Re-Examining TID Hardness Assurance Test Protocols for SiGe HBTs

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Abstract—We investigate the applicability of current total ionizing dose (TID) test protocols in the context of advanced transistor technologies such as Silicon-Germanium heterojunction bipolar transistors (SiGe HBTs). In SiGe HBTs, an unexpected shift in collector current is observed during total dose irradiation. Using both device and circuit measurements, we investigate this phenomenon and assess its potential importance in hardness assurance of SiGe components. TCAD simulations were performed to explain the observed current shifts.

Index Terms—Anneal, BGR, dose rate, gamma, Gummel, phase-shifter, proton, Silicon-Germanium heterojunction bipolar transistors (SiGe HBTs).

I. INTRODUCTION

TO ensure adequate on-orbit reliability, space electronics are extensively pre-flight tested under various radiation environments. One such reliability concern is total ionizing dose (TID), in which charge is accumulated in devices over time, inevitably degrading the performance of the transistors and the circuits built from them. Standard TID testing protocols for hardness assurance of space-borne military and aerospace electronics systems exist [1], and generally follow a testing sequence consisting of: 1) measure the target device-under-test (DUT) before radiation exposure, 2) irradiate the DUT to a certain total dose, and 3) re-measure the DUT in a radiation-free environment to quantify the impact of the radiation exposure. In practice, however, there is a time lapse between steps 2 and 3, and as a result critical information could be potentially lost

due to the complex time-dependent nature of charge dynamics in silicon devices [2]. This is why Section 3.10 of the military standard MIL-STD-883G Test Method 1019.7 [1] particularly recommends that the time from end of irradiation to start of electrical measurement be as short as possible, and that maximum delay time should be 1 hour (for regular radiation testing). If any radiation-induced damage mechanisms are missed in such TID qualification testing, the impact to mission lifetime can be potentially significant. Given the complexity of mixed-signal circuits and space radiation physics, it would seem prudent to re-evaluate this common practice, particularly as it relates to new, more advanced devices technologies such as Silicon-Germanium heterojunction bipolar transistors (SiGe HBTs) that have emerged in recent years.

SiGe HBTs have been extensively tested for radiation hardness assurance for space applications, as can be seen in the numerous publications in the past decade. Performed under the standard test procedure, virtually no degradation in collector current (I_C) post-exposure [3], [4] is observed, whereas the base current (I_B) typically shows a near $2kT$ slope leakage component in the base current. A typical pre-irradiation and post-irradiation Gummel characteristic is shown in Fig. 1 to illustrate. Many studies have been focused on the degradation of base current, since it affects common device figures-of-merit such as current and RF gain [4].

The question still remains, though, as to whether the current testing protocol underestimates degradation due to the annealing that potentially occurs in the time lapse between steps 2 and 3. In this paper, we explore this question by conducting TID testing in a manner that differs from the traditional total dose testing protocol: device and circuit terminal currents were monitored in real-time before, during, and after irradiation, so that no time gap exists between exposure and re-measurement. Using our new testing method, we observed excess I_C in addition to I_B leakage during exposure. In order to better gauge the severity and the underlying mechanism behind the excess I_C, proton and gamma irradiation at a wide range of dose rates were performed. Several SiGe technology platforms were tested, at different bias conditions, to confirm whether this is a process-specific issue.

