Extraction of True Finger Temperature from Measured Data in Multi-Finger Bipolar Transistors

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***Abstract*—In this brief, we propose a step-by-step strategy to accurately estimate the finger temperature in a silicon based multi-finger bipolar transistor structure from conventional measurements. First we extract the nearly zero-power self-heating resistances ($R_{th,ii}(T_a)$) and thermal coupling factors ($c_{ij}(T_a)$) at a given ambient temperature. Now, by applying the superposition principle on these variables at nearly zero-power, where the linearity of the heat diffusion equation is preserved, we estimate an effective thermal resistance ($R_{th,i}(T_a)$) and the corresponding revised finger temperature $T_i(T_a)$. Finally, the Kirchhoff's transformation on $T_i(T_a)$ yields the true temperature at each finger ($T_i(T_a, P_d)$). The proposed extraction technique automatically includes the effects of back-end-of-line metal layers and different types of trenches present within the transistor structure. The technique is first validated against 3D TCAD simulation results of bipolar transistors with different emitter dimensions and then applied on actual measured data obtained from state-of-the-art multi-finger SiGe HBT from STMicroelectronics B5T technology. It is observed that the superposition of raw measured data at around 40 mW power underestimates the true finger temperature by around 10%.**

***Index Terms*—SiGe HBT, multi-finger transistor, measurement, self-heating, thermal coupling, parameter extraction**

I. INTRODUCTION

In order to increase the current handling with minimized current crowding, multi-finger bipolar transistor structures are preferred in power amplifier applications [1]. Eventually, a large amount of power is dissipated in the base-collector junctions of all the fingers. Since, the fingers are thermally coupled through the common substrate (although electrically isolated by shallow trenches), modeling of such transistors requires accurate estimation of both self-heating in each finger and thermal coupling among the fingers [2], [3], [4], [5]. In order to develop a reliable thermal model, accurate characterization of thermal resistances and junction temperatures for all the fingers is of utmost importance. State-of-the-art measurement techniques allow us to determine the self-heating thermal resistance ($R_{th,ii}$) and corresponding rise in junction temperature (ΔT_{ii}) for each (i^{th}) finger [6], [7]. On the other hand, thermal coupling effects are determined from measurements of coupling coefficients (c_{ij}) based on heat-sense technique [5], [8] between a given pair of fingers (i, j). This is done by passing high current through one (j^{th}) finger, raising its temperature to ΔT_{jj}, while sensing temperature (ΔT_{ij}) at the other (i^{th}) finger. The ratio $\Delta T_{ij}/\Delta T_{jj}$ yields c_{ij}. From these measurements, the total rise in junction temperature above the ambient temperature (T_a) for the i^{th} finger, in an n-finger system, is estimated as [3], [5],

$$\begin{aligned}\Delta T_i &= \Delta T_{ii} + \sum_{j=1, j\neq i}^{n} \Delta T_{ij} \\ &= P_{d,i} R_{th,ii} + \sum_{j=1, j\neq i}^{n} c_{ij} P_{d,j} R_{th,jj}\end{aligned} \tag{1}$$

where the first term indicates the rise in junction temperature due to self-heating and the second term considers the effect of thermal coupling from all other fingers. $P_{d,i}(P_{d,j})$ is the electrical power dissipation in the i^{th} (j^{th}) finger.

Although the accuracy of the thermal characterization is improved over the decades of research, the fundamental problem lies in using superposition to obtain the overall finger temperature from self-heating and thermal coupling temperatures as done in (1). This is because any measurement automatically includes the temperature dependence of thermal conductivity of substrate Si (or any other material in the heat flow path). Eventually, the resulting model based on the heat diffusion equation will be non-linear [9], [10]. Therefore, one cannot use superposition principle to obtain the total finger temperature from two separate measurements. Although the work reported in [11] attempted to obtain the c_{ij} without ignoring the self-heating in the sensing finger, the original problem of handling the non-linearity with superposition could not be avoided. To the best of the authors' knowledge, a suitable technique to accurately estimate the true finger temperature from the measurements of self-heating and thermal coupling in a multi-finger transistor system under real operating condition (when all fingers are heating simultaneously) is not only missing in the literature, but also in high demand in the modeling community. This paper addresses this fundamental research gap. In section II, we present the extraction methodology in detail. Section III demonstrates a primary validation of our technique using 3D TCAD simulation data. Note that TCAD simulation cannot substitute the actual measurements required to extract compact model parameters and subsequently to develop the process design kit. Therefore, after validating with TCAD simulation, we apply the proposed technique on

