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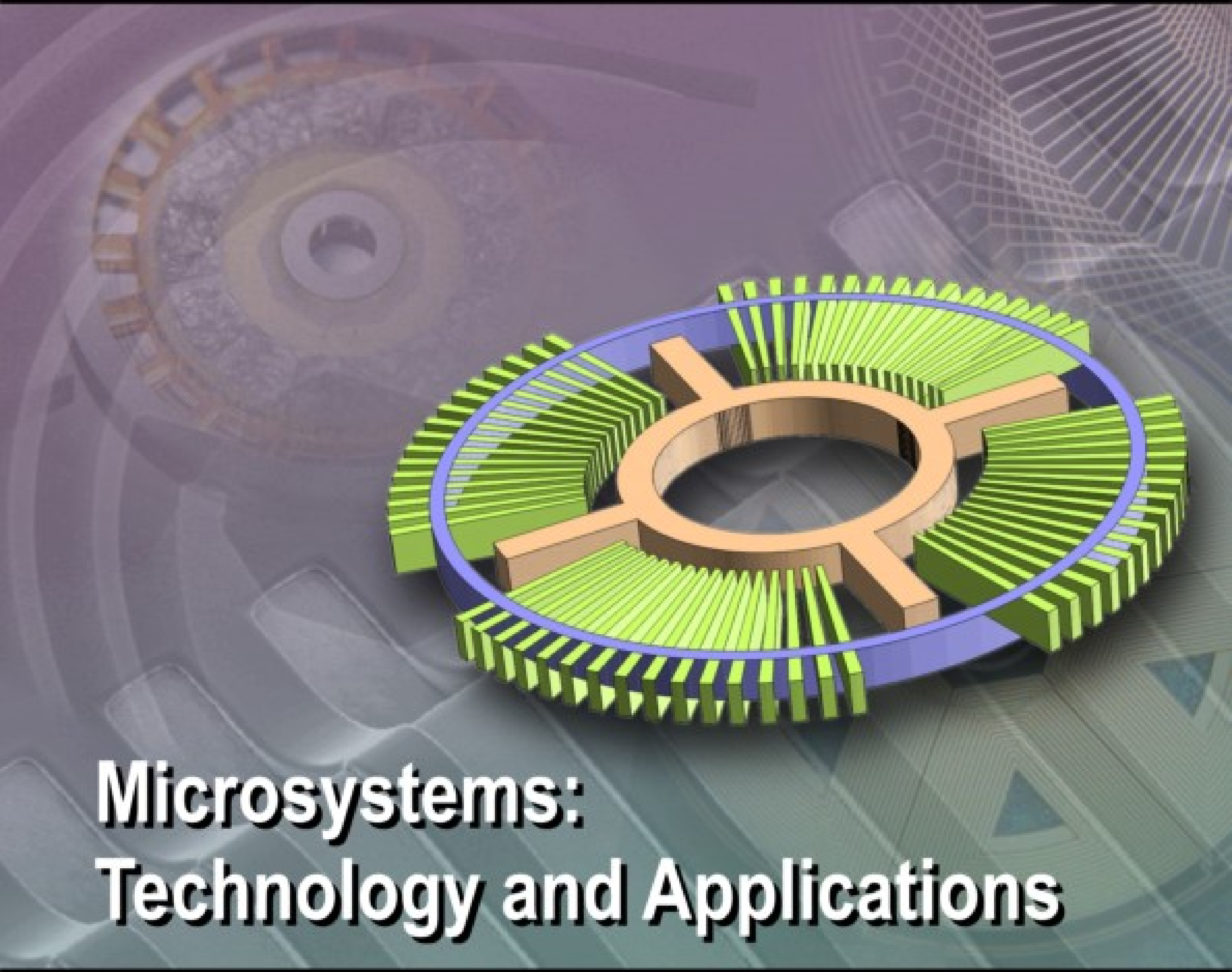

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Contribution of NIEL for Gain Degradation (β) in Si^{8+} Ion Irradiated Silicon Power Transistor

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Abstract: The concept of non-ionizing energy loss (NIEL) has been found useful for characterizing displacement damage defects in materials and devices. When NPN power transistors (2N6688 manufactured by BEL, India) are exposed for 110 MeV Si^{8+} ion irradiation in the fluence range 5 x 10^{9} to 1 x 10^{13} ions cm^{-2} at room temperature (300 K) and at liquid nitrogen temperature (77 K) cause functional failure due to surface and bulk defects. The output collector characteristics are studied as a function of total ionizing dose (TID) and total displacement damage dose (D_d) obtained using TRIM Monte Carlo code. It is observed that the shift in the output saturation voltage is considerably less for heavy ion irradiation compared to lighter ions like lithium ion irradiation. The gain of the transistor degrades with ion irradiation. Base reverse biased leakage current (BRBLC) increases with increase in ion fluence. The observed results are almost independent of the irradiation temperature. These studies help to improve the device fabrication technology to make Radiation Hard Devices for advanced applications. *Copyright © 2008 IFSA.*

