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^{60}Co γ-ray induced gain degradation in bipolar junction transistors

S R Kulkarni[1] and R Damle[2]*
[1]Institute of Experimental and Applied Physics, Leibniz Strasse 11, University of Kiel, 24118, Kiel, Germany
[2]Department of Physics, Bangalore University, Bangalore-560 056, India

E-mail : ramkrishnadamle@bub.ernet.in

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Abstract : Commercial indigenously made *npn* and *pnp* bipolar junction switching transistors used for space applications are investigated for ^{60}Co γ-ray induced effects. The on-line as well as off-line measurements indicate that the forward current gain of the transistors decreases significantly as the accumulated dose increases. Excess base current model is employed to account for the current gain degradation. The *pnp* transistor undergoes as much degradation as the *npn* type. It is found that bulk degradation by displacement damage is the dominant mechanism leading to reduction in forward current gain of *npn* transistors. On the other hand it appears that, in addition to bulk damage, surface degradation due to accumulation of interface states at the silicon-silicon dioxide interface also contributes significantly to gain degradation in *pnp* transistor as evident from thermal annealing studies. Further, estimation reveals that the transistor with larger base width has higher displacement damage factor.

Keywords : Gamma ray irradiation, bipolar junction transistor, radiation effects, gain degradation, excess base current.

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1. Introduction

High-energy gamma rays interact primarily with the atomic electrons of the semiconductor devices. Depending on the energy of the gamma rays, the predominant processes are photoelectric effect, Compton effect and pair production reactions. Gamma energies of 0.1 MeV are predominantly in the photoelectric regime. Gamma rays of 0.7 MeV, which are typical of fission product radiations, interact primarily *via* Compton process. Gamma rays of 2 MeV are also in the Compton range, and these gamma rays are typical of those emitted during fission process. Higher energy gamma rays typically produced by Bremsstrahlung from high-energy electrons, interact primarily by positron-electron pair production. They are also capable of inducing photonuclear reactions. The nuclear

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*Corresponding Author

recoiling from such a photonuclear reaction can frequently produce a large number of atomic displacements.

The secondary electrons which result from the photoelectric, Compton or pair – production reaction can undergo processes similar to those of electrons. Hence the radiation effects by a gamma ray beam depend primarily upon the efficiency with which these gamma rays are converted into secondary electrons and the subsequent interaction of these electrons with semiconductor. In most practical cases, the radiation effects of the photonuclear reactions can be ignored unless specific precautions are taken to enhance their importance by minimizing secondary electrons in the environment.

Low energy gamma ray photons are known to interact with semiconductors by generating secondary electrons by Compton process. These secondary electrons produce atomic displacements. In the Compton scattering process, the scattered photon energy and the kinetic energy of the scattered secondary electrons when gamma ray photons interact with silicon can be calculated using the equation

$$T = \frac{h\upsilon\left(1-\cos\theta\right)}{(1-\cos\theta\ )+\left(\dfrac{m_0c^2}{h\upsilon}\right)} \tag{1}$$

where T is kinetic energy of the scattered electron, $h\upsilon$ is the incident energy of the photon, θ is angle between the incident and scattered photons and m_0c^2 is the rest mass energy of the electron [1]. The calculation predicts the energy of the scattered electrons to vary from 0.2 to 1 MeV. These energies of the secondary electrons are sufficient to produce atomic displacements in silicon material.

Although the space environment does not contain low energy gamma ray photons (E < 2 MeV) in abundance, the study of gamma ray induced effects on devices is of primary importance in understanding the mechanism of device degradation. Further, ^{60}Co gamma ray induced studies are useful to correlate with particle radiation effects.

A number of Bipolar Junction Transistors (BJT's) from international manufacturers have been investigated for gamma ray induced effects earlier and excellent data base is available in the literature. However, devices manufactured indigenously in India have not been characterized for radiation response. A few important BJT's manufactured by Continental Device India Limited (CDIL) which are used for space applications have been investigated for the effect of gamma ray exposure. This paper describes the effect of ^{60}Co γ-rays on the electrical characteristics of two *npn* and one *pnp* switching BJT's.

