$1/f$ Noise in Proton Irradiated SiGe HBTs

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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/cm^2 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 $0.5 \times 10\mu m^2$. Because of the offset during lithography and processing, there is a difference of $0.08\mu m$ between the drawn emitter width and effective emitter width. "The effective emitter length is coincidently the same as drawn emitter length after processing. So the effective emitter areas are 0.42×1, 0.42×2.5, and $0.42 \times 10\mu m^2$, 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/cm^2 protons with floating terminals at the Crocker Nuclear Laboratory cyclotron located at the University of California at Davis. The total irradiation energy is $63.5MeV$ 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/cm^2/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-wounded 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]."

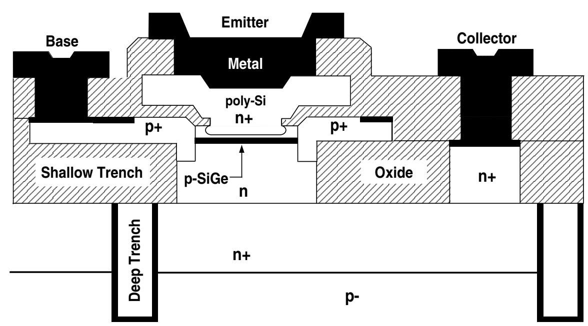

Fig. 1. The schematic cross section of the SiGe HBT.

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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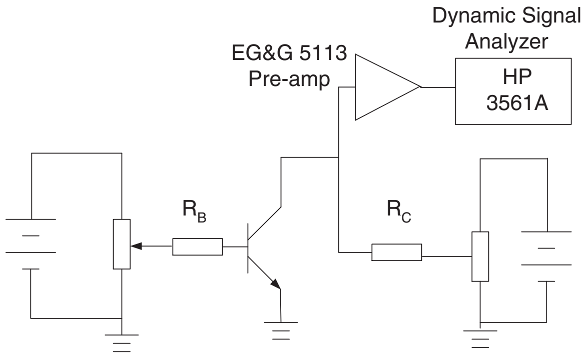

Fig. 2. 1/f noise measurement setup.

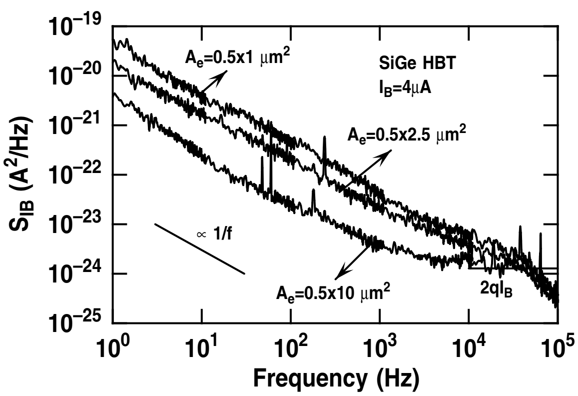

Fig. 3. Pre-irradiation low-frequency noise power spectra in three SiGe HBTs with different emitter area: A_e=0.5 × 1μm^2, 0.5 × 2.5μm^2 and 0.5 × 10μm^2. I_B=4μA.

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 ($A_e = 0.5 \times 1, 0.5 \times 2.5$, and $0.5 \times 10 \mu m^2$). 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 4μA. At all the biases, S_{I_B} shows a $1/A_e$ dependence. At the same I_B, the S_{I_B} in the $0.5 \times 10 \mu m^2$ device is 1/10 of that in the $0.5 \times 1 \mu m^2$ device.

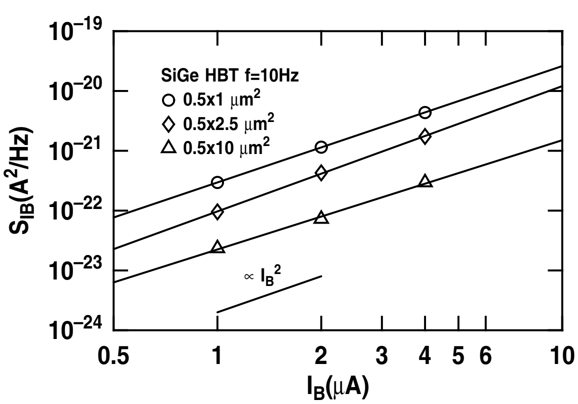

Fig. 4. Pre-irradiation S_{I_B} versus I_B in three SiGe HBTs with different emitter area: A_e=0.5 × 1μm^2, 0.5 × 2.5μm^2 and 0.5 × 10μm^2. f=10Hz.

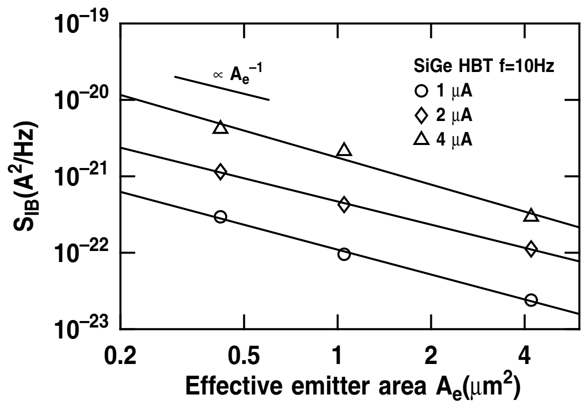

Fig. 5. Pre-irradiation S_{I_B} versus effective emitter area A_e in three SiGe HBTs at different bias current: I_B=1μA, 2μA, and 4μA. f=10Hz.

