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Original Article

High energy swift heavy ion irradiation and annealing effects on DC electrical characteristics of 200 GHz SiGe HBTs

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ABSTRACT

The total ionizing dose (TID) and non ionizing energy loss (NIEL) effects of 100 MeV phosphorous (P^{7+}) and 80 MeV nitrogen (N^{6+}) ions on 200 GHz silicon-germanium heterojunction bipolar transistors (SiGe HBTs) were examined in the total dose range from 1 to 100 Mrad(Si). The *in-situ* I–V characteristics like Gummel characteristics, excess base current (ΔI_B), net oxide trapped charge (N_{OX}), current gain (h_{FE}), avalanche multiplication ($M - 1$), neutral base recombination (NBR) and output characteristics (I_C-V_{CE}) were analysed before and after irradiation. The significant degradation in device parameters was observed after 100 MeV P^{7+} and 80 MeV N^{6+} ion irradiation. The 100 MeV P^{7+} ions create more damage in the SiGe HBT structure and in turn degrade the electrical characteristics of SiGe HBTs more when compared to 80 MeV N^{6+}. The SiGe HBTs irradiated up to 100 Mrad of total dose were annealed from 50 °C to 400 °C in different steps for 30 min duration in order to study the recovery of electrical characteristics. The recovery factors (RFs) are employed to analyse the contribution of room temperature and isochronal annealing in total recovery.

1. Introduction

The SiGe BiCMOS technology plays a critical role in many electronic applications. The SiGe HBTs exhibit better parametric responses and excellent cryogenic performance when compared to Si BJTs. Along with this, the inherent robust TID tolerance up to multi Mrad (SiO_2) of total dose make them a suitable candidate for extreme environment applications [1–3]. In applications such as space systems, high energy physics experiment (HEP), military, medical facilities and nuclear installations these SiGe HBTs may be exposed to radiation. Therefore, parametric degradation and failures, in other words, the reliability of SiGe HBTs is an important aspect when operating in radiation rich environments. It is known that the ionizing radiation induces damages in both Si-SiO_2 interface and bulk silicon (Si) [2,3]. Therefore, it is useful to understand the mechanism and location of damages in the device structure and also the response of emitter-base (E-B) spacer and shallow trench isolation (STI) oxides to different radiation species, not only for scientific reason but also to examine the reliability and to design radiation-harden devices. Many researchers have studied the TID effects on different semiconductor devices [4–10]. However, most of those studies are focused on bipolar transistors and MOSFETs, mostly on gamma, proton and neutron irradiations [7,10,11]. Very few reviews on the performance and reliability of SiGe HBTs under the influence of high linear energy transfer (LET) swift heavy ions (SHI) irradiation are available. Sun et al. have studied the effects of different LET ions such as Si, Cl, Br on SiGe HBTs. They reported that degradation in the device characteristics is a function of fluence and also the biasing conditions [12–15]. The synergistic effect of total ionizing dose (TID) and single event effect (SEE) in SiGe heterojunction bipolar transistor (HBT) is investigated by Zhang et al. [16]. They observed that the influence of positive oxide-trap charges induced by TID on the distortion of electric field in SEE is the major factor of the synergistic effect. Moreover, the recombination of interface traps also plays a role in charge collection. Dong et al., have studied the annealing of point defects and their influence on the electrical degradation and recovery behaviours of irradiated SiGe HBTs. They observed that high concentrations of divacancy

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and vacancy-oxygen complexes are introduced in irradiated silicon, which is responsible for the enhanced carrier recombination and in turn decreases the carrier lifetime. The incomplete recovery was observed even after annealing at 500 °C due to the enhanced carrier-recombination from the survival defects with deep levels at $E_C - 0.24$ eV and $E_C - 0.44$ eV during annealing [17]. In our previous work, we have got proven that SiGe HBTs are radiation harden up to 100 Mrad(Si) of total dose to ^{60}C0 gamma and different low LET ions without any intentional hardening [12,13]. The SHIs can create displacement damages along with ionization damages in the transistor structure. Besides, one can greatly save the irradiation time by utilizing the SHI facility like Pelletron accelerators. Hence ion irradiation is the better alternative for reliability testing of SiGe HBTs when compared to conventional gamma or neutron facility for high total dose environments. However, there are few reports available for low LET ion irradiation on HBTs [13–15]. Hence, it is essential to study the effects induce by the different LET SHIs on the electrical parameters of SiGe HBTs. To the best of our knowledge, this is the first report on the degradation of SiGe HBTs under high energy N^{6+} and P^{7+} ion irradiation. The *in-situ* DC I-V parameters were measured for the same SiGe HBT after each incremental total dose to avoid any variation in measured data.

2. Experimental methods

The IBM 8HP (third-generation) NPN SiGe HBTs with a peak cut off frequency of 200 GHz were employed in the present investigation. The 8HP SiGe BiCMOS ICs integrates a 0.12 μm, 1.7 V of BV_{CEO}, 200 GHz peak f_T (300 K) SiGe HBTs, together with 0.12 μm L_{eff}, 1.2 V standard Si CMOS devices. The samples were received as 200 mm SiGe BiCMOS wafers and 200 GHz SiGe HBTs were selected by dicing. The SiGe HBTs mounted on 28 pin DIPs and emitter (*E*), base (*B*) and collector (*C*) terminals along with substrate terminal were wire bonded. The SiGe HBTs with different emitter areas (A_E) such as 0.12 × 2 μm^2, 0.12 × 4 μm^2, 0.12 × 8 μm^2 were exposed to 80 MeV N^{6+} and 100 MeV P^{7+} ions at 15 MV Pelletron Accelerator at Inter University Accelerator Centre (IUAC), New Delhi, India in the total dose ranging from 1 to 100 Mrad (Si) at 300 K. The beam current was 0.66 pnA and 0.14 pnA respectively for 80 MeV N^{6+} and 100 MeV P^{7+} ions. All the terminals of transistors i.e., E, B and C were grounded during the irradiation. The isochronal annealing was conducted on 100 Mrad (Si) irradiated devices from 50 °C to 400 °C in the duration of 30 min. The DC electrical parameters such as the Gummel characteristics, ΔI_B, h_{FE}, *NBR*, *M-1* and output characteristics (I_C-V_{CE}) were characterized before and after irradiation as well as annealing. The results of SiGe HBTs with $A_E = 0.12 \times 2.0$ μm^2 were presented in this paper since the other geometry devices showed similar behavior.

