A New Method to Extract HBT Thermal Resistance and Its Temperature and Power Dependence

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***Abstract*—This paper introduces a new technique for the measurement of the thermal resistance of HBTs. The method is very simple, because it requires only standard dc I_C–V_{CE} measurements taken at different baseplate temperatures, but it is able to account for the dependence of the thermal resistance on both the baseplate temperature and the dissipated power (under the simplifying assumption that the thermal resistance increases linearly with the dissipated power). We have obtained and shown consistent results extracted from devices with an emitter area ranging from 90 μm^2 (1 finger) to 1080 μm^2 (12 fingers). The thermal-resistance values extracted with a standard and well–known technique are seen to fall inside the range of our results. We have also applied an alternative method that assumes a linear dependence between thermal resistance and junction temperature, and we have shown that both models lead to similar results, which points to the consistency and robustness of our extraction technique.**

***Index Terms*—Heterojunction bipolar transistors (HBTs), microwave transistors, power amplifiers, thermal resistance.**

I. Introduction

THE experimental characterization and modeling of the thermal behavior of heterojunction bipolar transistors (HBTs) has been a major research topic accompanying the development of HBT technologies to the present day [1]–[11]. Like all bipolar transistors, HBTs have a tendency to become locally unstable in the hottest regions, and the problem is exacerbated for GaAs HBTs by the poor thermal conductivity of the substrate. Current-gain compression sometimes leading to collapse is typically observed as a result of self-heating. Besides, all of the most significant degradation mechanisms of HBTs are accelerated by temperature. Therefore, thermal characterization is a key factor for the modeling and the reliability evaluation of HBT technologies.

Among the indirect techniques for the measurement of the thermal resistance (R_{TH}) of bipolar devices (i.e., those not involving microscopic observation of the device surface), a few methods exist that allow relatively easy and rapid R_{TH} extraction using dc measurements at different temperatures (see for example [12]–[19]). However, they all suffer from specific limitations or inconveniences. For instance, [12], which uses the temperature dependence of the common-emitter current gain β as a thermometer, is somewhat cumbersome, because it requires a calibration phase where measurements are taken at several values of the ambient or baseplate temperature (T_B) (21 values in a 100 °C range, in [12]), and both in the calibration and measurement phases, the device must be biased at constant I_C over varying T_B and dissipated power (P_D), which implies manual adjustment of V_{BE} at each measured point. Dawson's technique [13], which again uses β or V_{BE} as temperature-sensitive parameters, neglects the dependence of R_{TH} on P_D, and in the calibration phase, also that on T_B (thus, being somewhat internally inconsistent). A modification of Dawson's technique proposed by Liu and Yuksel [14] allows the highlighting of some dependence of R_{TH} on P_D, but at the expense of neglecting that on T_B, which is again inconsistent, while [15] and [16] introduce corrections to Dawson's results accounting for the effect of self-heating during the measurement, but still under a constant-R_{TH} assumption. On the other hand, the technique introduced by Grossman *et al.* [17] elaborates on Dawson's method, showing that assuming a linear dependence of R_{TH} on the junction temperature leads to an exponential dependence of R_{TH} on P_D; however, this technique also requires a separate calibration phase and nonstandard constant-I_C measurements. The method proposed in [18] requires calculating the differences between I_C values measured at slightly different values of T_B and P_D, as well as some interpolation of the output curves, thus, being prone to measurement errors. Finally, the simple method by Marsh [19] can give very limited, if any, information about the dependence of R_{TH} on T_B and P_D.

Of course, pulsed techniques are also available [20], [21], which rely on the assumption of isothermal operation during short pulses and compare pulsed characteristics measured at different ambient temperatures with dc ones. In principle, these technique have the advantage that they do not require specific assumptions on the temperature dependence of the HBT parameters; on the other hand, performing accurate short-pulsed measurements is no easy task, especially for high-power devices, and the equipment is significantly more expensive than that required for dc measurements. Besides, other dynamic effects, like those due to surface and bulk traps, can interfere with thermal transients, and make the picture quite complicated. On the other hand, a point in favor of pulsed techniques is that they allow, through the observation of long-pulse transients, the extraction of dynamic thermal models, including thermal capacitances: an example of dynamic thermal characterization of AlGaAs/GaAs HBTs can be found in [22].

