The Impact of Irradiation on DC Characteristics and Low-Frequency Noise of Advanced SiGe:C HBTs

B. Sagnes, A. Adebabay Belie, M. Bouhouche, J. El Beyrouthy, F. Pascal, J. Boch, P. Chevalier, and D. Gloria

Abstract—**SiGe:C heterojunction bipolar transistors (HBTs) have emerged to address the high demand of high-speed applications in telecommunications and more recently in the space domain. But the ramifying effects of radiation on the DC characteristics and low-frequency noise of SiGe HBTs reveal the degradation in performance and reliability of SiGe HBTs and their associated circuits. Consequently, it is important to understand the impacts of total ionizing dose on SiGe HBTs to design radiation-tolerant and viable electronic devices. This presentation investigates the impacts of X-ray irradiations on advanced SiGe:C HBTs, specifically the ones developed in the B55 BiCMOS technology with f_T/f_{max} of 320/370 GHz, supplied by STMicroelectronics in the framework of the European SHIFT project. Different degradation parameters, such as relative base current and base current noise spectral density, are used in this work. Moreover, the impacts of collector doping, geometry, and annealing will be explored in detail.**

Index Terms—**Annealing, base current, collector doping, degradation, low-frequency noise, X-ray irradiation.**

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B. Sagnes, A. Adebabay Belie, M. Bouhouche, J. El Beyrouthy, F. Pascal, and J. Boch are with IES, University of Montpellier, CNRS, 34095 Montpellier, France (bruno.sagnes@umontpellier.fr)

P. Chevalier and D. Gloria are with STMicroelectronics, 38926 Crolles France

I. INTRODUCTION

THE demand for high-speed (HS) wireless communication and niche high-frequency applications is continuously growing at present. Transistors such as SiGe: C heterojunction bipolar transistors (HBTs) and III-V HBTs offer high performance for HS applications although the latter requires complex manufacturing steps, which results in expensive cost. Studies have shown SiGe:C HBTs provide huge performance in wide temperatures, ranging from 4.2 to 573 K [1]. Nevertheless, the radiation-rich environment has a negative impact on the reliability and performance of electronic devices, which has been attracting the attention of the radiation society for many years.

In general, the radiation environment induces two effects on devices, namely single event effect and cumulative effects. The former is caused by a single particle as it passes through or near a sensitive node in a circuit, and results in either a

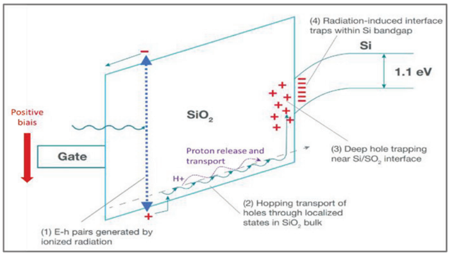

Fig. 1. Process of radiation-induced charge generation in MOS devices [4].

hard error such as single event latch-up or a soft error like single event upsets [2]. Cumulative effects can be divided into two categories: total non-ionizing dose, also known as displacement damage [3], and total ionizing dose (TID), called simply dose, which is the main focus of this study.

The TID effect corresponds to the trapping of charge in the oxide of electronic devices over a period of time leading to the degradation of the component's electrical characteristics. The process that leads to the trapping of charges in semiconductor devices can be illustrated based on a metal–oxide–semiconductor (MOS) structure as depicted in Figure 1.

TID is caused by energetic particle or photon that ionizes the atoms along its path, leading to the generation of electron–hole pairs. Some of these electron–hole pairs recombine due to initial recombination (referred to as charge yield). The uncombined electrons tend to move away from the oxide (in the order of tens of picoseconds) due to their high mobility, whereas holes tend to move slowly to the silicon-oxide interface by hopping mechanism, which results in holes trapping in both oxide and interface traps. These trapped holes in oxide (N_{ot}) and interface traps (N_{it}) later lead to the degradation of the component's electrical characteristics of electronic devices. One of the most important and well-studied effects of N_{ot} is the negative shift in the drain current versus gate-to-source voltage for both N- and P-channel metal–oxide–semiconductor field-effect transistors. The main effect of N_{it} is an increase in the sub-threshold swing of MOS devices.

