Low-Frequency Noise Properties of SiGe HBT's and Application to Ultra-Low Phase-Noise Oscillators

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***Abstract*—This paper presents an extensive electrical characterization of Si/SiGe/Si heterojunction bipolar transistors (HBT's) grown by molecular beam epitaxy (MBE). These devices are designed for microwave and millimeter-wave applications since they present a maximum oscillation frequency in the 40-GHz range. The processing technology, featuring a high-quality oxide passivation, results in ideal Gummel plots and an input noise corner frequency of 250 Hz at lowest. A dielectric resonator oscillator (DRO) at 4.7 GHz has, therefore, been realized. The measured phase-noise level of this oscillator is below −135 dBc/Hz at 10-kHz offset frequency, which is at least 10 dB better than the best FET or HBT state-of-the-art DRO's.**

***Index Terms*— Dielectric resonator oscillators, Ge–Si alloys, heterojunction bipolar transistors, low-frequency noise, microwave oscillators, noise, $1/f$ noise, phase noise, SiGe alloys, silicon.**

I. Introduction

SiGe MICROWAVE heterojuction bipolar transistor (HBT) bipolar/BiCMOS technology has a great potential in the wireless communication market because it can provide both low-cost technology and, in several areas, improved performance over the III–V competitive technologies. The low-frequency (LF) noise and relative additive phase noise or oscillator phase noise is one of the areas where SiGe devices outperform III–V devices, as will be shown in this paper.

LF noise is a crucial parameter for very broad-band-range analog circuits and for the spectral purity of nonlinear microwave functions where the LF noise impacts directly on the nonlinear microwave function performance (e.g., oscillator, A/D converter, low-phase distortion amplifier) [1]. Recently, many works [2]–[5] have been focused on LF noise performance of SiGe HBT's since Vempati *et al.* [2] have reported an excess noise corner frequency (i.e., the frequency where excess noise and white noise have the same magnitude) as low as 500 Hz on ultrahigh vacuum/chemical vapor deposited (UHV/CVD) HBT's. This outperforms the best results obtained in III–V HBT's [6]. Plana *et al.* [3] have also reported an excess noise corner frequency in the 10-kHz range for molecular beam epitaxy (MBE) research-type SiGe devices. The SiGe technology is now more developed and there is a need to know the LF noise performance of preproduction devices and their impact on phase noise. This paper deals with the LF noise properties of recently processed devices and investigates how the LF noise impacts on the phase-noise performance of low additive phase-noise amplifiers and low phase-noise oscillators.

The paper is organized as follows. Section II presents a brief overview on the HBT processing technology involved in this work. Device dc characteristics are reported and discussed in Section III. Section IV deals with the LF noise performance as a function of bias and geometry. Section V addresses both microwave performance and phase-noise data, while the conclusion is presented in Section VI.

II. Device Fabrication

Device fabrication starts with 4-in 1.5 mΩ·cm n^+ substrates. After an RCA clean, the wafers are loaded into the MBE system where the complete HBT layer structure is grown without interruption. The sensitive base–emitter (BE) or base–collector (BC) interfaces are, therefore, never exposed to air or the other process environments, unlike in the cases of an epitaxially grown base or a polysilicon emitter. Growth starts after a 900 °C flashoff with the 300-nm-thick collector layer Sb-doped 4×10^{16} cm^{-3}. The 47-nm-thick SiGe base doped 5×10^{19} cm^{-3} is grown by co-evaporation, and contains 24%–30% of germanium. Undoped spacer layers on both the collector and emitter side allow a limited diffusion of the boron within the base during subsequent processing. The emitter is 100-nm-thick doped 1–2 $\times$ 10^{18} cm^{-3} with Sb followed by a 80-nm-thick n^+ emitter contact layer.