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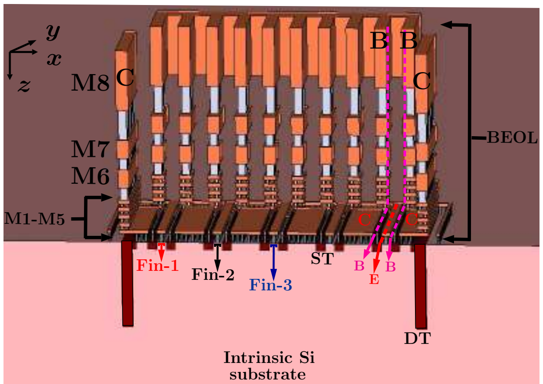

Fig. 1. 3D cross-sectional view of a five-finger TCAD structure of STMicroelectronics B55 process [12] containing shallow and deep trenches along with the eight metal layers (M1 to M8) in BEOL. A set of emitter (E), base (B), and collector (C) contacts are indicated for the rightmost corner finger.

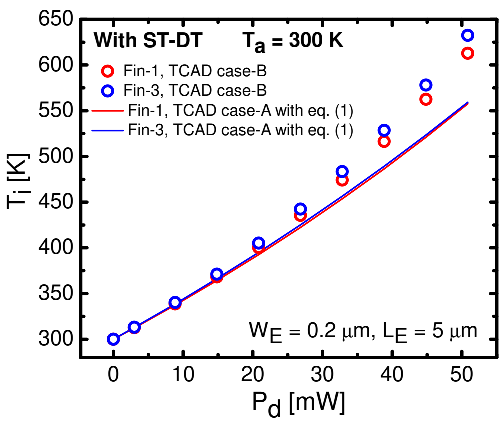

Fig. 2. Dissipated power-dependent true temperature (T_i) of 1^{st} and 3^{rd} finger in a five finger transistor. Circles correspond to case-B TCAD simulation. Solid lines are the results obtained following (1) from case-A TCAD simulations by exciting one finger at a time.

measured data of multi-finger transistor fabricated in state-of-the-art B5T technology from STMicroelectronics and provide a true finger temperature. We also demonstrate the underestimation of finger temperature compared to the true value if (1) is applied directly on the measured data. Finally, we conclude in section IV.

II. Extraction of True Finger Temperature

We start with a set of TCAD simulated data of a five-finger bipolar transistor whose dimensions correspond to the state-of-the-art SiGe HBT from STMicroelectronics B55 technology [12]. Fig. 1 shows the device structure where each finger is electrically isolated by shallow-trenches (ST) and all the five-fingers are additionally housed within deep-trenches (DT) on all four sides. Note that for TCAD simulation we have included back-end-of-line (BEOL) metal layers till M1 as most of the BEOL thermal resistance is offered by M1 [13], [14]. Essentially two types (case-A and B) of TCAD simulation are carried out on the same five-finger device structure. Case-A refers to the situation when one finger is excited at a time (analogous with the heat-sense measurement condition) and summing up the effects of self-heating and thermal coupling using (1) for the overall finger temperature. Case-B corresponds to a situation when all fingers are excited simultaneously which emulates the real operating condition of the device, yielding true finger temperature. Fig. 2 shows the dissipated power-dependent temperatures of finger-1 and finger-3 obtained from case-A and case-B simulations. One can observe a significant difference between the true finger temperature (case-B result) and the ones obtained following (1) (case-A approach), particularly at large P_d. Since, the temperature dependence of thermal conductivity of Si is considered in both the TCAD simulations, the original heat diffusion equation becomes non-linear. Therefore, the application of (1) results into underestimation of finger temperature as shown in Fig. 2. In the following we present the methodology to achieve the true finger temperature (results of case-B) from the conventional heat-sense measurement (case-A) technique.