Unlike MOS transistors, for which the active current layer is at the surface of the semiconductor and in direct link with the Si/SiO_2 interface and the oxide layer above it, bipolar devices are "bulk" devices, in that the currents mostly flow through silicon PN junctions. One would therefore expect these bipolar devices to be relatively insensitive to TID, but this is not the case. The most efficient way to highlight TID degradation in a bipolar transistor is to study the influence of increasing TID levels on the Gummel plot, showing the collector and base currents versus the base–emitter voltage, for a constant reverse collector–base voltage. Most of the degradation directly impacts the forward current gain, which decreases with increasing TID level, due to an increase in base current while collector current remains almost unchanged.

As we have seen, trapped charge will have an impact on the behavior of the component, but this effect is not definitive. Indeed, a long time or a high temperature can lead to an annealing effect. Annealing experiments are widely practiced in the radiation community, aiming to remove trapped charges by increasing the temperature of the device over a period of time. Such annealings are also preconized in test methods in accordance with standards [5].

To have a rad-hard device, it is compelling to harden the device either by process or by design as shielding the system from irradiation that leads to an increase in both system weight and complexity, and reduces system reliability [6]. Studies show that SiGe:C HBTs are able to operate in the extreme radiation environment without the need for hardening, with adequate performance and acceptable reliability [7] [8]. Despite this, it is necessary to do extensive characterization in order to model, understand, and investigate the DC characteristics and low-frequency noise (LFNoise) of SiGe HBT in the extreme irradiation environment.

This study presents the impacts of X-ray irradiation on the DC characteristics and LFNoise of SiGe:C HBTs. The impacts of geometry, collector doping, and annealing on the degradation of base current will be explored in the next sections.

II. EXPERIMENTAL SET-UP

The HBTs are issued from a 55 nm CMOS node of BiCMOS technology, B55, developed by STMicroelectronics.

A single-finger CBEBC configuration of HBTs with an emitter area range of 1–4.2 µm² was used for the measurement. The HBTs have three flavors, HS, medium-voltage (MV), and high-voltage (HV), which differ by their selectively implanted collector (SIC) doping, aimed to meet the power and speed requirements [9].

The irradiation experiments were carried out by using 320 keV high-energy X-ray generators located at the PRESERVE platform in the Institute of Electronics and Systems (IES) laboratory, University of Montpellier. It was performed at the dose and dose rate of 40 krad and 11.33 rad/sec respectively in seven steps until it reached a maximum TID of 280 krad. In each step, the forward Gummel measurements and LFNoise experiments were done for approximately one hour. Moreover, the samples were unbiased during irradiation.

After the samples were exposed to a maximum TID of 280 krad, the impact of room temperature was investigated for 10 weeks. After this, annealing experiments were conducted at 100 and 130 °C for a total of 282 annealing hours. To test whether or not thermal annealing has any effect on the DC and LF noise characteristics of non-irradiated transistors, we annealed four pristine transistors at 130 °C for 160 hours. In all cases, no impact was observed.

III. DC CHARACTERISTICS

To understand the static characteristics of the device and determine the range of biasing current or voltage used for LFNoise measurements, it is compelling to first investigate the DC characteristics of the device.

The forward pre-rad and post-rad Gummel characteristics of 0.42 × 10 µm² HBT are presented in Figure 2.

As shown in Figure 2, unlike the collector current (I_C), the base current (I_B) increases with TID. For instance, at 280 krad, I_B is significantly greater than the pre-irradiation I_B as labeled in Figure 2. The significant increase of I_B, subsequently resulting in a reduction of current gain, is majorly shown within the V_{BE} ranging from 0.3 to 0.6 V. While negligible degradation is observed for V_{BE} greater than 0.6 V.

