Sub-1-K Operation of SiGe Transistors and Circuits

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Abstract—We present the first measurement results for silicon–germanium (SiGe) heterojunction bipolar transistors (HBTs) and SiGe BiCMOS circuits operating in the sub-1-K regime. Robust transistor operation of a first-generation $0.5 \times 2.5 \times 4$-μm^2 SiGe transistor is demonstrated at package temperatures as low as 300 mK. In addition, a SiGe BiCMOS bandgap voltage reference is verified to be fully functional at operating temperatures below 700 mK. The SiGe voltage reference exhibits a temperature coefficient of 160 ppm/°C over the temperature range of 700 mK–300 K.

Index Terms—Analog integrated circuits, BiCMOS, cryogenic temperatures, heterojunction bipolar transistor (HBT), silicon germanium (SiGe), SiGe HBTs, voltage reference.

I. MOTIVATION

SUBMILLIMETER-WAVELENGTH astronomical instrumentation generally requires readout circuits and detectors that can reliably operate in the deep cryogenic temperature regime (typically sub-1 K) so that thermal noise is strongly suppressed. Analog circuits such as voltage and current references, as well as amplifiers, are essential components of such detectors and readout circuits [1]–[4]. Due to severe limitations in functionality of conventional semiconductor devices at such extremely low temperatures, these requisite electronic circuits are required to be operated at temperatures that are considerably higher than the detector's sub-1-K operating temperature. Therefore, such detector systems, which are often flown into space, necessarily consist of several cryogenic coolers so that multiple temperatures can be provided (one for the electronic circuits and one for other detector components) [2], [4]. If the electronic circuits could be designed to operate at the detector's sub-1-K operating temperature, the need for large numbers of signal wires providing connections between intermediate cryogenic coolers would be eliminated, resulting in dramatic reductions in system weight and volume, and the cost of the overall mission.

Silicon–germanium (SiGe) BiCMOS technology has emerged as a compelling technology platform for implementing electronic circuits intended for extreme environment applications (e.g., when exposed to low temperatures, high temperatures, and/or ionizing radiation) [5]. Due to the beneficial effects of bandgap engineering, the electrical properties of SiGe transistors such as the current gain, cutoff frequency, and broadband noise all improve with cooling. Below about 100 K, where Si bipolar junction transistors suffer strongly from base freeze-out [6], carrier freeze-out is minimized in SiGe HBTs since the base, emitter, and significant portions of the collector are doped well above 3×10^{18} cm^{-3}, a minimum required doping level in Si for the occurrence of the semiconductor–metal (Mott) transition [5]–[7]. To date, a substantial amount of the available information on the cryogenic operation of SiGe HBTs and circuits has been limited to a lower temperature bound of about 4.2 K (liquid-helium temperature) [8]–[14], and no data are available on the capability of SiGe HBTs and circuits for operation below 4.2 K. We point out that many transistor-relevant parameters (e.g., carrier density) are thermally activated [proportional to $\exp(E/kT)$], and thus, the impact of temperature on the carrier distributions, which determine both current flow and transistor action, between, for example, 4.2 K and 300 mK, is enormous (e.g., if $E = 1$ eV, a change by a factor of $e^{17\,943}$ theoretically exists in intrinsic carrier concentration between 4.2 K and 300 mK). As a result, it is widely believed that Si bipolar transistors will not function at sub-1-K temperatures. In this letter, we present the first dc measurement results for SiGe HBTs operating in environments as low as 300 mK. In addition, the operation of a SiGe bandgap voltage reference (BGR) is fully verified for operation in the sub-1-K regime.

II. PROCESS TECHNOLOGY AND CIRCUIT DESCRIPTION

The transistors used for this letter are from a first-generation SiGe (IBM's SiGe 5AM) BiCMOS technology, which features SiGe HBTs with an emitter width of 0.5 μm, BV_{CEO} of 3.3 V, and a unity-gain cutoff frequency and a maximum oscillation frequency of 45 and 60 GHz at 300 K, respectively. This four-level metal platform also offers CMOS transistors with a nominal L_{eff} of 0.35 μm, as well as polysilicon and diffused resistors, and various capacitors. To fully evaluate the capability of SiGe technology for operation in the sub-1-K regime, an exponentially compensated BGR [15] was implemented. The schematic of the circuit is shown in the inset of Fig. 4, and the dimensions of the transistors and resistors are summarized in Table I. The start-up circuit consists of transistors M_1, M_2, and

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TABLE I
DIMENSIONS OF SiGe HBTs AND CMOS
TRANSISTORS IN THE BGR CIRCUIT

M_1: (W/L)= 300 μm/1 μm	M_{10}, M_{11}: (W/L)= 40 μm/1 μm
M_2, M_4-M_7: (W/L)= 20 μm/1 μm	Q_1, Q_3, Q_4, Q_5: A_E = 4 x 0.5 x 2.5 μm²
M_3: (W/L)= 2 μm/90 μm	Q_2: A_E = 32 x 0.5 x 2.5 μm²
M_8, M_9: (W/L)= 10 μm/1 μm	R_1= 2 kΩ, R_2=15.4 kΩ

M_3. Transistors Q_1 and Q_2, along with resistor R_1, generate a proportional-to-absolute-temperature (PTAT) current for the following stages. This PTAT current is mirrored and amplified through the pMOS current mirrors and transistor Q_5 into the last two stages, generating a PTAT voltage across resistor R_2 that compensates the negative temperature coefficients of the base–emitter voltage of transistor Q_3, creating a temperature-stable output voltage.

