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Original Article

Study on changes in electrical and switching characteristics of NPT-IGBT devices by fast neutron irradiation

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ABSTRACT

We studied the irradiation effects of fast neutron generated by a 30 MeV cyclotron on the electrical and switching characteristics of NPT-IGBT devices. Fast neutron fluence ranges from 2.7×10^9 to 1.82×10^{13} n/cm^2. Electrical characteristics of the IGBT device such as I–V, forward voltage drop and additionally switching characteristics of turn-on and -off were measured. As the neutron fluence increased, the device's threshold voltage decreased, the forward voltage drop increased significantly, and the turn-on and turn-off time became faster. In particular, the delay time of turn-on switching was improved by about 35% to a maximum of about 39.68 ns, and that of turn-off switching was also reduced by about 40% −84.89 ns, showing a faster switching.

1. Introduction

The non-punch-through insulated gate bipolar transistor (NPT-IGBT) is a power semiconductor widely used as a switch device in applications such as high power and high frequency power [1–3]. It was developed by combining the fast switching characteristics of metal-oxide-semiconductor (MOS) transistors with the low forward voltage drop characteristics of bipolar junction transistors [2–4]. The structure of an NPT-IGBT consists of a MOS gate connecting the n + emitter and n− drift regions, which are separated by the p base region, and of the p + layer at the collector.

In the on-state of the device, the p + collector layer injects holes, called minority carriers, into the n-drift region. Due to hole injection, the effective resistance to current flow in the n-drift region decreases, resulting in a lower on-state voltage of the IGBT devices. Holes injected into the n-drift region require a much longer time to recombine with electrons and disappear when the device is in an off-state, since the mobility is much slower than that of electrons. This causes a tail current to occur inside the device and slows down the switching speed [5–7]. Ultimately, this problem becomes a major obstacle to the implementation of fast-speed switching of IGBT devices.

The methods to form deep level-related defects such as vacancy-oxygen (V–O) and divacancy (V_2) using high-energy protons and electron beam irradiation for fast recombination of injected holes during turn-off have been proposed [8–12]. When a high-energy proton or electron beam is irradiated using an accelerator, displacement damage occurs when these particles strike an atom in the semiconductor lattice resulting in non-uniform formation of deep-related defects in the device, as shown in Table 1. In addition, it is known that a total ionization dose (TID) effect occurs through a process in which energy is transferred to a device due to a primary ionization effect [13–17]. The TID effect by irradiation with protons and electrons induces two major modifications, oxide-trapped charge and interface-trapped charge, on the gate oxide and Si/SiO_2 interface. Already, many studies have shown deterioration (negative shift in threshold voltage and decreased breakdown voltage) in the electrical characteristics of IGBTs due to the charge trapped in the gate oxide and Si/SiO_2 interface by proton and electron beam irradiation [13–17]. In addition, the uniformity and amount of defects formed by proton and electron beam irradiation depend greatly on the energy and direction of the irradiation, making it necessary to set accurate irradiation conditions.

In order to overcome the deterioration characteristics of devices, research on fast neutron irradiation, which is known to have a positive effect on electrical properties by stably and uniformly

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1738-5733/

Table 1
Comparison of particle radiations.

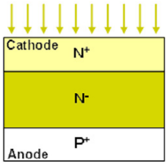
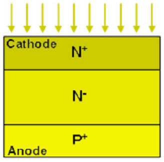
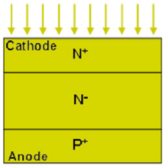
Division	Proton	Electron	Fast Neutron
Method	Accelerator	Accelerator	Reactor
Trade-off	Good	Normal	Best
Reproducibility	Good	Good	Good
Uniformity	Normal	Normal	Best
Leakage Current	High	Low	Low
Distribution of defect			

Table 2
Fast neutron irradiation conditions.

Case	Distance [cm]	Neutron Flux [n/cm^{2}s]	Irradiation Time [s]	Neutron Fluence [n/cm^2]
1	35.71	9.0×10^7	30	2.7×10^9
2	11.25	6.07×10^8	30	1.82×10^{10}
3	35.71	9.0×10^7	3000	2.7×10^{11}
4	11.25	5.5×10^8	3000	1.65×10^{12}
5	3.45	6.07×10^9	3000	1.82×10^{13}

forming V—O and V_2 defects, has recently emerged [18–20]. Fast neutrons with uniform energy of 10 keV to 2 MeV are irradiated to the device, and atomic collisions caused by interaction with materials cause displacement damage, which is the primary effect, and very uniform defects are formed inside the device. It is known that this method can increase the production yield of semiconductors because the performance and quality of devices after irradiation are superior to other radiations such as protons and electrons. Also, defects formed due to fast neutron irradiation have the advantage of being able to be stabilized or restored through heat treatment.

There are many kinds of neutron sources for fast neutron irradiation. The main fast neutron sources are: (1) nuclear reactor and (2) large accelerator-based neutron sources. In the past, researches for fast neutron irradiation were mainly carried out using nuclear reactors [21]. However, in recent years, many researchers have built dedicated beamlines for semiconductor research, such as spallation sources. One instance is ChipIr, a neutron beamline situated at the ISIS spallation source, which is specifically designed for fast testing of microelectronics. ChipIr offers a neutron spectrum resembling that of the Earth's atmosphere, enabling the investigation of Single Event Effects which is an important issue affecting the dependability of contemporary electronics both on the ground and at various altitudes during flight [22].