The normalized relative I_B and I_C help to understand the impacts of irradiation quantitatively by comparing the

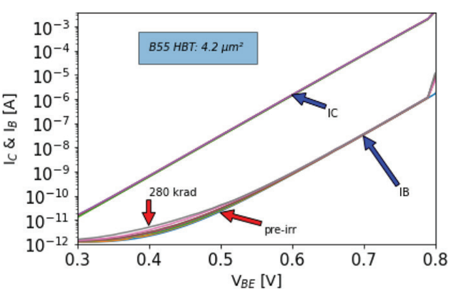

Fig. 2. Pre- and post-irradiation forward Gummel plot of 0.42 × 10 µm² B55 HBT.

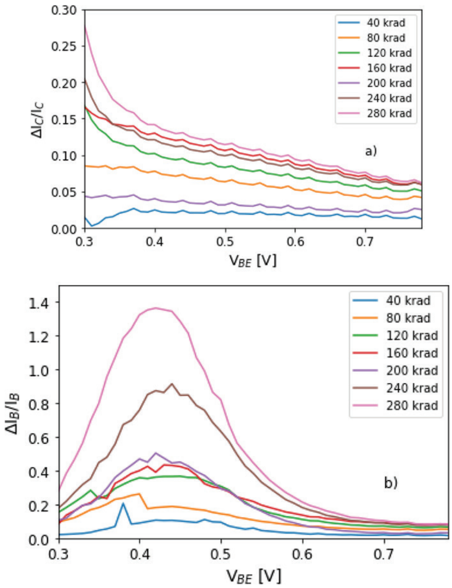

Fig. 3. Examples of: (a) $\Delta I_{C/}I_C$ and (b) $\Delta I_{B/}I_B$ versus V_{BE} at different TIDs.

post- and pre-irradiation currents, which are expressed as:

$$\frac{\Delta I_C}{I_C} = \frac{IC_{post-irr} - IC_{pre-irr}}{IC_{pre-irr}} \quad (1)$$

$$\frac{\Delta I_B}{I_B} = \frac{IB_{post-irr} - IB_{pre-irr}}{IB_{pre-irr}} \quad (2)$$

The $\Delta I_{C/}I_C$ and $\Delta I_{B/}I_B$ are plotted versus V_{BE} in Figure 3. The normalized collector current, as illustrated in Figure 3a, exhibits a negligible increase with TID. For instance, the maximum degradation was less than 0.1 in the high V_{BE} range. Whereas, the normalized base current showed a maximum increase of 1.4 at a V_{BE} of 0.4 V and TID of 280 krad. But for higher V_{BE}, the degradation of I_B gets very small, especially in the diffusion region where V_{BE} is greater than 0.6 V. Note that for V_{BE} less than 0.6 V, it is the low-injection region where the detrimental impact of irradiation likely happened.

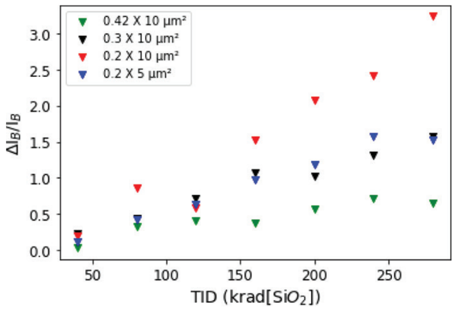

Fig. 4. $\Delta I_{B/}I_B$ versus TID at V_{BE}=0.54 V for HS devices.

Comparing the normalized collector and base current, it is important to focus on the base current rather than the collector current to investigate the impact of irradiation as the base current shows a significant degradation by irradiation [10].

A. Impact of Geometry

TID has different responses for different geometries of SiGe:C HBTs. Figure 4 is a plot of four geometries HS B55 HBTs $I_{B/}I_B$ versus with TID at V_{BE} of 0.54 V to avoid the influence of tunnel component.

As shown in Figure 4, a linear increase of $\Delta I_{B/}I_B$ with TID is observed. For TID less than 120 krad, the impact of geometry on $\Delta I_{B/}I_B$ is negligible, and this was also shown in previous results [11]. But for TID greater than 120 krad, smaller geometry HBTs showed a greater degradation compared to larger geometry B55 HBTs [12]. Therefore, it could be a better solution to use larger geometry HBTs for rad-hard circuits.

