GaInAs/GaInAsP/InP heterostructure bipolar transistors with very thin base (150 Å) grown by chemical beam epitaxy

W. T. Tsang and A. F. J. Levi
AT&T Bell Laboratories, Murray Hill, New Jersey 07974
E. G. Burkhardt
AT&T Bell Laboratories, Holmdel, New Jersey 07733

(Received 29 February 1988; accepted for publication 5 July 1988)

It is demonstrated that chemical beam epitaxy (CBE) is suitable for growing high quality GaInAs(P)/InP heterostructure bipolar transistors. Step-graded double-heterostructure bipolar transistors with very thin base (150 Å) and very high p doping ($\sim 5\times10^{19}$ cm^{-3}), and with an added "grading layer" of 200 Å GaInAsP ($E_g = 0.94$ eV) between the GaInAs/InP base-collector junction, have shown good current drive capability and excellent current gain ($\beta = 2500$). In addition, CBE-grown standard single-heterostructure bipolar transistors with a 1000 Å base and 2×10^{18} cm^{-3} p doping are characterized by high gain, $\beta\sim3500$, which is only weakly dependent on the collector current.

Heterojunction bipolar transistors (HBT's) made from III-V compound semiconductors are important for microwave and high-speed switching applications.[1-6] GaInAs/InP HBT's are particularly attractive for optoelectronic integrated circuit applications because of their material compatibility with long-wavelength sources and detectors in the 1.3–1.55 μm wavelength range. Compared with GaAlAs/GaAs HBT's, superior high-frequency performance is also expected because of the higher electron mobility of GaInAs and greater drift velocity at high fields of InP relative to GaAs. The low surface recombination velocity of GaInAs/InP also ensures an excellent current gain at low collector current densities,[7] making the device very attractive for analog applications.

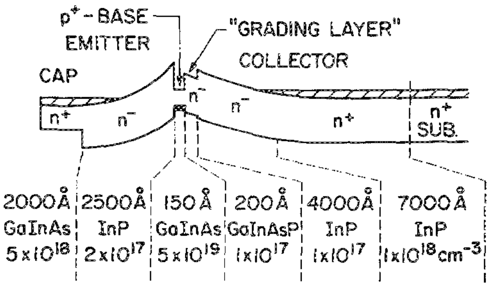
To date, most of the HBT's studied[7-9] have the thickness of the GaInAs base in the range of 0.1–0.2 μm and p dopings $\sim 1\times10^{17}$–1×10^{18} cm^{-3}. These parameters were chosen for achieving high current gains. The low p-doping level in the base increases the minority-carrier diffusion length and hence increases the gain, while the relatively thick base layer is needed for reducing the base resistance. For microwave performance it is desirable to have a thin base layer to reduce the base transit time. To keep the base sheet resistance at a low value (and hence minimize the base charging time), the base doping has to be increased to $\sim 5\times10^{19}$ cm^{-3}. However, at these very high base doping levels the reduced minority-carrier lifetime limits the base transport efficiency and thus the current gain, if a thick base layer is used; this was shown by Nottenberg *et al.*[10] They studied the base doping effects in step-graded double-heterostructure bipolar transistors (DHBT's) and obtained current gains, $\beta\sim100$, at base doping levels of $\sim 3\times10^{19}$ cm^{-3} with a 0.12-μm-thick base. In order to increase the current gain, we investigate the static transistor characteristics of DHBT's having a very thin base (150 Å) and very high p doping of $\sim 5\times10^{19}$ cm^{-3}. A 200-Å-thick GaInAsP ($E_g = 0.94$ eV) "grading layer" is also grown between the GaInAs/InP base-collector junction. This effectively reduces the conduction-band spike at this heterointerface [see Fig. 1(a)] and hence improves the collection efficiency of the electrons injected into the base, making it capable of higher current drive over standard DHBT's.

Previously, a few bipolar-type transistors have been proposed which employ a voltage-induced two-dimensional hole base as in the bipolar inversion channel field-effect transistor[11] and inversion base bipolar transistor.[12] Recently, Malik *et al.*[13] also proposed a planar-doped base HBT in which the base is formed by depositioin of Be atoms on a GaAs surface during growth interruption by molecular beam epitaxy (MBE). The effective neutral base width was estimated to be ~100 Å.

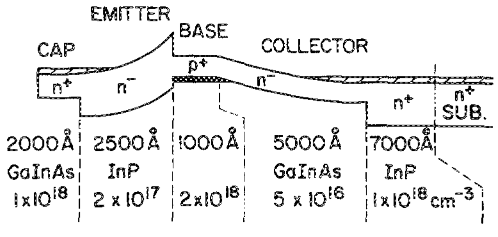
Reduction of device dimensions to such short-length scales imposes special demands on crystal growth. High quality emitter/base heterojunction diodes require exact spatial placement of the necessarily heavily doped p-n junction at the heterointerface. The purpose of this letter is to demonstrate that high-purity, low-temperature chemical beam epitaxy (CBE)[14,15] is a suitable method for preparing sophisticated, high-performance GaInAs(P)/InP heterojunction bipolar transistors. We present results from studies of both single- and double-heterojunction bipolar transistors (SHBT and DHBT, respectively).

