Design consideration of the thermal and electro stability of multi-finger HBTs based on different device structures

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Abstract: The thermal and electro stability of multi-finger heterojunction bipolar transistors (HBTs) with different structures were analyzed and discussed simultaneously. The thermal stability of the devices with different layout structures was assessed by the DC-IV test and thermal resistance calculation. Their electro stability was assessed by the calculation of the stability factor K based on the S parameter of the HBT. It is found that HBTs with higher thermal stability are prone to lower electro stability. The trade-off relationship between the two types of stability was explained and discussed by using a compact K-factor analytic formula which is derived from the small signal equivalent circuit model of HBT. The electro stability of the device with a thermal ballasting resistor was also discussed, based on the analytic formula.

Key words: heterojunction bipolar transistor; thermal stability; electro stability
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1. Introduction

Recently, because of the rapid growth of the wireless communication market, heterojunction bipolar transistor (HBT) technology is widely used for RF amplifier application due to their excellent RF and power performance[1−3]. In order to meet the requirement of output power for different applications, the designer often uses the multi-emitter-finger structure of HBTs. The analysis and design of thermal stability and electro stability (self-oscillation) in multi-finger HBTs is a classical problem for the device and circuit designer[4−8]. High thermal stability with high electro stability is expected by the designer. Several stabilization strategies are developed and effectively improve the thermal and electro stability of HBTs[5−8]. But unfortunately whether one type of stability design can be helpful for the other one by using a certain stabilization strategy is not well understood. This is partly because the analysis and design of the two types of stability are often researched independently. So a combined study is valuable for the stability design of multi-finger HBT.

First, for the electro stability design, in general a loss stability impedence network is added to the HBT. The stability factor K can be larger than unity 1 in a wide frequency band. So the stability of the HBT is improved[6]. The loss network is external for the HBT. Then it can neither change the thermal resistance of the HBT nor balance the current of each HBT emitter finger by negative feedback. Therefore the network for the electro stability design does not improve or degenerate the thermal stability.

On the other hand, for the thermal stability design, the strategies that are often used are special layout structure and emitter or base ballasting resistance[7, 8]. These suppress the current gain collapse and improve the thermal stability by decreasing the thermal resistance or equalizing the distribution of emitter finger current, and they also change the device parameters of the HBT. The effect on the electro stability due to the change in device parameters cannot be judged intuitively because of the complex relationship between the stability factor K and device parameters. In this paper, from the experimental and theoretical point of view, the effect of thermal stability design on the electro stability was studied deeply. First, two HBTs with different layout structures were used to assess the thermal and electro stability by the DC-IV test and thermal resistance calculation. The experimental results show that the HBT with higher thermal stability is prone to lower electro stability. Then the experimental results were discussed and explained by using a compact K-factor analytic formula which is derived from the small signal equivalent circuit model of HBTs. In addition, expediently, the effect of ballasting resistance on the electro stability was determined using the formula.

2. Device design and analysis

Two GaAs multi-finger HBTs, namely devices A and B, were designed and fabricated with different layout structures. They have the same emitter areas and use the same HBT subcell. The photo of the HBTs with different layout structures is shown in Figs. 1(a) and 1(b).

The device A consists of four HBT cells. The dimensions of the HBT cell are 2 (finger number) × 2 μm (emitter-width) × 40 m (emitter-length). The HBT cells are laid out with uniform emitter length and uniform emitter spacing. The interconnect metal of the eight emitter fingers is outside the active thermal emitter area.

The device B consists of a through-wafer-via (TWV) and four HBT cells, which are the same as those used in device A. The layout strategy of thermal stability is adopted for device B.

