Reliability Analysis of SiGe Heterojuncion Bipolar Transistor

Yogesh Kumar Verma[1], Santosh Kumar Gupta[2], Varun Mishra[3], Rajeev Kumar Chauhan[4]
Department of Electronics and Communication Engineering
Motilal Nehru National Institute of Technology, Allahabad-211004, UP, India[1, 2, 3]
Madan Mohan Malaviya University of Technology, Gorakhpur-273010, UP, India[4]
rel1607@mnnit.ac.in[1], skg@mnnit.ac.in[2], varun20mishra@gmail.com[3], rkchauhan27@gmail.com[4]

Abstract-: **This paper covers and contrasts the various reliability issues of SiGeHBTs. Self heating and elevated junction temperature are focused as emerging major reliability issues which effects both reliability and performance of the device. As a foundation for study, an analytical thermal model is developed. Based on the model different parameters of 200 GHz SiGeHBT are measured.**

Keywords-: **SiGeHBT; reliability; scaling**.

I.INTRODUCTION

SiGeHBT are vertical transport devices. Commercially there exists four generations of SiGeHBT technology. These generations are classified as first generation, second generation, third generation, and fourth generation. First generation comprises of peak unity gain cut-off frequency of 50GHz, followed by 100-120 GHz of second generation SiGeHBT technology. Third generation has peak unity-gain cut off frequency of 200 GHz range. Fourth generation also called as research level has record peak unity-gain cutoff frequency of 350GHz. SiGeHBT technology exists in BICMOS implementation (SiGeHBT+SiCMOS). This BICMOS implementation of SiGeHBT provides the optimum advantages of its potential and

makes it an excellent contender in radar systems, communications, THz sensing, Imaging and communications, analog applications, electronic warfare, and the most important domain of “mixed-signal” ICs.

II.RELIABILITY ISSUES OF SiGeHBTs

The reliability of a system is defined as the ability of the system to perform successfully in both expected and unexpected circumstances. There are different reliability issues for different devices. Consider a capacitor, its main reliability issues are operating temperature, ripple current, inrush current, and operating voltage. In the same fashion for SiGeHBT, temperature solely is the key concern.

According to J. D. Cressler et al. [1] reliability issues of SiGeHBTs are low temperature conditions, high temperature conditions and radiation rich environment. He proposed that SiGeHBT can successfully operate under all these three extreme environment conditions.

J. D. Cressler also proposed that reliability issues for mixed circuit applications of SiGeHBTs are thermal effects; impact ionization induced bias point instabilities, and operating voltages.

According to J. Kuchenbecker et al. [6], reliability issues of SiGeHBTs may be two factors. First is electrical degradation due to DC life tests and second due to the influence of hot electron stress on electrical behavior of devices. He provided the curve between normalized DC current Gain and stress time (hours) that clearly indicated that no major problem occurs during life tests. He also proposed hot carrier stress experiments which provide a degradation mechanism located at the surface of device.

According to Zhang Wan-rong et al. [7], the major reliability issues for a single MBE SiGe HBT are DC current gain and increase in turn-on voltage. AC current gain degrades slowly. He proposed that introduction of Ge into base potentially maintain the junction reliability of bipolar transistors.

Greg Freeman et al. [8] proposed that increase in collector concentration is the most important reliability concern. As increase in collector concentration affects the current density and avalanche current. He proposed that reduction in strip widths of SiGeHBTs will reduce electro migration and self heating effects. He also proposed that the ratio of emitter polysilicon to single-crystal interface needs to be minimized to reduce base current and emitter resistance shifts. He proposed that reduction in base resistance is needed to maintain a high pinch in voltage. At high voltage designing, avalanche introduces a degradation mechanism which cannot be ignored.

SiGeHBT has ability to operate in extreme environment. Extreme environment is the important profitable corner of the market for electronics. Extreme environment includes very low operating temperatures, very high operating temperatures, and radiation rich environment. Very low temperatures mean temperatures below 70K or even 4.2K. Very high temperatures mean temperatures up to 473K or 573K. Radiation rich environment may be space, a high vibration environment, a high pressure environment, a low pressure environment, or a caustic or chemically corrosive environment (inside the human body). The unique band gap engineered feature of SiGeHBT offers great potential to make it operate successfully without need of any modification. This ultimately makes SiGeHBT economically strong at both IC and system level. This unique feature of SiGeHBT to operate successfully outside the domain of conventional commercial specifications maintains its reliability [9-16].

