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# Effects of X-ray and Gamma irradiation on advanced Si/SiGe:C HBTs DC characteristics

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**Abstract**— Total-ionizing-dose response of two BiCMOS technologies Si/SiGe:C HBTs, the 130 nm BiCMOS9MW and the 55 nm B55, was compared during X-ray and Gamma irradiation. TID degradation effect on the DC characteristics is analyzed showing the main role of the Emitter-Base oxide region, this is supported by TCAD simulations. Impact of short and long-time intervals between measurements was undertaken demonstrating that the degradation of the base current is stable in time. Each irradiation technique was followed by a thermal annealing process. A higher healing impact for the induced damages was more pronounced after the Gamma-ray exposure. In both irradiation cases, an enhanced healing behavior was recorded by the B55 technology.

Promising results are found for BiCMOS Si/SiGe HBTs technology in extreme environments especially for the B55 BiCMOS technology.

**Keywords**—HBTs, Si/SiGe, Gamma irradiation, X-ray irradiation, Total Ionizing Dose (TID), Gummel-plot, Annealing, Healing.

## I. INTRODUCTION

Now a days the demand of high-speed wireless communication and various niche high frequency applications has ever expanding. SiGe HBT is the first practical band gap engineered device, is the most promising transistor used in those applications' arena. It embodies high integration [1] and enormous performance in extreme environments from low temperature (4.2K) range to high temperature (300°C) [2]. Unlike SiGe HBT, the efficacy of electronics devices in harsh radiation realm is destitute except circuitry hardening either by process or design [3] is done. This has been a major concern for the radiation society not only reliability issue but also expensive cost [4]. SiGe HBTs are viable in unfriendly environment due inherent multi-Mrad Total Ionizing Dose without modifying the structure [5].

TID happens when a photon or particle with sufficient energy ionizes atoms or molecules and create electron-hole (eh) pairs in the oxide region and the uncombined electron hole pairs induce oxide and interface traps after recombination takes place [3][6]. This may lead to increase off state leakage current [7], increment of low frequency noise (LFN) [8] and decrease dc current gain, [8]. The emitter-base(E-B) spacer oxide and shallow trench isolation (STI) are regions where ramifying action of TID happens [9], [10]. As previous studies have shown, radiation induced generation recombination (G-R) mechanism in the former region increases base current in forward mode [11], [12]. But the increase generation-recombination centers in the EB space charge region doesn't increase collector current [12] as the number of injected carriers depends only on the base doping and applied bias [8]. Inverse Gummel plot is used to understand the irradiation induced traps in the collector-base space charge region and STI [5], [8]. The space charge G-R traps induced by the

ionizing irradiation are dependent on perimeter/area. As the perimeter/area increases, the generation-recombination reduces [7], [8]. Moreover, to recover the original characteristics of the transistor, annealing process is practiced [13], [14].

In this work, the effects of X-ray and gamma irradiation in two BiCMOS technologies of advanced Si/SiGe:C HBTs is investigated. In section III, in order to locate the induced traps, different area samples' DC characteristics are compared and to support the experiment, TCAD simulation is performed. In order to investigate the effect of time interval between each irradiation steps, HBTs response is studied after a few days. In addition, long-time interval effects are also studied. Finally, in section IV to probe further and understand a possible recovery mechanism behavior, a two steps thermal annealing experiment is conducted.

## II. EXPERIMENTAL

The studied HBTs are from STMicroelectronics 130nm BiCMOS9 [15] and 55nm B55 [16] advanced Si/SiGe:C BiCMOS technologies with Ft/Fmax of 220/280GHz and 320/370 GHz respectively.

TID experiments were conducted using the X-ray and Cobalt 60 source generator facility from the University of Montpellier PRESERVE platform located at IES laboratory, with a dose rate of a 14 rad/s and 50 rad/hr respectively. X-ray and Gamma irradiation were done for 10 and 8 steps until reaching a total dose of 151krad and 330krad respectively. Each irradiation steps were interrupted from 2 to 10 days for DC electrical characterization. And during irradiation, the transistors were unbiased.

Annealing measurements were performed after the HBTs were subjected to thermal annealing for 950hrs and 434hrs at 100°C and 130°C for HBTs irradiated by X-ray and Gamma irradiation sources respectively.

To evaluate the effect of X-ray and Gamma irradiations and the effect of annealing, the relative excess base current,  $\Delta I_B/I_B$ , is used in the forward Gummel-Plot measurements.

