Electrical Measurement of the Junction Temperature and Thermal Resistance of HBTs

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***Abstract*—A simple method is proposed to derive the junction temperature and the bias- and temperature-dependent thermal resistance of heterojunction bipolar transistors (HBTs) using a radio frequency (RF) signal. The method exploits the thermal dependence of the current gain of a transistor whose dissipated power is modified by applying an RF signal. The new method is used to derive the junction temperature and thermal resistance of a power HBT. The results are compared with state-of-the-art techniques.**

***Index Terms*—Heterojunction bipolar transistors (HBTs), thermal impedance, thermal resistance.**

I. Introduction

HETEROJUNCTION bipolar transistors (HBTs) have shown excellent power densities and thus are widely used in telecommunication monolithic microwave integrated circuit (MMIC) power amplifiers (PAs). Power density, however, is often limited by device reliability, which has been shown to depend on junction temperature T_j. Moreover, the behavior of the thermal resistance R_{th} with temperature and power dissipation is important to characterize the electro-thermal models used in PA design. Most of the proposed techniques to derive the junction temperature and thermal resistance of HBTs from electrical measurements are based on pulsed or dc measurements and exploit the thermal dependence of the current gain β, the base-emitter voltage V_{BE}, or the base current [1], [2] (and references therein). Direct techniques [1] derive the junction temperature for a certain bias condition, whereas indirect techniques make use of a previously calculated R_{th} to obtain the junction temperature. The distinction is not important if the behavior of R_{th} with junction temperature and dissipated power is known, but can become relevant when estimating the junction temperature using an R_{th} obtained at a different junction temperature or dissipation condition. Moreover, indirect techniques such as [2] rely on a linearization of the β or V_{BE} characteristics around a certain operating condition. As the reported variations of β with case temperature can deviate from a straight line up to 10% [3], small increments of the case temperature might be necessary during the measurement, thus involving greater errors. To mitigate this problem, we propose a direct technique which, differently from [1], can be applied under any bias condition (i.e., not only under high self-heating, as required in [1]).

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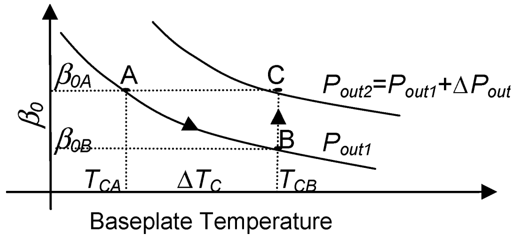

Fig. 1. Qualitative behavior of β_0 versus T_c for two different levels of RF power (within the active region).

II. Proposed Method

Let's consider the dc current gain β of an HBT biased in the forward active region. For fixed base current I_B, β can be assumed to be a function of T_j only.[1] Moreover, most HBT models [4] consider β to be independent of I_B when the device is deeply biased in the active region. In order to measure R_{th}, we employ the current gain as the temperature-sensing magnitude, and apply a radio frequency (RF) signal at the input of the device in order to vary its dissipated power. Considering that an RF sinusoidal signal is applied to the base of the transistor, we define parameter β_0

$$\beta_0 \triangleq \frac{\overline{i_C}}{\overline{i_B}} \tag{1}$$

as the ratio of the dc components of the instantaneous collector and base currents in the presence of RF. If the RF level does not push the device into cut-off region or into high collector currents where β is reduced due to the Kirk effect, β_0 will be approximately equal to β. Fig. 1 shows qualitatively two typical characteristics β_0 versus case temperature T_c for the same I_{B0} and two different amplitudes of RF output power.

