CHAPTER 5

60Co GAMMA AND HIGH ENERGY ION IRRADIATION STUDIES ON 200 GHz SiGe HBTs

5.1. Introduction

The state-of-the-art advanced third generation SiGe HBTs were fabricated at IBM Microelectronics (IBM 8HP) and achieve a peak cut off frequency (peak $f_T$) of 200 GHz. The high performance of 200 GHz SiGe HBT was achieved by making radical changes in the structure of previous generation of SiGe HBT. The 200 GHz SiGe HBT technology employs a novel, reduced thermal cycle, “raised extrinsic base” structure. The conventional deep trench and shallow trench isolation, in addition to an in situ doped polysilicon emitter were maintained from prior technology nodes. The SiGe base region features an unconditionally stable 25% peak Ge and a C-doped SiGe profile deposited using UHV/CVD epitaxial growth techniques [58]. The device structure has been scaled laterally to 0.12 $\mu$m emitter strip width in order to minimize the base resistance and to improve the frequency response and noise characteristics. The raised extrinsic base structure facilitates the elimination of any out-diffusion of the extrinsic base, thereby significantly lowering the collector-base junction capacitance. The emitter-base (EB) spacer and the shallow trench isolation (STI) of the new structure are different from that of the first and second generation (IBM SiGe 5 HP and SiGe 7 HP) technologies. In the previous chapter we have identified that the emitter–base (EB) and shallow trench isolation (STI) oxide interface area are most prone to the formation of radiation induced traps. Since the overall processing thermal cycles have been significantly reduced, the robustness of the oxide interfaces to ionizing radiations has to be tested up to very high total dose [71]. Previously it was shown that 200 GHz SiGe HBTs demonstrate an increased proton and gamma tolerance over other previous SiGe technology nodes like 50 GHz and 100 GHz SiGe HBTs up to a total dose of 6 Mrad (Si) [72, 119]. The main advantage of 200 GHz SiGe HBT technology is that it offers substantial (multi-Mrad) total dose hardness without any intentional radiation hardening. Therefore the technology is favourable for high luminosity applications in high energy physics experiments like in upgrading the LHC at CERN, Geneva, Switzerland. Therefore, high dose irradiation data are essential to ascertain the device/circuit survivability for interplanetary space missions and LHC applications. In this work for the first time we have studied high energy ion irradiation effects on electrical characteristics of SiGe HBTs in addition to $^{60}$Co gamma irradiation. The devices were exposed to the same total doses of gamma and high energy ions to understand the effects of different species of radiation on the degradation of electrical characteristics.
5.2. Results and discussions

The 200 GHz SiGe HBTs were exposed to $^{60}$Co gamma radiation and different high energy ions such as 50 MeV lithium ions, 75 MeV boron ions and 100 MeV oxygen ions. The SiGe HBTs were irradiated at different total doses from 600 krad to 100 Mrad. The *in-situ* electrical measurements were carried after exposure to different total doses. The electrical characteristics like forward mode and inverse mode Gummel characteristics, excess base current, current gain, damage constant, neutral base recombination, avalanche multiplication of carriers and output characteristics are presented in the following sections.

5.3. The effects of $^{60}$Co gamma and high energy ion irradiation on the electrical characteristics of 200 GHz SiGe HBTs

The important electrical characteristics of $^{60}$Co gamma and ion irradiated SiGe HBT were studied before and after irradiation and the results are discussed below.

