Nuclear Engineering and Technology 54 (2022) 501–506

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original article

Turn-off time improvement by fast neutron irradiation on pnp Si Bipolar Junction Transistor

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ARTICLE INFO

Article history:
Received 10 March 2021
Received in revised form
28 October 2021
Accepted 8 November 2021
Available online 13 November 2021

Keywords:
Turn-off time
Fast neutron
Irradiation
BJT
Switching

ABSTRACT

Long turn-off time limits high frequency operation of Bipolar Junction Transistors (BJTs). Turn-off time decreases with increases in the recombination rate of minority carriers at switching transients. Fast neutron irradiation on a Si BJT incurs lattice damages owing to the displacement of silicon atoms. The lattice damages increase the recombination rate of injected holes with electrons, and decrease the hole lifetime in the base region of pnp Si BJT. Fast neutrons generated from a beryllium target with 30 MeV protons by an MC-50 cyclotron were irradiated onto pnp Si BJTs in experiment. The experimental results show that the turn-off time, including the storage time and fall time, decreases with increases in fast neutron fluence. Additionally, it is confirmed that the base current increases, and the collector current and base-to-collector current amplification ratio decrease due to fast neutron irradiation.

1. Introduction

A Bipolar Junction Transistor (BJT) is a device in which emitter and collector currents are controlled by base voltage. A BJT can be used as a switch device that drives from an on state to an off state or vice versa with this control feature. When a BJT is used as a switch device, it can have a long turn-off time because it takes a long time to remove the minority carriers by the recombination process in the turn-off transient [1]. The turn-off time can be decreased by shortening of the minority carrier lifetime via creation of recombination centers in the lattice.

Two methods are used to control the lifetime of minority carriers [2]. The first method involves thermal diffusion of impurities that exist at deep levels. Platinum and gold are mainly used in this method. Device characteristics can be easily changed by small variations of the diffusion temperature in this method. The second method is based on creation of lattice damages in Si by irradiation with high energy particles [3,4]. This damage can be created by bombardment using electrons, gamma rays, protons, and neutrons [5–8]. When high energy particles are used to irradiate semiconductors, the incident energetic particles create ionization and non-ionizing energy loss [9,10]. When energetic particles collide with atomic electrons, they lose energy and become excited or ionized. The non-ionizing energy loss caused by interaction with nuclei creates displacement damage. High energy radiation produces defect complexes in semiconductor materials that reduce the minority carrier lifetime and change the majority carrier density and mobility. The lifetime of minority carriers can be precisely controlled using high energy particles at room temperature [11,12]. When gamma rays are used to irradiate BJTs, the effects of Total Ionization Dose (TID) caused by ionization are more common than the effects of displacement damage. On the other hand, the special feature of fast neutron irradiation is that it predominantly causes displacement damages in Si bulk, rather than effects of TID. The advantage of fast neutron irradiation is that the uniform and precise damage control is possible in Si bulk of BJT. Therefore, fast neutron irradiation is an effective method of reducing the lifetime of minority carriers in Si bulks of BJT.

The effects of fast neutron irradiation on BJT have been studied. Meng studied the fast neutron irradiation effects on SiGe HBT (Silicon-Germanium Heterojunction Bipolar Transistor) and Si BJT [13]. Oo studied the effects of neutron irradiation on a pnp BJT [14], and Ahn studied the effects of the fast neutron irradiation on a pnp BJT [15,16]. These studies showed that the collector current and current amplification ratio decreased, and the base current increased, with increases in fast neutron fluence.

When BJT is used in a switching device for application to high frequency operation, turn-off switching time is a more important

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https://doi.org/10.1016/j.net.2021.11.009
1738-5733/

performance factor than current gain, and gain degradation is acceptable because it is not critical in switching performance. The major power loss of the BJT is the on-state loss during low frequency switching, when it is used as a switch device. However, the power loss of the turn-off switching transient increases rapidly in high frequency switching. The long turn-off time limits the high frequency operation of the BJT. Therefore, a short turn-off time is needed in the BJT for high frequency applications. This study investigated turn-off switching as well as current characteristics through fast neutron irradiation on a pnp Si BJT.

