Low-frequency noise in millimeter-wave Si/SiGe Heterojunction Bipolar Transistors

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Abstract
In this paper we report on the low-frequency (L.F) noise properties of Si/SiGe HBT's. Our results indicate that these devices exhibit very interesting L.F noise performance which compares well with those obtained on BJT Si. However further improvements of the input referred noise current are still needed and our investigations show that they could be achieved through a reduction of the recombination processes at the Emitter-Base heterojunction and at the emitter periphery

Introduction
Actually, there is a need for millimeter-wave circuits in the frequency region above 40 GHz for various applications including inter-satellite communications, environmental survey systems and various radar applications. A key component of a millimeter-wave emitter is related to the spectral purity of the local oscillator (L.O). Therefore, as the oscillator phase noise is a function of the low-frequency (L.F) noise up-converted in the millimeter-wave range, it becomes necessary to use microwave active devices where the L.F noise can be minimized. Among the wide variety of the microwave active devices, Heterojunction Bipolar Transistors (HBT's) are the most promizing candidates for oscillation applications because of their vertical structures. HBT's based on GaAs or InP system have been the subject of widespread investigation. If their potentialities in the millimeter-wave range have been largely demonstrated, their capabilities concerning the L.F noise are not yet fully established because of the high traps and defects density in III-V materials. Recent advances in the fabrication of HBT's using thin SiGe alloy as the base and Silicon for the emitter and collector have yielded record cut-off frequencies above 100 GHz [1,2] and f_{max} values of 65 GHz. First investigations on 1/f noise indicate very attractive performances for these devices [3].
This paper deals with the L.F noise properties of millemeter-wave passivated Si/SiGe HBT's. The first part addresses a comparative L.F noise study between a SiGe HBT and a commercial microwave Bipolar junction transistor on Silicon (BJT Si) which is today the less noisy microwave device with respect to its L.F noise. In a second part, we focus on the understanding of excess noise scaling with device dimensions and electrical properties in order to propose possible solutions to reduce L.F noise in these devices.

I Device Fabrication
The structure and technology procedure have been previously described [4]. The epitaxial structures are grown by MBE which provides a moderate growth temperature to ensure a layer thickness control in the nm range and maximum doping above 10^{20} cm^{-3}. The complete HBT structure was grown by the following step process, i.e a 150 nm collector (3.10^{17} cm^{-3}), a 30 nm SiGe base with a constant Ge fraction of 33 % (18 nm boron doped 6.10^{19} cm^{-3}), a 70 nm emitter ($1.5.10^{18}$ cm^{-3}) and a 230 nm emitter contact (2.10^{20} cm^{-3}).
The current gain of the devices range between 100 to 200. They feature both different emitter and base sizes. They exhibit a current cut off frequency of 60 GHz and a maximum oscillation frequency of 30 GHz.

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3F

II L.F Noise Measurements
One of more widely used equivalent representation of noisy two-ports involve a noise free two-ports

with a serie voltage (en : input referred noise voltage) plus a parallel correlated current generator (in : input referred noise current) connected at its input terminal (Fig.1).

The complete L.F noise characterization of HBT's in a common emitter configuration is based on the determination of the input referred noise current (i_n) and noise voltage (e_n) generators including their correlation. To get these three quantities we used the multiple resistance technique (Fig.1).

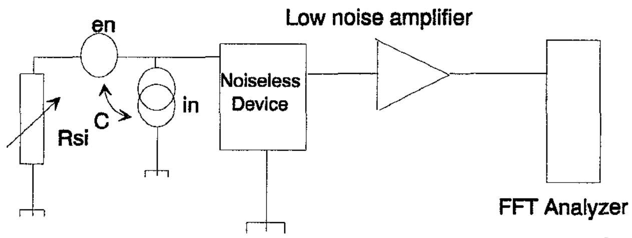

***Fig.1** : 2 port indirect L.F. noise measurements using the multiple resistance technique*

It relies on the variations of the 2 ports noise figure Fi, versus its input terminal resistance Rsi=1/Gsi which are given as :

