High Total Dose Proton and ^{60}Co Gamma Irradiation Effects on Silicon NPN RF Power Transistors

Bharathi. M. N[1], Pushpa. N[2], Praveen. K. C[1], Gnana Prakash. A. P[1*]

[1]*Department of Studies in Physics, University of Mysore, India-570006*
[2]*Department of PG Studies in Physics, JSS College, India-570025*

gnanaprakash@physics.uni-mysore.ac.in

***Abstract*— The effects of high total dose proton irradiation on silicon NPN *rf* power transistors were examined using 1 MeV and 3 MeV protons in the dose range of 100 krad to 100 Mrad. The SRIM simulation study was conducted to understand the energy loss and range of 1 MeV and 3 MeV protons in the transistor structure. The SRIM simulation was used to calculate ionizing dose (D_i) and displacement dose (D_d) of protons. The electrical characteristics such as Gummel characteristics, excess base current ($\Delta I_B = I_{Bpost} - I_{Bpre}$), dc current gain ($h_{FE}$) transconductance ($g_m$) and output characteristics were systematically studied before and after irradiation. The damage factor (K) was calculated using Messenger- Spratt relation. The significant degradation in current gain and other electrical parameters were observed after proton irradiation. The proton irradiation results are compared with ^{60}Co gamma irradiation results in the same dose range to understand the linear energy transfer (LET) effects on the electrical characteristics of the NPN transistors. The recovery in the I-V characteristics of the irradiated NPN transistor were studied by isochronal and isothermal annealing methods. Considerable recovery in the electrical characteristics of the irradiated transistors was observed after annealing.**

***Keywords*— BJT, proton irradiation, ^{60}Co gamma radiation, dc current gain, G/R trap centers, isochronal annealing**

I. Introduction

The bipolar junction transistors (BJTs) have major role in modern electronics applications such as BiCMOS (Bipolar Complementary Metal Oxide Semiconductor) circuits. The BJTs are the basic elements in the integrated circuits (ICs) that are being extensively employed in space, military and other radiation environments like large hadron colliders (LHCs) [1]. In space and planetary explorations, BJTs would be exposed to various types of radiations like gamma, high energy protons and electrons. In nuclear detonation environment the BJTs would be exposed to burst of transient radiations where the devices are exposed to high doses in a fraction of a second. In addition to space and nuclear detonation environment, BJTs are extensively used in high energy physics experiments like LHCs, where these devices are exposure to 100's of Mrad of total doses in their 5 year life time [2]-[3]. However, BJTs are sensitive to radiation and are prone to parametric or even functional damage on exposure to ionizing radiation. When Si BJTs are exposed to high energy radiation, trapped oxide charge and interface states accumulate in the oxides that lie over the surface of the intrinsic base, leading to an increase in surface recombination current in the emitter-base diode. Consequently, there is an increase in the base current of the device and the bipolar transistor suffers from a loss of dc current gain [4]-[6]. The high-energy radiation can also create different trap levels in the band gap of silicon which reduces the minority carrier lifetime and in turn degrades the current gain of the transistors [5]. Therefore in order to overcome this problem, electronic devices need to be 'radiation hardened' to use in extreme environment electronics. Development of hardness assurance test for these devices requires understanding of the mechanism which causes functional failure. The study of radiation effects on semiconductor devices is important to assess the performance of the devices in radiation rich environments. The ^{60}Co gamma and proton irradiation tests on BJTs are the conventional test methods to check the operating life time of the devices to work in radiation environment. With the proton irradiation, the irradiation time taken to reach a particular total dose is less when compared to ^{60}Co gamma irradiation facilities. Therefore it is very much essential to study the effects of different LET protons on the electrical characteristics of Si BJTs in the same dose levels to correlate with ^{60}Co gamma irradiation effects. Here, we present a comprehensive investigation of the effects of 1 MeV and 3 MeV proton irradiations on the electrical properties of silicon NPN *rf* power transistors. The electrical characteristics such as Gummel characteristics, excess base current ($\Delta I_B = I_{Bpost} - I_{Bpre}$), dc current gain ($h_{FE}$), transconductance ($g_m$) and output characteristics were systematically studied before and after irradiation. The ionizing dose 'D_i' and displacement dose 'D_d' of 1 MeV and 3 MeV proton were estimated from SRIM 2011 software and the ratio $D_d/(D_d+D_i)$ is calculated. An attempt is made to explain the radiation induced degradation based on these calculations. These results are compared with ^{60}Co gamma irradiation results in the same dose range to quantify the influence of proton irradiation on the various damage mechanisms in these devices. The recovery in the I-V characteristics of the irradiated BJTs were studied by annealing the irradiated transistors at 200°C up to 100 hrs (isothermal annealing) and by varying temperature from 50°C to 500°C (isochronal annealing).

II.EXPERIMENTAL

The semiconductor devices studied in the present investigation are silicon NPN overlay *rf* power transistors (2N 3866) manufactured by Bharath Electronics Limited (BEL), India. They are extensively used as high power gain drivers for VHF/UHF applications in military, space and communication equipments. The cross sectional view of the NPN transistor is shown in Fig. 1.

