THERMAL BEHAVIOR USING ANALYTICAL AND NUMERICAL MODEL IN MULTI-FINGER POWER HETEROJUNCTION BIPOLAR TRANSISTORS

R.HOCINE*, M.A.BOUDGHENE STAMBOULI * and A.BOUDJEMAI**

*Department of Electronics Engineering, BP 1505 EL M'Naour
University of Sciences and Technology of Oran Algeria, Fax :231-6-42-15-81.
**CNTS-Arzew-Oran, Spatial Instrumentation Laboratory,
1 Avenue de la Palestine, BP 13, Fax: 231-6-47-34-54.

Abstract

The Transmission Line Matrix (TLM) explicit method has been used to model the transient thermal proprieties of various microwave HBT's power structure. Control of the self-heating is of a paramount importance and changes the electronic performance of the device. The thermal effect is important to the AlGaAs / GaAs multiple emitter heterojunction bipolar transistors (HBT's) due to the high current handling capability of such devices. Aimed toward predicting the HBT behavior and physical trends, we developed an analytical model incorporating the high current as well as thermal effects. The temperature distribution along the depth direction of the substrate is obtained from a three-dimensional analysis by solving the steady-state heat flow equation. In this paper, an investigation of the thermal behavior of single emitter and multi-emitter finger HBT microwave power device is exposed.
For the validity, we compare the results found from the theoretical analysis with the results obtained from the three-dimensional TLM method.

Keywords

Thermal, HBT, Diffusion, Finger, Heat source elements, Nodes.

Introduction

The AlGaAs/ GaAs heterojunction bipolar transistor is superb for high power and high frequency applications[1]. HBT current density often exceeds 10^5 A/cm² under normal biased condition. Such a high current density, together with the poor thermal conductivity of GaAs, inevitably gives rise to a lattice temperature considerably higher than the ambient temperature (self-heating effect). As a result, the power density demonstrated with the HBT falls notably short of the value expected from its electronics limitation.

In an HBT with multiple emitter fingers, a structure commonly used in microwave applications, the thermal effect in this device becomes more complex. In additional to the self-heating effect occurred in the single-finger HBT, thermal-coupling effect among the neighboring fingers is also important [2,3].

The temperature rise within a device can be predicted by thermal analysis [4].

Solving the three-dimensional heat diffusion equation investigated the temperature in each emitter finger as a function of emitter spacing, the number of fingers, and the geometry of substrate.
In this paper, we analyzed the thermal characteristics of single emitter and multi-emitter finger AlGaAs/ GaAs HBT's, focusing on the 3-D distribution of the temperature. We solved the steady-state heat-flow equation and developed an accurate expression of the collector current as a function of junction temperature at each finger. After, the Transmission Line Matrix (TLM) is used to model the thermal behavior of this thypical microwave power device.
For the validity, we compare the results found from the theoretical analysis with the results obtained from the three-dimensional TLM method.

1.Theoretical Model

A power HBT with N heat source elements,i.e.,N emitter fingers is schematically shown in figure.1. In steady state, the temperature distribution is governed by the heat-flow equation $\nabla^2T=0$.
The temperature at an arbitary point (x,y,z) is given by [3],[5].

$$
\begin{aligned}
T(x,y,z) = A_{mn} \sum_{i=1}^{N} \Bigg\{ & \frac{1}{2} \sum_{m=1}^{N} \frac{1}{\lambda_m^2} F_z F_{xi} \cos(\lambda_m x) \\
& + \frac{1}{2} \sum_{n=1}^{\infty} \frac{1}{\delta_n^2} F_z F_{yi} \cos(\delta_n y) \\
& + \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{1}{\lambda_m \delta_n \gamma_{mn}} F_z F_{xi} F_{yi} \cos(\lambda_m x) \cos(\delta_n y) \\
& + \frac{1}{4}(t - z) \Bigg\} I_C^i + T_0
\end{aligned} \tag{1}
$$