As known, β (and consequently β_0) decreases with increasing T_c due to the increase in T_j.[2] This relationship can be linear as in [2], or almost linear (within 10% of a straight line) as in [3]. However, β and β_0, can be assumed to be univocal functions of T_j only. Analogously to what has been done in [1], it can reasonably be expected that the points A and C, which share the same β_0 in Fig. 1 will also have the same T_j. Using the classical definition for Rth, we can write the following equations for point A in Fig. 1:

$$T_{jA} = T_{cA} + R_{th}(T_{jA}, P_A) \cdot P_A \tag{2}$$
$$P_A = (\beta_{0A} I_B V_{CE} - P_{\mathrm{out1}}) \tag{3}$$

[1]The variation of β_{f} with V_{CE} (basewidth modulation) is usually negligible when base doping is high, as is usually the case for HBT devices.

[2]For the same average dissipated power.

where P_A stands for the average dissipated power in the device, comprising the dc term[3] and the output RF power P_{out1}. An analog set of equations can be written for point C in Fig. 1, which, combined with (2) and (3), can be solved for T_j

$$T_{ja} = T_{jC} = T_j = T_{cA} + \Delta T_c \cdot \frac{P_A}{\Delta P_{\text{out}}} \tag{4}$$

$$\Delta T_c \triangleq T_{cB} - T_{cA}, \quad \Delta P_{\text{out}} \triangleq P_{\text{out2}} - P_{\text{out1}}. \tag{5}$$

In (2)–(5), we have assumed, for the sake of simplicity, that R_{th} does not vary with T_c. It would be nonetheless possible to model an R_{th} that varies with the case temperature (three points would then be necessary to extract T_j for a linear-with-temperature R_{th} as in [1]). Our experience, however, shows that this is usually an unnecessary complication, since the variation of the R_{th} is usually negligible for ΔT_c up to 20 K.

One way of measuring equi-β_0 points such as A and C in Fig. 1 is to exploit the typical negative slope of the dc characteristics under high self-heating as in [1]. This last method is very simple and has been validated against other techniques giving accurate results. However, it has the disadvantage that it can be applied only under high self-heating conditions. We propose instead to vary the device junction temperature by means of an auxiliary RF signal applied at the input of the device, allowing for a change in T_j at constant case temperature. We can therefore apply (4) for two points having different case temperatures but the same β_0, owing to the different levels of RF power. This new method is therefore applicable under general bias conditions (i.e., not only for high self-heating devices or bias conditions). The procedure, illustrated in Fig. 1, can be summarized as follows.

1) Measure β_{0A} as in point A, for case temperature T_{cA} and with RF output power P_{out1}.
2) Increase case temperature by ΔT_c, maintaining the RF power and record β_{0B}, which will be smaller than β_{0A} due to the increase in the junction temperature from A to B.
3) Increase RF power to return to the original β_{0A}. In fact, the increase in the RF level will cool the device to the original junction temperature, from point B to point C.
4) Use (4) to derive the junction temperature.

The only assumption of the method is that the variation of β_0 due to electrical nonlinear phenomena is negligible with respect to it's thermal sensitivity. This is a mild assumption, as in most HBT models β_f has only a thermal dependence [4]. Moreover, it can be demonstrated that if one assumes a dependence on the output power for β_0, such as

$$\beta_0 = \beta_0(T_j, P_{\text{out}}) \tag{6}$$

the relative error in the junction temperature of points A and C in Fig. 1, having the same β_0 (but a different P_{out}) is given by

$$\text{err}_{T_j} \triangleq \frac{(\Delta T_j - \Delta T_c)}{(T_j - T_c)} = \frac{\Delta\beta_0|^{\text{equithermal}}}{\Delta\beta_0|^{\text{thermal}}}. \tag{7}$$

[3]Neglecting the dc power dissipated at the base. Also the RF input power has been neglected as the power gain is normally quite high in HBTs.

