In-situ recovery of the base current of SiGe NPN HBTs at high gamma dose levels

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***Abstract*— The base current Ib of a 0.13 µm SiGe HBT (Heterojunction Bipolar Transistor) is measured during gamma irradiation. Three different regions are observed: an initial degradation region (0-20 kGy) in which Ib decreases, a saturation region (20-60 kGy), showing a saturation of Ib, and a recovery region (60-100 kGy) where the excess Ib starts to decrease. This technology is compared with two older technologies: a 0.35 µm SiGe HBT from AMS and a discrete transistor from Infineon. Both technologies show, after an initial increase in Ib a slight decrease of Ib. It is observed that the end of the initial degradation shifts to a lower dose as technology scales down.**

Index Terms— SiGe Heterojunction Bipolar Transistor, Gamma radiation, online measurements, base current recovery

I. INTRODUCTION

WHITIN the radiation community there is a trend to use commercial-off-the-shelf (COTS) parts wherever possible as a cost-saving measure and to have access to high performance components. In this view, it is not only important to know the worst case degradation of the COTS-elements, but also to understand how these parts decay. In-situ measurements during irradiation can reveal important information and hence help to design a radiation hard electronic circuit.

Due to their high total ionizing dose (TID) tolerance, SiGe HBTs are possible candidates to be used in harsh radiation environments.

In this paper, first the physical basis of the radiation effects in HBTs is given. Further, the evolution of the base current during gamma irradiation is discussed for an advanced 0.13 µm SiGe:C HBT technology. These results are compared with the degradation of a commercially available 0.35 µm SiGe HBT and a discrete SiGe NPN transistor. An evaluation of these experiments indicates that after an initial increase, the base current starts to decrease at a certain threshold dose. This threshold dose is the lowest for the 0.13 µm SiGe:C HBT and the highest for the discrete transistor.

II. RADIATION INDUCED DEGRADATION IN HETEROJUNCTION BIPOLAR TRANSISTORS

When HBTs are irradiated, the current gain decreases, especially at low bias levels. This reduced current gain results primarily from an increased base current at a fixed emitter bias. Typically, the collector current remains roughly constant. This is illustrated in Fig. 1.

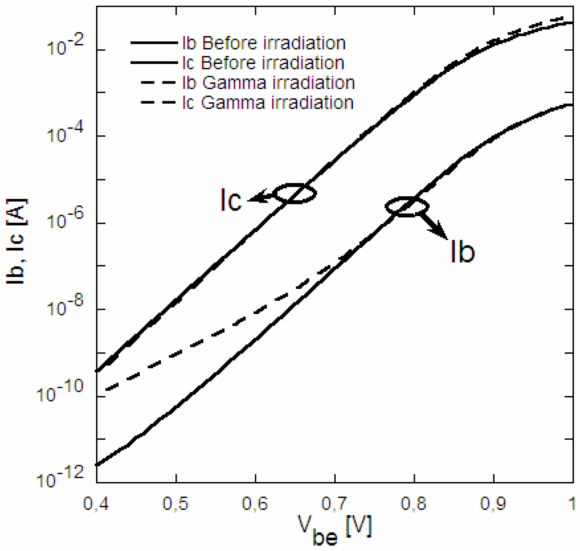

Fig.1. Typical degradation of Gummel-plot when a SiGe:C NPN transistor is exposed to 100 kGy gamma radiation.

There are three significant components of the base current: the current due to the recombination in the emitter-base depletion region, the recombination current in the neutral base and the current due to back-injection of carriers from base to emitter. Before irradiation the latter current dominates. After irradiation both other currents increase. When exposed to ionizing irradiation, the recombination current in the emitter-base depletion region will dominate. The increased recombination occurs around the edge of the emitter in the vicinity of the emitter-base oxide, so the amount of excess base current is proportional to the perimeter-to-area ratio [1].

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The base current can be represented by the form:

$$Ib = Ib_0 \cdot e^{\frac{V_{be}}{\eta \cdot V_{th}}} \qquad (1)$$

In this equation, V_{th} is the thermal voltage and η is the ideality factor. When η=1, the diffusion current dominates and when η=2, the recombination current dominates [2].

