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The Effects of Proton and X-Ray Irradiation on the DC and AC Performance of Complementary (npn + pnp) SiGe HBTs on Thick-Film SOI

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***Abstract*—The impact of 63.3 MeV proton and 10 keV x-ray irradiation on the DC and AC performance of complementary ($npn+pnp$) SiGe HBTs on thick-film SOI is investigated. Proton and x-ray induced changes in the forward and inverse Gummel characteristics, the output characteristics, and avalanche multiplication are reported for both *npn* and *pnp* SiGe HBTs, at both room temperature (300 K) and at cryogenic temperatures (down to 30 K). Comparison of room temperature and cryogenic data suggests interface trap formation at two distinct physical locations in the transistors. Experimental data and calibrated TCAD simulations are used to compare the radiation response of both thick-film SOI devices and thin-film SOI SiGe HBTs.**

***Index Terms*—C-SiGe, heterojunction bipolar transistors, radiation effects, SiGe HBT, silicon-on-insulator, SOI, TCAD.**

I. Introduction

SILICON-GERMANIUM Heterojunction Bipolar Transistor (SiGe HBT) technology is increasingly recognized as a competitor to III-V technologies for analog/mixed-signal and RF through mm-wave circuits, due to its excellent frequency response, high-gain, low noise, and capability for high levels of integration. To date, most research in SiGe technology has focused on very high f_T, low BV_{CEO} *npn* SiGe HBTs because the Ge-induced offset in the valence band naturally favors *npn* SiGe HBTs instead of *pnp* SiGe HBTs [1]. Recently, however, a complementary-SiGe (C-SiGe) BiCMOS technology featuring both *npn* and *pnp* SiGe HBTs has been demonstrated for analog/mixed-signal applications, and is integrated on thick-film SOI. This C-SiGe IC platform has been designed for 5 V analog applications, and carefully optimized for balanced *npn* and *pnp* performance, low base resistance, low noise, and high β V_A product [2], [3].

The adoption of a thick-film SOI technology for C-SiGe not only improves device isolation, but also reduces parasitics, cross-talk, and substrate capacitance. Moreover, for applications in space radiation environments, this technology is expected to provide significant immunity to single-event upsets (SEU) without additional hardening. The intended applications of this C-SiGe technology include a wide variety of low-power, high-frequency, precision analog/mixed-signal circuits such as data converters and amplifiers. A good example of the utility of this C-SiGe analog IC platform includes the recent announcement of a record-performance 12-bit, 500 MS/s C-SiGe analog-to-digital converter [4].

Previous studies [5], [6] of C-SiGe devices focused exclusively on the dependence of $1/f$ noise on transistor size and temperature, and on the degradation of the low frequency noise after 63.3 MeV proton irradiation. The present work addresses more generally the impact of irradiation on the AC and DC device performance, particularly as it relates to analog circuit design, as well as inherent differences between *npn* and *pnp* device response. The *pnp* and *npn* SiGe HBTs were irradiated at room temperature with 63.3 MeV protons, to a total fluence of 7.4×10^{12} p/cm^2 [equivalent to 2 Mrad(SiO_2)] and with 10 keV x-rays up to a total dose of 3.6 Mrad(SiO_2). The Gummel characteristics, output characteristics, and avalanche multiplication (breakdown voltage) have been measured as a function of total dose at room temperature for both proton and x-ray irradiated devices. Additionally, a complete DC characterization of the SiGe HBTs-on-SOI before and after 63.3 MeV proton irradiation has been performed down to cryogenic temperatures as low as 30 K, in order to better understand the device response and damage processes. The impact of irradiation on the AC performance has also been investigated up to 3 Mrad(SiO_2) for protons and 5.4 Mrad(SiO_2) for x-rays, by measuring f_T and f_{max}. Furthermore, we compare these SiGe HBTs on thick-film SOI with a recently-demonstrated SiGe HBT on thin-film SOI technology, in order to gain deeper insight into the differences in physical behavior and the tradeoffs for SiGe-on-SOI technology [7]–[9].