As can be seen in Figure 5, the radiation-induced trap centers in the SiGe:C HBTs potentially could arise in spacer oxides, pedestal oxides, shallow trench isolation (STI), and deep trench isolation. The traps that arise in the emitter–base spacer oxide lead to the depletion

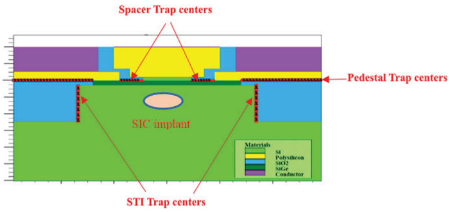

Fig. 5. The possible induced irradiation trap centers in SiGe HBT.

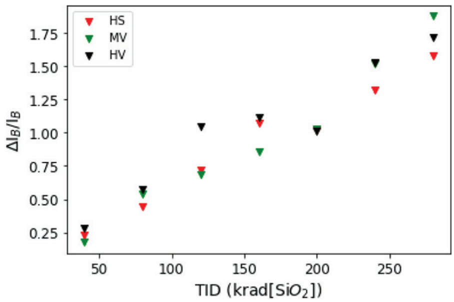

Fig. 6. $\Delta I_{B/}I_B$ versus TID of 0.3 × 10 µm^2 HS, MV, and HV HBTs.

of the emitter–base junctions, which later increase the base current in forward Gummel measurements [13]. Studies have shown that the traps present within STI, and collector–base spacer oxide are responsible for the increase of base current in inverse Gummel measurements [14].

B. Impact of Collector Doping

B55 HBTs are available in three flavors of transistors to meet the power and high-frequency requirements. The transistors are HS, MV, and HV, which differ by their SIC doping.

To investigate the impact of collector doping on the increases of base current of forward Gummel measurements, the $\Delta I_{B/}I_B$ of HS, MV, and HV HBTs are plotted at different TIDs in Figure 6.

As illustrated in Figure 6, the $\Delta I_{B/}I_B$ of HS, MV, and HV HBTs at different TIDs are approximately equal. This in turn leads us to say that the collector doping could have a negligible impact on the degradation of I_B.

C. Annealing

To investigate and study the possible recovery of radiation-induced traps, an annealing experiment was carried out. After the samples were exposed to a maximum TID of 280 krad, the weekly responses had been studied for 10 weeks, to ensure the room temperature has no

TABLE 1
ANNEALING MECHANISM

Annealing temperature (°C)	Annealing hours
100	100
	68
130	24
	90

effect on the recovery of traps. After that, the annealing experiments were performed as summarized in Table 1.

To understand the degradation and detrapping, $\Delta I_{B/}I_B$ is plotted at three V_{BE} of 0.4, 0.54, and 0.62 V for 0.3 × 10 µm^2 HBT.

As shown in Figure 7, the maximum recovery of I_B is approximately 70% at annealing temperature of 100 °C for 168 hours. During the final annealing experiment conducted at 130 °C for a duration of 114 hours, the recovery was noted to be around 90%. Nonetheless, the recovery is different at different V_{BE}. For instance, it is 90% at V_{BE} of 0.4 V, 79% at V_{BE} of 0.54 V, and 55% at V_{BE} of 0.62 V. Note that the degradation of I_B varies with V_{BE} ranges. The highest degradation of I_B was observed at V_{BE} of 0.4 V in comparison to V_{BE} of 0.54 and 0.62 V. This confirms our prior results that the generation–recombination base current component is the main responsible current for the increase of I_B compared to the diffusion base current. But, at high TIDs, the

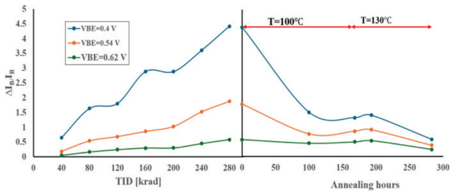

Fig. 7. $\Delta I_B/I_B$ with function of TID and annealing time at $V_{BE} = 0.4$, 0.54, and 0.62 V.

diffusion current also contributes to the degradation of base current. Our measurement result also clearly shows that the room temperature has no impact on the charge detrapping or recovery of radiation-induced traps. For example, in Figure 7, $\Delta I_{B/}I_B$ at zero annealing hour, measured after 10 weeks at room temperature, is approximately equal to $\Delta I_{B/}I_B$ at 280 krad.

