# Cryogenic Operation of Third-Generation, 200-GHz Peak-$f_T$, Silicon–Germanium Heterojunction Bipolar Transistors

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***Abstract*—We present a comprehensive investigation of the cryogenic performance of third-generation silicon–germanium (SiGe) heterojunction bipolar transistor (HBT) technology. Measurements of the current–voltage (dc), small-signal ac, and broad-band noise characteristics of a 200-GHz SiGe HBT were made at 85 K, 120 K, 150 K, 200 K, and 300 K. These devices show excellent behavior down to 85 K, maintaining reasonable dc ideality, with a peak current gain of 3800, a peak cut-off frequency ($f_T$) of 260 GHz, a peak $f_{\max}$ of 310 GHz, and a minimum noise figure ($\mathrm{NF}_{\min}$) of approximately 0.30 dB at a frequency of 14 GHz, in all cases representing significant improvements over their corresponding values at 300 K. These results demonstrate that aggressively scaled SiGe HBTs are inherently well suited for cryogenic electronics applications requiring extreme levels of transistor performance.**

***Index Terms*—Broad-band noise, cryogenic temperature, extreme environments, heterojunction bipolar transistor (HBT), high-frequency noise, silicon-germanium (SiGe).**

## I. INTRODUCTION

SILICON–GERMANIUM (SiGe) heterojunction bipolar transistor (HBT) technology has recently emerged as an important alternative to III-V device technologies for RF and mixed-signal applications. Commercial SiGe technologies with transistor performance in the range of 50–100 GHz now exist today in many companies worldwide, and recent work [2] has demonstrated that manufacturable SiGe HBT technologies with performance well above 200 GHz can be achieved by careful profile and structural design. It is well established that, due to bandgap engineering, SiGe HBTs are naturally suited for use in the cryogenic environment (e.g., at 77 K or even down to 4.2 K) [3], an operational regime traditionally forbidden to conventional silicon (Si) bipolar junction transistors (BJTs).

At present, cryogenic electronics represent a small but important niche market, with applications such as high-sensitivity cooled sensors and detectors, satellite systems, deep-space and planetary space missions, very high-precision instrumentation and detector electronics, superconductor–semiconductor hybrid electronic systems, and very-low-noise receivers for astronomy. In this study, we present a comprehensive investigation of the cryogenic performance of a scaled 200-GHz SiGe HBT technology.

## II. SiGe TECHNOLOGY AND MEASUREMENT SETUP

The SiGe HBTs used in the investigation are from a commercial third-generation SiGe HBT process technology which employs a new reduced-thermal-cycle "raised extrinsic base" structure and utilizes deep and shallow trench isolation, an *in situ* doped polysilicon emitter, a silicided extrinsic base, and a carbon-doped graded UHV/CVD epitaxial SiGe base (Fig. 1 [2]) with a minimum emitter width of 0.12 $\mu$m, a measured peak $f_T$ of 200 GHz, and peak $f_{\max}$ of 285 GHz at room temperature (300 K). It was not optimized for cryogenic operation in any way.

Measurements were performed using a custom-designed cryogenic probing system which enables on-wafer microwave measurements across the temperature range of 18–350 K [4]. S-parameters were measured to 26 GHz using an HP 8510C VNA. Noise parameters were measured from 2 to 26 GHz using an automated ATN noise measurement system, employing a "multiple source impedance" parameter extraction methodology. The thermometry of the cryogenic setup was carefully verified using transistor dc measurements dipped in a bath of liquid nitrogen (i.e., 77.3 K). Conventional "open" structure, Y-subtraction parasitic de-embedding was used for both the S-parameter and noise parameter measurements, and system calibration was performed at each temperature to ensure accuracy across the entire temperature range.

## III. SiGe HBTs OPERATING AT CRYOGENIC TEMPERATURES

It has long been known that conventional Si BJTs are not suitable for operation at cryogenic temperatures because of the combined detrimental effects of: 1) the exponential decrease in

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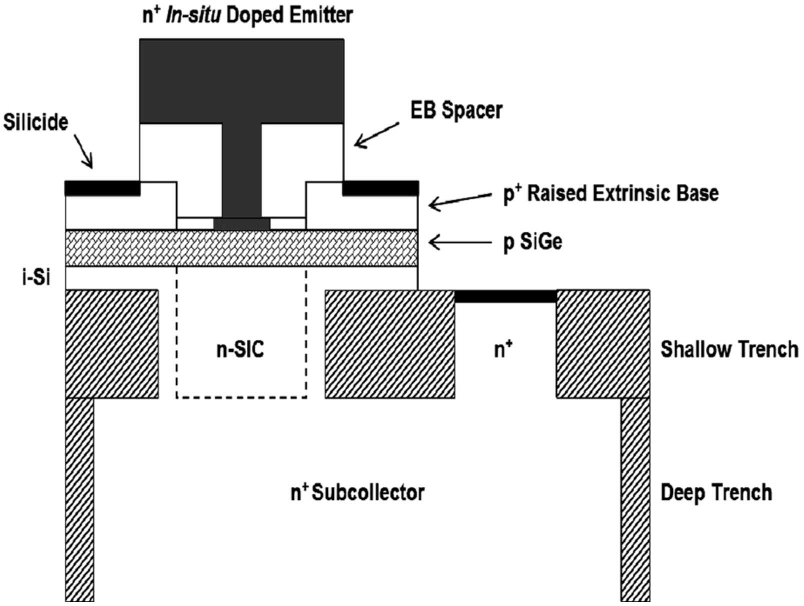

