# Reliability of Microwave SiGe/Si Heterojunction Bipolar Transistors

Zhenqiang Ma, *Student Member, IEEE*, Pallab Bhattacharya, *Fellow, IEEE*, Jae-Sung Rieh, *Member, IEEE*, George E. Ponchak, *Senior Member, IEEE*, Samuel A. Alterovitz, *Member, IEEE*, and Edward T. Croke

***Abstract*—The degradation behavior of NPN Si/SiGe/Si heterojunction bipolar transistors, grown by solid-source molecular beam epitaxy (MBE), has been studied by accelerated lifetime testing at different ambient temperatures. The degradations of the dc current gain and the microwave performance of the devices are explained in terms of recombination enhanced impurity diffusion (REID) of boron atoms from the base region and the subsequent formation of parasitic energy barriers at the base–emitter and base–collector junctions.**

***Index Terms*—Accelerated lifetime testing, HBT reliability, REID, SiGe HBT.**

## I. Introduction

THE FAVORABLE high-frequency characteristics exhibited by Si/SiGe heterojunction bipolar transistors (HBTs) [1], [2] have made them suitable for microwave applications. One of the concerns regarding the SiGe HBT in microwave circuit applications is its long-term reliability. To our knowledge, very limited report on this subject exists in the literature [3]–[5]. The present paper describes, for the first time, the degradation of NPN Si/SiGe/Si HBTs under forward current/thermal stress. The experimental results are analyzed with low-level injection theory taking into account recombination-enhanced impurity diffusion (REID) of boron dopant atoms in the base layer.

## II. Experiment

The device heterostructure and layout are shown in Fig. 1. Except for the 1.5 $\mu$m-thick As-doped sub-collector layer of the SiGe heterostructure, which is grown by chemical vapor deposition (CVD) on a (001)-oriented high-resistivity Si substrates, the rest of the heterostructure is grown by solid-source molecular beam epitaxy (MBE). The devices have a 30 nm boron-doped $Si_{0.7}Ge_{0.3}$ base layer with two undoped SiGe spacers of thickness 5 nm on each side of it. Antimony was used to dope the emitter and collector layers. The Ge composition of the spacers is the same as that of the base layer. The epitaxial heterostructures are fabricated into double-mesa type devices with 5 $\times$ 20 $\mu m^2$ emitter size, using standard photolithography and wet and dry etching techniques. Details of these procedures have been described by Rieh *et al.* [6].

The stressing of the devices was carried out on wafer by applying a forward active bias to the device in the common-emitter configuration at different junction temperatures. The collector–emitter voltage ($V_{CE}$) was fixed at 3 V. The base current ($I_B$), which was supplied by a current source, was feedback-controlled by a computer in order to maintain a constant collector current ($I_C$) of 13.5 mA, which corresponds to a very low bias level (the base–emitter voltage $V_{BE}$ was estimated to be 0.65–0.7 V) with an emitter current density ($J_C$) of only $1.35 \times 10^4$ A/cm$^2$ and dissipated dc power ($P_{diss}$) of 40.5 mW. It is necessary to maintain a constant collector current level in order to maintain the device at a fixed stress level throughout the entire duration of each test run. The test at each temperature was performed without any interruption and the value of the dc current gain $\beta$ was automatically recorded by the computer at intervals of 30 minutes. The test was terminated when the recorded $\beta$ reached a negligible value. Post-stress measurements of the dc and RF characteristics were then made on-wafer. The junction temperatures ($T_j$) were calculated from the temperature of the hot chuck with the procedure described by Samelis [7]. Identical devices on the same wafer, which were only subjected to thermal stress without any electrical stress during each test run are classified as control devices and post-stress measurements, were also performed on these devices.