In this study, fast neutron irradiation was conducted to enhance the switching performance of IGBTs and minimize degradation in electrical characteristics. Fast neutron irradiation experiments were performed using a proton accelerator with an energy of 30 MeV to achieve uniform and high fluence. The electrical and switching properties of NPT-IGBT devices were evaluated after the fast neutron irradiation, and based on this, the optimal conditions for fast neutron irradiation were determined.

2. Methods

2.1. Sample preparation

The IGBTs used in this study were NPT-IGBT and were manufactured by Trino Technology Co., Ltd. The collector-emitter voltage and current ratings were 600 V and 30 A, respectively. The p + collector layer and the 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 thicknesses of the p + collector layer and the p base layer were 0.2 μ m and 4 μ m, respectively. The total thickness of the device was about 105 μ m including a 4 μ m thick front electrode and a 0.45 μm thick back electrode. Fig. 1 shows the IGBT device manufactured on a 6-inch Si wafer. After the completion of IGBT device fabrication, it was packaged in a TO-3 form for electrical characteristic measurement and fast neutron irradiation testing.

2.2. Fast neutron irradiation

The Fast neutron irradiation utilized the neutron beam generated by colliding protons produced by the MC-50 cyclotron at the Korea Institute of Radiological & Medical Sciences (KIRAMS) with a Be target. In order to establish precise neutron irradiation conditions, reference was made to research results that calculated the neutron spectrum based on the (p,n) nuclear reaction in the MC-50 cyclotron [23]. The neutron beam spectrum generated when 20 MeV and 30 MeV proton energies collided with a Be target of 5 mm thickness and 44 mm diameter was measured using a LiI scintillation detector and a multi-channel analyzer. The final unfolded neutron spectrum was obtained using the MAXED code from the UMG unfolding package, and the results can be observed in Fig. 2(a). To obtain high-fluence fast neutrons, based on the results in Fig. 2(a), a proton with an energy of 30 MeV and a current of 10 μA was used to collide with the target, and the neutron flux within a distance of 30 cm from the target was calculated. The results are shown in Fig. 2(b).

To generate a high fluence of fast neutrons, the proton energy and beam current of the MC-50 cyclotron were set to 30 MeV and 10 μA, respectively. Additionally, for uniform fast neutron irradiation, it was performed in the horizontal directrion as shown in Fig. 3.

In order to compare the electrical characteristics of the IGBT device according to the fast neutron fluence, it was irradiated under

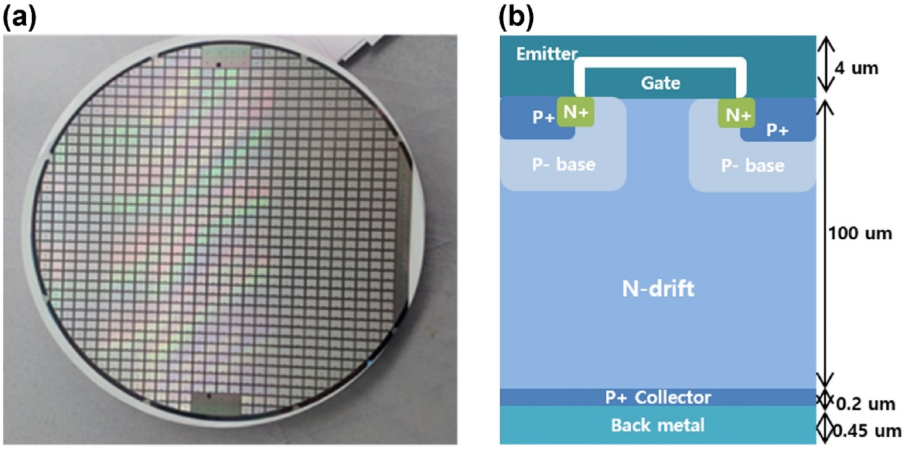


Fig. 1. 600 V NPT-IGBT, (a) IGBT devices manufactured on 6 inch n-epi wafer, (b) Schematic of the cross-sectional structure of IGBT device.

