The Effects of Radiation on 1/f Noise in Complementary ($nnp + pnp$) SiGe HBTs

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Abstract—We present the first study of the effects of radiation on low-frequency noise in a novel complementary ($nnp + pnp$) silicon-germanium (SiGe) HBT BiCMOS technology. In order to manipulate the physical noise sources in these complementary SiGe HBTs, 63.3 MeV protons were used to generate additional (potentially noise-sensitive) trap states. The base currents of both the nnp and pnp SiGe HBTs degrade with increasing proton fluence, as expected, although in general more strongly for the nnp transistors than for the pnp transistors, particularly in inverse mode. For the pnp SiGe HBTs, irradiation has almost no effect on the 1/f noise to proton fluence as high as 5.0×10^{13} p/cm², while the nnp SiGe HBTs show substantial radiation-induced excess noise. In addition, unlike for the pnp devices, which maintain an I_B^2 bias dependence, the 1/f noise of the post-irradiated nnp SiGe HBTs change to a near-linear dependence on I_B at low base currents following radiation. That suggests a fundamental difference in the noise physics between the two types of devices.

Index Terms—1/f noise, proton irradiation, SiGe heterojunction bipolar transistor (HBT).

I. INTRODUCTION

HIGH-SPEED complementary ($nnp + pnp$) bipolar transistor technology has long been recognized for its many advantages in high-performance analog IC design, particularly for low voltage circuits and push-pull architectures. In such complementary technologies, however, maintaining adequate performance in the pnp transistor is very difficult, partially compromising the utility of complementary analog technologies. It is generally recognized that bandgap engineering using silicon-germanium (SiGe) alloys has a very favorable impact on key analog figures-of-merit such as gain, frequency response, output conductance, βV_A product, and noise [1]. Such SiGe heterojunction bipolar transistor (HBT) technologies are in wide-spread use today. Exclusively, however, such SiGe technologies are based around nnp SiGe HBT configurations. SiGe HBTs using pnp 's are known to be more challenging in

their design and optimization [1], and the successful monolithic integration of SiGe nnp 's and SiGe pnp 's to form a complementary SiGe analog technology has proven exceptionally challenging to achieve. Recently, however, a novel complementary SiGe HBT BiCMOS technology on silicon on insulator (SOI) technology has in fact been reported [2], opening the way to a new level of performance in analog IC design.

Low-frequency noise in transistors usually exhibits a 1/f-like spectrum. This sets the lower limit on the detectable signal level, can be up-converted to higher frequencies corrupting spectra purity (phase noise). Hence, it is a key design constraint in nearly all analog ICs and systems. Radiation experiments have proven to be very useful in probing the physical noise sources in nnp SiGe HBTs [3], [4]. Besides that, proton radiation experiments are also proven to be a useful method to test the reliability of electron devices worked in the out-space [5].

In this work, we present the first radiation results of complementary SiGe HBTs, and use radiation to probe the differences in the underlying physics of 1/f noise between nnp and pnp SiGe HBTs.

II. DEVICE TECHNOLOGY AND EXPERIMENT

This novel complementary SiGe HBT BiCMOS technology (Fig. 1) was fabricated by Texas Instruments, and involves dual depositions of SiGe epitaxy (boron doped for the nnp , and arsenic doped for the pnp), shallow and deep trench isolation, polysilicon emitter contacts with thin, interfacial oxide layers (more process details can be found in [2]). Both nnp and pnp SiGe HBTs, as well as the Si CMOS devices, were integrated on SOI material. In addition, both pnp and nnp devices have been optimized with separate emitter processes in the standard process to reach cutoff frequencies $f_T = 28$ GHz. Due to the need to achieve comparable current gain between the nnp and pnp transistors, a controlled emitter interfacial oxide between the single crystal Si emitter (part 18 or 19 in Fig. 1) and the heavily doped polysilicon contact (part 12 or 13 in Fig. 1) was used to independently adjust the nnp and pnp transistors. Because such interfacial oxides are known to affect low-frequency noise, we have also compared two complementary SiGe HBT processes fabricated identically, except with differing interfacial oxide thicknesses on the nnp SiGe HBT (the pnp emitter process was held fixed).

Transistors of varying geometries were measured. The width of both the nnp and pnp devices was fixed at $0.4 \mu\text{m}$, while the

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Fig. 1. Schematic device cross section of novel complementary SiGe HBT technology.

