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Original Article

Improvement of Switching Speed of a 600-V Nonpunch-Through Insulated Gate Bipolar Transistor Using Fast Neutron Irradiation

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ABSTRACT

Fast neutron irradiation was used to improve the switching speed of a 600-V nonpunch-through insulated gate bipolar transistor. Fast neutron irradiation was carried out at 30-MeV energy in doses of 1×10^8 n/cm^2, 1×10^9 n/cm^2, 1×10^{10} n/cm^2, and 1×10^{11} n/cm^2. Electrical characteristics such as current–voltage, forward on-state voltage drop, and switching speed of the device were analyzed and compared with those prior to irradiation. The on-state voltage drop of the initial devices prior to irradiation was 2.08 V, which increased to 2.10 V, 2.20 V, 2.3 V, and 2.4 V, respectively, depending on the irradiation dose. This effect arises because of the lattice defects generated by the fast neutrons. In particular, the turnoff delay time was reduced to 92 nanoseconds, 45% of that prior to irradiation, which means there is a substantial improvement in the switching speed of the device.

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1. Introduction

Insulated gate bipolar transistors (IGBTs) have been widely used for high power switching devices owing to low on-state voltage drop and fast switching speed [1]. Recently, they have therefore become the main switching device in power semiconductor applications. However, in IGBTs operating at a higher frequency, long minority carrier lifetime (MCLT) can cause many problems such as turnoff switching time delay and excessive power loss during the switching [2].

A lattice defect is intentionally formed in the n-drift region of an IGBT to realize the deep energy level within the energy band. Such deep energy level acts as the recombination center, which controls the lifetime of minority carriers injected during the device operation [3,4].

The thermal diffusion of metal impurities, such as gold and platinum, has been used to control the MCLT of a silicon power semiconductor device for a long time. Meanwhile, particle beam irradiation methods, such as electron beam, proton, and neutron, have been recently used [5–11].

The thermal diffusion of metal impurities suffers from disadvantages in that the concentration control of the lattice defect is almost impossible and the lifetime control must be carried out in the middle of the device fabrication. The other

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electrical characteristics easily deteriorate during the succeeding fabrication processes [12]. These problems in thermal diffusion can be overcome by using energetic particle irradiation. Even after complete fabrication of the device, we can apply the particle beam irradiation method to form the lattice defects such as vacancy, vacancy–oxygen, and divacancy. Moreover, particle irradiation has a major advantage in that it can be used to control the generation of lattice defects easily by adjusting the kinetic energy and dose.

The irradiation characteristics of the electron, proton, and fast neutron are summarized in Table 1. The accelerator-based electron and proton beams are usually used. The energetic electrons make the defects uniformly within the medium. The large portions of the recoiled atoms may recombine their vacancy, which is explained by the fact that the recoiled atoms remain around their original lattice site because of the small momentum transfer of electrons. The protons make the defects very efficiently by transferring enough momentum to the lattice atoms to recoil far away from their original sites, although the defects are localized because of its inherent stopping power with Bragg peak prior to full-stopping. It is evident that the electron and proton irradiation methods improve the characteristic of switching, but induce a sharp rise of forward voltage drop and leak current. By contrast, the fast neutron irradiation method has minimized the effect on forward voltage drop and leak current by generating the uniform lattice defects via transferring enough momentum to the target atoms, and the switching characteristic is highly improved by reducing the MCLT.

Table 1 – Comparison of particle irradiations.

Division	Electron	Proton	Fast neutron
Method	Accelerator	Accelerator	Reactor
Energy (MeV)	0.4–10	1.5–15	10 keV–10
Effective particle	Electron	Proton	Fast neutron
Leakage current	High	High	Low
Switching speed	Fast	Fast	Fast
Uniformity	Almost uniform	Concentrated near a depth	Extremely uniform
Trade-off	Normal	Good	Best

In this study, 600-V nonpunch-through IGBT (NPT-IGBT) devices were irradiated under various dose conditions of fast neutrons with a maximum energy of 30 MeV. Electrical characteristics such as current–voltage, forward on-state voltage drop, and switching speed of the device were examined in detail.

