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Theoretical and Experimental Study on Thermal Characteristics of InP/InGaAs Single Heterojunction Bipolar Transistors

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1. Introduction

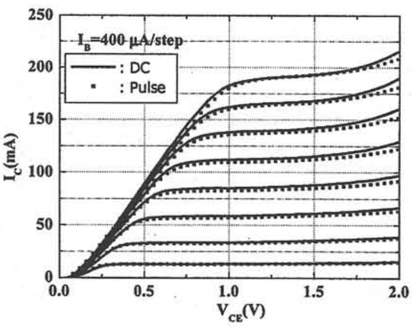
InP-based heterojunction bipolar transistors (HBT's) have emerged as one of key technologies for micro/millimeter -wave and ultrahigh-speed applications due to inherent excellent transport-related properties [1]. One of the areas, where the InP HBT is considered to be a strong candidate among other current technologies, is the power amplifier application. Recent investigations have shown that InP-based HBT's are very promising because of their superior high-frequency as well as high-linearity performance under even low battery-voltage operation, which results from their low device turn-on voltage [2]. Compared to more mature GaAs-based HBT's, the characteristics of InP-based HBT's, especially those related to thermal effects at high power levels, have not been studied to a great extent so far.

In this paper, the thermal characteristics of InP/InGaAs single HBT's (SHBT's) at high power levels are investigated based on the results obtained both experimentally and theoretically.

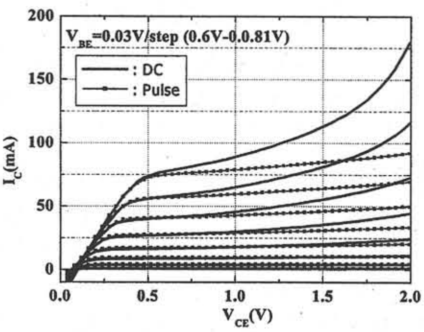
2. Thermal Characteristics of InP based HBT's

In order to investigate the thermal behavior of InP based HBT's, the output DC characteristics of InP SHBT's with an emitter dimension of *4-finger*×*2*×*10* μm^2 were measured under both the continuous and pulsed bias conditions. The device used in this investigation was fabricated with a new self-aligned CDC (Crystallographically Defined emitter Contact) technology [3] and showed peak f_T and f_{max} of 94 GHz and 124 GHz, respectively. To fully understand the effects of heat generation in InP SHBT's, the output I-V characteristics of the device were measured under two different operating configurations of common-emitter and common-base by applying different bias conditions, including constant I_B, constant V_{BE} and constant I_E. The measured I-V characteristics of the device are shown in Fig. 1.

As can be seen in Fig. 1, the thermal effects in InP SHBT's are drastically different from those of GaAs HBT's [4]. Significant thermal effects are observed when measured under a continuous bias condition due to the device self-heating effects. In order to investigate the device self-heating effects, the characteristics measured under a pulsed bias condition (a pulse width of *400 ns* with a period of *100* μs), where the self-heating effect is negligible, are also compared. The output characteristics measured under the constant I_B condition are shown in Fig. 1(a). As shown in Fig. 1(a), I_C of the InP/InGaAs SHBT increases slightly with increasing V_{CE} under both the continuous and pulsed bias conditions. This



(a)



(b)

Fig. 1. The measured common-emitter I_C-V_{CE} characteristics of the device under bias condition of (a) constant I_B (b) constant V_{BE}

behavior of InP HBT's is opposite to that observed in GaAs HBT's, where the collector current decreases as the DC bias increases. The output characteristics measured under the constant V_{BE} bias condition are shown in Fig. 1(b). Compared to the case of constant I_B bias condition, the effects due to device self-heating under the continuous DC bias are much more significant. As observed from the I-V characteristics shown in Fig. 1, the InP SHBT exhibits the following thermal-related characteristics: (i) the collector current increases as V_{CE} increases even under the pulsed condition, (ii) the self heating effect under the constant I_B condition is relatively insignificant up to a collector current density of ~$3x10^5$ A/cm^2, (iii) the collector current increase becomes much severe under the constant V_{BE} bias condition. The first phenomena of (i) mainly arise from the impact ionization process occurring across the InGaAs narrow-bandgap (E_g=0.75eV) B-C junction. In order to understand the contribution from the impact ionization process, the impact-ionization multiplication coefficient (*M-1*) was extracted by measuring the device characteristics under the common-base mode with a constant emitter-current bias condition [5]. The equations used for *M-1* calculation are;

$$M-1=\frac{\Delta I_B}{I_C(V_{CB})-\Delta I_B} \qquad (1)$$
$$\Delta I_B = I_B(V_{CB}=0)-I_B(V_{CB}).$$

