Investigation of SiGe Heterojunction Bipolar Transistor over an Extreme Temperature Range

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Abstract. Dc, high frequency (hf) characteristics and noise of SiGe HBTs were investigated in a wide ambient temperature ($T$) range from 4 K to 423 K. SiGe HBTs with low emitter concentration (LEC) and trapezoidal Ge base doping were found good candidates for cryogenic applications. Both hydrodynamic (HD) device simulation and compact model (CM) HICUM show good agreement with experimental data in the temperature range of 300 K-423 K. The collector current did not show any leakage related to electric field assisted tunneling via traps in the base. Rapid decrease of transit frequency ($f_T$) with $T$ is explained in terms of the carrier delay distribution. Noise figure ($NF_{min}$) analysis reveals that the main noise contributors are related to collector current fluctuations (shot-like noise) and thermal noise in the base at high $T$. Base current fluctuations related noise becomes of importance only at high injection. Simulated diffusion noise distribution shows that collector terminal electronic noise originates at the emitter-base (BE) junction but not in base-collector (BC) junction area.

Keywords: SiGe HBTs, temperature dependence, transit frequency, diffusion noise, hydrodynamic device simulation, HICUM.

INTRODUCTION

SiGe heterojunction bipolar transistor technology nowadays offers high speed transistors capable to operate in cryogenic environment. Compared to BJTs, SiGe HBTs are naturally suitable for cryogenic temperatures, including 4 K [2],[3], and have achieved $f_T$ beyond 600 GHz at 45 K [1]. Careful SiGe HBT profile optimization can yield an improved hf performance at very low temperatures [2],[4],[5]. It was shown that SiGe HBTs can be used for cryo-applications, such as LNAs for satellite electronics [6], amplifiers for cooled Analog Digital Converters [7] and operational amplifiers working at 4 K [8]. Profile optimization suggests to lower the emitter concentration and to use a trapezoidal Ge profile with constant base doping. Along with high speed, reduced high frequency noise of cooled SiGe HBTs is an advantageous feature for LNA design. It was shown that significant improvement of $NF_{min}$ was achieved at cryogenic temperatures even for SiGe HBTs with conventional doping profiles [5],[11],[12],[13]. Circuit design for these applications requires accurate physics based compact models (CM),
which capture all important effects of HBTs operating within a large temperature range. It was shown in [10] that SiGe HBTs are also reliable devices for high temperature applications. In this work we present experimental and modeling results of LEC SiGe HBTs at different ambient temperatures.

**DUT, EXPERIMENTAL AND MODELING TOOLS**

LEC SiGe HBTs with an emitter area $A_{E0}=0.5*20.3 \, \mu m^2$ and a peak transit frequency $f_{T(300 K)}=80$ GHz [9] were investigated. This technology enabled an increase of base doping, resulting in reduced base resistance. The high doping reduces carrier freeze-out at cryogenic temperature (CT). Almost constant base doping along with a trapezoidal Ge composition provide already an optimum profile for SiGe HBT operation at CT without any further profile optimization as required in [4]. Details about the measurement set-up can be found elsewhere [3],[15]. HD device simulations were performed with Galene III [16]. The compact model (CM) HICUM/Level 2 v.2.3 [14] was compared to measured and HD data. Note, that HD simulations were performed only for available temperature range due to limitations by unreliable or unverified mobility models for deep cryogenic temperatures.

**RESULTS AND DISCUSSION**

Measured and simulated Gummel characteristics at different $T$ are presented in Fig.1a, b. Good agreement of CM and HD with experimental data in the range of 300 K- 423 K and also between HD and CM at $T=473$ K is obtained. At CT the collector current density ($J_C$) does not show additional leakage associated with the field assisted tunneling via trap states in the base [5], resulting in increasing nonideality. As expected, $J_C$ at CT shows steep and shifted (in $V_{BE}$) behavior. HICUM can capture $J_C$ behavior down to 75 K. Toward higher $T$, $J_C$ increases at constant $V_{BE}$, which is caused mainly by the temperature dependence of the bandgap. The transit frequency behavior is well captured by CM and HD at high $T=300-423$ K (Fig.3, a). The $f_T$ peak decrease is caused by the decrease of the mobility in the various transistor regions (Fig.2, b). $T$ increase from 323 K to 423 K increase overall electron delay: in the emitter $\Delta \tau_E(\%)= 127\%$, base $\Delta \tau_B(\%)= 181\%$ and collector $\Delta \tau_C(\%)= 144\%$. Compared to peak $f_T$ of 70 GHz at 300 K, $f_T$ reaches 160 GHz at CT (Fig.3, a). The peak value of $f_T$ exhibits a linear dependence on $T$ (Fig.3, b), which partially can be explained by the current gain $\beta (T)$ dependence, including band-gap narrowing $\Delta E_B(T)$ (Fig.2, a). The current gain of SiGe HBT

$$\beta \sim \left(N_E I_E / P_B W_B \right) \exp \left(\frac{\Delta E_B}{kT} \right),$$

where $N_E$ and $P_B$ are doping concentrations of emitter
and base respectively and $L_E$ is emitter length and $W_B$ is base width, $ΔE_B$ is band-gap reduction of the base. At CT $β$ increases due to exponential term and decreases due to enhanced recombination of the minority carriers in the base, so compensating the current gain increase [17]. Electron delay distribution in collector exhibits peak, which was also given in [5] and is associated with HD model peculiarities.

![Figure 1](image1.png)

**FIGURE 1.** (a) $J_C (V_{BE})$ and (b) $J_B (V_{BE})$ at different $T$.

![Figure 2](image2.png)

**FIGURE 2.** HD simulated: (a) energy band (b) total delay distribution at $V_{CE} = 1.5$ V, $V_{BE} = 0.8$ V.

![Figure 3](image3.png)

**FIGURE 3.** (a) $f_T$ vs. $J_C$ at $V_{CE} = 1.5$ V, thick line: HD, solid line HICUM (b) peak $f_T$ vs. $T$.

HD simulated $NF_{min}$ versus $J_C$ is in perfect agreement with experimental data for higher $T$ range (Fig.4, a, b). $NF_{min}$ analysis revealed that the main noise contributors are related to collector current fluctuations (shot-like noise) (Fig.4, a) and thermal noise in the base at higher $T$ (Fig.4, b). At both $T$ base current fluctuation related noise becomes important at high injection only. Simulated diffusion noise spectral density distribution (Fig. 5) demonstrates that electron noise origins at the BE junction but not in BC junction area.
FIGURE 4. \( N_{F_{\text{min}}} \) vs. \( J_C \), thick line: HD, solid line: HICUM. (a): \( T=323 \) K (b): \( T=423 \) K.

FIGURE 5. (a): Collector terminal electron noise density distribution (b): Base terminal hole noise density distribution.

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REFERENCES