$$Fi = F\min + \frac{Rn}{Gsi}(Gopt - Gsi)^2 \qquad (1)$$

where Ropt=1/Gopt represents the optimum terminal resistance with respect to the minimum noise figure. The multiple impedance technique [5,6] requires a set of n (n>3) different Fi measured for different Rsi and an appropriate mathematical fitting procedure [7] which provides the three noise parameters (Fmin, Rn, Ropt) involved in Eq (2). Subsequently the different spectral intensities are derived as :

$$Sen = 4kToRn$$

$$Sin = 4kTo\frac{Rn}{Ropt^2} \qquad (2)$$

$$Senin^* = 2kTo(F\min - 1 - 2\frac{Rn}{Ropt})$$

where To stands for the standard temperature (290 K) from eq 3 we can write $Ropt = \sqrt{\frac{Sen}{Sin}}$ which represents the input terminal resistance value below which the voltage noise predominates over the current noise. We define also another quantity : the correlation resistance defined as follows :

$$Rcor = \frac{Senin^*}{Sin} \qquad (3)$$

which is a useful indicator of the correlation between the input noise generators. In a case of HBT, the correlation resistance gives us the value of the sum $r_{bb'}+r_{ee}$ where $r_{bb'}$ and r_{ee} are respectively the spreading base resistance and the emitter access resistance [8]. L.F noise measurements between 250 Hz and 100 kHz have been performed on Si/SiGe HBT (referred to as T1) and on BJT Si (referred to as T2) devices biased at a constant collector current density of $Jc=10^4$ A/cm^2. The corresponding input noise voltage spectral intensities ($S_{en}(f)$) are displayed in Fig.2.

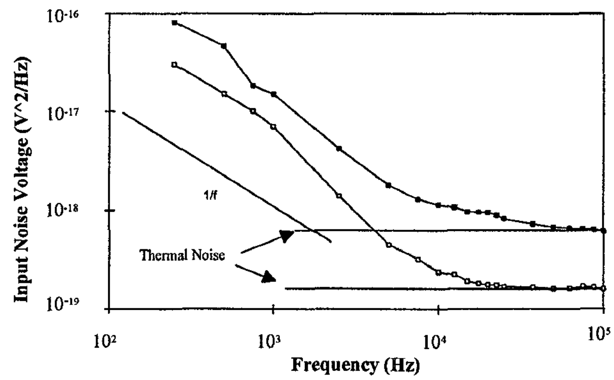

Fig 2 : Input Noise Voltage for a TBH SiGe (■) and a BJT Si (□) Biased at $Jc=10^4$ A/cm^2

The excess noise level features a $1/f^{\alpha}$ shape ($1<\alpha<2$) and reaches a thermal noise level in the 10 kHz region (the voltage noise corner frequency is in the 10 kHz range) which is a relevant result comparatively to III-V HBT's where the noise corner frequency is usually in the 1 MHz range. On Fig.3, we have also plotted the variations versus frequency of the excess noise current ratio $S_{in}(f)/2qIb$.

It can be seen that all spectra are 1/f type. The current noise corner frequency is still in the 10 kHz range for T2 while it is beyond for T1. Therefore device T1 exhibits a larger 1/f noise level probably as a consequence of trapping-detrapping effects at the pseudomorphic heterointerface between Emitter and Base.

Nevertheless, it can be stated that in Si/SiGe HBT's, excess noise current sources are mostly 1/f type comparatively to III-V HBT's where Lorentzian noise components attributed to DX center in the emitter [9] and deep traps in the base region [10] in the 10 kHz range degrades the noise level of the device.

