# Transient Analysis of Collector Current Collapse in Multifinger HBT's

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***Abstract*—The authors report for the first time a time-domain analysis of thermal instability in multifinger heterojunction bipolar transistors (HBT's). This is based on a transient quasi-three-dimensional (3-D) electrothermal model that selfconsistently solves the thermal and electrical equations. This model is designed to evaluate the thermal time constant of GaAs-based power HBT's employing emitter thermal shunt and emitter ballast resistance.**

***Index Terms*— Current collapse, electrothermal model, HBT, transient analysis.**

## I. Introduction

For high-efficiency high-power microwave applications from $S$ to $Ku$ band, the GaAs-based heterojunction bipolar transistor (HBT) is a promising alternative to the field effect transistor. However, a combination of poor GaAs thermal conductivity and positive electrothermal feedback within the device results in a thermal limitation in HBT's that can occur well before the onset of electrical limitations, especially in multifinger designs. This thermal limitation involves a current collapse phenomenon [1] that limits the dc operating range of large-area devices. The sudden decrease of current gain is a combination of nonlinear thermal effects and localized high collector current density effects. Although neither a simple electrical nor thermal study can explain this effect, several groups have studied the current collapse phenomenon using analytical calculations [2], [3]. Unfortunately, these models do not consider the time constant for the onset of current collapse, nor do they predict the thermal time constant of structures having a thermal shunt. However, such analysis is useful in the study of devices operating under pulsed-power conditions. For this reason we have developed a quasi-three-dimensional (3-D) nonlinear electrothermal model that computes the temperature distribution in multifinger HBT's in the time domain.

## II. Thermal Model

The transient temperature distribution is calculated in two dimensions from the general heat flow equation with adapted boundary conditions [4]

$$\nabla \cdot (k \cdot \nabla T) + q''' = \rho c \frac{\partial T}{\partial t} \tag{1}$$

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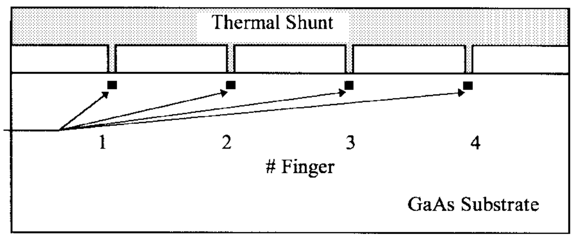


Fig. 1. Simulated structure showing location of nonlinear heat sources and placement of thermal shunt.

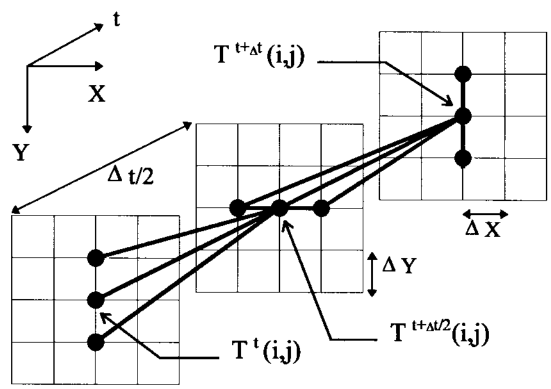


Fig. 2. The ADI method.

where $T$ is temperature, $k$ is thermal conductivity (W/m $\cdot$ K), $q'''$ is the heat generation term (W/m$^3$), $\rho$ is density (kg/m$^3$) and $c$ is specific heat (J/kg $\cdot$ K). Equation (1) is a parabolic equation which is solved with a two-dimensional (2-D) finite-difference method (assuming uniform temperature distribution in the third dimension). The simulated structure is depicted in Fig. 1.

This cross section is meshed using squares of $1 \times 1$ $\mu$m$^2$. We observed that smaller squares increased substantially computing time while giving approximately the same results. To simplify the resulting system of equations and enhance convergence, we use the alternative direction implicit (ADI) method to compute the temperature distribution in the structure for a given time increment. The ADI formalism is depicted graphically in Fig. 2. The time increment $\Delta t$ is divided into two equal parts. When (1) is expressed using a finite-difference decomposition and the second spatial derivatives $\partial^2 T/\partial x^2$ and $\partial^2 T/\partial y^2$ are expressed at $T^{t+\Delta t}$, we obtain implicit linear relations for $T^{t+\Delta t/2}$ and $T^{t+\Delta t}$ that depend on just three terms at $T^t$ and $T^{t+\Delta t/2}$, respectively. This simplification allows us to efficiently solve the characteristic matrices with a Gauss elimination procedure.

The boundary conditions for the sides and bottom of the device incorporate a Dirichlet condition which approximates continuous heat flow into a thermal mass. For the upper surface we use a coupled convection and radiation condition. The heat flow $q''$ (W/m$^2$) is expressed as

$$q'' = h(T_s - T_o) + \sigma T_s^4 \quad (2)$$

where $T_o$ is ambient temperature, $T_s$ is surface temperature, $h$ is the heat transfer coefficient (W/m$^2$K), and $\sigma$ is the Stephan–Boltzmann constant (W/m$^2$K$^4$).