## III. Results and Discussion

Fig. 2(a) shows the typical $\beta$ degradation behavior for the tested HBTs. The test was concluded when the device is characterized by a current gain $\beta$ tending to zero (not shown) as a result of negligible collector current. For comparison, $\beta$ was measured on the control devices for each test run and negligible current gain degradation was observed. It has been reported that electromigration (EM) induced compressive stress on the top of the emitter can degrade the dc current gain $\beta$ for current densities of 1 $\times$ $10^6$ A/cm$^2$ or higher [8]. In our experiment, the interconnect metal is not encapsulated [Fig. 1(b)], and the current density is about two orders of magnitude lower than the reported values [8]. In addition, the $\beta$ degradation behavior observed in this experiment [Fig. 2(a)] is different from that caused by compressive stress in the reported Si-based devices [8]. The distinct behavior observed in EM-induced $\beta$ degradation is a double minimum in the value of $\beta$ with increasing stress (or time) [8]. However, this trend was not observed in our data, in spite of data being recorded at time intervals of 30 minutes. We,

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Z. Ma, P. Bhattacharya, and J.-S. Rieh are with the Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109-2122 USA.

G. E. Ponchak and S. A. Alterovitz are with the NASA Glenn Research Center, Cleveland, OH 44135 USA.

E. T. Croke is with HRL Laboratories, LLC, Malibu, CA 90265 USA.

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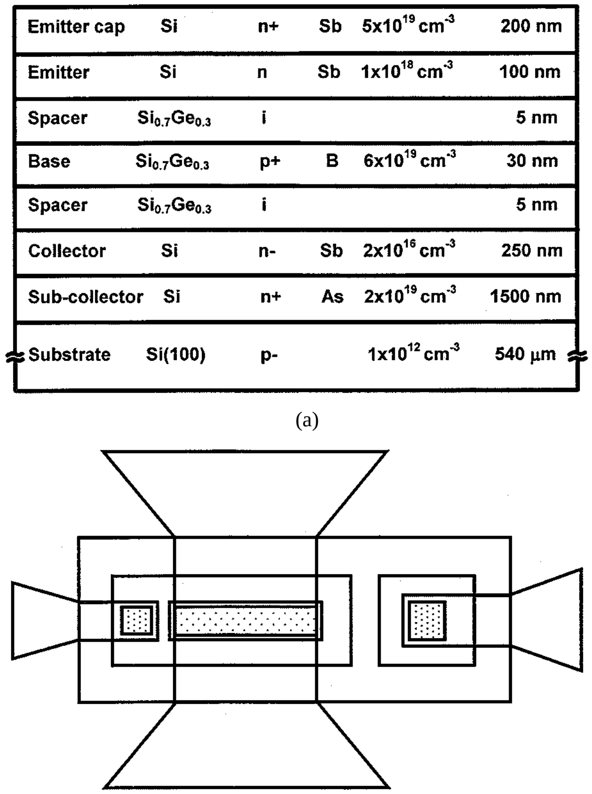


Fig. 1. (a) Schematic of $Si/Si_{0.7}Ge_{0.3}/Si$ HBT, in which the As-doped subcollector layer is grown by CVD and the rest of the heterostructure is grown by MBE. (b) Layout of the tested double-mesa type single-finger Si/SiGe/Si HBTs with emitter area of $5 \times 20\ \mu m^2$ and no encapsulation layer on the top of interconnection lines.

