Modeling of Low-Frequency Noise in GaInP/GaAs Hetero-Bipolar Transistors

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***Abstract* — Accurate low-frequency noise modeling is a prerequisite for oscillator phase-noise simulation. In this paper, the LF noise sources of GaInP/GaAs HBTs are investigated. It turns out that the 1/*f*-noise model must contain two sources, the base-emitter diode and the emitter resistance. Quantitatively, excess noise power at 100 kHz scales with the square of collector current-density.**

I. INTRODUCTION

Heterojunction bipolar transistors (HBTs) play an increasing role as active devices for microwave oscillators due to their high maximum frequency of oscillation f_{max} in the order of 100 GHz and their good LF noise characteristics. These features make them excellent candidates for low phase-noise oscillator MMICs up to millimeter wave frequencies [1, 2, 3]. Several authors have shown that GaInP/GaAs and Si/SiGe are favorable material systems due to the low level of generation-recombination noise [4, 5].

In order to achieve highest performance of integrated oscillators, considerable efforts in circuit design and device technology are necessary. These require a detailed knowledge of the LF noise characteristics of the HBT, both for device technology optimization and for phase-noise simulation of an oscillator.

For process development, it is important to know where the LF noise is generated in the device physically in order to reduce its magnitude. For circuit simulation, on the other hand, one needs an appropriate noise description. In this case, the questions are: which is the minimum number of noise sources required and where in the circuit topology one should locate them?

This paper is to contribute to both aspects. We present an investigation of LF noise in state-of-the-art GaInP/GaAs HBTs extracting the effective noise sources of the equivalent circuit from measurements. The aim is a comprehensive scaleable LF noise model for microwave oscillator phase-noise or mixer design.

II. NOISE MODEL

Starting point is the high-frequency microwave noise model [6], which generally holds also for low-frequency noise. When considering this frequency range, however, situation changes in two ways. On the one hand, there are simplifications of the network as frequency approaches DC ($j\omega C \to 0$, $j\omega L \to 0$). On the other hand, the nature and the correlation between the LF excess noise sources appears to be more difficult to describe. The main question is: Where in the equivalent-circuit network are the most important noise sources located? Under what external circuit condition do they contribute to port noise?

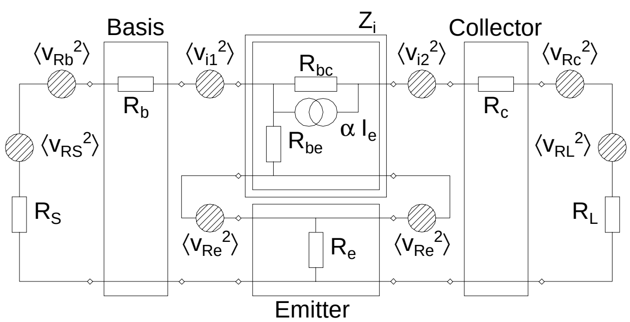

Fig. 1. HBT common-emitter noise equivalent circuit. The total noise voltage spectral density is measured at $R_L = 50\ \Omega$ with $10\ \Omega \le R_S \le 10\ \text{k}\Omega$.

The noise equivalent circuit is depicted in Fig. 1. The structure is adapted to the common noise correlation-matrix formalism. In a first step, we start with the most general description, i.e., with all possible noise sources. The intrinsic transistor is represented by the two series noise voltage-sources $\langle v_{i1}{}^2\rangle$ and $\langle v_{i2}{}^2\rangle$. They are related to the noise current-sources associated with the base-emitter $\langle i_b{}^2\rangle$ and collector-emitter $\langle i_c{}^2\rangle$ currents, respectively, by

$$\begin{aligned}\left\langle v_{i1}^2\right\rangle &= \left|Z_{i11}\right|^2\left\langle i_b^2\right\rangle + \left|Z_{i12}\right|^2\left\langle i_c^2\right\rangle,\\ \left\langle v_{i2}^2\right\rangle &= \left|Z_{i21}\right|^2\left\langle i_b^2\right\rangle + \left|Z_{i22}\right|^2\left\langle i_c^2\right\rangle\end{aligned} \quad (1)$$

