

Chapter 5

HIGH-ENERGY PROTON INDUCED EFFECTS ON BIPOLAR JUNCTION TRANSISTOR

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5.1 Introduction

Proton with a mass of about 1 amu (937 MeV) is heavier than electron. The interaction of proton with semiconductor material is different from that of γ -radiation. Interactions of energetic protons with silicon and the subsequent effects of proton bombardment on material and device properties have been treated by various workers. In general, protons interact with Si atoms by elastic and inelastic processes. The total elastic interaction process includes Rutherford (or coulomb) scattering and nuclear elastic scattering. Deviation from Rutherford scattering occurs when nuclear scattering becomes important. Both of these elastic processes can produce atomic displacements, although the nuclear elastic interaction is much more effective because, in this case, a larger amount of energy is transferred to a Si primary recoil atom by an incident proton [1]. The Si recoil atom subsequently loses its energy to ionization and displacement processes. Inelastic nuclear interactions are also important in silicon for proton energies greater than 10 MeV. Inelastic processes include all nuclear reactions except elastic scattering. Inelastic scattering (p, p^1) and alpha particle production (p, α) are examples of inelastic proton interaction [1]. Energetic recoils are produced by inelastic interaction, which give rise to displacement damage and ionization. Protons with energies below 500 MeV, the collisions produce displacements by Rutherford scattering, in which the Coulomb charge field of the proton and the nucleus interact to permit exchange of momentum and energy. The number of atoms displaced per centimeter by a proton in silicon is given by the following equation

$$\zeta_D(E) = \frac{964}{E_K} (9.43 + \ln E_K) \quad (5.1)$$

where E_K is the kinetic energy of the proton [2].

From the above equation, calculation predicts that a single 24 MeV proton can produce about 506 displaced atoms per cm. This displaced atoms lead to defect centers. However, proton produces displacement cascades of the order of three to eight per proton collision. There is a good probability that these vacancies will escape the damage centers and moves by thermal diffusion into the undamaged lattice and become trapped by impurity centers. Hence, proton damage is strongly dependent on impurity concentrations and the type of impurity.

Protons are the main constituent of space environment. Inner and outer Van Allen belts and cosmic radiation consists mainly of H-nuclei (protons) of various energy. At poles and south atlantic region, the population of the high energy protons is found to be very large. Energies of protons trapped in the geo-magnetic field range from 1 MeV to 800 MeV. However, the actual or observed spectrum of protons lie in the range 20-60 MeV [3-7]. In the past two decades, a great deal of interest has been generated in the study of proton induced effects in semiconductor devices and electronic systems. In 1993, the malfunctioning of one of the payloads of on board ERS-1 spacecraft was attributed to the failure in the memory device due to proton bombardment. In the Indian scenario also, some errors were detected in the normal functioning of the memory devices of IRS-1C remote sensing satellite launched by ISRO in 1995 [8]. High energy protons in the south

atlantic region was thought to be main source for causing single hard error of the memory devices. As a result, the study of proton induced effects in semiconductor devices has gained the attention of most researchers in this field. A large number of devices including BJT, MOS, CMOS, IC's and VLSI devices have been investigated for proton induced effects [1,8-13]. The bipolar junction transistors are particularly known to be vulnerable to protons and the transistor gain degradation is the primary cause for parametric shifts and functional failures of electronic systems [14]. Although there are many reports of proton-induced displacement damage leading to gain degradation in BJT, many of these are theoretical in nature and only a few reports are available on the actual measurement of dependence of gain as a function of accumulated proton fluence. One possible reason for this could be that proton beam is very hazardous and experiments with proton beam is rather difficult and cumbersome.

To understand the extent and nature of proton induced damage in indigenously made devices as compared to other devices of the same family, a study of proton induced effects in a BJT and MOSFET has been undertaken. In this chapter, the result of the effects of 24 MeV proton on collector characteristics and forward current gain of commercial bipolar junction transistor, 2N 2219A (*npn*) is described.

