J. Nano- Electron. Phys.
3 (2011) No1, P. 348-357

PACS numbers: 72.20.Jv, 61.82.Fk, 61.80.Ed

ANALYSIS OF HIGH ENERGY ION, PROTON AND Co-60 GAMMA RADIATION INDUCED DAMAGE IN ADVANCED 200 GHz SiGe HBTs

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Third generation advanced Silicon-Germanium Heterojunction Bipolar Transistors (200 GHz SiGe HBTs) were exposed to different radiations like 50 MeV lithium ions, 63 MeV proton and Co-60 gamma radiation in the dose range of 300 krad to 10 Mrad. The DC electrical characteristics like forward mode Gummel characteristics, inverse mode Gummel characteristics, excess base current, current gain, neutral base recombination, avalanche multiplication and output characteristics were measured before and after irradiation for three different radiations and the results are compared in this paper. The results show that the Li^+ ions impart more energy and create significant amount of damage in the surface and bulk of the transistor when compared to gamma and proton irradiation.

Keywords: *200 GHz SiGe HBT, Co-60 GAMMA, PROTON, LITHIUM ION IRRADIATION, EB SPACER OXIDE, STI OXIDE.*

(Received 04 February 2011, in final form 29 April 2011)

1. INTRODUCTION

SiGe HBT BiCMOS technology represents a compelling low-cost, highly integrated, silicon-based solution for wide variety of IC applications. SiGe HBT technology is particularly exciting because of its ability to take the advantage of highly developed silicon processing techniques. Impressive improvements in high-speed SiGe bipolar technology have been made through the growth of device quality strained $Si_{1-x}Ge_x$ layers [1]. The performance of SiGe HBTs has also improved rapidly because of the advantages of bandgap engineering and comparative ease of vertical and lateral device scaling in SiGe technology. Simultaneously, understanding the physics and location of radiation induced damage is also important not only for scientific reasons but for circuits especially those where exposure to radiation may be an issue. In particular, the SiGe HBTs have demonstrated excellent radiation hardness to both total dose and displacement damage without intentional radiation hardening, making them attractive for space and high energy physics experiment applications [2-3]. In space applications, the high probability for the impact of high energy particles (cosmic rays) with electronic circuits is the main reason for temporary or permanent malfunctions of the electronic equipments. Besides, the ability to operate in the presence of high doses of ionizing radiation is a basic requirement for the electronic circuits used in the high-energy physics (HEP) experiments like in large hadron colliders (LHCs). These reasons explain the strong interest of researchers for developing and designing radiation tolerant SiGe BiCMOS technology for use in radiation rich environment. When SiGe HBTs are exposed to high energetic particles, the resulting effects from this radiation can cause severe degradation in the device performance and of its operating life. The device reliability is defined as the ability to properly operate while accumulating high levels of total ionization dose (TID) and to be insensitive to single event effects caused by the passage of single ionizing particles through the active volumes of the device. Many researchers have studied single event effects and charge collection in SiGe HBT due to heavy ion and micro beam irradiation [4-6]. The total dose effects of heavy ions are well studied for conventional devices like power devices. In the present investigation, we have studied the total dose effects of heavy ion irradiation on SiGe HBTs. Further we compare the different LET radiation induced damages in the EB and CB junctions of SiGe HBT through I-V characteristics to better understand the influence of different LET on the I-V characteristics of SiGe HBTs. This work assesses the potential use of radiation tolerant SiGe HBTs in the electronics used for HEP experiments. Also, this paper comprehensively discusses the advantage of high energy ions in radiation hardness testing of SiGe HBTs over gamma and proton radiation.

2. EXPERIMENT

The 8 HP SiGe BiCMOS ICs integrate 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 Si CMOS devices. To achieve simultaneously high f_T and f_{MAX}, the NPN vertical and lateral dimensions have been reduced compared to the earlier SiGe IC generations [7]. The epitaxial layer thickness, collector and base doping concentrations were scaled to be similar to that described in [8] to achieve a target of 200 GHz. The boron dose in the as-grown SiGe base layer is 5×10^{13} cm^{-2}. A low pinched-base sheet resistance is targeted along with the high f_T to maintain good manufacturing control of f_T as well as f_{MAX}, with process variations in emitter and spacer width, as well as when using above-minimum emitter widths for tight matching. The emitter in this new structure is defined by a disposable mandrel. A raised extrinsic base is formed self-aligned to this mandrel. The mandrel is then etched away and an in situ phosphorus-doped polysilicon emitter is formed by deposition and annealing. Base resistance (R_{BB}) is reduced by minimizing the resistance of the extrinsic base polysilicon and narrowing the emitter and the emitter to extrinsic base spacer dimension [9]. The schematic device cross-section of SiGe HBT used for the present study is shown in Fig. 1.

