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Influence of Total Ionizing Dose Irradiation on Low-Frequency Noise Responses in Partially Depleted SOI nMOSFETs *

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Total ionizing dose effect induced low frequency degradations in 130 nm partially depleted silicon-on-insulator (SOI) technology are studied by ^{60}Co γ-ray irradiation. The experimental results show that the flicker noise at the front gate is not affected by the radiation since the radiation induced trapped charge in the thin gate oxide can be ignored. However, both the Lorenz spectrum noise, which is related to the linear kink effect (LKE) at the front gate, and the flicker noise at the back gate are sensitive to radiation. The radiation induced trapped charge in shallow trench isolation and the buried oxide can deplete the nearby body region and can activate the traps which reside in the depletion region. These traps act as a GR center and accelerate the consumption of the accumulated holes in the floating body. It results in the attenuation of the LKE and the increase of the Lorenz spectrum noise. Simultaneously, the radiation induced trapped charge in the buried oxide can directly lead to an enhanced flicker noise at the back gate. The trapped charge density in the buried oxide is extracted to increase from $2.21 \times 10^{18}\ eV^{-1}cm^{-3}$ to $3.59 \times 10^{18}\ eV^{-1}cm^{-3}$ after irradiation.

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The high insulating properties of silicon-on-insulator (SOI) substrates, in particular with the use of high resistivity material, lead to high performance mixed-signal circuits.[1,2] The low-frequency noise, which can directly impact analog or radio frequency (RF) integrated circuits, is an importance parameter for these kinds of applications.[3] The most commonly low-frequency noise is flicker noise which has a $1/f$-like spectral intensity. There is a long lasting debate about the mechanism of the flicker noise.[4−6] The ΔN model contributes the origin of flicker noise to the fluctuation in the carrier number, which is caused by the carrier tunneling between the conduction channel and the traps located in the oxide close to the interface. However, the $\Delta\mu$ model implies that flicker noise is generated by the fluctuation in carrier mobility, which has resulted from the scatter mechanism related to the lattice quality or process defect. The aggressive shrinking of gate oxide thickness leads to a sharp increase of the gate tunneling current, which has been reported to be responsible for the linear kink effects (LKEs) in advanced SOI devices.[7] Low-frequency excess noise associated to LKEs is reported, which is manifested as a Lorentzian spectrum ($1/f^2$-like, but not $1/f$-like).[8−10] Meanwhile, the SOI technology is widely used in the radiation environment because of its major advantages over bulk substrates (including their latch-up immunity and less sensitive volume of charge collection) thanks to the complete dielectric isolation of transistors.[11−13] Radiation will introduce trapped-charge and interface traps in the oxide, which can alter the low-frequency responses of the MOS device.[14−16] However, the radiation induced low-frequency degradation in SOI MOSFETs is not thoroughly studied. In this study, we focus on the influence of total ionizing dose (TID) irradiation on low-frequency responses of partially depleted (PD) SOI MOS transistors. Both the Lorenz spectrum noise, which is related to the linear kink effect, and the $1/f$-like low-frequency noise at front and back gates are investigated.

All the devices used in our experiment are 130 nm PDSOI NMOS with ∼2 nm gate oxide, 100 nm top silicon film and 145 nm buried oxide. A T-shape gate is introduced as the body contact and the structure diagram of the MOSFET is shown in Fig. 1. The shallow trench isolation (STI) connected with the buried oxide at the bottom is introduced for isolation. Different transistor sizes were chosen, $W/L = 5\,\mu m/0.13\,\mu m$, $10\,\mu m/10\,\mu m$. The threshold voltage V_{th} of the device is approximately 0.3 V. All the samples are DIP ceramic packaged. The operating supply voltage is 1.2 V. The irradiation experiments were conducted in Xinjiang Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, and ^{60}Co γ-ray was used as the radiation source. The dose rate was 100 rad(Si)/s. During radiation exposure, the devices were under ON state with gate biased at 1.2 V and the other terminal grounded. The temperature was monitored and kept at room temperature. Low-

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frequency noise measurements were obtained prior to irradiation and after step irradiations up to 500 and 1000 krad(Si). The noise test system consists of an Agilent 35670 A dynamic signal analyzer, an HP4156 semiconductor parameter analyzer, and an impedance matching network. The entire tests were taken within half an hour following exposure.