The new method proposed in this paper is believed to offer a better compromise between ease of measurement and data processing on one side, and accuracy of R_{TH} characterization

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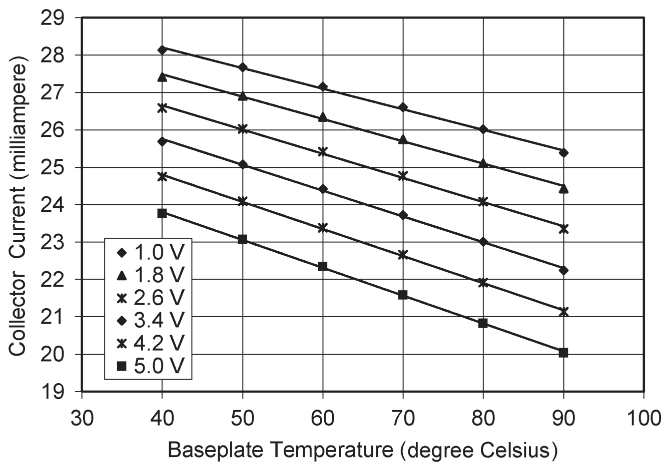

Fig. 1. Collector current measured at $I_B = 0.35$ mA on a 1-finger $3 \times 30\ \mu m^2$ HBT at different T_B and V_{CE} values.

on the other, since: 1) it requires only temperature-dependent standard I_C–V_{CE} measurements at fixed I_B, i.e., neither a calibration phase nor any ad hoc measurement like the constant-I_C or constant-I_E sweeps of [12]–[17]; 2) only a few values of T_B need to be considered (e.g., here we use 5–7 T_B values in the 25–90 °C range); 3) the effects of both T_B and P_D are taken into account. This last aspect, in particular, has significant implications as far as reliability predictions are concerned: neglecting the increase of R_{TH} with P_D, as dc techniques generally do, leads to underestimating the junction temperature more and more as power increases, thus offsetting measured lifetimes in mean time to failure (MTTF) extrapolations. We, therefore, believe this new technique to offer a simple and inexpensive way to improve reliability predictions.

II. The New R_{TH} Extraction Technique

It is a common observation that a roughly linear dependence exists in the forward active region between the common-emitter current gain β and T_B [13], [18]. Fig. 1 shows a good linear dependence observed on a 1-finger $3 \times 30\ \mu m^2$ HBT for T_B ranging from 40 to 90 °C and V_{CE} ranging from 1 to 5 V. This linearity must descend from a linear dependence of I_C on the junction temperature T_J, so if we consider an HBT biased in the forward-active region at a fixed I_B, we may write

$$I_C(T_J) = I_{C00} \cdot (1 - k \cdot (T_J - T_{J00})) \quad (1)$$

where I_{C00} and T_{J00} are the collector current and junction temperature corresponding to a reference point where $V_{CE} = V_{CE0}$ and $T_B = T_{B0}$.

However

$$T_J - T_{J00} = T_B - T_{B0} + R_{TH} \cdot P_D - R_{TH00} \cdot P_{D00} \quad (2)$$

where $R_{TH} = R_{TH}(T_B, P_D)$, $R_{TH00} = R_{TH}(T_{B0}, P_{D00})$, and $P_{D00} = V_{CE0} \cdot I_{C00}$.

Replacing (2) into (1), and assuming a linear dependence of R_{TH} on P_D [5], whereby we can write, at each T_B

$$R_{TH} = R_{TH0} + \frac{dR_{TH}}{dP_D} \cdot (P_D - P_{D0}) \quad (3)$$

with $R_{TH0} = R_{TH}(T_B, P_{D0})$, and $P_{D0} = V_{CE0} \cdot I_C(T_B, V_{CE0})$, we get a second-order polynomial relationship between I_C and P_D

$$I_C(T_B, P_D) = a_2 \cdot P_D^2 + a_1 \cdot P_D + a_0. \quad (4)$$

The coefficients in (4) are

$$a_2 = -I_{C00} \cdot k \cdot \frac{dR_{TH}}{dP_D} \quad (5)$$

$$a_1 = -I_{C00} \cdot k \cdot \left(R_{TH0} - \frac{dR_{TH}}{dP_D} \cdot P_{D0}\right) \quad (6)$$

$$a_0 = I_{C00} \cdot (1 - k \cdot (T_B - T_{B0} - R_{TH00} \cdot P_{D00})). \quad (7)$$

From (5)–(7), we can extract R_{TH0} and dR_{TH}/dP_D at each value of T_B, as shown in Section III.

Before moving on to show and discuss the experimental results, it is worth spending a few lines to examine the explicit and implicit assumptions underlying this new extraction technique.

First of all, the starting assumption is that of (1), i.e., the linear dependence of β on T_J. While this cannot be independently verified here, a slightly indirect proof can be obtained by the dependence of β on T_B. As we will show in the next section, at fixed I_B, I_C shows a very good linear dependence on T_B over the whole temperature range explored (40–90 °C). Obviously enough, should the measured linearity of I_C on T_B be less than satisfactory, the method can still be applied locally with the desired accuracy by restricting the temperature range.

Equation (1) also implicitly assumes that, in the forward-active region and at fixed I_B, I_C depends only on T_J, i.e., that the Early effect is negligible. If this is obviously questionable for homojunction bipolar junction transistors (BJTs), when measured under isothermal conditions (e.g., using short bias pulses) HBTs enjoy practically Early-free characteristics due to very heavy base doping.