3. Result and discussion

3.1. SRIM studies

It is interesting and essential to study the impacts of ion irradiation in device structures and related energy loss phenomenon. When devices are exposed to high energy ions, the ions deposit or lose energy through elastic collision with the nuclei known as nuclear energy loss (S_n) and inelastic collision with the atomic electrons is defined as electronic energy loss (S_e). The SRIM associated with TRIM, gives a detailed treatment of ion distribution and the damage cascades within the device structure [16]. SRIM simulation results are given in Table 1. Figs. 1–4 show the 3D pictorial representation of ionization and displacement damages induced by 80 MeV N^{6+} and 100 MeV P^{7+} ions simulated by SRIM-2013 programme. The compact lines in the figures represent the metallization layers between SiO_2 and Si layers of SiGe HBT. From Figs. 1 and 3, it can be observed that the ionization is more at the metallization layers for both ions. From Figs. 2 and 4, it can be observed that the displacement damage is non-uniform throughout the device structure and increases with increase in the range of ions. The amount of displacement damages and the ion atomic number are proportional to each other. The amount of displacement damage is more for 100 MeV P^{7+} ions in HBT structure when compared with that of 80 MeV N^{6+} ions. The SRIM simulations showed that 80 MeV N^{6+} and 100 MeV P^{7+} ions create 49 and 662 vacancies respectively in the device structure. However, when a semiconductor material is exposed to higher LET ions and if ions have sufficiently high electronic stopping component (S_e), the material melts along the ion trajectory followed by fast cooling and re-solidification. This results in the formation of an amorphous track within the crystalline material. The density of the damages produced by electronic excitations depends on the LET of the ions and for lower LET ions, only point defects and point defect

Table 1
Comparison of SRIM simulation results of 80 MeV N^{6+} and 100 MeV P^{7+} ions.

Parameter	Nitrogen ion	Phosphorous ion
Energy (MeV)	80	100
Atomic Number	7	15
Range in Si (μm)	89.23	32.48
S_e (MeV-cm^2/g)	2.62×10^3	12.53×10^3
S_n (MeV-cm^2/g)	1.45	10.45
Total ionization keV/ion	99.97×10^3	99.95×10^3
Total Target damage keV/ion	1.19	2.76
Average vacancies/ion	49	662
Total phonons keV/ion	27	52

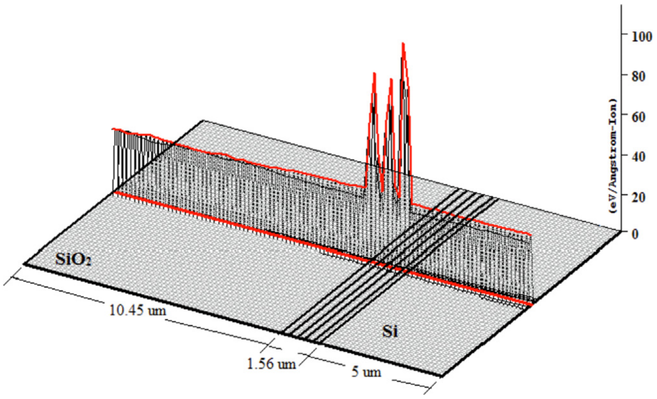

Fig. 1. SRIM simulation showing ionization damage in 80 MeV N^{6+} ion irradiated SiGe HBT structure.

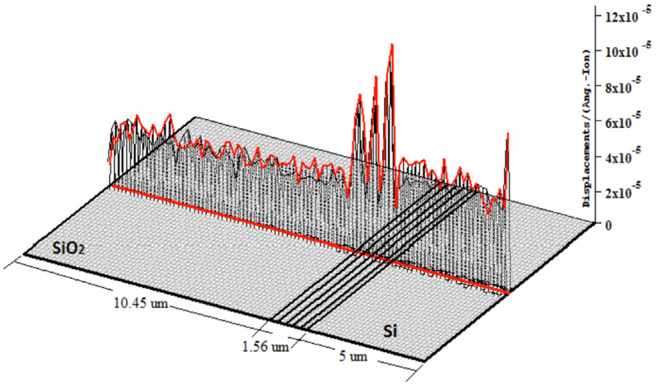

Fig. 2. SRIM simulation showing displacement damage in 80 MeV N^{6+} ion irradiated SiGe HBT structure.

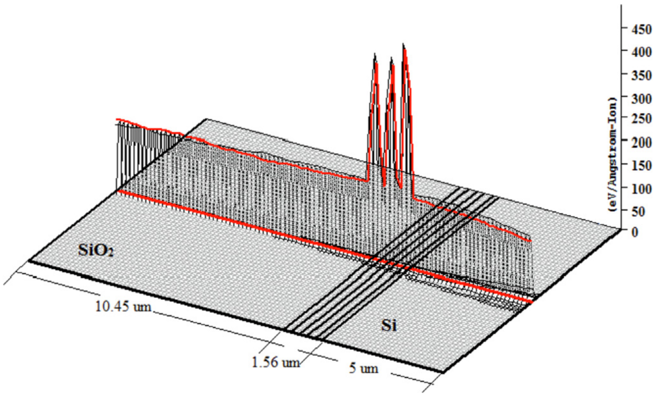

Fig. 3. SRIM simulation showing ionization damage in 100 MeV P^{7+} ion irradiated SiGe HBT structure.

