Numerical Simulation of Self-heating InGaP/GaAs Heterojunction Bipolar Transistors

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Abstract. We numerically simulate effects of the self-heating on the current-voltage characteristics of InGaP/GaAs heterojunction bipolar transistors (HBTs). A set of coupled nonlinear ordinary differential equations (ODEs) of the equivalent circuit of HBT is formed and solved numerically in the large-signal time domain. We decouple the corresponding ODEs using the waveform relaxation method and solve them with the monotone iterative method. The temperature-dependent energy band gap, the current gain, the saturation current, and the thermal conductivity are considered in the model formulation. The power-added efficiency and the 1-dB compression point of a three-finger HBT are calculated. This approach successfully explores the self-heating and the thermal coupling phenomena of the three-finger transistors under high power and high frequency conditions. The numerical algorithm reported here can be incorporated into electronic computer-aided design software to simulate ultra-large scale integrated and radio frequency circuits.

1 Introduction

High power heterojunction bipolar transistors (HBTs) operated at micrometer- and millimeter-wave frequencies have been of great interest; in particular, for the advanced wireless and fiber communication [1], [2], [3], [4], [5]. These transistors, fabricated for high power applications, usually have a structure of multiple fingers to spread the current and the dissipated heat. Therefore, effects of the self-heating and the thermal coupling among fingers is one of the important issues for design and fabrication of advanced radio frequency (RF) circuits. Electrical characteristics depend on the surrounding temperature, so the thermal effect significantly influences the linearity of operating transistors [6]. Therefore, a self-heating model should be considered when exploring power dissipations of InGaP/GaAs devices and related RF circuits.

In this paper we examine effects of the self-heating on a three-finger InGaP/GaAs HBT operated at high frequency. Using the waveform relaxation

Fig. 1. An equivalent circuit of the simulated three-finger HBT under constant current and high frequency excitations

(WR), the monotone iterative (MI), and Runge-Kutta methods [7], [8], [9], [10], a set of nonlinear ordinary differential equations (ODEs) with thermal models is solved numerically in the time domain. The governing ODEs of the equivalent circuit of HBTs are formulated by the Kirchhoff's current law [11]. This solution technique has recently been developed by us for circuit simulations [7], [8], [9], [10]. The temperature-dependent physical quantities are modeled and several important engineering factors, such as the power-added efficiency and the 1-dB compression point of the simulated three-finger HBT are calculated. Our modeling and simulation successfully explores the self-heating and the thermal coupling phenomena of the studied three-finger transistors circuit operated under high power and high frequency conditions.

This paper is organized as follows. In Sec. 2, we state the physical model and numerical method. In Sec. 3, we present the simulation results. Finally, we draw conclusions.

2 Self-heating Modeling and Numerical Method

A multifinger HBT is formed by several sub-HBTs with their own collector and emitter, where their base is connected together. As shown in Fig. 1, an equivalent circuit with a thermal network of the three-finger HBT is studied in this work, where each finger is theoretically assumed to be identical. A thermal model that describes the relation between the power dissipation and the junction temperature is adopted. The electrical model of HBT considered in our simulation is based on the Gummel-Poon (GP) large signal model [7], [8], [9], [10]. For the thermal-electrical feedback mechanism, the temperature-dependant equations are introduced to the GP model

$$E_g(T_J) = E_g(T_A) + \frac{E_a \cdot T_A^2}{T_A + E_b} + \frac{E_a \cdot T_J^2}{T_J + E_b}, \quad (1)$$

Fig. 2. A plot of the maximum norm error of the junction temperature versus the number of iterations of the WR loop

$$IS(T_J) = IS \cdot \left(\frac{T_J}{T_A}\right)^{XTI} \cdot \exp\left[\left(\frac{E_g(T_A)}{k \cdot T_A}\right) - \left(\frac{E_g(T_J)}{k \cdot T_J}\right)\right], \quad (2)$$

$$ISE(T_J) = ISE \cdot \left(\frac{T_J}{T_A}\right)^{\frac{XTI}{NE} - XTB} \cdot \exp\left[\left(\frac{E_g(T_A)}{NE \cdot k \cdot T_A}\right) - \left(\frac{E_g(T_J)}{NE \cdot k \cdot T_J}\right)\right], \quad (3)$$

$$ISC(T_J) = ISC \cdot \left(\frac{T_J}{T_A}\right)^{\frac{XTI}{NC} - XTB} \cdot \exp\left[\left(\frac{E_g(T_A)}{NC \cdot k \cdot T_A}\right) - \left(\frac{E_g(T_J)}{NC \cdot k \cdot T_J}\right)\right], \quad (4)$$

$$BF(T_J) = BF \cdot \left(\frac{T_J}{T_A}\right)^{XTB}, \quad (5)$$

$$BR(T_J) = BR \cdot \left(\frac{T_J}{T_A}\right)^{XTB}, \quad (6)$$

where T_J and T_A are the junction and the ambient temperature, respectively. We note that for high power devices, T_A is the temperature on the back of the substrate. Above equations include the temperature dependance of energy band gap (E_g), the saturation current (IS), the collector and emitter leakage current (ISC and ISE), and the current gain (BF and BR). The thermal model expresses the relation between the power dissipation and the junction temperature. The junction temperature with considering the temperature-dependent thermal conductivity for the three-finger HBT is given by

$$\mathbf{T}_J = T_A \left\{ 1 - \frac{(BB-1)}{T_A} [\mathbf{R}_{TH} \cdot \mathbf{P}_D] \right\}^{\frac{-1}{BB-1}} = \begin{bmatrix} T_{J1} \\ T_{J2} \\ T_{J3} \end{bmatrix}, \quad (7)$$

where T_{Jn} is the junction temperature of the n^{th} finger, $n = 1, 2, 3$. $\mathbf{R}_{TH} \cdot \mathbf{P}_D$ is given by

$$\mathbf{R}_{TH} \cdot \mathbf{P}_D = \begin{bmatrix} R_{T11} & R_{T12} & R_{T13} \\ R_{T21} & R_{T22} & R_{T23} \\ R_{T31} & R_{T32} & R_{T33} \end{bmatrix} \cdot \begin{bmatrix} P_{D1} \\ P_{D2} \\ P_{D3} \end{bmatrix}. \quad (8)$$