2. Materials and methods

2.1. *Sample preparation*

There are two ways to develop the IGBT devices both statically and dynamically. One way is to make IGBTs with a punch-through (PT) path to block the injection of the minority carriers by inserting an n-buffer layer as lifetime killer. It has low on-state losses. The other way is to make IGBTs with a nonpunch-through (NPT) path, which is simpler and has lower switching losses. The NPT-IGBT has a high blocking capability, whereas the PT-IGBT is difficult to control when higher blocking voltage is applied [13]. In this study, an NPT-IGBT device was chosen for fast neutron irradiation because it is currently used for mass production and is expected to show more obvious improvement of performance by fast neutron irradiation. We designed the NPT-IGBT device, and a 6-inch wafer of the IGBT devices was completely fabricated. The schematic structure of the device and its picture are shown in Fig. 1. The thickness of the n-drift region was finely adjusted to 100 μm for the maximum blocking voltage to be 600 V and the thickness of the P^+ collector is also adjusted to 0.2 μm for the current to be 30 A. The thickness of the entire device including the A1 electrode is 107 μm. Each device has a dimension of 4 mm × 4.5 mm, and a set composed of six devices was arranged for fast neutron irradiation.

The experiment was carried out on the horizontal beam (Beamline #2) of the MC-50 cyclotron at the Korea Institute of Radiological and Medical Sciences, as shown in Fig. 2. To generate the neutron beam, the proton beam with a kinetic energy of 30 MeV was irradiated on a beryllium target with a thickness of 0.5 cm [14]. The neutron spectrum of the position, 1 cm away from the opening of the graphite collimator, was simulated using MCNP6 [15]. Fig. 3 shows the simulated neutron spectrum generated by 10-μA incident protons. Table

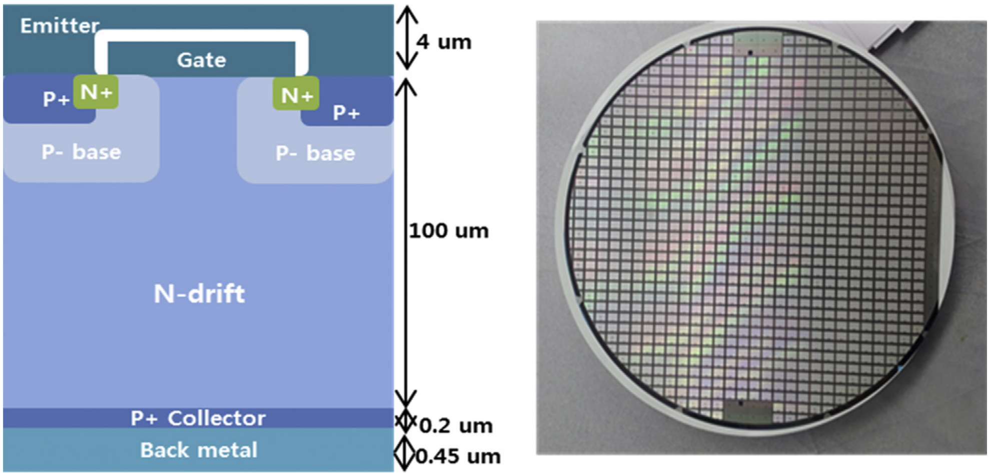

Fig. 1 – Schematic structure and wafer of 600-V NPT-IGBT.

Fig. 2 – MC-50 cyclotron and sample mounting at the end of beam line #2.

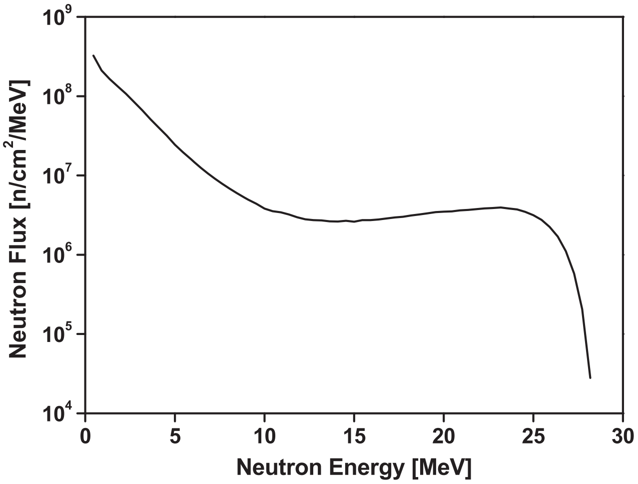

Fig. 3 – Calculated energy spectrum of neutrons generated by the ^{9}Be(p,n) reaction.

