InGaP/GaAs/InGaP DOUBLE HETEROSTRUCTURE BIPOLAR TRANSISTORS WITH CARBON-DOPED BASE GROWN BY CBE

Y. K. Chen, R. Rapre, W. T. Tsang and M. C. Wu

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Carbon-doped InGaP/GaAs/InGaP double heterostructure bipolar transistors with 25-A setback layer are grown by chemical beam epitaxy. Transistors with notalloyed base contacts show a very high common emitter current gain of 120 and very low collector saturation voltage of 75 mV at room temperature.

Introduction: Conventional GaAs-based heterostructure bipolar transistors (HBTs) which use Si as an emitter have demonstrated excellent device and circuit performance [1]. A large valence band offset $\Delta E_v$ at the emitter/collector heterojunction in a HBT is very advantageous to effectively confine holes in the heavily-doped base. This hole confinement permits a high base-to-emitter doping ratio to enhance the high frequency performance of the HBT without sacrificing current gain [2]. Recently, there has been much interest in replacing the commonly used Si-doped, heavily-doped GaAs substrate with In$_{0.53}$Ga$_{0.47}$As, which is lattice-matched to GaAs substrate, as the wide-gap emitter for HBTs [3-7]. The aluminum-free In$_{0.53}$Ga$_{0.47}$As/GaAs heterojunction bipolar transistor (HBT) is a high-speed device with large frequency performance [5, 8-10]. A recent report using the internal photomission measurement [11] of In$_{0.53}$Ga$_{0.47}$As/GaAs photodiodes indicates a conduction band discontinuity of 108 meV. Nevertheless, the large valence band offset energy $\Delta E_v$ of 0.3 eV of the In$_{0.53}$Ga$_{0.47}$As/GaAs heterointerface is high enough for HBT applications. Similar valence band discontinuity can only be obtained with an Al$_{x}$Ga$_{1-x}$As/GaAs heterointerface with high aluminum concentration and a large conduction band discontinuity. A large $\Delta E_v$ value is desirable in designing double heterostructure bipolar transistors (DHBTs) which use a wide-gap collector to enhance the breakdown voltage of the transistors. Because of the quantum reflection of the injected electrons from the potential spike at the base-collector junction, the current gain of DHBTs will be reduced, as shown in Fig. 1. Usually, a compositionally graded collector region or an extended small bandgap collector region is needed to lower the potential spike for the injected minority carriers at the base-collector interface. Minority carriers trapped by the potential barrier at the base-collector interface reduce current gain and generate an undesirable charge storage effect in the collector depletion region during large switching transients. With the smaller $\Delta E_v$ of InGaP/GaAs, very little charge accumulation is generated and the collector depletion region in the small bandgap material is reduced. The use of carbon doping promises high doping concentration in the GaAs base and a p-type doping concentration as high as $10^{21}$ cm$^{-3}$ has been reported [12]. Compared to the commonly used Be dopants in GaAs [13], the low diffusion of carbon dopants preserves the integrity of the emitter/base heterojunction during the growth and improves the reliability of transistors [14]. In this Letter, the advantages of the large $\Delta E_v$/$\Delta E_c$ ratio of the InGaP/GaAs heterointerface and the high carbon-doped GaAs base are illustrated by an InGaP/GaAs/InGaP double heterostructure bipolar transistor.

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It can be shown that arbitrary bit lines and input bridging faults in DPLA can be detected by a test set $T \cup \bar{T}$, where $\bar{T}$ is obtained by complementing each bit in the test set $T$. Acknowledgment: This work was supported in part by National Science Foundation grant MIP-9111886.

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Fig. 1 Schematic diagrams of InGaP/GaAs/InGaP and InGaP/GaAs/GaAs heterostructure bipolar transistors.
GaAsIlnCaP DHBT with bipolar transistors with carbon-doped base. Characteristics of a carbon-doped InGaPiGaAslInGaP DHBT (Vol., 1229).