Equation (3) clearly embodies a bolder assumption, namely, the linear dependence of R_{TH} on P_D. Although other authors have shown results consistent with this hypothesis (see, for instance, [5, Fig. 3], which shows a very linear R_{TH} versus P_D data, and [6], which arrives at a second-order dependence of T_J on P_D that is fully consistent with our model), (3) should be considered as a first-order approximation that allows the development of a simple model and a corresponding extraction method, while at the same time, significantly improving the situation with respect to the techniques that altogether neglect the effect of P_D on R_{TH}. We will show in Section IV that assuming a linear dependence of R_{TH} on T_J instead leads to results that are not very dissimilar to those of Section III.

III. Results

The devices under test are via-grounded InGaP/GaAs HBTs that we measured on-wafer using a coplanar probe station with

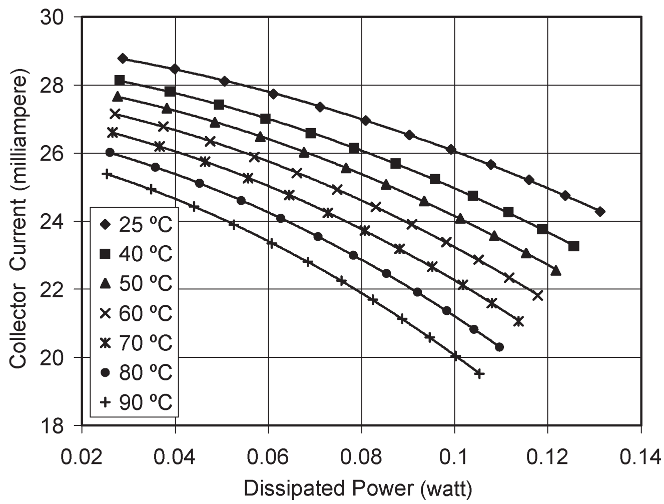

Fig. 2. Collector current measured at $I_{\mathrm{B}} = 0.35$ mA on a 1-finger 3×30 $\mu\mathrm{m}^2$ HBT as a function of P_{D}. The lines are second-order polynomial fits.

TABLE I
COEFFICIENTS OF (4) AS EXTRACTED FOR THE 1-FINGER 3×30 $\mu\mathrm{m}^2$ HBT FROM THE QUADRATIC FITS OF FIG. 2

T_B [°C]	a_0 [mA]	a_1 [mA/W]	a_2 [mA/W^2]
25	29.348	-15.127	-177.94
40	28.731	-15.446	-221.86
50	28.298	-16.233	-252.44
60	27.834	-17.722	-281.83
70	27.345	-19.930	-309.53
80	26.833	-22.739	-335.64
90	26.279	-25.993	-362.09

accurate (± 0.1 °C) chuck temperature control. The HBTs are via grounded and not ballasted. The wafer thickness is 100 μm. We have characterized devices with 1, 4, 6, and 12 emitter fingers, each with an area of 3×30 $\mu\mathrm{m}^2$.

A. 1-Finger 3×30 $\mu\mathrm{m}^2$ HBT

In these experiments, $I_{\mathrm{B}} = 0.35$ mA, $T_{\mathrm{B0}} = 40$ °C, $V_{\mathrm{CE0}} = 1$ V, $I_{\mathrm{C00}} = 28.134$ mA.

Fig. 2 shows that the measured dependence of I_{C} on P_{D} at various baseplate temperatures is indeed a second-order polynomial, which is consistent with (4) of our model. From the second-order polynomial fits of Fig. 2 we get, at each T_{B}, the three coefficients a_2, a_1, a_0, as given in Table I.

Now, (7) tells us that a_0 must be linearly dependent on T_{B}, which is verified with good accuracy in Fig. 3. From the slope of the linear best-fit and from (7), we get $k = 1.741 \times 10^{-3}$ °C^{-1}, and from a_0 (40 °C) we obtain $R_{\mathrm{TH00}} = 443$ °C/W. Since now k is known, from (5) we extract $\mathrm{d}R_{\mathrm{TH}}/\mathrm{d}P_{\mathrm{D}}$ at each T_{B}, using which, in (6), we get the corresponding R_{TH0}, thus completing the extraction procedure. Table II gives the values of R_{TH0} and $\mathrm{d}R_{\mathrm{TH}}/\mathrm{d}P_{\mathrm{D}}$ for the different baseplate temperatures.