Where

$$A_{mn} ? \frac{4V_{CE}}{?_0 L_x W_y l ?}$$

$$?_m ? \frac{m ?}{L_x}$$

$$?_n ? \frac{n ?}{W_y}$$

$$?_{mn} ? \sqrt{?_m^2 ? ?_n^2}$$

$$F_{xi} ? \sin ?_m \left(x_i ? \frac{l}{2}\right) ? \sin ?_m \left(x_i ? \frac{l}{2}\right)$$

$$F_{yi} ? \sin ?_n \left(y_i ? \frac{?}{2}\right) ? \sin ?_n \left(y_i ? \frac{?}{2}\right)$$

$$F_z ? \tanh(?_{mn} t)\cosh(?_{mn} z) ? \sinh(?_{mn} z)$$

And where x_i and y_i are the center coordinate of the *i*th heat source (emitter), and K_0 is the thermal conductivity at T_0. The kirchhoff's transformation can be applied to account for the temperature-dependent thermal conductivity. Assuming $k(T) ? k_0 (T/T_0)^{?1.22}$ [6], the correct temperature which yields the nonlinear steady-state temperature can be obtained.

The temperature-dependent collector current flowing the through *i*th finger I_C^i can be obtained from the drift-diffusion emission model [7]. The expression is:

$$I_C^i ? I_{C0} \left(\frac{T_j^i}{T_0}\right)^{(9/4n) ? 2..3} \exp\left(\frac{q}{n k T_j^i}\left(V_j^i ? ?(T_j^i ? T_0)\right)\right) \quad (2)$$

Where

$$I_{C0} ? l ? q ?_{d0} N_E ?$$

$$\exp\left(?\frac{q}{n k T_0}\left(E_{gB} ? ?E_C ? \frac{kT_0}{q} \ln\left(\frac{N_E N_B}{N_{cE0} N_v N_{B0}}\right)\right)\right)$$

$$V_j^i ? V_{BE} ? \left(R_{Bal}^i ? \frac{R_B}{h_{FE}}\right)$$

$$? ? \frac{E_{gB} ? ?E_C}{T_0}$$

And where *n* is an ideality factor, v_{d0} is the electron drift velocity at T_0, E_{gB} is the bandgap energy in the base, $?Ec$ is the conduction band discontinuity at the heterojunction, N_E and N_B are the doping levels in the emitter and the base regions, and N_{cE0} and N_{vB0} are the effective state densities in the emitter conduction and base valence bands, respectively.

Ballast resistance R^i_{bal} includes emitter contact resistance. The current gain h_{FE} is relatively high in HBT's. A set of (1) and (2) is resolved by the Newton-Raphson iteration method and self-consistent solutions for both the temperature and collector current density distributions are obtained.

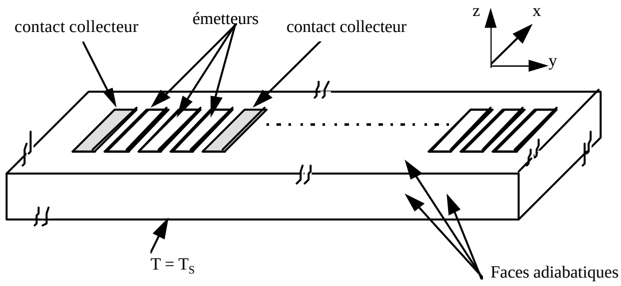

Figure.1 HBT geometry assumed for power devices

2. Numerical Model

2.1 TLM Basics

The technique can be extended to deal with heat flow through three-dimensional system by representing each block of materiel by an RC network as shown in figure.2. The capacitance, C, represents the specific heat capacity and the resistances Rx, Ry and Rz represent the thermal resistances in the direction X,Y and Z of a 3-D Cartesian coordinate system .The variables R_x, R_y ,R_z and C are given by [8]:

$$R_x ? \frac{?x}{2.K.?y.?z} \quad (3)$$

$$R_y ? \frac{?y}{2.K.?x.?z} \quad (4)$$

$$R_z ? \frac{?z}{2.K.?x.?y} \quad (5)$$

$$C ? C_p.?.?x.?y.?z \quad (6)$$

where $?x$, $?y$ and $?z$ are the dimensions of the block, in the Cartesian space.