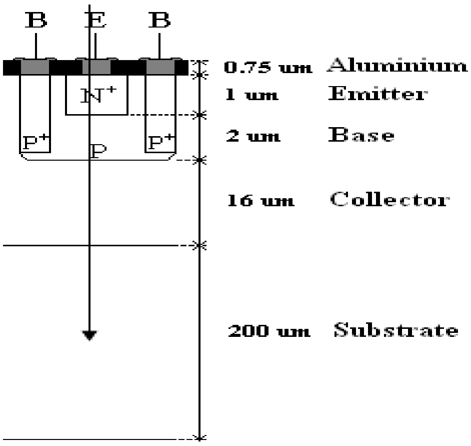

Fig. 1: Cross sectional view of the NPN transistor

This is an epitaxial silicon NPN transistor employing an advanced version of the RCA developed ‘overlay’ emitter electrode design. This electrode consists of sixteen isolated emitters connected together through the use of a diffused grid structure and a metal overlay which is deposited on a silicon dioxide (SiO_2) insulating layer by means of photo-etching technique. The device specification details of 2N 3866 NPN transistor are given below;

Device Specification

Emitter perimeter ≅ 2432 μm
Intrinsic base surface doping ≅ 1 x 10^{18} atoms/cm^3
Insulating oxide thickness ≅ 0.75 μm
Emitter (n^+) thickness ≅ 1 μm
Base (p^+) thickness ≅ 2 μm
Collector (n^-): Silicon <111> 2 Ω cm, 16 μm
Substrate (n^+): Silicon <111> 0.01 Ω cm, 200 μm

The decapped transistors were irradiated by 1 MeV and 3 MeV protons using 3 MV Pelletron accelerator facility available at Institute of Physics (IOP), Bhubaneshwar, India. The transistors were mounted on a vertical ladder enabling direct exposure of transistor to the proton beam. The proton beam current was maintained at 1 p-nA (particle-nano ampere). The fluence on the sample kept in cylindrical secondary electron suppressed geometry was estimated by integrating the total charge accumulated on the sample using a current integrator and then counting by a scalar meter. The proton beam was scanned over the samples in an area of 10 mm x 10 mm by a magnetic scanner in order to get a uniform dose. The NPN transistors are also irradiated by ^{60}Co gamma radiation using gamma chamber 1200 at Inter university accelerator centre (IUAC), New Delhi with the same dose range. The proton and gamma irradiation was performed at room temperature in the total dose ranging from 100 krad to 100 Mrad. The devices were characterized at room temperature before and after irradiation by using the computer interfaced Keithley dual source meter model 2636A. The irradiated transistors were characterized within 30 min after irradiation following MIL-STD 883H method 1019.8 to avoid any time dependent annealing which can potentially change the electrical effects due to damage formation. The electrical characteristics such as Gummel characteristics, excess base current, dc current gain (h_{FE}), transconductance and output characteristics were systematically studied before and after irradiation.

The Gummel characteristics is a combined plot of collector current (I_C) and base current (I_B) on logarithmic scale versus base emitter voltage (V_{BE}) in linear scale to directly measure the integrated base charge at constant collector emitter voltage [12]-[13]. The forward Gummel characteristics of unirradiated and irradiated transistors are obtained by sweeping the base-emitter voltage (V_{BE}) from 0 to 1 V, in step size of 0.01 V at constant V_{CE} = 1 V. The excess base current ($\Delta I_B = I_{Bpost} - I_{Bpre}$) and current gain ($h_{FE}$) were extracted from these Gummel characteristics. The transconductance (g_m) of the transistor is obtained by differentiating the I_C versus V_{BE} curve and is plotted against V_{BE}.

The I_C - V_{CE} characteristics curve of a transistor is a plot of collector current (I_C), versus collector emitter voltage (V_{CE}) at constant base current (I_B) The I_C of unirradiated and irradiated transistors has been measured by varying V_{CE} from 0 to 5 V (step size of 0.1 V) for different I_B (0.5 mA and 0.75 mA). From these characteristic curves collector saturation current (I_{CSat}) is extracted at V_{CE} = 3 V for different total doses [14].

The recovery in the I-V characteristics of proton irradiated transistors were studied by isothermal and isochronal annealing using high temperature oven and furnace. The BJTs irradiated up to 100 Mrad of total dose are subjected to isothermal annealing at 200°C for different time periods up to 100 hr. The BJTs irradiated up to 100 Mrad of total dose are also subjected to isochronal annealing from 50°C to 500°C at 1hr duration for each temperature. The annealed BJTs were allowed for natural cooling to attain room temperature before measuring the I-V characteristics. The recovery in the important electrical parameters like current gain (h_{FE}) and collector saturation current (I_{CSat}) of irradiated NPN transistors after isothermal and isochronal annealing has been investigated systematically.