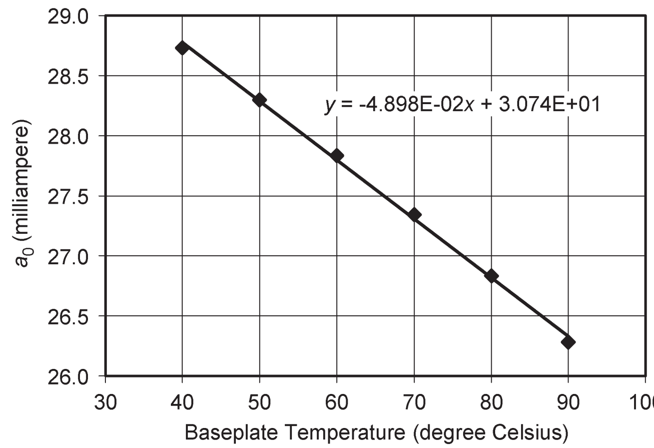

Fig. 3. Coefficient a_0 extracted from the data of Fig. 2 as a function of T_{B}. The linear best-fit is also shown.

TABLE II
VALUES OF $\mathrm{d}R_{\mathrm{TH}}/\mathrm{d}P_{\mathrm{D}}$ AND R_{TH0} EXTRACTED FROM (5) AND (6), RESPECTIVELY, FOR THE 1-FINGER 3×30 $\mu\mathrm{m}^2$ HBT

T_B [°C]	dR_{TH}/dP_D [°C/W^2]	R_{TH0} [°C/W]
25	3633	413
40	4529	443
50	5154	474
60	5754	518
70	6319	575
80	6852	643
90	7392	718

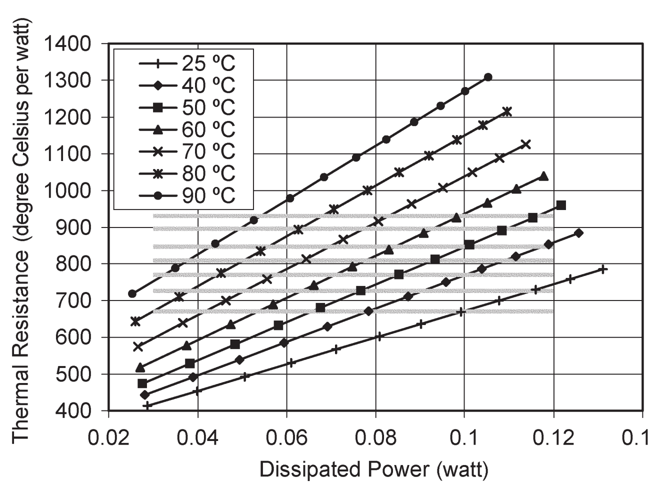

Fig. 4. R_{TH} extracted for a 1-finger 3×30 $\mu\mathrm{m}^2$ HBT as a function of P_{D} for different baseplate temperatures. The gray lines show the results obtained using the technique of [13]; from bottom to top, the lines correspond to $T_{\mathrm{B}} = 25, 40, 50, 60, 70, 80, 90$ °C, respectively.

Fig. 4 shows the extracted values of R_{TH} as a function of P_{D} and for the different T_{B} values.

As a comparison, Dawson's method [13] applied to the same device, with P_{D} ranging from 30 to 120 mW, yields thermal resistance values ranging from $R_{\mathrm{TH}}(T_{\mathrm{B}} = 25\ °\mathrm{C}) = 670$ °C/W to $R_{\mathrm{TH}}(T_{\mathrm{B}} = 90\ °\mathrm{C}) = 931$ °C/W. The thermal

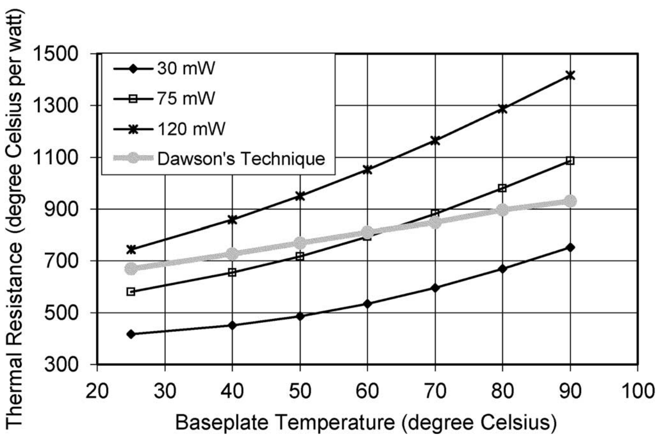

Fig. 5. R_{TH} extracted for a 1-finger $3 \times 30\ \mu\mathrm{m}^2$ HBT as a function of T_{B} for three different values of P_{D}. The gray line shows the results obtained using the technique of [13].