Excess I_C has been previously observed in BJTs [5], [6]; however, for aggressively scaled SiGe HBTs the picture remains unclear. Indeed, I_C degradation has been observed in SiGe HBTs, but its response to total dose and dose rate are still not well-understood [7]–[9]. Using our new measurement approach, radiation-induced changes in I_C were monitored
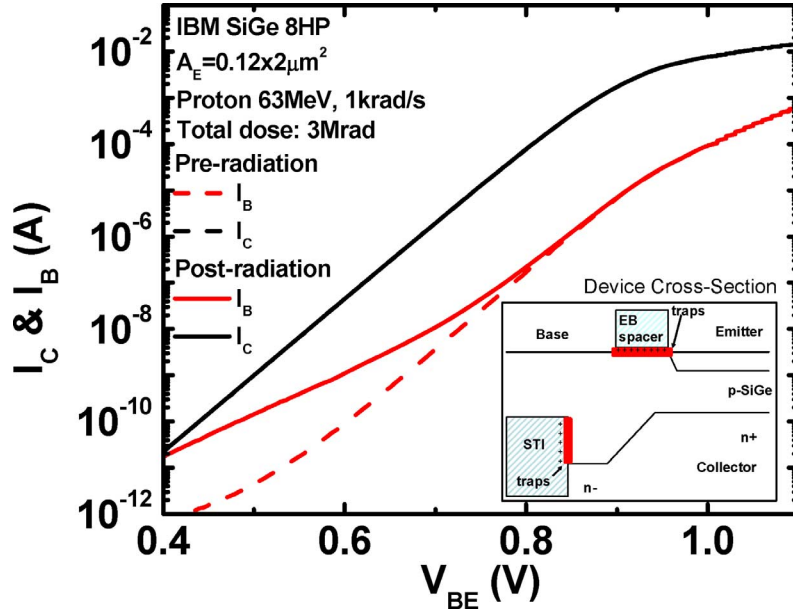
Fig. 1. Typical pre- and post-irradiation Gummel characteristics, showing that I_C remains unchanged but I_B is increased due to excess $2kT$ recombination component.
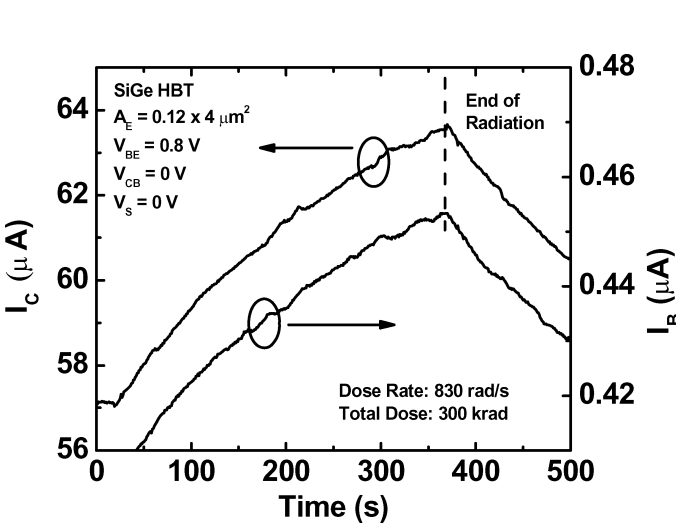

Fig. 2. Collector and base currents of a SiGe HBT under irradiation of 300 krad. Radiation stopped at 360 s, but biasing continued for 140 s.
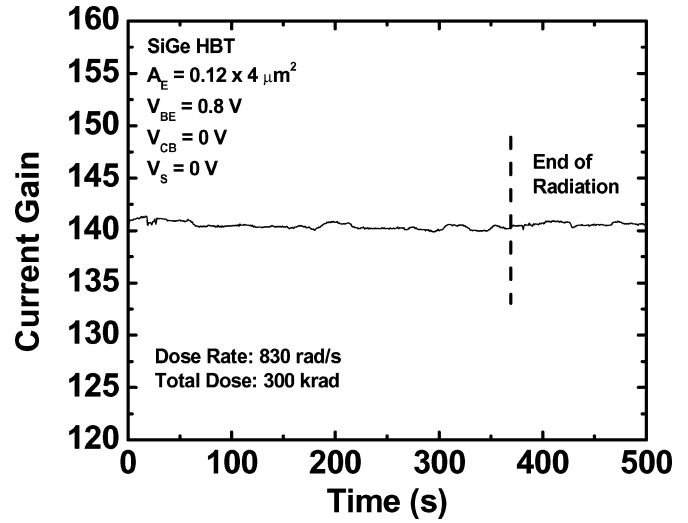

Fig. 3. Current gain for the SiGe HBT from Fig. 4, for a total dose irradiation of 300 krad(Si).

continuously, allowing very repeatable trends to be demonstrated and understood.

SiGe BiCMOS circuits were also irradiated in order to probe the potential coupling between transistor-level effects and circuit and system effects. In this case, the bias currents of selected SiGe analog and RF circuits were also monitored before, during, and after irradiation to assess the impact at the circuit level. An explanation for this excess I_C phenomenon and its implication to orbital electronic circuit design are discussed.

Hardness assurance results from this paper reveal differences when compared with the literature, which we believe raise fundamental questions about the applicability of current hardness assurance procedures for SiGe HBT technologies, and these implications will also be discussed.

