Thermal stability improvement of a multiple finger power SiGe heterojunction bipolar transistor under different power dissipations using non-uniform finger spacing*

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A method of non-uniform finger spacing is proposed to enhance thermal stability of a multiple finger power SiGe heterojunction bipolar transistor under different power dissipations. Temperature distribution on the emitter fingers of a multi-finger SiGe heterojunction bipolar transistor is studied using a numerical electro-thermal model. The results show that the SiGe heterojunction bipolar transistor with non-uniform finger spacing has a small temperature difference between fingers compared with a traditional uniform finger spacing heterojunction bipolar transistor at the same power dissipation. What is most important is that the ability to improve temperature non-uniformity is not weakened as power dissipation increases. So the method of non-uniform finger spacing is very effective in enhancing the thermal stability and the power handing capability of power device. Experimental results verify our conclusions.

Keywords: heterojunction bipolar transistor, thermal coupling, power dissipation

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1. Introduction

SiGe heterojunction bipolar transistors (HBTs) have demonstrated high power outputs and power dissipations at microwave frequencies.[1−3] This performance advantage makes the HBT a better candidate for power applications requiring high voltage, high current density, and high efficiency. However, the HBT power performance is often limited by the thermal effect.[4−10] For an HBT with a single-emitter finger structure, the heat generated in the HBT cannot be dissipated quickly to the ambient area, and thereby increase the lattice temperature in the HBT(self heating).[11] To reduce the self-heating effect in the emitter finger and thus increase the HBT power handing capability, a multi-emitter finger structure is usually used. Another reason for using such a structure is to avoid the signal delay along the direction of emitter finger length. However, an additional mechanism called the thermal-coupling effect is present in the multi-finger HBT. Such an effect is a result of the thermal interaction among the neighboring emitter fingers, and can cause the inner fingers to be hotter than the outer fingers. Because of the positive temperature coefficient of emitter current, the inner fingers conduct higher current and consequently generate more heat, which eventually gives rise to a local hot spot and possibly permanent device damage. A common solution to this problem is to use a large ballast resistor at the emitter or base. Such a resistor gives rise to a large voltage drop and thus reduces the voltage drop across the emitter–base junction. This in turn reduces the current density and the heat generated in each unit HBT. Evidently, this approach limits the output power by electronic means. At low power density, for an HBT with a ballast resistor, the non-uniformity of the temperature profile is indeed reduced compared with that of an HBT without a ballast resistor. However, the ability to reduce temperature non-uniformity is weakened with increasing power dissipation. It can also degrade the HBT high frequency performance due to the extra delay time through the ballast resistor.[12−15]

In order to improve the thermal stability of a

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multi-finger power HBT without a ballast resistor under different power dissipations, a novel multi-finger power SiGe HBT with non-uniform finger spacing structure is proposed. Through a comprehensive model for the multi-finger HBT, temperature profiles of the HBT under different power dissipations are investigated. The non-uniformity of the temperature profile is reduced compared with that of traditional uniform finger spacing under identical power. At the same time, the improvement is retained for the HBT with non-uniform spacing even under the condition of high power dissipation. Finally, a power SiGe HBT with non-uniform finger spacing is fabricated, and the experimental results verify our conclusion.

2. Model development

Figure 1 schematically illustrates the power HBT device layout used in this calculation of temperature profile. The transistor has five emitters, each with an area of 3 μm × 60 μm. Each emitter finger is divided into several subregions (N elements), each with coordinates of x_k and y_k. The current and the temperature in each subregion are both assumed to be uniform. Listed in Table 1 are the transistor layout parameters and some relevant device physical parameters used in this calculation. Unless otherwise stated, the calculation is based on the parameters listed in Table 1.

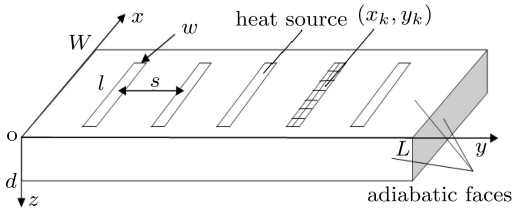


Fig. 1. Schematic power HBT layout with all the essential geometrical parameters clearly labeled.

