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Verification of the Simultaneous Local Extraction Method of Base and Thermal Resistance of Bipolar Transistors

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Abstract—In this paper an extensive verification of the extraction method (published earlier) that consistently accounts for self-heating and Early effect to accurately extract both base and thermal resistance of bipolar junction transistors is presented. The method verification is demonstrated on advanced RF SiGe HBTs were the extracted results for the thermal resistance are compared with those from another published method that ignores the effect of Early effect on internal base-emitter voltage and the extracted results of the base resistance are compared with those determined from noise measurements. A self-consistency of our method in the extracted base resistance and thermal resistance using compact model simulation results is also carried out in order to study the level of accuracy of the method.

Keywords—Avalanche, Base resistance, Bipolar transistor, Compact modeling, Early voltage, Thermal resistance, Self-heating, parameter extraction.

I. Introduction

In modern application of bipolar junction transistors, accurate extraction of the base resistance R_B and thermal resistance R_{TH} is of great importance mostly in compact modeling and device characterization. A number of advanced extraction methods, such as the method we published earlier in [1] need an extensive verification to determine there level of accuracy. This means that standard verification approaches need to be developed or employed in order to achieve trusted verification results.

In this paper, we carry out an extensive verification of our extraction method for R_B and R_{TH} we published in [1]. In this verification, the extracted results for thermal resistance using our method [1] are compared with results from another published method (Section IV), and the extracted results for the base resistance using our method are compared with those determined from the noise measurements (Section V). Using simulation results from the standard compact model as the input data, we also carry out a self-consistency check of our method (Section VI) over a wide range of bias and parameter values; and based on this, we study the level of accuracy of our extraction method presented in [1].

II. Extraction Method for R_B and R_{TH}

The extraction method for the base resistance ($\mathrm{R_B}$) and the thermal resistance ($\mathrm{R_{TH}}$) used in this work was published earlier in [1]. Therefore, here we will only give a summary highlighting the key equations that are important for the work in this paper.

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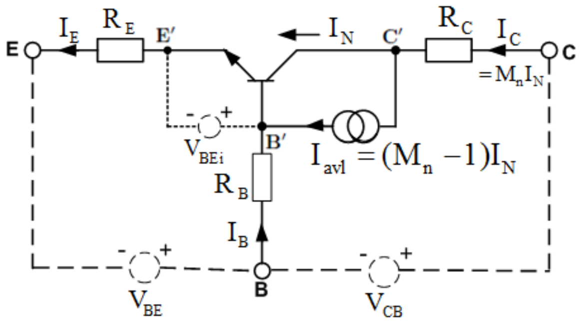


Fig. 1. Schematic picture of the vertical bipolar junction transistor (in common base configuration) showing the different current components. Due to impact ionization in the collector-base space charge region of an npn-transistor, the avalanche current I_{avl} is generated and it leads to the reversal of the base current I_B for large V_{CB}.

According to Fig. 1, the external base-emitter voltage (V_{BE}) is given by [1]

$$V_{BE} = V_{BEi} + I_B R_B + I_E R_E \ . \tag{1}$$

By forcing a constant emitter current (I_E), it ensures that the voltage drop across the emitter resistance (R_E) is constant (provided the emitter resistance can be assumed to be constant). Also by considering small variations in bias and temperature space, the variations in R_E, R_B, and R_{TH} due to temperature effects are assumed to be of higher order. Employing these conditions together with $dI_B = -dI_C$ for a fixed emitter current, yields the relation

$$dV_{BE} = dV_{BEi} - R_B dI_C \ . \tag{2}$$

The changes in V_{BEi} (dV_{BEi}) are assumed to be due to self-heating and collector-base Early effect. These two effects were taken into account in [1] by considering the changes in junction temperature due to the dissipated power and small changes in ambient temperature and by adopting a simple model for the main forward current that takes into account the Early effects. After a few substitutions and simplifications together with consideration of the regime where $I_C = I_E - I_B \approx I_E$ and $V_{CB} \ll V_A$ (see [1] for details), the following final expression was obtained

$$-\frac{dV_{BE}}{dI_C} \approx R_B + \left[\alpha_T R_{TH} + \frac{V_T}{V_A}\frac{1}{I_E}\right](V_{CB} + V_A^{eff}) \,. \quad (3)$$

