Analysis of Temperature Dependence of GaAs DHBT Terminal Resistances Using the Observed Kink Effect

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Abstract — **Large parasitic series resistances of heterojunction bipolar transistor (HBT) are shown to cause a sharp kink in the base current (I_B) of the Gummel plot at elevated temperatures under high collector currents (I_C) and low base-collector (*b-c*) applied bias (V_{BC}). This effect was analyzed and attributed to the temperature dependence of low-field and high field mobilities of undepleted and depleted areas at the *b-c* region. Using this observed kink a simple technique is presented to extract terminal resistances variation with temperature for an InGaP/GaAs DHBT. These extracted values are compared and verified with those extracted from s-parameter measurements. By incorporating these values into a temperature-dependent large signal DHBT model more accurate thermal behavior of I_B at high current is demonstrated.**

I. Introduction

Wireless communication systems require high-frequency power amplifiers, which perform efficiently in wide-ranging thermal environments. To accomplish this designers require more physically meaningful device models as well as greater understanding of their semiconductor material processes. When PA's are subjected to high power levels, the transistors typically operate under elevated junction temperatures that may thermally trigger undesirable effects such as increase in parasitic resistances.

Large series resistances in HBTs are shown to cause the *b-c* junction to become forward biased when operated under high I_C. This causes a sharp increase in I_B. Tiwari first reported this effect in the study of AlGaAs/GaAs DHBTs and demonstrated that by applying reverse bias to b-c junction the kink effect can be minimized [1]. In our earlier work [2] we also observed the same effect for an InGaP/GaAs SHBT and showed that by reverse biasing steps one can deduce the terminal resistances of the transistor.

The effect of kink is more pronounce when the device is operated at elevated temperatures. Frick et al [3] have observed this effect for a single AlGaAs/GaAs HBT; however no detailed analysis was reported in their study. The most reliable method to extract temperature dependent HBT parasitic resistances is based on *s*-parameters, which involves accurate high frequency measurements over temperature. In this paper for the purpose of accurate HBT modelling we propose a simple technique to extract directly the terminal resistances variation with temperature utilizing the observed kink. It is also shown that the main contribution to the enhanced kink at elevated temperature arises from the temperature dependence of specific contact resistance in metal/n$^+$(or p$^+$)- GaAs contacts and from the temperature dependence of low field and high field mobilities associated with the undepleted part of n-InGaP collector and n$^+$-GaAs sub-collector.

II. Experimental and Analysis

The layer structure and fabrication for the InGaP/GaAs DHBTs studied is given in [4, 8]. *DC* and high frequency s-parameters were carried out using Cascade Microtech's thermal probing system over the temperature range of 298K to 383K using InGaP/GaAs DHBTs with emitter geometry of 16x20μm^2.

Fig. 1 shows the variation of I_C and I_B versus V_{BE} of a 16x20μm^2 InGaP/GaAs DHBT in the temperature range from 248K to 383K. Under high I_C and low applied reverse bias (or $V_{BC} \approx 0$) the large voltage drop due to collector resistance (R_C) forming the undepleted part of the collector, sub-collector and the contact causes the *b-c* junction to become forward biased, which gives rise to an additional *b-c* junction current (I_{BC}) causing a sharp increase in I_B. This kink effect is seen to enhance with increasing ambient temperature (T_A), however the direction of I_{BC} is the opposite to that of the conventional I_C causing I_C to reduce as depicted in Fig. 1.

One would expect the saturation velocity (v_{sat}) to decrease with rise in temperature due to lattice perturbations [5]. Any reduction in v_{sat} would effectively reduce the peak electric field and increase the undepleted region (W_C - X_C) of collector thickness (W_C) [6, 7]. The voltage drop in the undepleted collector ($\approx I_CA\ (W_C$-$X_C)/qN_C\mu_n$) [6, 7] at high I_C (low V_{BC}) would increase due to electron mobility (μ_n) degradation with T_A and increase of W_C. For $I_C \approx I_O$ and V_{BC} low, where $I_O = qAv_{sat}N_C$ is the saturated drift velocity current, the electron density (n) exceeds the collector doping density (N_C) diminishing the electric field leading to base-pushout. For $I_C > I_O$, the potential drop across undepleted base (R_B) eventually becomes significant limiting the *b-c* forward bias. The latter is the reason for the second saturation observed in I_B as depicted in Fig. 1.