Device fabrication starts with the deposition of a 300-nm CVD masking oxide. Optical lithography defines the emitter areas. The oxide and the top n^+ layer around the emitter are dry etched. The SiGe remains covered by the n^- silicon layer. An oxide spacer is then formed on the emitter mesa in order to keep a safety distance of the following external base BF2 implantation to the n^+ emitter. Next, the collector mesa is dry etched, thereby removing the SiGe layer outside the device area. Note that this mesa is again very shallow, as it is not necessary to etch down to the n^+ substrate because the collector contact will be formed on the backside of the wafer. The mesa is then surrounded by a 1.5-μm-thick pad oxide. Now, a few nanometers of thermal oxide are grown at 690 °C–750 °C for 10 min. This is the most crucial step of the fabrication process. Its provides the necessary passivation of the surfaces and acts as an implantation anneal. The thermal budget, however, has to be carefully controlled so that the

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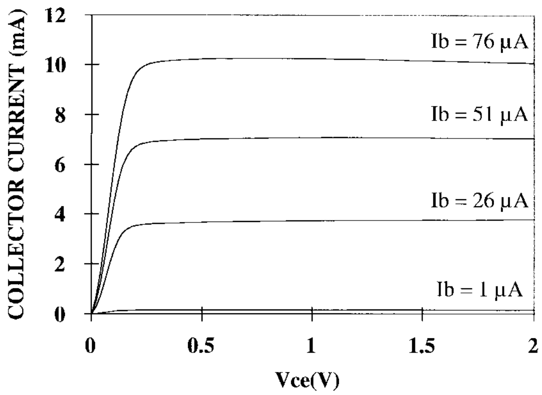

Fig. 1. Collector current–voltage characteristic for a 8 × 1.6 μm × 9 μm SiGe HBT (#B).

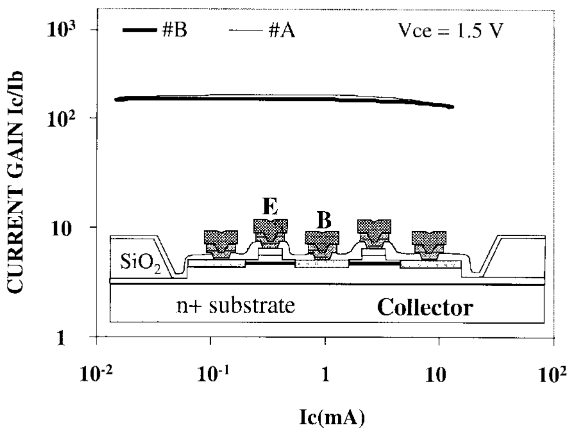

Fig. 2. Current gain versus collector current at $V_{ce} = 1.5$ V. The inset shows a cross section view of a #A SiGe HBT sample.

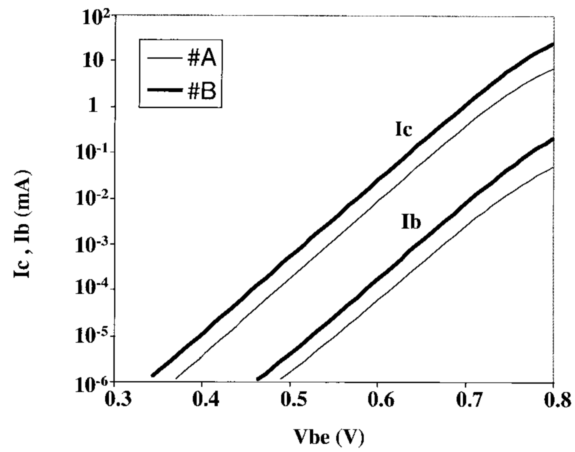

Fig. 3. Forward Gummel plots for #A and #B SiGe HBT samples.

unavoidable boron diffusion in the base will not reach emitter or collector and form parasitic barriers. Finally, a 0.3-μm CVD oxide is deposited and contact holes are opened. After a PtSi salicide process, a 1-μm-thick TiW/Au metallization is formed. The emitter fingers are 1.6 μm × 9 μm and the distance between adjacent gold lines is 2.5 μm.

Two different samples of either two (#A) or eight (#B) fingers were used. Devices are bounded into 100-mil ceramic packages. The inset in Fig. 2 shows the cross-sectional view of a #A sample.