5.2 Experimental details

Commercial indigenous transistors of the type 2N2219A (*npn*) of Continental Device India Limited (CDIL) make have been exposed to 24 MeV proton beam (flux $\sim 10^9$ p/cm²/s and beam current ~ 1 nA) in the biased condition. Pelletron facility at Nuclear

Science Centre, New Delhi has been utilized for the purpose. As protons 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 proton beam [15-16]. During irradiation, V_{CE} was kept at 5V, the base current was fixed at 50 μA and the base emitter voltage V_{BE} was held at 0.65 V corresponding to the active region of the transistor. The collector current I_C was measured as a function of base current I_B for a fixed V_{CE} and the measurement of the collector characteristics were made as a function of accumulated dose immediately after the beam is turned off. To verify the reproducibility of the results, two transistors of the same batch (date code) were exposed and measurements were made. Both the devices give almost identical results. The results shown are for one of the transistor. Facility for obtaining Gummel plots was not available at NSC, New Delhi.

5.3 Results and discussion

Figure 5.1 shows the variation of collector current as a function of V_{CE} for different accumulated proton fluence. The variation in I_C as a function of I_B for different proton fluence for the transistor is also shown in Figure 5.2. The variation of I_B as a function of proton fluence for different collector current extracted from plots shown in Figure 5.2 is shown in Figure 5.3. The variation of h_{FE} (estimated for fixed value of I_C) as a function of accumulated proton fluence for the transistor is plotted in Figure 5.4. As can be seen from Figure 5.2, the collector current decreases substantially as the accumulated fluence increases. As a result, the forward current gain h_{FE} is observed to decrease considerably as the accumulated proton fluence increases. The h_{FE} degradation estimated at constant base current also exhibits similar behaviour.

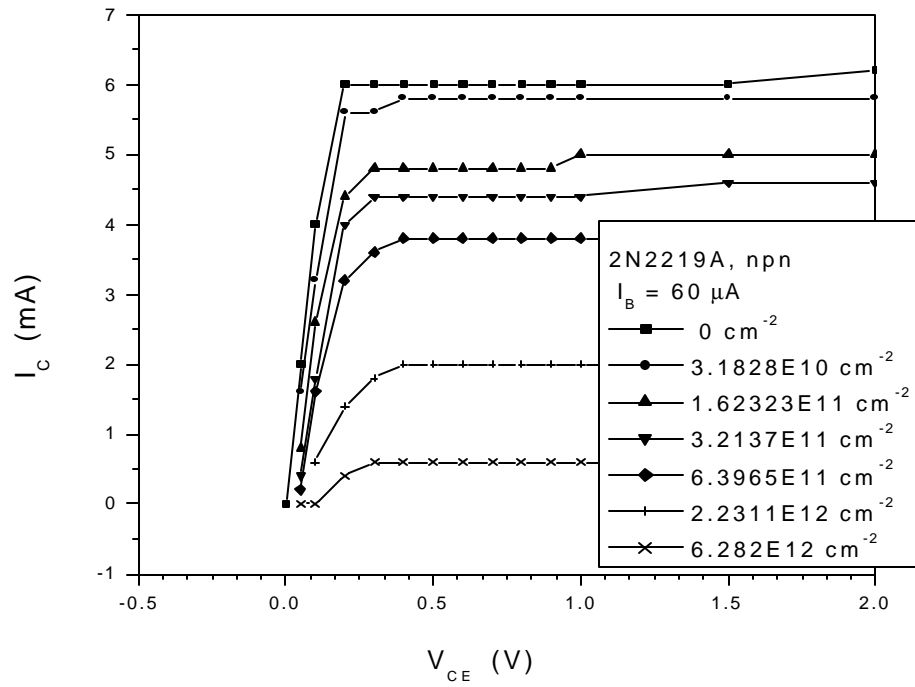


Figure 5.1 Collector current (I_C) as a function of collector emitter voltage (V_{CE}) for different proton fluence.

