Suppression of Heavy-Ion induced Current in SOI Device

S. Ogura[*1], T. Komiyama[1], Y. Takahashi[1], T. Makino[2], S. Onoda[2], T. Hirao[2], and T. Oshima[2]
1 Nihon University, Japan
2 Japan Atomic Energy Agency (JAEA), Japan
*Email: cssu11011@g.nihon-u.ac.jp, ytaka@ecs.cst.nihon-u.ac.jp
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Abstract

We have investigated the transient current in a SOI p$^+$n junction diode induced by single heavy-ions. The amount of radiation induced total collected charge exceeds the generated charge in active SOI layer because some of generated charge in handle substrate is collected through a BOX layer by displacement current. The displacement current is caused by the charges collected at surface of handle substrate due to an electric field in depletion layer. In this paper, we show that the amount of collected charge can be suppressed by reducing the width of depletion layer at the surface of handle substrate.

1. Introduction

One of the most detrimental effects on semiconductor devices in radiation environment is single-event effects (SEE). When a high-energy heavy ion strikes the device, electron-hole pairs are generated along the ion-track and they can create sufficient transient current to cause an incorrect action such as single-event upset (SEU). Recently, silicon–on-insulator (SOI) devices have been developed for higher SEE tolerance device, because it has been believed that the charge collection is suppressed by the existence of a buried oxide (BOX) layer [1-2]. However, anomalous charge collection in the SOI device was reported [3-5]. That indicates some of generated charge in handle Si substrate is collected through a BOX layer. From the results of heavy-ion induced gate current in MOS structure, we have concluded that the radiation-induced current through an oxide layer is dominated by a displacement current [6].

In this paper, the transient current in p$^+$n junction diode on SOI substrate induced by single heavy-ion has been investigated. From the results of the transient current from each electrode in the device, we show the anomalous charge collection is caused by the displacement current through BOX layer. The displacement current is generated by the charges collected at surface of handle substrate due to an electric field in depletion layer. We also show the displacement current can be suppressed by reducing the width of depletion layer using SOI wafer with highly doped handle substrate.

2. Experiments

Two types of Al gate SOI-p$^+$n junction diodes, n/n and n/n$^+$ devices, with the junction area of 100 µm in diameter were used in this study. Figure 1 shows the device structure of these devices. The n/n device were fabricated on a SOI substrate in which active SOI layer and handle substrate layer are n-type and the donor concentration of both layers are about 10^{15} cm^{-3}. The n/n$^+$ device is fabricated on the wafer with highly doped handle substrate. In these devices, the thicknesses of active layer and BOX layer are 1.5 µm and 0.3 µm, respectively. The devices were fabricated at Micro Functional Device Research Center of the Nihon University.

The transient currents in these devices induced by 15 MeV Oxygen ions were measured. The LETs and project range of the ions are 6.5 MeV/(mg/cm^2) and 12.3 µm, respectively. Heavy-ion irradiation tests were carried out using the Single Ion hit (SIH) system in JAEA [7] and the transient current caused by the single ion was measured by Transient Ion Beam Induced Current (TIBIC) measurement system [8]. Figure 2 shows the experimental setup of the irradiation. The cathode and back contact electrode were connected to ground and the reverse

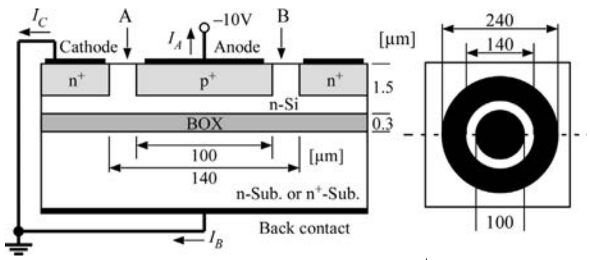

Fig. 1. Device structure of SOI p$^+$n diode

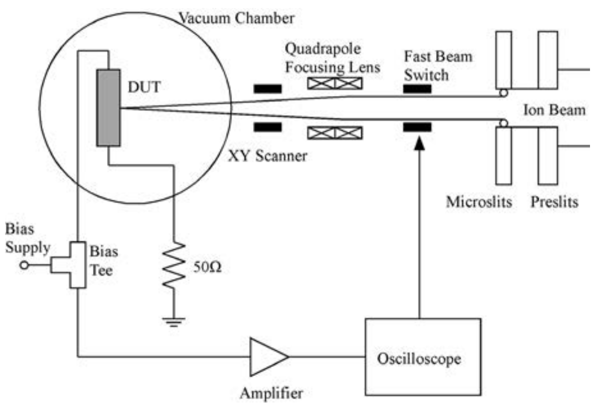

Fig. 2. Experimental setup of irradiation test

bias of 10V was applied to anode electrode during irradiation test. DC bias voltage is applied through a bias tee, and the transient current induced by heavy-ion irradiation is measured with a high-speed oscilloscope with a bandwidth of 3 GHz (Tektronix TDS 694C). In this system, the sample carrier is set on a high precision XYZ stage and the typical spot size of the focused ion beam is about 1 μm on DUT.