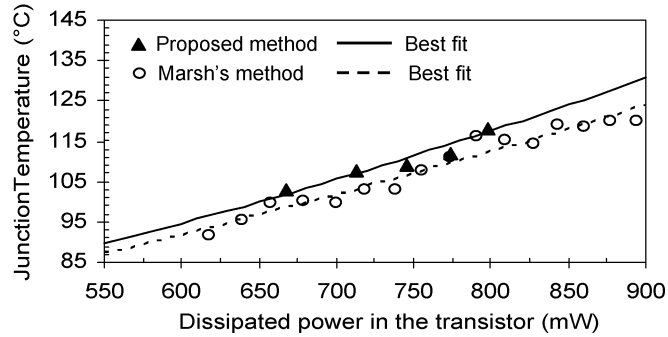

Fig. 2. Measured T_j versus dissipated power: applying Marsh's method (○) and the proposed technique (▲).

The "equithermal" increment in the numerator of (7) refers to the change in β_0 at constant junction temperature due to the change in the RF level only (assumed to be zero in most HBT models). The denominator, instead, represents the change in β_0 due to a change in both the junction temperature and the RF level. Once T_j has been calculated it is possible to verify, using (7), if the assumption of the method was valid.

III. Experimental Results

The proposed method was applied to derive the junction temperature and Rth of an InGaP/GaAs power HBT having ten emitter fingers of 2×40 μm^2 of active area on a 100-μm substrate. The transistor is rated to give about 1.25 W of RF power in X band with a collector efficiency around 60%. The method was applied in two different bias regions and was confronted with the technique proposed by Marsh [1] and Bovolon [2]. Measurements were also made to confirm the validity of the assumption that equi-β_0 points correspond to equithermal points. In all the measurements, the transistor was biased with a dc current source at the base and a dc voltage source at the collector. An RF signal of 1 GHz was applied at the base, and bias tees were employed to assure 50-Ω terminations at RF frequencies.

The new technique was first applied to derive the junction temperature in an operating condition where Marsh's technique could also be used. Accordingly, the transistor was biased with a base current $I_B = 4$ mA and collector voltage $V_{CE} = 4.5\ V(P_{DC} \approx 1$ W). The β_0 versus T_C characteristics were measured on-wafer for T_C from 38 °C to 52 °C and P_{out} from 0 to 216 mW of RF power as in Fig. 1. Standard polynomial least-squares approximation was applied to the measurements to obtain the points A, B, and C in Fig. 1. The I_C versus V_{CE} characteristics were also measured in order to apply Marsh's method ($I_B = 4$ mA, $T_2 = 45\ °$ C, $\Delta T = 10\ °$ C, $I_C = 200$ to 222 mA, and $V_{CE} = 2.78$ to 5 V). Fig. 2 allows the comparison of the junction temperature obtained with Marsh's method with the one derived using the new method, for the same case temperature. Although a relatively accurate thermal chuck was employed ($|\Delta \text{T}| < 0.1\ °$ C), we found the thermal resistance given by Marsh's technique to be almost independent of the case temperature for case temperatures from 35 °C to 55 °C. We did observe, however, an almost linear dependence of R_{th} on the junction temperature T_j and therefore the approximating curves in Fig. 2 account for a linear-with-T_j

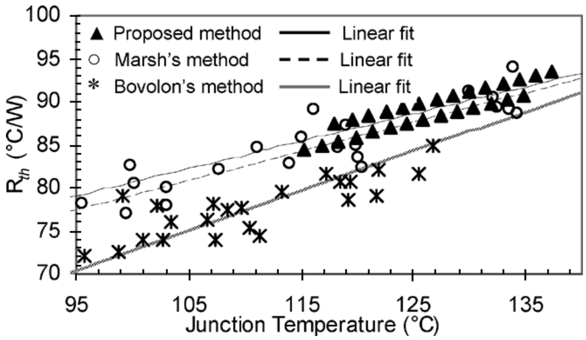

Fig. 3. R_{th} versus T_j under high self-heating condition: applying Marsh's (o) and Bovolon's (∗) method, and the new technique (▲) ($P_{\text{out}} = 42$ mW and $P_{\text{out}} = 54$ mW).