III. DOSE CALCULATION USING SRIM

The SRIM-2011 simulation program is used to calculate the stopping power and range of ions in matter [15]. The SRIM simulations confirm that 1 MeV and 3 MeV protons induce uniform ionization in the active region of the transistor. The electronic energy loss S_e (ionization) and nuclear energy loss S_n (displacement) in different layers of transistors is also estimated from SRIM program. The total dose accumulated in the device is the sum of electronic energy loss (S_e) and nuclear loss (S_n). The electronic energy loss is caused by the ionization of the atoms in target material. The nuclear energy loss is the result of displacement damage in the target material. The effects of electronic and nuclear energy loss can be separated as ionizing dose (D_i) and displacement damage dose (D_d). The D_i results in trapping of charges in the spacer oxide which reduce the surface recombination rate of minority carriers, where as D_d results in bulk damage. The total ionizing absorbed dose D_i and displacement absorbed dose D_d produced by the irradiation are separately calculated using the following equations,

$$Di = 1.6 \times 10^{-8} \times S_e \times \Phi \quad (1)$$

$$D_d = 1.6 \times 10^{-8} \times S_n \times \Phi \quad (2)$$

where, D_i and D_d are expressed in rad (radiation absorbed dose); Φ is the fluence of the protons in particles/cm^2. The D_i, D_d and the ratio $D_d/(D_d+D_i)$ are calculated for 1 MeV and 3 MeV protons and are tabulated in Table I and II.

Table I. The proton fluence, D_i, D_d and $D_d/(D_d+D_i)$ for 1MeV proton

Dose in Mrad	1 MeV Proton		
	Fluence x10^{10} (p/cm^2)	D_d krad	D_i Mrad
0.1	3.559	0.0079	0.099
0.3	10.68	0.2368	0.2998
0.6	21.36	0.4737	0.5996
1	35.59	0.7896	0.9994
3	106.7	2.368	2.998
6	213.5	4.737	5.996
10	355.9	7.896	9.994
30	1068	23.68	29.98
60	2135	47.37	59.96
100	3559	78.96	99.94
$\frac{D_d}{D_d+D_i}$	7.894 x10^{-4}		

Table II. The proton fluence, D_i, D_d and $D_d/(D_d+D_i)$ for 3MeV proton

Dose in Mrad	3 MeV Proton		
	Fluence x10^{10} (p/cm^2)	D_d krad	D_i Mrad
0.1	7.403	0.0063	0.099
0.3	22.2	0.1887	0.2998
0.6	44.41	0.3775	0.5994
1	74.03	0.6293	0.9994
3	222	1.887	2.998
6	444.1	3.775	5.994
10	740.3	6.293	9.994
30	2220	18.87	29.98
60	4441	37.75	59.94
100	7403	62.93	99.94
$\frac{D_d}{D_d+D_i}$	6.293 x10^{-4}		

From these calculations we can infer that most of the proton energy goes into ionization process that is excitation and pair production. The average ratio $D_d/(D_d+D_i)$ in Si bulk is a critical value in estimating displacement capabilities of incident particle [16]. The average ratio $D_d/(D_d+D_i)$ for 1 MeV and 3 MeV protons is 7.894 x 10^{-4} and 6.293 x10^{-4} respectively. Thus the displacement capability of proton decreases as energy of proton is increased.

IV. RESULTS AND DISCUSSIONS

The effects of 1 MeV and 3 MeV protons on the electrical characteristics of NPN transistors were studied for various doses ranging from 100 krad to 100 Mrad. Fig. 2 illustrates the effects of 3 MeV protons on Gummel characteristics. From the figure it can be seen that the base current (I_B) of the irradiated transistor increases monotonically with increase in radiation dose. The change in collector current (I_C) was found to be negligible after proton irradiation and is shown in Fig. 3. Similar results were also observed for 1 MeV proton and ^{60}Co gamma irradiated transistors. The increase in I_B is the result of increased recombination current in the emitter–base (E-B) depletion region due to radiation-induced generation recombination (G-R) centers. In addition to G-R centers, the incident protons can also create point defects and their complexes in the transistor structure and they reduce the minority carrier lifetime and this in turn increases the I_B of the transistor [4]-[8]-[9]. Therefore both ionization and displacement damage effects are responsible for the observed increase in the I_B of the proton irradiated transistors [17].

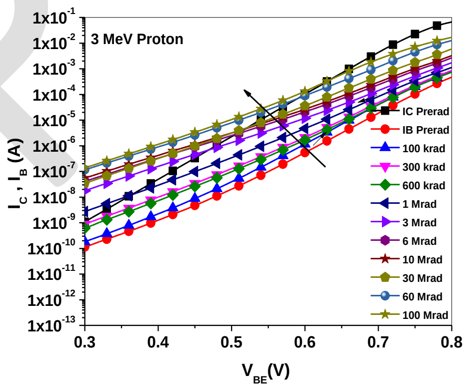

Fig. 2 Gummel characteristics of 3 MeV proton irradiated transistor

The normalized I_B of 3 MeV proton irradiated transistor is shown in Fig. 4 and it can be clearly seen that the I_B of irradiated transistor increases around three orders of magnitude at lower V_{BE}.