III. Static Measurements

A complete dc characterization has been performed including $Ic = f(Vce)_{ib}$, forward Gummel plots, and dc current gain versus collector current. Experiments have been carried out on a set of ten #A and #B devices. We have plotted in Fig. 1 the output characteristics $Ic = f(Vce)_{Ib}$ for a #B sample. The offset voltage is near 0 V due to the absence of a conduction band offset as in GaAlAs HBT's, and due to a large inverse current gain [7]. The slope of the characteristics in the normal regime indicates no Early effect due to the high base doping level. The devices exhibit a constant current gain of about 150 over about three decades of collector current (see Fig. 2), which indicates a good device quality with respect to surface recombinations. The forward Gummel plots for sample #A and #B (see Fig. 3) indicates an ideal behavior and, furthermore, an absence of any leakage current. The ideality factor of the collector current component and of the base current component are close to $n = 1.00$. This confirms the absence of any parasitic barrier due to the out diffusion of the base doping [8]. Furthermore, no recombination at the extrinsic base region or emitter periphery are involved. This behavior results from the excellent quality of the passivation oxide.

The evaluation of the series emitter and collector resistances from dc measurements give, respectively, $r_{ee} = 2.6\ \Omega$ and $r_c = 2.4\ \Omega$ for the #B transistor. The observed low value of the base resistance ($r_{bb'} < 15\ \Omega$ for #B), evaluated by LF noise measurements agrees with the high base doping level. The attractive dc properties of these MBE-grown SiGe HBT should also result in excellent LF noise performance, which is the point of interest of Section IV.

IV. LF Noise

A. Noise Theory and Measurement Method

Noise characterization of HBT's in a common emitter configuration has been carried out at room temperature, between 10 Hz and 10 kHz, through output noise measurements for various input resistive terminations, as previously described in [9]. In this approach, an appropriate numerical extraction technique [10] must be used to obtain the spectral intensity $S_x(f)$ of the input referred noise–current $(x = i_n)$ and noise–voltage $(x = e_n)$ generators in addition to their cross correlation $(x = e_n i_n^*)$. According to Kleinpenning [11] and Van der Ziel [12], the input referred noise current, the input referred noise voltage, and the cross-correlation spectral densities can be written as

$$S_{\text{in}} = S_{\text{ieb}} + \frac{S_{\text{iec}}}{\beta^2} \tag{1}$$

$$S_{en} = 4kTr_b' + r_b'^2 S_{\text{ieb}} + \frac{S_{\text{iec}}}{\beta^2}(r_b' + r_\pi)^2 + Ib^2 S_{\text{rbb}'}^{1/f} + Ic^2 S_{\text{ree}}^{1/f} \tag{2}$$

and

$$S_{\text{enin}^*} = r_b' S_{\text{ieb}} + \frac{r_b' + r_\pi}{\beta^2} S_{\text{iec}} \tag{3}$$

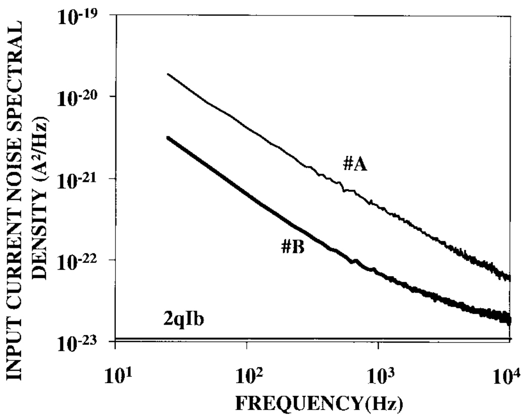

Fig. 4. Input current noise spectral density for #A and #B HBT samples at $Ib = 34$ μA and $V_{ce} = 1$ V from 25 Hz to 10 kHz.

