Study on Electrical Characteristics of IGBT by Gamma-ray Irradiation Followed by Thermal Annealing

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1. Introduction

Silicon-insulated gate bipolar transistors (Si-IGBTs) are widely used as next-generation power semiconductor switching devices, offering the convenience of driving and high conductivity of minority carriers. The switching speed of the IGBT is characterized by the turn-on time and turn-off time. The minority carriers that do not disappear during turn-off generate tail-current, and this causes the switching speed to decrease as the turn-off time is delayed[1-2].

In order to reduce the power loss during switching, which is the major contribution of the the energy consumption of electrical devices, a high-speed switching characteristic is a prerequisite. One of the novel methods to increase the switching speed of the IGBT is to irradiate silicon with radiation such as protons or fast neutrons. By irradiation of energetic radiation, lattice defects or damages are caused, and traps between the conduction band and the valence band are formed in the silicon. These traps make electron and hole recombine each other, and reduces the lifetime of minority carriers, which improves the turn-off delay time[3-5].

Among the types of high energy radiation, fast neutrons have the advantage of uniformly forming lattice defects in the IGBT to control the lifetime of minority carriers effectively. In addition, switching characteristics of the device can be improved by the irradiation of fast neutrons. Meanwhile, a fast neutron source generally uses a research reactor, which accompanies high-intensity gamma rays. The gamma rays induce oxide-trap charges and defects in the silicon, which affect the electrical characteristics of the IGBT[6-7]. This study presents the formation of interface traps and oxide-trap charges of the gate-oxide by gamma-ray irradiation on an NPT-trench gate IGBT. The electrical characteristics of the device were measured in consideration of the effects of thermal annealing.

2. Experiments

An NPT-trench gate IGBT with an n-channel manufactured by Trinno Technology Co., Ltd was used as a sample for gamma-ray irradiation. The ratings of the collector-emitter voltage and current were 600 V and 30 A at, respectively. The NPT-trench IGBTs were fabricated on a 6-inch n-type Si wafer involving six different masks in the fabrication by a CMOS process. A p+ collector layer and a p base, including the n+ emitter regions, were formed on the back and top surface of the Si wafer, respectively, by ion implantation and diffusion. The total thickness of the IGBTs was about 105 μm with a 4 μm thick front electrode and a 0.45 μm thick back electrode. The thickness of the p+ collector layer and the p base layer was 0.2 μm and 4 μm, respectively. Fig 1(a) shows NPT-trench gate IGBT devices, and (b) shows a FE-SEM (Field Emission-Scanning Electron Microscope) image of a cross-section of a fabricated device.

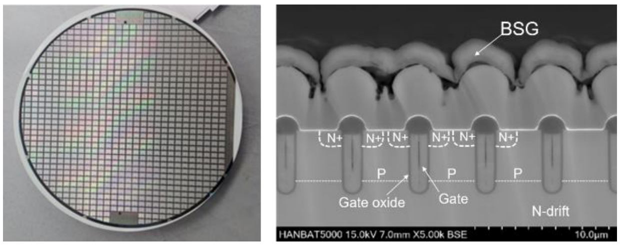

Fig 1. (a) Fabricated 6-inch NPT-trench gate IGBT wafer (b) Cross-section image of NPT-trench gate IGBT obtained using FE-SEM

The manufactured IGBTs were irradiated by a pencil-type Co-60 source at the low-level gamma-ray irradiation facility of the Advanced Radiation Technology Institute (ARTI) in Korea Atomic Energy Research Institute (KAERI). The activity was 38000 Ci, and the IGBTs were irradiated with a dose rate of 5 krad/hour at room temperature. The irradiated devices were retrieved periodically at total doses of 2.5, 10, 30, 70, 100 krad(Si).

Five devices irradiated under each gamma irradiation condition were thermally annealed at 300 ℃ for 15 minutes. The electrical characteristics of the thermally annealed and unannealed NPT-trench gate IGBTs were compared.

For the three cases of samples, 1) a bare device, 2) a gamma-ray irradiated device, and 3) a gamma-ray irradiated thermal annealed device, the threshold voltage, forward voltage drop were measured by using Keithley 2636 and 2651 power source measure unit instruments for low and high current, respectively. To measure the switching times, the samples were packaged in a three-pin plastic TO-3 and were installed in a switching test circuit with an inductive load. A forward collector-emitter voltage (VCE) of 400 V was applied to the device under test. A drive pulse of 15 V was delivered to the gate voltage (VGE) and the voltages were measured by using a Tektronix MD3054 oscilloscope. All measurements were conducted at room temperature (~ 25 ℃).