The extraction procedure for R_B and R_{TH} from dc-measurements is defined using (3). The region (extraction region) where input data is taken from is determined first using for a method described extensively in [2]. Over this extraction region, the intercept on the vertical axis of a plot of $-dV_{BE}/dI_C$ as a function of $(V_{CB} + V_A^{eff})$ yields R_B and the slope S_{TOT} is equivalent to $(\alpha_T R_{TH} + V_T/(V_A I_E))$. From the intercept $(\alpha_T R_{TH})$ on the vertical axis of a plot of S_{TOT} as a function of $1/I_E$, the thermal resistance (R_{TH}) is determined [1].

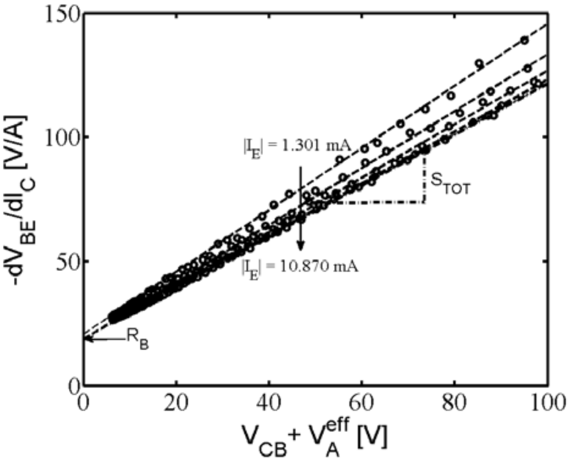
III. Experimental Results

To demonstrate the above extraction method for R_B and R_{TH}, dc-measurement data taken on QUBiC4Xi SiGe HBT [3] with emitter area $A_E = 0.40\ \mu\text{m} \times 1.0\ \mu\text{m}$ was employed. The measurement procedure is demonstrated in [1], were the base-emitter voltage (V_{BE}), the base current (I_B), and the collector current (I_C) are measured as a function of the collector-base voltage (V_{CB}) at sequence of constant emitter currents and at constant ambient temperature (i.e., $T = 25\,^\circ\text{C}$). The voltage-temperature gradient α_T, was determined by linear regression using the dc-measurements (taken on the same device) of the extrinsic base-emitter voltage as a function of temperature for $V_{CB} = 0\text{V}$ and constant $|I_E| = 4.309$ mA. This yielded $\alpha_T = 1.006$ mV/K [1].

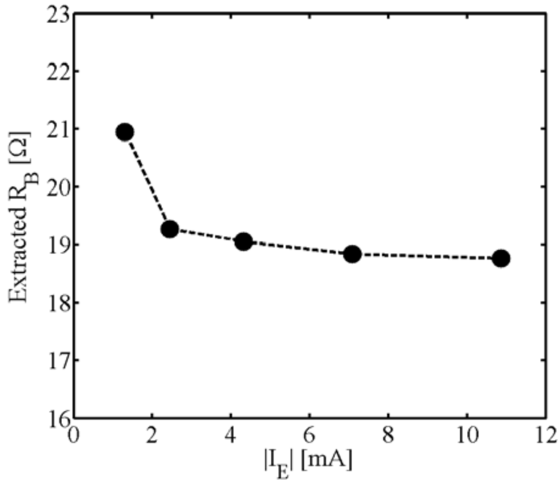
Following the extraction procedure discussed at the end of Section II together with the measurement data, R_B and R_{TH} were extracted for this device from a plot of $(-dV_{BE}/dI_C)$ as a function of $(V_{CB} + V_A^{eff})$ for different I_E as presented in Fig. 2a. The extracted results for R_B as a function of $|I_E|$ are presented in Fig. 2b. From Fig. 2b, we observed that the variations in the extracted R_B as a function of I_E are small and for this device we find $R_B \approx 19\,\Omega$. From the slope S_{TOT} of Fig. 2a, the thermal resistance $R_{TH} = 1.01 \times 10^3$ K/W is determined [1].