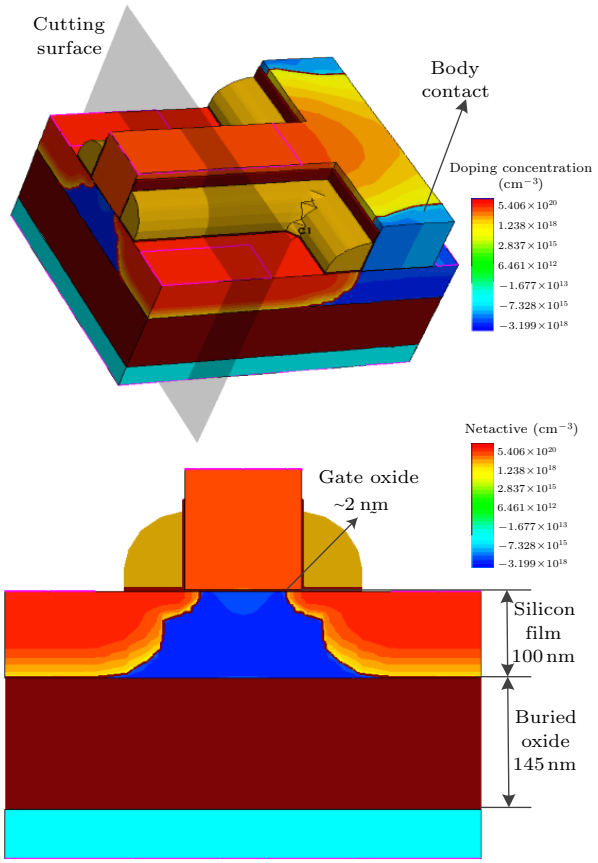

Fig. 1. Structure diagram and cross section of the PDSOI NMOS device with T-shape gate body contact.

Figure 2 shows the normalized drain current noise power spectral density $S_{\rm Id}/I_{\rm d}^2$ and input referred noise power spectral density $S_{\rm Vg}$ as a function of the front gate voltage before irradiation for a 5 μm/0.13 μm device. At $V_{\rm fg} < 1$ V, $S_{\rm Vg}$ is a constant and the line ($S_{\rm Id}/I_{\rm d}^2$ versus $V_{\rm fg}$) is parallel with the line ($g_{\rm m}^2/I_{\rm d}^2$ versus $V_{\rm fg}$). Based on the ΔN model, the input referred noise power spectral density of MOSFET in the linear region can be calculated by[4]

$$S_{\rm Vg} = \frac{q^2 kTN_{\rm t}}{\alpha_{\rm t} WLC_{\rm ox}^2 f}. \tag{1}$$

The normalized drain current noise power spectral density can be expressed as

$$\frac{S_{\rm Id}}{I_{\rm d}^2} = \left(\frac{g_{\rm m}}{I_{\rm d}}\right)^2 S_{\rm Vg}, \tag{2}$$

where $N_{\rm t}$ is the trap density near the interface in the gate oxide (eV^{-1}cm^{-3}), $\alpha_{\rm t}$ is the tunneling constant (approximately equal to 10^8 cm^{-1}), $g_{\rm m}$ is the transconductance, $C_{\rm ox}$ is the capacitance per unit area of the front gate, $I_{\rm d}$ is the drain current, T is the temperature, while W and L are the width and length of the MOSFET, respectively. The ΔN model predicts that $S_{\rm Vg}$ is independent of gate voltage. The experimental data at $V_{\rm fg} < 1$ V are consistent with the ΔN model. According to Eq. (1), $N_{\rm t}$ is extracted to be 3.7×10^{17} eV^{-1}cm^{-3} before irradiation for the 5 μm/0.13 μm device, while at $V_{\rm fg} > 1$ V, the test results are consistent with the $\Delta\mu$ model, which is manifested as $S_{\rm Vg}$ increases with the gate voltage. Based on the $\Delta\mu$ mode, the input referred noise power spectral density of the MOSFET in the linear region can be calculated by[4]

$$S_{\rm Vg} = \frac{q\alpha_{\rm H}}{C_{\rm ox} WLf}(V_{\rm fg} - V_{\rm th}), \tag{3}$$

where $V_{\rm fg}$ is the gate voltage, and $\alpha_{\rm H}$ is the silicon lattice quality parameter near the front channel, which can be extracted to be $\sim 2.7 \times 10^{-4}$ before irradiation.

