Cs^{137} γ-RAY IRRADIATION EFFECT ON THE ELECTRICAL CHARACTERISTICS OF TRANSISTORS

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1 Introduction

Bipolar Junction transistors (BJT) have superior electrical performance over conventional silicon bipolar junction transistors for high-speed/high-frequency applications. HBTs are very attractive candidates for the applications in radiation-rich environment such as nuclear reactor, high-energy particle accelerators, and artificial satellites. Hence, the issues of reliability of these devices in high-energy radiation environment should be paid much attention.[1] Most of the radiation studies on BJTs reported so far have mainly focused on experimental results on the radiation induced changes in the measured electrical characteristics of the devices (e.g., excess base current, current gain, etc.) [2–5].

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 bremssstrahlung 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.

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.

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 Cs^{137} 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.

2 Experimental details

Irradiation of devices, without biased, was performed in a ''Gamma-Cell'' with a Cs^{137} source providing a dose rate of about 50 rad(Si)/s equivalent to a gamma total dose of 10 M rad (Si) used for the test samples. The devices are exposed to Cs^{137} γ-rays in the biased condition and measurements of the electrical parameters are made in-situ using Semiconductor Parameter Analyzer (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} = 5V), have also been obtained after every accumulated dose [2-4].

3 Results and discussion

The collector characteristics of transistors at constant base current I_B = 50 μA and V_{BE} = 0.65V as a function of the accumulated dose are shown in the Figure 1, 2 and 3 for the transistors of the type 2N2219AS (npn), 2SD590 (npn) and BC294 (pnp) 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 is shown in Figures 4, 5 and 6 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 7, 8 and 9 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.

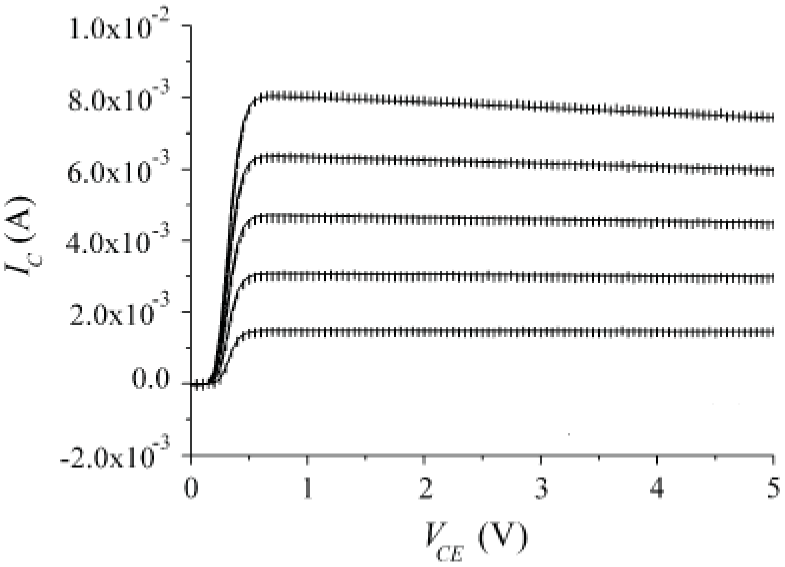

Figure 1: Variation of collector current (Ic) as a function of collector-emitter voltage (V_{CE}) for different accumulated γ–does (Si).

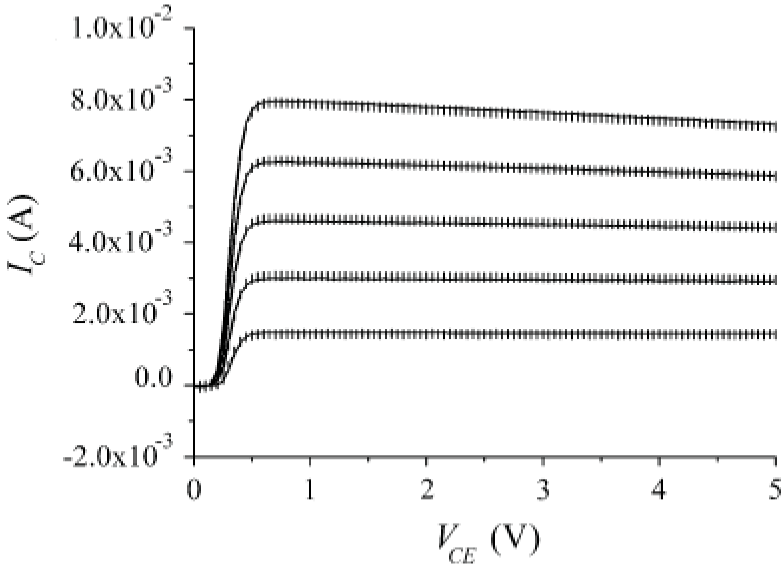

Figure 2: Variation of collector current (IC) as a function of collector-emitter voltage (V_{CE}) for different accumulated γ–does (Si).

