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Influence of characteristics' measurement sequence on total ionizing dose effect in PDSOI nMOSFET

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The influence of characteristics' measurement sequence on total ionizing dose effect in partially-depleted SOI nMOSFET is comprehensively studied. We find that measuring the front-gate curves has no influence on total ionizing dose effect. However, the back-gate curves' measurement has a great influence on total ionizing dose effect due to high electric field in the buried oxide during measuring. In this paper, we analyze their mechanisms and we find that there are three kinds of electrons tunneling mechanisms at the bottom corner of the shallow trench isolation and in the buried oxide during the back-gate curves' measurement, which are: Fowler–Nordheim tunneling, trap-assisted tunneling, and charge-assisted tunneling. The tunneling electrons neutralize the radiation-induced positive trapped charges, which weakens the total ionizing dose effect. As the total ionizing dose level increases, the charge-assisted tunneling is enhanced by the radiation-induced positive trapped charges. Hence, the influence of the back-gate curves' measurement is enhanced as the total ionizing dose level increases. Different irradiation biases are compared with each other. An appropriate measurement sequence and voltage bias are proposed to eliminate the influence of measurement.

Keywords: total ionizing dose (TID), silicon-on-insulator (SOI), measurement sequence, tunneling effect

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1. Introduction

Compared with bulk technology, silicon-on-insulator (SOI) technology has good immunity to single event effects (SEEs) and latchup for its fully dielectric isolation of shallow trench isolation (STI) and buried oxide (BOX) layer.[1] Hence, it has been widely used in radiation hardening for many years. However, due to the additional buried oxide layer, the total ionizing dose (TID) effect in SOI technology is more complex than bulk technology.

In SOI technology, radiation-induced positive charges are trapped in gate oxide, STI, and BOX. In deep-submicron SOI technology, the thickness of gate oxide is below 10 nm, the radiation-induced positive trapped charges in the gate oxide is very small, which means that the effect from the trapped charges in the gate oxide is negligible.[2] The radiation-induced positive trapped charges in the STI can reduce the threshold voltage of the STI sidewall parasitic transistor and induce the hump effect on the transfer characteristic curve of the front-gate transistor.[3,4] The radiation-induced positive trapped charges in the BOX can deplete the body silicon film, and induce a lot of effects, such as body current lowering,[5,6] coupling effect,[7] drain-induced barrier lowering (DIBL),[8,9] and so on. When the radiation-induced positive trapped charges in the BOX are enough and inverse the body silicon film, the device will suffer a large leakage current from the bottom body silicon film and fail to work.[1,4]

In many studies of TID effect, the characteristics of the front-gate transistor and the characteristics of the back-gate transistor were both analyzed.[4–7,10–18] Hence, both of them were all measured in experiment. In their papers, they only stated that the characteristics of the front-gate transistor and the characteristics of the back-gate transistor were measured before irradiation and after a certain total ionizing dose level. However, the measurement sequence was not stated clearly. Sometimes, we first measure the characteristics of the back-gate transistor for convenience. When we measure the characteristics of the back-gate transistor, the back gate is biased at a very high voltage (about 40 V–50 V). This high voltage may affect the device and influence the TID effect. Hence, if we first measure the characteristics of the back-gate transistor, then the characteristics of the front-gate transistor may be measured inaccurately. However, there is no paper which focuses on the influence of characteristic measurement sequence.

In this paper, we first study the influence of characteristics' measurement sequence and the influence of double test on TID effect experimentally. The ON irradiation bias and Pass-Gate (PG) irradiation bias are compared with each either. An explanation to the influence is proposed. Finally, we give an appropriate measurement sequence and voltage bias in TID effect experiment to reduce the influence.

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2. Experimental details

All of the devices in this paper were fabricated in 130 nm partially-deplete (PD) SOI CMOS process. The SOI wafer was 200 mm diameter UNIBOND®wafer from SOITEC corporation. The thickness of top silicon and BOX were 100 nm and 145 nm, respectively. All devices were isolated by STI structure, and TGate layout was used to contact the body silicon. Figure 1 shows the detail of the device structure. The body doping concentration was about 4.7×10^{17} cm^{-3}. The input/output (I/O) NMOS devices with 6-nm gate oxide and 3.3-V operating voltage (VDD) were selected. All of the samples were 24-pin DIP ceramic packaged. And they were divided into two groups (group-front and group-back) for different measurement sequences. Radiation experiments were conducted in Xinjiang Technical Institute of Physics and Chemistry, Chinese Academy of Sciences. The ^{60}Co γ ray with a 100 rad(Si)/s dose rate was used as a radiation source. The ON bias (when gate is biased at 1.1 VDD, and others are grounded) and PG bias (when source and drain are biased at 1.1 VDD, others are grounded) were used during the radiation exposure. The typical characteristic curves as shown in Table 1 were measured by a Keithley 4200B parameter analyzer at room temperature before irradiation and after irradiation up to 50 krad(Si) and 100 krad(Si) respectively. As for the samples from group-front, the typical curves of the front-gate transistor were first measured, then the curves were measured the second time. When they were all finished, the typical curves of the back-gate transistor were measured the first time and the second time. As for the samples from group-back, the typical curves of the back-gate transistor were first measured, then the curves were measured the second time. When they were all finished, the typical curves of the front-gate transistor were measured the first time and the second time. What should be noted was that the second measurement was started after the first measurement has finished. To avoid experimental error and the difference among samples, we measured three samples from each group. The final characteristic curves were obtained by averaging the two samples that are most consistent with each other. All measures were taken within half an hour to avoid anneal effect.

