THERMAL RESISTANCE EXTRACTION OF POWER TRANSISTORS USING ELECTRIC FIELD SIMULATION

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ABSTRACT

The use of electric field simulation to extract thermal resistance of power transistor for circuit analysis is described. Compared with conventional techniques based on thermal field simulation, our approach provides directly usable results for circuit analysis, and is easier to be accessed by device and circuit engineers. Instead of conventionally used lumped elements, a multi-port black box is used to represent the thermal circuit, which makes the thermal circuit implementation easy for multi-finger devices. The technique proposed is illustrated by the example of multi-finger HBT.

INTRODUCTION

Heterojunction bipolar transistors (HBTs) are attractive for their power capability and linearity in microwave and millimeter wave applications as shown in Asano et al (1) and Muller et al (2). The thermal effect has, however, been shown to significantly affect HBT performance, which is particularly important for multi-finger HBTs where the self-heating in a unit emitter finger and the thermal coupling among the fingers leads to a non-uniform temperature distribution. Electro-thermal models have been proposed to describe multi-finger HBT behavior by Snowden (3) and Marty et al (4), in which each finger is represented by a unit finger HBT model and all fingers are thermally coupled through a thermal equivalent circuit (thermal network). The thermal network of an n-finger HBT can be represented by an n x n thermal resistance matrix. The diagonal values of the matrix represent the self-heating of each finger, and the off-diagonal values represent the thermal coupling among the fingers. The thermal resistance matrix can be obtained from thermal filed simulation as described in (3), (4).

However, the results obtained from thermal field solver are not directly useable for circuit analysis. The thermal field solvers available provide only field solutions, and multiple separate calculations must be performed for extracting the thermal resistance matrix. Additionally, because the thermal equivalent circuit is conventionally realized with lumped elements, the implementation into a circuit simulator becomes topologically complex with increasing emitter fingers.

In this study, an electric field solver (Ansoft SI3D) was used to extract the thermal resistance matrix, which solves the field solution and provides equivalent resistance matrix via a single calculation. A simple yet accurate method to implement the multi-port thermal network into a circuit simulator is also presented. Generally speaking, an electric field solver is easier to be accessed by electronics device and circuit engineers.

THERMAL RESISTANCE EXTRACTION

It is well known that the density of heat flow, q, and the density of current, j, can be expressed as

$$q = -s_{th} \nabla T \tag{1}$$

and

$$j = -s \nabla V \tag{2}$$

respectively, where T is the temperature, V the electric potential, and σ and σ_{th} are the electric and thermal conductivity, respectively. The heat flow can be calculated by regarding the current as heat flow and the potential as the temperature. The thermal resistance of a given structure can thus be calculated from the corresponding electric resistance as Eq. (3). By substituting thermal conductivity for electrical conductivity, the equivalent resistance matrix generated is identical to the thermal resistance matrix.

$$R_{th} = \frac{s_{th}}{s} R \tag{3}$$

An extraction was first performed on a HBT having 2 fingers of 2x50mm2. The thickness and the thermal conductivity of the GaAs substrate are 100µm and 46W/M ·K, respectively. The dependence of the thermal coupling resistance (off-diagonal matrix value) on the distance between the fingers is shown in Fig. 1. Superimposed are the results obtained with thermal field calculations given in Liu (5). Excellent agreement has been achieved between the electric and thermal field calculations.

In Fig. 2, an 8-finger HBT with 2x20μm^2 fingers is set at the center of a 1x1mm2 GaAs substrate. The thickness of the substrate is 20µm. Since the current (heat flow) flows from a source terminal to a sink terminal in SI3D, source terminals are assigned at the HBT fingers, and a sink terminal is assigned at the back of the substrate. The thermal resistance matrix for a 8-finger HBT extracted is shown in Eq.(4), which was obtained via single calculation. Because the electric field solver uses true 3D structure models, the thermal effect of complex structures, for example, the via holes in the substrate and the thin solder layer between the substrate and thermal sink, can easily be investigated.

$$[R_{th}] = \begin{pmatrix} 1066 & 102 & 33 & 12 & 5.0 & 2.1 & 0.87 & 0.37 \\ 102 & 1066 & 102 & 33 & 12 & 5.0 & 2.1 & 0.87 \\ 33 & 102 & 1066 & 102 & 33 & 12 & 5.0 & 2.1 \\ 12 & 33 & 102 & 1066 & 102 & 33 & 12 & 5.0 \\ 5.0 & 12 & 33 & 102 & 1066 & 102 & 33 & 12 \\ 2.1 & 5.0 & 12 & 33 & 102 & 1066 & 102 & 33 \\ 0.87 & 2.1 & 50. & 12 & 33 & 102 & 1066 & 102 \\ 0.37 & 0.87 & 2.1 & 5.0 & 12 & 33 & 102 & 1066 \end{pmatrix}. \tag{4}$$

