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The modification of SIMOX (separated by implantation of oxygen) material to improve the total-dose irradiation hardness

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Abstract. F^+ ions with different energies and doses were implanted into SIMOX (separated by implantation of oxygen) materials to improve their irradiation hardness characteristics. Capacitors were fabricated on the SIMOX material after removing the top silicon layer. The high-frequency C–V characteristics of the capacitors after irradiation with ^{60}Co γ-rays were investigated. It is found that the process of F^+ implantation can effectively improve the total-dose irradiation hardness of the buried oxide (BOX) layer of the SIMOX materials. In addition, with the change of dose and energy of the F^+ implantation, the distribution of F in the SIMOX material was also changed; in particular, for the dose of 5×10^{13} F^+ cm^{-2} and 90 keV implantation, a nearly uniform fluorine doping is produced in the BOX layer upon 900 °C annealing.

1. Introduction

The technology relating to SOI (silicon-on-insulator) material, which has been called the electronic material for the next century, has been developing quickly in recent years [1, 2]. Compared with bulk silicon CMOS devices, SOI devices have higher speed and higher tolerance to transient irradiation and single-event upset (SEU) because of their insulated structure [3, 4]. However, the BOX layer in SOI material has to some extent a negative influence on the tolerance to irradiation.

It is well known that the BOX layer of a fully depleted device will couple with the top gate [2, 5], which will exert a negative influence on the electrical characteristics of the device. During irradiation, the charges induced in the BOX layer will couple with that in the top gate, and the device will be unable to operate. So, it is important to investigate the influence of charges in SOI material induced by irradiation.

In this paper, F^+ ions with different energies and at different doses were implanted into SIMOX materials to improve the irradiation hardness. Capacitors were then fabricated on the F^+-implanted SIMOX material after removing the top silicon layer. The distribution of F in the SIMOX material and the electrical characteristics of the capacitors were then investigated following γ-ray irradiation.

2. Experimental procedure

The p-type (100) Si wafers, with resistivities of 20–30 Ω cm, were cleaned by a standard IC procedure. The oxygen was implanted to a dose of 0.6×10^{18} cm^{-2} at 200 keV. During the implantation, the wafers were maintained at 650 °C. The subsequent annealing was performed at 1300 °C for two hours. This implantation–thermal-annealing process was repeated twice [6, 7]. The SIMOX material substrate consisted of a top single-crystalline silicon layer about 200 nm thick and a BOX layer about 400 nm thick.

The conditions of the F implantation for SIMOX material samples No 1, No 2 and No 3 were as follows:

No 1	energy: 90 keV	dose: 5×10^{12} cm^{-2}
No 2	energy: 90 keV	dose: 5×10^{13} cm^{-2}
No 3	energy: 45 keV	dose: 1×10^{15} cm^{-2}
No 4	non-implanted material.	

After F^+ implantation, all of the samples were annealed at 900 °C for 30 min in nitrogen ambient. These samples were analysed by the secondary-ion mass spectroscopy (SIMS) technique using the O^+ as the ion-sputter beam, with a sputtering rate of 3 nm min^{-1}. Capacitors were then fabricated on the SIMOX material wafers after removing top silicon layer, and then the capacitors were irradiated with ^{60}Co γ-rays. The dose rate of the irradiation was 0.35 Gy(Si) s^{-1}, and the total dose was 1000 Gy(Si). A bias voltage, $V_{gs} = 2.5$ V, between the gate and the substrate was applied to the samples during the irradiation. High-frequency C–V curves were measured before and after each irradiation.

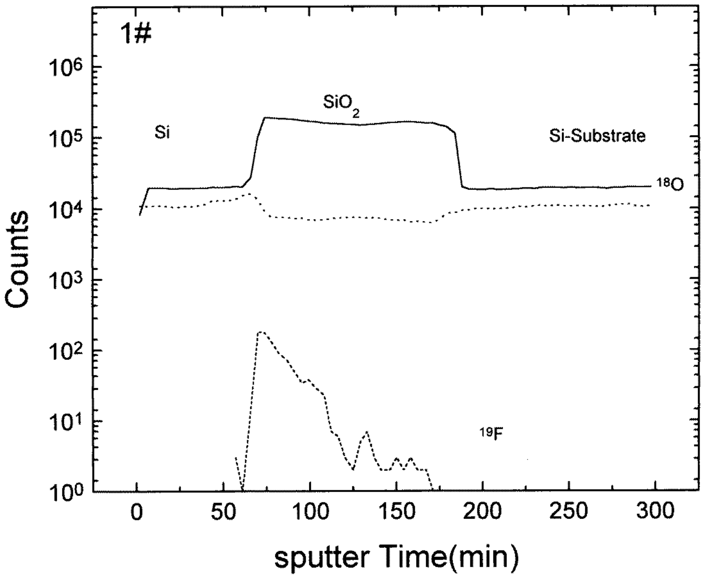

Figure 1. The SIMS profile of sample No 1, implanted with F^+ ions at 90 keV, to a dose of 5×10^{12} F^+ cm^{-2}.