Fig. 2. Schematic block diagram for the automatic dual-channel noise measurement system.

length was varied from $0.8 \mu\text{m}$ to $6.4 \mu\text{m}$. Measured preradiation f_T of the complementary SiGe HBTs are both 19 GHz, with Early voltages (V_A) of the *nnp* and *pnp* transistors of 150 V and 100 V, respectively [2]. The samples were grounded and irradiated with 63.3 MeV protons at the Crocker Nuclear Laboratory at the University of California at Davis. Experiments with proton fluxes from 10^6 to 10^{11} $\text{p/cm}^2/\text{s}$ can be achieved in the beam current range from about 5 pA to 50 nA. The details of the dosimetry system, which is accurate to about 10%, are described in [5] and [6]. At proton fluence of 1.0×10^{12} and 5.0×10^{13} p/cm^2 , the measured equivalent gamma dose was approximately 135 and 6,759 krad(Si), respectively.

An automatic noise measurement system was developed to measure the noise power spectral densities of the devices. The block diagram of the system is shown in Fig. 2.

Wire-wound potentiometers R_{PB} and R_{PC} are controlled by a computer through two stepping motors. Since the control system between the stepping motors and the computer is isolated by relays, the 60 Hz fluctuations from the ac power source

do not degrade the measured data. An Agilent 35 670A Dynamic Signal Analyzer was used to measure the voltage power spectrum densities S_{VB} and S_{VC} from resistors R_S and R_L , which are series-connected with the base and the collector terminals, respectively. Typical measured S_{VB} and S_{VC} data are shown in Fig. 3. The coherence between those two power spectral densities is found to be close to unity (Fig. 4), which indicating a dominant noise source existing in the device [7].

According to the equivalent hybrid- π model [8], S_{VB} and S_{VC} are given by

$$S_{VB} \approx \left(\frac{R_S r_\pi}{R_S + r_\pi} \right)^2 S_{IB} \quad (1)$$

and

$$S_{VC} \approx \left(\frac{R_L R_S \beta}{R_S + r_\pi} \right)^2 S_{IB} \quad (2)$$

where the dynamic current gain $\beta = dI_C/dI_B$, the dynamic emitter-base input impedance $r_\pi = dV_{BE}/dI_B$, and S_{IB} is the

Fig. 3. Typical power spectral densities S_{VB} and S_{VC} measured from the dual-channel system. The power spectral densities shown are for a pnp SiGe HBT with $A_E = 0.4 \times 6.4 \mu\text{m}^2$, $I_B = 8.0 \mu\text{A}$, and $V_{BC} = 0.5 \text{ V}$.

Fig. 4. Extracted power spectral densities S_{IB} from S_{VB} and S_{VC} and measured coherence data. The data shown are for a pnp SiGe HBT with $A_E = 0.4 \times 6.4 \mu\text{m}^2$, $I_B = 8.0 \mu\text{A}$, and $V_{BC} = 0.5 \text{ V}$. The arrows in the figure indicate the appropriate axis for the data.

dominant current noise generator in the base. A $1 \text{ M}\Omega$ metal film resistor is chosen for R_S to avoid the parasitic effects from the internal base and emitter resistance and the resistance from the biasing circuits [9]. As shown in Fig. 4, S_{IB} extracted from S_{VB} and S_{VC} are nearly identical, which proves that S_{IB} is the dominant noise source.

III. RESULTS

Fig. 5 shows the radiation response of the Gummel characteristics for both device types as a function of proton fluence. With increasing fluence, the nonideal base current component increases, as expected, indicating that radiation-induced G/R traps are being added to the device as the proton fluence increases. Fig. 6–8 show the current gain, and normalized base current change for both npn and pnp SiGe HBTs in both forward and inverse mode (emitter-base terminals swapped) as a function of proton fluence. Interestingly, the pnp SiGe HBTs generally show significantly better radiation tolerance than the npn SiGe HBTs, particularly in inverse mode, although clearly there is a strong dependence on device geometry. This suggests that the damage thresholds between the two device types are fundamentally different, despite the near-identical processing associated with the damage sensitive regions (i.e., the emitter-

Fig. 5. Gummel characteristics for pre- and post-irradiated complementary SiGe HBTs. The Gummel plots are for devices in forward mode with $A_E = 0.4 \times 3.2 \mu\text{m}^2$, and $V_{CB} = 0.0 \text{ V}$.