Fig. 1. Schematic device cross section of a raised extrinsic base SiGe HBT.

current gain with cooling due to heavy-doping-induced bandgap narrowing in the emitter; 2) the increase in base resistance with cooling due to carrier freeze-out in the base; and 3) the decrease in frequency response due to the degradation of the minority carrier diffusivity in the base region with cooling [5]. Thus, for Si BJTs optimized for high-speed operation at 300 K, current gain $(\beta)$ degrades quasi-exponentially with cooling, the $f_T$ and $f_{\max}$ degrade with cooling, and, not surprisingly, the circuit delay (e.g., ECL) increases (degrades) with cooling, precluding their use at cryogenic temperatures.

Bandgap engineering has a very positive influence, however, on the low-temperature operation of SiGe HBTs. The thermal energy $(kT)$, *in every instance*, is arranged in the SiGe HBT equations such that it favorably affects the low-temperature performance metric in question. For an SiGe HBT optimized for 300-K operation, when compared to a similarly constructed Si BJT, $\beta(T)$ should increase exponentially with decreasing temperature, since

$$\left.\frac{\beta_{\text{SiGe}}}{\beta_{\text{Si}}}\right|_{V_{\text{BE}}} \simeq \left\{ \frac{\tilde{\gamma}\tilde{\eta}\Delta E_{g,\text{Ge}}(\text{grade})/kT e^{\Delta E_{g,\text{Ge}}(0)/kT}}{1-e^{-\Delta E_{g,\text{Ge}}(\text{grade})/kT}} \right\} \quad (1)$$

where

$$\tilde{\eta} = \frac{(D_{\text{nb}})_{\text{SiGe}}}{(D_{\text{nb}})_{\text{Si}}} \quad (2)$$

is the ratio of the minority electron diffusivity between SiGe and Si and

$$\tilde{\gamma} = \frac{(N_C N_V)_{\text{SiGe}}}{(N_C N_V)_{\text{Si}}} \quad (3)$$

is the "effective density-of-states ratio" between SiGe and Si. The Ge-induced reduction in the base bandgap occuring at the emitter–base edge of the quasi-neutral base is $\Delta E_{g,\text{Ge}}(x=0)$ and

$$\Delta E_{g,\text{Ge}}(\text{grade}) = \Delta E_{g,\text{Ge}}(W_b) - \Delta E_{g,\text{Ge}}(0) \quad (4)$$

where $W_b$ is the neutral base width. This indicates that one should expect a quasi-exponential increase in the SiGe-to-Si current gain ratio with decreasing temperature. In addition, $V_A(T)$ should also increase exponentially with decreasing temperature when compared to Si BJT, since

$$\left.\frac{V_{A,\text{SiGe}}}{V_{A,\text{Si}}}\right|_{V_{\text{BE}}} \simeq e^{\Delta E_{g,\text{Ge}}(\text{grade})/kT} \left[ \frac{1-e^{-\Delta E_{g,\text{Ge}}(\text{grade})/kT}}{\Delta E_{g,\text{Ge}}(\text{grade})/kT} \right]. \quad (5)$$

The frequency response of SiGe HBTs should also improve with decreasing temperature, as can be seen from

$$\begin{aligned} \frac{\tau_{b,\text{SiGe}}}{\tau_{b,\text{Si}}} &= \frac{2}{\tilde{\eta}} \frac{kT}{\Delta E_{g,\text{Ge}}(\text{grade})} \\ &\quad \times \left\{ 1 - \frac{kT}{\Delta E_{g,\text{Ge}}(\text{grade})} \left[ 1 - e^{-\Delta E_{g,\text{Ge}}(grade)/kT} \right] \right\} \end{aligned} \quad (6)$$

$$\frac{\tau_{e,\text{SiGe}}}{\tau_{e,\text{Si}}} \simeq \frac{J_{C,\text{Si}}}{J_{C,\text{SiGe}}} = \frac{1-e^{-\Delta E_{g,\text{Ge}}(\text{grade})/kT}}{\tilde{\gamma}\tilde{\eta}\frac{\Delta E_{g,\text{Ge}}(\text{grade})}{kT} e^{\Delta E_{g,\text{Ge}}(0)/kT}} \quad (7)$$

both of which are favorably influenced by cooling. We assume here that the influence of the graded SiGe profile is also sufficient to overcome the inherent electron diffusivity degradation on $\tau_b$ with cooling. Detailed derivations of these equations can be found in [5].