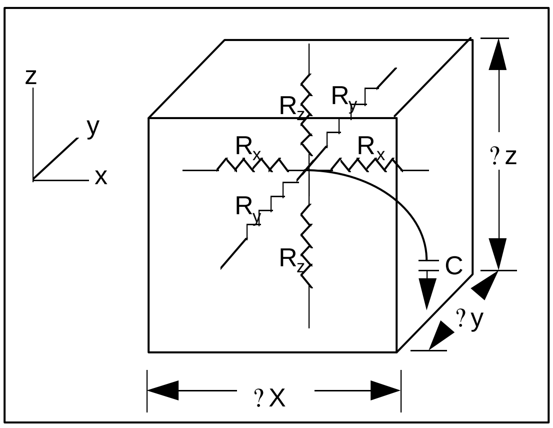

Figure 2 Three-dimensional RC representation of elemental block of material.

The corresponding three-dimensional TLM shunt node for the above RC network of figure.2 is shown in figure.3. Where Z is the characteristic impedance of the transmission line given by:

$$Z = \frac{3.\Delta t}{C} = \frac{3.\Delta t}{\rho C_p.\Delta x.\Delta y.\Delta z} \tag{7}$$

Where Δt is the time taken for an incident pulse to travel from the node to any of its ports.
A solid-state device can be thought of as a network consisting of an array of nodes (matrix points). The current generator is used to model the generation of heat within the device.
A TLM solution is obtained by repeatedly considering heat flow pulses (current) or associated temperature (voltage) to be incident simultaneously on all parts of all nodes. These incident pulses are scattered instantaneously at the nodes to become reflected pulses which, during the time step Δt, travel along link transmission lines to become incident upon neighbouring nodes. Applying Thevenin's theorem to the node shown in figure.3 gives [8]:

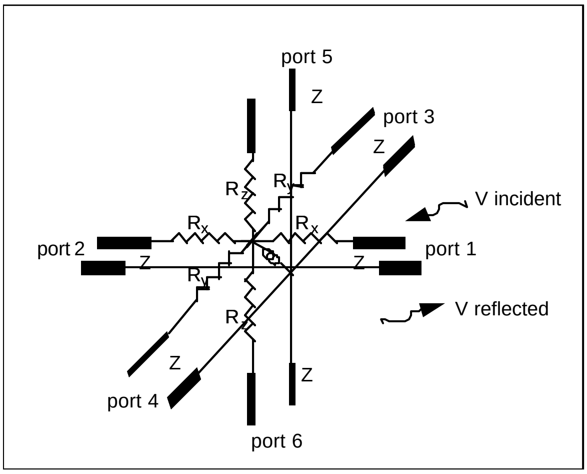

Figure 3 Three dimensional TLM shunt node representation of an RC network.

$$_kV(N) = \left[\frac{2\left({}_kV_1^i + {}_kV_2^i\right)}{R_x + Z} + \frac{2\left({}_kV_3^i + {}_kV_4^i\right)}{R_y + Z} + \frac{2\left({}_kV_5^i + {}_kV_6^i\right)}{R_z + Z}\right]\frac{1}{Y} \tag{8}$$

Where $Y = \frac{2}{R_x + Z} + \frac{2}{R_y + Z} + \frac{2}{R_z + Z}$ and ${}_kV_n^i$ are incident pulses, at the K^{ieme} iteration. Reflected pulses are calculated according to:

$${}_kV_{1,2}^r = \frac{1}{R_x + Z}\left(Z.{}_kV + (R_x - Z).{}_kV_{1,2}^i\right) \tag{9}$$

$${}_kV_{3,4}^r = \frac{1}{R_y + Z}\left(Z.{}_kV + (R_y - Z).{}_kV_{3,4}^i\right) \tag{10}$$

$${}_kV_{5,6}^r = \frac{1}{R_z + Z}\left(Z.{}_kV + (R_z - Z).{}_kV_{5,6}^i\right) \tag{11}$$

These pulses travel to adjacent nodes to become, at the k+1 iteration, incident pulses given by:

$${}_{k+1}V_j^i(x,y,z) = \Gamma_j\,{}_kV_j^r(x,y,z) + (1 + \Gamma_j)\,{}_kV_{j'}^r(u,v,w) \tag{12}$$

Where (x, y, z) are node N co-ordinate and the reflection coefficient in direction (j) is given by :

$$\Gamma_j = \frac{Z(u,v,w) - Z(x,y,z)}{Z(u,v,w) + Z(x,y,z)} \tag{13}$$

The corresponding values of j', u, v, w for j=1,2,... of equations (12) and (13) are listed in table 1[8].

j	j'	u	v	w
1	2	x-1	y	z
2	1	x+1	y	z
3	4	x	y-1	z
4	3	x	y+1	z
5	6	x	y	z-1
6	5	x	y	z+1

Table1. The Values of j, j', u, v, and w Used for (12) and (13)

Equation (8) to (13) form the TLM routine. Its action is to keep a record of the incident pulses at each node at a particular instant in time and to calculate the scattered or reflected pulses in preparation for the next instant in time.