3. Results and discussion

3.1. The SIMS analysis of F-implanted SIMOX material

In order to reduce the damage of the BOX layer caused during implantation [8, 9], the F^+ ions were implanted into the top silicon layer or the front Si/BOX layer interface. Then, the F atoms were diffused into the BOX layer by high-temperature annealing at 900 °C for 30 min. The F^+-ion energy was selected by means of a transport of ions in matter (TRIM) calculation. For samples No 1 and No 2, 90 keV implantation gives a projected range of 182 nm, placing the F^+ at the front Si/BOX layer interface. For sample No 3, 45 keV implantation gives a projected range of 93 nm, placing the F^+ at the centre of the Si surface layer.

The SIMS result for sample No 1 is shown in figure 1. The fluorine can be seen to be distributed around the front Si/BOX layer interface for the SIMOX material after F^+ implantation and annealing. Hardly any fluorine can be seen in the top silicon layer and at the back BOX layer/Si interface. This indicates that the F^+ ions were mainly captured by the front Si/BOX layer interface traps.

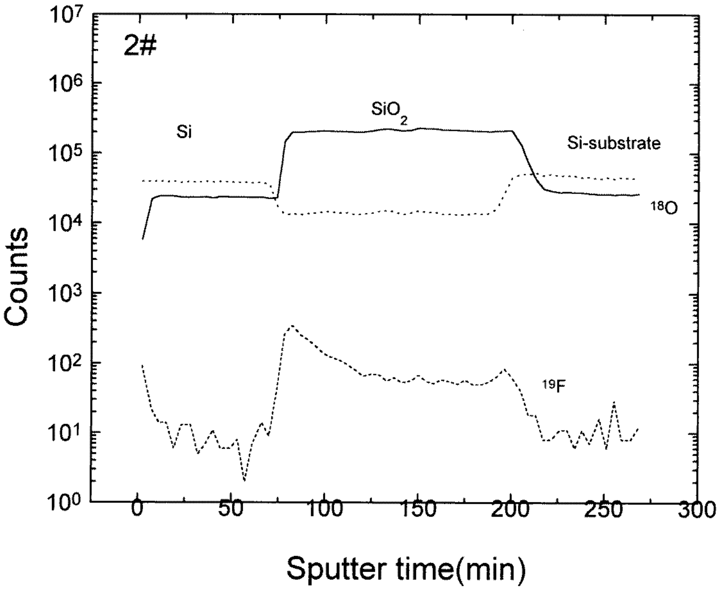

Figure 2. The SIMS profile of sample No 2, implanted with F^+ ions at 90 keV, to a dose of 5×10^{13} F^+ cm^{-2}.

The fluorine depth profile in the SIMOX material sample No 2 implanted to a dose of 5×10^{13} cm^{-2} at 900 keV is shown in figure 2. The fluorine ions were distributed throughout the whole silicon layer and the BOX layer, but the concentration of F in the silicon layer is much lower than that in the BOX layer. Throughout the whole BOX layer, a nearly uniform fluorine doping is introduced. This result provides a technique which not only introduces a uniform F^+ doping in the BOX layer, but also does not create defects in the top silicon layer or in the BOX layer upon implantation and annealing.

Figure 3 shows the fluorine depth profile in the SIMOX material sample No 3 implanted to a dose of 1×10^{15} cm^{-2} at 45 keV. The result shows that there are two peaks of F content