Keywords: BJT, Irradiation, Defects, Junction, NIEL

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1. Introduction

In recent years, for semiconductors, attempts have been made to establish a correlation between the damage coefficients for different types of radiations. Furthermore, as a part of space technology mission, the irradiation effects of protons and heavy ions on different types of semiconductor devices have been investigated. The energy deposited by swift ions through the process of nuclear collisions has been used for tailoring the switching characteristics of silicon devices [1]. NPN transistors are being extensively used in space and radiation rich environments [2–7]. A number of researchers have extensively investigated and reported the radiation effect of high energy proton, neutron, electron and gamma-ray on semiconductor devices. However, only little literature is available on the effect of high energy heavy ion irradiation on bipolar junction transistors (BJT). BJTs have important applications in analog and mixed – signal ICs and bipolar complementary metal oxide semiconductor (BICMOS) circuits because of their current drive capacity, linearity and excellent matching characteristics [2]. Victor A.J. et. al. have studied the correlation of displacement effects produced by electrons, protons, and neutrons in silicon [8]. The degree to which displacement effects may be correlated in order to predict semiconductor device response based on response data to another type of radiation have been discussed in their study. Burke E. A. has studied the energy dependence of proton-induced displacement damage in silicon [9]. He has reviewed the calculations of non-ionizing energy deposition in silicon as a function of proton energy and has made measurements of displacement damage factors for bipolar transistors. Summers G.P. et. al, have measured displacement damage factors as a function of collector current for proton irradiation of switching and power transistors [10].

The aim of this work is to study the effect of 110 MeV Si^{8+} ion irradiation on the electrical behavior of commercial BJT. An attempt is made to explain the radiation induced degradation based on linear energy transfer (LET), total ionizing dose (TID), displacement damage (D_d).

2. Device

The device examined here is silicon NPN power transistor (2N6688) manufactured by Bharath Electronics Limited (BEL), INDIA. It is one of the Switch Max series of silicon NPN power transistor with feature high-voltage capability, fast switching speeds and low saturation voltages, together with high safe-operating-area (SOA) ratings. It is specifically designed for converters, inverters, pulse-width-modulated regulators and variety of power switching circuits. The device specifications are as in Table 1. A cross section of these devices is shown in Fig. 1.

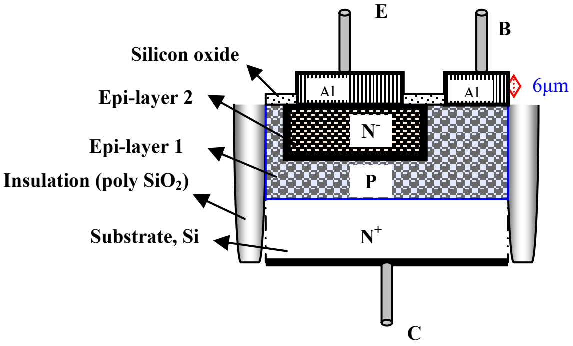

Fig. 1. Representative cross section of the device studied in this work.

Table 1. Device specification.

Device Code	2N6688
Structure	Si <111 > $N^-/N/N^+$
Doping Substrate	Sb/525 μm / 0.01 – 0.02 Ω - cm
Dopents	P (epilayer1) 32.370 μm / 2.820 Ω-cm P (epilayer2) 34.970 μm/26.630 Ω-cm
Application	Amplification and Power Switching

3. Experimental

The transistor is irradiated by 110 MeV Si^{8+} ion beam using 15 UD, 16 MV Tandem accelerator facility [13], available at Inter University Accelerator Centre (IUAC), New Delhi, India. The irradiation is performed in Material Science (MS) beam chamber having a typical pressure of 8×10^{-9} torr. The decapped transistor is mounted on a vertical metal ladder enabling direct exposure of chip to the beam, which avoids the energy loss in the protective metal cap. The irradiation is performed at two different temperatures. One set of transistors are irradiated at room temperature (300 K) and another set of devices are irradiated at liquid nitrogen temperature (77 K). The low temperature for irradiation is obtained by filling hollow target ladder with liquid nitrogen, after confirming the temperature at the device end. During irradiation all the terminals of the transistor are grounded. The fluence is varied from 5×10^{9} to 1×10^{13} ions cm^{-2}. To avoid heating effect the beam current (measured by a Faraday cup at a relatively large distance before the actual target assembly) is maintained at 0.3 and 3 pnA [1 pnA (particle nano ampere) = 6.25×10^{8} particles/cm^2/s]. A beam spot of 2 mm × 2 mm is scanned over 12 mm × 12 mm area using a magnetic scanner to irradiate the device uniformly. For the present experiment at each temperature, five different devices were used from the same batch of manufacturing.