## III. DC CHARACTERIZATION

First results concerning X-ray and Gamma impact on the normalized excess input current,  $\Delta I_B/I_B$ , measured in low injection in the recombination region (i.e. for  $V_{BE}$  in the range of 0.4-0.6 V where the degradation is maximum), has been presented in [17]. The main results, independently from the irradiation sources, are a linear increase with the TID and a higher excess base current level for the BiCMOS9MW technology by a factor ranging between one and two order of magnitude comparing to the B55. A particularity concerning BiCMOS9MW technology is that the degradation induced by Gamma irradiations are less important than the one induced by X-Ray.

### A. Study versus emitter structure

The geometry dependency ( $A_E$  or  $P_E$ ) on the base current degradation response induced by X-ray exposure is investigated in Fig. 1. A slight dispersion is found for the B55's HBTs that can be related to the low irradiation impact, less than 10%. However, an independency to emitter geometry can be estimated for both technologies. But, due to a small and erratic variation plus a limited range of the geometry values (range of  $A_E$  or  $P_E$  less than one decade), it is difficult, at first sight, to discriminate between an areal or peripheral effect.

Same trends are found after the Gamma irradiation steps.

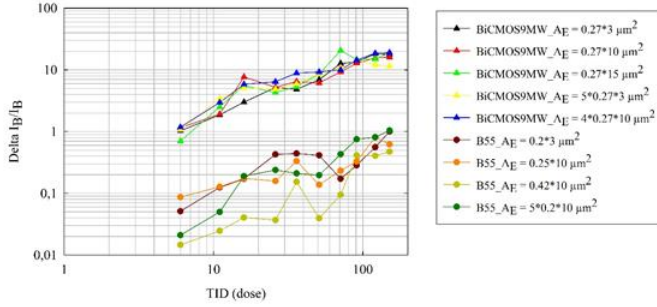


Figure 1. B9MW and B55 excess current base dependency to  $A_E$  versus TID (X-ray).

One of the technological aspects that was developed moving towards the newest B55 technology is shrinking its oxide thicknesses. Decreasing the oxide layers, especially the spacer oxide in the E-B area, is suspected to be the key parameter responsible for creating more resistive HBT components to the X-ray irradiation.

The increase of  $I_B$  level was attributed to induced Generation-Recombination centers in the emitter-base region [9][18] especially at: - The E-B spacer oxide. The induced trapped charge in the E-B spacer oxide is responsible for the increase of the base current. - The Collector side, some authors identified the STI oxide as a localization area of the induced traps [19]. Nevertheless, the created traps in the STI oxide are not examined since  $I_C$  did not presented a significant irradiation response. Generally speaking, to investigate the impact on STI oxide, the inverse Gummel mode must be studied.

The suspected areas of the induced trap centers are illustrated in Figure 2.

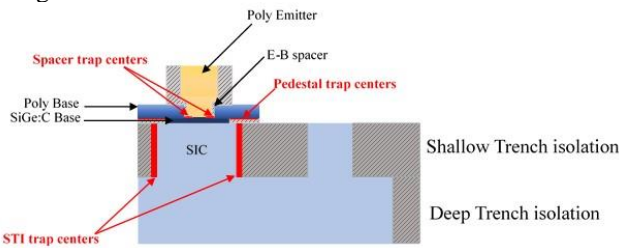


Figure III.2. Possible induced oxide trap centers in the schematic cross section of an HBT.

By considering the induced excess current as a peripheral current component, the base current is presented as followed [20]:

$$I_{B \text{ post\_rad}} = I_{B \text{ pre\_rad}} + P_E J_{bl} \exp\left(\frac{qV_{BE}}{n_{BG-R}KT}\right) \quad (1)$$

where  $n_{BG-R}$  represents the Generation-Recombination ideality factor respectively,  $P_E$  the emitter perimeter and  $J_{bl}$

the leakage current at the emitter-edge length expressed in  $\text{pA}/\mu\text{m}$ .

Eq. 1 is composed of two terms: the first one corresponds to the initial HBT state before irradiation. While the second term constitutes the induced current (recombination current) proportional to emitter perimeter  $P_E$  and presenting an ideality factor  $n_{BG-R}$  of 2.

