Proton Tolerance of Third-Generation, 0.12 μm 185 GHz SiGe HBTs

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***Abstract*—We present results on the impact of proton irradiation on the dc and ac characteristics of third-generation, 0.12 μm 185 GHz SiGe HBTs. Comparisons with prior technology generations are used to assess how the structural changes needed to enhance performance between second and third generation technology couple to the observed proton response. The results demonstrate that SiGe HBT technologies can successfully maintain their a Mrad-level total dose hardness, without intentional hardening, even when vertically-scaled in order to achieve unprecedented levels of transistor performance.**

***Index Terms*—Bipolar transistors, HBT, proton irradiation, silicon-germanium (SiGe).**

I. INTRODUCTION

BANDGAP-engineered SiGe HBTs are receiving increasing attention for terrestrial communications IC applications, because they enable a dramatic improvement in transistor-level performance while simultaneously maintaining strict compatibility with conventional low-cost, high-integration level, high-volume Si CMOS manufacturing [1]. SiGe HBT technologies with 50 GHz (first-generation) and 120 GHz (second-generation) peak cutoff frequency are currently in commercial production worldwide from multiple sources, and are being deployed in both the commercial and defense sectors. SiGe HBT technology has also generated significant recent interest in the space community, because it offers substantial (multi-Mrad) total dose hardness without any (costly) radiation hardening (SEU tolerance is still under active investigation).

It is logical to wonder (and often asked) what the upper limit is on achievable frequency response in using epitaxial SiGe alloys to engineer SiGe HBTs. The recent announcement of a third-generation SiGe HBT technology with 200 GHz peak cutoff frequency [2] pushed this upper bound considerably higher than previously believed possible. While it might be argued that 200 GHz is not needed to support most IC applications (which are clustered currently in the 1–40 GHz range, such extreme levels of performance afford a much broader circuit design space, where, for instance, a designer might choose to reduce the frequency response in order to realize dramatic power savings (10× reduction in bias current in this case over second-generation technology operating at 120 GHz), as indicated in Fig. 1. Third-generation SiGe HBTs are in fact quite competitive now with best-of-breed commercial InP HBTs, and out-perform such devices when thermal effects are also considered [1].

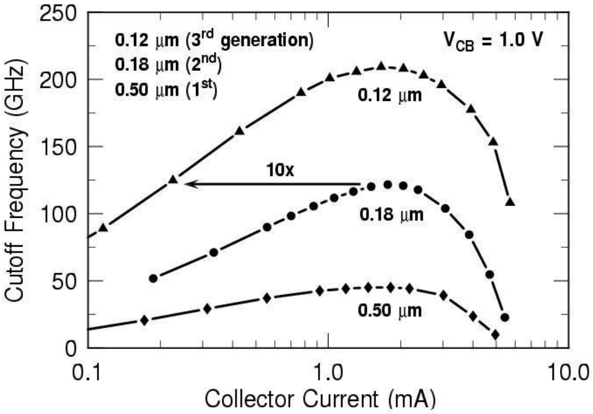

Fig. 1. Measured cutoff frequency as a function of bias current for three SiGe technology generations.

This advance in the SiGe state-of-the-art to 200 GHz performance was only achieved by radically altering the structure of previous SiGe HBT design points. The third-generation SiGe HBT technology used in the present investigation (IBM's SiGe 8 HP technology) employs a novel, reduced thermal cycle, "raised extrinsic base" structure, and utilizes conventional deep and shallow trench isolation, an *in situ* doped polysilicon emitter, and an unconditionally stable, 25% peak Ge, C-doped, graded UHV/CVD epitaxial SiGe base (Fig. 2) [2]. The device structure has been scaled laterally to 0.12 μm emitter stripe width in order to minimize base resistance and thus improve the frequency response and noise characteristics. Such a raised extrinsic base structure facilitates the elimination of any out-diffusion of the extrinsic base, thereby significantly lowering the collector-base junction capacitance. From a radiation tolerance perspective, however, the emitter-base (EB) spacer and the shallow trench isolation (STI) of the new structure are both fundamentally different than that found in first and second generation (IBM SiGe 5 HP and SiGe 7 HP) technologies, and the composite films and processing/thermal