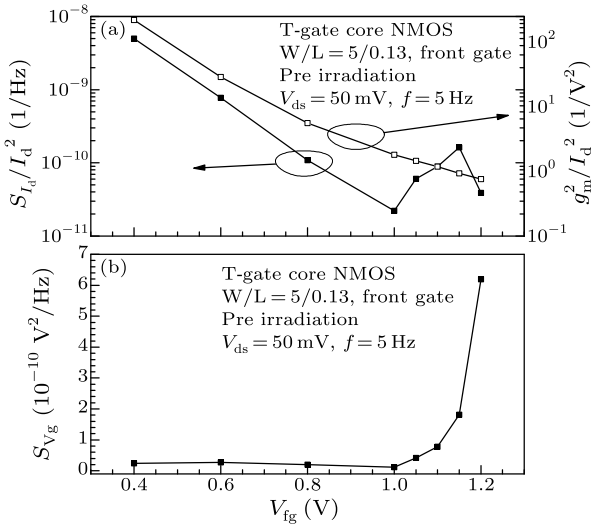

Fig. 2. (a) Normalized drain current noise power spectral density and (b) input referred noise power spectral density as a function of front gate voltage before irradiation for a 5 μm/0.13 μm device.

Figure 3(a) shows $S_{\rm Vg}$ as a function of frequency before and after irradiation at the front gate for a 5 μm/0.13 μm NMOS. A $1/f$-like noise power spectrum is observed at $V_{\rm fg} = 0.4$ V and 1.2 V. No significant change in the $1/f$ noise is observed after the total dose is up to 1 Mrad(Si). It implies that irradiation does not increase the gate oxide trap density or change the silicon lattice quality. Since the gate oxide is very thin, the radiation induced oxide traps can be ignored. Similarly, no increase of $S_{\rm Vg}$ at $V_{\rm gt} = V_{\rm fg} - V_{\rm th} = 0.6$ V is observed for the 10 μm/10 μm device. However, when overdrive voltage $V_{\rm gt}$ is up to 1.1 V, radiation induced low-frequency noise increase is observed for the 10 μm/10 μm device (Fig. 3(b)).

Figure 4 shows the drain current noise power spectral density as a function of frequency at different front gate biases before irradiation for a 10 μm/10 μm

NMOS. The overdrive voltage V_{gt} increases from 0.9 V to 1.1 V during the test. At $V_{gt} = 0.9$ V, the low-frequency noise is manifested as a $1/f$-like spectrum. As the gate voltage continues to increase, the valence-band electron tunneling occurs through the ultrathin gate oxide and leaves excess holes in the floating body. It leads to the linear kink effects which feature as a second peak of the transconductance at $V_{fg} = 1.25$ V, as shown in Fig. 4(b).

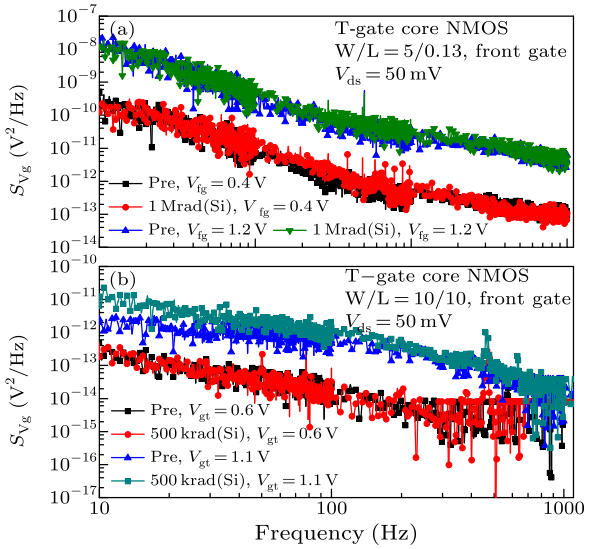

Fig. 3. Input referred noise power spectral density as a function of frequency before and after irradiation at front gate: (a) $W/L = 5\,\mu m/0.13\,\mu m$, and (b) $W/L = 10\,\mu m/10\,\mu m$.

