Direct Extraction Technique to Derive the Junction Temperature of HBT's Under High Self-Heating Bias Conditions

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***Abstract*—A new technique is presented that can directly extract the mean device junction temperature of heterojunction bipolar transistors (HBT's) under high self-heating operating conditions. The method uses three trivial dc measurements of the device where the junction temperature is known to be the same. This paper details the technique and applies it to both closely and widely spaced multi-finger HBT's, and compares the results to methods already known.**

***Index Terms*—Heterojunction bipolar transistors, power transistors, reliability management, semiconductor device thermal factors, self-heating, temperature measurement, thermal impedance.**

I. Introduction

THE reliability, and mechanisms affecting the stability of the current gain, of a heterojunction bipolar transistor (HBT) have been shown to be functions of both the collector current density and the device mean junction temperature [1]. The current density is easily measured, but the junction temperature is more difficult to find. One method for calculating the junction temperature is to find the thermal impedance of the device and determine the temperature rise above ambient temperature by multiplying the thermal impedance by the power dissipated in the device [2], [3]. However, in high power dissipation HBT's, as used for power amplifiers, the thermal impedance of the device is not constant but a function of both the power dissipation and the ambient temperature [4], [5]. The method outlined in this paper bypasses the need to find a thermal impedance and derives the mean junction temperature (at the specified operating ambient temperature and power dissipation) directly from three simple voltage and current measurements.

II. Extraction Technique

Previous methods to determine the device mean junction temperature (via derivation of the thermal resistance) have either used the fact that the current-gain (β) decreases with increasing junction temperature [3], [4], or that the base-emitter voltage $(V_{\rm be})$, for fixed emitter current, is only a function of the junction temperature [2], [3], [5], [6]. One consequence of this functionality is that the current–voltage (*I-V*) curves of an HBT shows the characteristic negative slope at high power dissipation due to self-heating. If the ambient temperature increases, β decreases and the *I-V* curve drops to lower collector current levels. The negative slope of the curve changes because the self-heating is dependent on the thermal impedance, which increases with higher junction temperatures [5].

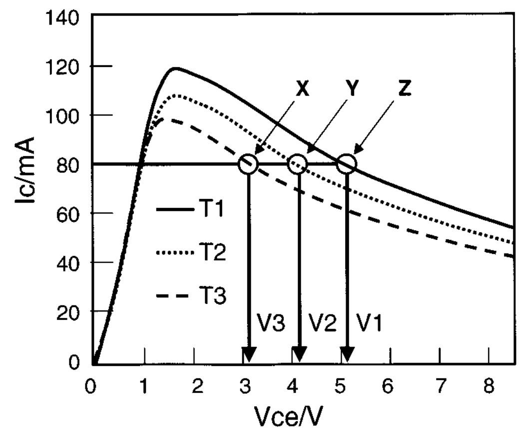

Fig. 1. I_c verses $V_{\rm ce}$ for three ambient temperatures and constant I_b.

These previous methods all rely on fitting a linear relationship between either β or $V_{\rm be}$ with the junction temperature, but the linearity with temperature was only within 10% and 4%, respectively [3]. A better way of determining the junction temperature is to take a number of measurements at exactly the same junction temperature where any nonlinear relationships between β, or $V_{\rm be}$, and the junction temperature become irrelevant.

Consider the curves in Fig. 1, where the collector current (I_c) is plotted versus the collector-emitter voltage $(V_{\rm ce})$ for a fixed base current (I_b), and three different base-plate ambient temperatures. Bias point Z is the nominal operating bias point for this HBT (from which the worst-case power dissipation, $P_1 = V_1 I_c$, can be calculated[1]), and the ambient temperature T_1 is the ambient temperature at which the operating junction temperature is to be found. Bias point X is at a higher ambient temperature (T_3), and lower power dissipation (P_3), but has the same collector current, and the same base current as bias point Z. Bias point Y is at an intermediate ambient temperature (T_2), and an intermediate power dissipation (P_2), but, again, has the same collector current, and the same base current as bias point Z. At each of these three bias points the base and collector currents are

[1]Strictly the power dissipation also includes the contribution of $V_{\rm be} I_b$, which is usually a factor of ~100 less than $V_{\rm ce} I_c$, and is the same value at each bias point.

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identical, and hence the current gain β is also identical. Therefore, as β is known to be a function only of the junction temperature and is the same at these three points, the mean device junction temperature must also be the same. Experimental observations have shown that $V_{\rm be}$ is also the same at each of these bias points, which adds weight to this supposition.

