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RF power performance improvement of multi-finger power bipolar transistor by non-uniform emitter finger spacing design without the use of emitter ballasting resistor

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Abstract: In this paper, the RF power performance and surface temperature distributions for a multi-finger power hetero-junction bipolar transistor (HBT) with non-uniform emitter finger spacing (NUEFS) without the use of emitter-ballasting-resistor (EBR) are measured, and are compared with a multi-finger power HBT with EBR. The experiment results show that for the multi-finger power HBT with NUEFS, the highest surface temperature is lowered, the uniformity of surface temperature distributions measured by US QFI Infrared TMS is improved, the RF power gain and power-added-efficiency (PAE) are increased compared with the multi-finger power HBT with EBR respectively. These results could be attributed to the improvement in positive thermoelectric feedback and thermal coupling effects among the fingers, and the riddance of adverse impact from emitter-ballasting-resistor used in traditional power HBT.

Key words: bipolar transistor, radio frequency (RF), thermal stability, power gain, power-added-efficiency (PAE), multi-finger

免镇流电阻的非均匀发射极指间距设计对多指功率双极晶体管射频功率性能的改善

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摘要：对不添加镇流电阻的非均匀发射极条间距的多发射极条异质结双极晶体管(HBT)的射频功率性能和表面温度分布进行了测量，并与常规采用镇流电阻的多发射极条功率HBT进行了比较。实验结果表明，对具有非均匀发射极条间距的多发射极条HBT，采用US QFI TMS红外测量系统测得的最高表面温度、温度分布均匀性以及采用射频测量系统测得的射频功率增益和功率附加效率，分别低于、好于和高于具有镇流电阻的多发射极条功率HBT的情况。这些结果的取得，得益于采用非均匀发射极条间距改善了多发射极条HBT的热电正反馈和不同发射极条之间的热耦合，以及摆脱了传统HBT加镇流电阻带来的对射频功率性能的负作用。

关 键 词：双极晶体管；射频；热稳定性；功率增益；功率附加效率；多指

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Introduction

Power bipolar junction transistor (BJT) and hetero-junction bipolar transistor (HBT) usually employ multiple emitter fingers in parallel to improve the current handling capability, thermal dissipation capability and RF power performance[1-4]. However, the self-heating effects (SHE) caused by the power dissipation in every emitter finger and thermal coupling effects (TCE) among emitter fingers result in the increase of temperature of HBTs and non-uniformity of temperature distributions among emitter fingers, and as a consequence, the thermal stability, reliability and RF power performance will degrade significantly[4-8]. It is obvious that the entire device will fail if

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any single emitter finger fails. Particularly, the temperatures at the center fingers are hotter than outer fingers. Therefore it will draw much current due to the nature of the positive temperature coefficient of emitter current. Hence additional joule heating is generated, the mechanism is thus regenerative and it ultimately destroys the device. To inhibit positive thermoelectric feedback between emitter current and temperature, and to improve thermal stability and increase current handling capability, the common method is to add a ballasting-resistor R_{E} at emitter so as to compensate for the variation of emitter-base junction voltage V_{BE} by using voltage drop across R_{E}[7-12]. For examples, Schuppen A. *et al.* [10] designed 10 fingers and 60 fingers power HBTs with uniform finger spacing, in which the R_{E} of 6 Ω is added at each emitter to improve thermal effects, the output power was 1W; Potyraj, P. A. *et al.* [11] reported multi-finger power HBTs with uniform emitter finger spacing, the TiW ballasting-resistor R_{E} was added at each emitter to improve current handling capability; Ma Z. *et al.* [12] investigated the effects of R_{E}, base-ballasting-resistor R_{B}, and non-ballasting-resistor on the thermal stability of three kinds of 160 fingers HBTs with uniform finger spacing, the results showed that three types of HBTs were all thermally stable under $V_{\mathrm{CE}}=3$ V, the two types of HBTs with R_{B} and R_{E} were thermally stable under $V_{\mathrm{CE}}=4$ V, but only the HBTs with R_{E} was thermally stable under $V_{\mathrm{CE}}=5$ V, and therefore the R_{E} was proved to be more effective in thermal stability improvement compared with R_{B} technique. However, the additional R_{E} at emitter will degrade HBT RF power performance, such as power gain (G_{p}) and power-added-efficiency (PAE)[8-12] no matter how to optimize the R_{E}. As an alternative method, a non-uniform finger spacing technique with large finger spacing in center fingers and small finger spacing in outer fingers for multi-finger HBTs can alleviate thermal coupling effects (TCE) among emitter fingers due to the improvements in thermal flow distribution. Our previous works [13-15] revealed that the non-uniform emitter finger spacing (NUEFS) technique is effective in lowering peak temperature and enhancing uniformity of the temperature profile among emitter fingers compared with uniform emitter finger spacing technique. As an extension of our previous works, in this paper, a comparative study between two types of multi-finger power HBTs with NUEFS and emitter ballasting-resistor (R_{E}) is performed to exhibit the superiority of NUEFS technique in improvements of RF power gain, power-added-efficiency (PAE), and temperature profile over emitter ballasting-resistor (R_{E}) technique. To the best of the authors' knowledge, the comparative study on RF power performances of the two types of multi-finger HBTs is not available in the literature. The paper is arranged as follows. In Section I, the mechanism and disadvantages of the introduction of R_{E} to improve HBT current handling capability are briefly analyzed; the structure and layouts of two types of multi-finger power HBTs with NUEFS and R_{E} are shown in Section II; the measurement results of surface temperature distributions by US QFI Infrared TMS, RF power gain (G_{p}), collector efficiency (η_{C}) and power-added-efficiency (PAE) are demonstrated in Section III; the conclusions are given in Section IV.