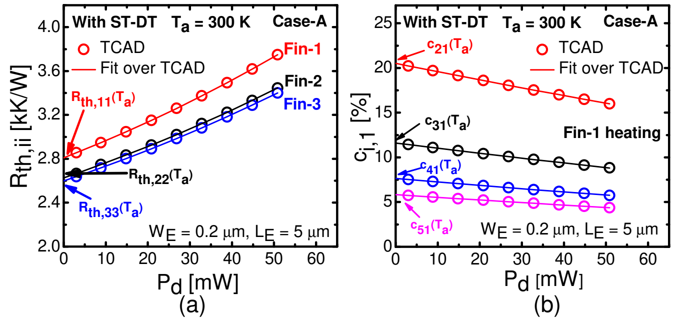

Fig. 3. Self-heating and thermal coupling results obtained from case-A TCAD simulations: (a) $P_{d,i}$-dependent self-heating thermal resistance $R_{th,ii}$ of all three individually heating fingers (Fin-1, 2 and 3) and (b) coupling coefficients obtained for case-A when only 1^{st} finger is heating ($j = 1$) and rest are sensing. Ambient variables $R_{th,ii}(T_a)$ and $c_{ij}(T_a)$ are also indicated.

Fig. 3(a) presents case-A TCAD simulation results of dissipated power ($P_{d,i}$) dependent self-heating thermal resistance ($R_{th,ii}$) of the first three fingers ($i = 1, 2, 3$) at an ambient temperature, $T_a = 300$ K. Note that symmetry of the structure ensures $R_{th,44} = R_{th,22}$ and $R_{th,55} = R_{th,11}$. The solid lines in Fig. 3(a) are polynomial fit capturing the non-linear $P_{d,i}$-dependent trend of TCAD data. Extrapolation of the solid line at zero $P_{d,i}$ yields $R_{th,ii}(T_a)$. Similarly, Fig. 3(b) contains TCAD simulated $P_{d,1}$-dependent coupling coefficients $c_{i,1}$ from which one can obtain $c_{i,1}(T_a)$ by extrapolating each solid line for $P_{d,1} \rightarrow 0$. Other $c_{ij}(T_a)$ can be obtained from similar plots of $P_{d,j}$-dependent c_{ij} data. Note that at $P_d \rightarrow 0$, thermal conductivity of Si depends only on T_a and the corresponding differential equation for heat diffusion remains linear. Therefore, one can apply the superposition principle to obtain a total effective thermal resistance corresponding to each finger as

$$R_{th,i}(T_a) = R_{th,ii}(T_a) + \sum_{j=1, j\neq i}^{n} c_{ij}(T_a) R_{th,jj}(T_a). \quad (2)$$

Subsequently, the rise in junction temperature $\Delta T_i(T_a)$ can be estimated as $\Delta T_i(T_a) = R_{th,i}(T_a) P_{d,i}$. Finally,

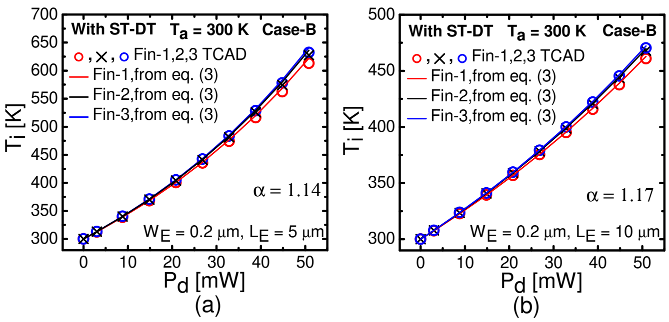

Fig. 4. A comparison of dissipated power-dependent temperatures T_i, at fingers 1, 2 and 3 obtained from the proposed extraction scheme (solid lines) against case-B TCAD simulation (symbols) for devices with emitter area (A_E) of (a) $A_E = 0.2 \times 5\ \mu m^2$ and (b) $A_E = 0.2 \times 10\ \mu m^2$.