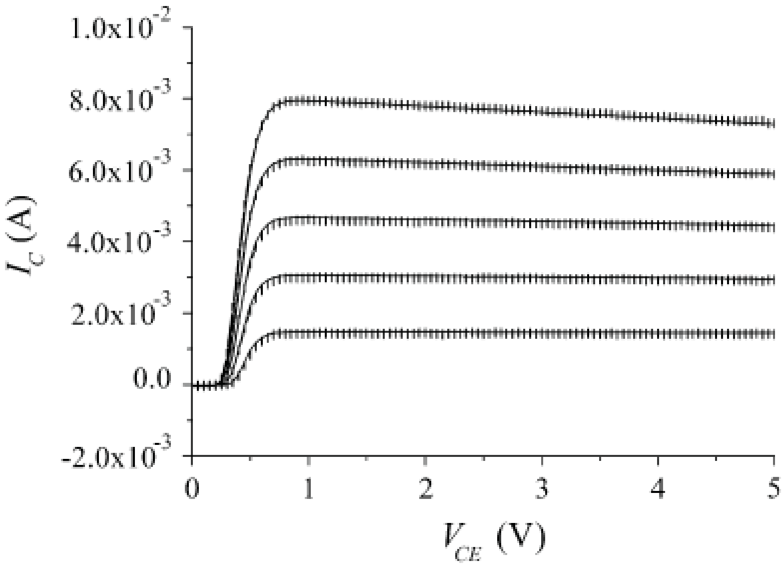

Figure 3: Collector current (I_C) as a function of collector--emitter voltage (V_{CE}) for different accumulated γ–does (Si).

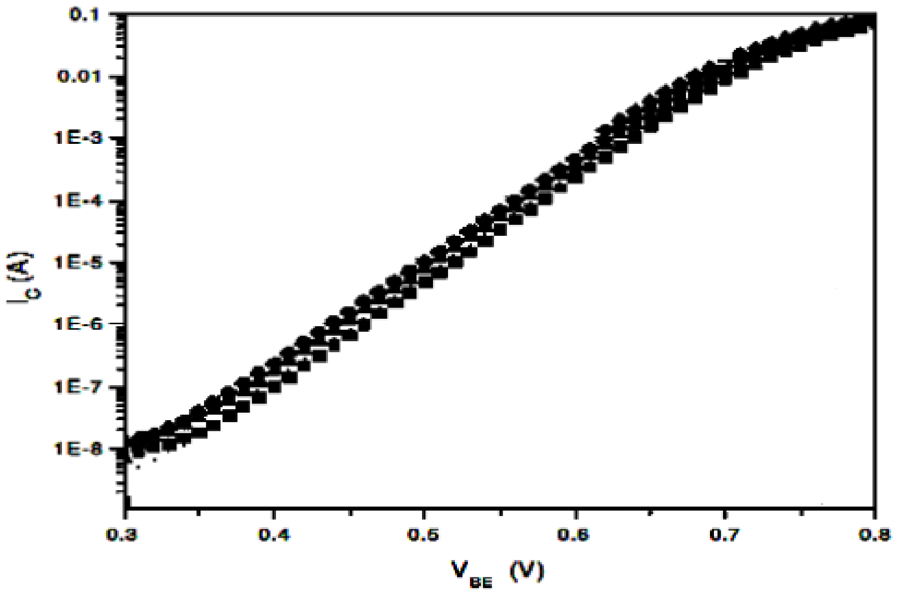

Figure 4: Collector current (I_C) as a function of base--emitter voltage (V_{BE}) for different accumulated γ–does (Si).