II. DEVICES AND TEST CONDITIONS

The devices and circuits used in this study are from several SiGe BiCMOS technologies. One of them was IBM's SiGe 8 WL technology, which is a cost-performance variant of the 130 nm node high-performance platform technology [10]. IBM 5AM [11], with peak cut-off frequency of 50 GHz, 0.5 μm SiGe process, was used for gamma irradiation. Samples were diced and packaged into 28-pin dual-inline packages, with two or three devices bonded out in each package. SiGe HBT and CMOS phase shifters were fabricated in the IBM SiGe 8HP process [12]. While both types of X-band (8 GHz -12 GHz) phase shifters (PS) use a switched high/low-pass filter topology, one circuit uses SiGe HBTs in diode-connected configurations for the RF switch, while the other circuit uses CMOS devices in pass-gate configuration. Precision bandgap voltage references
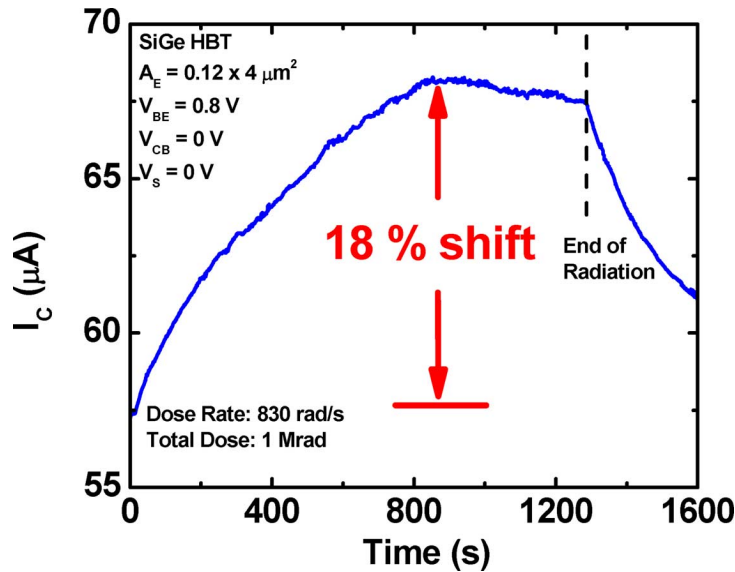
Fig. 4.   Collector and base currents of a SiGe HBT under irradiation of 1 Mrad. Radiation stopped at 1,275 s, but biasing continued until a total of 1,600 s was reached.
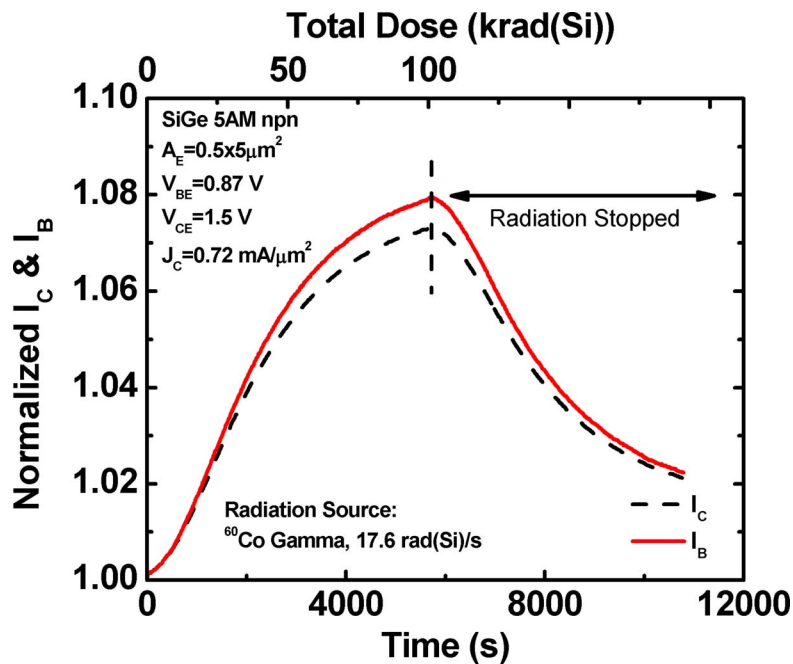

Fig. 5.   Normalized collector and base current during gamma TID testing. The device was forward-biased, and the dose rate was set to be 17.6 rad(Si)/s. After 100 krad TID was reached in approximately 6000 s, the device was continued to be biased for another 5000 s.

