Total dose radiation response of modified commercial silicon-on-insulator materials with nitrogen implanted buried oxide

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Nitrogen ions of various doses are implanted into the buried oxide (BOX) of commercial silicon-on-insulator (SOI) materials, and subsequent annealings are carried out at various temperatures. The total dose radiation responses of the nitrogen-implanted SOI wafers are characterized by the high frequency capacitance–voltage (C–V) technique after irradiation using a Co-60 source. It is found that there exist relatively complex relationships between the radiation hardness of the nitrogen implanted BOX and the nitrogen implantation dose at different irradiation doses. The experimental results also suggest that a lower dose nitrogen implantation and a higher post-implantation annealing temperature are suitable for improving the radiation hardness of SOI wafer. Based on the measured C–V data, secondary ion mass spectrometry (SIMS), and Fourier transform infrared (FTIR) spectroscopy, the total dose responses of the nitrogen-implanted SOI wafers are discussed.

Keywords: silicon-on-insulator, total dose radiation hardness, nitrogen implantation

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1. Introduction

As is well known, silicon-on-insulator (SOI) devices have many advantages, such as smaller leakage current, higher speed performance, lower power consumption and immunity to classical latchup, over their bulk-silicon counterparts.[1,2] Particularly, the SOI device has greatly reduced the charge collection volume and p–n junction area, resulting in less sensitivity to ion strikes for its space applications.[3,4] However, the total dose radiation damage of the buried insulator layer in the SOI structure reduces the total-dose radiation tolerance of the SOI device in the space radiation environment.[5,6] Radiation-induced trapped positive charges in the buried layer will affect the performance and the reliability of the SOI device and integrated circuit. Especially, for advanced fully-depleted (FD) SOI technology, the radiation-induced charge buildup in the insulator layer can cause a complex total-dose response because of the electrical coupling between the top and bottom channels through the very thin silicon film, compared with that for the partially-depleted (PD) SOI technology.[7,8] This makes a FD SOI device much more sensitive to insulator layer charge trapping. Therefore, the total-dose radiation hardness of the buried layer has become one of the most crucial factors affecting the total-dose radiation tolerance of the SOI device and circuit.

On the other hand, in advanced SOI technologies, the very thin silicon film makes it difficult to apply the hardening methods commonly used for PD SOI devices to FD ones. Consequently, the improvement of the total-dose hardness of SOI buried layer has been attracting a great deal of attention, and many hardening techniques and processes have been explored. For example, the radiation hardened SOI wafers with multilayer buried dielectric, SiO_2–Si_3N_4–SiO_2, and silicon oxynitride buried layer were prepared respectively by the Zone Melting Recrystallization (ZMR) process and the co-implantation of oxygen and nitrogen, increasing SOI resistance to total-dose radiation damage.[9,10] In recent years, for separation by implanted oxygen (SIMOX) SOI materials, nitrogen and silicon were separately implanted into the buried oxide (BOX) layer to improve BOX radiation hardness.[11−16] However, so far the effects of nitrogen implantation into SIMOX BOX under different conditions on the total dose response of SIMOX SOI wafers have not been studied systematically. In particular, although nitrogen

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implantation doses and post-implantation annealing temperatures are certainly two main factors affecting the total dose response of nitrogen-implanted SIMOX wafers, there has been no relevant research report.

In addition, compared with hardening methods based on synthesized buried layers like those used in Refs. [9] and [10], the hardening of commercial SIMOX wafer by employing an additional low dose ion implantation into the BOX is much more promising for practical applications for its simpler process, fewer considerations, and lower cost, with the original high quality BOX layers kept . So, this work focuses on the total dose responses of commercial SIMOX SOI materials modified by nitrogen implantation into the BOX at various doses and the influence of post-implantation annealing temperature on the radiation hardness of the nitrogen implanted BOX. The capacitance–voltage (C–V) technique is used for characterizing the total dose responses of tested SIMOX wafers. Secondary ion mass spectrometry (SIMS) and Fourier transform infrared (FTIR) spectroscopy technique are also used for analysing the experimental results.