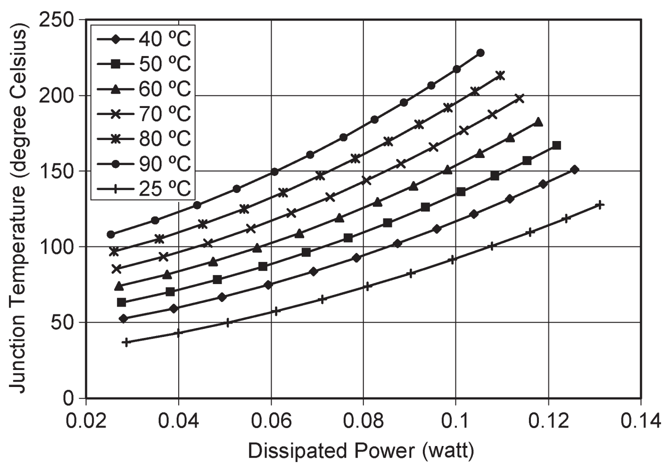

Fig. 6. Junction temperatures calculated for a 1-finger $3 \times 30\ \mu\mathrm{m}^2$ HBT using the R_{TH} values of Fig. 4. The corresponding values of T_{B} are shown in the legend.

resistances extracted using Dawson's technique are shown as gray lines in Fig. 4; since this method neglects the dependence of R_{TH} on the dissipated power, we have plotted horizontal lines spanning the P_{D} range used in the extraction procedure. Although a direct comparison is not possible, it is worth noticing that the values yielded by Dawson's technique fall within the range of those extracted by the new technique. In particular, if we compare Dawson's values with those yielded by the new method for $P_{\mathrm{D}} = 75$ mW, i.e., the average power dissipated in the Dawson's measurement, we get differences ranging from $+15\%$ ($T_{\mathrm{B}} = 25\ ^\circ\mathrm{C}$) to -12% ($T_{\mathrm{B}} = 90\ ^\circ\mathrm{C}$); this means that, if we consider Dawson's R_{TH} as an average value over the $P_{\mathrm{D}} = 30$–120 mW range, the two techniques do not appear to be very far from each other.

Fig. 5 shows the baseplate temperature dependence of R_{TH} at three different power levels. Again, the gray line represents Dawson's results; as pointed out above, they are not far from those obtained with our new method for $P_{\mathrm{D}} = 75\ \mathrm{mW}$, i.e., the average P_{D} used in the extraction according to Dawson.

We plot, in Fig. 6, the values of T_{J} calculated using the thermal resistances of Fig. 4.

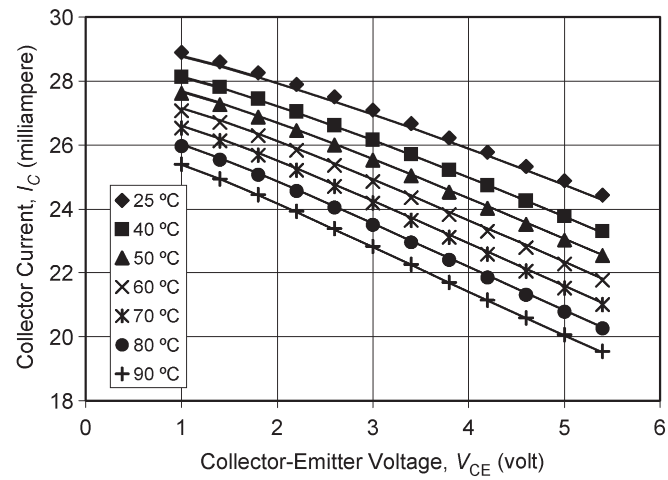

Fig. 7. Measured (symbols) and modeled (lines) I_{C} as a function of V_{CE} for a 1-finger $3 \times 30\ \mu\mathrm{m}^2$ HBT. The model is that of (1), with $k = 1.741 \times 10^{-3}\ ^\circ\mathrm{C}^{-1}$, $T_{\mathrm{J00}} = 52.5\ ^\circ\mathrm{C}$, and the T_{J} values are those of Fig. 6. The values of T_{B} are shown in the legend.

Finally, it is worth pointing out that (1)–(7) embody not just a technique for R_{TH} extraction, but a very simple model of the collector current in the forward-active region. Therefore, using the thermal-resistance values we extracted and the corresponding junction temperatures (Fig. 6), we should be able to model the I_{C}–V_{CE} dependence over the range of baseplate temperatures we considered. Fig. 7 shows the comparison between measured (symbols) and modeled (lines) I_{C}, for T_{B} ranging between 25 and 90 °C. The excellent match highlights the consistency of our model.

B. Multifinger HBTs

The new extraction technique was applied to HBTs with 4, 6, and 12 $3 \times 30\ \mu\mathrm{m}^2$ emitter fingers, corresponding to emitter areas of 360, 540, and 1080 $\mu\mathrm{m}^2$, respectively. The multifinger devices belong to the same process and wafer as the single-finger HBT characterized above. All of the results were as well behaved as, and consistent with, the ones obtained on the single-finger HBT. For example, the values of k extracted are 1.809 $^\circ\mathrm{C}^{-1}$ (4 fingers), 1.780 $^\circ\mathrm{C}^{-1}$ (6 fingers), 1.786 $^\circ\mathrm{C}^{-1}$ (12 fingers); relative to the 1-finger value (1.741 $^\circ\mathrm{C}^{-1}$), the maximum difference is less than 4%.