3. Results

Fig 2 shows the measured VGE-ICE curves of the bare device, gamma-ray irradiated devices, and gamma-ray irradiated with thermal annealed devices. Upon increasing the total ionizing dose from 2.5 krad to 100 krad, the VGE-ICE curves are shifted to negative voltage.

In the ionization damage process, charge carriers of the insulating layer (SiO2) are released and diffused or drift to the position where they are trapped by absorbed energy. Unintended charge concentration is thereby caused. In other words, electron-hole pairs in the SiO2 are generated by gamma-ray irradiation, and electrons move to the outside of the SiO2 layer with relatively high speed by the applied voltage. However, remaining holes in the SiO2/Si interface form a trap center, resulting in SiO2 trapped charges, which is a major cause of deterioration of device performance[8].

After thermal annealing at 300 ℃ for 15 minutes, it can be seen that the shift to negative voltage is restored according to the total ionizing dose. However, it did not recover enough compared with the unirradiated. The gamma-irradiation causes defects that generate numerous trapped charges in the SiO2/Si interface region, resulting in deterioration of the device and failure to fully recover from thermal annealing.

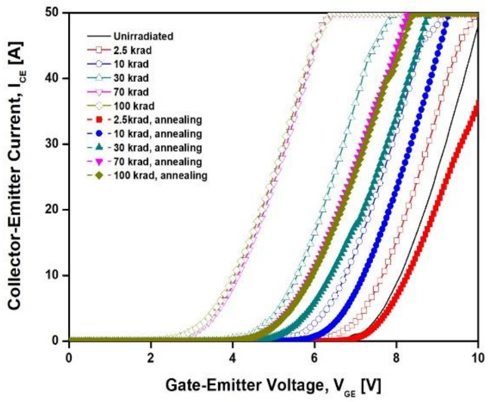

Fig 2. Gate-emitter voltage and collector-emitter current transfer curves for gamma-ray irradiation dose with and annealed.

Fig3 (a) shows the measured VCE-ICE curves of IGBTs with gamma-ray irradiation and thermal annealing at gate voltage (VGE) of 7 V and 8 V. For the IGBT with a VTH of 6.3 V before gamma-ray irradiation, ICE does not flow when 7 V is applied to the gate, whereas a saturation current of 7 A flows when 8 V is applied to the gate. However, after gamma-ray irradiation, the IGBT has a ICE with a saturation current of 15 A even when the gate voltage is only 7 V, and a ICE of 35 A flows when the gate voltage is 8 V.

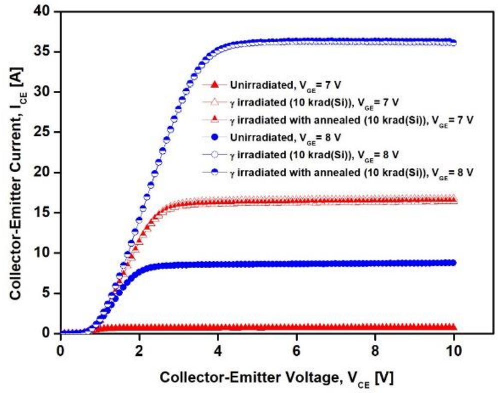

Fig . Collector-emitter voltage and current curves at a gate voltage of 7 and 8 V for the unirradiated and irradiated (10 krad (Si)) and thermal annealing device

After gamma-ray irradiation, the current in both the linear and saturated regions of the IGBT increased. Before the gamma-rays are irradiated, the VTH of the IGBT is high at 6.3 V. This is because the increase in the IGBT current due to the decrease in the VTH is greater than the reduction effect of the IGBT current due to the decrease in electron mobility.

After thermal annealing, the IGBTs ICE recovered to about 6 A at 7 V gate voltage and to about 22 A at 8 V gate voltage, respectively, constituting respective increases of about 60 % and 35 % compared to the values after gamma-ray irradiation. This appears to affect the ICE by recovering the VTH after thermal annealing. However, did not recover completely tot he level before gamma-ray irradiation, which is similar to the VTH characteristics.

As shown in Fig 4 the turn off time is comprised of turn-off delay time (t_d^{off}), current fall time (t_f^I) and voltage rise time (t_r^I).