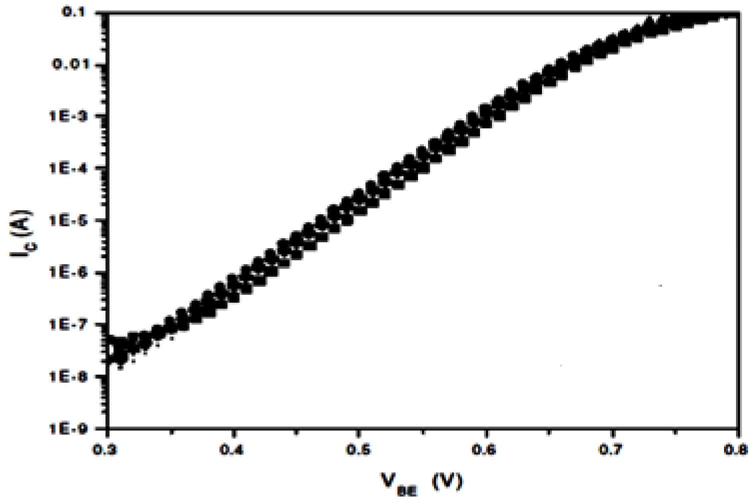

Figure 5: Collector current (IC) as a function of base--emitter voltage (V_{BE}) for different accumulated γ–does (Si).

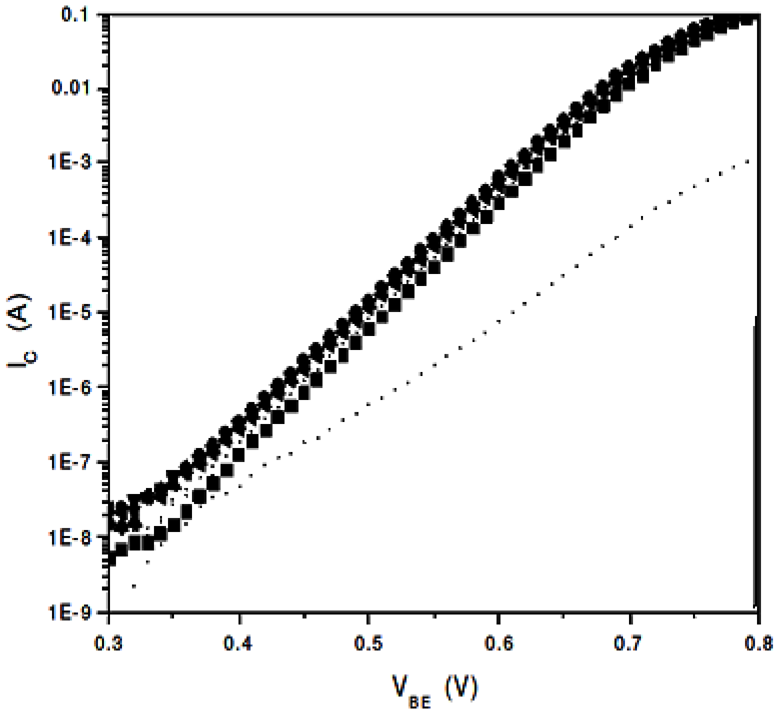

Figure 6: Collector current (IC) as a function of base--emitter voltage (V_{BE}) for different accumulated γ–does (Si).

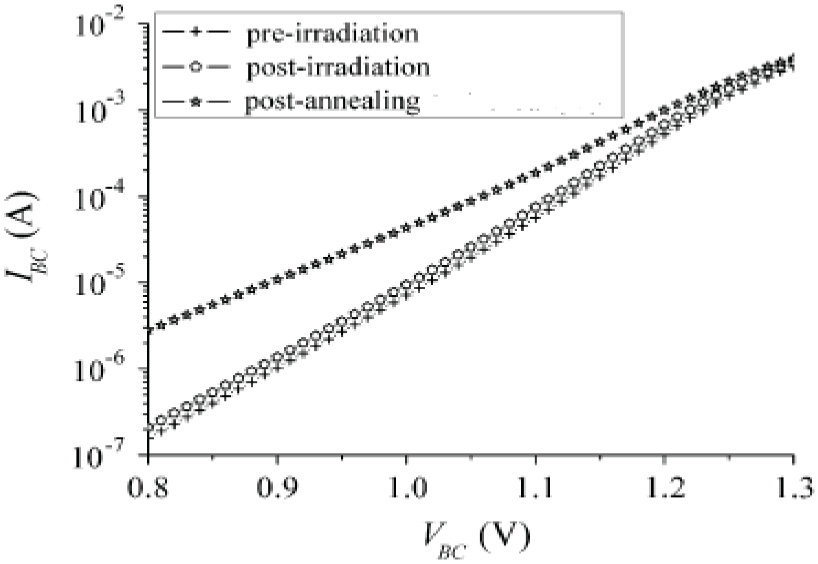

Figure 7: Base current (I_B) as a function of base--collector voltage (V_{Bc}) for different accumulated γ–does (Si).

