

Chapter 3

EFFECT OF ^{60}Co γ - RAY IRRADIATION ON THE ELECTRICAL CHARACTERISTICS OF BIPOLAR JUNCTION TRANSISTORS

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3.1 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 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, such a produced by bremsstrahlung from high-energy electrons, interact primarily by positron-electron pair production. They are also capable of introducing photonuclear reactions. The nuclear 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 production of radiation effects by a gamma ray beam depends primarily upon the efficiency with which these gamma rays are converted into secondary electrons and the subsequent interaction of those 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 kinetic energy of the scattered secondary electrons when gamma ray photons interact with silicon can be calculated using the equation

$$T = \frac{h\tilde{\omega}(1 - \cos\theta)}{(1 - \cos\theta) + \left(\frac{m_0c^2}{h\tilde{\omega}}\right)} \quad (3.1)$$

where T is kinetic energy of the scattered electron, $h\nu$ 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 rays studies are useful to correlate with particle radiation effects.

A number of Bipolar Junction Transistors (BJT's) from international manufacturers have been investigated earlier for gamma ray induced effects 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 chapter describes the effect

of ^{60}Co γ -rays on the electrical characteristics of two *npn* and one *pnp* switching BJT's. A switching transistor is designed to function as a switch, that can change its state, say from the high-voltage low-current (OFF) condition to the low-voltage high-current (ON) condition, in a very short time. Important parameters for a switching transistor are current gain and switching time.

3.2 Experimental details

A schematic diagram of the standard structure of the bipolar junction transistor is given in Figure 3.1. The manufacturer specifications of the investigated devices are given in Table 3.1. 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. 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 versus 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} (= 5 V), have also been obtained after every accumulated dose [2-4].

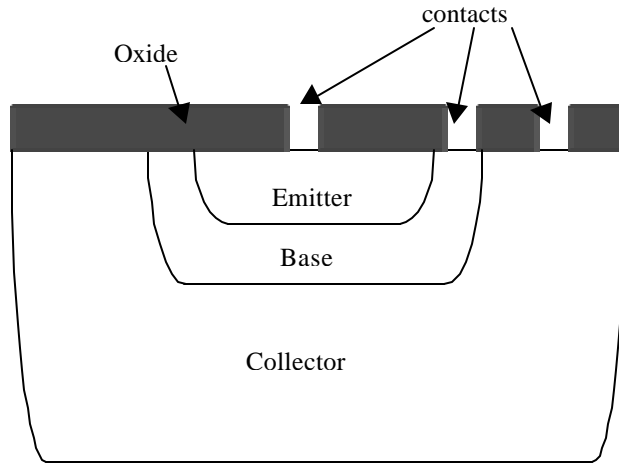


Figure 3.1 Cross section of a discrete transistor.

Table. 3.1 Specification of the transistors investigated.

Specifications	2N2219A	2N3019	2N2905A
Polarity	<i>npn</i>	<i>npn</i>	<i>pnp</i>
Application	Switching	Switching	Switching
Package	TO-39 Metal Can Package	TO-39 Metal Can Package	TO-39 Metal Can Package
Frequency	Low/High	High	Low/High
Emitter thickness (μm)	1.5	2.5	1.5
Emitter concentration	2.21×10^{15} atoms of P^{31} per cc	3.3×10^{16} atoms of P^{31} per cc	7.3×10^{15} atoms of B^{11} per cc
Base thickness (μm)	2.0	3.3	1.8
Base concentration	1.0×10^{15} atoms of B^{11} per cc	1.0×10^{15} atoms of B^{11} per cc	6.10×10^{13} atoms of P^{31} per cc
Collector thickness (μm)	11.5	14.2	9.4
Collector concentration	1.1×10^{15} atoms of P^{31} per cc	6.0×10^{14} atoms of P^{31} per cc	2.4×10^{15} atoms of B^{11} per cc
Oxide thickness SiO_2 (μm)	1.2	1.2	1.2

3.3 Results and discussion

The collector characteristics of transistors at constant base current $I_B = 50 \mu\text{A}$ and $V_{BE} = 0.65 \text{ V}$ as a function of the accumulated dose are shown in the Figure 3.2, 3.3 and 3.4 for the transistors of the type 2N2219A (*nnp*), 2N3019(*nnp*) and 2N2905A(*npn*) respectively. As can be seen from the figures, the collector current decreases as the accumulated dose increases for all the transistors [5-6]. The variation of collector current I_C as a function of V_{BE} for different accumulated dose (Gummel plots) for the three transistors are shown in Figures 3.5, 3.6 and 3.7 respectively. 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 3.8, 3.9 and 3.10 exhibit the variation of I_B as a function of V_{BE} with increasing accumulated gamma dose for the three transistors.

As discussed in Chapter 1, 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 (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].

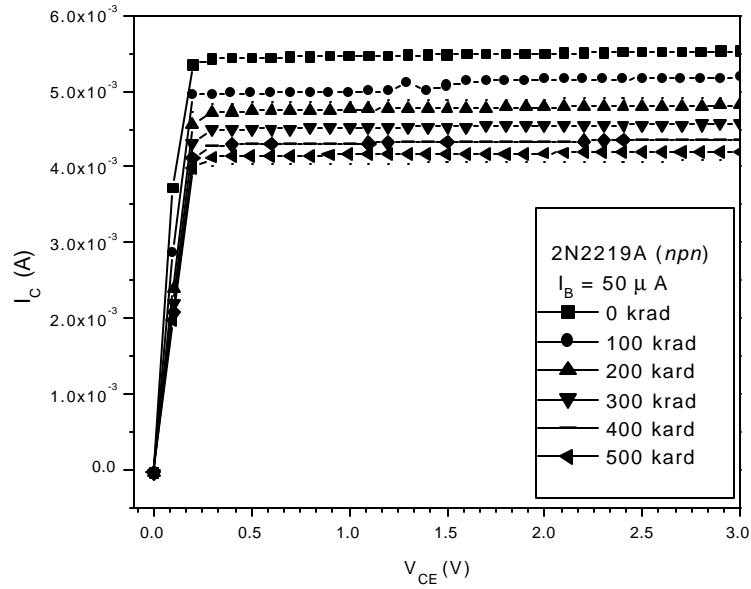


Figure 3.2 Variation of collector current (I_C) as a function of collector-emitter voltage (V_{CE}) for different accumulated γ -dose(Si).