2. Characteristics of a pnp BJT

2.1. Current flow

In a pnp BJT, the holes are injected from the emitter to the n-type base region under the forward-biased emitter junction, and these holes are collected at the collector under the reverse-biased collector junction. The base current is very small compared to the emitter current because the emitter and collector currents are mostly hole current. The base current can be formed by the following three mechanisms [1]. First, the injected holes from the emitter region recombine with electrons in the base region. Electrons lost by recombination are resupplied from the base current. Second, there is electron injection from the base to the emitter under the forward-biased emitter junction. These injected electrons are also resupplied by the base current. Third, some electrons are swept into the n-type base region from the p-type collector region at the reverse-biased collector junction generated by thermal generation. These electrons decrease the base current. Recombination is the main mechanism of the base current.

BJTs are widely used as amplifiers and switches because emitter and collector currents can be controlled by the base current (i_B). The emitter current (i_E) is composed of hole current (i_{Ep}) and electron current (i_{En}). The collector current (i_C) is created by those holes injected from the emitter and reached the collector without recombination at the base, ignoring the saturation current of collector.

The collector current (i_C) is made up entirely of those holes injected at the emitter that are not lost to recombination at the base, ignoring the collector saturation current. The collector current is

$$i_C = B i_{Ep}, \tag{1}$$

where B is the base transit factor of holes to the collector [1]. The base current is

$$i_B = i_{En} + (1 - B) i_{Ep}, \tag{2}$$

if the collector saturation current is ignored. $(1 - B)$ is the recombination factor in the base [1]. The base-to-collector current amplification ratio ($\beta = i_C/i_B$) is given by (3) from (1) and (2).

$$\beta = \frac{B I_{Ep}}{I_{En} + (1 - B) I_{Ep}}. \tag{3}$$

If the base transit factor is small, the current amplification ratio is small.

2.2. Turn-off switching

A BJT switch is driven back and forth between the saturation and cutoff states. Fig. 1 shows the switching characteristics of a pnp BJT [1]. When the input voltage v_B is zero, the BJT is in the cutoff state, and the collector voltage $v_C = -V_{CC}$, and $i_C = 0$ in the ideal case. Thus, BJT acts as a turn-off switch in this case. When the large input voltage v_B is applied by positive bias, the BJT is operated at the saturation state, and $v_C = 0$, $i_C = -V_{CC}/R_C$ in the ideal case. Thus, the BJT acts on the turn-on switch in this case.

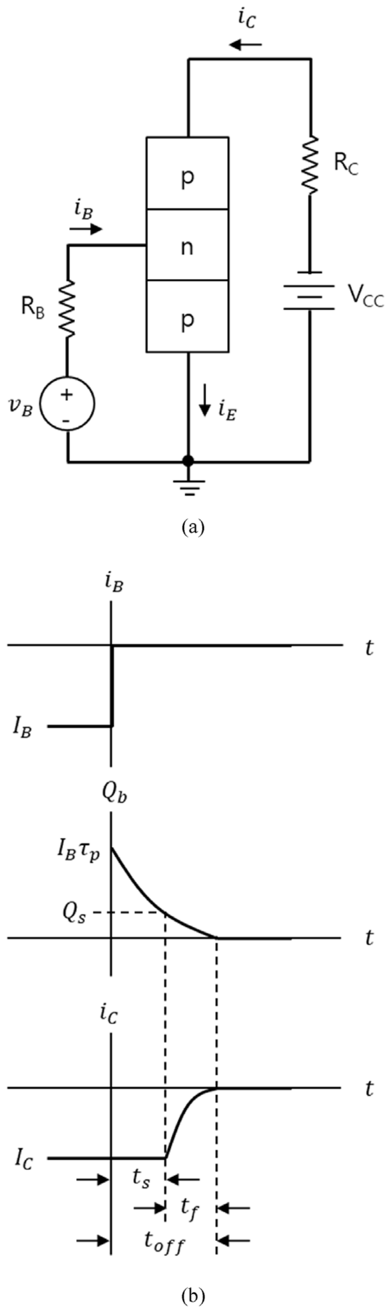

Fig. 1. Switching characteristics of a pnp BJT: (a) switching circuit and (b) turn-off transient.

Fig. 2 shows the switching delay time in the turn-off transition [17]. The turn-off time (t_{off}) consists of storage time (t_s) and fall time (t_f). The storage time is the time required for device to exit the saturation state. The fall time is the time required for the BJT to make the transition from saturation state to cutoff state. The stored charge at the beginning of turn-off transient is $Q_b = I_B\tau_p$. τ_p is the hole lifetime, which is the minority carrier in the base. The stored charge falls exponentially from this value to zero with the time constant τ_p.