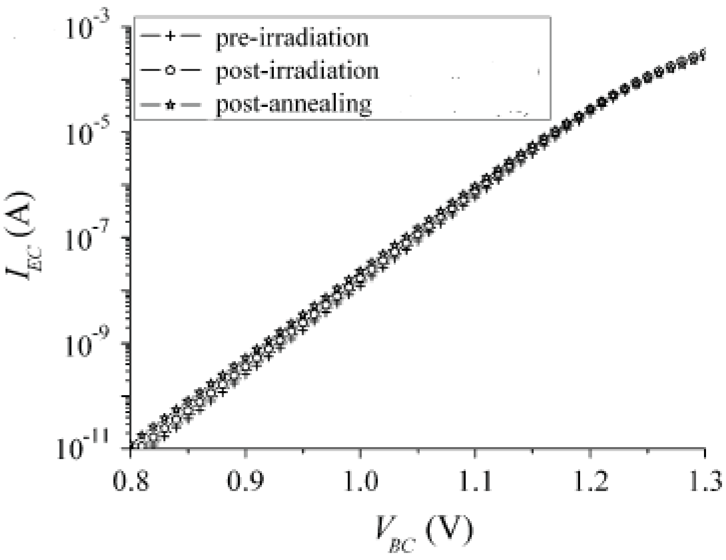

Figure 8: Base current (I_B) as a function of base-collector voltage (V_{Bc}) for different accumulated γ–does (Si).

The increase in the base current can be defined as ΔIB = IB-IB0, where IB0 is the pre irradiation base current and IB is the post-irradiated ion base current. From equation 1 we can write the excess base current as [3- 4, 7]

$$\Delta I_B = \Delta I_{BO} \exp\left(\frac{qV_{BE}}{nkT}\right) \tag{1}$$

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 10, 11 and 12 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 that 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 recombination perhaps occur in pnp transistors also. The gain degradation thus appears to be similar in both npn as well as pnp transistors. Figure 13 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.

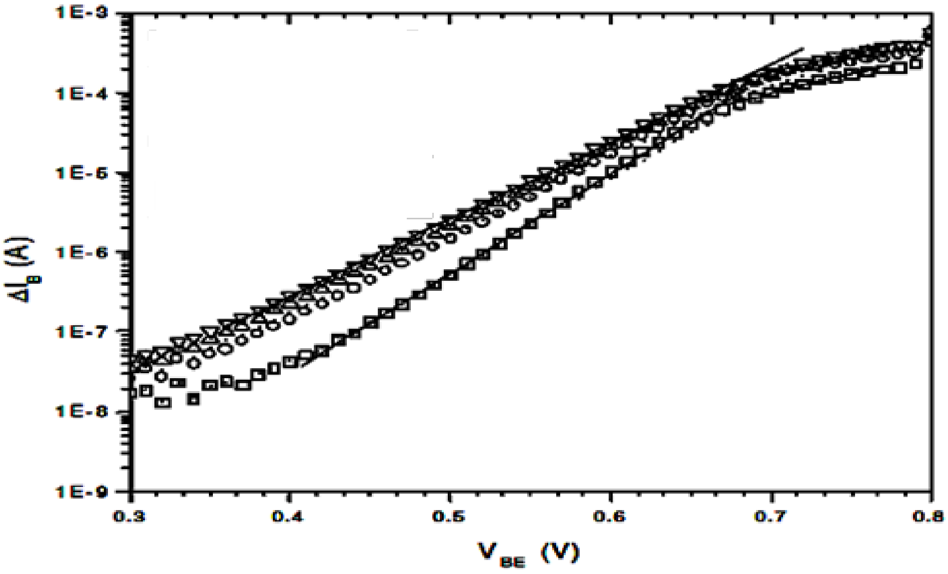

Figure 9: Excess base current (I_B) as a function of base-emitter voltage (V_{BE}) for different accumulated γ–does (Si).