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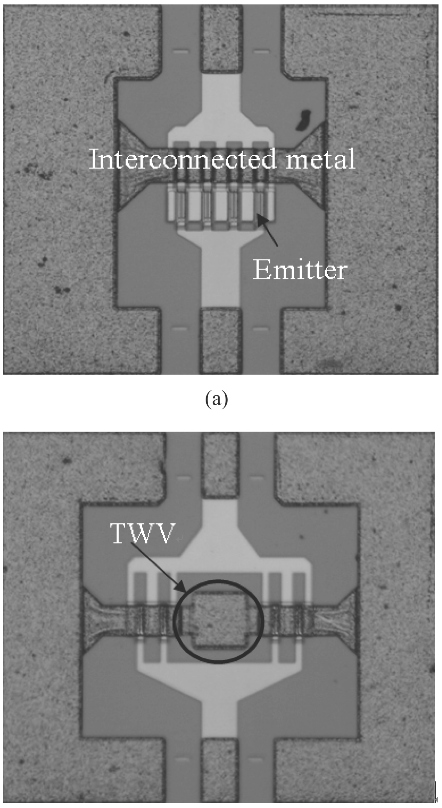

(a)

(b)

Fig. 1. (a) Device A. (b) Device B.

The TWV was inserted into the center of the HBT where the thermal couple is the most in the whole transistor. In this case, no active emitter finger is located in the center of the thermal couple. So the thermal-electric feedback would like to be suppressed effectively. Simultaneously, the heat coupling to the center can be collected and conducted to the substrate of the device by the through-wafer-via. Second, the emitter finger was connected by a wide metal layer that was exactly on the active thermal emitter area.

3. Experimental results and discussion on thermal and electro stability

3.1. DC performance

The DC I–V curves were measured in order to compare the thermal stability of devices A and B. In general, for multi-finger HBTs, current gain collapse occurred at the I–V curves when a "local hot spot" formed due to thermal effects in the central area of the device. The collapse implied that the devices operate in the instability state. According to the results shown in Fig. 2, current collapse occurs at a power density of about 0.76 mW/μm^2 for device A, while device B has been taken up to a power density of 1.14 mW/μm^2 without showing obvious current collapse. So device B has higher thermal stability than device A.

3.2. Thermal resistance

In order to further analyze the thermal properties of the two HBTs, their thermal resistances were calculated based on the

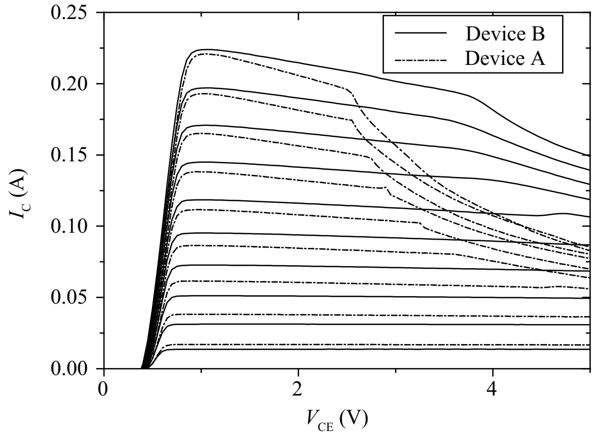

Fig. 2. DC-IV curve of the devices A and B.

DC-IV test by using the following compact expression[9]:

$$R_{\text{th}} = \frac{\Delta V_{\text{BE}}}{\Phi I_{\text{C}} \Delta V_{\text{CE}}}, \tag{1}$$

where ΔV_{BE} and ΔV_{CE} represent changes in ΔV_{BE} and ΔV_{CE} when the power changes, while keeping I_{C} constant, and $\Phi = \partial V_{\text{BE}}/\partial T$ is the temperature coefficient of the emitter–base voltage. In our fabricated devices, the typical value of Φ is about 1.1 mV/C for the InGaP/GaAs HBT when the collector density is 10^4A/cm^2[9]. The calculated thermal resistances for devices A and B were 163 ℃/W, 242 ℃/W, respectively. The important device operational parameter, namely device temperature T, is changed due to the differentiation of the thermal resistance. Device B with higher thermal stability has lower thermal resistance and lower operational temperature T at the same bias of V_{CE} and I_{C}, according to the following equation[9]:

$$T = T_{\text{A}} + R_{\text{th}} V_{\text{CE}} I_{\text{C}}, \tag{2}$$

where T_{A} is the ambient temperature.

3.3. Electro stability assessment

The device's stability can be simply evaluated by stability factor K. K is calculated from small signal S parameter data, which was measured for the power device with a network analyzer. The calculating equation is[10]

$$K = \frac{1 - |S_{11}|^2 - |S_{22}|^2 + |\Delta|^2}{2\,|S_{12}S_{21}|}, \quad \Delta = S_{11}S_{22} - S_{12}S_{21}. \tag{3}$$

When K is larger than 1, the device is unconditionally stable. Figures 3–5 shows the stability factor K of the two types of device under different collector bias currents (I_{C} = 35 mA, 55 mA, 75 mA; V_{CE} = 5 V).