One of the geometrical shrinking dimensions consequences in the newest BiCMOS generation is the reduction of the oxide thicknesses in the HBTs. Thus, compared to BiCMOS9MW, B55 technology presents reduced oxide thicknesses especially at the spacer oxide located at the E-B periphery. Thereby, we can suggest that by reducing the peripheral oxide, the created trap number in the emitter periphery decreases and so the impact of the second term of (1) is reduced. The reduction of the oxide layer can be considered as the key parameter to explain the higher robustness of the B55 technology. This behavior is consistent with previous studies on the irradiation impact in response to the gate oxide thickness of MOSFET devices [21].

In order to confirm the important role of the EB perimeter traps, TCAD simulations are undertaken

Figure :

### B. Time interval impact on DC measurements

In this section, time and measurements effects after the first X-ray irradiation step (10 krad) are investigated over 12 days. Two HBT geometries are selected from each technology,  $0.27*5 \mu\text{m}^2$  and  $0.4*5 \mu\text{m}^2$  for the BiCMOS9MW and  $0.2*5 \mu\text{m}^2$  and  $0.2*10 \mu\text{m}^2$  for the B55. Two dice were specifically reserved for this study with a total of 4 HBTs per technology. DC characterization is carried out during this test at 4 states: before irradiation, directly after irradiation exposure, after 5 and 12 days.

Figure 3 presents the time relaxation impact on the Gummel plots for the  $2 \mu\text{m}^2$   $A_E$  HBTs of each technology. On the contrary to the B55, BiCMOS9MW marked a degradation response after exposure. A negligible relaxation impact is

detected along the investigated period for  $I_B$  and  $I_C$  levels of both technologies.

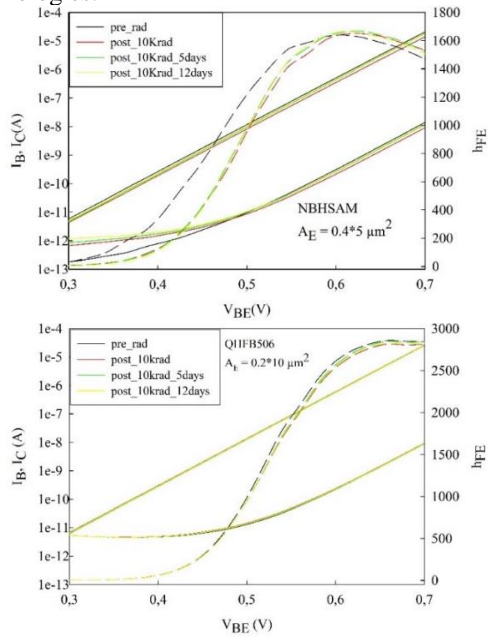


Figure 3. Impact of time relaxation on DC measurements for both BiCMOS9MW (upper figure) and B55. Solid lines:  $I_B$  and  $I_C$  currents – Dash lines: DC current gain  $hFE$

The effect of time was also studied, at room temperature, for a long interval of time, i.e. during 8 months after the last irradiation step with a dose of 151 krad and 330 krad respectively for X-ray and Gamma irradiations. Through this period several DC characterizations were held to investigate any possible relaxation effect.

As can be seen on Fig. 4 a negligible effect was found on forward Gummel plots analysis during the investigated time domain. The same tendency was respected by the two technologies.

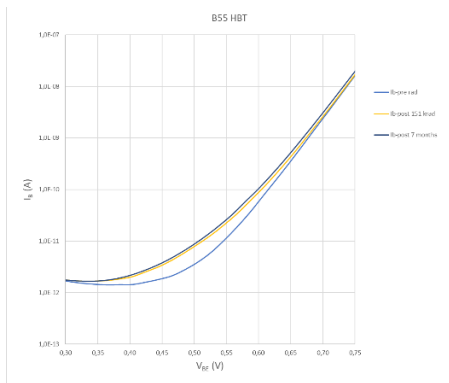


Figure 4. Representative example of the impact of long time relaxation on forward Gummel-Plot.

#### IV. ANNEALING EFFECT

As mentioned in introduction, in order to study a possible healing effect for the induced damages after X-ray and Gamma irradiations, an annealing procedure is carried out. HBTs are placed in a furnace and held at a constant temperature for a specific time scale. First, the components are annealed at 100°C, then the temperature is increased up to 130°C for the rest of the experiment. During the two-temperature steps several I-V measurements are carried out.

This study was performed on X-ray and Gamma irradiated HBTs after the 8 months interval period.