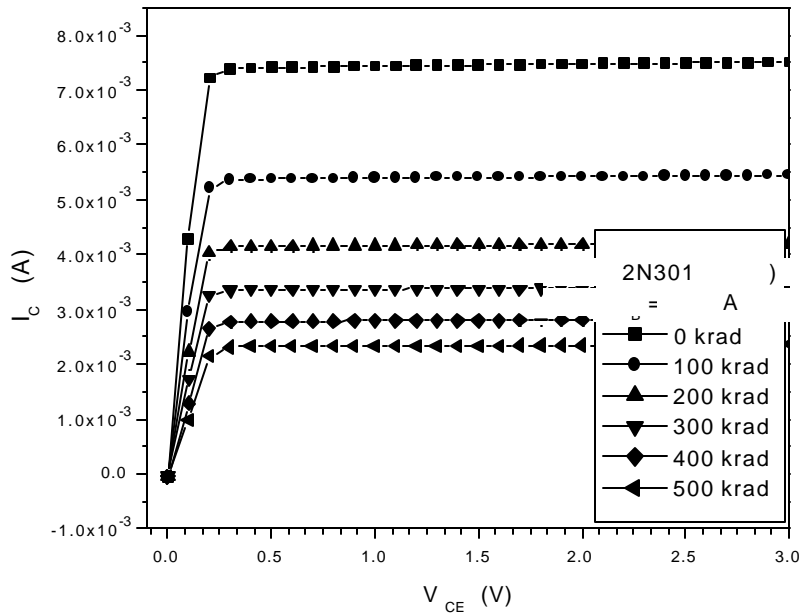


Figure 3.3 Variation of collector current (I_C) as a function of collector-emitter voltage (V_{CE}) for different accumulated γ -dose(Si).

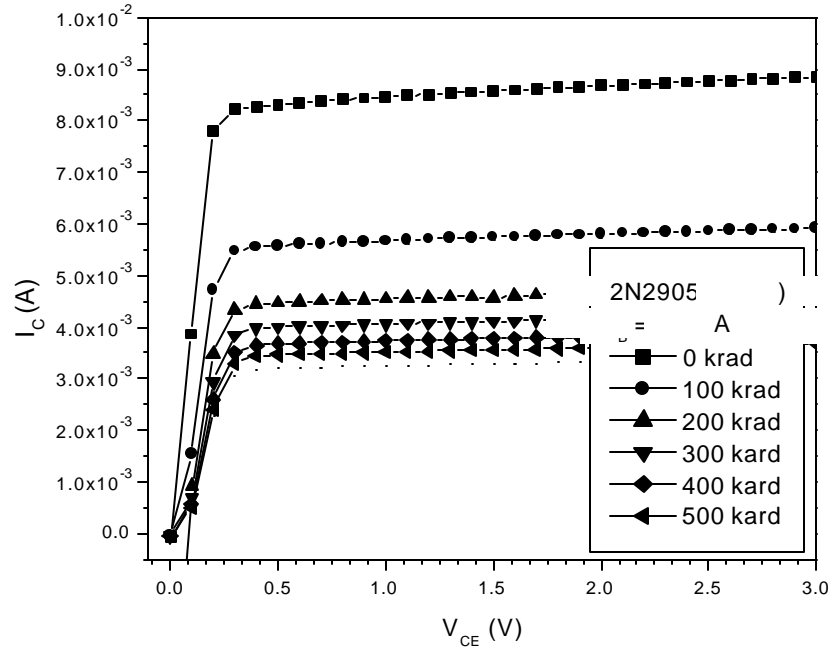


Figure 3.4 Variation of collector current (I_C) as a function of collector-emitter voltage(V_{CE}) for different accumulated γ -dose(Si).

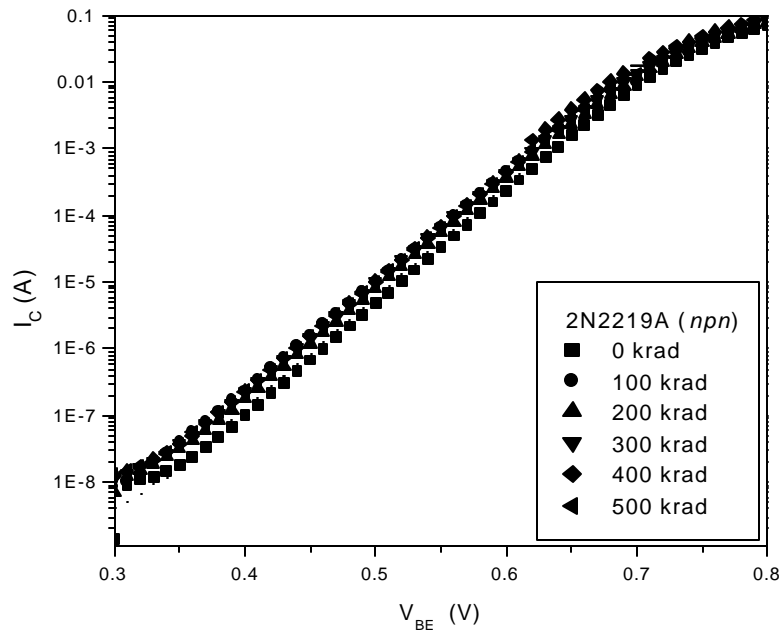


Figure 3.5 Collector current (I_C) as a function of base-emitter voltage(V_{BE}) for different accumulated γ -dose (Si).

