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High-energy electron induced gain degradation in bipolar junction transistors

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Abstract

This paper describes the effect of 8 MeV electron beam on the forward current gain of space borne commercial indigenous bipolar junction transistors 2N2219A (npn), 2N3019 (npn) and 2N2905A (pnp). The devices are exposed to 8 MeV electron in the biased condition. The collector characteristics and Gummel plots are obtained as a function of accumulated dose. An excess base current model as well as Messenger–Spratt equation have been used to account for the observed gain degradation. The results indicate that 8 MeV electrons of high dose rate induce gain degradation by increasing the base current as well as decrease in collector current. The current gain degradation appears to be predominantly due to displacement damage in the bulk of the transistor. Off-line measurements of the h_{FE} of the irradiated transistors indicate that the displacement induced defect and recombination centers do not anneal even at 150 °C.

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Keywords: High-energy electron irradiation; Gain degradation; Excess base current; BJT; Thermal annealing

1. Introduction

The study of radiation-induced effects in semiconductor devices, in general, is important both from the basic as well as applied point of view. From the basic point of view, it is important to have a broader understanding of the damage process. From the applied point of view, it is important to assess the device performance when they need to be operated in radiation environment. A number of non-radhard versions of the devices from international vendors have been characterized for radiation-induced effects for use in space applications. However, several semiconductor devices, which are not available in radhard versions, are still being used in spacecraft systems. In the recent years, there is an increasing need for some space agencies to employ indigenously made devices for space applications. As a result, it is essential to characterize these for radiation induced effects and qualify the parts for use in spacecraft systems.

Discrete BJTs are still employed for space applications due to their current drive capability, linearity and excellent matching characteristics. One of the important aspect of the characterization of BJTs for radiation-induced effects is the radiation-induced gain degradation. The BJTs are particularly found to be vulnerable to ionizing radiation and transistor gain degradation is the primary cause for parametric shifts and functional failures. Although there are several studies looking into the mechanism of gain degradation in BJTs subjected to radiation, a widely accepted model accounting for the same has not emerged. The degradation of the forward current gain in the bipolar junction transistor when exposed to radiation is dependent on many factors including the nature of radiation particulate and

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dose rate. The radiation-induced degradation is also found to be dependent on the manufacturing technology. The effects of ionizing radiation on vertical linear bipolar junction transistors have been studied extensively [1–6]. Vertical npn transistors exhibit very significant gain degradation, particularly when they are irradiated at low dose rates (less than about 10 rad (SiO_2)/s). In contrast, vertical pnp transistors are relatively hard to ionizing radiation [1].

The effect of γ-radiation on BJTs is well understood. It is known that there are basically two possible mechanisms contributing to current gain degradation in transistors exposed to γ-radiation: (i) surface degradation and (ii) bulk degradation. Nowlin et al. [1], Kosier et al. [2] and Schmidt et al. [3] have proposed excess base current model for the total dose effect in bipolar devices to account for current gain degradation. This model is based on the Shockley–Read–Hall (SRH) recombination theory. This model is applicable to both npn as well as pnp transistors. Several mechanisms have been proposed which may cause the current gain degradation viz., (1) depletion of the p-type emitter, (2) recombination at the base surface, (3) electron injection into the emitter and (4) surface hole depletion. However, due to competing nature of these mechanisms, it is rather difficult to identify the dominant mechanism.

On the other hand, there are relatively less reports on the displacement damage effects in discrete BJTs. Displacement damage in silicon due to Co^{60} γ-ray exposure can be analyzed in terms of the photon induced secondary electron spectrum. The secondary electron spectrum of Co^{60} source is known to generate secondary electrons in the energy range 0.2–1 MeV. These electrons produce displacement damage in the bulk of the semiconductor, which is analyzed in terms of the Messenger–Spratt equation [4]. Several npn type transistors have been investigated in the literature for current gain degradation based on these arguments [5,6]. In general, the pnp type transistors are also expected to exhibit the same type of degradation. However, it appears that there is little experimental evidence to support this. Dale et al. [4] have studied the high energy electron induced gain degradation in terms of displacement of atoms. Burke [7], Summers et al. [8,9] and Xapsos et al. [10] have studied the displacement damage produced by high energy electrons and neutrons. In this work an attempt is made to assess the radiation response of vertical discrete npn and pnp transistors manufactured in a indigenous technology from Continental Device India Limited (CDIL) in comparison with the devices of similar configurations reported already in the literature. The study of the effect of high dose 8 MeV electron irradiation on two npn and one pnp transistors has been undertaken to identify the mechanism responsible for device degradation and to compare their radiation tolerance with the devices from international vendors.