IV. Method Verification using DC Method

The extracted results for thermal resistance R_{TH} from our method are compared with similar results from the method that determines R_{TH} by considering the change of V_{BEi} due to self-heating only [1]. This method described in [4], ignores the influence of the collector-base Early effect on the internal base-collector voltage V_{BEi}; and this can result into an over estimate of the extracted R_{TH}. In Fig. 3, the solid line with closed symbols are the results from this work and the dashed line with open symbols are results from the method in [4]. From this figure, it can be observed that neglecting the base-collector Early effects leads to an over estimate of the extracted R_{TH}. These results do not specify which of the two methods yields the correct value of the extracted R_{TH}, this will be discussed in Section VI.



(a)



(b)

Fig. 2. Extraction of R_B and R_{TH} using the vertical intercept and slope of (3) for a device with $A_E = 0.40\ \mu\text{m} \times 1.0\ \mu\text{m}$. (a) Plot of $-dV_{BE}/dI_C$ as a function of $(V_{CB} + V_A^{eff})$ and I_E [measurements (symbols) and linear fits (dashed lines)]. (b) Extracted R_B (from vertical intercept of Fig. 2a) as a function of $|I_E|$. From the corresponding slope $\mathrm{S_{TOT}}$, R_{TH} is extracted.

V. Method Verification using Noise Measurements

To carry out a verification of our extraction method [1] for the extracted R_B, we used dc-measurements taken on an advanced QUBiC4mmW SiGe HBT devices [5] to extract the base resistance R_B. The QUBiC4mmW process is similar to the advanced QUBiC4Xi process (used earlier) but with a reduced total base resistance. The extracted total based resistance R_B using our method in [1] is compared with corresponding results from the noise parameter measurements method (described below) that were taken on the same QUBiC4mmW devices with different geometries and layouts.

The method of determining R_B from the noise measurements is based on the observation that the noise

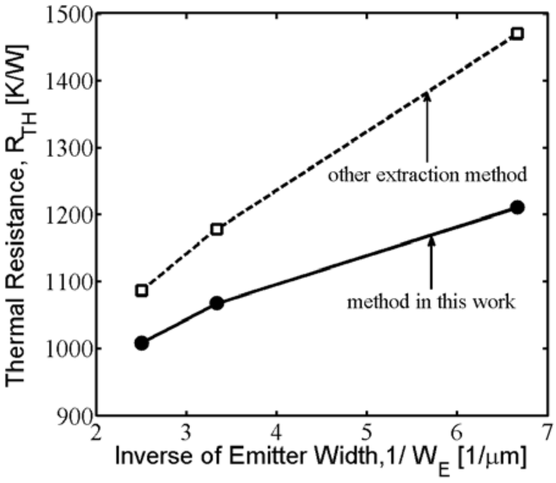


Fig. 3. Extracted thermal resistance R_{TH} as a function of emitter width (with constant emitter length $L_E = 1.0$ μm) using the method described in this work (solid line with closed symbols) and verification using an alternative extraction method in [4] (dashed line with open symbols). We observe that the extraction method suggested in [4] over estimates the extracted R_{TH}, since it ignores the influence of collector-base Early effect on V_{BEi}.

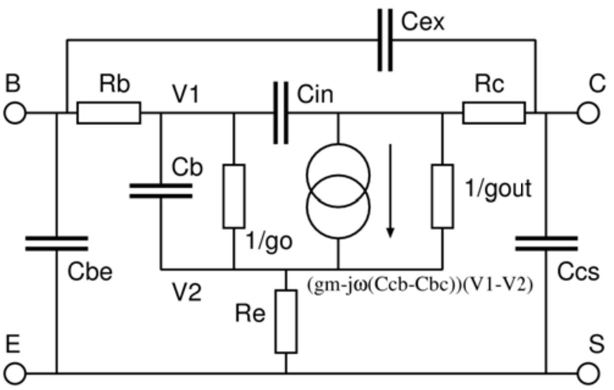


Fig. 4. Equivalent circuit assumed for R_B extraction from S-parameter and noise parameter data.