III. EXPERIMENTAL SETUP

Device structures and the SiGe voltage reference were mounted into a 48-pin ceramic flat package and wire bonded. The package was epoxied into a copper sample holder that was then mounted on the copper cold stage of a pumped ³He refrigerator capable of reaching a base temperature of less than 300 mK under a 40-μW heat load. A calibrated ruthenium oxide temperature sensor was located nearby to obtain the temperature of the cold stage. In addition, a Cernox temperature sensor, CX-1010-BR [16], was mounted adjacent to the die in the package to closely monitor the die's temperature during the experiment. This temperature sensor is a sputter-deposited thin-film resistor with a negative temperature coefficient. The measured resistance of the Cernox resistor as a function of the ³He-pot temperature, at 252 mK, and for a temperature range of 400–800 mK, is shown in Fig. 1. A photomicrograph showing the location of the sensor and die in the package is shown in the inset of Fig. 1. It can be seen that a sensor resistance value of 600 Ω or larger corresponds to die temperatures lower than 800 mK. Transistor dc characterization was performed using an Agilent 4155 Semiconductor Parameter Analyzer. The output voltage of the BGR circuit was recorded as a function of temperature, during both cooldown and warm-up, using precision Agilent meters.

IV. EXPERIMENTAL RESULTS

The refrigerator reached a base temperature of 252 mK with no extra heat load injected into the system. The system was maintained in this state for 50 min prior to performing dc characterization to ensure equilibration. In order to verify the functionality of SiGe HBTs at this base temperature, forced-I_B output characteristics were measured at nanoampere-level currents to establish transistor action. During these measurements, the total power injected into the system was kept below 40 μW. Shown in Fig. 2 are the output characteristics of the SiGe HBT taken at 4.0 K, 1.4 K, and 252 mK for base currents of 40–100 nA. The package temperature (as read out by the Cernox sensor) remained below 300 mK (Fig. 1). As can be seen, clear transistor functionality is observed, and at the base current of 100 nA, a maximum current gain of 9.2 is achieved at package temperatures lower than 300 mK. At a V_{CE} of 1.0 V,
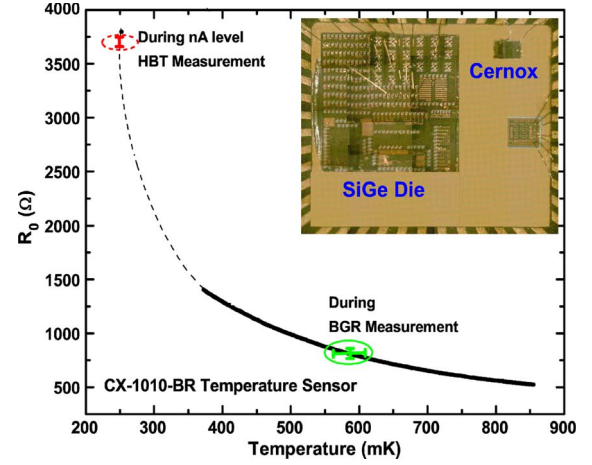

Fig. 1. Measured characteristics of the on-package Cernox resistor as a function of the measured ³He-pot temperature.
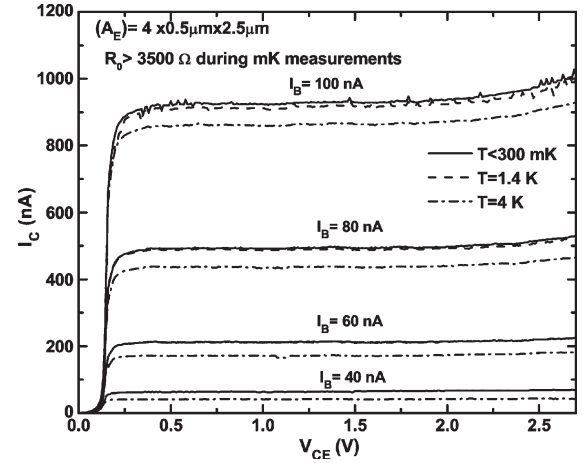

Fig. 2. Measured forced-I_B output characteristics of a $4 \times 0.5 \times 2.5$ μm² SiGe HBT at 4 K, 1.4 K, and below 300 mK.