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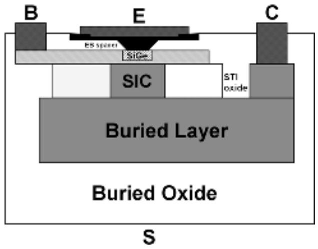

Fig. 1. Schematic cross-section of SiGe HBT.

TABLE I
PERFORMANCE OF THE NPN AND PNP SIGE HBTS AT 25 C [2]

Parameter	*npn*	*pnp*
β	200	200
V_A	150 V	100 V
f_T at V_{CE} = 5 V	25 GHz	25 GHz
f_{max} at V_{CE} = 5 V	90 GHz	60 GHz
BV_{CE0}	5.5 V	5.5 V
BV_{CB0}	7 V	6 V

II. DEVICE STRUCTURE AND EXPERIMENT SETUP

The key issue in developing a C-SiGe HBT technology is balancing the performance of the *npn* and *pnp* transistors, since the Ge-induced valence offset and the smaller hole mobility inherently make *pnp* SiGe HBTs more challenging to implement [1]. Current gain optimization in the *pnp* SiGe HBT has been solved by introducing a controlled emitter interfacial oxide (IFO), which significantly reduces the base current I_B, with negligible effects on the collector current I_C, hence improving its current gain. This C-SiGe technology platform, commercially-available from Texas Instruments under the name BiCOM3X, features a 1.5 μm thick-film SOI layer on top of a 0.145 μm buried oxide (BOX) insulating layer, as shown in Fig. 1, [3]. Deep trenches (DT) are used to electrically insulate the device, and a boron-doped base is deposited for the *npn* SiGe HBT and an arsenic-doped base is used for the *pnp* SiGe HBT. An ultra-thin (< 10 Å) IFO is grown before the emitter is deposited, followed by emitter polysilicon, which is implanted with either arsenic (*npn*) or BF_2 (*pnp*). The resulting device parameters at room temperature are shown in Table I, [2], [3].

In the present work, *pnp* and *npn* SiGe HBTs with different emitter areas (1.2×2.0 μm^2 and 0.6×4.0 μm^2) were irradiated in de-lidded packages using both 63.3 MeV protons and 10 keV x-rays, up to a total dose of respectively 2 Mrad (SiO_2) and 3.6 Mrad(SiO_2), and immediately measured *in-situ*. Two different back substrate voltages V_S (0 V and 20 V) were applied during exposure (with the remaining terminals grounded), in order to evaluate the possible impact of substrate bias on the radiation response, considering that thin-film SiGe HBTs-on-SOI are significantly affected by V_S [7]–[9]. An additional package was irradiated with protons to a final dose of 3 Mrad(SiO_2) with all terminals grounded, and measured before and after irradiation across the temperature span ranging from 300 K to 30 K. Passive exposure (terminals floating) of AC test structures with an emitter geometry of 0.4×0.8 μm^2, and configured in a parallel array of 10×12 *npn* SiGe HBTs and 0.4×3.2 μm^2 in an array of 10×3 *pnp* SiGe HBTs, was performed to a dose of 3 Mrad(SiO_2) for protons and 5.4 Mrad(SiO_2) for x-rays. The devices were measured using an Agilent 4155 Semiconductor Parameter Analyzer (DC), an Agilent 8510 Vector Network Analyzer (AC) and a customized DC cryogenic probe station.

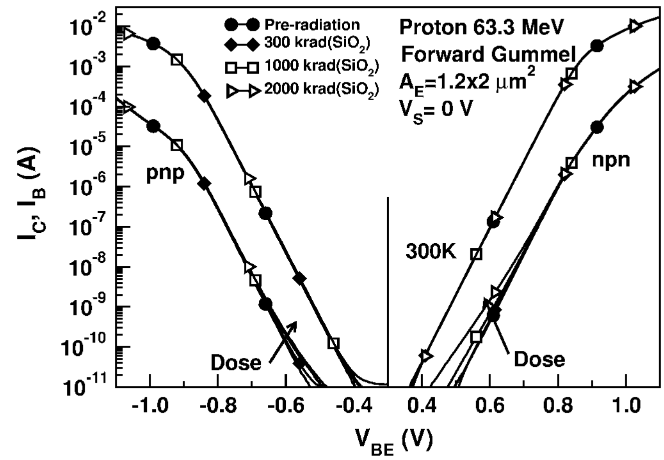

Fig. 2. Forward Gummel characteristics of *pnp* (left) and *npn* (right) transistors as a function of cumulative proton dose in krad(SiO_2).

