

1/f Noise in Proton Irradiated SiGe HBTs

Zhenrong Jin, Guofu Niu, John D. Cressler, Cheryl J. Marshall,
Paul W. Marshall, Hak S. Kim, Robert Reed, and David L. Harame

Abstract—This paper investigates the impact of proton irradiation on the 1/f noise in UHV/CVD SiGe HBTs. The relative degradation of 1/f noise shows a strong dependence on device geometry. Both the geometry dependence and the bias dependence of 1/f noise change significantly after exposure to 2×10^{13} p/cm² protons. "An expression describing the 1/f noise is derived, and used to explain the experimental observations."

Index Terms: SiGe HBT, 1/f noise, proton irradiation.

I. Introduction

SiGe Heterojunction Bipolar Transistor (HBT) technology is making its mark in various high-speed mixed signal, RF and optical networking applications because of its high performance and high integration level. SiGe HBTs have the typical low 1/f noise of Si bipolar transistors, which is of great importance because it can be upconverted to phase noise and limits the spectral purity of a communication system. The impact of irradiation on the 1/f noise in SiGe HBTs, however, has not been systematically examined. For instance, to reduce the 1/f noise at a given bias current, a large transistor is often used, because the 1/f noise level is in proportion to the reciprocal of emitter area ($1/A_e$). It is not clear, however, how irradiation affects the emitter area dependence of 1/f noise. The purpose of this work is to examine the impact of proton irradiation on the 1/f noise in SiGe HBTs with different emitter areas.

II. Device Technology and Experiment

Fig. 1 shows a schematic device cross-section of the SiGe HBTs used in this work [1]. The SiGe HBT has a planar, self-aligned structure with a conventional poly emitter contact, silicided extrinsic base, and deep- and shallow-trench isolation. The SiGe base was grown using UHV/CVD. Details of the fabrication process can be found in [2].

Three SiGe HBTs were used in this experiment to examine the geometry dependence. Their drawn emitter areas are 0.5×1 , 0.5×2.5 , and $0.5 \times 10 \mu\text{m}^2$. Because of the offset during lithography and processing, there is a difference of $0.08 \mu\text{m}$ between the drawn emitter width and effective emitter width. "The effective emitter length is coincidentally the same as drawn emitter length after processing. So the effective emitter areas are 0.42×1 ,

0.42×2.5 , and $0.42 \times 10 \mu\text{m}^2$, respectively. The dies were diced to 0.5 by 1 inches rectangles and were used as samples. Samples were attached on a ceramic base and directly exposed to 2×10^{13} p/cm² protons with floating terminals at the Crocker Nuclear Laboratory cyclotron located at the University of California at Davis. The total irradiation energy is 63.5 MeV protons." The dosimetry measurements used a 5-foil secondary emission monitor calibrated against a Faraday cup. Ta scattering foils located several meters upstream of the target establish a beam spatial uniformity of 15% over a 2 cm radius circular area. Beam currents from about 5 pA to 50 nA allow testing with proton fluxes from 10^6 to 10^{11} protons/cm²/sec. The dosimetry system has been previously described [3] [4] and is accurate to about 10%.

"The noise power spectrum was measured from 1 to 10^5 Hz both before and after irradiation for each device using a measurement circuit as shown in Fig. 2. The wire-wound resistors were used and the bias voltage was supplied from a battery to minimize the noise from the measurement setup. The transistors were measured in common emitter configuration. The collector voltage noise was amplified by "EGG" 5113 low-noise pre-amplifier and then was sent to HP 3561A dynamic signal analyzer. Thus the collector voltage noise spectrum S_{V_c} was obtained from HP 3561A. The resistor R_B was chosen to be much greater than r_b , r_π , and $(\beta + 1)r_e$. The input referred base current noise spectrum S_{I_B} was converted by dividing S_{V_c} by the square of the current gain and the load resistance [5]."