Hence, we expect that SiGe HBTs, even without optimization for cryogenic operation, will naturally have improved performance with cooling, provided carrier freeze-out is prevented by using an abrupt and heavily doped (above the Mott transition) epitaxial base. As will be shown, this is indeed the case for the present SiGe technology.

## IV. MEASUREMENT RESULTS AND DISCUSSION

### A. DC Performance

Current–voltage measurements across the 85–300-K temperature range were made on SiGe HBTs with an emitter area

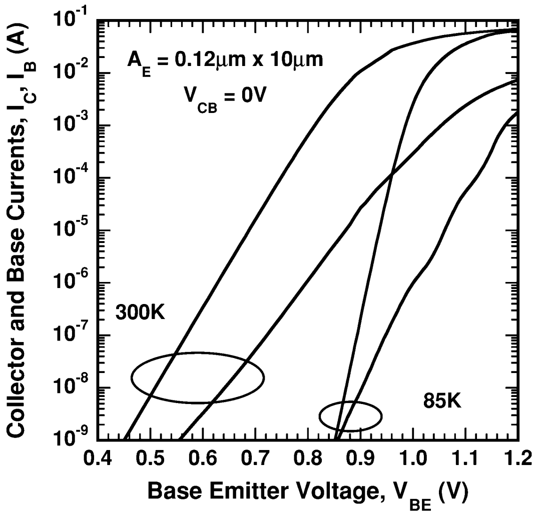

Fig. 2. Forward Gummel Characteristics at 300 K and 85 K for a $0.12 \times 10.0\ \mu\text{m}^2$ SiGe HBT.

of $0.12 \times 10.0\ \mu\text{m}^2$ [6]. The forward-gummel characteristics at 300 K and 85 K are shown in Fig. 2, for $V_{\text{CB}} = 0$ V. In spite of the high peak base and emitter doping levels associated with these aggressively scaled SiGe HBTs ($>10^{19}$ $\text{cm}^{-3}$), the base current remains reasonably ideal at 85 K. This is the result of the lightly doped epitaxial spacer layer inserted between the base and emitter regions and helps limit field-assisted tunneling and recombination at low temperatures. The base–emitter turn-on voltage increases with cooling, as expected, due to the exponential decrease of the intrinsic carrier concentration with cooling. The base and emitter regions in this device are both doped well above the Mott transition and ensure that carrier freeze-out does not negatively impact the base or emitter resistance below 100 K. As can be seen in Fig. 2 at 85 K, this device is capable of very high current density operation ($>25$ mA/$\mu$ m$^2$), and thus the high collector doping level effectively limits the impact of heterojunction barrier effects at low temperatures, which can be a key design issue for the cryogenic operation of SiGe HBTs [3]. It can be noted that the slope of the collector current $(g_m)$ increases with the base–emitter voltage as we decrease the temperature from 300 K to 85 K. For low injection, we can write

$$g_m = \frac{\partial I_C}{\partial V_{\text{BE}}} \simeq \frac{qI_C}{kT} \propto \frac{q}{kT} e^{qV_{\text{BE}}/kT}. \tag{8}$$

Fig. 3 shows the collector current as a function of the base–emitter voltage for various temperatures illustrating the change in the transconductance with temperature. Fig. 4 shows the base current as a function of the base–emitter voltage for various temperatures. It is interesting to note that the the nonideal base current increases dramatically at 85 K compared to the collector current. This is because, at a given $V_{\text{BE}}$, both the base and collector currents decrease strongly going from 300 K to 85 K. The leakage current in the base, induced by the tunneling and field-assisted recombination processes associated with the high electric field in the emitter–base junction, though, remains largely constant over temperature (i.e., they are only weakly temperature-dependent mechanisms). This parasitic base leakage current increases the nonideal base current as we go from 300 K to 85 K.

