the modeling level the TCAD (Technology Computer-Aided Design) programs are used to predict the radiation induced degradation of characteristics of electronic components with different geometry and/or operation conditions. The increasing knowledge of radiation induced defects received in recent years allows implementing the physical models with realistic defect parameter sets into the TCAD software tools. So the TCAD device simulation becomes the integral part of every IC and/or sensor system chip development project taking into account radiation influence.

2. State-of-the-art

The BJT/HBT [1-3], MOSFET [4-7] and special bipolar and MOS radiation sensor [8-11] structures were simulated with respect to radiation influence. The analysis of published works shows that in most projects for BJTs/HBTs and MOSFETs the universal commercial TCAD software tools Sentaurus Synopsys [12] and ATLAS Silvaco [13], also the special rad-oriented system Cagenda [14] were used. For bipolar and MOS radiation sensors and dosimeters the software tools Geant [15], FLUKA [16], FOTELP [17], and PENELOPE [18] were used to simulate the interactions of particles and/or radiation with a given materials. In all mentioned simulators, only gamma and single events models demonstrate the satisfied results agreed with measurements. Moreover the investigations demonstrate that in many cases the presently available gamma radiation models lead to significantly different results especially for novel device structures. In several works the authors have used the special fitting procedure of defect parameter set to correct the simulated results [19]. It is usually performed manually due to the complexity and the corresponding time consumption of the simulation [11]. So further work is need to increase the accuracy and efficiency of the device simulation taking into account gamma radiation effects.

Unfortunately, the radiation damage models for neutrons and protons used in the different version of TCAD device simulators are incomplete. For silicon devices subjected to neutron or proton irradiation not only ionization but displacement damage effects must be taken into account.

In this work, we try to solve the problems mentioned above[1]. The set of effective radiation damage models for gamma, neutron and proton irradiation is developed and included into TCAD Sentaurus tool as a complete library. It is very handy for the device designers to have a full set of radiation models concentrated in one software tool instead of the set of models distributed to the different version of TCAD tools.

3. TCAD-RAD Subsystem

In our previous work [20], the universal TCAD-RAD subsystem was developed. It consists of two parts: standard Sentaurus Synopsys software core [12] and the special library of radiation models for physical parameters and electrical characteristics of BJT/HBT and MOSFET structures taking into account neutron, gamma-rays and proton irradiation (see Fig. 1). Note that the models for neutrons and protons were not included in TCAD formerly.

The LIBRARY consists of 4 segments:

Common controller carries two functions:

1) Selection for given type of irradiation the set of radiation-dependent physical parameters and their models which are responsible for device electrical characteristics degradation;

2) Conversion the energy or dose rate of particles into total dose D and/or fluence Φ;

Gamma radiation models are based on carrier ionization effects. The adequate models of radiation-dependent parameters (N_{ox}, N_{it}, S_0, μ) for novel Si BJT/ SiGe HBT and for MOSFET/SOI MOSFET with high-k gate oxide structures are added [21];

Neutron models are based on displacement effects. The adequate models of radiation-dependent parameters (τ, μ, n/p) are included. They take into account the dependencies on neutron fluence, doping levels, injection effectivities of electrons and holes [22];

Proton model was developed by authors [23]. It is based on additive approach combined the ionization and displacement effects influence on device structure.

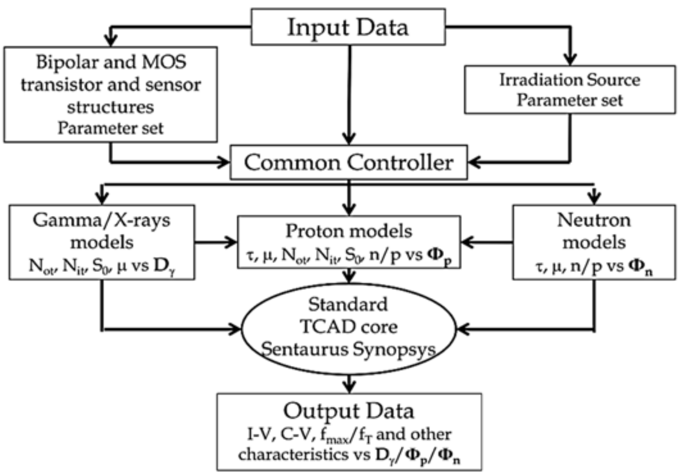

Fig. 1. TCAD-RAD Subsystem taking into account gamma, neutron, proton irradiation influence on electrical device characteristics.