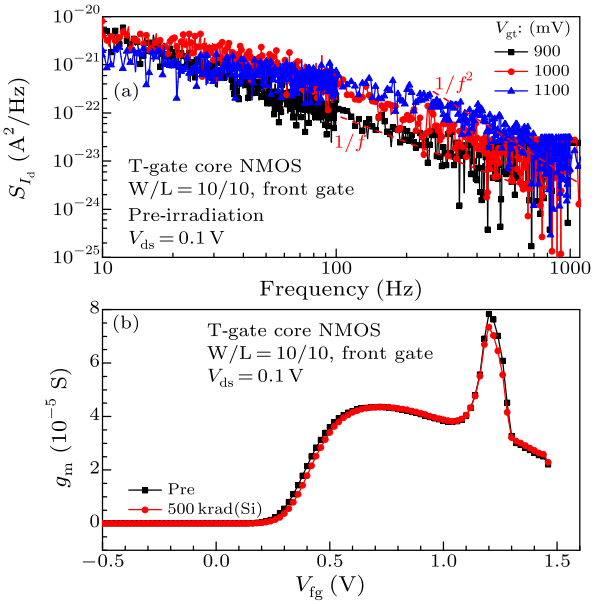

Fig. 4. (a) Drain current noise power spectral density as a function of frequency at different front gate biases before irradiation. (b) Front gate transconductance as a function of gate voltage before and after irradiation. Here $W/L = 10\,\mu m/10\,\mu m$.

Simultaneously, the low-frequency noise in the linear kink region changes from l/f-like in a Lorentzian noise spectrum, i.e., a flat low-frequency plateau with constant amplitude, followed by an l/f^2 roll-off, as shown in Fig. 4(a). Simoen *et al.*[17] suggested that the physical origin of this type of noise relies on the capture/release of excess holes by the generation-recombination (GR) center in the depletion region. The LKE introduces a Lorenz spectrum noise to replace the $1/f$ noise. Thus the observed increase of low-frequency noise in Fig. 3(b) is the Lorenz spectrum noise, instead of $1/f$ noise.

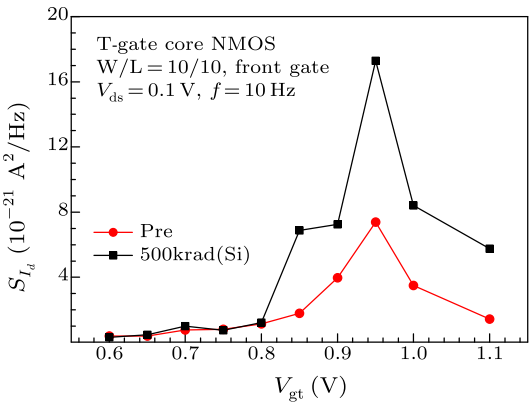

Fig. 5. Drain current noise power spectral density as a function of front gate overdrive voltage before and after irradiation for a $10\,\mu m/10\,\mu m$ device.

Figure 5 shows the drain current noise power spectral density as a function of front gate overdrive voltage before and after irradiation for a $10\,\mu m/10\,\mu m$ device. The occurrence of the Lorenz spectrum noise leads to a noise overshoot at $V_{gt} = 0.95$ V in Fig. 5, which is in accordance with the second peak of the transconductance. The noise overshoot is significantly enhanced after 500 krad(Si) irradiation. Based on the GR noise model, the LKEs related Lorenz spectrum drain current noise power spectral density can be expressed as[18]

$$S_{Id} = g_m^2 \frac{q^2 N_t w_d}{C_{ox}^2 WL} \frac{4}{(\tau_c + \tau_e)\left[\left(\frac{1}{\tau_c} + \frac{1}{\tau_e}\right)^2 + (2\pi f)^2\right]}, \quad (4)$$