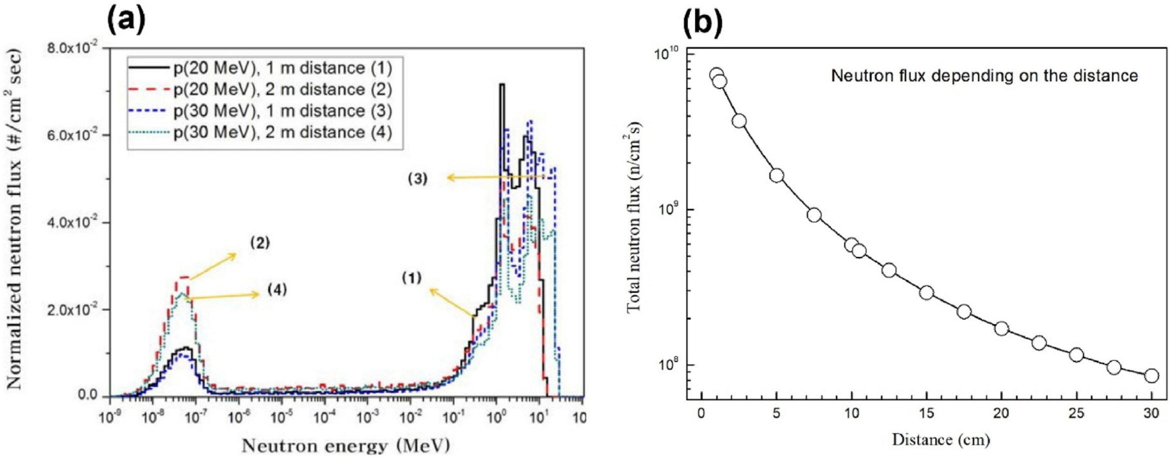


Fig. 2. (a) Unfolded neutron spectra according to incident proton energies and distances in MC50 cyclotron [23], (b) The calculated results of neutron flux depending on the distance.

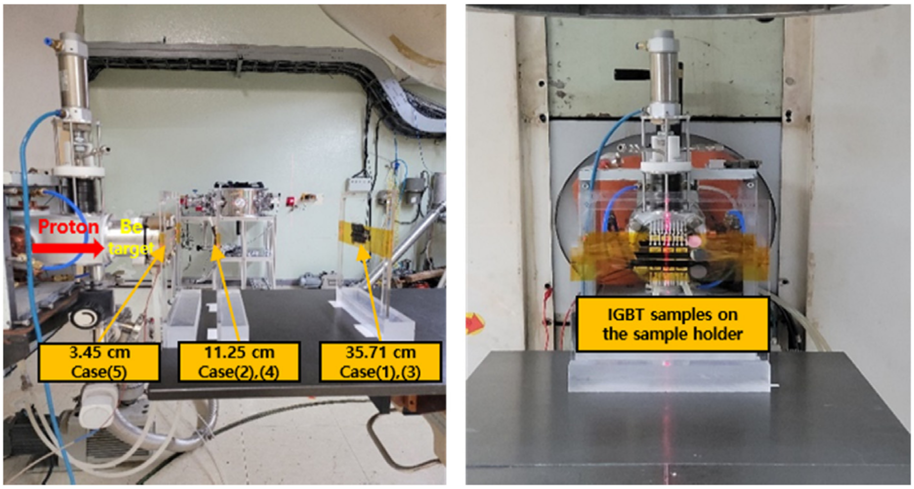


Fig. 3. Fast neutron irradiation experiment for IGBT devices.

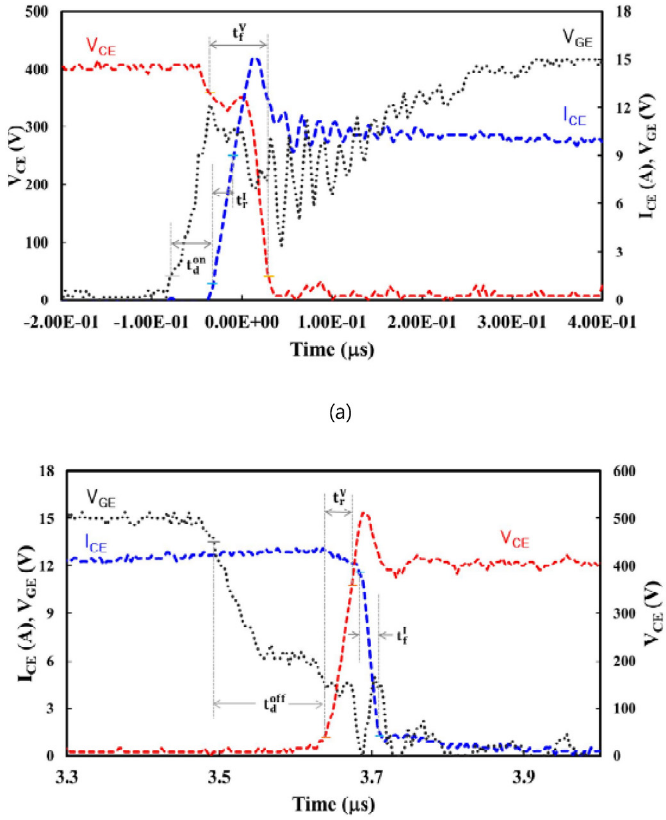
the condition of 2.7×10^9–1.82×10^{13} n/cm^2 at ambient temperature (~25 °C) without applying any gate bias. Furthermore, to ensure clear verification of the results from the fast neutron irradiation, six packaged IGBT devices were tested for each condition (see Table 2).

The radiation-induced activation of aluminum metal used in the packaging of the IGBT devices has not been considered due to its very short half-life, which is expected to have minimal impact on the characteristics of the devices.