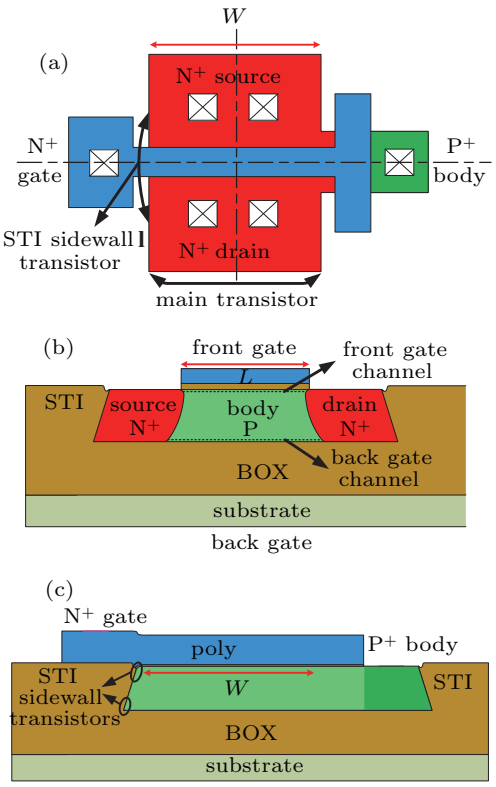


Fig. 1. (color online) Layout of PDSOI nMOSFETs, showing (a) top view, (b) side view, and (c) front view.

Table 1. Characteristic curves of PDSOI nMOSFETs and their voltage biases

Group	Curve	Front gate/V	Drain/V	Source/V	Body/V	Back gate/V
Front gate curves	I_d–V_{fg}	−0.5–3.3	0.1	0	0	0
	I_d–V_{fg}, I_b–V_{fg}	−0.5–3.3	3.63	0	0	0
	I_d–V_d	3.3	0–3.3	0	0	0
Back-gate curves	I_d–V_{bg}	0	0.1	0	0	−5–45
	I_d–V_{bg}	0	3.3	0	0	−5–45

3. Results

3.1. Influence on front-gate transfer characteristic curves

Figure 2 shows the I_d–V_{fg} curves under ON bias and PG bias. The I_d–V_{fg} curves all humps as the TID level increases. The I_d–V_{fg} curves under ON bias hump more significantly than those under PG bias. These are all in agreement with the previous studies.[13,16] However, at the first test, the samples from group-back show more subdued hump than the samples from group-front. As the TID increases, the hump is subdued more significantly. These results reveal that the back-gate curves' measurement has a negative influence on the radiation-induced hump, and the negative influence is enhanced as the TID level increases. For the samples from the same groups, the hump at the second test, compared with the hump at the first test, is weakened a little. This reveal that the double test of the front-gate curves has a little negative influence on the radiation-induced hump. What is more interesting is that there is no obvious difference between the I_d–V_{fg} curves before irradiation. It seems that the measurement sequence only influences the I_d–V_{fg} curves after irradiation.