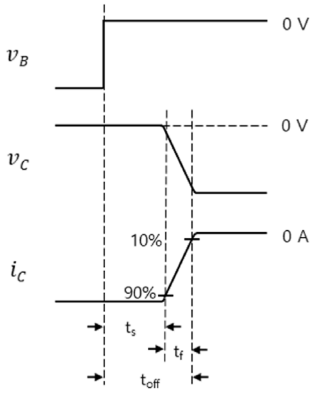

Fig. 2. Switching delay times in the turn-off transient.

If τ_t is the hole transit time from the emitter to the collector, the collector current remains at its saturated value I_C ($I_C = -V_{CC}/R_C$) until Q_b falls to the value for the minimum saturation $Q_s = I_C\tau_t$. The storage delay time is given by [1].

$$t_s = \tau_p ln \frac{\beta I_B}{I_C}, \tag{4}$$

where $\beta = \tau_p/\tau_t$. The storage delay time is shortened by employing a small τ_p and a small β, as shown in (4). Therefore, the storage delay time is shortened by reducing the hole lifetime.

The collector current is exponentially decreased from I_C to zero with the time constant τ_p after getting out of the stored delay time, and it is given by (5) [1].

$$i_c(t) = I_C e^{-(t-t_s)/\tau_p} \tag{5}$$

The fall time is given by (6) from (5)

$$t_f = \tau_p ln \frac{I_{C_{90\%}}}{I_{C10\%}} \tag{6}$$

The fall time is shortened by employing a small τ_p, as shown in (6). Therefore, the fall time can be decreased by shortening the hole lifetime.

3. Fast neutron irradiation effects

The special feature of fast neutron irradiation is that it predominantly causes atomic displacement damages in Si bulk of BJT, rather than effects of TID. Therefore, fast neutron irradiation is an effective method of reducing the lifetime of minority carriers because uniform and precise damage control is possible in Si bulk of BJT. Cluster defects are produced by displacement of Si atoms from their lattice sites due to fast neutron irradiation [10]. Atomic displacement is the dislodging of an atom from its lattice site. Displacement creates vacancies and interstitial positioning of Si atoms and changes the periodicity of the lattice. The disruption of lattice periodicity in Si creates energy levels in the band gap. These energy levels serve as generation and recombination centers of carriers [2,10]. Recombination-generation centers caused by fast neutrons decreases the minority carrier lifetime in BJTs. The decreased minority carrier lifetime affects the electrical and switching properties of BJTs. The damages caused by fast neutron irradiation can be restored through annealing [18]. Unnecessary energy levels within the band gap can be removed by appropriate annealing methods. However, annealing can increase the lifetime of minority carriers. If restoration from the damages is required, an appropriate annealing method should be considered.

4. Experimental results

In the experiment, packaged pnp Si BJTs were irradiated with fast neutrons. The pnp Si BJTs were used in a general purpose application such as switching or amplification. The maximum ratings and electrical characteristics of the BJTs are given in Tables 1 and 2. An MC-50 cyclotron at the Korea Institute of Radiological & Medical Sciences was used for fast neutron irradiation. The fast neutrons were generated from a beryllium target with 30 MeV protons. The BJTs were irradiated at 5×10^8 and $5 \times 10^9\ neutrons/cm^2$.

4.1. Current flow

The recombination rate of the minor carriers in the base region increases with increases in the displacement damages by fast neutron irradiation. Thus, τ_p decreases with increase in the recombination rate. Fig. 3 shows the measurement results of the base current before and after fast neutron irradiation. The base currents increased with increases in fast neutron fluence, as shown in Fig. 3. The experimental results indicate that the recombination of injected holes from the emitter with electrons in the base increased and the base transit factor decreased. Thus, the electrons lost by recombination were supplemented from the base terminal, and the base current increased by fast neutron irradiation.

Fig. 4 shows the measurement results of the collector current before and after fast neutron irradiation. The collector currents decreased with increases in fast neutron fluence, as shown in Fig. 4. The experimental results indicate that the recombination of injected holes from the emitter with electrons in the base increased, and the collected holes to the collector decreased because the base transit factor decreased. As a result, the collector currents decreased.

Fig. 5 shows the measurement results of the base-to-collector current amplification ratio before and after fast neutron irradiation. β decreased with increases in fast neutron fluence, as shown in Fig. 5. β_0 is the base-to-collector current amplification ratio before irradiation. The β/β_0 ratios were 94.54% (for 5×10^8) and 71.95% (for 5×10^9) at $v_{CE} = -6V$. These results indicate that displacement damage caused by fast neutron irradiation increases the recombination rate of injected holes with electrons in the base. Thus, the hole lifetime decreased and the collector current decreased because the base transit factor decreased. The base current increased because the electrons lost to recombination in the base were supplemented through the base terminal. As a result, β decreased.