2.3. Measurement of electrical and switching characteristics

The electrical characteristics of the fast neutron irradiated IGBT devices were measured using Keithley 2636 and 2612 source-meters, respectively. To measure the switching turn-on and turn-off time characteristics of the IGBT device, we used an inductive circuit that is widely used in the industry. A forward collector-emitter voltage (V_{CE}) of 400 V is applied to the IGBT device, and a driving pulse of 15 V is applied to the gate voltage (V_{GE}). At this time, the instantaneously changing collector-emitter current (I_{CE}) and voltage were measured using a Tektronix MD3054 oscilloscope.

The switching times were characterized on the turn-on and turn-off waveforms of V_{CE}, I_{CE}, and V_{GE} as shown in Fig. 4(a) and (b), respectively. The switching turn-on time characteristics of the IGBT devices were evaluated by measuring the turn-on delay time (t_d^{on}), current rise time (t_r^I) and voltage fall time (t_f^V). t_d^{on} is defined as the time from when V_{GE} rises above 10% of voltage until I_{CE} rises above 10% of the current. t_r^I is the time between the rise of the I_{CE} from 10% to 90%. t_f^V is the time between V_{CE} falling from 90% to 10%. Switching turn-off time characteristics were evaluated by measuring turn-off delay time (t_d^{off}), current fall time (t_f^I), and voltage rise time (t_r^V). t_d^{off} is defined as the time from when the V_{GE} drops to below 90% of voltage until V_{CE} reaches 10%. t_f^I is the time between I_{CE} falling from 90% to 10% and t_r^V is the time between the rise of the V_{CE} from 10% to 90%.



(a)

(b)

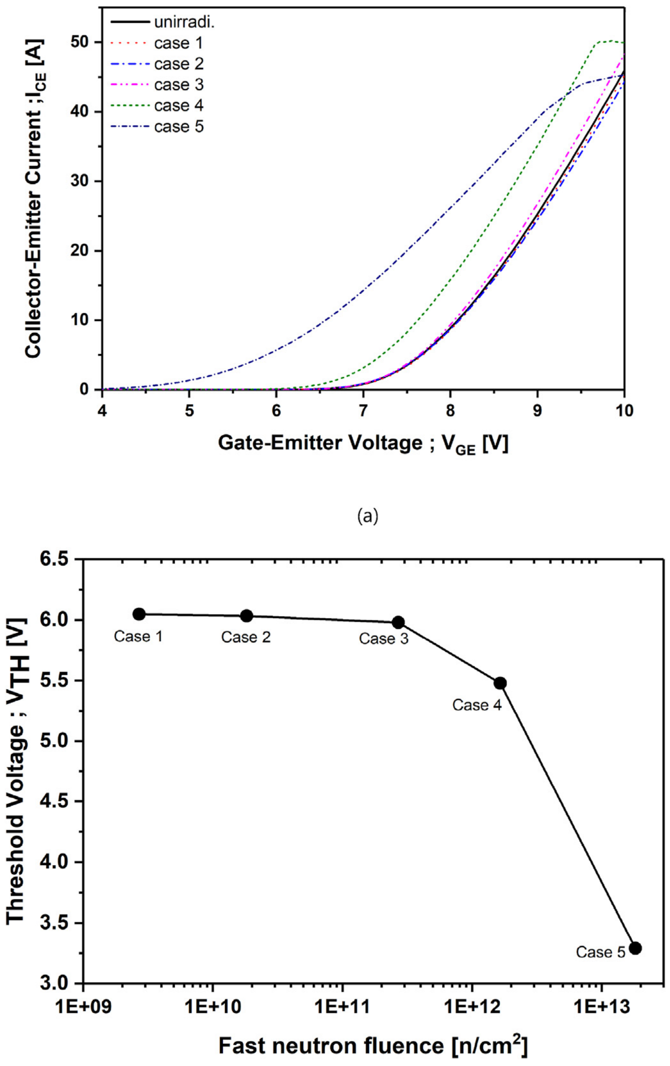
Fig. 4. Measured (a) turn-on and (b) turn-off switching waveforms of IGBTs un-irradiated with fast neutron.

3. Results and discussion

3.1. I–V characteristics of the fast neutron-irradiated IGBT devices

Fig. 5(a) shows the I_{CE}-V_{GE} transfer characteristic curve of the device measured by shorting the gate-collector and applying a forward bias to both terminals. The threshold voltage (V_{TH}) was calculated as the V_{GE}=V_{CE} value corresponding to I_{CE} = 30 mA from the I_{CE}-V_{GE} graph and is shown in Fig. 5(b).

As the fluence of fast neutrons increased, the I_{CE}-V_{GE} graphs shifted towards negative voltages. In addition, the V_{TH} of the IGBT device before fast neutron irradiation was about 6.07 V, but the V_{TH} tended to decrease as the fluence increased. However, in case 1–4 conditions, the normal operating V_{TH} value of 5.5–6.5 V was



(a)

(b)

Fig. 5. Current-voltage characteristics of IGBT device unirradiated and fast neutron irradiation (a) Transfer current-voltage characteristics of the IGBT devices before and after neutron exposures. (b) Threshold voltage versus neutron fluence.

maintained, and the device was found to operate stably even after irradiation with fast neutrons. The IGBT device is a MOS structure including a gate-oxide region, it seems that the TID effect, a secondary effect, partially occurred in the gate oxide region of the device and the Si/SiO$_2$ interface due to fast neutron irradiation. In particular, as the fast neutron fluence increased, the TID effect increased, and in the case 5 condition, a lot of positive oxide charges were formed, which greatly increased the internal electric field and greatly reduced the V_{TH} value [24].