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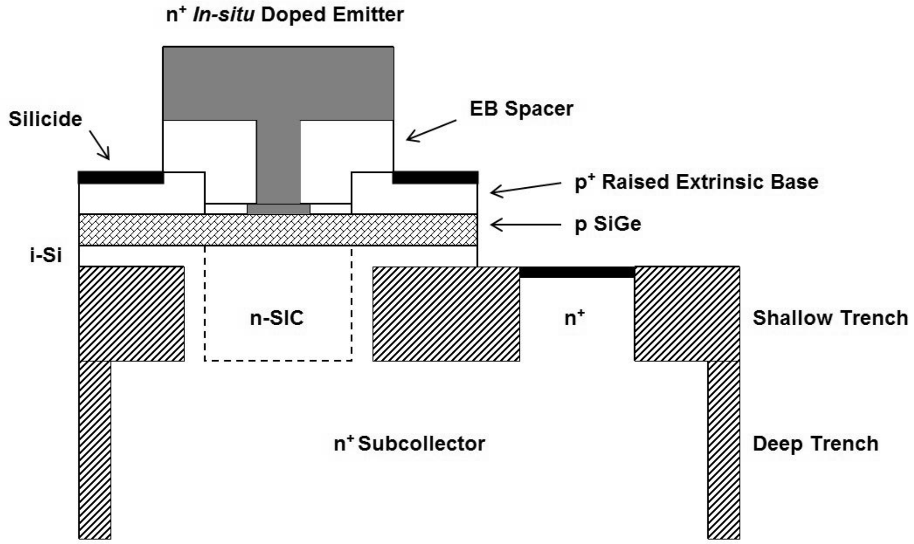

Fig. 2. Schematic cross-section of the 185 GHz SiGe HBT.

cycles are significantly altered, raising a valid question as to the overall radiation tolerance of the new device structure with respect to previous SiGe technology generations. This question is particularly relevant given that the overall processing thermal cycles have also been significantly reduced, thus raising questions on the overall robustness of the oxide interfaces, primary damage points in a ionizing radiation environment. In this work, we report the first results on the proton tolerance of a third-generation SiGe HBT technology, and compare it with prior SiGe technology generations to quantify the differences.

II. EXPERIMENT

The third-generation SiGe HBT technology (IBM SiGe 8 HP) examined in this work has a 0.12 $\mu\mathrm{m}$ emitter stripe width and 185 GHz peak f_T (this was off a different fabrication lot than that reported in [2], but is essentially the same technology, with a slightly different vertical profile). Two earlier SiGe HBT technology generations were also measured in order to assess the impact of vertical scaling, lateral scaling, and structural changes on the radiation response, and included: a 0.50 $\mu\mathrm{m}$ 50 GHz f_T SiGe HBT (IBM SiGe 5 HP) and a 0.20 $\mu\mathrm{m}$ 120 GHz f_T SiGe HBT (IBM SiGe 7 HP). In the case of 7 HP SiGe technology, the effects of radiation on the *ac* performance are reported here for the first time.

