Double humps and radiation effects of SOI NMOSFET

Cui Jiangwei(崔江维)[1,2,3,†], Yu Xuefeng(余学峰)[1,2], Ren Diyuan(任迪远)[1,2],
He Chengfa(何承发)[1,2], Gao Bo(高博)[1,2,3], Li Ming(李明)[1,2,3], and Lu Jian(卢健)[1,2,3]

[1]Xinjiang Technical Institute of Physics & Chemistry, Chinese Academy of Sciences, Urumqi 830011, China
[2]Xinjiang Key Laboratory of Electronic Information Materials and Devices, Urumqi 830011, China
[3]Graduate University of the Chinese Academy of Sciences, Beijing 100049, China

Abstract: Radiation experiments have been carried out with a SOI NMOSFET. The behavior of double humps was studied under irradiation. The characterization of the hump was demonstrated. The results have shown that the shape of the hump changed along with the total dose and the reason for this was analyzed. In addition, the coupling effect of the back-gate transistor was more important for the main transistor than the parasitic transistor.

Key words: SOI; radiation; double humps
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1. Introduction

Silicon-on-insulator (SOI) devices have many inherent advantages over bulk-silicon devices, such as high velocity and density, low power, and no latch-up[1]. In particular, their great tolerance of SEU and dose-rate radiation hardness[2,3] makes them widely used in various kinds of radiation environment. However, there exist several problems with the oxide layers in the devices, particularly with the buried oxide and isolated oxide layers[4,5]. The back-gate transistor formed by the buried oxide may affect the performance of the top-gate transistor[6]. The parasitic transistor formed by isolated oxide can generate several problems, such as abnormal kinks, double humps, and excessive leakage current[7]. In particular, when the device is radiated, the generated defects in these two oxide layers can seriously affect its regular performance.

As the device is scaled down and the circuit is much more intense than before, the problems due to isolation especially under a radiation environment become more serious than before[8]. In this work, the behavior of double humps under irradiation was studied for SOI NMOSFET with LOCOS isolation. Characterization of the hump was demonstrated. The shape of the hump changed with total dose and the reason for this is discussed in detail.

2. Irradiation

The studied SOI NMOSFETs are fabricated on SIMOX with LOCOS isolation, having double humps in the initial sub-threshold curves. The thickness of the buried oxide and the top silicon film is 375 and 50 nm, while the channel length is 0.8 μm. These samples are irradiated with a certain dose with ^{60}Co γ-rays in Xinjiang Technical Institute of Physics & Chemistry, CAS, with a dose rate of 0.05 Gy(Si)/s. The bias condition during irradiation is transmission-gate state, i.e. the top-gate and substrate are grounded, and the source and drain are at +5 V. The sub-threshold curves for top-gate transistors are measured before and after irradiation with a semiconductor parametric analyzer, HP4142, of pA current accuracy.

The test after each irradiation was within 20 min to avoid the annealing effects of the oxide traps and the interface traps generated during irradiation.

3. Experiment

Figure 1 shows the sub-threshold curves of a NMOSFET before and after irradiation to some certain total dose, with zero back-gate voltage ($V_{\rm BS} = 0$).

From Fig. 1, we can see that the sub-threshold curve shifts negatively after each period of irradiation. More important, the hump at low gate voltages (called the middle hump below) becomes smoother and smoother as the total dose increases. Finally, the middle hump is almost invisible when the device is irradiated to 1000 Gy(Si).

We realize that it is a new, interesting and somewhat complex phenomenon shown in this figure. Firstly, it is quite the reverse course compared with those shown in previous work[9],

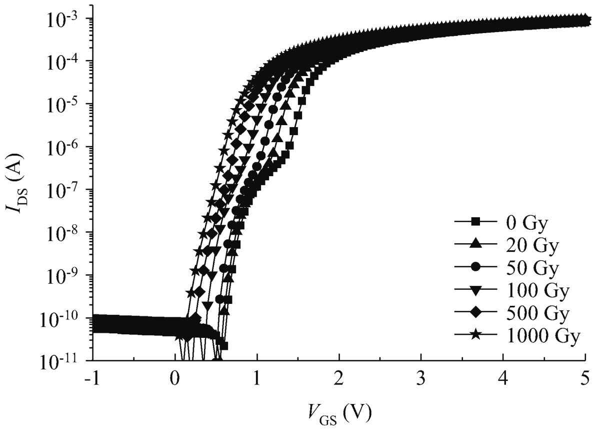

Fig. 1. Sub-threshold curves before and after irradiation, while $V_{\rm BS} = 0$.

