GalnAs/GalnAsP/lnP heterostructure bipolar transistors with very thin base (150 Å) grown by chemical beam epitaxy

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It is demonstrated that chemical beam epitaxy (CBE) is suitable for growing high quality GaInAs(P)/lnP heterostructure bipolar transistors. Step-graded double-heterostructure bipolar transistors with very thin base (150 Å) and very high \( p \) doping (\( \sim 5 \times 10^{19} \text{ cm}^{-3} \)), and with an added "grading layer" of 200 Å GaInAsP (\( E_g = 0.94 \text{ eV} \)) between the GaInAs/lnP 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 \( 2 \times 10^{18} \text{ cm}^{-3} \) \( p \) doping are characterized by high gain, \( \beta \sim 3500 \), 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. GaInAs/lnP 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 lnP relative to GaAs. The low surface recombination velocity of GaInAs/lnP also ensures an excellent current gain at low collector current densities, making the device very attractive for analog applications.

To date, most of the HBT’s studied have the thickness of the GaInAs base in the range of 0.1–0.2 μm and \( p \) dopings \( \sim 1 \times 10^{17}–1 \times 10^{18} \text{ cm}^{-3} \). 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 \( \sim 5 \times 10^{19} \text{ cm}^{-3} \). 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. 

They studied the base doping effects in step-graded double-heterostructure bipolar transistors (DHB TT’s) and obtained current gains, \( \beta \sim 100 \), at base doping levels of \( \sim 3 \times 10^{19} \text{ cm}^{-3} \) with a 0.12-μm-thick base. In order to increase the current gain, we investigate the static transistor characteristics of DHB TT’s having a very thin base (150 Å) and very high \( p \) doping of \( \sim 5 \times 10^{19} \text{ cm}^{-3} \). A 200-Å-thick GaInAsP (\( E_g = 0.94 \text{ eV} \)) “grading layer” is also grown between the GaInAs/lnP 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 DHB TT’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 and inversion base bipolar transistor. Recently, Malik et al. 

also proposed a planar-doped base HBT in which the base is formed by deposition of 3Be atoms on a GaAs surface during growth interruption by molecular beam epitaxy (MBE). The effective neutral base width was estimated to be \( \sim 100 \text{ Å} \).

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) is a suitable method for preparing sophisticated, high-performance GaInAs(P)/lnP heterojunction bipolar transistors. We present results from studies of both single- and double-heterojunction bipolar transistors (SHBT and DHB TT, respectively).

Figure 1 shows the energy-band diagrams and layer structures for the SHBT’s and DHB TT’s studied. These heterostructures were grown by CBE at 540 °C on (100) n + InP substrates. Details of the growth conditions were described previously. 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 \( \beta \) plot.
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.

First DHBT's having such thin base layers. 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 thick base and maximum current drive capability over the standard DHBT's. From Fig. 4 it is seen that $I_e > 350 \text{ mA}$ ($\geq 4.5 \text{ kA/cm}^2$) can be obtained. The current drive capability of these devices is comparable with step-graded DHBT's. 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. 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, $5 \times 10^{16}$ cm$^{-3}$ n-p doping, and a 200 Å GaInAsP "grading layer" at high collector drive currents.

$\beta = 20 \mu A/\text{step}$
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, 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-A-thick base and $\sim5 \times 10^{19} \text{cm}^{-3}$ 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 $n = 1.03$.

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