Analysis of Collapse Patterns in Multi-finger Power AlGaAs/GaAs HBTs

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Abstract

A new theory is developed in this paper to explain the collapse of current gain in multi-finger power AlGaAs/GaAs Heterojunction Bipolar Transistors. Two different collapse patterns are investigated. The reasons behind this unwanted phenomenon are clarified using a simple model to investigate the thermo-electrical interaction between the fingers. The method has been used to predict the collapse in AlGaAs/GaAs HBTs and the agreement is excellent.

I. Introduction

AlGaAs/GaAs Heterojunction Bipolar Transistors (HBTs) have been widely accepted by the microwave industry as an excellent candidate for many high-frequency applications. The combination of the high current density during operation and the relatively low thermal conductivity of the GaAs substrate elevates the junction temperature of HBTs severely, which leads to the collapse of current gain in multi-finger power HBTs [1,2,3,4]. A new theory is demonstrated in this paper for explaining the collapse of the current gain in multi-finger HBTs. The reasons behind this unwanted phenomenon are fully clarified using a simple model to investigate the thermo-electrical interaction between the fingers. The existence of multi-value equilibrium points in the model's constitutive equations is shown to be the necessary condition for the prediction of current gain collapse. Two different collapse patterns, under constant I_B and constant V_{BE} conditions, are investigated in this paper. The method is used to predict the collapse in AlGaAs/GaAs HBTs and is also used to investigate the influence of the ballasting resistance and thermal resistance on the collapse behaviour of HBTs.

II. Theoretical Analysis of Current Gain Collapse in HBTs

Figure 1 shows the simple model which is used to describe a single HBT finger of a multi-finger power HBT. The final constitutive nonlinear equation to determine the DC bias point for a single finger is:

$$V_T \cdot \log\left(\frac{I_B}{I_{SB0}}\right) = V_{BE} + \frac{\beta_{F0} \cdot I_B}{1 - K_\beta \cdot R_{TH} \cdot V_{CE} \cdot I_B} \cdot (K_{EG} \cdot R_{TH} \cdot V_{CE} - R_E) \quad (1)$$

where K_β, K_{EG} are the temperature coefficients for the current gain and energy bandgap, and R_{TH} is the self-thermal resistance for the finger [5]. Other symbols keep their conventional meanings. The solutions of equation (1) can be obtained using graphical methods or numerical methods. For example, the intercept points of the following two curves represent the possible solutions of equation (1):

$$F_1(I_B) = V_{BE} + \frac{\beta_{F0} \cdot I_B}{1 - K_\beta \cdot R_{TH} \cdot V_{CE} \cdot I_B} \cdot (K_{EG} \cdot R_{TH} \cdot V_{CE} - R_E) \quad (2)$$

$$F_2(I_B) = V_T \cdot \log\left(\frac{I_B}{I_{SB0}}\right) \quad (3)$$

Since two nonlinear functions are involved here, there are many possible solution patterns. For example, the two curves may have only one intercept point but they may alternatively have two or three intercept points, (see Figure 2). Since these intercept points represent the possible equilibrium points (or stable states) for a single finger, the different fingers in a multi-finger HBT can stay in the different states as long as the following conditions are satisfied:

$$I_{Btotal} = I_{B1} + I_{B2} + ... + I_{BN} \tag{4}$$

for a constant I_{Btotal},

or

$$V_{BE} = V_{BE1} = V_{BE2} = ... = V_{BEN} \tag{5}$$

for a constant V_{BE}, where N is the number of emitter fingers.

For a common-emmiter configuration with a constant I_{Btotal}, the following analysis is applied. In the low-power region, all fingers can only support the low-current state ($I_{Btotal} = N \cdot I_{Blow}$). In the high-power region, the following possible combinations correspond to current gain collapse: $I_{Btotal} = (N-1) \cdot I_{Blow} + I_{Bmedium}$, $I_{Btotal} = (N-2) \cdot I_{Blow} + 2 \cdot I_{Bmedium} \ldots$ The first case corresponds to one hot finger pattern and is the most common case. The other possible combinations can also appear in a real HBT. For example, for an HBT with fish-bone layout, the up-row of the emitter-fingers can become hotter than the down-row and the current distribution becomes $I_{Btotal} = 0.5 \cdot N \cdot I_{Blow} + 0.5 \cdot N \cdot I_{Bmedium}$.

For the constant V_{BE}, the following analysis is applied (see Figure 3). In the low-power region, all fingers can stay in the low-current state as far as no serious perturbation happens to a single finger which may force it to jump to the high current state (this could happen if the device is working under large-signal AC operating conditions). With the increase of V_{BE}, the first and the second intercept points move towards each other. When the first and second intercept points meet, a single point is formed. A further increase in V_{BE} results in the disappearing the first (and second) intercept point, forcing the state of the finger to jump to the third intercept points. This jumping process corresponds to a sharp increase in the current. For a real multi-finger HBT, there are always some small differences between fingers. So this jumping process will not happen to all the fingers simultaneously. A particular finger will first jump from the low-current state to the high-current state. Further increase in the bias will cause another finger to jump from the low-current state to the high-current state. The phenomenon observed in this case is then a series of current steps. Given that the third intercept point corresponds in many cases to a high current value then it is often likely that the hot finger will fail after a period of time.