The SiGe HBTs (NPN) are selected by dicing a 200 mm SiGe wafer and the emitter, base and collector terminals are wire bonded to a 28 pin dual inline package (DIP). Two sets of three different emitter area (A_E) geometries 0.12×2 μm^2, 0.12×4 μm^2 and 0.12×8 μm^2 are selected for irradiation studies, but for brevity the devices with $A_E = 0.12 \times 4$ μm^2 will be shown (the other geometry devices showed the same results). The DIP packages containing different emitter area 8HP SiGe HBTs are irradiated with 50 MeV Li^{3+} ion in a 15 UD (16 MV) Pelletron Accelerator at Inter

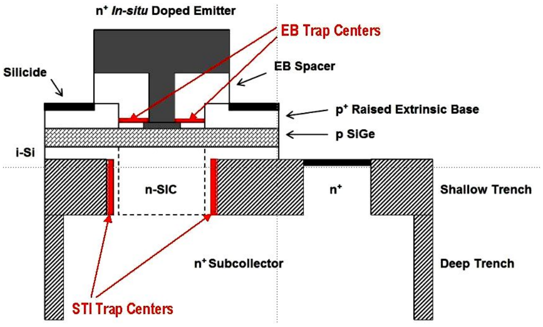

Fig. 1 *– The schematic device cross-section of* 200 *GHz SiGe HBT*

University Accelerator Centre (IUAC), New Delhi. The typical Li^{3+} ion beam current is 0.833 pnA and SiGe HBTs are irradiated for different total doses ranging from 300 krad to 10 Mrad. The Li^{3+} ion irradiated SiGe HBT results are compared with Co-60 gamma and 63 MeV proton irradiation results in the same dose range. DC electrical characteristics like forward mode Gummel characteristics, inverse mode Gummel characteristics, excess base current ($\Delta I_B = I_{Bpost} - I_{Bpre}$), dc current gain ($h_{FE}$), neutral base recombination (NBR), avalanche multiplication ($M - 1$) and output characteristics are characterized for three different radiations. The devices are characterized within 30 min after irradiation following MIL-STD 883 Method 1019 to avoid time dependent annealing, which changes the electrical effects of damage formation.

3. RESULTS AND DISCUSSIONS

Fig. 2 shows the forward mode Gummel characteristics for 50 MeV Li^{3+} ion irradiated SiGe HBT. From Fig. 2 it is clear that the base current (I_B) increases at lower V_{BE}, as expected, with increasing Li^{3+} ion total dose. Similarly, the I_B increases for Co-60 gamma and 63 MeV proton irradiated SiGe HBTs. The radiation induces generation-recombination trapping centers in emitter-base (EB) spacer oxide. The increase in I_B is the result of increased recombination current in the EB depletion region due to radiation-induced G/R traps near EB spacer oxide. Previous studies have shown that the ionizing radiations damage the periphery of the EB spacer oxide and ion irradiation creates damage inside the EB spacer oxide [10-11]. The collector current (I_C) remains almost same even after 10 Mrad of total doses and hence only one I_C curve is shown in the figure for brevity.

Fig. 3 shows the forward mode excess base current ($\Delta I_B = I_{Bpost} - I_{Bpre}$) for Co-60 gamma, 50 MeV Li^{3+} ion and 63 MeV proton irradiated SiGe HBTs. The I_B is extracted at $V_{BE} = 0.65$ V to reduce high injection effects where large carrier densities severely diminish the G/R effects of radiation induced traps. From the figure it is evident that the increase in ΔI_B is more for Li^{3+} ion irradiated SiGe HBT when compared to gamma and proton irradiated SiGe HBT. Therefore more damage is induced in SiGe HBT structure after Li^{3+} ion irradiation when compared to gamma and proton irradiation. A closer look at the figure shows that ΔI_B is more for proton irradiated SiGe HBT when compared to gamma irradiated SiGe HBT.