The reliability issues due to radiation environment are categorized into three classes.

1. TOTAL IONIZING DOSE EFFECTS (TID):

These types of damage are caused due to the destruction of semiconductor-dielectric interface. This occurs when energy of incident photons induces incomplete bonding at surfaces, which causes excessive leakage, shifts in operating points and performance degradation.

2. DISPLACEMENT DAMAGE (DD):

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As the name suggests such types of damage are caused due to displacement of host Si atom in the lattice. This occurs due to high momentum of the incident high energy particles.

3. SINGLE EVENT EFFECTS (SEE):

Particles of high energy (GeV) cannot be shielded. These particles easily pass through the spacecraft. This causes the deposition of electron-hole pairs. This "heavy –ion induced charge" sweeps easily into the transistor terminals. This causes nanosecond-scale voltage and/or current transients occur. This finally degrades the performance and functionality of circuit.

Description of model:

The device structure used in this work is represented by Fig. 1. The Germanium concentration of the base is 14%.

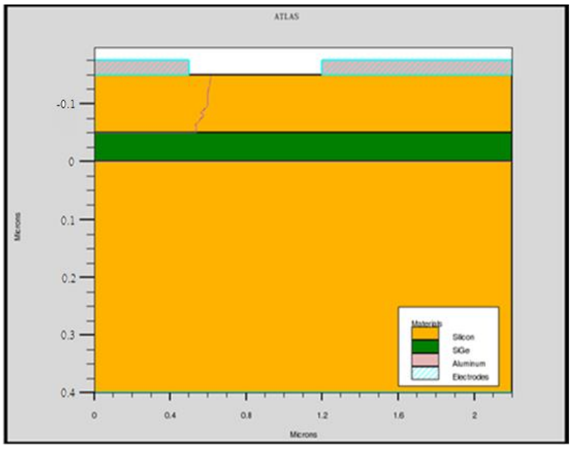


Fig. 1: Structure of SiGe HBT

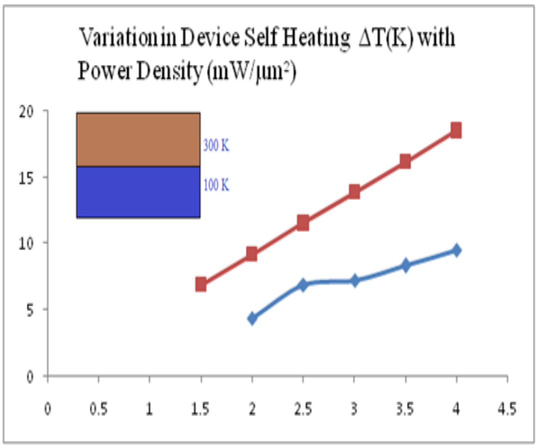
III. SELF HEATING AND SCALING

Temperature is responsible for most device failure mechanisms. Temperature variation in SiGe HBT may be internally in device or due to extreme environment conditions. Temperature variation may be due to rise in junction temperature ΔTj which is an important reliability concern. This basically occurs due to self heating. Since increased temperature causes most of the device degradation problems, so its suppression is mandatory.

$$\Delta T_j = R_{th} * P_{diss} \qquad (1)$$

R_{th} is thermal resistance and P_{diss} is the dissipated power. A straightforward procedure to suppress ΔT_j is the reduction of both R_{th} and P_{diss} . Rth and ΔTj both vary with emitter strip length and emitter strip width. The base transit time is given by

$$\frac{\tau_{b,SiGe}}{\tau_{b,Si}} = \frac{2}{\eta}\frac{KT}{\Delta E_{g,Ge(grade)}}\left[1-\frac{KT}{\Delta E_{g,Ge(grade)}}\left[1-e^{(-\Delta E_{g,Ge(grade)})/KT}\right]\right] \qquad (2)$$