Table 1. Geometrical and physical parameters of device, used in the calculation of temperature profile and current distribution of a power HBT.

emitter length l/μm	60
emitter width w/μm	3
substrate thickness d/μm	100
chip area $L \times W/\mu$m^2	210×153
ambient temperature T_0/K	300

The steady state heat flow equation is

$$\nabla[k_{\rm th}(T)\nabla T] = 0 \tag{1}$$

with the following boundary conditions:

$$\frac{\partial T}{\partial x}\,|_{x=0,W} = 0, \tag{2}$$

$$\frac{\partial T}{\partial y}\,|_{y=0,L} = 0, \tag{3}$$

$$k_{\rm th}(T)\frac{\partial T}{\partial z}\,|_{z=0} = -P(x,y), \tag{4}$$

$$T\,|_{z=d} = T_0, \tag{5}$$

where $k_{\rm th}(T)$ is the thermal conductivity of Si substrate material $P(x,y)$ is the power density, and T_0 is the ambient temperature.

This equation can be solved by the Kirchoff transform by defining a linearized temperature $U(x,y,z)$ as

$$U(x,y,z) = T_0 + \frac{1}{k_{\rm th0}}\int_{T_0}^{T(x,y,z)} k_{\rm th}(T){\rm d}T. \tag{6}$$

The temperature dependence of the thermal conductivity can be expressed as

$$k_{\rm th}(T) = k_{\rm th0}(\frac{T}{T_0})^{-b}, \tag{7}$$

where $k_{\rm th0}$ is the thermal conductivity at T_0, and b is the fitting parameter whose value is 1.24.[16] So the actual junction temperature $T(x,y,z)$ can be obtained as

$$T = T_0\left[1 - \frac{b-1}{T_0}(U - T_0)\right]^{-1/(b-1)}. \tag{8}$$

The temperature-dependent collector current density $J_{\rm ck}$ in the $K_{\rm th}$ element can be expressed as a function of base-emitter junction voltage $V_{\rm BE}$ and T;

$$J_{\rm ck} = J_{\rm c0}\exp\{\frac{1}{k_0T_0/q}V'_{\rm BE}\}, \tag{9}$$

$$V'_{\rm BE} = V_{\rm BE} - \frac{lwJ_{\rm ck}R_{\rm Ek}(\beta_k+1)}{\beta_k} - \varphi(T-T_0), \tag{10}$$

$$\beta_k = \beta_0\exp\left[\frac{\Delta E}{k_0T(x_k,y_k,0)}\right], \tag{11}$$

where $J_{\rm c0}$ is the collector saturation current density and ϕ is the parameter in which all the changes in physical parameters, such as energy bandgap, free-carrier mobility, and temperature variation are taken into account, $R_{\rm Ek}$ is the emitter resistance, β_k is the current gain in the $K_{\rm th}$ element, β is the pre-exponential factor, and ΔE is the activation energy, also referred to as the 'apparent' valence band discontinuity.

The temperature in each element is calculated from the heat transfer equation. This temperature

is used to re-calculate the temperature dependent collector current. This updated current distribution is used to recalculate the temperature profile. This sequence of calculations is repeated until self-consistent solutions exist simultaneously for both the temperature profile and the current distribution.

3. Numerical results and discussion

Figure 2 illustrates the calculated temperature distributions among the fingers for two cases: one with uniform finger spacing and the other with non-uniform finger spacing. The temperature distributions on the top surface of the SiGe HBT with traditional uniform emitter finger spacing ($s = 20$ μm) are shown in Fig. 2(a) for different power dissipations ($P = 1.8$ W, 2.4 W, 3 W). When the power dissipations are small, the temperature variations are small across the five emitter fingers. As the power dissipation increases, the temperature distributions show large differences between the central emitter finger and the other emitter fingers. This can be explained as follows. As shown in Eq. (9), when the junction temperature of a finger rises, the current flowing through that particular finger increases exponentially. As the thermal coupling effect is more prominent at the central portion of the device, the central finger is naturally hotter than the other fingers. Therefore the current in the central finger increases proportionally much larger than those in the rest of the fingers. Finally, when the central finger rises to a certain temperature that is much higher than the temperatures in the other fingers, the central finger will conduct essentially the entire current. The non-uniform temperature distribution and the non-uniform current conduction are undesirable since the entire device power is dissipated in one finger, rather than distributed uniformly in all the fingers.

In order to obtain uniform temperature distribution and current conduction, it is very important to reduce the thermal coupling effect at the central portion of the device. The coupled thermal resistance due to heating from the neighbouring emitter finger is used to describe the thermal coupling effect. We know that coupled thermal resistance will increase as emitter finger spacing s decreases and subsequently the likelihood of thermal runaway will increase. So we keep the total spacing constant, and the emitter finger spacing values from left to right are 14.5 μm, 25.5 μm, 25.5 μm, 14.5 μm, respectively.