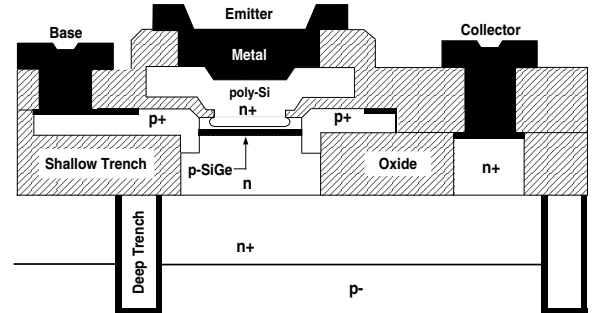


Fig. 1. The schematic cross section of the SiGe HBT.

III. Noise Degradation

It has been established experimentally that the main 1/f noise source in a bipolar transistor is the base current 1/f noise. The noise is typically proportional to I_B^α and inversely proportional to the emitter junction area A_e in modern transistors:

$$S_{I_B} = \frac{K}{A_e} I_B^\alpha \frac{1}{f} \quad (1)$$

where K is a technology dependent constant, and α has a typical value of 2. The physical origin of 1/f noise is the number fluctuation of carriers due to defects [5]-[7].

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Cheryl J. Marshall and Robert Reed are with NASA-GSFC, Code 562, Greenbelt, MD 20771, USA.

Paul W. Marshall is a consultant to NASA-GSFC, Code 562, Greenbelt, MD 20771, USA.

Hak S. Kim is with Jackson and Tull Chartered Engineers, Washington, DC 20018, USA.

David L. Harame is with IBM Microelectronics, Essex Junction, VT 05401, USA.

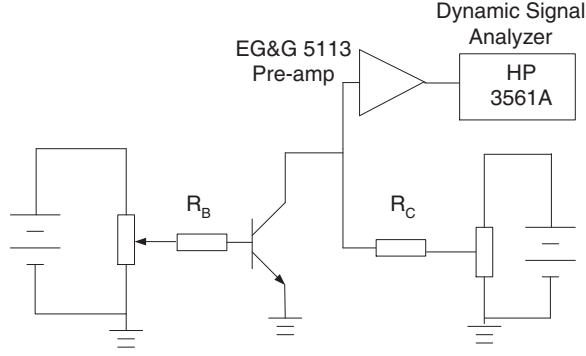


Fig. 2. 1/f noise measurement setup.

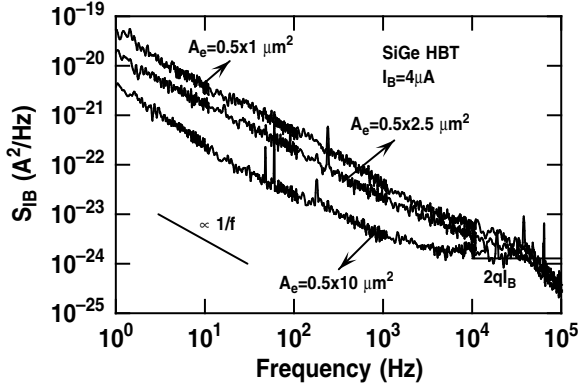


Fig. 3. Pre-irradiation low-frequency noise power spectra in three SiGe HBTs with different emitter area: $A_e = 0.5 \times 1 \mu\text{m}^2$, $0.5 \times 2.5 \mu\text{m}^2$ and $0.5 \times 10 \mu\text{m}^2$. $I_B = 4 \mu\text{A}$.

A. Pre-irradiation 1/f Noise

The pre-irradiation low-frequency noise spectrum in these SiGe HBTs is typically $1/f$, as shown in Fig. 3. Fig. 4 shows the pre-irradiation $1/f$ noise S_{I_B} at 10 Hz as a function of I_B for all of the emitter areas ($A_e = 0.5 \times 1$, 0.5×2.5 , and $0.5 \times 10 \mu\text{m}^2$). The $1/f$ noise shows approximate I_B^2 dependence for all of the SiGe HBTs. Fig. 5 shows the pre-irradiation $1/f$ noise at 10 Hz as a function of effective emitter area A_e at $I_B = 1$, 2, and $4 \mu\text{A}$. At all the biases, S_{I_B} shows a $1/A_e$ dependence. At the same I_B , the S_{I_B} in the $0.5 \times 10 \mu\text{m}^2$ device is 1/10 of that in the $0.5 \times 1 \mu\text{m}^2$ device.