Fig. 6. Current gain degradation for the complementary SiGe HBTs in forward mode at $V_{CB} = 0.0 \text{ V}$.

Fig. 7. Base current degradation as a function of fluence in forward mode for the complementary SiGe HBTs at $|V_{BE}| = 0.6 \text{ V}$, and $V_{CB} = 0.0 \text{ V}$.

base spacer oxide and the shallow trench edge). We also consistently observed significant spontaneous self-annealing at room temperature over the span of about 6 weeks.

For the pre-irradiated devices, the noise spectrum is $1/f$ type in shape and is generally similar to that observed in conventional

Fig. 8. Base current degradation as a function of fluence in inverse mode for the complementary SiGe HBTs at $|V_{BC}| = 0.6$ V, and $V_{EB} = 0.0$ V.

Fig. 9. Extracted power spectral densities S_{IB} at different base currents. The densities shown are for a *pnp* SiGe HBT with $A_E = 0.4 \times 6.4 \mu\text{m}^2$, and $V_{BC} = 0.5$ V.

Fig. 10. Extracted power spectra densities S_{IB} at 10 Hz as a function of the emitter area. The densities are for the complementary SiGe HBTs with standard process, and $|V_{BC}| = 0.5$ V.

Si bipolar junction transistors (BJTs) [9] (Fig. 9) with the equivalent current noise source S_{IB} exhibiting an I_B^2 dependence and inverse proportionality to the emitter area A_E (Fig. 10).

We scanned the noise in the devices from $I_B = 0.1 \mu\text{A}$ to $I_B = 8 \mu\text{A}$. As shown in Fig. 9, all of the spectra show clear $1/f$ dependence over this base current range and increase with base

Fig. 11. Comparison of the pre-radiation and the post-radiation S_{IB} spectra for both *nnp* and *pnp* SiGe HBTs. The densities are for the complementary SiGe HBTs with standard process, $A_E = 0.4 \times 6.4 \mu\text{m}^2$, $I_B = 1.0 \mu\text{A}$, and $|V_{BC}| = 0.5$ V.

Fig. 12. Effects of irradiation on the bias dependence of the noise at 10 Hz for both *nnp* and *pnp* SiGe HBTs. The densities are for the complementary SiGe HBTs with standard process, $A_E = 0.4 \times 6.4 \mu\text{m}^2$, and $|V_{BC}| = 0.5$ V.

current I_B . This is also the case for all of the *nnp* transistors. To avoid small size effects [10], we focus our studies here on the largest device with $A_E = 0.4 \times 6.4 \mu\text{m}^2$. For the preradiation case, The *nnp* transistor noise is consistently smaller than that of the *pnp*'s (Fig. 11 and Fig. 12).

Interestingly, the post-irradiated devices demonstrate a strongly dissimilar behavior between the *nnp* and *pnp* SiGe HBTs, which is shown in Fig. 11 and Fig. 12. For the *pnp* transistors, the $1/f$ noise remains nearly unchanged up to proton fluence of $5.0 \times 10^{13} \text{ p/cm}^2$. For *nnp* transistors, however, the magnitude of the $1/f$ noise significantly increases after irradiation. This difference in noise response to radiation occurs in spite of the similar response between the *nnp* and *pnp* device current-voltage characteristics at the same proton fluence. Even more surprising, in the *nnp* SiGe HBTs, at low base currents ($I_B < 0.8 \mu\text{A}$) the quadratic dependence of the noise changes to a near linear dependence on base current after radiation exposure, remaining as an I_B^2 dependence at higher bias levels. No such behavior is seen in the *pnp* transistors.

S_{IB} at 10 Hz comparison for the devices with the different *nnp* interfacial oxide are shown in Fig. 13. As expected, the *nnp* SiGe HBT with the thicker interfacial oxide has a larger $1/f$ noise

Fig. 13. Effects of irradiation on the bias dependence of the noise at 10 Hz for *npn* SiGe HBTs with different interfacial oxide thickness. The densities are for the *npn* SiGe HBTs with $A_E = 0.4 \times 6.4 \mu\text{m}^2$, and $V_{CB} = 0.5 \text{ V}$.