2 lists the irradiation condition of fast neutrons, whose dose varied between 1 × 10^8 n/cm^2 and 1 × 10^{11} n/cm^2.

After neutron irradiation, the samples were thermally treated at 300°C for 1 h to stabilize the generated lattice defects. It was packaged in TO-3 type after the thermal treatment was completed. After packaging the devices, the electrical characteristics of threshold voltage (V_{TH}), forward voltage drop (V_{CE}), and switching speed (T_{off}) were measured by using a source measurement unit (Keithley 2636 and 2651) and a packing box tool (Keithley 8010).

Table 2 – Irradiation condition of the fast neutrons.

Proton energy	Neutron flux	Irradiation direction
	Without irradiation	
30 MeV proton	1 × 10^8	Front
	1 × 10^9	Front
	1 × 10^{10}	Front
	1 × 10^{11}	Front

2.2. *Threshold voltage characteristics*

Fast neutron was uniformly irradiated on the entire device. The irradiation defects formed in the gate silicon oxide layer act as a trap center to increase the leakage current and reduce the threshold voltage. The threshold voltage is defined as the gate voltage for a collector current of 30 mA. It was determined by measuring the output curve after shorting the gate and collector and applying a forward voltage at both ends of the gate and emitter.

2.3. *Collector saturation current and forward voltage drop*

The collector saturation current is saturated when the gate voltage is 15 V. Forward voltage drop is defined as the collector voltage at a collector current of 30 A. To measure the forward voltage drop, a positive voltage was applied to the gate electrode, and a forward voltage was applied to both ends of the collector and emitter.

2.4. *Turnoff delay time characteristics*

To measure the turnoff delay time, we fabricated an inductance load switching circuit to switch a high current as shown in Figs. 4 and 5. It has been used for most IGBT applications

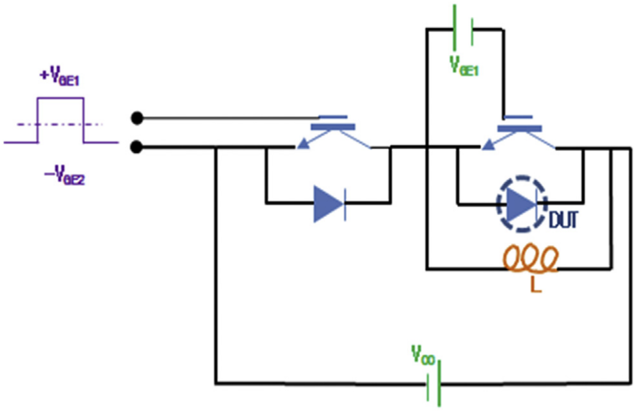

Fig. 4 – Circuit of the system for the turn-off delay time measurement.

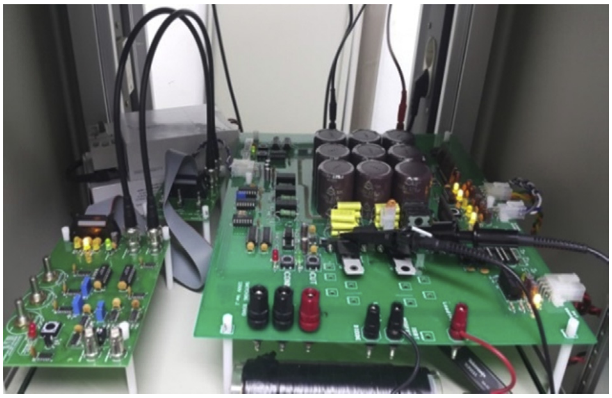

Fig. 5 – Circuit of the system for the turn-off delay time measurement.

such as the inverter, velocity variable motor, power distributor, and rail traction. A forward voltage of 300 V was applied to both ends of the collector and emitter, and a voltage pulse is applied to the gate. In the on-state of the IGBT, 0 V was applied to both ends of the collector and emitter, and 300 V was applied when it was in the off-state. Turnoff delay time is defined as the time for a 10% to 90% change in the current at both ends of the collector and emitter as shown in Figs. 6A and 6B, which show the signal measured using a Tektronix MD3054 oscilloscope unit.

