A Simple Technique for Measuring the Thermal Impedance and the Thermal Resistance of HBTs.

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Abstract — **This paper presents a new and simple method for characterizing the thermal behavior of Heterojunction Bipolar Transistors, based on DC, AC and low frequency small signal measures of H (hybrid) parameters. Static characterization of the thermal behavior is achieved through the calculation of a thermal resistance, while a thermal impedance is used to describe thermal dynamic behavior. Validation results for the method obtained from both simulations and experimental data are included in the paper for a 10x2x40 µm InGaP/GaAs power HBT.**

INTRODUCTION.

Thermal phenomena characterization of active device is a key issue for the design of microwave power amplifiers. Specifications on maximum operating junction temperature, critical to ensure reliability as in the case of space-borne amplifiers, require an accurate determination of device thermal resistance. Characterization of thermal phenomena is also necessary for thermal stability analysis. Power Amplifiers performance in terms of linearity specifics as intermodulation and spectral re-growth is also influenced by dynamic self heating effects of the power devices. Good thermal impedance characterization is also important when dealing with power amplifiers operating in pulsed-mode, as those used in SAR radars. A lot of effort has been made in characterizing steady state self heating effects by means of thermal resistance identification and, generally, the methods are based on DC measures at different case (ambient) temperatures [1-2-3-4-5]. On the other hand, there is not much work in the literature about thermal impedance characterization [6-7]. In [7] the thermal impedance is determined on the basis of DC and low frequency Y_{22} parameter measures. This method, however, does not allow to characterize the thermal impedance over the complete range of frequencies of interest because of the influence of device junction capacitance at higher frequencies. Moreover, the use of Y parameters adopted by the method makes necessary to bias the base of the transistor with a voltage source; otherwise, the DC and very low frequency Y parameters cannot be correctly determined. Adopting a voltage polarization for the base makes the transistor thermal behavior strongly non linear, and this makes very difficult the accurate determination of thermal derivatives used for thermal impedance characterization. The proposed method, on the other hand, overcomes these difficulties using two-port H parameters measurements and therefore allows biasing the base of the transistor with a current source, eliminating the need for thermal derivatives in order to characterize the dynamic thermal behavior.

THERMAL RESISTANCE DETERMINATION.

HBTs do not present relevant trap dispersion phenomena; therefore it is acceptable to suppose that all dispersive phenomena presented by these devices at frequencies bellow the cut-off of reactive effects (usually a few MHz for microwave HBT devices) is caused by thermal self-heating dynamics. This assumption leads to a transistor model, for frequencies bellow the cut-off frequency of reactive effects, where the collector current (I_C) an base emitter voltage (V_{BE}) behavior are described by means of two nonlinear algebraic equations functions of base current (I_B), collector emitter voltage (V_{CE}), and junction temperature (T_J):

$$V_{BE} = F_1(I_B, V_{CE}, T_J) \qquad \mathrm{I}_C = F_2(I_B, V_{CE}, T_J) \quad (1)$$

The junction temperature as intended in this equations represents an equivalent "mean" temperature constant along the junction, as is usually assumed in the most of modeling approaches. The choice of base emitter voltage and collector current as dependent variables ensure an accurate description of the two dominant thermal effects presented by HBT devices, which are current gain and base emitter voltage modulation with temperature.

Eq. (1) represents equithermal characteristics, intending by equithermal a condition where the junction temperature is fixed to a determinate value and are difficult to measure because they require a pulsed measurement system. Besides, these measures are usually not as accurate as DC ones. Instead, the easily measurable DC characteristics are not equithermal in terms of the junction temperature but in terms of a case or baseplate temperature (T_C), which is kept constant during the measurement by means of a thermal chuck. That is

$$V_{BE} = F_1^{DC}(I_B, V_{CE}, T_C) \qquad \mathrm{I}_C = F_2^{DC}(I_B, V_{CE}, T_C) \quad (2)$$

Non equithermal H parameters expressions can be derived by differentiating Eq (1). The value of these H parameters can be determined from low frequency small signal measures, performed at constant case temperature ensuring that variations in junction temperature depend only on dissipated power variations (self-heating). The choice of h_{21} as the temperature sensitive parameter allows for the high frequency identification of thermal dynamics without the problems described in [7] related to the junction capacitance of the device. Parameter h_{21} can be expressed as in Eq (3).

$$h_{21}(\omega) = \left.\frac{\partial F_2}{\partial I_B}\right|_{non-equithermal} =$$

$$= \left.\frac{\partial F_2}{\partial I_B}\right|_{equithermal} + \frac{\partial F_2}{\partial T_J} \cdot \frac{\partial T_J}{\partial I_B} = h_{21}^{AC} + \frac{\partial F_2}{\partial T_J} \cdot \frac{\partial T_J}{\partial I_B} \tag{3}$$

Where $\partial F_2 / \partial T_J$ is the thermal derivative of F_2.