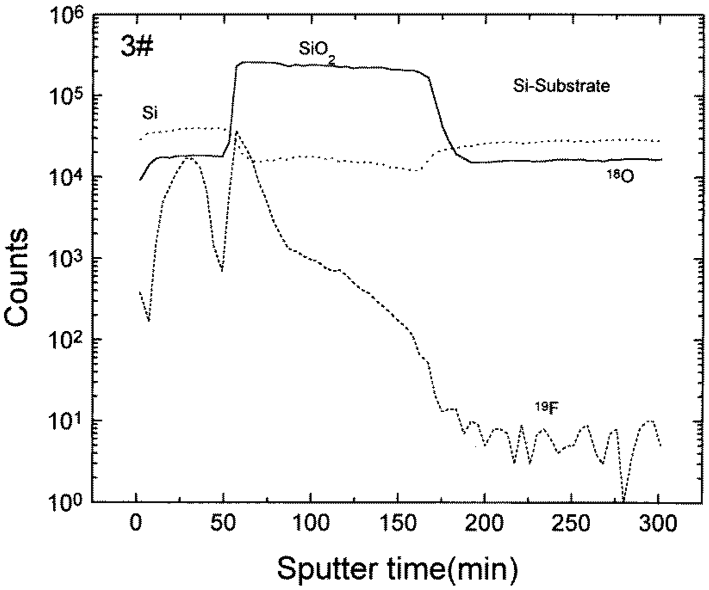

Figure 3. The SIMS profile of sample No 3, implanted with F^+ ions at 45 keV, to a dose of 1×10^{15} F^+ cm^2.

in the SIMOX material after implantation and annealing. One is less pronounced and occurs in the top silicon layer, at a depth of about 90 nm; the other occurs at the front Si/BOX layer interface. The peaks cannot be attributed to different secondary-ion yields in Si and SiO_2 because the distribution of oxygen or silicon shows a typical SOI characteristic in figure 3. In our experience, if there are any different secondary-ion yields, an oxygen peak is observed for the front Si/BOX layer interface.

The SIMS analysis shown in figures 1, 2 and 3 indicates that when the implantation energies and doses of F^+ ions are different, the distributions of F in the SIMOX material are different too. It is well known that in the SIMOX material, the Si/BOX layer interface is a transition region where there are many Si dangling bonds. After F implantation, the Si dangling bonds can capture F^+ ions and form covalent bonds [10–12]. In this case, the Si/BOX layer interface acts as a large trap.

In addition, during the F^+ implantation, there will be some damage to the target material. The degree of damage depends on the stopping power of F^+ ions in the target material. TRIM calculation results show that the nuclear stopping power $(\mathrm{d}E/\mathrm{d}X)_n$ and the electronic stopping power $(\mathrm{d}E/\mathrm{d}X)_e$ are functions of the F^+-ion energy. When the F^+ implantation energy is 45 keV or 90 keV, the F^+-ion energy decreases with increase of the F^+ penetration depth. Therefore $(\mathrm{d}E/\mathrm{d}X)_e$ decreases rapidly; but $(\mathrm{d}E/\mathrm{d}X)_n$ increases gradually, and there is a peak when the F^+ energy drops to 7 keV. It is well known that the ionization of target atoms is mainly due to the electronic stopping power, and the displacement of target atoms is attributed to the nuclear stopping power. So, the larger the nuclear stopping power, the greater the displacement, and, therefore, the more serious the damage.

For samples No 1 and No 2, the projected range of F^+ places it at the front Si/BOX layer interface; therefore the maximum damage caused by F^+ implantation is near the interface. The damage region and the interface are almost overlapping. This is why the distributions of fluorine in samples No 1 and No 2 are concentrated at the interface. For sample No 2, the number of F atoms distributed in the BOX layer is much higher than the number distributed in the top silicon layer. This proves that F^+ ions diffuse into the BOX layer upon high-dose F^+ implantation and annealing.

For sample No 3, the projected range of F^+ is less than the depth of the Si/BOX layer interface, so the damage caused by F^+ implantation is located in the silicon film and the maximum-damage region does not overlap with the front Si/BOX layer interface. During the annealing, many F^+ ions were captured by both the damage region and the interface. This was why the fluorine distribution had two peaks in the SIMOX material wafer.

3.2. The C–V characteristics of SIMOX material capacitors

The midgap voltage, V_{mg}, was chosen as the parameter to investigate in order to study the effects of total-dose irradiation on capacitors [13]. V_{mg} depends on the number of parasitic charges in the SiO_2 layer. There are four kinds of parasitic charge.

(i) The first is fixed oxide charges which exist close to the Si/SiO_2 interface. Their generation is related to the mechanism of growth of the oxide layer.

(ii) The second is the trapped oxide charges which are induced by irradiation with photons, or ions, or the injected carriers of high energy. They exist throughout the whole SiO_2 layer.

(iii) The third is the trapped interface charges which lie at the Si/SiO_2 interface. They can exchange carriers with the semiconductor, and have the characteristics of donors or acceptors. For p-type Si they act as acceptors while for n-type Si they act as donors.