5.3.1. Forward Gummel characteristics

The SiGe HBTs with emitter area $0.12 \times 2 \, \mu m^2$, $0.12 \times 4 \, \mu m^2$ and $0.12 \times 8 \, \mu m^2$, were irradiated up to a total dose of 100 Mrad (Si). The typical forward mode Gummel characteristics of $^{60}$Co gamma, 50 MeV Li$^{3+}$ ion, 75 MeV B$^{5+}$ ion and 100 MeV O$^{7+}$ ion irradiated SiGe HBTs with emitter area of $0.12 \times 4 \, \mu m^2$ are shown in Figure 5.1 to 5.4. The results of the SiGe HBTs with $A_E$ of $0.12 \times 4 \, \mu m^2$ will be discussed and other devices showed similar degradation after gamma and ion irradiation. It is evident from the figures that, at low injection level the base current ($I_B$) increases with increasing radiation dose. The increase in $I_B$ with increase in radiation dose shows that the degradation mechanism is similar to the degradation mechanism observed in silicon BJTs and 50 GHz SiGe HBTs [136-141]. The radiation-induced damage in the EB spacer oxide increases the emitter-base depletion region. The recombination current in the depletion region can be observed as an additional $I_B$ in the lower emitter base voltage ($V_{BE}$) regime. However, the collector current ($I_C$) does not change with the increase in radiation dose, because the recombination in the depletion region does not affect the flow of electrons through the base. Therefore only the pre-rad $I_C$ is shown in the forward mode Gummel characteristics.
The post-irradiation forward mode $I_B$ normalized to the pre-rad $I_B$, (i.e., $I_{B\text{Post}} / I_{B\text{Pre}}$) for $^{60}$Co gamma, 50 MeV Li$^{3+}$ ion, 75 MeV B$^{5+}$ ion and 100 MeV O$^{7+}$ ion irradiated SiGe HBTs are shown in Figures 5.5 to 5.8. It is can be seen from the figures that the $I_B$ increases significantly at the lower $V_{BE}$ with increase in total dose since the trapped charges in the EB spacer oxide increases with increase in dose. It can be also seen that the normalized $I_B$ is more for higher linear energy transfer (LET) radiation, therefore higher LET radiation induce more G/R trapped charges in EB spacer oxide. The increase in the normalised $I_B$ for 75 MeV B$^{5+}$ ion irradiated SiGe HBT is more when compared to 100 MeV O$^{7+}$ ion and is unexpected.
The $I_B$ is extracted at $V_{BE} = 0.65$ V for various doses ($I_{Bpost}$) from forward mode Gummel characteristics. The excess base current ($\Delta I_B = I_{Bpost} - I_{Bpre}$) is calculated and plotted versus total dose for SiGe HBTs irradiated with gamma and different ions. Figure 5.9 shows the forward mode excess base current ($\Delta I_B$) and Figure 5.10 shows the forward mode normalised excess base current ($\frac{\Delta I_B}{I_B} \times 100$) for gamma and ion irradiated SiGe HBTs. The forward mode $\Delta I_B$ increases by around 90% after ion irradiation and around 80% after gamma irradiation. The increase in forward mode $\Delta I_B$ is more after ion irradiation when compared to $\Delta I_B$ after gamma irradiation. Therefore high energy ions create more G/R trapped charges in SiGe HBTs when compared to gamma irradiation. In SiGe HBT, the EB spacer oxide is an oxide/nitride
composite and the effects of nitrogen near the insulator/silicon improves the radiation hardening by undergoing recombination in short time, thereby leaving fewer radiation induced G/R traps [2, 130].

Figure 5.9: The variation in forward mode excess base current at $V_{BE} = 0.65$ V after gamma and ion irradiation.

Figure 5.10: The variation in forward mode excess base current normalised to 100 for gamma and ion irradiated SiGe HBT.

5.3.2. Inverse Gummel characteristics

The inverse mode Gummel characteristic was measured after every cumulative dose to study the charge build-up in the STI oxide. The inverse mode Gummel characteristics of $^{60}$Co gamma, 50 MeV Li$^{3+}$ ion, 75 MeV B$^{5+}$ ion and 100 MeV O$^{7+}$ ion irradiated SiGe HBTs are shown in Figures 5.11 to 5.14 respectively. It is evident from the figures that as the total dose increases, the $I_B$ at the lower $V_{BE}$ increases monotonically. The increase in inverse mode $I_B$ is the result of increased trapped charge in the STI oxide. The post-irradiation inverse mode $I_B$ normalized to the pre-irradiation $I_B$ for $^{60}$Co gamma, 50 MeV Li$^{3+}$, 75 MeV B$^{5+}$ and 100 MeV O$^{7+}$ ion irradiated SiGe HBTs are shown in Figure 5.15 to 5.18 respectively. It is clear from the figures that after every cumulative dose the trapped charge build up in the STI oxide increases. The oxide trapped charges near the silicon/oxide interface increase the depletion region near the CB junction. Therefore, the inverse mode $I_B$ increases with increase in charge build-up near the STI oxide. The inverse mode normalised $I_B$ is increased around two orders of magnitude after gamma and ion irradiation.
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Figure 5.11: Inverse mode Gummel characteristics of $^{60}$Co gamma irradiated SiGe HBT.