## III. Electrical Model

In (1), the term $q'''$ is computed at each time increment. Assuming a unity length $\Delta z$, we define $q''$ as

$$q''(i,j) = (V_{\text{ce}} - Re \cdot (ib_n + ic_n)) \times Jc_{i,j} \times \Delta x/\Delta y \quad (3)$$

where $V_{\text{ce}}$ is collector–emitter voltage, $ib_n$ and $ic_n$ the total base and collector current for finger number $n$, $Re$ is emitter ballast resistance, and $Jc_{i,j}$ is collector current density in cell $(i,j)$, which is computed as

$$Jc_{i,j} = \beta(Jb_{i,j}, T_{i,j}) \times Jb_{i,j}(V_{be}, T_{i,j}). \quad (4)$$

To model base current density $J_b$ and current gain $\beta$, an analytical law of the form $\exp(qV_{be}/\eta \text{ kT})$ is used to fit the measured $I_b$ versus $V_{be}$ characteristics of our devices [5], and an empirical law for $\beta$ as a function of temperature and current density was used. Current gain collapse due to the Kirk effect is modeled as a linear decrease in current gain as collector current density surpasses a threshold value.

## IV. Results

Our transient electrothermal model permits us to examine the phenomenon of current collapse in multifinger HBT's. Fig. 3 shows the step response of total collector current and current in each finger for a four-finger structure similar to that of Fig. 1, although without thermal shunt or ballasting resistance. Applied collector voltage is 6 V, and the base current step is 2 mA. In zone I, current and temperature distributions are uniform among the fingers. In zone II, the central fingers conduct more and more current, whereas the lateral fingers conduct less and less current. It is evident that the central fingers are subject to strong thermal coupling. In zones III and IV, finger 2 begins to conduct the majority of the base current, while the adjacent fingers become inactive. The current density for finger 2 in zone IV is very large, which results in base widening (Kirk effect); this incurs a sharp decrease in current gain as base current is held constant. In this example, the establishing time of current collapse phenomenon is about 20 $\mu$s.

Fig. 4 shows the temperature distribution in the structure at 16 $\mu$s. At this point in the step response, the outside fingers are nearly turned off, while the central fingers conduct most of the base current and are thus the hottest. The thermal runaway effect for this bias condition can be avoided by the addition of a thermal shunt, as seen in Fig. 5. For a thermal shunt thickness of 6 $\mu$m, the maximum temperature is uniform among the

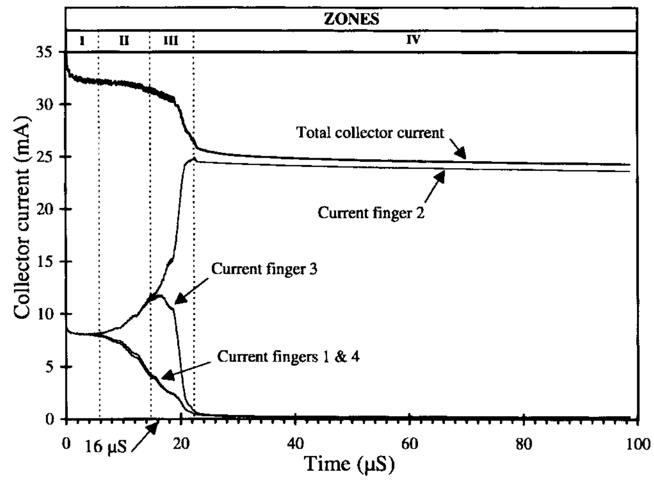


Fig. 3. Step response of collector current versus time for a four-finger HBT without thermal shunt, $V_{ce} = 6$ V, $Ib = 2$ mA.

fingers, and maximum junction temperature has decreased to below 45°C.

In addition to the study of current collapse, we have used this model to evaluate the influence of topology on the thermal time constant in HBT's. We define the thermal time constant as the time it takes for device temperature to increase from 10% to 90% of its equilibrium value for a step base current input. Fig. 6 shows the evolution of the thermal time constant versus the distance between fingers for a thermally shunted four-finger HBT. The base current step is 4.5 mA, and the collector voltage is 3 V. As finger spacing is reduced, thermal coupling is increased and temperature rises quickly. For large finger separations, the time constant approaches that of a single-finger device since the fingers are thermally isolated. It is seen that the maximum value occurs for a finger spacing near 60 $\mu$m. This distance appears to be desirable for high-power pulsed applications, although the impact of finger spacing on the electrical characteristics of the device needs to be considered simultaneously. We performed pulsed measurements on a four-finger thermally shunted HBT having a 30-$\mu$m finger separation. By varying the base current pulse width and amplitude, we estimated the thermal time constant of this device to be approximately 20 $\mu$s, which is in good agreement with the simulation result of 18 $\mu$s.

We also studied the effect of thermal shunt thickness on the thermal time constant. For a four-finger device, as thermal shunt thickness is increased from 2 to 12 $\mu$m, the thermal time constant increases linearly from 4 to 22 $\mu$s. This is an expected result since the thermal capacity of the shunt increases linearly with thickness.

