WP28

# HIGH-GAIN InAlAs/InGaAs Npn SINGLE HETEROJUNCTION BIPOLAR TRANSISTORS GROWN BY MOLECULAR BEAM EPITAXY

Hao-Hsiung Lin and Chao-Hsing Huang

Department of Electrical Engineering,
National Taiwan University,
Taipei, Taiwan, R. O. C.

## Introduction

Recently, heterojunction bipolar transistors (HBT's) of InP related materials have received a great deal of interest. The heterojunction systems of these HBT's include InP/InGaAsP (1,2), InAlAs/InGaAs (3-5), InP/InGaAs (6), InAlGaAs/InGaAs (7), and etc.. Their base materials, i.e., InGaAs and InGaAsP, have superior electrical properties to GaAs. And the material system is suitable for the long-wavelength optical communications. So far, high current gain (1-4,6,8) and high unit current gain frequcency (5) have been demonstrated. Among the above heterojunction systems, InAlAs/InGaAs owns the largest conduction band discontinuity (9). Hot electron transport in the base of InAlAs/InGaAs abrupt heterojunction bipolar transistor has been reported (10,11).

In this study, we demostrate the growth, fabrication, and characteristics of InAlAs/InGaAs heterojunction bipolar transistors (HBT's). The effect of lattice-mismatch on the device characteristics was firstly studied. It is found that the tolerance of lattice mismatch is $4 \times 10^{-3}$. The abnormal non-1kT collector current and non-2kT base current due to the bias-dependent heterojunction spike were also disscussed. Finally, the I-V characteristics of abrupt and graded HBT's were compared. It is found that the abrupt HBT has smaller output resistance and breakdown voltage. These results are due to the hot electron launching from the potential spike of the abrupt junction. However, the abrupt HBT shows higher current gain, which is as high as 10,000. To our knowledge, this is the highest reported value so far for InAlAs/InGaAs HBT.

## Experiments

The epilayers of the HBT's were grown by using a VG V80-H Mark-II solid source molecular beam epitaxy (MBE) system. The starting material was (100) Sn-doped n$^+$-InP substrate. The details of the basic HBT structure are summerized in Table 1. The compositions of the layers were controlled by measuring the beam equivalent pressure ratios between In, Ga and Al sources. The growth temperatures were 510 °C and 530 °C for InGaAs and InAlAs, respectively. For graded HBT, a 300-Å-thick InAlGaAs graded layer was inserted between the emitter and spacer layer, it was grown by using pulsed molecular beam method (12). In each growth batch, single layer InGaAs and InAlAs were grown on Fe-doped InP substrates with the same growth conditions. These layers were used to determine the lattice mismatch.

Table 1: The layer structure of InAlAs/InGaAs HBT.

| Layer | Material | Dopant | Thickness ($\mu$m) | Doping (cm$^{-3}$) |
|---|---|---|---|---|
| Cap 1 | InGaAs | Si | 0.2 | $4 \times 10^{18}$ |
| Cap 2 | InAlAs | Si | 0.1 | $4 \times 10^{18}$ |
| Emitter | InAlAs | Si | 0.2 | $2 \times 10^{17}$ |
| Spacer | InGaAs | undoped | 0.03 | $\sim 10^{15}$ (n) |
| Base | InGaAs | Be | 0.15 | $2 \times 10^{18}$ |
| Spacer | InGaAs | undoped | 0.2 | $\sim 10^{15}$ (n) |
| Collector | InGaAs | Si | 0.6 | $2 \times 10^{17}$ |
| Buffer | InGaAs | Si | 0.2 | $4 \times 10^{18}$ |
| Substrate | InP | Sn | 350 | $1 \times 10^{18}$ |

To fabricate the HBT's, an 1200-Å-thick Au-Ge-Ni was firstly deposited and lifted-off on the cap layer for the emitter ohmic contact. Solution 1 $H_3PO_4 : 1\ H_2O_2 :$ 20 $H_2O$ was then used to remove both the cap and the emitter layer to expose the base layer. The followed

1500-Å-thick Au/Ti nonalloyed contact was then deposited and lifted-off on the base layer. Finally, the devices were isolated by mesa etching in a 1 $H_3PO_4$ : 1 $H_2O_2$ : 20 $H_2O$ solution. The area of the E-B junction and B-C junction are $1.3 \times 10^{-4}$ $cm^2$ and $9.7 \times 10^{-4}$ $cm^2$, respectively.