2. Experimental

The devices are exposed to ^{60}Co γ-rays in the biased condition and measurements of the electrical parameters are made *in situ* using Semiconductor Parameter Analyser

(HP-4145B). The devices are exposed to γ-rays as it is, without removing the lid or the cap as the γ-rays can penetrate the lid. A γ-irradiator (Blood Irradiator-2000) consisting of ^{60}Co γ-source with a dose rate of 36 rad(Si)/s was employed to irradiate the devices to various accumulated doses. To get an accumulated dose of about 500 krad, the exposure time was about 4 hours. In order to verify the reproducibility of the measurements, 3-4 transistors of the same batch (date code) were exposed and the measurements are made for all of them. All devices of the same batch roughly give identical results. The plots shown are for one of the representative device. For making measurements of collector characteristics (I_C *vs.* V_{CE}), the base current I_B was fixed to 50 μA. After every accumulated dose, the measurements are made within one minute. Apart from collector characteristics, *Gummel plots*, log (I_C) *vs.* V_{BE} and log(I_B) *vs.* V_{BE} at constant V_{CE}, have also been obtained after every accumulated dose [2–4].

3. Results and discussions

The collector characteristics of transistors at constant base current I_B = 50 μA as a function of the accumulated dose are recorded (plots are not shown) for the transistors of the type 2N2219A (*npn*), 2N3019 (*npn*) and 2N2905A (*pnp*). The collector current decreases as the accumulated dose increases for all the transistors [5,6]. We have also recorded variation of collector current I_C *vs.* V_{BE} as a function of accumulated dose (Gummel plots) for the three transistors (plots are not shown). No considerable change in the collector current has been observed with increasing gamma dose. However, the base current I_B is found to increase with accumulated dose for all the three transistors. Figures 1, 2 and 3 exhibit the variation of I_B as a function of V_{BE} with increasing accumulated gamma dose for the three transistors.

The most striking and common effect of radiation on bipolar transistor is the gain (h_{FE}) degradation. 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 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 [3,4].

The increase in the base current can be defined as $\Delta I_B = I_B - I_{B0}$, where I_{B0} is the pre-irradiation base current and I_B is the post-irradiation current. The excess base current is given by [3,4,7]

$$\Delta I_B = \Delta I_{B0} \exp\left(\frac{qV_{BE}}{nkT}\right) \tag{2}$$

where q, V_{BE}, k and T are having usual meaning and n is known as ideality factor

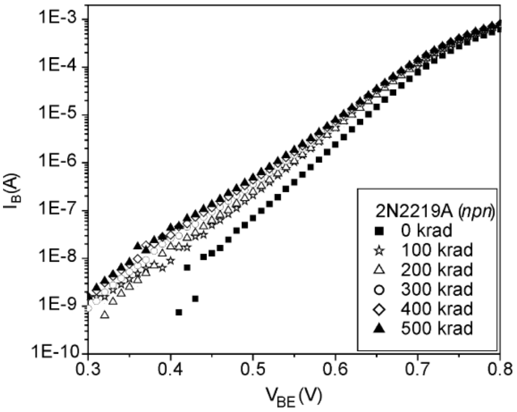

Figure 1. Base current (I_B) as a function of base-emitter voltage (V_{BE}) for different accumulated γ-dose (Si).

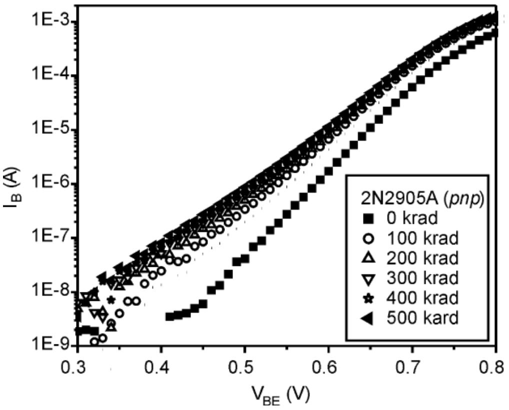

Figure 2. Base current (I_B) as a function of base-emitter voltage (V_{BE}) for different accumulated γ-dose (Si).