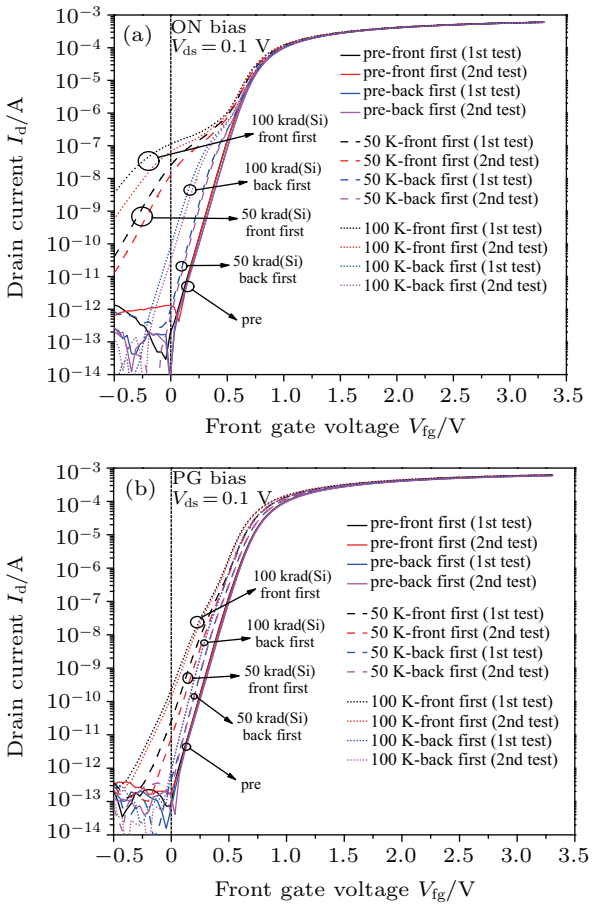


Fig. 2. (color online) Front-gate transfer characteristic curves of the PDSOI nMOSFETs with $W/L = 10$ μm/0.35 μm (a) under ON bias and (b) under PG bias. The "front first" means that front-gate curves of samples from group-front are first measured, and the "back first" means that back-gate curves of samples from group-back are first measured. The "first test" and the "second test" mean the curves are measured the first time and the second time, respectively. These legends hold true for the following figures.

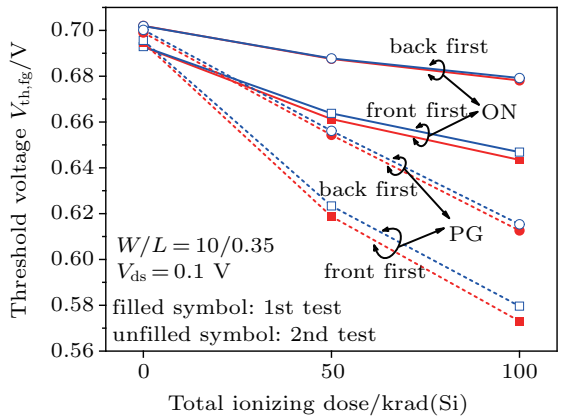


Fig. 3. (color online) Plots of front-gate threshold voltage *versus* total ionizing dose for PDSOI nMOSFETs with $W/L = 10$ μm/0.35 μm under ON bias and PG bias.

Figure 3 shows the threshold voltages extracted from Fig. 2 by using the standard maximum transconductance.[19] Before irradiation, the measurement sequence has no influence on the threshold voltages. After a TID level irradiation, the samples from group-back show higher threshold voltage than the samples from group-front, which reveals that the measurement of the back-gate curves has a negative influence on the radiation-induced negative shift of threshold voltage. There is no big difference between the first test and the second test.

3.2. Influence on front-gate body current

Figure 4 shows the I_b–V_{fg} curves under ON bias and PG bias. In the same measurement sequence, the body current lowers both under ON bias and under PG bias as the TID level increases. These are in accordance with the Xiao-Nian Liu *et al.*'s research results.[6] However, the samples from group-back show higher absolute body current than the samples from group-front before irradiation and after a TID level irradiation. These results reveal that the back-gate curves' measurement has influence on the front-gate body current not only after irradiation, but also before irradiation. There is no big difference between the first test and the second test.

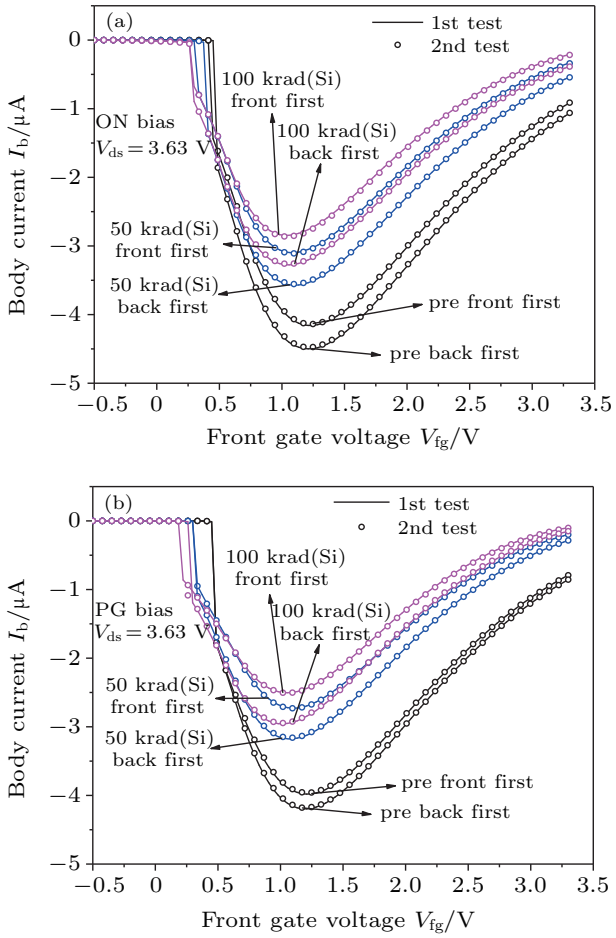


Fig. 4. (color online) Plots of body current of *versus* front gate voltage for PDSOI nMOSFETs with $W/L = 10$ μm/0.35 μm (a) under ON bias and (b) under PG bias.