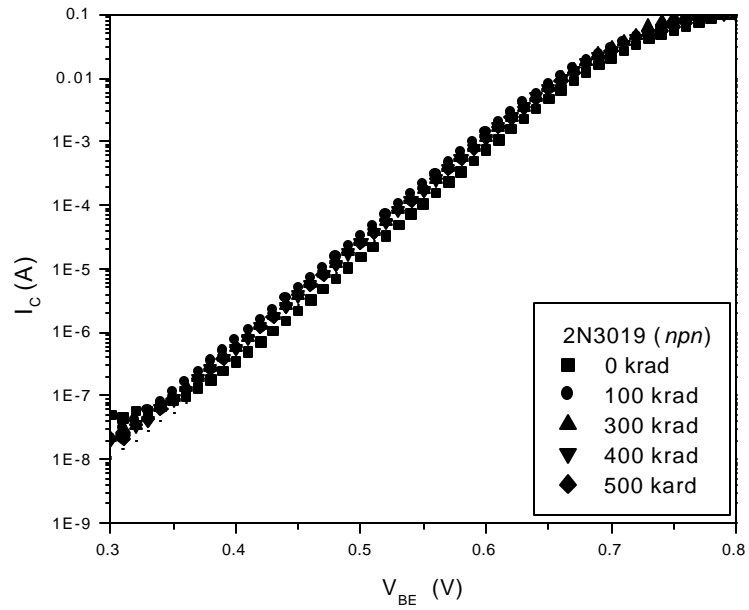


Figure 3.6 Collector current (I_C) as a function of base-emitter voltage (V_{BE}) for different accumulated γ -dose (Si).

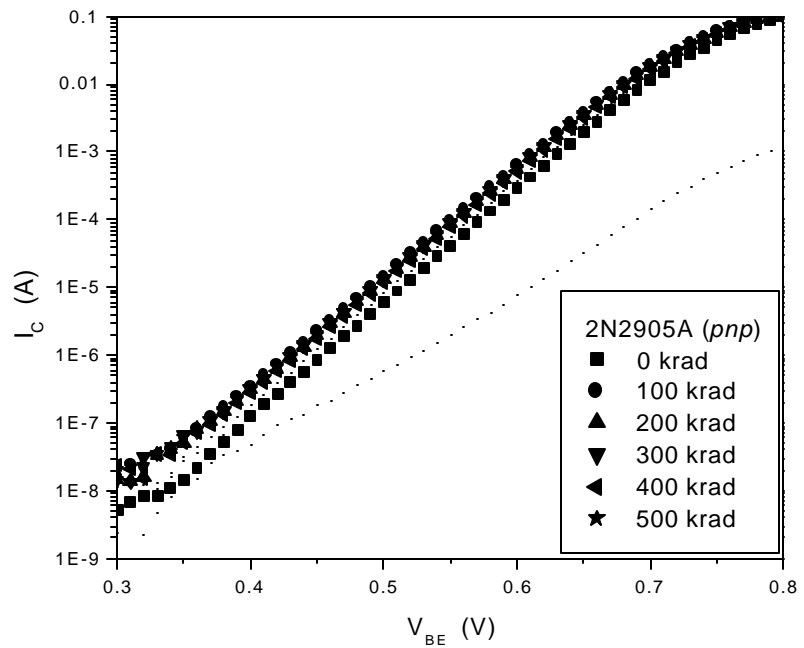


Figure 3.7 Collector current (I_C) as a function of base-emitter voltage (V_{BE}) for different accumulated γ -dose (Si).

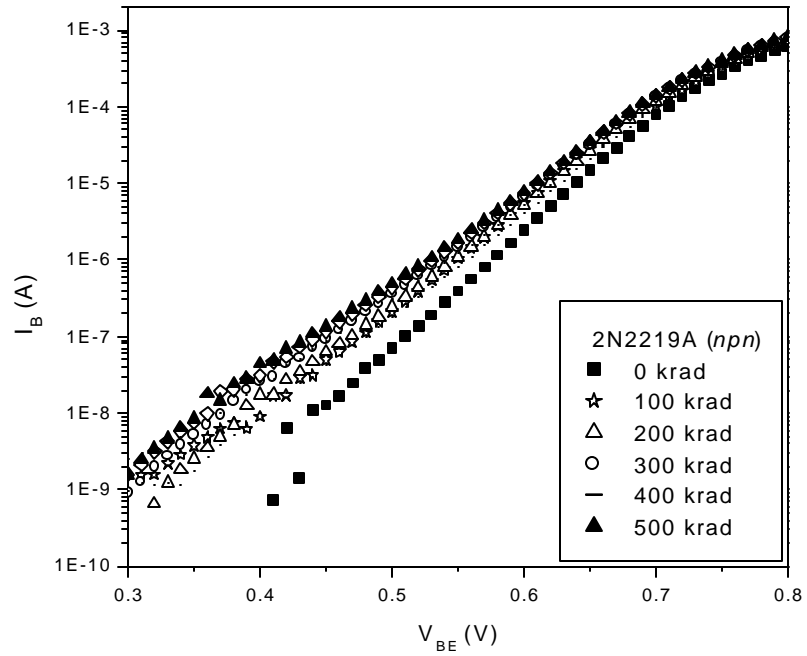


Figure 3.8 Base current (I_B) as a function of base-emitter voltage (V_{BE}) for different accumulated γ -dose (Si).

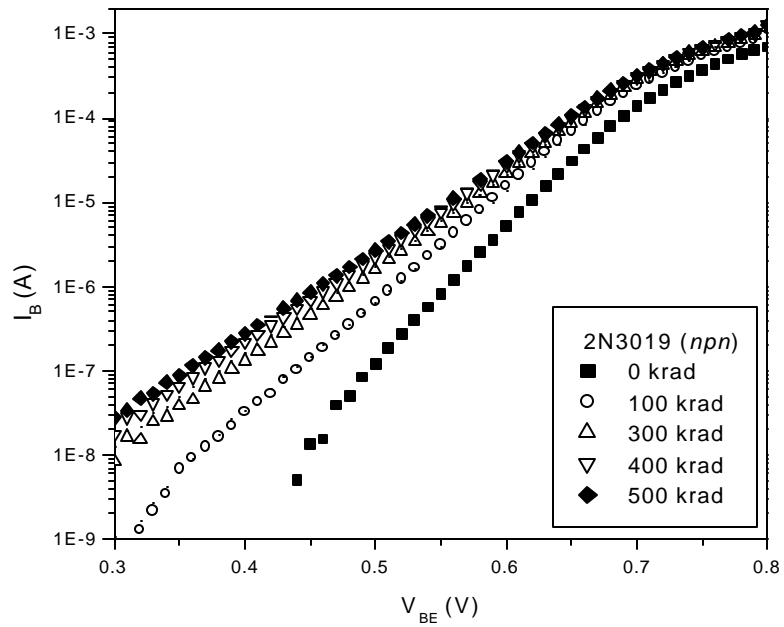


Figure 3.9 Base current (I_B) as a function of base-emitter voltage (V_{BE}) for different accumulated γ -dose (Si).