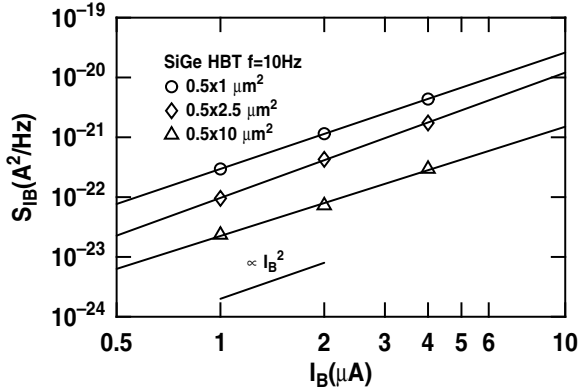


Fig. 4. Pre-irradiation S_{I_B} versus I_B in three SiGe HBTs with different emitter area: $A_e = 0.5 \times 1 \mu\text{m}^2$, $0.5 \times 2.5 \mu\text{m}^2$ and $0.5 \times 10 \mu\text{m}^2$. $f = 10 \text{Hz}$.

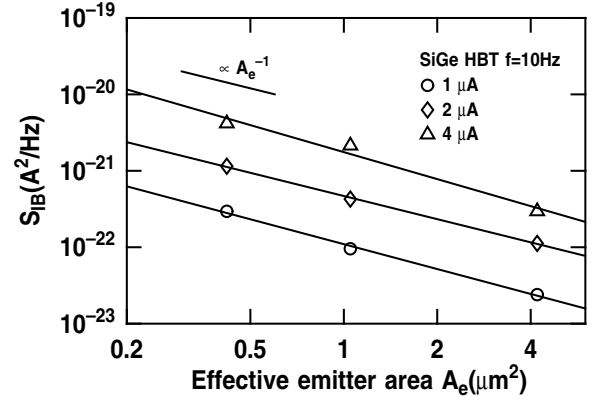


Fig. 5. Pre-irradiation S_{I_B} versus effective emitter area A_e in three SiGe HBTs at different bias current: $I_B = 1 \mu\text{A}$, $2 \mu\text{A}$, and $4 \mu\text{A}$. $f = 10 \text{Hz}$.

B. Post-irradiation 1/f Noise

After $2 \times 10^{13} \text{p/cm}^2$ proton irradiation, the low-frequency noise spectrum remains $1/f$, and free of burst noise as shown in Fig. 6. Interestingly, the relative increase of $1/f$ noise ($S_{I_B, \text{post}}/S_{I_B, \text{pre}}$) is minor in the $0.5 \times 1 \mu\text{m}^2$ transistor, but significant in the $0.5 \times 10 \mu\text{m}^2$ transistor, as shown in Figs. 7 and 8, respectively. An I_B of $4 \mu\text{A}$ was used. As a result, S_{I_B} is no longer in proportion to $1/A_e$ after irradiation. Note that the $0.5 \times 10 \mu\text{m}^2$ transistor had a $1/f$ noise that is 1/10 of the $1/f$ noise in the $0.5 \times 1 \mu\text{m}^2$ transistor before irradiation. However, after irradiation, the $1/f$ noise in the $0.5 \times 10 \mu\text{m}^2$ transistor becomes only 1/3 of the $1/f$ noise in the $0.5 \times 1 \mu\text{m}^2$ transistor. The benefit of lower $1/f$ noise from using a larger transistor is thus significantly compromised by irradiation, as can be seen from the S_{I_B} vs effective emitter area A_e data measured after irradiation (Fig. 9).