2. Experimental

Electrons are a convenient form of laboratory radiation and can simulate quite accurately the effect of high-energy ionizing radiation. Discrete space borne indigenous commercial BJTs of the type 2N2219A, 2N3019 (both npn) and 2N2905A (pnp) of CDIL make have been investigated for electron induced effects. All the transistors are switching transistors with standard configurations. The transistors have been manufactured by diffusion process. The transistors have vertical structure and silicon is used for the emitter. The two npn transistors selected for the study differ in dimension of the emitter and collector, base thickness and doping concentration. The base thickness of the transistors 2N2219A, 2N3019 and 2N2905A are 2.0, 3.3 and 1.8 μm respectively. However, the SiO_2 oxide thickness of all the transistors are the same (1.2 μm). The transistors were exposed to 8 MeV electrons at Microtron Centre, Mangalore University, Mangalore. The devices are exposed to a beam of electrons in the biased conditions, $V_{CE} = 10$ V and $I_B = 50$ μA. Exposure of the devices to radiation with or without bias application should not have, in principle, any effect on the degradation of the device parameters. The transistors are decapped using a decapping tool and the die of the transistor was exposed to the electron beam [8,9]. Although 8 MeV electrons can penetrate the lid of the device (range of 8 MeV electrons in Silicon is about 10 mm), the devices are decapped to eliminate the energy loss of the electrons in the lid. The collector characteristics and Gummel plots were obtained after every 100 krad accumulated electron dose and upto 500 krad. After a dose of 500 krad, the next measurement was made at 1 Mrad electron dose. All measurements of the electrical characteristics were made using Keithley instrument (Model No. 236) as a function of accumulated dose (the electron beam facility was calibrated for dose instead of fluence). The measurements are made immediately when the beam is turned off after a particular accumulated dose. To verify the reproducibility of the results, two transistors of the same batch (date code) were exposed. The results obtained are identical for both the devices. Hence, results of only one transistor are presented here.

3. Results and discussion

The collector characteristics (I_C versus V_{CE}) of the transistors at constant base current $I_B = 50$ μA and $V_{BE} = 0.65$ V have been measured as a function of accumulated electron dose. The collector current in the plateau region decreases by about 4–7 mA as the accumulated electron dose is increased from 0 krad to 1 Mrad (these plots are not shown). Fig. 1 shows the variation of collector current as a function of accumulated dose for all the three transistors at $V_{CE} = 2$ V, $V_{BE} = 0.65$ V and $I_B = 50$ μA. Gummel plots are also obtained by measuring the collector current I_C and base current I_B as a function of V_{BE} when V_{CE} is held constant at 5 V [3,11]. Fig. 2 exhibits the variation of collector current as a function of V_{BE} for different accumulated electron dose at a fixed value of $V_{CE} = 5$ V. The results show that there is hardly any change in the collector current (even on an extended scale of the plot). The

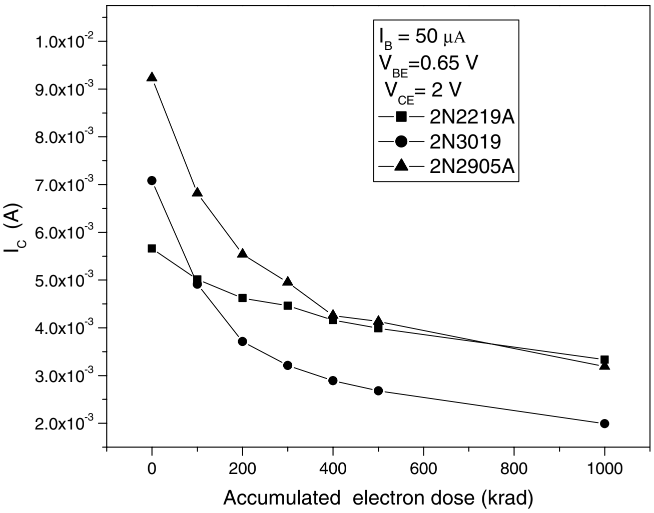

Fig. 1. Collector current (I_C) as a function of accumulated electron dose. The lines are guide to the eye.