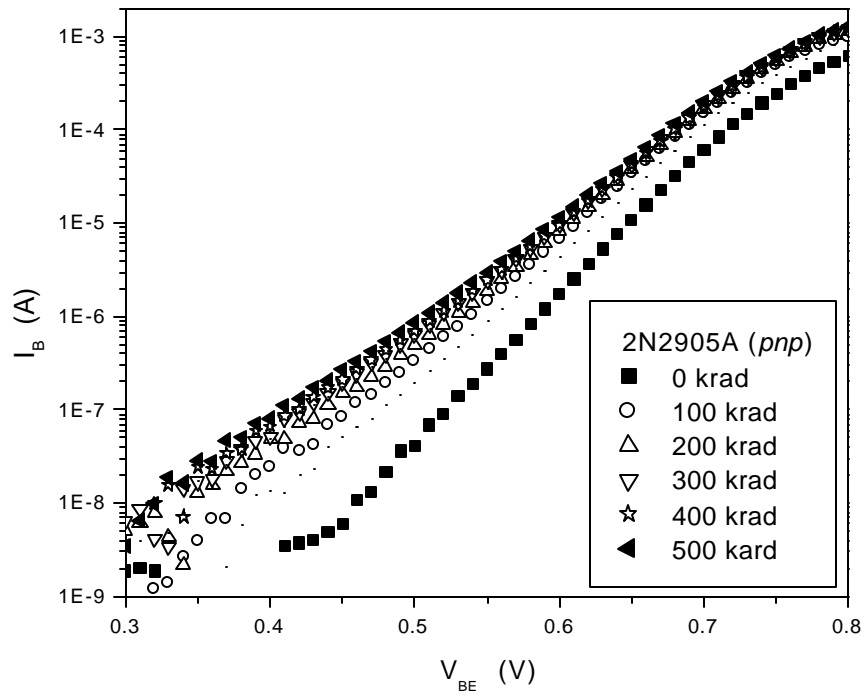


Figure 3.10 Base current (I_B) as a function of base-emitter voltage (V_{BE}) for different accumulated γ -dose (Si).

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-irradiated ion base current. From equation 1.10, we can write the excess base current as [3-4,7]

$$\Delta I_B = \Delta I_{B0} \exp\left(\frac{qV_{BE}}{nkT}\right) \quad (3.2)$$

where q , V_{BE} , k and T have usual meaning and n is known as ideality factor which may vary with base-emitter voltage ($1 < n < 2$). Figures 3.11, 3.12 and 3.13 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 that the recombination peak is beneath the surface [8-12]. For *pnp* transistors, there appears to be little information on the excess base current measurements. The present studies in *pnp* transistor has shown that surface recombinations perhaps occur in *pnp* transistors also. The gain degradation thus appears to be similar in both *npn* as well as *pnp* transistors. Figure 3.14 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.

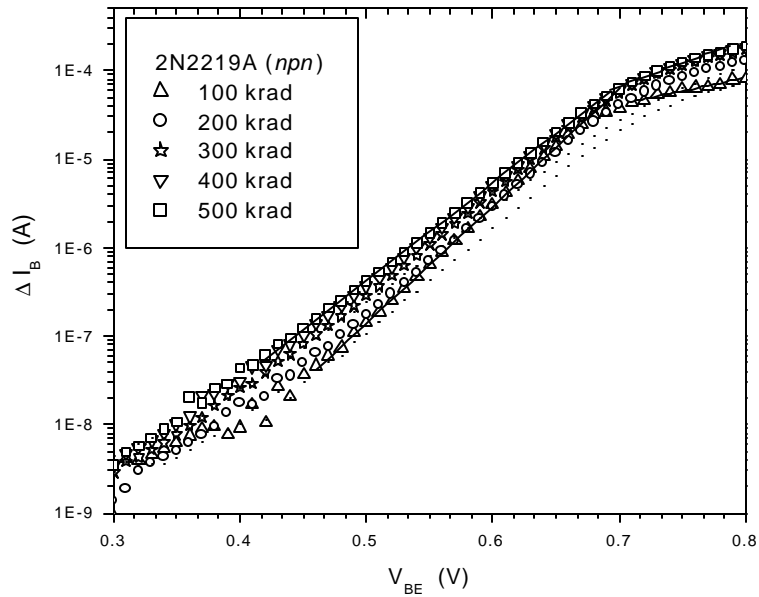


Figure 3.11 Excess base current as a function of base-emitter (V_{BE}) for different accumulated γ -dose (Si).