The radiation-induced increase of the recombination rate in the emitter-base depletion region is attributed to the creation of interface traps that serve as recombination centers. The number of newly created surface states per unit length ΔN_{ss} can be obtained by following equation:

$$\Delta N_{ss} = \frac{2 \cdot Jb_1}{q \cdot \sigma \cdot v_{th} \cdot n_i} \qquad (2)$$

Where q is the electron charge, v_{th} is the thermal velocity of carriers, σ the capture cross section of the recombination centers, and n_i the intrinsic carrier density. The value of Jb_1 can be obtained from the equation of the excess base current [A/µm emitter edge length] [3]:

$$\Delta Jb = Jb_1 \cdot e^{\left(\frac{q \cdot V_{be}}{2 \cdot k \cdot T}\right)} \qquad (3)$$

III. EXPERIMENTAL RESULTS

The quasi self-aligned 200 GHz NPN SiGe:C HBT is implemented in a 0.13 µm BiCMOS generation. The emitter area A_e of the device is 1.3 µm^2 (emitter width W_e = 0.13 µm, emitter length L_e= 10 µm). A schematic cross section is shown in Fig. 2. More information about this technology can be found in [4].

The gamma irradiation has been performed in the RITA facility at SCK•CEN in Mol, Belgium. The components have been irradiated for 100h at a dose rate of 1 kGy/h. 1Gy corresponds to the absorption of one joule of radiation energy by one kilogram of matter. During irradiation, the temperature was 28-30°C. The Gummel-Poon characteristic was measured every 30 min. When not measured, all contacts are grounded.

The online DC-characterization of the NPN transistors consists of forward-mode Gummel measurements. It is measured with grounded base and collector contacts and sweeping the emitter to negative voltages.

The relative degradation of the base current Ib as a function of time is shown for 3 different V_{be} in Fig. 3. The curves at V_{be}= 0.44 V and V_{be}= 0.64 V clearly show three different regions. In the initial degradation region (0-20 kGy) Ib increases. Next, the degradation of Ib saturates (saturation region: 20-60 kGy). Ib starts to decrease at a total dose of 60 kGy (recovery region). Finally, when irradiation is stopped, a further, more rapid decrease of Ib takes place. Also after radiation, the contacts are grounded when the devices are not measured. The increase of Ib (region 0-20 kGy) is larger for lower V_{be}. Also, the decrease in Ib (region 60-100 kGy) is more pronounced for lower V_{be}. Almost no recovery is found for the curve at V_{be}= 0.72 V.

In Fig. 4, Ib is shown for 4 different doses as a function of V_{be}. It can again be observed that for the devices studied, the highest degradation occurs at a dose of 40 kGy (region 20-60kGy).

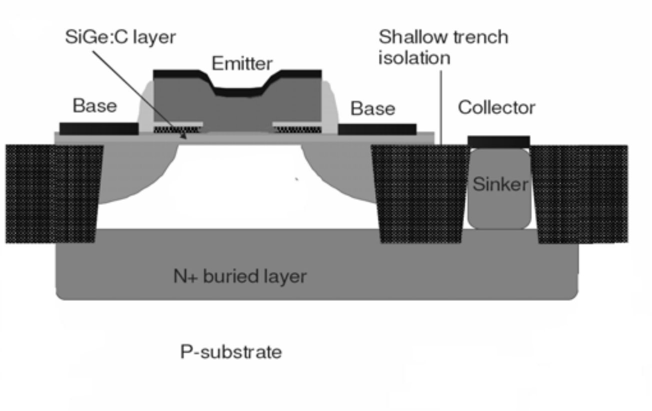

Fig. 2. Schematic cross section of a 0.13 µm SiGe:C NPN transistor.

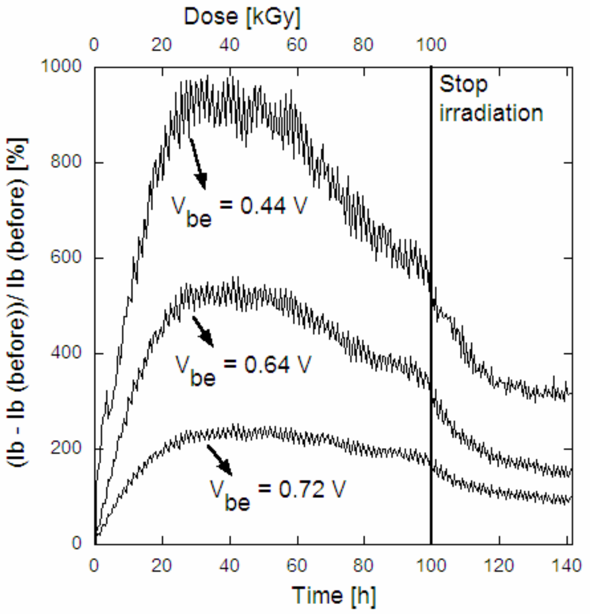

Fig. 3. Relative degradation of Ib of a 0.13 µm SiGe:C HBT for 3 different V_{be}. Radiation starts at time=0h and stops at time=100h. The dose rate is 1kGy/h.

