

Chapter 4

***EFFECT OF HIGH-ENERGY ELECTRON IRRADIATION ON
ELECTRICAL CHARACTERISTICS OF BIPOLAR JUNCTION
TRANSISTORS***

4.1 Introduction

Electrons are negatively charged with a rest mass of 1.6×10^{-31} kg (0.511 MeV). The dominant mechanism of interaction of electrons with matter is Rutherford scattering. The maximum energy that can be transferred in a collision of electron with target atom is given by

$$E = \frac{2(E_K + m_0c^2)E_K}{M_1c^2} \quad (4.1)$$

where E_K is the kinetic energy of the electron, c is the velocity of light, m_0 is the electron rest mass, and M_1 is the mass of the target particle [1]. The interaction of electrons with target atoms produces displaced atoms. The displacement per centimeter is calculated from the following equation

$$\zeta_D(E) = N_a [\sigma_D(E)] [\langle V(E) \rangle] \quad (4.2)$$

where N_a is lattice atoms/cm³, σ_D is the displacement cross section, and $\langle V(E) \rangle$ is the mean number of secondary displacements per primary recoil [1]. This equation is shown in the graph form for silicon in Figure 4.1.

Electrons of energy < 20 keV are incapable of producing atomic displacement in medium and heavy mass elements. In a head-on collision, a 20 keV electron is capable of imparting only about one-tenth of the threshold energy for displacement to a silicon atom. On the other hand, electrons of energy near 200 keV are capable of providing sufficient energy to displace silicon atom but not enough additional energy to the recoil atom as to produce any secondary displacements. Hence, electrons in the energy range between

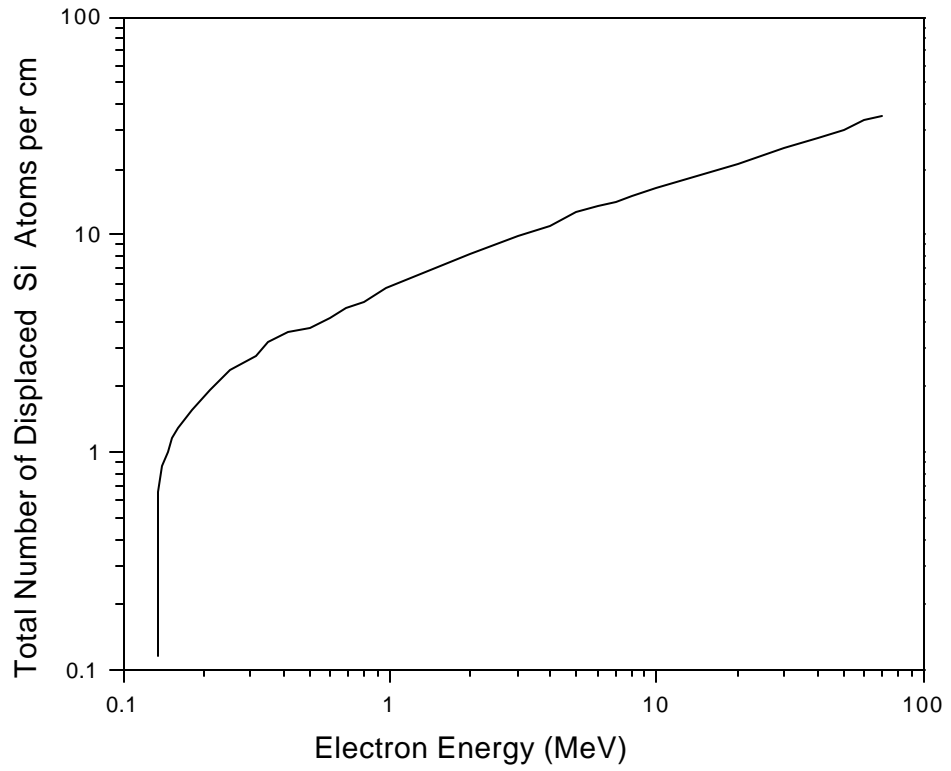


Figure 4.1 Total number of displaced Si atoms versus electron energy.

100 keV-1 MeV are usually used to evaluate the threshold energy for displacements. High energy electrons (> 40 MeV) are capable not only of producing primary displacements but also of imparting the recoil atom sufficient energy that it in turn can displace a large number of other atoms [1-5].

