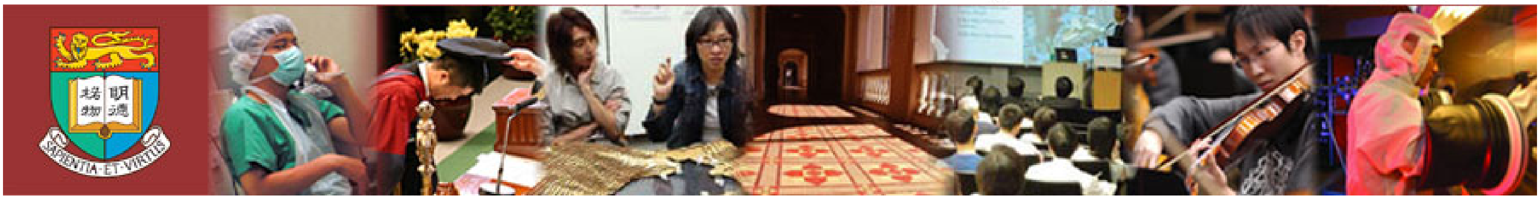

Title	Temperature dependence of current gain of GaInP/GaAs heterojunction and heterostructure-emitter bipolar transistors
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Temperature Dependence of Current Gain of GaInP/GaAs Heterojunction and Heterostructure-Emitter Bipolar Transistors

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***Abstract*—The temperature effect on current gain is presented for GaInP/GaAs heterojunction and heterostructure-emitter bipolar transistors (HBT's and HEBT's). Experimental results showed that the current gain of the HEBT increases with the increase of temperature in the temperature range of 25–125 °C and decreases slightly at temperatures above 150 °C. The smaller the collector current, the larger is the positive differential temperature coefficient. At high current levels, the current gain dependence on temperature is significantly reduced. On the other hand, a large negative coefficient is observed in the HBT in all current range. This finding indicates that the HEBT is a better candidate than the HBT for power devices.**

I. Introduction

In a bipolar transistor, the current gain has a definite temperature coefficient. When current crowding exists in a device, the temperature dependence can provide an electrical-thermal positive feedback loop giving rise to thermal runaway for a positive coefficient and current collapse for a negative coefficient. To avoid the catastrophic effect one could attempt to eliminate current crowding or making the current insensitive to temperature variation. Current crowding may come from the nonuniformity of material, device structure or the lateral field established by the base current. For the latter, a heavy base doping such as in a typical heterojunction bipolar transistor (HBT) produces a small and negligible lateral potential drop in the active base. Although the difference between fingers is unavoidable, the temperature coefficient, however, may be controllable by manipulation of the heterojunction. This paper reports some experimental results using a GaInP heterostructure-emitter to make the gain less sensitive to temperature variation.

In a power GaAs HBT the current gain decreases with the increase of junction temperature which results in a negative differential resistance and current collapse in the $I-V$ curves [1], [2]. Although GaInP/GaAs power HBT's have less temperature dependence on current gain than AlGaAs HBT's [3], there is still observable gain degradation and negative differential resistance, especially for the semi-ordered GaInP/GaAs HBT's [4]. The main reason of gain degradation in HBT's is believed to be the low valence band offset (ΔE_V) at the heterojunction [3]. It is based on the assumption that diffusion dominates the hole current injected from the base to the emitter. If, however, the mechanism of the hole current is controlled by thermionic emission rather than diffusion, the temperature dependence of current gain will be modified significantly.

The heterostructure-emitter bipolar transistor (HEBT) with the separation of electron injection and hole confinement [5] has been proposed by taking advantage of both the heterojunction and homojunction. It can effectively eliminate the emitter potential spike and offers a low offset voltage [6]. The heterostructure-emitter can also accommodate the base dopant outdiffusion which increases the device life time [7]. We have also found that the HEBT provides better current gain uniformity [8]. Moreover, the hole current injected from base to emitter is likely to be dominated by thermionic emission current at high temperature similar to the poly-Si emitter [9]. Since the thermionic emission current has a temperature dependence of $\sim T^2$ instead of T^3 in a diffusion current (excluding the exponential kT term contained in both) [10], the current gain should be less dependent on the junction temperature. In this paper, we present the experimental results of the temperature dependence on the current gain of GaInP/GaAs HBT's and HEBT's.

