World Academy of Science, Engineering and Technology
International Journal of Electronics and Communication Engineering
Vol:12, No:6, 2018

Modification of Electrical and Switching Characteristics of a Non Punch-Through Insulated Gate Bipolar Transistor by Gamma Irradiation

Hani Baek, Gwang Min Sun, Chansun Shin, Sung Ho Ahn

***Abstract*—**Fast neutron irradiation using nuclear reactors is an effective method to improve switching loss and short circuit durability of power semiconductor (insulated gate bipolar transistors (IGBT) and insulated gate transistors (IGT), etc.). However, not only fast neutrons but also thermal neutrons, epithermal neutrons and gamma exist in the nuclear reactor. And the electrical properties of the IGBT may be deteriorated by the irradiation of gamma. Gamma irradiation damages are known to be caused by Total Ionizing Dose (TID) effect and Single Event Effect (SEE), Displacement Damage. Especially, the TID effect deteriorated the electrical properties such as leakage current and threshold voltage of a power semiconductor. This work can confirm the effect of the gamma irradiation on the electrical properties of 600 V NPT-IGBT. Irradiation of gamma forms lattice defects in the gate oxide and Si-SiO_2 interface of the IGBT. It was confirmed that this lattice defect acts on the center of the trap and affects the threshold voltage, thereby negatively shifted the threshold voltage according to TID. In addition to the change in the carrier mobility, the conductivity modulation decreases in the n-drift region, indicating a negative influence that the forward voltage drop decreases. The turn-off delay time of the device before irradiation was 212 ns. Those of 2.5, 10, 30, 70 and 100 kRad(Si) were 225, 258, 311, 328, and 350 ns, respectively. The gamma irradiation increased the turn-off delay time of the IGBT by approximately 65%, and the switching characteristics deteriorated.

***Keywords*—**NPT-IGBT, gamma irradiation, switching, turn-off delay time, recombination, trap center.

I. Introduction

IGBTs have been widely used for high power switching devices due to its low forward voltage drop and high input impedance [1]. Switching times and energies such as turn-on/off delay time and switching losses are, however, the main drawbacks of IGBTs, and various attempts have been made to improve these characteristics.

One of such efforts is to generate lattice defects in the drift region of an IGBT so as to increase the recombination of minority carriers. Irradiation using neutrons, protons, or electrons is a possible way to generate recombination centers for minority carriers. Among various particle irradiations, fast neutron irradiation in a nuclear reactor is the most effective way to improve switching characteristics and short circuit durability of IGBTs because of its ability to produce recombination centers uniformly distributed in the devices.

The IGBTs irradiated in a nuclear reactor are exposed not only to fast neutrons, but also to thermal neutrons and gamma rays. Hence, the effects of thermal neutron irradiation and gamma irradiation are also of concern. Thermal neutrons can induce transmutation doping in silicon. Gamma rays may induce damages by heating and producing recoil atoms. The effects of gamma irradiation on various metal oxide semiconductor (MOS) devices have been actively studied [2] including IGBTs [3]-[5].

In this study, we evaluated the effects of gamma irradiation dose on a Non Punch-Through (NPT) IGBT's static electrical characteristics such as gate threshold voltage, collector-emitter voltage/leakage current, and switching characteristics such as turn-off delay time.

II. Experimental

The schematic cross-sectional structure of the NPT IGBT used in this study and a 6-inch wafer of the fabricated IGBT devices are shown in Fig. 1. The devices are mass-produced by CMOS fabrication process involving six different mask steps. The thicknesses of n- drift and p+ collector region are 100 and 0.2 µm, respectively. P+ collector region was formed on the backside surface of the N-type substrate by ion implantation and diffusion. 4-µm thick p-base and n+ emitter regions were also formed on the top surface of the substrate by ion implantation and diffusion. The total thickness of the device was about 105 µm including the 4-µm-thick front electrode and the 0.45- µm -thick back electrode. The IGBT devices are rated at a collector current of 30A@25 ℃ with a collector blocking voltage of 600 V.

The gamma irradiation was performed using a pencil-type ^{60}Co (cobalt-60) source at the low-level gamma irradiation facility of Advanced Radiation Technology Institute (ARTI) in Korea Atomic Energy Research Institute, Korea. The initial activity was 3800 Ci, and the dose rate was 5 kRad(Si)/h. The devices were irradiated at a fixed distance of 27.8 cm from the source with TID from 2.5 to 100 kRad(Si) at nominal room temperature. Fig. 2 shows the experimental set-up for gamma irradiations.