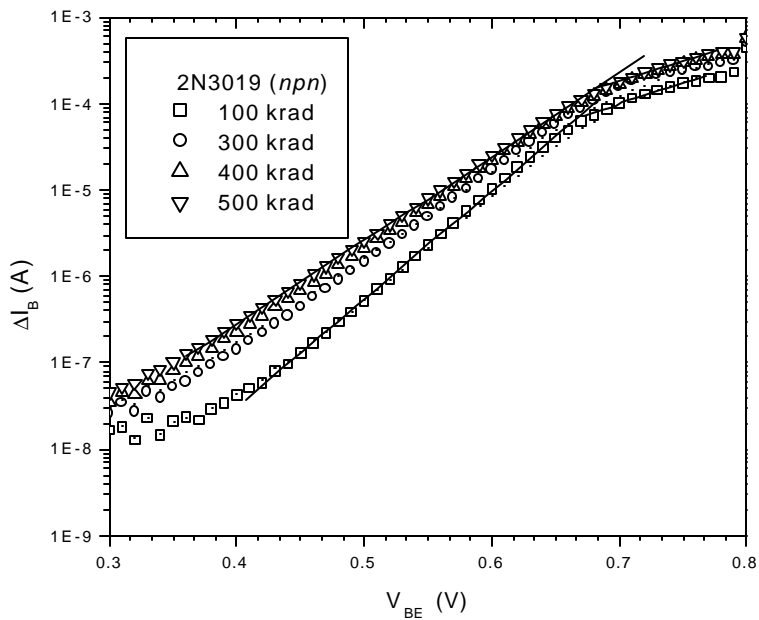


Figure 3.12 Excess base current as a function of base-emitter (V_{BE}) for different accumulated γ -dose (Si).

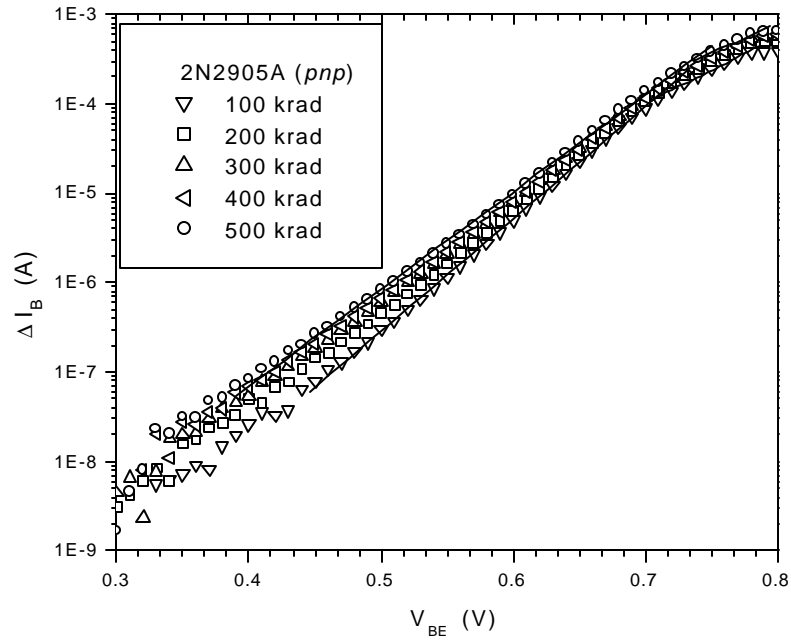


Figure 3.13 Excess base current as a function of base-emitter (V_{BE}) for different accumulated γ -dose (Si).

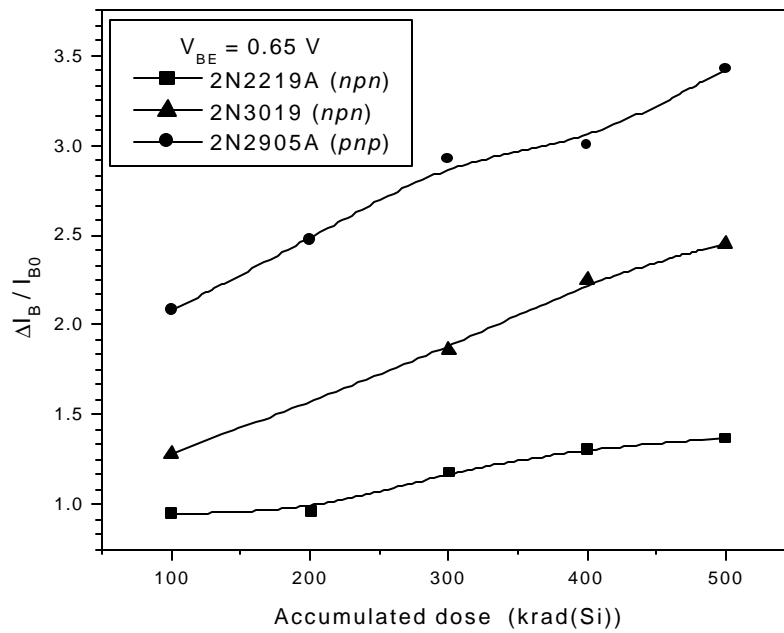


Figure 3.14 Normalized excess base current as a function of accumulated γ -dose (Si). The lines are guide to the eye.

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 reduces the minority carrier lifetime and hence increase the base current and decrease the gain. Gain degradation in silicon bipolar transistors exposed to particle radiation is due to the production of a spectrum of primary knock-on-atoms (PKAs) and is directly related to displacement damage. But in the case of α -irradiation, the displacement damage in silicon from ^{60}Co γ -ray exposure can be analyzed in terms of photon induced secondary electron spectrum [13-16]. Exposure of the devices to γ -radiation produces displacement damage by generating secondary electrons. Displacement damage reduces the forward current gain (dc) 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. Figure 3.15, 3.16 and 3.17 exhibit the plot 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 $V_{\text{BE}} > 0.7 \text{ V}$ is due to the collector current reaching the maximum limit of 100 mA of the measurement system. Figure 3.18 shows the variation of forward current gain as a function of accumulated dose.

