Three-Dimensional Modeling of Thermal Flow in Multi-Finger High Power HBTs

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ABSTRACT

Three-dimensional modeling of thermal flow in multi-finger HBTs has been investigated with thermal network method to find out the optimal structure which can effectively reduce the junction temperature uniformly in whole fingers under the high power operation. Thermal cross-talk effects and temperature distribution in a finger or between the fingers are examined. The HBT structure with emitter air-bridge connected to via hole is proposed as an optimal structure. The estimation accuracy of the calculation was confirmed from the good agreement between the calculation result and the measured value of the thermal resistance in HBT with the emitter air-bridge structure.

1.INTRODUCTION

Recently, AlGaAs/GaAs heterojunction bipolar transistors (HBTs) have made rapid progress in microwave power applications. The high power density operations in excess of 5 W/mm have been attained at X- and Ku-bands[1,2]. However, junction heatings on such high power density operations are the serious problems for the device performances and their reliabilities[3-7]. Especially for the multi-finger HBTs, the uniform and effective reduction of the thermal resistances for all of the fingers is indispensable for the high power operation. Therefore, many efforts have been paied for the uniform reduction of the thermal resistance to improve the characteristics of the high power operation HBTs.

Self-consistent calculation of the electrical and thermal aspects is necessary for the theoretical modeling of temperature distributions in HBTs. It is very difficult, however, to simulate the compricated HBT structures with such as Au air-bridges or via holes for thermal conducts to heat sink. With enough reduction of the junction temperature uniformly in whole finger, it will not necessary to solve self-consistently the electro-thermal aspects. To find out the optimal thermal structure, which can effectively reduce the junction temperature uniformly in whole fingers under high power operation, we focused on calculation of three-dimensional thermal flows in HBTs with fixed current flow considering the epitaxial structures, electrode metals, emitter air-bridges and via holes.

We have also fabricated the actual devices with the emitterair-bridge structre and checked the calculation accuracy by measuring the thermal resistances of the devices from the temperature dependence and the power dependence of the base-emitter voltage (V_{BE}) at the constant collector current (I_C).

2.THREE-DIMENSIONAL MODELING

Three dimensional modelings of thermal flow are carried out by the thermal network method with the diffusion equation solver of Meltherfy. Subjects for analysis are divided into 4,000 -5,000 nodes of 0.5μm-2μm cubics which are connected with thermal resistances each other. The thermal resistances are given by the thermal resistivities of the materials and the dimensions of the nodes. As presented in Figure 1, three emitter finger HBTs are modeled here, which fingers are 2μm-width × 20μm-length and in 22μm spacing with each other. Operation condition is fixed to V_{BC}=7V and I_C=10mA for each finger, and junction heating per finger is considered as 70mW at the base-collector depletion layer of 0.5μm-width. The epitaxial structures including AlGaAs emitter layers and InGaAs contact layers, WSi emitter contact electrodes and SiO passivation films are also considered for the thermal conduction.

The effects of substrate thinning and emitter air-bridge structures, which connect emitter fingers to the substrate or the heat sink with Au air-bridges as thermal conduction paths, are examined from the view point of uniform reduction of the junction temperature at whole finger.

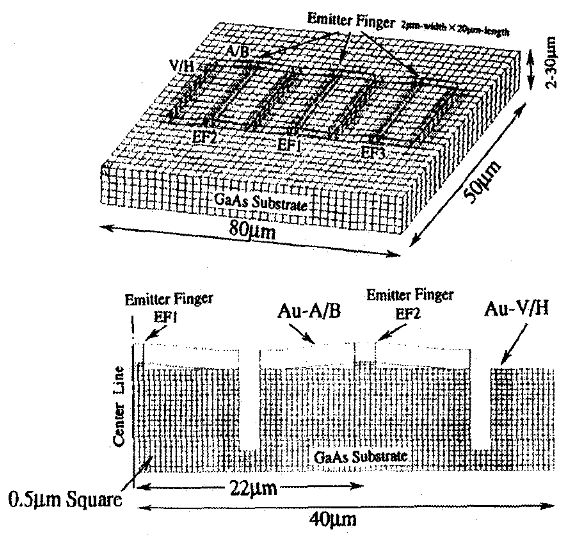

Figure 1 Three-dimensional modeling of three-finger HBTs

3.RESULTS

1) Substrate Thinning Effects

Figure 2 shows the thermal flow in the cross-sections of perpendicular to the fingers and their temperature distributions along the surfaces, which are the left-side of half of the HBTs centered at middre emitter finger (EF1). Figure 3 shows the junction temperature rise ΔT_j as a function of substrate thickness. ΔT_j are increased by the thermal cross-talk effect with more than the 10μm thick substrate. However, ΔT_j exceed over 60℃ even with 5μm thick substrate. Forming such a thin substrate is not only very difficult but also possibly causes the additional problems on the wafer processing. Therefore, the substrate thining is not the effective method for the junction temperature reduction.

