Effects of gamma-ray radiation on channel current of the uniaxial strained Si nano-scale NMOSFET

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Abstract: An analytical model of channel current for the uniaxial strained Si nanometer NMOSFET has been developed with the degradation due to total dose irradiation taken into consideration. Based on this model, the numerical simulation has been carried out by Matlab, and the influence of the total dose on channel current was simulated. Furthermore, to evaluate the validity of the model, the simulation results were compared with experimental data, and good agreements were confirmed. Thus, the proposed model provides good reference for research on irradiation reliability of uniaxial strained Si nanometer NMOSFET.

Keywords: uniaxial strained Si, nano NMOSFET, total dose, channel current

Classification: Electron devices, circuits and modules

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1 Introduction

Strained technology has been widely used to improve the performance of Si CMOS devices, and strained-Si technologies have caught much attention as device size is scaling down [1, 2], especially in the applications of strained IC under the total dose irradiation. Hence, researches on the irradiated characteristics and the radiation hardening technique are of great significance [3, 4]. Channel current characteristic is an important foundation for the analysis of DC, transient, AC small signal, noise of the uniaxial strained Si nanometer NMOSFET device and circuit. A number of papers reported about current of the MOS device under the radiation effect [5, 6], which were based on experiment but lack of mature theory. Moreover, the channel current model of the uniaxial strained Si nanometer NMOSFET has rarely been reported under the total dose irradiation. In this paper, the channel current model of the uniaxial strained Si nanometer NMOSFET were proposed due to the total dose radiation.

2 Channel current model

The schematic structure of uniaxial strained Si NMOSFET is shown in Fig. 1.

Fig. 1. Structural diagram of uniaxial strained Si nanometer NMOSFET device.

The threshold voltage model of the uniaxial strained Si nanometer NMOSFET devices after considering the quantum effect and total dose radiation effect is calculated by [7]:

$$V_{th,ssi} = V_{FB,ssi} - V_{DIBL} + \frac{\psi_{th,ssi} + \left[1 - 2 \frac{\sinh(\frac{L}{2l})}{\sinh(\frac{L}{l})} \right] \frac{qN_a}{\epsilon_{si}} l^2 - \frac{\sinh(\frac{L}{2l})}{\sinh(\frac{L}{l})} (2\psi_{bi,ssi} + V_{ds})}{\left[1 - 2 \frac{\sinh(\frac{L}{2l})}{\sinh(\frac{L}{l})} \right] \left[1 - \frac{6}{W_d^2} l^2 \right]} \quad (1)$$

where L , l and W_d are channel length, characteristics scaling length and the maximum width of the depletion-layer, respectively. $V_{FB,ssi}$, V_{DIBL} , $\psi_{th,si}$, $\psi_{th,ssi}$, N_a , V_{ds} and ϵ_{si} are flat band voltage, drain-induced barrier lowering, threshold surface potential of relaxation and strained silicon, doping concentration in the channel, drain voltage and dielectric constant of silicon, respectively. $V_{FB,ssi}$ can be modified due to total dose radiation effect, which is rewritten as:

$$V_{FB,ssi} = \left(\frac{\phi_M - \phi_{ssi}}{q} \right) - \frac{(Q_{ox} + qN_{ot} - qN_{it})}{C_{ox}} \quad (2)$$

where ϕ_M and ϕ_{ssi} are the work function of metal gate and the substrate of strained Si, respectively. Q_{ox} , C_{ox} , N_{ot} and N_{it} are the initial density of surface charge and capacitance in the oxide layer, oxide-trapped charge and interface-trap charge, respectively.

Because the channel length is the same magnitude as or less than mean free path of the channel carrier, which are not subject to scattering for the small size device. Therefore, the formation speed is too fast, and the current caused by the velocity overshoot effect can't be ignored. Therefore, the equation of channel current for uniaxial strained Si nanometer NMOSFET can be obtained by $I_{ds} = (Wt_{ssi})J$, which is expressed as:

$$I_{ds} = Wt_{ssi}J = Wt_{ssi} \left[qu_{n,ssi}n(x)E(x) + qu_{n,ssi}n(x)\delta(E) \frac{dE(x)}{dx} \right] \quad (3)$$

where $\delta(E) \approx 2/3 v_{sat}\tau_w$ is energy relaxation length. v_{sat} , J , W , $u_{n,ssi}$, $n(x)$ and t_{ssi} are saturated velocity, current density and gate width, electron mobility, concentration and thickness of strained silicon, respectively. $E(x)$ and τ_w are electric field and energy relaxation time, which varies with the magnitude of stress [8]. The electrons are confined to the surface of the quantum well channel, and its concentration can be obtained as:

