Silicon Germanium Cryogenic Low Noise Amplifiers

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Abstract. Silicon germanium heterojunction bipolar transistors have emerged in the last decade as an excellent option for use in cryogenic low noise amplifiers. This paper begins with a review of the critical developments that have led to today’s cryogenic low noise amplifiers. Next, recent work focused on minimizing the power consumption of SiGe cryogenic amplifiers is presented. Finally, open issues related to the cryogenic noise properties of SiGe HBTs are discussed.

1. Introduction

Microwave cryogenic low noise amplifiers (LNAs) are an enabling element in a number of scientific systems and are widely used in fields ranging from radio astronomy to quantum computing. The first such amplifiers were developed in the early eighties at the National Radio Astronomy Observatory (NRAO). While the initial impetus for research in this area was the desire to realize solid-state amplifiers that could serve as follow-on gain blocks for parametric amplifiers, it was quickly realized these devices—which demonstrated noise temperatures below 10 K and 30 K at 1.5 GHz and 10.7 GHz, respectively—could be used to replace parametric amplifiers altogether, resulting in a significant reduction in system complexity [1, 2, 3, 4].

High carrier mobility is important for a low-noise field-effect transistor and a limitation to the MESFET technology used in these early proof-of-concept-amplifiers is that the channel of a MESFET is doped, which reduces mobility. This problem is resolved in high electron mobility transistors (HEMTs), which were just becoming available in the early eighties. Initial experiments carried out between 1983 and 1984 showed the performance of HEMTs improved dramatically with cryogenic cooling [5, 6]. Encouraged by these results, a collaborative effort to develop HEMTs appropriate for high-performance cryogenic low noise amplifiers was initiated between NRAO and General Electric. As a result of this highly successful program, devices capable of achieving noise temperatures of 0.65 K/GHz were demonstrated in quarter micron InP technology [7, 8, 9]. As HEMT processes improved in subsequent years, so did the cryogenic noise performance of these devices. Today, wideband amplifiers based upon HEMTs are commercially available from Low Noise Factory in Sweden (e.g., [10, 11, 12]) and Cosmic Microwave Technology in California, USA (e.g., [13, 14]).

Over the past decade, silicon germanium (SiGe) heterojunction bipolar transistors have emerged as a viable alternative for the implementation of cryogenic low noise amplifiers. These devices have been developed as part of commercial silicon technology platforms, which have benefits such as large industry investment in process development, synthesizable CMOS logic, and high yield. Thus, SiGe BiCMOS technologies are quite attractive for use in future scientific
sensor systems. In this paper, key developments in cryogenic SiGe LNAs will be reviewed and recent developments in ultra-low-power cryogenic SiGe LNAs will be presented. The paper will conclude with a discussion of open issues related to the cryogenic performance of SiGe HBTs.

2. A Brief History of SiGe Cryogenic LNAs

The idea of a heterojunction bipolar transistor was first proposed by Kroemer in 1957 [15], but it was not until the late eighties that CMOS-compatible SiGe HBTs were demonstrated [16]. Interest in using these devices in cryogenic applications grew shortly thereafter, but before diving into the historical details, it is worth briefly reviewing the properties which make SiGe HBTs attractive for use in these applications. The doping profile and basic band structure of a SiGe HBT appear in Fig. 1. The key improvement in a SiGe HBT over a silicon BJT is the SiGe base alloy which results in a reduced bandgap in the base region compared to that of the collector and emitter regions. Compared to a silicon homojunction bipolar transistor with an otherwise identical composition, the collector current and DC current gain of a SiGe HBT are enhanced by a factor of