III. Numerical Algorithm

The above theory has been coded into an ANSI C program to analyze real multi-finger HBTs. The program uses a Newton-Raphson algorithm to search for the equilibrium point of each finger. After the current across each finger is obtained, the dissipation power of this finger is estimated. Then the temperature of each finger is evaluated based on the dissipation power. The new temperatures at each finger is fedback to the single finger model to re-calculate the current and voltage of the finger. The above procedure forms a closed loop and the program will iterate the above procedure until convergence has been reached (see Figure 4). Since the constitutive nonlinear equations, relating to collapse theory, have multi-equilibrium points, the Newton-Raphson method is not guaranteed to converge. On this situation, a trigger-method is used to make the procedure converge successfully and quickly to a particular collapse pattern.

IV. Examples

The above analysis has been applied to the two-finger HBT fabricated and characterised by Liu [4]. Figure 5 demonstrates the simulated and measured collapse behaviours under the constant I_B bias. Figure 5 shows that the current distribution becomes asymmetric after the HBT enters the collapse region. In the deep collapse region, one finger carries nearly all of the current and the other finger is completely inactive. The agreement between the measured and simulated results is excellent. Figure 6 demonstrates the simulated and measured collapse characteristics for a constant V_{BE}. Importantly, the steps in the current value are simulated correctly by the model, providing corroborative evidence for the accuracy of the theory presented in section 2 and 3. The model and algorithm developed in this paper can also be used to investigate the influence of the ballasting resistance and self-thermal resistance.

V. Conclusions

A new method has been presented in this paper to analyze the gain collapse effect found in multi-finger power HBTs. By analyzing the nonlinear $I-V-T$ relationships for multi-finger devices, the true reasons behind this complex phenomenon have been clarified. The multi-value equilibrium solutions for the nonlinear $I-V-T$ relationships of the device have been shown to be the main reason for the device entering the gain collapse state. Two different collapse patterns have been analyzed and the agreement between simulated and measured results has been presented to support this theory.

Acknowledgment

The authors would like to acknowledge the support of HP-EEsof Inc., Santa Rosa, USA, and M/A-COM Corporate Research and Development, USA.

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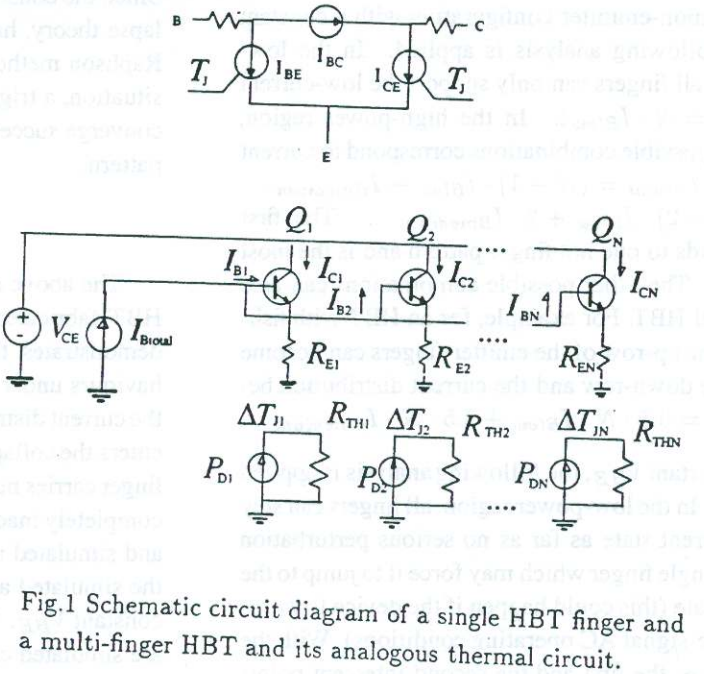

Fig.1 Schematic circuit diagram of a single HBT finger and a multi-finger HBT and its analogous thermal circuit.

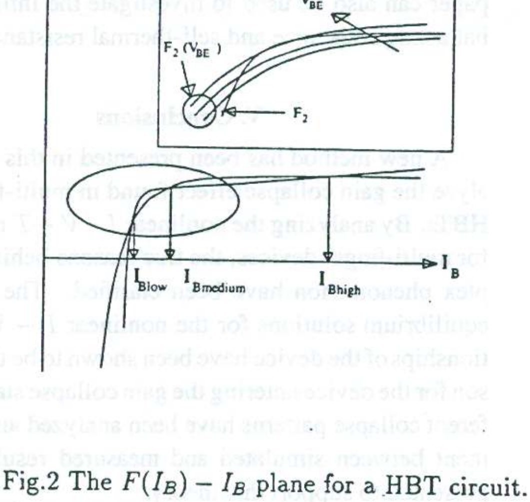

Fig.2 The $F(I_B) - I_B$ plane for a HBT circuit.

