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Pseudo-MOSFET Analysis of Proton Irradiated and Annealed SOI Wafer

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The total dose irradiation effect on the SOI wafer is analyzed at the material level by pseudo-MOSFET technique. The proton irradiation induces positively charged traps in the buried oxide (BOX) and amphoterically charged traps at the film-BOX interface. The amphoteric interface trap charges contribute to the shift in threshold and flatband voltages by modifying the effect of the positive fixed charge in the BOX. The inherent ambipolar pseudo-MOSFET characteristics reveal both NMOS and PMOS properties, making it possible to identify and separate the charges that contribute to the shift of the turn-on voltage. The negatively charged acceptor-like states are located in the upper part of bandgap whereas the positively charged donor-like states are situated in the lower part of bandgap. These interface trap states can be removed by low-temperature annealing, so that only the oxide trapped charges continue to govern the turn-on voltage shift.

Introduction

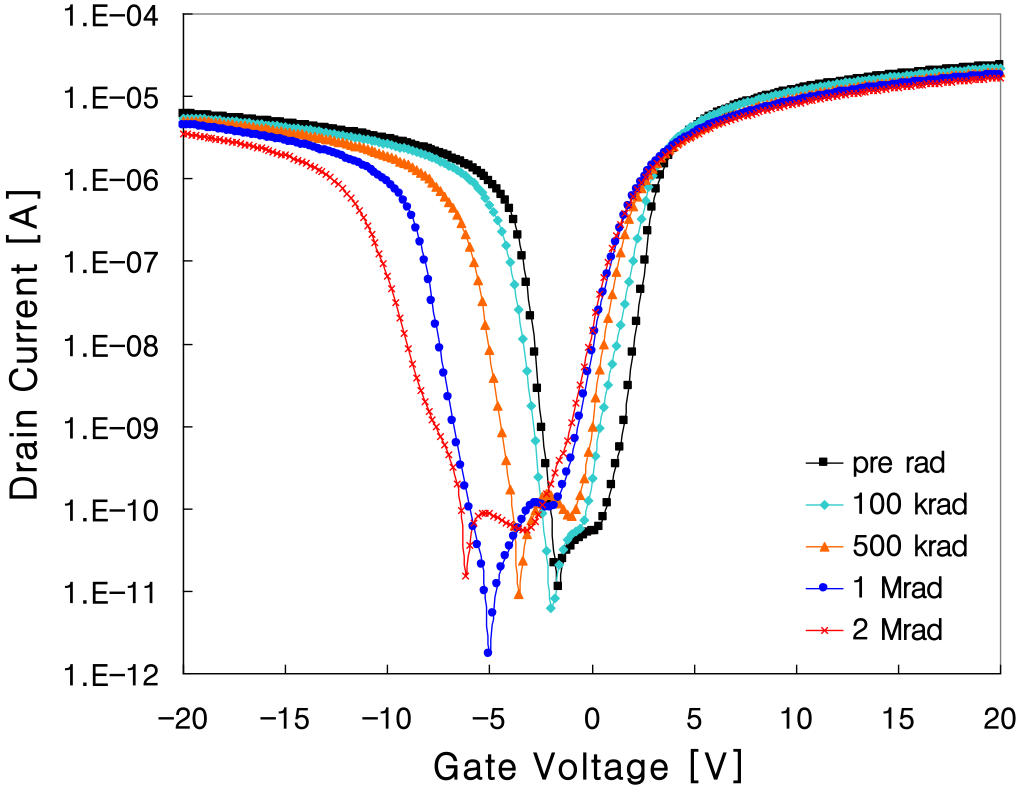
SOI structures are traditional materials for radiation hardened semiconductor devices, utilized for example in aerospace applications. SOI has advantage of outstanding immunity to single event upsets due to its structure composed of a thin silicon layer on top of the buried insulator (BOX). Still, SOI has drawbacks such as trapped charge generation in buried oxide which gives rise to total dose irradiation effects (1). Understanding the behavior of irradiation-induced interface traps and fixed charges in the BOX is important. Although it has been studied for a long time, still it is not clear what the polarity of the interface trapped charge is and where the charge states are located in the bandgap (2-3). In general, characterization of irradiation effects on SOI is carried out at the device level. Pseudo-MOSFET is a method to evaluate SOI at the wafer level. Two pressure-adjustable point probes contacted on the film surface act as source and drain. Buried oxide acts as gate insulator and the substrate is the gate electrode. This measurement technique is very useful because it needs minimum device fabrication, hence the change in material properties during device processing can be avoided (4). In this paper, protons are irradiated into SOI wafers under various dose conditions and annealed to study the total dose irradiation effect on the buried oxide.