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where Z_i is the impedance matrix of the intrinsic transistor. The correlation of $\langle i_b^2 \rangle$ and $\langle i_c^2 \rangle$ is determined by the base transit time and thus is effective only in the microwave range [6]. The noise voltage-sources of the entire device, including the parasitic resistances R_b, R_e, and R_c, are obtained by eqn. (2):

$$\begin{aligned} \langle v_{tot1}^2 \rangle &= \langle v_{i1}^2 \rangle + \langle v_{Rb}^2 \rangle + \langle v_{Re}^2 \rangle \\ \langle v_{tot2}^2 \rangle &= \langle v_{i2}^2 \rangle + \langle v_{Rc}^2 \rangle + \langle v_{Re}^2 \rangle \end{aligned} \qquad (2)$$

Accordingly, the contribution of all sources to the total noise current in the collector is:

$$\langle i_{RL}^2 \rangle = \left(\frac{|A|}{R_L} \right)^2 \Big\{ |B|^2 \left(\langle v_{RS}^2 \rangle + \langle v_{tot1}^2 \rangle \right) + \langle v_{RL}^2 \rangle + \langle v_{tot2}^2 \rangle + 2\,\mathrm{Re}\left(B \langle v_{tot1} v_{tot2}^* \rangle \right) \Big\} \qquad (3)$$

$$A = \left(\frac{Z_{21} Z_{12}}{(R_S + Z_{11}) R_L} - \frac{Z_{22}}{R_L} - 1 \right)^{-1}, \; B = \frac{-Z_{21}}{R_S + Z_{11}}$$

Eqn. (3) provides the noise current at the output for any value of R_S and R_L, where Z denotes the impedance matrix of the entire transistor. It is related to the noise spectral density S_k by

$$S_{Ic} = \frac{\langle i_{RL}^2 \rangle}{\Delta f} \quad \left(\frac{\mathrm{A}^2}{\mathrm{Hz}} \right). \qquad (4)$$

Measuring S_{Ic} for a set of source resistances R_S one can determine the influence of each source and extract its parameters. This corresponds to the well-known source-pull technique in the microwave range. Quantitatively, R_S must be related to the input resistance of the transistor

$$R_{in} \approx R_b + (R_{be} + R_e)\beta \quad , \qquad (5)$$

which is in the range 100…200 Ω for the single-finger GaInP/GaAs-HBTs under consideration here.

The two extreme cases of R_S are known from the literature [7]. At high values ($R_S = 10$ kΩ, input open-ended) the noise of the base-emitter diode dominates:

$$S_{Ic} = \beta^2 S_{Ib} \qquad (6)$$

In the opposite case, with short-circuited input ($R_S = 10$ Ω), there is only the resistance noise effective because the base-emitter diode is short-circuited.

$$S_{Ic} = \left(\frac{AB}{R_L} \right)^2 S_{VR} \qquad (7)$$

It remains to be clarified whether these two sources are already sufficient. The second and even more important question is that of the nature and parameter-dependence of the resistance noise sources. Therefore, in the next section the LF noise generated in resistances consisting of semiconductor material is studied in more detail.

III. Resistance and Diode Noise

It is clear that parasitic resistances contribute thermal noise. Less well-known is the fact that they generate 1/*f*-noise as well. According to the Hooge relation [8] the total noise power reads:

$$S_{VR} = 4kTR + \frac{\alpha \; R^2 I^2}{N} \frac{1}{f} \qquad (8)$$

Here α denotes the Hooge parameter, which is in the range of 10^{-6}…10^{-3}. N is the total number of carriers involved in the current through the bulk material that forms the resistance R. The level of the resistor 1/*f*-noise is determined by α, which can be extracted from measurements. On the other hand, its order of magnitude is known and together with the knowledge of N from device layout and layer doping, the 1/*f*-term can be calculated. Both results must be in reasonable agreement.

For the diode, the equivalent noise-power spectral density is well known. It consists of three terms: 1/*f*-noise, shot noise, and generation-recombination noise. According to the notations in commercial CAD software we write for the base-emitter diode:

$$S_{Ib} = KF \frac{I_b^{AF}}{f^{FB}} + 2qI_b + KL \frac{I_b^{AL}}{1 + \left(\frac{f}{FL} \right)^2} \qquad (9)$$

The exponents associated with the current, AF and AL, are determined by the nature of the spontaneous fluctuations. For dominant surface recombination, $AF \cong 2$ is expected. $AL \cong 0.8$ is a typical value if the last term is to describe trap effects in the emitter. The time constant of trapping and detrapping determines FL. The constants KF and KL must be extracted from measurements.