We now have three ambient temperatures and associated power dissipations that produce the same mean junction temperature within the device.

$$T_j = T_{\rm base} + \theta P_{\rm diss}. \quad (1)$$

Taking the classical definition of device thermal impedance (θ in (1), and acknowledging that the thermal impedance at each bias point may be different, we have the following three equations:

$$T_j = T_1 + \theta_1 P_1 \quad (2)$$

$$T_j = T_2 + \theta_2 P_2 \quad (3)$$

$$T_j = T_3 + \theta_3 P_3. \quad (4)$$

To solve these equations, we must reduce the number of unknown variables by examining the dependence of the thermal impedance on the other parameters. It is proposed that the thermal impedance, for a fixed junction temperature, is a linear function of the ambient base-plate temperature. In other words, the thermal impedance from a fixed junction temperature to the base-plate is a linear function of the temperature difference, as follows:

$$\theta(T_j) = A + BT_{\rm base}. \quad (5)$$

This relationship was investigated using finite difference thermal simulation of a typical HBT three—dimensional (3-D) structure, with the temperature dependent GaAs thermal conductivity. Fig. 2 shows the simulation results for a single, 40 µm length, finger on a 100 µm thick substrate. The simulation shows that, for fixed junction temperatures of 130° and 188°C, the thermal impedance is a linear function of the ambient temperature of the base-plate.

Given that this relationship is correct, (5) may be substituted into (2), (3) and (4) to give

$$T_j = T_1 + (A + BT_1)P_1 \quad (6)$$

$$T_j = T_2 + (A + BT_2)P_2 \quad (7)$$

$$T_j = T_3 + (A + BT_3)P_3. \quad (8)$$

We now have three simultaneous equations and three unknowns (A, B, and T_j), which can be solved by the usual method to give the device mean junction temperature, T_j. If the three ambient temperatures are chosen to be equally spaced ($T_3 = T_2 + \Delta T$ and $T_1 = T_2 - \Delta T$) then the solution simplifies to the expression

$$T_j = T_2 + \Delta T\left(\frac{P_2}{P_3} - \frac{P_2}{P_1}\right) \Big/ \left(\frac{P_2}{P_3} + \frac{P_2}{P_1} - 2\right). \quad (9)$$

The spacing of the ambient temperatures (ΔT) is arbitrary because the junction temperature (T_j) is not dependant on its value, and this has been confirmed experimentally for ΔT ranging from 10°C to 40°C. However, to minimize the effect of measurement errors, ΔT should be as large as possible while ensuring that bias point X remains clearly within the saturation region of the transistor *I-V* curve.

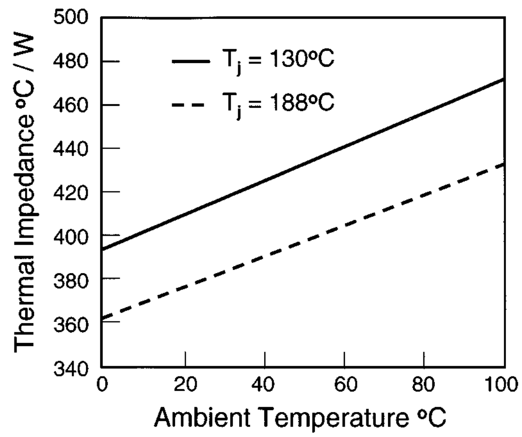

Fig. 2. Simulated thermal impedance verses ambient temperature for two fixed junction temperatures.

III. Analysis of HBT 4x40 InGaP/GaAs Devices

This technique was used to derive the mean device junction temperature of two different layouts of InGaP/GaAs HBT's, manufactured at Marconi Technology Ltd., Caswell, U.K. Each HBT had four emitter fingers, of 40 µm in length and 2 µm in width, with one device (P4 × 40C) having four widely separated (50 µm) fingers, and the other device (4 × 40C) having closely spaced (6 µm) fingers. Both layouts were measured on the same, 100 µm thick, wafer. The devices were biased at a collector voltage of 5 V, a collector current of 80 mA, and an ambient temperature of 25°C for determination of the junction temperature . Bias point Z in the analysis is chosen to be the operating bias point at 25°C ambient and this fixes the base current for the $V_{\rm ce}$ sweep. The same base current is also used for the $V_{\rm ce}$ sweeps at the higher ambient temperatures of 55, and 85°C. The resulting curves and analysis bias points are shown in Figs. 3 and 4.

Three different devices of each type were measured, and the mean junction temperature calculated for each one. The resulting average from the three devices gave a junction temperature of 105.3°C for the widely spaced P4 × 40C device, and 182.5°C for the closely spaced 4 × 40C device. This shows that the extra self-heating in the closely spaced devices leads to a temperature increase of 77.2°C.