The identification of h_{21}^{AC} can be achieved by means of small signal H parameters measurements performed in a frequency range above the cut-off of thermal effects but low enough to be able to neglect the reactive effects. Generally, for microwave HBT devices, a frequency of a few MHz should be adequate. For the determination of $\partial F_2 / \partial T_J$ and $\partial T_J / \partial I_B$ we can use a linear approach for T_J as in Eq (4).

$$T_J = T_C + \int_{-\infty}^{\infty} z_{th}(\tau) \cdot p(t-\tau) d\tau =$$

$$= T_C + Z_{th}(\omega) \cdot P(\omega) \tag{4}$$

Where $Z_{th}(\omega)$, the Fourier transform of $z_{th}(t)$, is the thermal impedance of the device, an $P(\omega)$ is the Fourier transform of p(t), the instantaneous power dissipated by the device.

Using equation (2), (3) and (4) evaluated at DC leads to the followng expression for the thermal resistance of the device:

$$R_{th} = \frac{\left(h_{21}^{DC} - h_{21}^{AC}\right)}{\left(A - \left(h_{21}^{DC} - h_{21}^{AC}\right) \cdot B\right)} \tag{5}$$

where

$$A = \frac{\partial F_2^{DC}}{\partial T_C} \cdot \left(h_{11}^{DC} \cdot IB + VBE + VCE \cdot h_{21}^{DC}\right)$$

and

$$B = \left(\frac{\partial F_2^{DC}}{\partial T_C} \cdot VCE + \frac{\partial F_1^{DC}}{\partial T_C} \cdot IB\right)$$

Thermal Impedance Determination.

Under low frequency excitation, where dynamic thermal effects are appreciable (from Hz to a few MHz) we can combine equations (3) and (4) to obtain an expression for computing the thermal impedance $Z_{th}(\omega)$.

$$Z_{th}(\omega) = \frac{h_{21}(\omega) - h_{21}^{AC}}{\frac{\partial F_2}{\partial T_J} \cdot \left(h_{11}(\omega) \cdot IB + VBE + VCE \cdot h_{21}(\omega)\right)} \tag{6}$$

Equation (6) allows to characterize the thermal impedance behavior without the need of measuring the thermal sensitivities, since the term $\partial F_2 / \partial T_J$ is just a scale factor and can therefore be omitted with the definition of a normalized thermal impedance, as in Eq. (7).

$$Z_{thN}(\omega) = \frac{Zth(\omega)}{Zth(0)} =$$

$$= \frac{\left(h_{21}(\omega) - h_{21}^{AC}\right) \cdot \left(h_{11}^{DC} \cdot IB + VBE + VCE \cdot h_{21}^{DC}\right)}{\left(h_{21}^{DC} - h_{21}^{AC}\right) \cdot \left(\left(h_{11}(\omega) \cdot IB + VBE + VCE \cdot h_{21}(\omega)\right)\right)} \tag{7}$$

The normalized thermal impedance in Eq. (7) can be easily de-normalized by multiplying it by the thermal resistance, which can be derived using Eq. (5) or any other technique [1], when the thermal derivatives are difficult to measure.

Method Validation

In a first place, and as a first order validation, the application of the method was simulated with Agilent ADS using a Gummel and Poon based electro thermal model for InGaP/GaAs power HBT having 10 emitter finger of 2 x40 μ^2. DC, AC, and low frequency H parameters were simulated, and a thermal resistance and impedance were computed. The model thermal resistance and impedance values were accessible to the user and could therefore be compared with the values obtained using the proposed method. The thermal resistance and thermal impedance obtained from the simulation of the method match exactly those specified inside the model* of the HBT device used, as can be seen in fig1.

* The thermal impedance inside the HBT model corresponds to data extracted from 3D thermal simulations corresponding to a 1Watt dissipated power

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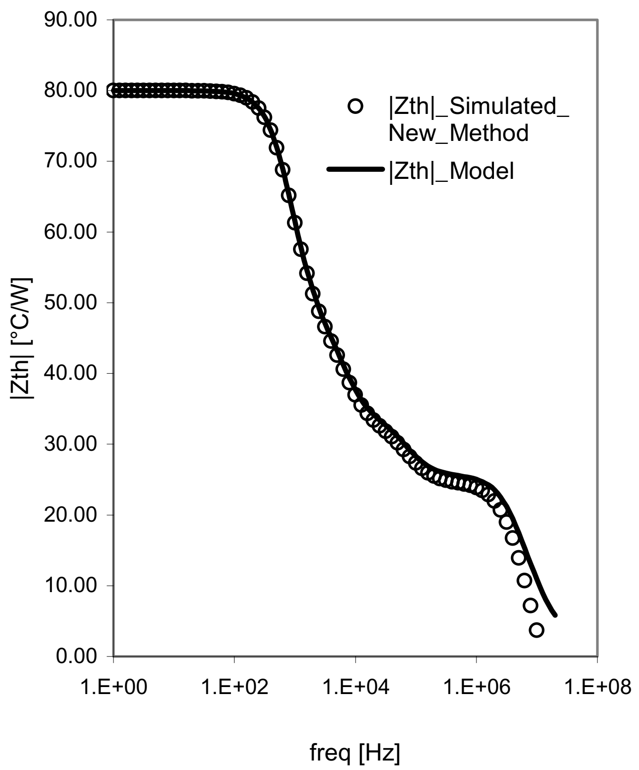

Fig.1. Simulated Method thermal impedance (obtained simulating the new method) and Model thermal impedance vs frequency.