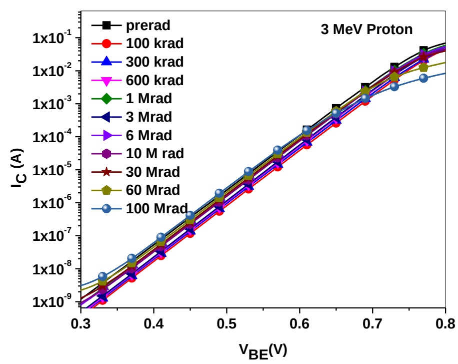

Fig. 3 The variation in I_C after 3 MeV proton irradiation

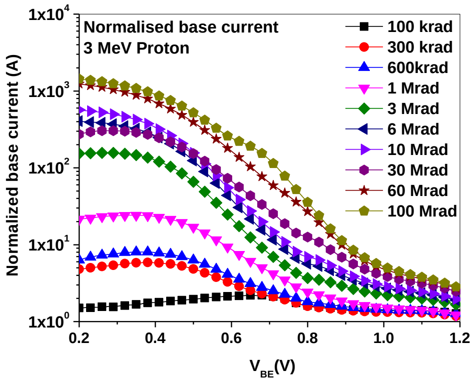

Fig. 4 Normalized base current (I_{BPost} / I_{BPre}) of 3MeV proton irradiated transistor

The increase in excess base current ($\Delta I_B = I_{Bpost} - I_{Bpre}$) for 3 MeV proton irradiated transistor in the dose range of 100 krad to 100 Mrad is shown in Fig. 5. It can be seen from the figure that the ΔI_B increases with increase in the proton dose.

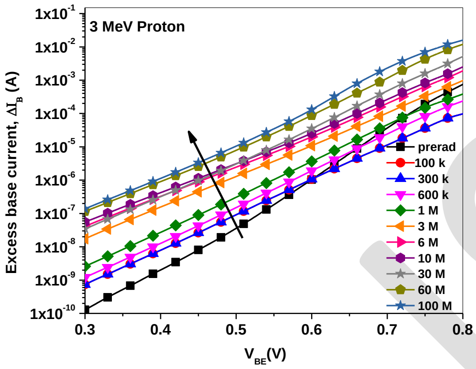

Fig. 5 The variation in excess base current after 3MeV proton irradiation

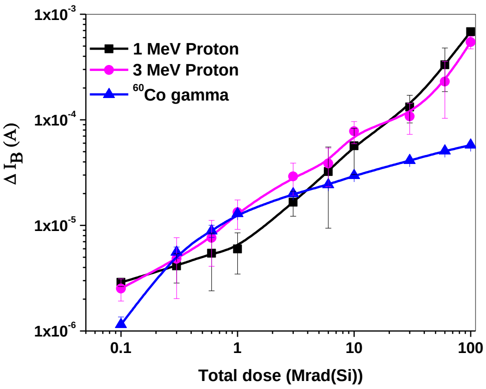

Fig. 6 The variation in ΔI_B at $V_{BE} = 0.65$ V after proton and ^{60}Co gamma irradiation

The change in excess base current (ΔI_B) at $V_{BE} = 0.65$ V for 1 MeV, 3 MeV proton and ^{60}Co gamma irradiated transistors for various doses is shown in Fig. 6. It is evident from this figure that the increase in ΔI_B is almost identical for 1 MeV and 3 MeV protons and increased around two orders of magnitude after 100 Mrad of total dose. In case of ^{60}Co gamma irradiated transistor, it can be seen that the increase in ΔI_B is almost same up to 6 Mrad, beyond this degradation is less when compared to protons. Therefore 1 MeV and 3 MeV protons create more trapped charges and defects when compared to ^{60}Co gamma irradiation [18].

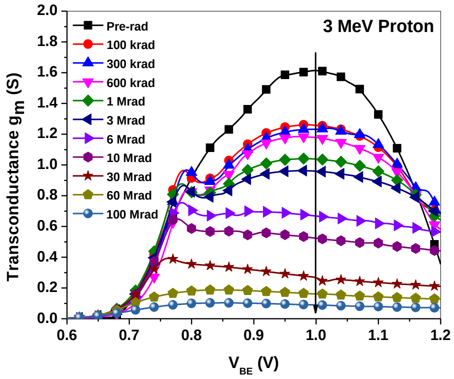

Fig.7 Variation of transconductance (g_m) of 3 MeV proton irradiated transistor

The stability of a transistor is often expressed in terms of device transconductance (g_m) which is defined as the ratio of change in output current to the change in input voltage: i.e.,

$$g_m = \frac{\Delta I_C}{\Delta V_{BE}} \approx \frac{q I_B h_{FE}}{kT} \approx \frac{q I_C}{kT} \qquad (3)$$

where q is elementary charge, k is Boltzmann constant and T is temperature. The carrier mobility and diffusion length in BJTs are affected by the high energy radiation and in turn decreases the minority carrier lifetime [19].

Fig. 7 shows the variation of g_m with V_{BE} for 3 MeV proton irradiated transistor and it can be seen from the figure that the g_m decreases with increase in total dose. Therefore it is very clear that the protons degrade the carrier mobility and diffusion length of charge carriers and hence degrade the g_m of the transistors. The similar kind of behavior was observed for 1 MeV proton and ^{60}Co gamma irradiated transistors.

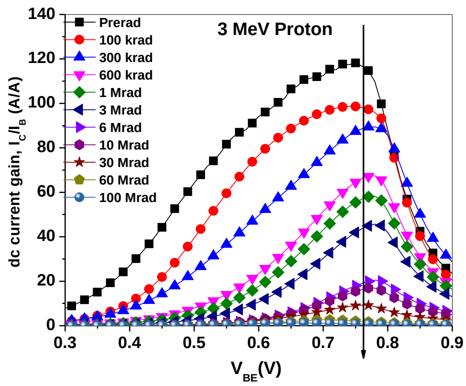

Fig. 8 Current gain (h_{FE}) of 3 MeV proton irradiated transistor

Fig. 8 illustrates the variation of dc current gain (h_{FE}) with respect to V_{BE} in case of 3 MeV proton irradiated transistor. It can be seen from this figure that the peak h_{FE} decreases drastically after irradiation and h_{FE} decreased from 120 to almost zero after 100 Mrad of total dose. Generation of recombination centers in the base region of the transistor leads to an increase in base current by decreasing the minority carrier lifetime. Thus the important parameter of the transistor, the current gain degrades.