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† Corresponding author. Email: cuijiangwei@sina.cn
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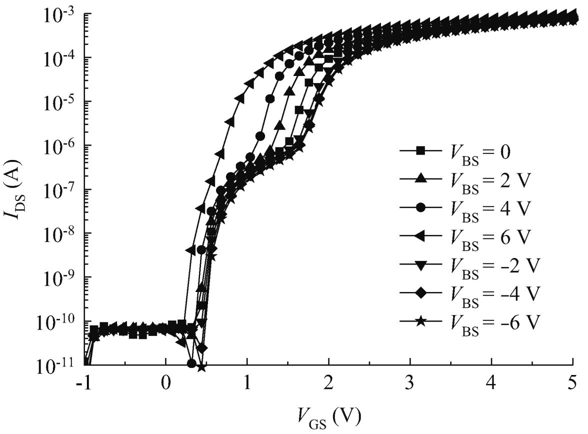

Fig. 2. Sub-threshold curves at different V_{BS}.

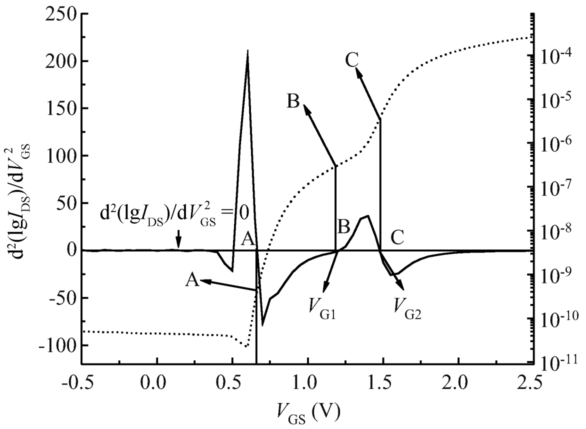

Fig. 3. Three inflexions of the sub-threshold curves.

in which the middle hump only turns up by irradiation to a certain total dose. Secondly, as we know, the middle hump included in the MOSFET sub-threshold curve was a problem related to the process. However, this problem was somehow "suppressed" by irradiation. So what happened during the irradiation, why can the problem in the process be suppressed by irradiation, and what is the internal mechanism? In the sections below, we will try to find answers to these questions and reach some instructive conclusions for future work.

With the purpose of analyzing the phenomenon in Fig. 1, we have carried out another experiment, in which no irradiation was applied but the back-gate voltages were changed, as shown in Fig. 2.

From Fig. 2, we can see that the curve shifts negatively at the positive back-gate voltage (V_{BS}) and the middle hump becomes smoother. In contrast, when negative V_{BS} is applied, the curve shifts towards the positive direction, and the deformation in the curve gets stronger.

4. Discussion

Double humps in the sub-threshold curves are due to the respective operation of two transistors, known as the main transistor and the parasitic transistor, while the latter one has a smaller threshold voltage (V_T) and would turn on in advance.

From the second derivative of the sub-threshold curve, we can clearly see the different actions of these two transistors. Figure 3 shows the second derivative and three inflexions of the sub-threshold curves. Point A represents the turn-on point of the parasitic transistor, point C indicates the threshold voltage of the main transistor, and point B shows where the parasitic transistor becomes saturated and the main transistor starts to dominate. The difference between points B and C could represent the degree of the hump[12]. As to the transistor without double humps in the sub-threshold curve, there is no difference seen between point B and point C. Both the first and second derivatives of the sub-threshold curves are shown in Fig. 4, where the dotted lines represent the first derivative and the solid lines indicate the second derivative. We can see that the second peak in the first derivative almost disappears and the difference between points B and C in the second derivative is just about invisible after irradiation by 1000 Gy(Si).

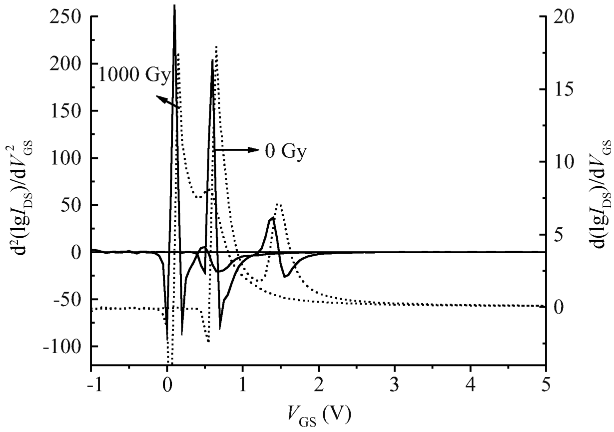

Fig. 4. The first and second derivatives of I_{DS} (V_{GS}) characteristic pre-radiation and after irradiated to 1000 Gy(Si).