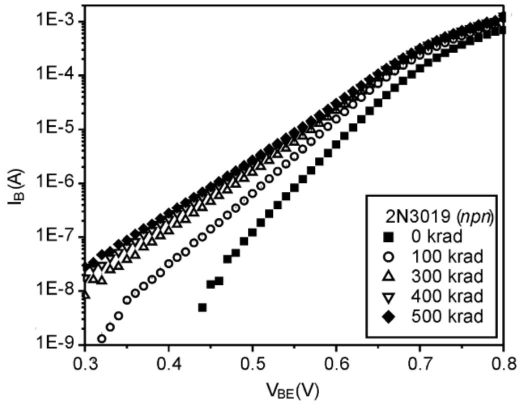

Figure 3. Base current (I_B) as a function of base-emitter voltage (V_{BE}) for different accumulated γ-dose (Si).

which may vary with base-emitter voltage ($1 < n < 2$). Figures 4, 5 and 6 exhibit the plot of excess base current as a function of V_{BE} for different accumulated gamma dose for the three transistors respectively. It is seen that the slope of the curve changes at a particular value of V_{BE} called the transition voltage (V_{tr}). The transition voltage increases with increasing dose. The ideality factor can be extracted from the slope of the plot of excess base current. It is seen that the slope ($\Delta I_B/\Delta V_{BE}$) for V_{BE} values less than 0.6 V lies between 1 and 2 and it approaches 2 for $V_{BE} > 0.6$ V. Two distinct regions of ideality factors have been observed previously in many γ-ray irradiated transistors of the same family by other workers. It is established that for *npn* transistors, an ideality factor between 1 and 2 signifies the surface recombination and an ideality factor of 2 indicates recombination peak is beneath the surface [8–12]. It is well known in the literature that vertical *npn* transistors exhibit significant gain degradation mainly by displacement damage, when exposed to ionizing radiation. However, it is assumed that the vertical *pnp* transistors are relatively resistant to

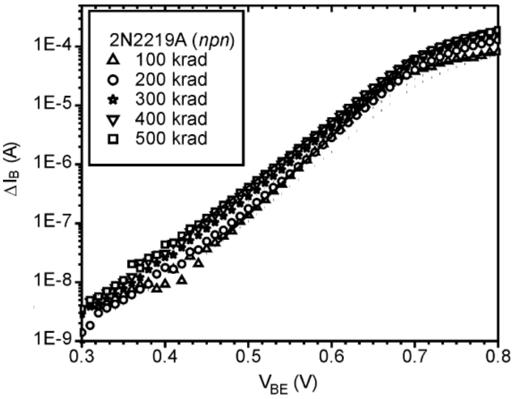

Figure 4. Excess base current as a function of base-emitter (V_{BE}) for different accumulated γ-dose (Si).

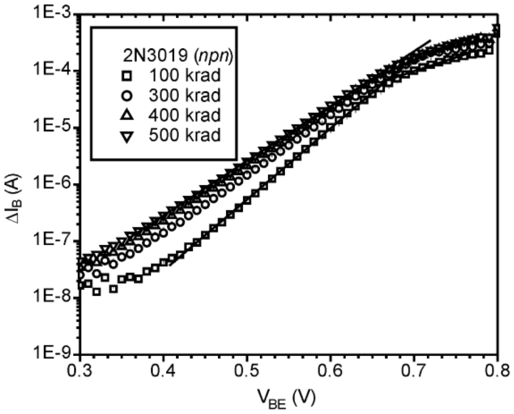

Figure 5. Excess base current as a function of base-emitter (V_{BE}) for different accumulated γ-dose (Si).

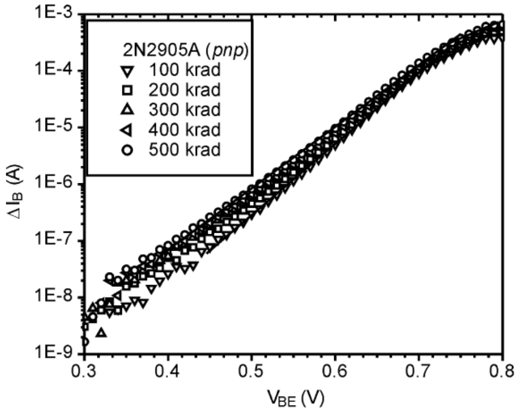

Figure 6. Excess base current as a function of base-emitter (V_{BE}) for different accumulated γ-dose (Si).

ionizing radiation, an assumption which is not well established since only a little studies are carried out on *pnp* transistors [7,13]. The present studies in *pnp* transistor has shown that surface recombination perhaps is also important in *pnp* transistors. Figure 7 shows the normalized excess base current plotted as a function of accumulated dose for the three devices. It is seen that for *pnp* transistor, the excess base current is more than that for *npn* transistors.