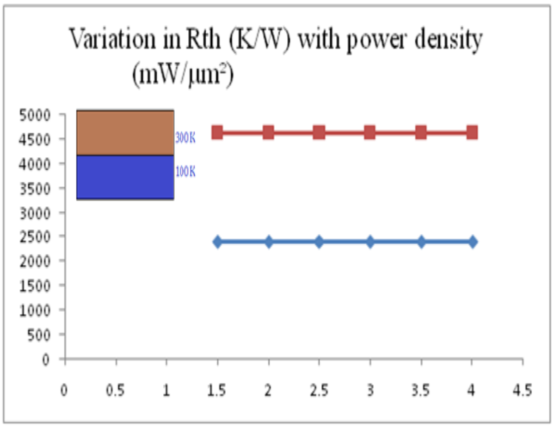


Figure 2: Variation in ΔT with power density

Figure 3: Variation in thermal resistance with power density

IV. RESULTS AND DISCUSSION

Variation in R_{th} and ΔT_j with L_E and W_E

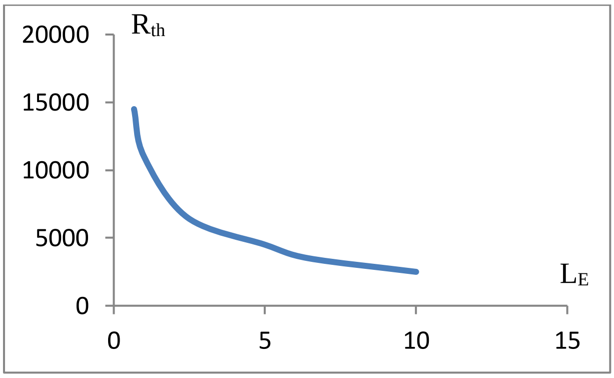


Figure 4: variation of $R_{th}(\Omega)$ with L_E (µm)

From Fig. 4 it is clear that on decreasing emitter strip length L_E , there is sharp increase in R_{th} . On the other hand for constant power density and constant emitter length L_E, on decreasing emitter strip width W_E, there is increase in R_{th} but variation is not as large as in case of L_E scaling, due to relatively small change in cross sectional area, as shown by Fig. 5.

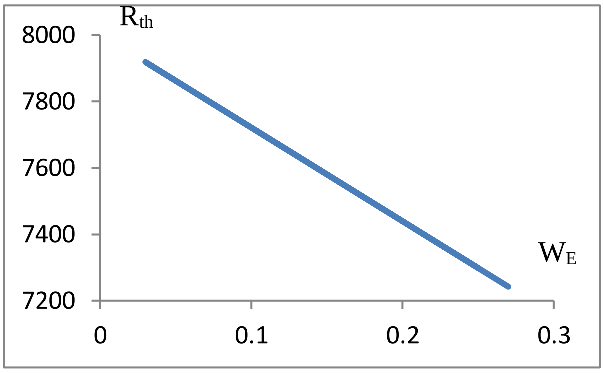


Figure 5: Variation of $R_{th}(\Omega)$ with W_E (µm)

For constant power density and constant emitter width, on decreasing emitter strip length, L_E (µm) there is smaller temperature rise ΔT_j as shown by Fig 6.

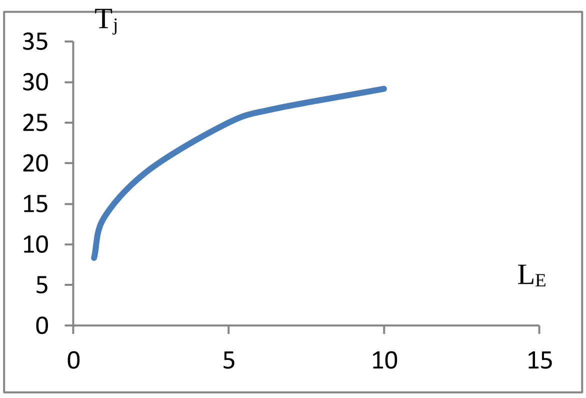


Figure 6: Variation of T_j(K) with L_E (µm)

On the other hand for constant power density and constant emitter strip length, on decreasing emitter strip width W_E , T_j suppression is more pronounced as shown by Fig. 7.