The frequencies where K is larger than 1 are, respectively, 3.1 GHz, 2.5 GHz, 1 GHz for device A and 3.7 GHz, 3.3 GHz, 3 GHz for device B. Device B with higher thermal stability is prone to lower electro stability due to the smaller bandwidth of unconditional stability.

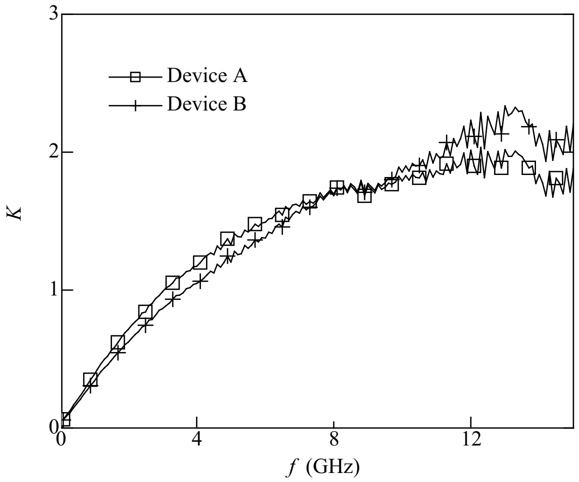

Fig. 3. Stability factor K of the two types of device under collector bias: I_C = 35 mA, V_{CE} = 5 V.

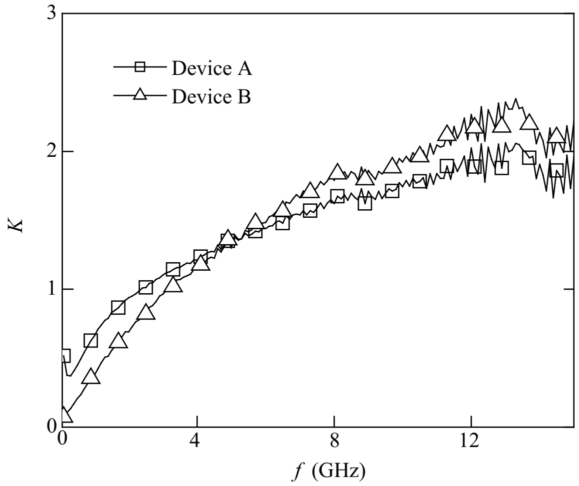

Fig. 4. Stability factor K of the two types of device under collector bias: I_C = 55 mA, V_{CE} = 5 V.

4. Theoretical explanation and discussion

According to the assessment results of Section 3, the thermal stability design is prone to reduce the elector stability of the HBT. A theoretical analysis and discussion was carried out as follows.

The HBT can be modeled by the small signal hybrid π-mode equivalent circuit, like Fig. 6. Based on the small signal model, the stability factor K, including the small signal parameters, is derived with some reasonable approximation by Ma *et al.*[11] and can be expressed as

$$K \approx \left[(r_{\mathrm{e}} + 2r_{\mathrm{b}})C_{\mathrm{be}} + r_{\mathrm{em}}C_{\mathrm{bc}}\left(1 + \frac{2r_{\mathrm{b}}}{r_{\mathrm{e}}}\right)\right]\omega, \tag{4}$$

where $r_{\mathrm{em}} = \alpha/g_{\mathrm{m}}, g_{\mathrm{m}} = qI_{\mathrm{C}}/kT$. Then the K formula changed as

$$K \approx \left[(r_{\mathrm{e}} + 2r_{\mathrm{b}})C_{\mathrm{be}} + \alpha\frac{kT}{qI_{\mathrm{C}}}C_{\mathrm{bc}}\left(1 + \frac{2r_{\mathrm{b}}}{r_{\mathrm{e}}}\right)\right]\omega. \tag{5}$$