Hani Baek is with the Korea Atomic Energy Research Institute, Daejeon, Korea and Department of Materials Science and Engineering, Myongji University, Yongin, Korea (e-mail: hani@ kaeri.re.kr).

Gwang Min Sun, is with the Korea Atomic Energy Research Institute, Daejeon, Korea (corresponding author, phone: +82-10-3055-7287; fax: +82-42-868-6209; e-mail: gmsun@kaeri.re.kr).

Chansun Shin, is with the Department of Materials Science and Engineering, Myongji University, Yongin, Korea (corresponding author, phone: +82-10-2217-9286; fax: +82-42-868-6209; e-mail: c.shin@mju.ac.kr).

Sung Ho Ahn, is with the Korea Atomic Energy Research Institute, Daejeon, Korea (e-mail: shahn2@kaeri.re.kr).

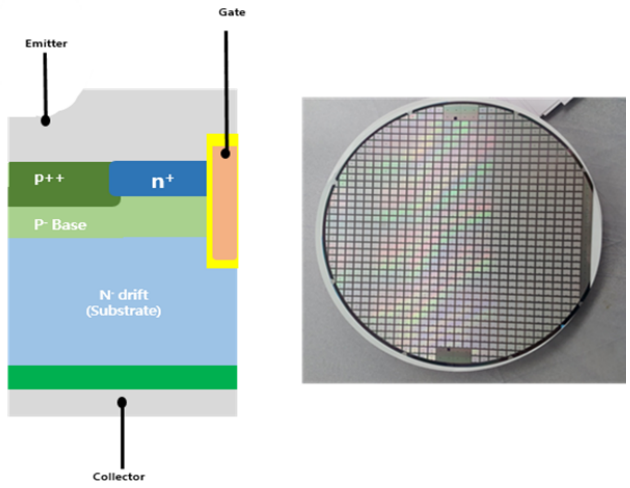


Fig. 1 Cross-sectional schematic structure of NPT-IGBT, and manufactured 600 V NPT-IGBT

Fig. 2 Experimental set-up of gamma-ray irradiation of NPT-IGBTs

After irradiation, the devices were packaged in three-pin plastic TO-3 packages. The current-voltage (I-V), the collector-emitter forward voltage drop (V_{CE}), and leakage current (I_L) before and after gamma-ray radiation were measured by using a Keithly 2636 and 2651 power electrometer as shown in Fig. 3 (a). The turn-off delay time was measured by using Tektronix MD3054 oscilloscope, which receives the timing signal from a circuit that permit instantaneous change of high current in inductive loads as shown in Fig 3 (b). More detailed information on the inductance load switching circuit can be found in [6].

III. Results and Discussion

A. Threshold Voltage

The gate threshold voltages (V_{TH}) of all the devices were measured at room temperature before and after irradiation. V_{TH} was defined as the gate-emitter voltage (V_{GE}) corresponding to collector current I_{CE} = 30 mA under the condition of the collector-emitter voltage (V_{CE}) equivalent to V_{GE} (V_{CE}=V_{GE}).

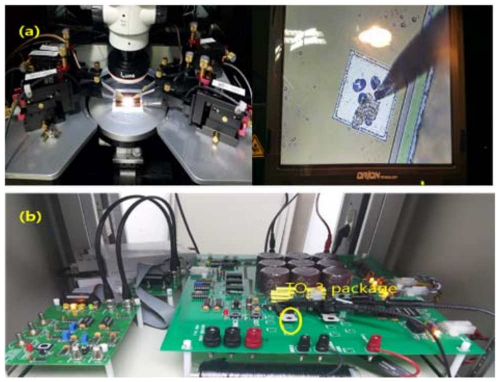
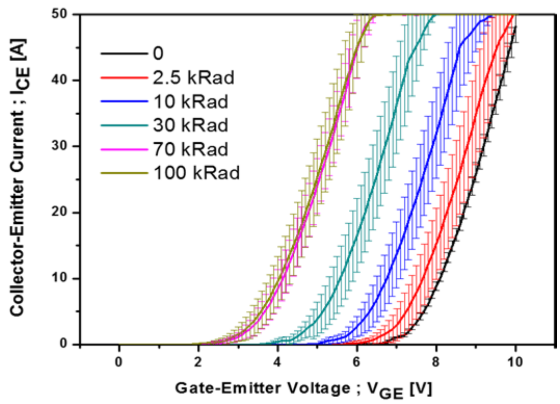


