Standard SiGe Technologies Operating at 4 K for Front-End Readout of SQUID Arrays

D. Prêle*(a), G. Klisnick(a), G. Sou(a), M. Redon(a), F. Voisin(b), E. Bréelle(b) and M. Piat(b)

(a) Laboratoire des Instruments et Systèmes d’Ile-de-France, Université Pierre et Marie Curie, Paris, France
(b) AstroParticule et Cosmologie, Collège de France, Paris, France
*Email: prele@lisif.jussieu.fr

Abstract
We present some experimental results showing that two different standard BiCMOS SiGe technologies can operate at 4 K. DC and low frequency measurements were carried out on two SiGe Hetero-junction Bipolar Transistors (HBT) of 0.8 µm and 0.35 µm AMS BiCMOS SiGe technologies. We report that for both SiGe HBTs, the transconductance gm increases at cryogenic temperature making possible the use of such devices down to 4 K for low noise voltage amplification. However, the current gain β remains highly dependant on the fabrication process. The discussion is centred on the effects which could explain the behaviors of β and gm measurements at temperature down to 4 K.

1. Introduction
For noise and cryogenic considerations, the front-end readout of a SQUID arrays should be achieved by a low frequency (< 100 kHz) electronic operating at cryogenic temperature. The use of a standard BiCMOS SiGe technology can lead to the realization of such ASICs.

2. Theory
Voltage amplification AV is an important parameter in most of analog applications if the amplifier input impedance is larger than the source output impedance and for a frequency range for which lumped elements hypothesis is valid. The temperature dependence of the voltage gain (1) is directly linked to the variation of transconductance gm with the temperature if R LOAD is kept temperature independent.

\[ AV = \frac{gm \cdot R_{LOAD}}{R_{LOAD}} \]  

From the classical Drift Diffusion (DD) theory, the bipolar collector current is given in (2) where \( I_{CB} \) is the saturation collector current and \( V_T = k_B T/q \) the thermal voltage with \( k_B \) the Boltzmann constant, T the temperature in Kelvin and q the electron electrical charge absolute value.

\[ I_C = I_{C0} \cdot \exp \left( \frac{V_{BE}}{V_T} \right) \]  

This expression is valid only in low injection regime, around the room temperature, if the HBT has flat Germanium and doping profiles in the base and if the base thickness is much greater than the carrier mean free path [1]. A circuit designer, as opposite to a device designer, does not necessarily have access to such technological characteristics. It is then interesting to investigate the behaviour at low temperature of standard SiGe technologies by adapting the classical DD theory by addition of an adjustment factor \( \alpha \). This parameter allows to modulate the thermal voltage \( V_T \) by taking into account various effects which occur at cryogenic temperatures. In fact, to adapt the model to the measurements for temperatures below 77 K, it is necessary to increase \( V_T \). Therefore, the expression of the transconductance (3) exhibits a \( \alpha \) factor taking into account the cryogenic effects which give a smaller transconductance than expected by a simple \( 1/T \) dependence.

\[ gm = \frac{\partial I_C}{\partial V_{BE}} = \frac{I_C}{\alpha \cdot V_T} \]  

This increase of \( \alpha \cdot V_T \) as compared to \( k_B T/q \) with cooling may be attributed to the non-equilibrium carrier transport in the base. This effect is due to the strong reduction of carrier scattering which occurs when temperature is decreasing. Under such conditions, the carrier transport becomes quasi-ballistic. The ballistic regime leads to a mean carrier temperature that is higher than expected from their equilibrium value [1]. Consequently, it is necessary to increase the thermal voltage \( V_T \) such as the HBT has an effective temperature \( (T_E) \) higher than \( T \).

3. Measurements
Measurements have been carried out up to 100 kHz with a common emitter topology (\( R_{LOAD} = 2.7 \, \text{k}\Omega \) being thermalized at 300 K outside the cryostat) showing a flat frequency response from DC to 100 kHz at 300 K, 77 K and at 4 K. This led us to limit further parameter measurements to DC characterisations. Low frequency HBT parameters can then be extracted from differential use of the static data. To only extract the temperature dependence of \( \beta \) and gm, it is important to remain in low injection regime.

Characterizations have been undertaken for two HBTs of different technologies: a HBT0.8, 4.8 µm² area of AMS SiGe BiCMOS 0.8 µm technology and a HBT0.35, 2.8 µm² area of AMS SiGe BiCMOS 0.35 µm technology.
3.1 Current Gain $\beta$

On Figure 1, the HBT0.8 current gain decreases at low temperature, even if the presence of Germanium in the base attenuates this effect [1]. Indeed, for a standard Si Bipolar Junction Transistors (BJT), the current gain decreases at low temperature because of a factor $e^{-\Delta E_g/kT}$ where $\Delta E_g$ is the band-gap reduction in the heavily doped emitter and $kT$ the thermal energy. However, the presence of Germanium in the base of HBTs compensates the reduction of the apparent energy gap. Therefore, HBT0.8 current gain looses only 40% when the operating temperature decreases from 300 K to 77 K, compared to 90% loss for BJTs [2]. Moreover, HBT0.8 are still operating at 4 K whereas BJTs are “freezed-out”.

![Fig. 1](image1)

Fig. 1. Current gain versus collector current as a function of temperature (300, 77 and 4 K) for HBT0.8.