Space environment consists of high-energy electrons of various energy. Especially in Van Allen belts, high-energy and high flux electrons are trapped and are continuously under motion between points near the north and the south poles, along a helical path [6-7]. Electron are a convenient form of laboratory radiation and can simulate quite accurately the effect of high energy proton radiation [1]. This chapter describes the studies on the effect of 8 MeV electrons on the electrical characteristics of bipolar junction transistors. The same type of transistors which were studied for the γ -ray induced effects have been taken up to study the electron beam induced effects.

4.2 Experimental details

Space borne indigenous commercial BJTs of the type 2N2219A, 2N3019 (both *npn*) and 2N2905A (*pnp*) are exposed to 8 MeV electron at Microtron Centre, Mangalore University, Mangalore. The transistors were exposed in the biased conditions, $V_{CE} = 10V$ and $I_B = 50 \mu A$. As electrons cannot penetrate the lid of the device, the transistors are decapped using a decapping tool and the die of the transistor was exposed to the electron beam [8-9]. 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.

4.3 Results and discussion

The collector characteristics of the transistors at constant base current, $I_B = 50 \mu\text{A}$ and $V_{BE} = 0.65 \text{ V}$ as a function of the accumulated electron dose are shown in the Figures 4.2, 4.3 and 4.4 for the transistors of the type 2N2219A, 2N3019 and 2N2905A respectively.

In order to extract more information from the transistor characteristics, Gummel plots are useful. These plots can be analyzed graphically or numerically to extract large amount of data. Gummel plots are obtained by measuring the base current I_B and collector current I_C as a function of V_{BE} when V_{CE} is held constant at 5 V [10-12]. The variation of collector current I_C as a function of V_{BE} for different accumulated electron dose for the three transistors are shown in Figures 4.5, 4.6 and 4.7 respectively. Figures 4.8, 4.9 and 4.10 exhibit the variation of I_B as a function of V_{BE} with increasing accumulated electron dose for the three transistors. Gummel plots clearly show that there is no considerable change in the collector current with increasing electron dose. However, the base current I_B is found to increase with accumulated electron dose for all the three transistors. The excess base current as a function of V_{BE} for all three transistors is shown in Figures 4.11, 4.12 and 4.13. Although there is little scattering of data points above $V_{BE} = 0.6 \text{ V}$, clearly there is no change in the slope of the plot of excess base current for V_{BE} values $> 0.7 \text{ V}$.

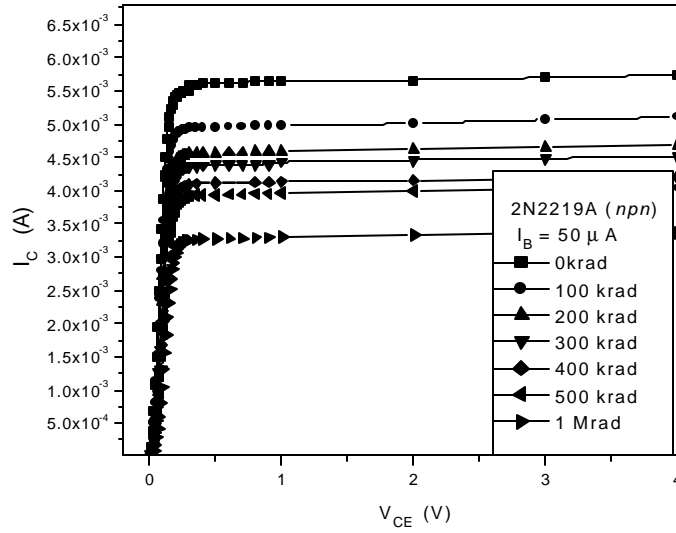


Figure 4.2 Collector current (I_C) as function of collector-emitter voltage (V_{CE}) for different electron dose.

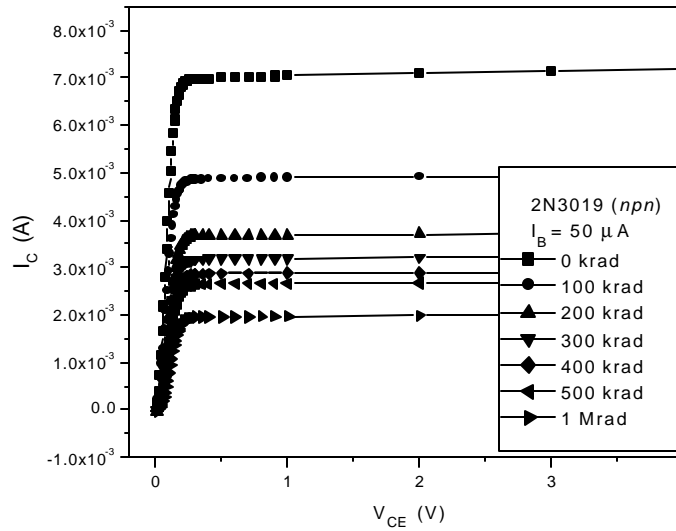


Figure 4.3 Collector current (I_C) as function of collector-emitter voltage (V_{CE}) for different electron dose.