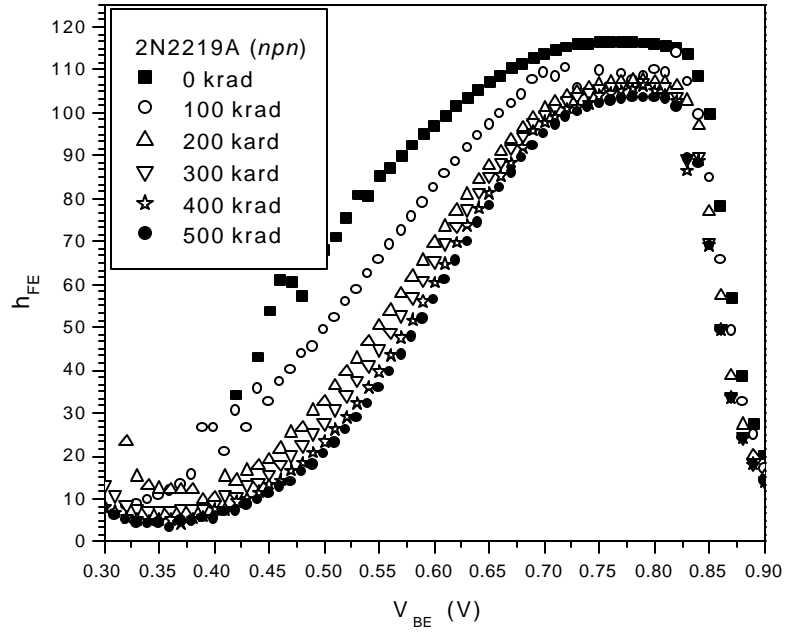


Figure 3.15 Forward current gain (h_{FE}) as a function of V_{BE} for different γ -dose (Si).

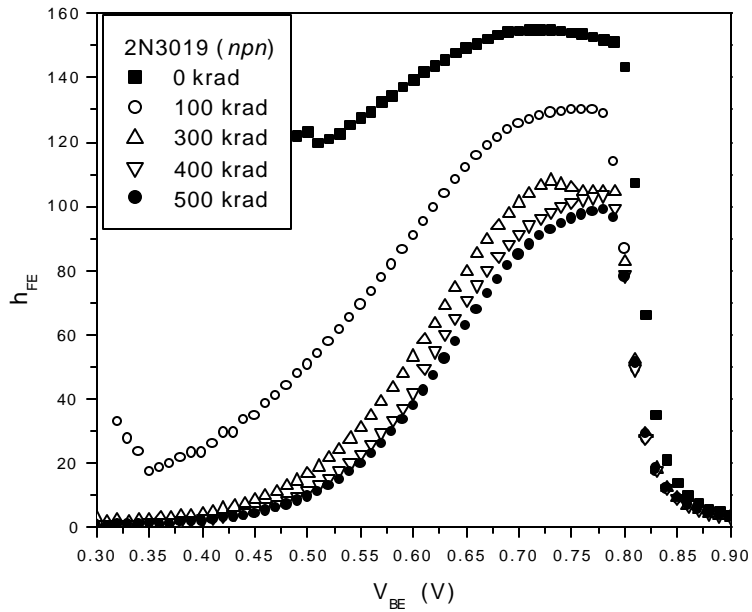


Figure 3.16 Forward current gain (h_{FE}) as a function of V_{BE} for different γ -dose (Si).

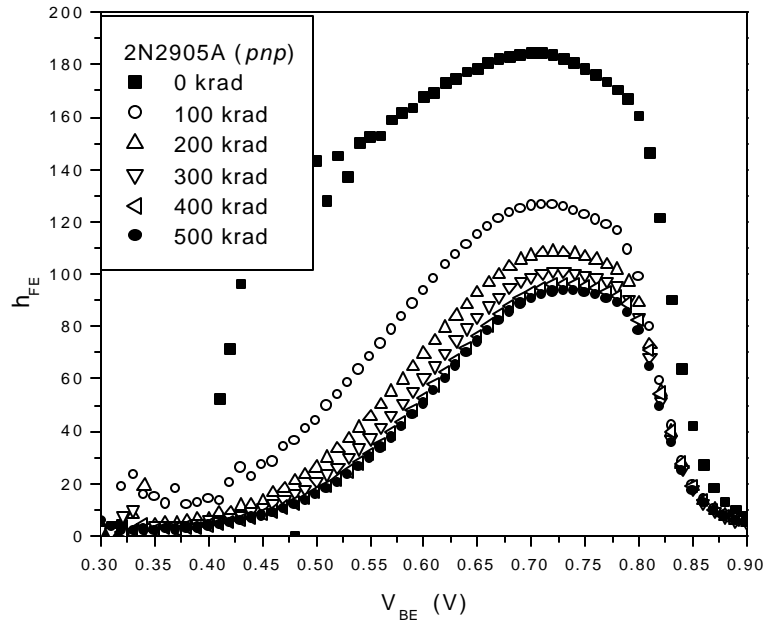


Figure 3.17 Forward current gain (h_{FE}) as a function of V_{BE} for different γ -dose (Si).

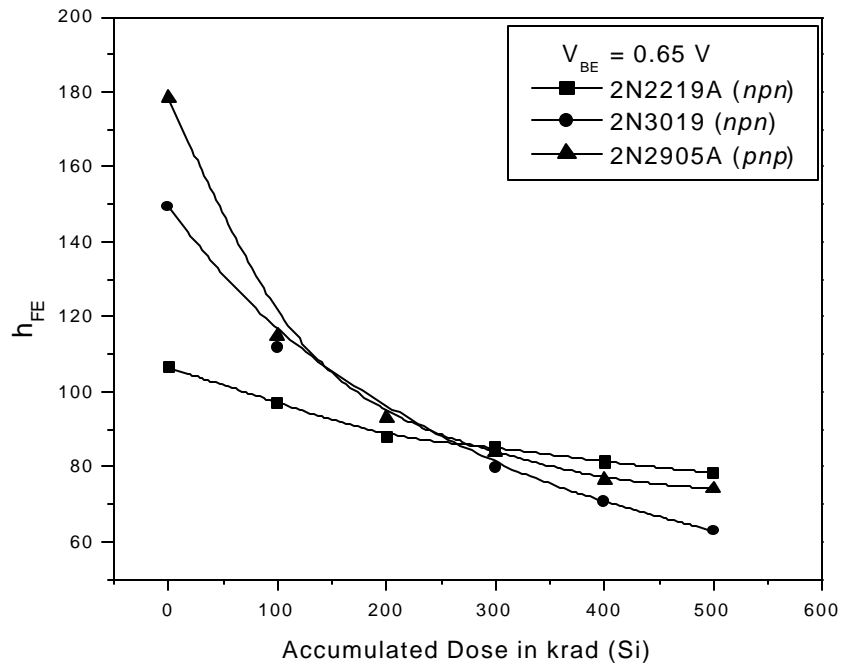


Figure 3.18 Forward current gain (h_{FE}) as a function of accumulated γ -dose (Si). The lines are guide to the eye.