Figure 5.12: Inverse mode Gummel characteristics of 50 MeV Li$^{3+}$ ion irradiated SiGe HBT.

Figure 5.13: Inverse mode Gummel characteristics of 75 MeV B$^{5+}$ ion irradiated SiGe HBT.

Figure 5.14: Inverse mode Gummel characteristics of 100 MeV O$^{7+}$ ion irradiated SiGe HBT.

Figure 5.15: Inverse mode normalised base current ($I_{Bpost}/I_{Bpre}$) of $^{60}$Co gamma irradiated SiGe HBT.

Figure 5.16: Inverse mode normalised base current ($I_{Bpost}/I_{Bpre}$) of 50 MeV Li$^{3+}$ ion irradiated SiGe HBT.
Figure 5.17: Inverse mode normalised base current ($I_{B\text{Post}}/I_{B\text{Pre}}$) of 75 MeV $^5\text{B}$ ion irradiated SiGe HBT.

Figure 5.18: Inverse mode normalised base current ($I_{B\text{Post}}/I_{B\text{Pre}}$) of 100 MeV $^7\text{O}$ ion irradiated SiGe HBT.

The $I_{B}$ is extracted at $V_{BE} = 0.65$ V for various doses ($I_{B\text{Post}}$) from inverse mode Gummel characteristics. The inverse mode excess base current ($\Delta I_B = I_{B\text{Post}} - I_{B\text{Pre}}$) plotted versus total dose for gamma and different ions irradiated SiGe HBTs are shown in Figure 5.19. The inverse mode normalised excess base current $\left(\frac{\Delta I_B}{I_B} \times 100\right)$ for gamma and ion irradiated SiGe HBTs is shown in Figure 5.20. It can be seen from the figures that the increase in inverse mode $\Delta I_B$ is more for gamma irradiated SiGe HBT when compared to ion irradiated SiGe HBTs. Therefore more G/R trapped charges are created in shallow trench isolation (STI) oxide after gamma irradiation when compared to high energy ion irradiation. In the previous section 5.3.1, it was shown that EB spacer oxide is more radiation tolerant to ionizing radiation, but susceptible to damages after high energy ion irradiation. Therefore the radiation response of EB spacer oxide is different from that of STI oxide for different type of radiation since EB spacer oxide is composed by oxide/nitride composite whereas STI oxide is purely silicon dioxide (SiO$_2$). The SiO$_2$ is more susceptible to damage after exposure to ionizing radiation (gamma radiation) when compared to high energy ions.
5.3.3. Current gain

The DC current gain \((h_{FE})\) versus collector current \((I_C)\) for gamma and different ion irradiated SiGe HBTs are shown in Figures 5.21 to 5.24. It can be seen from the figures that \(h_{FE}\) decreases as expected with increase in total dose. The decrease in \(h_{FE}\) is consistent with the increase in the forward mode \(\Delta I_B\). The radiation-induced recombination centers decrease the minority-carrier lifetime, which in turn is the dominant mechanism for gain degradation in addition to G/R centers created in the EB spacer oxide. In gamma irradiated SiGe HBT, the deviation of DC \(h_{FE}\) at 10 Mrad is due to the raise in \(I_B\) (between \(V_{BE} = 0.4\) to 5.5 V). The subsequent roll back of \(I_B\) after 10 Mrad is due to hydrogen passivation of G/R trap centers during the extended period of irradiation time [142]. Therefore from 30 Mrad the current gain follows the previous trend which was before 10 Mrad and continues up to 100 Mrad. The \(h_{FE}\) decreases systematically in ion irradiated SiGe HBTs. The \(h_{FE}\) decreases and shifts towards higher \(V_{BE}\) or higher \(I_C\) and the shift in peak \(h_{FE}\) is due to non-ideal increase in \(I_B\). The biasing voltage for SiGe HBTs in front-end readout electronics in LHC is taken around 0.75 V. The corresponding collector current density at 0.75 V is about 100 \(\mu A/\mu m^2\). The decrease in \(h_{FE}\) at this particular collector current density is around 35% to 50% for SiGe HBTs irradiated with different radiations after 100 Mrad of total dose. Therefore one can conclude that the gain degradation is still acceptable under normal circuit biasing conditions.
The change in peak $h_{FE}$ with total doses for gamma and ion irradiated SiGe HBTs is shown in Figure 5.25. It is evident from the figure that the peak $h_{FE}$ decreases from 425 to 210 for $^{60}$Co gamma irradiated SiGe HBT after 100 Mrad of total dose. Similarly, the peak $h_{FE}$ decreases from 326 to 157 after 50 MeV Li$^{3+}$ ion irradiation, from 218 to 100 after 75 MeV B$^{5+}$ ion irradiation and from 382 to 137 after 100 MeV O$^{7+}$ ion irradiation. The peak $h_{FE}$ for all the SiGe HBTs irradiated with different radiation is well above 50. It is reported that the $h_{FE}$ of about 50 is required for the efficient circuit design in case of bipolar front-end readout for silicon detectors [143]. Therefore the $h_{FE}$ of irradiated SiGe HBTs is acceptable even after 100 Mrad of radiation total dose and one can conclude that the gain degradation is still acceptable under normal circuit biasing conditions. The normalised peak current gain for SiGe
HBTs irradiated with different radiations is shown in Figure 5.26. It is clear from the figure that the peak $h_{FE}$ decreases by 46%, 52%, 54% and 65% following $^{60}$Co gamma, 50 MeV Li$^{3+}$ ion, 75 MeV B$^{5+}$ ion and 100 MeV O$^{7+}$ ion irradiation. The decrease in peak $h_{FE}$ is more for higher LET radiation when compared to lower LET radiation.