Now if one applies sufficient large reverse bias to the *b-c* junction, the electric field on the collector side of the SCR would increase with V_{CRIT} pushed forward diminishing the observed kink on I_B as depicted in Fig. 2. The measured I_B characteristics for T = 298K and 343K under zero and reverse bias conditions are shown in Fig. 2.

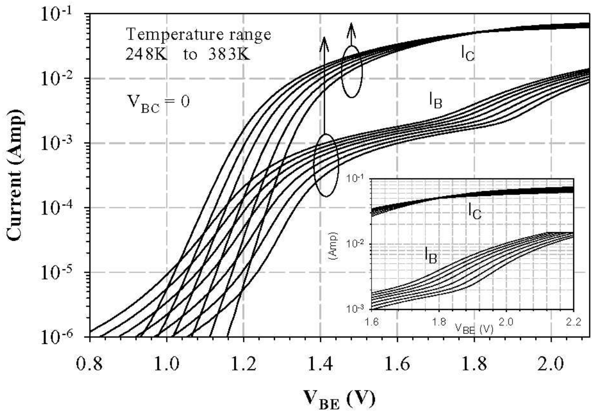

Fig. 1: Variation of Gummel plots with temperature for an InGaP/GaAs DHBT showing the effect of kink on I_B. The inset shows the reoccurrence of I_B characteristics at higher V_{BE}.

From Fig. 2, two observations on I_B with temperature can be made. Firstly, current gain (β) of the device at V_{BE} = 1.8V varies from h_{FE} = 25 (when V_{BC} = 0V and T = 298K) to h_{FE} = 22 (when V_{BC} = 1.2V and T_A = 343K). The temperature dependence of saturation currents in DHBTs generally is complicated due to the fact that both base transport and *b-e* and *b-c* barrier transport limitations may be important. Bearing this in mind, we attribute this increase in the I_B to activation energies and pre-exponential terms associated with saturation current components of I_B [5].

Secondly, h_{FE} = 16 (when V_{BC} = 0V and T = 343K) indicating β drop due to an extra current component (I_{BC}) flowing at elevated temperatures, which adds to I_B causing the onset of the kink to shift to lower V_{BE}. As discussed this phenomenon was attributed to the v_{sat} and temperature dependence of μ_n associated with R_C and R_B. Furthermore, in this region of interest the variation of I_C is independent of temperature as depicted in Fig. 1; therefore one could eliminate the possibility of any contributions resulting from the temperature dependence of I_C on V_{BE}.

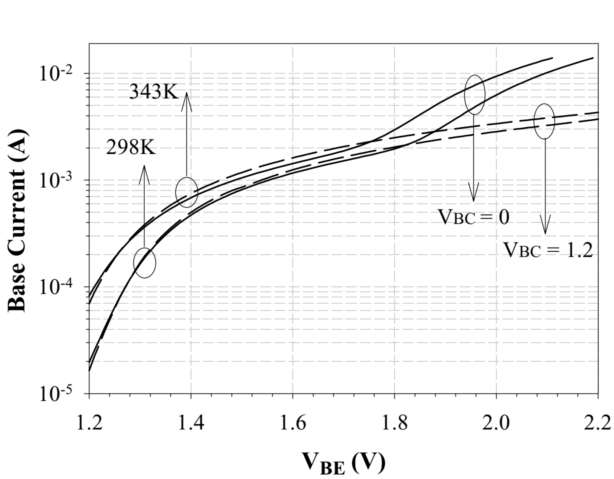

Fig. 2: Measured I_B vs. V_{BE} at T = 298K and 343K under zero and reverse bias conditions.

III. Theoretical model and extraction

According to the Ebers-Moll DC model for the bipolar transistor, at medium to high currents, I_B and I_C can be expressed as:

$$I_B(T) = I_{BES}(T)\cdot\exp\left(\frac{V_{B'E'}}{n_{BE}(T)\cdot V_T}\right) + I_{BCS}(T)\cdot\exp\left(\frac{V_{B'C'}}{n_{BC}(T)\cdot V_T}\right) \quad (1)$$

$$I_C(T) = I_{CCS}(T)\cdot\exp\left(\frac{V_{B'E'}}{n_{CC}(T)\cdot V_T}\right) - I_{BCS}(T)\cdot\exp\left(\frac{V_{B'C'}}{n_{BC}(T)\cdot V_T}\right) \quad (2)$$