III. RESULTS AND DISCUSSION

Fig. 2 shows the radiation-induced degradation with increasing proton dose for the forward Gummel characteristics, for both the *pnp* and the *npn* SiGe HBTs ($A_E = 1.2 \times 2.0 \mu m^2$). In general, the amount of damage produced in the forward mode of the *npn* devices is consistently larger than that exhibited by the *pnp* devices. Radiation-induced degradation in the base current of the *npn* transistors is attributed to an increase in interface traps where the emitter-base (EB) junction intersects the overlying oxide, leading to a higher surface recombination velocity, as well as the buildup of positive charge in the emitter-base oxide, resulting in a larger EB depletion region [10]. When the concentrations of holes and electrons are comparable, recombination caused by interface traps is maximized [10]–[12]. In the case of a *pnp* device, however, positive charge trapped in the oxide accumulates the n-doped base, and the resulting higher electron concentration decreases the excess base current due to surface recombination. Accumulation in the base also increases the electron current in the emitter, increasing the total base current and thus reducing the overall current gain [13]. Depletion actually occurs in the p-doped emitter, but its impact in this case is negligible because of the high emitter doping [10], [13]. From a circuit perspective, the observed radiation-induced degradation in the DC characteristics of the transistors, 10% current gain reduction measured at the peak f_T collector current in the *npn* SiGe HBTs (only 5% in the *pnp* SiGe HBTs) after the final radiation dose, can be considered negligible for most circuit applications. The normalized excess current $\Delta I_B/I_{B0}$ exhibits a linear dependence on the perimeter-to-area ratio P/A as shown in Fig. 3 and suggests the presence of recombination due to interface traps located at the Si/SiO_2 interface surrounding the periphery of the EB junction [10], [14]–[16]. We also observe that the radiation response of

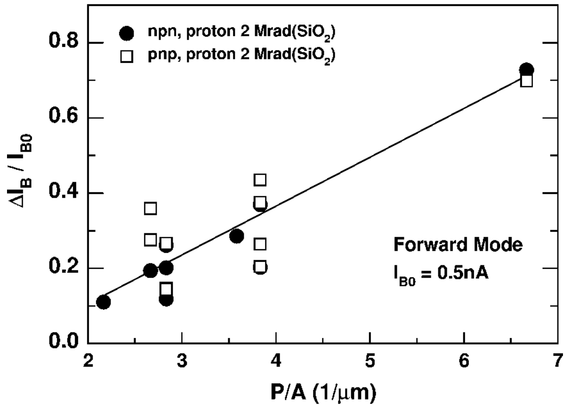

Fig. 3. Excess normalized base current $\Delta I_B/I_{B0}$ versus emitter perimeter over area ratio of the thick-film SiGe HBT-on-SOI.

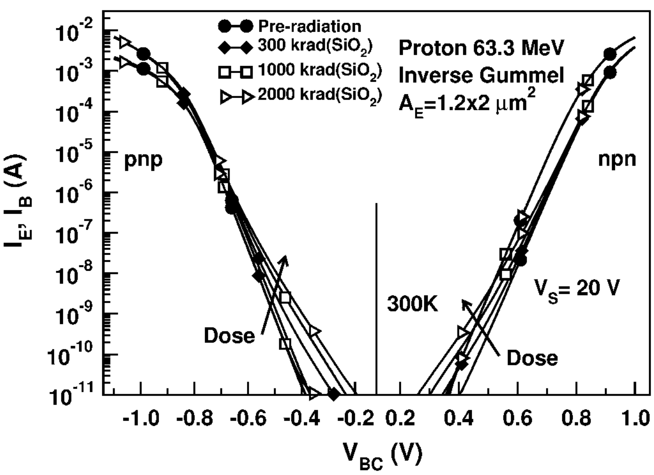

Fig. 4. Inverse Gummel characteristics of *pnp* (left) and *npn* (right) transistors as a function of cumulative proton dose in krad(SiO_2).