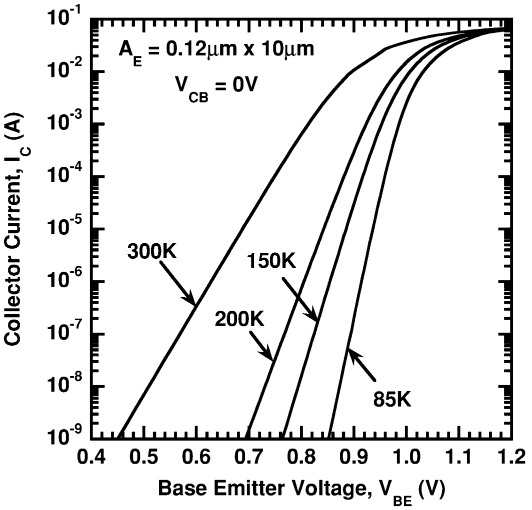

Fig. 3. Collector current as a function of base–emitter voltage at various temperatures for a $0.12 \times 10.0\ \mu\text{m}^2$ SiGe HBT.

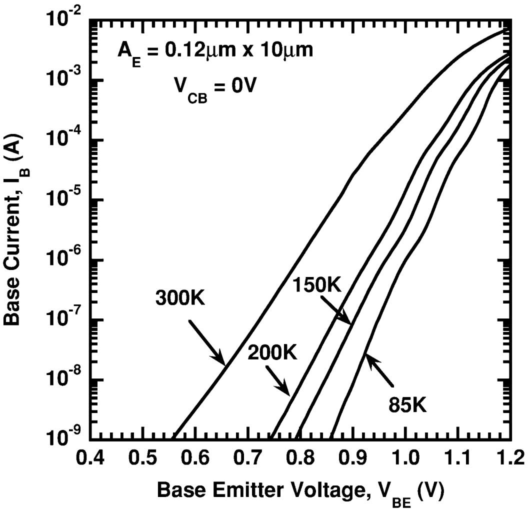

Fig. 4. Base current as a function of base–emitter voltage at various temperatures for a $0.12 \times 10.0\ \mu\text{m}^2$ SiGe HBT.

Shown in Fig. 5 are typical output characteristics of the SiGe HBTs at 300 K and 85 K. The output characteristics remain reasonably ideal at 85 K with the breakdown voltage $(\text{BV}_{\text{CEO}})$ reducing from about 1.8 V at 300 K to about 1.6 V at 85 K.

A "negative-differential-resistance" (NDR) effect is observed in the forced-$I_B$ output characteristics, which causes the overshoot-like characteristics in the collector current at 85 K [8]. A "hysteresis" in the voltage sweep direction of the $I$–$V$ characteristics appears in the NDR region at cryogenic temperatures. We observe (Fig. 5), at 85 K, that in the quasi-saturation region $I_C$ decreases as $V_{\text{CE}}$ increases, thus producing an NDR-like behavior. The effect of the NDR is also observed in the forward-gummel (Fig. 2), where we can observe "dips" in the $I_B$ curve (decreasing and then increasing $I_B$) as can be seen in

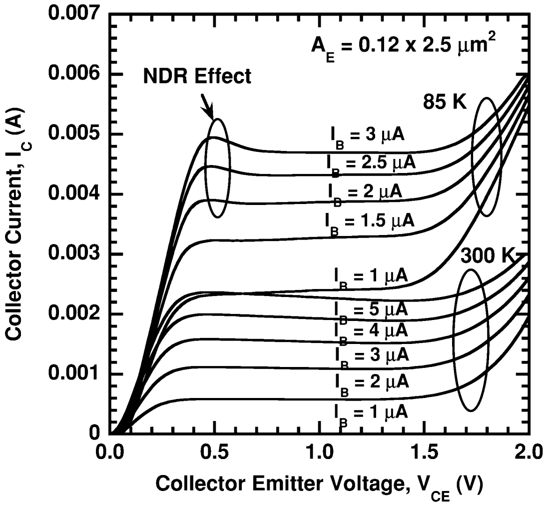

Fig. 5. Common-emitter output characteristics at 300 K and 85 K for a $0.12 \times 0.25\ \mu\mathrm{m}^2$ SiGe HBT.

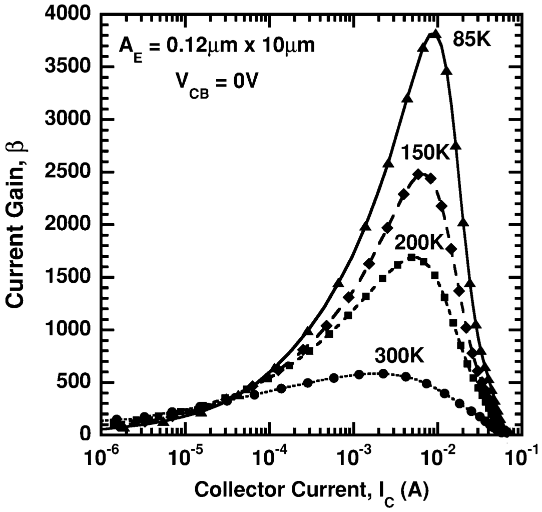

Fig. 6. Current gain as a function of bias current and temperature for a $0.12 \times 10.0\ \mu\mathrm{m}^2$ SiGe HBT.