![Figure 5.25: The peak current gain versus total dose for gamma and ion irradiated SiGe HBTs.](image1.png)

![Figure 5.26: The current gain normalised to pre irradiation value $[(h_{FEpost}/h_{FEpre})\times100]$ as a function of total dose for gamma and ion irradiated SiGe HBTs.](image2.png)

The variation of $\Delta \left( \frac{1}{h_{FE}} \right)$ versus total dose for $^{60}$Co gamma and different ion irradiated SiGe HBTs is shown in Figure 5.27 and the damage constant ($K$) is calculated from the slope. The damage constants for $^{60}$Co gamma and different ion irradiated SiGe HBTs are tabulated in Table 5.1. It can be seen that the damage constant increases with increase in LET of the incident radiation. However the damage constant is slightly more for 75 MeV B$^{5+}$ ion irradiated SiGe HBT when compared to 100 MeV O$^{7+}$ ion irradiated SiGe HBT and it is unexpected. After heavy ion irradiation more number of secondary electrons produces and inturn more displacement damage occurs in SiGe HBTs. The irradiation with the higher LET ion will create more number of secondary electrons and therefore the displacement damages also increases. The higher LET ion impart more energy in the target material in short span of time which lead to more ionizations/excitations and the residual energy of the ionized electrons (secondary electrons) furthur result in ionization and displacement damages.
Table 5.1: Damage constant for gamma and different high energy ion irradiated SiGe HBTs.

<table>
<thead>
<tr>
<th>Radiation</th>
<th>Damage constant, ( K ) (Mrad(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{60})Co gamma</td>
<td>0.4061 ± 0.036</td>
</tr>
<tr>
<td>50 MeV lithium ions</td>
<td>0.4389 ± 0.045</td>
</tr>
<tr>
<td>75 MeV boron ions</td>
<td>0.5746 ± 0.032</td>
</tr>
<tr>
<td>100 MeV oxygen ions</td>
<td>0.5098 ± 0.064</td>
</tr>
</tbody>
</table>

Figure 5.27: The \( \Delta \left( \frac{1}{h_{FE}} \right) \) versus total dose for gamma and ion irradiated SiGe HBTs.

5.3.4. Neutral base recombination

The impact of \(^{60}\)Co gamma radiation, 50 MeV Li\(^{3+}\) ion, 75 MeV B\(^{5+}\) ion and 100 MeV O\(^{7+}\) ions on the neutral base recombination (NBR) characteristics of SiGe HBTs are shown in Figures 5.28 to 5.31. The radiation induced trap states in the base region can be assessed through the NBR measurements after irradiation. 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 \( V_{BE} \) [61, 144, 145]. It can be clearly seen from the figures that the slope of the NBR curve at lower \( V_{CB} \) is almost same for pre-rad and 100 Mrad curves. There is negligible amount of displacement damage in the neutral base region of SiGe HBT even after 100 Mrad total doses. However the collector-base breakdown voltage (\( BV_{CBO} \)) increases with increase in radiation total dose. The radiation induced electric field in the CB junction negatively impacts the device performance after irradiation.
5.3.5. Avalanche multiplication