## Results and Discussion

Four growth batches with different InGaAs and InAlAs compositions were grown for the study of the effect of lattice mismatch. The lattice mismatch, $\Delta a_{\perp}/a$, of InGaAs and InAlAs layers, and the best current gain obtained were summerised in Table 2. As can be seen, the HBT's show very high current gain except Run No. 119. The HBT's of this run show very leaky output characteristics, and the best current gain is only 70. From the table, it is clear that the tolerance of lattice mismatch is $4 \times 10^{-3}$. Notice that this mismatch is about four times of that of AlGaAs emitter in AlGaAs/GaAs HBT's.

The common emitter $I_C$ versus $V_{CE}$ output characteristics of HBT No. 127 is shown in Fig. 1. As can be seen, the differential current gain is about 7,500 at a collector current of 10 mA. Fig 2 shows the Gummel plot of the transistor. The collector current, $I_C$, exhibits a very high junction ideality factor of 1.64. This non-1-kT transfer $I_C$ characteristics is due to the bias-dependent potential spike at the emitter-base heterojunction (13). Theoretical calculation of the junction ideality factor based on thermionic emission model and depletion approximation is in good agreement with the experimental result (14). The other interesting phenomenon is the junction ideality factor of $I_B$. As can be seen in Fig. 2, its value is 3.10 which is much larger than 1 or 2. However, the value is almost two times of that of $I_C$. Our explaination is as follows. The base current is dominated by the recombination process which takes place in the depletion region of InGaAs side. We believe that it is recombination current because its junction ideality factor is close to two times of that of $I_C$. And only the recombination process which takes place in the depletion region of InGaAs side suffers from the same heterojunction spike effect as $I_C$ does.

In order to study the effect of heterojunction spike on the device characteristics, two HBT's, i. e., abrupt HBT and graded HBT were grown in same batch, their layer structures were identical except the graded band-gap layer of the graded HBT. Fig. 3 shows the common emitter output characteristics of abrupt HBT No. 190. As can be seen, the differential current gain is about 10,000 at a collector current of 6 mA. This very high current gain is comparable to the result of InAlGaAs/InGaAs HBT (8). It indicates that InAlAs emitter still can get very high current gain. Fig. 4 shows the common emitter output characteristics of graded HBT No. 191. As can be seen, the maximum current gain drops to about 2,500. But, its output resistance and breakdown voltage

Table 2: The lattice mismatch and best current gain

| Run No. | Lattice Mismatch, ($\Delta a_{\perp}/a$) InAlAs | InGaAs | Best $\beta$ |
|---|---|---|---|
| 72 | $3.4 \times 10^{-3}$ | $7.1 \times 10^{-4}$ | 2500 |
| 119 | $8.4 \times 10^{-4}$ | $7.9 \times 10^{-3}$ | 70 |
| 127 | $2.4 \times 10^{-3}$ | $2.2 \times 10^{-3}$ | 7500 |
| 136 | $8.6 \times 10^{-4}$ | $-2.2 \times 10^{-3}$ | 6000 |

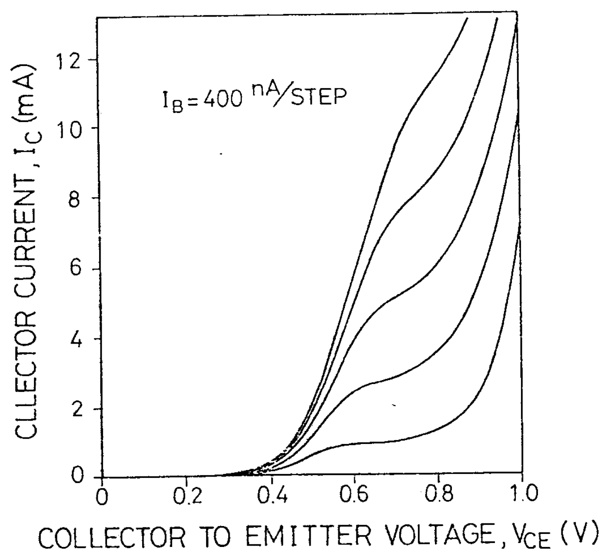


Figure 1 Common emitter output characteristics of HBT No. 127.