3. Results and Discussions

Figure 3 shows the peak of transient current and the amount of total collected charge from the anode electrode in n/n device as a function of the heavy-ion hitting location. The peak current depends on the location and larger current is observed when the heavy-ion hits to the edge of p^+ diffusion region. On the other hand, the amount of total collected charge is almost constant whenever the ion hits to the p^+ diffusion region. The charge generated in active layer due to irradiation is 100 fC and the measured collected charge is 2~3 times as much as the generated charge in active SOI layer.

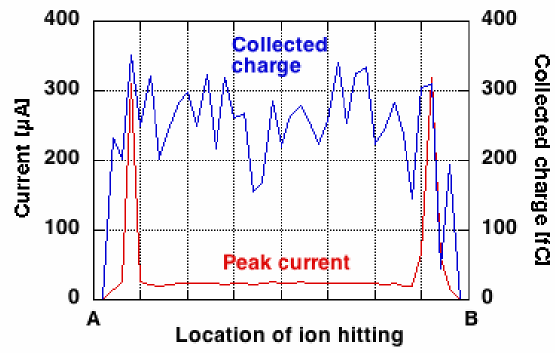

Fig. 3. Peak of transient current and total collected charge from anode electrode in n/n device as a function of the heavy ion hitting location

Figure 4 shows the transient current and the collected charge from each electrode (anode, cathode, and back contact electrodes) in n/n device when the ion hits to the center area of p^+ diffusion region. The collected charges by anode and back electrodes are almost same and the charge from cathode electrode is much smaller than that from other electrodes. These results indicate that the charges collected by anode electrode are mostly caused by the radiation induced generated charges in handle Si substrate and these charges were collected through the BOX layer.

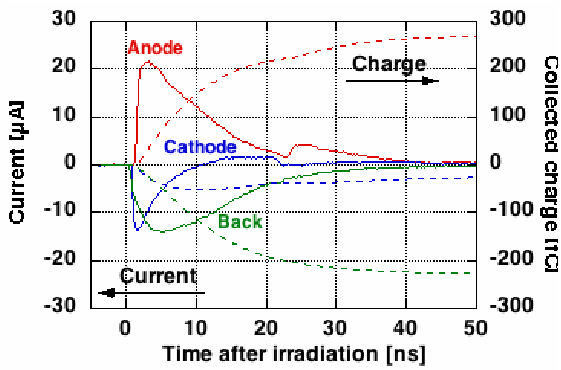

Fig. 4. Transient current and collected charge in n/n device when ion hits to the center area of p^+ region

Figure 5 shows the transient current and the collected charge in n/n device when the ion hit to the edge of p^+ diffusion region. The current peaks of anode and cathode electrodes are almost same and these are much higher than in case when the ion hits to the center area of p^+ region. When reverse bias is applied to the diode, lateral electric field is concentrated at the edge of p^+ region. The charges generated in active layer due to irradiation are collected quickly to anode and cathode electrodes by the electric field. It is considered that the quick charge collection causes the large current. The current form back electrode is much smaller than that from the other electrodes. However the current and collected charge are almost same as the result when the ion hits to the center of p^+ region, shown in Fig. 4. From these results, it is found that about half of collected charge by anode electrode is caused by the charges collected through the BOX layer.

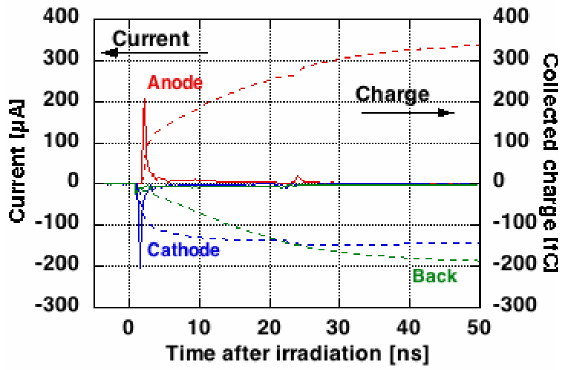

Fig. 5. Transient current and collected charge in n/n device when ion hit to the edge of p^+ region

In our present work, we concluded that the radiation-induced current through an oxide layer was dominated by a displacement current. So it is very important to suppress the displacement current through the BOX layer in order to improve radiation immunity of SOI devices. If the project range of irradiated heavy ion is much longer than the thickness of active SOI layer, electron-hole pairs are generated in handle substrate. In the case when the reverse bias is applied to the n/n device, depletion layer is formed at the surface of handle substrate under p^+ diffusion region. Some of generated electron-hole pairs escape from recombination and holes are accumulated to the surface by the electric field in depletion layer. The accumulated charges generate the displacement current through the BOX layer. So it is considered that the current can be suppressed by reducing of the width of depletion layer. The width changes with doping level of substrate and can be reduced using SOI substrate with highly doped substrate, n/n^+ device.