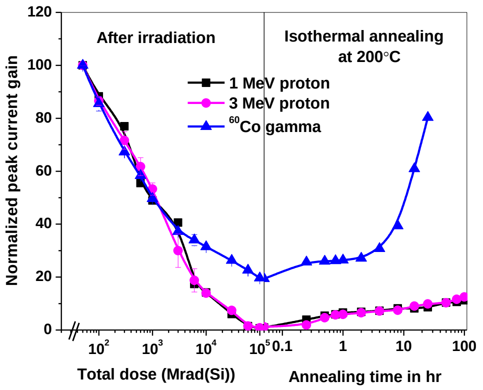

Fig. 9 The normalised h_{FE} as a function of total dose and annealing time for proton and ^{60}Co gamma irradiated transistors

Fig. 9 shows the variation in normalized peak h_{FE} as a function of total dose for 1 MeV, 3 MeV proton and ^{60}Co gamma irradiated transistor along with the recovery in normalized h_{FE} annealed to 200°C for different cumulative time. The normalized h_{FE} at 100 Mrad is almost zero for proton irradiated transistors and around 20 for ^{60}Co gamma irradiated transistor. It is also evident from the figure that the h_{FE} degrades linearly as the proton dose increases. Hence the proton irradiation effects follow Messenger-Spratt equation only at larger fluence [16].

When the transistors were exposed to 1 MeV and 3 MeV protons, the protons deposit their energy in the device via S_e and S_n. The S_e and S_n will produce ionization damage and displacement of atoms along their path during proton irradiation. The S_e is generally realized by inelastic interaction of the protons with the target electrons, producing large number of electron-hole pairs (e-h) along their path. Some of the ionized e-h pairs in the oxide recombine and the remaining e-h pairs move in the oxide due to electric field. The electrons are rapidly swept out of the oxide and the holes are trapped in the oxide and at the interface, resulting in the oxide positive charges and the interface charges near the oxide/Si interface. The S_n is mainly due to elastic scattering by the target nuclei. When the energy of incident proton is high enough to displace the lattice atoms, then the primary knock-on atoms (PKA) are created. Simultaneously, the PKAs can displace other atoms, creating secondary knock-on atoms, etc. and thus a cascade of atomic collision is created in the target material. The formation of atomic collision leads to the distribution of vacancies, interstitial atoms and other types of lattice disorder [23]. Hence S_e and S_n degrade the h_{FE} of an irradiated transistor.

The h_{FE} degradation in proton irradiated transistor is due to the production of primary knock-on-atoms (PKAs) in addition to ionization. But in case of ^{60}Co gamma irradiated transistor very few displacement damages are created by the photon induced secondary electrons [20]. Hence we can observe more degradation in h_{FE} for proton irradiated transistors when compare to ^{60}Co gamma irradiated transistor.

Fig. 9 also shows that the h_{FE} recovers with increase in annealing time (isothermal annealing), it can be observed that there is about 15% recovery in the h_{FE} for 1 MeV and 3 MeV proton irradiated transistors but around 85% recovery in the h_{FE} of ^{60}Co gamma irradiated transistors. In isothermal annealing, the recovery of h_{FE} is significant of ^{60}Co gamma irradiated transistor when compared to that of proton irradiated transistors. The ^{60}Co gamma radiation mainly creates interface and oxide trapped charges and these trapped charges are annealed at 200°C. The proton irradiation creates defects and their complexes in addition to the trapped charges, these defects and their complexes will not be annealed during isothermal annealing even after annealing for 100 hrs.

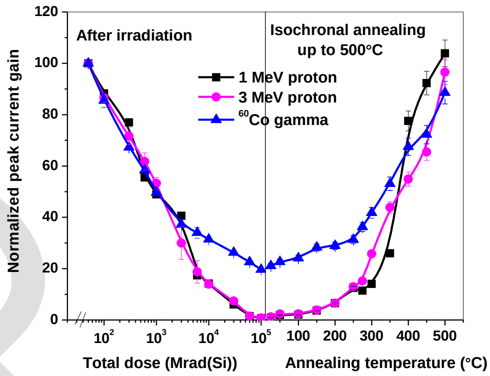

Fig. 10 The normalised h_{FE} as a function of total dose and annealing temperature for proton and ^{60}Co gamma irradiated transistors

Fig. 10 shows the recovery of normalized h_{FE} as a function of annealing temperature (isochronal annealing) for 1 MeV, 3 MeV proton and ^{60}Co gamma irradiated transistors. It can be seen from the figure that the h_{FE} recovers with increase in annealing temperature and the recovery in h_{FE} is due to annealing of point defects in addition to oxide and interface trapped charges in EB spacer oxide [4]. The H_2 molecules get requisite thermal energy to passivate more Si dangling bonds during isochronal annealing at higher temperature [21]. Hence more recovery in h_{FE} was observed above 200°C for both proton and gamma irradiated transistors.