these thick-film SOI devices is much closer to that of a traditional bulk SiGe HBT than to a SiGe HBT on thin-film SOI, such as described in [8]. The thick SOI layer and the highly doped sub-collector result in a completely vertical current flow that is not affected by V_S or irradiation, as evidenced by the lack of substrate effect on I_B, I_C or the collector resistance R_C [7], [8], [17].

The inverse mode (emitter and collector terminals swapped) Gummel characteristics, shown in Fig. 4 for proton irradiation, show for both devices an excess base current ΔI_B larger than in the forward mode. Surprisingly, the degradation in inverse mode is larger for devices irradiated with $V_S = 0$ V than for those irradiated with $V_S = 20$ V, while the forward mode shows no such substrate bias dependence (Fig. 5). This trend has been also confirmed with x-ray irradiation, as shown in Fig. 6. As can be seen in Fig. 7, TCAD simulations employing ISE-DESSIS, as described in [17], [18], confirm that biasing the substrate results in a significantly larger positive charge in the BOX and DT with respect to a device irradiated with a grounded substrate. The higher positive charge yield is caused by the applied electric field that more efficiently separates the electron hole pairs generated in the oxide by the incident radiation [19], as confirmed by the electric field plot in Fig. 8. In addition, simulations show

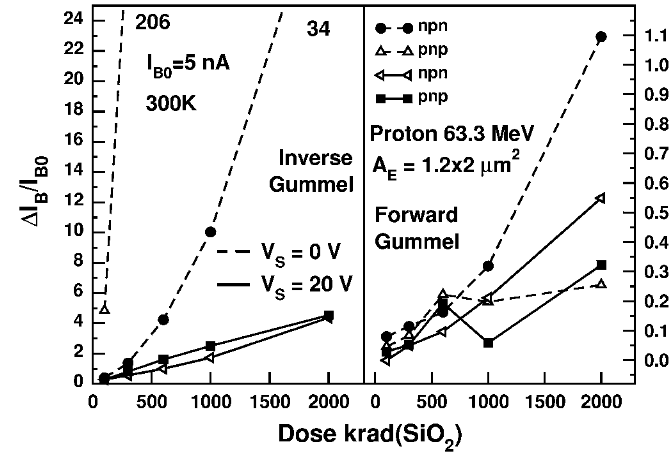

Fig. 5. Excess normalized base current I_{B0} versus cumulative proton radiation dose in krad(SiO_2) for both device in forward and inverse mode operation.

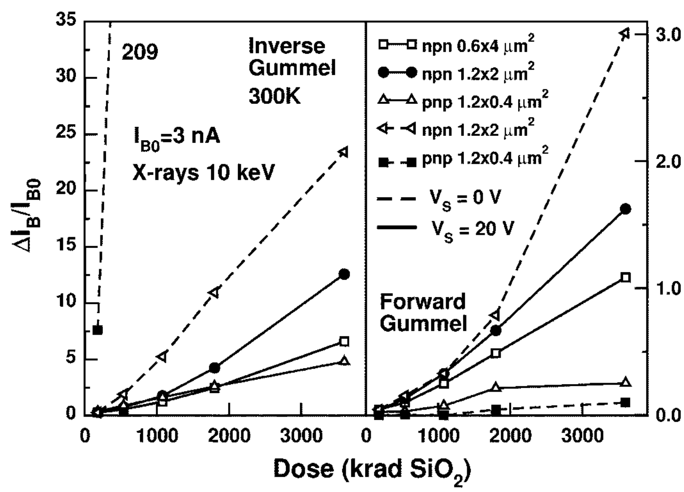

Fig. 6. Excess normalized base current I_{B0} versus cumulative x-ray radiation dose in krad(SiO_2), for both device in forward and inverse mode operation.