The reduction in h_{FE} with incident particle fluence is given by Messenger Spratt equation [14]

$$\hat{\alpha} = \frac{\hat{\alpha}_0}{1 + \hat{\alpha}_0 K \phi} \quad (3.3)$$

where β_0 and β are the gain value before and after irradiation, ϕ is the 0.6 MeV electron fluence and K is displacement damage factor. In order to calculate the displacement damage produced by secondary electrons, it is required to convert the γ -dose into equivalent electron fluence [17-20]. The conversion can be accomplished using the following considerations. For γ -rays emitted by Co^{60} 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 1g of the material.

Dose = Fluence x Stopping Power

$$\begin{aligned} &= \phi (\#/cm^2) \times S (\text{MeV-cm}^2/\text{g}) \quad \text{MeV/g} \\ &= \phi (\#/cm^2) \times S (\text{MeV-cm}^2/\text{g}) \times 10^6 \times 1.6 \times 10^{-12} \quad \text{ergs/g} \\ &= 1.6 \times 10^{-8} \times \phi (\#/cm^2) \times S (\text{MeV-cm}^2/\text{g}) \quad \text{rads} \end{aligned}$$

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. It can be expressed in (MeV-cm²/g) by dividing S by the material density (g/cm³). S is a function of energy of electron.

$$\text{Dose equivalent fluence} = \frac{\text{rad}}{1.6 \times 10^{-8} \times S (\text{MeV - cm}^2/\text{g})} \quad (3.4)$$

The calculation shows that one rad equivalent of 0.6 MeV electron fluence comes out to be 3.9063×10^7 electrons/cm² [19]. Figure 3.19 shows the variation of estimated displacement damage factor K as a function of accumulated dose for all the three transistors. 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 (3.3 μm). Figure 3.19 shows that for transistor with larger 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 150⁰C for two hours are given in the Tables 3.2- 3.4. 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 150⁰ 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 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

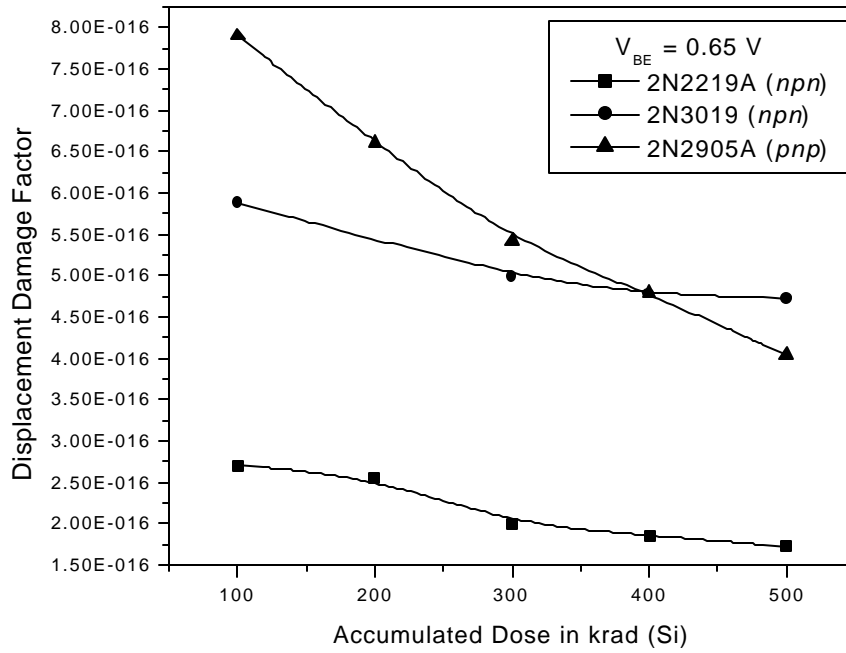


Figure 3.19 Displacement damage factor as a function of accumulated γ -dose (Si).
The lines are guide to the eye.

Table 3.2 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 ⁰ C for 2 hours
h_{FE}	$V_{CE} = 10.0 \text{ V}$ $I_C = 0.10 \text{ mA}$	93.45	38.18	43.10
	$V_{CE} = 10.0 \text{ V}$ $I_C = 1.0 \text{ mA}$	107.8	65.06	77.88
	$V_{CE} = 10.0 \text{ V}$ $I_C = 10 \text{ mA}$	117.0	90.49	95.87
	$V_{CE} = 10.0 \text{ V}$ $I_C = 150 \text{ mA}$	113.5	97.78	100.6
	$V_{CE} = 10.0 \text{ V}$ $I_C = 500 \text{ mA}$	66.58	57.94	61.94

Table 3.3 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 ⁰ C, for 2 hours
h_{FE}	$V_{CE} = 10.0 \text{ V}$ $I_C = 0.10 \text{ mA}$	39.37	16.28	19.05
	$V_{CE} = 10.0 \text{ V}$ $I_C = 1.0 \text{ mA}$	155.0	54.08	58.61
	$V_{CE} = 10.0 \text{ V}$ $I_C = 10.0 \text{ mA}$	158.9	69.78	73.04
	$V_{CE} = 10.0 \text{ V}$ $I_C = 150 \text{ mA}$	152.4	100.7	101.6
	$V_{CE} = 10.0 \text{ V}$ $I_C = 500 \text{ mA}$	115.4	84.40	84.57
	$V_{CE} = 10.0 \text{ V}$ $I_C = 1.0 \text{ A}$	36.50	30.25	30.91

Table 3.4 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 ⁰ C, for 2 hours
h_{FE}	$V_{CE} = 10.0 \text{ V}$ $I_C = 0.10 \text{ mA}$	172.8	27.53	75.41
	$V_{CE} = 10.0 \text{ V}$ $I_C = 1.0 \text{ mA}$	187.5	56.68	104.8
	$V_{CE} = 10.0 \text{ V}$ $I_C = 10 \text{ mA}$	197.0	85.39	128.3
	$V_{CE} = 10.0 \text{ V}$ $I_C = 150 \text{ mA}$	166.8	85.81	117.1
	$V_{CE} = 10.0 \text{ V}$ $I_C = 500 \text{ mA}$	97.33	49.75	69.67

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 *npn* transistors while in the case of *pnp* transistors, the surface degradation may also be contributing to some extent.