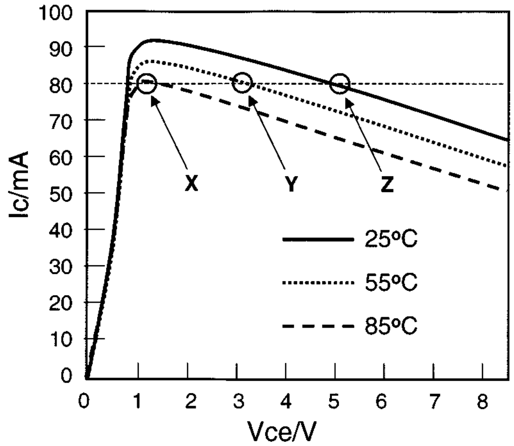

Fig. 3. I_c verses V_{ce} of device P4 × 40C, for ambient of 25°, 55°, and 85°C, and I_b fixed to give 80 mA at 5 V and 25°C.

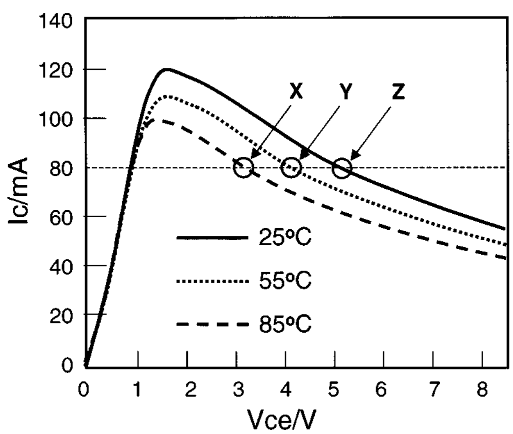

Fig. 4. I_c versus V_{ce} of device 4 × 40C, for ambient of 25°, 55°, and 85°C, and I_b fixed to give 80 mA at 5 V and 25°C.

IV. Comparison with Alternative Techniques

This technique has been compared to other dc junction temperature, or thermal impedance, measurement techniques. The technique used by D. E. Dawson *et al.* [3], using $V_{\rm be}$ measurements at constant I_e, is valid only where the power dissipation levels are low enough to give small self-heating effects [7], as in the case of the widely spaced P4 × 40C device. The thermal impedance of this device derived by Dawson's method was 179°C/W, giving a mean device junction temperature of 96.8°C, which agrees within 9% of the new technique. The high self-heating within the closely spaced 4 × 40C device makes the calculation of the junction temperature by Dawson's method inappropriate.

The technique used by Bovolon *et al.* [7], which can derive the thermal impedance at any dissipated power level, linearises the β (or $V_{\rm be}$) variation with temperature, locally to the bias point at which the thermal impedance is required. The values derived for the P4 × 40C device by this method were thermal impedance of 212°C/W and mean device junction temperature of 110°C, which is within 5% of the new technique.

As the new technique, as presented in this paper, and that used by N. Bovolon [7] can be used at high power dissipation levels and high self-heating, these two methods were compared for the closely spaced 4 × 40C device. The technique used by N. Bovolon gave a mean device junction temperature of 178°C, which is within 3% of the value derived using the new technique (182.5°C).

Previous methods have either been very complex in the required measurements or analysis [5], or not been valid at high power-dissipation levels [3]. The most comparable technique [7] derives the junction temperature by extracting the thermal impedance first, which is valid only for that particular power dissipation, and then calculating the junction temperature. In contrast to this, the new technique can derive the mean device junction temperature directly, for high self-heating and high power dissipation, and achieve this from three simple dc measurements.

The technique used by Bovolon *et al.* [7] also relies on small differences in the ambient wafer-chuck temperature, β, and power dissipation to ensure the local β linearity. This has the effect of making any measurement errors large proportions of the differences, which appear in the formulas' denominator. Accurate control of the chuck temperature during the comparison measurements has given good agreement with the new technique in this case, but care must be taken to ensure that measurement errors do not impact on the derived junction temperature. The new technique is less susceptible to measurement errors as it does not depend on the three data points being close for linearization of β or $V_{\rm be}$, but effectively nulls β variations by taking measurement points at the same junction temperature. The three data points in the new technique may be spaced at much wider chuck temperatures because the relationship of thermal impedance verses ambient chuck temperature for fixed junction temperature (Fig. 2), is linear over a very wide range of ambient chuck temperature.

This new technique is limited to devices operated under high self-heating bias conditions, i.e., devices with sufficient negative slope in their *I–V* characteristics such that the three points can be plotted within the saturation region of the transistor *I–V* curves.

V. Conclusion

A new technique has been developed to obtain the mean junction temperature of a InGaP/GaAs HBT device under high self-heating or high power dissipation operating conditions. The technique makes use of three simple dc measurements, where the junction temperature has been shown to be the same, and so does not rely on linearization of either β or $V_{\rm be}$ with temperature. The results obtained are in good agreement with the junction temperature derived by methods previously published [3], [7], but this direct extraction technique is less susceptible to measurement error.

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