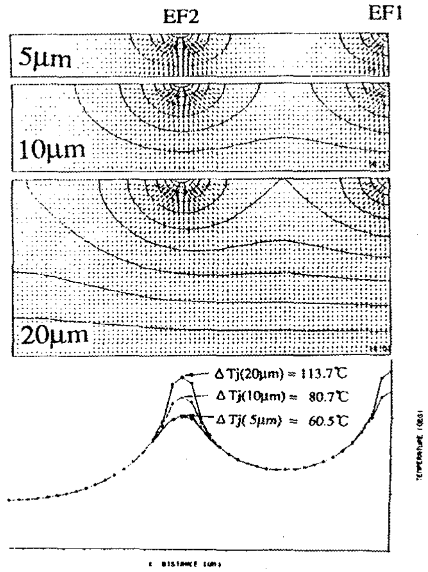

Figure 2 Thermal flows and temperature distributions at the cross-sections with different sbstrate thickness

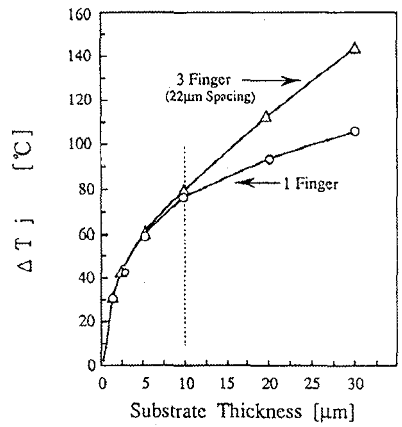

Figure 3 Junction temperature riseΔTj as a fuction of the substrate thickness

2) Emitter Air-Bridge Structure

Figure 4 shows the model with Au air-bridges (A/B) along the emitter fingers and Au filled via holes (V/H) with 10μm thick substrates. Figure 5 and Table 1 show the ΔT_j distributions in the fingers for some combinations of V/H and Au plating thickness for A/B. Large ranged ΔT_j cannot be reduced by A/B and V/H applications.

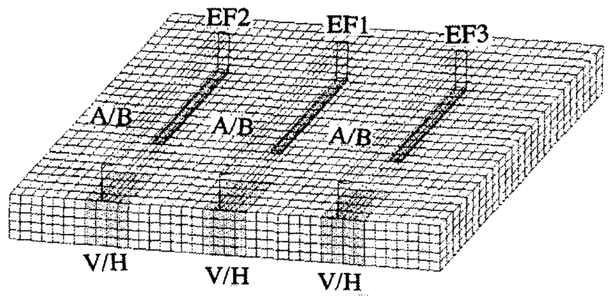

Figure 4 Calculation model for the HBT with the emiiter A/B along the emitter finger connected Au filled V/H

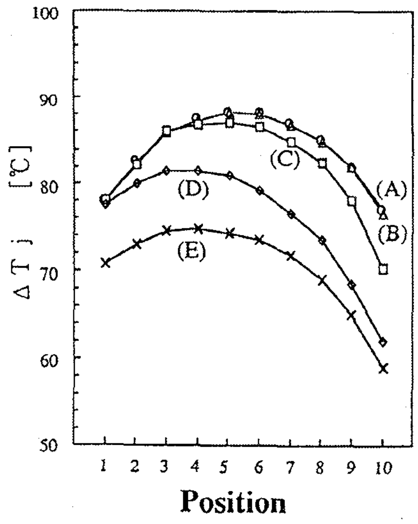

Figure 5 ΔTj distribution in the emitter finger

Table 1

Structure	Δ Tj	Δ Rj	Tjmax-Tjmin
(A) Standard	88.4℃	(100%)	21℃
(B) V/H(without A/B)	88.3℃	-0%	21℃
(C)V/H-0.3μmA/B	87.8℃	-1%	28℃
(D)V/H-2.0μmA/B	81.9℃	-7.4%	20℃
(E)V/H-12μmA/B	74.3℃	-16%	14℃

Figure 6 shows the left-side cross-section of the model with emitter A/B directly connected to the 10μm thick substrates. Table 2 lists some results of different Au plating thickness for A/B, where ΔR_j is the relative thermal resistance to that of the standard structure without A/B and $T_j(1)$-$T_j(2)$ is the junction temperature difference between the center finger (EF1) and the side finger (EF2). With the 2μm thick A/B, ΔR_j is effectively reduced in -41%. However, $T_j(1)$-$T_j(2)$ is increased from 1.3℃ to 3.1℃. This may be caused by the thermal cross-talk in the substrate from the A/B contacts and fingers.