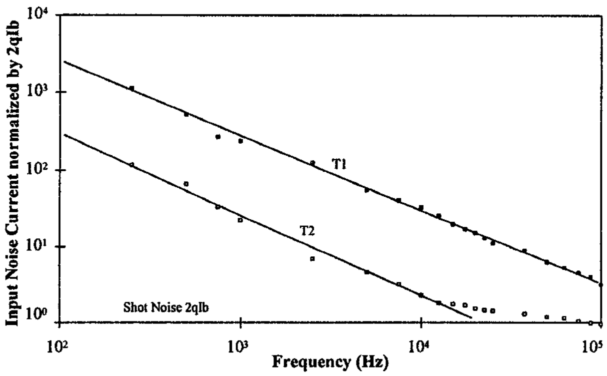

Fig3 : Input Noise Current Normalized by 2qIb for a TBH SiGe (■) T1 and a BJT Si (□) T2 biased at Jc=10^4 A/cm^2

We will now address the influence on L.F noise of technological and/or electrical parameters of the devices in order to investigate possible solutions to further reduce the excess noise in Si/SiGe HBT's.

III Noise Scaling versus some electrical and physical features of the devices

Fig.4 displays the voltage noise spectra $S_{en}(f)$ of two devices featuring different spreading base resistances ($r_{bb'}$). It can be observed that the noiseless device also features the lowest $r_{bb'}$.

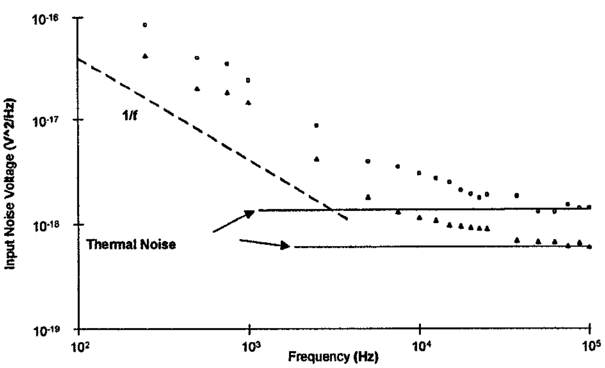

Fig 4 : Input Noise Voltage for two devices featuring different spreading base resistances at Jc=3.10^4 A/cm^2 and Vce=1 V

Fig.5 displays the noise current spectra of three devices featuring different ideality factor nb of the emitter-base heterojunction (obtained from forward "Gummel Plots" measurements). It could be observed that the smallest nb corresponds to the lowest noise current. This important statement provides a strong evidence that the noise current is generated at the Emitter-Base heterojunction since nb is an indicator of the heterointerface quality. Therefore nb can be also considered as an indicator of the device capability to provide a low L.F noise.

Finally, we have performed noise measurements on devices featuring different emitter lengths and the results reported in Fig.6 indicate that a fraction of the current noise is generated by recombination along the emitter finger since the noisiest device exhibit the largest emitter length.

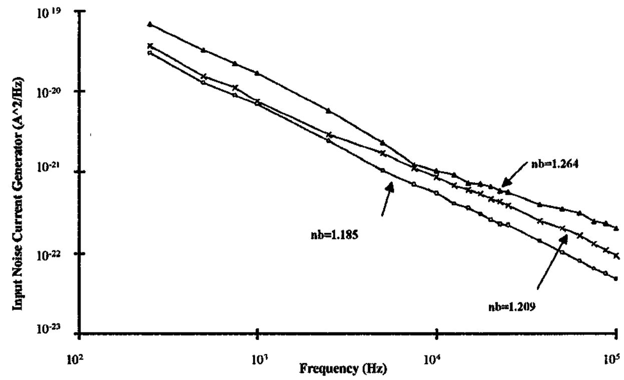

Fig 5 : Input Noise Current versus the ideality factor nb of the Emitter-Base heterojunction for three identical devices biased at Ic=6 mA and Vce=1 V

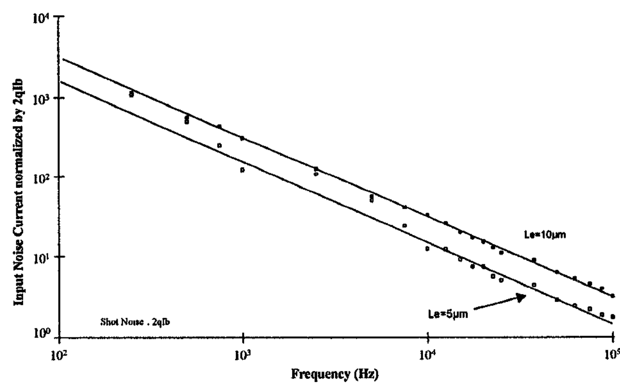

Fig 6 : Input Noise Current for two devices featuring different emitter lengths at Jc=Cte and Vce=1V

The improvement of the passivation layer is therefore an other solution for the L.F noise minimization of SiGe HBT's.