IV. IMPACT OF IRRADIATION ON LOW-FREQUENCY NOISE

Compared to electrical *I–V* measurements, LFNoise is a very sensitive characterization technique used to probe and analyze defects, traps, or generation–recombination centers in materials and devices. Hence, it is a very good tool for monitoring the development of a technology and for predicting device reliability [15]. Moreover, due to the nonlinearity in devices, LFNoise can be up-converted and then affects the high-frequency performance of analog circuits such as mixers, oscillators, and amplifiers.

Since the 1990s, intensive LFNoise studies in bipolar junction transistors (mainly PE Si BJTs), III-V heterojunction bipolar transistors (GaAs- or InP-based HBTs), or SiGe HBTs have been undertaken [16] [17]. Concerning the latter, our team has characterized different BiCMOS technologies supplied by STMicroelectronics. In particular, the B55 technology has been extensively studied as part of the European TARANTO project [18]. For part of the current European SHIFT project, we are studying more specifically the effect of X-ray and gamma irradiations on this technology.

First, we present the main LFNoise results obtained on non-irradiated components. Then, we will discuss the results concerning the effect of irradiations, mainly the effect of X-ray TID.

A. Main LFNoise Results Obtained on Pristine B55 HBTs

We directly measured the fluctuations of the input base current, S_{IB}; thus, the expected white noise is the shot noise $2qI_B$. Die-to-die dispersion can lead to different spectra as presented in Figure 8. Excess noise is composed of at least a 1/f component (slope −1), which can be hidden by the presence of one or two generation–recombination components, presented by Lorentzian spectra (plateau + slope −2) and associated with a trapping/de-trapping process [19]. Each spectrum can be analytically approached by the classical deconvolution relation (3), and the second term, relating to the components of G-R, is optional.

$$S_{I_B} = \frac{K_F \cdot I_B^{A_F}}{f} + \sum_{i=1}^{n} \frac{B_i \tau_i}{1 + (2\pi f \tau_i)^2} + 2qI_B \qquad (3)$$

Whether as a technological indicator or for circuit simulation, the 1/f noise component has been, and still is, widely studied in comparison with G-R noise. The random presence of the latter makes its study more complicated.

As far as the 1/f noise of HBTs based on B55 technology is concerned, based on our previous studies [20] and on literature data, we can say that:

- the study of K_F versus base bias current and emitter area leads to very

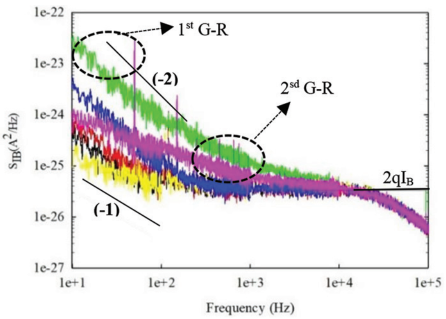

Fig. 8. Base current spectral density for six HBTs with the same geometry of the B55 technology (A_E = 2 µm² at I_B of 100 nA).

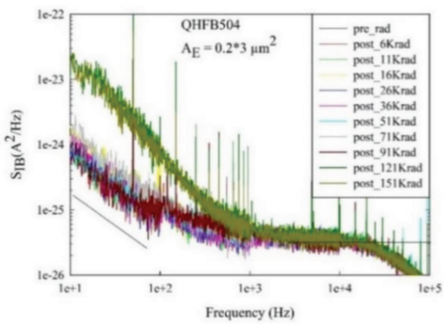

Fig. 9. Various irradiation responses of S_{IB}, for I_B = 100 nA, after X-ray exposure.

