A Novel Approach to HF-Noise Characterization of Heterojunction Bipolar Transistors

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Abstract

We present a numerical HF noise analysis of $Si/Si_{1-x}Ge_x/Si$ heterojunction bipolar transistors based on the time-dependent solution of the drift-diffusion equations. For the MHz range an analytical expression for the noise figures is derived.

1. Introduction

$Si/Si_{1-x}Ge_x/Si$ heterojunction bipolar transistors (HBTs) are expected to become important in certain HF applications, where the use of a single technology for the complete microwave part of the system may reduce cost [1]. Therefore, the investigation of HF noise figures (NF) of these devices is an important task. The aim of our paper is to calculate the dependence of the minimum NF on frequency and current using a two-dimensional solver for the drift-diffusion equations.

2. Theory

In [2] the authors developed a quantum statistical approach to thermal noise in semiconductor devices for arbitrary space-dependent carrier temperatures including low ones. Especially, a general expression for the NF of bipolar transistors was derived which relates the NF to the y-parameters and effective carrier temperatures. We will simplify the result of [2] by some reasonable assumptions: First, quantum statistical corrections are neglected since at room temperature the classical limit is a very good approximation. Secondly, electron heating in the collector is neglected since this effect turns out to be small for $f < f_T$. Finally, the noise generator is assumed to be at ambient temperature T. Then we obtain the NF defined as the ratio of input to output signal-to-noise ratios

$$F = 1 + \frac{e|I_B| + 2k_BT\mathrm{Re}(y_{11})}{2k_BT\mathrm{Re}(y_G)} + \frac{e|I_C| + 2k_BT\mathrm{Re}(y_{22})}{2k_BT\mathrm{Re}(y_G)}\frac{1}{|G|^2} \qquad (1)$$

with e being the elementary charge, G the current gain of the terminated fourpole, and $y_G = g_G + ib_G$ the complex generator admittance. The crosscorrelation between the noise sources i_B and i_C has been neglected since this contribution turns out to be small for $f < f_T$. If the condition $b_G = -\mathrm{Im}(y_{11})$ is fulfilled we arrive at the tuned-out NF for optimum load

$$\tilde{F} = 1 + \frac{e|I_B| + 2k_BT\mathrm{Re}(y_{11})}{2k_BTg_G} + \frac{e|I_C| + 2k_BT\mathrm{Re}(y_{22})}{2k_BTg_G}\left|\frac{\mathrm{Re}(y_{11}) + g_G}{y_{21}}\right|^2 \tag{2}$$

In this formula the tuned-out NF is expressed by the y-parameters and the direct currents. The minimum NF F_{min} is defined as the minimum of $\tilde{F}$ with respect to g_G. It is important to note that, according to the three-dimensional derivation independent of transistor geometry [2], the y-parameters refer to the whole transistor, that is, series resistances are included. Furthermore, the distributed nature of the base resistance is properly taken into account.

3. Noise Figure at High Frequencies

The calculation of the y-parameters is based on the idea to solve the drift-diffusion equations in the time domain for sufficiently small voltage perturbations applied to the base or collector contact, respectively. We use the two-dimensional device simulation code TOSCA [3]. The Fourier decomposition of small-signal voltages and currents is performed as postprocessing. This approach may give an advantage over solving the equations in the frequency domain, especially, if a great number of points in the frequency domain is required as in our case. In contrast to many other HF noise models, the input for the simulation are device geometry and doping profiles instead of circuit element values. Thus, our approach is closely related to the technological process. Geometry and doping profile of our $\mathrm{Si}_{1-x}\mathrm{Ge}_x$-HBT model device are represented in Fig. 1 and Fig. 2.

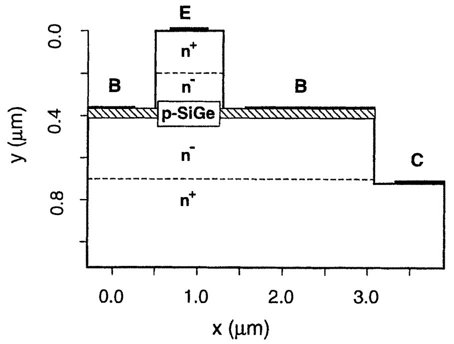

Figure 1: Geometry of the model device.

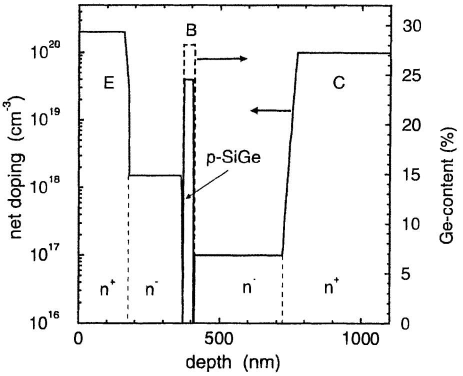

Figure 2: Vertical profile.