Where $n_{BE}(T)$, $n_{CC}(T)$ and $n_{BC}(T)$ are the ideality factors of *b-e* current (I_{BE}), collector current (I_C) and *b-c* current (I_{BC}) respectively. The actual internal junction potentials $V_{B'E'}$ and $V_{B'C'}$ should be corrected by taking into account of the emitter (R_E), collector (R_C) and base (R_B) resistances accordingly as:

$$V_{B'E'} = V_{BE} - R_E I_E - R_B I_B \quad (3)$$

$$V_{B'C'} = V_{BC} + R_C I_C - R_B I_B \quad (4)$$

From the measured base current characteristics of Fig. 2 if one subtracts I_B from the I_B in which the kink is observed at any given temperature ($\Delta I_B(T) = I_B(T, V_{BC} = 0) - I_B(T, V_{BC} > 0)$, then the resultant difference should equal to the second term of (1), which gives

$$\Delta I_B(T) = I_{BCS}(T)\cdot\exp\left(\frac{V_{BC} + I_C\left(R_C - \frac{R_B}{\beta(T, I_C)}\right)}{n_{BC}(T)\cdot V_T}\right) \quad (5)$$

If ΔI_B (T)'s for different T's are plotted logarithmically against I_C, the graphs will show exponential behaviors (straight lines) in the medium I_C range as shown in Fig. 3. According to (5) the straight lines fitted to the log (ΔI_B) vs. I_C plots for different temperatures have a slope of $(R_C-(R_B/\beta))/(n_{BC}*V_T)$, where at moderate I_C, β>10.

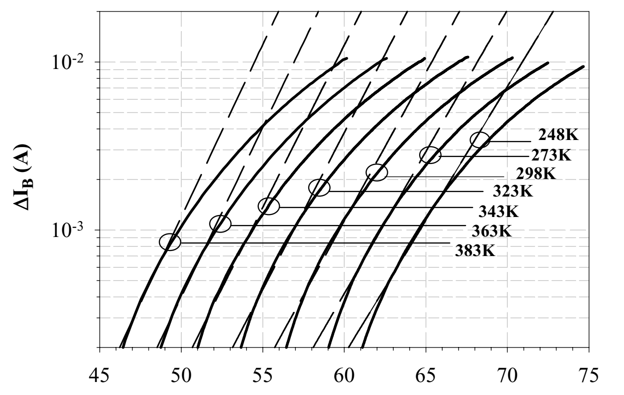

Fig. 3: Plots of ΔI_B (I_B (V_{BC} = 0) - I_B (V_{BC} < 0)) vs. I_C. The dashed lines are fits to the exponential regions.

Therefore in the moderate I_C range, (R_B/β) can be neglected, the slopes of ΔI_B vs. I_C will yield R_C if the temperature dependence of n_{BC} is known. It is also shown in Fig. 3 that with I_C increasing β will eventually decrease making R_B significant in the slope of ΔI_B vs. I_C.

When extracting R_C in the moderate I_C range care must be taken due to sensitivity of this region. The lines fitted must be in the linear region of the observed kink on I_B. For this particular device the linear range of kink on I_B varies from I_C = 55 - 64mA at T = 298K to I_C = 43 - 47mA at T = 383K.

In the DHBTs, the conduction and valance band discontinuities (ΔE_C and ΔE_V) generated at the junctions will have an important role in tunneling transport mechanisms at high temperature. To correct for this effect the temperature dependence of n_{BC} need to be taken into account when extracting terminal resistances in (5). As discussed in the previous section using Fig. 2, (4) can be rewritten to include the Kirchoff's current components of I_B generated at the onset of junction potential reversal.

$$V_{B'C'} = V_{BC} - R_C I_{BC} - R_B I_{BE} + I_C R_C \tag{6}$$

Where I_{BC} $(= I_B - I_{BE})$ is the current generated at the onset of the kink, the corresponding voltage at which this kink occurs is given as V_{KINK}. Under moderate I_C, I_{BE} dominates and at high I_C, I_{BC} dominates. The $R_C I_{BC}$ term of (6) becomes significant due to the potential drop across R_C forward biasing the b-c junction.