The measured *M-1* values from the device, shown in Fig. 2, agree well with those reported from similar InGaAs p-n junctions [6]. On the other hand, the thermal behaviors of the InP HBT discussed in (ii) and (iii) can be explained by the temperature-dependent characteristics of the current gain (β) and turn-on voltage. The I_C increase observed under the constant I_B condition of Fig. 1(a) due to self-heating effect is attributed to the temperature dependence of the current gain (β) given by [7];

$$\frac{1}{\beta}=\frac{1}{\beta_0}+f_1\exp\left(-\frac{\Delta E_v}{kT}\right) \qquad (2)$$

where β_0 denotes the gain component associated with the base-region recombination, having a weak temperature dependence, and the second term represents the effect due to the base-to-emitter back-injection current (I_{Bp}). Here, ΔE_v is the valence-band offset of the abrupt InP/InGaAs heterojunction and f_1 is a constant. Compared to the AlGaAs/GaAs HBT's with ΔE_v of 0.1 eV, the valence-band discontinuity (0.366 eV) in InP/InGaAs HBT's is much larger. Therefore, the phenomena of significant β decrement with temperature, observed in GaAs HBT's occurring due to a small value of ΔE_v, is negligible in InP/InGaAs HBT's under the bias condition of constant I_B because of the large ΔE_v. So, β remains almost constant with temperature in InP/InGaAs HBT's as shown in Fig. 1(a).

The large increase in collector currents shown in Fig. 1(b), measured under the continuous bias condition with constant V_{BE}, is attributed to the temperature dependence of the device turn-on voltage with the self-heating effect. The relation between V_{BE} and I_C can be expressed as [8];

$$I_C = I_{S0}\exp\left[q\left(V_{BE}-I_C R_e-\frac{E_{g0}}{q}+\frac{\beta^*}{q}T\right)\Big/\eta kT\right] \qquad (3)$$

where η is the ideality factor; I_{S0} is a modified saturation current; E_{g0} is the bandgap energy at 0K; β^* is the bandgap shrinkage coefficient, and T is the junction temperature. As the junction temperature of the device increases with an increase of DC power dissipation, the effective turn-on voltage of the HBT decreases. In order to estimate the junction temperature increase in the InP HBT, thermal simulations were performed for the device structure investigated here by using the developed 3-D thermal-simulation numerical code [9]. The theoretical I_C increase due to the device self-heating calculated from the simulation is compared with that of experimental results in Fig. 3. The simulation results indicate that the significant I_C increase under the bias condition of constant V_{BE} arises from a reduction of the E-B junction turn-on voltage of about –0.9 *mV/°C* for the InP/InGaAs HBT. The theoretically obtained value is found to be in reasonably good agreement with the experimental value reported elsewhere [10].

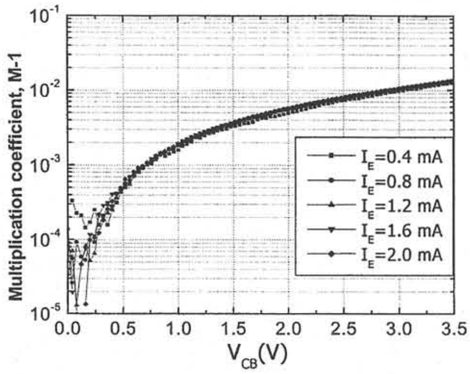


Fig. 2. Multiplication coefficient M-1 as a function of V_{CB} measured in constant I_E mode for 4-finger 2 ×10 μm² InP/InGaAs HBT

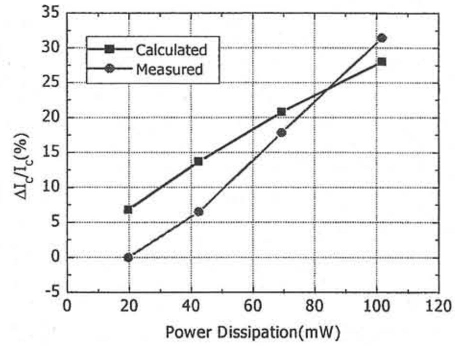


Fig. 3. Comparison of the percentage increase of I_C measured and calculated under the constant V_{BE} bias condition.

3. Conclusion

Thermal characteristics of InP-based SHBT's were analyzed and discussed based on the results obtained both experimentally and theoretically. The results demonstrate that the thermal behaviors of InP/InGaAs SHBT's arising from the device self-heating effects are different under different operating configurations. It is also shown that the configuration of common-emitter under the constant base-current condition is less sensitive to self heating, thus more favorable to the application for high-gain power amplification due to the better thermal stability and linearity at high power levels.

Acknowledgments

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