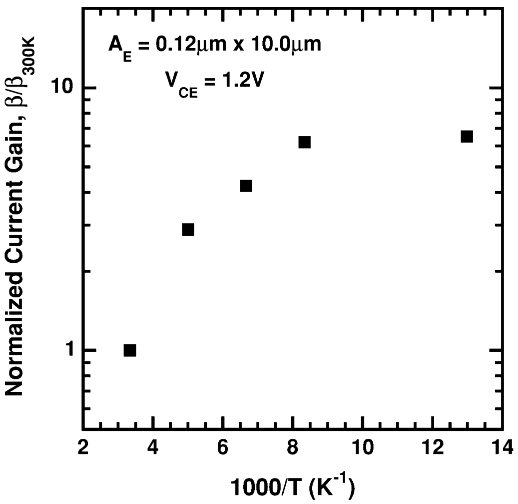

Fig. 7. Normalized peak current gain as a function of reciprocal temperature $1000/T$ for a $0.12 \times 10.0\ \mu\mathrm{m}^2$ SiGe HBT.

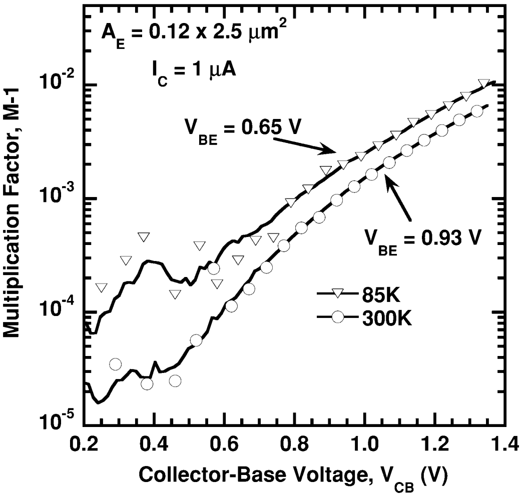

Fig. 8. Multiplication factor versus collector-base bias at 300 K and 85 K for a $0.12 \times 0.25\ \mu\mathrm{m}^2$ SiGe HBT.

Fig. 4. These dips become much pronounced as we reach temperatures 150 K and lower.

The current gain increases monotonically with cooling from 600 at 300 K to 3800 at 85 K, as shown in Fig. 6. Two mechanisms are responsible for this improvement with cooling: 1) the (sizeable) Ge-induced band offset in this device (exponentially) increases the current gain with cooling (1) and 2) the heavily doped base region partially offsets the doping-induced bandgap narrowing associated with the emitter region. The strong decrease in the current gain above its peak value at 85 K is associated with the "Ge-grading" effect [9], but the current gain remains above 2000 at 85 K at the current density at which peak $f_T$ is reached, effectively minimizing any emitter charge storage at low temperatures. Fig. 7 shows a normalized peak $\beta$ as a function of reciprocal temperature $(1000/T)$, illustrating the increase in peak $\beta$ with the decrease in temperature (about 7 × from 300 K to 85 K).

Avalanche multiplication effects were also studied at 300 K and 85 K to ascertain the effects of temperature on the breakdown and reliability of this aggressively scaled SiGe HBTs. The $M-1$ is calculated from $I$–$V$ measurements using

$$M-1=\frac{\Delta I_B}{I_C-\Delta I_B}. \tag{9}$$

Fig. 8 shows the measured multiplication factor $(M-1)$ versus collector–base voltage $(V_{\mathrm{CB}})$ at 85 K and 300 K. Since the collector current decreases strongly with $V_{\mathrm{BE}}$ as we go from 300 K to 85 K, to obtain similar $I_C$ at 300 K and 85 K, the $V_{\mathrm{BE}}$ was increased from 0.65 V at 300 K to 0.93 V at 85 K. Only a weak increase in $M-1$ with cooling is observed, as expected from previously reported work [10]. This modest temperature dependence of $M-1$ with cooling alleviates the power supply limit posed by the base-current reversal voltage and indicates the suitability for these aggressively scaled SiGe HBTs for low-temperature circuit applications requiring higher $V_{\mathrm{CB}}$.