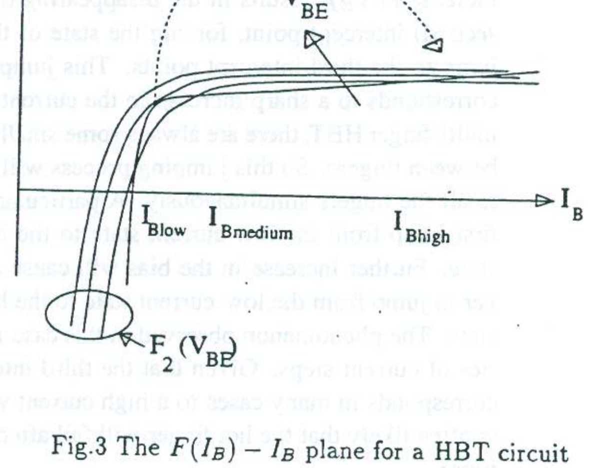

Fig.3 The $F(I_B) - I_B$ plane for a HBT circuit under constant V_{BE} bias condition.

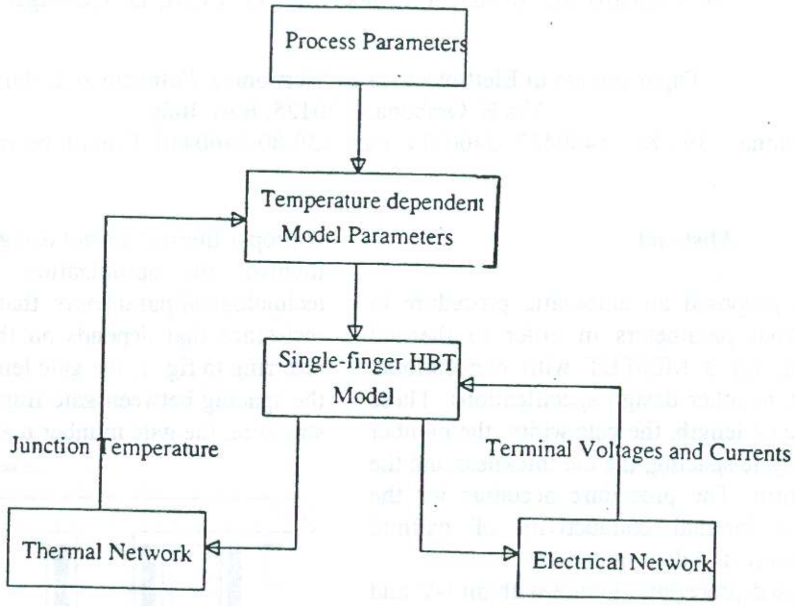

Fig.4 Flow chart of the HBT solver.

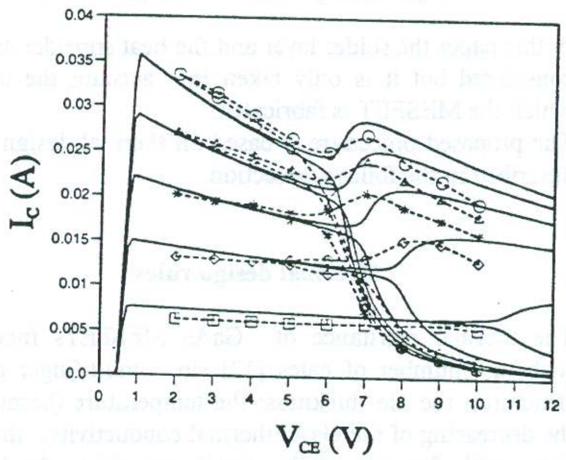

Fig.5 Comparison between measured and simulated results for a two-finger HBT, $I_B = 0.5, 1.0, 1.5, 2.0, 2.5 (mA)$. Solid lines are the simulation results and the symbols are the measurement results.

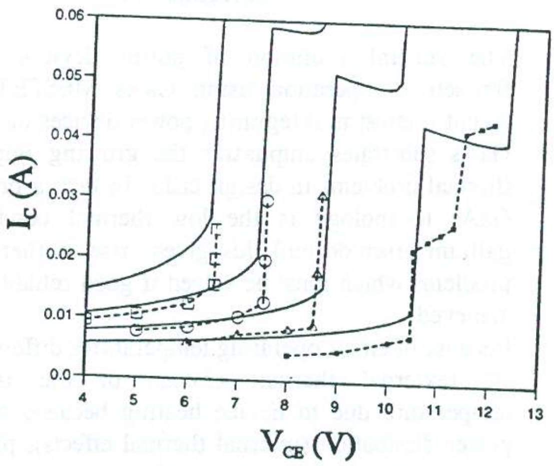

Fig.6 Comparison between measured and simulated results for a two-finger HBT, $V_{BE} = 1.41, 1.42, 1.43, 1.44 (V)$. Solid lines are the simulation results and the symbols are the measurement results.