We also extract the maximum of body current from Fig. 4 and the results are shown in Fig. 5. As we can see, there is no difference between the first test and the second test. However, the samples from group-back show that their maxima of body current are larger than the samples from group-front. And before irradiation, the influence from the back-gate curves' measurement is also significant.

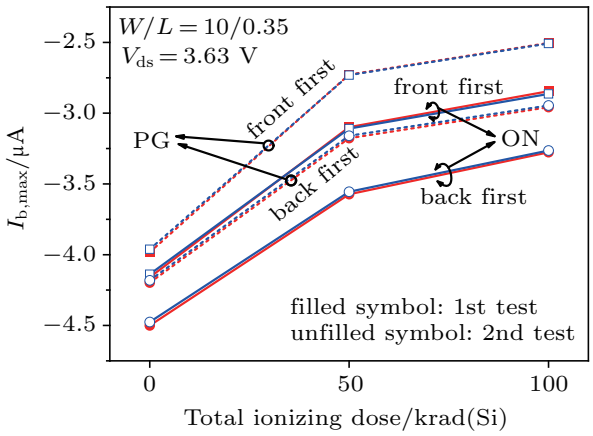


Fig. 5. (color online) Plots of maximum of body current *versus* total ionizing dose for PDSOI nMOSFETs with $W/L = 10$ μm/0.35 μm under ON bias and PG bias.

From the analysis of the front-gate body current, we can obtain the similar conclusions to those presented in the Subsection 3.1. The double test of the front-gate curves does not influence the I_b–V_{fg} curves significantly. However, the back-gate curves' measurement can weaken the TID effect on the I_b–V_{fg} curves.

3.3. Influence on drain saturation current and drain leakage current

Figure 6 shows the drain saturation current under ON bias and PG bias. There is no difference between the first test and the second test under ON bias nor under PG bias. And the samples from group-back show smaller I_{dsat} than the samples from group-front. According to previous studies,[4,16,18] the radiation-induced trapped charges negatively shift the front-gate threshold voltage, then the I_{dsat} increases as TID increases. Hence, we can conclude that the back-gate curves' measurement weakens the TID effect.

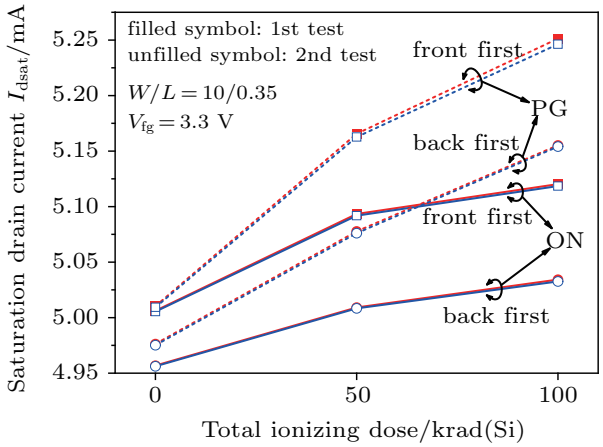


Fig. 6. (color online) Plots of drain saturation current *versus* total ionizing dose for PDSOI nMOSFETs with $W/L = 10$ μm/0.35 μm under ON bias and PG bias.

The drain leakage currents under ON bias and PG bias are also studied as shown in Fig. 7. There is no significant difference between the first test and the second test, except the samples from group-front under PG bias at 50 krad(Si) dose level. The bigger difference at that position may be induced by measurement error. The samples from group-back show smaller leakage current than the samples from group-front. These reveal that the back-gate curves' measurement weakens the effect of TID on the leakage current.

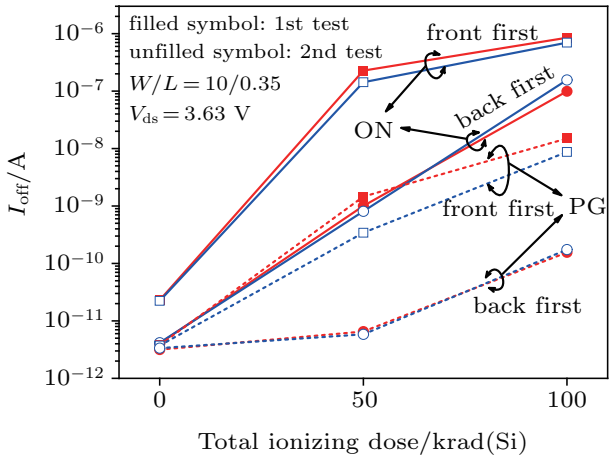


Fig. 7. (color online) Plots of drain leakage current *versus* total ionizing dose for PDSOI nMOSFETs with $W/L = 10$ μm/0.35 μm under ON bias and PG bias.