1 Mechanism and disadvantages of the introduction of emitter ballasting resistor to improve HBT current handling capability

For an HBT, emitter-base junction voltage V_{BE} varies with temperature T. Figure 1 shows the measured V_{BE} as a function of T under different emitter currents of 3 mA, 1 mA, 100 μA and 10 μA respectively for our a SiGe HBT. The temperature coefficient ($\mathrm{d}V_{\mathrm{BE}}/\mathrm{dT}$) of V_{BE} can be obtained as -1.53 mV/℃, -1.59 mV/℃, -1.76 mV/℃ and -1.92 mV/℃, respectively. The $\mathrm{d}V_{\mathrm{BE}}/\mathrm{d}T$ is a negative value. Therefore, for an HBT, as the current increases, the temperature increases due to SHE and TCE. As a result, interior V_{BE} decreases. Under external bias keep unchanged, the emitter current will increase, which will further increase dissipation power and lead to temperature rise. Ultimately, the device will be burned out if the measures to restrict the increase of current is not taken.

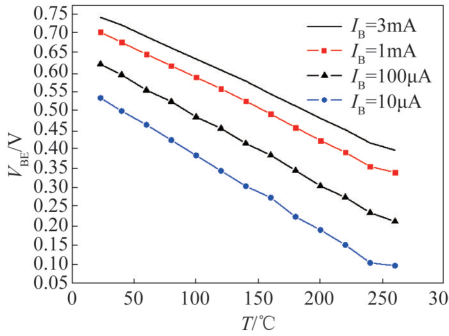

Fig. 1 The measured emitter-base junction voltage V_{BE} as a function of T under different emitter currents of 3 mA, 1 mA, 100 μA and 10 μA respectively

图1 在发射极电流分别为3 mA，1 mA，100 μA和10 μA下，发射结电压与温度关系的测量结果

In order to alleviate positive thermoelectric feedback between emitter current and temperature, and protect the HBT from thermal burn-out, it is common to add a ballasting-resistor R_{Ei} at emitter as shown in Fig. 2 so as to compensate the variation of emitter-base junction voltage V_{BE} by using voltage drop across R_{Ei}.

To guarantee thermal stability of HBT within a certain limit of emitter current (I_{E}), the engineering regulation for ballasting resistor R_{E} is as follows: when emitter-base junction temperature varies by ±5 K, the added R_{E} at emitter finger could able to restrict the variation of I_{E} within ±5%, so the minimum emitter ballasting-resistor R_{Emin} can be expressed as[8-9]

$$R_{\mathrm{Emin}} = \frac{\Delta V}{\Delta I} = \frac{5 \times (\mathrm{d}V_{BE}/\mathrm{d}T)}{0.05 \times I_{\mathrm{E}}} = 100\frac{\mathrm{d}V_{BE}/\mathrm{d}T}{I_{\mathrm{E}}} \quad , \qquad (1)$$

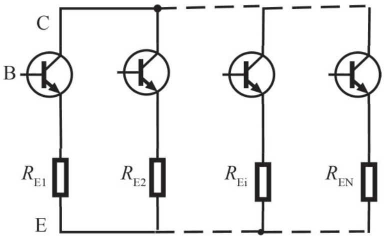

Fig. 2 The schematic diagram of an *N*-finger HBT, where R_{Ei} is the emitter ballasting resistor of the *i*th emitter finger[8-9]

图2 具有*N*个发射极指的HBT的示意图，R_{Ei}是第*i*个发射极指上的镇流电阻

where units of dV_{BE}/dT and I_E are mV/℃ and mA respectively.