$$\gamma_{DC} = \exp\left\{ \frac{\Delta E_{G0}}{kT_a} \right\},$$

where $k$ is Boltzmann’s constant, $T_a$ is the ambient temperature, $\Delta E_{G0} = E_{G,\text{Si}} - E_{G,\text{SiGe}}(0)$, $E_{G,\text{Si}} \approx 1.12 \text{ eV}$ is the bandgap of silicon, and $E_{G,\text{SiGe}}(0)$ is the bandgap of the SiGe alloy on the base side of the base–emitter space charge region. In the context of device design, this enhancement of the DC current gain is important since it allows for the design of a device which simultaneously has high DC current gain and low base resistance. In fact, to reduce the base resistance, doping levels well beyond the Mott transition are typically used in the base region, meaning that carrier freeze out in the base at cryogenic temperatures is not an issue [17]. In addition, the Ge content is typically graded across the base region, with increasing Ge towards the collector side of the base. This leads to a sloped conduction band (see Fig. 1(b)), which speeds the carriers as they drift towards the collector. The net result is that the unity current gain cutoff frequency ($f_t$) of the device is enhanced by a factor of

$$\Delta f_t = \frac{\Delta E_{G,\text{grade}}}{kT_a},$$

where $\Delta E_{G,\text{grade}} = E_{G,\text{SiGe}}(0) - E_{G,\text{SiGe}}(t)$ and $E_{G,\text{SiGe}}(t)$ is the bandgap at the base side of the base–collector space charge region. Before returning to our historical discussion, it is worth emphasizing that, from the discussion above, both $\beta$ and $f_t$ would be expected to improve tremendously with cryogenic cooling.

Much of the initial research in the cryogenic performance of SiGe HBTs was carried out by Cressler and collaborators at IBM. This work was initially motivated by a desire to improve the switching speeds of emitter coupled logic (ECL). In 1991, this team reported the first

![Figure 1.](image-url)
measurements of SiGe circuits at liquid nitrogen temperatures [18]. In this initial measurement, the authors observed a marginal increase in $f_t$, but found that the switching speed of 28 ps obtained using a test device was similar to that observed at room temperature. However, shortly thereafter they found that, by designing a device for operation at cryogenic temperatures, it was feasible to achieve improved values of switching speed, $\beta$, and $f_t$ when the device was cooled to 77 K [19]. Significant research in the design of SiGe devices for cryogenic temperatures continued over the next years with both numerical TCAD studies [20] as well as experimental studies in which sophisticated devices were designed with operation at liquid nitrogen temperatures in mind [21, 22, 23].

Today’s cryogenic low noise amplifiers must operate at temperatures well below 77 K, where carrier freeze-out and other higher order effects can become significant. The first measurements of SiGe transistors at liquid helium temperatures (4.2 K) were carried out by the IBM team in 1995 [24]. They found that the device did in fact work, but, in comparison to what would be expected from drift-diffusion equations, they found that the transconductance at a given current was lower than expected. Shortly thereafter, this reduced collector current ideality factor was explained as non-equilibrium transport [25, 26].

The first commercial SiGe technology was reported in 1996 [27], and since then, the vast majority of cryogenic SiGe research has been focused on using commercial processes, which are optimized for room temperature operation. The basic cryogenic operation of these technologies has been studied extensively and it now known that state-of-the-art devices operate well at temperatures below 1 K [17] and, with cryogenic cooling, they experience typical increases in $\beta$ and $f_t$ of approximately 10 x and 50%, respectively [28]. In fact, the best cryogenic results reported for $\beta$ and $f_t$ are an impressive 80,000 and 798 GHz, respectively [28, 29]. To understand why these improvements are beneficial from a noise perspective, it will be helpful to briefly review the factors that determine the noise performance of a bipolar transistor.

The minimum noise temperature of a bipolar transistor can be expressed as a function of frequency as

$$T_{MIN} \approx n_c T_a \sqrt{\frac{1}{\beta} \left( 1 + 2 \frac{g_m R_B}{n_c} \right) + 2 \frac{g_m R_B}{n_c} \left( \frac{f}{f_t} \right)^2}, \hspace{1cm} (1)$$

where $T_a$ is the ambient temperature, $\beta = I_C/I_B$ is the DC current gain, $g_m$ is the intrinsic transconductance, $R_B$ is the base resistance, $f_t$ is the unity current gain cutoff frequency, $n_c = q I_C / k T_a g_m$ is the collector current ideality factor, $q$ is the charge of an electron, and $k$ is Boltzmann’s constant. Thus, if no device properties were to change with cryogenic cooling, the achievable noise performance would improve proportionally as the physical temperature is reduced. However, as described above, significant improvements in both $\beta$ and $f_t$ are typically observed with the cryogenic cooling of a SiGe HBT. Moreover, the base resistance tends to be weakly dependent upon temperature [28], so, as long as the ideality factor is only weakly temperature dependent and a bias consistent with a fixed transconductance is employed, one may deduce that a dramatic improvement in noise performance may be expected when a SiGe HBT is cooled to cryogenic temperatures. 