For a large range of displacement damage, the reciprocal of h_{FE} increases linearly with the dose and therefore damage constant can be estimated from the Messenger-Spratt equation [22],

$$1/h_{FE\,(\Phi)} = 1/h_{FE\,(0)} + K\Phi \qquad (4)$$

where $1/h_{FE\,(0)}$ is the initial reciprocal gain, K is the composite displacement damage factor and Φ is the incident particle fluence. Figure 11 shows the variation of $1/h_{FE\,(\Phi)}$ - $1/h_{FE\,(0)}$ versus total dose for proton and gamma irradiated transistors. The displacement damage factors (K) for proton and gamma irradiated transistors are estimated from the slope and the damage constants are summarized in Table III. The K for gamma irradiated transistor is less when compared to that of the proton irradiated transistor. This implies that high energy protons create more displacement damage in transistors when compared to ^{60}Co gamma radiation.

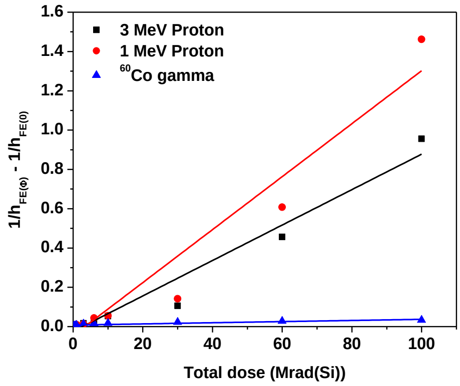

Fig. 11 Variation of $1/h_{FE(\Phi)}$ -$1/h_{FE(O)}$ with total dose after proton and ^{60}Co gamma irradiation

Type of radiation	Damage factor (10^{-6} krad^{-1})
^{60}Co gamma	0.29 ± 0.003
1 MeV proton	10.8 ± 0.011
3 MeV proton	9.02 ± 0.004

Table III. Comparison of damage factor of proton and ^{60}Co Gamma radiation

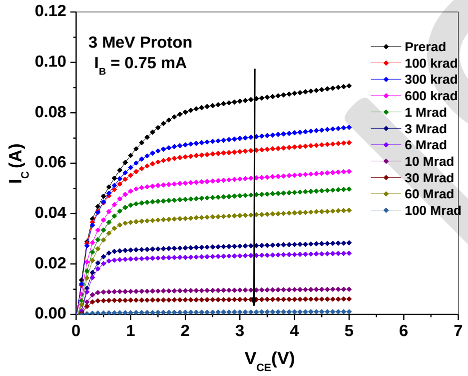

Fig. 12 Output characteristics of 3 MeV proton irradiated transistor

The I_C-V_{CE} characteristics at I_B= 0.75 mA for 3 MeV proton irradiated transistor is shown in Fig. 12. It can be seen that the I_C at saturation and active region decreases with increase in radiation total dose. The radiation induced defects are responsible for the increase in the collector series resistance and in turn reduces I_C in saturation region [24].

The variation in the I_{CSat} measured at V_{CE} = 3 V as a function of total dose for 1 MeV, 3 MeV proton ^{60}Co gamma irradiation radiation is shown Fig. 13. The decrease in I_{CSat} was found to be more for proton irradiated transistor when compared to ^{60}Co gamma irradiated transistor. The high energy radiations are capable of producing different defects like vacancies, interstitials and devaccancies in collector series resistance and thereby reducing I_{CSat} [25]. Fig. 13 also shows the recovery in I_{CSat} as a function of annealing time at 200°C for proton and gamma irradiated transistors. It can be seen from the figure that the recovery is around 90% for ^{60}Co gamma irradiated transistor and only 20% for proton irradiated transistors.

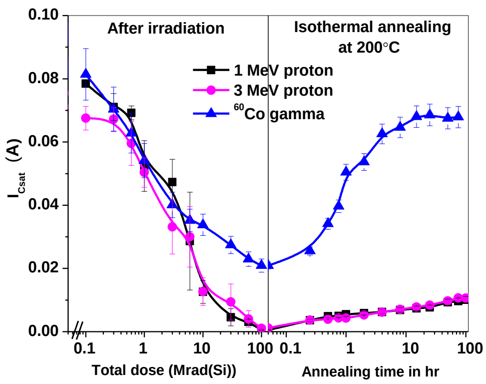

Fig. 13 The variation in I_{CSat} as a function of total dose and annealing time for proton and ^{60}Co gamma irradiated transistors

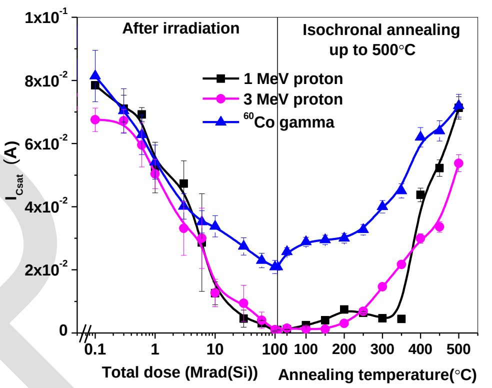

Fig. 14 The variation in I_{CSat} as a function of radiation total dose and annealing temperature for proton and ^{60}Co gamma irradiated transistors

The variation in I_{CSat} as a function of annealing temperature for proton and ^{60}Co gamma irradiated transistors is shown in Fig. 14. From the figure it can be seen that the I_{CSat} recovers with increase in annealing temperature and the I_{CSat} is significantly recovered after annealing at 500°C.