B. *Post-irradiation* $1/f$ *Noise*

After 2×10^{13}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 ($S_{I_{B,post}}/S_{I_{B,pre}}$) is minor in the $0.5 \times 1 \mu m^2$ transistor, but significant in the $0.5 \times 10 \mu m^2$ transistor, as shown in Figs. 7 and 8, respectively. An I_B of 4μA was used. As a result, S_{I_B} is no longer in proportion to $1/A_e$ after irradiation. Note that the $0.5 \times 10 \mu m^2$ transistor had a $1/f$ noise that is 1/10 of the $1/f$ noise in the $0.5 \times 1 \mu m^2$ transistor before irradiation. However, after irradiation, the $1/f$ noise in the $0.5 \times 10 \mu m^2$ transistor becomes only 1/3 of the $1/f$ noise in the $0.5 \times 1 \mu m^2$ 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).

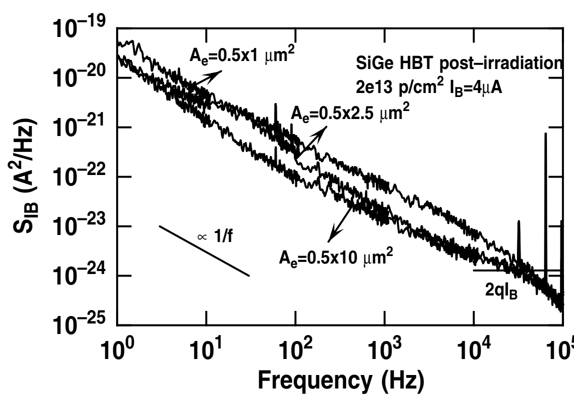

Fig. 6. Post-irradiation low-frequency noise power spectra in three SiGe HBTs with different emitter area: A_e=0.5 × 1μm^2, 0.5 × 2.5μm^2 and 0.5 × 10μm^2. I_B=4μA.

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 ($S_{I_{B,post}}/S_{I_{B,pre}}$) is minor in the smallest device ($0.5 \times 1 \mu m^2$), 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 $\propto I_B^{1.5}$.

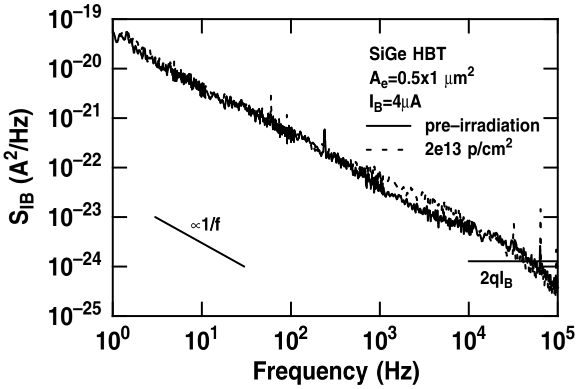

Fig. 7. Low-frequency noise power spectra pre- and post-irradiation. A_e=0.5 × 1μm^2, I_B=4μA.

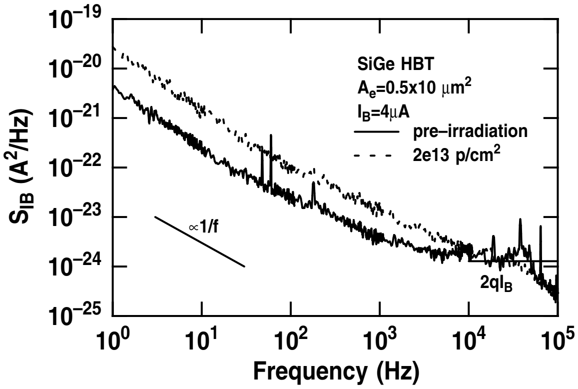

Fig. 8. Low-frequency noise power spectra pre- and post-irradiation. A_e=0.5 × 10μm^2, I_B=4μA.

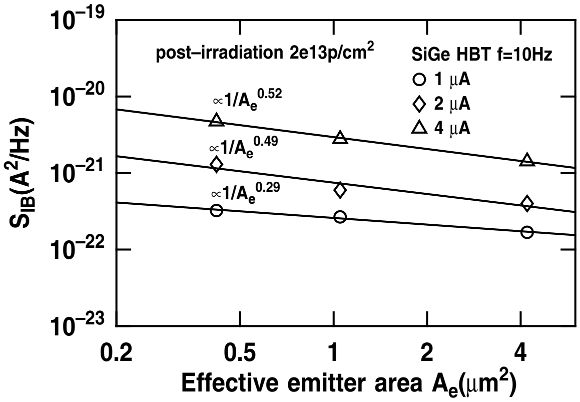

Fig. 9. Post-irradiation S_{I_B} versus effective emitter area A_e in three SiGe HBTs at different bias current: I_B=1μA, 2μA, and 4μA. f=10Hz.