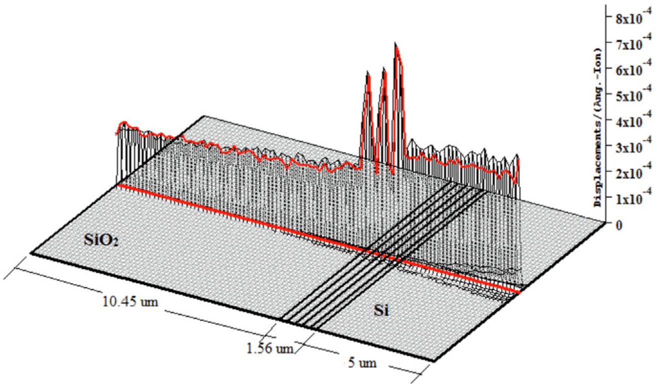

Fig. 4. SRIM simulation showing displacement damage in 100 MeV P^{7+} ion irradiated SiGe HBT structure.

complexes are formed. The degree of disorders can range from point defects to a continuous amorphized zone along the ion path, commonly called the latent track. Due to the formation of an amorphous zone, both the physical and electrical properties of the material changes significantly [18]. However, in the present study, the energy of phosphorous ions when it reaches the active region of SiGe HBTs is in the order of 54 MeV and corresponding S_e is 3.3 keV/nm. Therefore, phosphorous ions create only point defects and their clusters but not the ion tracks. However, further studies are required to analyse these results.

3.2. *Current-voltage (I-V) measurement*

The post-radiation impact on I-V characteristics of HBTs can be measured by Gummel characteristics. The forward Gummel characteristics after 100 MeV P^{7+} ion irradiation is shown in Fig. 5. The characteristic increase in base current (I_B) at lower base-emitter voltage (V_{BE}) or at lower injection is clearly evident from the figure. The degradation in I_B is mainly due to two factors namely; i) ionization damage – which produces positive oxide-trapped charges and interface states in oxide layer that leads to increase in the base surface recombination current and ii) displacement damage - which creates point defects and defect clusters, they may be active recombination and trapping centers, leads to a decrease in the lifetime of minority carrier and thereby an increase the I_B [17–19]. However, even for a total dose of 100 Mrad(Si), the collector current (I_C) remains same as that of pre-rad. Increased recombination in the EB depletion region does not decrease the I_C, reason is that the number of carriers injected into the base depends only on the doping of the base and the applied bias. If recombination increases in the depletion region, the I_E and I_B increase, but the I_C remains unchanged. The similar behavior was observed in case of 80 MeV N^{6+} irradiation.

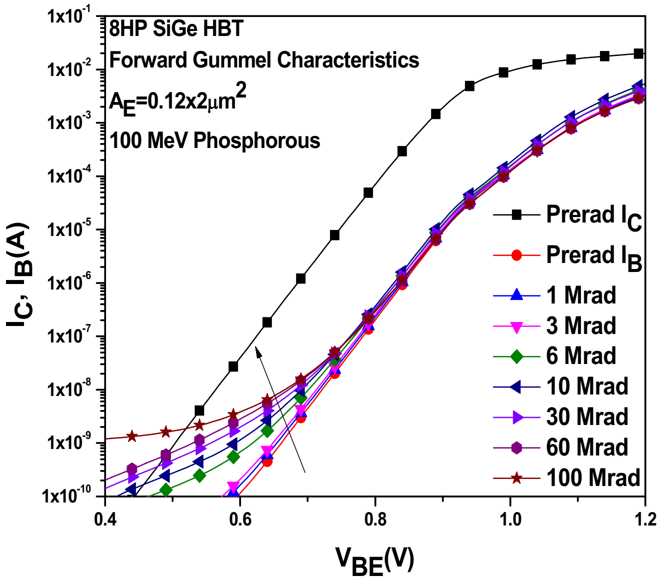

Fig. 5. Forward mode Gummel Characteristics of 100 MeV P^{7+} ion irradiated SiGe HBT.

The impact of radiation in STI oxide can be assessed by inverse Gummel characteristics, where *E* and *C* terminals were interchanged during Gummel measurement. Fig. 6 shows the inverse mode Gummel characteristics after 100 MeV P^{7+} ion irradiation. From the figure, one can see that the inverse I_B is increasing with increase in ion dose. This classical signature of ion induced damage in SiGe HBTs is attributed to ion induced G-R centers, physically located near the STI oxide (SiO_2) where they are able to perturb the mechanism of charge transport at the CB junction. The charge trapped in the oxide modulates the surface potential and affects the surface recombination.

The primary effect of ionizing radiations on HBTs is usually an increase in the I_B resulting from enhanced recombination in the EB depletion region and STI region. The amount by which the I_B increases above its pre-rad value is called the excess I_B and that can be

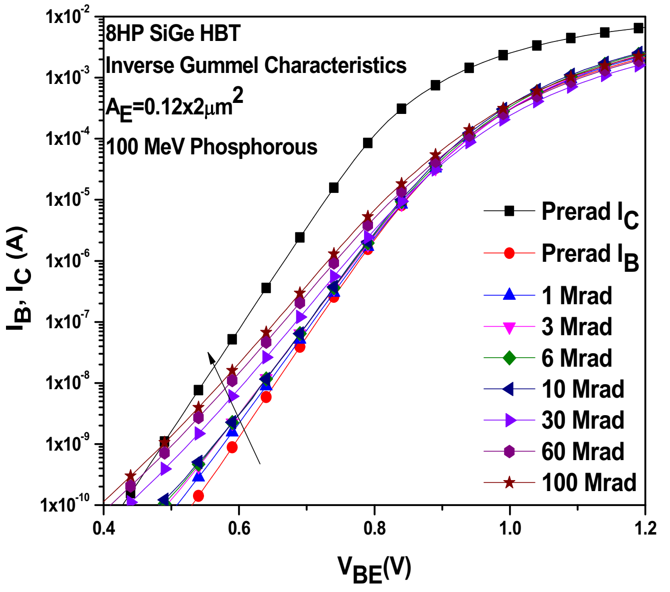

Fig. 6. Inverse mode Gummel Characteristics of 100 MeV P^{7+} ion irradiated SiGe HBT.

defined as $\Delta I_B = I_{Bpost} - I_{Bpre}$. The forward mode and inverse mode ΔI_B, extracted at $V_{BE} = 0.65$ V plotted versus total dose are shown in Figs. 7 and 8 respectively for 100 MeV P^{7+} and 80 MeV N^{6+} ion irradiated SiGe HBTs. From the figures, it can be seen that both forward and inverse mode ΔI_B increasing with increase in radiation dose and is more for 100 MeV P^{7+} ion irradiated SiGe HBTs when compared to 80 MeV N^{6+} ion irradiation. From the figures , it is also observed that inverse mode ΔI_B is more when compared to forward mode ΔI_B. Therefore both ions induce more degradation in STI oxide than EB spacer oxide. This may be due to the increased area that is available for interface trap build up and fixed charge trapping in the STI region when compared to EB spacer oxide [20,21].