[1] The radiation models based on Monte-Carlo approach 0-0 are not discussed in this paper. They are the subject of original research.

4. Library of Radiation Models

The basic physical parameters describing the carrier transportation (μ_n, μ_p), surface (S_n, S_p) and volume (R_n, R_p) recombination, charge collection in bulk (Q_n, Q_p) and oxide (Q_{ox}) volumes, and on semiconductor/oxide interfaces (Q_{it}) are radiation-dependent.

So the library of physical parameter models for different types of irradiation is the key element of the TCAD-RAD software tools. In the wide-used commercial TCAD tools [12-13] the library of radiation models is poor and not always applicable for practical requirements.

In this work the version of Synopsys Sentaurus RAD tool with the complete library of radiation-dependent physical parameter models valid for gamma rays, neutron and proton irradiation is presented (see Fig. 2).

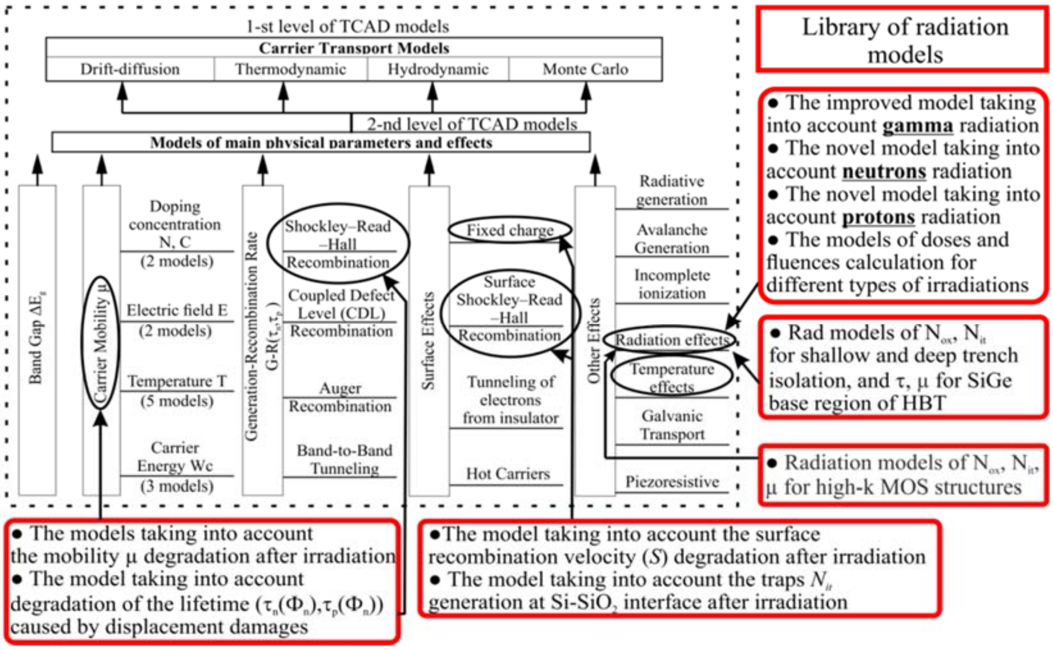

Fig. 2. Radiation models of device electro physical parameters included in the TCAD-RAD system.

a. Gamma radiation models. Irradiation of BJTs/HBTs, bulk/SOI MOSFETs and bipolar and MOS sensor structures by gamma-rays results in the generation of electron-hole pairs in bulk silicon regions; the increase of surface recombination velocity (S) and volume recombination rate (R); creation of traps at the $Si\text{-}SiO_2$ interfaces (N_{it}); collection of positive charge in the gate/STI/BOX oxide (Q_{ox}); decrease of carrier mobility (μ).