Experimental

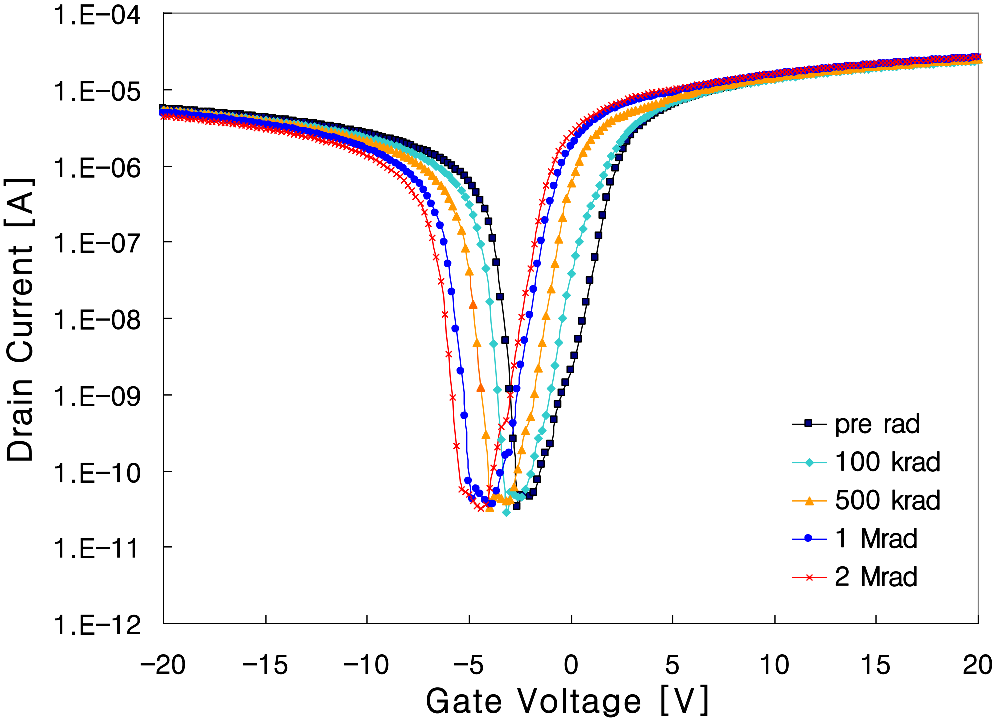
The SOI wafer used for this work was standard Unibond with thickness of 65nm and 145nm for silicon film and buried oxide, respectively. Large silicon islands (5mm x 5mm) were isolated to prevent the leakage current through the possible pinholes of buried oxide and wafer edges during pseudo-MOSFET measurements. Wet etching was used to minimize the process-induced defect generation during the island isolation (5). Proton irradiation was carried out with doses of 100 krad, 500 krad, 1 Mrad, 2 Mrad(Si). The dose rate and energy of proton irradiation were fixed at 334 rad/sec and 36.5 MeV. The wafers were annealed at 300°C for 1 hour in nitrogen ambient to stabilize the irradiation-induced defects. The electrical properties, such as turn-on voltage shift and interface trap density, were characterized by pseudo-MOSFET technique before and after annealing.

Results and Discussions

Figure 1 shows drain current-gate voltage curves for several doses. These curves illustrate the behavior of holes (for $V_G < 0$) and electrons (for $V_G > 0$). As the dose increases, the I-V curves are shifted to negative direction. This means that a net positive oxide charge is generated during proton irradiation. The amount of curve shift on the hole side is greater than that on the electron side, as shown in Figure 1(a). Therefore, as-irradiated I-V curves are 'asymmetrical'. The key point is that, after low-temperature annealing, the amount of I-V curve shift changes from asymmetrical to symmetrical (*i.e.*, equal shifts for electrons and holes), as demonstrated in Figure 1(b). This change is the interesting aspect which motivates our work.



(a)



(b)

Figure 1. Drain current versus gate voltage I_D-V_G characteristics of Pseudo-MOSFET for increased total dose radiation. (a) after irradiation, (b) after subsequent annealing.

It is known that the radiation induces positive oxide trapped charges and amphoteric interface traps which can be positively charged (donor-like) or negatively charged (acceptor-like) (2). The position of each charge state in the energy gap is still under debate. It has been showed that acceptor-like states are located in the upper part of the bandgap and also that donor-like states may be situated in the upper part of bandgap. Our aim is to clarify this issue.