2. Experimental details and C–V characterization

Commercial SIMOX SOI wafers used in this work have about 150 nm BOX, and a 190 nm ⟨100⟩ p-type top silicon layer with a resistivity of 10–20 Ω·cm. For SIMOX wafers #1–#5, nitrogen ions of various doses were implanted into the BOXs at 90 keV. For wafers #1–#3, the nitrogen implantations were performed with three different doses (2.5×10^{15}, 7.5×10^{15}, and 2.0×10^{16} cm^{-2}), respectively. The subsequent annealing was carried out at 1200 °C for 2 h in N_2 ambient. For wafers #4 and #5, the nitrogen implantation was done with the same dose, 5.0×10^{15} cm^{-2}, and the post-implantation annealings were performed at 1100 °C and 1000 °C, respectively, for 2 h in N_2 ambient. The implantation doses and the corresponding annealing temperatures for this work are summarized in Table 1, where the experimental results are also presented for comparison. During nitrogen implantation, all the wafers were maintained at 300 °C. In addition, wafer #0 serving as a control was not treated with nitrogen implantation, while wafer #6 used as a supplementary for SIMS and FTIR analysis was implanted with a nitrogen dose of 1.0×10^{16} cm^{-2} at 90 keV, and the subsequent annealing was done at 1100 °C for 2.5 h in N_2 ambient.

Table 1. Results of C–V measurements and their corresponding $D_{\rm rad}$ values.

MBS	Nitrogen	Annealing	50 krad(Si)		300 krad(Si)		500 krad(Si)	
	Dose/cm^{-2}	T/°C	$-\Delta V_{\rm FB}$/V	$D_{\rm rad}$/cm^{-2}	$-\Delta V_{\rm FB}$/V	$D_{\rm rad}$/cm^{-2}	$-\Delta V_{\rm FB}$/V	$D_{\rm rad}$/cm^{-2}
#0	–	–	2.2	3.25×10^{11}	12.7	1.88×10^{12}	17.6	2.53×10^{12}
#1	2.5×10^{15}	1200	2.0	2.90×10^{11}	11.6	1.68×10^{12}	11.6	1.68×10^{12}
#2	7.5×10^{15}	1200	2.4	3.54×10^{11}	11.0	1.62×10^{12}	16.0	2.36×10^{12}
#3	2.0×10^{16}	1200	1.9	2.92×10^{11}	11.1	1.71×10^{12}	12.8	1.97×10^{12}
#4	5.0×10^{15}	1100	2.3	–	10.1	–	15.0	–
#5	5.0×10^{15}	1100	3.0	–	11.8	–	17.4	–

In order to characterize the total dose responses of the nitrogen implanted SIMOX SOI wafers using the metal-oxide-semiconductor (MOS) C–V technique, the capacitors of metal-BOX-silicon (MBS) structure as shown in Fig. 1, were fabricated by removing the top silicon layers of the wafers through reactive-ion etching (RIE). The capacitors named MBS#0–#5 were done on wafers #0–#5, respectively. All the capacitors each have a 4.4×10^{-3} cm^2 Al-gate formed by vacuum evaporation. The high frequency C–V curves of the packaged MBS#0–#5 samples were obtained by a computer-controlled HP4275 LCR meter at 1 MHz at room temperature before and after irradiation. For irradiation, a Co-60 source was used and the capacitor samples were irradiated with three different total doses (5.0×10^4, 3.0×10^5, and 5.0×10^5 rad(Si)), respectively, at room temperature. During irradiation, a positive 3 V bias was applied to the Al-gate.

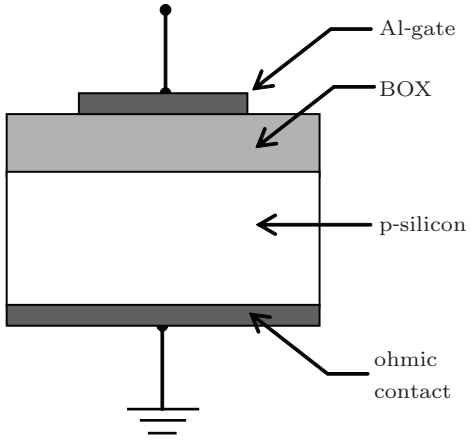


Fig. 1. Cross section of an MBS capacitor.