Bulk degradation occurs due to atomic displacement in the bulk of the semiconductor when incoming energetic particle transfers momentum to atoms of the target silicon. If sufficient energy is transferred, the silicon atom can be ejected from its location, leaving a vacancy or defect. This displacement damage is a bulk effect deep inside the semiconductor and produces an increase in the number of recombination centers. Recombination centers in the base region of the transistor reduce the minority carrier life-time which in turn increases the base current and decreases the gain. It is known that gain degradation in silicon bipolar transistors exposed to particle radiation

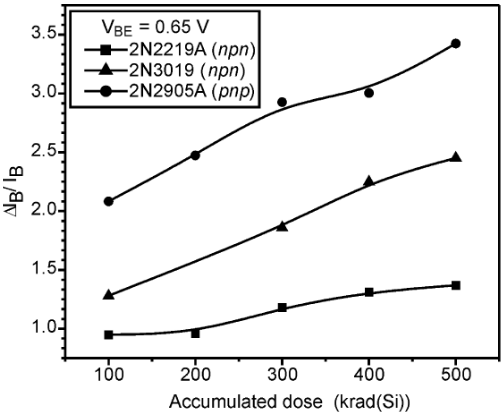

Figure 7. Normalized excess base current as a function of accumulated γ-dose (Si).

is due to the production of a spectrum of primary knock-on-atoms (PKAs) and is directly related to displacement damage. However, in the case of γ-irradiation, the displacement damage in silicon from ^{60}Co exposure can be analyzed in terms of photon induced secondary electron spectrum [14–17]. Exposure of the devices to γ-radiation produces displacement damage by first generating secondary electrons. Displacement damage reduces the forward current gain by shortening the minority carrier lifetime. For a given value of V_{BE}, h_{FE} is calculated by measuring collector current and base current from the Gummel plots. Figures 8, 9 and 10 exhibit the plots of forward current gain as a function of V_{BE} for different accumulated gamma dose for the three transistors. It is seen that the h_{FE} decreases as the accumulated dose increases for all the transistors. The decrease in h_{FE} for V_{BE} > 0.7 V is due to the collector current reaching the maximum limit of 100 mA of the measurement system. Figure 11 shows the variation of forward current gain as a function of accumulated dose. The plots show that the *pnp* transistor undergoes as much degradation as the *npn* transistors.

The reduction in h_{FE} with incident particle fluence is given by Messenger-Spratt equation [17]

$$h_{FE} = \frac{h_{FE0}}{1 + h_{FE0} k \Phi} \tag{3}$$

where h_{FE0} and h_{FE} are the gain value before and after irradiation, Φ is the 0.6 MeV electron fluence and k is displacement damage factor expressed in cm^2/number. In order to calculate the displacement damage produced by secondary electrons, it is required to convert the γ-dose into equivalent electron fluence [18–20]. The conversion can be accomplished using the following considerations. For γ-rays emitted by ^{60}Co source, the energy of the secondary electrons lie in range 0.2–1 MeV. The average electron energy is 0.6 MeV. 1 rad is equal to 100 ergs of energy deposited by the radiation in 1 g of the material.

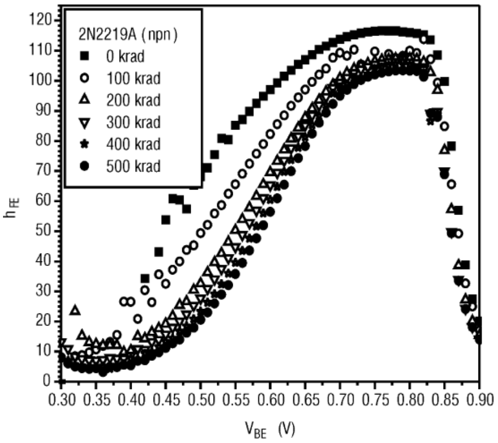

Figure 8. Forward current gain (h_{FE}) as a function of V_{BE} for different γ-dose (Si).