For BJTs/HBTs it leads to base and collector leakage currents increase, current gain and maximal/cut-off frequencies degradation; for MOSFETs – to gate/drain leakage current increase, threshold voltage (V_{th}) and subthreshold slope (S) degradation.

In the commercial TCAD version only one degradation factor – the space charge in SiO_2 oxide (Q_{ox}) dependence on gamma dose is taken into account correctly.

Therefore, in order adequately to take into account all the factors caused by gamma radiation influence on the characteristics of Si BJTs/SiGe HBTs and bulk/SOI MOSFETs it is necessary additionally to introduce into TCAD tool the physical expressions for the concentration of traps N_{it} and the surface recombination velocity S at the interfaces $Si\text{-}SiO_2$ depending on the absorbed dose of gamma radiation $D\gamma$:

$$N_{it}(D_\gamma) = a_{it} \cdot D_\gamma^{\,b_{it}}, \qquad (1)$$

where a_{it}, b_{it} are the fitting parameters that have different values for EB spacer and STI/DTI surfaces.

The model parameters a_{it}, b_{it} are defined from experimental dependencies of $Si\text{-}SiO_2$ interface traps concentrations on absorbed dose D_γ [24] (see Fig. 3).

The surface recombination velocity is proportional to the density of traps at $Si\text{-}SiO_2$ interfaces [25-26]:

$$S(D_\gamma) \cong \sigma v_{th} N_{it}(D_\gamma), \qquad (2)$$

where $\sigma = \sqrt{\sigma_n \cdot \sigma_p}$, σ_n, σ_p are the capture cross-sections for electron and hole traps; v_{th} is the thermal velocity.

The modified dependence on radiation dose for the charge carrier mobility μ_{eff} was introduced. The model takes into account the mobility decrease caused by radiation induced surface states on the SiO_2/Si interfaces:

$$\mu_{\text{eff}}(\text{D}) = \frac{\mu_0}{1+\alpha N_{it}(D)}, \qquad (3)$$

where μ_0 is the pre-rad mobility, $N_{it}(D)$ is the silicon-oxide interface trap density, α is a fitting parameter.

Note that the developed models of radiation-dependent parameters (N_{it}, S, Q_{ox}, μ) for novel deep submicron SiGe HBT [23] and high-k gate SOI MOSFET [21], [27] structures differ from the corresponding models for conventional BJT and MOSFET structures. For example in Fig. 4. the radiation-dependent parameter N_{it} at HfO_2, BOX and STI interfaces of 45 nm MOSFET with HfO_2 gate oxide is presented.

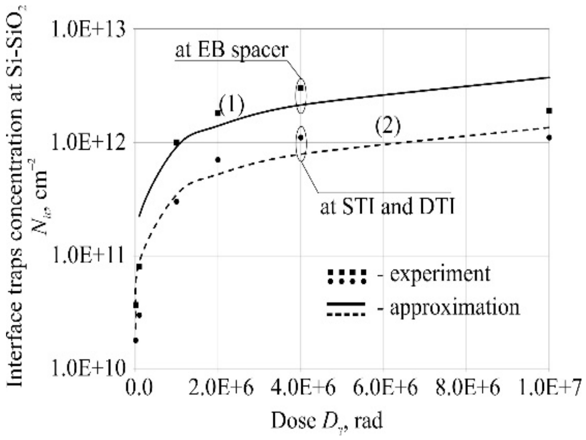

Fig. 3. Dependence of traps concentration at Si-SiO_2 interfaces of EB spacer and shallow and deep trench isolation on absorbed dose D_γ.