According to the MOS C–V theory,[17] radiation induced BOX charges will cause only a parallel shift of the C–V curve along the gate voltage $V_{\rm G}$ axis, while BOX/silicon interface trapped charges will distort ones. So, the total dose responses of the SOI wafers can be directly reflected by the changes of C–V curves of the MBS capacitors between pre- and post-irradiation. The shift of flat-band voltage, $\Delta V_{\rm FB}$, for an irradiated capacitor C–V curve, can be expressed as

$$\Delta V_{\rm FB} = -(Q_{\rm ox} + Q_{\rm i})/C_{\rm BOX}, \tag{1}$$

where $Q_{\rm ox}$ is the radiation induced BOX equivalent charge, $Q_{\rm i}$ is the radiation-induced interface charge, and $C_{\rm BOX}$ is the BOX capacitance. Figure 2 schematically illustrates Eq. (1) for an MBS capacitor with a p-type silicon substrate, with the flat-band voltage shift components, $-\Delta V_{\rm FB1}$ and $-\Delta V_{\rm FB2}$, induced by $Q_{\rm ox}$ and $Q_{\rm i}$, respectively. Furthermore, the radiation induced equivalent charge number density, $D_{\rm rad}$, under flat-band condition is given by

$$D_{\rm rad} = (Q_{\rm ox} + Q_{\rm i})/qS, \tag{2}$$

where q is the elementary charge, and S the MBS capacitor gate area. By Eq. (1), we can also write Eq. (2) as

$$D_{\rm rad} = -\Delta V_{\rm FB} C_{\rm BOX}/qS. \tag{3}$$

Both $\Delta V_{\rm FB}$ and $C_{\rm BOX}$ can be obtained from the measured C–V characteristics. So, the total dose responses can be characterized quantitatively by calculating $D_{\rm rad}$ from Eq. (3). In most cases, $\Delta V_{\rm FB2}$ is much smaller than $\Delta V_{\rm FB1}$, therefore, $Q_{\rm ox}$ usually is a main factor leading to flat-band voltage shift.

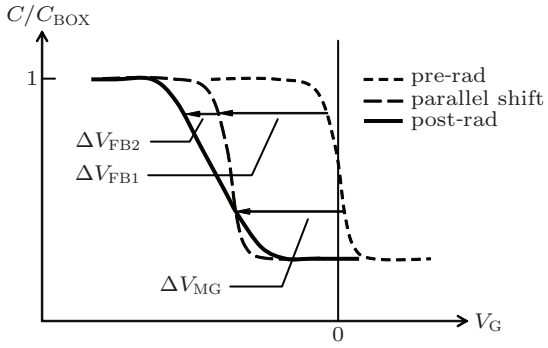


Fig. 2. Schematic C–V curves of an MBS capacitor with a p-silicon substrate before and after irradiation.

3. Results and discussion

Figures 3–7 show the typical high-frequency C–V curves of the MBS#0–#5 capacitors, respectively, before and after irradiation, with $V_{\rm FB0}$ denoting pre-irradiation flat-band voltage. From these figures, it can be seen that nearly all of the post-rad C–V curves warp seriously near their midgap voltages, owing to the lateral spreading of the effective gate area of the tested capacitors with the increase of the positive charge density in the irradiated BOX.[18] Therefore, it is difficult to use the midgap voltage shift, $\Delta V_{\rm MG}$ (as shown in Fig. 2), to accurately characterize the total dose hardness of the nitrogen-implanted BOX. Also, it can be found that almost only a negative parallel shift occurs for each of the post-rad C–V curves except for the warped bottoms as compared with the pre-rad ones. This means that $\Delta V_{\rm FB}$ approximately equals $\Delta V_{\rm FB1}$, or $\Delta V_{\rm FB}$ is nearly the same as $\Delta V_{\rm MG}$. So, $D_{\rm rad}$ depends almost only on radiation induced BOX charges. In addition, for easily comparing the total dose response between the tested samples, for all the C–V curves in Figs. 3–7, the parallel $-V_{\rm FB0}$ ($V_{\rm FB0} < 0$) shifts