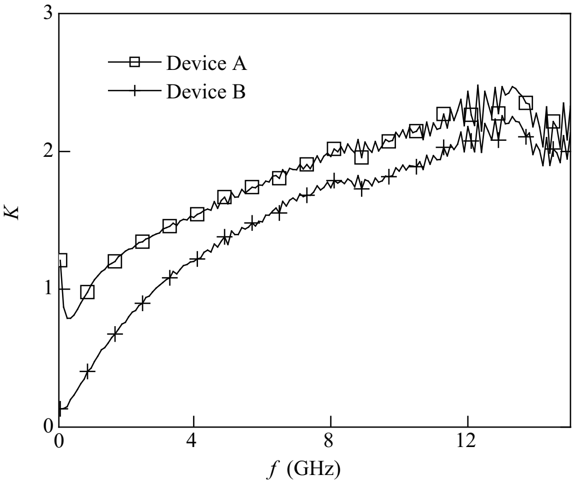

Fig. 5. Stability factor K of the two types of device under collector bias: I_C = 75 mA, V_{CE} = 5 V.

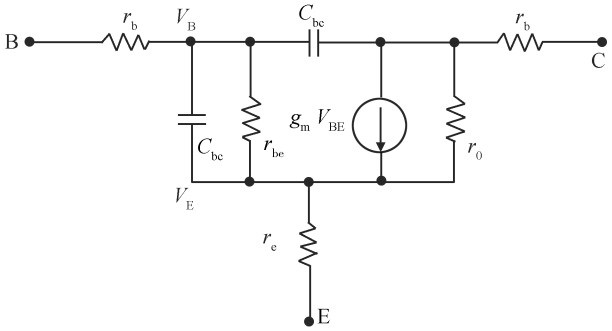

Fig. 6. Small signal hybrid π-mode equivalent circuit of HBT.

From Eq. (5), the frequency when $K = 1$ was derived as

$$\omega_{k=1} = \frac{1}{(r_{\mathrm{e}} + 2r_{\mathrm{b}})C_{\mathrm{be}} + \alpha\dfrac{kT}{qI_{\mathrm{c}}}C_{\mathrm{bc}}\left(1 + \dfrac{2r_{\mathrm{b}}}{r_{\mathrm{e}}}\right)}. \tag{6}$$

According to Eq. (6), $\omega_{k=1}$ is the inverse ratio of temperature T. Since the temperature of device B is lower due to its lower thermal resistance, the result that device B has higher $\omega_{k=1}$ and smaller unconditional stability bandwidth than device A is reasonably explained by the formula. Also, for one device, as the bias power is increased, the device temperature increased and its electro stability is prone to strengthen based on the formula. This is proved by the results of Figs. 3–5. Therefore, the thermal stability design by special layout structure to lower the thermal resistance is likely to decrease the electro stability, and this is mainly attributed to the decrease in device temperature.

In fact, Equation (6) can also be used to analyze the electro stability of the device with ballasting resistance to improve its thermal stability. From the formula, as the emitter resistance r_{e} is increased from zero to a critical value (about 100 Ω), $\omega_{k=1}$ also increases. After the critical value $\omega_{k=1}$ decreases with r_{e}. However, $\omega_{k=1}$ is monotonously in the inverse ratio of the base resistance r_{b} of the device. So an emitter ballasting resister with generally several ohm to improve the thermal stability would increase $\omega_{k=1}$ and decrease the electro stability. In contrast, the base ballasting resistance is helpful to improve the electro stability.

5. Conclusion

In this paper the thermal and electro stability of HBT devices were analyzed and discussed systematically. In general, the electro stability design is to insert a loss stability impedence network to the external part of the HBT and has no effect on the thermal stability of the HBT. But the effect of the thermal stability design on the electro stability is complicated. Based on the experimental results and a compact theoretical formula from a small signal model, it can be concluded that the thermal stability design by lowering the thermal resistance and device temperature is likely to reduce the unconditional bandwidth and decrease the electro stability of the HBT device. Also, from the theoretical formula it can be implied that the thermal stability design of the emitter ballasting resistance is likely to reduce the electro stability and, in contrast, the base ballasting resistance design would be helpful to improve the electro stability of the device. Since designers often hope to obtain high thermal stability HBT devices with high electro stability simultaneously, the results of the paper are a helpful guide to the designer in selecting reasonable strategies and achieving a trade-off between the two types of stability design of the HBT device.

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