3.4. Influence on back-gate transfer characteristic curves

Figure 8 shows the back-gate transfer characteristic curves under ON bias and PG bias. There are big differences between the first test and the second test both under ON bias and under PG bias. After the first test, the hump in the subthreshold region and the negative shift of threshold voltage are all weakened significantly. These results reveal that the back-gate curves' measurement significantly influences the TID effect. Furthermore, it even influences the subthreshold region of device before irradiation. Compared with the samples from group-back, the samples from group-front show a little hump under ON bias. This reveals that the front-gate curves' measurement has a little influence on TID effect under ON bias. However, the influence of the front-gate curves' measurement is negligible under the PG bias.

The threshold voltages of the back-gate main transistor are also extracted as shown in Fig. 9. Before irradiation, the measurement sequence has no influence on the back-gate threshold voltage. However, after irradiation, the back-gate curves' measurement weakens the radiation-induced negative shift of the back-gate threshold voltage, and the influence is more severe as TID level increases. The front-gate curves' measurement has a little influence on back-gate threshold voltage. Compared with the influence from the back-gate curves' measurement, it is negligible.

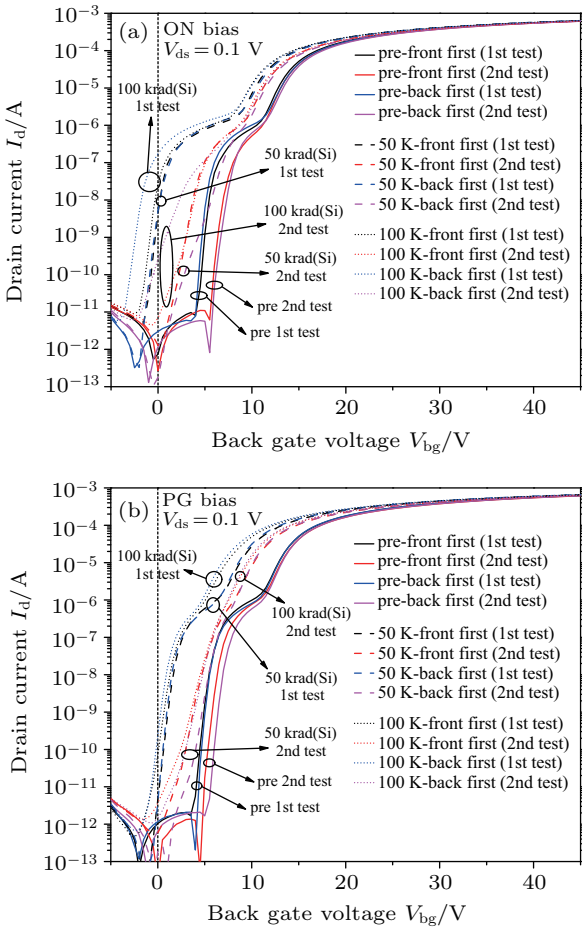


Fig. 8. (color online) Back-gate transfer characteristic curves of the PDSOI nMOSFETs with $W/L = 10$ μm/0.35 μm (a) under ON bias and (b) under PG bias.

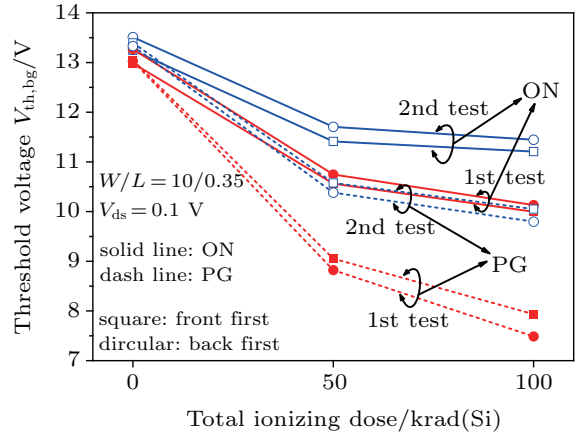


Fig. 9. (color online) Plots of back-gate threshold voltage *versus* total ionizing dose for PDSOI nMOSFETs with $W/L = 10$ μm/0.35 μm under ON bias and PG bias.

3.5. Comparisons between ON bias and PG bias

From the previous sections, we find the back-gate curves' measurement has big influence on TID effect. In this subsection, we compare the influences of the back-gate curves' measurement under ON bias and PG bias.

