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Letter

The effect of vertical emitter ballasting resistors on the emitter current crowding effect in heterojunction bipolar transistors

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Abstract

In order to improve thermal stability and extend their safe operation region, epitaxial emitter ballasting resistors have been incorporated into power heterojunction bipolar transistors (HBTs). In this report, we show that this lightly doped layer not only can function as ballasting resistors used in multi-finger power HBT cells, but also can reduce the emitter current crowding effect which is an important limitation in bipolar transistors operating at high emitter current densities.

Keywords: Heterojunction bipolar transistors; Ballasting resistors; Current crowding effect

Power hetorojunction bipolar transistors (HBTs) are designed to deliver large amounts of power at high frequencies. Because these HBTs are operated at high power densities, the ultimate limit on their performance is imposed by thermal considerations. Thermal instability phenomena, such as emitter collapse and interdependence between collapse and avalanche breakdown, have been observed when a multi-finger HBT is operated at high power densities [1]. This instability originates from the positive thermal-electric feedback nature of bipolar devices. To increase current handling capability and improve thermal stability are very important for power HBTs. The most popular approach is introducing ballasting resistors connecting with each emitter stripe in series. However, the common practice to incorporate these resistors consumes extra chip area. In order to improve thermal stability to extend their safe operation region as well as to save chip area, epitaxial emitter ballasting resistors have been incorporated into power HBTs [2,3]. In this letter, we will show that a lightly doped layer not only can function as ballasting resistors used in multi-finger power HBT cells, but also can reduce the emitter current crowding effect which is an important limitation in bipolar transistors operating at high emitter current densities.

The lateral voltage drop across the emitter–base junction in bipolar transistors can cause emitter current crowding at emitter's periphery and thus cause localized heating and thermal problems. Liu and Harris [4] recently showed that for npn HBTs, though having a heavily doped base, the emitter current crowding effect cannot be neglected. In order to reduce this effect, both heavily doped base and narrow emitter stripes are employed. However, this heavily doped base will cause another reliability problem, due to the diffusion of the interstitial Be atoms when the doping level is higher than

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2×10^{19} cm^{-3}. Actually, this emitter current crowding effect can be reduced through introducing vertical ballasting resistors. When the emitter junction is forward biased, the current densities at emitter edges are higher than that at the center due to the lateral voltage drop along the emitter junction. When vertical ballasting resistors are introduced, the voltage drop across the resistor at emitter edges will be larger than that at the center of emitter junction. This larger voltage drop across the ballasting resistors at emitter edges will reduce the current density exponentially there. Therefore, this negative feedback will reduce the current crowding effect very efficiently.

In order to study this intuitive argument quantitatively, the computer simulation of typical AlGaAs/GaAs HBTs with a 100 nm-thick Be-doped (1×10^{19} cm^{-3}) base layer has been conducted. For the HBT with vertical ballasting resistors, a thin lightly Si-doped GaAs layer has been introduced to form the emitter ballasting resistor. This layer, with properly selected layer doping density and thickness, is treated as a linear resistor, whose value is set to 5 Ω for a emitter cell size of 4×20 μm^2, which corresponds to $8kT/qI_E$ for a emitter current density of 5×10^4 A/cm^2.

For transistors without the ballasting resistor, the equations about base current and voltage can written as

$$dV_B = \frac{I_B \rho_b}{W_b W_E} dy$$
$$dI_B = J_E(y) W_E (1-\alpha)\, dy$$

where W_b is effective base width. Thus we have

$$V_{BE}(y) = V_B(y) - V_{E0} = V_B(y)$$

$$\begin{cases} \dfrac{d^2 V_B(y)}{dy^2} = \dfrac{\rho_b(1-\alpha)}{W_b} J_E(y) \\ J_E(y) = J_0 e^{V_{BE}(y)/V_T} = J_0 e^{V_B(y)/V_T} \end{cases} \qquad (1)$$

where I_B is the base current, W_E is the emitter stripe width, $J_E(y)$ is the local emitter current density, $V_B(y)$ and $V_E(y)$ are voltage distributions respectively, and V_T is kT/q. When the vertical ballasting resistor is introduced, we have

$$V_{BE}(y) = V_B(y) - V_E(y) - V_{E0} = V_B(y) - J_E(y)\,\Delta s R_e$$

$$\begin{cases} \dfrac{d^2 V_B(y)}{dy^2} = \dfrac{\rho_b(1-\alpha)}{W_b} J_E(y) \\ J_E(y) = J_0 \exp\left(\dfrac{V_B(y) - J_E(y)\Delta S R_e}{V_T}\right) \end{cases} \qquad (2)$$

where R_e is the resistance of the ballasting resistor. The boundary conditions are

$$\begin{cases} V_B(0) = V_0 \\ \left.\dfrac{dV_B(y)}{dy}\right|_{y=0} = 0 \\ \int_E J_E(y) L_E\, dy = I_E \end{cases}$$

In Eqs. (1) and (2), we have assumed that V_{E0} equals to 0, which is emitter contact potential.

