Low Phase-Noise GaInP/GaAs-HBT MMIC Oscillators up to 36 GHz

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***Abstract* — Monolithic coplanar 18 and 36 GHz oscillators with GaInP/GaAs-HBTs and on-chip resonators are presented. Measured phase-noise reaches -93 dBc/Hz and -91 dBc/Hz at 100 kHz offset for 18 and 36 GHz, respectively. These values demonstrate that GaAs-HBT oscillators yield a phase-noise performance comparable to SiGe-HBTs, with the potential for higher frequencies.**

I. INTRODUCTION

Low phase-noise oscillators are key components in communication as well as in sensor systems. In order to meet the low-cost requirements, monolithically integrated solutions (MMICs) with on-chip resonators are highly favorable. Since the quality factors of such circuits are low, however, this demands for transistors with extremely low 1/f-noise.

Traditionally, Si bipolar junction transistors offer the lowest noise levels. But these devices are restricted to the lower GHz range and cannot cover the emerging wireless market for frequencies beyond 20 GHz up to 77 GHz. The GaAs HEMT, on the other hand, reaches these frequencies but yields only moderate phase-noise levels due to its high 1/f noise (see, e.g. [1]).

Recent work brought changes to this situation in two ways: First, the SiGe-HBT pushed the frequency limits of MMICs on low-resistivity Si to 30 GHz [2,3,4], at SSB phase-noise levels in the -90 dBc/Hz range at 100 kHz offset (for high-resistivity substrate, the record value is 47 GHz [5]). Second, the InGaP/GaAs HBT, which exhibits considerably less 1/f noise than the HEMT, opened new possibilities for GaAs-based MMICs. So far, however, only few results were published. Uchida et al. [6], for instance, reports a frequency as high as 106 GHz, though at larger phase-noise (-88 dBc/Hz at 1 MHz offset). In the 40 GHz range, which is of special interest for wireless links, phase-noise values between -80 and -89 dBc/Hz were achieved for GaAs-HBT MMICs [7].

Beyond this, the objective of the present paper is a twofold one:

(i) To exploit the phase-noise potential of mm-wave MMIC oscillators with InGaP/GaAs HBTs fabricated on a 4" industry-compatible process line.

(ii) To assess usefulness and accuracy of the microwave CAD environment for phase-noise optimization.

II. PROCESS TECHNOLOGY

The MMICs presented here are based on the 4 inch GaAs-HBT process at the FBH. The epitaxial HBT design consists of a 55 nm n-InGaAs graded emitter-contact layer, a 100 nm thick n-GaAs layer, a 30 nm n-InGaP emitter, and a 100 nm uniformly doped p-GaAs base layer (4×10^{19} cm^{-3}). The HBT structure is completed with a 1000 nm thick n-GaAs collector, a 20 nm n-GaInP etch stop layer and a 700 nm thick n^{+}-GaAs subcollector.

Device processing starts with emitter metalization, followed by emitter-base mesa etching and base metalization. Then the base-collector mesa is etched and He^{+}-implantation is employed to achieve isolation between devices. Finally, the collector contact is realized (for process details, see [8,9]). Fig. 1 presents a REM photo of the HBT after collector metalization showing the double mesa approach of the base-collector mesa in order to minimize the parasitic base-collector capacitance.

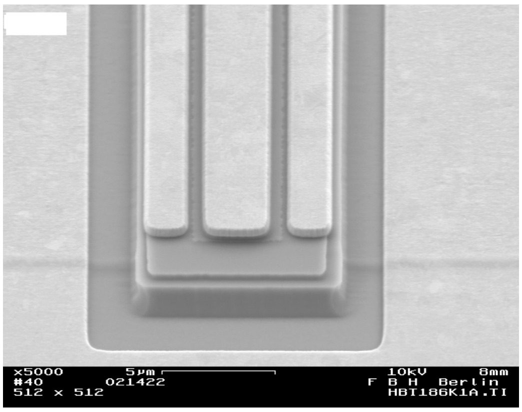

Fig. 1: REM photo of 1x3x30 µm^2 HBT after collector metalization

DC measurements yield an average gain β_{max} over a 4-inch wafer of 120 at an intrinsic base resistance R_{SBI} of 215 Ω/sq. The corresponding β_{max}/R_{SBI} ratio of

$0.56\ (\Omega/\mathrm{sq})^{-1}$ indicates both excellent epitaxial material and device process. An f_{max} above 95 GHz is obtained. To suppress recombination at the surface of the GaAs-base-layer a fully depleted GaInP legde technology is applied.

The MMIC process includes additional layers providing SiN_x MIM-capacitors, NiCr thin-film resistors, and air-bridges. The electroplated Au metalization is 3 µm thick. The circuits are realized as coplanar MMICs, thus back-side processing is not required.