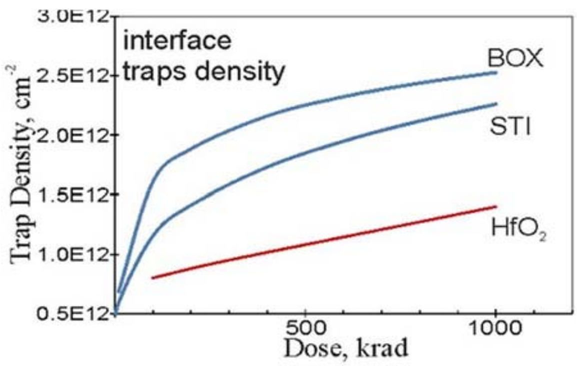

Fig. 4. Trap densities N_{it} at different interfaces of 45 nm MOSFET with HfO_2 gate oxide structure.

The dependences of recombination velocity $S(D_\gamma)$, the traps concentration $N_{it}(D_\gamma)$ at Si-SiO_2 interfaces of EB spacer and STI/DTI and carrier mobility $\mu(D_\gamma)$ on absorbed dose were included in the Synopsys Sentaurus using the physical model interface (PMI).

b. Neutron radiation models. The silicon physical parameters, such as the lifetime of the minority charge carriers (τ), mobility (μ) and the concentration of nonequilibrium charge carriers (n/p), are degraded after impact of neutrons in consequence of the displacement defects formation [28]. The decrease of the minority carrier lifetime is the main factor that influences on the device characteristics. For BJTs/HBTs it is the increase of base current, reduction of the current gain and cut-off/maximum frequencies.

For MOSFETs it is the transconductance g_m and saturation current I_{sat} decrease, and the shift of threshold voltage ΔV_{th}.

In all the commercial versions of TCAD the minority carrier lifetimes τ_n, τ_p are not depended on radiation influence.

So for simulation of minority carrier lifetime decrease due to displacement effects after neutron irradiation the following equation was introduced:

$$\frac{1}{\tau_\Phi} = \frac{1}{\tau_0} + \Phi_n \cdot K_\tau, \qquad (4)$$

where τ_0, τ_Φ are the minority carrier lifetimes before and after irradiation; Φ_n is the neutron fluence; K_τ is the coefficient of radiation-induced alteration of carrier lifetime.

It was shown experimentally that for modern npn and pnp Si BJTs/SiGe HBTs the parameter K_τ in (4) depends on the doping concentration N_{dop} and the injection efficiency $\delta = n_{min}/n_{maj}$ (where n_{min}, n_{maj} are the minority and majority carrier concentrations) [29-30]. Therefore, the special equation for K_τ (δ, N_{dop}) was introduced [23].

The expression (4) for the lifetime with alteration coefficient K_τ (δ, N_{dop}) was added to the standard Shockley-Read-Hall recombination model using the PMI. Along with the radiation effects, the developed model (4) takes into account the dependence of the lifetime on the temperature. The combined influence of radiation and temperature is the important factor for modern Si BJTs and SiGe HBTs working in harsh conditions.

In Fig. 5 the current gain damage factor $d = \beta(\Phi_n)/\beta(0)$ for the SiGe HBT 8WL after neutron irradiation is presented. It is seen that the improved model (4) provides better results than the classic Gregory model [31].

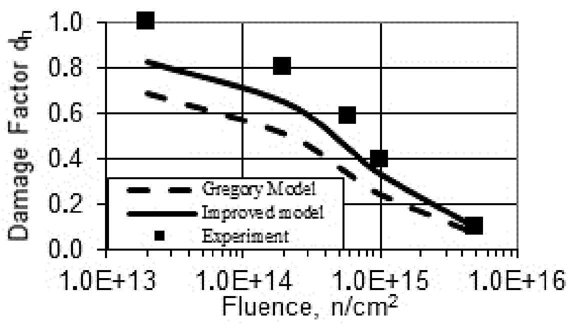

Fig. 5. The current gain damage factor for the SiGe HBT 8WL after neutron irradiation.

c. Proton radiation model. The proton irradiation involves simultaneously the ionization and displacement damages in semiconductor device structures. Conformably to TCAD modeling of BJT/HBT and MOSFET structures the radiation model for protons was first developed in our works [23], [32]. It is based on additive approach combined two models: model for gamma rays describing the ionization effects and model for neutrons describing the displacement effects. Both models were discussed above.