The equations for both cases have been solved numerically. In the computer simulation, the current gain is assumed as 10, 20, and 30, respectively. In real applications, when devices work at high current density and high frequency, the current gain is small, which makes current crowding effect more serious on the performance of transistors. The voltage drop from the edge to the center of the emitter stripe in both case is shown in

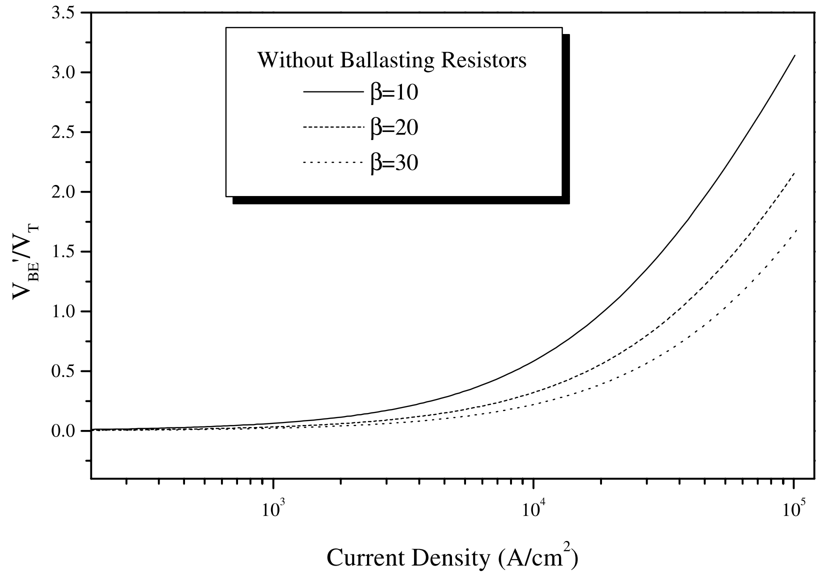

Fig. 1. Ratio of V_{BE}' and V_T as function of average emitter current density for various values of current gain without ballasting resistor.

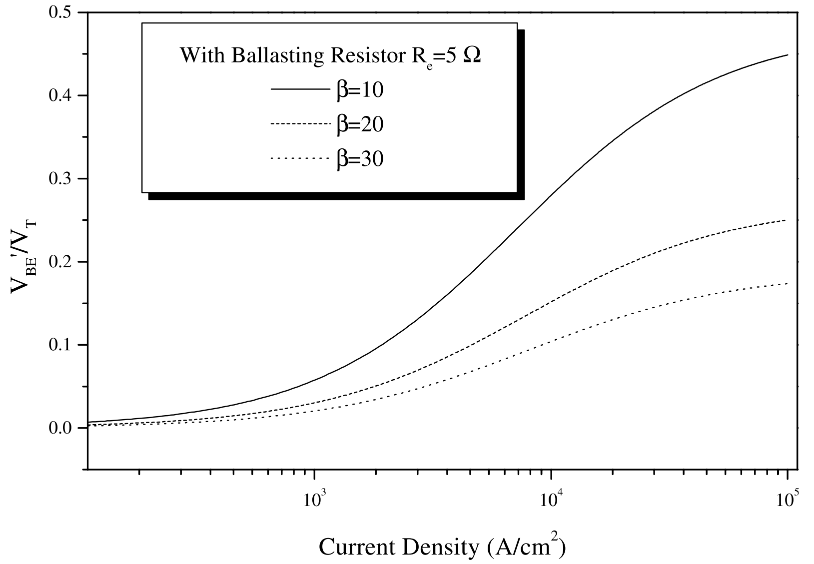

Fig. 2. Ratio of V'_{BE} and V_T as function of average emitter current density for various values of current gain with ballasting resistor.

Figs. 1 and 2. The local current densities depend on the local voltage exponentially. A voltage drop of V_T will result in a current drop of more than 60% compared with the current at the emitter edge. From the figures, it can be seen clearly that the effect of the ballasting resistor on reducing current crowding is very effective. The effect of the ballasting resistor is more important to make the current relatively uniform along the emitter width. The current distribution along the emitter width is shown in Fig. 3. The current distribution along the emitter width is still quite uniform when the emitter average current density is as high as 5×10^4 A/cm^2.