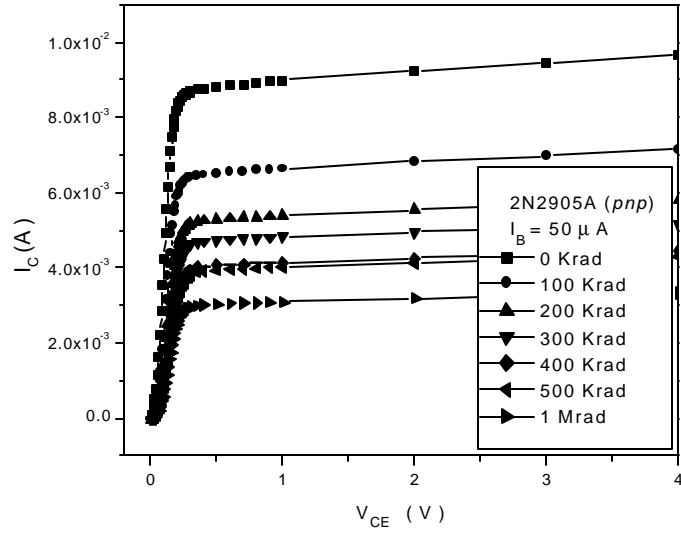


Figure 4.4 Collector current (I_C) as function of collector-emitter voltage (V_{CE}) for different electron dose.

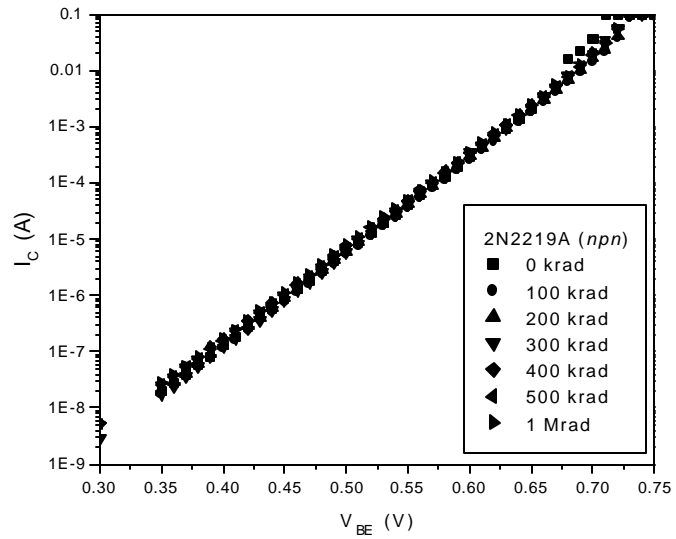


Figure 4.5 Collector current (I_C) as a function of base-emitter voltage (V_{BE}) for different electron dose.

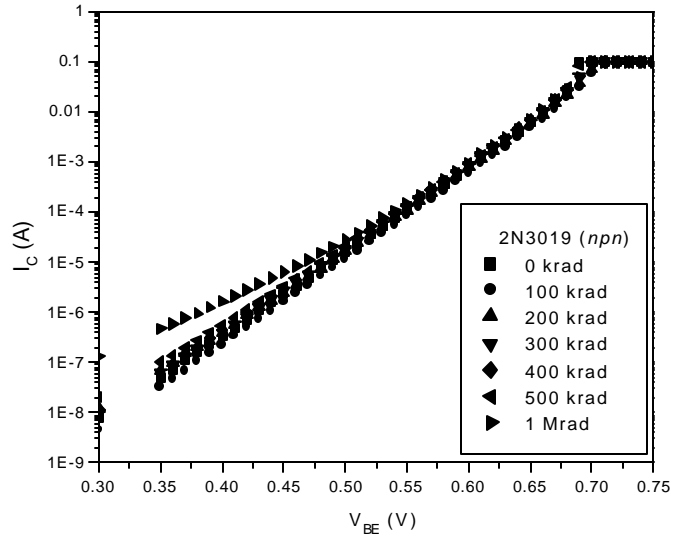


Figure 4.6 Collector current (I_C) as a function of base-emitter voltage (V_{BE}) for different electron dose.