I_C-V_{CE} characteristics are performed using Keithley – 2400 source meters together with computer interface before and after the irradiation. The I_C-V_{CE} characteristic curve of a transistor is a plot of collector current, I_C versus collector-emitter voltage, V_{CE} at constant base current (I_B = 50 μA). The I_C of unirradiated and irradiated transistor has been measured by varying V_{CE} from 0.0 to 2.0 V (step size of 0.02V) for different I_B from 0 to 150 μA in steps of 50 μA. From these characteristic curves, excess base current, $I_{Bexcess}$ the collector saturation current, I_{Csat} and the corresponding collector-emitter saturation voltage, V_{CEsat} for various fluences are obtained. Gummel plots are acquired by sweeping the base-emitter voltage from 0 V to 0.6 V in steps of 0.01 V at constant collector voltage of 2 V. Base reverse bias leakage current characteristics of the transistor device is obtained with the collector shorted to ground.

The excess base current is used to characterize the irradiation effect, is extracted from I-V curves mentioned above. To correct the temperature influence on the base current after irradiation $I_{Bpostrad}$, the measured base current, $I_{Bmeasured}$ was normalized by the postrad to the prerad collector current ratio [1]

$$I_{Bpostrad} = \frac{I_{Bmeasured} \times I_{Cprerad}}{I_{Cpostrad}} \tag{1}$$

the excess base current was then normalized with its prerad value according to the equation

$$ExcessI_{B} = \frac{I_{Bpostrad} - I_{Bprerad}}{I_{Bprerad}}\ , \tag{2}$$

where $I_{Bprerad}$ is the base current value before irradiation.

4. Results and Discussions

4.1. Effects of Ion-irradiation

While passing through a semiconductor, high energy heavy ions deposit a large fraction of energy by the process of ionization and excitation of electrons, S_e and small fraction through elastic collisions with the medium atoms, S_n. The lattice atoms of the medium are dislodged mostly through the phenomenon of nuclear energy loss. However, recent studies indicate that the energy deposited through S_e can also induce defects in the surface region of the semiconductor.

To understand the degradation in 110 MeV Si^{8+} ion irradiated transistor, it is important to analyze the effect of irradiation on device structure and the role of the associated energy loss mechanism. The elastic collisions with the nuclei known as nuclear energy loss S_n, dominates at an energy of about 1 keV/ amu; and inelastic collisions of the highly charged projectile ion with the atomic electrons of the matter known as electronic energy loss S_e, dominates at an energy of about 1 MeV/amu or more. In the inelastic collision (cross-section $\sim 10^{-16}$ cm^2) the energy is transferred from the projectile to the atoms through excitation and ionization of the surrounding electrons. The amount of electronic energy loss in each collision varies from tens of eV to a few keV per Angstrom [11]. The nuclear energy loss of 110 MeV Si^{8+} ion is much smaller than the electronic energy loss (3 order of magnitude, Table. 2) in a Si-target material due to smaller elastic scattering cross-section. Therefore the maximum energy deposited to the material is expected mainly due to the electronic energy loss during its passage through the Si-material [3]. The device suffers non-uniform irradiation effects as the projected ion range (39.46 μm) (Table 2) is lower than the device thickness (~600 μm) and it expected to implant at base-collector region (Table 1). The damage caused due to the linear energy transfer [LET = $S_e + S_n \sim 10.2177$ MeV/ (mg/cm^2)] in the Si target is obtained using TRIM calculations [12]. SRIM includes a comprehensive Monte Carlo program called transport of ions in matter (TRIM), which provides a detailed treatment of ion damage cascades and the ion distribution within the target. This can give us a quantitative estimate of the damage on the layer structure of the transistor. NIEL is the rate at which energy is lost to non-ionizing events (energy per unit length) [13]. In the present work the procedure established by our earlier work [7] is followed to calculate defects induced in silicon transistor. The results obtained are tabulated in Table 2.

Table 2. SRIM simulated results for 110 MeV Si ion irradiation for silicon target.