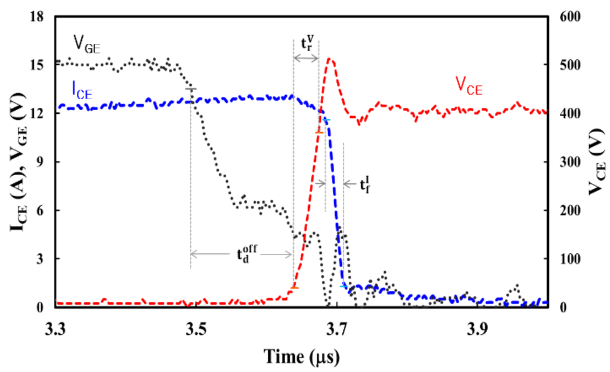

Fig 4. Switching time waveforms of the turn-off (b) t_d^{off}, t_f^I, t_r^V

The turn-off switching times of the IGBTs are summarized in table 2. The switching time of the IGBT was measured at each irradiation dose and at thermal annealing conditions, respectively. In the table, are the turn-off time (toff) for unannealed and annealed devices.

Table 1. Switching time of turn-off

Switching time parameters		Dose [krad]				
		2.5	10	30	70	100
Turn-off Time, w/o annealing	$t_d^{off}[ns]$	141	160	177	203	217
	$t_f^I[ns]$	29	29.9	37.3	51.2	60.2
	$t_r^V[ns]$	34.3	37.3	41.6	51.9	56.6
Turn-off Time, with annealing	$t_d^{off}[ns]$	146	153	163	181	190
	$t_f^I[ns]$	38.3	38	32	49.3	34.5
	$t_r^V[ns]$	40	39	42	51.2	52

The values of t_d^{off}, t_f^I, and t_r^V of the unirradiated devices were measured to be 135.9, 29.9, and 35.7 ns, respectively. After gamma-ray irradiation, t_d^{off} increased to 141, 160, 177, 203, and 217 ns at gamma-ray doses of 2.5, 10, 30, 70, and 100 krad, respectively.

The switching turn-off delay times of the IGBTs that were irradiated by gamma rays are shown in Figure 5 The due to the defects formed by gamma-ray irradiation.

In the case of t_d^{off}, the switching time after thermal annealing was reduced by about 10 % relative to post-irradiation, and decreased to 146, 152.5, 162.5, 181, and 190 ns, respectively, depending on the total ionizing dose.

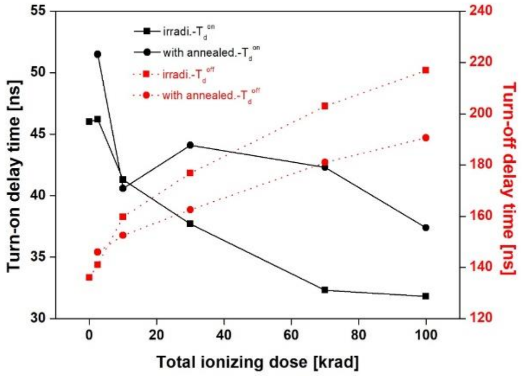

Figure 5 Turn-on and turn-off delay time due to gamma-ray irradiation dose and annealing.

The gamma-ray induced oxide-trapped charges in the gate oxide change the gate-emitter and gate-collector capacitances. The change in these capacitances affects the behavior of the gate-emitter voltage and induces a shift of the switching time. More significant changes observed in the IGBTs are attributed to the relatively thick gate oxide of the IGBTs. The after gamma-rays irradiation annealing and irradiaton condition are known to affect the switching times. In other words, the oxide-trapped charges formed by gamma-ray irradiation are removed by thermal annealing and change the capacitance of the gate-emitter and gate-collector of the IGBTs and recover the switching t_d^{on} and t_d^{off}.

4. Conclusion

We evaluated the gamma-ray irradiation and thermal annealing effects on electrical characteristics of NPT trench-gate IGBTs. The results showed that the electrical properties of the gamma-ray irradiated NPT trench-gate IGBTs are highly variable due to defects and thermal annealing effects caused by irradiation. After irradiation, a negative shift of the threshold voltage and an increase in the collector leakage current were observed, and after thermal annealing, the threshold voltage and the collector leakage current were recovered. This degradation was caused by the accumulation of positive oxide trapped charges in the gate-oxide due to gamma-ray irradiation. The electrical characteristics were recovered as the trapped charges were removed by the thermal annealing. The turn-off switching times increased, owing to irradiation. After thermal annealing, the turn-off switching times decreased owing to irradiation. The oxide-trapped charges formed by gamma-ray irradiation caused a change in the gate capacitance, which affected the shift of the switching time, resulting in a change in the switching time. Afterwards, the oxide-trapped charges due to the thermal annealing effect were resolved, and the gate capacitance was changed, which recovered the switching time. Although all electrical characteristics of the NPT trench-gate IGBT thermal-annealed after gamma-ray irradiation were recovered, they did not recover to the same levels as before gamma-ray irradiation. In future studies, the electrical characteristics of NPT trench-gate IGBTs will be analyzed by varying the thermal annealing conditions.

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