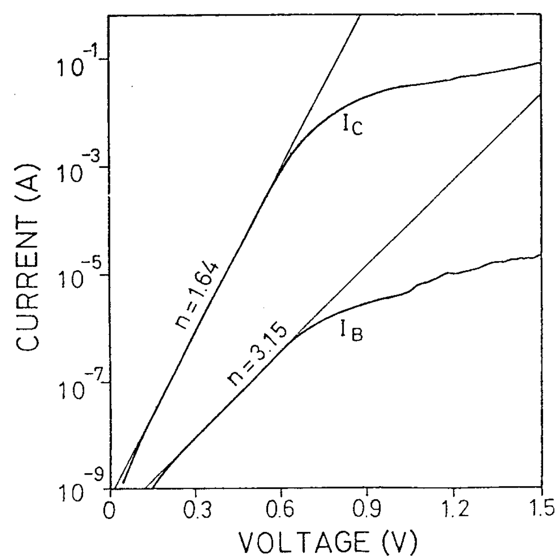


Figure 2 Gummel plot of HBT No. 127.

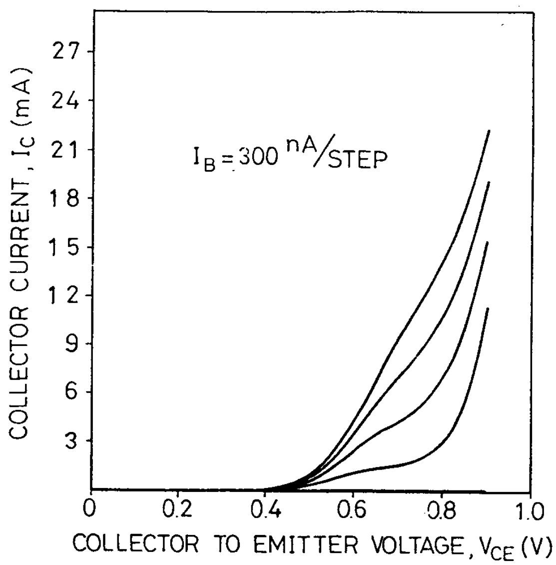


**Figure 3** Common emitter output characteristics of abrupt HBT No. 190.

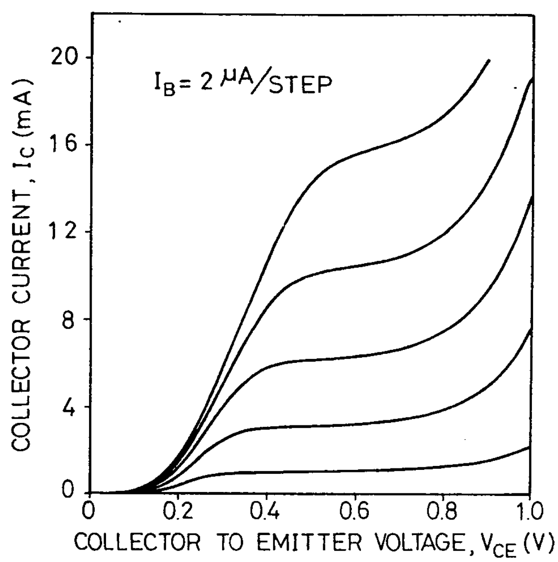


**Figure 4** Common emitter output characteristics of graded HBT No. 191.

are significantly improved. The offset voltage of HBT No. 191 is only 0.04V, while that of HBT No. 190 is as high as 0.2V. It indicates that in HBT No. 191, the heterojunction spike has been smoothed out already (15). Since the HBT's have the same structure except the InAlGaAs graded band-gap layer, the difference between the output resistances and breakdown voltages must be due to the hot electrons induced impact ionization in the base-collector junction. The graded HBT has no heterojunction spike and shows better output resistance and breakdown voltage. However, with the shorter transit time due to the hot electrons and the carrier multiplication due to impact ionization, the abrupt HBT shows very high current gain.

## Conclusions

In conclusion, the I-V characteristics of InAlAs/InGaAs HBT's were studied. The tolerance of lattice mismatch on the device characteristics is as high as $4\times10^{-3}$. The I-V characteristics of abrupt HBT and graded HBT were compared. It is found that the abrupt HBT has smaller output resistance and breakdown voltage. These results are due to the hot electron launching from the heterojunction spike. However, its current gain is as high as 10,000. To our knowledge, this is the highest reported value so far for InAlAs/InGaAs HBT.

## Acknowledgement

This study was supported by the National Science Council of the Republic of China and Telecommunication Laboratories of the Ministry of Communication of the Republic of China under contract No. NSC 81-0404-E002-104.