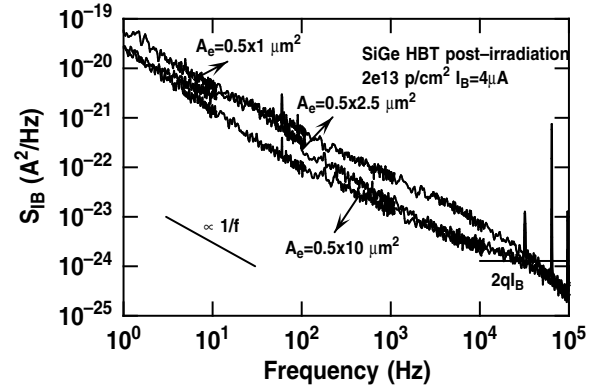


Fig. 6. Post-irradiation low-frequency noise power spectra in three SiGe HBTs with different emitter area: $A_e = 0.5 \times 1 \mu\text{m}^2$, $0.5 \times 2.5 \mu\text{m}^2$ and $0.5 \times 10 \mu\text{m}^2$. $I_B = 4 \mu\text{A}$.

The bias current dependence of $1/f$ noise also changes after irradiation, depending on the emitter area, as shown by the S_{I_B} vs I_B data measured after irradiation (Fig. 10). The relative degradation of $1/f$ noise ($S_{I_B, \text{post}}/S_{I_B, \text{pre}}$) is minor in the smallest device ($0.5 \times 1 \mu\text{m}^2$), and S_{I_B} remains $\propto I_B^2$. For the largest device whose relative $1/f$ noise degradation is the highest, S_{I_B} becomes $\propto I_B^{1.5}$.

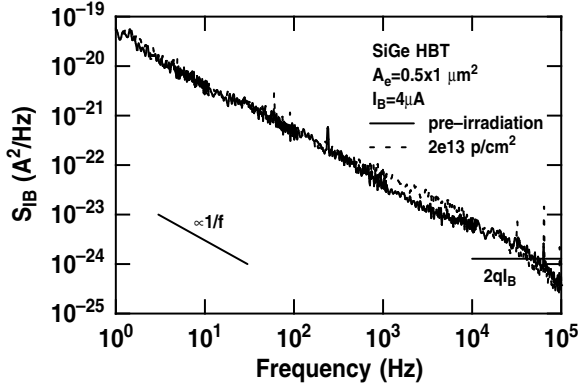


Fig. 7. Low-frequency noise power spectra pre- and post-irradiation. $A_e = 0.5 \times 1 \mu\text{m}^2$, $I_B = 4 \mu\text{A}$.

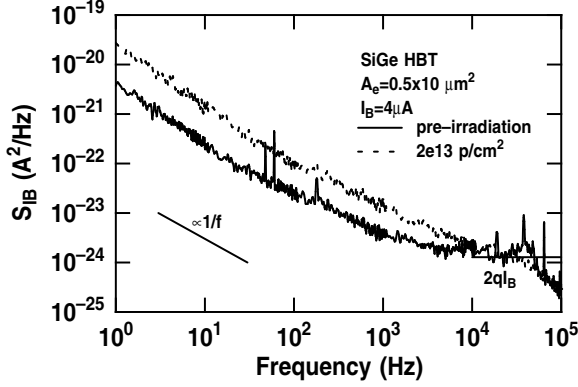


Fig. 8. Low-frequency noise power spectra pre- and post-irradiation. $A_e = 0.5 \times 10 \mu\text{m}^2$, $I_B = 4 \mu\text{A}$.