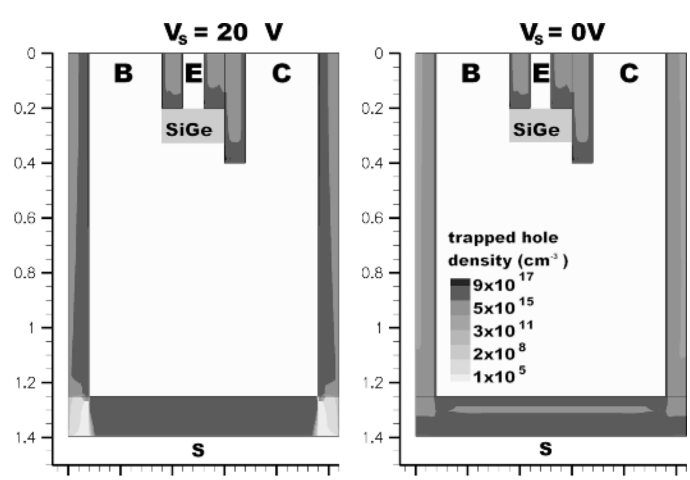

Fig. 7. ISE-DESSIS TCAD simulation of oxide trapped charge in a *npn* transistor irradiated at a 2.1 Mrad(SiO_2) dose.

no charge variation with changing substrate bias in the EB and STI oxides near the EB and CB junctions, respectively, which

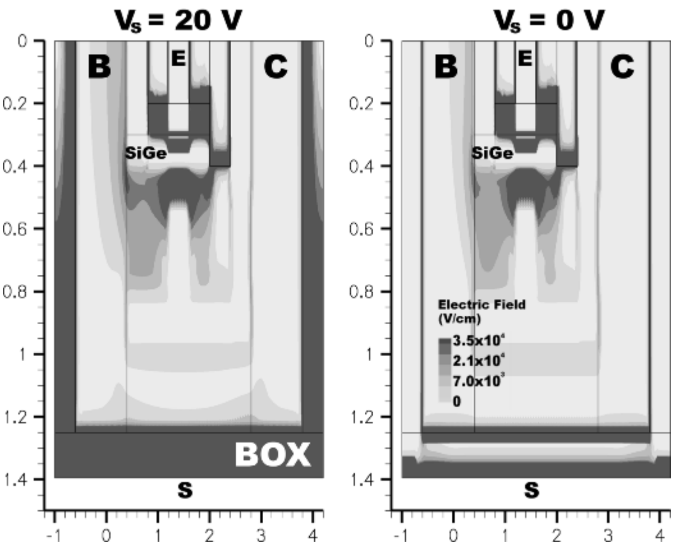

Fig. 8. ISE-DESSIS TCAD simulation of electric field in a *npn* transistor irradiated at a 2.1 Mrad(SiO_2) dose.

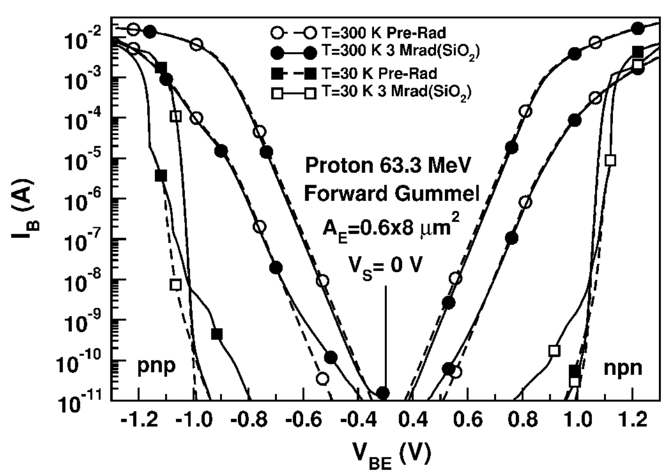

Fig. 9. Forward Gummel plot of *pnp* and *npn* transistors before and after a 3 Mrad(SiO_2) proton dose at temperatures between 30 K and 300 K.