As a representative example, Fig. 8 shows the thermal resistance of the 12-finger HBT, together with the corresponding results according to Dawson's method.

Fig. 9 shows values of the thermal resistance (normalized to the 1-finger case) measured on 1-, 4-, 6-, and 12-finger devices, at $T_{\mathrm{B}} = 40\ ^\circ\mathrm{C}$ and power densities of 50 and 68 $\mathrm{kW/cm^2}$, respectively. The thermal resistance is normalized by multiplying the measured value by the number of fingers. As expected, as the number of fingers grows, the per-finger thermal resistance increases as well, due to less efficient thermal dissipation from the central fingers. The increase of the normalized R_{TH} with the finger number is dramatic: going from 1-finger to 12-finger HBTs, the specific thermal resistance more than doubles. It should be noted that the very well-behaved scaling behavior is another indicator of the consistency of our method. As a

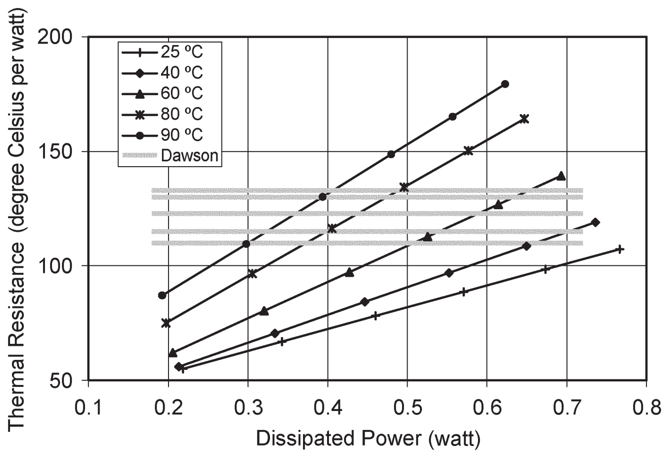

Fig. 8. R_{TH} extracted for a 12-finger (1080 $\mu\mathrm{m}^2$) HBT as a function of P_{D} for different baseplate temperatures. The gray lines show the results obtained using the technique of [13]; from bottom to top, the lines correspond to $T_{\mathrm{B}} = 25, 40, 60, 80, 90\ ^{\circ}\mathrm{C}$, respectively.

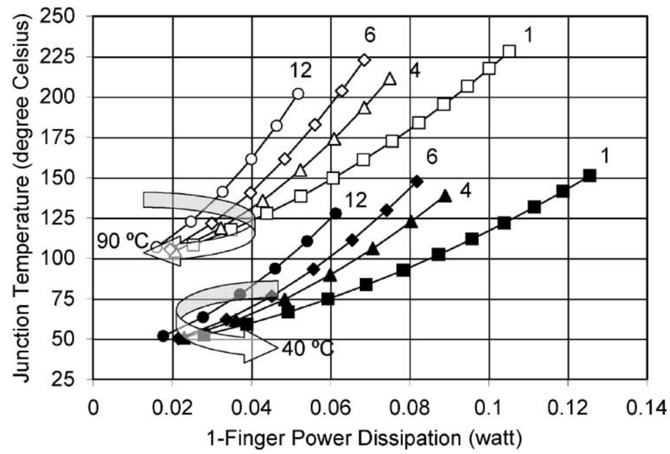

Fig. 10. Junction temperatures calculated for a 1-finger (squares), 4-finger (triangles), 6-finger (diamonds), and 12-finger (circles) HBT as a function of the power dissipation (normalized to 1 finger), for $T_{\mathrm{B}} = 40\ ^{\circ}\mathrm{C}$ (full symbols) and $T_{\mathrm{B}} = 90\ ^{\circ}\mathrm{C}$ (open symbols). The area of each emitter finger is $3 \times 30\ \mu\mathrm{m}^2$.

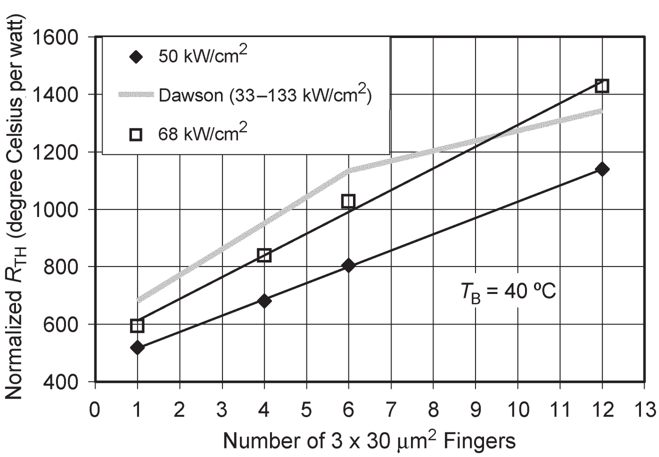

Fig. 9. Normalized (1-finger) R_{TH} extracted at a power density of $50\ \mathrm{kW/cm^2}$ and $68\ \mathrm{kW/cm^2}$ for 1-, 4-, 6-, and 12-finger HBTs, at $T_{\mathrm{B}} = 40\ ^{\circ}\mathrm{C}$. The emitter finger area is $3 \times 30\ \mu\mathrm{m}^2$. The thermal resistance is normalized by multiplying the measured R_{TH} by the number of fingers. The values obtained using Dawson's method are shown for comparison (gray line).

comparison, the corresponding values yielded by Dawson's technique are also shown.