We can see that R_{Emin} is determined by threshold emitter current (I_E), it is only effective for an HBT to thermally stable operate under a certain of emitter current (I_E).

However, on the other hand, the additional emitter ballasting-resistor R_E will degrade RF power performance no matter how to optimize the R_E. The parameters of power gain (G_p) and power-added-efficiency (PAE), which are employed to characterize RF power performance, are related to ballasting-resistor R_E as follows:

$$G_p = \frac{p_{out}}{p_{in}} = \frac{f_T}{8\pi f^2 (r_b + R_E) C_{TC}} \quad , \tag{2}$$

$$PAE = \frac{p_{out} - p_{in}}{p_{DC}} = \left(1 - \frac{1}{G_p}\right) \frac{p_{out}}{p_{DC}} = \left(1 - \frac{1}{G_p}\right) \eta_C \ , \tag{3}$$

where p_{out} is RF output power, p_{in} is RF input power, f_T is transit frequency, r_b is base resistance, C_{TC} is collector output capacitance, P_{DC} is DC power, $\eta_C = p_{out}/P_{DC}$ is collector efficiency.

Therefore, G_p and PAE are degraded due to the existence of R_E. Furthermore, in order to guarantee the thermal stability of HBT within a certain of emitter current (I_E) and power, it is usually suggested that $R_E > R_{Emin}$, this could further degrade G_p and PAE.

2 Structure and layouts of multi-finger power HBTs

The schematic cross section of a cell of multi-finger HBTs based on SiGe process and the material parameters of various layers of the device are shown in Fig. 3 and Table 1, respectively. The power HBTs is fabricated in Institute of Microelectronics, Tsinghua University.

Fig. 4 and Fig. 5 are the micrographs of the fabricated multi-finger power SiGe HBTs with polysilicon as emitter ballasting resistor and non-uniform finger spacing, respectively.

3 Measurement results and discussion

In this section, the measured surface temperature distributions by US QFI Infrared TMS, and the measured power gain (G_p), collector efficiency (η_C) and power-added-efficiency (PAE) for two types of multi-fingers SiGe HBTs with non-uniform finger spacing (NUEFS) and emitter ballasting resistor (EBR) respectively are shown and compared.

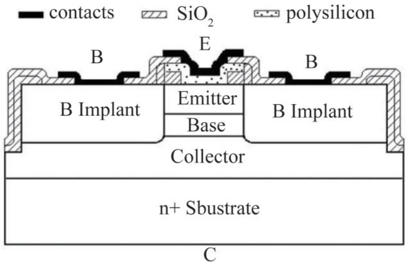

Fig. 3 The schematic-cross section of a cell in multi-finger HBTs

图3 多指HBTs中一个单元的剖面示意图

Table 1 The material parameters of various layers for SiGe HBTs.

表1 SiGe HBT各层的材料参数

	composition	Thickness/nm	Doping concentration/cm^{-3}
Emitter	Si	12	1×10^{18}
Base	$Si_{0.84}Ge_{0.16}$	30	2×10^{19}
Collector	Si	4.4×10^{3}	1×10^{16}
Substrate	Si	1.5×10^{5}	1×10^{19}

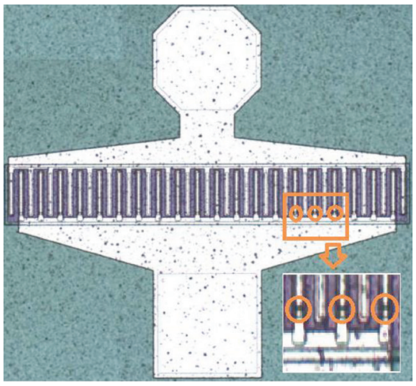

Fig. 4 Micrographs of the fabricated multi-fingers SiGe HBTs with emitter ballasting resistor. (Note: polysilicon emitter ballasting resistors locate at root terminal of each emitter finger, see the enlarged image)

图4 制作的具有发射极镇流电阻的多指SiGe HBTs的显微照片(注:多晶硅发射极镇流电阻在每个发射极指的根部，见局部放大图)