4.2. Turn-off time

In the experiment, the switching circuit was configured as shown in Fig. 1. While maintaining the on-state, 0 V was applied to the base voltage to turn-off at 0 s. Fig. 6 shows the measurement results of the collector voltage (v_C) and the collector current (i_C) at the turn-off switching transient before and after fast neutron irradiation. The experimental results indicate that the turn-off time decreased with increases in fast neutron fluence.

Table 1
Maximum ratings of pnp BJT at 25 °C.

Characteristic	Symbol	Rating
Collector-Base Voltage	V_{CBO}	−100V
Emitter-Collector Voltage	V_{CEO}	−100V
Emitter-Base Voltage	V_{EBO}	-5V
Collector Current	I_C	-5A
Base Current	I_B	−0.5A

Table 2
Electrical characteristics of pnp BJT.

Characteristic	Test condition	Rating
Collector cut-off current	$V_{CB} = -100V$, $I_E = 0$	Max. −100 μA
Emitter cut-off current	$V_{EB} = -5V$, $I_C = 0$	Max. -1 mA
Collector-emitter Breakdown voltage	$I_C = -50mA$, $I_B = 0$	Min. −100V
DC current gain	$V_{CE} = -5V$, $I_C = -1A$	40–240
Collector-emitter saturation voltage	$I_C = -4A$, $I_B = -0.4A$	Max. −2.0V

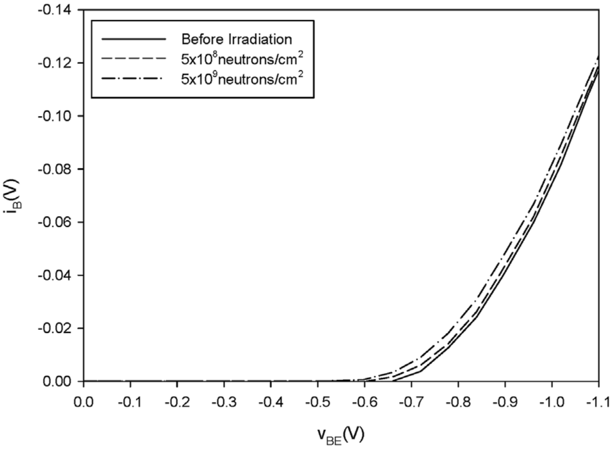

Fig. 3. Base currents on fast neutron fluence.

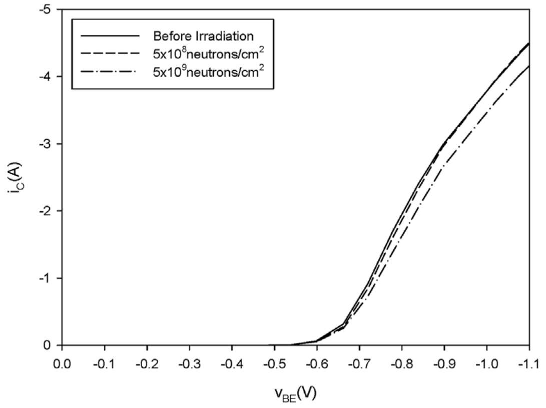

Fig. 4. Collector currents on fast neutron fluence.

Fig. 7 shows the measurement results of the storage time before and after fast neutron irradiation. The measured storage times were 13.80 μs (before irradiation), 6.80 μs (for 5×10^8), and 1.18 μs (for 5×10^9). t_{s0} is the measured storage time before irradiation. The t_s/t_{s0} ratios were 49.28% (for 5×10^8) and 8.58% (for 5×10^9). The storage time decreased by reducing of τ_p and β, as shown in (4). The experimental results indicate that the recombination rate of minor carriers in the base region increased with increases in displacement damages by fast neutron irradiation, and τ_p and β decreased with increase in the recombination rate. As a result, the storage time decreased with increases in fast neutron fluence.