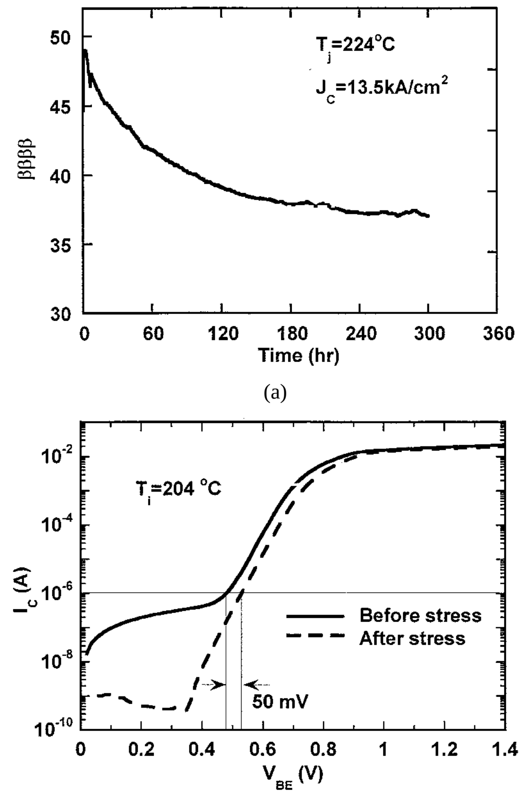


Fig. 2. (a) Typical degradation behavior of dc current gain $\beta$ for a $Si/Si_{0.7}Ge_{0.3}/Si$ HBT. (b) Collector current $I_C$ versus $V_{BE}$ of the forward Gummel plots of a $Si/Si_{0.7}Ge_{0.3}/Si$ HBT before any stressing and after finishing electrical-thermal stressing.

therefore, believe that the EM-induced $\beta$ degradation mechanism is not operative in our devices. Gummel plots of the devices were measured at each junction temperature before and after a test cycle. Typical collector current $I_C$ versus $V_{BE}$ of the forward Gummel plot for $T_j = 204$ °C is shown in Fig. 2(b). It is seen that, after the test, the collector current profile is shifted to higher $V_{BE}$ values ($\Delta V_{BE} = 50$ mV). A similar behavior is exhibited by the emitter current in the reverse Gummel plot. This shift of collector (and emitter) current profile is also observed for other testing temperatures: $T_j = 189$ °C, 224 °C, 254 °C, and 289 °C. However, the Gummel plots measured with the control devices show no observable shift of collector (and emitter) current profiles at all temperatures. We believe that the shift in the Gummel plots is an indication of increase of the base–emitter (base–collector) junction turn-on voltage, possibly caused by boron outdiffusion from the base region into the emitter and collector regions. Since Si has a wider bandgap and lower intrinsic carrier concentration than $Si_{0.7}Ge_{0.3}$, parasitic energy barriers will be formed [9], [10] at the base–emitter and base–collector junctions, which can account for an increase in the turn-on voltages of the diodes [11]. Boron outdiffusion from the base region also results in an increase of base width and a decrease of emitter length, and all these effects reduce the emitter injection efficiency and the current gain. On the other hand, since the control devices were not subjected to any electrical stress and the testing temperatures (up to 289 °C) are too low to induce thermally activated boron diffusion, the current gain degradation was negligible. The RF performance was also measured before and after the application of electrical stress. While all the devices exhibited $f_T = 22$ GHz and $f_{max} = 25$ GHz values before the test, the cut-off frequency were reduced to lower than 2 GHz after the tests. No degradation of RF performance was observed for the control devices.

It is well known that thermal outdiffusion of boron dopant atoms from SiGe layers can only occur at very high temperatures (over 550 °C). The highest ambient temperature in this study was only 275 °C. However, with biasing, a phenomenon, called recombination-enhanced impurity diffusion (REID) [11], [12] occurs. For boron-doped NPN $Si/Si_{0.7}Ge_{0.3}/Si$ HBTs under forward active bias, electrons are injected from the emitter into the base. A fraction of the injected electrons will be captured by traps and recombination centers in this layer. The excess energy of the electrons is released nonradiatively and transferred to boron atoms, thereby enhancing their diffusivity. Because of the high efficiency of the nonradiative energy transfer, the enhancement of boron diffusivity should be more significant than thermally activated diffusion, and , as a result, REID can be operative at very low ambient temperatures. It should be pointed out that, although the electron injection for an NPN Si/SiGe/Si HBT is from the emitter side under forward active bias, the recombination process can occur anywhere in the thin neutral base region. As a result, the diffusion process of the boron atoms in the base region is expected to be isotropic.