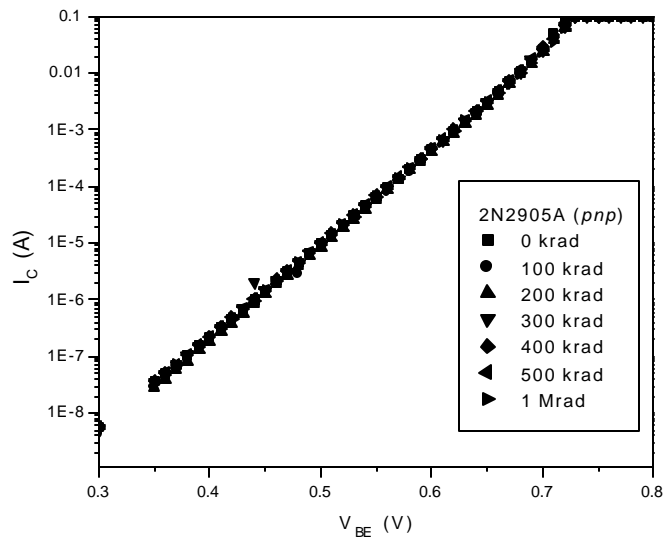


Figure 4.7 Collector current (I_C) as a function of base-emitter voltage (V_{BE}) for different electron dose.

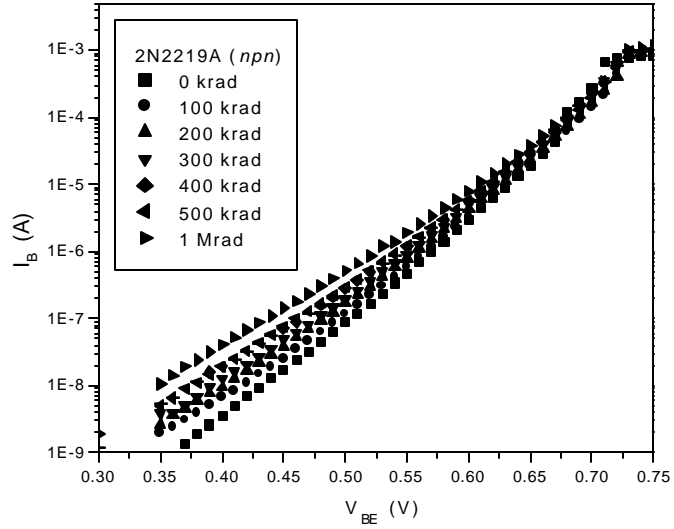


Figure 4.8 Base current (I_B) as a function of base-emitter voltage (V_{BE}) for different electron dose.

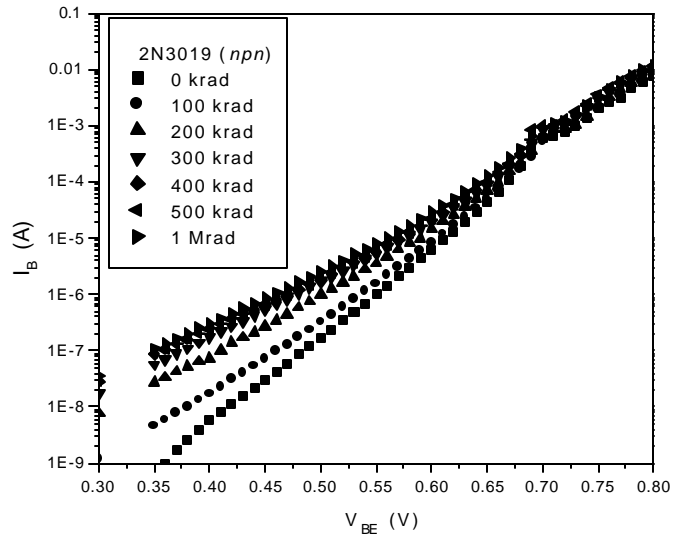


Figure 4.9 Base current (I_B) as a function of base-emitter voltage (V_{BE}) for different electron dose.