### *B. Small-Signal Characteristics*

On-wafer S-parameter measurements were performed at various temperatures. Fig. 9 shows the measured small-signal

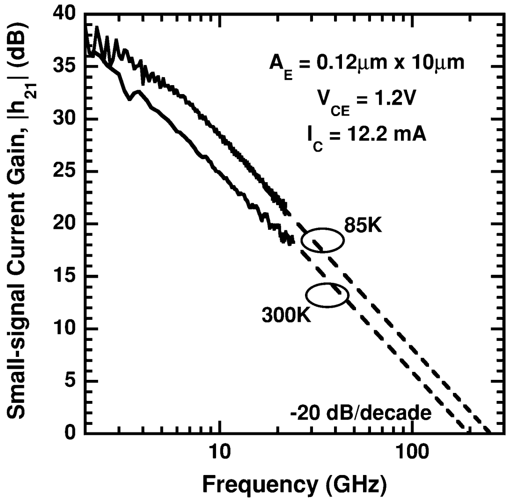

Fig. 9. Small-signal gain as a function of frequency at 300 K and 85 K for a $0.12 \times 10.0$ $\mu$m$^2$ SiGe HBT. Lines are drawn at 20 dB/decade.

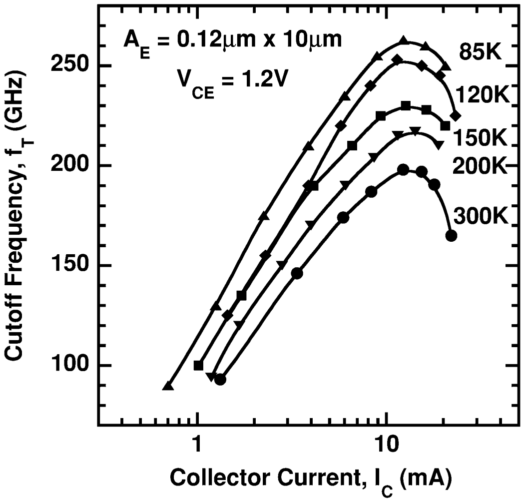

Fig. 10. Extracted cutoff frequency as a function of bias current for various temperatures for a $0.12 \times 10.0$ $\mu$m$^2$ SiGe HBT.

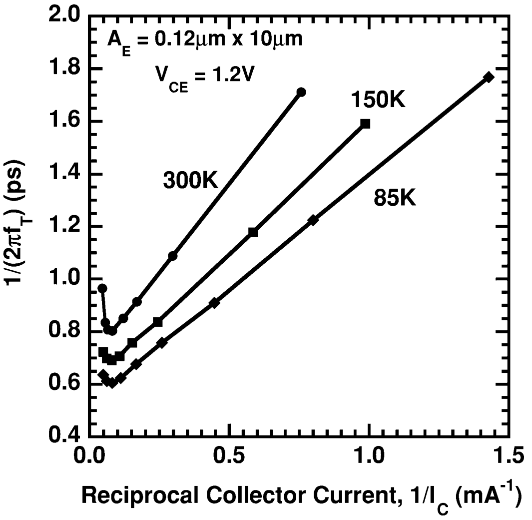

Fig. 11. Extrapolated transit time as a function of reciprocal current $1/I_C$ at various temperatures for a $0.12 \times 10.0$ $\mu$m$^2$ SiGe HBT.

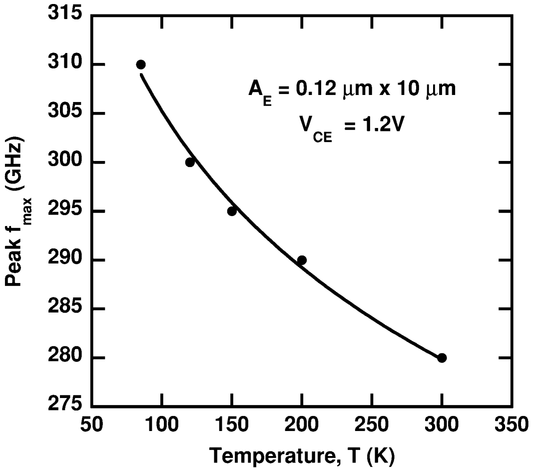

Fig. 12. Peak $f_{\max}$ as a function of temperature for a $0.12 \times 10.0$ $\mu$m$^2$ SiGe HBT.

gain on frequency at peak $f_T$ for a $0.12 \times 10.0$ $\mu$m$^2$ SiGe HBT at 300 K and 85 K ($V_{\mathrm{CE}} = 1.2$ V). A near $-20$-dB/decade slope is obtained across a wide frequency range for all temperatures. Fig. 10 shows the extracted cutoff frequency versus bias current data at 300 K, 200 K, 150 K, 120 K, and 85 K for the $0.12 \times 10.0$ $\mu$m$^2$ SiGe HBT. An increase in peak $f_T$ from 200 GHz at 300 K to 260 GHz at 85 K is observed. This increase in the peak $f_T$ with cooling is proportionately smaller than has been reported in first-generation SiGe HBTs operated at 85 K [11]. This is because, in the present case, the base and emitter transit times in this 200-GHz device, which are favorably affected by both the Ge-grading and cooling, are already small compared to the collector delay time, and thus their relative influence on the total transit time with cooling is smaller. We observe very little difference between the cutoff frequencies for 120 K and 150 K at low currents, which is likely the result of measurement accuracy limitations. Fig. 11 shows a plot of $1/(2\pi f_T)$ against $1/I_C$ at 300 K, 150 K, and 85 K. The extrapolated transit time decreases from 0.7 ps at 300 K to 0.6 ps at 150 K and 0.5 ps at 85 K, and the total depletion capacitance of the device decreases with cooling, as expected, since the junction built-in voltages increase with cooling. $f_{\max}$ is extracted from the measured S-parameters by extrapolating the unilateral gain at a $-20$-dB/decade slope. The peak $f_{\max}$ as a function of temperature is shown in Fig. 12. We observe that the peak $f_{\max}$ increases from about 280 GHz at 300 K to 310 GHz at 85 K.