Using the I_D/sqrt(g_m) vs V_G curve, the turn-on voltages of both electron and hole channels are extracted and plotted in Figure 2. They correspond to the flatband voltage for hole channel and to the threshold voltage for the electron channel. Comparing the shift of turn-on voltage before annealing, the amount of flatband voltage shift with irradiation is larger than that of the threshold voltage. However, after annealing, the flatband and threshold voltage shifts become quite similar, as the I-V curves in Figure 1 implied. Before annealing, the amphoteric interface trap charge can shift the turn-on voltage in negative or positive directions depending on its charge polarity and location in the bandgap. For the threshold voltage, the amount of shift is smaller because of the compensating effect of negative interface traps on the electron inversion channel. In this case, the surface band bending is downward, and the interface traps are occupied by electrons (acceptor-like negative traps). This is why after annealing the radiation-induced negative shift increases more rapidly with dose.

For the hole channel, the amount of flatband voltage shift is larger before annealing, meaning that there is more positive charge at the interface. In this case, the band bending due to negative gate bias is upward. So, the interface states emit electrons and are positively charged (donor-like states).

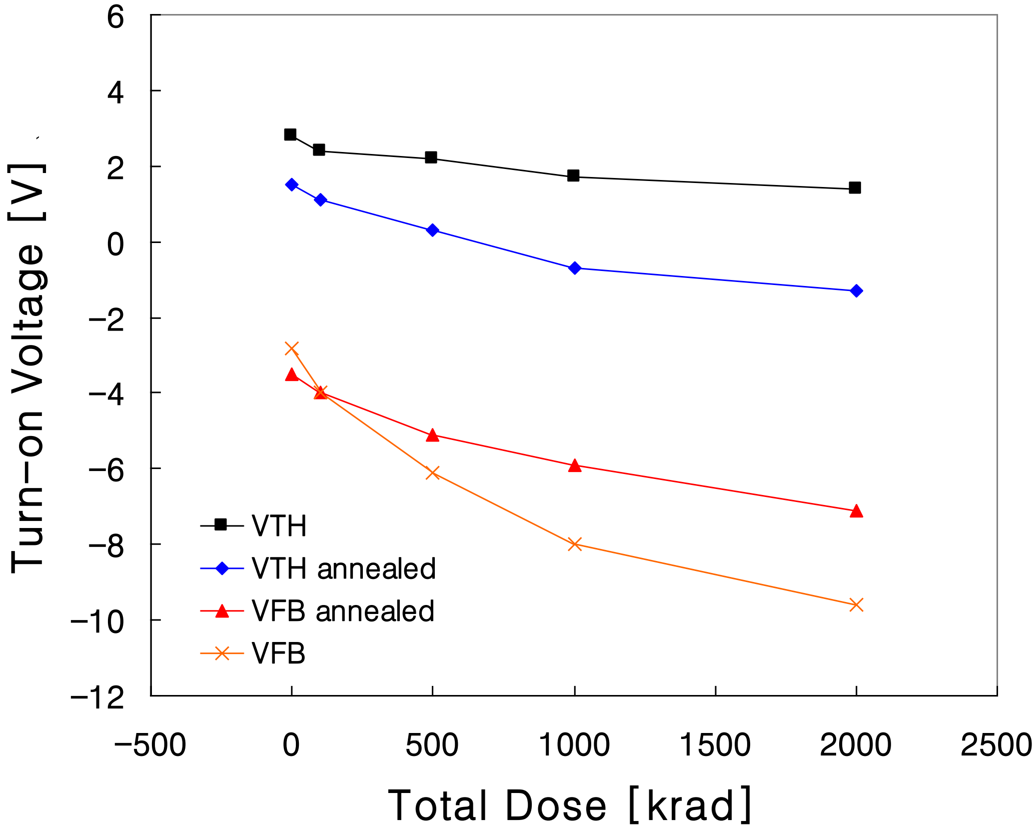


Figure 2. Comparison of threshold and flatband voltage shifts with total dose, before and after annealing.

It is concluded that acceptor-like interface states are in the upper part of bandgap and donor-like interface states are in the lower part of bandgap. After annealing, these amphoteric interface charges are removed and only the positive charges trapped inside the BOX subsist. Hence, the amount of turn-on voltage shift with dose increases equally for both polarities (electron and holes).