The post processing features of the electric solver designed for viewing the electric current and potential are also useful for viewing the temperature and heat flow distribution. Based on the field solution, the 1D, 2D and 3D distribution of the temperature and heat flow anywhere inside the structure can be displayed. The temperature distribution along the line AA’ in Fig. 2 is shown in Fig.3. The non-uniform temperature distribution due the thermal coupling can be observed. Figure 4(a) and (b) shows a 2D temperature distributions on the surface of the substrate and inside the substrate, respectively. The heat flow distribution along the finger (line BB’ in Fig. 2) is shown in Fig. 5; the heat flow along the edge of the finger is shown to be much stronger than that in the middle of the finger.

THERMAL RESISTANCE IMPLEMENTATION

Conventionally the thermal resistance matrix has to be converted into a lumped element circuit to form an electro-thermal device model (3), (4), which becomes topologically complex with an increase in the number of fingers. Comparing the definition of the thermal resistance matrix (3))

$$Rij = \left. \frac{Ti - T0}{Pj} \right|_{Pi \ldots Pj-1, Pj+1 \ldots Pn = 0} \tag{5}$$

with that of impedance (Z) matrix

$$Zij = \left. \frac{Vi - V0}{Ij} \right|_{Ii \ldots Ij-1, Ij+1 \ldots In=0} \quad (6)$$

it can be understood that the thermal resistance matrix is exactly the Z-parameters of the thermal network. Therefore, the thermal equivalent circuit in our approach is represented by a multi-port black-box component, which is available in most circuit simulators, with the thermal resistance matrix given as Z-parameters. The conversion from a matrix to a lumped elements circuit can thus be omitted.

As an example, an electro-thermal model of a 5-finger HBT implemented in a nonlinear circuit simulator (Ansoft Serenade) is shown in Fig. 6. A temperature-dependent unit finger HBT model represents each finger, and the thermal network is represented by a 5-port black-box with the thermal resistance matrix extracted as Z-parameters. The thermal node of each HBT is connected to a port of the thermal network. The electric current fed into the thermal network represents the power dissipated in each HBT, while the voltage at the port of the thermal network equals the temperature increase in each HBT. The calculated Ic-Vce behavior of the 5 finger HBT under constant base current is shown in Fig. 7. The current collapse, a unique behavior of multi-finger HBT, can be observed with increasing Vce.

CONCLUSION

An electric field solver has been used instead of its thermal counterpart to extracting the thermal resistance matrix, and a black-box component has been used instead of lumped elements to implement a thermal network into a circuit simulator. Our approach provides accurate and directly usable results for circuit analysis, which we believe to be a practical tool for device and circuit design.

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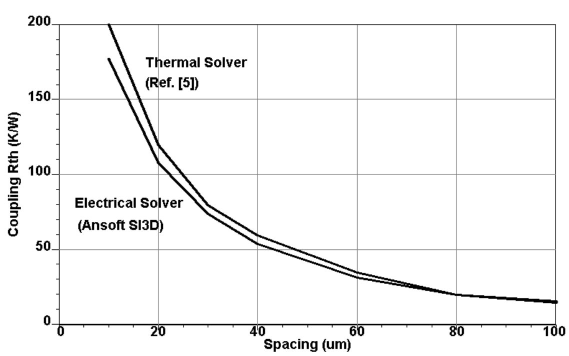

Fig. 1. Extracted coupling thermal resistance using thermal and electrical field solvers

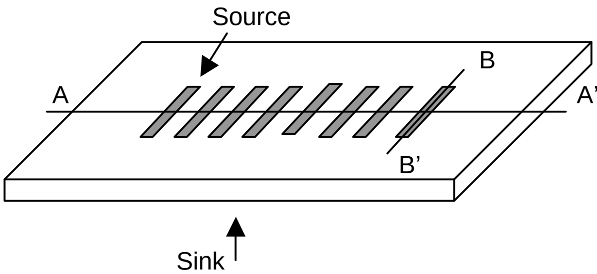

Fig. 2. 3D structure of 8 finger HBT.