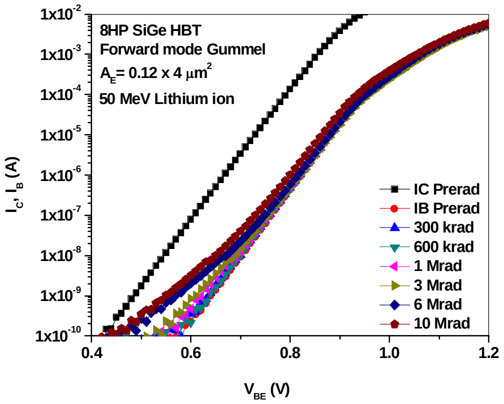

***Fig. 2** – Forward mode Gummel characteristics*

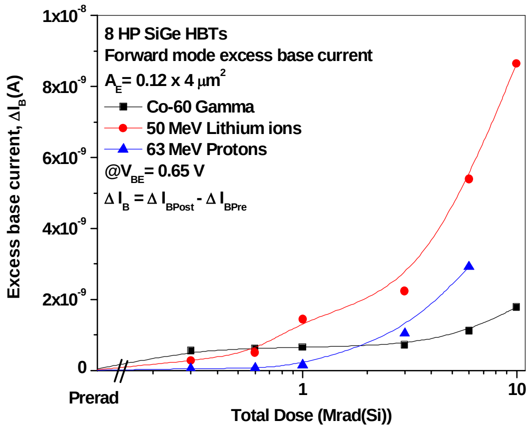

***Fig. 3** – Forward mode excess base current for Co-*60 *gamma,* 50 *MeV Lithium ion and* 63 *MeV proton irradiated* 8 *HP SiGe HBTs*

Fig. 4 shows the inverse mode Gummel characteristics for SiGe HBT irradiated with 50 MeV Li^{3+} ions. From the figure one can observe that as the Li^{3+} ion total dose increases the I_B increases at low injection. In this case, the Li^{3+} ion induced traps in the shallow trench isolation (STI) oxide now act as G/R trap centers in the inverse EB junction. These G/R traps increase the I_B by generation-recombination process and hence the I_B increases at lower V_{BE} [2].

Fig. 5 shows the inverse mode excess base current (ΔI_B) for Co-60 gamma, 50 MeV Li^{3+} ion and 63 MeV proton irradiated SiGe HBTs. The increase in inverse mode ΔI_B is more for gamma irradiated SiGe HBT when compared to proton and Li^{3+} ion irradiated SiGe HBT up to 4 Mrad of total dose. Therefore more G/R trapped charges are created by gamma radiation when compared to proton and Li^{3+} ions. But in EB spacer oxide (see Fig. 3), the Li^{3+} ions create more damage than proton and gamma radiation. Therefore the radiation response of EB spacer oxide is different from that of STI oxide for different radiations. This different behavior of EB spacer oxide and STI oxide to different radiation is because the EB spacer oxide is

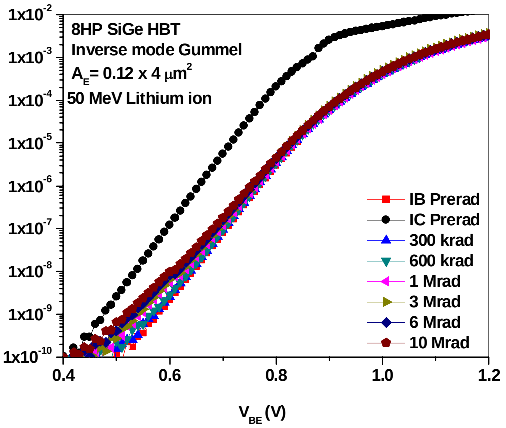

***Fig. 4** – Inverse mode Gummel characteristics*

oxide/nitride composite whereas, the STI oxide is silicon dioxide (SiO_2). The effect of nitrogen near the insulator/silicon improves the radiation hardening by undergoing very small amount of ionization and creating less number of radiation induced *G/R* traps [10-12]. Hence the EB spacer oxide is immune to gamma radiation and STI oxide undergoes more ionization for gamma radiation. Above 4 Mrad of total dose the increase in inverse mode ΔI_B is more for Li^{3+} ion irradiated SiGe HBT when compared to gamma irradiated SiGe HBT. The inverse mode ΔI_B for proton irradiated SiGe HBT is slightly less when compared to Li^{3+} ion and gamma irradiated HBT.