For the correct modeling of the Si BJT/SiGe HBT and MOSFET characteristics, it is necessary to determine the values of the neutron fluence Φ_n and the gamma dose D_γ equivalent to proton fluence Φ_p. For this purpose, the following equations were used:

$$\Phi_n = K_D \cdot \Phi_p \, ; \; D_\gamma = K_{I\_p}(E) \cdot \Phi_p \, , \qquad (5)$$

where $K_D = \delta_{cp}(E)/\delta_{cn}(E)$, K_D is the proportion coefficient; $\delta_{cp}(E)$, $\delta_{cn}(E)$ are the energy-dependent non-ionization energy losses (NIEL) for protons and neutrons respectively [28]; $K_{i\_p}(E)$ is the proton linear energy transfer (LET) in material with the same energy [33]. The special converter was developed and included in model library for realization of the procedure (5).

5. Simulation Results

The potentialities of TCAD-RAD subsystem are illustrated by means of examples of Si BJTs/ SiGe HBTs and SOI MOSFETs which are used for rad-hard BiCMOS ICs design (see Fig. 6 – Fig. 15).

a. Neutron irradiation. The radiation-hardness of two devices after neutron irradiation was analyzed with developed model. The discrete Si npn BJT 2T378 with following parameters: current gain $\beta = 70$, cut-off frequency $f_T = 1.9$ GHz and maximal frequency $f_{max} = 5.1$ GHz is used in microwave amplifier hybrid ICs. The BJT structure for TCAD simulation is presented in Fig. 6.

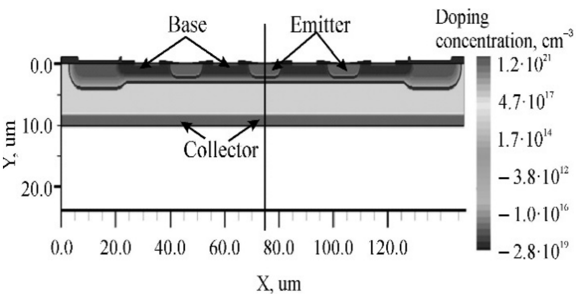

Fig. 6. TCAD interpretation of the Si BJT 2T378 structure.

The 2 um p-MOSFET (L = 2 um, W = 72 um, $t_{ox} = 30$ nm, $t_{Si} = 80$ nm, $t_{BOX} = 400$ nm, $N_{ch} = 2.4 \cdot 10^{16}$ cm^{-3}) was used as a part of the detector for strong neutron background in high-energy physics experiments at CERN [34]. The MOSFET structure for TCAD simulation is presented in Fig. 7.

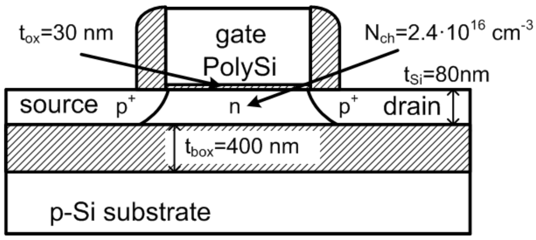

Fig. 7. Cross-section of 2 um SOI p-MOSFET (L/W = 2/72 um, t_{ox} = 30 nm, t_{Si} = 80 nm, t_{BOX} = 400 nm).

In Fig. 8 experimental and simulated results for the current gain of the Si BJT characteristics before and after neutrons irradiation are shown. It is seen that the radiation hardness is limited by fluence $\Phi_n = 4 \cdot 10^{13}$ 1/cm^2 at which the pick values of current gain decrease twice.