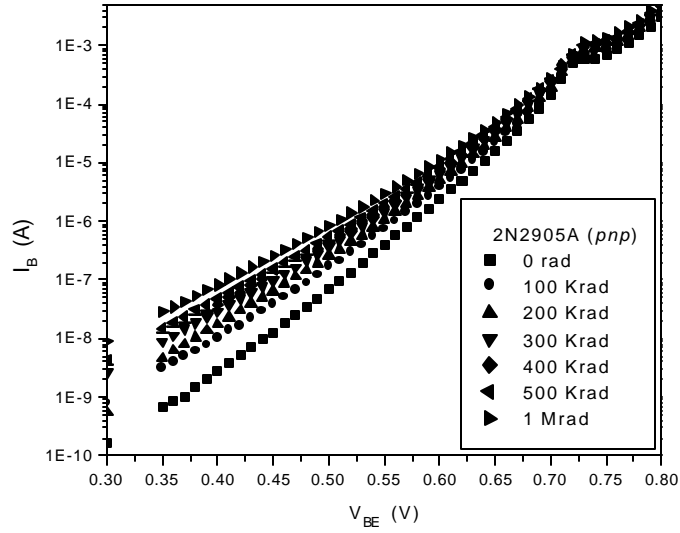


Figure 4.10 Base current (I_B) as a function of base-emitter voltage (V_{BE}) for different electron dose.

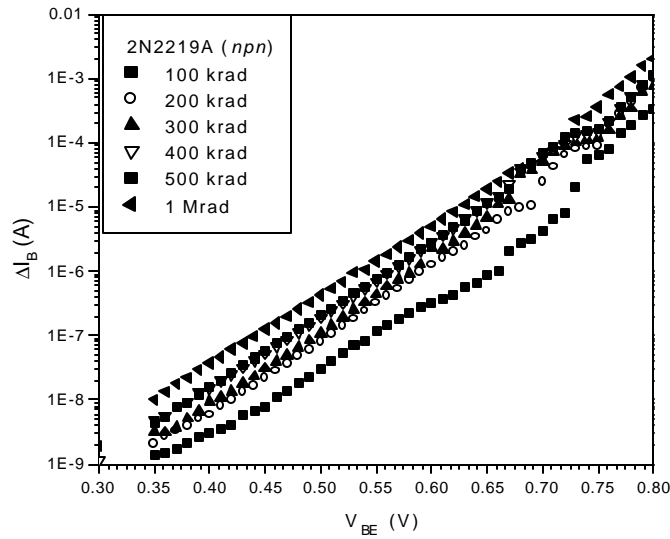


Figure 4. 11 Excess base current as a function of base-emitter voltage (V_{BE}) for different electron dose.

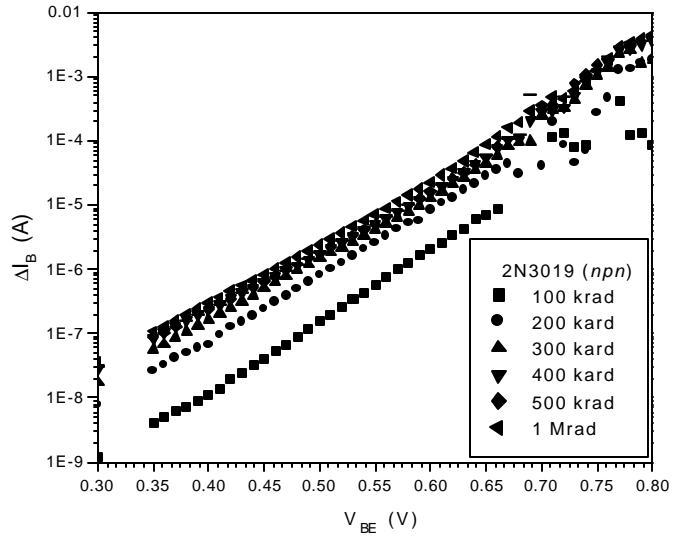


Figure 4. 12 Excess base current as a function of base-emitter voltage (V_{BE}) for different electron dose.

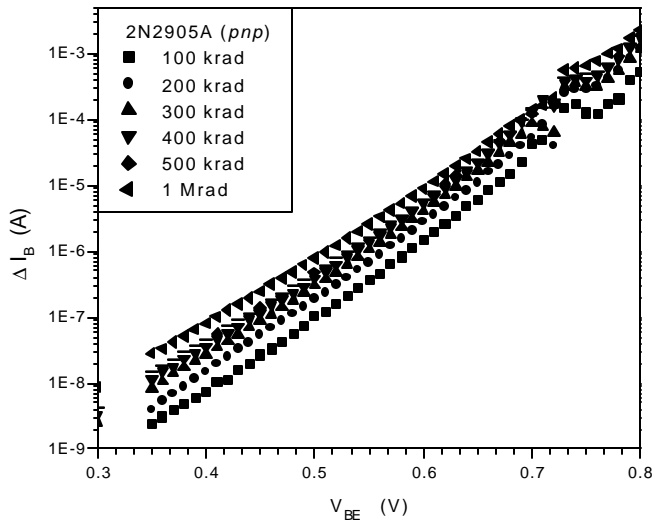


Figure 4. 13 Excess base current as a function of base-emitter voltage (V_{BE}) for different electron dose.