III. MODELING

All circuit elements are embedded in a coplanar environment. The passive element library was developed using the CPW model of [10] and electromagnetic simulation in conjunction with measurements up to 50 GHz.

To describe the $1\mathrm{x}3\mathrm{x}30\ \mu m^2$ HBT, a standard Gummel-Poon model is used. The extrinsic elements are extracted from S-Parameter measurements, while output characteristics and Gummel plots provide large signal model data. Nonlinear and phase-noise analysis is performed using MDS from Agilent. The 1/f-noise parameters AF and KF are extracted from 1/f-noise measurements of the HBT device, accounting for the restrictions of the model implemented, i.e., that only a single 1/f-noise source located at the base-emitter terminal is included.

Additionally, for reference calculations of oscillation frequency and output power, an in-house large-signal model is applied [11].

IV. CIRCUIT DESIGN

In order to cover a broad range of frequencies, oscillators for 18 and 36 GHz were fabricated. Moreover, to investigate the influence of bias circuitry on phase-noise performance, biasing of the 18 GHz type is designed both in common-base (CB) and common-emitter (CE) configuration with the microwave-relevant part remaining unchanged.

The MMICs are designed as negative-resistance circuits. The 36 GHz type contains only distributed elements, while the 18 GHz oscillator uses both distributed and lumped ones. This is in order to keep the 18 GHz oscillator layout as small as possible and to improve the circuit's Q-factor by choosing the spiral inductor. The 50 ohm CPW with 50 µm ground-to-ground spacing yields a Q-factor of 20 at 18 GHz, while the 1.5 turn spiral inductor offers a higher value.

Figs. 2 and 3 provide chip photos of the two MMIC oscillator versions. For oscillator and phase-noise simulation, the MDS built-in tools are employed, which are based on the harmonic balance method.

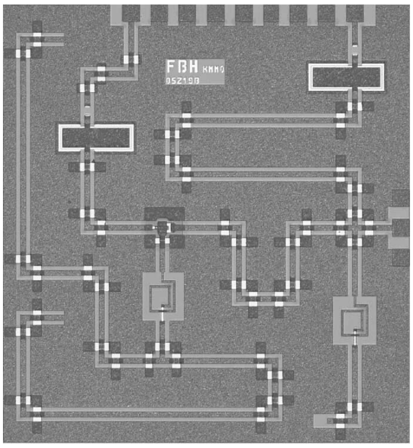

Fig. 2: Chip-photo of the 18 GHz MMIC oscillator (common-emitter bias, size: $1.45 \times 1.55\ \mu m^2$).

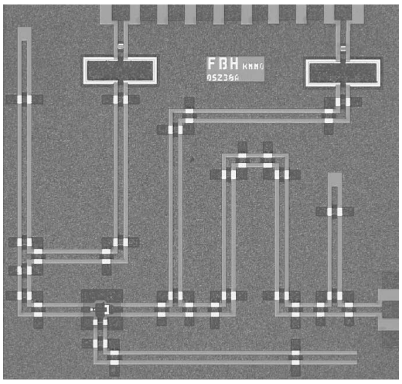

Fig. 3: Chip photo of the 36 GHz MMIC oscillator (common-emitter bias, size: $1.42 \times 1.34\ \mu m^2$).

V. RESULTS

A total of 3 oscillator types were investigated: the 18 GHz circuit with common-base (CB) and common-emitter (CE) bias and the 36 GHz circuit (CE bias). All three types exhibit excellent stability. The measured output power is 6 dBm for the 18 GHz circuits and 0 dBm for the 36 GHz oscillators.

We found that simple phase-noise measurements by means of the spectrum analyzer yield a good estimate but are limited in accuracy. Therefore, the frequency discriminator method is applied. The MMIC oscillator output is mixed with a reference source (LO) and thus downconverted to the frequency range of the HP11848 Phase Noise Interface input (1.2 GHz...18 GHz); for details see [12]. Tab. 1 summarizes measured phase-noise values of the 3 circuits at 100 kHz offset frequency.

TABLE 1:
MEASURED SSB PHASE-NOISE VALUES

type	SSB phase-noise [dBc/Hz] at 100 kHz offset
18 GHz (CE)	-93
18 GHz (CB)	-75
36 GHz (CE)	-91

This data indicate that the common-emitter bias configuration reduces phase-noise compared to the common-base version, which is in line with [7]. Moreover, one observes a considerable deviation between measured and simulated phase-noise. A more detailed study shows that the results obtained by different simulators (Agilent MDS and Ansoft SERENADE) do not coincide neither. Also, it is not only the values at a fixed frequency that differ [13], but the simulators partly fail to describe frequency dependence correctly.