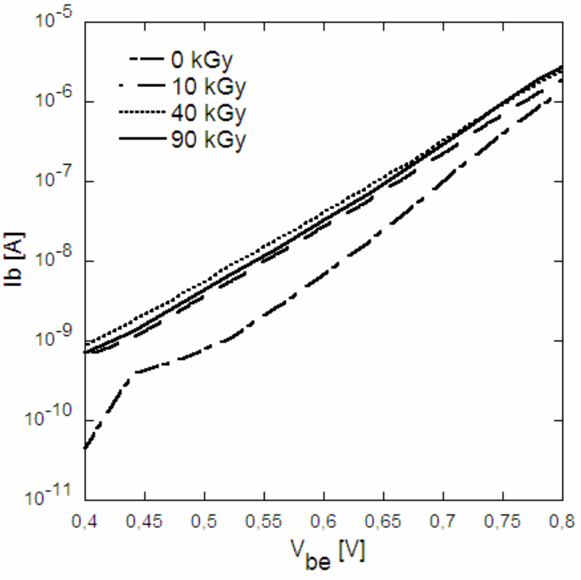

Fig. 4. In-situ measured Ib as a function of V_{be} at a dose of 0 kGy, 10 kGy, 40 kGy and 90 kGy.

The noise on the curves in Fig. 3 is attributed to the variation of temperature during the measurement of the device. The noise on Ib during irradiation is larger than after irradiation, showing an increased temperature sensitivity during irradiation. The base current as a function of temperature measured after irradiation is shown in Fig. 5.

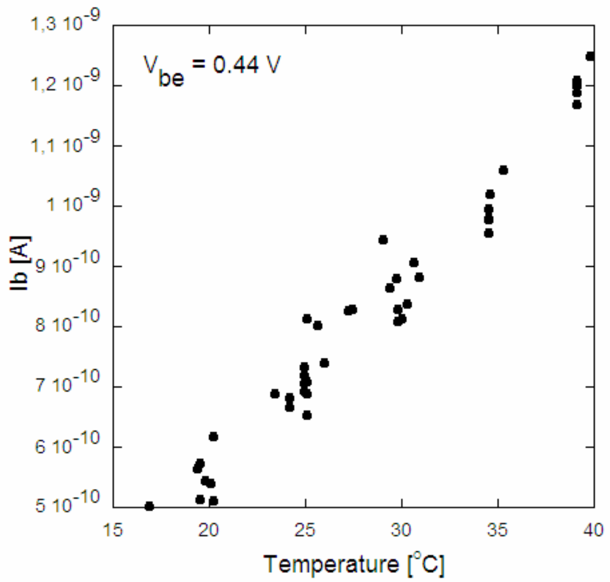

Fig. 5. Ib versus temperature, measured after irradiation at V_{be} = 0.44 V.

IV. DISCUSSION

In this section, the variation of the excess base current during irradiation is studied into more detail. The ideality factor η is extracted with the help of equation 1. It is illustrated in Fig. 6 as a function of time. It can be observed that in the initial degradation region (0-20 kGy) η increases to a value larger than 2, indicating that the recombination current dominates the base current. In the saturation region (20-60 kGy), η decreases only slightly, but the ideality factor remains larger than 2. In the recovery region (60-100 kGy) η drops to a value of 1.83, indicating a reduced influence of the recombination current on Ib. After irradiation is stopped η further decreases to 1.66.

The number of newly created surface states per unit length is extracted with formula 2 and 3, using an intrinsic carrier density n_i=2.9·10^{11} cm^{-3}, a thermal velocity of carriers v_{th}=10^{7} cm/s and a capture cross section of σ= 10^{-15} cm^{2}. The result is displayed in Fig. 7. The amount of surface states first increases to a maximum value of 1.4·10^{6} cm^{-1} at the beginning of the saturation region. In the recovery region, the concentration drops faster compared to the saturation region. A further annealing of surface states, to a value of 2.5·10^{4} cm^{-1} is observed after the irradiation has stopped.

The onset of the saturation region can be explained in the following way. When large amount of oxide charges are created due to irradiation, the surface of the p-type base becomes accumulated. The recombination peak will move below the oxide/silicon interface and the recombination at the surface will decrease. This results in a decrease of effective surface state concentration as is illustrated in Fig. 7. When this happens the excess base current will saturate [1].