Additional information is obtained by extracting the interface trap density D_{it} from the subthreshold region

$$S = 2.3\frac{kT}{q}\left(1+\frac{C_{si}+qD_{it}}{C_{ox}}\right) \qquad [1]$$

where S is the subthreshold swing, $dV_G/d\log I_D$.

Figure 3 shows the variation of interface trap density with total dose. Before annealing, D_{it} steadily increases with dose. But after low-temperature annealing, the trap density is reduced and becomes rather independent of total dose. Note that this D_{it} value is slightly higher than that before irradiation. This small increase is attributed to the residual traps, which have not been totally cured by annealing, and also to the top surface, exposed to air in pseudo-MOSFET measurements. Indeed, in thin SOI structures the channel-to-surface coupling cannot be ignored (6). It is reasonable to assume that the surface condition (traps and charges) changes during low-temperature annealing and modifies the channel characteristics. Nevertheless, the radiation-induced traps at the film-BOX interface are removed during annealing process, and then only the oxide trapped charge in the BOX continues to govern the turn-on voltage shift. This is why the two curves in Fig. 2 become parallel. The radiation-induced interface trapped charge is more easily annealed out than the fixed oxide trapped charge.

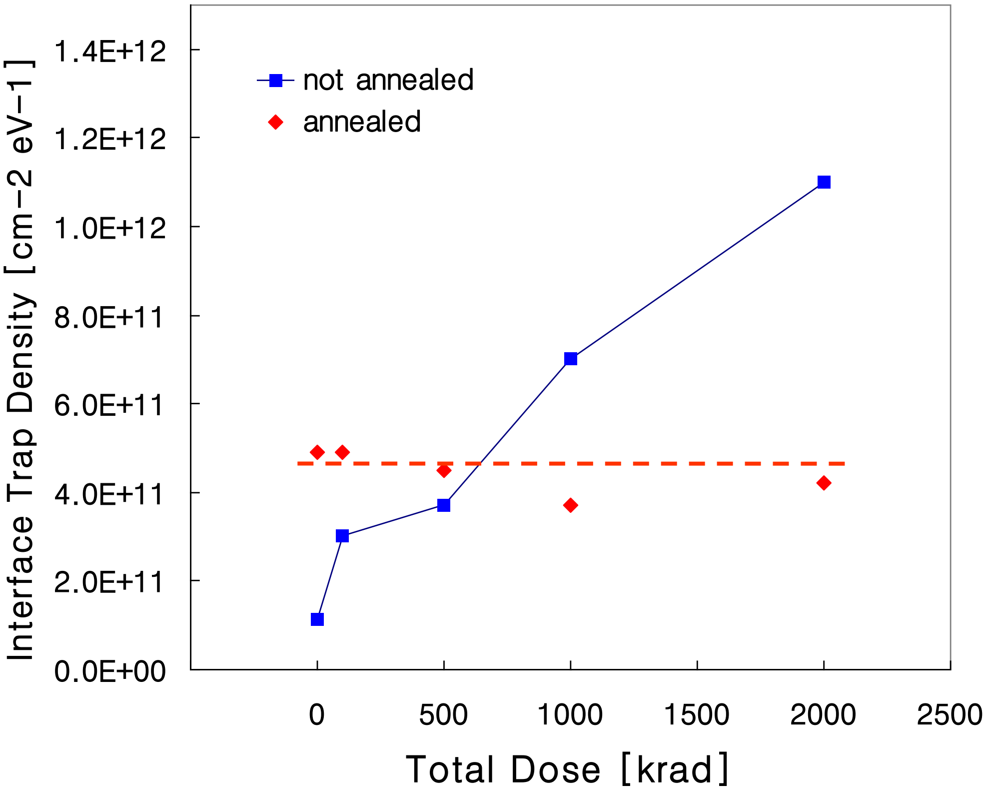


Figure 3. Density of interface trap with total dose before and after annealing.

Conclusion

The irradiation effect on SOI wafers, investigated by pseudo-MOSFET technique, shows that proton irradiation induces positively charged oxide traps and amphoteric interface traps. The negatively charged acceptor-like states, located in the upper part of the bandgap, compensate the reduction of the electron channel threshold voltage imposed by the positive BOX charge. The positively charged interface states located in the lower part of the bandgap enhance the negative shift of flatband voltage (hole channel). These radiation-induced interface trapped charges can be removed easily by low-temperature annealing process, leading to similar shifts in turn-on voltage for electron and hole channels.

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