where $r'_b = r'_{bb} + r_{ee}$ (r'_{bb} represents the spreading base resistance), r_π represents the dynamic resistance of the emitter–base heterojunction defined by $r_\pi = n_{bf} \cdot Ut/Ib$, and β is the dc current gain. Finally, $S_{\rm ieb}$ and $S_{\rm iec}$ are the short-circuited spectral intensities at the emitter–base heterojunction and at the emitter–collector terminals of the intrinsic device. In our case (as will be later observed), the intrinsic excess noise sources are mostly of $1/f$ type and the $S_{\rm ieb}$ and $S_{\rm iec}$ can be expressed as

$$S_{\rm ieb} = 2qIb + S_{\rm ieb}^{1/f} \tag{4}$$

$$S_{\rm iec} = 2qIc + S_{\rm iec}^{1/f} \tag{5}$$

where $2qIb$ and $2qIc$ stand for the shot noise sources, and $S_{\rm ieb}^{1/f}$ and $S_{\rm iec}^{1/f}$ stand for the flicker noise spectral intensities at intrinsic device terminals. Finally, $S_{r_{bb'}}^{1/f}$ and $S_{\rm ree}^{1/f}$ represent the $1/f$ resistance fluctuation spectral densities in the extrinsic resistive regions of the device (access base and emitter resistances).

B. Input Noise–Current Generator Characterization

According to (1), the $S_{\rm ieb}$ predominates over $S_{\rm iec}$ for high gain devices such as those under investigation. In Fig. 4, the input $S_{\rm in} = S_{\rm ieb}$ noise–current spectra are displayed for #A and #B devices at a constant base current $Ib = 34$ μA ($Ic \approx 5$ mA) and $V_{ce} = 1$ V. The spectra indicate a $1/f$ behavior below 250 Hz. The variation of the $1/f$ noise amplitude between #A and #B devices at a given current is approximately $1/Ae$ (Ae is the global emitter area) which proves unlikely an extrinsic surface origin of this noise.

In order to further clarify the physical origin of this noise, extra $1/f$ noise measurements have been performed versus base current ranging from 5 to 200 μA at a constant V_{ce} voltage (1 V), and are reported in Fig. 5. The input $1/f$ noise–current variation scales as Ib^2, and thus, indicates that the $1/f$ noise source is homogeneously distributed over the emitter region according to the analysis of Kleinpenning *et al.* [11] for conventional silicon devices. This proves that the oxide layer over the extrinsic region acts as a very efficient passivation and confirms that the extrinsic regions do not significantly contribute to the LF noise compared with previous unpassivated HBT's [3].

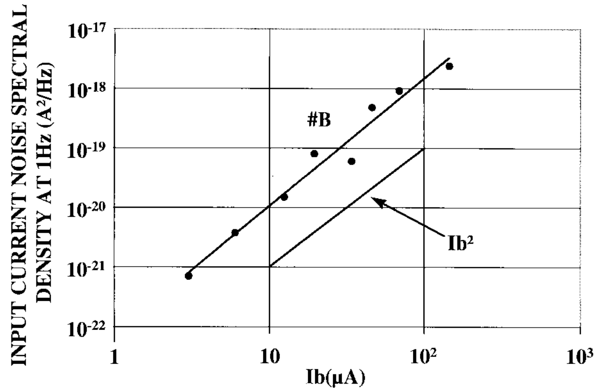

Fig. 5. Input current noise spectral density at 1 Hz versus base current for a #B sample biased at $V_{ce} = 1$ V.

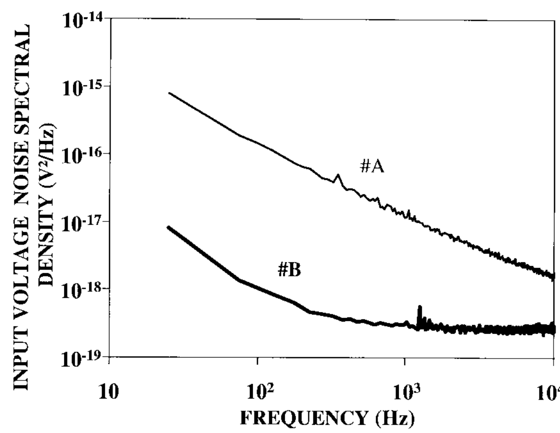

Fig. 6. Input voltage noise spectral density for #A and #B HBT samples at $Ib = 34$ μA and $V_{ce} = 1$ V from 25 Hz to 10 kHz.