2.2 Calculated Results

The semiconductor device under consideration is shown schematically in figure.1. The diagram represents one quarter of the device due to the symmetry of its structure. The symmetry boundaries are represented by an electrical open circuit (O/C) at which the reflection coefficient Γ is unity.

In first work, a HBT structure is considered with one emitter finger. Later on, a quarter of the device volume containing three fingers is also modeled, figure.1.
The power dissipated in whole device is 6W. This value corresponds to a power density of 8.10^4 W/cm^2. A heat-sink temperature was assumed to be 300°K corresponding to the boundary condition of an electrical short circuit (S/C), or Γ=-1 in TLM modeling.

Table 2 lists the thermal conductivity, specific heat, and density of the materials used.

The temperature-dependent thermal parameters (typically thermal conductivity $k_t(T)$) can be incorporated conveniently point by point into the TLM routine [10].

	AlGaAs	GaAs
Thermal conductivity (W/cm.K)	1.75	$0.47\left(\frac{T}{300}\right)^{-1.22}$
Specific heat (J/g.K)	0.896	0.35
Density (g/cm³)	2.707	5.32

Table 2. Some Physical Parameters for Selected Materials

* Formula according to the data given in [9] for n-type GaAs with a doping concentration 3.510^{17} cm^{2}

3. Results And Discussion

Figure.4 illustrates the three-dimensional temperature distribution in a HBT operating at an ambient temperature of 300°K. In the figure, a peak temperature of 400°K for pulse duration of 5µs is found near the base-collector junction. These results are obtained for Vbe=1.5V and Vce=3V.

This high temperature, which results from the very large electric field in the base-collector junction, will rise the velocity overshoot and enhance the cut-off frequency of the HBT. The lattice temperature decreases rapidly to the ambient temperature in the extrinsic region adjacent to the substrate and between fingers showing the role of the finger spacing and substrate in heat dissipation.

Figure.5. shows the variation of the temperature distribution along the depth direction of the substrate when the substrate thickness is 100 µm. The heat-sink temperature was assumed to be 300°K. A peak temperature of 400°K is obtained under the power dissipation condition P = 1.7 W at V_{CE} = 5V.

Figure.6. shows the three-dimensional lattice temperature in three emitter fingers HBT's microwave power device using the TLM method for thermal analysis.

The numerical results agree with the theoretical results with a little difference, it can explained by considering that the capability of heat dissipation decreases as nonuniform operation in enhanced.

In figure.5. and figure.6., the HBT layout in the y-z space, and the emitter fingers are located. The lattice temperature decreases rapidly to the ambient temperature in the extrinsic region adjacent to the substrate and between fingers showing the role of the finger spacing and substrate in heat dissipation.

All fingers have similar temperature, with the centre finger slightly hotter than the outer fingers, as show in figure.7. This is due to the thermal-coupling effect which becomes significant and elevates the HBT lattice temperature beyond that caused by self-heating in a single finger HBT.

TLM has been successful in modelling heat diffusion problems and has proven to be efficient in terms of stability, complex geometry and the incorporation of non linear material properties. The three-dimensional results show that the method has a considerable potential in small devices thermal analysis and design.

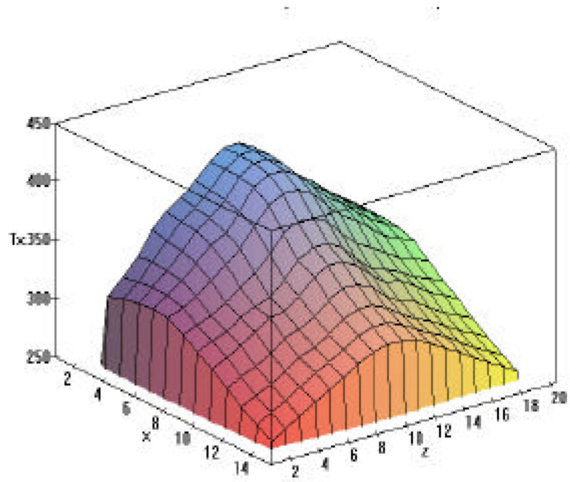

Figure 4 Three-dimensional lattice temperature contours in the HBT operating at the collector current density Jc of 8. 10^{4} W/cm^{2}.