As for the front-gate parameters, there is no obvious difference between the first test and the second test, hence we only choose the front-gate parameters from the first test. We calculate the change rate of the front-gate threshold voltage ($V_{th,fg}$), the maximum of the body current ($I_{b,max}$), and the drain saturation current (I_{dsat}) by using the following equation:

$$C_{front} = \frac{P_{back_1st} - P_{front_1st}}{P_{front_1st}},$$

where C_{front} is the change rate of the front-gate parameter, P_{back_1st} is the front-gate parameter of the sample from the group-back at the first test, P_{front_1st} is the front-gate parameter of the sample from the group-front at the first test.

Figure 10 shows the change rates of the front-gate parameter under ON bias and PG bias. As we can see, before irradiation, the change rate under ON bias is larger than that under PG bias. This may be induced by the difference between the samples. After irradiation, the change rate under PG bias is larger than that under ON bias, and this phenomenon is more significant as TID increases.

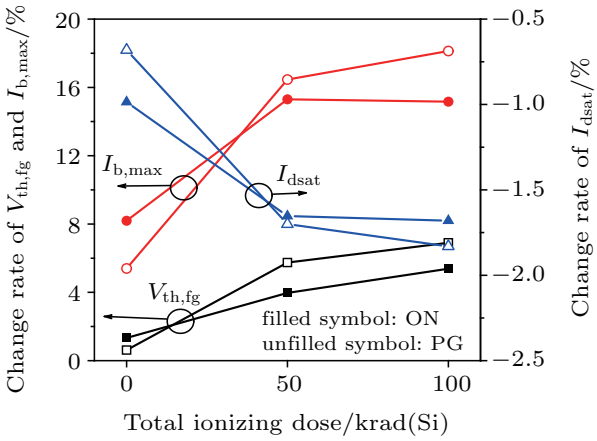


Fig. 10. (color online) Plots of change rate of $V_{th,fg}$, $I_{b,max}$, and I_{dsat} *versus* total ionizing dose under ON bias and PG bias. After irradiation, change rate under PG bias is larger than that under ON bias.

Figure 11 is the differences in drain leakage current between the samples from the group-front and the samples from group-back. It can be seen that the difference under ON bias is bigger than that under PG bias.

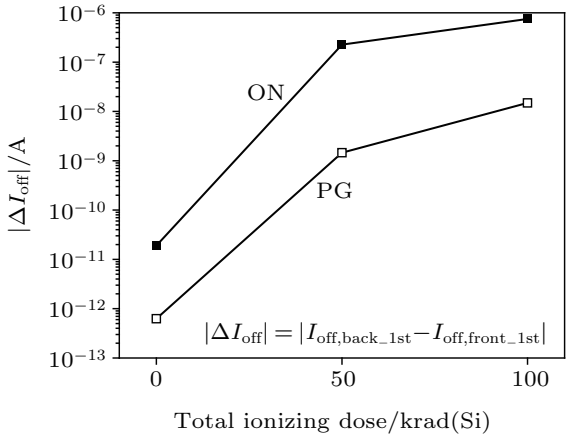


Fig. 11. Plot of difference in drain leakage current (ΔI_{off}) between the samples from group-front and samples from group-back under ON bias and PG bias, which are all values from the first test.

As for the back-gate parameters, the influence of the back-gate curves' measurement is reflected in the difference between the first test and the second test. Hence, the change rate of the back-gate parameter $V_{\mathrm{th,bg}}$ is calculated from

$$\text{Change rate of } V_{\mathrm{th,bg}} = \frac{V_{\mathrm{th,bg(back_2nd)}} - V_{\mathrm{th,bg(back_1st)}}}{V_{\mathrm{th,bg(back_1st)}}}.$$

Figure 12 shows the change rate of $V_{\mathrm{th,bg}}$. As we can see, the change rate under PG bias is much lager than that under ON bias after irradiation.

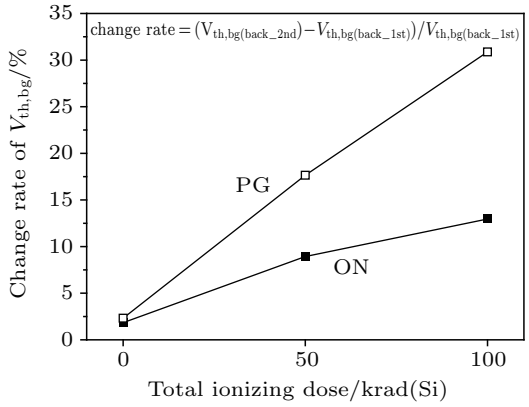


Fig. 12. Plot of change rate of $V_{\mathrm{th,bg}}$ *versus* total ionizing dose under ON bias and PG bias. After irradiation, change rate under PG bias is larger than that under ON bias.

What is more, from Figs. 2 and 8, we can find that the change of the hump under ON bias is lager than that under PG bias.