Name			Value	
Range, R (μm)			39.62	
S_e	(MeV cm^2/mg)		10.21	
S_n	(MeV cm^2/mg)		7.698×10^{-03}	
Displacement energy of Si (eV)			15	
Binding energy of Si (eV)			2	
Surface binding energy of Si (eV)			4.7	
Average Displacements/ion			9925.7	
Average Replacements/ion			773.5	
Average Vacancies/ion			9152.2	
NIEL up to R (MeV cm^2/g)			42.67	
Fluence (ions/cm^2)	5x10^9	1x10^{11}	1x10^{12}	1x10^{13}
TID (rad)	0.8174	16.348	163.482	1634.82
D_d (rad)	3143.4	68268	6.8268×10^5	6.8268×10^6

Most of the studies so far have indicated that the impact of displacement damage is marginal compared with the total dose effect. However, it has been shown that total – dose irradiation may indirectly affect the silicon substrate by reducing the active p-type base dopant concentration.

4.2. I-V Measurements

Figures 2, 3 show the variation of base and collector current as a function of base-emitter voltage (forward Gummel plots) before and after exposure to various fluences of 110 MeV Si^{+8} ion at two different temperatures. From Fig. 2, it is clear that with increase in ion fluence the base current enhances. The enhanced I_B is related to an increase in the surface recombination velocity, as the density of electron and holes is comparable, due to base neutralization. It has in addition been observed that the collector current increases, resulting from a higher emitter injection efficiency. This is again related to the reduction of the base doping concentration after exposure. In BJTs the excess base current depends on number of interface traps (recombination centers) near midgap. The excess base current due to changes in surface potential depends on the total radiation-induced oxide charge and the base condition. At higher total doses, sufficient charge has been accumulated in the oxide to cause significant recombination to occur through-out the lightly dopped base region. Once this condition occurs, the excess base current is proportional to the total area. The increase in base current with dose is relatively small. J. Boch et. al., reported that the effect of high-temperature irradiation on commercial bipolar transistors, where the irradiation was performed at temperatures ranging from 300 K to 443 K. The observed results are enhancement of the degradation with both the irradiation temperature and dose-rate [14].

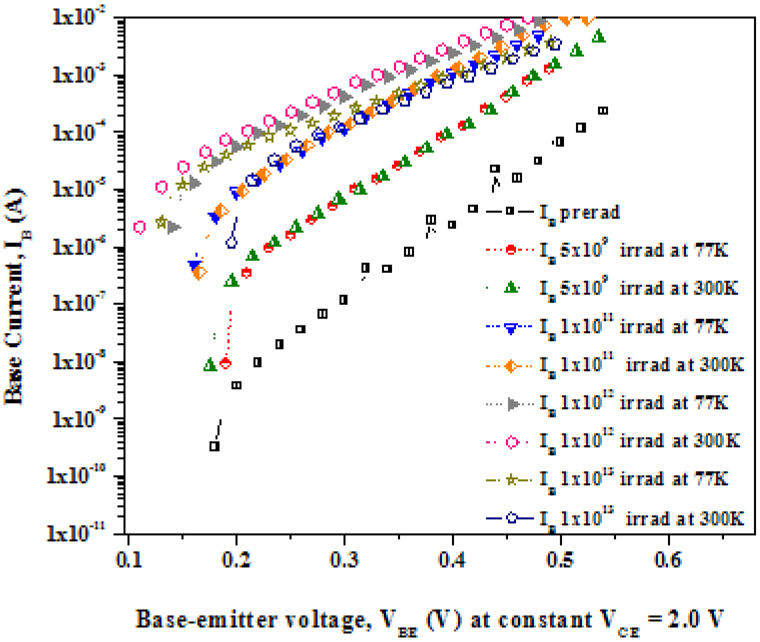

Fig. 2. Variation of I_B with V_{BE} for different ion fluences (at constant V_{CE} = 2 V) for the transistor irradiated by 110 MeV Si^{8+} ions at 77 and at 300K.

D. Zupac et.al., reported the effect of radiation induced interface-trapped charge and oxide-trapped charge on the inversion-layer hole mobility in p-channel double-diffused metal-oxide-semiconductor transistors at 300 K and 77 K. The mobility degradation is more pronounced at 77 K than at 300 K, due to an increased Coulomb scattering from trapped charge when phonon scattering is significantly reduced [15]. In the present work of 110 MeV Si^{+8} ion irradiation, the base and collector current increase with dose is almost independent of irradiation temperature except at highest fluence.