3.2. Forward voltage drop ($V_{CE(Sat)}$) characteristics of the fast neutron-irradiated IGBT device

Fig. 6 shows the $V_{CE(sat)}$ characteristics of the IGBT device according to the fast neutron fluence. The $V_{CE(sat)}$ was defined as the collector-emitter saturation voltage value when the gate voltage was 15 V and the collector current was 30 A.

The $V_{CE(sat)}$ of the unirradiated device was found to be about 2.058 V. $V_{CE(sat)}$ tended to increase as the fast neutron fluence increased, but in the cases 1 to 4, the $V_{CE(sat)}$ characteristics were within the normal operating range. But, under the condition of case 5, the $V_{CE(sat)}$ of the device increased by about 250% compared to before irradiation to about 5.25 V, exceeding the normal operating range of 2–3 V for IGBT devices.

The displacement damage effect, which is known to occur as a primary effect due to fast neutron irradiation, affects the increase in the forward voltage drop of the IGBT device. As known in the literature, defects such as V–O and V$_2$ are uniformly formed in the n-drift region of the device due to the DD effect caused by fast neutron irradiation. Formed defects are injected from the P+ collector and act as recombination centers that reduce the lifetime of minority carriers remaining in the n-drift region. This reduces the diffusion length of the minority carriers and reduces the conductance modulation of the n-drift region in the on-state of the device, increasing the forward voltage drop [25]. Therefore, under high irradiation conditions such as in case 5, a large DD effect occurs in the n-drift region, and many defects such as V–O and V$_2$ are formed. Due to the large number of defects formed, the lifetime of minority carriers inside the device is significantly reduced and the diffusion length becomes very short. As a result, a rapid change in conductivity modulation occurred in the n-drift region, and $V_{CE(sat)}$ increased by more than twice compared to other irradiation conditions, leading to deterioration of the device characteristics.

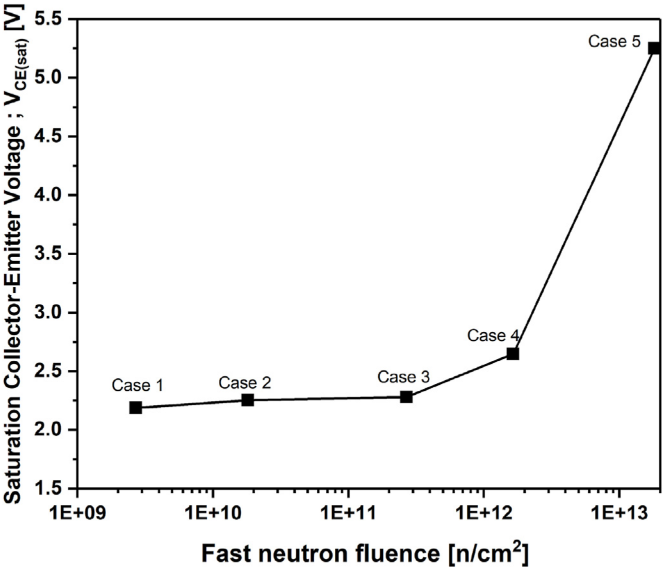


Fig. 6. Comparison collector-emitter saturation voltage of IGBT device by the fast neutron irradiation fluences.

3.3. Leakage current (I_{CES}) characteristics of the fast neutron-irradiated IGBT device

The leakage current of the IGBT device was measured by applying a collector-emitter voltage of 600 V while shorting the gate. The measured leakage current, I_{CES}, is shown in Fig. 7.

The leakage current of the IGBT device without fast neutron irradiation exhibits a very low characteristic of approximately 0.3 nA. However, under the irradiation condition of 2.7×10^9 n/cm^2, the leakage current increased to approximately 1.3 nA. Furthermore, the leakage current of the IGBT device increased significantly with increasing fast neutron fluence. The leakage current values corresponding to different neutron fluences were 5.2, 12.5, 67.8, and 138.4 nA, respectively.

The observed phenomenon can be explained by the DD effect and TID effect caused by fast neutron irradiation. In the off state of the IGBT device, when a high voltage is applied between the anode and cathode, the depletion region expands based on the p-body and n-drift junction, causing most of the drift region to become depleted. Thermally generated electrons and holes within the depletion region contribute to the leakage current component, depending on the area of the depletion region and the minority carrier lifetime.

The DD effect induced by fast neutron irradiation leads to the formation of V–O and V$_2$ A-center defects. These defects act as recombination centers, promoting the rapid recombination of holes and thereby reducing the minority carrier lifetime. This is believed to be the cause of the increased leakage current. Also, the E-center defects formed in the gate-oxide region due to TID effect act as paths for leakage current during forward blocking, resulting in an increase in leakage current.