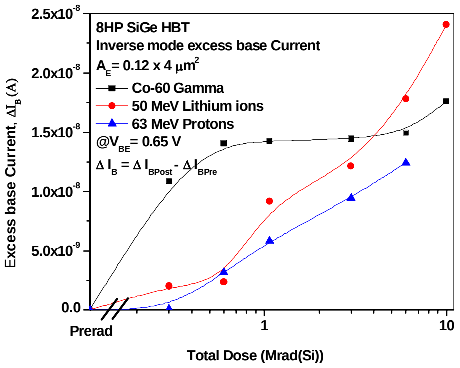

***Fig. 5** – Inverse mode excess base current for Co-60 gamma, 50 MeV Lithium ion and 63 MeV proton irradiated 8 HP SiGe HBTs*

Fig. 6 shows the dc current gain for Li^{3+} ion irradiated SiGe HBT. It can be seen that as the Li^{3+} ion total dose increases the current gain decreases due to increase in I_B. The peak current gain decreases and shifts towards to higher I_C with increasing Li^{3+} ion total dose and the shift in peak current gain is due to increase in I_B at low V_{BE}. Similar trend in current gain degradation was observed for proton and gamma irradiated 8 HP SiGe HBTs. Fig. 7 shows the decrease in peak current gain for Co-60 gamma, 50 MeV Li^{3+} ion and 63 MeV proton irradiated SiGe HBTs. The decrease in peak current gain is more for Li^{3+} ion irradiated SiGe HBT and the results are consistent with forward mode ΔI_B. The results are very clear from the Fig. 8, which shows $\Delta(1/h_{FE})$ vs total dose up to 10 Mrad for Co-60 gamma, 50 MeV Li^{3+} ion and 63 MeV proton irradiated SiGe HBTs. The curves in the figure represent the intensity of damage created by different radiations according to the Messenger-Spratt equation [13]. The figure shows the increase in $\Delta(1/h_{FE})$ with total dose. The increase in $\Delta(1/h_{FE})$ is almost two times more for Li^{3+} ion irradiated SiGe HBT when compared to gamma and proton irradiated SiGe HBTs. Since 50 MeV Li^{3+} ions have higher linear energy transfer (LET) than 63 MeV proton and Co-60 gamma radiation, ions can degrade current gain of SiGe HBTs more when compared to proton and gamma radiations. Hence the increase in $\Delta(1/h_{FE})$ is more for Li^{3+} ion irradiated HBTs. The gamma and proton irradiated SiGe HBT have shown moreover same amount of degradation and there is no significant difference in the LET of 63 MeV protons and 1 MeV of electron (equivalent to Co-60 gamma radiation) [14]. Hence there is no much difference in $\Delta(1/h_{FE})$ for proton and gamma irradiated SiGe HBTs.