(BGR) were also examined: they were fabricated in IBM SiGe 5AM technology. The 63.3 MeV proton irradiation was performed at Crocker Nuclear Laboratory at the University of California at Davis, which achieves 15% uniformity over a 2.0 cm radius (the dosimetry system is accurate to about 10%) [13]. Gamma TID irradiation was performed using a ^{60}Co source, and the dosimetry was measured using chamber probes.

III. EXPERIMENTAL RESULTS: SiGe HBTs

For all radiation experiments discussed in this paper, the SiGe HBTs were biased in forward-active mode, as they would be used in a circuit. The I_C and I_B before, during, and after irradiation were recorded. Shown on Fig. 2 is an 8 WL device during proton irradiation, at dose rate of 830 rad(Si)/s. Instead of measuring the Gummel characteristics, I_B and I_C are sampled at real-time at a fixed V_{BE} and V_{CB}. While they are constant before irradiation, the currents suddenly increase sub-linearly during irradiation, and decay logarithmically afterwards. The current gain of the device is plotted in Fig. 3, and clearly it remains constant throughout the experiment. Fig. 4 shows another SiGe HBT irradiated up to a total dose of 1 Mrad(Si). The I_C increases up to a certain level, and then begins to recover, even during irradiation. The recovery process accelerates once
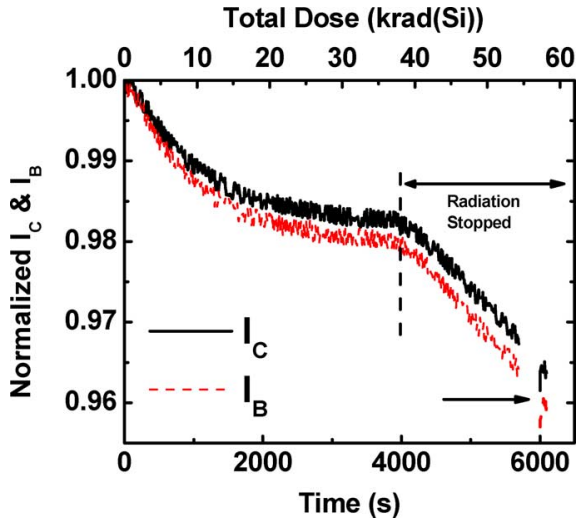
Fig. 6. Normalized collector and base currents during gamma TID testing. The device was forward-biased with dose rate 9.5 rad(Si)/s.

Fig. 7. Normalized collector current during gamma TID testing. Each device was forward-biased at the same V_{BE} and V_{CE}, and the dose rates were 17.6, 11.8, 2.08, 1.17, and 0.22 rad(Si)/s.

irradiation was halted. A maximum of 18% excess I_C was observed, which is clearly significant. For comparison, SiGe HBTs were also tested using traditional protocols, in which devices were taken out of the radiation chamber after exposure, and then re-measured. Post-irradiation collector current data in this case showed no observable change compared to pre-irradiation data, indicating that traditional test protocols and our present test protocol give different results.

Since one dose rate is inadequate in determining radiation hardness, and 830 rad/s is higher than what is suggested in MIL-STD-883G Test Method 1019.7[1], ^{60}Co gamma irradiation was used for lower dose rate experiments. The devices used in the gamma irradiation experiments were 5AM SiGe HBTs, and the dose rate varied from 17 rad(Si)/s to 0.23 rad(Si)/s. Shown in Fig. 5 are the normalized I_C and I_B during gamma irradiation, at dose rate of 16.6 rad(Si)/s. Similar to the proton results, the currents increase sub-linearly during irradiation to about 8%, and then recovered afterwards. Compared with the 830 rad(Si)/s proton experiment, the 16.6 rad(Si)/s gamma I_B and I_C changes much more gradually.

Going to even lower dose rates reveals quite different results. Shown in Fig. 6 are normalized I_B and I_C at a dose rate of 9.5 rad(Si)/s. The currents unexpectedly *decreased* during irradiation, and even continued to drop afterwards the exposure was stopped. The degradation rate during the annealing period is actually higher than during irradiation. Previous gamma irradiation studies have also reported shifts in I_C [14], which was attributed to ambient temperature change. In order to ensure that shifts in current are not due to any temperature fluctuation (perhaps during irradiation), these devices were monitored continuously for half an hour following irradiation. To further confirm the repeatability of the degradation, the measurement was stopped for approximately 5 minutes and then continued. As can be seen in Fig. 6, I_C and I_B shifts still exist, continuing from where they would be had the measurement not been stopped.