and I_B of 100 nA, the power dissipated by the SiGe HBT is estimated to be around 1 μW at this temperature. Forced-I_B output characteristics at higher base current levels, as well as the full Gummel characteristics, were also measured, and the transistor showed reasonably ideal behavior. However, due to the injection of relatively large amounts of heat during these measurements, a temperature rise was observed in the package. Fig. 3 shows the measured output voltage of the SiGe BGR circuit operating over a 1200-s window at a sub-1-K operating temperature. The average output voltage obtained during this period was 1.1562 V, and the voltage deviation from the average value was less than 800 μV. With a 3.3-V power supply, the circuit consumes an average current of 39.5 μA and dissipates about 130 μW. During the measurements, the package temperature stayed below 700 mK (Fig. 1). The observed fluctuations in the output voltage can be further decreased by adding an on-chip capacitor at the output node. The measured output voltage as a function of package temperature is shown in Fig. 4. As explained in the previous section, the output voltage of the BGR circuit can be estimated to be

$$V_{\text{out}} \approx V_{\text{BE},Q3} + \frac{\Delta V_{\text{BE}}}{R_1}\left(k_1 R_2 + \frac{k_2 R_2}{\beta_{Q3}}\right) \quad (1)$$
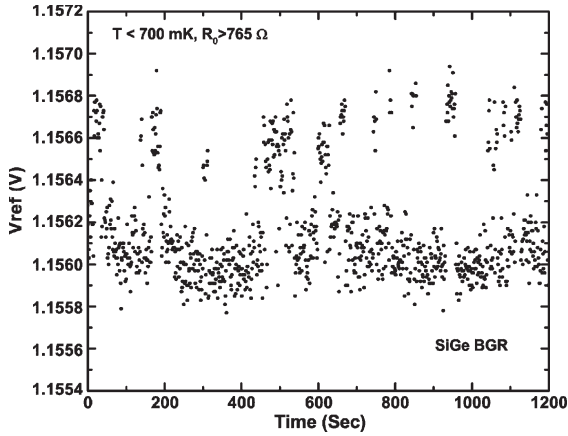
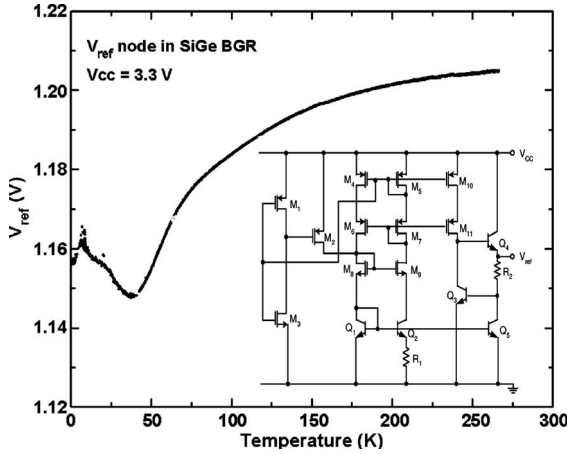Fig. 3.   Measured output voltage of a SiGe BGR over 1200-s window when operating at temperatures below 700 mK.

Fig. 4.   Measured output voltage (1 526 900 points) of the SiGe BGR as a function of temperature.

where $V_{BE,Q3}$ is the base–emitter voltage of transistor Q_3, which is a decreasing function of temperature; ΔV_{BE} is the PTAT voltage, which is generated by the voltage difference between the base–emitter voltages of transistors Q_1 and Q_2; k_1 and k_2 are the amplification factors of the PTAT current in the last two stages; and β_{Q3} is the current gain of Q_3. The circuit was originally designed and optimized for the mil-spec temperature range (from $-55\,°C$ to $+125\,°C$). As the temperature drops below 220 K, the rate of increase in the base–emitter voltage is dominated by the rate of decrease in the PTAT voltage, and as a result, the output voltage decreases as the temperature is reduced. Below 36 K, however, the output voltage begins to rise. This is due to the fact that the nonlinearity in the temperature variation of the base–emitter voltage becomes more severe at these extremely low temperatures [17] and that its first-order temperature coefficient is therefore decreased. As a result, the ΔV_{BE} voltage [second term in (1)] will no longer vary linearly with temperature, and instead, it becomes a weak function of temperature. Therefore, the output voltage starts to increase, as the negative temperature coefficients of $V_{BE,Q3}$ become the dominant factor. Although we expect this trend to continue down to millikelvin temperatures, a slight decrease in the output voltage is observed when the temperature is further decreased below about 4 K. More investigation is required to

understand this behavior. Fig. 4 verifies that the BGR circuit is fully functional across the temperature range of 700 mK–300 K, with a temperature coefficient of 160 ppm/$°C$.

V. SUMMARY

We have demonstrated the first dc measurements of SiGe HBTs operating in environments below 1 K. The SiGe HBTs remain functional, with usable current gain. A SiGe BGR circuit was also fully characterized and verified to operate reliably at sub-1-K temperatures.

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