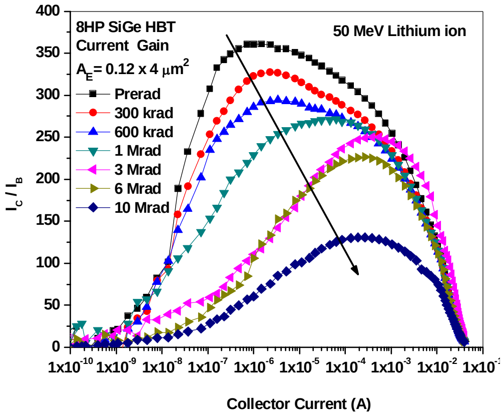

Fig. 6 – *Current gain for Li^{3+} ion irradiated 8HP SiGe HBT*

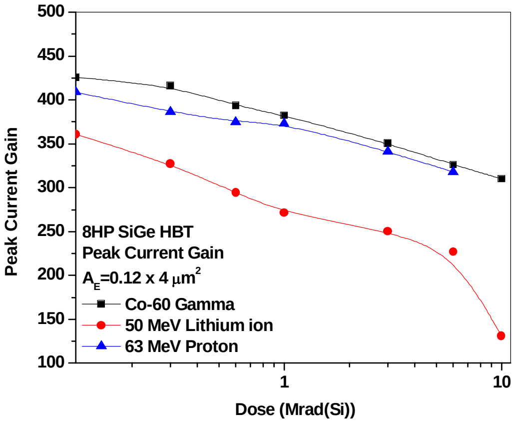

Fig. 7 – *Peak current gain for Co-60 gamma, 50 MeV Lithium ion and 63 MeV proton irradiated 8HP SiGe HBTs*

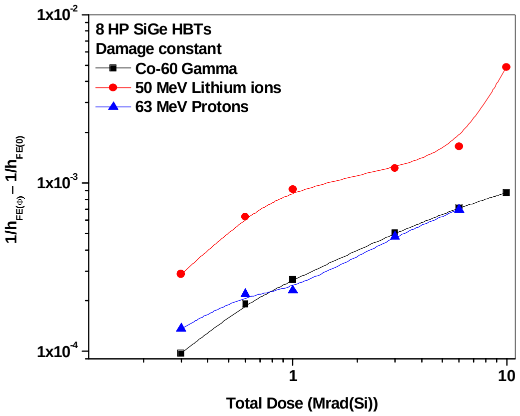

***Fig. 8** – $\Delta(1/h_{FE})$ vs total dose up to 10 Mrad of total dose for Co-60 gamma, 50 MeV Lithium ion and 63 MeV Proton irradiated 8 HP SiGe HBTs*

Fig. 9 shows the neutral base recombination (NBR) results for Li^{3+} ion irradiated SiGe HBT. The Li^{3+} ion induced trap states in the base region can be assessed through the NBR studies before and after irradiation. For a NPN transistor with non-negligible parasitic base current leakage, under arbitrary forward-active bias is the sum of hole current injected into the emitter, hole current due to impact ionization in the collector-base region and the NBR component. For small values of V_{CB}, the hole current due to impact ionization is negligible and I_B is dominated by the other two components. The NBR component of I_B is proportional to the total electron charge injected into the base region and inversely proportional to the electron lifetime in the neutral base region. Therefore, the NBR component can become increasingly important either by an increase in total electron charge injected to base region or by a decrease in electron lifetime in neutral base region. An increase in the trap states in the base region decreases electron lifetime in neutral base region and therefore decreases the electron diffusion length. When the electron diffusion length gets comparable to the neutral base width the NBR component of I_B becomes increasingly important. Non-negligible NBR implies that the effective electron diffusion length in the base region is comparable to the neutral base width (W_B) because of the reduction in electron lifetime due to the presence of traps in the base region. For a given electron lifetime in the base region, the NBR component of I_B is proportional to the total base charge. Therefore, any change in the base charge will change the NBR component of I_B. 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} [15]. The slope of the NBR curve at lower V_{CB} is almost same after 6 Mrad of total dose. Therefore one can expect negligible displacement damage in the base region of SiGe HBT. Similar behavior was observed in proton and gamma irradiated devices also. Fig. 10 shows the avalanche multiplication (M – 1) of carriers for SiGe HBT irradiated with Li^{3+} ions. The decrease in M – 1 is very negligible; hence the electron/hole pairs generated in the CB space-charge region have apparently failed to multiplicate the impact ionization with lattice atoms due to the formation of displacement damages by Li^{3+} ion irradiation [3]. Similar trend was observed for gamma and proton irradiated SiGe HBTs.