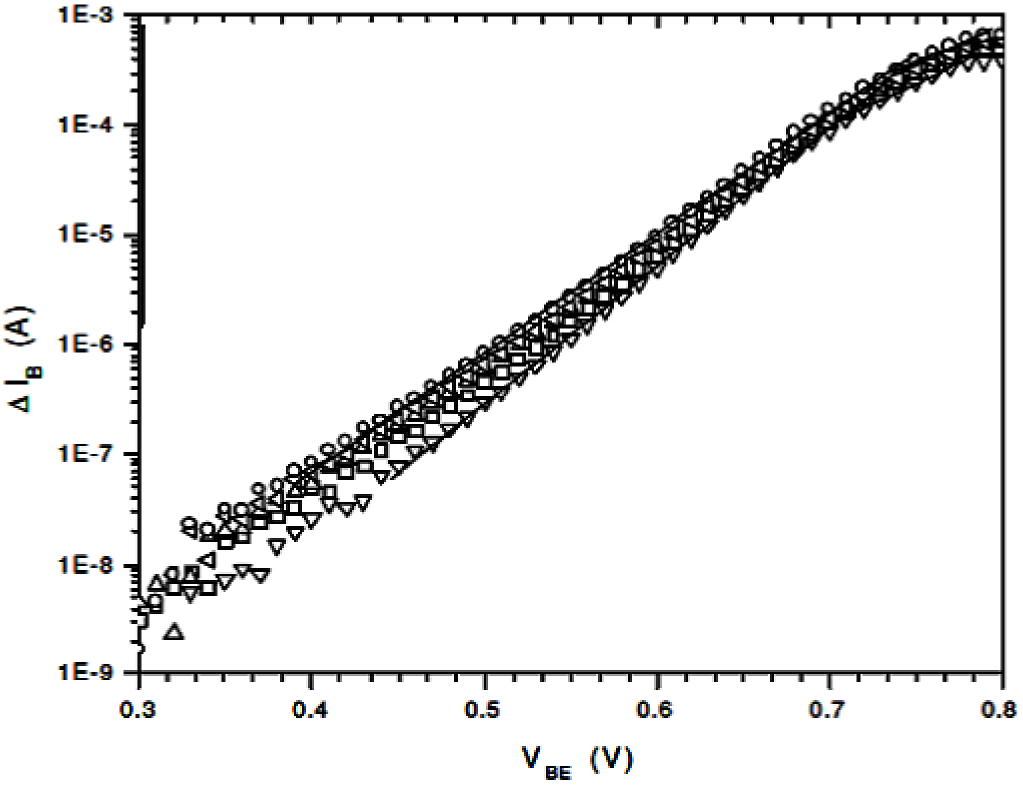

Figure 10: Excess base current (I_B) as a function of base--emitter voltage (V_{BE}) for different accumulated γ–does (Si).

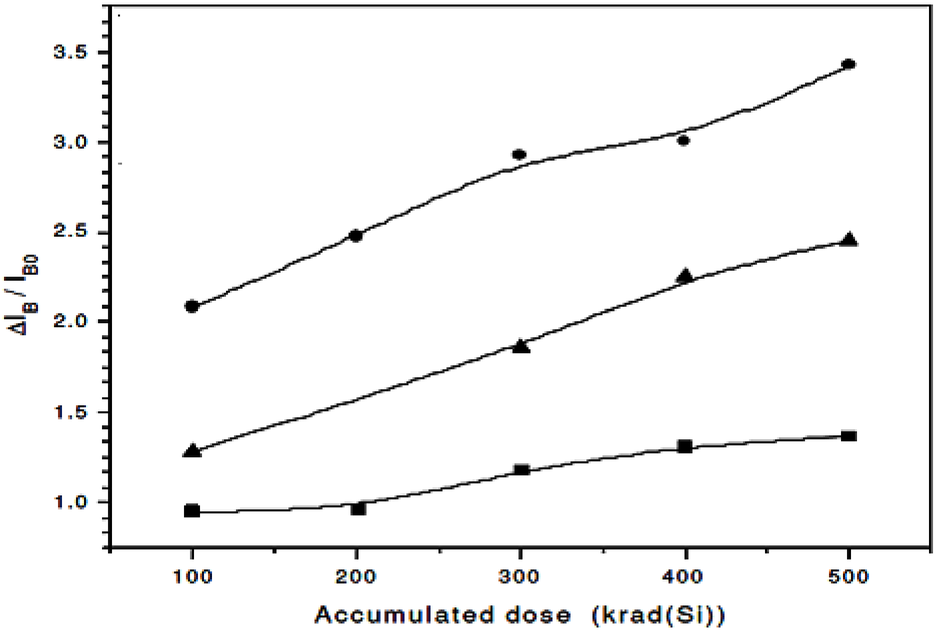

Figure 11: Excess base current (I_B) as a function of base-emitter

voltage (V_{BE}) for different accumulated γ–does (Si).