$$n(x) = C_{ox}(V_{gs} - V_{th,ssi} - V(x))/qt_{ssi} \quad (4)$$

where $V(x)$ is the voltage drop along the channel direction. V_{gs} is gate voltage. For the strong electronic field, u_{ssi} is expressed as [9]:

$$u_{ssi} = u_{0,ssi} \left(1 + \frac{u_{0,ssi}}{2v_{sat}} E(x) \right)^{-1} \quad (5)$$

where $u_{0,ssi}$ is the low field electron mobility.

The influence of γ -ray total dose radiation effect on mobility can be obtained by [10]:

$$\frac{u_{n,ssi}}{u_{ssi}} = \frac{1}{1 + a_{it}N_{Si-H}} = 1/[1 + a_{it}N_{Si-H} \times (1 - e^{-\frac{1}{2}\sigma_{DH}\sigma_{pt}N_{DH}K_g f_y t_{ox}^2 D't})] \quad (6)$$

where the total dose $D = D't$, K_g and a_{it} are irradiation time, the number of electron-hole pairs (EHP) generated per unit dose and an empirical constant related to interface state density, respectively. f_y , σ_{pt} and N_{DH} are the hole yield as a function of oxide electric field, the hole capture cross section and the trap concentration of hydrogen, respectively. σ_{DH} , N_{Si-H} and t_{ox} are the trapped cross section of holes with hydrogen traps the silicon dangling bond density of hydrogen passivation and oxide thickness, respectively. When the speed is too fast, $(dE(x))/dx = \theta V_{ds}/L^2$, θ is related to the technology, and its value is about 0.2.

Substituting $E(x) = (dV(x))/dx$ in Eq. (5), the integral analysis of the Eq. (3) is performed, and the channel current I_{ds} (linear region and saturation region) of the uniaxial strained Si nanometer NMOSFET device after considering the velocity overshoot effect of small-scale device and total dose radiation effect can be given by:

$$I_{ds} = \frac{Wu_{n,ssi}C_{ox}}{L\left(1 + \frac{u_{n,ssi}V_{ds}}{2v_{sat}}\right)} \times \left(\left((V_{gs} - V_{th,ssi})V_{ds} - \frac{V_{ds}^2}{2} \right) \times \left(1 + \frac{\theta\delta(E)}{L} \right) + \frac{\theta^2\delta(E)}{12L} V_{ds}^2 \right) \quad (7)$$

$$I_{ds} = \frac{Wu_{n,ssi}C_{ox}}{L\left(1 + \frac{u_{n,ssi}(V_{gs} - V_{th,ssi})}{2v_{sat}}\right)} \times \left(\frac{1}{2} (V_{gs} - V_{th,ssi})^2 \left(1 + \frac{\theta\delta(E)}{L} \right) + \frac{\theta^2\delta(E)}{12L} (V_{gs} - V_{th,ssi})^2 \right) \quad (8)$$

When the device operates in the sub-threshold region, channel current is mainly dominated by diffusion current. Based on reverse charge of the sub-threshold region, sub-threshold current can be obtained by:

$$I_{ds} = \frac{W}{L} V_t u_{n,ssi} [Q_i(L) - Q_i(0)] \quad (9)$$

where V_t is the thermal voltage. $Q_i(0)$ and $Q_i(L)$ are electron areal density of source and drain in channel, respectively. When the device operates in the sub-threshold region, the surface potential from the source to the drain can be approximated as constant. By solving the Poisson equation, the surface potential is given by:

$$\varphi_s = \left(-\frac{\gamma}{2} + \sqrt{\frac{\gamma^2}{4} + V_{gs} - V_{th,ssi}} \right)^2 \quad (10)$$

where $\gamma = \frac{\sqrt{2q\epsilon_{si}N_a}}{C_{ox}}$, electron-sheet-density in channel is obtained by:

$$Q_i(X) = \sqrt{\frac{q\epsilon_{si}N_a}{2\varphi_s}} V_t \exp\left(\frac{V_{gs} - V_{th,ssi}}{nV_t}\right) \times \exp\left(-\frac{v(x)}{V_t}\right) \quad (11)$$

where $n = 1 + \frac{\sqrt{q\epsilon_{si}N_a}}{C_{ox}}$, thus sub-threshold current of the uniaxial strained Si nanometer NMOSFET device after considering total dose radiation effect is expressed as:

$$I_{ds} = u_{n,ssi} \frac{W}{L} \sqrt{\frac{q\epsilon_{si}N_a}{2\varphi_s}} V_t^2 \left[1 - \exp\left(-\frac{V_{ds}}{V_t}\right) \right] \times \exp\left(\frac{V_{gs} - V_{th,ssi}}{nV_t}\right) \quad (12)$$

