New Extraction Algorithm for GaAs-HBTs With Low Intrinsic Base Resistance

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Abstract—**A new algorithm for extraction of the small-signal equivalent circuit elements of HBTs is presented. An analytical non-iterative approach is used in order to ensure physical significance of the extracted parameters. In order to enhance the robustness and reliability of the extraction routine, a simplified formula to determine the intrinsic base resistance R_{b2} is presented. The new algorithm is verified by extraction of GaInP/GaAs HBT equivalent-circuit elements.**

I. Introduction

Since a few years, GaAs-based HBT MMIC technology has become a mature and widely available standard technology. On the other hand, many issues of modeling and parameter extraction are still under discussion. So far, even a commonly accepted standard method to extract the small-signal equivalent-circuit parameters does not exist, although huge efforts were spent on this issue. This documents itself in the large amount of papers published recently on the topic. However, reliable extraction of the small-signal equivalent-circuit parameters remains a key issue regarding device modeling and technology monitoring.

The main difficulty of parameter extraction results from the topology of the intrinsic HBT's equivalent circuit, and from the relative value of its parameters. In addition to the elements describing the active HBT (marked A_{II} in Fig. 1), we have further bias-dependent elements describing the extrinsic base and collector regions under the base contact, which are part of the intrinsic equivalent circuit (marked A_I in Fig. 1). It turns out that the crucial part of the extraction is the determination of the intrinsic base resistance R_{b2}, in order to distinguish properly between the base-collector capacitances C_{bc} and C_{ex}, and to deembed A_I from A_{II}. The main difficulty lies in the fact that R_{b2} in state-of-the-art GaAs HBTs is significantly reduced (but still cannot be neglected). This improves HBT behavior, but makes extraction difficult.

In order to ensure physical significance of the extracted parameters, analytical algorithms are favorable over algorithms involving numerical optimizations. Also, a-priori knowledge such as technological details should not be required for extraction. However, most analytical algorithms rely on simplifications [1-7] instead of exact formulations, in order to cancel out inaccuracies and accumulation of errors in subsequent calculations.

While the extraction of the intrinsic parameters is still under discussion, the determination of the extrinsic parameters is performed commonly using open-collector and off-state bias points [8].

The new algorithm presented in this paper relies on the chain (or ABCD) matrix description of the HBT in common-collector configuration, which is calculated from measured S-parameters of common-emitter HBTs after deembedding of the parasitics. For this approach, first exact formulas are derived for all parameters. Since it turned out that this algorithm fails to determine R_{b2} correctly in some cases, an approximation is given that has proven to yield good results even if the exact solution fails. The new algorithm can be understood as an alternative to the determination of R_{b2} given in [3]. While that algorithm has shown to yield reliable results, it needs an engineer's eye to choose the frequency range of extraction. The new algorithm promises improvements with respect to automization.

In order to give an example and to verify the algorithm, parameters of InGaP/GaAs HBTs are extracted.

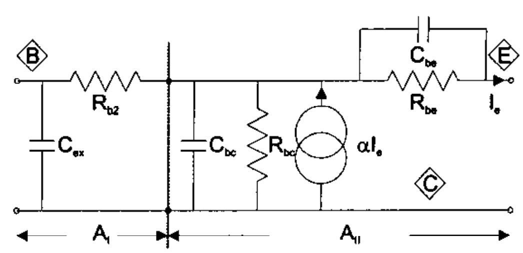

Fig. 1. Equivalent circuit of intrinsic HBT in common collector configuration.

II. The Closed-Form Solution

The extrinsic elements are determined from open collector and off-state measurements [8]. After deembedding, usually the admittance parameters of the intrinsic HBT in common-emitter configuration Y_e are used for extraction. These equations can be found in [3]. A much simpler set of equations is obtained, if the equivalent circuit of the intrinsic HBT is transformed in common-collector configuration Y_c:

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$$Y_c = \begin{bmatrix} Y_{e11} & -(Y_{e11}+Y_{e12}) \\ -(Y_{e11}+Y_{e21}) & (Y_{e11}+Y_{e12}+Y_{e21}+Y_{e22}) \end{bmatrix} \tag{1}$$