## References


1. T. Ohishi, Y. Abe, H. Sugimoto, K. Ohtsuka, and T. Matsui, "Ultra-high current gain InGaAsP/InP heterojunction bipolar trarsistor, " Electronics Letters, 26, pp.392-393, 1990.
2. H. Fukano, Y. Itaya, and G. Motosugi, "InGaAsP /InP heterojunction bipolar transistor with high current gain, " Jpn. J. Appl. Phys., 25, pp.L504-506, 1986.
3. R. J. Malik, J. R. Hayes,, F. Capasso, K. Alavi, and A. Y. Cho, "High-gain $Al_{0.48}In_{0.52}As/In_{0.53}Ga_{0.47}As$ vertical n-p-n heterojunction bipolar transistors grown by molecular-beam epitaxy", IEEE Electron Device Lett., EDL-4, pp.383-385, 1983.
4. C. K. Peng, T. Won, C. W. Litton, and H. Morkoc, "A high-performance InGaAs/InAlAs double heterojunction bipolar transistor with nonalloyed $n^+$-InAs cap layer on InP (n) grown by molecular beam epitaxy, " IEEE Electron Device Lett., EDL-9, pp.331-333, 1988.
5. R. N. Nottenburg, Y. K. Chen, M. B. Panish, D. A. Humphrey, and R. Hamm, "Hot-electron InGaAs/InP heterostructure bipolar transistors with $f_T$ of 110 $GH_Z$, " IEEE Electron Device Lett.,EDL-10, pp.30-32, 1989.
6. O. Sugiura, A. G. Dentai, C. H. Joyner, S. Chandrasekhar, and J. C. Campbell, "High-current-gain

InGaAs/InP double-heterojunction bipolar transistors grown by metal organic vapor phase epitaxy," IEEE Electron Device Lett., EDL-9, pp.253-255, 1988.

7. C. S. Kyono, P. Cheung, C. J. Pinzone, N. D. Gerrard, T. Bustami, C. M. Maziar, and R. D. Dupuis, "High-gain, high-speed InGaAs/InP heterojunction bipolar transistors," IEDM Tech. Dig., 1990, pp.677-680.

8. A. Dodabalapur, and T. Y. Chang, "High-gain resonant InGaAlAs/InGaAs heterojunction bipolar phototransistors grown by molecular beam epitaxy," 49th Annual Device Research Conference, IEEE Trans. Electron Devices, ED-38, pp. 2705, 1991.

9. Y. Sugiyama, T. Inata, T. Fujii, Y. Nakata, S. Muto, and S. Hiyamizu, "Conduction band edge discontinuity of $In_{0.52}Ga_{0.48}As$ / $In_{0.52}(Ga_{1-x}Al_x)_{0.48}As$ $(0 \leq x \leq 1)$ heterostructures," Jpn. J. Appl. Phys., 25, pp. L648-650, 1986.

10. B. Jalali, Y. K. Chen, R. N. Nottenburg, D. Sivco, D. A. Humphrey, and A. Y. Cho, "Influence of base thickness on collector breakdown in abrupt AlInAs/InGaAs heterojunction bipolar transistors, " IEEE Electron Device Lett., EDL-11, pp.400-402, 1990.

11. R. N. Nottenburg, A. F. J. Levi, B. Jalali, D. Sivco, D. A. Humphrey, and A. Y. Cho, "Nonequilibrium electron transport in heterostructure bipolar transistors probed by magnetic field," Appl. Phys. Lett., 56, pp. 2660-2662, 1990.

12. T. Fujii, Y. Nakata, Y. Sugiyama, and S. Hiyamizu, "MBE growth of InGaAlAs lattice-matched to InP by pulsed molecular beam method," Jpn. J. Appl. Phys., 25, pp. L254-L256, 1986.

13. H. H. Lin, and S. C. Lee, "Direct measurement of the potential spike energy in AlGaAs/GaAs single-heterojunction bipolar transistors', IEEE Electron Device Lett., EDL-6, pp. 431-433, 1985.

14. H. H. Lin, and C. H. Huang, "I-V characteristics of InAlAs/InGaAs abrupt heterojunction bipolar transistor," Submit to Jpn. J. Appl. Phys.

15. S. C. Lee, J. N. Kau, and H. H. Lin, "Origin of high offset voltage in an AlGaAs/GaAs heterojunction bipolar transistor," Appl. Phys. Lett., 45, pp. 1114-1116, 1984.