II. Experiment

GaInP/GaAs HEBT's were grown by MOCVD on a SI GaAs substrate. The HEBT structure consists of a 5000 Å GaAs subcollector layer $(n = 3 \times 10^{18}$ cm$^{-3})$, a 5000 Å GaAs collector layer $(n = 3 \times 10^{16}$ cm$^{-3})$, a 1000 Å GaAs base layer $(p = 6 \times 10^{19}$ cm$^{-3})$, a 150 Å GaAs emitter layer $(n = 1 \times 10^{17}$ cm$^{-3})$, a 500 Å GaInP confinement layer $(n = 3 \times 10^{17}$ cm$^{-3})$, a 1500 Å GaAs emitter cap layer $(n = 4 \times 10^{18}$ cm$^{-3})$, and a 600 Å graded $In_xGa_{1-x}As$ $(x$ from 0 to 0.5) contact layer $(n = 5 \times 10^{18}$ cm$^{-3})$. A GaInP/GaAs HBT without emitter setback layer was also fabricated for comparison. Si and C were used as n- and p-type dopants, respectively.

HEBT's were fabricated using the conventional mesa structure described in [8]. A thin depleted GaInP ledge was

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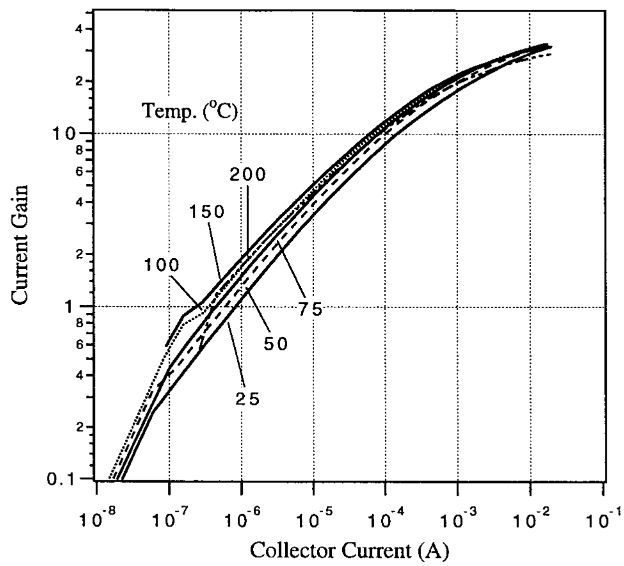

Fig. 1. Current gain versus collector current for the GaInP/GaAs HEBT with emitter size of 3 × 16 μm^2 at various substrate temperatures.

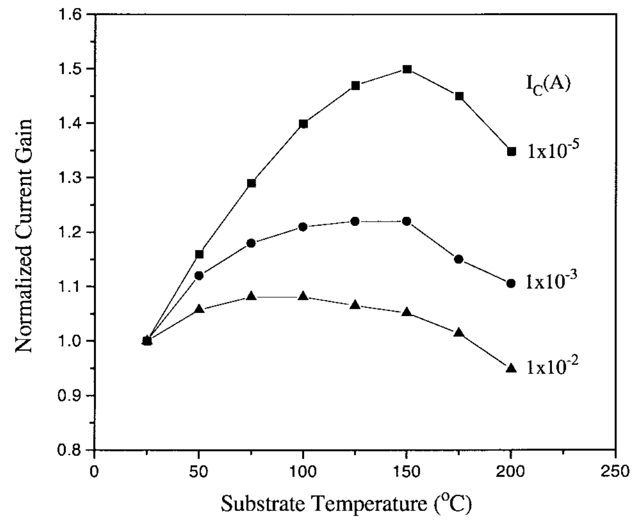

Fig. 2. Current gain versus substrate temperature for the GaInP/GaAs HEBT at collector current of 1×10^{-5}, 1×10^{-3}, and 1×10^{-2} A.

employed as a passivation layer for the extrinsic base surface to reduce the surface recombination current. A large emitter size of 40 × 100 μm^2 was used to further cut down the periphery effect on the current gain. After the HEBT's were fabricated, the devices were packaged in a chip carrier. Gummel plots at a base-collector bias of 0 V were measured at the temperature range from 25 to 175 °C by putting the sample in a temperature-controlled chamber. Because the base-collector was biased at 0 V, the device junction temperature was assumed to be the same as the substrate temperature, $T_{\rm sub}$.