It is well known that the ionizing radiation cause degradation via increases in positive oxide charges and surface recombination velocity [22]. The relation between transition voltage (V_{tr}) and net positive oxide charge (N_{ox}) is given by;

$$N_{ox} = \sqrt{\frac{2\varepsilon_{Si}N_s}{q}\left(\frac{1}{\beta}\ln\left(\frac{N_s}{n_i}\right)-\frac{V_{tr}}{2}\right)} \qquad (1)$$

where n_i is the intrinsic carrier concentration, $\beta = q/kT$ is the inverse thermal voltage, N_s is the surface concentration in the intrinsic base, ε_{Si} is the permittivity of silicon and q is the charge of an electron. In general, N_{ox} is a sum of interface and oxide trapped charges [22]. The variation of N_{ox} versus total dose for ion irradiated SiGe HBTs is shown in Fig. 9. It can be seen that, both forward and inverse mode N_{ox} are increasing with increase in total dose and are more for P^{7+} ion irradiated SiGe HBT. It is evident that the inverse mode N_{ox} is more when compared to forward mode N_{ox} hence more oxide trapped charges are created in STI oxide than EB spacer oxide and one can observe similar trend in Figs. 7 and 8.

The variation of h_{FE} with ion dose for 100 MeV P^{7+} ion irradiated SiGe HBTs is shown in Fig. 10, similar trend was also observed after 80 MeV N^{6+} ion irradiation. The h_{FE} degrades substantially for both types of ions and the degradation is more at lower V_{BE}. The peak h_{FE} decreases with increase in ion dose along with a shift in peak h_{FE} towards higher values of I_C. This is due to the fact that the excess I_B generated by G/R traps, is only dominant in low injection of transistor operation as the dynamics of carrier interaction with the trap level are depend on the carrier density itself [23]. Fig. 11 shows the comparison of normalized peak h_{FE} versus total dose for 80 MeV N^{6+} and 100 MeV P^{7+} ion irradiated SiGe HBTs. As dose increases, the peak h_{FE} decreases due to degradation of the non-ideal I_B. After 100 Mrad of total dose, the peak h_{FE} is found to be decreased by 60% and 45% for 100 MeV P^{7+} and 80 MeV N^{6+} ion irradiated SiGe HBTs respectively.

In order to qualify the degradation in the device, one can calculate a damage coefficient which can be obtained by Messenger-Spratt equation [24];

$$1/h_{FE(\Phi)} = 1/h_{FE(0)} + K\Phi \qquad (2)$$

where $h_{FE(0)}$ is the gain before irradiation, $h_{FE(\Phi)}$ is the gain after irradiation, K is the composite displacement damage factor and Φ is the incident ion fluence. The secondary electrons are the product of ionization caused by the incident radiations. When a solid target is irradiated with high energy radiation, it loses its energy through multiple elastic and inelastic scattering processes, which mainly produces secondary electrons. If these secondary electrons have sufficiently higher energy cause displacement damages. For example, the gamma irradiation causes displacement damage mainly through the secondary electrons produced through the Compton interaction. These Compton electrons have a maximum energy of around 1 MeV and so the primary defects created by gamma irradiation will be of a similar nature as those from direct electron irradiation [22]. The number of secondary electrons generated in the device is proportional to LET of the ions and the generation of more number of secondary electrons leads to more displacement damages. The damage constant were found to be $2.28 \times 10^{-5} \pm 0.38 \times 10^{-5}$ and $2.63 \times 10^{-5} \pm 0.37 \times 10^{-5}$ for 80 MeV $N^{6+}$and 100 MeV P^{7+} ions respectively. The damage constant is more for 100 MeV P^{7+} that means high LET P^{7+} ion irradiation produces more secondary electrons leads to displacement damages in the lattice, which results in degrading minority carrier lifetime.

It is well known that ion irradiation causes both ionization and displacement damages in the device structure. TID has more impact on oxides and interfaces than on bulk Si properties. However,

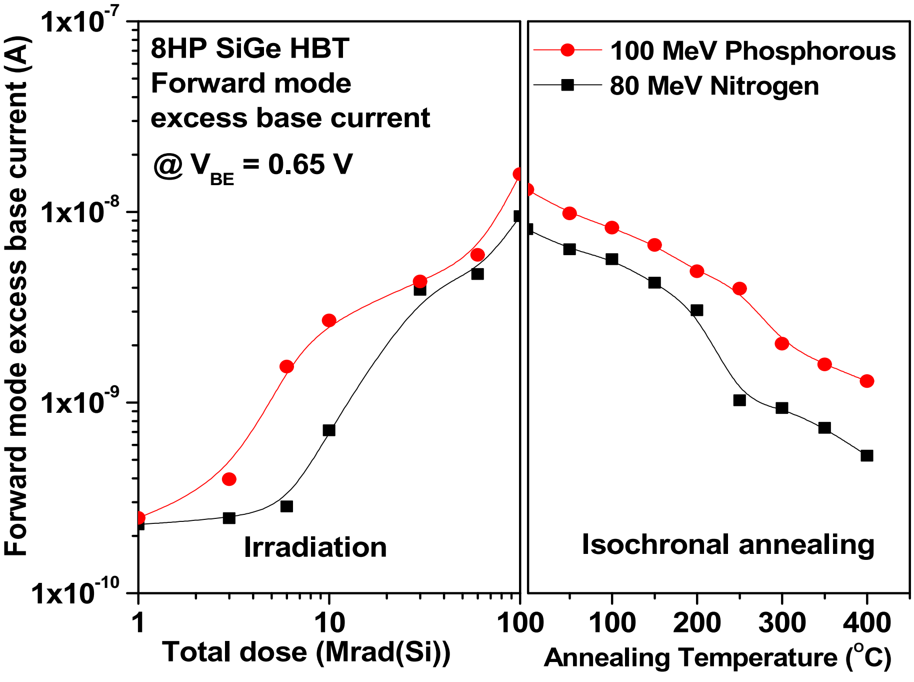

Fig. 7. The variation in forward mode excess I_B at $V_{BE} = 0.65$ V.