As shown in Fig. 2(b), the junction temperatures among the fingers in the device with non-uniform finger spacing are almost the same under different power dissipations. Even at the highest power dissipation of 3 W, the temperature difference between the adjacent fingers is only about 26 K. In contrast, for a device with uniform finger spacing, the junction temperature of the central finger rises sharply compared with those of the other fingers where the temperature difference ranges from 22 K to 90 K as power dissipation increases to 1.8 W, 2.4 W, and 3 W respectively. A comparison between Fig. 2(a) and Fig. 2(b) clearly demonstrates the advantage of non-uniform finger spacing: that the uniformity of temperature distribution is maintained as the power dissipation increases, which cannot be achieved using ballast resistors at the emitter or base.

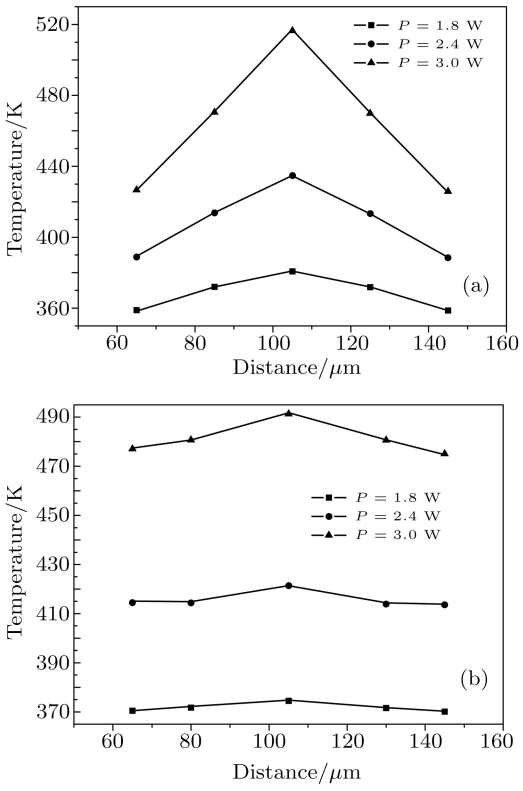


Fig. 2. Calculated temperature profiles among the fingers at three different power dissipations for HBTs with (a) uniform finger spacing, and (b) non-uniform finger spacing.

4. Experimental results

Based on the simulation results, a non-uniform finger spacing power SiGe HBT was designed and fabricated. Figure 3 is the schematic cross-sectional view

of a SiGe HBT with multiple emitter fingers. Figure 4 shows the micrographs of the surface view of the fabricated 20-finger power SiGe HBTs with uniform and the non-uniform finger spacing. Because of the symmetry, there are ten spacing values to be designed for a 20-fnger HBT, which are 16 μm, 16 μm, 18 μm, 18 μm, 20 μm, 20 μm, 22 μm, 22 μm, 24 μm, 28 μm from the two sides to the central spacing. The finger spacing of the 20-finger SiGe HBT with uniform spacing is 20 μm. Both devices have the same structure in each finger (3 μm $\times$ 45 μm) and have the same total spacing.

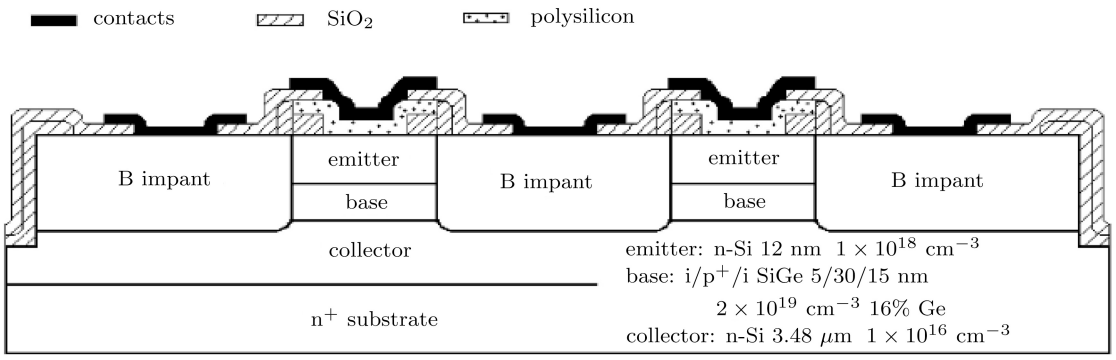


Fig. 3. Cross section of a SiGe HBT with multiple emitter fingers.

