Critical Spacing Between Emitter and Base in InGaP Heterojunction Bipolar Transistors (HBTs)

Chung-Er Huang, Chien-Ping Lee, *Fellow, IEEE*, Hsien-Chang Liang, and Ron-Ting Huang

***Abstract*—In this paper, the influence of the spacing between the emitter and the base on the performance of InGaP heterojunction bipolar transistors (HBT) was experimentally studied. We found that the emitter to base spacing can be reduced to as small as 0.6 μm without causing a significant drop in the current gain. The reduction in emitter-to-base spacing, however, leads to improvement in high-frequency performance and device phase noise. For optimal dc, RF, and low-frequency noise performances, we have determined that a critical spacing of 0.6$\sim$0.8 μm between the emitter and the base of an InGaP HBT is required.**

***Index Terms*—Critical spacing between emitter and base, flicker noise, InGaP HBT, ledge length.**

I. INTRODUCTION

HETEROJUNCTION bipolar transistors (HBTs) are attractive for high-speed digital circuit applications as well as power amplification applications [1], [2]. In modern communication systems, high-speed, high-power, high-linearity, and highly reliable devices are essential. The recently developed InGaP-GaAs HBT technology is ideal for such applications and is superior to the conventional AlGaAs-GaAs HBT technology for several reasons: 1) the absence of Al element in the epitaxial materials eliminates the problems associated with the DX centers; 2) the relatively lower surface recombination velocity results in lower $1/f$ noise; 3) the high etching selectivity between InGaP and GaAs makes the process more controllable and makes a high-yield process easier to achieve; and 4) InGaP-GaAs HBTs have a large valence band discontinuity (ΔE_v), which is good for obtaining high-electron injection efficiency [3], [4].

In the HBT process, a thin and depleted emitter ledge is commonly used to passivate the extrinsic base in order to reduce the surface recombination.Fig. 1 However, the extra emitter ledge increases the base–collector (b–c) junction area, which in turn increases the b–c junction capacitance and the base resistance, both of which degrade the device performance. So the length for the emitter ledge should be carefully optimized. On one hand, it should be long enough to minimize the surface recombination but on the other hand, not too long to seriously degrade the device's speed performance.

Lee *et al.* and Liu *et al.* [6], [7] have studied the effect of ledge on AlGaAs-GaAs and InGaP-GaAs HBTs performance, respectively. They found that the critical spacing between the emitter and the base was 1$\sim$2 μm for AlGaAs-GaAs HBT and less than 1 μm for InGaP-GaAs HBT. For manufacturing process, the safe spacing between the emitter and the base is 1.2 μm for AlGaAs-GaAs HBTs. But the corresponding value remains unknown for InGaP-GaAs HBTs. In this letter, we did a careful experimental study of the optimization of the emitter–base spacing for InGaP HBTs. The dc, RF, and low-frequency noise performances were used as the criteria for the optimization.

II. HBT STRUCTURE AND MEASUREMENT RESULTS

The epitaxial wafer was grown by metal–organic chemical vapor deposition (MOCVD). The epitaxial structure consists of a Si-doped (3×10^{17} cm^{-3}) 500-Å In$_{0.49}$Ga$_{0.51}$P emitter, a carbon-doped (4×10^{19} cm^{-3}) 1200-Å GaAs base, and an Si-doped (3×10^{16} cm^{-3}) 1-μm GaAs collector. HBTs with various emitter-to-base (e–b) spacing were fabricated. InGaP emitter was used to form the HBT ledge. The spacing values selected for the study were 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, and 2 μm. Fig. 1 shows the schematic cross section of the HBT structure. The distance between the edge of the ledge to the base metal was fixed at a value of less than 0.05 μm. The base pedestal width and its length were fixed at 11.4 μm and 8.4 μm, respectively, for all devices in this study. Only the ledge width was a variable. Since the base–collector (b–c) area was fixed, the base–collector b–c capacitance was the same for all devices. Since the cutoff frequency (F_t) is essentially determined by the epitaxial structure, the maximum frequency of oscillation ($F_{\max}$) of our test devices will be largely a function of the base resistance Rb only as born out by our experimental results.

Fig. 2 shows the measured Gummel plots of 2×6 μm^2 devices with the emitter–base (e–b) spacing varied from 0.2 to 2 μm. The measured collector currents are seen to be almost identical for different spacing values while the base currents differ depending on the e–b spacing. The same measured collector current indicates that all the devices have the same emitter area and the emitter ledge is fully depleted. The increase in the base current when the spacing is reduced is due to an increase of the electron recombination at the base contact.