Tj

WE

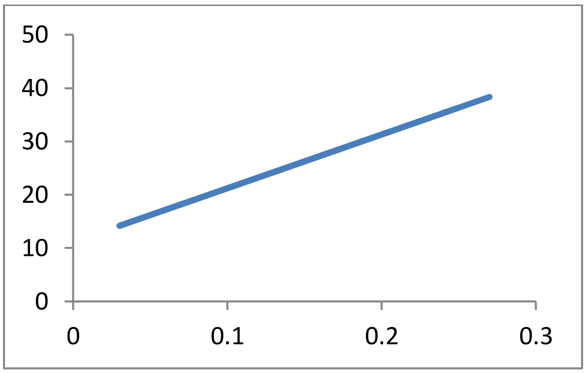


Figure 7: Variation of T_j(K) with W_E(µm)

Lateral scaling imposes positive impacts on devices in terms of self-heating management. Vertical scaling is expected to have a much less impact on R_{th} than lateral scaling. It is because no significant impact exists on heat dissipation path due to vertical scaling. But, increment in J_C for vertically scaled devices, results in raised dissipated power which causes increase in ΔT_j, although R_{th} remains unchanged.

V. EFFECT OF PROTON IRRADIATION ON GUMMEL CHARACTERISTICS OF SIGE HBT

The base current increases after a sufficiently high proton influence due to the production of G/R trapping centers, and hence current gain of the device degrades. There are two main physical origins of this degradation. The base current density is inversely proportional to the minority carrier life time in the emitter, so that a degradation of the hole life time will induce an increase in the base current. The G/R centers also degrade the base current, particularly if they are placed inside the EB space-charge region, where they will yield an additional non-ideal base current component (non KT/q exponential voltage dependence).

At proton influence of 1×10^{12} p/cm², the measured total ionizing dose is 135 Krad (Si). At 5×10^{13} p/cm² the measured total ionizing dose is 6759 Krad (Si). 6759 Krad (Si) is far larger than most orbital missions require. So, 6759 Krad (Si) is the worst case of exposure level. So, proton influence of 63 MeV energy is considered in this work.

The major effect of proton irradiation is the creation of Generation-Recombination (G/R) trap centers. This mechanism leads to the observed increase of base current leakage in the SiGe HBTs. An important phenomenon to notice is that at low V_{BE} base current increases after proton influence increases, and collector current remains unchanged. On the other hand, at high V_{BE}, the base current decreases as the proton influence increases; but the collector current increases with the proton influence. The possible mechanism that is responsible for this anomalous behavior is the decrease in the quasi-saturation effect through the decrease of the collector resistance.

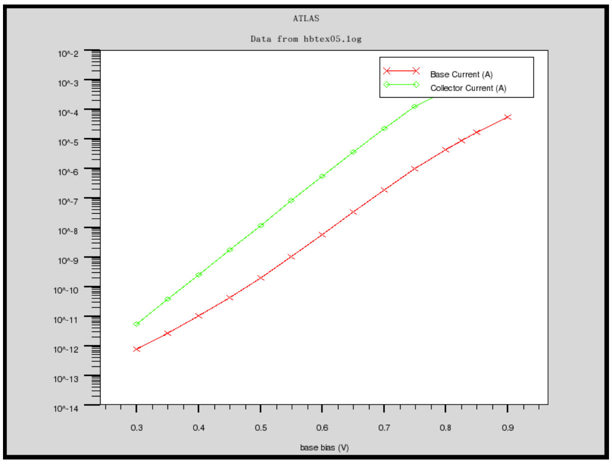


Figure 8: Pre irradiation characteristics of SiGe HBT

In Fig. 8, the pre-irradiation characteristics of SiGe HBT are observed. From the conduction current density equation of SiGe HBT before radiation exposure et al. [15], it

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can be noticed that J_C is directly proportional to $e^{\frac{qV_{BE}}{K_BT}}$. Thus on increasing V_{BE}, J_C increases and hence I_C gets increased as shown in Fig. 8.

$$J_C = \frac{qe^{\frac{qV_{BE}}{K_BT}}}{\int_0^{W_B} \frac{N_A(x)dx}{D_n(x)n_{ie}^2(x)} + \frac{N_A(W_B)}{v_{sat}n_{ie}^2(W_B)}}$$

(3)

But after proton radiation exposure I_C remains unchanged but I_B is increased as shown in Fig. 9.