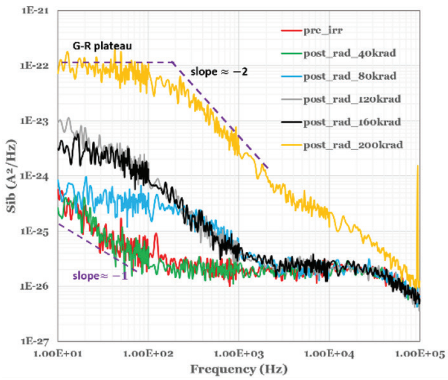

Fig. 10. S_{IB} for I_B = 50 nA at different X-ray TID (A_E = 3 µm²).

good values of the 1/f noise level, with a figure of merit $K_B = K_F \times A_E$ in the range of 2–6 10^{-10} µm² close to the best values published [20][21];

- the study of K_F versus different technological parameters (i.e., doping, interface cleaning, etc.) leads to the conclusion that the 1/f noise sources are located at the E-B junction mainly at the poly/mono interface [12][17].

B. Post-rad Spectral Analysis

At low TID, below 100 krad and much more rarely up to 150 krad, 1/f noise component is systematically dominated by the presence of one or two G-R components whose cut-off frequency and plateau do not vary much with dose. An example is given in Figure 9. As can be seen from Figure 10, at higher doses (>150 krad) on a few transistors, we observed a very significant increase in the plateau of the second G-R component.

In parallel with the DC characterizations, we studied the effect of thermal annealing on noise spectra after a cumulative dose of 150 krad. Whatever the geometry, we systematically recovered the initial spectra following annealing at 130 °C, notably with the complete disappearance of irradiation-induced G-R components, while native G-R components and 1/f noise were unaffected by annealing.

C. Post-rad 1/f Component

After irradiation, when 1/f noise is unambiguously observed, its amplitude is studied as a function of the emitter surface. As shown in Figure 11, compared with the initial level, the 1/f noise changes very little with dose. Note also that we have always verified the quadratic evolution of noise in 1/f with base current.

We can therefore conclude that sources of 1/f noise, located at the Si/polySi interface, are not affected by X-ray irradiation.

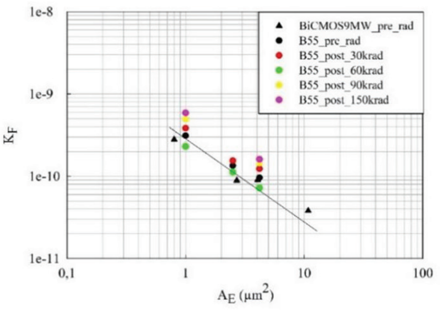

Fig. 11. 1/f noise amplitude, K_F, as a function of A_E for B55 HBTs, before and after irradiation exposure to X-ray. For comparison, the pre-rad of the previous technology (B9MW) is given.

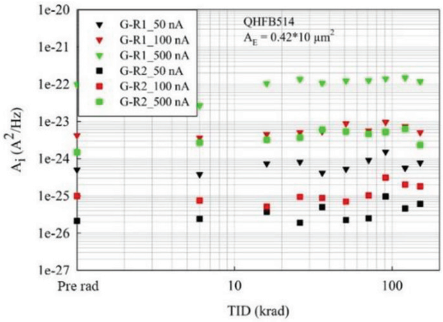

Fig. 12. G-R1 and G-R2 magnitudes as a function of TID.

D. Post-rad Generation–Recombination Components

As can be seen in Figures 8, 9, and 10, when G-R components are present (initial or induced by irradiation), one or two components were found with cut-off frequencies in the range of 20 and 200 Hz. Cut-off frequencies f_{ci} presented an independency to the input current bias as well as to the irradiation dose. Concerning the plateau magnitudes, as can be seen in Figure 12, no significant evolution with the cumulative dose is observed at low dose (i.e., < 150 krad). On the other hand, on the same figure, we can see that the evolution with the base bias current is very pronounced, with an almost quadratic law.