This observation is unlike that observed when the same transistors were exposed to γ -radiation. In the case of γ -irradiated devices, the change in slope of the excess base current is analysed in terms of the surface recombinations [10-11]. But in the case of electron irradiation, the surface recombinations perhaps do not contribute [12-14]. Figure 4.14 shows normalized excess base current plotted as a function of electron dose for all the three transistors.

As already pointed out, 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]. 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 [6]. The decrease in the minority carrier lifetime will be reflected on the degradation in the forward current gain of the transistor. Figures 4.15, 4.16 and 4.17 exhibit forward current gain as a function of V_{BE} for different accumulated electron dose and Figure 4.18 shows the degradation of forward current gain as a function of accumulated electron dose for all the three type of transistors.

The displacement damage factors for the all three transistors are calculated using the Messenger-Spratt equation (equation 3.3) by converting the accumulated electron dose into 8 MeV electron fluence (discussed in Section 3.3, Chapter 3) [12, 16-17]. Figure 4.19 shows the displacement damage factor as a function of accumulated electron dose.

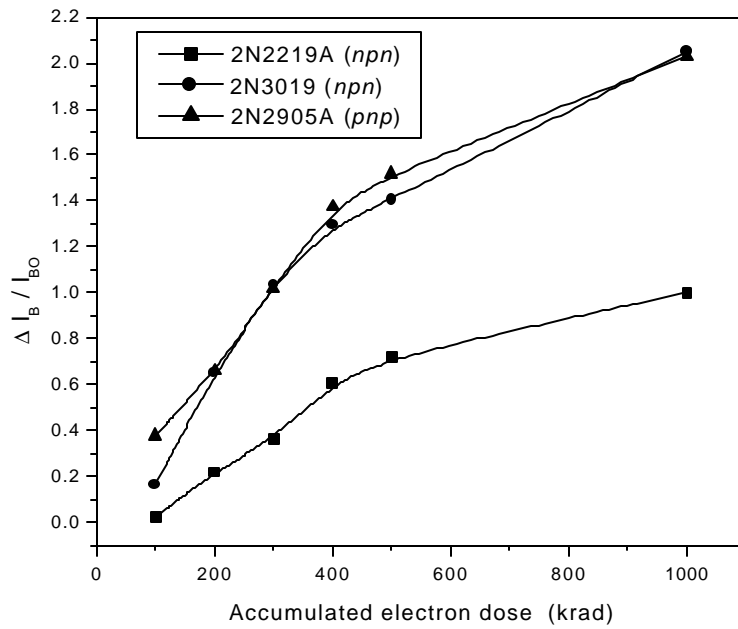


Figure 4.14 Normalized base current as function of accumulated electron dose. The lines are guide to the eye.

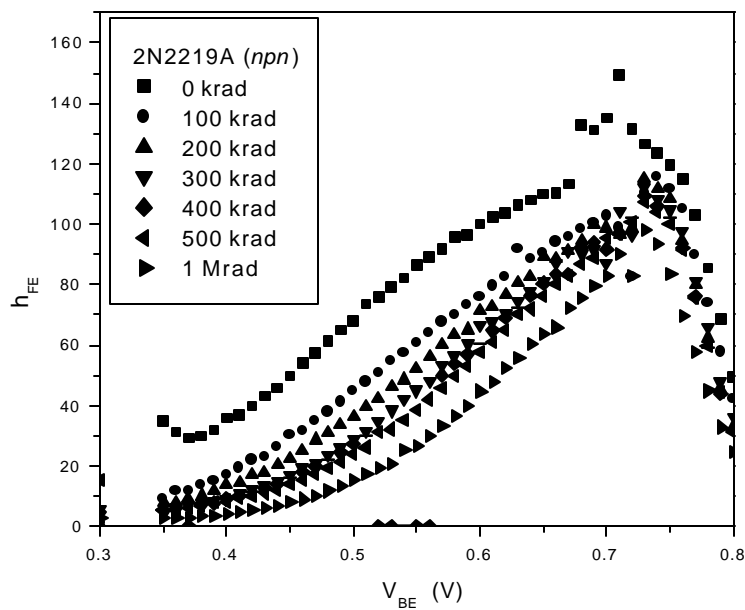


Figure 4.15 Forward current gain as a function of V_{BE} for different electron dose.