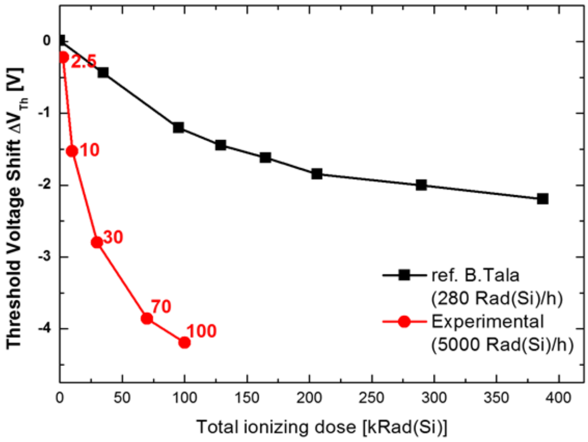
Fig. 3 (a) Measurement set-up with Keithly 2636 and 2651 power electrometer, (b) Circuit of system for turn-off delay time measurement

Fig 4 (a) shows the current (I_{CE}) and voltage (V_{GE}) curves of the devices irradiated at different doses. As the TID increases, the current-voltage curve shifts to the left, i.e., the current begins to flow at a lower voltage. Fig 4(b) shows the threshold voltages evaluated by intercepting the I_{CE}-V_{GE} curves with I_{CE} = 30 mA line of each device before and after gamma irradiation. Small variations in V_{TH} were measured between devices before irradiation, and V_{TH} decreases substantially as the TID increases: V_{TH} are 5.98, 3.42, 2.35 and 2.04 V for 10, 30, 70 and 100 kRad(Si), respectively.

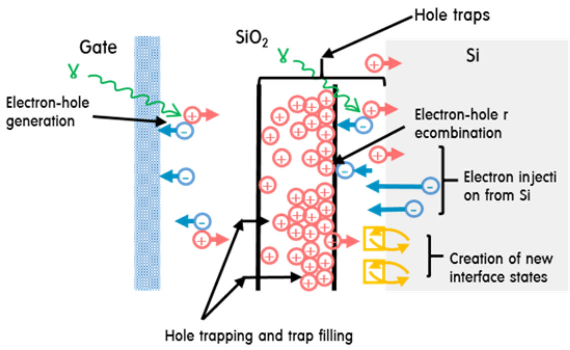
The negative shift of I_{CE}-V_{GE} curves and the decrease in V_{TH} with dose can be attributed to the oxide trapped charge, which is normally positive [7]. Fig. 4 (c) shows the schematic energy band diagram for MOS structure, indicating major physical processes underlying gamma irradiation response. In the gate oxide exposed to gamma irradiation, a large number of electron-hole pairs are created. When a positive gate voltage is applied, holes move toward the Si-SiO_2 interface and trapped by oxygen-vacancies. Hence, the gate oxide is normally positive due to these oxides trapped charge. This net positive build-up of charges in the gate oxide induces the decrease in the threshold voltages and the shift in the I_{CE}-V_{GE} curves.



(a)



(b)



(c)

Fig. 4 (a) Current-Voltage characteristics of 600 V NPT-IGBT measured at room temperature, (b) Threshold voltage shift (ΔV_{TH}) as a function of TID, (c) Schematic energy band diagram for MOS structure, indicating major physical processes underlying radiation response

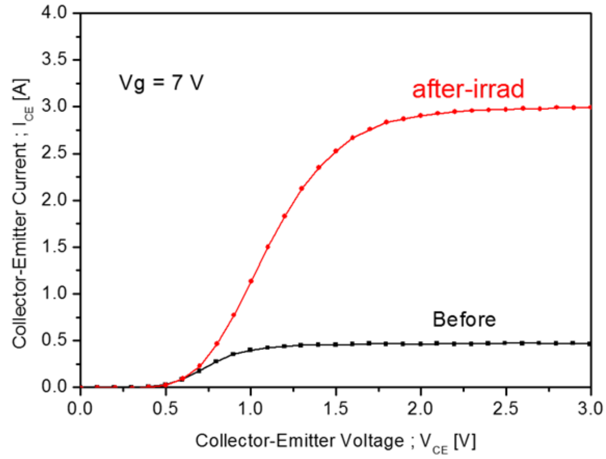
B. Forward Voltage Drop

The collector-emitter voltages across the IGBT at V_{GE} = 15V, and I_{CE}=30 A were measured at room temperature for the devices before and after irradiation. Fig. 5 shows the evaluated collector-emitter voltages $V_{CE(SAT)}$. The devices before irradiation exhibit variation in $V_{CE(SAT)}$, whose average value is approximately 1.83 V. As shown in Fig. 5, V_{CE} decreases as TID increases: $V_{CE(SAT)}$ are 1.82, 1.79, 1.78, 1.76 and 1.77 V for 2.5, 10, 30, 70 and 100 kRad(Si), respectively.