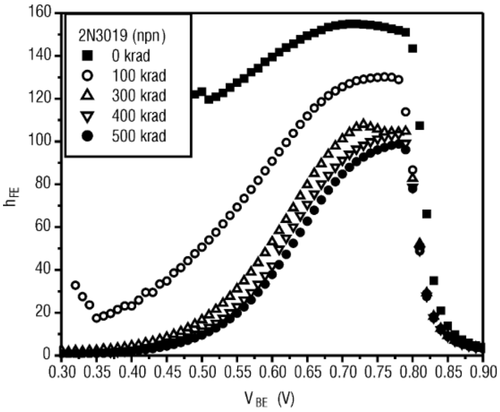

Figure 9. Forward current gain (h_{FE}) as a function of V_{BE} for different γ-dose (Si).

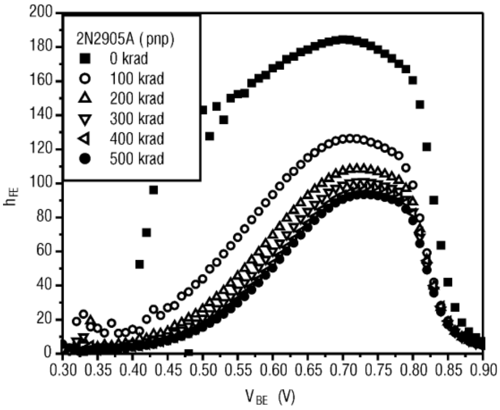

Figure 10. Forward current gain (h_{FE}) as a function of V_{BE} for different γ-dose (Si).

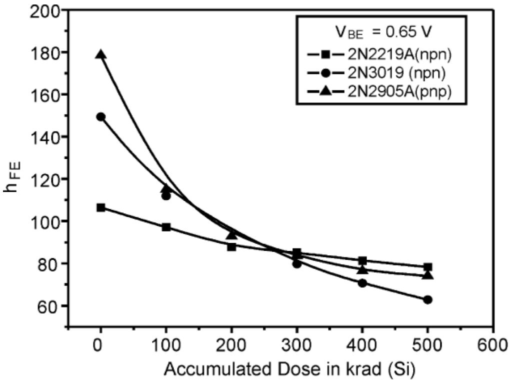

Figure 11. Forward current gain (h_{FE}) as a function of accumulated γ-dose (Si).

Dose = Fluence x Stopping Power

= Φ (#/cm^2) × S (MeV-cm^2/g)MeV/g

= Φ (#/cm^2) × S (MeV-cm^2/g) × 10^6 × 1.6 x 10^{-12} ergs/g

= 1.6 x 10^{-8} × Φ (#/cm^2) × S (MeV-cm^2/g)rads

S (MeV/cm) is the energy deposited by the electron in the silicon over a unit path length (cm) and it is called stopping power or Linear Energy Transfer (LET). It can be expressed in (MeV-cm^2/g) by dividing S by the material density (g/cm^3).

$$\text{Dose equivalent fluence} = \frac{\text{rad}}{1.6 \times 10^{-8} \times S\,(\text{MeV} - \text{cm}^2/g)}. \tag{4}$$

The calculation shows that one rad equivalent of 0.6 MeV electron fluence comes out to be 3.906 × 10^7 electrons/cm^2 [21]. Figure 12 shows the variation of estimated

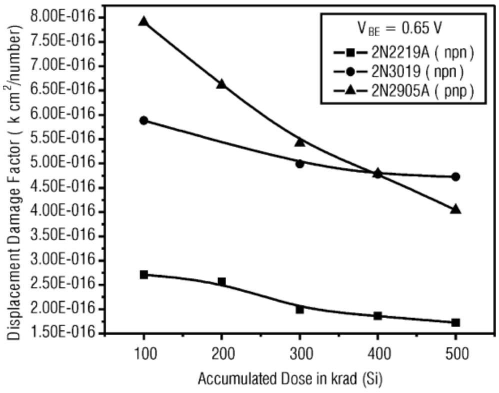

Figure 12. Displacement damage factor as a function of accumulated γ-dose (Si)

displacement damage factor *k* as a function of accumulated dose for all the three transistors. It is seen that as accumulated dose increases, *k* decreases. Such variation in *k* has been observed in a number of devices investigated for radiation induced effects.

Of the three transistors investigated, one of the *npn* transistor 2N2219A has smaller base thickness (2.0 μm) than the other *npn* transistor 2N3019 (base width = 3.3 μm). Figure 12 shows that for transistor with lager base width, the *k* values are higher.