(iv) The last is the mobile ions which exist within the oxide layer and arise from the pollution with alkaline ions. They can move in an external electric field. The modern process of producing MOS devices has almost overcome the influence of mobile ions.

For the high-frequency C–V measurement [14, 15], the trapped interface charge cannot respond to the voltages used, so the change in V_{mg} depends on the changes in the number of fixed and trapped oxide charges. Because the number of fixed oxide charges cannot be changed during the irradiation, the shift of V_{mg} is due only to the change in the number of oxide-trapped charges during irradiation. The higher the number of trapping charges, the bigger the V_{mg}-shift.

The characteristic of the capacitor which was made using sample No 3 is poor; that is, the p-type silicon film became n-type, and the C–V curve deformed upon high-dose F^+ implantation. ΔV_{mg} versus the total-dose irradiation for samples No 1, No 2 and No 4 is shown in figure 4. With the increment of the total dose, ΔV_{mg} increases for all samples. The biggest shift of V_{mg} among those for all of the samples is that for sample No 4, the second biggest is that for sample No 1, and the smallest is that for sample No 2. These facts prove that the quality of the BOX layer can be improved by F^+ implantation. So the SIMOX material can be hardened against total-dose irradiation by this method.

For the SIMOX material, there are a lot of neutral traps in the BOX layer. During the irradiation, a large number of electron–hole pairs are generated. While the electrons are swept away quickly by the external electric field, the holes move slowly along the direction of the field because of their larger mass. Some of the holes are trapped by neutral traps and change into oxide-trapped charges which shift V_{mg} in the negative direction. With increase of the total dose, the number of trapped holes increases too. This makes V_{mg} shift further in the negative direction.

Figure 4 shows that F^+ implantation can effectively reduce the number of neutral traps in a BOX layer and result in there being fewer charges trapped during irradiation. Therefore

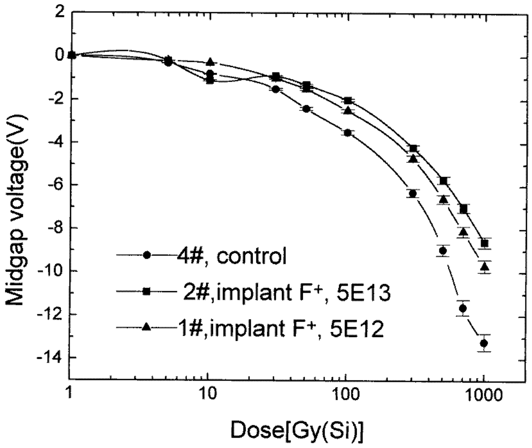

Figure 4. The midgap voltage (V_{mg}) versus the total γ-dose for the SIMOX material capacitors.

the shift of V_{mg} can be reduced and the total-dose irradiation hardness of the BOX layer in SIMOX material can be improved. This result can be explained by the bonding of Si and F atoms. In the BOX layer, because of the uneven distribution of oxygen, there are some E′-centre defects in the regions that are lacking in oxygen [10, 11, 16]. The E′ defect is a silicon atom which bonds to three oxygen atoms. So, in the defect every Si atom retains a dangling bond, and can bond to a hydrogen atom. Therefore, a weak Si–H covalent bond (the affinity of a H atom is only 2.2) is formed. This is called a neutral trap. During irradiation, the Si–H bond will break easily and an irradiation-induced hole can substitute for a H atom. Upon F^+ implantation and annealing, the fluorines were doped into the BOX layer; because of the strong affinity (it is 4.0) of F atoms, a F atom can substitute for a H atom and form a strong Si–F covalent bond. This bond cannot be destroyed easily during irradiation. So the irradiation-induced holes cannot substitute for the F atoms and the material is hardened against γ-ray irradiation.

In addition, the leakage currents of the three kinds of capacitor were also measured after γ-ray irradiation, and it was found that the leakage increased slightly with increment of the total dose of the γ-ray irradiation.

4. Conclusions

SIMOX material has been implanted with F^+ ions and then annealed, The distribution of F in the SIMOX material is related to the implantation energy and F^+ dose. With the dose of 5×10^{13} F^+ cm^{-2} for 90 keV implantation, a nearly uniform F^+ doping is produced in the BOX layer upon 900 °C annealing, and defects are not created in the silicon layer or the BOX layer during F^+ implantation. In addition, F^+ implantation can reduce the number of neutral traps in the BOX layer, so the SIMOX material can be improved as regards its response to the total-dose irradiation by this method.

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