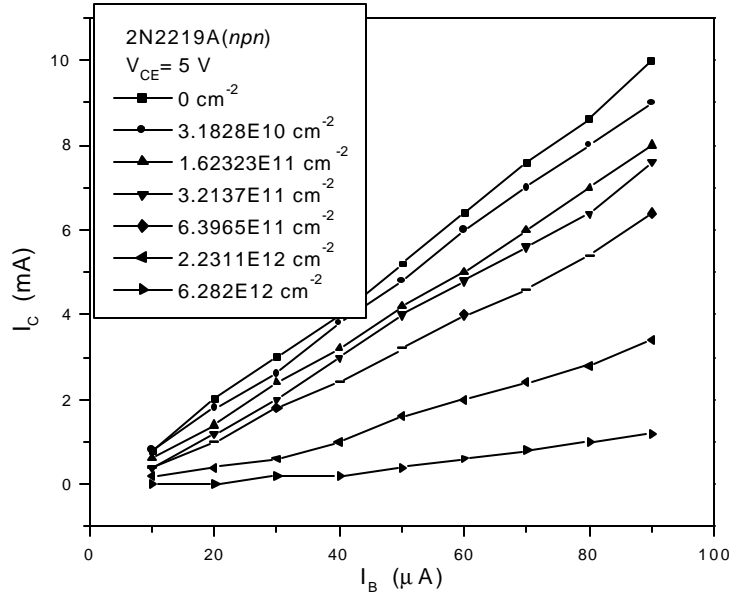


Figure 5.2 Collector current (I_C) as a function of base current (I_B) for different proton fluence.

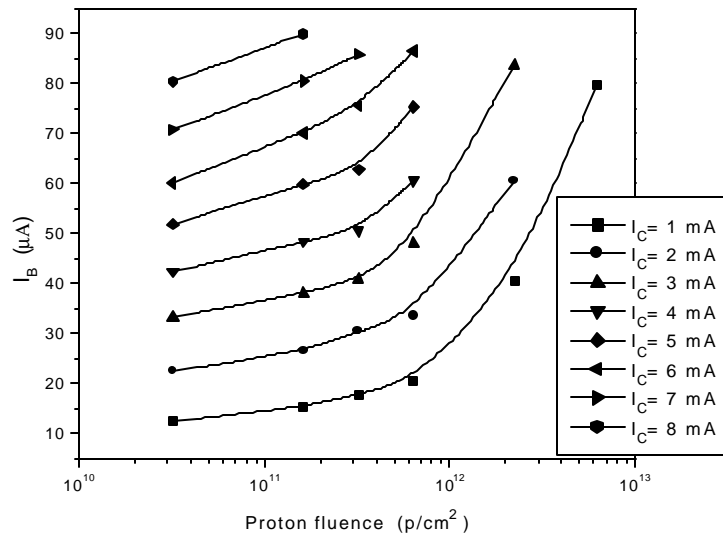


Figure 5.3 Base current (I_B) as a function of proton fluence for different collector current.

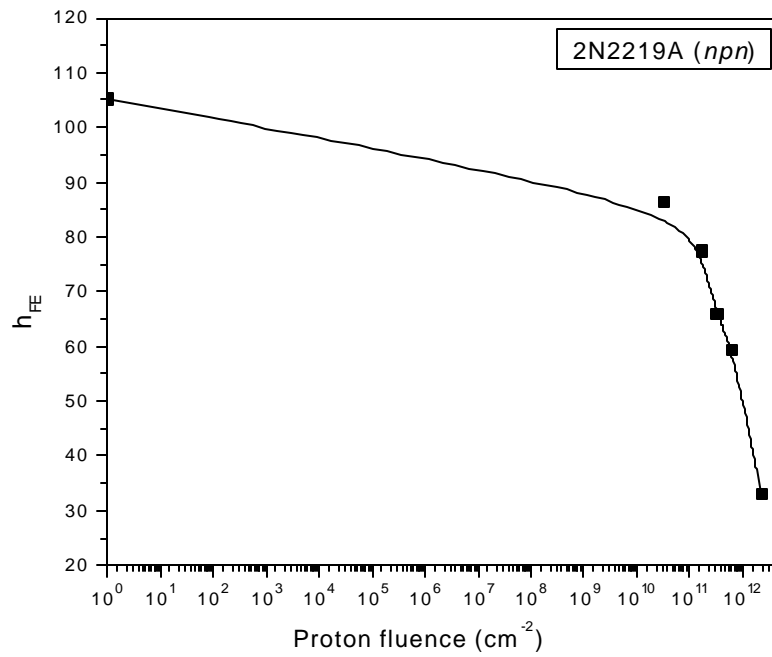


Figure 5.4 Forward current gain as a function of proton fluence.