In order to investigate more in detail the noise mechanism in the low-frequency range, we report now the evolution of the correlation of the input noise generators versus the base contact size.

On fig 7 we have plotted the evolution of the correlation coefficient defined as the ratio Rcor/Ropt versus the base contact width Wb for three devices which exhibit the same emitter size geometry.

The results indicate that the correlation decreases when the base contact width increases. This behavior show us that there is an excess noise sources generated in the extrinsic base region and then we must to minimize this parameter with respect to the minimization of the low-frequency noise.

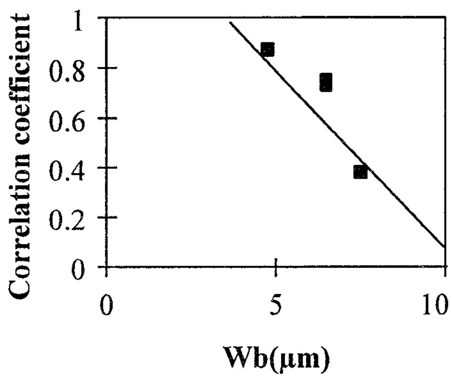

***Fig.7** : Evolution of the correlation coefficient between the input noise generators versus the base contact width Wb at Ic=6 mA and Vce=1 V*

In order to confirm this result, we have reported on Fig.8 the frequency evolution of the input referred noise voltage for two devices with different base contact size and the plot indicate that the noisy device is the device which exhibit the larger extrinsic base region.

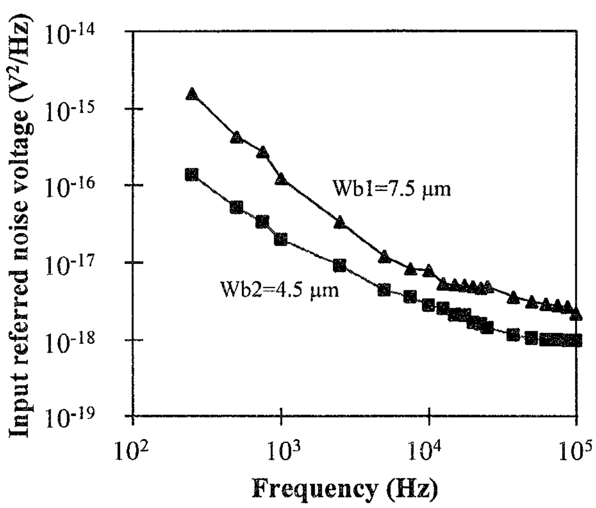

***Fig.8** : Frequency evolution of the input noise voltage versus base contact width at Ic=6 mA and Vce=1 V.*

Conclusion

In this paper, we have investigated the L.F noise on millimeter-wave passivated Si/SiGe HBT's. These devices exhibit very attractive performance since we have reported a low-frequency noise corner frequency in the 10 kHz range for the noise voltage which is in the same order than that obtained on BJT on Si. However, these devices still exhibit a relatively high noise current source which is probably related to trapping effects at the heterointerface between the emitter (E) and the base (B). Additionally we have shown that the noise voltage amplitude is strongly dependent on the spreading base resistance and that the noise current amplitude is correlated with the ideality factor of the E-B heterojunction and the emitter length. In order to investigate more in detail the location of the excess noise sources, further work on the measurement of the correlation between the noise generators on devices featuring different base contact size show that a large part of the noise voltage is generated in the extrinsic base region. Finally, we believe that Si/SiGe are very promizing candidates for the realization of high spectral purity oscillator in the millimeter-wave range.

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