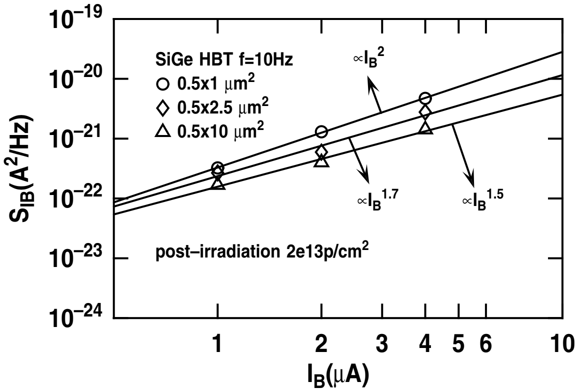

Fig. 10. Post-irradiation S_{I_B} versus I_B in three SiGe HBTs with different emitter area: A_e=0.5 × 1μm^2, 0.5 × 2.5μm^2 and 0.5 × 10μm^2. f=10Hz.

C. Absolute vs Relative Degradation

As mentioned above, the relative $1/f$ noise degradation (increase) is negligible for the smallest transistor (0.5 × 1μm^2), but significant for the largest transistor (0.5 × 10μm^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 $\Delta S_{I_B}(S_{I_{B,post}} - S_{I_{B,pre}})$ 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 × 1μm^2 and 0.5 × 10μm^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) recombination current. Fig. 12 shows I_C and I_B as a function of V_{BE} both before and after irradiation for the 0.5 × 10μm^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

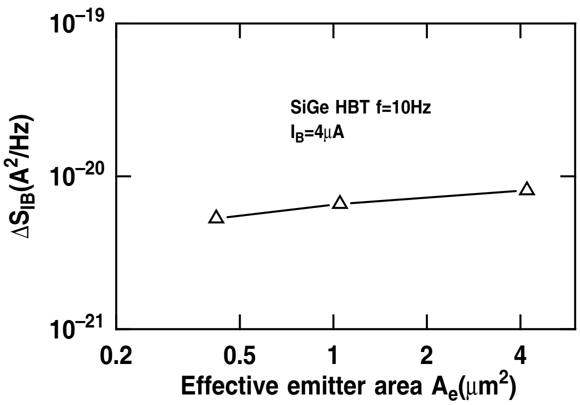

Fig. 11. $\Delta S_{I_B}(S_{I_{B,post}} - S_{I_{B,pre}})$ versus effective emitter area A_e in three SiGe HBTs. I_B=4μA, f=10Hz.

from Fig. 12. I_B is given by:

$$I_B \propto e^{qV_{BE}/kT} A_e \tag{4}$$

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):

$$I_{BSCR} \propto \frac{I_B^{0.5}}{A_e^{0.5}} P_e n_T \tag{5}$$

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

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

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:

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

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 propotional 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.

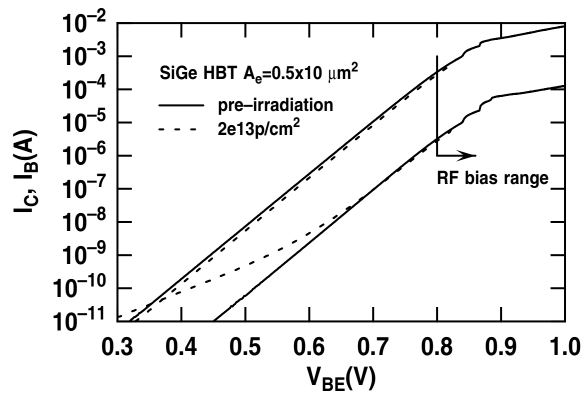

Fig. 12. I_C and I_B versus V_{BE} pre- and post-irradiation. A_e=0.5 × 10μm^2.

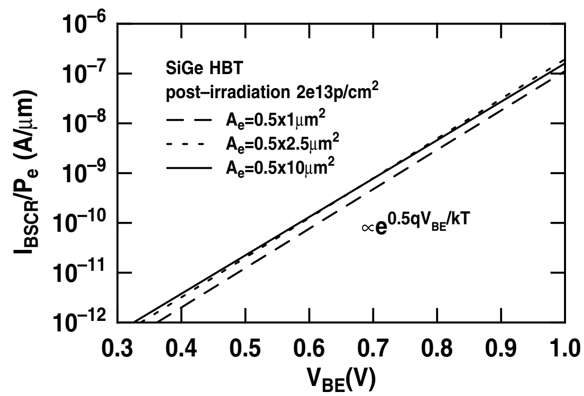

Fig. 13. Peripheral density of irradiation-induced base space charge region recombination current in three SiGe HBTs with different emitter area: A_e=0.5 × 1μm^2, 0.5 × 2.5μm^2 and 0.5 × 10μm^2.

V. Summary

We have presented the experimental results of $1/f$ noise in SiGe HBTs after 2 × 10^{13}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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