Unlike the 1/f noise, fewer results or physical models exist for initial G-R noise components [22] and, concerning irradiation induced ones, no extended results have been published. Nevertheless, both initial and induced G-R noise sources are suspected at the vicinity of the emitter periphery, E-B spacer oxide, or its interface with the intrinsic E-B junction. Further studies based on technological and geometric parameters are required to confirm this hypothesis.

V. CONCLUSION

The effect of X-ray irradiation on DC characteristics (forward Gummel plot) was observed on the low-injection base current at the recombination–generation component. However, at the highest cumulative dose (i.e., TID > 250 krad), the diffusion regime begins to be impacted (V_{BE} > 0.6 V) and, even if the nominal bias point of the transistor for circuit operation is higher, this could have an influence on its operation and/or reliability. An impact of geometry was observed at high doses (i.e., TID > 120 krad), leading to an increase in base current degradation for the smallest emitter surface areas. In contrast, no significant effect was observed with collector doping. Finally, the various thermal annealing processes recovered more than 80% of the initial characteristics. Following the dynamic of annealing at 130 °C, we can logically expect a 100% recovery after a longer annealing time.

As far as LFNoise is concerned, the effect of X-ray irradiation is reflected in the systematic appearance of one or two recombination–generation components. The level of TID at which G-R components appear fluctuates depending on the transistors, but at a cumulative dose of around 120 krad, all transistors were affected. As a result, 1/f noise was rarely observed above this dose level. Nevertheless, on each occasion, no significant impact on the 1/f noise component was observed. After their appearance, the G-R components showed little sensitivity to low doses of X-ray irradiation. Indeed, we observed that the cut-off frequency as well as the level of these components did not change at all or very little. However, a fairly radical change was highlighted at higher doses (i.e., TID > 160 krad) with, in particular, a strong increase in the plateau of the second G-R. Just as for the Gummel plots, the effect of thermal annealing allowed us to find the initial noise spectra.

Our results, whether in terms of DC characteristics or LF noise, clearly show that the defects induced by X-ray irradiation are localized at the level of the peripheral oxides of the E-B junction. Finally, it should be noted, as we have shown in the reference [11], that gamma irradiations with a cobalt source led to similar results for equivalent cumulative doses of low level (i.e., TID < 130 krad).

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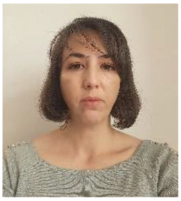
B. Sagnes received the Ph.D. degree in components, signals, systems from the University Montpellier 2 in 1992. He was the first to elaborate the CuInSe2 material by OMCVD for photovoltaic applications. He stayed one year at the FORTH in Heraklion, Greece. He studied the MBE elaboration of III-V and SiC devices. From 1993 to 1998, he was an assistant professor in semiconductor physics at the Marseille's engineer school ENSPM. He was interested in MOS technologies reliability. He returned to the University Montpellier 2 in 1998 and studied radiations effects by TCAD simulations, especially single event upset in CMOS SRAM cells. Since September 2010, he has been an assistant professor HDR with the Institut d'Electronique et des Systèmes of the Université de Montpellier. His research interests are is low-frequency noise characterizations of HBTs developed in advanced BiCMOS technologies. His research currently focuses on the effects of X-ray and gamma radiation on these transistors. He has authored or co-authored 98 international publications and conferences.

A. Ayenew received the European master's degree from Ku Leuven (Belgium), the University of Jyvaskyla (Finland), and the University of Montpellier (France) in radiation and its effects on microelectronics devices in 2023. He is currently a Ph.D. student at the Institute of Electronics and Systems (IES), University of Montpellier. His research focuses on radiation effects on the DC characteristics and low-frequency noise of SiGe:C heterojunction bipolar transistors and circuits.



M. Bouhouche received the Ph.D. degree in electronics from the University of Constantine, Algeria, in 2012. She joined the University of Oum El Bouaghi as an assistance professor in 2015. Her area of research interest includes modeling and characterization of HBTs developed in advanced BiCMOS technology. Her current research focuses on effects of radiation on SiGe HBTs, and RF-integrated circuit designed in BiCMOS technology for wireless communications.