Figures 5.32 to 5.35 show the extracted avalanche current multiplication factor for pre-irradiated and post-irradiated M-1 curves for gamma and ion irradiated SiGe HBTs respectively. This is a particularly important issue for the 200 GHz SiGe HBTs technology, since the higher frequency response of the 200 GHz SiGe HBTs comes partially as a result of a high collector doping profile and hence lower breakdown voltage (1.2 V in this case). M-1 in the CB junction is sensitive to local electric field and hence determines breakdown voltage [73]. The M-1 represents the number of electron/hole pairs generated in the CB space charge region per electron as a function of \( V_{CB} \). The charge build-up in the STI oxide changes the electric field in the CB junction thereby M-1 increases. From the figure it can be seen that M-1 slightly decreases after gamma irradiation. At lower \( V_{CB} \) the change in M-1 is negligible and at higher \( V_{CB} \) there is no much change in M-1 after 100 Mrad of ion total dose.
Therefore the radiation induced electric field in CB junction is very small and the displacement damages in CB junction are negligible in 200 GHz SiGe HBTs.

Figure 5.32: The avalanche multiplication of carriers for 60Co gamma irradiated SiGe HBT.

Figure 5.33: The avalanche multiplication of carriers for 50 MeV Li3+ ion irradiated SiGe HBT.

Figure 5.34: The avalanche multiplication of carriers for 75 MeV B5+ ion irradiated SiGe HBT.

Figure 5.35: The avalanche multiplication of carriers for 100 MeV O7+ ion irradiated SiGe HBT.

5.3.6. Output characteristics

The output characteristics of SiGe HBTs measured at IB = 2.25 μA for un-irradiated and 60Co gamma, 50 MeV Li3+, 75 MeV B5+ and 100 MeV O7+ ion irradiated SiGe HBTs are shown in Figures 5.36 to 5.39. From the figures it can be seen that, IC at saturation and active region decreases after irradiation. The gamma and ion irradiation produce secondary electrons and induce small number of point defects in collector region and this increases the collector series resistance and thereby reducing the IC at saturation and active region.
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The ICsat extracted at V_{CE} = 1 V from output characteristics is plotted versus total dose for gamma and ion irradiated SiGe HBTs and is shown in Figure 5.40. From the figures it is evident that the I_c decreases with increase in total dose. The gamma radiation and heavy ions produce secondary electrons and induce small number of point defects in collector region and this increase the collector series resistance and thereby reducing the I_c at saturation region. The difference between pre-rad I_c and post-rad I_c (ΔI_c = I_{C Pre-rad} – I_{C Post-rad}) is plotted versus total dose in Figure 5.41. The ΔI_c increases with increase in radiation total dose for different radiation. After 100 Mrad of total dose the decrease in I_c is around 30% for gamma, lithium and boron irradiated SiGe HBTs. The decrease in ΔI_c is minimal (15%) for oxygen ion irradiated SiGe HBT when compared to other radiation.
The above results show that the SiGe HBTs are still working satisfactorily even after 100 Mrad of total dose. In case of analog or RF circuits the current gain required is typically large but in digital circuits the current gain is not a key design parameter affecting circuit performance. The $I_C$ at which the transistor is operated depends on the circuit and may not necessarily be near the peak current gain [146]. The peak current gain of SiGe HBT is well above 50 and hence the SiGe HBTs can be considered for digital applications. Therefore the SiGe HBTs can be considered for the upgrade of front-end electronics of the ATLAS detector in LHC, CERN in Geneva, Switzerland. The radiation tolerance of SiGe HBTs is not due to the presence of the Ge in the base region. The inherent structural design of SiGe HBTs lends itself to an enhanced tolerance to radiation damage. The raised extrinsic base structure of SiGe HBTs lends it the inherent enhanced radiation tolerance over other generations of SiGe HBTs. The small active volume of the transistor reduces the effects of displacement damage. The emitter-base spacer is also relatively thin and comprised of an oxide/nitride composite, which increases radiation tolerance. In addition, the heavily doped extrinsic base layer ($<10^{19}$ cm$^{-3}$ peak doping) directly underneath the spacer effectively confines ionization damage of the EB spacer and helps prevent degradation of the $I_B$ ideality under ionizing radiation. Also very small active volume of the transistor with high emitter, base and collector doping profile, reduces the impact of displacement damage [3]. These factors combine to make 200 GHz SiGe HBTs robust to ionizing radiation without intentional radiation hardening, which makes them a potential candidate for space and LHC applications.
It is evident from the results that high energy ions create slightly more damage in I-V characteristics when compared to $^{60}$Co gamma radiation even though there is large difference in LET. As mentioned earlier, the irradiation time required to reach high total dose is more for gamma irradiation facility when compared to ion irradiation facility. The irradiation time taken to reach 100 Mrad of total dose for different radiation is given in Table 2.1. It can be seen from the table that the ion irradiation time substantially reduces when compared to gamma irradiation time. In case of $^{60}$Co gamma radiation, the irradiation time to reach 100 Mrad of total dose is about one week (166 hrs 40 min). But for the same total dose, with 50 MeV Li ion irradiation time is 43 min 52 s, with 75 MeV B ion irradiation time is 27 min 48 s and with 100 MeV O ion the irradiation time is 18 min 4s. For a same total dose the ion irradiation time is less because the ion fluence will be different for different ions. The ion fluence decreases with increase in atomic number of the impinging ions and hence the irradiation time decreases. For a particular total dose, different ions create almost same amount of damage in SiGe HBTs. Therefore different ions create almost same density of trapped charges due to difference in LET of the ions. Hence, the degradation observed in ion irradiated SiGe HBTs is almost same. It is clear from these results that heavy ion irradiation facilities such as Pelletron accelerators can be used to study worst case total dose radiation effects on SiGe HBTs.