The samples were irradiated with 62.5 MeV protons at the Crocker Nuclear Laboratory at the University of California at Davis. The dosimetry measurements used a five-foil secondary emission monitor calibrated against a Faraday cup. The radiation source (Ta scattering foils) located several meters upstream of the target establish a beam spatial uniformity of about 15% over a 2.0 cm radius circular area. Beam currents from about 5 pA to 50 nA allow testing with proton fluxes from 1×10^6 to 1×10^{11} $\mathrm{proton/cm^2sec}$. The dosimetry system has been previously described [3], [4], and is accurate to about 10%. At a proton fluence of 1×10^{12} $\mathrm{p/cm^2}$, the measured equivalent gamma dose was approximately 136 krad(Si). The SiGe HBTs were irradiated with all terminals grounded for the *dc* measurements and with all terminals floating for the *ac* measurements at proton fluences ranging from 1.0×10^{12} $\mathrm{p/cm^2}$ to 5.0×10^{13} $\mathrm{p/cm^2}$. We have previously shown that SiGe HBTs are not sensitive to applied bias during irradiation. Wirebonding of ac test structures is not compatible with robust broadband measurements, and hence on-wafer probing of S-parameters (with terminals floating) was used to characterize the high-frequency performance. The samples were measured at room temperature with an Agilent 4155 Semiconductor Parameter Analyzer (*dc*) and an Agilent 8510C Vector Network Analyzer (*ac*) using the techniques discussed in [5].

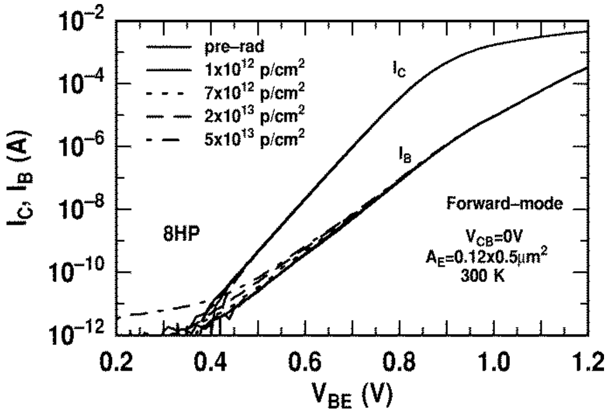

Fig. 3. Forward-mode Gummel characteristics of the 8 HP SiGe HBT.

III. *dc* RESULTS

The resultant 8 HP forward-mode Gummel characteristics are shown in Fig. 3 and Fig. 4 as a function of proton fluence, and reveal a remarkably minor degradation in the base current at a few Mrad equivalent gamma dose. As has been previously discussed [6], this base current degradation is physically the result of proton-induced G/R center, physically located at the emitter-base spacer at the emitter periphery.

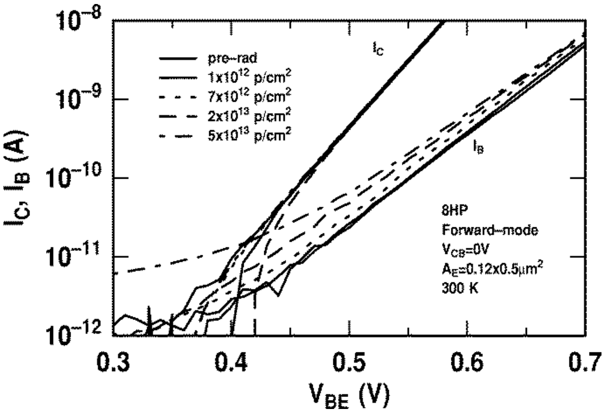

Fig. 4. Forward-mode Gummel characteristics $(\mathrm{Vbe} = 0.3 - 0.7\ \mathrm{V})$ of the 8 HP SiGe HBT.

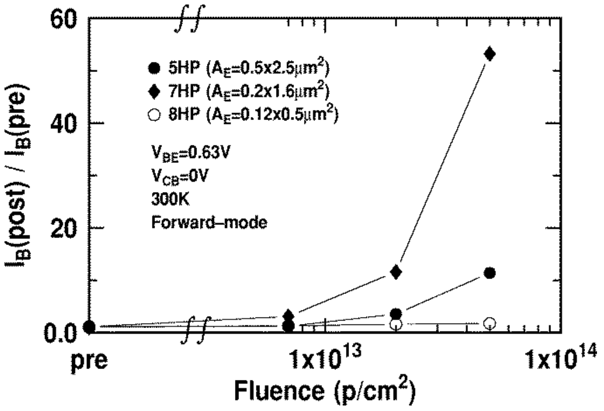

Fig. 5. Comparison of the normalized base current in *forward*-mode as a function of proton fluence for the 5, 7, and 8 HP SiGe HBT technology generations.