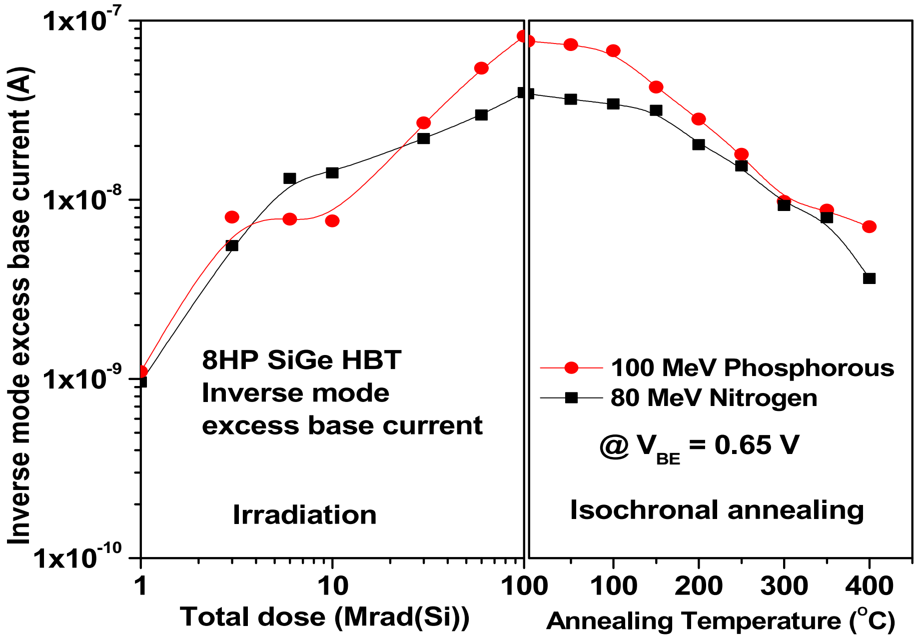

Fig. 8. The variation in inverse mode excess I_B at $V_{BE} = 0.65$ V.

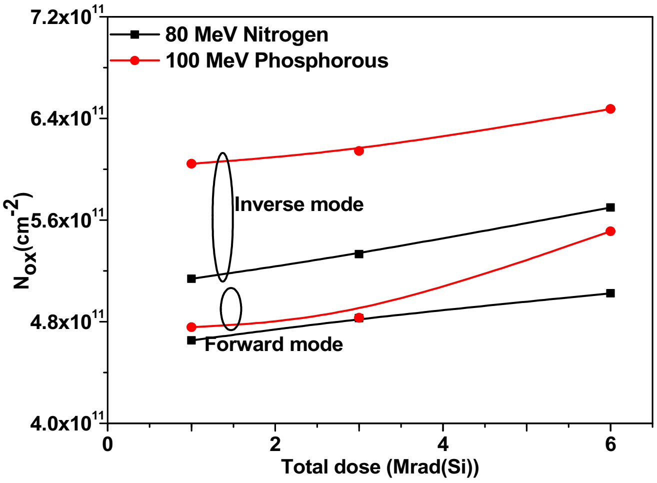

Fig. 9. The variation of forward mode and inverse mode N_{OX} versus total dose.

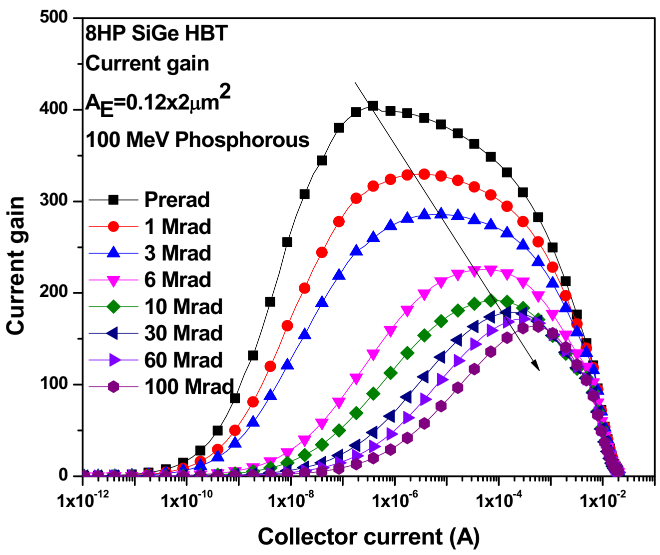

Fig. 10. The variation in current gain after 100 MeV P^{7+} ion irradiation.

displacement damages can affect recombination in both the bulk and at the Si-SiO$_2$ interface. From the SRIM studies, it is evident that the ionization dominates at the interfaces and displacement damage in the bulk of the transistor. The displacement damages and defects are the product of non-ionizing energy deposited by particle irradiation, some of which are electrically active. The amount of energy that goes to the process of creating displacement damage is defined in terms of the NIEL. The important device parameters such as leakage current, inverse lifetime and current gain are proportional to NIEL and irradiation conditions. Therefore it important to correlate the degradation in electrical characteristics with the displacement damage and NIEL deposited in the device structure. The displacement damage dose (D) is the product of the NIEL and the fluence φ induced by incident radiation with an energy E and is given by Ref. [25],

$$\mathrm{D} = 1.6 \times 10^{-8} \times \varphi \times \mathrm{NIEL} \tag{3}$$

NIEL is the rate at which energy is deposited from the impinging radiation to the target lattice through non-ionizing mechanisms. 1.6×10^{-8} is a conversion factor - a factor of 1.6×10^{-6} converts MeV to ergs, and a factor of 1×10^{-2} converts ergs to rad. The equivalent displacement damage dose (D_{eq}) is obtained by Ref. [25],

$$D_{eq} = D \times \frac{NIEL(E)}{NIEL\left(E_{ref}\right)} \tag{4}$$

where $NIEL(E)$ is non-ionization energy loss at the desired energy and $NIEL(E_{ref})$ is the non-ionization energy loss at reference energy, normally taken as 1 MeV. The displacement damage dose and equivalent displacement damage dose corresponding to the 100 MeV $P^{7+}$and 80 MeV N^{6+} ion irradiation are given in Table 2. The D_{eq} values infer that point defects/displacement damages are more in the case of 100 MeV P^{7+} irradiated SiGe HBTs when