In Fig. 9 experimental and simulated I_dV_g characteristics in OFF regime (V_{ds} = 50 mV) for the 2 um SOI p-MOSFET are shown. It is seen that the threshold voltage shift is ΔV_{th}=1.2 V, and the drain leakage current is not sensitive to neutron irradiation fluence up to $2.2 \cdot 10^{14}$ cm^{-2} in OFF regime.

For both examples the simulation error is not more than 15 %.

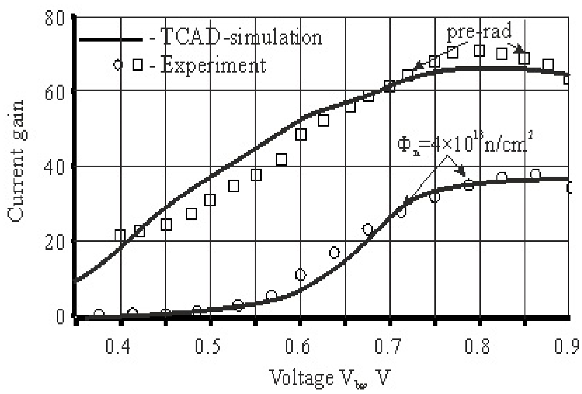

Fig. 8. Current Gain of Si BJT 2T378 with f_T/f_{max}=2.0/5.1 GHz after neutron irradiation.

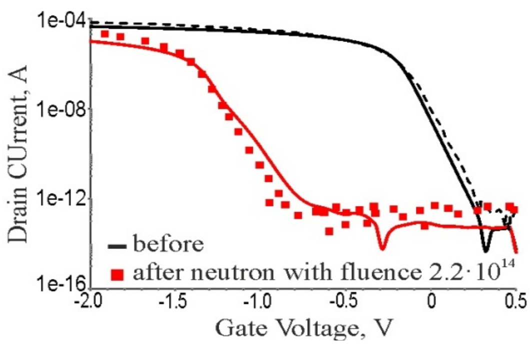

Fig. 9. I_dV_g characteristics of 2 um SOI p-MOSFET after neutron irradiation with fluence $2.2 \cdot 10^{14}$ cm^{-2}.

b. Gamma irradiation. Three examples illustrate the results of the radiation hardness modeling after gamma irradiation for modern deep submicron devices with bipolar and MOS structures.

The SiGe HBT with parameters $\beta = 450$, $f_T = 100$ GHz, $f_{max} = 200$ GHz fabricated by 0.13 µm BiCMOS 8HP technology was investigated [35]. The Gummel I-V characteristics of I_b and I_c for different gamma doses are presented in Fig. 10 and confirm the experimentally observed fact that in SiGe HBTs only the base current is growing after irradiation; at the same time the collector current does not change their values. It is seen a good agreement between simulated and measured characteristics in dose range up to 30 Mrad.

The 45 nm high-k SOI n-MOSFET (W = 0.45 um, $t_{HfO2} = 2$ nm) before and after gamma irradiation [36] was modeled (Fig. 11). It is seen that the SOI MOSFET drain leakage current is growing after radiation influence. The total I_d leakage current is caused basically by parasitic STI channel induced by gamma irradiation. The maximum value of I_{dleak} is limited as 1.0 µA, so the transistor radiation hardness is limited by dose 1.0 Mrad.

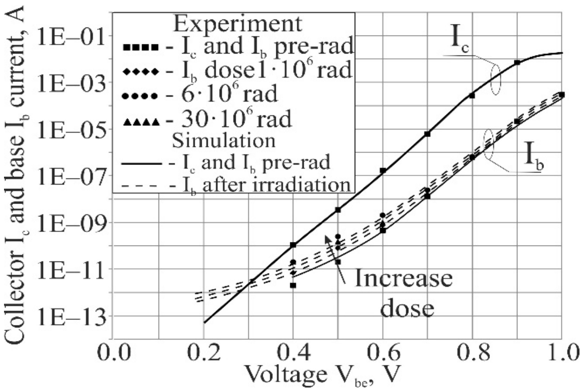

Fig. 10. Gummel characteristics of I_b, I_c for SiGe HBT 8HP after gamma irradiation.