### *C. Broad-Band Noise Characteristics*

The main sources of broad-band noise in these SiGe HBTs are the base and collector shot noise components and the base resistance-induced thermal noise. High $f_T$ and $\beta$, along with low base resistance, can be used to produce SiGe HBTs with excellent broad-band noise performance at 300 K [12], [13]. The minimum noise figure $\mathrm{NF}_{\min}$ as a function of the collector current $I_C$ (through $g_m$) can be written as

$$\mathrm{NF}_{\min} = 1 + \frac{1}{\beta} + \sqrt{2 g_m r_{bb}} \sqrt{\frac{1}{\beta} + \left(\frac{f}{f_T}\right)^2}. \tag{10}$$

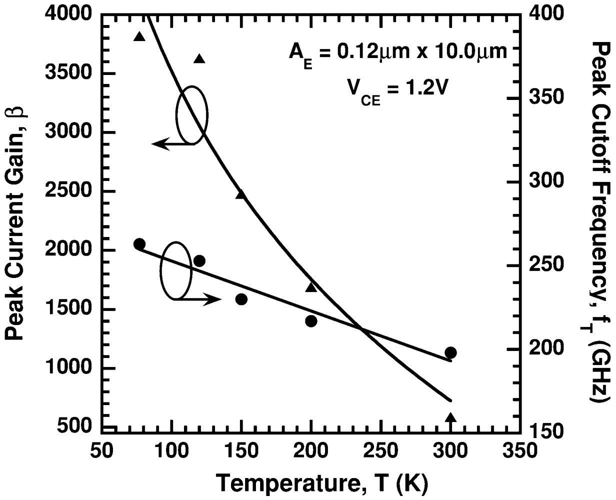

Fig. 13. Cutoff frequency and current gain as a function of temperature for a $0.12 \times 10.0\ \mu m^2$ SiGe HBT.

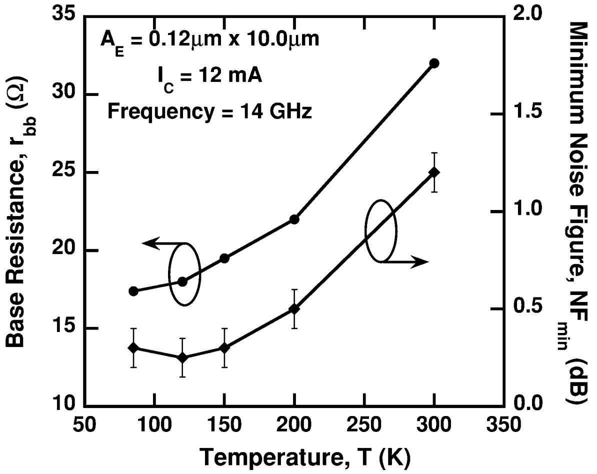

Fig. 14. Base resistance and minimum noise figure as a function of temperature for a $0.12 \times 10.0\ \mu m^2$ SiGe HBT.

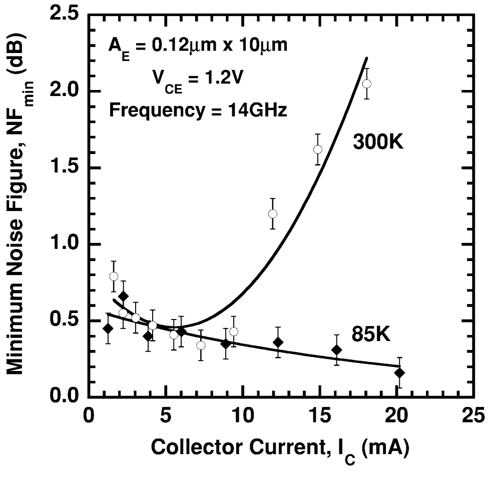

Fig. 15. Minimum noise figure as a function of bias current at 300 K and 85 K for a $0.12 \times 10.0\ \mu m^2$ SiGe HBT.