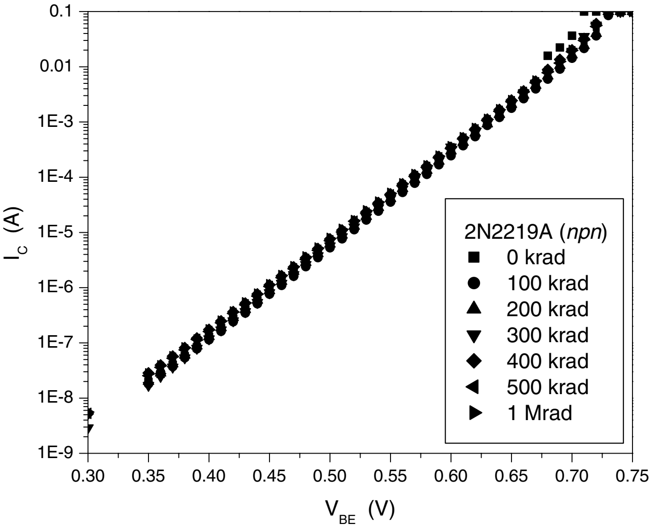

Fig. 2. Collector current (I_C) as a function of base–emitter voltage (V_{BE}) for different electron dose ($V_{CE} = 5$ V).

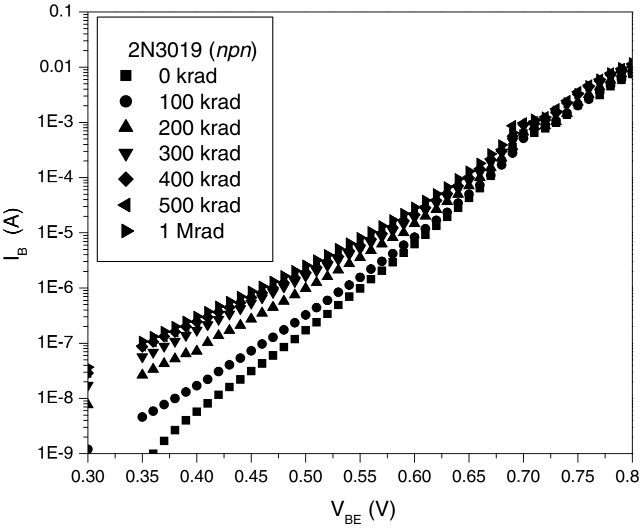

Fig. 3. Base current (I_B) as a function of base–emitter voltage (V_{BE}) for different electron dose ($V_{CE} = 5$ V).

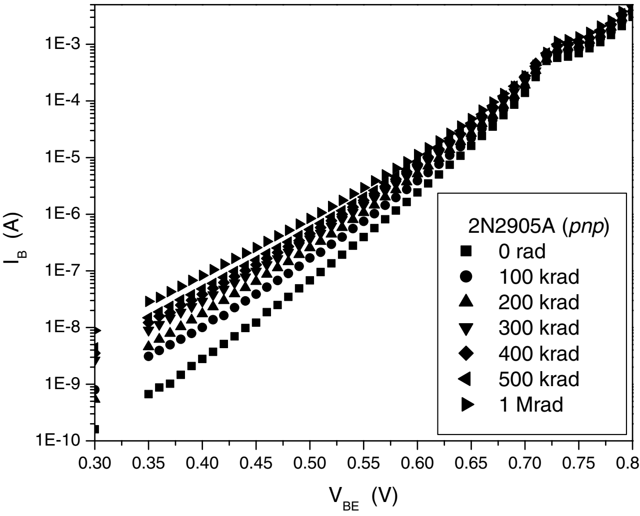

Fig. 4. Base current (I_B) as a function of base–emitter voltage (V_{BE}) for different electron dose ($V_{CE} = 5$ V).

other npn and pnp transistors also show no variation in the collector current. Similar type of results have been obtained when vertical pnp BJTs devices are exposed to 10 keV X-ray and Co^{60} γ-ray by Schmidt et al. [3]. But Ohyama et al. have observed a decrease in the collector current when npn Si transistors are exposed to 2 MeV electrons [12] which is attributed to an increase in the collector series resistance. Figs. 3 and 4 exhibit the variation of I_B as a function of V_{BE} with increasing accumulated electron dose for the npn and pnp transistors respectively. The other npn transistor (2N2219A) also shows the same trend. The base current I_B is found to increase with accumulated electron dose for all the three transistors.