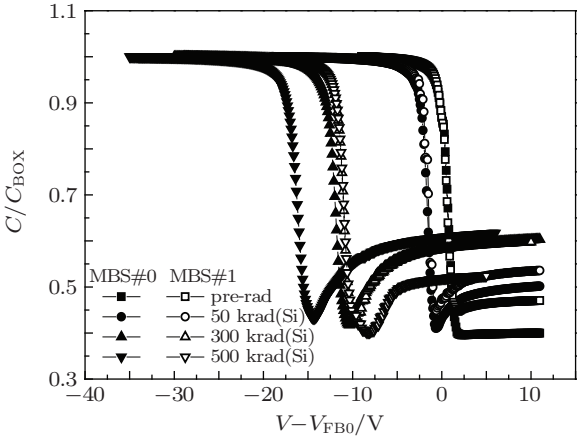


Fig. 3. The C–V curves of the MBS #0 and #1 capacitors before and after irradiation.

along the positive direction of the V_G axis are purposely made, respectively. Table 1 gives the measured and calculated results for the tested MBS #0–#5 capacitors.

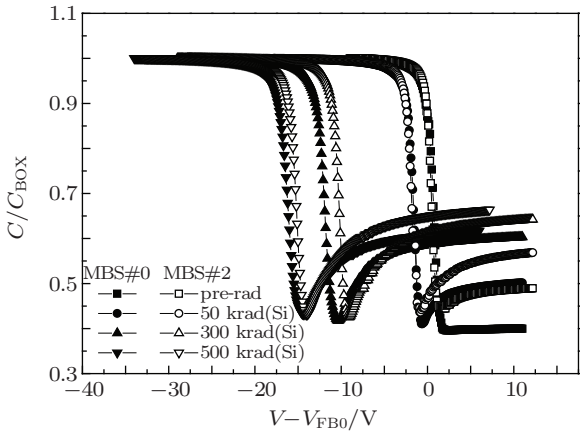


Fig. 4. The C–V curves of the MBS #0 and #2 capacitors before and after irradiation.

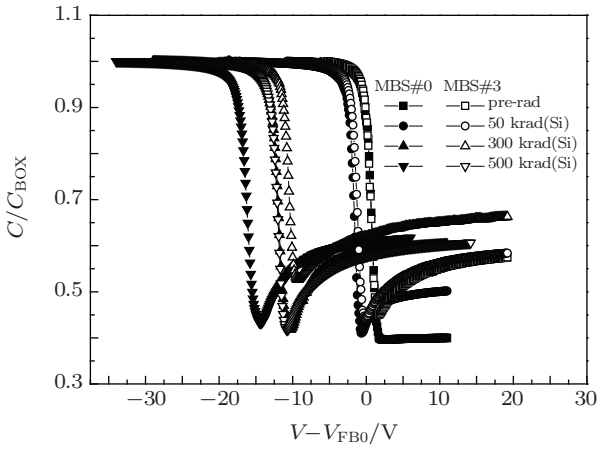


Fig. 5. The C–V curves of the MBS #0 and #3 capacitors before and after irradiation.

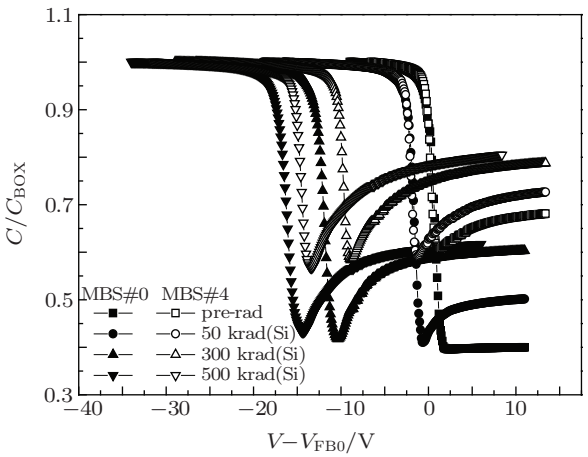


Fig. 6. The C–V curves of the MBS#0 and #4 capacitors before and after irradiation.