C. Input Noise–Voltage Generator

We will now investigate the input noise–voltage data. The *Sen* spectra observed on #A and #B ($Ib = 34$ μA) samples are displayed in Fig. 6. It shows that #A samples exhibit greater noise levels than #B ones. The latter device features both a lower $S_{\rm ieb}^{1/f}$ (see Fig. 6) and a lower base resistance $r_{bb'}$, which impacts on $S_{\rm ieb}$ [see (4)] and r'_b and, subsequently, on S_{en} as expected from (2). Using $S_{\rm ieb}^{1/f}$ provided by noise–current measurements and (2), we can achieve a rough fit of S_{en} from static parameters only while neglecting $Si_{ec}^{1/f}$, $S_{\rm rbb'}^{1/f}$, and $S_{\rm ree}^{1/f}$. It turns out that the flicker noise $S_{\rm ieb}^{1/f}$ produced at the emitter base junction is the predominant excess noise source in our devices. However, the other noise sources should be taken into account if a better fit of S_{en} is needed. Work is in progress to identify their physical origins.

D. Performance Evaluation

From the spectra displayed in Fig. 7, we have extracted the voltage (f_{cv}) and current (f_{ci}) excess noise corner frequencies for the #B sample biased at $Ib = 3$ μA (the minimum current needed for an $f_{\rm max}$—see the following section—beyond 10 GHz). The obtained values of $f_{ci} = 1$ kHz and $f_{cv} = 250$ Hz outperform results measured on III–V HBT's [6].

Finally, a comparison of these current LF noise data with respect to other bipolar technology can be performed

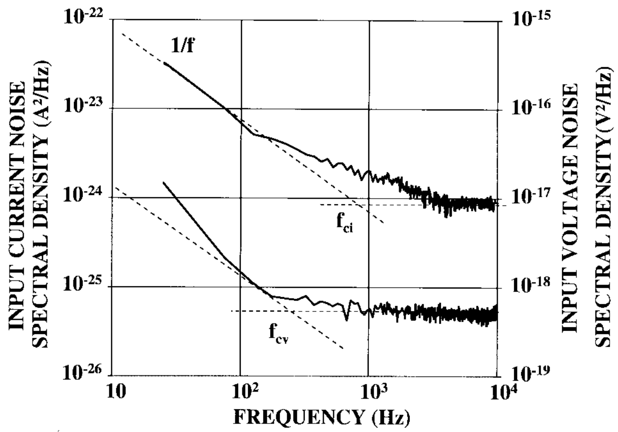

Fig. 7. Input current and voltage noise spectral density for a #B HBT sample at $Ib = 3$ μA and $V_{ce} = 1$ V from 25 Hz to 10 kHz.

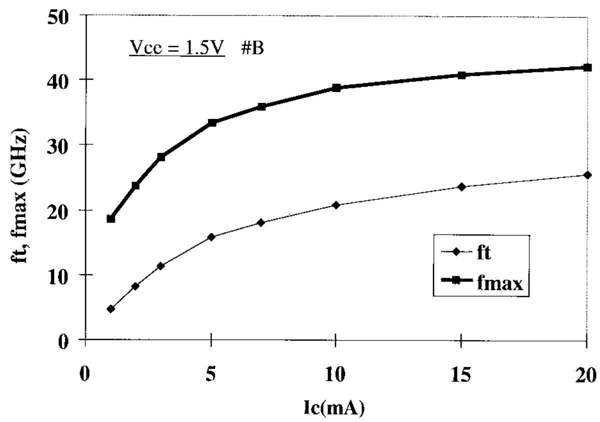

Fig. 8. Microwave performance of #B sample versus collector current.

through a $1/f$ coefficient K derived from the input referred noise–current generator [13]. This coefficient can be defined as $K = (f \cdot S_{\rm ieb}^{1/f} \cdot Ae/I_b^2)$.