The gain degradation in discrete bipolar junction transistors can basically occur in two ways: (1) degradation by ionization and (2) bulk degradation. Degradation by ionization is a surface effect and mainly occurs in the oxide passivation layer, particularly the oxide covering the emitter–base junction region. Degradation by ionization (surface degradation) leads to increase in base current primarily due to two mechanisms: (i) the accumulation of trapped charges in the oxides, (ii) the accumulation of interface states at the silicon–silicon dioxide interface [3,11,13]. Increase in base current can also occur due to total ionizing dose (TID) effect in the emitter–base region.

The increase in the base current can be defined as $\Delta I_B = I_B - I_{B0}$, and is given by the expression

$$\Delta I_B = \Delta I_{B0} \exp\left(\frac{qV_{BE}}{nkT}\right),$$

where I_{B0} is the pre-irradiation base current, I_B is the post-irradiated base current and ΔI_{B0} is the intercept current in

ΔI_B versus V_{BE} graph; q, V_{BE}, k and T have usual meaning and n is known as ideality factor which may vary with base–emitter voltage and is extracted from the slope of the plot of excess base current ($1 < n < 2$). Schmidt et al. [3] have observed two distinct regions of ideality factors with a transition from $n = 1$ to $n = 2$ in the total-dose effects (TDE) in bipolar transistors. For npn transistors, value of n between 1 and 2 (for $V_{BE} < 0.7$ V) is attributed to the surface recombination and n of 2 (for $V_{BE} > 0.7$ V) to the recombination peak being beneath the surface.

The excess base current as a function of V_{BE} for npn and pnp transistors are shown in Figs. 5 and 6. In the present measurements, although there is little scattering of data points above $V_{BE} = 0.6$ V (possibly due to voltage fluctuations and consequent measurement errors), clearly there is no change in the slope of the plot of excess base current for V_{BE} values > 0.7 V. The observed value of n is 1.1 for almost the entire voltage range. Further, as accumulated dose increase, there is no significant change in n. Thus it appears that both surface degradation at the oxide layer as well as TID effect in the emitter–base region could be contributing to the observed excess base current.

It is known that electrons with kinetic energy greater than 220 keV can produce displacement damage in the bulk of the transistor. This bulk damage generates various types of defects, which could act as recombination centers [15,16]. A detailed analysis of the nature of the defects and their densities require a DLTS study of the emitter–base junction. When recombination centers are created in the base region of the transistor, it leads to increases the base current by decreasing the minority carrier lifetime [13–16]. The decrease in the minority carrier lifetime will be reflected on the degradation in the forward current gain of the transistor. Fig. 7 shows the degradation of forward current gain as a function of accumulated electron dose for all the three types of transistors.

The displacement damage factor is a measure of gain degradation; it can be calculated using the Messenger–Spratt equation. In our case displacement damage factors for the all three transistors are calculated using the Messenger–Spratt equation by converting the accumulated electron dose into 8 MeV electron fluence [17–19]. The reduction in h_{FE} with incident particle fluence is given by Messenger–Spratt equation [4]

$$h_{FE} = \frac{h_{FE0}}{(1 + h_{FE0}k\varphi)},$$

where h_{FE0} and h_{FE} are the gain values before and after irradiation, φ is the fluence and k is the displacement damage constant. Fig. 8 shows the displacement damage factor as a function of accumulated electron dose.

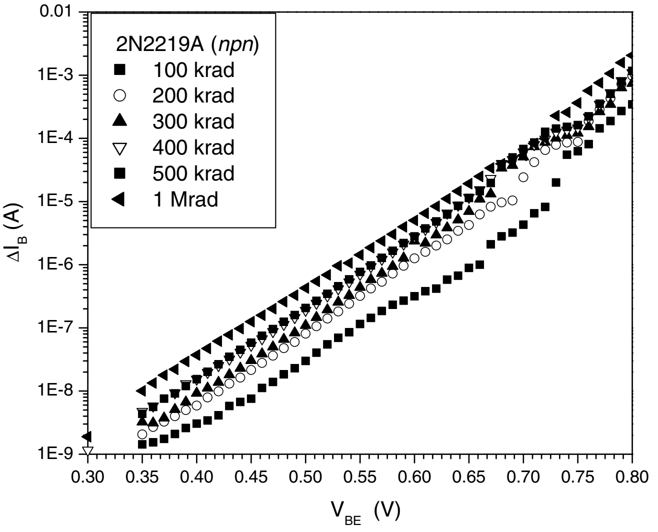

Fig. 5. Excess base current as a function of base–emitter voltage (V_{BE}) for different electron dose.