Despite the potential impact of SiGe devices on the field of cryogenic low noise amplifiers, the initial growth of research in this area was somewhat slow. In 2003, cryogenic noise measurements were carried out on a device with a room temperature $f_t$ of 200 GHz. Through on-wafer measurements in an open-cycle cryostat, it was found that the minimum noise temperature was roughly 21 K±8 K at 85 K physical temperature [30]. Similar measurements were later carried out on other device technologies [31, 32, 33, 34], but due to the major challenge associated with the measurement of on-wafer noise temperature measurements with accuracy on the order of ±1 K, no direct measurement of the noise performance in the low GHz frequency range has been carried out.
In 2007, the first serious attempt to use SiGe HBTs in an ultra-low-noise cryogenic amplifier was reported [35]. In this work, a simple method to predict the low-frequency cryogenic noise parameters of a SiGe HBT based upon DC measurements was presented. An IBM (now Global Foundries) 8HP device was then characterized and a narrowband LNA with a noise temperature of approximately 2.5 K was demonstrated at a physical temperature of 15 K. This result was consistent with theory and within 1 K of the best reported noise temperature of an amplifier in this frequency range.

Following this initial success, the noise performance of the IBM 8HP technology was further investigated and a detailed modeling effort was reported at the IEEE International Microwave Symposium the following year [36]. The key result of this paper was that it appeared feasible to realize high-gain cryogenic SiGe HBT amplifiers with noise temperatures as low as 1 K and 6 K at 1 and 10 GHz, respectively. To further explore the capabilities of commercial SiGe technologies, a comprehensive study was carried out in which seven different SiGe HBT technologies were compared in terms of noise performance at 18, 50, 77, 200, and 300 K [28]. As part of this study, the detailed properties of transistors fabricated by IBM, ST, IHP, and TowerJazz were studied and the theoretical limitations for each technology were determined as a function of frequency. Despite the fact that none of these technology platforms were designed with cryogenic operation in mind, the performance was consistently found to improve with cooling. However, it was also discovered that the low-injection collector current ideality factor consistently increased with cooling below 77 K, and for each technology the low-injection product of \( n_cT_a \) appeared to settle to a constant value at low enough physical temperatures. The potential mitigation of this effect is an open research topic that will be discussed further in 4.1.

At the same time as these basic device studies, work towards using SiGe HBT technology for practical systems was also underway. In 2008, it became clear that the IF bandwidth of hot electron bolometer (HEB) mixer based THz receivers could be greatly extended if a wideband IF amplifier could be interfaced to an HEB mixer without the use of an isolator. To this end, a proof-of-concept discrete transistor amplifier employing resistive feedback to achieve input matching was developed. The amplifier was subsequently integrated with an HEB receiver [37, 38]. This work was later extended to produce an amplifier that relied on packaged off-the-shelf SiGe transistors, and thus could be replicated as needed for use in various scientific systems [39]. Other research focused on demonstrating amplifiers with the lowest possible noise. In 2009, an impedance matched amplifier with a noise temperature below 2 K was reported [28]. This amplifier employed experimental transistors fabricated by ST and its noise performance is believed to be the lowest reported to date for an impedance matched amplifier covering the 1–3 GHz frequency range.

An advantage of SiGe technology platforms is the capacity for integration and a key research area that has also been explored is the realization of MMIC cryogenic SiGe LNAs. The first high-performance cryogenic SiGe MMIC LNA was reported in 2009 [40]. This amplifier employed resistive feedback to achieve an input match from 0.1–5 GHz, with the lower frequency limit determined by an off-chip coupling capacitor. The chip measured just 0.6 mm × 0.5 mm (see Fig. 2(a)) and the packaged noise performance was found to be better than 5 K over the majority of the frequency range (see Figs. 2(b) and 2(c)). This amplifier was the first high-performance microwave cryogenic LNA that achieved noise and impedance match over a microwave frequency range that extended well below 1 GHz.