3. Results

3.1. *Threshold voltage characteristics*

Fig. 7 shows the transfer characteristics of each IGBT device using the relationship between the collector current and the gate voltage. These transfer characteristics were used to obtain the threshold voltage. The threshold voltage of each device depending on the fast neutron irradiation condition is shown in Fig. 8. The threshold voltage of the device without

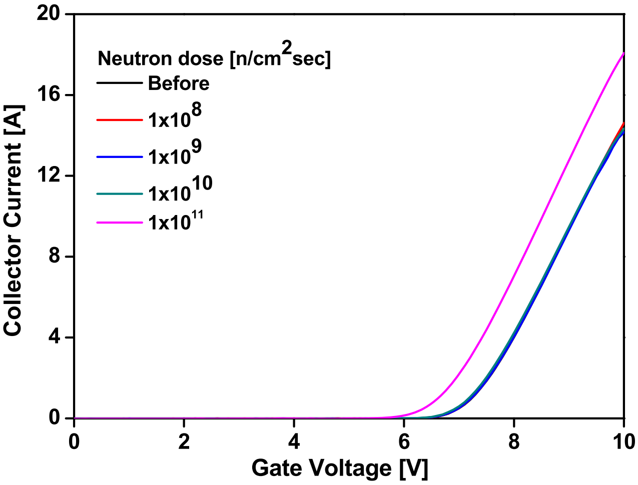

Fig. 7 – Transfer characteristics of the 600-V NPT-IGBT.

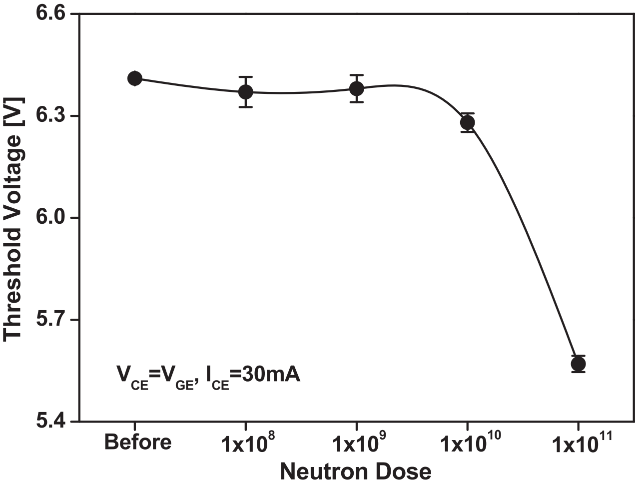

Fig. 8 – Threshold voltage of the 600-V NPT-IGBT.

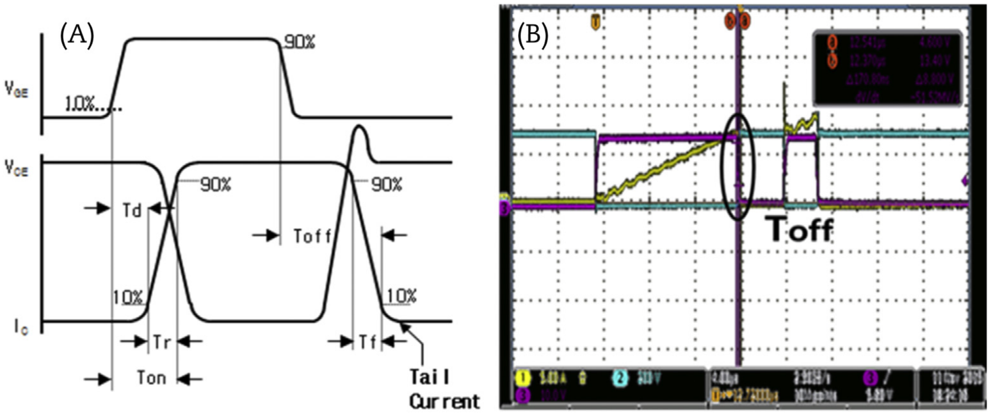

Fig. 6 – Turn-off delay time of the 600 V NPT- IGBT (a) and (b).