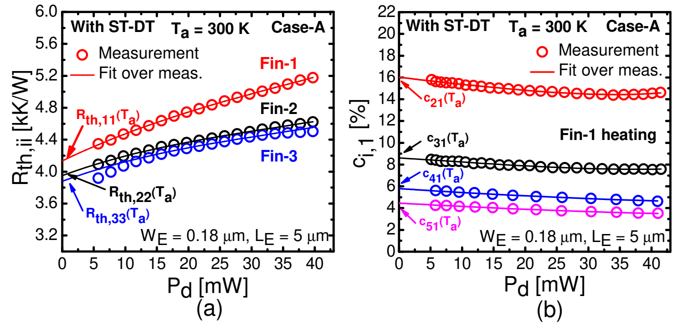

Fig. 5. Measured dissipated power-dependent (a) self-heating thermal resistance of 1^{st}, 2^{nd} and 3^{rd} finger, and (b) coupling coefficients obtained when only 1^{st}finger is heating. Extracted $R_{th,ii}(T_a)$ and $c_{ij}(T_a)$ are also marked.

the application of Kirchhoff's transformation [15] on the calculated $\Delta T_i(T_a)$ takes care of the temperature dependence of material thermal conductivity and provides us with the true finger temperature as

$$T_i(T_a, P_d) = T_a \left(1 + \frac{(1-\alpha)\, R_{th,i}(T_a) P_{d,i}}{T_a}\right)^{\frac{1}{1-\alpha}}. \quad (3)$$

Here the parameter α is originated from the temperature dependent thermal conductivity of the heat flow medium which is modeled as $\kappa(T) = \kappa(T_a)(T/T_a)^{-\alpha}$. All the terms in the r.h.s. of (3) are already known except $(1-\alpha)$ which can be obtained by non-linear parametric fitting of $P_{d,i}$-dependent $R_{th,ii}$ data (Fig. 3(a)) using the well-known relation [16]

$$R_{th,ii}(T_a, P_d) = \frac{T_a}{P_{d,i}} \left[\left(1 + \frac{(1-\alpha)\, R_{th,ii}(T_a) P_{d,i}}{T_a}\right)^{\frac{1}{1-\alpha}} - 1\right]. \quad (4)$$

Thus the true finger temperature T_i can be obtained as a function of $P_{d,i}$ using (3) with extracted $R_{th,ii}(T_a)$, $c_{ij}(T_a)$ and $(1-\alpha)$.

III. Validation of Proposed Technique and Application on Measured Data

Figs. 4 (a) and (b) compare the dissipated power-dependent true temperatures obtained from the proposed extraction method (solid lines) following (3) against case-B TCAD simulations (circles) for first three fingers in two different five-finger transistors with $A_E = 0.2 \times 5\ \mu m^2$ and $A_E = 0.2 \times 10\ \mu m^2$, respectively. Note that the temperatures of 4^{th} and 5^{th} fingers are identical with those of 2^{nd} and 1^{st} fingers, respectively. Highest temperature of the central finger is due to high amount of coupling from the neighboring fingers. An excellent agreement of the extracted temperatures with case-B TCAD data demonstrates the accuracy of the overall extraction methodology. The values of α extracted from our approach are 1.14 and 1.17 for $A_E = 0.2 \times 5\ \mu m^2$ and $A_E = 0.2 \times 10\ \mu m^2$, respectively. Note that the proposed technique automatically takes into account the effects of trenches and BEOL metal layers as the extraction deals directly with the characterised data. Therefore, the extracted α does not necessarily correspond to that of the Si material but also incorporates the effect of trenches and BEOL.