The leakage current of the IGBT device appears to increase due to the combined occurrence of these two phenomena. In particular, as the amount of fast neutron irradiation increases, the defects related to recombination centers formed in the n-drift region become more prevalent. As a result, the lifetime of minority carriers decreases significantly, leading to a rapid increase in leakage current.

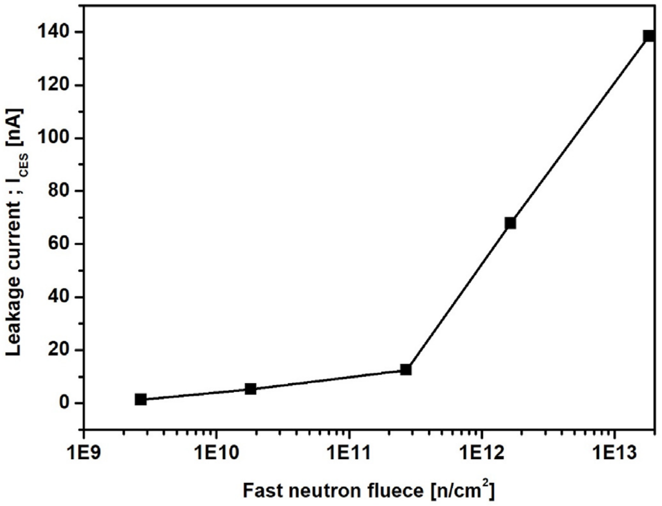


Fig. 7. Comparison collector-emitter leakage current of IGBT device by the fast neutron irradiation fluences.

3.4. Breakdown voltage (BV) characteristics of the fast neutron-irradiated IGBT device

Fig. 8 shows the breakdown voltage characteristics of the IGBT device measured before and after fast neutron irradiation. Breakdown voltage value was confirmed based on the collector-emitter leakage current value of 250 μA generated when reverse bias was applied. The breakdown voltage before irradiation with fast neutrons was 757.7 V, and after irradiation with fast neutrons, the breakdown voltage decreased. The n-drift region of the IGBT device plays the most important role in determining the breakdown voltage. The decrease in breakdown voltage may be due to defects formed in the n-drift region as a result of fast neutron irradiation. These imperfections can form a path for leakage current, allowing leakage current to flow even at low reverse bias. However, it can be seen that while the breakdown voltage decreased under the high-speed neutron irradiation conditions used in this study, there was no impact on the deterioration of the device characteristics.

3.5. Switching turn-on time characteristics of the fast neutron-irradiated IGBT device

The turn-on wave forms of I_{CE} and V_{CE} are shown in Fig. 9 (a) and (b), respectively. The turn-on I_{CE} and V_{CE} waveforms of the IGBT device irradiated with fast neutrons shift more to the left as the irradiation fluence increases. Also, the overshoot decreased as the amount of fast neutron irradiation increased in the I_{CE} waveform.

Table 3 listed the turn-on delay time, current rise time and the voltage fall time. The turn-on switching time characteristics of t_d^{on}, t_r^I, and t_f^V were calculated using the turn-on switching waveform as mentioned in the previous section. The t_d^{on}, t_r^I and t_f^V of the device before fast neutron irradiation were 60.15, 28.36, and 78.02 ns, respectively. However, after irradiation with fast neutrons, the t_d^{on}, t_r^I and t_f^V characteristics of the device decreased. The decrease in t_d^{on}, t_r^I and t_f^V indicates that the switching turn-on characteristics of the IGBT device have become faster. Fast neutron irradiation creates positive oxide charges at the gate-oxide and Si/SiO_2 interfaces, which accumulate significantly in the n-channel region of IGBT devices. Due to the accumulated charges, the device operates at a lower V_{TH} value, leading to faster switching turn-on times.