According to previous studies,[1,6,16] the irradiation under ON bias induces more significant hump and higher drain leakage current, whereas the irradiation under PG bias induces the larger shift of threshold voltage, drain saturation current, and body current. What is very interesting is that the measurement-sequence-induced change of hump and drain leakage current under ON bias are larger than those under PG bias. The measurement-sequence-induced change rate of threshold voltage, drain saturation current, and body current under PG bias are larger than those under ON bias. Hence, we draw the following conclusions from these phenomena: the back-gate curves' measurement weakens the TID effect; the more significant the TID effect, the more significant the weakening will be.

4. Discussion

From Subsections 3.1–3.4, we can obtain the following results. (i) The back-gate curves' measurement has big influence on the TID effect both under ON bias and under PG bias, whereas the front-gate curves' measurement has a negligible influence on the TID effect both under ON bias and under PG bias. (ii) The double test of the back-gate curves' measurement shows subdued TID effect, whereas the double test of the front-gate curves' measurement displays no influence. From Subsection 3.5, we find that the back-gate curves' measurement weakens the TID effect, and the more significant the TID effect, the more significant the weakening will be.

As shown in Table 1, the back gate is biased up to 45 V when we measure the back-gate curves. This large voltage induces very high electric field in the BOX. A TCAD simulation is performed to calculate the distribution of electric field during back-gate curves' measurement. As shown in Fig. 13, when the back gate is biased up to 45 V, the electric field in the BOX rises up to 4 MV/cm, and the electric field at the bottom corner of STI reaches up to 6.5 MV/cm. According to the Nazarov *et al.*'s study,[20] when the electric field exceeds 5.8 MV/cm, electrons will be injected into BOX from the body silicon by Fowler–Nordheim (FN) tunneling in UNIBOND wafer. Hence, at the bottom corner of STI, the electrons can tunnel into oxide by FN tunneling mechanism during the back-gate curves' measurement. The electrons of FN tunneling neutralizes the radiation-induced positive trapped charges, which induces the negative influence on the TID effect. Due to the low electric field in the BOX, there is no FN tunneling of the electrons in the BOX.

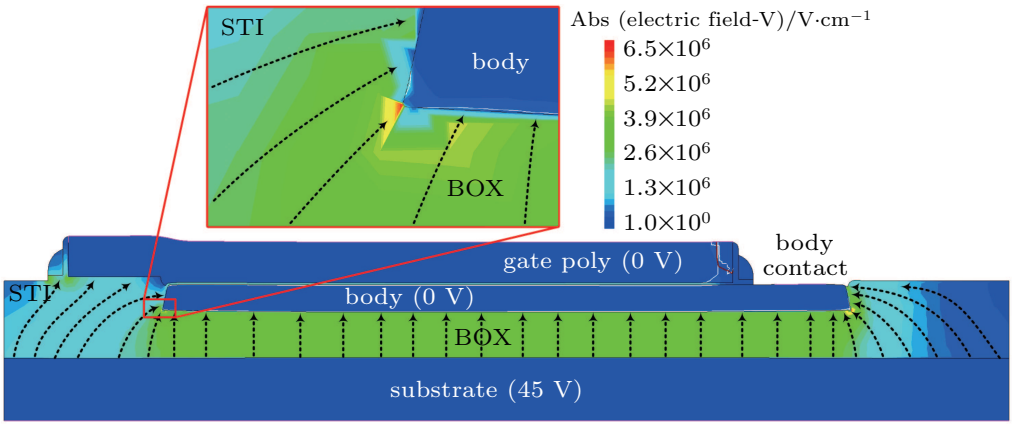


Fig. 13. (color online) Distribution of electric field during back-gate curves' measurement. Back gate is biased at 45 V.

However, there are anther two tunneling mechanisms called trap-assisted tunneling (TAT) and charge-assisted tunneling (CAT) which are easier to occur in SOI wafer. Figure 14 describes the two tunneling mechanisms of electrons and shows the energy band diagrams, respectively, at the bottom corner of STI and in the BOX.

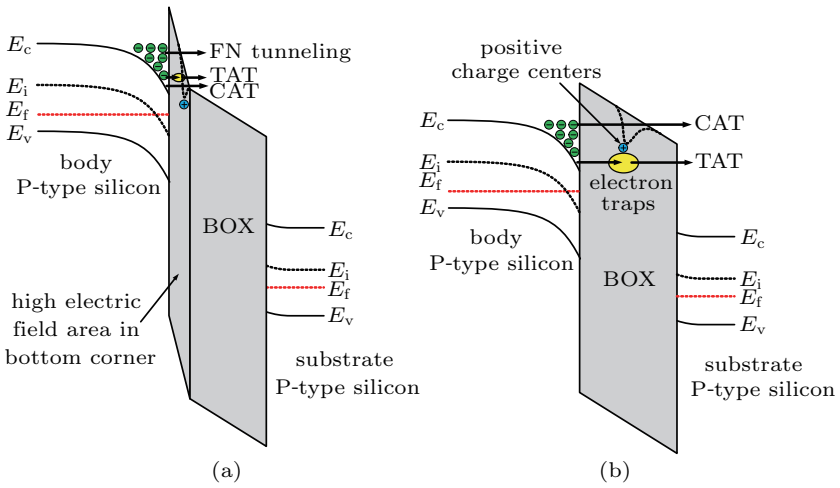


Fig. 14. (color online) Energy band diagrams of PDSOI nMOSFETs, respectively, (a) at the bottom corner of STI and (b) in the BOX. TAT is trap-assisted tunneling. CAT is positive charge-assisted tunneling. Yellow region is electron trap. Blue circles are positive charge centers.