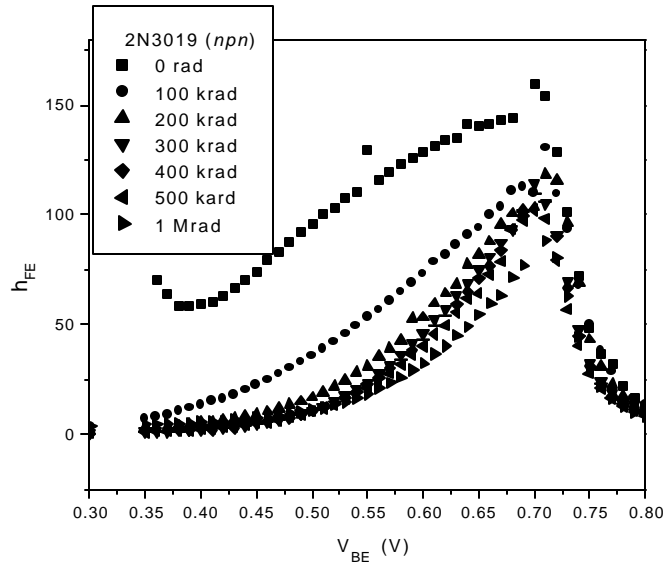


Figure 4.16 Forward current gain as a function of V_{BE} for different electron dose.

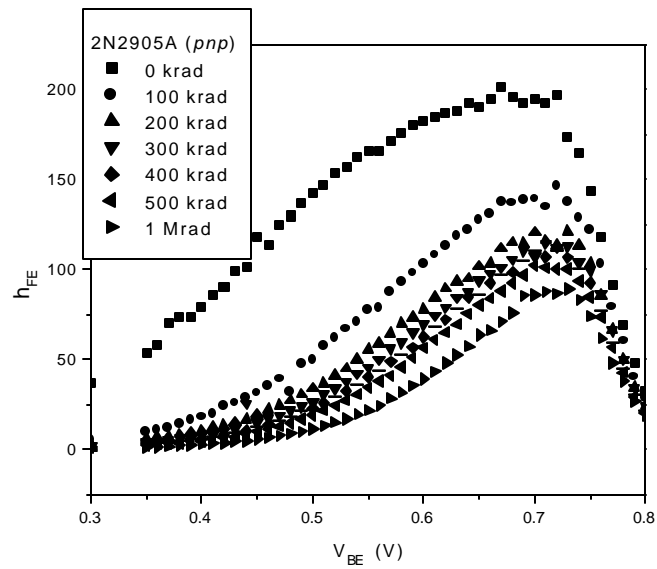


Figure 4.17 Forward current gain as a function of V_{BE} for different electron dose.

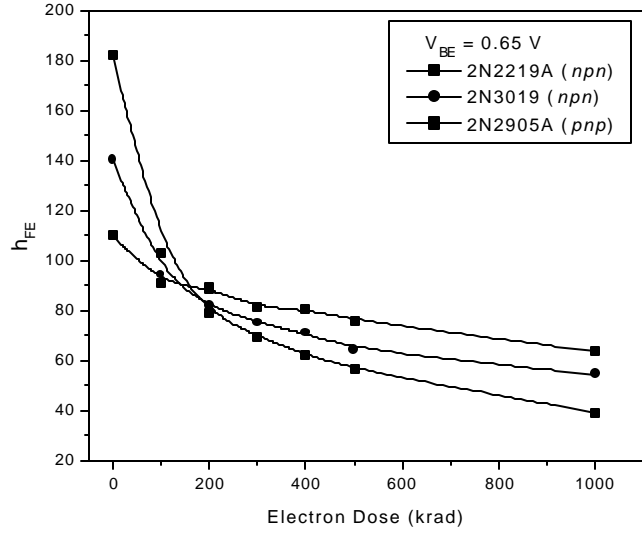


Figure 4.18 Forward current gain as a function of accumulated electron dose. The lines are guide to the eye.