parameter R_n is approximately [6]:

$$R_n \approx R_B + \frac{1}{2g_m}. \tag{4}$$

To get good accuracy, the extended transistor equivalent circuit depicted in Fig. 4 was assumed. S-parameters and noise parameters were measured in the 1 GHz to 50 GHz range at $V_{BE} = 0.8$ V and $V_{CE} = 1.0$ V. In the first extraction step the values of g_m, g_o, g_{out}, R_B, R_E, R_C, $C_{cb} - C_{bc}$, C_{in}, C_b, C_{be}, C_{ex}, and C_{cs} were optimized to fit the measured Y-parameters after de-embedding. After, the equivalent circuit depicted in Fig. 4 was embedded between the measured test-structure parasitics, as inferred from the open and short dummy structures, a second comparison between measured and simulated S-parameters at the probe tips was made. Finally shot noise currents given by

$$S_{i,bc} = 2kT\jmath\omega(C_{cb} - C_{bc}), \tag{5}$$

$$S_{i,cb} = -S_{i,bc},$$
$$S_{i,cc} = 2qI_c,$$
$$S_{i,bb} = 2qI_b + S_{i,bc}S_{i,cb}/S_{i,cc},$$

were added to the intrinsic transistor, and the usual thermal noise voltages were added to R_B, R_E, and R_C, and to the parasitic resistances found in the test-pads. Then in a second extraction step the values of R_B, R_E, R_C, $C_{cb} - C_{bc}$, C_{in}, C_b, C_{be}, C_{ex}, and C_{cs} are readjusted for a best fit of both the simulated S-parameters and the simulated noise parameters to the measured ones. In this extraction step deviations between measured and simulated S-parameters and Γ_{opt} values are weighted equally, whereas deviations between measured and simulated F_{min} and R_n values are weighted stronger. Typical, after the fit to the de-embedded Y-parameters, the extracted R_B is roughly the same as obtained from the circle impedance method, which does not come as a big surprise, as the methods are very similar. As soon as we take the measured noise parameters into account we find that R_B needs to be increased by about 50% to get a proper fit to the measured R_n value.

The bipolar devices used in the analysis have 20 emitter fingers ($MULT$) with the first two having emitter area $A_E = 0.30$ μm $\times$ 1.0 μm either with a standard or a reduced(*) base resistance layout, and the third one with a square emitter of area $A_E = 0.40$ μm $\times$ 0.40 μm. In Table I the extracted R_B for each device using our extraction method are compared with those determined from the noise parameter measurements. As can be seen from Table I the difference between R_B values extracted using our dc extraction method [1] and those determined from the noise measurements (for all different devices) is less than 22.0%. These results shows that two different methods applying different types of measurements yields R_B results that are within an acceptable error range.

TABLE I
COMPARISON OF OUR EXTRACTED VALUES OF R_B WITH THOSE DETERMINED FROM THE NOISE MEASUREMENTS

$W_E \times L_E \times MULT$	R_B [Ω] (our method)	R_B [Ω] (noise)
0.3 × 1.0 × 20	12.85	10.63
0.3 × 1.0 × 20*	10.58	8.76
0.4 × 0.4 × 20	20.65	17.19

VI. SELF CONSISTENCY CHECK OF THE EXTRACTION METHOD

We carried out a self consistency check of our extraction method [1] using simulation results from the World Standard Compact model for bipolar transistors MEXTRAM [7]. In the analysis, Mextram 504.10.01 version with self-heating was used. QUBi4Xi RF SiGe HBT [3] parameter set was used in generation of the simulation results. The relevant Mextram parameters used in the simulations are shown in Table II, were the parameter R_B comprises of the variable and constant parts of the base resistance.

In order to carry out a self consistency check of our extraction method, output data of Mextram simulations was used as the input data for the extraction method [1] instead of

TABLE II
BASE AND THERMAL RESISTANCE PARAMETERS USED IN MEXTRAM SIMULATIONS

Model Parameter	Value
R_B	20 [Ω]
R_{TH}	1027 [K/W]

the measurement data. The corresponding R_B and R_{TH} are extracted over the extraction region (determined by the method described in [2]). In Table III, we compare our extracted value of R_{TH} with the exact value (corresponding to the Mextram operating point information (OP-info) which takes into account the temperature scaling) and the value from the extraction method proposed by Vanhoucke and Hurkx [4]. Our extraction method yields a smaller percentage error in