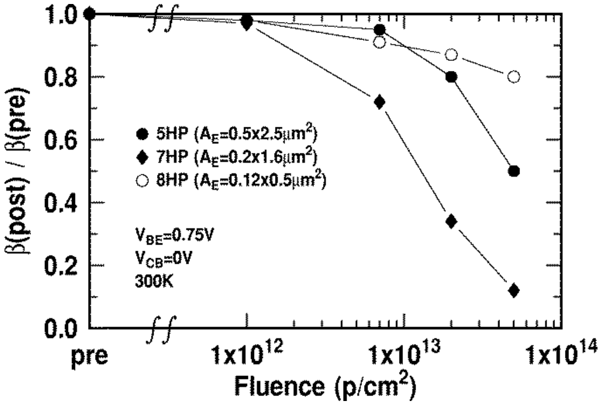

Fig. 6. Comparison of the normalized current gain as a function of proton fluence for the 5, 7, and 8 HP SiGe HBT technology generations.

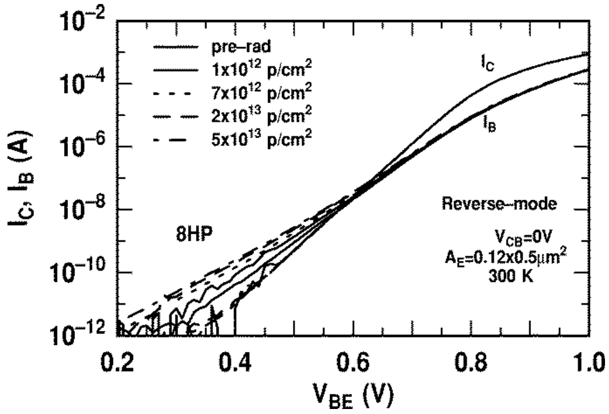

Fig. 7. Inverse-mode Gummel characteristics of the 8 HP SiGe HBT.

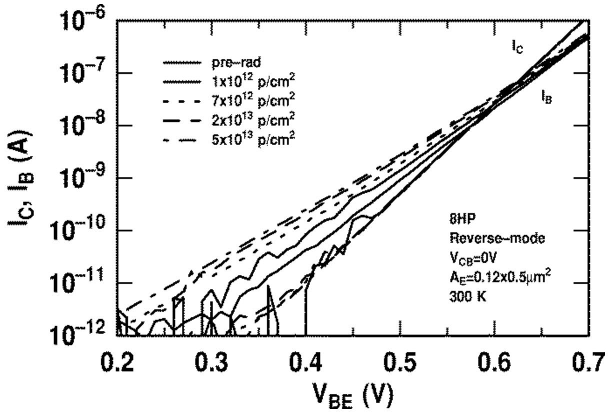

Fig. 8. Inverse-mode Gummel characteristics $(\mathrm{Vbe} = 0.3 - 0.7\mathrm{V})$ of the 8 HP SiGe HBT.