Following the demonstration of proof-of-concept 50 Ω amplifiers, follow on research was carried out with the goal of implementing broadband 270 Ω differential amplifiers for integration with self-complimentary feeds. A number of designs were implemented, an example of which appears in Fig. 3. This particular design was reported in [41] and, from DC–4 GHz, it provided a gain of around 30 dB, input and output return losses better than 10 dB, and a common-mode rejection ratio better than 30 dB. Using the novel measurement technique described in [41], the
Figure 2. 0.1–5 GHz cryogenic low noise amplifier. (a) Die photo. The chip measures approximately 0.6 mm × 0.5 mm. (b) Photograph of packaged chip. The die is mounted within a via hole. (c) Noise and gain of the amplifier at a physical temperature of 15 K. The noise was measured to be 5 K or lower from 0.1–5 GHz. Reproduced with permission from [40]. ©2009 IEEE.

Figure 3. DC–4 GHz cryogenic 270 Ω differential amplifier. (a) Die photograph, (b) package photograph depicting the differential interconnects, and (c) measured and modeled noise. The noise measurement method was reported in [41] and was somewhat error prone due to a complicated de-embedding procedure and limited gain in the configuration employed for characterization. Reproduced with permission from [41]. ©2010 IEEE.

differential noise temperature was measured at a physical temperature of 24 K and the results appear in Fig. 3(c). Additional fully differential amplifier designs were later reported in [28].

3. Ultra-Low-Power SiGe LNAs
Recent research in SiGe cryogenic MMIC LNA design has been largely driven by a desire to improve the scalability of THz SIS focal plane arrays and other systems with severe power constraints. The ultimate limit to the scaling of a cryogenic receiver system lies in the ability to cool the active electronics. For SIS based systems, the IF LNA must be at a physical temperature of 4 K. Since typical cryocoolers can provide a maximum of 1.5 W heat lift at 4 K [42], the total power consumed by cryogenic amplifiers is limited to a fraction of this. To enable the implementation of kilapixel-scale sideband-separating dual-polarization cameras, the power consumption of each IF amplifier must be reduced to a couple hundred microwatts. This represents about a factor of ten improvement over the current state-of-the-art low-power
Figure 4. Unity current gain cutoff frequency/maximum frequency of oscillation of a SiGe HBT versus collector–emitter voltage at 300 K (left), 77 K (center), 7 K (right). Data are plotted for current densities of 0.22 mA/µm² (solid blue line), 0.46 mA/µm² (green dash-dot line), 0.92 mA/µm² (red dotted line), and 1.67 mA/µm² (purple dashed line). Reproduced with permission from [44]. ©2016 IEEE.

commercial cryogenic LNA, which consumes 4 mW [10].

The initial work in the area of low-power cryogenic SiGe LNAs was reported in 2012 by Russell and Weinreb, who demonstrated a MMIC feedback amplifier that consumed 2 mW while providing a gain of 17 dB and a noise temperature of around 10 K from 2–4 GHz [43]. While DC coupled resistive feedback is a convenient method to supply bias to the base of the transistor while realizing a broadband input match, from the vantage point of power dissipation, it is not necessarily the optimum way to implement a cryogenic low-noise amplifier. The base–emitter turn-on voltage for a typical SiGe HBT operating at cryogenic temperatures is just above 1 V and, if self-biasing is used, the collector must be at a slightly higher potential. Thus, the collector current is the sole degree of freedom available in reducing power consumption if such a topology is employed. However, $T_{\text{MIN}}$ is strongly dependent upon current density, so there is a direct trade-off in a self-biased amplifier between noise, power consumption, and bandwidth.

Around 2012, a basic experiment was carried out to determine the minimum collector–emitter voltage that could be used to bias a simple differential pair operating at cryogenic temperatures. It was found that the gain of the circuit was constant for collector–emitter voltages down $\approx 150$ mV [45]. This unexpected result had a clear implication: by operating SiGe transistors with low collector–emitter voltages and at the nominal bias current for minimum noise, it should be feasible to realize cryogenic LNAs in SiGe technologies without compromising noise performance.