The degradation in the electrical characteristics of irradiated transistors is mainly due to ionization and displacement damage in surface and bulk region of the devices. The incident radiation creates oxide trapped charges and interface state in EB spacer region and in turn increases I_B and decreases $h_{FE.}$ The displacement damages reduce the minority carrier lifetime in the transistor. The base transport factor and emitter efficiency decrease as the minority carrier lifetime decreases, which also contribute to the h_{FE} degradation. The protons ionize the transistor structure and create very few displacement damages [26]. Therefore, more degradation is observed for proton irradiated transistor when compared to gamma irradiated transistor. The important electrical parameters of the transistors can be recovered from the high temperature annealing. In case of isothermal annealing, the electrical characteristics of ^{60}Co gamma irradiated transistors recover completely. Whereas for proton irradiated transistors the recovery in the electrical characteristics is incomplete after isothermal annealing. In isochronal annealing, around 90%

to 100% recovery is observed in the electrical characteristics of ^{60}Co gamma and proton irradiated transistors.

The time required to reach high total doses using gamma facility is higher when compared to the proton irradiation facilities. The comparison of irradiation time for 3 MeV protons and ^{60}Co gamma radiations is calculated. From these calculations we can infer that the proton irradiation time is substantially less when compared to the gamma irradiation time. That is for 100 Mrad of total dose, the gamma irradiation time is 166 hours 40 minutes where as 1 MeV proton irradiation time is 1 hour 35 minutes. The above comparison shows that we can use proton irradiation test facility to study total dose effects on semiconductor devices such as BJTs.

CONCLUSION

The total dose effects of 1 MeV and 3 MeV protons on the electrical characteristics of Si NPN *rf* power transistors were studied systematically in the dose range of 100 krad to 100 Mrad. The proton irradiation results were compared with ^{60}Co gamma irradiated results in the same total dose range. The I_B of the irradiated transistors is found to increase with increase in total dose. The g_m and h_{FE} of the transistors were found to degrade drastically after irradiation. The damage factor calculated from peak current gain is of the order of 10^{-6} $krad^{-1}$ and is found to be higher for 1 MeV proton irradiated transistors when compared to 3 MeV proton and ^{60}Co gamma irradiated transistors. The effect of proton irradiation on I_C -V_{CE} characteristics showed a significant decrease in the I_{CSat} after irradiation. The degradation in the electrical characteristics of the transistors is mainly due to G/R centers created in the EB spacer oxide and displacement damage in the bulk of the transistor structure. The recovery in the important electrical parameters of the proton irradiated transistor during isothermal annealing is incomplete when compared to that of the ^{60}Co gamma irradiated transistor. Isochronal annealing up to 500°C is found to be more effective than isothermal annealing in order to completely recover the electrical characteristics of irradiated transistors.

ACKNOWLEDGEMENT

Authors thank the Pelletron group at Institute of Physics, Bhubaneswar for providing the stable proton beam. This work is carried out under the research project sanctioned by UGC-DAE Consortium for Scientific Research, Kolkata Center, Government of India, (No.UGC–DAP– CSR–KC/CRS/13/MS01/0810).

REFERENCES

[1]. F. Gianotti, M. L. Mangano, T. Virdee, S. Abdullin, G. Azuelos, A. Ball and et. al., "Physics potential and experimental challenges of the LHC luminosity upgrade", *The European Physical Journal C,* Vol. 39 (3), 2005, pp. 293-333.

[2]. E. Stassinopoulos and J. P. Raymond,"The space radiation environment for electronics", *Proceedings of the IEEE,* Vol. 76 (11), 1988, pp. 1423-1442.

[3]. J. L. Barth, C. Dyer and E. Stassinopoulos, "Space, atmospheric, and terrestrial radiation environments", *IEEE Transactions on Nuclear Science,* Vol. 50 (3), 2003, pp. 466-482.

[4]. N. Pushpa, K. C. Praveen, A. P. GnanaPrakash, S. K. Gupta and D. Revannasiddaiah, "An analysis of 175 MeV Nickel ion irradiation and annealing effects on silicon NPN rf power transistors", *Current Applied Physics,* Vol. 13, 2012, pp. 66-75.

[5]. K. C. Praveen, N. Pushpa, P. S. Naik, J. D. Cressler, H. B. Shiva, S. Verma, A. Tripathi and A. P. Gnana Prakash, "In situ investigation of 75 Mev boron and 100 MeV oxygen ion irradiation effects of 50 GHz silicon- germanium heterojunction bipolar transistors", *Radiation Effects and Defects in Solids,* Vol. 168 (7-8), 2013, pp. 620-624.

[6]. K. C. Praveen, N. Pushpa, P. S. Naik, J. D. Cressler, A. Tripathi and A. P. Gnana Prakash, "Application of a Pelletron Accelerator to Study Total Dose Radiation Effects on 50 GHz SiGe HBTs", *Nucl. Inst. and Meth*. B, Vol. 273, 2012, pp. 43-46.