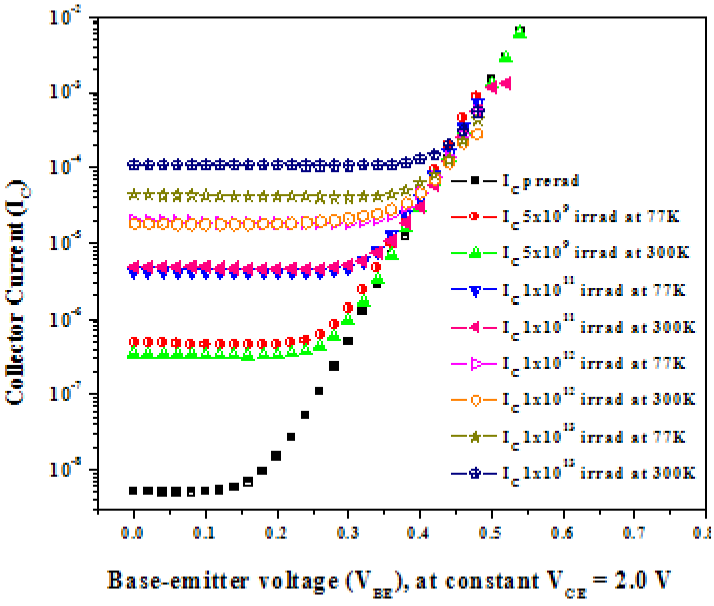

Fig. 3. Variation of I_C with V_{BE} for different ion fluences (at constant V_{CE} = 2 V) for the transistor irradiated by 110 MeV Si^{8+} ions at 77 K and at 300 K.

The 110 MeV Si^{8+} ions produce defects like vacancies, displacements (simulated values are listed in Table 2) and di-vacancies in collector region which reduces the minority carrier lifetime. A decrease in the minority carrier lifetime will be reflected in the degradation of forward current gain of the transistor [6-8]. The variation of gain (β) normalized to pre-irradiation gain (β_0) (at V_{BE} = 0.5 V) value as a function of fluence at 300 K and at 77 K is as shown in Fig. 4. From figure it is clear that the gain of the device decreases as dose increases. Gain degradation in irradiated bipolar transistor is a significant problem, for linear integrated circuits. Understanding the mechanisms responsible for radiation-induced gain degradation in bipolar transistors is important in developing appropriate hardness assurance methods.

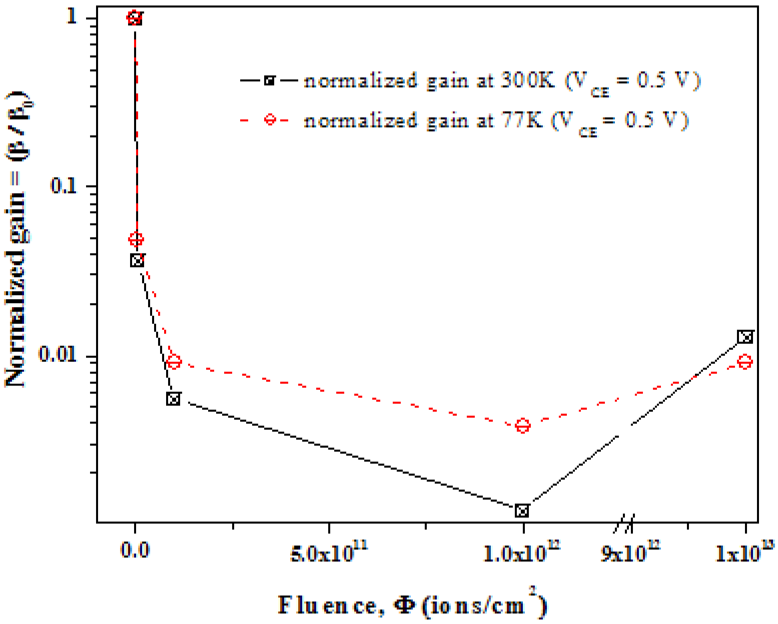

Fig. 4. Relationship between current gain (β) normalized to pre-irradiation gain (β_0) (V_{BE} = 0.5 V) value and fluence of ion irradiation.

In most bipolar technologies that are used in linear integrated circuits, the total-dose failure mechanism is reduction of the current gain. The lattice damage degrades the electrical characteristics of BJTs by increasing number of trapping, scattering and recombination centers. The trapping centers remove carriers from the conduction process. n^- and p^- type silicon gradually changes towards intrinsic material with the increase of radiation exposure [16 – 18]. Hence the observed degradation may be possibly due to the displacement damage (simulated D_d is listed in the Table 2 for various fluences).