C. Absolute vs Relative Degradation

As mentioned above, the relative $1/f$ noise degradation (increase) is negligible for the smallest transistor ($0.5 \times 1 \mu\text{m}^2$), but significant for the largest transistor ($0.5 \times 10 \mu\text{m}^2$). The “minor” relative degradation in the small transistor, however, can be deceptive, because its pre-irradiation $1/f$ noise is 10x the $1/f$ noise of the large transistor. A possible situation is that the absolute increases of $1/f$ noise are comparable in the two devices with different geometries. These increases are minor compared to the pre-irradiation $1/f$ noise of the small transistor, but significant compared to the pre-irradiation $1/f$ noise of the large transistor (1/10 the pre-irradiation $1/f$ noise in the small transistor). This is indeed the case, as shown by the ΔS_{IB} ($S_{IB, \text{post}} - S_{IB, \text{pre}}$) vs effective emitter area A_e data in Fig. 11. The proton-induced absolute increase (degradation) of $1/f$ noise is comparable for the $0.5 \times 1 \mu\text{m}^2$ and $0.5 \times 10 \mu\text{m}^2$ transistors, despite a 10x emitter area difference. Such a weak emitter area dependence of irradiation-induced $1/f$ noise is counterintuitive, and cannot be explained by existing $1/f$ noise theories. We present in the following a theory that allows us to qualitatively explain the geometry independent increase of $1/f$ noise.

IV. Noise Theory

It is well known that proton irradiation introduces G/R centers in the transistor, and hence creates a non-ideal base current component due to increased space-charge region (SCR) recom-

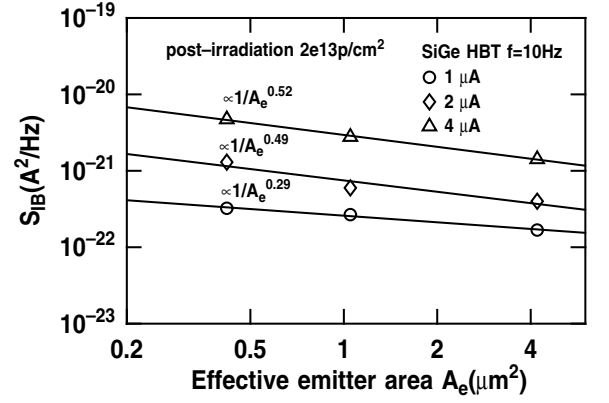


Fig. 9. Post-irradiation S_{IB} versus effective emitter area A_e in three SiGe HBTs at different bias current: $I_B = 1 \mu\text{A}$, $2 \mu\text{A}$, and $4 \mu\text{A}$. $f = 10\text{Hz}$.

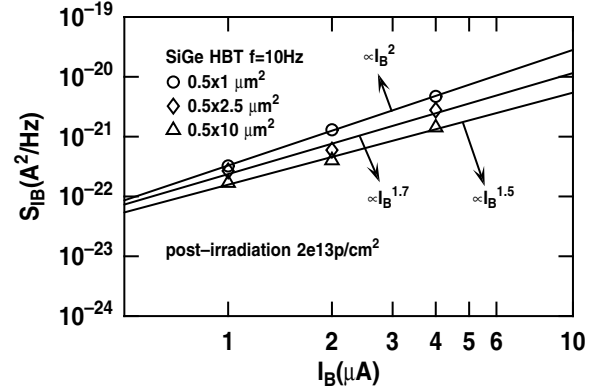


Fig. 10. Post-irradiation S_{IB} versus I_B in three SiGe HBTs with different emitter area: $A_e = 0.5 \times 1 \mu\text{m}^2$, $0.5 \times 2.5 \mu\text{m}^2$ and $0.5 \times 10 \mu\text{m}^2$. $f = 10\text{Hz}$.