Fig. 8 shows the measurement results of the fall time before and after fast neutron irradiation. The measured fall times were 3.84 μs (before irradiation), 3.54 μs (for 5×10^8), and 2.34 μs (for 5×10^9). t_{f0} is the measured fall time before irradiation. The t_f/t_{f0} ratios were 92.16% (for 5×10^8) and 61.06% (for 5×10^9). The fall time

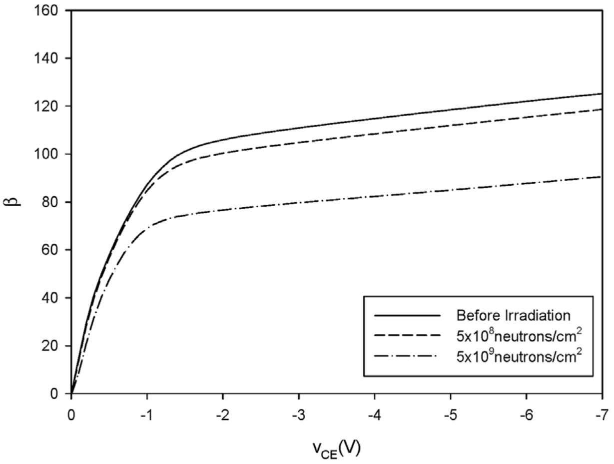

Fig. 5. Base-to-collector current amplification ratios on fast neutron fluence.

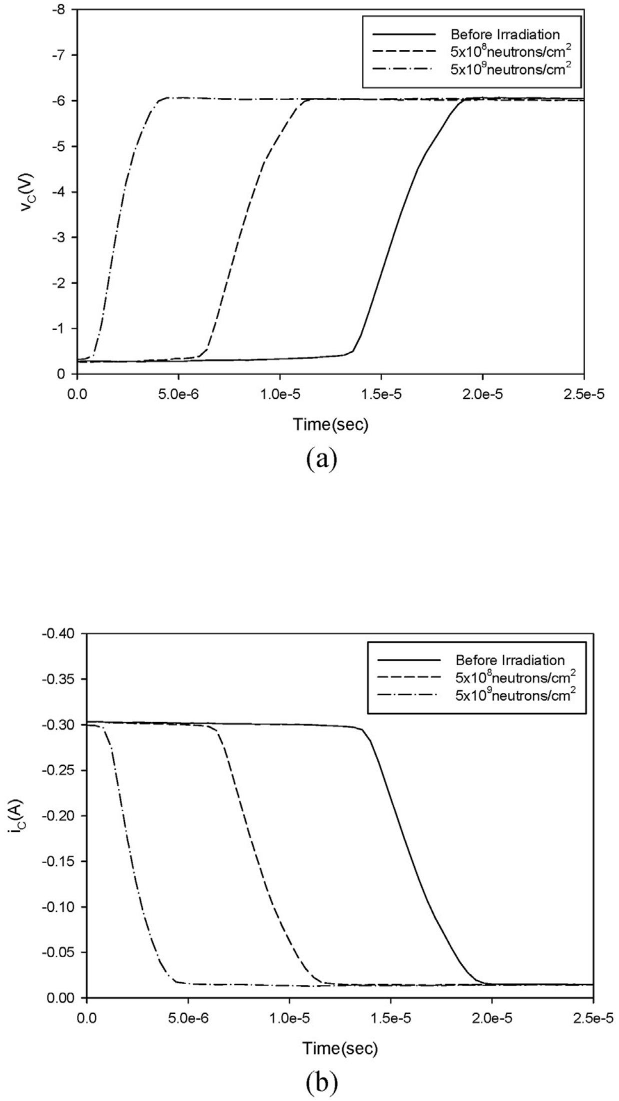

Fig. 6. Turn-off transient on fast neutron fluence: (a) collector voltages and (b) collector currents.

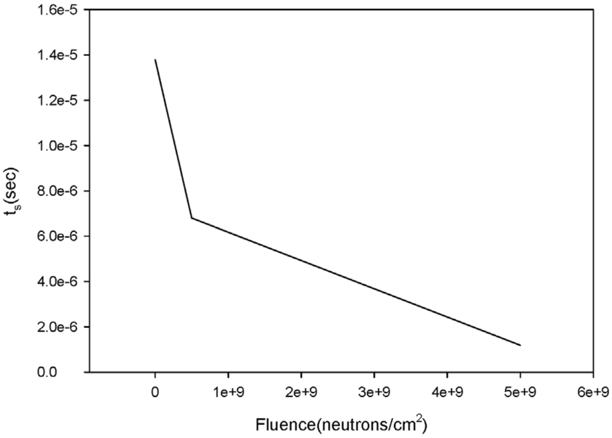

Fig. 7. Variation of storage time on fast neutron fluence.