Finally, we plot in Fig. 10 the calculated junction temperatures as a function of the normalized (to 1 finger) power dissipation for all the HBTs under testing; two values of T_{B} are shown here, namely, 40 °C (full symbols) and 90 °C (open symbols). As can be expected, for the same power density, larger HBTs get significantly hotter than smaller ones, due to less efficient heat removal from the central fingers.

IV. An Alternative Technique

In order to check the impact of our assumption (3) (namely, the linear dependence of R_{TH} on P_{D}), we have applied a different approach (similar to that of Yeats [23]) to the thermal resistance extraction of the single-finger HBT. We assume a linear dependence of R_{TH} on T_{J} (thus, neglecting the second-order effects of lattice temperature on thermal conductivity), namely

$$R_{\mathrm{TH}} = R_{\mathrm{TH00}} + \frac{\mathrm{d}R_{\mathrm{TH}}}{\mathrm{d}T_{\mathrm{J}}} \cdot (T_{\mathrm{J}} - T_{\mathrm{J00}}) \tag{8}$$

which leads, together with (1) and after straightforward manipulations, to

$$I_{\mathrm{C}}(T_{\mathrm{J}}) = I_{\mathrm{C00}} \left(1 - k\frac{T_{\mathrm{B}} - T_{\mathrm{B0}} + R_{\mathrm{TH00}}(P_{\mathrm{D}} - P_{\mathrm{D00}})}{1 - \frac{\mathrm{d}R_{\mathrm{TH}}}{\mathrm{d}T_{\mathrm{J}}} P_{\mathrm{D}}}\right). \tag{9}$$

Equation (9) can obviously be written as

$$1 - \frac{I_{\mathrm{C}}(T_{\mathrm{J}})}{I_{\mathrm{C00}}} = k\frac{T_{\mathrm{B}} - T_{\mathrm{B0}} + R_{\mathrm{TH00}}(P_{\mathrm{D}} - P_{\mathrm{D00}})}{1 - \frac{\mathrm{d}R_{\mathrm{TH}}}{\mathrm{d}T_{\mathrm{J}}} P_{\mathrm{D}}} \tag{10}$$

hence, plotting $(1 - I_{\mathrm{C}}/I_{\mathrm{C00}})$ versus T_{B} at each fixed value of P_{D} should yield a straight line.

Using polynomial interpolation of the measured data of Fig. 2, we, therefore, calculated, at each T_{B}, the values of I_{C} corresponding to a few fixed values of P_{D}, and plotted (10) as in Fig. 11. As predicted by (10), we observe a good linearity. If we call α the reciprocals of the slopes of the best-fit lines in Fig. 11, we get, according to (10)

$$\alpha = \frac{1}{k} - \frac{\frac{\mathrm{d}R_{\mathrm{TH}}}{\mathrm{d}T_{\mathrm{J}}}}{k} P_{\mathrm{D}}. \tag{11}$$

Thus, if we plot α as a function of P_{D}, from a best-fit linear regression, we will be able to extract k and $\mathrm{d}R_{\mathrm{TH}}/\mathrm{d}T_{\mathrm{J}}$. This is shown in Fig. 12, which gives us $k = 1.767 \times 10^{-3}\ ^{\circ}\mathrm{C}^{-1}$ (in excellent agreement with the $k = 1.741 \times 10^{-3}\ ^{\circ}\mathrm{C}^{-1}$ found in Section III) and $\mathrm{d}R_{\mathrm{TH}}/\mathrm{d}T_{\mathrm{J}} = 4.988\ \mathrm{W}^{-1}$. Now, R_{TH00} can be calculated using (10) for each of the data points of Fig. 2; disregarding the points at $V_{\mathrm{CE}} = 1$ V and $V_{\mathrm{CE}} = 1.4$ V, where the small values of $(P_{\mathrm{D}} - P_{\mathrm{D00}})$ lead to large errors when R_{TH00} is extracted from (10), we get an average $R_{\mathrm{TH00}} = 436\ ^{\circ}\mathrm{C/W}$ (again, in excellent agreement with the $R_{\mathrm{TH00}} = 443\ ^{\circ}\mathrm{C/W}$ found in Section III).

