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 $2 \times 10^{13}$ 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, siliconized 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 $0.5 \times 1$, $0.5 \times 2.5$, 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 $0.42 \times 1$, $0.42 \times 2.5$, 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 $2 \times 10^{13}$ 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 $63.5 MeV$ 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/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 $r_b$, $r_e$, 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.](image)

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 $I_B^\alpha$ and inversely proportional to the emitter junction area $A_e$ in modern transistors:

$$S_{I_B} = \frac{K}{A_e} \frac{I_B^{1-\alpha}}{f}$$

where K is a technology dependent constant, and $\alpha$ has a typical value of 2. The physical origin of 1/f noise is the number fluctuation of carriers due to defects [5]-[7].
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 $S_{1B}$ at 10 Hz as a function of $I_B$ for all of the emitter areas ($A_e = 0.5 \times 1 \mu m^2$, $0.5 \times 2.5 \mu m^2$, and $0.5 \times 10 \mu m^2$). 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 $4 \mu A$. At all the biases, $S_{1B}$ shows a $1/A_e$ dependence. At the same $I_B$, the $S_{1B}$ 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.

### 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 ($S_{1B, \text{post}}/S_{1B, \text{pre}}$) 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 $4 \mu A$ was used. As a result, $S_{1B}$ 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 $S_{1B}$ vs effective emitter area $A_e$ data measured after irradiation (Fig. 9).

The bias current dependence of $1/f$ noise also changes after irradiation, depending on the emitter area, as shown by the $S_{1B}$ vs $I_B$ data measured after irradiation (Fig. 10). The relative degradation of $1/f$ noise ($S_{1B, \text{post}}/S_{1B, \text{pre}}$) is minor in the smallest device ($0.5 \times 1 \mu m^2$), and $S_{1B}$ remains $\propto I_B^2$. For the largest device whose relative $1/f$ noise degradation is the highest, $S_{1B}$ becomes $\propto I_B^{1.5}$.
component due to increased space-charge region (SCR) recom-
ters in the transistor, and hence creates a non-ideal base current
area difference. Such a weak emitter area dependence of
\( I_{B} \) vs effective emitter area

\[ \text{Fig. 7. Low-frequency noise power spectra pre- and post-irradiation. } A_{e}=0.5 \times 10\mu m^2, I_{B}=4\mu A. \]

\[ \text{Fig. 8. Low-frequency noise power spectra pre- and post-irradiation. } A_{e}=0.5 \times 10\mu m^2, I_{B}=4\mu A. \]

C. Absolute vs Relative Degradation

As mentioned above, the relative 1/f noise degradation (in-
crease) is negligible for the smallest transistor (0.5 \( \times 1 \mu m^2 \)), but
significant for the largest transistor (0.5 \( \times 10 \mu m^2 \)). The “mi-
nor” relative degradation in the small transistor, however, can be
decreptive, because its pre-irradiation 1/f noise is 10x the 1/f
noise of the large transistor. A possible situation is that the ab-
solute 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 signif-
ificant compared to the pre-irradiation 1/f noise of the large tran-
sistor (1/10 the pre-irradiation 1/f noise in the small transistor).
This is indeed the case, as shown by the \( \Delta S_{IB} (S_{IB, post} - S_{IB, pre}) \)
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 \( \times 1 \mu m^2 \) and 0.5 \( \times 10 \mu m^2 \) 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 follow-
ing a theory that allows us to qualitatively explain the geom-
etry independent increase of 1/f noise.

IV. Noise Theory

It is well known that proton irradiation introduces G/R cen-
ters in the transistor, and hence creates a non-ideal base current
component due to increased space-charge region (SCR) recom-
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 \( \times 10 \mu m^2 \) HBT. A
significant non-ideal base current component due to SCR recom-
bination \( (I_{B,SCR}) \) can be observed post-irradiation. The contribu-
tion 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 re-
combination near surface is a very noisy process, and the asso-
ciated 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 \( S_{BSCR} \) due to this process can be expressed by a
modified Hooge-type equation:

\[ S_{BSCB} = \frac{I_{BSCR}^{2} \alpha_{H}}{N_{T}} \]  \hspace{1cm} (2)

where \( N_{T} \) is number of traps at the SCR surface, and \( \alpha_{H} \) 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
usual \( e^{qP_{f}V_{BE}/kT} \) 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 \( P_{e} \):

\[ I_{BSCR} \propto e^{0.5qP_{f}V_{BE}/kT} P_{e} n_{T} \]  \hspace{1cm} (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
from Fig. 12. \(I_B\) is given by:

\[
I_B \propto e^{\phi V_{BE}/kT} A_e
\]  

(4)

It is desirable to express \(I_{BSiCR}\) 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):

\[
I_{BSiCR} \propto \frac{I_B^{0.5}}{A_e^{0.5}} P_e n_T
\]  

(5)

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

\[
S_{I_{BSiCR}} = C I_B n_T \frac{P_e \alpha_H}{A_e} \frac{1}{f}
\]  

(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:

\[
S_{I_{BSiCR}} = S_{I_{BSiCR \; pre}} + S_{I_{BSiCR \; post}}
\]

\[
= \frac{K}{A_e} \frac{1}{I_B} \frac{1}{f} + C I_B n_T \frac{P_e \alpha_H}{A_e} \frac{1}{f}
\]  

(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 \(S_{I_{BSiCR}}\) 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 \(I/A_e\). The three transistors used have approximately the same \(P_e/A_e\), and thus should have approximately the same \(S_{I_{BSiCR}}\). 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 \(S_{I_{BSiCR}}\), and should show a \(I_B^\beta\) dependence with \(1 < \beta < 2\). "Because the relative ratio of the pre-irradiated to the irradiation-induced 1/f noise is propotional to \(1/P_e\), \(\beta\) 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.

V. Summary

We have presented the experimental results of 1/f noise in SiGe HBTs after 2 \times 10^{13} p/cm² 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 \(I_{BSiCR}\) can be observed after irradiation. Although \(I_{BSiCR}\) 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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