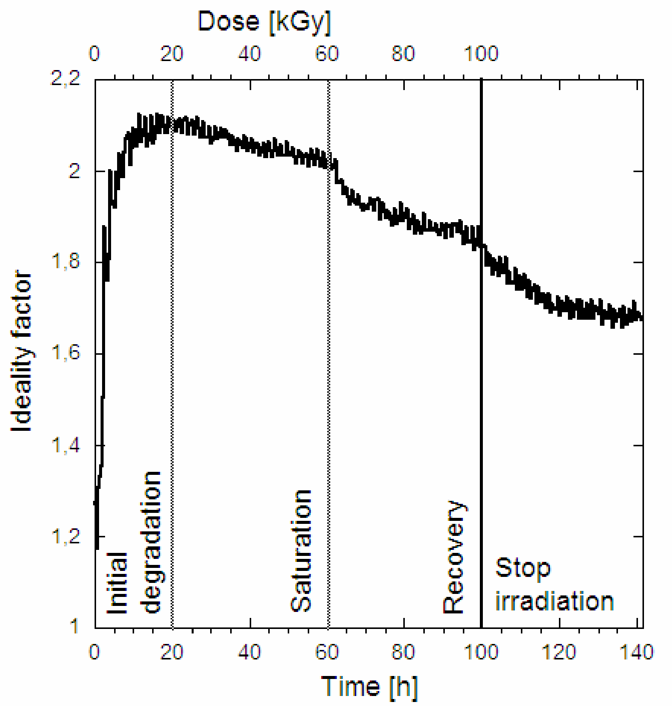

Fig. 6. Ideality factor of Ib as a function of time. Radiation starts at time=0h and stops at time=100h.

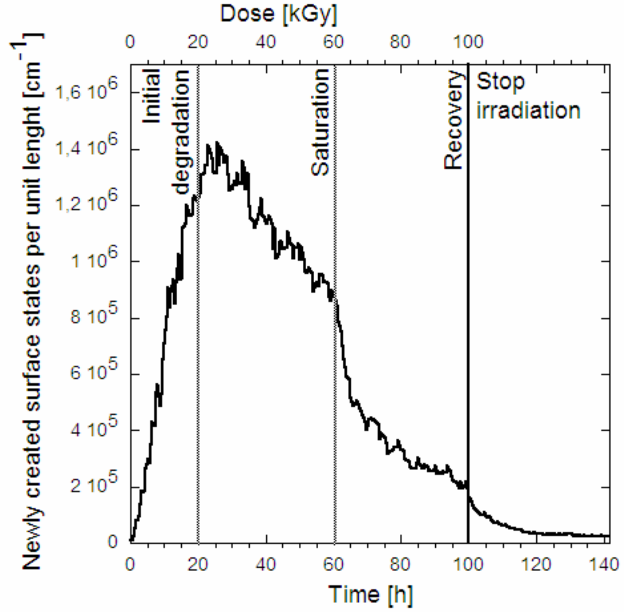

Fig. 7. Newly created surface states per unit length as a function of time. Radiation starts at time=0h and stops at time=100h.

A possible explanation for the recovery of Ib during radiation is the fact that hydrogen can be released from the metal-Si and poly-Si boundaries. The hydrogen can passivate the dangling bonds near the poly-mono interface. This will effectively reduce the recombination velocity in the emitter region. This is indicated by the exponential decrease in surface state concentration in Fig. 7.

This behavior of Ib during irradiation can be linked to the Ib-recovery when the HBT is subjected to very high forward current stress conditions. Also in that case there will be an initial increase of Ib and finally, after a certain stress time, Ib will start to decrease [3] ,[5].

V. COMPARISON WITH OLDER TECHNOLOGIES

A. 0.35 µm SiGe HBT

The Ib variation during irradiation has also been studied for 2 other technologies, i.e. a 0.35 µm technology and discrete transistors. In Fig. 8, the relative degradation of Ib for a commercial 0.35 µm SiGe HBT from AMS with an emitter area of 4 µm^2 (W_e = 0.4 µm, L_e = 12 µm) is illustrated. These devices have also been irradiated in the RITA facility at a dose rate of 1 kGy/h. In this case the degradation region extends from 0-140kGy. At a total dose of 140 kGy, the excess Ib starts to show a slight decrease.