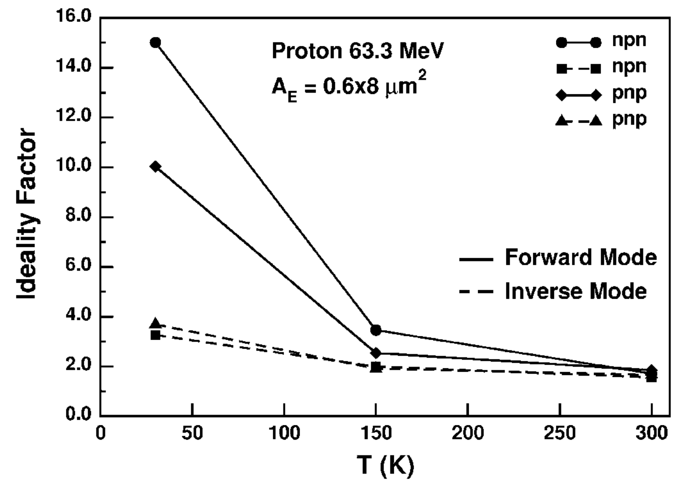

Fig. 10. Ideality factor n of excess base current ΔI_B versus temperature for *pnp* and *npn* transistor.

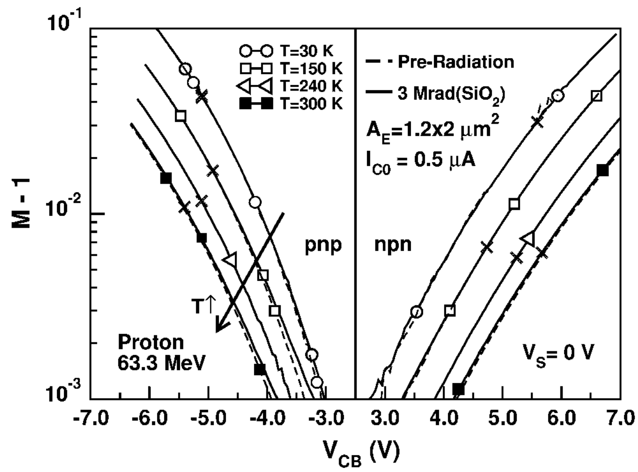

Fig. 11. M-1 and BV_{CEO} (crosses) of SiGe HBTs before and after a 3 Mrad (SiO_2) proton dose at temperatures between 30 K and 300 K.

is consistent with the fact that substrate voltage has no effect on the DC and AC characteristics.

Given that temperature has a significant impact on SiGe HBT physics, the pre- and post-irradiation DC behavior of the devices was measured over a wide temperature range to gain better insight into the relevant damage mechanisms. Fig. 9 shows the forward Gummel characteristics of the *pnp* and *npn* SiGe HBTs, both before and after irradiation, measured at temperatures of 300 K, 150 K, and 30 K. The base current of the *pnp* device shows a "hump" at moderately high $|V_{BE}|$, caused by the accumulation of holes in the base due to the Heterojunction Barrier Effect (HBE) [1], which is magnified by the relatively low collector doping N_C. The I_C at which HBE occurs in the *pnp* SiGe HBTs is about 2.4 times higher than for the *npn* SiGe HBTs, possibly due to a higher local N_C. As shown by Fig. 10, the ideality factor (n) of the excess base current ΔI_B is around 1.7 at 300 K, confirming an interface trap origin of ΔI_B at the Si/SiO_2 interface around the EB junction, as suggested also by Fig. 3. At 150 K n rises to 3 and at 30 K it surpasses 10, implying that a trap-assisted tunneling mechanism is dominant at low temperatures [20]. It should be noted that a very high ideality factor n was observed also in the 300 K irradiation of a 1st generation *npn* bulk SiGe HBT when measured at 77 K, but not when the device was irradiated and measured at 77 K [21].