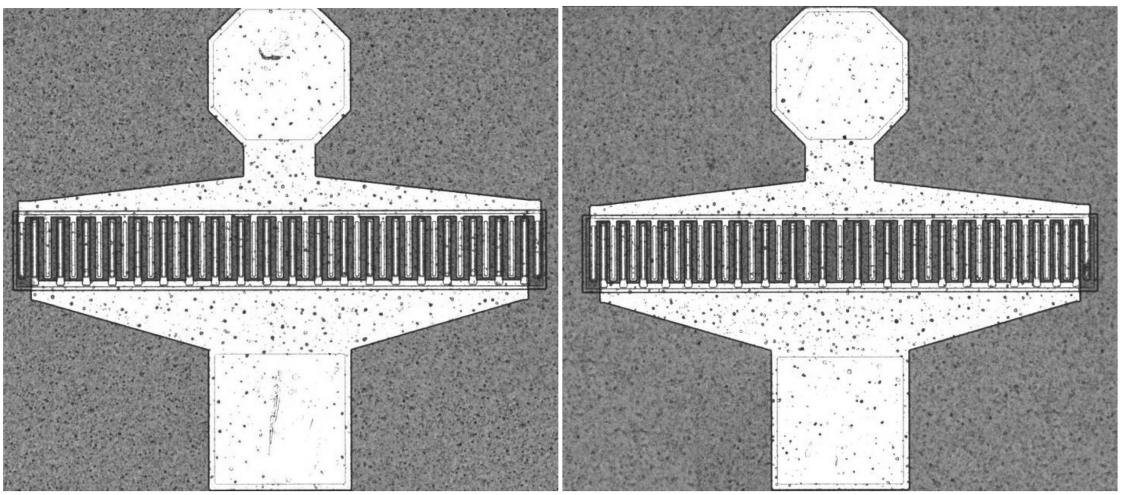


Fig. 4. Scanning electron microscope (SEM) images of 20-finger power SiGe HBTs for (a) uniform finger spacing, (b) non-uniform finger spacing.

The temperature profiles of a 20-finger SiGe HBT with uniform and non-uniform finger spacing along the central line across the multi-emitter fingers at different power dissipations (P = 2 W, 3 W, 4 W) are shown in Fig. 5. The HBT with non-uniform finger spacing shows a small temperature difference between fingers compared with the uniform finger spacing HBT. The non-uniformity of the temperature profile in the central region of the device is reduced more significantly. The most important point is that for the non-uniform finger spacing HBT, the ability to reduce both the peak temperature and the temperature non-uniformity is not weakened as power dissipation increases. The uniformity of temperature distribution is maintained as the power dissipation increases, which is greatly consistent with our simulation results. There-

fore, non-uniform finger spacing is very effective to keep the thermal stability under different power dissipations.

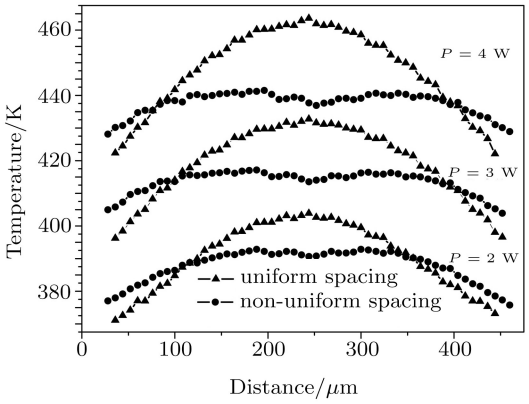


Fig. 5. Temperature profiles measured by infrared microimages for 20-finger SiGe HBTs under different power dissipations.

5. Conclusions

To obtain high thermal stability under different power dissipations, a multi-finger power SiGe HBT with non-uniform finger spacing is proposed. A numerical electro-thermal model and experiment are used to investigate the thermal behaviours of multiple finger heterojunction bipolar transistors (HBTs) each with non-uniform multiple-finger spacing. The results show that the SiGe HBT with non-uniform finger spacing has a small temperature difference between fingers compared with the SiGe HBT with uniform finger spacing under the same power dissipation. Moreover, uniformity of temperature distribution is maintained as the power dissipation changes. These results indicate that the method of non-uniform finger spacing is very useful for multiple finger SiGe HBTs to retain their high thermal stability under different power dissipations.

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