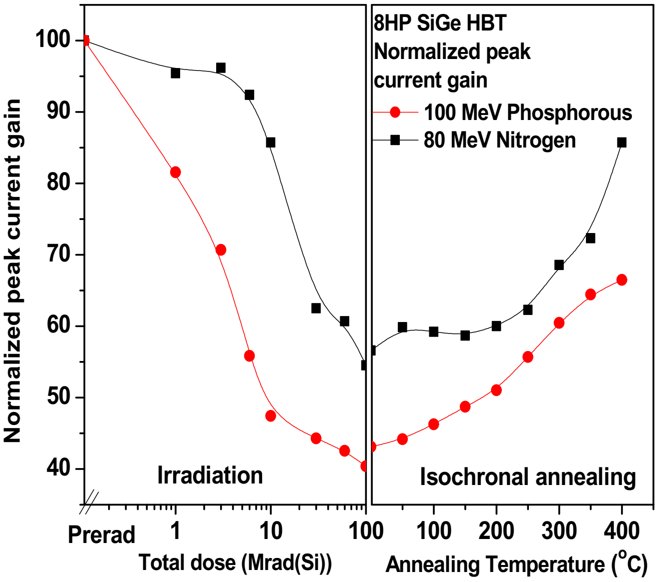

Fig. 11. Normalized peak current gain versus total dose.

compared to 80 MeV N^{6+} ion irradiated SiGe HBTs. Therefore, the D_{eq} results are consistent with damage constant calculations and also with the h_{FE} degradation.

The effect of 100 MeV $P^{7+}$and 80 MeV N^{6+} ion irradiation on NB region was studied. The NBR is due to the recombination of electrons with holes in NB region via intermediate trap levels induced by ions and is proportional to the minority carrier density. Physically, NBR increases the hole density by removing the desired electron injections from the I_C via recombination, thereby affecting the base transport factor. For a transistor, the I_B under any random bias is the sum of hole current due to impact ionization, hole current injected into the emitter and the NBR component. For small V_{CB}, impact ionization is negligible hence only other two components contribute to I_B. Non-negligible NBR implies that the effective electron diffusion length in the base is comparable to the NB width (W_B) because of the decrease in electron lifetime due to the presence of trapped centers in the base. For a given electron lifetime in the base region, the total base charge is proportional to I_B due to NBR. Therefore, any change in the base charge will change the NBR component of I_B. An easy method to vary the base charge is by modulating W_B by varying V_{CB}. Therefore one can experimentally estimate the impact of NBR in a transistor by observing the slope of I_B as a function of V_{CB} at a fixed V_{BE} [12,15,17]. The NBR of irradiated SiGe HBTs are shown in Fig. 12. It can be seen that the slope of the NBR curve at lower V_{CB} is almost same for pre-rad and 100 Mrad curves. Therefore ions induced negligible amount of displacement damage in NB. However, the CB break down voltage (BV_{CBO}) increases with increase in total dose representing the increase in electric field in CB junction, negatively impact the post irradiation device performance.

Table 2
The displacement damage dose and equivalent displacement damage dose corresponding to the 80 MeV N^{6+} and 100 MeV P^{7+} ion irradiation.

Dose (Mrad)	80 MeV Nitrogen		100 MeV Phosphorous	
	D (rad)	D_{eq} (rad)	D (rad)	D_{eq} (rad)
1	231.96	3.95	370.05	7.46
3	695.96	11.85	1110.06	22.39
6	1383.50	23.69	2220.33	44.77
10	2319.62	39.49	3700.55	74.62
30	6959.60	118.46	11101.67	223.86
60	13833.50	236.95	22203.34	447.72
100	23196.20	394.88	37005.57	746.20

The avalanche multiplication (*M-1*) of carriers in the CB junction is studied and Fig. 13 illustrates the measured multiplication factor, that is, the amount of electron or hole pairs created in the CB depletion region per electron as a function of V_{CB} [15,17]. The decrease in the *M-1* is less, hence the electron-hole pairs produced in the CB space charge region impotent to multiplicate the impact ionization with lattice due to the formation of displacement damages by the irradiation [15,17].

The output characteristics (I_C-V_{CE} at $I_B = 3.75$ mA) for 100 MeV P^{7+} ion irradiated SiGe HBTs and variation of I_{CSat} are shown in Figs. 14 and 15 respectively. It can be observed that, I_C at active and saturation regions decrease after ion irradiation. The ion irradiation may induce point defects in collector region and this increases the collector series resistance and thereby reduce the I_C at saturation and the active region of the transistor. From Fig. 15, it is evident that the degradation in I_C is more for P^{7+} ion irradiation when compared to N^{6+} ion. Since high LET P^{7+} ions introduce more displacement damage in the SiGe HBT structure when compared to N^{6+} ions.

3.3. *Isochronal annealing*

It is well known that irradiation degrade the electrical parameters of devices and there is a possibility of recovering some of the original characteristics either by relaxation (annealing at room temperature) or by thermal annealing. Basically, after the creation of ion induced defects, junctions and lattice tend to relax to equilibrium conditions in order to form more stable states. The defect reordering depends on the nature of the device and on the conditions during irradiation. These defects can be recovered by isochronal annealing technique. In this section, the effect of isochronal annealing on the irradiated SiGe HBTs has been studied. The 100 Mrad(Si) irradiated SiGe HBTs were subjected to isochronal annealing from 50 °C to 400 °C for 30 min duration.

It can be seen from Figs. 7 and 8 that the room temperature annealing is less in irradiated SiGe HBTs. During isochronal annealing, forward and inverse I_B decreases with increase in annealing temperature because of the annealing of oxide and interface trapped charges in EB spacer and STI oxide. It is also observed that the recovery of forward mode and inverse mode I_B is more for N^{6+} ion irradiated SiGe HBT. From Fig. 11, it evident that the degraded h_{FE} is found to increases with an increase in temperature.