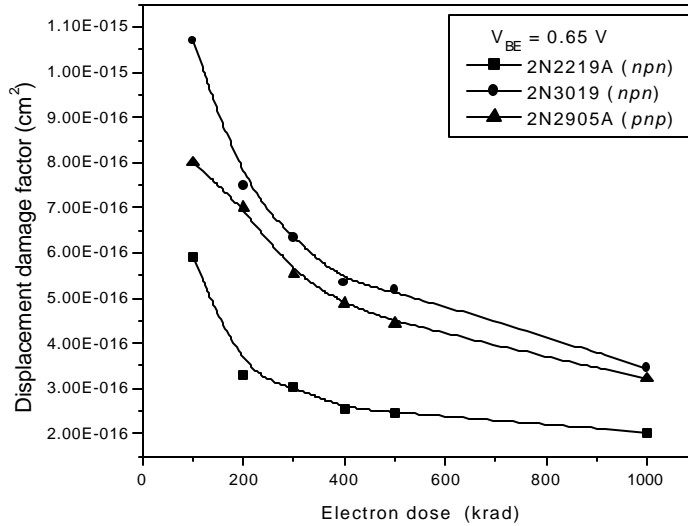


Figure 4.19 Displacement damage factor as a function accumulated electron dose. The lines are guide to the eye.

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 150⁰C for two hours are given in the Tables 4.1- 4.3. It is seen that exposure of the devices to electrons, results in considerable reduction in h_{FE} . When the irradiated devices are annealed at 150⁰ C for two hours, the gain of the transistors is found to recover only marginally. This suggests that the observed degradation of forward current gain of the transistor, when exposed to high-energy electron beam is permanent and do not anneal easily and is due to displacement damage produce in the bulk of the device.

Table 4.1 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 ⁰ C for 2 hours
h_{FE}	$V_{CE} = 10.0 \text{ V}$	$I_C = 0.10 \text{ mA}$	92.85	35.56	38.00
	$V_{CE} = 10.0 \text{ V}$	$I_C = 1.0 \text{ mA}$	107.8	58.03	60.35
	$V_{CE} = 10.0 \text{ V}$	$I_C = 10 \text{ mA}$	116.5	79.49	82.03
	$V_{CE} = 10.0 \text{ V}$	$I_C = 150 \text{ mA}$	111.9	88.28	90.68
	$V_{CE} = 10.0 \text{ V}$	$I_C = 500 \text{ mA}$	65.34	53.58	54.38

 Table 4.2 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 ⁰ C, for 2 hours
h_{FE}	$V_{CE} = 10.0 \text{ V}$	$I_C = 0.10 \text{ mA}$	116.8	16.82	16.86
	$V_{CE} = 10.0 \text{ V}$	$I_C = 1.0 \text{ mA}$	49.38	49.38	49.89
	$V_{CE} = 10.0 \text{ V}$	$I_C = 10.0 \text{ mA}$	62.11	62.11	62.53
	$V_{CE} = 10.0 \text{ V}$	$I_C = 150 \text{ mA}$	90.47	90.47	90.14
	$V_{CE} = 10.0 \text{ V}$	$I_C = 500 \text{ mA}$	75.31	75.31	76.12
	$V_{CE} = 10.0 \text{ V}$	$I_C = 1.0 \text{ A}$	29.52	29.52	30.53

 Table 4.3 TESEC measurement results of the transistor of the type 2N2905A (*pnp*).

Test Item	Biasing Conditions		Pre Irradiation	Post Irradiation 1 Mrad	Post-Irradiation, 1 Mrad, annealed at 150 ⁰ C, for 2 hours
h_{FE}	$V_{CE} = 10.0 \text{ V}$	$I_C = 0.10 \text{ mA}$	187.1	29.66	32.96
	$V_{CE} = 10.0 \text{ V}$	$I_C = 1.0 \text{ mA}$	200.6	54.37	56.03
	$V_{CE} = 10.0 \text{ V}$	$I_C = 10 \text{ mA}$	210.1	82.98	85.49
	$V_{CE} = 10.0 \text{ V}$	$I_C = 150 \text{ mA}$	176.6	88.28	90.98
	$V_{CE} = 10.0 \text{ V}$	$I_C = 500 \text{ mA}$	102.6	53.05	55.58

4.4 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. Thus as far as the radiation response is considered, the indigenous devices are in par with other devices of the same family. 8 MeV electrons induce current gain degradation by displacement damage in the bulk of the transistor. The displacement induced defect and recombination centers do not anneal even at 150⁰ C, so that the damage may be called permanent damage.

References

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