At the onset of the kink, the forward biasing of the *b-c* junction can be approximated as: $V_{BC} = V_{BCO} + \Delta V_{BC} = V_{BCO} + \Delta V_{BE}$, where ΔV_{BE} is the difference (V_{BE} - V_{KINK}) and V_{BCO} is a constant. It is noted that ($V_{BC} = V_{C'} - V_{B'}$) = ((V_C - $R_C I_C$) - $V_{B'}$), knowing that V_C and R_C are constants and I_C is approximately constant in this region as depicted in Fig. 1. This gives V_{BC} (ΔV_{BC}) $\approx \Delta V_{BE}$. When one observes the kink then I_{BE} becomes negligible. Hence $I_B \approx I_{BC}$, which approximate (5) as:

$$\Delta I_B = I_{BC} = I_{BCO} \cdot \exp\left(\frac{I_{BC} R_C (\beta - 1)}{n_{BC} \cdot V_T}\right) \cdot \exp\left(\frac{\Delta V_{BC}}{n_{BC} \cdot V_T}\right) \tag{7}$$

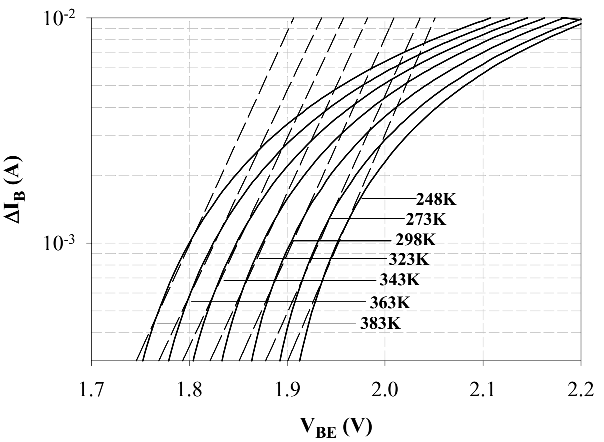

Fig. 4: Plots of ΔI_B (I_B (V_{BC} = 0) - I_B (V_{BC} < 0)) vs. V_{BE}. The dashed lines are fits to the exponential regions.

As demonstrated in Fig. 4 if ΔI_B's are plotted logarithmically against ΔV_{BC} (V_{BE} - V_{KINK}) for each temperature the plots will show exponential behaviors in the moderate I_C range, the gradient of the best-fit line of each curve will yield n_{BC}. When extracting ideality factors (n), it is important to identify a common range of I_B where the log I versus V curves are straight lines. It is useful to plot ideality factor (n = $I_B/kT^*(\Delta V_{BE}/\Delta I_B)$) versus I_B to identify the region where n is flattest.

Once n_{BC} and R_C are known, then one can utilize the plot of ΔI_B vs. ΔV_{BC} to extract R_B of the device. For a known ΔI_B (or I_{BC}), $\Delta V_{B'C'}$ can be found from a straight line fit to the low current range in the logarithmic plot of ΔI_B vs. ΔV_{BC}. From (4) it can be given as:

$$I_B = \frac{R_C I_C + \partial \Delta V_{BC}}{R_B} \tag{8}$$

Where $\partial\Delta V_{BC}$ is the difference ΔV_{BC} - $\Delta V_{B'C'}$. If one plots $R_C I_C$ + $\partial\Delta V_{BC}$ against I_B the gradient will yield R_B at each temperature. Similarly R_E can be extracted from the Gummel plot when one does not observe the kink (V_{BC} > 0), where the second term of (2) can be neglected. For a known I_C, $V_{B'E'}$ can be found from a straight line fit to the moderate I_C range in Fig. 1. The difference ΔV_{BE} (= V_{BE} - $V_{B'E'}$) is plotted against I_E (= I_B + I_C), where (3) can be written as $\Delta V_{BE} = I_E (R_E + R_B^* (1/\beta + 1))$. This plot should be a straight line and if $\beta > 10$, the slope of the line will give R_E.

IV. Results & discussion

The extracted R_C, R_B and R_E from the observed kink effect were compared with those deduced from a small signal *s*-parameter extraction technique [8]. The extracted values are depicted in Fig. 6. Over the temperature range studied R_C rose by 30% (dc) and 22% (*s*-parameter). R_B rose by 10% (*dc*) and 18% (*s*-parameter). It was noted that R_E did not change with varying temperature. From the measured specific contact resistances using TLM measurements at room temperature when calculated gave R_E = (9.1 ± 0.7)Ω, R_B = (29.4 ± 1.2)Ω and R_C = (10.5 ± 0.6)Ω. These are in close agreement with the terminal resistances extracted from *s*-parameter data, indicating that the main contribution is related to the contact resistances.