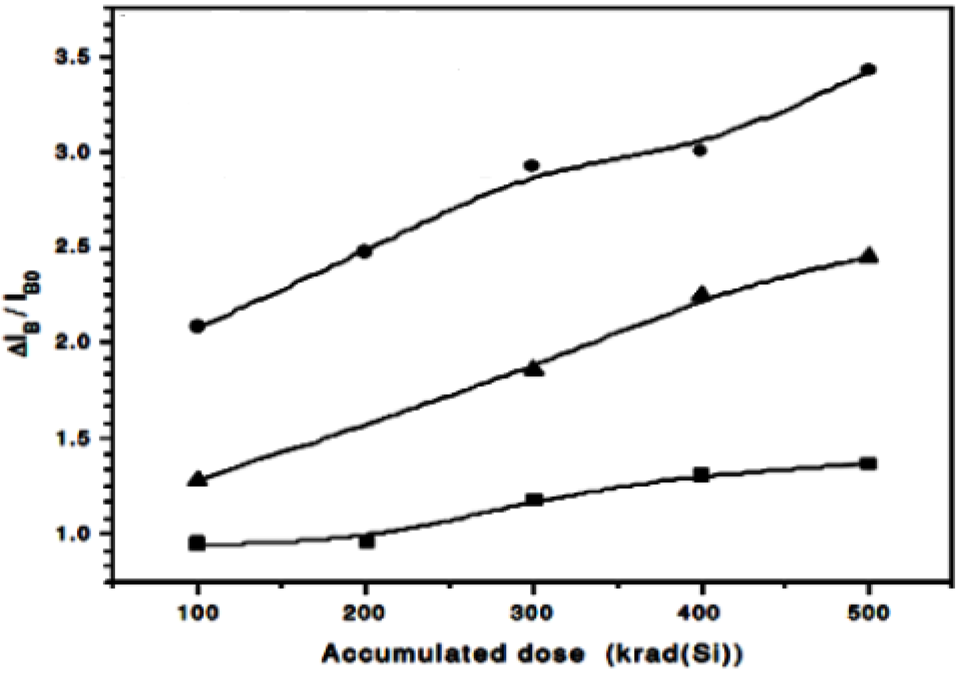

Figure 12: Normalized excess base current as a function of accumulated

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 reduce 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 γ-irradiation, the displacement damage in silicon from Cs^{137} 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 14, 15 and 3.16 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 $V_{BE} > 0.7$ V is due to the collector current reaching the maximum limit of 100 mA of the measurement system. Figure 17 shows the variation of forward current gain as a function of accumulated dose.

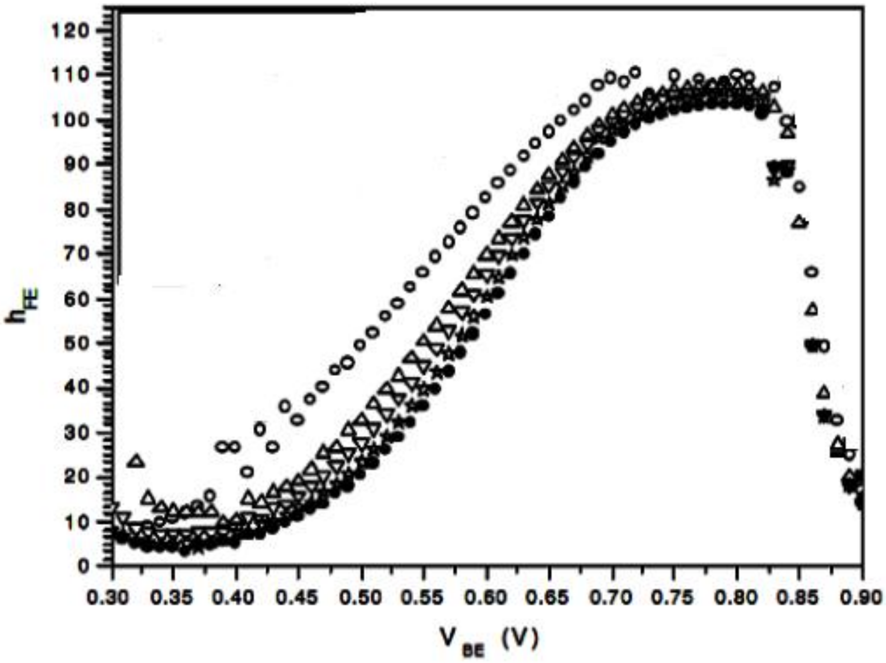

Figure 13: Forward current gain (h_{FE}) as a function of V_{BE} for different γ- dose (Si)