3.1 Surface temperature distributions measurements of multi-fingers power HBTs

The surface temperature distributions measured by temperature measurement microscope systems (TMS) from US quantum focus instruments (QFI) Corporation for two types of multi-fingers HBTs with emitter ballasting resistor (EBR) and with non-uniform emitter finger spacing (NUEFS) under I_C=800 mA, V_{CE}=5 V and

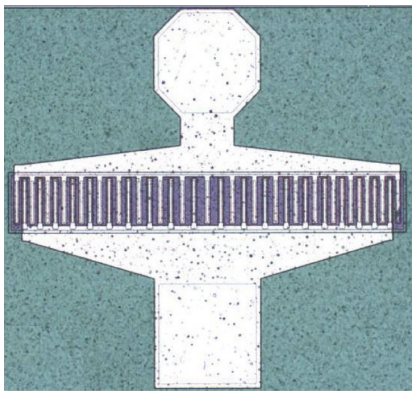

Fig. 5 Micrograph of the fabricated multi-fingers SiGe HBTs with non-uniform finger spacing

图5 制作的具有非均匀指间距的多指SiGe HBTs的显微照片

case temperature of T_C=80℃ are shown in Fig. 6. We can see that the highest temperature is lowered and the maximum temperature difference is improved for the HBTs with NUEFS compared with the HBTs with EBR. Therefore, the temperature distribution uniformity is improved as expected. These results could be attributed to the decrease of the heat flow from adjacent fingers to the center fingers by increasing the spacing between fingers in center region where the thermal-coupling effects are strongest and the alleviation of non-uniform variation of V_{BE} with temperature T.

3.2 RF power performance measurements

The package and RF power measurements of two types of multi-finger power HBTs with non-uniform finger spacing (NUEFS) and emitter ballasting resistor (EBR) are performed by The 13th Research Institute of China Electronic Technology Corporation. The measurement system mainly consists of a power signal source, isolator, directional coupler, test fixture, attenuator, power meter, bias power supply, and so on, as shown in Fig 7.

The measured output power (p_{out}) *versus* input power (p_{in}), collector efficiency (η_C) *versus* input power (p_{in}), and power-added-efficiency (PAE) *versus* input power (p_{in}) for two types of multi-fingers SiGe HBTs with emitter ballasting resistor (EBR) and non-uniform emitter finger spacing (NUEFS) under class C operation and at the frequency of 1.2 GHz are shown in Figs. 8~10, respectively.

As shown, for the multi-fingers SiGe HBTs with EBR, p_{out} increases with the increase of p_{in}, but p_{out} tends to saturate. At p_{in}=0.9 W, the p_{out}=1.9 W, power gain G_p =3.25dB, η_C=72%, and PAE=40%. For the multi-fingers SiGe HBTs with NUEFS, p_{out} increases linearly with the increase of p_{in} and does not saturate. At p_{in}=0.9 W, the p_{out}=4W, power gain G_p=6.48dB, η_C=63%, and PAE =49%. The comparison between the HBT with NUEFS and the HBT with EBR indicates that the p_{out} is increased by 2.1W. This is because that for the same RF input voltage signal, there is not voltage drop across R_E in the HBT with NUEFS. Therefore, the current gain is improved, and the collector current i_c is increased [16]. As a result, the p_{out} is increased according to the expression $p_{out} = i_c^2 \times R_L$, where R_L is output load impedance. Furthermore, G_p is increased by 3.23 dB, η_C is decreased by 9%, and PAE is increased by 9%. As expected the RF power performance is improved.

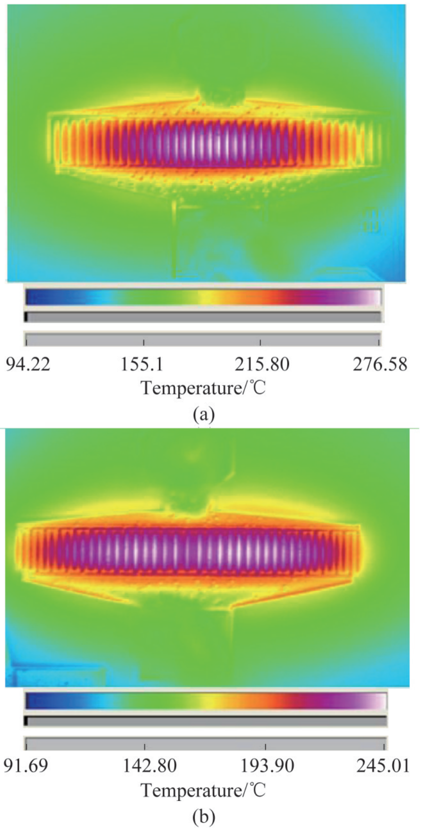

Fig. 6 Measured surface temperature distribution by US QFI Infrared TMS for (a) a multi-finger power HBT with emitter ballasting resistor, and (b)for a multi-finger power HBT with non-uniform finger spacing under I_C=800 mA, V_{CE}=5 V and case temperature of T_C=80 ℃