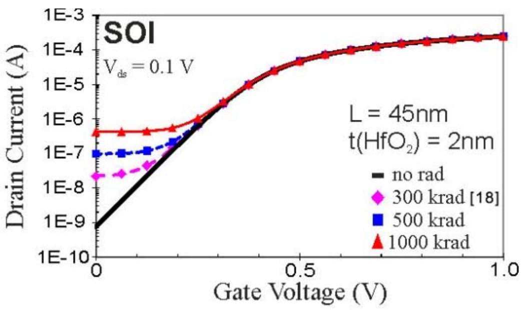

Fig. 11. I_dV_g characteristics of 45 nm SOI high-k MOSFET after gamma irradiation (W=0.45 um, t_{HfO2}=2 nm).

The third object of gamma influence investigation is CMOS image sensors. For this purpose the thick oxide field effect transistors (FOXFET) are used (see. Fig. 12). The n-FOXFET structure with L/W=0.84/300 um, t_{ox}=150 nm was modeled before and after gamma irradiation in ON and OFF regimes. The values of interface state density N_{it} and trapped charge density N_{ot} were taken from experimental work [37]. In Fig. 13 FOXFET subthreshold characteristics are presented. For image sensors the most critical parameter is the dark current. It is seen that the drain leakage current increases significantly with absorbed dose, so the maximal value of gamma dose is limited by 100 krad.

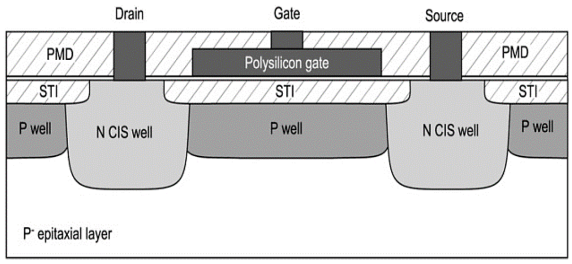

Fig. 12. Cross-sectional view of n-FOXFET structure with L/W=0.84/300 um and thick STI gate oxide t_{ox}=150 nm.

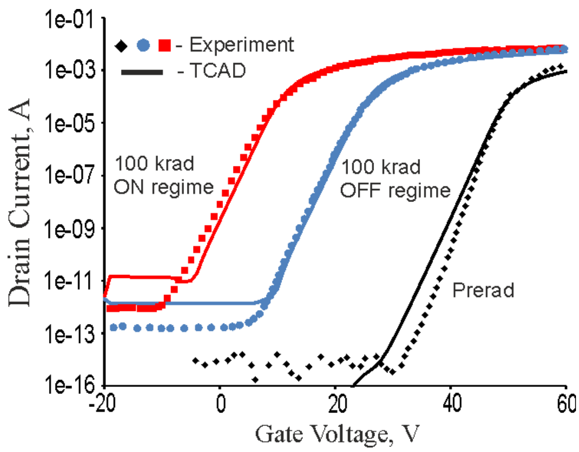

Fig. 13. FOXFET subthreshold characteristics before irradiation and after 100 krad.

c. Proton irradiation. Fig. 14 and Fig. 15 illustrate the results obtained using the developed models taken into account proton irradiation effects.

The 180 nm SiGe HBT with $\beta = 250$, $f_T = 120$ GHz, $f_{max} = 100$ GHz [38] was selected for proton radiation hardness investigation with the Synopsys Sentaurus. The comparison of simulated results with experimental data for current gain is presented in Fig. 14 for the irradiated and non-irradiated device. Using 50 % current gain fall down criteria the proton irradiation upper limit is defined as $5 \cdot 10^{13}$ 1/cm^2.

In Fig. 15 the measured [39] and simulated I_dV_g characteristics of 0.25/8 um SOI n-MOSFET before and after proton irradiation are presented. The protons cause a stronger impact than gamma radiation so in comparison with Fig. 11 for gamma irradiation we can see in Fig. 15 not only leakage current increase but also threshold voltage shift. As a result the transistor radiation hardness in this case is limited by dose 500 krad.