where w_d is the width of the depletion region in the body, N_t is the GR center density in the depletion region, while τ_c and τ_e are the capture and emission time constants, respectively. According to Eq. (4), S_{Id} is proportional to the effective area density of the GR center in the depletion region, i.e., $w_d \times N_t$. The radiation induced positive trapped charge in the STI and buried oxide will deplete the nearby body and will introduce an extra depletion region. It is equivalent to an increase of the effective area density of GR center. The radiation activates extra hole recombination centers and accelerates the consumption of the accumulated holes in the floating body. Thus an increase of the excess Lorentzian noise is observed (Fig. 5). Simultaneously, the consumption of extra holes results in the attenuation of the LKE, which is manifested

as a weakened second peak of transconductance after irradiation (Fig. 4(b)).

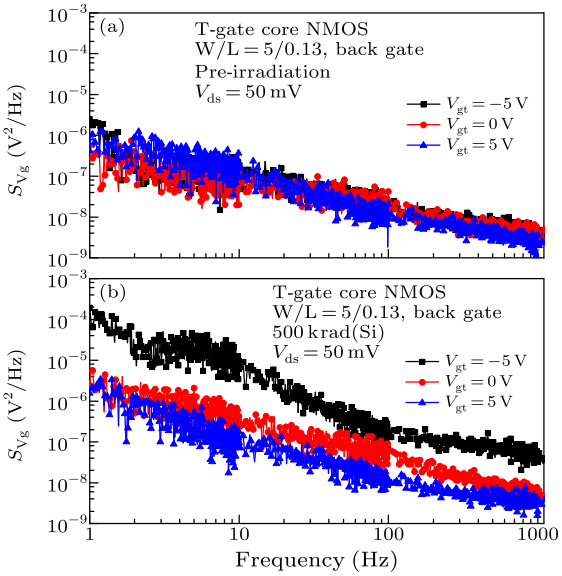

Fig. 6. Input referred noise power spectral density as a function of frequency at the back gate (a) before and (b) after irradiation for a 5 μm/0.13 μm device.

Figure 6 shows S_{Vg} as a function of frequency before and after irradiation at the back gate for a 5 μm/0.13 μm NMOS. Since the material quality near the back channel is worse than that in the front channel, the low-frequency noise level at the back gate is much higher than that at the front gate, as shown in Fig. 6(a). The same S_{Vg} at different back gate biases ($V_{gt} = -5$ V, 0 V and 5 V) indicates that the $1/f$ noise at the back gate follows the ΔN model. According to Eq. (1), the trap density in the buried oxide near the back channel is calculated to be 2.21×10^{18} eV^{-1}cm^{-3} at $V_{gt} = 0$ V and $f = 1$ Hz. Radiation induced trapped charge in the buried oxide leads to the increase of S_{Vg} at the back gate. The trap density in the buried oxide can be extracted to be 3.59×10^{18} eV^{-1}cm^{-3} after 500 krad(Si) irradiation.

In summary, the influences of the TID effect on low-frequency noise in a 130 nm PDSOI MOSFET have been investigated in detail. According to the pre-irradiation test, the flicker noises at the front gate obey the ΔN model at $V_{fg} < 1$ V and obey the $\Delta\mu$ model at $V_{fg} > 1$ V. The radiation does not increase the trap charge density or change the silicon lattice quality due to the ultra-thin gate oxide. Thus no flicker noise degradation is observed at the front gate for a 5 μm/0.13 μm device. However, the buried oxide is relatively thick, and the radiation induced trapped charge leads to a significant increase of flicker noise at the back gate. It is worth noting that the low-frequency noise increase at the front gate is observed for a 10 μm/10 μm device. The observed increase of low-frequency noise is proved to be the Lorentzian spectrum noise related to the LKEs, but not the $1/f$ noise. According to the GR noise model, the trapped charge in STI or buried oxide leads to the activation of an extra GR center and finally results in the enhancement of the Lorentzian noise. Furthermore, our research also proves that the low-frequency noise is a strong technology sensitive parameter, which in some cases can be used as a predictive or diagnostic tool for device radiation reliability.

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