Fig. 14. Cross section of emitter-base space charge region at the spacer oxide edge.

magnitude, indicating the low frequency noise is mainly caused by the interfacial oxide before irradiation exposure. Note, however, that the *npn* device with the thicker interfacial oxide also exhibits the same anomalous I_B dependence at low base currents as seen in the standard process, suggesting that the observed differences in noise physics between the *npn* and *pnp* SiGe HBTs is fundamental, and not dependent on differences in the emitter interface preparation.

IV. THEORY AND DISCUSSION

The “tunneling-assisted trapping” model predicts a *linear* dependence of S_{IB} on the base current I_B [11]. This model assumes that the 1/f noise results from the dynamic carrier trapping and detrapping processes when carriers are close to the spacer oxide covering the emitter-base junction. The surface recombination base current I_S (in a *npn* transistor) has exponential dependence on the surface potential ψ_s at the emitter-base space charge region, shown in Fig. 14, as $I_S \propto \exp(q\psi_s/kT)$, while the surface potential can be modulated by the change in the surface charge Q_S at the $\text{Si} - \text{SiO}_2$ interface. Therefore, the departure from the steady surface potential is given by

$$\Delta\psi_s = \frac{\Delta Q_S}{A_S C_S} \quad (3)$$

with A_S being the effective surface area of the space charge region and C_S the effective surface capacitance per unit area. The

fluctuation of the surface recombination current, consequently, is expressed in the form

$$\frac{\Delta I_S}{I_S} = \frac{\partial \ln(I_S)}{\partial \psi_s} \Delta\psi_s = \frac{q}{kT} \cdot \frac{\Delta Q_S}{A_S C_S}. \quad (4)$$

Then, the power spectral density of the surface recombination current fluctuation S_{IS} reads

$$S_{IS} = \frac{q^2}{k^2 T^2} \cdot \frac{S_{QS}}{A_S C_S^2} I_S^2 \quad (5)$$

where S_{QS} is the surface charge spectral density per unit area. The surface charge fluctuation originates from the trapping-de-trapping of carriers between the slow states inside the spacer oxide and the space charge region through the tunneling process. Assuming only the traps close to the carrier quasi-Fermi level contribute to fluctuations and the trap density is nearly uniform in space, the spectral density S_{QS} in the element tunneling depth Δz is [12]

$$\Delta S_{QS} = 4kTq^2 N_t \frac{\tau(z)}{1 + \omega^2 \tau^2(z)} \Delta z \quad (6)$$

with N_t being the trap density in units of ($\text{cm}^{-3} \cdot \text{eV}^{-1}$) and $\tau(z)$ the trapping time constant for a slow state trap at position z , which is given by

$$\tau(z) = \tau_s \cdot \exp\left(\frac{z}{\lambda}\right) \quad (7)$$

with τ_s the mean time constant and λ the effective attenuation tunneling distance. Substituting (7) into (6) and assuming the spacer oxide thickness is much larger than λ , which is generally accepted, the entire oxide charge spectral density S_{QS} is expressed by

$$S_{QS} = \int 4kTq^2 N_t \frac{\tau(z)}{1 + \omega^2 \tau^2(z)} dz = 4kTq^2 N_t \lambda \frac{\frac{\pi}{2} - \tan^{-1}(\omega \tau_s)}{\omega}. \quad (8)$$

Since τ_s is in the order of μs , $\tan^{-1}(\omega \tau_s)$ is negligible up to $f = 100 \text{ KHz}$. Therefore, S_{QS} can be revised to

$$S_{QS} \approx kTq^2 N_t \frac{\lambda}{f}. \quad (9)$$

Substituting (9) into (5) and assuming the surface recombination fluctuation is the dominant noise source ($S_{IB} \approx S_{IS}$), S_{IB} can be expressed as

$$S_{IB} = \frac{q^4 N_t \lambda}{kT A_S C_S^2 f} I_S^2. \quad (10)$$

Since the base current I_B is composed of a diffusion current and the surface recombination current, it can be defined by

$$I_B = I_D + I_S \approx I_{B0} \cdot \exp\left(\frac{qV_{BE}}{kT}\right) + I_{S0} \cdot \exp\left(\frac{qV_{BE}}{2kT}\right) \quad (11)$$

where I_D is the diffusion current; I_{B0} and I_{S0} are the diffusion and surface saturation currents, respectively. Therefore, the base current fluctuation can be expressed by

$$S_{IB} = \frac{q^4 N_t \lambda}{kT A_S C_S^2 f} \frac{I_{S0}^2}{I_{B0}} I_B. \quad (12)$$