Fig. 3 shows the plot of current gain versus the e–b spacing at a collector current of 10 mA. It is clearly seen that the current gain drops dramatically when the spacing is reduced to below

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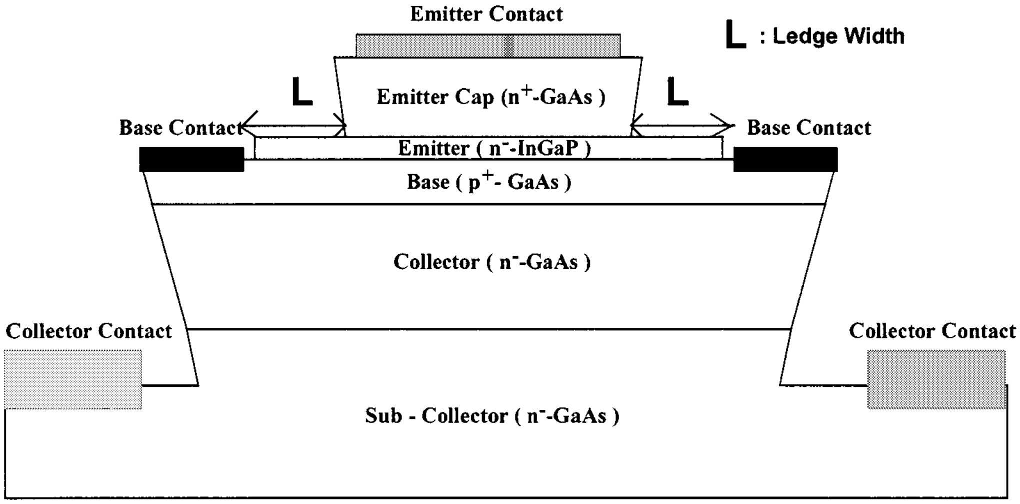

Fig. 1. Schematic cross section of an InGaP HBT structure.

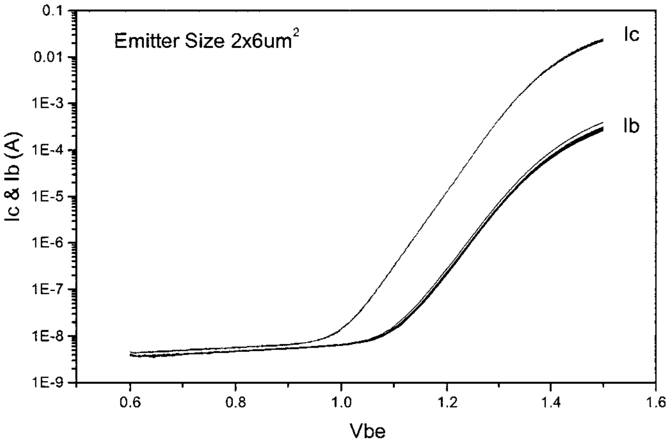

Fig. 2. Gummel plots of the $2 \times 6\ \mu\mathrm{m}^2$ HBTs with the e–b spacing equal to 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 2.0 $\mu\mathrm{m}^2$.

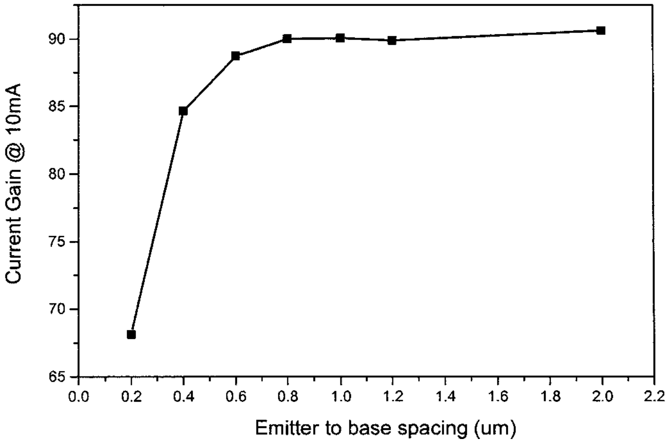

Fig. 3. Current gain as a function of the emitter to base spacing. (Emitter size $2 \times 6\ \mu\mathrm{m}^2$.)

0.6 μm. It saturates when the spacing is above 0.8 μm. From this result, one can infer that the lateral diffusion of the injected electrons in the base is of the order of approximately 0.6 μm.