Fig. 5. shows the output I_C –V_{CE} characteristic curve for unirradiated and for the silicon ion irradiated transistor for various fluence varied at two different irradiation temperatures at constant I_B (I_B = 50 μA). From figure it is clear that the output collector current of the irradiated transistor reduces to almost negligible value at a total fluence of 1×10^{13} ions cm^{-2}. It is also observed that there is a decrease in I_{Csat} with increase in fluence. The decrease in I_{Csat} is mainly due to the production of Si ion induced displacements, vacancies and interstitials (defects listed in Table 2). These MeV ion induced defects reduce the minority carrier lifetime and are responsible for the increase in series resistance in turn in the shift of I_{Csat} and V_{CEsat}.

Table 2 shows fluence dependent total ionizing dose (TID) and displacement damage (D_d). The total ionizing dose leads to the degradation of the transistor, which is due to the increase in recombination of emitter-base region. The TID is mainly dependent on LET of the MeV ion in the target; hence electronic excitations contribution is more compared to nuclear displacements by 3 orders of magnitude. The displacement damage, D_d contribution is more compared to TID by a factor of 5. This may be a considerable factor at higher fluence range for the semiconductor devices.

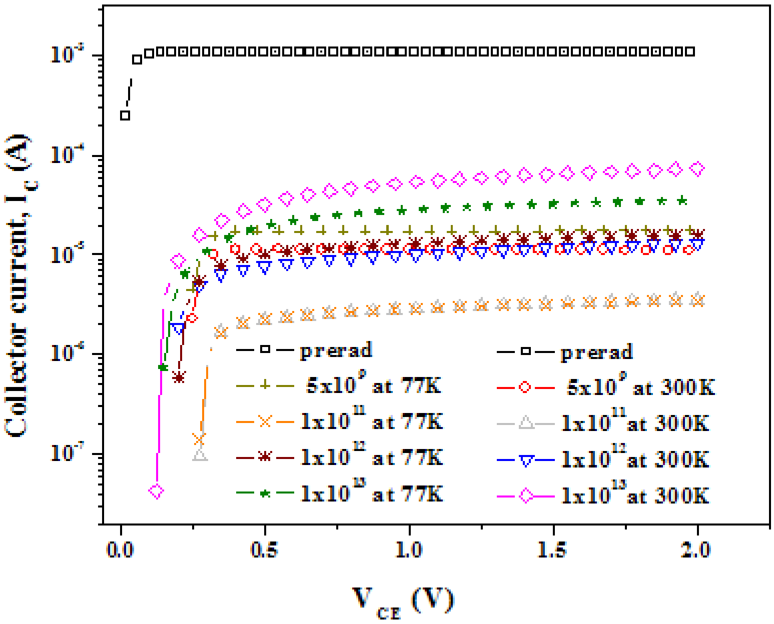

Fig. 5. The output collector current characteristic curves at I_B = 50 μA before and after 110 MeV Si^{8+} ion irradiation at 77 K and at 300 K.

The displacement damage increases the recombination in the neutral base region, which leads to the decrease in collector saturation current. It is found that the number of recombination centers produced in silicon is proportional to the energy going into atomic displacement process [2].

It is also observed from Fig. 6, the collector saturation current abruptly decreased with ion fluence of 5×10^{13} ions cm^{-2} and it remained constant with increase in fluence. From Fig. 7, the output saturation voltage V_{CEsat} increases from 0.1 to 0.6 V with the increase of the ion fluence. This shows that the BJT of the type in the present the study are found to be very sensitive to the ionizing radiation and transistor gain degradation is the primary cause for the parametric shifts and functional failures.

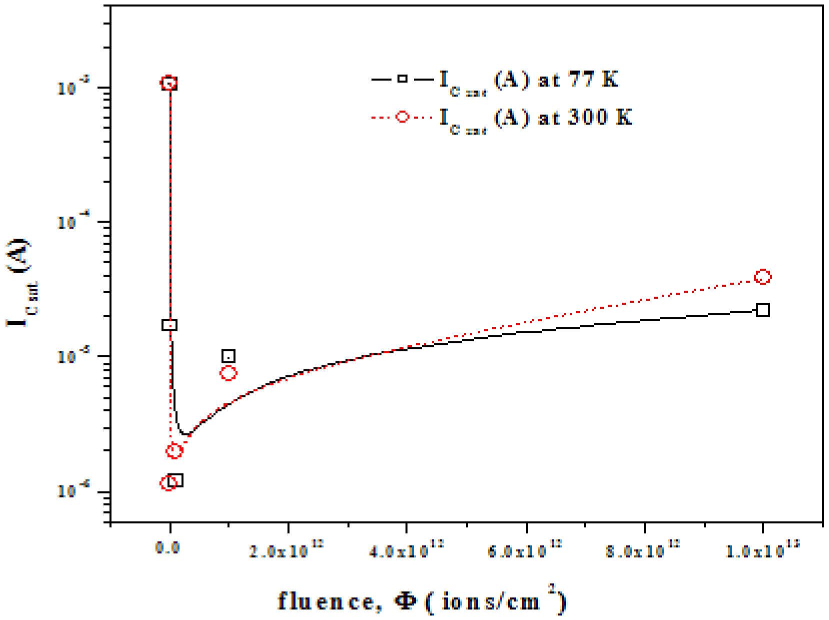

Fig. 6. Relationship between collector saturation current and fluence of ion irradiation for two irradiation temperatures (I_B = 50 µA constant).