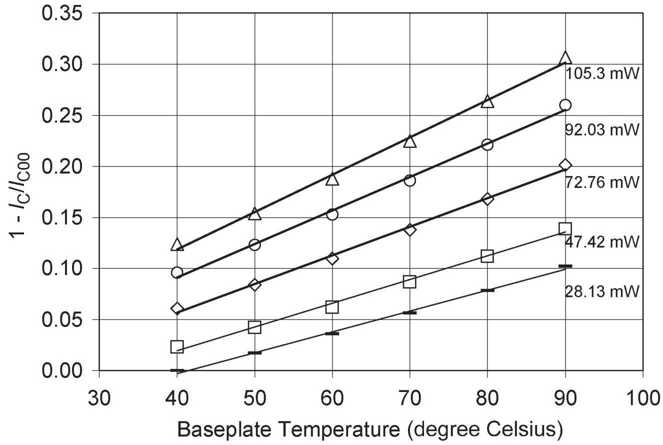

Fig. 11. Plot of (10) for values of the dissipated power $P_{\rm D}$ ranging from 28.13 to 105.3 mW (symbols) in a 1-finger 3×30 μm^2 HBT. The best-fit lines are also shown (solid lines).

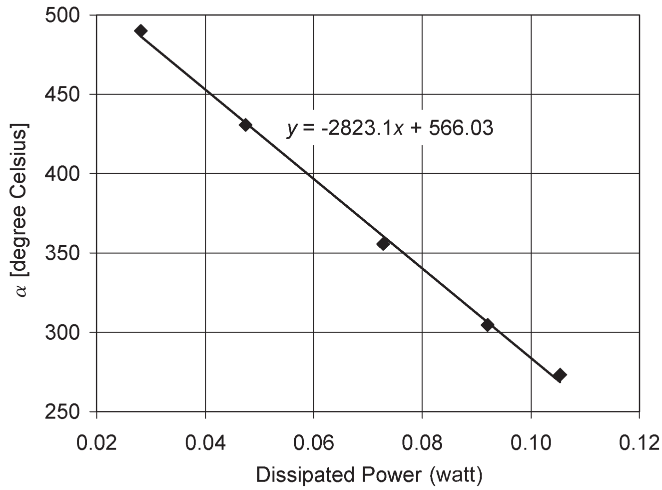

Fig. 12. Plot of (11) for a 1-finger 3×30 μm^2 HBT (diamonds). The best-fit line is also shown (solid line).

Fig. 13 shows the values of $R_{\rm TH}$ we get following this procedure (solid lines). There is substantial agreement with the corresponding values obtained in Section III (here shown as symbols); this indicates that the assumption (3) does not have a significantly negative impact on the new extraction procedure.

V. Conclusion

This paper introduced a new dc technique for the measurement of the thermal resistance of HBTs. The method is very simple, because it requires only standard $I_{\rm C}$–$V_{\rm CE}$ measurements at different baseplate temperatures, and it is able to account for the dependence of the thermal resistance on both the baseplate temperature and the dissipated power. We have obtained and shown consistent results extracted from devices with emitter area ranging from 90 (1 finger) to 1080 μm^2 (12 fingers). The thermal resistances yielded by the well-known Dawson's extraction technique are seen to fall inside the range of our results.

We have considered two different models of the dependence of the thermal resistance on the dissipated power, namely:

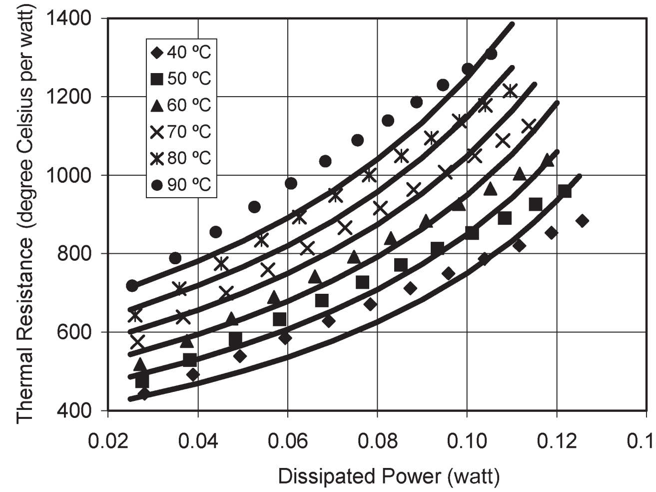

Fig. 13. $R_{\rm TH}$ extracted for a 1-finger 3×30 μm^2 HBT as a function of $P_{\rm D}$ for different baseplate temperatures, following the alternative procedure of Section IV (solid lines). The symbols show the corresponding values obtained with the technique described in Sections II and III.

1) linear dependence between thermal resistance and dissipated power, and 2) linear dependence between thermal resistance and junction temperature, and we have shown that both models lead to similar results. We believe this to be an indicator of the consistency and robustness of our extraction method.

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