In Fig. 1, the equivalent circuit of the intrinsic HBT in common-collector configuration is shown. The chain matrix A_c of the network can be divided into two separate subnetworks A_I, containing the weakly bias-dependent elements C_{ex} and R_{b2} and A_{II} with the other elements:

$$A_I = \begin{bmatrix} 1 & R_{b2} \\ j\omega C_{ex} & (1 + j\omega C_{ex} R_{b2}) \end{bmatrix} \tag{2}$$

$$A_{II} = \begin{bmatrix} 1 & \frac{1}{Y_{be}} \\ Y_{bc} & \left(1 - \alpha + \frac{Y_{bc}}{Y_{be}}\right) \end{bmatrix} \tag{3}$$

$$A_c = \begin{bmatrix} A_{c11} & A_{c12} \\ A_{c21} & A_{c22} \end{bmatrix} = A_I \cdot A_{II} \tag{4}$$

with

$$Y_{bc} = \frac{1}{R_{bc}} + j\omega C_{bc} \tag{5}$$

$$Y_{be} = \frac{1}{R_{be}} + j\omega C_{be} \tag{6}$$

$$\alpha = \frac{\alpha_0 \, e^{-j\omega\tau}}{1 + j\omega/\omega_\alpha} \tag{7}$$

Eqns. (2) to (7) can be solved in order to determine the small signal parameters as follows:

$$C_{ex} = \frac{-\mathrm{Im}\left\{(A_{c11} - 1) A_{c21}^*\right\}}{\omega \, \mathrm{Re}\left\{(A_{c11} - 1) A_{c11}^*\right\}} \tag{8}$$

$$R_{b2} = \frac{\mathrm{Re}\left\{(A_{c11} - 1) A_{c11}^*\right\}}{\mathrm{Re}\left\{A_{c21} A_{c11}^*\right\}} \tag{9}$$

$$Y_{bc} = \frac{A_{c11} - 1}{R_{b2}} \tag{10}$$

$$Y_{be} = \frac{A_{c11} - 1}{R_{b2}\left(A_{c22} - j\omega C_{ex} A_{c12} - |A_c|\right)} \tag{11}$$

$$\alpha = 1 - |A_c| \tag{12}$$

with

$$R_{bc} = \frac{1}{\mathrm{Re}\{Y_{bc}\}} \qquad C_{bc} = \frac{\mathrm{Im}\{Y_{bc}\}}{\omega} \tag{13}$$

$$R_{be} = \frac{1}{\mathrm{Re}\{Y_{be}\}} \qquad C_{be} = \frac{\mathrm{Im}\{Y_{be}\}}{\omega} \tag{14}$$

The three parameters α_0, τ, and ω_0 describing current gain are extracted using the frequency dependence of α as described in [3]. All other small signal parameters can be calculated from eqns. (8) – (14) at each frequency point. Afterwards the value can be estimated with averaging.

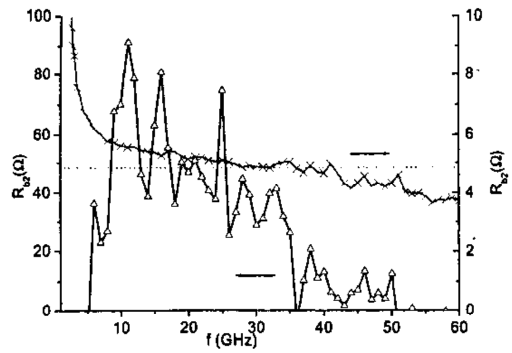

Fig. 2. Example of R_{b2} extraction: Closed form solution (triangles) fails, practical approach (crosses) yields good results (3x30 μm^2 GaInP/GaAs HBT, $V_c = 3$ V, $I_c = 20$ mA).

However, applying the method to different samples of GaInP/GaAs HBTs we observed that the closed-form algorithm does not work in all cases. This occurs especially in state-of-the-art HBTs with values of R_{b2} that are low but cannot be neglected (e.g., around 5 Ω). The extracted values for R_{b2} are sometimes not constant in frequency. Since Y_{be} and Y_{bc} depend on R_{b2} (see eqns. (10) and (11)) this holds for them, too. In Fig. 2, a negative example for a 3x30 μm^2 HBT is shown. For these cases, where the exact algorithm fails, a practical approach is developed, which is described in the next section.