The sheet resistance of the base amounts to 700 Ω/□. Maximum transit frequency of f_T=46 GHz is reached at collector current of about 10 mA and f_{max} amounts to 120 GHz. In Fig. 3 F_{min} and associated gain are plotted versus frequency for different

Ge contents.

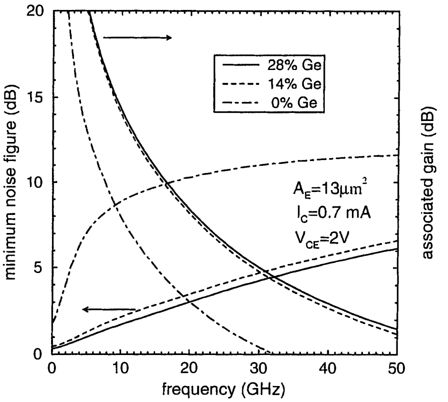

Figure 3: Minimum NF and associated gain versus frequency

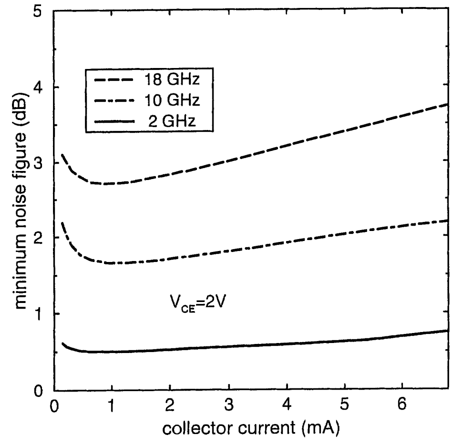

Figure 4: Minimum NF versus collector current.

This figure illustrates the noise reducing influence of Ge both at medium and high frequencies. Furthermore, we realize that for our reference device (28% Ge) the static limit applies for frequencies f <1GHz. Looking at Fig. 4 we see that the noise optimum collector current for f ≈10 GHz is about 1 mA, i.e., one order of magnitude lower than the f_T peak position. This agrees well with experimental experiences.

4. Noise Figure at Medium Frequencies

Now we are going to discuss medium frequencies (MF) where the NF is independent of frequency. In this case the NF can be calculated from the static characteristics. In order to obtain a basic understanding we use the ideal characteristics $I_{C,B} \propto exp(\Delta V_{BE}/V_T)$ with $V_T = (kT)/e$ and neglect the thermal noise contribution from the collector since it is small. With these assumptions the minimum NF in the MF range F^0_{min} can be calculated analytically as a function of the static differential current gain β_0:

$$F^0_{min} = F^0_{opt} = 1 + \frac{1}{\beta_0} + \sqrt{\frac{3}{\beta_0} + \frac{1}{\beta_0^2}} \approx 1 + \sqrt{\frac{3}{\beta_0}} . \qquad (3)$$

Note, that F^0_{min} does not depend on I_C. Hence, it equals the MF optimum NF which represents the minimum of the NF with respect to b_G, g_G and I_C as well. From Eq. (3) we conclude that at medium frequencies the static current gain is the only criterion for the optimum NF. Since the current gain of HBTs can be increased by orders of magnitude in comparison to BJTs, they are suited for low-noise amplification in the MHz range. The optimum NF as a function of current gain is shown in Fig. 5.

Additionally, we plotted the values corresponding to Hawkins' model [4].

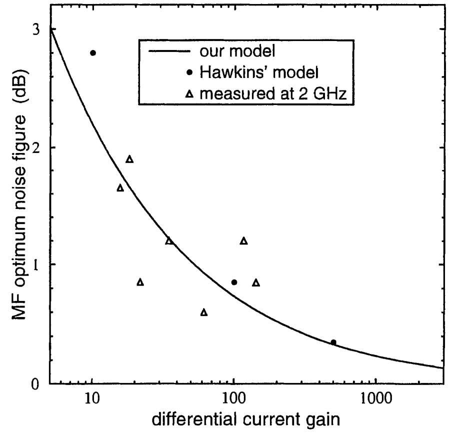

Figure 5: Optimum NF at medium frequencies as a function of static differential current gain. The circuit model values (circles) and the experimental values (triangles) are taken from [1].

The two models show a relatively good agreement. The small difference is due to the assumption of an ideal Gummel plot. Our result is identical to that resulting from Hawkins' theory for a base resistance small compared to the generator resistance.

Finally, we want to remark that our approach is not confined to simulation but also allows to extract HF noise figures at relatively little effort from small-signal parameters only.

References

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