A comparison of the normalized base current degradation of the 8 HP transistor to that of the first (5 HP) and second (7 HP) generation SiGe devices shows that 8 HP experiences significantly *smaller* radiation-induced damage than the earlier technology generations (Fig. 5). This result is a pleasant surprise, and would appear to be in direct contradiction with results on SiGe HBT scaling presented in 2002 [6], in which vertical and lateral device scaling generally degraded the forward-mode proton response. It should be noted, however, that this result can be easily misinterpreted, since the base current ideality of the pre-radiation device influences the final base current change. That is, in the case of 8 HP, there is clearly a pre-existing G/R center dominated base current leakage component, as evidenced by the nonideal base current slope (about 120 mV/decade, consistent with classical G/R leakage). For the 5 and 7 HP devices, however, the starting base currents are significantly more ideal, and hence even a small absolute degradation of the base current due to proton exposure will produce a larger damage ratio in those devices. In effect, the 8 HP base current damage is still present, but effectively “hidden” beneath the pre-radiation, nonideal base leakage component. As the 8 HP technology has matured, its pre-radiation, nonideal base current has become more ideal, thus facilitating a more meaningful comparison with 5 and 7 HP devices, and an experiments aimed at addressing this are underway and will be reported at a later date. Nevertheless, at the low-end of practical circuit operating currents (e.g., $I_C = 1.0\ \mu A$), the change in the current gain (β) for the 8 HP device is less than 20% at $5 \times 10^{13}\ p/cm^2$, significantly better than either 5 HP or 7 HP (Fig. 6). This is clearly very good news, and speaks well of the inherent tolerance of the various potentially sensitive interfaces in the modified, low-thermal budget, 8 HP device structure (e.g., EB spacer, and STI edge).

In Figs. 7 and 8, measurements of the inverse-mode Gummel characteristics (emitter and collector swapped, which effectively samples the physical collector-base junction) indicate

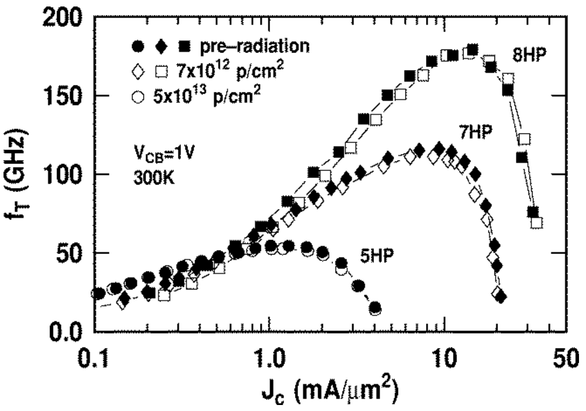

Fig. 9. Pre-radiation and post-radiation cutoff frequency versus collector current density for 8, 7, and 5 HP SiGe HBTs.

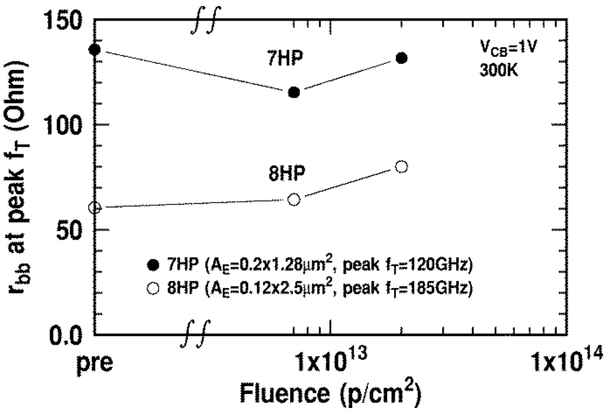

Fig. 10. Dynamic base resistance dependence on proton fluence.

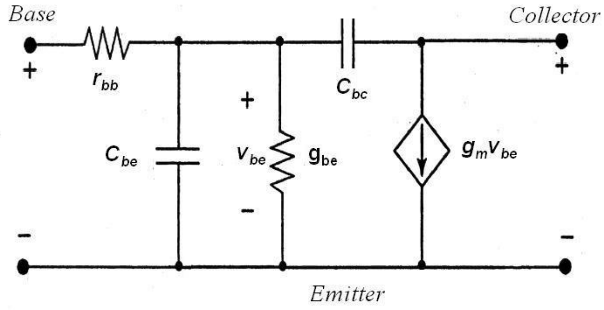

Fig. 11. Small signal model for SiGe HBTs.

