Thermal resistance modelling of RF high power bipolar transistors

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Abstract

Thermal modelling of RF high power bipolar transistors, including the thermal resistance of the silicon die and the beryllium oxide package as well as the temperature dependence of their thermal conductivities, is considered. To model power transistors the non-linear heat conduction equation is converted to a linear heat equation using Kirchhoff's transformation. The linear problem is solved using a Green's function method and the Kirchhoff transformation is effectuated via a non-linear voltage transformation.

1 Introduction

RF high power transistors are used in base stations for mobile radio, radar and satellite communications to amplify signals to a power level of a few Watts or more. Basically these devices consist of a package, one or more matching capacitances, bonding wires and a silicon die. The silicon (Si) die has a number of active areas and each active area has a number of base- and emitter fingers.

The accurate modelling of the thermal behaviour is of particular relevance since the temperature influences the electrical behaviour of the transistor and plays an important role in determining the safe operating area (SOA) of the device.

Several methods, such as the Finite Element Method (FEM) [1] and the Finite Difference Time Domain method (FDTD), can be used to calculate the temperature at the junction of the devices. These methods easily incorporate the temperature dependence of the thermal conductivity of the materials involved. Simulation times, however, can be in the order of minutes or hours for the accurate modelling of practical problems. Dramatic time savings can be achieved when Green's function methods [2] are employed. A principal drawback of this approach is that it fails to incorporate the temperature dependence of the thermal conductivity so that the method is limited to linear problems.

In this work a robust and efficient implementation of a method for calculating the temperature distribution and the thermal resistance matrix in Hewlett Packard's Microwave Design

System (MDS) is demonstrated. The method is based on proper splitting of the thermal problem in a linear problem, solved using a Green's function method, followed by a non-linear Kirchhoff transformation. This division is advantageous in that we obviate the need to recompute the thermal matrix at every simulation point as is done for example in [3]. Simulation times for practical problems are in the order of seconds, making the method amendable to CAD applications.

2 Computation of the thermal resistance matrix

In the thermal model the Si die is placed on top of the beryllium oxide (BeO) substrate of the package, as illustrated in figure 1. The BeO substrate is on top of the mounting base, which is maintained at a constant reference temperature. Junctions are located in the active areas just below the surface of the Si die where heat is generated due to power dissipation.

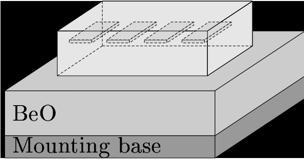

Figure 1: Silicon die, with 4 heat generating volumes placed on top of a BeO block and mounting base.

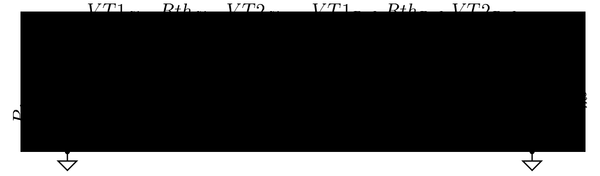

Figure 2: Nonlinear model for one heat generating volume including the Si and BeO substrate.

The temperature distribution $T(r)$ is calculated by solving the steady-state heat conduction equation:

$$\nabla \cdot (\kappa(T)\nabla T(r)) = -g(r) \tag{1}$$

where $\kappa(T)$ (W/m·K) is the temperature dependent thermal conductivity and $g(r)$ is the heat generation per unit volume (W/m^3). The heat equation is difficult to solve due to the temperature dependence of the thermal conductivity κ. The non-linearity can be removed by introducing Kirchhoff's transformation and the "linear" temperature θ [4]:

$$\theta(r) = T_0 + \frac{1}{\kappa(T_0)} \int_{T_0}^{T(r)} \kappa(T')dT' \tag{2}$$

where T_0 denotes a reference temperature. Substituting Kirchhoff's transformation in the heat conduction equation results in a linear heat equation:

$$\kappa(T_0)\nabla^2\theta(r) = -g(r) \tag{3}$$

Instead of solving the non-linear equation (1) the linear heat equation (3) is solved and the linear temperature θ is transformed to the actual temperature T using Kirchhoff's transformation (2).

In our MDS implementation the thermal problem is split in two and may be represented by an electrical equivalent as is illustrated for one heat generating volume in figure 2. In the first step the linear thermal resistances of the silicon die (Rth_{Si}) and of the BeO substrate (Rth_{BeO}) are computed using a Green's function method. In the case of multiple heat areas a thermal resistance matrix is used, the elements are computed using Cartesian coordinates:

$$R_{ij} = \frac{1}{\kappa(T_0)} \int_{V_j} G(x_i, y_i, z_i|x', y', z')g(x', y', z')dx'dy'dz' \tag{4}$$

where g is the uniform heat generation in the active area with volume V_j, $G(x, y, z|x', y', z')$ is Green's function for the problem at hand and (x_i, y_i, z_i) are the Cartesian coordinates of the

center of the heat volume i. A homogeneous Green's function was employed in combination with a triple image series. The computation of the linear thermal resistance matrix has been implemented in MDS using a User Compiled Linear Model. Please note that the computation time of a thermal resistance matrix can be in the order of (milli-)seconds.