Figure 1 shows the energy-band diagrams and layer structures for the SHBT's and DHBT's studied. These heterostructures were grown by CBE at 540 °C on (100) n^+-InP substrates. Details of the growth conditions were described previously.[16,17] Trimethylindium, triethylgallium, arsine, and phosphine were used as the main vapor sources. Tin and beryllium evaporated from solid elements in Knudsen cells were used as the n and p dopants, respectively. The relatively low growth temperature results in minimal Be outdiffusion from the base layer even at the high doping levels employed. After epitaxial growth, 100-μm-diam emitter mesa structures were formed with standard selective wet chemical etching and ohmic contact formation.

Figure 2 shows the common emitter current gain β plot-



(a) STEP-GRADED DHBT WITH THIN BASE



(b) STANDARD SHBT

FIG. 1. Schematic energy-band diagrams of (a) a step-graded double-heterostructure bipolar transistor and (b) a standard single-heterostructure bipolar transistor. The layer thicknesses and doping levels are given in the figures.

ted as a function of collector current I_c for a SHBT. At current densities as low as 1 mA/cm^2, $\beta \gtrsim 100$ is measured. Such high β values at these very low current levels attest to the high quality of the emitter-base heterojunction. This is also confirmed by the InP/GaInAs *n-p* junction diode characteristics measured from these SHBT's. A *typical* current-voltage (*I-V*) characteristic measured at 300 K is shown in Fig. 3. The ideality factor is $n = 1.07$, and the best ideality value we have measured is $n = 1.03$. Such an ideal *n-p* emitter-base heterojunction is consistent with the observed weak dependence of gain on the collector current.[9] At a very high current density of ~ 6.4 kA/cm^2 (~ 500 mA), $\beta \sim 3500$ was obtained. These performance characteristics obtained from standard SHBT's confirm that CBE is capable of producing high quality HBT's.

We then fabricated the more sophisticated step-graded DHBT structure shown in Fig. 1(b). Note that these are the first DHBT's having such thin base layes. Figure 4 shows the common-emitter characteristic of such a DHBT with a 150 Å GaInAs base and a 200 Å GaInAsP "grading layer" at high collector currents. The important results obtained from this step-graded DHBT are the greatly increased current gain due to the use of thin base and maximum current drive capability over the standard DHBT's. From Fig. 4 it is seen that $I_c > 350$ mA ($\gtrsim 4.5$ kA/cm^2) can be obtained. The current drive capability of these devices is comparable with step-graded DHBT's.[10] The conduction-band spike at the base/collector interface can impair the performance of standard DHBT in that the maximum current gain peaks at relatively low current densities.[18] Transistors with high current drive properties are very attractive in applications such as

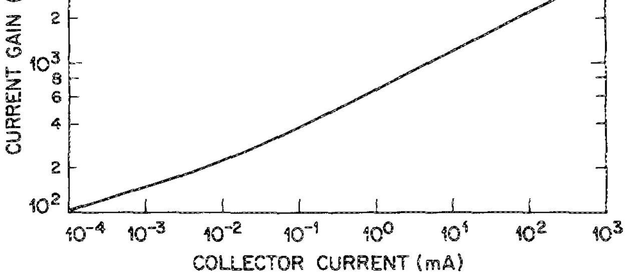


FIG. 2. Plot of current gain vs collector current of a GaInAs/InP SHBT.

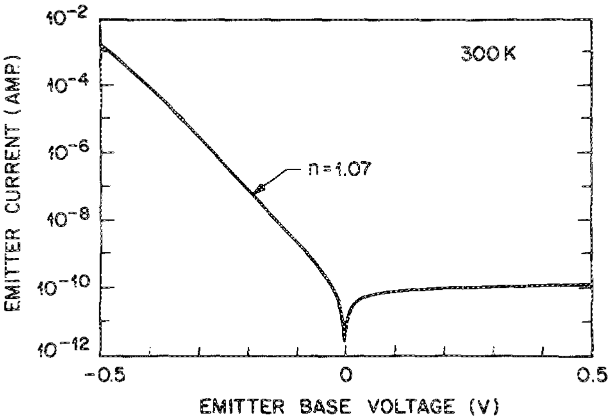


FIG. 3. Current-voltage characteristics of the emitter-base junction. Ideality factor n is typically 1.07, with $n = 1.03$ measured from the best diodes.