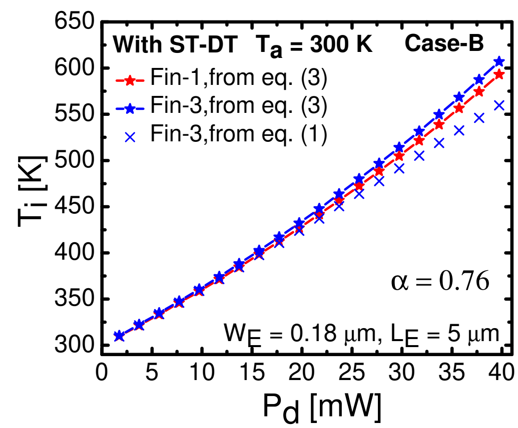

Fig. 6. Extracted values of true finger temperatures (star-lines) for 1^{st} and 3^{rd} finger of a five finger device from B5T technology [17]. An underestimated finger-3 temperature (crosses) obtained from a direct superposition of measured self-heating and thermal coupling temperatures is also shown for comparison.

Now we present the outcomes of our technique when applied on the actual measured data. For this purpose we chose a five-finger SiGe HBT transistor fabricated in B5T technology from STMicroelectronics with six metal layers at BEOL [17]. Each transistor finger is isolated from the neighbouring fingers with shallow trenches and the whole transistor structure is housed within deep trenches from all four sides. The emitter fingers of the test structure (each with $A_E = 0.18 \times 5\ \mu\text{m}^2$) are individually accessible with a common collector while the bases are all connected to ground as detailed in [8]. On-wafer measurements were carried out on the test structure using a SUSS MicroTec probing station equipped with a thermal chuck to obtain the self-heating thermal resistances ($R_{th,ii}$) and coupling coefficients (c_{ij}) following the techniques elaborated in [7] and [8], respectively. Heating and sensing bias conditions of the test structures used to extract coupling coefficients in our work are the same as in [8]. Base-emitter voltage (V_{BE}) of the heating finger is varied from 0.4 to 0.98 V while a constant emitter current (I_E) of 1 μA is forced at the sensing fingers. Collector-base voltage (V_{CB}) is kept constant at 0.5 V for all the fingers. Fig. 5(a) shows the dissipated power-dependent $R_{th,ii}$ values obtained from measurements (circles) for the first three fingers. Fig. 5(b) shows the measured c_{ij} values (circles) of the neighboring fingers when finger-1 is heating. Subsequently, $R_{th,ii}(T_a)$ and $c_{ij}(T_a)$ are extracted from the polynomial fit (solid lines) over the measured data at $P_d = 0$. Finally, using the extracted values of $R_{th,ii}(T_a)$, $c_{ij}(T_a)$ and $(1-\alpha)$ we estimate the true junction temperature (T_i) following (3). Fig. 6 presents the true temperatures of 1^{st} and 3^{rd} fingers obtained from measurements following the proposed technique. The temperature of the 3^{rd} finger obtained from a direct superposition over the measured data following (1) is also shown on the same plot for comparison. It is observed that the conventional approach of direct superposition underestimates the total junction temperature (T_i) by around 10% at around 40 mW power dissipation. Such an underestimation will not only influence a self-heating aware device design with insufficient data, but also the error is not acceptable from the perspective of an accurate model development.

IV. Conclusion

We presented an extraction technique to accurately estimate the true finger temperature in a multi-finger transistor under real operating condition when all the fingers are heating simultaneously. The proposed technique requires no additional measurements than the conventional heat-sense based approach. The methodology is first validated against TCAD simulations and then applied on actual measured data. The effects of back-end-of-line metal layers and different types of trenches present within the transistor structure are automatically included in this approach. However, any potential error that can originate from measurement uncertainty is not ruled by the proposed method. Therefore, one has to be careful while extracting the $R_{th,ii}(T_a)$ and $c_{ij}(T_a)$ by means of non-linear fitting and extrapolation towards zero dissipated power since the measurement uncertainty tends to increase at lower dissipated power. It is demonstrated that an application of superposition of self-heating and thermal coupling directly on the measured data underestimates the true finger temperature (under real operating condition) by around 10% at around 40 mW power dissipation.

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