For the device #B, K can be extracted from Fig. 4, yielding a value of $8 \cdot 10^{-9}$ μm^2. Different measurements [14] on similar silicon SiGe HBT's have shown values as low as 2.6 $\cdot$ 10^{-10} μm^2. Other authors have reported $2 \cdot 10^{-9}$ μm^2 on UHV/CVD-grown SiGe HBT's [5] and $4 \cdot 10^{-9}$–$20 \cdot 10^{-9}$ μm^2 for Si bipolar junction transistors (BJT's) [13], [15]. These K-values of silicon-based bipolar transistor are more than an order of magnitude lower than the best-reported AlGaAs/GaAs results [11], [16]. The reason is the high-quality oxide passivation only available on silicon.

V. Phase-Noise Properties

The LF noise of an active device, which is converted into phase noise by the devices nonlinear elements, heavily impacts on the microwave close to carrier performance. Three different noise figures can be considered to evaluate the suitability of an active device for low phase-noise applications:

1) equivalent input LF noise;
2) microwave residual phase noise near the carrier for an open loop configured device (i.e., the added phase noise when the device is operated as a microwave amplifier);
3) near-carrier oscillator microwave phase noise.

In Section IV, we have already investigated the LF noise performance. We will now examine the other two noise figures. First, the S-parameters were measured from 100 MHz to 18 GHz. After an appropriate package deembedding, the cutoff frequency ft and the maximum frequency oscillation $f_{\rm max}$ have been extracted versus bias as reported in Fig. 8 (for #B sample). The obtained maximum values of 42 GHz $(f_{\rm max})$ and 25 GHz (ft) at $Ic = 20$ mA shows that these devices are suitable for microwave and millimeter-wave oscillators.

Through appropriate cross-correlation phase-noise measurement techniques [17], residual phase-noise measurements have been performed at 10 GHz and low input power $(P_{\rm in} < 0$ dBm). The devices are embedded in a coaxial test fixture and placed between two 50-Ω isolators. Additionally, the device input sees a short circuit at low frequencies in order

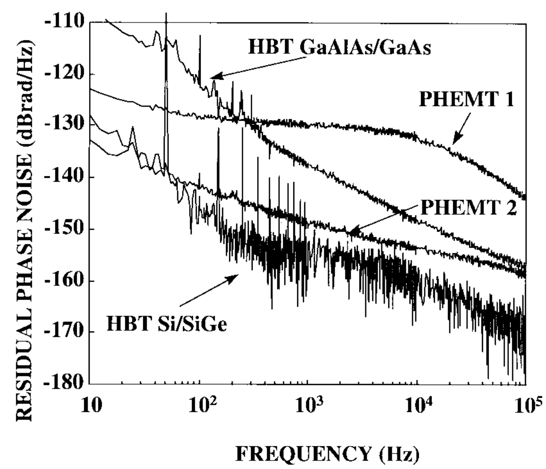

Fig. 9. Measured residual phase noise at 10 GHz for #B SiGe HBT's ($Ic = 26.1$ mA and $V_{ce} = 0.5$ V) and other microwave devices (GaAlAs/GaAs HBT and GaAlAs/GaInAs PHEMT's).

to enhance the input noise–voltage influence over the current noise since the former one has the lowest corner frequency. This technique has already been used successfully to improve the phase noise of other HBT oscillators, as described in [18] and [19]. In Fig. 9, the measured residual phase-noise spectra are shown, both for the #B sample and other more conventional microwave devices, for comparison purposes. In fact, the SiGe HBT data is not far from the test-set noise floor as is observed from the noisy curve which is typical of the limit of the cross-correlation technique. However, the residual phase noise at 10-kHz offset can be evaluated to be less than -160 dB $\cdot$ rad/Hz. This outperforms the best III–V HBT's, high electron-mobility transistor (HEMT), and pseudomorphic high electron-mobility transistor (PHEMT) data obtained in the same conditions in our laboratory.