The forward current gain β at low temperatures is limited at high I_C by the HBE effect. The radiation-induced degradation in β, however, is negligible at collector currents used in most practical circuits. Interestingly, the inverse mode behavior at low temperatures displays an excess base current ΔI_B smaller than that for forward mode operation, suggesting that the degradation in forward mode I_B at low temperatures may be due to traps generated in the IFO itself or at the IFO-silicon interface, consistent with [5]. The inverse mode excess I_B ideality factors n are about 1.5, 2, and 3 at 300 K, 150 K and 30 K, respectively.

Fig. 11 shows that proton exposure has negligible impact on impact ionization (or M-1) at all temperatures in the range between 300 K and 30 K [22]. The behavior exhibited by these thick-film SOI SiGe HBTs is again close to that seen in standard bulk vertical devices. Conversely, fully-depleted SiGe HBTs on thin-film SOI are typically characterized by a significant

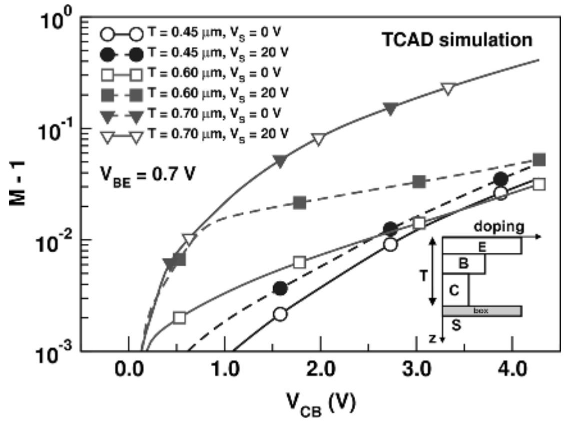

Fig. 12. TCAD simulation of impact ionization at $V_{BE} = 0.7$ V and $V_S = 0$ V and $V_S = 20$ V at different SOI thicknesses (T).

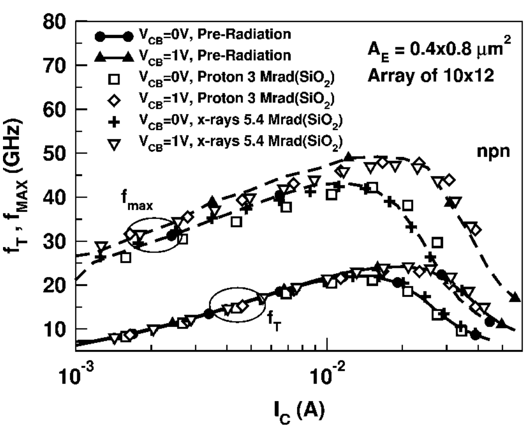

Fig. 13. AC performance of *npn* SiGe HBT before and after a 3 Mrad (SiO_2) proton and a 5.4 Mrad (SiO_2) x-ray dose measured with $V_{BC} = 0$ V and $V_{BC} = 1$ V.

change in M-1 with applied substrate bias or irradiation, and partially-depleted SiGe HBTs on thin-film SOI by a small but noticeable change in M-1, as discussed in [8], [17]. This suggests again that in SiGe HBTs on thick-film SOI, the current flow remains completely vertical, even after irradiation. Radiation has negligible effect on the M-1, BV_{CBO} and BV_{CEO}, similar to the vertical bulk devices. This is an important result, since one of the highlights of this technology is the large breakdown voltage (> 5 V at 300 K), especially in comparison to fully-depleted thin-film SiGe HBTs-on-SOI, in which radiation increases AC performance at the expense of avalanche multiplication, clearly a potential reliability issue. TCAD simulations shown in Fig. 12 indicate that the limited impact of substrate voltage and hence radiation-induced charge at the SOI/BOX interface is due to the thickness of the SOI layer rather than to the collector doping N_C.