图6 在I_C=800 mA和V_{CE}=5 V条件下，通过美国QFI Infrared TMS红外测量系统得到的(a)具有发射极镇流电阻的多指HBT，(b)具有非均匀发射极指间距的多指HBT器件的表面温度分布

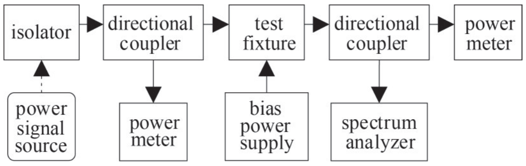

Fig. 7 The block diagram of RF power measurement system

图7 射频功率测量系统方块图

4 Summary and conclusions

A comparative study of two types of multi-finger power HBTs with non-uniform emitter finger spacing (NUEFS) and emitter-ballasting-resistor (EBR) is performed experimentally in terms of surface temperature distributions, RF power gain and power-added-efficiency (PAE). The experiment results show that for the multi-

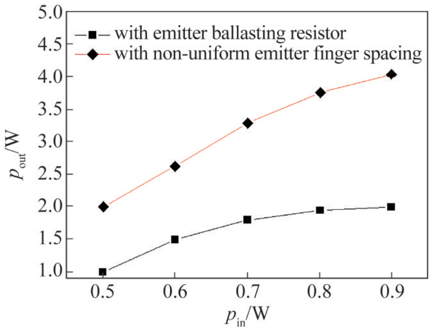

Fig. 8 RF Output power p_{out} *versus* RF input power p_{in} for two types of multi-fingers power HBTs with emitter ballasting resistor and with non-uniform emitter finger spacing respectively

图 8 具有发射极镇流电阻的多指功率HBT与具有非均匀指间距的功率HBT的射频输出功率p_{out}与射频输入功率p_{in}的关系

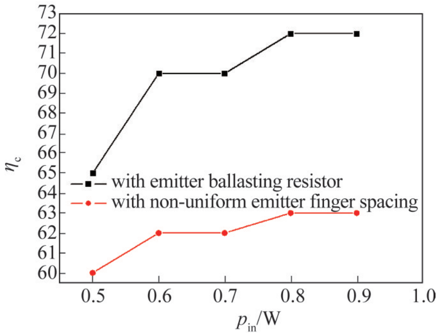

Fig. 9 Collector efficiency η_C *versus* RF input power p_{in} for two types of multi-fingers power HBTs with emitter ballasting resistor and with non-uniform emitter finger spacing respectively

图 9 具有发射极镇流电阻的多指功率HBT与具有非均匀指间距的功率HBT的集电极效率η_C与射频输入功率p_{in}的关系

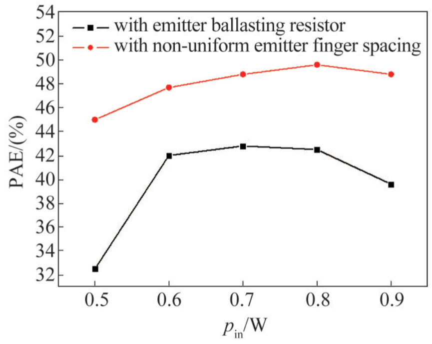

Fig. 10 Power-added-efficiency (PAE) *versus* RF input power p_{in} for two types of multi-fingers power HBTs with emitter ballasting resistor and with non-uniform emitter finger spacing respectively

图 10 具有发射极镇流电阻的多指功率HBT与具有非均匀指间距的功率HBT的功率附加效率PAE与射频输入功率p_{in}的关系

finger power HBT with NUEFS, not only the uniformity of surface temperature distributions measured by US QFI Infrared TMS but also RF power gain and power-added-efficiency (PAE) is improved compared with a multi-finger power HBT with EBR. These results could be attributed to improvement in positive thermoelectric feedback and thermal coupling effects among the fingers, and the riddance of adverse impact from emitter-ballasting-resistor used in traditional power HBTs.

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