TABLE III
COMPARISON OF OUR EXTRACTED VALUE OF R_{TH} WITH THE EXACT VALUE AND THAT FROM THE METHOD IN [4]

	Exact value	Our Method	Method in [4]
R_{TH} [K/W]	1048	1039	1212
Percentage error [%]	-	0.86	15.65

R_{TH} in comparison to the method proposed by Vanhoucke and Hurkx [4]. This explains the deviations observed in Fig. 3 and demonstrates the importance of consistently correcting for the influence of the collector-base Early effect on intrinsic base-emitter voltage (V_{BEi}).

In Fig. 5, we compare the extracted total base resistance R_B with the exact value (from OP-info of the Mextram model). Here the exact R_B value differs from the Mextram model parameter value mainly due to the variations in the variable part of the base resistance (R_{BV}) due to changes in the base diffusion charge and variations in the constant part of the base resistance (R_{BC}) caused by self-heating. The offset between the extracted and exact values of R_B yields a percentage error in the extracted R_B that is less than 2% (as can be seen from the bottom plot in Fig. 5), which shows that our method [1] is self-consistent in the extracted R_B.

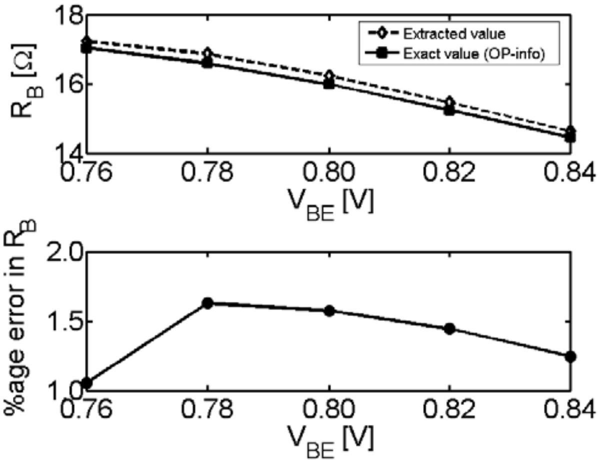


Fig. 5. Exact value (from operation point information of the Mextram model) and extracted value of R_B as a function of V_{BE} (top figure). From the top figure, we observe a gentle decrease in both extracted and exact R_B with V_{BE}. The bottom plot shows the percentage error in the extracted R_B as a function of V_{BE}. This error is within a 2.0% range. Here, the model parameter $R_B = 20\ \Omega$ (with realistically $R_{BV} = 11.47\ \Omega$ and $R_{BC} = 8.53\ \Omega$).

VII. CONCLUSION

We presented an extensive verification of the extraction method (we published earlier in [1]) that consistently accounts for both self-heating and Early effect to accurately extract both the base resistance (R_B) and thermal resistance (R_{TH}) of bipolar junction transistors. In this verification, we compared the extracted R_{TH} using our method with corresponding results from the method published by Vanhoucke and Hurkx [4] that ignores the effect of Early effect on the internal base-emitter bias, which we showed that it leads to an over estimate of the extracted thermal resistance. In the verification of the extracted base resistance, we showed that the difference between the extracted R_B values and those determined from the noise measurements is less than 22%. This is really remarkable as two different methods (DC- and AC-methods) yield results for R_B that are within an acceptable error range. The verification was demonstrated on measurements taken on advanced QUBiC4Xi and QUBiC4mmW devices.

Using the Mextram compact model simulation results (with input model parameters corresponding to QUBiC4Xi devices) as the input data for our extraction method [1], we carried out a self-consistency check of our method in both extracted R_B and R_{TH}. Results from the self-consistency check showed that our method is self-consistent in both extracted R_B and R_{TH} within an error margin of 2.0% and 1.0%, respectively. This shows that our extraction method [1] yields reasonably accurate results for both extracted R_B and R_{TH}, thus it can be used to accurately extract these parameters for bipolar junction transistors.

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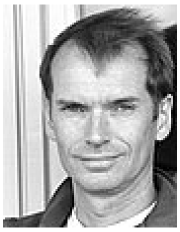

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