3.4 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 the 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. 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. γ -radiation produces bulk damage through the generation of secondary electrons. These secondary electrons in turn produces 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 150⁰ C and do not anneal.

References

- [1] Evans R. D. "The Atomic Nucleus", Ch. 23, TMH edition, Tata McGraw Hill, New Delhi, 1955.
- [2] Sze S.M. "Semiconductor Devices: Physics and Technology" Ch. 2. John Wiley & Sons, New York, 1985.
- [3] Schrimpf R.D., "Recent Advances in Understanding Total-Dose Effects in Bipolar Transistors", Proceeding of *Third European Conference on Radiation and its Effects on Components and Systems*, pp.9, September 18-22, 1995, Arcachon, France.
- [4] Schmidt D.M., Fleetwood D.M., Schrimpf R.D., Pease R.L., Graves R.J., Johnson G.H., Galloway K.F. and Combs W.E., "Comparision of Ionizing-Radiation-Induced Gain Degradation in Lateral, Substrate and Vertical PNP BJTs", *IEEE Trans. Nucl. Sci.*, **Vol. 42**, 1541 (1995).
- [5] *Radiation Design Handbook*, European Space Agency - PSS – 01 - 609, 1993, Section 3.
- [6] Bhat B.R. and Sahu R.P., "Radiation Shielding of Electronic Components in INSAT-2", *Journal of Spacecraft Technology*, **Vol.3**, 36(1993).
- [7] Nowlin R.N., Enlow E.W., Schrimpf R.D., Combs W.E. "Trends in the Total-Dose Response of Modern Bipolar Transistors", *IEEE Trans. Nucl. Sci.*, **Vol. 39**, 2026(1992).
- [8] Kosier S.L., Combs W.E., Wei A., Schrimpf R.D., Fleetwood D.M., DeLaus M., Pease R.L. and Combs W.E., "Physically Based Comparison of Hot-Carrier-Induced and Ionizing-Radiation-Induced Degradation in BJT's", *IEEE Trans. Electron Devices*, **Vol. 42**, 436 (1995).
- [9] Kosier S.L., Combs W.E., Wei A., Schrimpf R.D., Fleetwood D.M., DeLaus M. and Pease R.L., "Bounding the Total-Dose Response of Modern Bipolar Transistors", *IEEE Trans. Nucl. Sci.*, **Vol. 41**, 1864 (1994).
- [10] Kosier S.L., Schrimpf R.D., Nowlin R.N., Fleetwood D.M., DeLaus M., Pease R.L., Combs W.E., Wei A. and Chai F., "Charge Separation for Bipolar Transistor", *IEEE Trans. Nucl. Sci.*, **Vol. 41**, 1276 (1993).
- [11] Nowlin R.N., Schrimpf R.D. Enlow E.W., Combs W. and Pease R.L., "Mechanism of Ionizing-Radiation-Induced Gain Degradation in Modern Bipolar Devices", Proc. 1991 *IEEE Bipolar Circuits and Tech. Mtg.*, 174 (1991).

- [12] Enlow E.W., Pease R.L., Combs W., Schrimpf R.D., and Nowlin R.N., "Response of Advance Bipolar Processes to Ionizing Radiation", *IEEE Trans. Nucl. Sci.*, **Vol. 38**, 1342(1991).
- [13] Kulkarni S.R., Asiti Sarma, Joshi G.R., Ravindra M. and Damle R., "Proton and gamma ray induced gain degradation in bipolar transistors", *Radiation Effects & Defects in Solids* **Vol. 158**, 647 (2003).
- [14] Nichols D.K., Price W.E. and Gauthier M.K. "A Comparison of Radiation damage in Transistors from ^{60}Co γ -ray and 2.2 MeV Electrons", *IEEE Trans. Nucl. Sci.*, **Vol. NS-29**, 1970(1982).
- [15] Xapsos M. A., Summers G. P., Blatchley C.C., Colerico C.W., Burke E. A. Messenger S.R. and Shapiro P., " ^{60}Co Gamma Ray and Electron Displacement Damage Studies of Semiconductors", *IEEE Trans. Nucl. Sci.* **Vol.41**, 1945(1994).
- [16] Messenger G.C., "Displacement Damage in Silicon and Germanium Transistors", *IEEE Trans. Nucl. Sci.* **Vol. NS-12**, 53(1965)
- [17] Dale C.J., Marshall P.W., Burke E.A., Summers P.G., and Wolicki E.A., "High Energy Electron Induced Displacement Damage in Silicon", *IEEE Trans. Nucl. Sci.*, **Vol. 35**, 1208(1988).
- [18] Raymond J.P. and Petersen E.L., "Comparison of Neutron, Proton and Gamma Ray Effects in Semiconductor Devices", *IEEE Trans. Nucl. Sci.*, **Vol. NS-34**,1622(1987).
- [19] Bhat B.R., Umesh S.B., Bhoopathy B.A.M., Shashikala, Bhoraskar V.N. and Sathyavathi P., "Electron Irradiation Test on Transistors and ICs", DOC.No.:ISRO-ISAC-TR-0320 (1998).
- [20] Summers G.P. Burke E. A., Dale C. J., Wolicki E. A., Marshall P. W. and Gehlhausen M. A. "Correlation of Particle-Induced Displacement damage in Silicon", *IEEE Trans. Nucl. Sci.*, **Vol. NS-34**, 1134(1987).