III. Results and Discussion

The fabricated HEBT has a common emitter current gain (β) of 35 at room temperature. RF devices with a small emitter have a cutoff frequency of 45 GHz and maximum oscillation frequency of 80 GHz.

Fig. 1 shows the current gain versus the collector current for the GaInP/GaAs HEBT at various substrate temperatures. The emitter size is 3 × 16 μm^2. As shown, the current gain changes only slightly with temperature for the wide range of collector current. The increase of current gain with temperature is also observed. For clarity, Fig. 2 shows the current gain, normalized by its value at room temperature, as a function of the substrate temperature for the HEBT at collector current of 1×10^{-5}, 1×10^{-3}, and 1×10^{-2} A. It is noted that the current gain increases with the increase of temperature at $T_{\rm sub}$ below 100 °C and starts to decrease at $T_{\rm sub} >$ 100–150 °C depending on the collector current. The smaller the collector current, the more the current gain increases with temperature.

In comparison, Fig. 3 shows the current gain versus collector current of a GaInP/GaAs HBT for the temperature range of 25–200 °C. The HBT has a similar structure and was grown under the same conditions as that of the HEBT except without an emitter setback layer. Some of the features in Fig. 3 are replotted in Fig. 4 for I_C of 10^{-5}, 10^{-4}, and 10^{-3} A, respectively. It is noted that the current gain of the

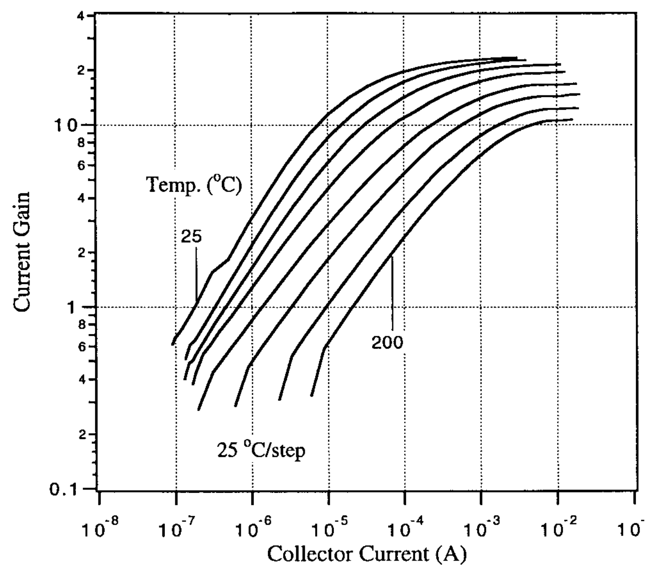

Fig. 3. Current gain versus collector current for the GaInP/GaAs HBT with emitter size of 3 × 16 μm^2 at various substrate temperatures.

HBT's has a negative temperature coefficient as defined by the slope of the curves. This coefficient is current dependent but is negative in all cases. On the other hand, the current gain of the HEBT shown in Fig. 2 shows a positive slope at low temperatures and it levels off before turning to a negative slope. As a comparison, the gain variation is within 10% at $I_C = 10^{-2}$ A for the HEBT in Fig. 2 and a factor of two (i.e., 100%) for the HBT in Fig. 3. The contrast is even greater for a lower collector current.