R_{Tnn} and R_{Tnm} denote the self-heating thermal resistance of the n^{th} finger and the coupling thermal resistance which counts the coupled heat from the m^{th} finger to the n^{th} finger, respectively. Furthermore, the power dissipation of the n^{th} finger is denoted by P_{Dn} . Equivalent circuit of the three-finger HBT is shown in Fig. 1. The finger 1 of this HBT is represented by $M1$, and $M2$ and $M3$ are the fingers 2 and 3, respectively. I_{BB} denotes the constant bias current at the base and P_{in} is the power of RF input signal. The behavior of Fingers 1 and 3 is the same for the identical fingers assumption. By considering the models above, the electrical and thermal feedback equations for the power HBTs are achieved and solved self-consistently in the time domain, where the temperature-dependent thermal conductivity is also included in our numerical solution.

The corresponding coupled nonlinear ODEs of the equivalent circuit of HBTs above is first decoupled using the WR method and then solved with the MI and Runge-Kutta methods. Compared with the conventional method, the Netwon's iteration method, used in the well-known SPICE circuit simulator [8], [9] our approach in solving the self-heating model is robust and cost-effective for the large-scale time domain circuit simulation of HBTs.

3 Results and Discussion

First of all, we verify the convergence of the solution method. The testing case is the device with the collector voltage $V_{CC} = 5V$, the input current bias $I_{BB} = 0.5mA$, the frequency is centralized at $1.8GHz$, and the convergence criterion is that the maximum norm error of the output voltage is less than $10^{-11}V$. Figure 2 shows a plot of the maximum norm error of the junction temperature versus the number of iterations. Simulation with our method demonstrates better convergence property than the result of the SPICE circuit simulator [9]. However, the simulation with the SPICE circuit simulator takes more than 100 iterations to meet the specified stopping criterion. For each time step, the CPU time of our method is of the order of 10^2 sec. running on a HP workstation XW 8000. The convergence of SPICE circuit simulator depends upon the selection of initial guess and the time steps which complicates the solution procedure for practical engineering application. Our solution algorithm converges monotonically and the DC solutions, in general, are used as the starting solution.

Fig. 3. The curves of I_{CC} - V_{CE} with respect to different I_{BB} for the simulated three-finger InGaP/GaAs HBT circuit. It is significantly different from the result without considering the self-heating [7], [8], [9]

Fig. 4. The simulated I_{CC} - V_{CE} curves with respect to different I_{BB} for the fingers 1 and 2 of the HBT. The result of Finger 3 is omitted according to the property of symmetry

The simulated I-V characteristics of the three-finger InGaP/GaAs HBT circuit are shown in Figs. 3 and 4. Each curve in these figures represents the col-

Fig. 5. The computed P_{OUT} , PAE, and Gain versus P_{in}

Fig. 6. Plots of the PAE of Fingers 1 and 2 versus the input power

lector current under constant I_{BB} . Due to the effect of self-heating, the total collector current decreases when the collector-emitter voltage increases, shown in Fig. 3. It results in a negative differential resistance region in the I-V characteristics and a collapse of current gain in the three-finger HBT circuit. As shown in Fig. 4, the collector current of the central finger (Finger 2) decreases rapidly, compared with the results of neighbor figures, such as Finger 1. It is due

to the strongly coupled heat from its neighbor two fingers, Finger 1 and Finger 3. As the collector-emitter voltage increases even more ($V_{CC} > 4V$), an abrupt reduction of the collector current of Finger 2 occurs. With the electrical and thermal interaction, our modeling and simulation can explore the phenomenon of collapse for the multifinger HBTs under high voltage and high current bias.

As shown in Fig. 5, it is the calculated output power (P_{OUT}), the power-added efficiency (PAE), and the power gain (Gain) versus the different values of the input power (P_{in}). The input excitation is a single tone signal at 1.8 GHz. The bias condition of this single tone simulation is with $V_{CC} = 3.6$ V and $I_{BB} = 0.6$ mA. In this simulation, we have taken the effect of heating of the input high frequency signal into consideration. It is found that, shown in Fig. 5, the Gain and PAE degrade as P_{in} increases, and the 1-dB compression point (P_{1-dB}) is -2.45 dBm. The effect of thermal coupling among fingers also influences the performance of the three-finger device structure. As shown in Fig. 6, the PAE of the central finger (Finger 2) is reduced and degraded when $P_{in} > -3$ dBm. In the meanwhile, the PAE of the neighbor finger (Finger 1) still increases as P_{in} increases. This phenomenon illustrates that the performance degradation of the whole transistor is mainly dominated by the hotter central finger.

4 Conclusions

In this paper, we have numerically solved a set of nonlinear and self-heating ODEs for exploring the electrical characteristics of InGaP/GaAs device. The solution approach is mainly based on the WR and the MI methods. Compared with the well-known SPICE circuit simulator, our approach has successfully shown its robustness. Different electrical characteristics have been calculated to examine effects of self-heating on the simulated three-finger HBT circuit. We believe that the solution method will benefit the community of electronic computer-aided design; in particular, for modern RF circuit simulation. To perform optimal designs for specified circuits, we are currently implementing intelligent algorithms with the developed method.

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