## V. Conclusion

In this letter we presented a time-domain analysis of the current collapse phenomenon in multifinger HBT's. This model computes the thermal time constant and the time constant for the appearance of current collapse phenomenon. This model has been used to optimize the topology of InGaP/GaAs HBT's designed for high-power pulsed amplifier applications.

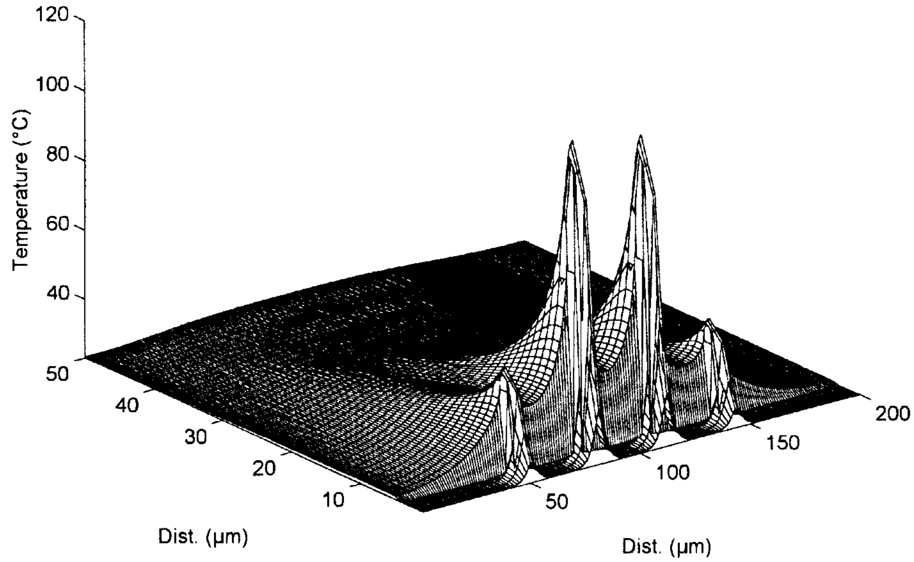


Fig. 4. Temperature distribution, four-finger HBT without thermal shunt, $V_{ce} = 6$ V, $Ib = 2$ mA, at $t = 16$ $\mu$S.

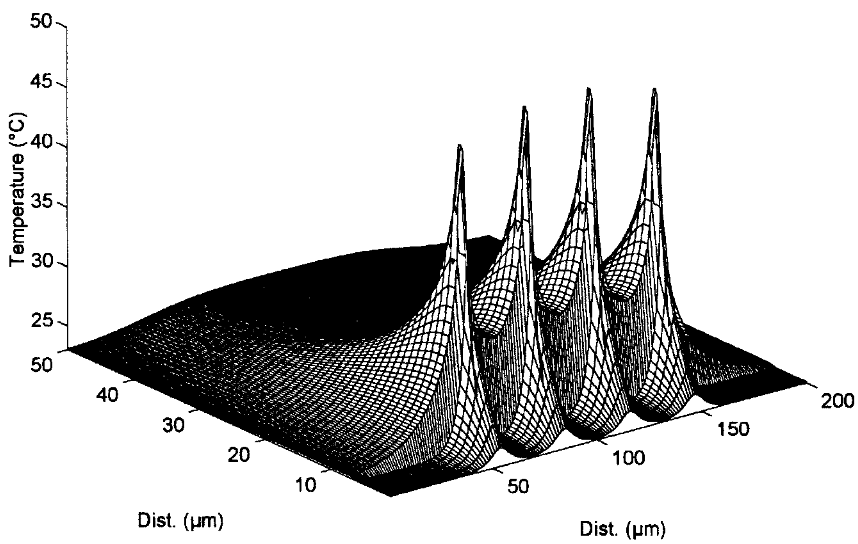


Fig. 5. Temperature distribution, four-finger HBT with thermal shunt, $V_{ce} = 6$ V, $Ib = 2$ mA, at $t = 16$ $\mu$S.

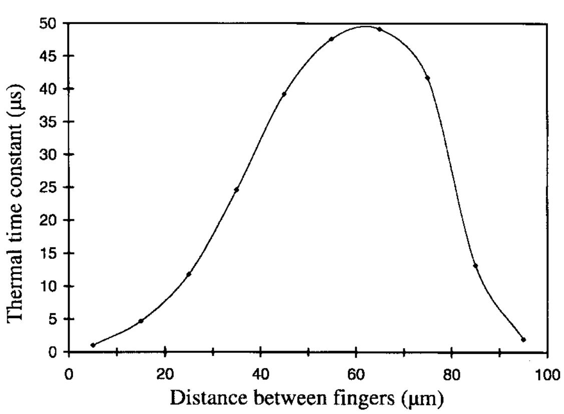


Fig. 6. Thermal time constant versus emitter finger spacing for four-finger HBT with thermal shunt.

## Acknowledgment

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