fast neutron irradiation was approximately 6.41 V. When fast neutrons were irradiated in doses of 1×10^8 n/cm^2, 1×10^9 n/cm^2, 1×10^{10} n/cm^2, and 1×10^{11} n/cm^2, the threshold voltage decreased to 6.37 V, 6.38 V, 6.28 V, and 5.57 V, respectively. It is explained by the fact that the threshold voltage of the device was reduced by the trap of the SiO_2 and Si interface generated after the irradiation, and the trap was formed in the silicon energy band by the crystal defect formed on the silicon lattice because of the decrease in the mobility of silicon [16]. If the threshold voltage is reduced, the device can be operated at a lower gate voltage, and the power loss decreases as more collector current is allowed to flow at the same gate voltage.

3.2. *Forward voltage drop characteristics*

Figs. 9–13 show the forward voltage drop characteristics prior to irradiation depending on the fast neutron irradiation dose. The basic turn-on feature of the IGBT device is shown in Fig. 9 for the case without fast neutron irradiation. The gate voltage (V_G) was varied from 7 V to 10 V, and the collector current (I_{CE}) rises according to the collector voltage (V_{CE}). Devices start to turn on at 0.7 V. The slope between V_{CE} and I_{CE} depends on the V_G. If the fast neutrons were irradiated, the slope at a given V_G decreases according to the dose as shown in Figs. 10–13. It is explained by the fact that a conductivity modulation in the n-drift region decreases owing to the reduction in MCLT caused by the lattice defects generated by the fast neutron irradiation.