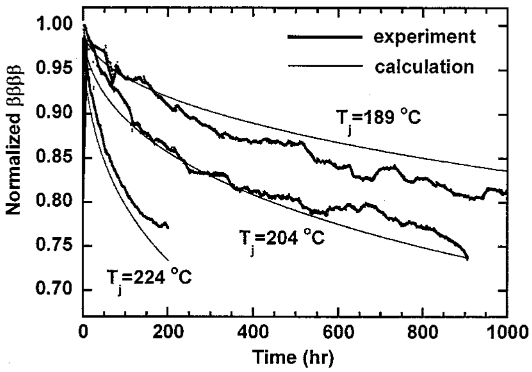


Fig. 3. Measured (solid lines) and calculated (dashed lines) normalized current gain of SiGe/Si HBTs as a function of stress time for different junction temperatures.

This can explain the observed increase of turn-on voltages at both base–emitter and base collector junctions. The REID process has been widely observed in Be-doped GaAs base regions of GaAs/AlGaAs HBTs [11], [12]. Si-based materials are believed to have lower trap densities than III–V materials. However, a 40 nm metastable $Si_{0.7}Ge_{0.3}$ base layer grown by solid-source MBE at 550 °C in the devices investigated is expected to have a higher defect density than conventional Si and these defects can serve as traps and recombination centers when the device is biased in forward active mode. Traps in SiGe have been reported by various groups [13], [14]. Although the experimental results in this study were obtained from SiGe/Si HBTs with high Ge content, they can be generalized to most boron-doped SiGe/Si HBTs. Higher boron doping concentration in the base region and higher Ge content incorporated at lower growth temperatures are expected to result in higher susceptibility of REID-related reliability concern for SiGe-based HBTs.

In order to verify that the REID process is responsible for the observed degradation, we have analyzed our results with a model based on low-level injection theory. In this model, we assume that the dopant atoms in the base region are fully ionized and both the boron dopant profile and Ge profile are box-like. The normalized current gain degradation can then be expressed as

$$\frac{\beta}{\beta_0} = \left(1 + \frac{\Delta W_E}{W_B} e^{\Delta E_b^e/kT} + \frac{\Delta W_C}{W_B} e^{\Delta E_b^c/kT}\right)^{-1} \quad (1)$$

where

$$\beta_0 = \frac{qD_n n_i^2(SiGe)}{W_B J_{B0} N_A} \quad (2)$$

and $W_B$ is the neutral base width, $\Delta W_E$ and $\Delta W_C$ are outdiffused region widths into emitter (subscript, E) and collector (subscript, C), respectively, $N_A$ is the base doping, $D_n(x)$ is the minority carrier diffusion coefficient, $J_{B0}$ is the reverse saturation current density of the base–emitter diode and $n_i(x)$ is the intrinsic carrier concentration of SiGe base. $\Delta E_b^e$ and $\Delta E_b^c$, are the parasitic energy barriers. It is also assumed that $\Delta W_E = \Delta W_C = \Delta L = \sqrt{D_S t}$, where $D_s$ is the effective boron diffusion (REID) constant (5–6 orders higher than the thermal diffusion constant) and $t$ is the stress time. The calculated variations of current gain with stress time are shown in Fig. 3 alongside measured data for several junction temperatures. The agreement between calculated and measured data is fairly good, indicating that the device degradation behavior at each testing temperature is largely due to recombination-enhanced boron outdiffusion.

## IV. Conclusion

In conclusion, we have characterized the degradation behavior of NPN $Si/Si_{0.7}Ge_{0.3}/Si$ HBTs under forward current/thermal stresses at different ambient temperatures. The experimental results indicate that recombination-enhanced impurity diffusion (REID) of boron dopant atoms in the base is probably responsible for the observed degradation. Analysis of the results with a REID model based on low-level injection theory leads to a similar conclusion.

## References


[1] A. Schüppen, U. Erben, A. Gruhle, H. Kibbel, H. Schumacher, and U. König, "Enhanced SiGe heterojunction bipolar transistors with 160 GHz-$f_{max}$," in *IEDM Tech. Dig.*, 1995, pp. 743–746.

[2] K. Oda, E. Ohue, M. Tanabe, H. Shimamoto, T. Onai, and K. Washio, "130 GHz-$f_T$ SiGe HBT technology," in *IEDM Tech. Dig.*, Dec. 1997, pp. 791–794.