The increase of the $\Delta E_g$ depends on the Germanium and doping profiles in the base and therefore may vary from a technology to another one. For this thinner HBT technology, the HBT0.35 current gain (Fig. 2) increases at low temperature. In such a case, the presence of Germanium in the base does not only compensate the reduction of the apparent energy gap, but also tends to increase it.

![Fig. 2](image2)

Fig. 2. Current gain versus collector current as a function of temperature (300, 77 and 4 K) for HBT0.35.

However, below 77 K a parasitic tunneling effect appears on $I_C(V_{CE})$ measurements on two HBTs limiting the increase of $\beta$ [3]. Indeed, at 4 K, the HBT0.35 $I_C(V_{CE})$ characteristic exhibits on Figure 3 a $V_{CE}$ offset of 280 mV as well as a Negative Differential Resistance (NDR) effect [4] that could arise from a tunneling effect, even if the considered devices are not designed for such tunneling purposes.

![Fig. 3](image3)

Fig. 3. Collector current versus collector-emitter voltage of HBT0.35 at 4 K for $I_b = 3.6, 5.4$ et $7.1 \, nA$.

Thus, we have at our disposal two technologies able to operate at 4 K. Furthermore, from the only current gain aspects, it appears that 0.35 µm technology is more suitable than the 0.8 µm one. But while current amplification is necessary with high output impedance sources (compared to the amplifier input one), it is in our case a signal from superconducting sensor with very low output impedance that has to be amplified. For that kind of application, it is the transconductance and not the $\beta$ evolution that is most significant.

3.2 Transconductance $g_m$

Transconductances of the two SiGe HBTs are presented on Figure 4 versus collector current at 300, 77 and 4 K.

![Fig. 4](image4)

Fig. 4. Measured (dots) and theoretical (solid line) transconductance versus collector current as a function of T (300, 77 and 4 K) for HBT0.8 (•) and HBT0.35 (×).
An increase of the gm is observed as temperature decreases down to 4 K. But this increase do not follow a 1/T law. Indeed, at 77 K and in a more pronounced way at 4 K, the gm(I_c) slope is not as steep as the ideal curve slope (I_c/V_T), represented by a solid line on Figure 4. This figure also shows that, for a fixed value of I_c, the 0.8 µm technology allows a larger voltage amplification at cryogenic temperatures despite a lower β. This smaller increase of gm is not predicted by the classical DD theory without α. However the DD theory can be adapted at cryogenic temperatures by the use of the adjustment factor (introduced in section 2) which is the ratio of the theoretical transconductance (I_c/V_T) over the measured transconductance (∆I_c/∆V_BE).

3.3 Adjustment Factor α

The adjustment factor α plays a paramount role for the prediction of the transconductance values at very low temperatures including ideality factor, high injections effects, parasitic resistance effects and effective temperature T_E [1].

Transconductance measurements, with very small collector currents to avoid high injection effects, given on Figure 4 seem to show that α has a value close to unity at 300 K and increases with cooling down (Fig. 5). In fact, this adjustment factor has a much larger value exceeding 10 at 4 K reducing by the same value the expected transconductance. The increase of α (or T_E/T) at temperatures T lower than 77 K has also been measured on other SiGe HBTs [1].

![Fig. 5. Adjustment factor α versus collector current as a function of temperature (300, 77 and 4 K) for HBT0.8 and HBT0.35.](image)

4. Discussion

High injection effects seem to appear at lower current values when the temperature of the transistors decreases, justifying partially the introduction of the adjustment factor. The access resistances to the emitter and to the base (respectively R_EE, R_BB) also decrease the transconductance with a reduction more pronounced at low temperatures. The expression (4) shows that the influence of R’ (R_EE/β + R_BB/(β+1)/β) is more important when I_c/V_T is large which is the case when temperature decreases.

\[ \text{gm} = \frac{\partial I_c}{\partial V_{BE}} = \frac{I_c/V_T}{1 + I_c/V_T \cdot R'} \] (4)

However, all these effects are easily identified because of their I_c dependence and they can be minimised by biasing HBTs with very low collector currents, as it is the case on Figure 4 and 5 (I_c < 10 µA). But, even with low biasing, Figure 5 shows that the adjustment factor is only temperature dependent and does not have a value close to unity. Indeed, under such biasing conditions, the adjustment factor only shows tiny variations with I_c.

This clearly demonstrates that another physical effect exists which is only temperature dependant and which increases the adjustment factor at cryogenic temperatures. This effect could be due to a non-equilibrium carrier transport in the base as mentioned in section II. This mode of carrier transport would increase the carrier temperature by a factor of 10 as compared to the crystal lattice temperature. Furthermore, this effect is more accentuated on the 0.35 µm technology either because of the fabrication process or because of the difference in the area of the transistors.

Conclusion

This paper shows the ability of standard technologies as BiCMOS SiGe AMS to operate at 4 K where the “Freeze-Out” effect prohibits the use of most of the standard technologies. We have demonstrated that a standard SiGe technology can exhibit an increase of the voltage gain at temperatures as low as 4 K in spite of large variations of β as a function of technology. The discussion brings physical interpretations of the transconductance evolution at very low temperatures for the bipolar transistors. This low frequency study of 0.8 µm and 0.35 µm BiCMOS SiGe HBTs has been completed with characterisations of MOS transistors, resisters and capacitors which show their aptitudes to operate at 4 K. This full set of characterisations will allow us to develop low noise amplifiers and multiplexers for SQUID arrays readout operating at 4 K.

References