Under the TAT mechanism, the electrons first tunnel into an intermediate trap (electron trap), they then tunnel out of the trap toward the anode.[20–23] According to previous studies,[23–25] there are many electron traps near the interface between BOX and body silicon. During the back-gate curves' measurement, trap-assisted tunneling occurs both at the bottom corner of STI and in the BOX. The electrons from trap-assisted tunneling neutralize radiation-induced positive trapped charges, and thus weakening the TID effect. Due to the mechanism of electron traps assistant, the TAT is easier to occur than FN tunneling, which means that the TAT is more dominant than FN tunneling.

Under the CAT mechanism, the local barrier is lowered by positive charge centers.[26,27] As shown in Fig. 14, the lower energy of the conduction band (E_c) is changed from the solid line to the dash line by the positive charge centers in the oxide. Hence, the tunneling of electrons is enhanced significantly. After irradiation, lots of positive trapped charges are induced in the STI and BOX. These positive trapped charges are the same as the positive charge centers, and thus inducing the charge-assisted tunneling. As the TID level increases, the positive trapped charges in the oxide increase, then the charge-assisted tunneling is enhanced more significantly, hence the back-gate curves' measurement induces more negative influence on TID effect. With the assistance of mechanism of positive charge centers, the CAT is easier to occur than FN tunneling, which means that the CAT is also more dominant than FN tunneling. As the TID level increases, the positive charge centers increase significantly. This means that the CAT is more dominant than the TAT as the TID level increases, which can be proven by the bigger change of the characteristic curves as TID level increases.

Because there are higher electric fields and three kinds of tunneling mechanisms at the bottom corner of STI, the negative influence on TID effect at the bottom corner of STI is more significant. Before irradiation, FN tunneling and trap-assisted tunneling can also occur, hence the back-gate curves' measurement can also influence the characteristics of device. However, compared with charge-assisted tunneling, FN tunneling and trap-assisted tunneling are unapparent. Hence, we do not find big changes of the characteristics of device before irradiation and we only observe a little change of hump and body current under ON bias.

5. Conclusions

In this paper, we investigate the influence of the characteristics' measurement sequence on TID effect. We find that the back-gate curves' measurement has big influence on TID effect, which weakens the radiation-induced hump, reduces the negative shift of threshold voltage, lowers the increment of the drain saturation current and leakage current, and subdues the radiation-induced body current lowering, We also find that the front-gate curves' measurement shows negligible influence on TID effect.

The ON bias and PG bias are compared with each other. We find that the back-gate curves' measurement weakens the TID effect: the more significant the TID effect, the more significant the weakening will be. Hence, the hump and drain leakage current are significantly influenced under the ON bias, whereas the threshold voltage, drain saturation current, and the body current are significantly influenced under PG bias.

In the TCAD simulation, we find that there is a high electric field at the bottom corner of STI during back-gate curves'

measurement. The electrons can tunnel into the bottom corner of STI by FN tunneling mechanism. The electric field in the BOX is not high enough. The electrons cannot tunnel into BOX by FN tunneling mechanism. However, there are electron traps and radiation-induced positive trapped charges in the oxide. The electrons can tunnel into the bottom corner of STI and BOX by trap-assisted tunneling and charge-assisted tunneling. The tunneling electrons neutralize the radiation-induced positive trapped charges, and thus weakening the TID effect. As the TID level increases, the radiation-induced positive trapped charges increase, thereby enhancing the charge-assisted tunneling and increasing the influence of back-gate curves' measurement on TID effect. With the assistance of electron traps and positive charge centers, the TAT and CAT are more dominant than FN tunneling. As the TID level increases, the CAT is more dominant than the TAT.

To achieve accurate value of TID effect, we must first measure the front-gate curves, then measure the back-gate curves. However, a double test is not suggested because it induces a little influence on the TID effect. To weaken the influence of the back-gate curves' measurement, the voltage biases can be appropriately lowered during measurement. Actually, we measure the transfer characteristic of the back-gate transistor to obtain the back-gate threshold voltage. The back-gate threshold voltage is below 15 V. There is no need to bias the back gate up to 45 V. If we reduce the voltage bias to 20 V, the electric field in the BOX will be lowered significantly. Hence, the influence from the back-gate curves' measurement will be weakened.

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