This noise model predicts that S_{IB} is inversely proportional to emitter periphery (P_E), since the surface area of the emitter-

Fig. 15. Effects of irradiation on the geometrical dependence of npn SiGe HBTs. The power spectral densities are for the npn SiGe HBTs with standard process, $I_B = 0.1 \mu A$, $V_{CB} = 0.5 V$, and $f = 10$ Hz.

base space charge region A_S is proportional to the emitter periphery. As can be seen in Fig. 15, the pre-irradiated devices exhibit a clear $1/A_E$ dependence, while the post-irradiated transistors deviate from this behavior. More noise data on devices with differing P/A ratios will be required to clearly differentiate if this follows a $1/P_E$ behavior, and is in progress.

The carrier number fluctuations in the diffusion component of the base current are much more complicated than that in the surface recombination component. Several noise models associated with different physical mechanisms, which predict an I_B^2 dependence of S_{IB} , have been reported in [13]–[16]. The “transparency fluctuation model” proposed by Klempner assumes that the thermal noise from the interfacial oxide can modulate the oxide barrier height. Hence, the oxide generates the so-called “transparency fluctuation,” or tunneling probability fluctuation, through the oxide [13]–[15]. Thus, the current passing through the emitter is modulated by the transparency fluctuation, which induces $1/f$ noise. This model predicts that the $1/f$ noise has a cubic dependence on the interfacial oxide thickness.

Another noise model worth mentioned here is the “two-step tunneling model,” used to explain the low frequency noise in the tunnel diode [16]. For the first step, the carriers recombined with the bound states at the $Si - SiO_2$ interface close to the monosilicon region. Then, some of the carriers were trapped by the slow states inside the oxide through tunneling process in the second step. This model, eventually, predicts a quadratic dependence of $1/f$ noise on the interfacial oxide thickness, assuming constant trap density in the interfacial oxide.

However, those models are not suitable to explain the exponential dependence of $1/f$ noise on the interfacial oxide thickness [17]. A possible physical mechanism for this strong oxide thickness dependence is that the $1/f$ noise comes from the trapping-detrapping process associated with the slow states inside the interfacial oxide. The approximate exponential energy distribution of the trap density, finally, leads to the exponential dependence of low frequency noise on the interfacial oxide thickness.

From all the experiments, we consistently found that the magnitude of the $1/f$ noise of pnp transistors is larger than npn tran-

sistors with the same process, except the npn 's $1/f$ noise associated with the surface recombination current. The difference between the $1/f$ noise of npn and pnp transistors is believed due to the different properties of electron and hole traps in the composite material used in the interfacial oxide. In our case, the hole trap density in pnp transistor might be several orders higher than that in npn transistors as other authors reported [18]. Hence, the additional trap density induced by irradiation might be comparable to that of npn devices, however, remains negligible for pnp devices. Therefore, the $1/f$ noise of pnp transistor has higher radiation tolerance than that of npn .

V. SUMMARY

This work presents the first radiation results of complementary SiGe HBTs, and used radiation to probe the differences in underlying physics of $1/f$ noise between npn and pnp SiGe HBTs. For pre-irradiation npn and pnp transistors, both types show $1/f$ type of low frequency noise spectrum, quadratic dependence on the base current and inverse proportionality on the emitter area, similar to the conventional complementary Si BJTs. The dominant low frequency noise source is found in the interfacial oxide layer between the monosilicon emitter and the polysilicon emitter. For post-radiation pnp transistors with radiation dose up to $5.0 \times 10^{13} p/cm^2$, the $1/f$ noise remains unchanged, indicating negligible trap centers have been added. However, the magnitude of the $1/f$ noise for the npn transistor increases significantly after irradiated with the same dose, as a result of a raised trap density. Additional traps induced by the radiation are added into both the interfacial oxide and the emitter-base spacer oxide. At low base current ($I_B < 0.8 \mu A$), the $1/f$ noise is dominated by the fluctuation of the surface recombination current. While, at the high base current, the $1/f$ noise is still caused by the traps inside the interfacial oxide.

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