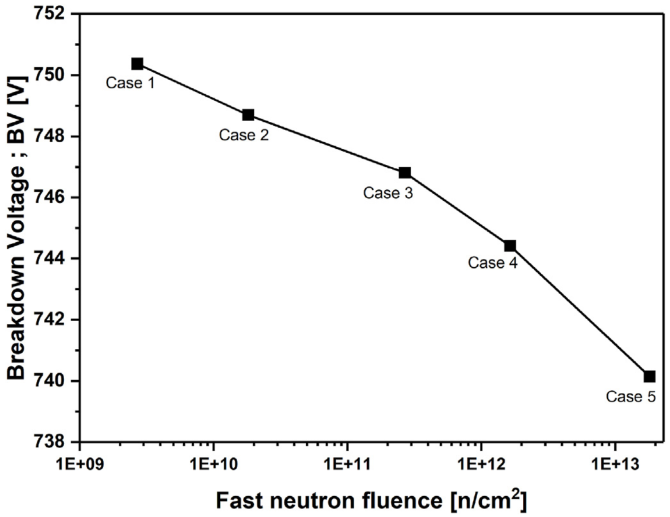
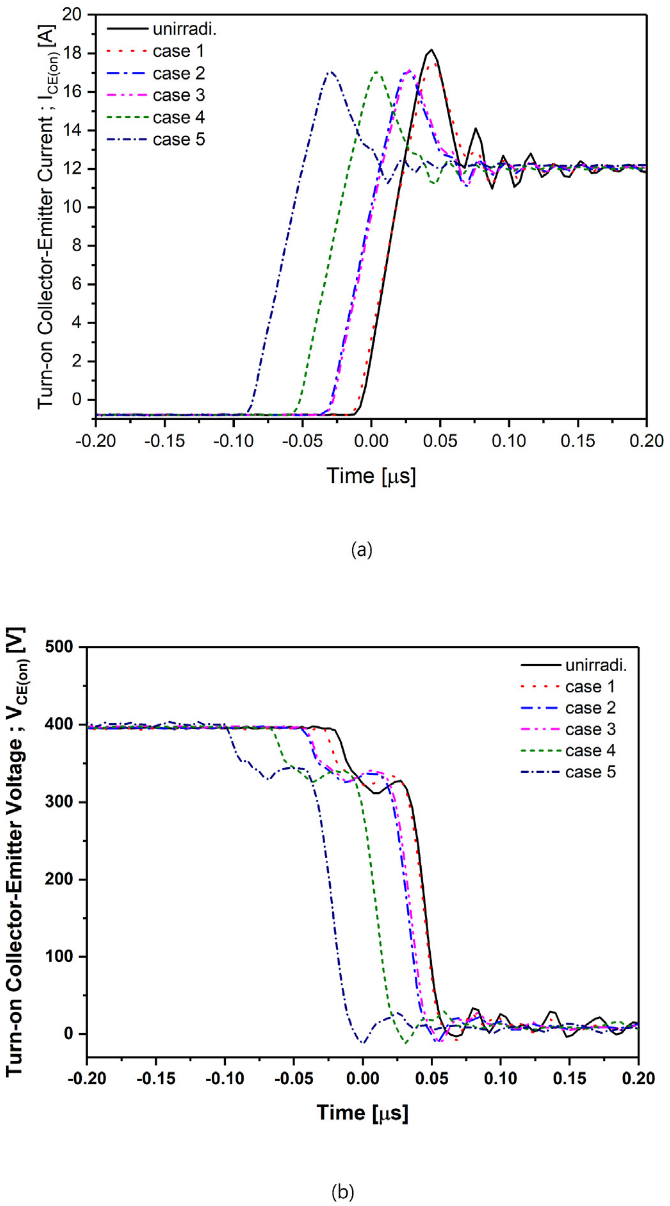


Fig. 8. Comparison Breakdown voltage of IGBT device by the fast neutron irradiation fluences, calculated of the Breakdown voltage.



(a)

(b)

Fig. 9. Characteristics of the turn-on switching waveforms, (a) collector-emitter current, (b) collector-emitter voltage.

3.6. Switching turn-off time characteristics of the fast neutron-irradiated IGBT device

Fig. 10 (a) and (b) show the I_{CE} and V_{CE} switching turn-off waveforms of the IGBT device, respectively. As the fast neutron fluence increases, the I_{CE} and V_{CE} waveforms have shifted to the left. The tail current phenomenon observed in the IGBT device's switching turn-off operation before irradiation, as shown in the I_{CE} waveform of Fig. 10 (a), exhibited a decreasing trend with increasing fast neutron irradiation conditions.

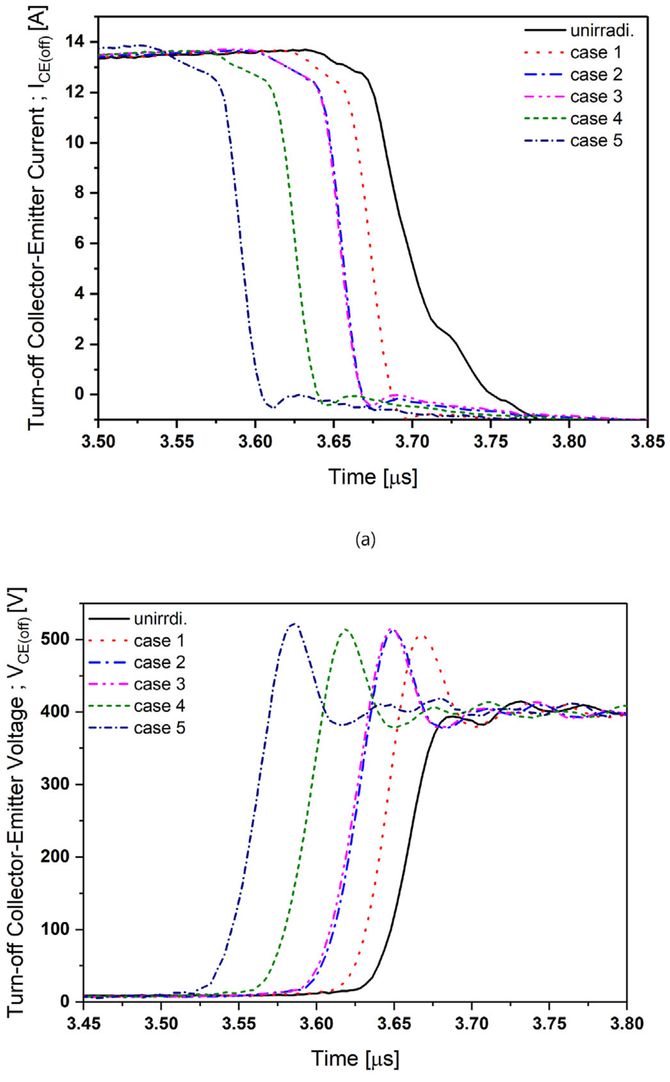
The switching turn-off time-related characteristics of t_d^{off}, t_r^V, and t_f^I were calculated using Fig. 4 (b). The t_d^{off}, t_f^I and t_r^V of the IGBT device before fast neutron irradiation were 142.61, 31.83 and 36.97 ns, respectively. After fast neutron irradiation, as seen in Table 4, the t_d^{off} of the IGBT device decreased with increasing irradiation conditions to 138.42, 127.79, 105.82, 103.28 and 84.89 ns. In addition,