Table I presents the value of thermal resistance corresponding to the thermal impedance implemented inside the Electro-Thermal model used for simulations, and the thermal resistance value computed applying the new method to simulated H parameters data.

	Electro-Thermal model	Simulated method
R_{th}[°C/W]	80	80

Table I. Simulated Method thermal resistance (obtained simulating the new method) and Model thermal resistance.

For a more realistic validation, the thermal resistance and the thermal impedance of the 10x40 InGaP/GaAs power HBT correspondent to the model used previously in simulation was measured applying the new method. DC measurement was carried out using a 4142 B Modular DC Source / Monitor. AC H parameters were obtained measuring the device S parameters at 50 MHz with an Agilent 8510 Network Analyzer, and then transforming S parameters into H parameters. For low frequency (10 Hz to 2 MHz) H parameters measures were performed using an Agilent (Hewlett-Packard) 4195A Network / Spectrum Analyzer. For the measures the transistor was biased with a 1 mA base current and a 9 V collector source, the correspondent dissipation was around 0.5 Watt.

As it can be seen in Table II the resultant thermal resistance matches exactly the datasheet value given by the foundry for this device, and agrees with results obtained using other methods [1-2].

Method	R_{th} [°C/W]
Datasheet	80
New Method	81,2
Marsh [1]	78,5
Bovolon [2]	83

Table II. Thermal resistance values correspondent to Datasheet, result obtained using the new method proposed, and results obtained using other methods proposed in literature [1-2].

A 3D thermal simulation of the device for a 0.5 Watt power dissipation was carried out. Data obtained from the 3D thermal simulation was used to extract an 8 element Lumped RC Model of the device thermal impedance. The extraction was achieved fitting the RC model transient response with the data obtained from 3D thermal simulation.

In Fig.2 the normalized thermal impedance obtained with the new method is compared with the normalized thermal impedance corresponding to data extracted from 3D thermal simulation for a 0.5 Watt dissipated power.

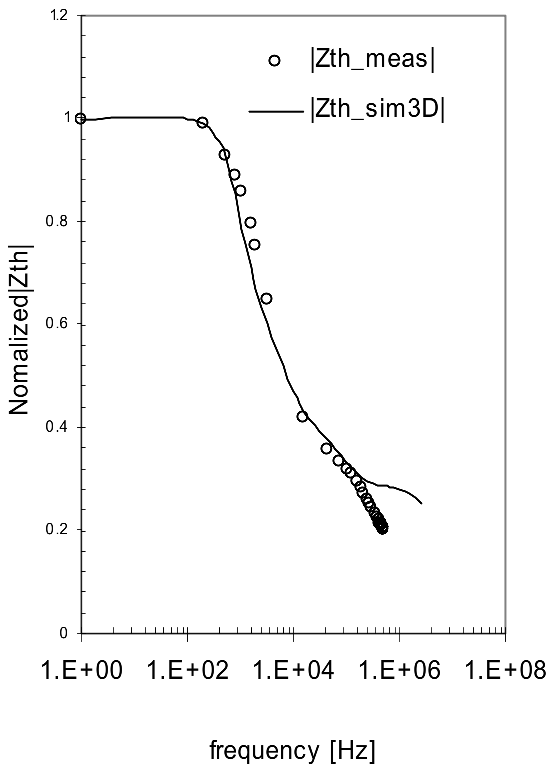

fig.2_Measured Thermal impedance and 3D Simulation Thermal Impedance for a 0.5 W power dissipation.

CONCLUSIONS.

The proposed method gives a simple and robust way for static and dynamic characterization of thermal effects in HBT devices. The use of H parameters gives the new method a superior accurateness compared to that of Y parameters based methods, since current base polarization implies rather linear thermal behavior, simplifying the thermal derivatives measurement. The proposed method offers also the possibility of describing the thermal impedance behavior on the basis of pure electric measurements without the necessity of identifying possible problematic thermal derivatives. A first order validation of the method was carried out through simulation with excellent results. For a more realistic validation the new method was applied for measuring the thermal resistance and thermal impedance of an 10x40 InGaP/GaAs power HBT. The obtained results were compared with other methods and 3D thermal simulation results. In all cases there is a perfect agreement that confirms the accurateness of new method.

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