Fig. 7 shows the dynamics of I_C across a wide range of dose rates. At dose rates above 11.8 rad(Si)/s, I_C shows a sub-
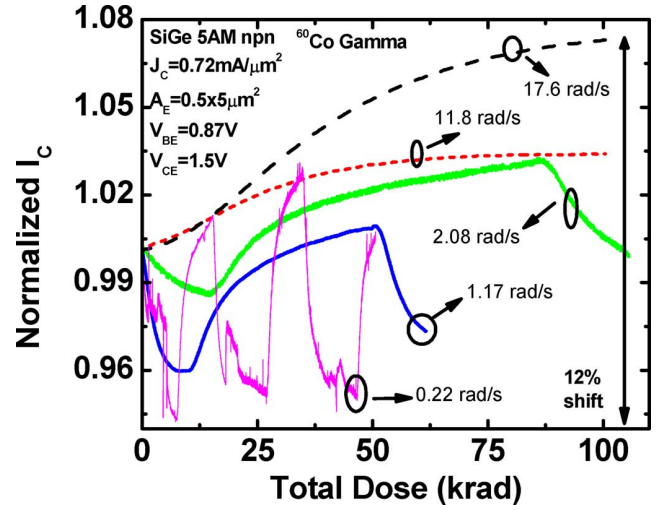
linear increase as a function of total dose; however, below 2.08 rad(Si)/s the currents can be seen to fluctuate, and the frequency of the fluctuation is higher for lower dose rates. As can be seen in Fig. 7, a maximum of 12% shift in I_C has been observed in gamma irradiation testing, which is clearly a significant change.

In all of the experiments, pre- and post-irradiation Gummel characteristics were measured. During most of the experiments, the devices continued to be biased for a long period after the radiation exposure ceased, in order to monitor the annealing behavior, and as can be seen in Figs. 4 and 5, most of the I_C and I_B shift would have been recovered by then. For these samples, the pre- and post-irradiation Gummel curves nearly overlap, with a maximum of 1% shift in the currents. For a few low-dose rate experiments, the post-rad Gummel curves were measured immediately (< 10 s) after irradiation. An example is shown in Fig. 8, where the device was exposed to 1.17 rad(Si)/s gamma irradiation. Indeed, the pre- and post-irradiation Gummel curves differ by 12% across V_{BE}, and the current shifts have nearly the same $1kT$ slope as the original I_B and I_C.

IV. CIRCUIT HARDNESS ASSURANCE

If the operating point (V and I bias) of a transistor shifts during radiation exposure, circuit performance can be potentially compromised. To observe the potential circuit impact of the observed changes in bias currents (I_{bias}), X-band (8–12 GHz) phase shifters from a radar chip set were irradiated. The I_{bias} of a SiGe HBT phase shifter is shown to increase by about 1 mA during exposure (Fig. 9). The SiGe phase shifter is biased using a set of current mirrors, with external reference current (I_{ext}) supplied through the Agilent 4155. The voltage at this terminal, V_{ext}, plotted also in Fig. 9, is essentially the V_{BE} of the mirroring SiGe HBT. The decrease of V_{ext} shows the same pattern as the excess I_C described above, with the result being that less V_{BE} is required to supply the same current. For the CMOS X-band phase shifters, I_{bias} increased from less than 0.3 μA
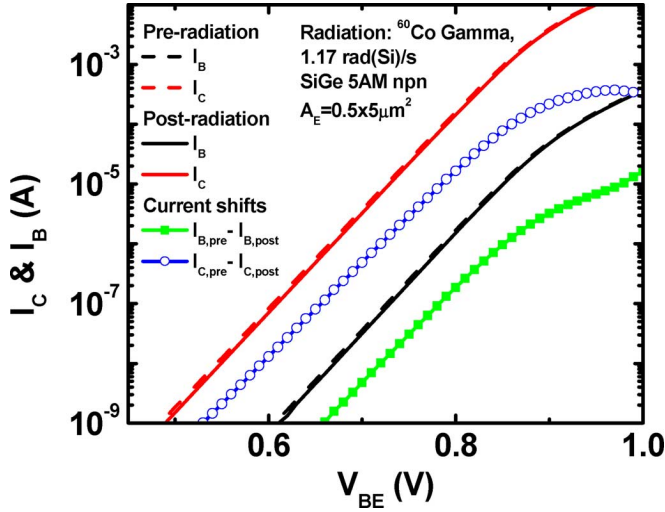
Fig. 8. Pre- and post-radiation Gummel characteristics. The post-irradiation measurements were done almost immediately after irradiation. Also shown are the I_B and I_C current shifts.
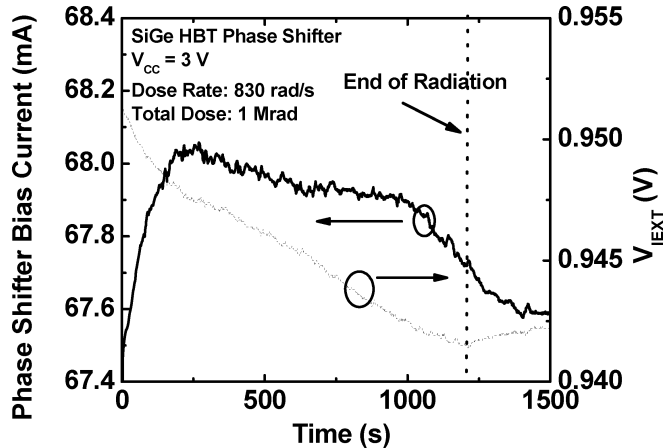