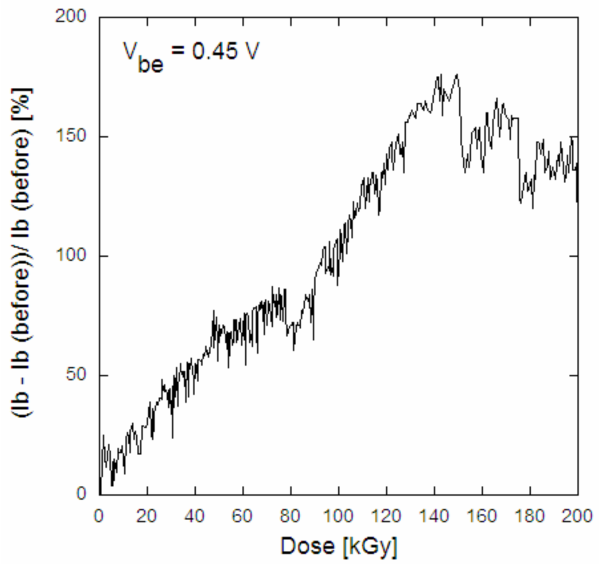

Fig. 8. Ib degradation of a 0.35 µm NPN SiGe HBT from AMS.

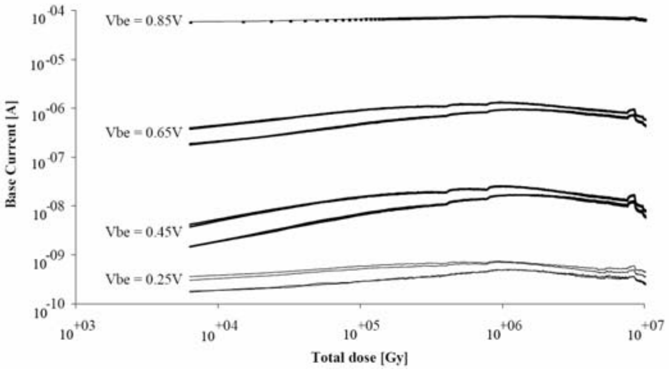

Fig. 9. Ib degradation of a NPN discrete transistor of Infineon (type BFP640) [7].

B. Discrete transistor of Infineon

The radiation induced drift in Ib for a discrete SiGe NPN transistor of Infineon (type BFP640) is shown in Fig. 9. The irradiation was performed in the CMF facility of SCK•CEN at a dose rate of 17 kGy/h and a temperature of 55°C. Complementary irradiations at lower dose rates confirmed the limited dose rate effect and hence allow a qualitative comparison with the other SiGe HBTs. Also in this case, the degradation region is directly followed by a decrease in base current. The latter begins at a total dose of 1 MGy. Degradation and recovery of Ib are more pronounced at lower V_{be}. Almost no degradation is found when V_{be} = 0.85 V [6]. More information about this experiment can be found in [7].

C. Comparison between the different technologies

In Table I, the end of the initial degradation region is listed for the three different technologies. When the technology scales down, Ib starts to decrease at a lower total dose.

In the older technologies the initial increase in Ib is followed by a slight decrease of Ib. However, because the decrease is only minor, this effect is probably more related to the onset of the saturation regime in the 0.13 µm technology than to the recovery regime.

The onset of the saturation regime is related to the oxide charges concentration needed to accumulate the p-type base. This concentration is independent of the emitter area. However, it is dependent of the surface doping of the extrinsic base [8]. In this view, the doping should be the largest for the discrete transistor and the lowest for the 0.35 µm SiGe HBT. Unfortunately, it can not be verified because this data is not available for the 0.35 µm SiGe HBT and the discrete transistor.

TABLE I: DOSE AT WHICH THE INITIAL DEGRADATION OF IB ENDS FOR THE THREE DIFFERENT TECHNOLOGIES.

	0.13 µm SiGe:C HBT	0.35 µm SiGe HBT	Discrete transistor
Start of recovery region	20 kGy	140 kGy	1 MGy

Earlier results presented in literature did not observe the radiation-induced healing because they either relate to a previous technology node or the total dose did not exceed the threshold value to observe this secondary effect.

VI. CONCLUSION

In this paper the evolution of the base current is studied by in-situ measurement for an advanced 0.13 µm SiGe:C HBT technology. The base current evolution can be divided into 3 regions: a degradation region (Ib increases), a saturation region (Ib stays more or less constant) and a recovery region (Ib decreases).

The onset of the saturation regime is related to the shift of the peak recombination away from the oxide/silicon interface.

A possible explanation for the recovery of Ib during radiation is the fact that hydrogen can be released from the metal-Si and poly-Si boundaries.

The radiation behavior of the 0.13 µm SiGe:C NPN transistor is compared with a 0.35 µm SiGe HBT and a discrete NPN transistor. After an initial degradation of Ib the two older technologies show a slight decrease in the excess Ib. However, because the decrease is only minor, this effect is probably more related to the onset of the saturation regime in the 0.13 µm technology than to the recovery regime. The end of the initial degradation of the excess Ib appears to shift to a lower dose when the technology scales down.

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