[3] A. Neugroschel, C.-T. Sah, J. M. Ford, J. Steele, R. Tang, and C. Stein, "Comparison of time-to-failure of GeSi and Si bipolar transistors," *IEEE Electron Device Lett.*, vol. 17, pp. 211–213, May 1996.

[4] J. A. Babcock, A. J. Joseph, J. D. Cressler, and L. S. Vempati, "The effects of reverse-bias emitter–base stress on the cryogenic operation of advanced UHV/CVD Si- and SiGe-base bipolar transistors," in *1996 IEEE Int. Reliability Phys. Proc.*, 1996, (Cat. no. 96CH38525), pp. 294–299.

[5] M. Borgarino, J. G. Tartarin, J. Kuchenbecker, T. Parra, H. Lafontaine, T. Kovacic, R. Plana, and J. Graffeuil, "On the effects of hot carriers on the RF characteristics of Si/SiGe heterojunction bipolar transistors," *IEEE Microwave Guided Wave Lett.*, vol. 10, pp. 466–468, Nov. 2000.

[6] J.-S. Rieh, L.-H. Lu, L. P. B. Katehi, P. Bhattacharya, E. T. Croke, G. E. Ponchak, and S. A. Alterovitz, "X- and Ku-band amplifiers based on Si/SiGe HBTs and micromachined lumped components," *IEEE Trans. Microwave Theory Tech.*, vol. 46, pp. 685–694, May 1998.

[7] A. Samelis, "Analysis of the nonlinear characteristics of microwave power heterojunction bipolar transistors and optoelectronic integrated circuits," Ph.D. dissertation, Univ. Michigan, Ann Arbor, 1996.

[8] R. S. Hemmert, G. S. Prokop, J. R. Lloyd, P. M. Smith, and G. M. Calabrese, "The relationship among electromigration, passivation thickness, and common-emitter current gain degradation within shallow junction NPN bipolar transistors," *J. Appl. Phys.*, vol. 53, pp. 4456–4462, 1982.

[9] J. W. Slotboom, G. Streutker, A. Pruijmboom, and D. J. Gravesteijn, "Parasitic energy barriers in SiGe HBTs," *IEEE Electron Device Lett.*, vol. 12, pp. 486–488, Sept. 1991.

[10] E. J. Prinz, P. M. Garone, P. V. Schwartz, X. Xiao, and J. C. Sturm, "The effects of base dopant outdiffusion and undoped $Si_{1-x}Ge_x$ junction spacer layers in $Si/Si_{1-x}Ge_x/Si$ heterojunction bipolar transistors," *IEEE Electron Device Lett.*, vol. 12, pp. 42–44, Feb. 1991.

[11] M. E. Hafizi, L. M. Pawlowicz, L. T. Tran, D. K. Umemoto, D. C. Streit, A. K. Oki, M. E. Kim, and K. H. Yen, "Reliability analysis of GaAs/AlGaAs HBTs under forward current/temperature stress," in *GaAs IC Symp.*, 1990, pp. 329–332.

[12] M. Uematsu and K. Wada, "Recombination-enhanced impurity diffusion in Be-doped GaAs," *Appl. Phys. Lett.*, vol. 58, pp. 2015–2017, 1991.

[13] S. H. Li, P. K. Bhattacharya, S. W. Chung, S. R. Smith, and W. C. Mitchel, "Deep levels in undoped $Si_{1-x}Ge_x$ grown by gas-source molecular beam epitaxy," *J. Electron. Mater.*, vol. 22, pp. 151–153, 1993.

[14] S. H. Li, S. R. Smith, P. K. Bhattacharya, S. W. Chung, and W. C. Mitchel, "Deep level transient spectroscopy and admittance spectroscopy of $Si_{1-x}Ge_x$ grown by gas-source molecular beam epitaxy," *J. Vac. Sci. Technol. B*, vol. 11, pp. 892–894, 1993.