Fig. 9. Bias current shift of an X-band SiGe HBT phase shifter during proton irradiation. The circuit was biased using current mirrors with $I_{EXT} = -1.85$ mA. V_{IEXT} (also plotted) is the voltage at this node.
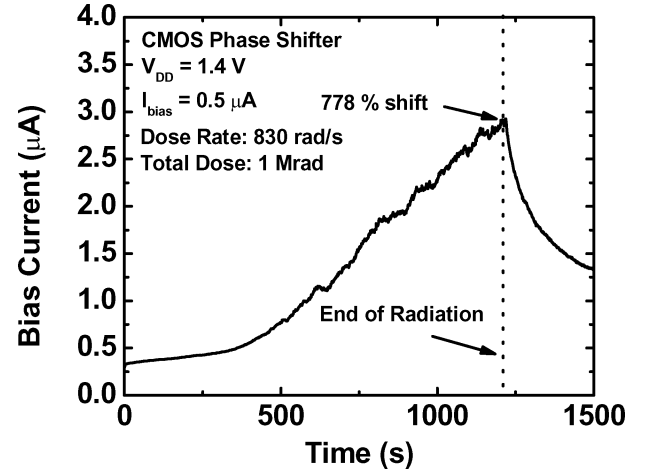

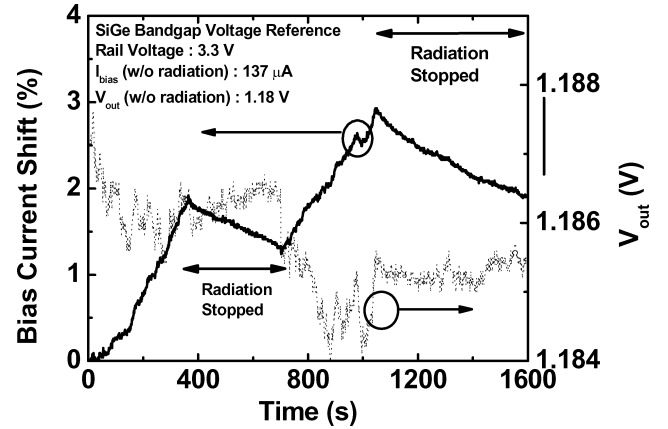Fig. 10. Bias current shift of X-band CMOS phase shifter during proton irradiation.

Fig. 11. Bias current shift in a SiGe voltage reference during proton irradiation. The circuit was irradiated to 500 krad(Si). Also plotted is the output voltage shift during irradiation.

to about 3 μA during irradiation (Fig. 10). This is a large percentage change; however, in terms of actual leakage magnitude, it is only 2.7 μA.