bination current. Fig. 12 shows I_C and I_B as a function of V_{BE} both before and after irradiation for the $0.5 \times 10 \mu\text{m}^2$ HBT. A significant non-ideal base current component due to SCR recombination (I_{BSCR}) can be observed post-irradiation. The contribution of I_{BSCR} to the total I_B , however, is quite negligible in the bias range of interest to analog and RF circuits, as shown in Fig. 12. Most of I_{BSCR} comes from the recombination at the surface of the EB junction near the oxide spacer. This SCR recombination near surface is a very noisy process, and the associated noise current is described as a current generator between the base and emitter. Van der Ziel *et al.* [8] showed that the noise power spectrum $S_{I_{BSCR}}$ due to this process can be expressed by a modified Hooge-type equation:

$$S_{I_{BSCR}} = I_{BSCR}^2 \frac{\alpha_H}{f N_T} \quad (2)$$

where N_T is number of traps at the SCR surface, and α_H is the so-called Hooge parameter [9] [10]. N_T is given by $n_T L_{SCR} P_e$, where n_T is the area trap density at the surface, L_{SCR} is the length of SCR at surface, and P_e is the emitter perimeter length.

Fig. 13 shows the peripheral density of irradiation-induced SCR base current (I_{BSCR}/P_e) as a function of V_{BE} . I_{BSCR}/P_e is approximately the same for all of the transistors, and shows the typical $e^{aqV_{BE}/kT}$ dependence. In our case, a has a value of 0.5, as can be seen from Fig. 13. I_{BSCR} also increases with n_T and P_e :

$$I_{BSCR} \propto e^{0.5qV_{BE}/kT} P_e n_T \quad (3)$$

In the RF bias range, I_B remains dominated by hole injection into the emitter, and is practically unaffected by I_{BSCR} , as can be seen

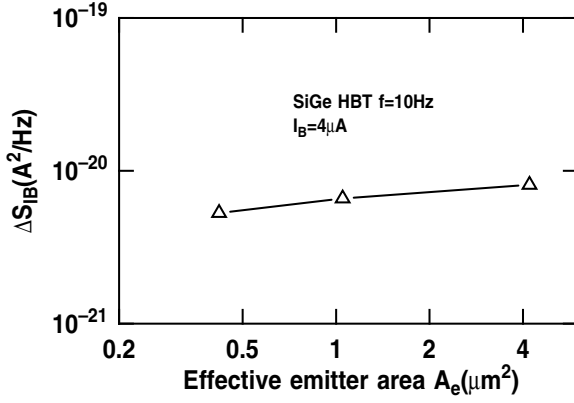


Fig. 11. $\Delta S_{IB}(S_{IB,post} - S_{IB,pre})$ versus effective emitter area A_e in three SiGe HBTs. $I_B=4\mu A$, $f=10\text{Hz}$.

from Fig. 12. I_B is given by:

$$I_B \propto e^{qV_{BE}/kT} A_e \quad (4)$$

It is desirable to express I_{BSCR} in terms of I_B to facilitate interpretation of measured $1/f$ noise data. Such an expression can be obtained by inspection of Eqs. (3) and (4):

$$I_{BSCR} \propto \frac{I_B^{0.5}}{A_e^{0.5}} P_e n_T \quad (5)$$

$S_{I_{BSCR}}$ can then be expressed in terms of I_B by substitution of Eq. (5) into Eq. (2):

$$S_{I_{BSCR}} = C I_B n_T \frac{P_e \alpha_H}{A_e f} \quad (6)$$

where C is a constant that is independent of bias and geometry. Assuming that the major irradiation-induced increase of $1/f$ noise comes from the SCR recombination current near surface, the post-irradiation noise is obtained as:

$$\begin{aligned} S_{I_{B,post}} &= S_{I_{B,pre}} + S_{I_{BSCR}} \\ &= \frac{K}{A_e} I_B^2 \frac{1}{f} + C I_B n_T \frac{P_e \alpha_H}{A_e f} \end{aligned} \quad (7)$$

where the pre-irradiation noise was described by Eq. (1). A number of important observations can be made from Eq. (7):