III. Practical Approach

The starting point for this approach is the observation that the locus of measured $Y_{11c} = Y_{11e} = A_{c22}/A_{c12}$ of the intrinsic HBT resembles that of a resistor in series with a capacitor. The following approximation shows that the resistive part is determined mainly by R_{b2}:

$$\frac{A_{c22}}{A_{c12}} = j\omega C_{ex} + \frac{Y_{bc} + (1-\alpha) Y_{be}}{1 + R_{b2}\left[Y_{bc} + (1-\alpha) Y_{be}\right]} \, .$$

$$\frac{1}{\frac{A_{c22}}{A_{c12}} - j\omega C_{ex}} = \frac{1}{Y_{bc} + (1-\alpha) Y_{be}} + R_{b2} \tag{15}$$

$$R_{b2} \approx \mathrm{Re}\left\{\frac{A_{c12}}{A_{c22}}\right\} \tag{16}$$

The assumption in eqn. (16) holds for higher frequencies. Typical results are shown in Fig. 3. Once R_{b2} is known, R_{bc} and C_{bc} are calculated by eqns. (10) and (13). To overcome the possible problems in C_{ex} extraction, we start with the parameter A_{c21}:

$$A_{c21} = j\omega C_{ex}\left(1 + R_{b2} Y_{bc}\right) + Y_{bc}$$

which leads to:

$$C_{ex} = \left(\frac{\operatorname{Im}\{A_{c21}\}}{\omega} - C_{bc} \right) / \left(1 + \frac{R_{b2}}{R_{bc}} \right)$$
$$\approx \frac{\operatorname{Im}\{A_{c21}\}}{\omega} - C_{bc} \quad (17)$$

The assumption in eqn. (17) holds for high values of R_{bc} (typically 100 kΩ). Using eqns. (11) and (12) the remaining parameters can be extracted.

IV. Results

As an example, the new approach described in Sec. III is applied to GaInP/GaAs HBTs, fabricated in-house using a 4" process [8]. In order to prove the enhancements in reliability of the new approach compared to the closed-form solution, parameters are extracted for the sample shown in Fig. 2, where the closed-form algorithm fails. Figs. 3 and 4 present the frequency dependence of extracted curves for R_{b2} , C_{bc} and C_{ex} for different collector currents. Smooth curves are obtained, which are averaged in the range 10-45 GHz (f_t = 40 GHz) in order to determine the equivalent-circuit parameters. The mean value of R_{b2} then is used to calculate the other parameters by means of eqns. (10), (17), and (11). Since the real part of Y_{bc} is very small, R_{bc} can be neglected. In practice, a value of 100 kΩ is used.

In order to further investigate the reliability of the algorithm, the bias dependence of the parameters of different HBTs are determined. The parameters for a single- and a four-finger device from the same wafer are plotted in Fig. 6. For better comparison, the parameters of the four-finger device are scaled down appropriately to the one-finger equivalent. All parameters exhibit smooth bias dependence as expected from physics, and also scale with finger number properly. Though R_{b2} is very small in case of the four-finger HBT, it is reliably determined for all bias points. A small deviation below 1 Ω results in a slight offset in case of C_{bc}. This demonstrates the capabilities of the algorithm presented here.

Fig. 5 shows a comparison between measured and modeled S-parameters of a 3x30 μm^2 HBT at V_c = 3 V and I_c = 20 mA in the frequency range to 60 GHz. The underlying small-signal parameters are calculated with the presented algorithm. No optimization is used at any step of the extraction. As can be seen, the agreement for all S-parameters is very good.

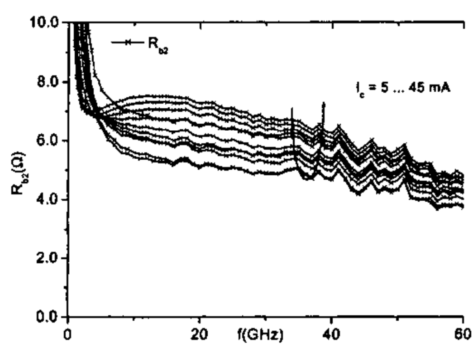

Fig. 3. R_{b2} extraction using eqn. (16) for a 3x30 μm^2 GaInP/GaAs HBT (bias condition: V_c = 3 V and I_c from 5 to 45 mA).