Inspired by this result, a detailed study of the cryogenic performance of SiGe HBTs operating at low collector–emitter voltages was carried out and the results were published in early 2016 [44]. This paper began with the theoretical implications of operating a transistor in weak saturation. Next, the terminal characteristics were presented as a function of collector–emitter voltage and it was found that, contrary to an InP HEMT [46], the small signal and noise performance of a SiGe HBT was insensitive to collector–emitter voltage down to $\approx 200$ mV (see Figs. 4 and 5). Interestingly, the linearity was also found to be insensitive to $V_{\text{CE}}$ over the same voltage range, provided the collector current density was below 0.5 mA/µm² (see Fig. 6). Finally, based upon
these results, a two stage high-gain cryogenic amplifier that achieved a noise temperature below 5 K from 1.8–3.6 GHz while consuming less than 300 µW was demonstrated.

Following these results, research efforts were shifted to the integration of microwatt SiGe LNAs with SIS mixers, with the goal of demonstrating a scalable THz receiver. In this work, which was a collaborative effort with the Harvard CFA, a discrete transistor amplifier was iteratively designed and characterized with SIS mixers operating in the 200 GHz frequency region. No isolator was employed and the amplifiers were optimized for a noise match to the output impedance of the SIS device. In the first iteration, a 3.3–6 GHz amplifier consuming less than 100 µW and providing an estimated gain of 10 dB was demonstrated [47]. The noise performance of the system using the SiGe amplifier was found to be within 15 K of that of a state-of-the-art setup using the same SIS junction.

Figure 5. Minimum noise temperature of a SiGe HBT as a function of collector–emitter voltage at 300 K (left), 77 K (center), 7 K (right). The top row is at 1 GHz and the bottom row is at 10 GHz. Data are plotted for current densities of 0.22 mA/µm² (solid blue line), 0.46 mA/µm² (green dash-dot line), 0.92 mA/µm² (red dotted line), and 1.67 mA/µm² (purple dashed line). Reproduced with permission from [44]. ©2016 IEEE.

Figure 6. Third order output intermodulation intercept at 3 GHz for a SiGe HBT as a function of collector–emitter voltage at 300 K (left), 77 K (center), and 7 K (right). Data are plotted for current densities of 0.22 mA/µm² (solid blue line), 0.46 mA/µm² (green dash-dot line), 0.92 mA/µm² (red dotted line), and 1.67 mA/µm² (purple dashed line). Reproduced with permission from [44]. ©2016 IEEE.
For this initial experiment, a high-power consumption second-stage amplifier was required to provide sufficient gain before exiting the cryostat. Thus, a follow-on effort was carried out to demonstrate that it is feasible to implement a microwatt power consumption SiGe LNA with sufficient gain to directly connect its output to room temperature electronics. An amplifier with approximately 30 dB gain was implemented and the photograph of the amplifier integrated with an SIS module appears in Fig. 7(a) [48]. The measured system noise performance, shown in Fig. 7(b), is both nearly constant for IF amplifier biases as low as 300 µW, and within 5 K of results obtained using a state-of-the-art setup. This is quite encouraging, as it indicates that scalable cryogenic systems employing ultra-low-power SiGe IF amplifiers are practical. To this end, ongoing work is focused on the implementation of MMIC amplifiers with similar performance.

4. Conclusions and Open Questions
In the last decade, it has been proven that commercial SiGe BiCMOS technology platforms can be used to implement state-of-the-art ultra-low-power cryogenic LNAs. However, there are still several open issues related to minimizing the noise of amplifiers using SiGe HBTs. The paper will be concluded with a brief description of two such areas.