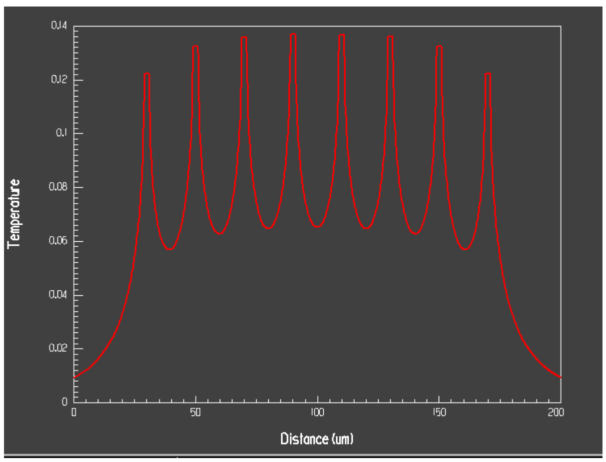

Fig. 3. Temperature distribution along AA' in Fig. 2.

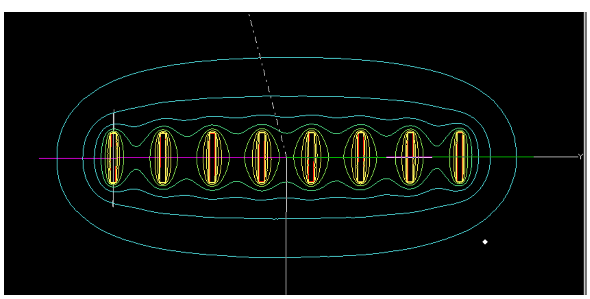

Fig. 4(a). Contour plot of substrate surface temperature.

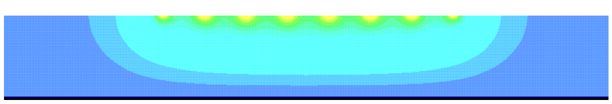

Fig. 4(b) Contours of constant temperature inside the substrate

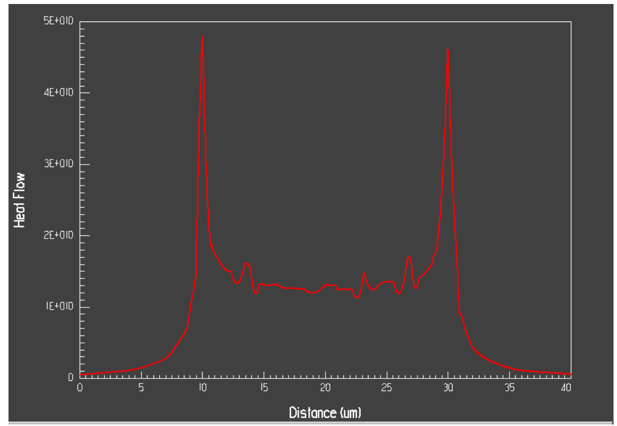

Fig. 5 Heat flow distribution along BB' in Fig. 2.

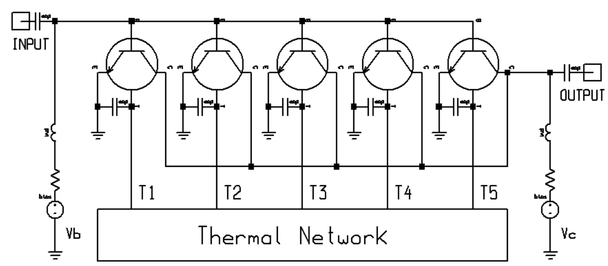

Fig. 6 Electro-thermal model of multi-finger HBT, the nodes voltage T1…T5 equals the temperature rise inside each HBT

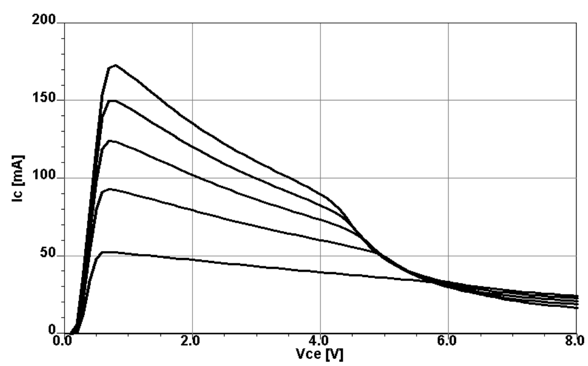

Fig. 7. Calculated collector current in a 5-finger HBT under constant base current, the base current levels are 0.5, 1.0, 1.5, 2..0 and 2.5mA.