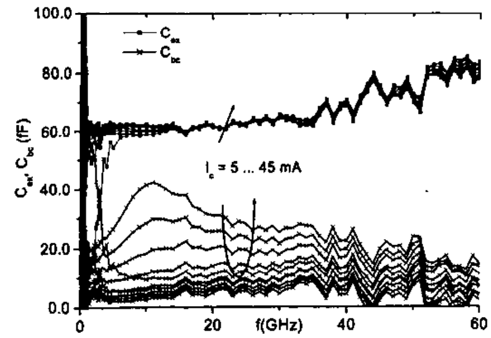

Fig. 4. C_{ex} and C_{bc} extraction using eqns. (10) and (17) for a 1x3x30 μm^2 GaInP/GaAs HBT (bias condition: V_c = 3 V and I_c from 5 to 45 mA).

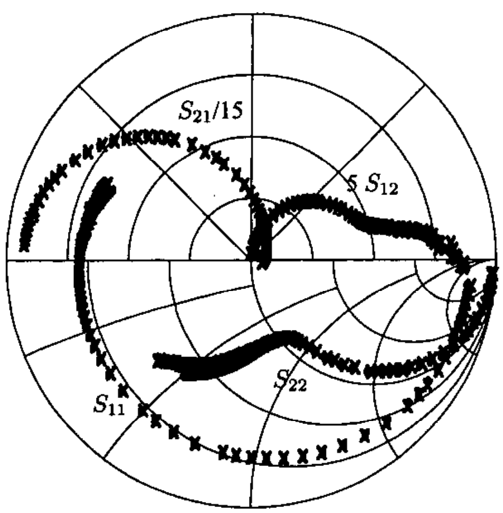

Fig. 5. Comparison between measured and modeled S-parameters of a 1x3x30 μm^2 GaInP/GaAs HBT under V_c = 3 V and I_c = 20 mA bias condition, measured up to 60 GHz.

V. CONCLUSION

A new procedure for extracting GaAs HBT small-signal parameters is presented. Approximations for R_{b2} and C_{ex} are derived which enhance the robustness of the algorithm, especially for HBTs with low, but non-negligible R_{b2}. Since all parameters are determined analytically, good insight into the HBT elements is obtained. The algorithm is verified comparing the bias-dependent equivalent-circuit elements of HBTs of varying emitter size.

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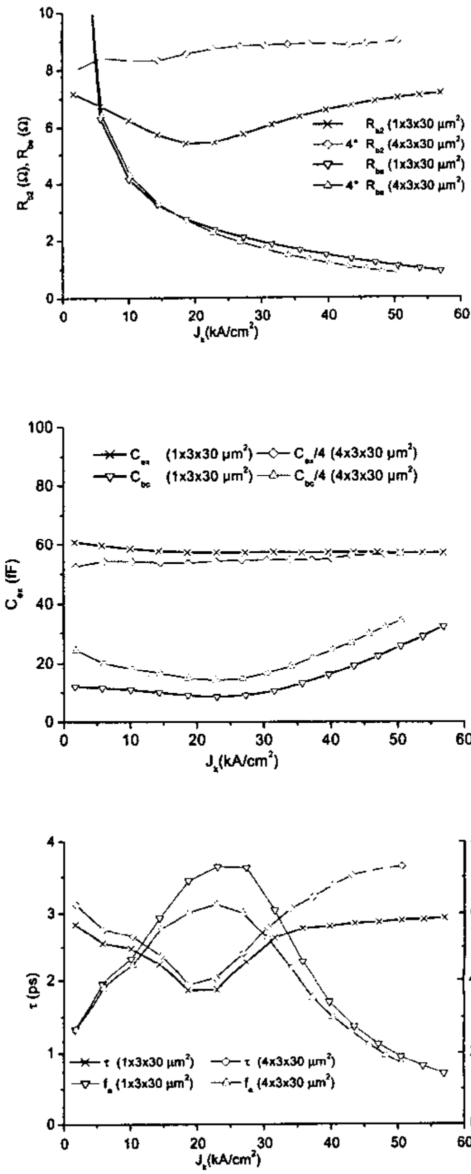

Fig. 6. Bias dependence and scaling of extracted values for 1x3x30 μm^2 and 4x3x30 μm^2 GaInP/GaAs HBTs, respectively, under $V_c = 3\,V$ bias.