In the second step the linear temperatures are transformed to the actual non-linear temperatures using Kirchhoff's transformation. The relationship between thermal conductivity and temperature is fitted to data given in [5] and given by:

$$\kappa(T) = \kappa(T_0) \left(\frac{T}{T_0} \right)^n \tag{5}$$

where $n \approx -1.3$ for Si in a wide temperature range and BeO in a limited temperature range. The reference temperature T_0 is taken 300 K and the thermal conductivity at this temperature $\kappa(T_0)$ is 150 K/W and 270 K/W for Si and BeO respectively.
The temperature transformation is obtained by substituting eq. (5) in eq. (2) and solving for the actual temperature T. In figure 2 the voltage sources $VT1_{Si}$ and $VT2_{Si}$ transform the linear temperature of the die to the actual temperature and the voltage sources $VT1_{BeO}$ and $VT2_{BeO}$ transform the linear temperature of the BeO substrate to the actual temperature. The non-linear transformations are implemented in MDS with so called Symbolically Defined Devices (SDD) which facilitate the definition of N-port non-linear models.
Note that with this strategy the thermal matrix is not computed in every simulation point as is done in [3], instead the linear thermal matrix is computed only once and the SDD's transform the linear temperature to the actual (non-linear) temperature. The implementation has proven very robust and efficient, simulation times being in the order of seconds for examples with 10 heat generating area's.

3 Modelling of an RF high power transistor

To demonstrate our strategy the thermal modelling of a 10 Watt power transistor operating at 960 MHz under class AB conditions with a V_{ce} of 26 Volts and more than 11 dB of power gain is considered. The length and width of the die are 1.1 by 1 mm and the height of the die is 120 μm. Eight active area's are located on the die and these areas are used in the thermal simulations as volumes of uniform heat generation. The bottom of the silicon die is assumed to have a homogeneous temperature distribution. Although this is not completely true, its effect on the total thermal resistance was found to be in the order of a few percent.

Heat flows from the active areas to the bottom of the die where it is injected into a square region of the beryllium-oxide. The length and width of the BeO are large and have no significant effect on the temperature, the height of the BeO substrate is 0.95 mm. In the simulation the temperature dependence of the thermal conductivities, as given in eq. (5), are taken into account. The computation time for this example was 1.5 seconds on an HP-735-100 workstation.

In figure 3 the thermal resistances from junction to the Si-BeO interface Rth_{j-i}, the resistance from interface to mounting base Rth_{i-mb} and the total thermal resistance from junction to mounting base Rth_{j-mb} ($\Delta T_{max}/P_{diss}$) are shown as function of the total dissipated power. The measured thermal resistance from junction to mounting base is indicated as Rth_{meas}. We note that the non-linearity of the thermal conductivity of the silicon die has far greater influence on the total thermal resistance as does the non-linearity in the thermal conductivity of the BeO substrate. The difference between simulation and measurement is relatively large for small power dissipations. Adjusting the n in equation (5) to obtain a better fit, gives unrealistic values for n. Note however that the electro-thermal interaction is not taken into account in

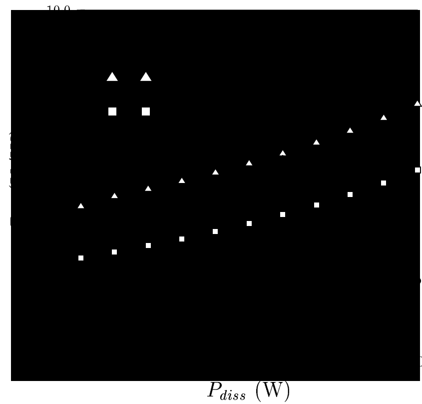

Figure 3: Thermal resistances Rth_{j-i}, Rth_{i-mb}, Rth_{j-mb} and Rth_{meas} as function of dissipated power.

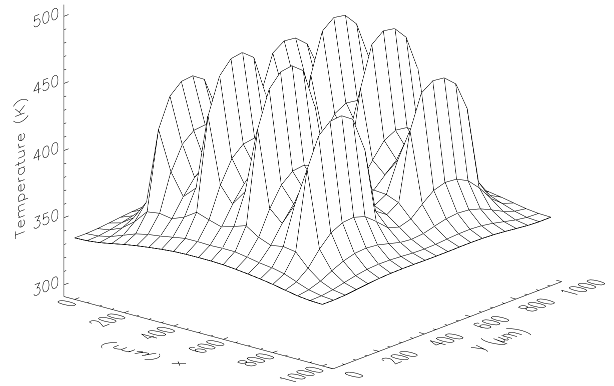

Figure 4: Temperature distribution in the plane of the transistor junctions.

this example, which may give better a agreement. To characterise the thermal resistance from junction to mounting base the dissipated power is increased until a maximum temperature of 200 degrees Celsius is reached (see also figure 4). Based on electrical- and IR measurements at Philips Semiconductors it has been established that this condition is satisfied if 30 Watts of power is dissipated in the transistor i.e. 3.75 Watts per active area. The computed temperature distribution in the plane of the heat generating volumes is shown in figure 4 for a dissipation of 30 Watts. In this figure a maximum temperature of $\approx$ 470 K is found at the four inner active areas and the maximum temperature at the outer four active areas is $\approx$ 440 K. Note that in between the active areas the temperature decreases rapidly to approximately 370 K. The total thermal resistance at 30 Watts of dissipation was calculated to be 5.75 W/K, 5.65 W/K having been measured for this transistor.

4 Conclusions

In conclusion, an effective strategy for modelling the thermal resistance of RF high power bipolar transistors is demonstrated. The effect of both the silicon die and the BeO heat spreader and the temperature dependent thermal conductivities of these materials are taken into account. The thermal problem is split into a linear and a non-linear (transforming) part. The implementation of this method in Hewlett Packard's Microwave Design System (MDS) proves to be robust and efficient, making it amendable to CAD applications.

5 Acknowledgement

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