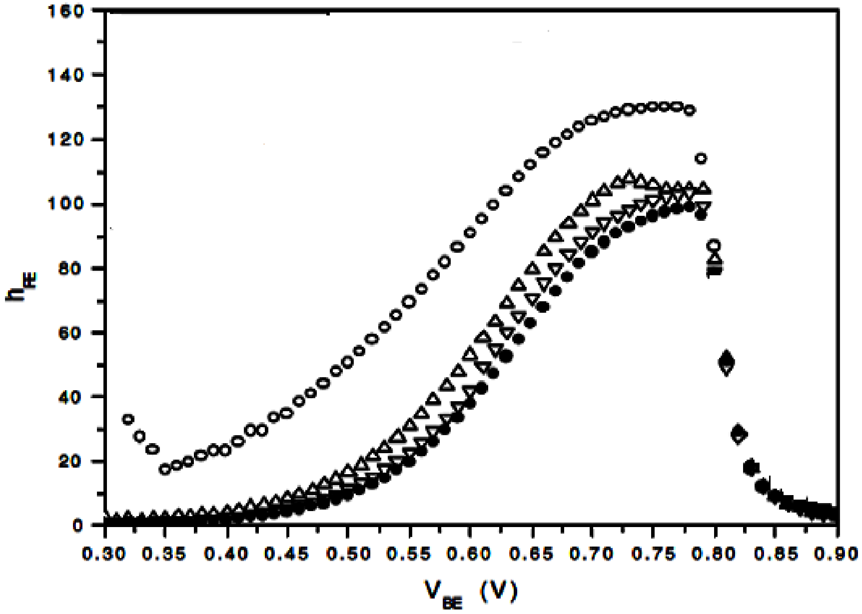

Figure 14: Forward current gain (h_{FE}) as a function of V_{BE} for different

γ-dose (Si)

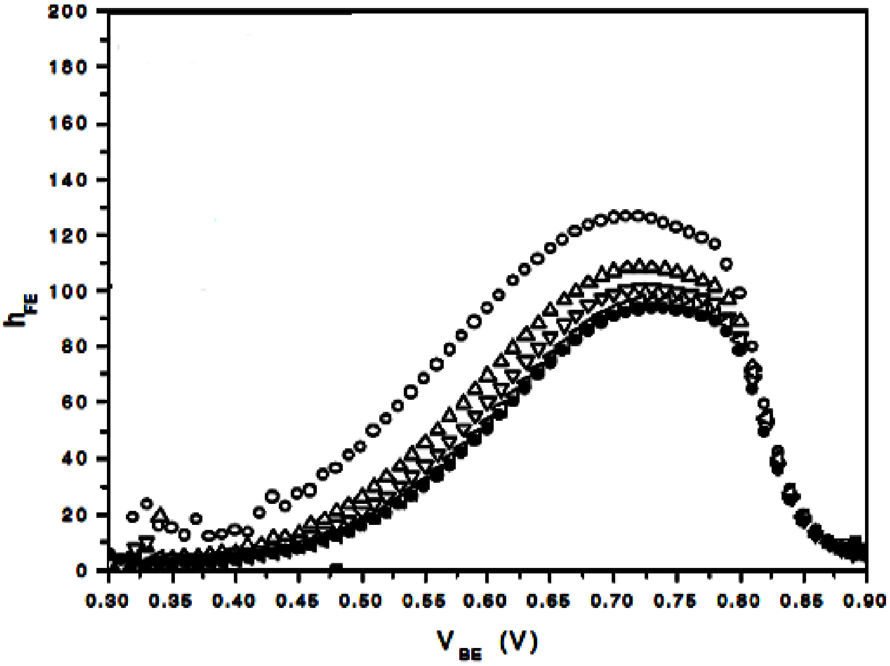

Figure 15: Forward current gain (h_{FE}) as a function of V_{BE} for different

γ-dose (Si)