Fig. 5 represents the variation of the normalized excess base current for the maximum normalized base current degradation as a function of X-ray irradiation dose and its annealing time. The investigated time effect after 8 months is reported in Fig. 5 at  $t_0$ . During the thermal annealing process, for a temperature of 100°C, a significant decrease of  $\Delta I_B/I_B$  level is marked for BiCMOS9MW related to the de-trapping of some of the induced positive charges in the oxide at the E-B region [22]. Contrarily to the BiCMOS9MW, no healing effect was recorded for the B55 technology.  $\Delta I_B/I_B$  is maintained at a stable level.

Nonetheless, the healing process of interface traps and positive oxide charges is more important at higher annealing temperature greater than 100°C, due to the thermal emission of trapped holes from SiO<sub>2</sub> bandgap to the valence band [22][23]. Thus, by imposing a thermal annealing process at 130°C a significant healing effect is depicted for both technologies as can be seen in Fig. 5. Both technologies presented a recovery of 1 decade over the annealing process. A 90% of recovery is reached for the B55 HBT.

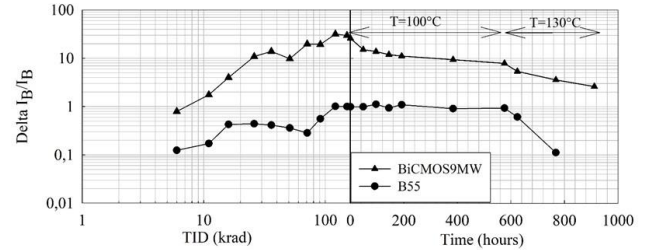


Figure 5. Variation of normalized excess base current for irradiated (X-ray) and annealed HBTs of both technologies.

Figure represents the variation of  $\Delta I_B/I_B$  as a function of the TID and the annealing time for the Gamma irradiated HBTs. After the first annealing step : 100 °C for 48 hours, a significant healing effect has marked both HBTs, particularly the BiCMOS9MW ones. By establishing other annealing steps at the same temperature of 100 °C till a cumulative total hour of 316 hours, the healing effect is less significant for the BiCMOS9MW that have presented a stable excess current level after 96 hours, contrarily to the B55 which have presented a decrease of nearly two orders of magnitude. After 316 hours, the DC performance of the B55 has regained a similar performance recorded on the pristine HBT.

Since the B55 has regained its pristine DC state, only the BiCMOS9MW was examined for the rest of the study. Before initializing new annealing process with an increased temperature, another annealing step of 70 hours was established inducing a low healing effect of the induced traps. After an annealing process of 386 hours, a new annealing temperature of 130 °C was introduced to examine the BiCMOS9MW response. A high decrease of  $\Delta I_B/I_B$  is observed, the resulted  $I_B$  current has presented a high recovery after 48 hours of annealing.

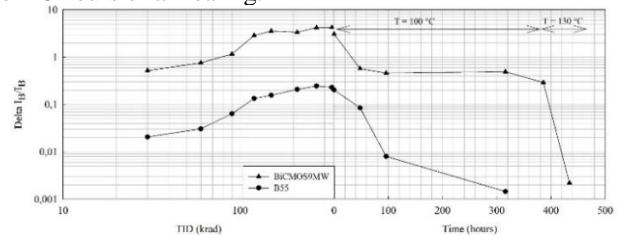


Figure 6 Variation of normalized excess base current for irradiated and isochronal annealed HBTs of both technologies.

## V. CONCLUSION

A comparison of each degradation source was examined, a similar degradation response is found for both technologies. Nonetheless, a variation in the degradation level was mainly pronounced for the BiCMOS9MW which is associated to the radiation response of E-B spacer oxide and STI oxide to each source. Independently to the applied stress, the E-B spacer oxide region was proposed/demonstrated as the main induced defect localization area. This is confirmed by the first results of the TCAD simulation. Each irradiation technique was followed by a time effect and a thermal annealing process. A higher healing impact for the induced damages was more pronounced after the Gamma-ray exposure. In both cases, an enhanced healing behavior was recorded by the B55 technology. These results are consistent with the recent ones published by Nergui et al [13] on the 130-nm BiCMOS-8HP SiGe HBT technology of GlobalFoundry.

The results presented on this paper are promising results concerning extreme environments integrated circuits based on BiCMOS Si/SiGe HBTs technology, especially for the B55 BiCMOS technology.

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