These discrepancies are the subject of further investigations. So far, it is clear that this is not due to the simplified HBT noise model (i.e., the approximation by only a single 1/f noise source – see [14]), because simulations are performed using two LF noise sources.

Beyond the phase-noise values at 100 kHz offset, it is important to study the frequency dependence in a broader range. This allows one, for instance, to separate the influence of the HBT properties, such as 1/f-noise, on one hand and of the circuit's Q-factor on the other hand. Figs. 4 and 5 present the relevant data for the 18 GHz and the 36 GHz CE oscillator.

In both cases, the curves exhibit a distinctive $1/f^3$ characteristic up to about 100 kHz offset frequency, which can be attributed to upconverted 1/f noise [15,16]. This range is followed by a transition region, which shows up more clearly for the 36 GHz oscillator, and finally a $1/f^2$ section. In the latter regime, noise magnitude does not depend on the transistor LF noise, but on the Q-factor of the circuit. The 18 GHz oscillator exhibits lower phase-noise in this $1/f^2$ region in comparison to the 36 GHz type, which can be attributed to its higher Q-factor.

The phase-noise values at 1 MHz offset are -117 dBc/Hz and -114 dBc/Hz, respectively. One observes that the HBT 1/f-noise is dominant in these oscillators up to about 100 kHz offset frequency, which is a value considerably larger than that in [7].

Additionally, in Figs. 4 and 5 the transformed low-frequency (LF) HBT device noise curves are plotted. They are generated by scaling the measured LF noise magnitude with a fitting factor and multiplying it by the appropriate offset-frequency dependence ($1/f^2$). Despite the simple approximation, one finds good agreement in the low-frequency region, which highlights the influence of the LF device noise on phase-noise.

The data of Figs. 4 and 5 also provide guidelines for improving phase-noise performance: Because at offset frequencies of 100 kHz and beyond the upconverted white noise prevails, further optimization should focus on the passive part of the circuit, i.e., on increasing the Q factor. Though the Q factor of the on-chip elements is restricted, this leaves room for some improvement. Of course, a systematic investigation requires first the simulation accuracy problems to be clarified.

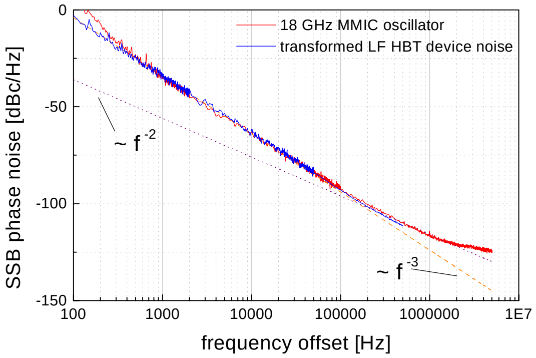

Fig. 4: Measured SSB phase-noise of 18 GHz MMIC oscillator (CE type).

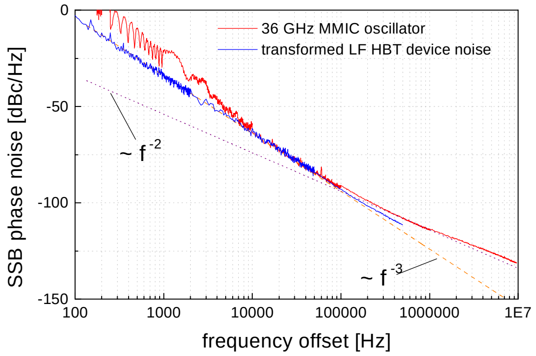

Fig. 5. Measured SSB phase-noise of 36 GHz MMIC oscillator (CE type).

VII. CONCLUSIONS

GaInP/GaAs-HBT MMIC oscillators for 18 GHz and 36 GHz with excellent phase-noise exceeding -90 dBc/Hz at 100 kHz offset were fabricated on a standard 4-inch HBT-MMIC process line. These results demonstrate that the GaAs-HBT indeed is the active element of choice when realizing low phase-noise mm-wave sources. It combines the superior 1/f-noise properties of the HBT with the high-frequency potential of GaAs-based transistors and the advantages of the semi-insulating GaAs substrate compared to standard low-resistivity Si.

The HBT low-frequency noise is found to be the major contributor to the oscillator phase-noise up to about 100 kHz offset frequency. At higher frequencies, the passive elements dominate the behavior. This finding leaves room for further optimizing.

A basic problem, however, is accuracy of the phase-noise description in the common commercial simulators. This requires in a first step improvements in terms of the low-frequency HBT noise model [14].

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