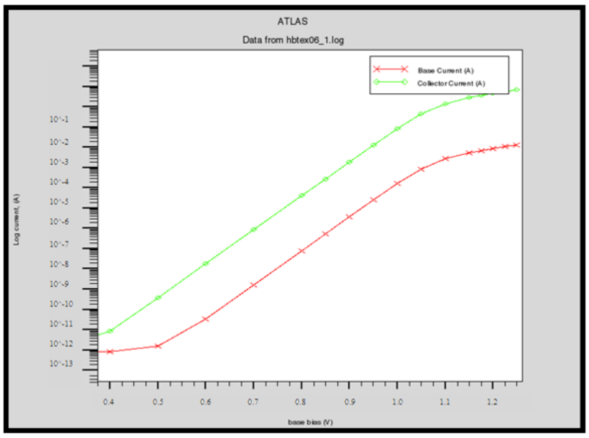

Figure 9: Post irradiation characteristics of SiGe HBT

In Fig. 9, the Post irradiation characteristics of SiGe HBT are observed. The Gummel Characteristics up to proton influence of 63 MeV, 1Krad/s with total dose of 3Mrad, are observed. The base current at low V_{BE} increases monotonically with increase in proton influence, which is the major reason for radiation induced damage. The major effect of proton irradiation is the creation of Generation-Recombination (G/R) trap centers. This mechanism leads to the observed increase of base current leakage in the SiGe HBTs. An important phenomenon to notice is that at low V_{BE} base current increases after increase in proton influence and collector current remains unchanged. On the other hand, at high V_{BE}, the base current decreases as the proton influence increases; but the collector current increases with the proton influence. The possible mechanism that is responsible for this anomalous behavior is the decrease in the quasi-saturation effect through the decrease of the collector resistance.

The reason of this anomalous behavior is also mathematically explained through equations,

I_B and I_C are given by et al [5],

$$I_B = I_D + I_S = I_{B_0} \exp\left(\frac{qV_{BE}}{KT}\right) + I_{S_0} \exp\left(\frac{qV_{BE}}{2KT}\right)$$

$$I_C = I_{C_0} \exp\left(\frac{qV_{BE}}{KT}\right)$$

From both equations it is clear that I_B is having an additional component of $I_{S_0} exp\left(\frac{qV_{BE}}{2KT}\right)$. This excess 2KT recombination component is responsible for increment in I_B. 2KT component is called thermal energy. In case of base current characteristics, more thermal energy is deposited as compared to collector current characteristics. Thus we see that proton influence of 63 MeV, 1Krad/s with total dose of 3Mrad creates no degradation in collector current in low bias region after radiation exposure as shown in figure 14. But the base current comprises of 2KT slope leakage component so it gets increased.

VI. CONCLUSION

In this paper the major reliability concerns of SiGe HBTs are observed including junction temperature. It has been observed that R_{th} variation with L_E for constant W_E and constant power density is more strongly dominating than R_{th} variation with W_E for constant L_E and constant power density. T_j Suppression is more pronounced with varying W_E for constant L_E and constant power density as compared with variation of T_j with L_E for constant W_E and constant power density. The effect of cooling on peak value of current gain through collector current is observed in medium injection region. It has been noticed surprisingly through simulated results that peak value of current gain through collector current decreases slightly with cooling. The base current at low V_{BE} increases monotonically with increase in proton influence, which is the major reason for radiation induced damage. The major effect of proton irradiation is the creation of Generation-Recombination (G/R) trap centers. This mechanism leads to the observed increase of base current leakage in the SiGe HBTs. An important phenomenon to notice is that at low V_{BE} base current increases after increase in proton influence and collector current remains unchanged. On the other hand, at high V_{BE}, the base current decreases as the proton influence increases; but the collector current increases with the proton influence. The possible mechanism that is responsible for this anomalous behavior is the decrease in the quasi-saturation effect through the decrease of the collector resistance. It has been observed that degradation due to irradiation is within the performance limits and the device can adequately perform for practical circuit applications.