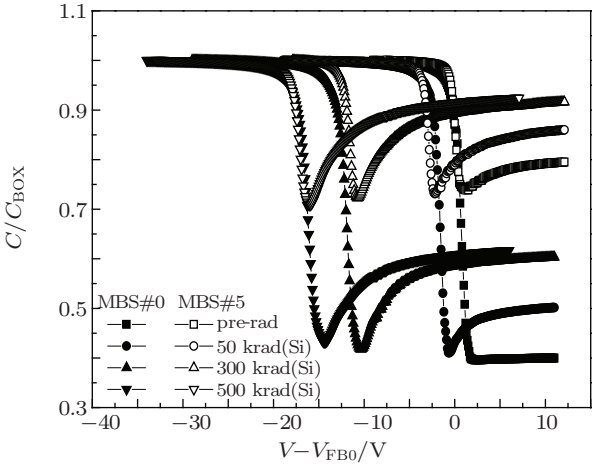


Fig. 7. The C–V curves of the MBS #0 and #5 capacitors before and after irradiation.

From Table 1, it is clear, according to ΔV_{FB}, that the total dose response of the nitrogen-implanted BOX is complex, varying with the nitrogen doses and the post-implantation annealing temperatures. For a lower total dose irradiation of 50 krad(Si), although MBS#1 and MBS#3 BOX each reveal that the total dose hardness increases to some extent, the nitrogen-implanted BOX hardly exhibits an improved total dose resistance at an average level compared with the control, MBS#0. Especially, the hardness of MBS#5 BOX is even much lower than that of the control. However, when irradiation increases up to 300 krad(Si), all the tested samples with nitrogen-implanted BOX display a limited increase in total dose hardness, with about 10% $-\Delta V_{FB}$ decrease relative to that of the control. Next, after 500 krad(Si) irradiation, the response becomes complex again. For MBS#1, the nitrogen-implanted BOX shows a significant hardness improvement, with the biggest resistance to total dose radiation, while MBS#5 shows the lowest hardness which is lower than the hardness of the control again. Basically, the lower the annealing temperature, the smaller the hardness is. However, there is no simple relationship between the nitrogen dose and the total dose hardness characterized by ΔV_{FB}. Nevertheless, the results from these three irradiations suggest that the combination of a lower nitrogen implantation dose and a higher post-implantation annealing temperature is suited for hardening these commercial SIMOX wafers. Additionally, it should also be noted that a higher dose nitrogen implantation, such as 10^{16} cm^{-2}, probably leads to some undesirable effects, such as a significant increase in the initial BOX charge density,[19] although a relative high radiation tolerance can be reached at this implantation

dose (just as seen in Table 1).

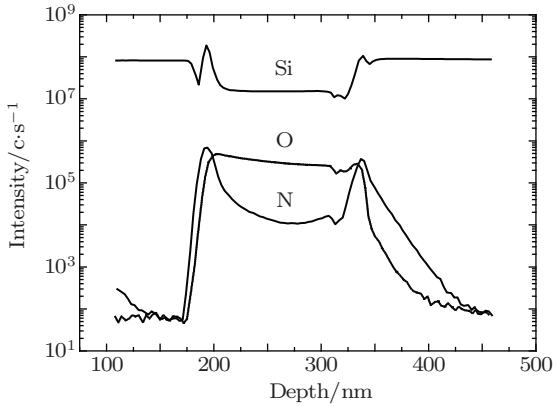


Fig. 8. The SIMS results of silicon, oxygen, and nitrogen depth profiles of wafer #6.