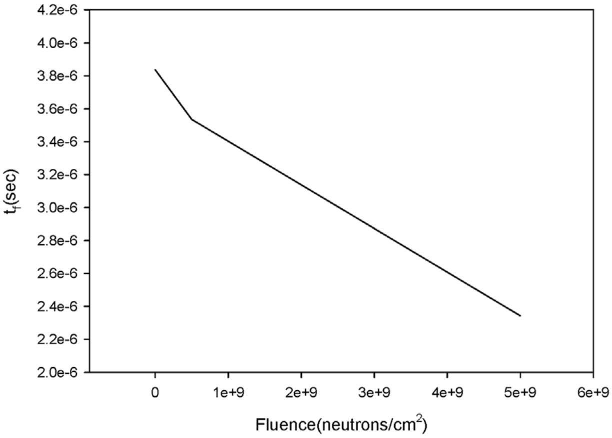

Fig. 8. Variation of fall time on fast neutron fluence.

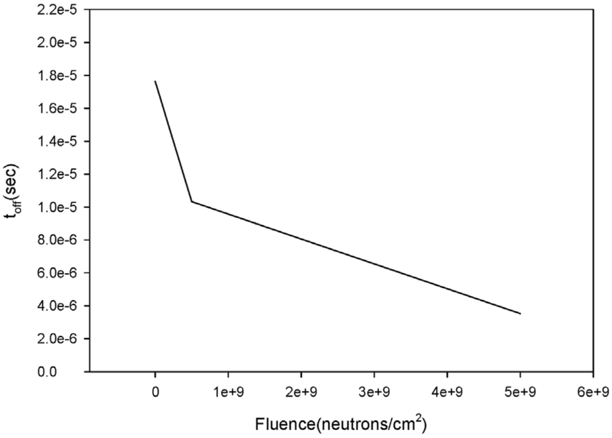

Fig. 9. Variation of turn-off time on fast neutron fluence.

decreased with decreasing τ_p as shown in (6). The experimental results indicate that τ_p decreased with increases in fast neutron fluence. As a result, the fall time decreased with increases in fast neutron fluence.

Fig. 9 shows the measurement results of the turn-off time before and after fast neutron irradiation. The turn-off time consists of storage time and fall time. The measured turn-off times were 17.64 μs (before irradiation), 10.34 μs (for 5×10^8), and 3.53 μs (for 5×10^9). t_{off0} is the measured turn-off time before irradiation. The t_{off}/t_{off0} ratios were 58.60% (for 5×10^8), and 20.00% (for 5×10^9). The turn-off time decreased by reducing of τ_p and β, as shown in (4) and (6). The experimental results indicate that τ_p and β decreased with increases in fast neutron fluence. As a result, the turn-off time decreased with increases in fast neutron fluence.

5. Conclusions

BJTs have a long turn-off time due to the long time required for the removal of minority carriers by recombination process in the turn-off transient. The long turn-off time of BJTs limits their application to high frequency switches. When BJT is used in a high frequency switching device, shortening of the turn-off time is an important performance factor, and gain degradation is acceptable because it is not critical in switching performance. Fast neutron irradiation on the Si BJT incurs lattice damage owing to the displacement of silicon atoms. Fast neutron irradiation is an effective method of reducing the lifetime of minority carriers because uniform and precise damage control is possible in Si bulk of BJTs. The turn-off time of Si BJTs can be decreased by reducing the lifetime of the minority carriers with the introduction of lattice damages by fast neutron irradiation. In a pnp Si BJT, the lattice damage increases the recombination rate of injected holes with electrons in the base region and decreases the hole lifetime. The storage time and fall time at the turn-off transient decrease with increasing recombination rate. This study investigated the variations of current characteristics and turn-off time on a pnp Si BJT by irradiation with fast neutrons. The experimental results show that the turn-off time, including the storage time and fall time, decreased with increases in fast neutron fluence. Also, it is shown that the collector current and base-to-collector current amplification ratio decreased, and the base current increased, with increases in fast neutron fluence. Fast neutron irradiation can be utilized to improve the switching time of BJTs for application to high frequency switches.

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.

Acknowledgements

This work was supported by the Ministry of Science and ICT of Korea government (1711078081) and Radiation Technology R&D program through the National Research Foundation of Korea funded by the Ministry of Science and ICT (NRF-2017M2A2A6A05018529).

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