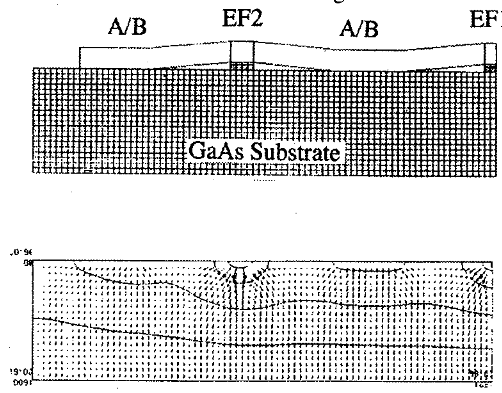

Figure 6 The cross-section of the model with the emitter A/B connected directly to the substrate and the calculation result of the thermal flow

Table 2

Structure	Δ Tj	Δ Rj	Tj(1)-Tj(2)
(A) Standard	98.2℃	(100%)	1.3℃
(B) A/B : 2μm^t	58.2℃	-41%	3.1℃
(C) A/B : 4μm^t	54.8℃	-44%	2.3℃
(D) A/B : 12μm^t	52.5℃	-46%	1.1℃

Finger 7 shows left-side cross-section of the model with emitter A/B connected to the 2μm thick Au plated V/H with the 10μm thick substrates and their thermal flows. The results for these models with some combinations of V/H and A/B are summarized in Table 3. With 2μm thick A/B connected to V/H, ΔR_j is effectively reduced in -55%, and $T_j(1)$-$T_j(2)$ is reduced from 1.3℃ to 0.2℃. More over, the temperature range in the finger is reduced from 21℃ to 0.07℃.

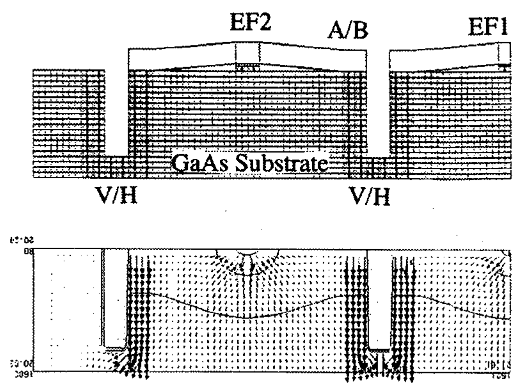

Figure 7 The cross-section of the model of the emitter A/B connected to V/H and the calculation result of the thermal flow

Table 3

Structure	Δ Tj	Rj	Δ Rj	Tj(1)-Tj(2)
(A) Standard	98.2℃	1403℃/W	(100%)	1.3℃
(B) V/H(without A/B)	92.8℃	1326℃/W	-5.5%	0℃
(C) V/H-2μm^{t}A/B	44.4℃	634℃/W	-55%	0.2℃
(D) V/H-4μm^{t}A/B	41.5℃	593℃/W	-58%	0.3℃
(E) V/H-12μm^{t}A/B	40.6℃	580℃/W	-59%	0.3℃

3) Accuracy of the calculations

We have fabricated the actual single-finger HBTs with the 2.0μm thick Au emitter air-bridge structure, and measured the thermal resistance (R_{th}) between the operating junction and the heat sink. R_{th} was estimated from the temperature and power dependences of V_{BE} at the constant I_C as the following equation[8].

$$R_{th} = \frac{\partial V_{BE}/\partial Power|_{I_C=Const.}}{\partial V_{BE}/\partial T_{Ambient}|_{I_C=Const.}}$$

Figures 8 (a) and (b) are the measurement results of the power dependence and the temperature dependence of V_{BE}, respectively. Figure 8 (a) shows the power dependences in different ambient temperatures. The slopes are slightly increased depending on the ambient temperatures, which are the results from the temperature dependence of the thermal conductivity of the GaAs substrate. At the ambient temperature of 30°C, the slope of the V_{BE} -Power line is -0.85V/W. The slope of the V_{BE}-Temperature line is -0.00125V/°C. Using the above equation, R_{th} is 680°C/W.

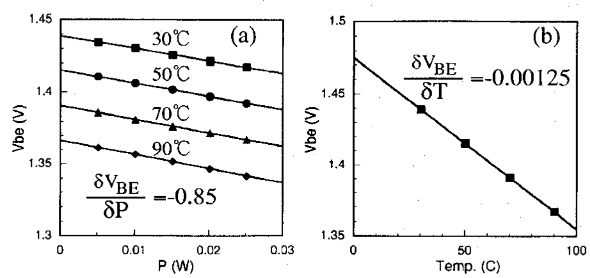

Figure 8 (a) Power dependence and (b) Temperature dependence of V_{BE} in the HBT with 2μmt Au emitter A/B connected to V/H

With the same manner, the measurement results of R_{th} for same samples are 650-700°C/W, which are in good agreement with the calculation result of structure(C) in Table 3. This good agreements indicate that our calculations are enough accurate on the estimation of the thermal flows in HBTs. The verification of the calculation accuracy for multi-finger structure have been the subject of the experimental work.

4.CONCLUSION

Three-dimensional modeling of thermal flow in HBTs was carried out to find out the optimal thermal structure for high power operation. A novel structure with emitter air-bridge connected to a via hole is proposed as the optimal structure, which offers effectively uniform reduction of the junction temperature in the multi-finger HBTs. The calculation accuracy for the single finger HBT with emitter air-bridge structure had been confirmed by the measurements of the operating junction temperature in the actual devices.

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