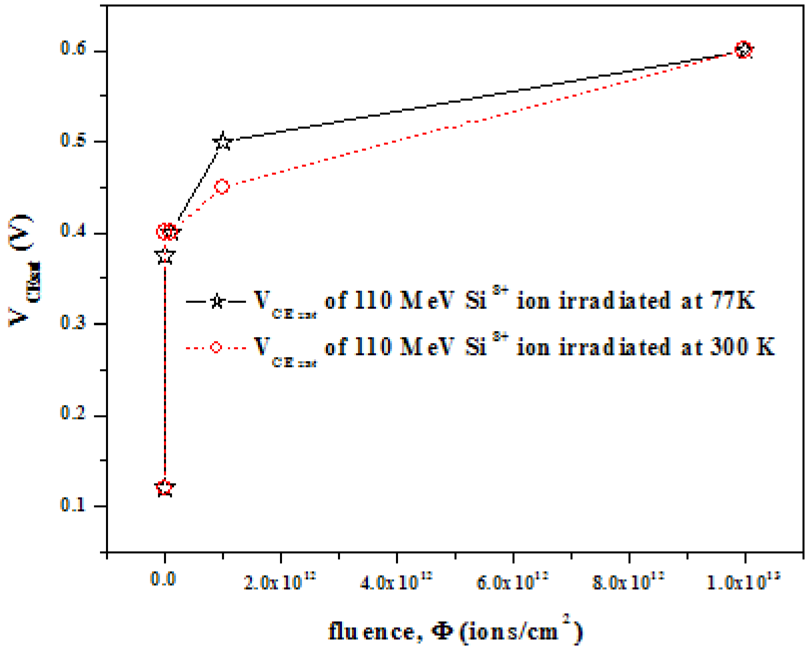

Fig. 7. Relationship between collector saturation voltage, V_{CEsat} and fluence of ion irradiation for two irradiation temperatures (I_B = 50 µA constant).

Fig. 8. shows un-irradiated and irradiated BRBLC characteristics for the transistor device at two different ion irradiation temperatures. The results presented in the figure clearly show the non monotonic variation in the leakage current at the two different irradiation temperatures. The observed

results may be possibly due to the radiation induced charge in the oxide and increased surface recombination velocity. The charge in the oxide increases the surface potential; causing the recombination rate near the emitter-base junction of NPN transistor to increase as the electron and hole concentrations becomes comparable [17].

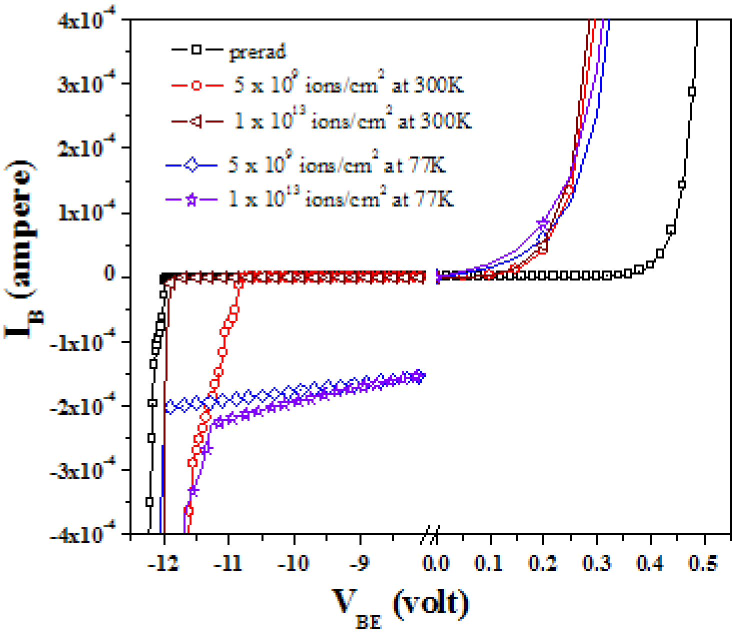

Fig. 8. BRBLC measured with the collector shorted to ground for 110 MeV Si^{+8} ion irradiated transistor at two fluences and at two different irradiation temperatures.