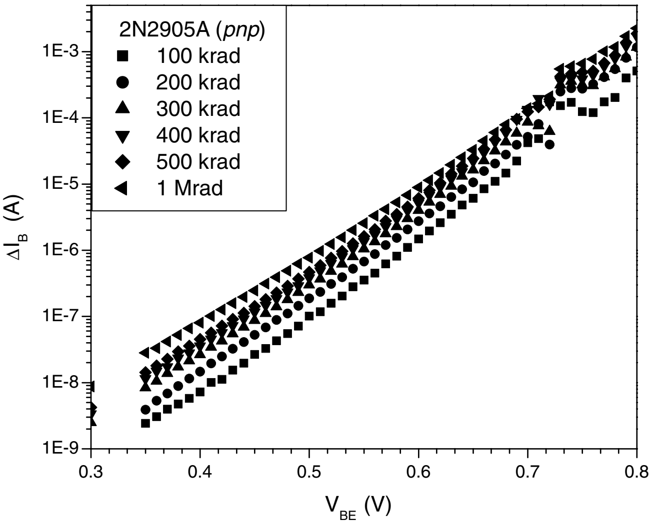

Fig. 6. Excess base current as a function of base–emitter voltage (V_{BE}) for different electron dose.

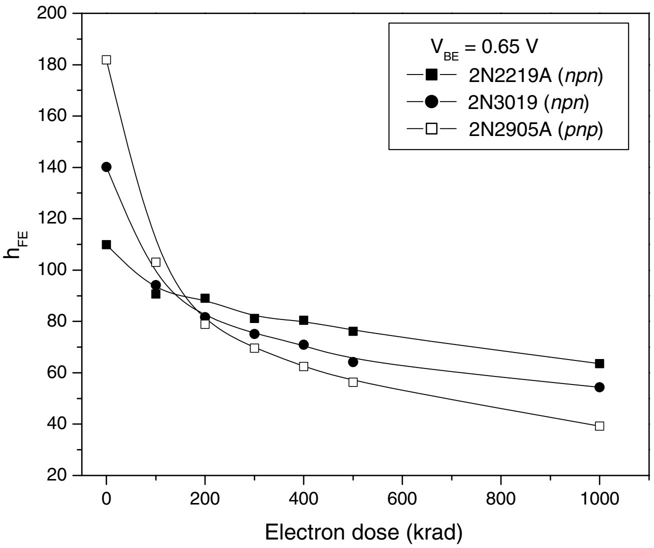

Fig. 7. Forward current gain as a function of accumulated electron dose. The lines are guide to the eye.

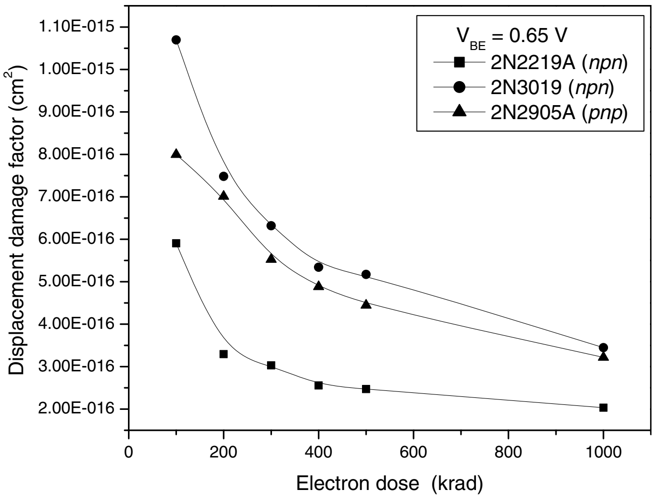

Fig. 8. Displacement damage factor as a function of accumulated electron dose. The lines are guide to the eye.

It is well known in the literature that the gain degradation in discrete BJTs could occur due to both increased recombination in the emitter–base region (TID effect) and increased recombination in the neutral base mainly by displacement damage. The decrease in the collector current as a function of accumulated dose shown in Fig. 1 and Gummel plot shown in Fig. 2 seem to indicate that both TID-induced damage and displacement damage in the bulk of the transistor seem to contribute to the observed gain degradation. To verify which of the two mechanisms is dominant, off-line measurements of the gain of the transistors after thermal annealing have been made.