C. Leakage Current

The leakage current is measured by the current that flows from collector to emitter with V_{CE}= ± 20 V, and the gate is grounded. Fig. 6 shows the change in the leakage current with respect to TID. The leakage current increases with TID: The leakage currents are 0.14, 1.08, 7.9, 21, 39.5 and 85.1 nA for 0, 25, 100, 300, 700 and 1000 Gy, respectively.

The increase in the leakage current by gamma irradiation is related to the decrease of V_{TH}, which is induced by the oxide trapped charge as explained above. The decrease in V_{TH} means a leakier device, which results in the increase of the leakage current [5]. The lattice defects generated by gamma irradiation may also contribute to the increased leakage current, since the lattice defects form deep levels in the silicon band gap and act as source for increasing generated current in the depletion layer.



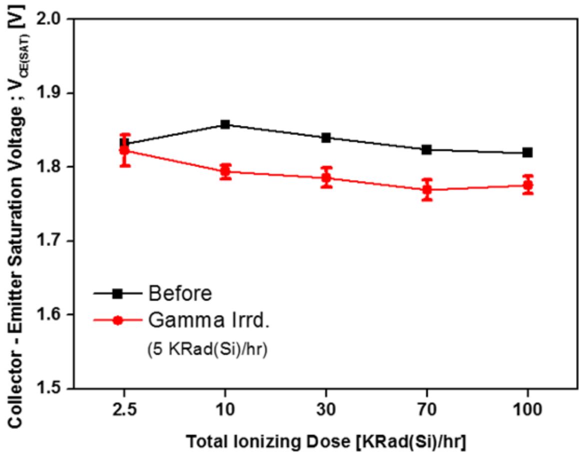


Fig. 5 On-state forward voltage drop of 600 V NPT-IGBT at room temperature

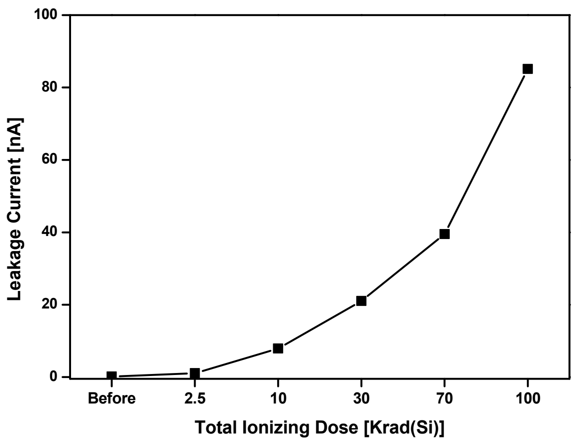


Fig. 6 Change in the leakage current of 600 V NPT-IGBT with respect to TID

D. Turn-off Delay Time

Turn-off delay time is defined by the time from the collector current rising from 10% to 90% in the transient collector-emitter current measured by applying a voltage pulse to the gate with V_{CE}=300 V shown in Fig. 7 [6].

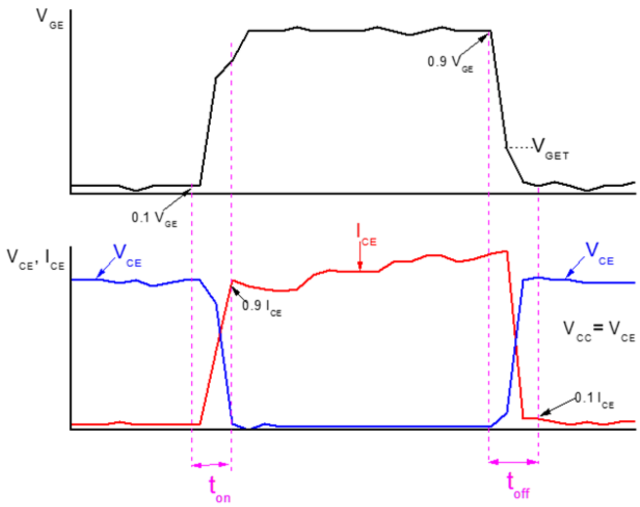


Fig. 7 Turn-on and turn-off switching waveform at oscilloscope

The evaluated turn-off delay times are shown in Fig. 8 for the devices before and after gamma irradiation. The turn-off delay time was 212 ns before irradiation, and the delay time increased to 225, 298, 311, 328 and 350 ns for 2.5, 10, 300, 70 and 100 kRad(Si), respectively.