Figure 8 shows the SIMS result of wafer #6. It can be found that a peak nitrogen concentration occurs near the BOX/silicon interface. The total dose response of the nitrogen implanted BOX probably depends on the nitrogen accumulation near the interface to a great extent. On the one hand, it is well known that near the thermal silicon dioxide/silicon interface, there are strained silicon–silicon bonds, which can become the positive E' center (a defect with a trapped hole) by capturing a hole during irradiation.[20] Thus, there should exist similar strained bonds near the BOX/silicon interface due to a similar structure, and the nitrogen accumulation near the interface will be likely to cause a portion of the trained bonds to fracture, and subsequently, a portion of the fractured trained bonds will be likely to form a new silicon–nitrogen–silicon bridge bond structure by combining a nitrogen atom. On the other hand, according to Ref. [21], the silicon–nitrogen–silicon bridge bonds act as electron traps. Therefore, when a silicon–nitrogen–silicon bridge bond is produced from strained Silicon–Silicon bonds, a potential radiation-induced positive centre disappears, and an electron trap occurs at the same time. The electron traps will increase the BOX radiation hardness, owing to the accumulation of radiation-induced positive charges in the BOX offset by trapped electrons. As a result, the nitrogen implanted BOX shows increased radiation hardness in most cases as seen in Table 1. In addition, lower post-implantation annealing temperatures will be likely to affect the formations of silicon–nitrogen–silicon bridge bonds, and the nitrogen accumulation near the interface will also be likely to make a portion of strained silicon–silicon bonds weaker, more easily trapping holes and turning into the E' centres during irradiation. Therefore, the total dose radiation response of the nitrogen-implanted BOX displays its complexity related to implantation and annealing conditions at different irradiation doses.

In order to obtain more information from the nitrogen-implanted BOX, the FTIR spectra of wafer #0 and #6 were measured, and the results are shown in Fig. 9. The two spectra are almost identical in position and shape of absorption band. In particular, for wafer #6, the absorption band located near 800 cm^{-1},corresponding to silicon–nitrogen bond in silicon oxynitride layers,[22,23] cannot be observed from Fig. 9 compared with the control, wafer #0. A probable reason for it is that only a minority of implanted nitrogen atoms combine with silicon ones to form nitrogen–silicon bonds and silicon–nitrogen–silicon bond structures in the silicon-rich region near the BOX/silicon interface during post-implantation annealing, while the majority of the ones remain interstitial. The diffusion of nitrogen interstitials towards the interface during annealing maybe forces the nitrogen ions to accumulate near the interfaces, so the nitrogen accumulation level is greatly dependent on nitrogen dose and subsequent annealing condition. A further study is necessary for gaining clear physical insights.

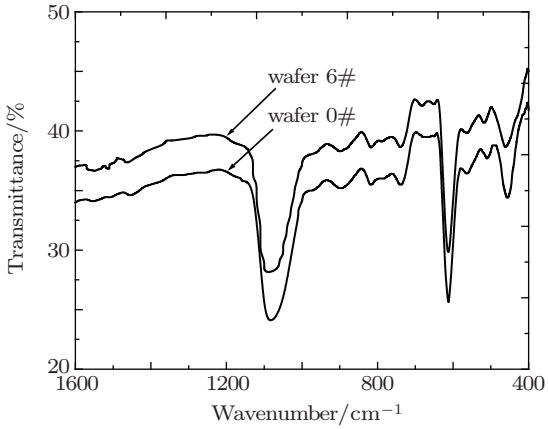


Fig. 9. The Fourier transform infrared (FTIR) spectra of wafer #0 and #6, with background corrections done with reference to air.

4. Conclusions

The total dose radiation response of the modified commercial SOI wafer by implanting nitrogen into the BOX depends on the nitrogen implantation dose, post-implantation annealing temperature, and irradiation dose. There is no simple relationship between the radiation hardness of the modified wafer and the

nitrogen implantation dose. For the studied commercial SOI wafer in this work, the radiation hardness can be improved considerably by a 2.5×10^{15} cm^{-2} nitrogen implantation at 90 keV and subsequent annealing at 1200 °C for 2 h. In particular, the experimental results suggest that a lower dose nitrogen implantation and a higher post-implantation annealing temperature are suited for improving the total dose radiation hardness of commercial SOI material.

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