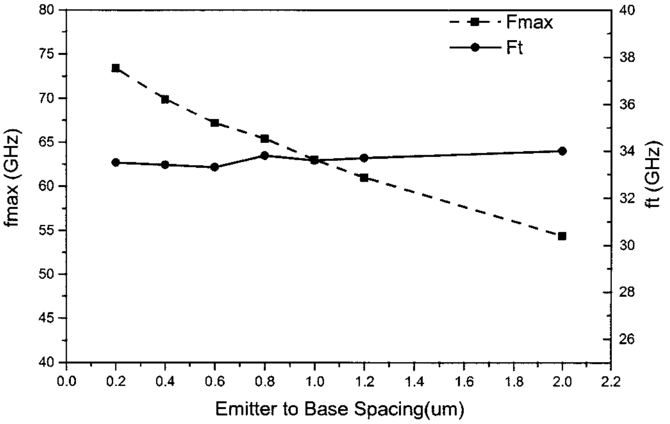

Fig. 4. f_t and $f_{\max}$ versus emitter to base spacing. (Emitter size $2 \times 6\ \mu\mathrm{m}^2$.) The device is operating at 2-V collector voltage and 4-mA (25 kA/cm^2) collector current.

We have also measured the RF performance of the devices. Fig. 4 shows the measured HBT F_t and $F_{\max}$ as functions of the e–b spacing. We can see clearly that F_t is nearly the same for all the devices, while $F_{\max}$ goes down as the e–b spacing is increased. This is readily understandable as the e–b spacing is increased, the base resistance increases too, which causes $F_{\max}$ to drop. F_t, on the other hand, depends only on the layer structure and therefore stays relatively constant. So for high-speed operation, it is necessary to minimize the e–b spacing.

The relationship between the low-frequency noise and the emitter to base spacing for the InGaP-GaAs HBTs was also studied. In HBTs, the generation–recombination (g–r) currents at the e–b space–charge region, the e–b heterointerface, and the exposed external base region are the major sources of low frequency current fluctuations [8]. We measured the equivalent input base noise current spectral density for different emitter-to-base spacing. Fig. 5 shows the measured low frequency noise at a collector current density of 8.33 kA/cm^2 ($Ic = 1$ mA) and a collector bias of 2 V. The reduction in low-frequency noise when the spacing is increased from 0.2 to 0.6 μm is mainly due to the reduced g–r current at the e–b space

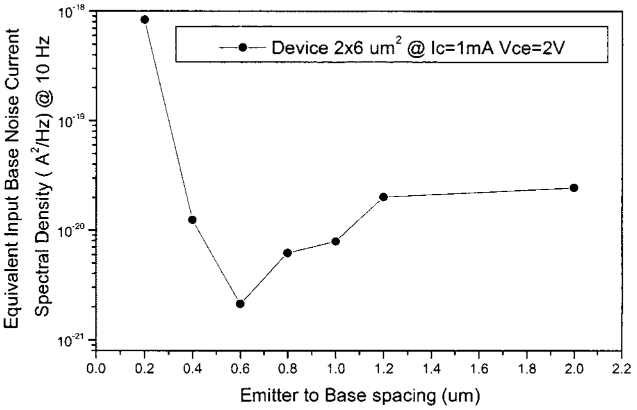

Fig. 5. Measured equivalent input noise current spectral density of different emitter to base spacing with $2 \times 6\ \mu\text{m}^2$ emitter area. The device is operating at collector current 1 mA and collector voltage 2 V.

charge region. When the emitter to base spacing is increased from 0.6 to 2.0 μm, the low-frequency noise is increased due to the increase in the noise sources between the emitter to base spacing.

III. Discussion and Conclusion

Qualitatively, we believe the minimum e–b spacing for optimal device performance is a result of the electron lateral diffusion. The phenomenon occurs because the electrons injected from the emitter diffuse laterally and recombine at the base contact. However the traps inside the ledge materials can significantly affect the recombination at the base contact. Since the AlGaAs material has a much higher trap density ($\sim$10 X) than that in InGaP [4], the net result is as if the base contact were pulled in toward the emitter for the case of AlGaAs-GaAs HBT. In other words, the critical spacing for the AlGaAs-GaAs HBT has to be longer to achieve the equivalent device performance. It should be noted that the theoretical critical spacing value as given in Liu *et al.*'s paper [8] was slightly lower than the experimental one. We attributed this small difference to the ledge trap enhanced recombination near the base contact region.

In conclusion, similar to the previous work done for the AlGaAs-GaAs HBT [9], the effect of e–b contact spacing on device dc, RF, and low-frequency noise performance have been investigated for InGaP HBTs. The extrinsic InGaP emitter layer was used as the ledge to protect the exposed extrinsic base region. The result of this study shows that the minimal value required for the e–b contact spacing for an InGaP HBT device is around 0.6$\sim$0.8 μm which is only about half that for the AlGaAs-GaAs devices. At this optimal spacing range, excellent performances in device maximum frequency of oscillation, dc current gain, and low-frequency noise can be simultaneously obtained.

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