There are two possible mechanisms responsible for causing gain degradation in discrete bipolar junction transistors namely, (1) Bulk degradation and (2) Degradation by ionization. At proton energy of 24 MeV, it appears that the bulk degradation is the dominant mechanism leading to gain degradation. Bulk degradation occurs due to atomic displacement in the bulk of the semiconductor when incoming energetic proton 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. Figure 5.3 shows that as the proton fluence increases the base current of the device also increases. In addition to recombination centers, displacement damage is also known to produce generation centers, trapping centers and scattering centers. Generation centers increases the reverse leakage current across the *pn* junction. Trapping centers remove charge carriers. Scattering centers decrease the mobility of charge carriers [5]. All these contribute to reduction in minority carrier lifetime and hence increase in the base current, leading to gain degradation [4].

In displacement damage produced by irradiation, when the incident particles collide with silicon nuclei, the process produces a spectrum of primary knock-on atoms (PKAs) and is dependent on the energy, mass and charge of the incident particle [17-19]. These PKAs in turn produce additional defects by further collision. Electron irradiation is known to produce primarily isolated defects or small grouping of defects [20]. On the other hand, in the high-energy proton and neutron cases, the PKAs further collide with other silicon atoms in the lattice producing secondary PKAs and vacancy interstitial pairs. Although

many of the vacancy interstitial pairs are known to recombine, the surviving ones migrate through the lattice and ultimately form stable defects with energy levels lying in the band gap of the silicon. Recombination of electron-hole pairs at these sites reduces the minority carrier lifetimes [4]. Displacement damage reduces the forward current gain (dc) by shortening the minority carrier lifetime. The reduction in h_{FE} with incident particle fluence can be analysed using the Messenger Spratt equation (equation 3.3, Chapter 3).

Customarily, the reciprocal gain is plotted as a function of particle fluence by measuring h_{FE} at a constant I_C . The above equation predicts a linear increase of $1/h_{FE}$ with particle fluence. However, nonlinearities are observed many times due to ionization effects in the oxide layer located close to the active device region. It is clear from Figure 5.4 that there is rather small change in h_{FE} below particle fluence of about 10^{10} p cm⁻². A theoretical fit of the data to Messenger Spratt equation is made for particle fluence greater than 10^{10} p cm⁻² (Figure 5.5). The value of k estimated from the above equation is 1.4×10^{-14} cm² for the transistor and agrees with the values reported earlier [17-20]. A displacement damage factor of the same order has been observed in similar family of transistors (2N 2222A and 2N 2907A) [18-19].

Apart from in-situ measurements of electrical characteristics, off-line measurement of forward current gain of the transistor is carried out using the TESEC transistor tester unit. The h_{FE} of the devices are measured at different biasing conditions. 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 Table 5.1. As can be seen from table, the reduction in h_{FE} due to