IV. LF Noise Measurements

A. Resistance Test Structure

In order to validate the assumption that resistances are an important source of 1/*f*-noise in GaAs HBTs, we fabricated test structures on the same wafer together with the transistors. The wafer processing steps enable the fabrication of n- and p-conducting resistor types. The first one consists of the subcollector layer (GaAs:Si, $n = 5\times10^{18}$ cm^{-3}), the second type is formed by the base layer (GaAs:C, $p = 4\times10^{19}$ cm^{-3}). A typical noise current spectrum is plotted in Fig. 2. The n-material shows only 1/*f* and thermal noise and can be described by a quadratic current dependence and a meaningful value $\alpha = 1\times10^{-5}$. The highly C-doped base layer, on the other hand, exhibits 1/*f*-noise with $\alpha = 1\times10^{-4}$ and several generation-recombination levels. This corresponds to observations of other authors [9]. The evolution with current is also quadratic.

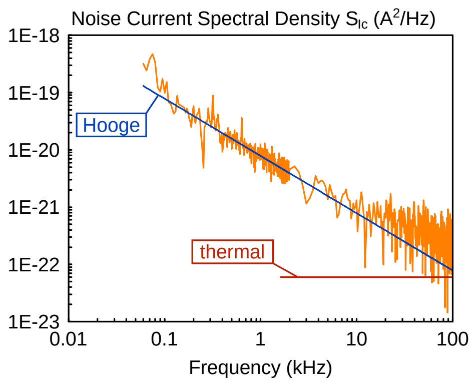

Fig. 2. Resistor excess noise $R = 300\ \Omega$, $I = 28$ mA. N-conducting subcollector material: $l = 100\ \mu$m, $w = 5\ \mu$m, $t = 0.7\ \mu$m, $n = 5\times10^{18}$ cm^{-3}. Straight lines: Hooge relation with $\alpha = 1\times10^{-5}$ and $4kT/R$.

B. The HBT

The transistor layout is determined by the microwave application. Usually, devices are available in common-emitter configuration in a coplanar environment on-wafer. In our case, they are fabricated in-house in an industrial 4-inch process on GaInP/GaAs-MOCVD material. Typical data are: emitter area $A_e = 3\times30\ \mu\text{m}^2$, ledge configuration, current density $J_c = 1\times10^4$ A/cm^2, $f_t = 38$ GHz, $f_{max} = 100$ GHz, current gain $\beta = 120$. The parasitic resistances are small: $R_b = 7\ \Omega$, $R_e = 4\ \Omega$, $R_c = 1\ \Omega$.

The noise voltage is measured at the output across a 50-Ω bias resistor. Due to the high broadband gain, precautions for avoiding device oscillations are very important. We measured the output noise spectra with seven source resistances between 10 Ω and 10 kΩ (source pull). Based on this data, the parameters of all sources of the noise model were obtained by a direct extraction algorithm. The equivalent circuit elements are determined from *S* parameters in exactly the same way as for the microwave frequency range. VNA measurements down to 10 kHz are recommended. Measurements examples are shown in Fig. 3.

V. Parameter Extraction

A. The Frequency Dependence

Figs. 3(a) and 3(b) present the frequency dependence of the collector noise-current spectral density for the extreme input cases open and short, respectively. In the first case, the noise spectrum is determined by the base-emitter diode only, and no other source is involved. In the second case, the noise originates entirely from the emitter resistance. From both input states, the parameters of (8) and (9) can be extracted.

B. The Current Dependence

An important criterion for the usefulness of the noise model is that the coefficients of the noise sources do not depend neither on current nor on frequency. Thus, one set of parameters extracted at a specific current must yield the noise levels at other currents of interest as well. Also, the evolution of noise power with current in certain frequency