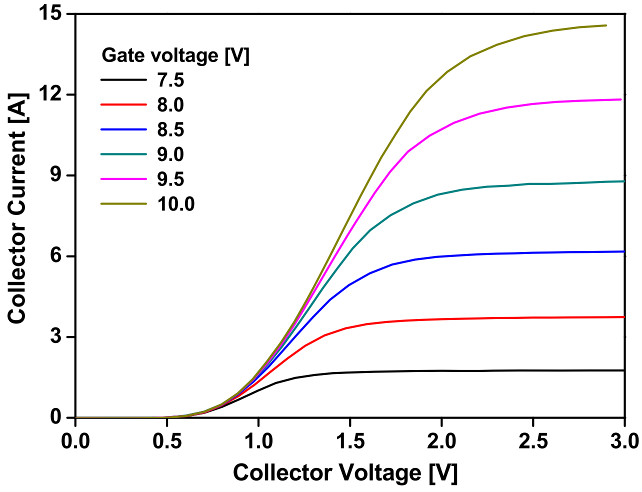

Fig. 9 – **Output characteristics of the 600-V NPT-IGBT (Before irradiation).**

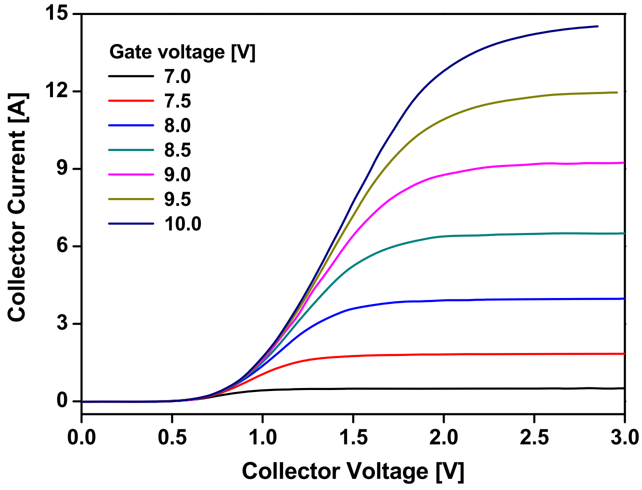

Fig. 10 – **Output characteristics of the 600 V NPT-IGBT (Dose = 1 × 10^8).**

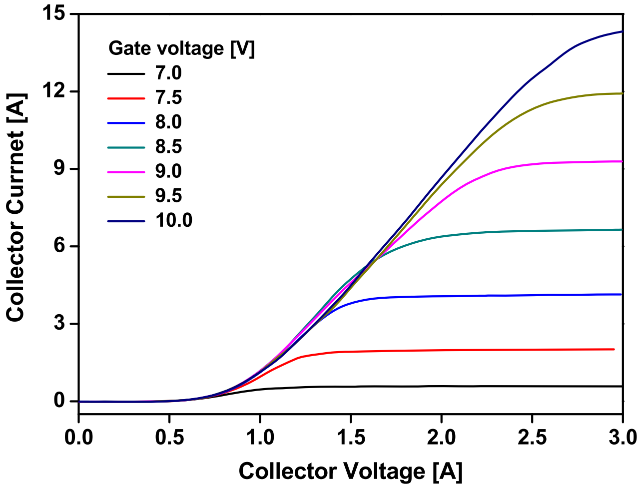

Fig. 11 – **Output characteristics of the 600-V NPT-IGBT (Dose = 1 × 10^9).**

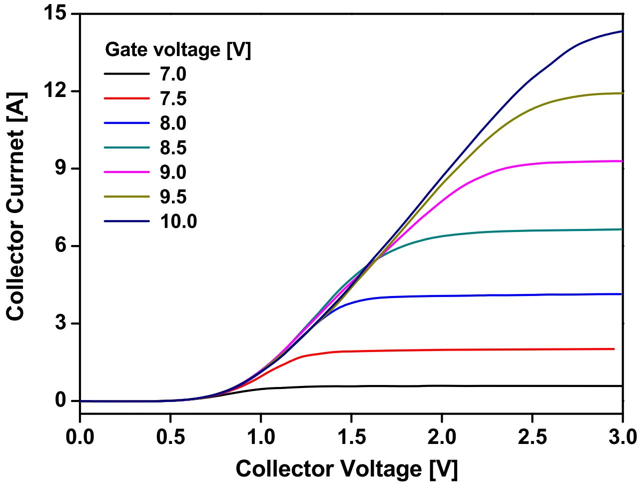

Fig. 12 – **Output characteristics of the 600-V NPT-IGBT (Dose = 1 × 10^{10}).**

Fig. 14 shows the forward voltage drop characteristics. The voltage drop of the device prior to fast neutron irradiation was 2.075 V, which increased to 2.1 V, 2.2 V, 2.315 V, and 2.445 V, respectively, depending on the irradiation doses. There are two terms contributing to the resistivity of the device. One is the surface resistivity generating the leakage current, and the

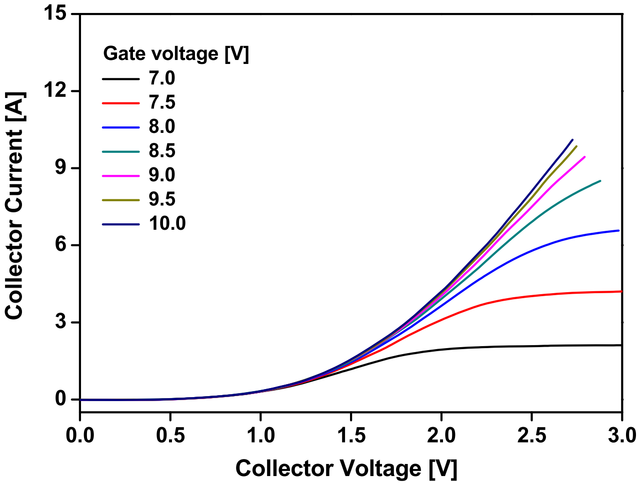

Fig. 13 – Output characteristics of the 600-V NPT-IGBT (Dose = 1 × 10^{11}).

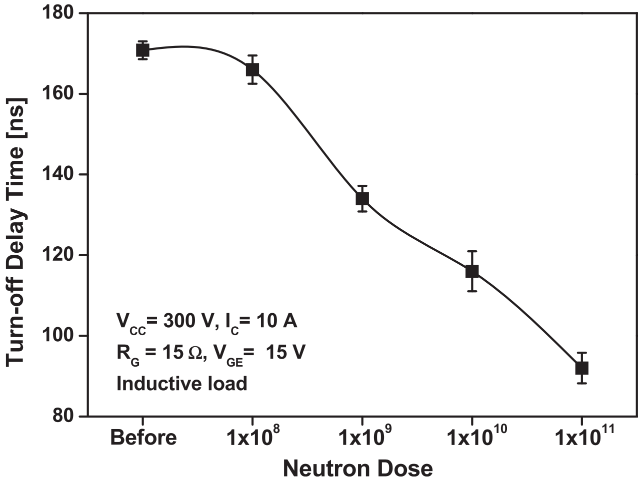

Fig. 15 – Turn-off delay time of the 600-V NPT-IGBT.