Table 3
Turn-on time characteristics after fast neutron irradiation.

Turn-on time parameters	Unirradiated sample	Fluence $\left[\frac{n}{cm^2}\right]$				
		2.7×10^9	1.82×10^{10}	2.7×10^{11}	1.65×10^{12}	1.82×10^{13}
t_d^{on} [ns]	60.15	50.05	48.53	49.63	46.62	39.68
t_r^I [ns]	28.36	27.69	27.44	27.28	25.74	22.65
t_f^V [ns]	78.02	76.94	76.46	75.97	73.27	69.91

Table 4
Turn-off time characteristics after fast neutron irradiation.

Turn-off time parameters	Unirradiated sample	Fluence $\left[\frac{n}{cm^2}\right]$				
		2.7×10^9	1.82×10^{10}	2.7×10^{11}	1.65×10^{12}	1.82×10^{13}
t_d^{off} [ns]	142.61	138.42	128.79	105.82	103.28	84.89
t_f^I [ns]	31.83	27.48	25.45	23.9	23.71	22.12
t_r^V [ns]	36.97	34.53	32.08	31.95	31.03	28.53



(a)

(b)

Fig. 10. Characteristics of the turn-off switching waveforms, (a)collector-emitter current, (b)collector-emitter voltage.

the t_f^I and t_r^V characteristics also decreased with increasing irradiation conditions, resulting in an improvement of the switching turn-off time-related characteristics of the IGBT device.

Fast neutron irradiation forms very uniform defects such as V–O and V_2 within the IGBT device due to the primary effect of the DD caused by the irradiation [26–29]. The formed defects, V–O and V_2, play a recombination center role by rapidly recombining minority carriers remaining in the n-drift region of the IGBT device [29]. As a result, the defects formed due to the DD effect effectively control the minority carrier lifetime inside the IGBT device, reducing the problematic tail current in the turn-off operation of the device and improving its switching turn-off time characteristics.

4. Conclusion

To minimize the TID effects from proton and electron beams and improve the turn-off time characteristics of IGBT devices, we evaluated the impact of fast neutrons on the performance characteristics of the device. The fast neutron irradiation was performed with a 30 MeV cyclotron under 5 case conditions. As a result of the fast neutron irradiation, the I_{CE}-V_{GE} characteristic curve shifted to a negative voltage and showed a tendency for the V_{TH} value to decrease as the fluence increased. The change in V_{TH} was caused by the TID effect induced by fast neutron irradiation, resulting in the accumulation of positive oxide charges in the gate-oxide and Si/SiO_2 interface regions of the IGBT device. The Fast neutron irradiation had two important effects on the switching characteristics of the IGBT device. Due to the DD and TID effects, the switching turn-off and turn-on time of the IGBT device were improved. First, the positive oxide charge formed by the TID effect during the device switching turn-on operation contributed to lowering the V_{TH}, thereby inducing fast switching-on of the device. Second, the V–O and V_2 defects formed by the DD effect induce recombination of minority carriers remaining inside the device, leading to a decrease in minority carrier lifetime and tail current, and an increase in turn-off switching speed.

The fast neutron irradiation of the NPT-IGBT device improved the switching speed, but at some high irradiation conditions, it showed a tendency of deteriorating in the I_{CE}-V_{GE} and forward voltage drop characteristics. However, under most fast neutron irradiation conditions, the IGBT device exhibited stable operating characteristics in terms of I_{CE}-V_{GE}, forward voltage drop, breakdown voltage, and switching characteristics. This demonstrates that, unlike proton and electron beam irradiation, fast neutron irradiation can be a way to minimize the degradation of the electrical characteristics of IGBT devices and improve their switching performance. In addition, fast neutrons are known to offer a means of easily controlling the amount of defects depending on the irradiation conditions and can be used to stabilize or remove defects through heat treatment. Therefore, we plan to perform further studies to analyze the characteristics of defects and evaluate their impact on the performance of IGBT devices by conducting additional heat treatment processes.

It is expected that further research will enable the development of NPT-IGBT devices with better switching and electrical characteristics.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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