- Irradiation-induced $1/f$ noise $S_{I_{BSCR}}$ increases with trap density n_T , and hence proton irradiation dose.
- At a given I_B , the irradiation-induced $1/f$ noise is in proportion to P_e/A_e instead of $1/A_e$. The three transistors used have approximately the same P_e/A_e , and thus should have approximately the same $S_{I_{BSCR}}$. This is consistent with the measured data shown in Fig. 11.
- The relative degradation is smaller for smaller devices, because of higher $1/f$ noise before irradiation.
- The irradiation-induced $1/f$ noise varies with I_B instead of I_B^2 . The total $1/f$ noise post-irradiation is the sum of the pre-irradiation $1/f$ noise and $S_{I_{BSCR}}$, and should show a I_B^β dependence with $1 < \beta < 2$. "Because the relative ratio of the pre-irradiated to the irradiation-induced $1/f$ noise is proportional to $1/P_e$, β should be close to 2 for the smallest device (least amount of relative degradation), and smaller than 2 for the largest device." This is also consistent with the experimental data shown in Fig. 10.

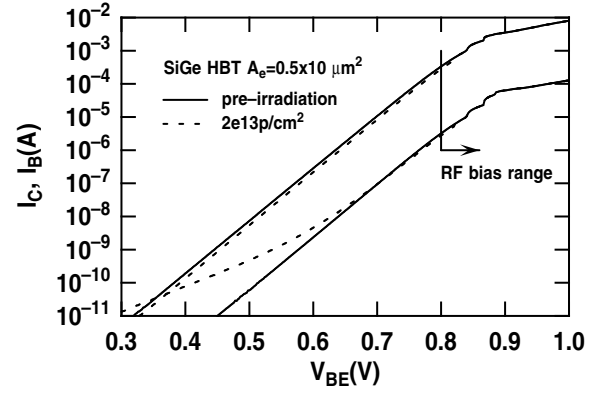


Fig. 12. I_C and I_B versus V_{BE} pre- and post-irradiation. $A_e=0.5 \times 10\mu m^2$.

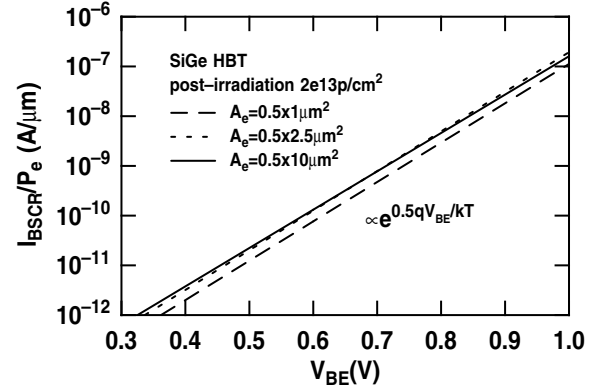


Fig. 13. Peripheral density of irradiation-induced base space charge region recombination current in three SiGe HBTs with different emitter area: $A_e=0.5 \times 1\mu m^2$, $0.5 \times 2.5\mu m^2$ and $0.5 \times 10\mu m^2$.

V. Summary

We have presented the experimental results of $1/f$ noise in SiGe HBTs after $2 \times 10^{13}\text{p/cm}^2$ proton irradiation. The pre-irradiation $1/f$ noise shows both I_B^2 and $1/A_e$ dependence. After irradiation the relative increase of $1/f$ noise is minor in transistor with small emitter area but significant in transistor with large emitter area. Thus the benefit of lower $1/f$ noise from using a larger transistor is significantly compromised by irradiation. A significant non-ideal base current component due to SCR recombination (I_{BSCR}) can be observed after irradiation. Although I_{BSCR} is negligible for the total I_B in the RF bias range, the major increase of $1/f$ noise comes from this SCR recombination process after irradiation. The $1/f$ noise produced by this process is shown to be in proportion to the irradiation-induced trap density n_T , the emitter perimeter to area ratio P_e/A_e , and the base current I_B as opposed to the $1/A_e$ and I_B^2 dependence before irradiation. Both the bias current and emitter area dependences are weakened after irradiation in the RF bias range.

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