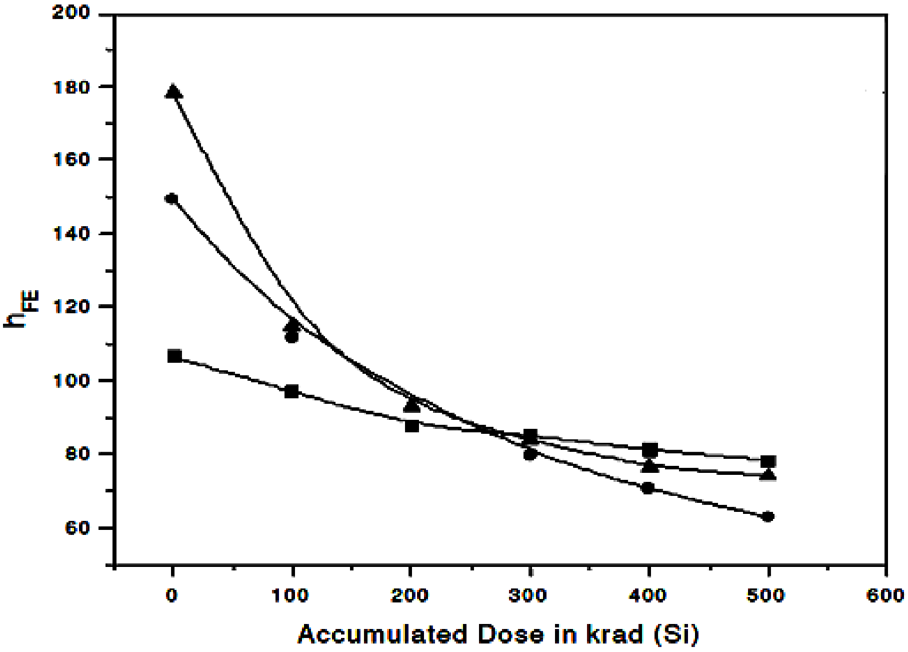

Figure 16: Forward current gain (h_{FE}) as a function of accumulated γ-

dose (Si). Te lines are guide to the eye.

In order to calculate the displacement damage produced by secondary electrons, it is required to convert the γ-dose into equivalent electron fluence [17-21]. The conversion can be accomplished using the following considerations. For γ-rays emitted by Cs^{137} 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

$= \varphi\ (Q/cm^2)\ X\ S\ (MeV\text{- } cm^2/g)\ \ MeV/g$

$= \varphi\ (Q/cm^2)\ X\ S\ (MeV\text{- } cm^2/g)\ X\ 10^6\ X\ 1.6\ X\ 10^{-12}\ ergs/g$

$= 1.6\ X\ 10^{-8}\ X\ \varphi\ (Q/cm^2)\ X\ S\ (MeV\text{- } cm^2/g)\ \ rads$

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. It can be expressed in ($MeV\text{-}cm^2/g$) by dividing S by the material density (g/cm^3). S is a function of energy of electron.

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

The calculation shows that one rad equivalent of 0.6 MeV electron fluence comes out to be 3.9063×10^7 electrons/cm^2 [19-21]. Figure 3.18 shows the variation of estimated displacement damage factor K as a function of accumulated dose for all the three transistors. A 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 2N2219AS has smaller base thickness (2.0 μm) than the other npn transistor, 2SD590 (3.3 μm). Figure 3.18 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. 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 150^0 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 (BC294), 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 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.

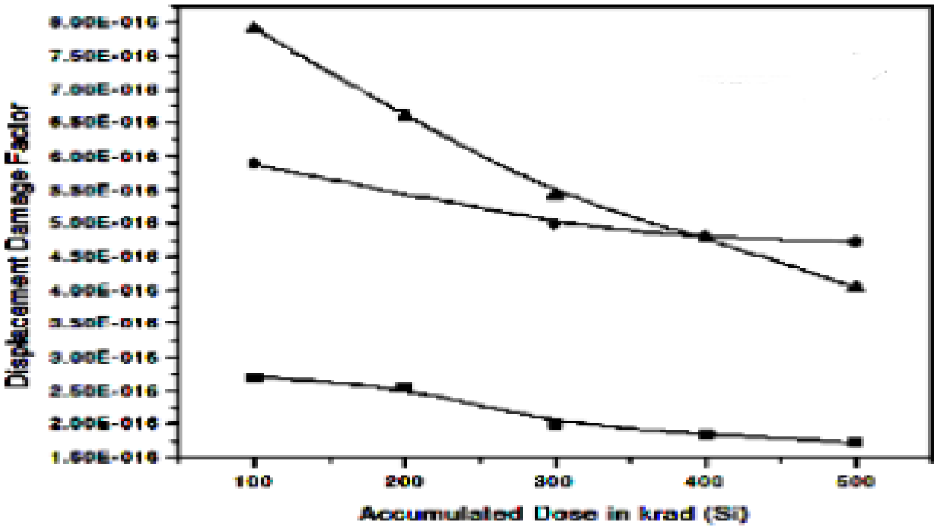

Figure 17: Displacement damage factor as a function of accumulated γ -

dose (Si).The lines are guide to the eye.

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 behavior of these indigenous parts type is similar to those of other vendors' (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 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 150^0 C and do not anneal.

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