Precision voltage references are critical components for virtually all analog/RF circuitry because they set the biasing conditions for many circuits in integrated electronic systems. SiGe bandgap references (BGRs), such as the ones used in a newly-developed data acquisition system for NASA lunar missions [15], were used for this experiment. The operating current and output voltage (V_{out}) of these SiGe BGRs were monitored during irradiation. Irradiation was halted for a period of approximately 150 seconds before resuming again. The percentage change of I_{bias} is plotted in Fig. 11 and only a 3% change in I_{bias} was observed, with V_{out} altered by about 3 mV, not insignificant for some applications (e.g., data converters). Fig. 11 shows that the BGR is still functioning correctly.

V. DISCUSSION

Based on these TID test results, several issues can be identified. First, we focus on the damage mechanisms behind the observed collector current changes of these SiGe HBTs, and then we evaluate the hardness assurance of SiGe BiCMOS processes from our results. Finally, we offer improved test protocol recommendations. Base current degradation due to traps has been studied extensively [3]–[5] and will not be discussed here. Instead, collector current degradation will be the focus here.

A. Damage Mechanisms

I_C shifts due to irradiation have been observed from the very first experimental studies of first generation SiGe HBTs. In [7] SiGe HBTs were gamma-irradiated up to 6 Mrad, and the collector current was observed to increase first and then decrease after 1 Mrad. It was observed that the devices showed approximately a 20% change in I_C (the devices were irradiated at dose rate of 48 rad(Si)/s). In [16], I_C was observed to fluctuate ($\sim 30\%$) with neutron irradiation, and seemed to be decreasing with increasing dose.
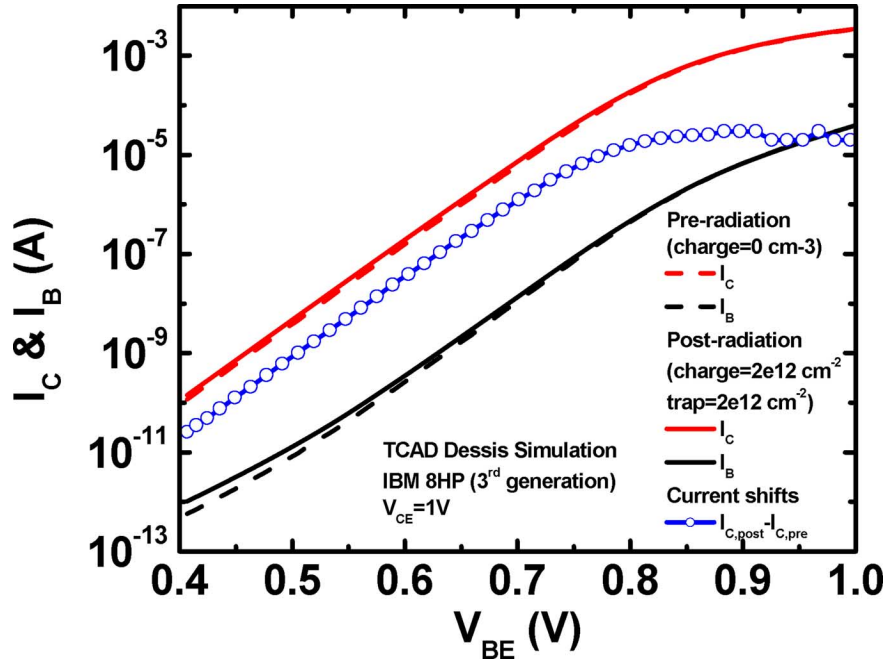
Fig. 12. TCAD Dessis Simulation of I_C and I_B shift. The traps and charges at the interface increase the base and collector leakage currents. The excess I_C is also shown.

A general framework for understanding the physical origin of the excess I_C can be taken from [17], which notes that radiation-induced excess I_C can be caused by an inversion layer generated under the EB spacer during irradiation. This inversion layer increases the effective emitter area, thus increasing the overall I_C. This is in agreement with results shown in Figs. 4 and 5. Measurements from [17] showed excess I_C in the range of 15%, which is close to our data.

However, one distinct difference between our measurements and the previous finding is that both collector and base current are shifting, thus maintaining a nearly constant current gain. Simulations [17], [18] have confirmed that the inversion layer alone could not affect the base current, since the base current predominately depends on the emitter Gummel number. TCAD simulations have been performed to determine if charges and/or traps are located in the polysilicon/silicon, silicon/silicon-dioxide, and silicon/silicon-germanium interfaces. Perhaps a possible explanation would be that during irradiation both interface charge and trap density increases; the former creates an inversion layer to increase I_C, whereas the latter increases the SRH recombination current in I_B. For I_B to increase as a $1kT$ slope (as seen in Fig. 8), the traps cannot be midgap traps but instead should be shallow traps near the conduction band. TCAD simulations using an 8HP calibrated model demonstrates that this can cause both I_C and I_B to shift in the same direction (see Fig. 12). In our simulations the interface charge and trap density was set to be $2 \times 10^{12} \text{ cm}^{-2}$, with the trap energy located 0.1 eV below the conduction band.