J. El Beyrouthy received the master's degree from the Lebanon University in microsystems and embedded electronics in 2017. He received the Ph.D. degree in electronics from the University Montpellier in 2020. His thesis work focused on the characterization and modeling of low-frequency noise in pre- and post-irradiated bipolar transistors developed in BiCMOS technology.

F. Pascal received the M.S. and Ph.D. degrees in electrical engineering from the University of Montpellier, France, in 1986 and 1989, respectively. He was promoted to the rank of Professor in 2004. He is involved in a research team working in electronic devices (MOS, MODFET, MESFET, Si-Ge HBTs, III-V HBTs, etc.) by means of their proper background IV/CV characteristics and noise spectral analysis. He is also working on the technological qualification of contacts, semiconductor materials, and carbon-nanotubes-based devices by the use of noise spectroscopy. He is currently working on low-frequency noise measurement and modeling in advanced SiGe:C heterojunction bipolar transistors in the Institut d'Electronique et des Systèmes, University of Montpellier. His more recent research concerns the effects of X-ray and gamma irradiations on SiGe:C HBTs and associated circuits. He is the author and co-author of more than 120 peer-review publications in international journals and conferences. In 2013 and 2019, he was co-chairman of the 22nd and 25nd editions of the *International Conference on Noise and Fluctuations* and co-editor of the proceedings.

J. Boch received the M.S. degree in 2000 from the Montpellier University and the Ph.D. degree in 2003 in microelectronics from the University of Reims Champagne-Ardenne, France. Prior to accepting a research and teaching position at the University of Nice Sophia-Antipolis, France, in 2003, he spent about a year at Vanderbilt University (USA). In 2004, he joined the RADIAtion and Component (RADIAC) team as a senior lecturer at the University of Montpellier and he is now a full time professor. His research activity has been directed to the study of dose effect in electronics, and reliability of semiconductor devices and systems. He led the RADIAC team from 2016 to 2024. He is now head of the Electrical Engineering Department at the Montpellier University Institute of Technology. He has authored or co-authored over 150 papers in referenced journals or conferences. He has been technical chair at RADECS 2010 in Langenfeld, Austria, and he served as the session chairman at various RADECS conferences.

P. Chevalier (Member, IEEE) received the Ph.D. degree in electronics from the University of Lille, France, in 1998, for his work on InP-based HEMT. He joined Alcatel Microelectronics, Belgium, in 1999, where he contributed to the start of RF BiCMOS. Since joining STMicroelectronics, Crolles, France, in 2002, he has been working on the development of SiGe BiCMOS and RF-SOI CMOS technologies and related devices, with a long-lasting research interest in SiGe HBT. He led the RF-SOI CMOS, BiCMOS & Photonics Technologies R&D team. He is currently Analog/RF Technology Architect and is a Fellow of Technical Staff. Dr. Chevalier has authored or co-authored over 200 technical journal papers and conference publications. He has served on the Technical Program Committees of the IEEE BCTM, the ECS SiGe Symposium, the IEEE BCICTS, and the IEEE IEDM conferences. He has been a member of the RF & AMS Technologies section of the ITRS of which he led the Silicon Bipolar & BiCMOS subgroup.

D. Gloria received in 1995 the engineering degree in electronics from the Ecole Nationale Supérieure d'Electronique et de Radioélectricité and the M.S.E.E. in optics, opto-electronics and micro-waves design systems from the Institut National de Grenoble (INPG).

He spent two years, from 1995 to 1997, in ALCATEL Bell Network System Labs, in Charleroi, Belgium, as an RF designer engineer and was involved in the development of the Cablephone RF front end and its integration in hybrid-fiber-coax telecommunication networks. Since 1997, he has been working within STMicroelectronics, in the Technology Design Platform Department, Crolles. His research interests are in the development and optimization of RF and photonics platforms for applications in BiCMOS and CMOS advanced technologies