4.1. Can the effective carrier temperature be improved?
By introducing the effective electron temperature $T_{\text{eff,elec}} = n_c T_a$, equation (1) can be rewritten as

$$T_{\text{MIN}} \approx \sqrt{\frac{T_{\text{eff,elec}}^2}{\beta} + 2T_a T_0 R_B \frac{I_C}{V_0} \left( \frac{1}{\beta} + \left( \frac{f}{f_t} \right)^2 \right)}.$$  (2)

where $T_0 = 290$ K is the reference temperature and $V_0 = kT_0/q$. The effective electron temperature is greater than the ambient temperature and is related to the fact that transport at cryogenic temperatures is no longer purely diffusive. Instead, at cryogenic temperatures, the mean free scattering path length for minority carriers in the base is comparable to the base thickness and transport is quasi-ballistic [25, 26]. Thus, the effective electron temperature describes the excess energy of the ballistic carriers. Fig. 8 shows the extracted values of $T_{\text{eff,elec}}$ as a function of physical temperature for several state-of-the-art SiGe technologies. These data were
obtained from Gummel curve slopes at current-collector densities several orders of magnitude below the onset of medium injection, and thus are unaffected by self heating. Interestingly, as the temperature tends to zero, the effective electron temperature appears to settle to a constant value, which varies significantly between different device technologies. Moreover, as the current density is increased, the minimum achievable value of $T_{\text{eff}}$ is also observed to become larger. Since the zero temperature limit of $T_{\text{MIN}}$ is $T_{\text{eff,elec}}/\sqrt{\beta}$, it is important to understand the physical limit of $T_{\text{eff,elec}}$. Thus, a study of the relationship between device structure and the low-temperature limit of $T_{\text{eff}}$ is recommended to try and determine the fundamental limit to this parameter.

4.2. Is shot-noise correlation significant at cryogenic temperatures?

A second open issue has to do with the frequency dependence of the noise parameters of SiGe HBTs at cryogenic temperatures. It is well known that the full shot-noise model of an HBT should include correlation between the base and collector shot-noise currents. This is due to the fact that, rather than being generated in the base–collector junction, the shot noise observed at the collector is actually due to electrons injected across the base–emitter junction. It can be shown that the complete shot-noise model can be written as [49]

$$|i_{n,b}|^2 = 2qI_B + 4qI_C (1 - \exp \{j\omega\tau_n\}), \quad (3)$$

and

$$|i_{n,c}|^2 = 2qI_C, \quad (4)$$

and

$$\overline{i_{n,b}^* i_{n,c}} = 2qI_C \left(\exp \{-j\omega\tau_n\} - 1\right) \quad (5)$$

where $\tau_n$ is a frequency-independent delay term describing the noise transit time to the collector and is a fraction of the overall transit delay ($\tau_t$). At room temperature, this delay term is typically equal to around 65% of $\tau_t$ [49, 50, 51] and is particularly important for frequencies above $\approx f_t/3$ [52].
Figure 9. Simulated minimum noise temperature for an IBM 8HP transistor at 18 K for different noise delay values. Model parameters from the study reported in [44] were employed. The bias points are (a) 0.5 mA/µm² and (b) 1 mA/µm². The values of \( f_t \) for the HBT at these two bias points were found to be 130 and 185 GHz, respectively.

Most cryogenic SiGe HBT noise modeling efforts have neglected shot-noise correlation (\( \tau_n = 0 \)) [28, 36, 43, 44], since determining \( \tau_n \) requires an error-prone high-frequency cryogenic noise measurement. It is important to note that assuming \( \tau_n = 0 \) is actually a pessimistic assumption, as the correlated part of the base shot-noise current can actually be leveraged to cancel part of the collector shot-noise current, thereby reducing the overall noise. To emphasize this point, simulated values of \( T_{\text{MIN}} \) appear in Fig. 9 for current densities of 0.5 and 1 mA/µm² and for \( \tau_n \) equal to 0, 0.65\( \tau_f \), and \( \tau_f \). Interestingly, the effect of shot-noise correlation appears to be quite significant when incorporated into the cryogenic models, especially at higher current densities. However, these optimistic results should be taken with a note of caution; transport in a SiGe HBT at deep cryogenic temperatures is quasi-ballistic rather than diffusive. Thus, there is no reason to believe that the relationship between \( \tau_f \) and \( \tau_n \) determined at room temperature could be directly applied at cryogenic temperatures. Thus, further work is required to better understand the effect, if any, that shot-noise correlation has at cryogenic temperatures.

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