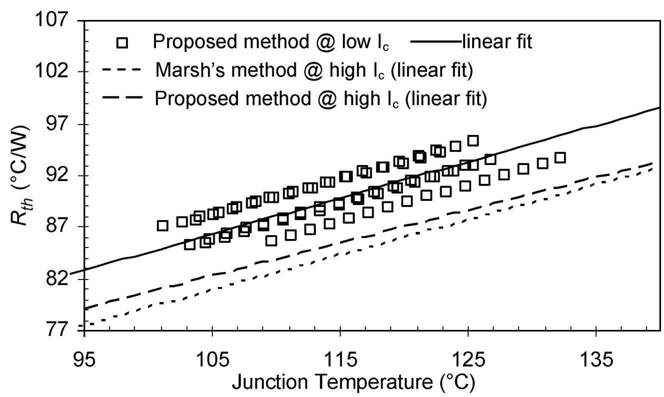

Fig. 4. R_{th} versus T_j at a low collector current applying the proposed method (□) ($P_{\text{out}} = 90$–216 mW). Results obtained at a higher collector current (but with a similar dissipated power): Marsh's method (− − −), proposed technique (—).

thermal resistance. As can be seen from Fig. 2, both methods are in good agreement (within 5%).

The new method can also be applied to calculate R_{th} using (2)–(5). From the same experimental data, Fig. 3 shows the thermal resistance obtained with the proposed technique, together with the ones obtained using Marsh's and Bovolon's technique.

In Fig. 3, the two traces corresponding to the proposed method reflect the results obtained with two different levels of RF output power P_{out}, to show that the value of R_{th} is almost independent of the level of RF signal employed. As can be seen from Fig. 3, the value of the thermal resistance obtained with the new method practically coincides with the corresponding values obtained using Marsh's method. Moreover, although the new method seems to overestimate the value of the thermal resistance with respect to Bovolon's method, the difference between both methods remains within the measurement error of the latter.

As a further validation of the proposed method, we used it to determine the junction temperature and R_{th} at a lower dc collector current ($I_B = 2$ mA, $V_{CE} = 9$ V), where the absence of a highly negative slope in the I_C versus V_{CE} characteristics precludes the use of Marsh's technique. However, we chose a bias condition with a similar dissipated power as in Fig. 3. In fact, having the same dissipated power (although at a different collector current), allows the comparison of the value of R_{th} in this new operating condition with that of the previous condition. Fig. 4 shows the comparison between R_{th} obtained with the proposed method at a low collector current, and the results from Fig. 3 that correspond to a high collector current for both the new method and Marsh's method. For the sake of clarity, the results for the high collector current condition were replaced by their linear approximation curves. As can be seen from Fig. 4, the new method can be employed with adequate results also at a low-current operating condition, where Marsh's method is inapplicable.

In order to verify that the underlying assumption of the method was true, i.e., that the thermal dependence of β_0 dominates over the dependence on P_{out}, we used the calculated values of R_{th} to evaluate (7), obtaining a relative error err_{Tj} of less than 5% for all the points. Moreover, we used the calculated junction temperature to plot the β_0 versus T_j characteristics for various levels of RF power. These characteristics, which are not shown here due to lack of space, showed that equi-β_0 points differ by less of 2.5 °C of junction temperature, for RF output powers from 90 to 216 mW.

IV. Conclusion

We have presented a new method to derive the junction temperature and thermal resistance of HBTs using an RF signal. The method has been compared with state-of-the-art techniques such as Marsh's [1] and Bovolon's [2]. In particular, the three methods give similar results for the junction temperature and the thermal resistance. However, Bovolon's technique relies on a linearization of the β or V_{BE} characteristics, thus requiring small increments of the case temperature. This can be a problem when nonlinear β versus T_j characteristics are involved or when the accuracy of the case temperature controller is poor. Instead, the proposed technique does not rely on a linearization of the β characteristics and therefore higher increments of case temperature can be used thus involving smaller measurement errors. Moreover, the proposed technique as opposed to Marsh's, can be used also for low-self-heating devices or bias conditions. This has been accomplished at the expense of a slightly more complicated measurement setup due to the use of an RF signal.

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