REFERENCES

[1] John D. Cressler "On the potential of SiGeHBTs for Extreme Environment Electronics", Proceedings of the IEEE, VOL93, No. 9, pp 1559-1582, SEPTEMBER 2005.
[2] Peter Ashburn, "SiGe Hetrojunction Bipolar Transistors", Jhon Wiley & Sons Publication, 2003.
[3] Jae-Sung Rieh, David Greenberg, Andreas Stricker, Greg Freeman , "Scaling of SiGe Heterojunction Bipolar Transistors", Proceedings of the IEEE, VOL 93, NO. 9, pp1522-pp1536, SEPTEMBER 2005.
[4] John D. Cressler,James H.Comfort, Emmanuel F. Crabbe, Gary L. Patton, Johannnes M.C.Stork, Jack Y.C.Suan and Bernard S. Meyerson, "On the profile Design and Optimization of Epitaxial Si- and SiGe-Base Bipolar Technology for 77K Applications-Part1:Transistor DC Design Considerations", IEEE Transactions on Electron Devices, VOL.40, NO.3, pp 525-541, March 1993.
[5] Greg Freeman, Jae-SungRieh, Zhijian Yang, Fernando Guarin, "Reliability and Performance scaling of very high speed SiGeHBTs", Introductory Invited Paper, Microelectronics Reliability, vol 44, pp397-pp410,2004.
[6] J. Kuchenbecker, M.Borgarino, L.Bary, G.Cibiel, O.Llopis, J.G.Tartarin, J.Graffeuil, S.Kovacic, J.L. Roux and R.Plana, "Reliability Investigation in SiGeHBTs", IEEE, pp131-pp134, 2001.
[7] Zhang Wan-rong, Wang Li-xin, Li Zhi-guo, Cui Fu-xian, Luo Jin sheng, Sun Yinghua, Chen Jian xin, ShenGuang-di, "Reliability Investigation of DC characteristics under Emitter-Base Reverse Bias Stress in Single-mesa Si/SiGe/Si HBTs Grown By Molecular Beam Epitaxy(MBE)", IEEE, pp620-pp622, 2001.
[8] Greg Freeman, Jae-Sing Rieh, Basanth Jagannathan, Zhijian Yang, Fernanado Guarin, Alvin Joseph, David Ahlgren, "SiGeHBT Performance And Reliability Trends through ft of 350 GHz", IEEE, pp322-pp338, 2003.
[9] John D. Cressler, "Emerging SiGeHBT Reliability Issues for Mixed –Signal Circuit Applications", IEEE Transactions on Devices and Materials Reliability, VOL4, NO2, pp222-pp236, June 2004.
[10] John D. Cressler "Using SiGeHBT Technology for Extreme Environment Electronics", IEEE, pp248-pp251, 2005.
[11] Chendung Zhu, Curtis Grens, Enhai Zhao, Adnan Ahmed, John D. Cressler, and Alvin J.Joseph, "Assessing Reliability Issues in Cryogenically-

ISSN NO: 2350-1146 I.F-5.11

operated SiGeHBTs", IEEE, pp41-pp44, 2005.

[12] John D. Cressler, "SiGeHBT Reliability Issues Associated with Operation in Extreme Environments", IEEE, pp3-pp7, 2006.

[13] F. Guarin, Z.Yang, G.Freeman, "Very High Speed SiGe Heterojunction Bipolar Transistor Reliability Overview", Proceedings of the International Caribbean Conference on Devices, Circuits and Systems, Mexico, IEEE, pp131-136, April 26-28, 2006.

[14] A. Shimukovitch, P. Sakalas, M. Ramonas,M. Schroter, C.Jungemann, W.Kraus, "Investigation of SiGeHBT over an extreme temperature range",pp -309-pp312,2009.

[15] Jun Fu and Konrad Bach, "Characterization of Neutral Base Recombination for SiGe HBTs", IEEE Transactions on electronic devices, VOL. 53, NO. 4, pages pp 844-pp 850, April 2006.

[16] Yogesh Kumar Verma, Santosh Kumar Gupta, Rajeev K. Chauhan, "Analysis of Inherent properties of SiGe heterostructure device using analytical modeling and simulation", IEEE Second International Conference for Convergence in Technology, 978-1-5090-4307-1/17/$31.00 ©2017IEEE, pages pp644-pp648, April 2017