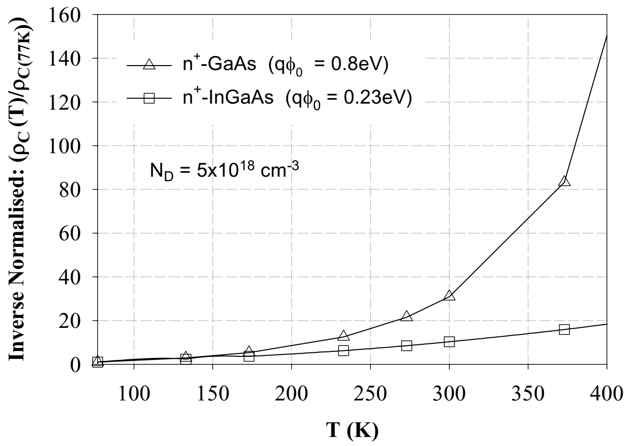

Fig. 5: Variation of normalized specific contact resistance with temperature for metal/n^+-GaAs and Metal n^+-InGaAs.

The effect of temperature on contact resistance was analyzed using a theoretical model for tunneling through metal-semiconductor barriers using the Fermi-Direc statistics and WKB approximation [9]. The simulated results of specific contact resistance showed that at 300K, the difference in temperature variation of metal/n^+-GaAs contact with respect to values at 77K is twice that of metal/n^+-InGaAs contact. This difference increased by a factor of 4 at 375K as shown in Fig. 5.

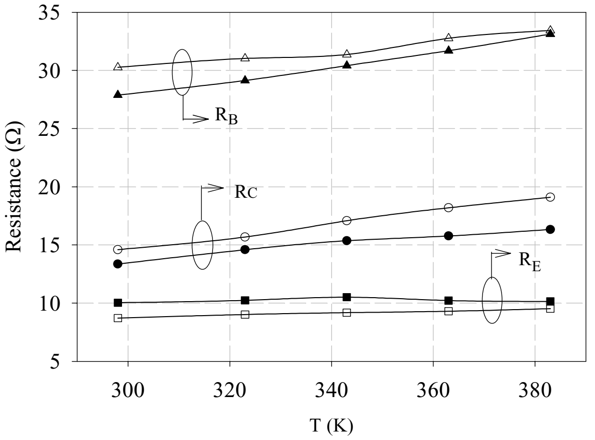

Fig. 6: Variation of measured R_E, R_C and R_B from *s*-parameter extractions (solid symbols) and from the observed kink (open symbols) over the temperature.

From Fig. 6, it is clearly seen that R_E does not change with varying temperature since the InGaAs cap layer is highly doped. The tunneling current through the barrier formed by InGaAs and metal is very slightly temperature dependent. The R_C variation with temperature can be explained due to temperature sensitivity of metal/n^+-GaAs contact and the lightly doped collector not being fully depleted. As a result the decrease in electron mobility of the undepleted InGaP collector and GaAs sub collector can contribute to this variation. The base layer is usually thin. The R_B variation can mainly result from the temperature dependence of metal/n^+-GaAs contact. By incorporating these values into a temperature-dependent DHBT large signal model more accurate thermal prediction of I_B at high currents is demonstrated in Fig. 7.

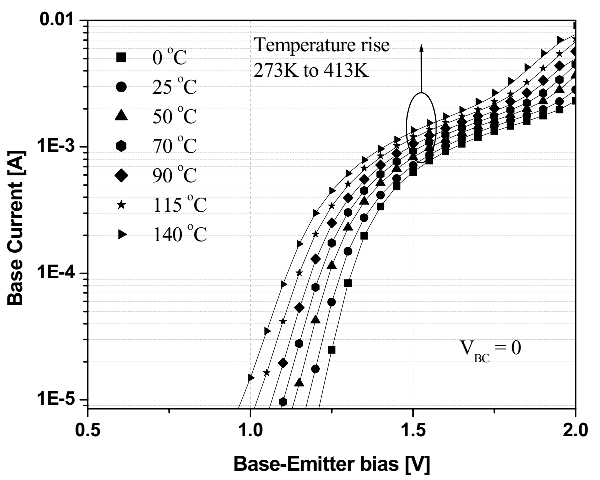

Fig. 7: Measured and simulated I_B characteristics at various temperatures for a 16x20μm^2 DHBT.

V. Conclusion

We showed a simple and efficient method to extract terminal resistances of DHBTs using the observed kink effect. These data were determined with adequate accuracy and verified by S-parameter extraction technique. Temperature dependence of terminal resistances was investigated from 298K to 383K. The results show positive coefficient of R_C and R_B, which can be originated from the specific contact resistance of metal/n$^+$-GaAs and temperature dependence of low field and high field mobilities associated with the undepleted and depleted collector thickness of n-InGaP collector and n$^+$-GaAs sub-collector. These features should be accounted for when modeling DHBT's.

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