The increase of the turn-off delay time is known to be strongly related to the behavior of the turn-off gate-emitter voltage, which is strongly dependent on the gate-emitter and gate-collector capacitances. The change in these capacitances are again caused by the radiation induced charge in the gate oxide [8].

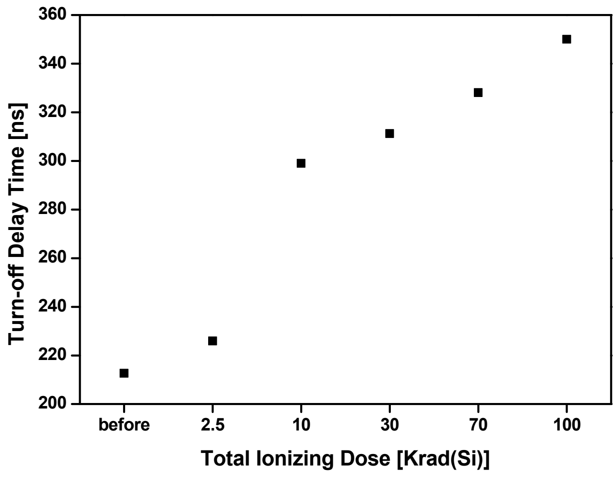


Fig. 8 Turn-off delay time of 600 V NPT-IGBT

IV. Conclusion

We evaluated the effects of gamma irradiation with a dose rate of 5 kRad(Si)/h on the gate threshold voltage, collector-emitter voltage, collector-emitter leakage current, and turn-off delay time of NPT-IGBT with ratings of 600V and 30A@25 °C. TID ranged from 2.5 to 100 kRad(Si). We found that with increasing TID, i) the gate threshold voltage significantly decreases, ii) the collector-emitter voltage at a constant V_{GE} and I_{CE} slightly decreases, iii) the collector-emitter leakage current increases, and iv) turn-off delay time increases. The effects of gamma irradiation on the electrical and switching characteristics of NPT-IGBTs observed in this study are coincident well with the results for PT-IGBTs [4], [5] and for NPT-IGBTs [3], even though the ratings of IGBTs and the dose rates are significantly different. The evaluated changes in the electrical and switching characteristics due to gamma irradiation are believed to be caused by the oxide and interface trapped charges in the gate oxide. We currently evaluate the effects of various particle irradiations on the characteristics of IGBTs, and will publish the results in near future.

Acknowledgment

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (NRF-2014M2A8A1029801).

References

[1] P. T. Mcdonald, B. G. Henson, W. J. Stapor, M. Harris, “Destructive heavy ion SEE investigation of 3 IGBT devices”, Radiation Effect Data Workshop(REDW), p11-15, July 2000.

[2] T. R. Oldham, F. B. McLean, “Total ionizing dose effect in MOS oxide and devices”, IEEE Trans, Nucl. Sci., vol. 50, NO. 3, p483-499, June 2003.

[3] Z. H. Tong, S. S. Ang, W. D. Brown, “Effects of gamma irradiation on the insulated-gate bipolar transistor”, Microelectron. Reliab., vol. 36, No. 10, pp. 1489-1498, 1996.

[4] M. Marceau, C. Brisset, M. Da Costa, “Study of dose effects on IGBT-type devices subjected to gamma irradiation”, IEEE Trans. Nucl. Sci., vol. 46, No. 1999

[5] B. Tala-Ighil, A. Oukaour, H. Gualous, B. Boudart, B. Pouderoux, J-L. Trolet, M. Piccione, “Total ionizing dose effects on punch-through insulated gate bipolar transistors turn-on switching behavior”, Microelectron. Reliab., vol. 51, pp. 2010-2014, 2011.

[6] H. N. Baek, G. M. Sun, J. S. Kim, S. M. T. Hoang, M. E. Jin, S.H. Ahn, “Improvement of switching speed of a 600-V nonpunch-through insulated gate bipolar transistor using fast neutron irradiation”, Nucl. Eng. Technol., vol. 49, pp. 209-215, 2017.

[7] K. F. Galloway, R. D. Schrimpf, “MOS device degradation due to total dose ionizing radiation in the natural space environment: a review”, Microelectron. Journal, vol. 21, pp. 67-81, 1990.

[8] B. Tala-Ighil, A. Oukaour, H. Gualous, B. Boudart, B. Pouderoux, J-L. Trolet, M. Piccione, “Analysis of commercial punch-through IGBTs behavior under 60Co irradiation: Turn-off switching performances evolution”, IEEE Trans. Nucl. Sci., vol. 59, pp. 3235-3243, 2012.