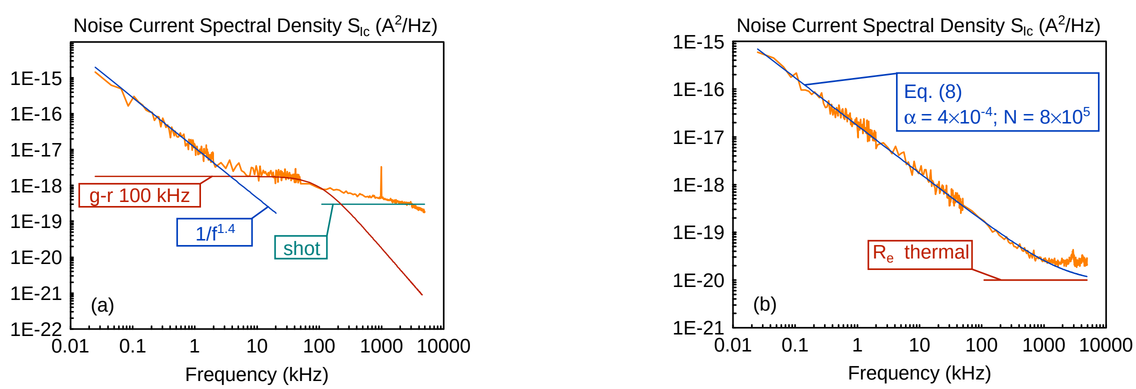

Fig. 3. HBT collector current noise spectra S_{Ic} as a function of frequency ($3\times30\ \mu\text{m}^2$; $V_{ce} = 3$ V, $I_c = 10$ mA, $\beta = 120$).
(a) $R_S = 10$ kΩ; $S_{Ic} = \beta^2 S_{Ib}$ is only the amplified noise of the base-emitter diode.
(b) $R_S = 10\ \Omega$; S_{Ic} is only the amplified noise of the emitter resistance $R_e = 4\ \Omega$.
Parameters of the model calculation (8), (9) are: $\alpha = 4\times10^{-4}$, $N = 8\times10^5$, $AF = 2.3$, $AL = 0.8$, $KF = 3\times10^{-8}$, $KL = 2\times10^{-19}$ cm, $FB = 1.4$, $FL = 100$ kHz.

ranges must agree with physical considerations. Examples are: The 1/*f*-noise of resistances has a quadratic current dependence. The white shot noise in the high frequency limit scales linearly with the current. The generation-recombination level has an exponent of 0.8. All these dependencies could be verified by our measurements. It is important to note that the current dependence of the output noise is not exactly that of the sources itself, because the non-linear transistor elements change with bias current as well.

VI. Consequences for CAD

Measurements of S_{Ic} of HBTs in common-emitter configuration with different R_S values and at different currents allow the decomposition of all relevant noise sources. It turns out, however, that the two extreme values ($R_S >> R_{in}$ and $R_S << R_{in}$) are sufficient because the contributions come only from the base-emitter diode and from the emitter resistance R_e. No other LF noise sources must be accounted for; even the base-collector diode can be neglected. The experimental data show a distinct dependence of S_{Ic} on collector current density. Fig. 4 displays the data for HBTs with varying emitter size and layout. The normalized noise power clearly follows a quadratic rule with regard to collector current density. This closely suggests that further reduction of the LF noise level can be achieved by increasing the emitter area and keeping the device current as low as possible.

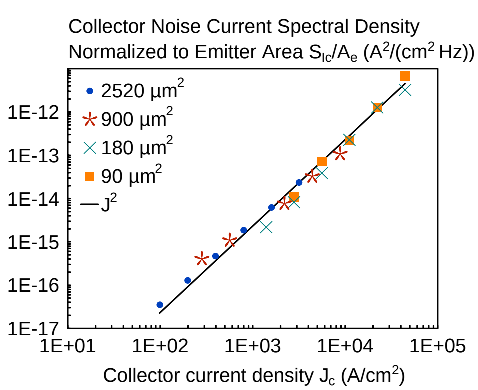

Fig. 4. Collector noise current spectral density at $f = 100$ kHz normalized to emitter area A_e as a function of collector current density J_c for different emitter areas.

VII. Conclusions

State-of-the-art GaInP/GaAs microwave HBTs with f_{max} around 100 GHz exhibit excellent LF noise properties. Regarding modeling one can state: two LF noise sources are required for the complete description of excess noise in the output current. Note that most HBT CAD-models do not account for resistor 1/*f*-noise. These two noise sources are:

(i) The base-emitter diode with 1/*f*, g-r, and shot noise, and

(ii) the extrinsic emitter resistance with 1/*f* and thermal noise.

Our investigations show that the coefficients for a quantitative modeling of these sources can be extracted from source-pull measurements with two input bias resistances.

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