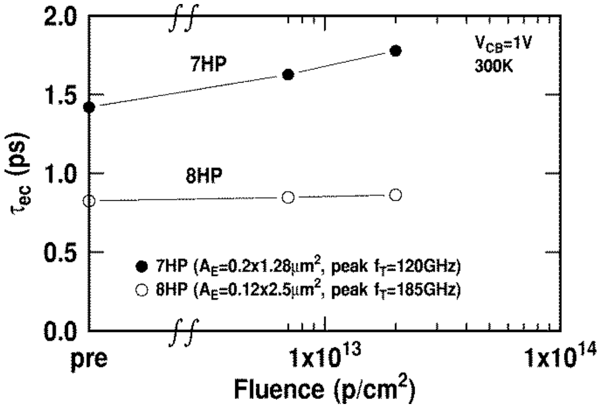

Fig. 12. Extrapolated transit time dependence on proton fluence.

that while the pre-radiation base current is less ideal than perhaps desired, the proton-induced change to the inverse-mode base current is minor at best, consistent with the fact that the STI is very thin in this technology (much less than 5 HP, but similar to 7 HP) and thus has less impact on the collector-base junction characteristics. This is significant, given that, unlike for the 5 and 7 HP devices, the overall thermal cycle of the 8 HP process is substantially reduced, and hence no out-diffusion of the extrinsic base is available to "cover" the exposured corners of the STI with high doping, effectively containing any proton-induced damage. This result suggests that this "raised extrinsic base" 8 HP structure should continue to enjoy substantial proton tolerance even as the technology is further scaled for even higher performance, as has in fact been very recently reported (a 350 GHz peak f_T SiGe HBT [7]).

IV. *ac* RESULTS

The transistor scattering parameters (S-parameters) were fully characterized to 26 GHz, from which the cutoff frequency f_T was extracted at each bias current point. The pre- and post-radiation cutoff frequency versus collector current density for the 8 HP devices are shown in Fig. 9, together with comparisons to the 7 HP (at 7×10^{12} p/cm^2 fluence) and 5 HP (at 5×10^{13} p/cm^2 fluence) SiGe technologies. As can be clearly seen, negligible degradation of f_T is observed in the 8 HP devices, well within the measurement error of about ±5%.

The *ac* small signal model for SiGe HBTs is shown in Fig. 11. From the measured S-parameters, the dynamic base resistance (r_{bb}) can also be extracted, as shown in Fig. 10. The 8 HP base doping level is higher than that for 7 HP, and thus the base resistance is smaller. Observe that the total base resistance increases slightly as the proton fluence increases above 1×10^{13} p/cm^2, presumably due to displacement effects in the neutral base region, and the deactivation of boron dopants. A similar trend can be seen in 7 HP. This effect is very minor, however, because the base profile is very thin (<30 nm), and very heavily doped $(> 1 \times 10^{19}$ $cm^{-3})$, and should not have a significant impact on the maximum oscillation frequency or the broadband noise performance.

The total emitter-to-collector delay time (τ_{EC}) and the total depletion capacitance (C_{total}) can be extracted from the measured cutoff frequency characteristics, and are shown as a function of proton fluence in Fig. 12 and Fig. 13. Interestingly, we can observe that the total transit time of the 7 HP devices monotonically increases (degrades) with fluence, while the 8 HP total transit time remains constant with fluence. This is clearly reflected in the change in the peak cutoff frequency of the respective technologies (the 8 HP peak f_T does not change, while there is a small but observable decrease in peak f_T in 7 HP (refer to Fig. 9). The small base observable increase in base resistance at high fluence coincides with a slight decrease in total depletion capacitance (Fig. 13), and is consistent with our claims above that small but finite displacement-induced acceptor de-ionization occurs in the base region of the device.