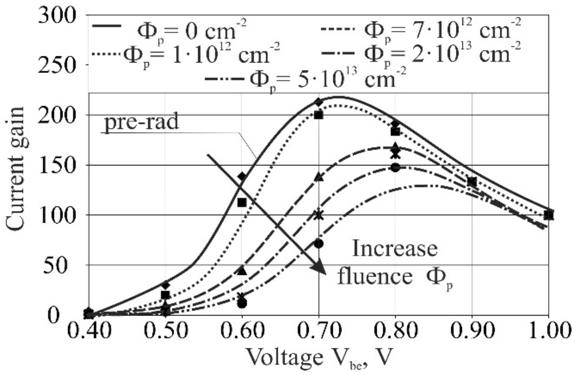

Fig. 14. Current Gain of SiGe HBT 7HP with A_E=0.2x4.52 um^2 f_T/f_{max}=150/180 GHz after proton irradiation.

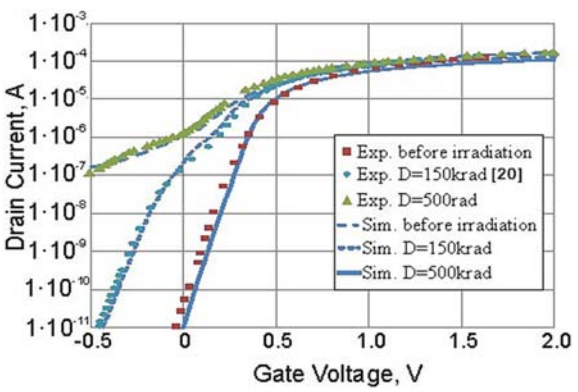

Fig. 15. SOI n-MOSFET characteristics after proton irradiation (L/W = 0.25/8 um, t_{ox} = 7.5 nm, t_{Si} = 50 nm, t_{BOX} = 190 nm).

6. Conclusions

The universal and complete library of radiation-dependent physical parameter models for Si BJT/SiGe HBT, bulk/SOI MOSFET and bipolar and MOS detector structures simulation taking into account neutron, gamma and proton irradiation was developed in the framework of Synopsys Sentaurus TCAD.

The following novelties were introduced into commercial TCAD physical model library:

1) New segment of neutron radiation models which include: improved equations for electron and hole carrier lifetime taken into account the dependence on neutron fluence, doping concentration and injection efficiency; improved equation for carrier mobility dependence on neutron fluence;

2) New segment of proton radiation model based on additive approach combined displacement and ionization damage mechanisms. Two partial models for neutrons and gamma rays are used to calculate simultaneously. The special converter was developed to determine the values of neutron fluence Φ_n and gamma dose D_γ equivalent to proton fluence Φ_p;

3) Segment of gamma radiation models was essentially improved:

- The modified dependence on dose for carrier mobility $\mu_{eff}(D_\gamma)$ was introduced;

- The surface recombination velocity $S(D_\gamma)$ for Si-SiO_2 interfaces was included;

- Approximations of experimental dependencies for traps concentrations $N_{it}(D_\gamma)$, $N_{ot}(D_\gamma)$ at the Si-SiO_2/Si-HfO_2 interfaces and in bulk volumes separately for gate oxide, p-n spaces, BOX, STI/DTI structures were introduced for modeling of conventional bipolar and MOS transistors and sensors, modern deep submicron Si BJTs/SiGe HBTs and bulk/SOI high-k MOSFETs.

Good agreement between simulated and experimental I-V and f_T/f_{max} characteristics for all the devices was achieved. The simulation error is not more then 10-20 %.

The possibilities of TCAD-RAD subsystem with the developed radiation models were illustrated by means of examples of Si BJTs/SiGe HBTs, and bulk/SOI MOSFETs and bipolar and MOS sensors which were used for BiCMOS ICs design taking into account radiation influence.

Acknowledgements

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