[7]. S. M. Sze, *Semiconductor Devices: Physics and Technology* (John Wiley & Sons, 2008).

[8]. N. Pushpa, K. C. Praveen, A. P. Gnana Prakash, P. S. Naik, J. D. Cressler, S. K. Gupta and D. Revannasiddaiah, "Reliability Studies on NPN RF Power Transistors Under Swift Heavy Ion Irradiation," *Nuclear Instruments and Methods in Physics Research,* Section B, Vol. 273, 2012, pp. 36-39.

[9]. N. Pushpa, K. C. Praveen, A. P. Gnana Prakash, Y. P. Prabhakara Rao, A. Tripati and D. Revannasiddaiah, "An analysis of 100 Mev F8+ ion and 50 MeV Li3+ ion irradiation effects of silicon NPN rf power transistors", *Nuclear Instruments and Methods in Physics Research* Section A, Vol. 620 (2), 2010, pp. 450-455.10.

[10].A. P. Gnana Prakash, S. C. Ke and K. Siddappa, "Swift heavy-ion irradiation effects on electrical and defect properties of NPN transistors", *Semiconductor Science and Technology,* Vol. 19 (8), 2004, pp. 1029-1039.

[11].A. P. Gnana Prakash, S. C. Ke and K. Siddappa, "I-V and deep level transient spectroscopy studies on 60 MeV oxygen ion irradiated NPN transistors", *Nuclear Instruments and Methods in Physics Research Section B*, Vol. 215 (3–4), 2004, pp. 457-470.

[12].H. K. Gummel and H. C. Poon, "An integral charge control model of bipolar transistors", *Journal of Bell Syst. Tech.* Vol. 49, 1970, pp.827.

[13].X. Montagner, P. Fouillat, R. Briand, R. Schrimpf, A. Touboul, K. Galloway, M. Calvet and P. Calvel, "Implementation of Total Dose Effects in the Bipolar Junction Transistor Gummel-Poon Model," *IEEE Trans. Nucl. sci*., Vol. 44, 1997, pp. 1922-1929.

[14].D. K. Schroder, *Semiconductor material and device characterization*. (*John Wiley & Sons*, 2006).

[15]. J. F. Ziegler, M. D. Ziegler and J. P. Biersack, "SRIM-The stopping and range of ions in matter (2010)", *Nuclear Instruments and Methods in Physics* Research B , Vol. 268, 2010, pp. 1818–1823.

[16]. X. Li, H. Geng, M. Lan, C. Liu, D. Yang and S. He, "Radiation effects on silicon bipolar transistors caused by 3-10 Mev protons and 20-60 MeV bromine ions",*Physica B: Condensed Matter,* Vol. 405 (6), 2010, pp. 1489-1494.

[17].R. Nowlin, E. Enlow, R. Schrimpf and W. Combs, "Trends in total-dose response of modern bipolar transistors", *Nuclear Science, IEEE Transactions on*", Vol. 39 (6), 1992, pp. 2026-2035.

[18].E. A. Burke, Nuclear Science, "Energy Dependence of Proton Induced Displacement Damage in Silicon *IEEE Trans. Nucl. Sci.,*Vol. 33 (6), 1986, pp. 1276-1281.

[19].M. G. Pecht, R. Radjojcic and G. K. Rao, Guidebook for managing silicon chip reliability. *CRC Press*, 1999.

[20].S. Kulkarni, A. Sarma, G. Joshi, M. Ravindra and R. Damle, "Proton and gamma ray induced gain degradation in bipolar transistor", *Radiation effects and defects in solids,* Vol. 158, 2003, pp. 647-654.

[21].M. L. Reed and J. D. Plummer, "Chemistry of Si-SiO_2 interface trap annealing", J*ournal of applied physics, Vol.* 63 (12), 1988, pp. 5776-5793.

[22].G. C. Messenger and J. P. Spratt, "A Summary of review of displacement damage from high energy radiation in semiconductors and semiconductor devices", *Proceedings of European conference on Radiation and its effect on Devices,* Vol. 46 (6), 1958, pp. 1038-1044.

[23].YaBin Sun, Jun Fu, Jun Xu, YuDong Wanga, Wei Zhou, Wei Zhang, Jie Cui, GaoQing Li and Z. Liu, "Irradiation effects of 25 MeV silicon ions on SiGe hetero junction bipolar transistors", *Nuclear Instruments and Methods in Physics Research B*, Vol. 312, 2013, pp.77–83.

[24].X. Li, H. Geng, C. Liu, Z. Zhao, M. Lan, D. Yang and S. He, "Radiation effects on bipolar junction transistors and integrated circuits produced by different energy Br ions", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* Vol. 612 (1), 2009, pp. 171-175.

[25].K. V. Madhu, S. R. Kulkarni and R. Damle, "I-V, C-V and deep level transient spectroscopy studies of 24 MeV proton-irradiated bipolar junction transistor", *Pramana* Vol. 74 (1), 2010, pp. 97-107.

[26].B. Rax, A. Johnston and T. Miyahira, Nuclear Science, "Displacement Damage in Bipolar Linear Integrated Circuits", *IEEE Trans. Nucl. Sci.*, Vol. 46 (6), 1999, pp. 1660-1665.