Finally, we have examined the impact of proton exposure on the cutoff frequency characteristics of two different breakdown voltage 8 HP transistors on the same wafer (Fig. 14). One of the key advantages offered by SiGe technology lies in its ability

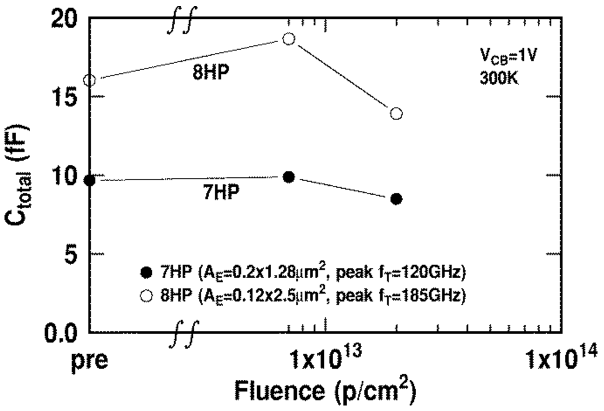

Fig. 13. Total depletion capacitance dependence on proton fluence.

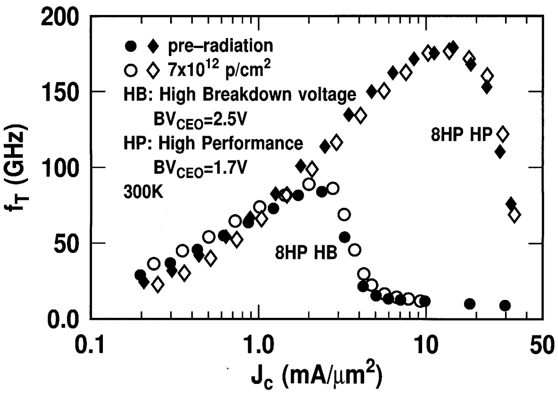

Fig. 14. Pre- and post-radiation cutoff frequency versus collector current density for both high breakdown and low breakdown 8 HP SiGe HBTs.

to trivially integrate transistors with multiple breakdown voltages on the same wafer (using only a collector implant blockout mask), thereby facilitating great flexibility for circuit designers. Clearly, the peak operating frequency does not depend strongly on proton fluence, which is good news. In addition, however, observe that the roll-off in f_T at high J_C does not change significantly with proton exposure. This is significant since the $f_T - J_C$ roll-off is very sensitive to any changes in the effective doping level in the collector region, and thus suggests that collector-region displacement damage is not a major concern in this technology, consistent with our observations above on base resistance. One can quantify this by plotting the current at which f_T falls by 20%, and normalizing to pre-radiation values (Fig. 15). As can be seen, the roll-off current density actually increases slightly with irradiation (more strongly in the low breakdown device).

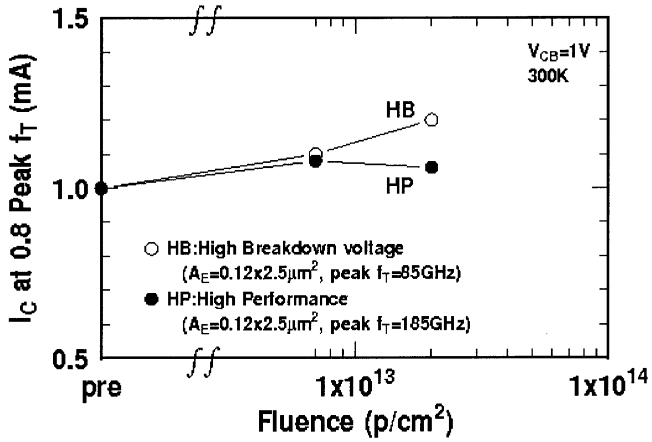

Fig. 15. Normalized collector current roll-off point for both high breakdown and low breakdown 8 HP SiGe HBTs.

V. SUMMARY

The impact of proton irradiation on the *dc* and *ac* characteristics of third-generation, 185 GHz SiGe HBTs is reported for the first time. The results demonstrate that SiGe HBT technologies can successfully maintain their inherent a Mrad-level total dose hardness, without intentional hardening, even when the device structure is fundamentally altered in order to achieve unprecedented levels of device performance.

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