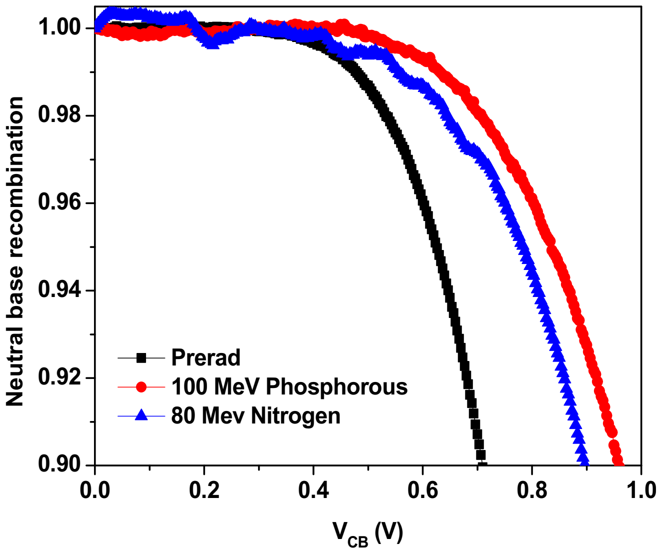

Fig. 12. Neutral base recombination for ion irradiated SiGe HBTs.

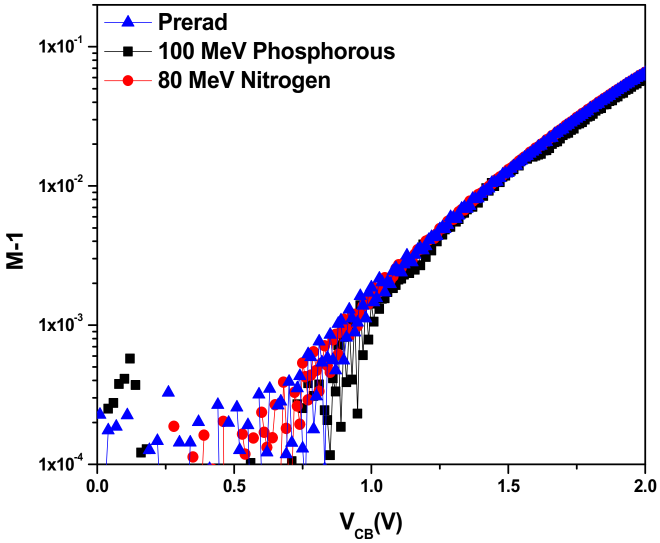

Fig. 13. The avalanche multiplication of carriers for ion irradiated SiGe HBTs.

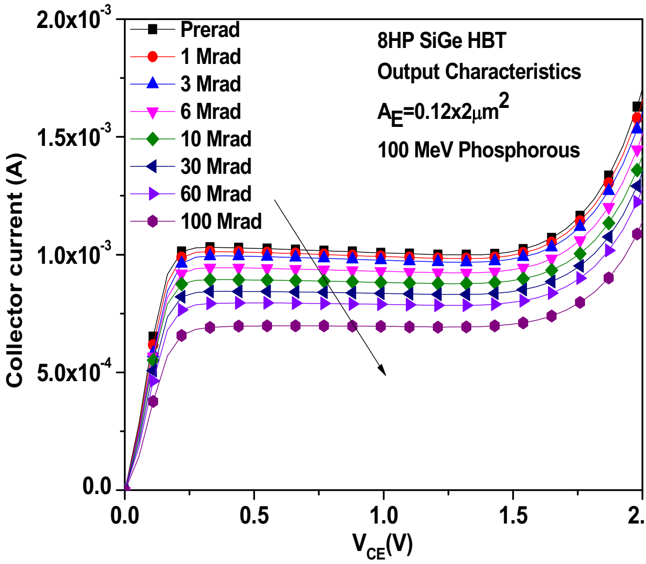

Fig. 14. Output Characteristics for 100 MeV P^{7+} ion irradiated SiGe HBT.

Almost 87% and 65% recovery in h_{FE} at the annealing temperature of 400 °C was observed for N^{6+} ion and P^{7+} ion irradiated devices respectively. The incomplete recovery in h_{FE} of ion irradiated HBTs is due to the presence of point defects and their complexes along with ionization damages. It can be seen from Fig. 15 that the I_{CSat} is almost completely ($\approx$96%) recovered after annealing up to 400 °C for both N^{6+} ion and P^{7+} ion irradiated transistors.

The recovery factors (RFs) namely, relaxation efficiency (Relax. eff.), annealing efficiency (Ann. eff.) and annealing contribution (Ann. cont.) are calculated to understand the contribution of room temperature annealing and thermal annealing in ion induced damage recovery process. The definition of these factors is represented according to the irradiation, room temperature annealing and isochronal annealing curves as schematically shown in Fig. 16. RFs can be defined as

$$Relax\,eff.(\%) = \frac{\varDelta Relax}{\varDelta Irrad} \times 100 \tag{5}$$

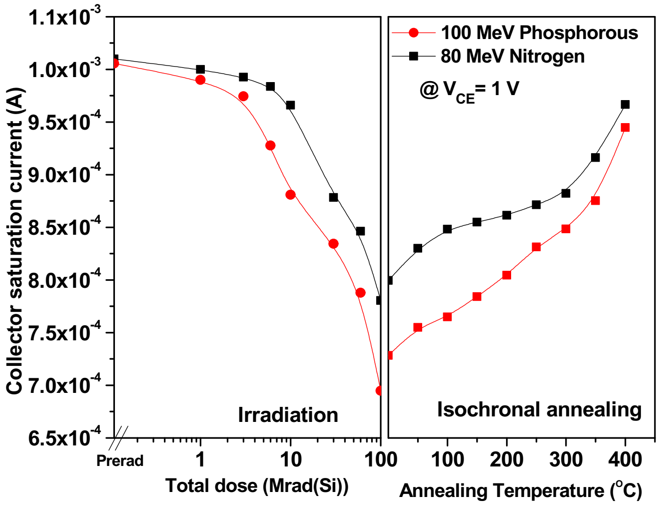

Fig. 15. Variation of collector saturation current (I_{CSat}) at $V_{CE} = 1$ V.