The current concern is to determine if such an attractive additive phase-noise performance is corroborated by low oscillator phase noise. A 4-GHz parallel feedback oscillator has been built using a resonator with a moderate loaded Q factor of 160. The control of the loop gain and phase shift have been achieved through a variable attenuator and a variable length line, respectively. The phase-noise test set is a delay

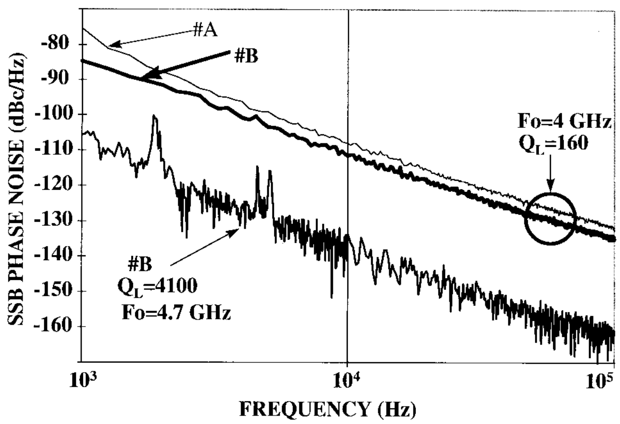

Fig. 10. Phase-noise spectra of SiGe HBT's at different bias conditions. $Fo = 4$ GHz, $Q_L = 160$, #A at $Ib = 104$ μA, $Ic = 10.4$ mA, and $V_{ce} = 2.5$ V. $Fo = 4$ GHz, $Q_L = 160$, #B at $Ib = 165$ μA, $Ic = 19.4$ mA, and $V_{ce} = 1.6$ V. $Fo = 4.7$ GHz, $Q_L = 4100$, #B at $Ib = 280$ μA, $Ic = 25.6$ mA, and $V_{ce} = 2.9$ V.

discriminator and is described in [20]. The single sideband (SSB) phase-noise measurements were carried out both on a #A and #B sample for offset frequencies ranging from 1 to 100 kHz, as reported in Fig. 10. The displayed phase-noise spectra show that the #B sample features a lower phase-noise magnitude than the #A sample, as expected from the previously reported LF noise data. Note that the minimum near-carrier spectra slope of −20 dB/decade is observed in the highest offset frequency range only (beyond 10 kHz), and thus, denotes some excess noise up-conversion below a 10-kHz corner frequency. The observed phase-noise corner frequency does not corroborate the LF noise–voltage corner frequency of about 300 Hz, as observed in Fig. 6. However, the transistor in the oscillator circuit is biased at higher collector current levels (about 20 mA) in order to reach the small-signal gain necessary for the oscillation start up. Other reasons for this discrepancy may be an enhancement of the LF noise when the transistor is operated in large-signal conditions [20] or an improper noise–current decoupling.

In order to further improve the oscillator phase noise, we have designed a dielectric resonator oscillator (DRO) using a Murata resonator featuring a loaded Q of 4100 at 4.7 GHz. To be able to characterize the phase noise of such a high-Q oscillator, the delay-line discriminator noise floor must be improved. This is easily done by using a similar high-Q resonator in place of the delay line in the discriminator. A phase-noise magnitude of about −135 dBc/Hz at 10-kHz offset frequency has thus been measured and, once again, the test set noise floor is reached (the extrapolated phase noise using the data obtained with the first lower Q factor resonator is close to −140 dBc/Hz at 10 kHz). However, this result is, to our knowledge, the best value obtained for FET and HBT room temperature ceramic DRO's [21], [22].

VI. Conclusion

This paper reports on the LF noise performance of microwave MBE SiGe HBT's with a low-voltage excess-noise corner frequencies down to 250 Hz. Residual X-band phase-noise measurements (<-160 dB · rad/Hz at 10-kHz offset) confirm the very attractive capabilities of SiGe HBT's for low phase-noise applications. Finally, we have realized a C-band microwave oscillator with a phase-noise performance better than −135 dBc/Hz at 10-kHz offset frequency. This is one of the highest spectral purities ever observed on a microwave solid-state oscillator. Since a maximum oscillation frequency beyond the 40-GHz range has already been demonstrated on these devices, they will be able to provide ultra-low phase-noise millimeter-wave sources in the future.

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