In order to further prove the simulation results, two HBT structures with and without the lightly doped (nominally 1×10^{16}/cm^3) ballasting resistor layer have been grown. The thickness of this layer is determined by the criteria of $R_0 = 8kT/qI_{E0}$, where, R_0 is the resistance of a resistor, and the I_{E0} is the current passes across one emitter at the current density of 4×10^4 A/cm^2. The base doping level is chosen to be 1×10^{19}/cm^3. In both structures, the collector layer is doped less than 10^{16}/cm^3 (nominally 8×10^{15}/cm^3) so that the Kirk effect can be used to monitor the degree of current crowding effect at higher current level. The structures were grown in

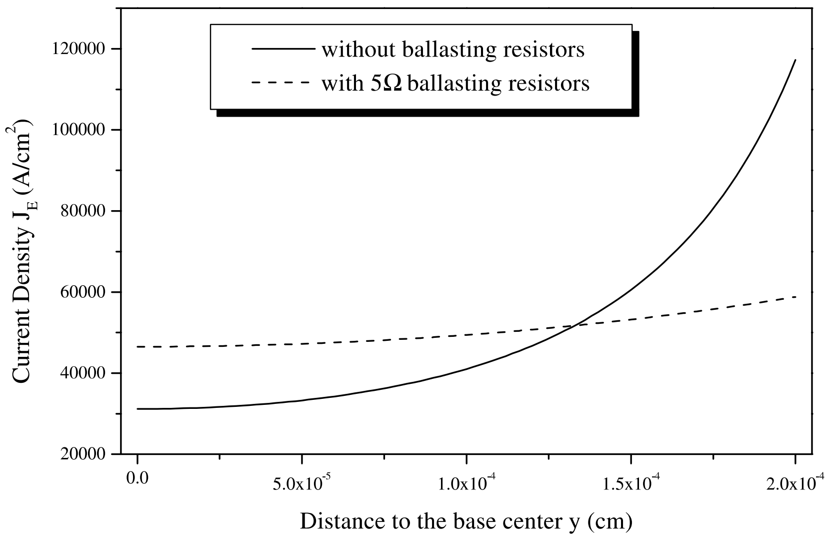

Fig. 3. $J_E(y)$ vs. distance from emitter center with and without ballasting resistor R_e.

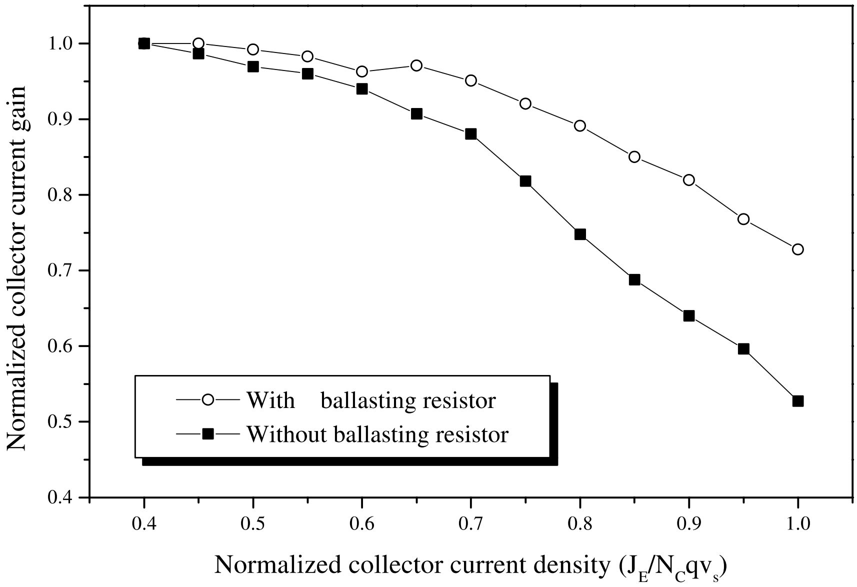

Fig. 4. Measured current gains vs. J_E.

GaAs/AlGaAs material system. The Al composition was chosen to be 15% so that the DC current gains would be low enough to observe the current crowding effect. The devices were fabricated by standard wet chemical process with an emitter stripe width of 6 μm. Then the current gain and its relation vs. collector current densities were measured. The result showed in Fig. 4. The DC current gain was measured about 25. In order to avoid the effect of temperature on current gain, the pulse measurement with a duty cycle of 1% was used. The measurements showed that the current gain degradation starts at lower collector current densities for transistors without the ballasting resistors compared with the transistors with the ballasting resistors. This can be explained by the fact that, for the transistors without ballasting resistors, the current crowded at the emitter edge more seriously than that of transistors with the ballasting resistors. Therefore, the Kirk effect happens at relatively lower average collector current densities. The extension of base under the emitter edge makes the current gain degradation.

In summary, we have proposed and demonstrated a unique way to solve the thermal instability and emitter current crowding effect simultaneously. Both computer simulation and experimental results have showed that the MBE grown vertical ballasting resistors not only can function as ballasting resistors used in multi-finger power HBT cells, but also can reduce the emitter current crowding effect significantly. This will make HBTs more reliable in microwave power applications.

Acknowledgements

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