### 5.4. Conclusions

The effects of $^{60}$Co gamma, 50 MeV Li$^{3+}$ ion, 75 MeV B$^{5+}$ ion and 100 MeV O$^{7+}$ ion irradiation on the electrical characteristics of 200 GHz SiGe HBTs are studied systematically. The following conclusions are drawn on the basis of experimentally observed results:

- The effects of gamma and ion irradiation on the electrical characteristics of 200 GHz SiGe HBTs were studied in the total doses from 600 krad to 100 Mrad. The important electrical characteristics such as forward and inverse mode Gummel characteristics, excess base current, current gain, neutral base recombination, avalanche multiplication of carriers and output characteristics were studied before and after irradiation. The radiation induced oxide trapped charges, interface trapped charges in the EB spacer oxide and STI oxide is responsible for the observed change in the electrical characteristics of 200 GHz SiGe HBTs.

- The ion irradiation creates more trapped charges in SiGe HBT when compared to $^{60}$Co gamma irradiation. The forward mode $\Delta I_B$ is almost same for different LET.
high energy ions after 100 Mrad of total dose, indicating that ions create same amount of damage when compared to $^{60}$Co gamma radiation

- The degradation in inverse mode $\Delta I_B$ is found to be more for $^{60}$Co gamma irradiated SiGe HBT when compared to ion irradiated SiGe HBTs. This indicates that $^{60}$Co gamma creates more trapped charges and defects in STI oxide when compared to ion irradiation

- The radiation response of EB spacer oxide is different from that of STI oxide for different radiations. The EB spacer oxide is oxide/nitride composite whereas, the STI oxide is silicon dioxide ($\text{SiO}_2$). The effect of nitrogen near the insulator/silicon improves the radiation hardening by increasing the recombination near the oxide/nitride interface

- The decrease in $h_{FE}$ is due to increased surface recombination current by radiation induced G/R trapped in EB spacer oxide. In addition the bulk damages reduce the minority carrier lifetime and hence $h_{FE}$ decreases

- The peak $h_{FE}$ decreases more rapidly with increase in LET of the incident radiation. The higher LET radiation has more damage constant when compared to lower LET radiation. But the damage constant for boron irradiated SiGe HBT show slight deviation from this observation

- The displacement damage is negligible in neutral base region after ion irradiation and after 100 Mrad of total dose, $B_{\text{CBO}}$ increases with increase in total dose

- The change in M-1 is very small for ion irradiated SiGe HBT and hence there is minimum change in the local junction electric field

- The $I_C$ at saturation and active region decreases with increase in total dose and the decrease in $I_C$ is not dependent on the LET of the incident radiation

- The 200 GHz SiGe HBTs exhibit better performance when compared to 50 GHz SiGe HBT. Therefore 200 GHz SiGe HBTs can be used for the readout ASIC built for the ATLAS detector in LHC, CERN, Geneva for 5 to 8 years of LHC operation