As also shown in Fig. 11, the increase in M-1 of the complementary devices with cooling is due to the increase in mean free path at low temperatures, resulting in more energetic carriers and higher multiplication [23]. In addition, M-1 is slightly higher in the *pnp* SiGe HBT, possibly due to higher N_C doping.

Finally, AC measurements of both *npn* SiGe HBTs (Figs. 13 and 14) and *pnp* SiGe HBTs, before and after a 3 Mrad(SiO_2) 63.3 MeV proton dose and a 5.4 Mrad(SiO_2) 10 keV x-ray dose, show negligible degradation in f_T and f_{max} within the measurement error of around ± 5%, clearly good news for use of this technology in circuit applications. The forward transit time τ_f and the total EB and CB capacitance per emitter area C'_τ, extracted according to [1] and presented in Table II, confirm that irradiation does not affect the intrinsic device performance. This conclusion is supported by the fact that the dynamic base resistance r_{bb} shown in Table I and extracted from h_{11} using a "circle impedance" extraction technique [1] show changes lying well within measurement and extraction error. Furthermore, the close agreement between τ_f, C'_τ and r_{bb} from devices before and after irradiation and the negligible change in the $f_T - I_C$ roll-off shown in Figs. 13 and 14 suggest that displacement-induced acceptor deactivation in the base is not a concern in this technology [24].

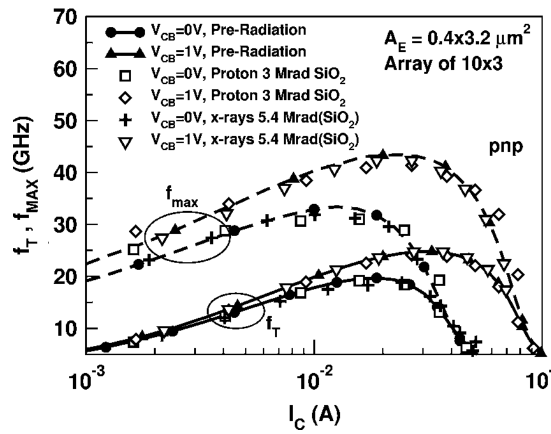

Fig. 14. AC performance of *pnp* SiGe HBT before and after a 3 Mrad (SiO_2) proton and a 5.4 Mrad (SiO_2) x-rays dose, measured with $V_{BC} = 0$ V and $V_{BC} = 1$ V.

TABLE II
AC PERFORMANCE BEFORE AND AFTER IRRADIATION

Device	τ_f (ps)	C'_t (pF/μm²)	r_{bb} (Ω)
Npn pre-radiation V_C=0 V, 0.4x0.8 μm² (array of 10x12 HBTs)	5.21	2.67	4.80
Npn proton 3 Mrad(SiO_2) V_C=0 V, 0.4x0.8 μm² (array of 10x12 HBTs)	5.52	2.75	6.07
Npn x-rays 5.4 Mrad(SiO_2) V_C=0 V, 0.4x0.8 μm² (array of 10x12 HBTs)	5.29	2.78	5.38
Pnp pre-radiation V_C=0 V , 0.4x3.2 μm² (array of 10x12 HBTs)	6.47	0.75	6.68
Pnp proton 3 Mrad(SiO_2) V_C=0 V , 0.4x3.2 μm² (array of 10x12 HBTs)	6.71	0.74	7.31
Pnp x-rays 5.4 Mrad(SiO_2) V_C=0 V , 0.4x3.2 μm² (array of 10x12 HBTs)	6.75	0.76	7.16

IV. Conclusion

We have performed a comprehensive analysis of proton and x-ray induced radiation response of the AC and DC characteristics of a complementary thick-film SiGe HBT-on-SOI technology. Substrate bias has been shown to affect the degradation in inverse mode but not in forward mode. DC characterization of the devices down to cryogenic temperatures is used to highlight interface trap formation in different regions. TCAD simulations have been used to understand the differences between thick and thin film SiGe HBTs-on-SOI. In summary, we conclude that this C-SiGe HBT on thick-film SOI technology offers considerable potential in the context of analog/mixed-signal circuits found in space systems.

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