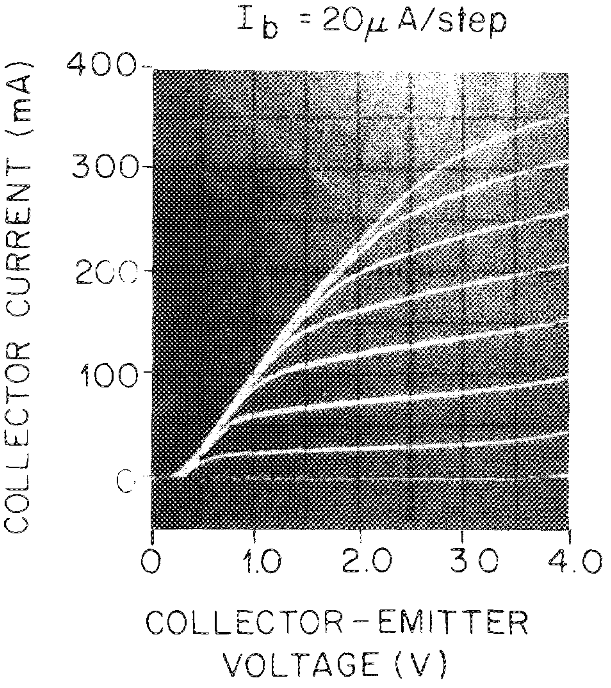


FIG. 4. Common-emitter characteristic for a step-graded DHBT with a 150 Å base, $\sim 5 \times 10^{19}$ cm^{-3} p doping, and a 200 Å GaInAsP "grating layer" at high collector drive currents.

semiconductor laser drivers where high-speed modulation of large currents is required. Note that the current drive capability of step-graded DHBT is similar to that of SHBT's which has a GaInAs base-collector homojunction. This indicates that the step grading is effective in reducing the conduction spike at the base-collector heterojunction.

In summary, the above results serve to demonstrate that CBE is suitable for growing high quality sophisticated bipolar transistors especially when a very thin base layer and a very high base p doping with minimum interdiffusion are required. Step-graded DHBT's with 150-Å-thick base and $\sim 5\times 10^{19}\,\mathrm{cm}^{-3}$ doping have shown greatly improved maximum current drive capability and current gain ($\beta \sim 2500$) compared to standard DHBT's with thick base. Conventional SHBT's are characterized by high gain, $\beta \sim 3500$, which is only weakly dependent on the collector current. The current-voltage characteristics of the emitter-base junction are near ideal, with the best diodes exhibiting an ideality factor $n = 1.03$.

The authors would like to thank R. N. Nottenburg for useful discussions.

[1] H. Kroemer, Proc. IEEE **70**, 13 (1982).

[2] D. Ankri, A. Scavennec, C. Courbet, F. Heliot, and J. Riou, Appl. Phys. Lett. **40**, 816 (1982).

[3] M. C. F. Chang, P. M. Asbeck, K. C. Wang, G. J. Sullivan, N. H. Sheng, J. A. Higgins, and D. L. Miller, IEEE Electron Device Lett. **EDL-8**, 303 (1987).

[4] T. Izawa, T. Ishibashi, and T. Sugeta, IEDM Tech. Dig. **1985**, 328 (Dec. 1985).

[5] T. Ishibashi and Y. Yamauchi, presented at the 45th Annual Device Research Conference, University of Colorado at Santa Barbara. 22–24 June 1987.

[6] H. Ito, T. Ishibashi, and T. Sugeta, IEEE Electron Device Lett. **EDL-5**, 214 (1984).

[7] R. N. Nottenburg, H. Temkin, M. B. Panish, R. Bhatt, and J. C. Bischoff, IEEE Electron Device Lett. **EDL-7**, 643 (1986).

[8] H. Kanbe, J. C. Vlcek, and C. G. Fonstad, IEEE Electron Device Lett. **EDL-5**, 172 (1984).

[9] R. N. Nottenburg, H. Temkin, M. B. Panish, and R. A. Hamm, Appl. Phys. Lett. **49**, 1112 (1986).

[10] R. N. Nottenburg, J. C. Bischoff, M. B. Panish, and H. Temkin, IEEE Electron Device Lett. **EDL-8**, 282 (1987).

[11] G. W. Taylor and J. G. Simmons, IEEE Trans. Electron Devices **ED-32**, 2345 (1985).

[12] K. Matsumoto, Y. Hayashi, N. Hashizume, T. Yao, M. Kato, T. Miyashita, N. Fukuhara, H. Hirashima, and T. Kinosada, IEEE Electron Device Lett. **EDL-7**, 627 (1986).

[13] R. J. Malik, L. M. Lunardi, J. F. Walker, and R. W. Ryan (unpublished).

[14] W. T. Tsang, Appl. Phys. Lett. **45**, 1234 (1984).

[15] W. T. Tsang, J. Cryst. Growth **81**, 261 (1987).

[16] W. T. Tsang, A. H. Dayeni, T. H. Chin, J. E. Cunningham, E. F. Schubert, J. A. Ditzenberger, J. Shah, J. L. Zyskind, and N. Tabatabase, Appl. Phys. Lett. **49**, 170 (1986).

[17] W. T. Tsang, E. F. Schubert, T. H. Chin, J. E. Cunningham, E. G. Burkhardt, J. A. Ditzenberger, and E. Agyekum, Appl. Phys. Lett. **51**, 761 (1987).

[18] H. Schumacher, J. R. Hayes, R. Bhatt, and M. Koza, Proc. IEDM **1987**, 852 (Dec. 1987).