Figure 6 shows the peak of transient current and the amount of total collected charge form the anode electrode in n/n$^+$ device as a function of the heavy-ion hitting location. The transient current can be observed only when the ion hits to the edge of p$^+$ diffusion region. The peak current and collected charge in n/n$^+$ device are smaller than that of n/n device, and the amount of collected charge is about 100 fC which is same as the amount of generated charge in active SOI layer by irradiation.

Figure 7 shows the transient current and the collected charge from each electrode in n/n$^+$ device when the ion hits to the edge of p$^+$ diffusion region. The amounts of collected charge of anode and cathode electrodes are almost same and are less than 100 fC. The amount of collected charge by back electrode is about 20 fC that is much less than the result of n/n device. That indicates the collected charge by anode electrode is mainly caused by the radiation induced generated charge in active SOI layer.

From these results, it was confirmed that the heavy ion induced displacement current through the SOI layer could be suppressed using the device with highly doped handle substrate.

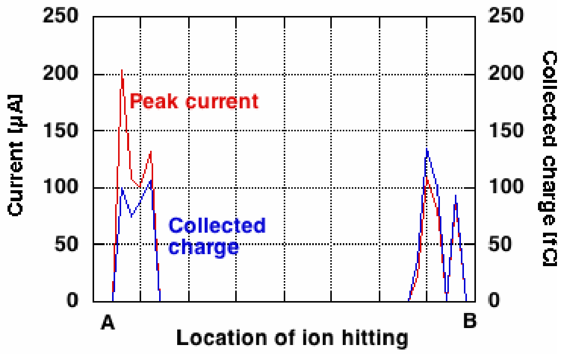

Fig. 6. Peak of transient current and total collected charge from anode electrode in n/n$^+$ device as a function of the heavy ion hitting location

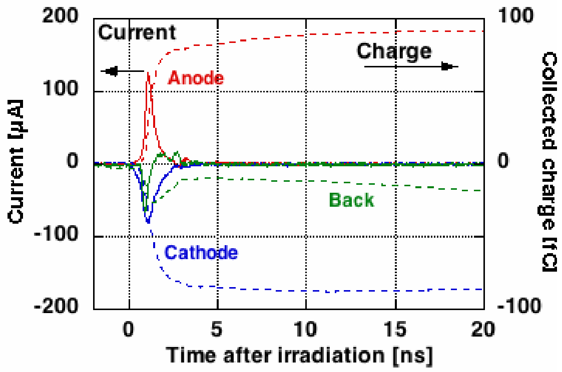

Fig. 7. Transient current and collected charge in n/n$^+$ device when ion hit to the edge of p$^+$ region

4. Conclusions

The heavy-ion induced transient current and collected charge in SOI p$^+$n diodes have been investigated. From the results of the device on n type SOI wafer, it was found that the amount of total collected charge by anode electrode exceeded the amount of radiation induced generated charge in active SOI layer and the anomalous charge collection is caused by displacement current through BOX layer. We also discussed the reduction of the displacement current by changing the width of depletion layer at surface of the handle substrate. By the experimental results, it was confirmed that the displacement current could be suppressed by decreasing the width of depletion layer, and the heavy-ion induced transient current and the total collected charge of SOI device can be reduced using the device with highly doped handle substrate.

Acknowledgments

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References

[1] O. Musseau, "Single-Event Effects in SOI Technologies and Devices," IEEE Trans. Nucl. Sci., Vol. NS-43, No. 2, pp. 603-613 (1996).
[2] T. Hirao, T. Hamano, T. Sakai, and I. Nashiyama, "Studies of charge collection mechanisms in SOI devices using a heavy-ion microbeam," Nuclear Instruments and Methods in Physics Research, Vol. B-158, pp. 260-263 (1999).
[3] P.E. Dodd, et al., "SEU-Sensitive Volumes in Bulk and SOI SRAMs From First-Principles Calculations and Experiments, " IEEE Trans. Nucl. Sci., Vol. NS-48, No. 6, pp. 1893-1903 (2001).
[4] T. Hirao, et al., "Study of single-event current pulses induced in SOI diodes by collimated swift heavy-ions micro-beams," Nuclear Instruments and Methods in Physics Research, Vol. B-206, pp. 457-461 (2003).
[5] J.R. Schwank, P.E. Dodd, et al., "Charge Collection in SOI Capacitors and Cirsuits and its Effect on SEU Hardness," IEEE Trans. Nucl. Sci., Vol. NS-49, No. 6, pp. 2937-2947 (2002).
[6] Y. Takahashi, et al., "Heavy-ion induced current through an oxide layer," Nuclear Instruments and Methods in Physics Research, Vol. B-260, pp. 309-313 (2007).
[7] T. Sakai, T. Hamano, T. Suda, T. Hirao, and T. Kamiya, "Recent progress in JAERI single ion hit system," Nuclear Instruments and Methods in Physics Research, Vol. B-130, pp. 498-502 (1997).
[8] J.S. Laird, T. Hirao, H. Mori, S. Onoda, T. Kamiya, and H. Itoh, "The development of a new data collection system and chamber for microbeam and laser investigations of SEU phenomena," Nuclear Instruments and Methods in Physics Research, Vol. B-181, pp. 87-94 (2001).