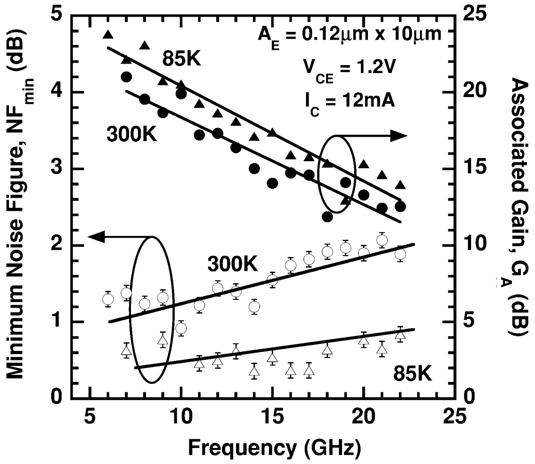

Fig. 16. Minimum noise figure and associated gain at $I_C = 12$ mA as a function of frequency at 300 K and 85 K for a $0.12 \times 10.0\ \mu m^2$ SiGe HBT.

Since, in this case, the current gain $\beta$ and the $f_T$ both increase with cooling (Fig. 13), one would expect improved noise performance at low temperatures, provided the base resistance $(r_{bb})$ does not increase due to carrier freezeout at low temperatures. The measured noise data were well behaved at all temperatures with near-ideal parabolic impedance surfaces. Nevertheless, error bars are estimated on the extracted noise data of approximately ±0.1 dB. Fig. 14 shows the behavior of both minimum $\mathrm{NF_{min}}$ and the extracted $r_{bb}$ as a function of temperature and shows that the base doping level is clearly above the Mott transition, effectively suppressing carrier freezeout. This decrease in the extracted $r_{bb}$ also indicates that the $f_{\max}$ should increase with cooling, which is the indeed the case here, as was shown in Fig. 12. At a fixed collector current $I_C(g_m)$ and frequency, $\mathrm{NF_{min}}$ depends on $f_T, \beta$, and $r_{bb}$, and hence $\mathrm{NF_{min}}$ decreases as the temperature is reduced from 300 K to 85 K [see (10)]. This combined effect leads to a substantial decrease in the $\mathrm{NF_{min}}$ with decreasing temperature, before it becomes dominated by the saturation of the base resistance, and the minimum noise figure thus tends to saturate. Fig. 15 shows the measured minimum noise figure $(\mathrm{NF_{min}})$ as a function of bias current at 14 GHz. Interestingly, the rapid increase in $\mathrm{NF_{min}}$ at high bias currents at 300 K, which is primarily determined by the base shot-noise component, disappears at cryogenic temperatures, again due to the combined increase in $\beta, g_m$, and $f_T$ with cooling (10), allowing lower $\mathrm{NF_{min}}$ to be achieved at peak $f_T$ at 85 K. Fig. 16 shows the $\mathrm{NF_{min}}$ and associated gain $(G_A)$ as a function of frequency at $I_C = 12$ mA (peak $f_T$) for a $0.12 \times 10.0\ \mu m^2$ SiGe HBT, at both 300 K and 85 K. Because of the increase in $f_T$ from 200 to 260 GHz, an increase in $\beta$ from 600 to 3800 and a decrease in $r_{bb}$ from 32 to 18 Ω as we go from 300 K to 85 K, at the same $I_C(g_m)$, the $\mathrm{NF_{min}}$ becomes a little weaker function of the frequency at 85 K than at 300 K. Hence, the $\mathrm{NF_{min}}$ increases at a slower rate with frequency at 85 K than at 300 K as shown in Fig. 16. At 85 K, this device achieves a minimum $\mathrm{NF_{min}}$ of about 0.3 dB ($G_A = 18$ dB) at 14 GHz, and a minimum $\mathrm{NF_{min}}$ of about 0.75 dB ($G_A = 15$ dB) at 20 GHz.

## V. SUMMARY

Current–voltage, small-signal ac, and broad-band noise characteristics of a 200-GHz SiGe HBT have been measured down to 85 K. At cryogenic temperatures, these SiGe HBTs maintain excellent dc ideality, with a peak current gain of 3800, a peak cut-off frequency of 260 GHz, a peak $f_{\max}$ of 310 GHz, and a minimum noise figure of approximately 0.30 dB at a frequency of 14 GHz and in all cases represent significant improvements over their corresponding 300 K values. These results were obtained from a SiGe HBT technology which is not optimized for cryogenic operation and suggest the inherent suitability of aggressively scaled SiGe HBT technology for cryogenic applications requiring extreme levels of transistor performance.

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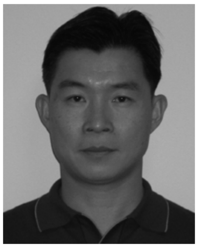

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