At low temperature, the reverse current of irradiated devices has increased considerably. These observed variations in the reverse breakdown voltage and the leakage currents are possibaly due the variation in their excess base and collector currents, which inturn depend on the number of interface traps (recombination centers) near midgap. The change in surface potential depends on the total radiation induced oxide charge and the biasing conditions. The switching time of the transistor decreases due to the decrease in forward breakdown voltage with increased leakage currents.

5. Conclusions

This work reports the effect of 110 MeV Si^{8+} ion irradiation on silicon NPN transistor device with fluences of 5 × 10^{9} ions cm^{-2} to 1 × 10^{13} ions cm^{-2}. An effort is made successfully to correlate the electrical degradation with non-ionizing energy deposition due to MeV ion irradiation using TRIM Monte Carlo Code. Fluence dependent TID and D_d is calculated for 110 MeV silicon ion in silicon target. The shift in collector saturation current and collector– emitter voltage is mainly due to the total displacement damage dose. In addition to these shifts, Si-ion irradiation causes increase in forward resistance of the collector–emitter region. Effect of irradiation on BRBLC characteristics of commercial bipolar junction transistor (2N6688) has been studied for different ion fluences. The shift in the breakdown voltage current do not vary monotonically with the ion fluence. At low temperature (77 K), the reverse current of irradiated devices has increased considerably. The switching time of the transistor decreases due to the decrease in forward breakdown voltage with increased leakage currents.

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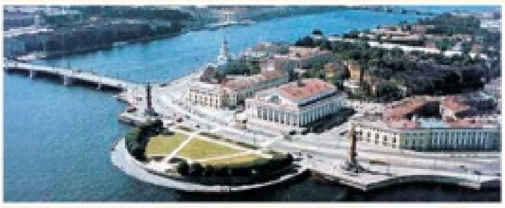

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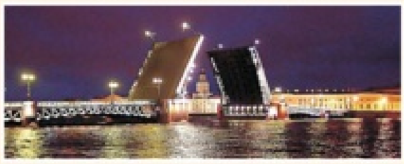

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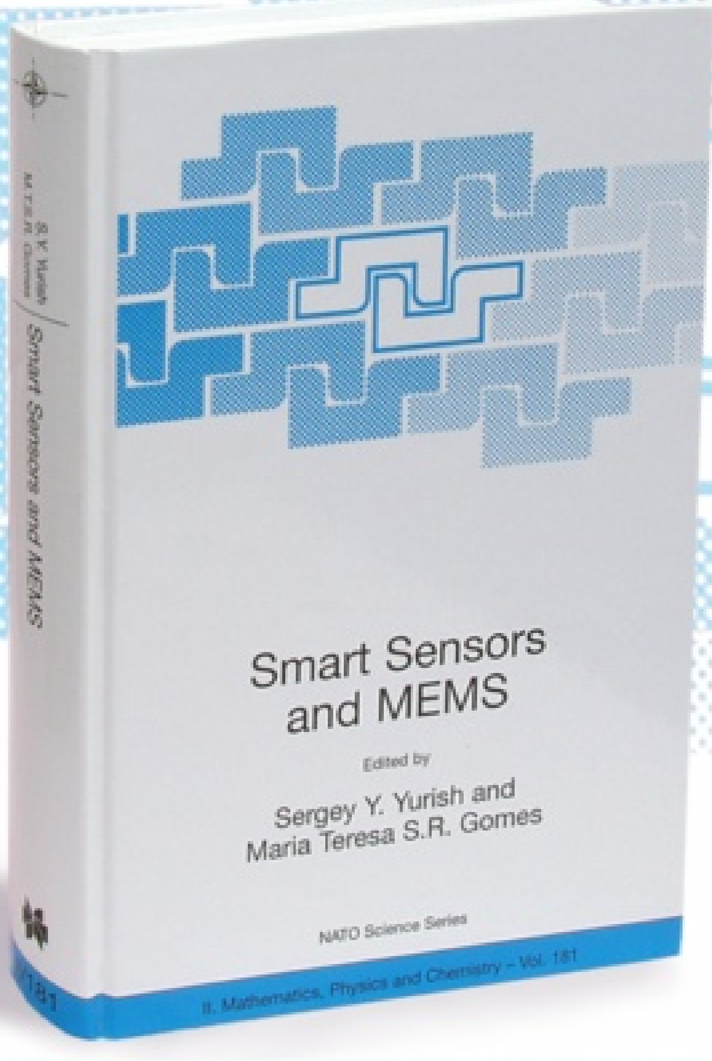

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