For the HBT, the temperature coefficient is not far from being a constant and a thermal-electrical feedback factor can be defined [11]. However, the same coefficient in an HEBT is highly nonlinear as it changes from positive to negative. This nonlinearity makes it difficult to define a feedback factor. Nevertheless, there is no question as to the less sensitive temperature dependence in a HEBT. The smaller coefficient gives rise to a smaller thermal-electrical feedback and a less

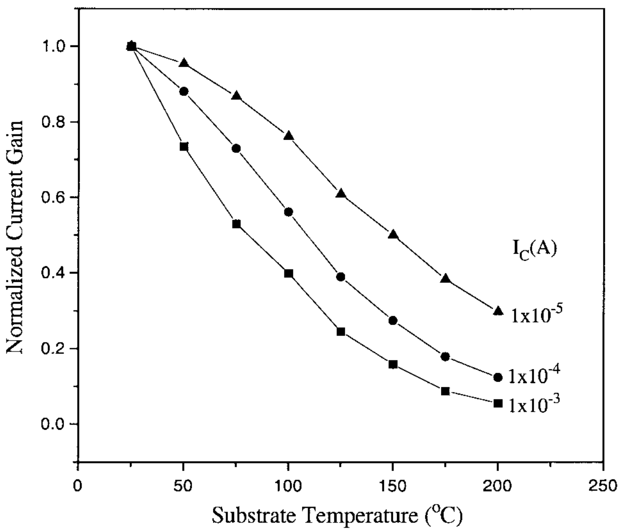

Fig. 4. Current gain versus substrate temperature for the GaInP/GaAs HBT at collector current of 1×10^{-5}, 1×10^{-4}, and 1×10^{-3} A.

likelihood of current collapse in the device. The current gain of the HBT decreases with increasing temperature in the entire current range. The lower the collector current, the more is the current gain reduction. As can be seen in Fig. 3, the current gain decreases in magnitude by a factor of 20 at I_C of 10^{-5} A but only 2 at 10 $^{-2}$ A, respectively, for the temperature range of 25–200 °C.

From the data shown in Figs. 2 and 4, the contrast of the thermal effect on the current gain between the HEBT and HBT is very striking. In general, current crowding will produce a thermal gradient within the transistor. However, if the current gain were independent of temperature, there would not be a feedback mechanism to produce a catastrophic effect. In reality, when the temperature coefficient of the gain is positive, thermal runaway will take place as in power silicon BJT. On the other hand, a negative temperature coefficient gives rise to gain depression thus the collapse of the collector current in the $I-V$ plot of the HBT. By assuming that the heterostructure-emitter is similar to the poly-Si emitter, the hole current from the base to emitter is dominated by thermionic emission at high temperature [9]. The temperature dependence of the diffusion current is described by $T^{3+\gamma/2}$ [10, Ch. 2, Eq. (46)]. The $\gamma/2$ term describes the temperature effect of the ratio of the diffusion coefficient and diffusion length that is negligible in most cases. Ignoring the exponential kT term which cancels out, the thermionic emission current has a temperature dependence of $\sim T^2$ and the diffusion current has a temperature dependence of $\sim T^3$. Hence, the current gain is less dependent on the junction temperature when the hole current is dominated by thermionic emission. A detailed analysis is too long to include here and will be published in a separate paper in the future.

One advantage of the current gain increase with temperature is for power applications. The negative differential resistance and current collapse in HBT's are commonly observed as due to the self-heating effect. In our devices, we have obtained a positive differential resistance in the $I-V$ curve. This positive differential resistance results directly from the positive temperature coefficient of the current gain. However, the current gain decrease at high temperature brings back the negative differential resistance at high current and high bias. This effect prevents the device from thermal runaway.

In summary, we have reported a significant difference in the thermal coefficient of the current gain for GaInP/GaAs HEBT and a HBT. It is showed that the current gain for the HEBT is controllable by design and can be much less dependent on the junction temperature. A positive differential resistance in $I-V$ curve is observed corresponding to the current gain increase with temperature. The results suggest that the HEBT structure can overcome the problem of current collapse and is a better candidate than the HBT for power devices.

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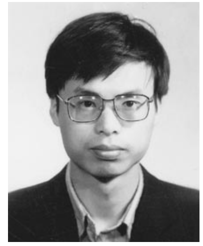

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