Apart from *in situ* measurements of electrical characteristics, off-line measurement of forward current gain for all the three types of transistors have been made after the devices are exposed to a maximum accumulated dose of 500 krad. 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 two hours are given in the Tables 1–3. It is seen that exposure of the devices to γ-radiation results in considerable reduction in h_{FE}. When the irradiated devices are annealed at 150°C for two hours, the gain of the *npn* transistors is found to recover only marginally. On the other hand, in the case of *pnp* transistor (2N2905A), thermal annealing results in considerable recovery of the gain. Thermal annealing is known to remove the charges

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

Test Item	Biasing Conditions		Pre irradiation	Post irradiation 500 krad	Post irradiation (500 krad) annealed at 150°C for 2 hrs
h_{FE}	V_{CE} = 10.0 V	I_C = 0.10 mA	93.45	38.18	43.10
	V_{CE} = 10.0 V	I_C = 1.0 mA	107.8	65.06	77.88
	V_{CE} = 10.0 V	I_C = 10 mA	117.0	90.49	95.87
	V_{CE} = 10.0 V	I_C = 150 mA	113.5	97.78	100.6
	V_{CE} = 10.0 V	I_C = 500 mA	66.58	57.94	61.94

Table 2. TESEC measurement results of the transistor of the type 2N3019 (*npn*).

Test Item	Biasing Conditions		Pre irradiation	Post irradiation 500 krad	Post irradiation (500 krad) annealed at 150°C for 2 hrs
h_{FE}	V_{CE} = 10.0 V	I_C = 0.10 mA	39.37	16.28	19.05
	V_{CE} = 10.0 V	I_C = 1.0 mA	155.0	54.08	58.61
	V_{CE} = 10.0 V	I_C = 10.0 mA	158.9	69.78	73.04
	V_{CE} = 10.0 V	I_C = 150 mA	152.4	100.7	101.6
	V_{CE} = 10.0 V	I_C = 500 mA	115.4	84.40	84.57
	V_{CE} = 10.0 V	I_C = 1.0 A	36.50	30.25	30.91

Table 3. TESEC measurement results of the transistor of the type 2N2905A (*pnp*).

Test Item	Biasing Conditions		Pre irradiation	Post irradiation 500 krad	Post irradiation (500 krad) annealed at 150°C for 2 hrs
h_{FE}	V_{CE} = 10.0 V	I_C = 0.10 mA	172.8	27.53	75.41
	V_{CE} = 10.0 V	I_C = 1.0 mA	187.5	56.68	104.8
	V_{CE} = 10.0 V	I_C = 10 mA	197.0	85.39	128.3
	V_{CE} = 10.0 V	I_C = 150 mA	166.8	85.81	117.1
	V_{CE} = 10.0 V	I_C = 500 mA	97.33	49.75	69.67

accumulated in silicon-silicon dioxide interface region as a result of irradiation. These accumulated charges partly contribute to gain degradation. However, gain degradation due to displacement damage is a permanent effect and can not easily be removed by thermal annealing. The results clearly indicates that bulk damage is a dominant process contributing to the gain degradation in the *npn* transistor, while surface degradation also contributes to degradation in the case of *pnp* transistor.

3. Conclusion

Indigenously made commercial bipolar junction transistors are found to degrade when exposed to γ-radiation. The forward current gain of the transistor decreases significantly as the accumulated dose increases. Our observation is that the gain degradation behaviour of these indigenous parts type is similar to those of other vendors's (International) parts of same family. One other observation is that the *pnp* transistor is found to degrade as much as the *npn* transistor do when exposed to γ-radiation, a fact not well established in the literature. Of the two possible mechanisms contributing to gain degradation *viz.* surface degradation and bulk degradation, it appears that the bulk degradation is the dominant mechanism in the case of degradation of *npn* transistors while surface degradation is also important in the case of *pnp* transistor. γ-radiation produces bulk damage *via* the generation of secondary electrons. These secondary electrons in turn produce atomic displacements. Displacement related defect centers contribute to reduction in minority carrier lifetime. A reduction in minority carrier lifetime results in the degradation of the forward current gain. The displacement related defects are stable even at 150°C and do not anneal.

Acknowledgments

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