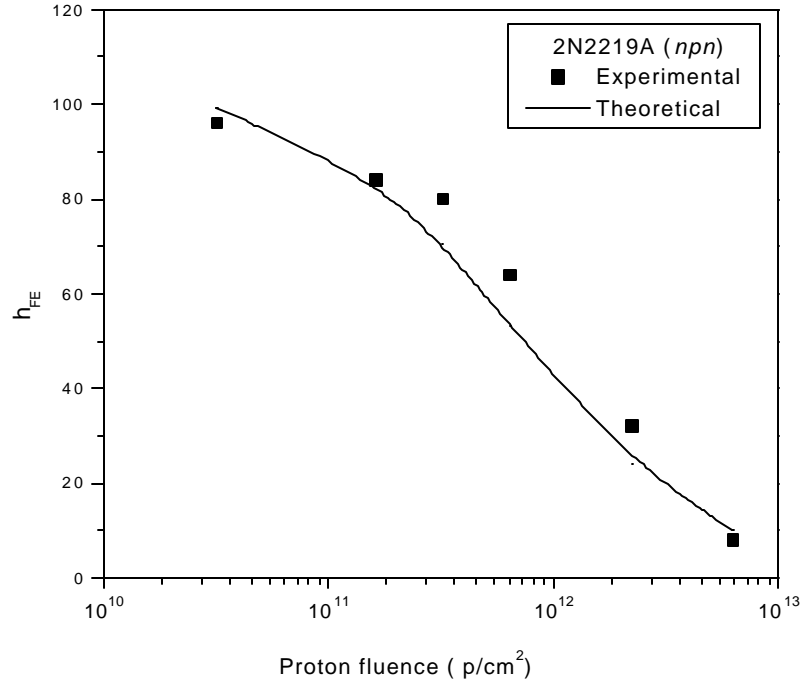


Figure 5.5 Forward current gain as a function of proton fluence (Solid line represents the theoretical fit to Messenger-Spratt equation).

Table 5.1 TESEC measurement results of the transistor of the type 2N2219A (*npn*).

Test Item	Biasing Conditions		Pre-Irradiated	Post-Irradiated (Fluence = 6.28×10^{12} p/cm^2)	Post-Irradiated (Fluence = 6.28×10^{12} p/cm^2) annealed at $150^{\circ}C$, for 2 hours
h_{FE}	$V_{CE} = 10.0$ V	$I_C = 0.10$ mA	80.00	8.888	8.900
	$V_{CE} = 10.0$ V	$I_C = 1.00$ mA	100.0	15.12	15.19
	$V_{CE} = 10.0$ V	$I_C = 10.0$ mA	113.9	25.92	26.00
	$V_{CE} = 10.0$ V	$I_C = 150$ mA	110.3	39.83	39.93
	$V_{CE} = 10.0$ V	$I_C = 500$ mA	64.64	24.09	24.29

proton irradiation is much more than that due to γ -ray or electron irradiation. There is no recovery of forward current gain observed after thermal annealing of the device. This would indicate that the gain degradation due to displacement damage is a permanent effect and can not easily be removed by thermal annealing. The result also clearly indicates that the bulk damage is a dominant process contributing to the gain degradation in the device.

Study of proton induced effects on the electrical characteristics of a *pn*p transistor, 2N2905A was also undertaken. However, it was observed that the *pn*p transistor forward current gain did not degrade much even after accumulated proton fluence of 10^{13} p/cm². These anomalous results were unexpected and questioned by a referee. It is expected that the *pn*p transistor should also degrade as much as the *np*n transistor. After careful thought and experimentation it was inferred that some experimental artifact must have been responsible for this. For example, proton beam not being ON during this study or (ii) beam could have been blocked by a filter or (iii) the target board and hence the device moved away from the beam and the positioning of the device die got shifted. As pointed out in Chapter 2, entry to beam hall during irradiation is not possible. So a camera was focussed on the target and the positioning of the device was continuously being monitored and observed remotely on a television set (Black and White). However, due to little instability of the beam and poor picture quality of the close circuit monitoring arrangement, it was not possible to decide conclusively whether the proton beam was bombarding the target device continuously. Thus, the results on *pn*p transistor are

inconclusive and due to limited beam time available to us it was also not possible to repeat this measurement.

5.4 Conclusion

The forward current gain of the investigated commercial BJT degrades considerably due to intermediate energy (24 MeV) proton irradiation. The gain degradation occurs most likely due to displacement damage produced in the bulk of the semiconductor. Further, the observed gain degradation is a permanent effect and does not recover after thermal annealing. The displacement damage constant is higher for proton irradiation than for γ -ray and electron irradiation.

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