It was reported in [19] that a $1kT$ slope I_B leakage can be created due to midgap traps, provided there is enough charge at the interface; however this would also generate a large $2kT$ I_B leakage, which is not the case in our measurements.

Another major difference between our measurement results and previous studies is the significant annealing observed in I_C. From a wide range of dose rates used in this study, we find that the annealing rate is observed to change with dose rate by nearly 2 orders of magnitude; the higher the dose rate, the faster the annealing after irradiation.

The fluctuation of I_C seen at low dose rates and the annealing characteristics (Figs. 2 and 7) are very characteristic of results shown in [20], [21]. In [21], for irradiated MOSFETs, the gate interface traps were observed to increase when positively biased and decrease once negatively biased. This bias-dependence of the traps was determined to be due to protons inside the oxide. When positively biased, the protons move towards the interface, and thus the trap generation process dominates. The sub-linear behavior of trap formation was most likely due to the diffusion process of hydrogen molecules. Once the bias becomes negative, protons are moved away from the interface, causing the trap annealing process to dominate.

However, as opposed to results in [21], where the gate oxide was biased, the EB spacer inside SiGe HBTs is inherently unbiased. For protons to move towards and away from the interface, the electric field inside the spacers must also change. To the authors' knowledge, no such explanation exists in the literature.

B. Hardness Assurance of SiGe BiCMOS Processes

Even though the damage mechanism in the present investigation is not yet well-understood, it can be seen from test results that I_C generally shifts around 10% to 12%, with a maximum shift (up to a TID of 1 Mad(Si)) of 18%. In the context of RF circuit design, where current densities are carefully fixed, this excess I_C could only negatively affect circuit performance. If devices are biased at high J_C to achieve the highest possible

gain, the excess I_C could cause premature base pushout and impedance mismatch, which will degrade RF performance.

In the context of analog circuit design, in situations where a given circuit specification is very demanding, excess I_C could pose a serious problem. As can be seen in the BGRs presented here, bias currents increased by no more than 3%, but changes in the output voltage can in certain circumstances be of serious concern. We suspect that the importance of our observations will depend on the specific application (hence circuit) in question, and for that reason alone should be carefully assessed.

C. Hardness Assurance Testing Recommendations

In previous studies, post-irradiation characterization of devices was performed by removing the packages from the radiation beam, taking the DUTs to a separate, radiation-free environment, and then re-measuring them. This may require a period of several minutes (or longer) in order to wait for the background radiation level in the chamber to become safe enough to enter [8]. For high dose rates, this waiting period can be significant, since most of the excess I_C would have already recovered. For low dose rates, the recovery rate is quite slow, and therefore the waiting period may not cause significant changes. However, since the excess I_C is fairly small (in the range of a few percent) it seems that the waiting period should be as short as possible, regardless of dose rate. Considering the small variation of this damage and the recommendation of Section 3.10 of MIL-STD-883G Test Method 1019.7, we believe that monitoring the bias currents continuously during irradiation is the best way to fully characterize the extent of the radiation damage in SiGe HBTs. It seems that revised TID hardness assurance protocols may be needed to meet the challenge of capturing damage characteristics for highly scaled, modern transistors.

VI. SUMMARY

We have investigated the applicability of current TID test protocols in the context of advanced transistor technologies such as SiGe HBTs. Annealing effects were observed immediately after irradiation, leading to a discrepancy between the actual damage measured real-time and that measured after a time delay. Thus, for hardness assurance we recommend monitoring the devices continuously before, during, and after irradiation. For SiGe HBTs, an unexpected excess collector current is observed during total dose irradiation, which was shown to have a different response to dose rate. We attribute this phenomenon to radiation-induced charge, which creates an inversion layer and increase the collector current, and interface traps, which increase the base recombination current. Our TCAD simulations are able to qualitatively match the measurement data. The impact of our observations is very likely circuit specific and application dependent and thus warrants careful assessment.

ACKNOWLEDGMENT

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