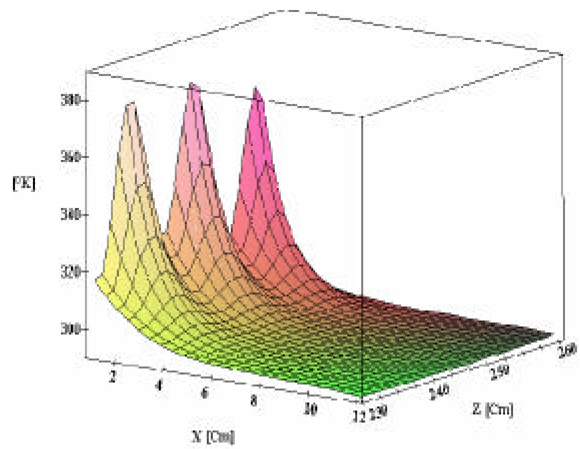

Figure 5 Plots of the temperature distribution at the surface of the 3-fingers HBT operating at a collector current density Jc of 8.10^{4} W/cm^{2} (Analytical Model).

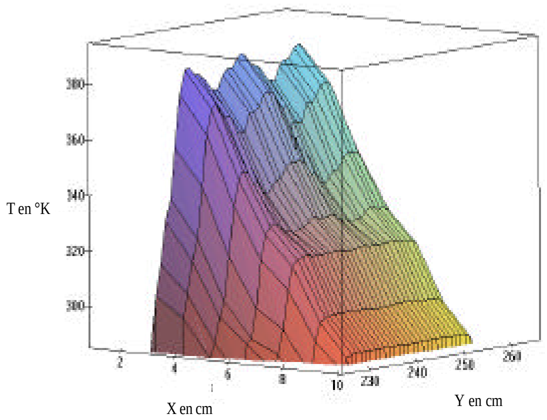

Figure 6 Plots of the temperature distribution at the surface of the 3-fingers HBT operating at a collector current density Jc of 8.10^4 W/cm^2 (Numerical model).

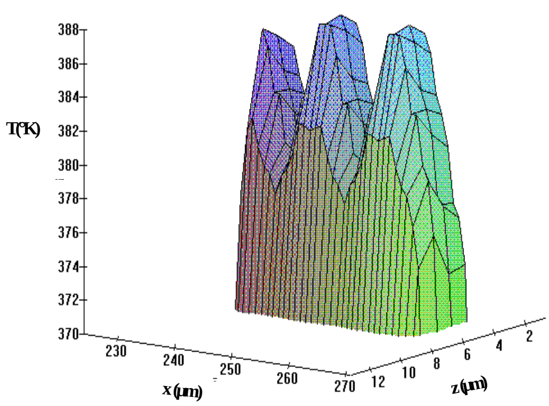

Figure 7 Zoom of the figure 6.

4. Conclusion

A three-dimensional numerical and theoretical analysis has been presented to investigate the effect of self-heating in AlGaAs / GaAs HBT. The elevated lattice temperature in this device resulting from the self-heating decreases the collector current and increases the base current, which then decreases the current gain at the high current region.

The results shows clearly that the HBT microwave device are capable of self-generating considerable amount of heat that should be dissipated very quickly to reduce thermo-electronic coupling effect and increase device lifetime. Furthermore, the results shows that substrate, and the geometry of the inter-finger spacing play an important role in dissipating the generated heat.

This work has also demonstrated that it is relatively simple to use the three-dimensional TLM method for thermal analysis of low dimensional semiconductor device structures. We believe that the unconditionally stable nature of the method and the ease with which complex geometry can be handled give the TLM technique some future. So a comprehensive thermal analysis is possible for any semiconductor device structure with complex geometry and fabricated with many different materials.

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