$$Ann\,eff.(\%) = \frac{\varDelta Ann}{\varDelta Ann + \varDelta Resid} \times 100 \tag{6}$$

$$Ann\,contr.(\%) = \frac{\varDelta Ann}{\varDelta Irrad} \times 100 \tag{7}$$

where, $\varDelta Irrad = h_{FEpre\text{-}rad}\text{-}h_{FEpost\text{-}rad}$ is the decrease in h_{FE} values due to irradiation. $\varDelta Relax = h_{FEpre\text{-}anneal}\text{-}h_{FEpost\text{-}rad}$ is the increase in h_{FE} due to room temperature annealing. $\varDelta Ann = h_{FEannealed}\text{-}h_{FEpre\text{-}anneal}$ is the increase in h_{FE} after isochronal annealing. $\varDelta Resid = h_{FEpre\text{-}rad}\text{-}h_{FEannealed}$ is the unrecovered h_{FE} even after 400 °C of annealing.

The variation of recovery factors for 100 MeV P^{7+} and 80 MeV N^{6+} ions are illustrated in Fig. 17. From the figure, it is observed that the RFs are more for 80 MeV N^{6+} ion irradiated SiGe HBTs when compared to 100 MeV P^{7+} ion irradiation. It is also observed that the Ann. eff. and Ann. contr. of both 100 MeV P^{7+} and 80 MeV N^{6+} ion irradiated SiGe HBTs are higher for isochronal annealing than those attributed to room temperature annealing or relaxation. Therefore isochronal annealing is more effective than relaxation. In room temperature detrapping of trapped charges is less due to the lack of energy to activate the trapped charges,

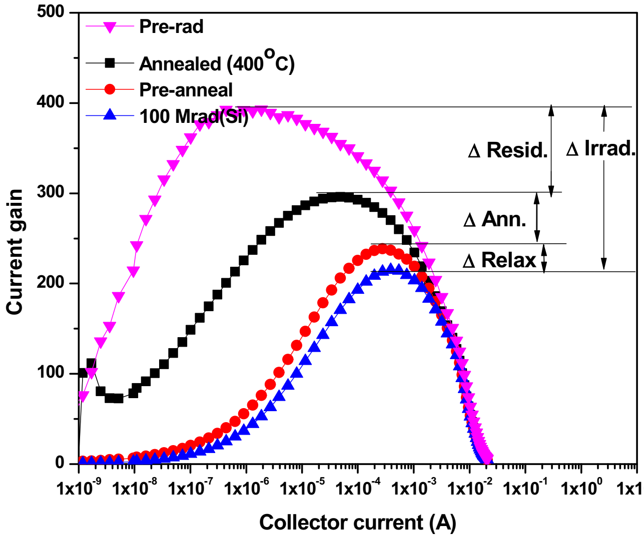

Fig. 16. Irradiation, relaxation and annealing curves schematically presented in order to define the recovery factors.

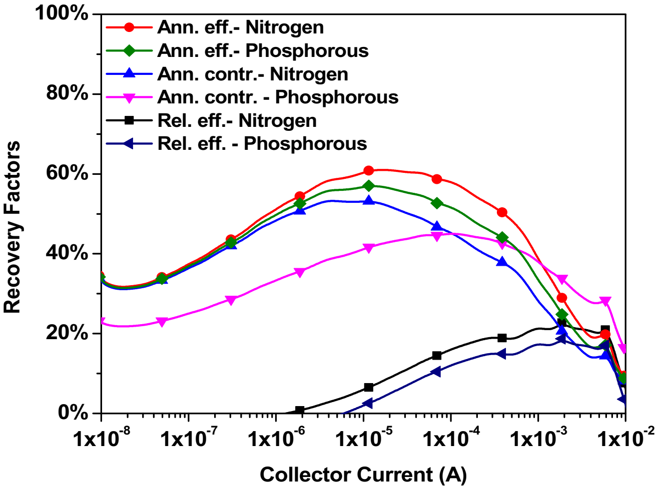

Fig. 17. The variation recovery factors for ion irradiated SiGe HBTs.

whereas, at sufficiently high temperature due to the thermal agitation, both vacancies and interstitial atoms in the lattice induced due to 100 MeV P^{7+} ions and 80 MeV N^{6+} ions become mobile and then recombined.

The annealing results show that the SiGe HBTs are still functioning even after a total dose of 100 Mrad and annealing up to 400 °C. The degradation in the transistor parameters is greater for P^{7+} ion irradiated SiGe HBT. Because of the high LET, P^{7+} ion transfers more energy to the lattice atoms of the SiGe HBT and creates more displacement damage along with the excitation and ionization when compared to N^{6+} ion. Even after the annealing up to 400 °C, ion induced defects are not completely recovered due to the bulk damages induced by the ions.

4. Conclusion

The present study reports the 100 MeV P^{7+} ions and 80 MeV N^{6+} ions tolerance of 200 GHz SiGe HBTs in the total dose range from 1 to 100 Mrad(Si). The DC electrical characteristics such as Gummel characteristics, ΔI_B, h_{FE}, *NBR*, *M-1 and* I_C-V_{CE} were studied systematically before and after irradiation and annealing. The SRIM simulation reveals that, 100 MeV P^{7+} ions have large LET and can create more damage in the SiGe HBTs structure when compared to 80 MeV N^{6+} ion. The degradation in the important parameter such as I_B as well as h_{FE} is mainly due to the radiation induced oxide trapped charges, interface states and displacement damages. The extracted damage constants show that the displacement damages increase with an increase in LET of incident radiation. The NBR study reveals that, BV_{CBO} increases with increase in radiation dose and is more in case of P^{7+} ion irradiated HBTs. The degradation of *M-1* is less, hence CB junction is more resilient to irradiation. Isochronal annealing studies reveal that, around 87% and 65% recovery in h_{FE} at the annealing temperature of 400 °C was observed for N^{6+} and P^{7+} ion irradiated devices respectively. The RFs show that the contribution of room temperature is less in recovery of degraded parameters when compared to isochronal annealing. The parameters of irradiated devices are acceptable even 100 Mrad(Si) of total dose.

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