Off-line measurements of the forward current gain for all the three types of transistors have been made after the devices are exposed to a maximum accumulated dose of 1 Mrad. The h_{FE} of the devices are measured at different biasing conditions. Off-line measurements are carried out using the TESEC transistor tester unit. The values of pre- and post-irradiation h_{FE} along with h_{FE} of post-irradiated devices annealed at 150 °C for 2 h are given in Table 1. It is seen that exposure of the devices to electrons, results in considerable reduction in h_{FE}. When the irradiated devices are annealed at 150 °C for 2 h, the gain is found to recover only very slightly. It is well known that the displacement damage is rather permanent and do not anneal after

Table 1a
TESEC measurement results of the transistor of the type 2N2219A (npn)

Test item	Biasing conditions		Pre-irradiation	Post-irradiation 1 Mrad	Post-irradiation, 1 Mrad, annealed at 150 °C for 2 h
h_{FE}	$V_{CE} = 10.0$ V	$I_C = 0.10$ mA	92.85	35.56	38.00
	$V_{CE} = 10.0$ V	$I_C = 1.0$ mA	107.8	58.03	60.35
	$V_{CE} = 10.0$ V	$I_C = 10$ mA	116.5	79.49	82.03
	$V_{CE} = 10.0$ V	$I_C = 150$ mA	111.9	88.28	90.68
	$V_{CE} = 10.0$ V	$I_C = 500$ mA	65.34	53.58	54.38

Table 1b
TESEC measurement results of the transistor of the type 2N3019 (npn)

Test item	Biasing conditions		Pre-irradiation	Post-irradiation 1 Mrad	Post-irradiation, 1 Mrad, annealed at 150 °C, for 2 h
h_{FE}	$V_{CE} = 10.0$ V	$I_C = 0.10$ mA	116.8	16.82	16.86
	$V_{CE} = 10.0$ V	$I_C = 1.0$ mA	49.38	49.38	49.89
	$V_{CE} = 10.0$ V	$I_C = 10.0$ mA	62.11	62.11	62.53
	$V_{CE} = 10.0$ V	$I_C = 150$ mA	90.47	90.47	90.14
	$V_{CE} = 10.0$ V	$I_C = 500$ mA	75.31	75.31	76.12
	$V_{CE} = 10.0$ V	$I_C = 1.0$ A	29.52	29.52	30.53

Table 1c
TESEC measurement results of the transistor of the type 2N2905 A (pnp)

Test item	Biasing conditions		Pre-irradiation	Post-irradiation 1 Mrad	Post-irradiation, 1 Mrad, annealed at 150 °C, for 2 h
h_{FE}	$V_{CE} = 10.0$ V	$I_C = 0.10$ mA	187.1	29.66	32.96
	$V_{CE} = 10.0$ V	$I_C = 1.0$ mA	200.6	54.37	56.03
	$V_{CE} = 10.0$ V	$I_C = 10$ mA	210.1	82.98	85.49
	$V_{CE} = 10.0$ V	$I_C = 150$ mA	176.6	88.28	90.98
	$V_{CE} = 10.0$ V	$I_C = 500$ mA	102.6	53.05	55.58

thermal annealing upto 175 °C [13]. This suggests that sufficient defect and recombination centers are produced in the present devices when exposed to 8 MeV electrons. The gain degradation of the transistors investigated thus appears to be predominantly due to displacement damage produced in the bulk of the device. The fact that the gain of the transistors do not recover after annealing indicates that the surface recombination and TID effect in the emitter–base region perhaps contribute little to gain degradation.

4. Conclusion

The indigenous commercial BJT's of type 2N2219A, 2N3019 and 2N2905A degrade, when exposed to high-energy electrons, as much as the devices of other vendors. 8 MeV electrons at high dose rate induce current gain degradation by decreasing the collector current and increasing the base current. There appears to be two competing mechanisms responsible for the observed gain degradation. The decrease in the collector current may be attributed to the displacement damage in the neutral base. The increase in the base current may be attributed to the defects and recombination centers generated in the emitter–base region of the transistor. However, gain measurements after thermal annealing at 150 °C indicates that the electron induced defects and recombination centers do not anneal. Thus, the observed gain degradation appears to be predominantly due to defects and centers induced by bulk damage. Measurements made at low dose rate of electrons would perhaps give additional information on the mechanism of gain degradation.

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