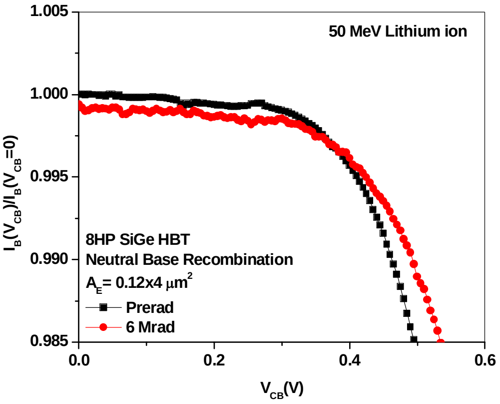

***Fig. 9** – Neutral base recombination for Li^{3+} ion irradiated 8HP SiGe HBT*

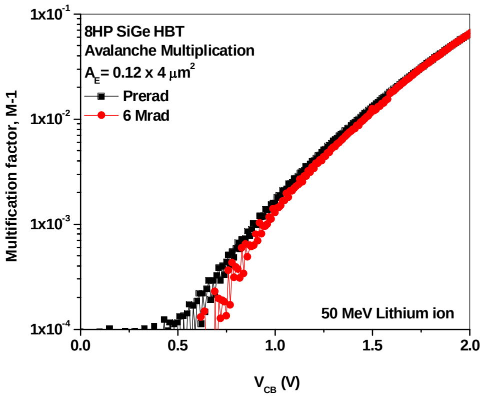

***Fig. 10** – Avalanche multiplication of carriers for Li^{3+} ion irradiated 8HP SiGe HBT*

Fig. 11 shows the output characteristics for Li^{3+} ion irradiated SiGe HBT at I_B = 2.25 μA. From the figure it is evident that as the Li^{3+} ion total dose increases the collector current at saturation region decreases. The radiation induced traps increase the collector series resistance of the SiGe HBT and hence the I_C at saturation decreases [2-3]. The increase in collector series resistance was observed more for Li^{3+} ion irradiated SiGe HBT when compared to gamma and proton irradiated SiGe HBT.

It is important to analyze the basic damage mechanisms in SiGe HBTs from different radiation sources. The main causes for degradation in DC electrical characteristics are ionization and displacement damage in surface and bulk region of HBT. Ionizing radiations create oxide trapped charges and interface state in EB spacer region, in turn increasing I_B and decreasing current gain. The displacement damages reduce the minority carrier life time in the device and also contribute to the gain degradation [16]. Since the minority carrier lifetime is inversely proportional to I_B, I_B increases and current gain decreases. The Li^{3+} ions and protons ionize and create displacement damage in the transistor structure whereas gamma radiation ionizes the transistor and create very few displacement damages. Therefore, more degradation is observed due to Li^{3+} ions when compared to

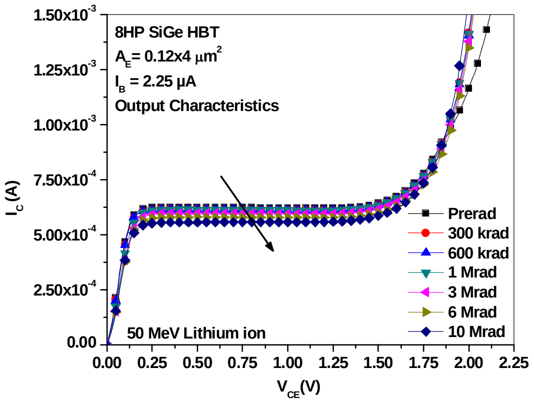

Fig. 11 *– Output characteristics for Li*$^{3+}$ *ion irradiated 8HP SiGe HBT at* $I_B = 2.25\ \mu A$

protons and gamma radiation; and protons create more damage when compared to gamma radiation. Though the degradation observed for Li^{3+} ion irradiated SiGe HBT is more when compared to other radiations, the SiGe HBT performance after 10 Mrad of total dose is acceptable. The inherent structural design of SiGe HBTs lends itself to an enhanced tolerance to radiation damage. The small active volume of the transistor reduces the effects of displacement damage. The emitter-base spacer (which is most susceptible to ionization damage) 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 base current ideality under ionizing radiation [11].

4. CONCLUSION

The effects of 50 MeV Li^{3+} ion irradiation on 200 GHz SiGe HBTs (NPN) are studied and the results are compared with gamma and proton irradiation results. The deterioration in DC IV characteristics in SiGe HBTs is more after Li^{3+} ion irradiation. The very high LET difference between Li^{3+} ion and 63 MeV proton or gamma is the main reason for the observed difference in device deterioration. However, the more degradation observed in the inverse mode operation of gamma irradiated SiGe HBT is related to the structure and composition of STI in SiGe HBT. The narrow emitter base spacer dimension of SiGe HBTs composing oxide/nitride composites improves the radiation tolerance of SiGe HBTs. It is reported that the current gain of about 50 is required for the efficient circuit design of bipolar front-end readout for silicon detectors [17] and the current gain of SiGe HBTs is acceptable even after 10 Mrad of Li^{3+} total dose. Hence, the inherent radiation tolerance of 8HP SiGe HBTs makes them a leading candidate for design of front-end readout ASICs for use in an upgraded LHC over other generations of SiGe HBTs [18].