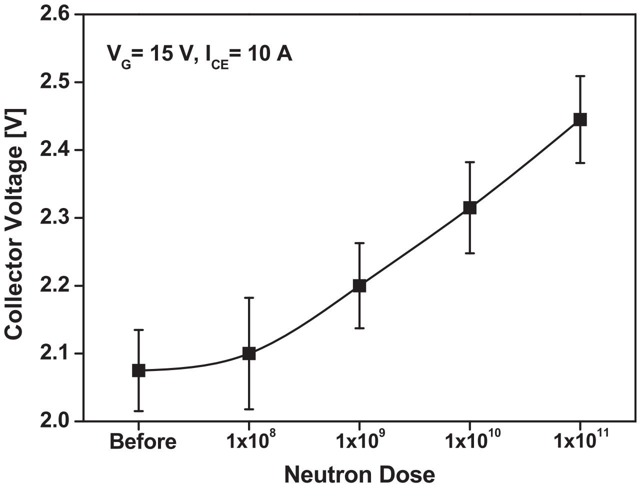

Fig. 14 – On-state voltage drop of the 600-V NPT-IGBT.

other is the intrinsic resistivity within the device. The lattice defects produced by the fast neutrons change the intrinsic resistivity especially in the n-drift region because they play as trapping centers and block the carrier stream.

3.3. *Turnoff delay time characteristics*

The switching time consists of the main component caused by the major carriers and tail component caused by the minority carriers. Because a minority carrier of the IGBT is always holes, it shows a long tail in the switching because the holes move more slowly than the major carriers. To reduce the switching time, it needs to reduce the minority carriers rapidly during the switching. Fig. 15 shows the comparison of the turnoff delay times prior to and after irradiation. The turnoff delay time of the device prior to irradiation was approximately 170 nanoseconds, which was significantly improved to 166 nanoseconds, 134 nanoseconds, 116 nanoseconds, and 92 nanoseconds for the doses of 1 × 10^8 n/cm^2, 1 × 10^9 n/cm^2, 1 × 10^{10} n/cm^2, and 1 × 10^{11} n/cm^2, respectively. This means that fast neutrons generate the lattice defects in the n-drift region, which recombine with the minority carriers during the turnoff switching and reduce the tail switching component, as a result of which the switching speed increases.

4. Discussion

To improve the turnoff switching speed of a 600-V NPT-IGBT, devices were produced by irradiating various doses of the fast neutron, and their characteristics were comparatively analyzed with the device where no fast neutron was irradiated. To improve and optimize the IGBT performance, appropriate conditions should be determined by trading off each characteristic. The switching characteristic of the device where a fast neutron was irradiated was improved by approximately 45% compared with those of the device where no fast neutron was irradiated.

The turnoff delay time of the device where no fast neutron was irradiated was approximately 170 nanoseconds, and those of the devices where fast neutrons were irradiated in doses of 1 × 10^8 n/cm^2, 1 × 10^9 n/cm^2, 1 × 10^{10} n/cm^2, and 1 × 10^{11} n/cm^2 were 166 nanoseconds, 134 nanoseconds, 116 nanoseconds, and 92 nanoseconds, respectively. The irradiation of 1 × 10^{11} n/cm^2 showed the fastest time. Also, the device can be operated at a lower gate voltage because the threshold voltage of the device was reduced by the trap in the SiO_2 and Si interface generated after the irradiation. The power loss can be minimized by allowing more collector current to flow under the same gate voltage.

The resistance component increased because of the lattice defect generated by the fast neutron irradiation in the on-state, resulting in a side effect of increasing the value of the forward voltage drop. Furthermore, although the reduction in the lifetime of the minority carrier flowing into the n-drift layer due to the lattice defect helps improve the switching characteristics of the device, it can potentially deteriorate the withstanding voltage characteristics of the device, such as reduction in the conductivity modulation of the n-drift layer.

Conflicts of interest

All authors have no conflicts of interest to declare.

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