Conventionally, the pre-open of the parasitic transistor results from the different ion doping concentrations respectively in the center and edge area of the transistor[10, 11], and the extent of the hump is different with various doping concentrations. Moreover, the non-uniformity distribution of doping concentration in the center and edge area is related to the fabrication process of trench recess and corner out-doping. However, the doping concentration is certain and unchangeable during irradiation, while the reason for the hump changing along with the total dose cannot be due to the ion doping concentration in this experiment.

When the device is irradiated, there are many radiation-induced charges generated in the oxide and at the Si–SiO_2 interface. Because it takes much time to form the interface-trapped charge, the oxide-trapped charge mainly affects the performance of the devices during irradiation[13, 14]. According to the thinner thickness, there would be much less trapped charges in the top-gate oxide than in the isolation oxide. Then, the main transistor should be less sensitive to irradiation than the parasitic transistor. However, the description above has suggested that the main transistor is more sensitive to the total dose than the parasitic transistor after irradiation. With serious analyzing, we think that the point may lie in the buried oxide. Many positive oxide-trapped charges are generated in the buried layer during irradiation and then induce plenty of negative charges in the back channel, forming the back-gate transistor. The top-gate transistor could be influenced by the back-gate transistor, causing the shift of the sub-threshold curve[15, 16]. The parasitic transistor is relatively insensitive to the back-gate transistor, and then shifts less than the main transistor. Finally, the main transistor catches up with the parasitic transistor, and the hump is invisible. In order to make it clearer, we have done another experiment, and the results are shown in Fig. 2 of Section 3.

According to Fig. 2, we can see that the deformation of the sub-threshold curve is more sever when negative back-gate voltages are applied, implying more depletion of the top-gate transistor together with the negative back-gate potential. The curve stops shifting when $V_{\rm BS} = -6$ V, indicating where the full depletion occurs. On the other hand, when $V_{\rm BS}$ is positive, the curve is shifting negatively, suggesting that the only reason could be the back-gate transistor. The shift of the curve is caused by the effect of the back-gate transistor. Generally, the parasitic transistor is relatively insensitive with the back-gate transistor, and changes little with $V_{\rm BS}$. However, when $V_{\rm BS}$ is large enough, the parasitic transistor is also influenced by the back-gate transistor, and shifts together with the main transistor.

To sum up, the middle hump results from the effect of the parasitic transistor and is not sensitive to the total dose and the back-gate transistor. Through the experiment, we find that the main transistor can be influenced by the back-gate transistor. In particular, when the device is irradiated, plenty of trapped charges in the buried oxide may have an important influence on the main transistor.

From the experimental results, we can obtain some instructive conclusions, as follows.

First, when irradiated, the main transistor may be easily influenced by the back-gate transistor, causing increasing current. The effect of the back-gate transistor under irradiation must be seriously considered. Measures for buried oxide toward radiation hardening of a SOI MOSFET should be taken.

In this paper, the hump in low gate voltages observed results from the advanced threshold of the parasitic transistor. This parasitic transistor is not sensitive to the total dose for the selected devices, and its effect can be mitigated by process measurements[7, 17].

As the device scales down and the circuit is much more intense than before, the isolation becomes a crucial problem. Particularly for the cases under irradiation, the isolation may determine the performance of the device. Both the LOCOS and the STI are faced with difficult challenges[8]. Studies related to the isolation under irradiation, especially for large scaled circuit systems, must be paid much more attentions.

5. Conclusions

In this work, an experimental phenomenon related to SOI NMOSFET during radiation was discussed. The compared experiment was also carried out. The behavior of double humps under irradiation was studied. The characterization of the hump was demonstrated by the second derivatives of the sub-threshold curves. The shape of the hump changed and the reason for this was analyzed in detail. The results show that the parasitic transistor is relatively insensitive to the back-gate transistor, while for the main transistor, the effect of the back-gate transistor cannot be ignored.

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