5. ACKNOWLEDGEMENTS

The authors are grateful to Prof. K. Navakanta Bhat, Mr. Deepak and Mr. Santosh Chiniwar, Center of Excellence in Nanoelectronics, IISc, Bangalore for their help during the I–V measurements. Authors thank Dr. Ambuj Tripathi, IUAC, New Delhi and Dr. G. Govindaraj, Pondicherry University, Puducherry for helping in ion and gamma irradiations. This work is carried out under the IUAC Project Code No. UFUP-43309.

REFERENCES

1. J.D. Cressler, SiGe *and Si Strained-Layer Epitaxy for Silicon Heterostructure Devices* (Florida, CRC Press: 2008).
2. A.P.G. Prakash, A.K. Sutton, R.M. Diestelhorst, G. Espinel, J. Andrews, B. Jun, et al., *IEEE T. Nucl. Sci.* **53(6),** 3175 (2006).
3. K.C. Praveen, N. Pushpa, Y.P.P. Rao, G. Govindaraj, J.D. Cressler, A.P.G. Prakash, *Solid State Electron.* **54,** 1554 (2010).
4. J.A. Pellish, R.A. Reed, D. McMorrow, G. Vizkelethy, V.F. Cavrois, J. Baggio, et al., *IEEE T. Nucl. Sci.* **56(6),** 3078 (2009).
5. R.A. Reed, P.W. Marshall, J.C. Pickel, M.A. Carts, B. Fodness, G. Niu, *IEEE T. Nucl. Sci.* 5**0 (6),** 2183 (2003).
6. J.A. Pellish, R.A. Reed, A.K. Sutton, R.A. Weller, M.A. Carts, P.W. Marshall, et al. *IEEE T. Nucl. Sci.* **54(6),** 2322 (2007).
7. A. Joseph, D. Coolbaugh, M. Zierak, R. Wuthrich, P. Geiss, Z. He, et al., *Proc. BCTM*, 143 (2001).
8. S.J. Jeng, B. Jagannathan, J.S. Rieh, J. Johnson, K.T. Schonenberg, D. Greenberg, et al., *IEEE Electron. Dev. Lett.* **22,** 542 (2001).
9. B. Jagannathan, M. Khater, F. Pagette, J.S. Rieh, D. Angell, H. Chen, et al., *IEEE Electron. Dev. Lett.* **23,** 258 (2002).
10. J.D. Cressler, G. Niu, *Silicon–germanium heterojunction bipolar transistors.* (Norwood (MA): Artech House: 2003).
11. J.D. Cressler, *P. IEEE* **93,** 1559 (2005).
12. N.S. Saks, M. Simons, D.M. Fleetwood, J.T. Yount, P.M. Lenahan, R.B. Klein, *IEEE T. Nucl. Sci.* **41,** 1854 (1994).
13. G.C. Messenger, J.P. Spratt, *Proc. IRE* **46,** 1038 (1958).
14. G.P. Summers, E.A. Burke, P. Shapiro, S.R. Messenger, R.J. Walters, *IEEE T. Nucl. Sci.* **40,** 1372 (1993).
15. A.J. Joseph, J.D. Cressler, D.M. Richey, R.C. Jaeger, D.L. Harame, *IEEE T. Electron. Dev.* **44,** 404 (1997).
16. G.C. Messenger, *Radiation and its Effects on Devices and Systems, RADECS 91,* 35 (1991).
17. J. Metcalfe, D.E. Dorfan, A.A. Grillo, A. Jones, F. Martinez-McKinney, P. Mekhedjian, et al., *Nucl. Instrum. Meth. A* **579,** 833 (2007).
18. F. Campabadal, *Nucl. Instrum. Meth. A* **552,** 292 (2005).