3 Experiment

The device of uniaxial strained Si nanometer NMOSTET were irradiated with ^{60}Co γ -ray at a dose rate of 29 rad (SiO_2)/s at room temperature, with a gate bias of 1 V. Device parameters were measured in the dose range from 0.5 kGy to 2.5 kGy, using an HP4155B parametric analyzer. Drain voltage V_{ds} is equal to source voltage V_s ($V_{ds} = V_s = 0$). Measurement bias: $V_{gs} = 0-1$ V, scanning voltage $V_{step} = 0.05$ V, $V_{ds} = 50$ mV, $V_s = 0$ V. Based on proposed model, numerical simulation has been carried out by Matlab, and the influence of the total dose on channel current was simulated. Furthermore, stress distribution and electron mobility distribution of simulation are made for uniaxial strained Si nanometer NMOSFET using the

Sentaurus TCAD. Because of the expansion of the silicon nitride film deposited in the source, drain and gate, the strained in the channel is generated. Fig. 2 is the micrograph and schematic cross-section of uniaxial strained Si nanometer NMOSTET device. TiAl material is used for the gate electrode. The oxide layer is SiO₂ and HfO₂, the equivalent oxide thickness being 1 nm. The junction depth of source/drain region is 25 nm and the gate length is 50 nm.

Fig. 2. (a) Micrograph (b) cross-section of uniaxial strained Si Nano NMOSTET

As can be seen from the Table I, the threshold voltage drift of relaxed Si nanometer NMOSFET is similar to that of uniaxial strained Si nanometer NMOSFET. It can be inferred that the stress does not change when compared with the case before irradiation.

Table I. The threshold voltage shift of relaxation and uniaxial strained Si nanometer NMOSFET device under the absorbed dose.

Dose/KGy	0.5	1.0	1.5	2.0	2.5
$\Delta V_{th,si}/V$	-0.0352	-0.0403	-0.0410	-0.0415	-0.0431
$\Delta V_{th,ssi}/V$	-0.0354	-0.0405	-0.0408	-0.0417	-0.0428

4 Results and discussion

Fig. 3 shows stress distribution and electron mobility distribution of uniaxial strained Si nanometer NMOSFET device under the pre-irradiation and post-irradiation. From Fig. 3(b), as can be seen that electron mobility sharply decreases under the post-irradiation. As is well known, channel current is directly proportional electron mobility. Therefore, as can be inferred that channel current will decrease under the post-irradiation.

Fig. 3. (a) The distribution of stress (b) electron mobility of uniaxial strained Si nanometer NMOSFET device under the pre-irradiation and post-irradiation.

Fig. 4 illustrated the transfer and output characteristics of drain-source current under the different total dose radiation effect. From Fig. 4, as can be seen that channel current decreases with increasing irradiation dose due to electron mobility sharply decreases after irradiation. Moreover, the calculation results from the model are consistent with the experimental data, indicating the validity of our proposed model.

Fig. 4. Transfer and output characteristics under the total dose radiation effect.

Fig. 5 is change of drain current under irradiation. As shown in Fig. 5(a), we can see that Drain-Source current increases with increasing gate voltage, but Drain-Source current decreases under the post-irradiation. From Fig. 5(b), sub-threshold current increases under the post-irradiation due to induced oxide-trapped positive charge, which cause the device is more likely to open. Thus, the threshold voltage drifts and the sub-threshold current increases under the post-irradiation.

Fig. 5. (a) Results contrast of drain-source current from model and experiment (b) relationship between sub-threshold current and TID.

5 Conclusion

Based on the different working regions of the device, the channel current model of the uniaxial strained Si nanometer NMOSFET was established in terms of the basic equation of drift-diffusion, and numerical simulations are carried out by Matlab. The results from the model are compared with the experimental data and they are found to be in good agreement. Thus, the proposed model provides good reference for research on irradiation reliability of uniaxial strained Si Nano NMOSFET.

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