**Fig. 2** Layer structure of InGaP/GaAs/InGaP double heterojunction bipolar transistors with carbon-doped base.

Undoped base setback layer is only 25 Å.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>n+ In0.2Ga0.8As</td>
<td>50 Å</td>
<td>2 × 10^{18}</td>
</tr>
<tr>
<td>p+ GaAs</td>
<td>2500 Å</td>
<td>2 × 10^{19}</td>
</tr>
<tr>
<td>N+ In0.4Ga0.6As</td>
<td>2500 Å</td>
<td>1 × 10^{18}</td>
</tr>
<tr>
<td>n+ GaAs</td>
<td>25 Å</td>
<td>2 × 10^{19}</td>
</tr>
<tr>
<td>p+ In0.4Ga0.6As</td>
<td>4000 Å</td>
<td>1 × 10^{17}</td>
</tr>
<tr>
<td>n+ GaAs</td>
<td>2500 Å</td>
<td>2 × 10^{18}</td>
</tr>
<tr>
<td>GaAs buffer</td>
<td>2500 Å</td>
<td>—</td>
</tr>
<tr>
<td>SI GaAs substrate</td>
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The room-temperature common-emitter current-voltage characteristics of a carbon-doped InGaP/GaAs/InGaP DHBT with 10 × 40 μm² emitter area is shown in Fig. 3. It shows a DC current gain of 120 with a very small collector saturation voltage (V_{CE(sat)}) of 75 mV. The collector breakdown voltage is 3.7 V which comes from the relatively thin and highly-doped collector region. The breakdown voltage can be further increased with a thicker and lightly-doped collector. The Gummel plot of the collector current and base current is shown in Fig. 4. A collector current ideality factor of 1.1 indicates a dominant thermionic electron injection process over the small InGaP/GaAs emitter-base heterojunction. The ideality factor of the base current is 1.6. The maximum current gain of 120 is obtained at a collector current density of 2 kA/cm². Current gain up to 18 is obtained at a low collector current of 10 μA which indicates excellent InGaP/GaAs emitter-base heterointerfaces and the effectiveness of nonalloyed base contact.

**Fig. 3** Room-temperature common-emitter characteristics of InGaP/GaAs/InGaP DHBT with 10 × 40 μm² emitter area.

Collector saturation voltage is 75 mV.

In summary, we have fabricated InGaP/GaAs/InGaP double heterojunction bipolar transistors which exploit the large ΔE_c of the InGaP/GaAs emitter, the small ΔE_v of the InGaP/GaAs collector, and heavily-doped GaAs base with carbon using the CBE growth technique. With a 25 Å base setback layer, a current gain of 120 is obtained at a collector current density of 2 kA/cm². Current gain up to 18 is obtained at a low collector current of 10 μA which indicates excellent InGaP/GaAs emitter-base heterointerfaces and the effectiveness of nonalloyed base contact.

**Fig. 4** Room-temperature Gummel plot of carbon-doped InGaP/GaAs/InGaP DHBT.

Idealities factors are 1.1 and 1.6 for collector current and base current, respectively.

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**References**

HIGH-FREQUENCY PERFORMANCE FOR SUB-0.1 µm GATE InAs-INSERTED-CHANNEL InAlAs/InGaAs HEMT

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InAlAs/InGaAs high electron mobility transistors (HEMTs) lattice-matched to InP substrates have demonstrated excellent high-frequency and low-noise performance, compared with AlGaAs/GaAs HEMTs [1-3]. The high performance is explained by the high electron mobility, saturation drift velocity, and sheet carrier density of the InAlAs/InGaAs two-dimensional electron gas (2-DEG) system.

Recently, we reported a 200 GHz cutoff frequency with a 0.12µm gate length HEMT. We also demonstrated that electron transport properties and device performances could be further improved using an InAlAs/InGaAs high electron mobility transistors (HEMT) grown by molecular beam epitaxy (MBE) on a semi-insulating InP substrate. The InAs layer thickness, designed to reduce the source and drain series resistance, has 25 Å. The total thickness of the channel layer including the InAs layer is 300 Å. The planar-doped InAlAs layer, which was deposited and lifted off. The sheet resistance for the whole layer was 115Ω/µm at a drain bias of 2 V.

For the fabrication process, first, mesa etching for device isolation was carried out by ECR (electron cyclotron resonance) type RIE (reactive ion etching) using a mixture of C3F8 and Ar gas. Ti/Pt/Al was deposited and lifed off to form the source and drain nonalloyed ohmic contacts. A T-shaped gate was formed using electron beam lithography as follows. After depositing a SiN passivation film 0.1 µm thick, the Schottky contact regions of the passivation layer were etched by RIE using a resist pattern formed by electron beam lithography as an etching mask. Next, the resist pattern for the gate-top portion was made by photolithography. Finally, after the gate recess etching, the gate metals of Ti/Pt/Al were deposited and lifed off.

The contact resistance, R0, of the InAs-inserted-channel HEMT was determined to be 0.07Ω·µm by TLM measurement. The sheet resistance for the whole layer was 115Ω/µm. The source series resistance, R1, of the InAs-inserted-channel HEMT was estimated to be 0.13Ω·µm.

Fig. 2 shows the current-voltage characteristics of the InAs-inserted-channel HEMT. Excellent pinchoff characteristics are obtained. The maximum extrinsic transconductance is ~215 S/µm at a drain bias of 2 V.

In this Letter, we report the excellent high-frequency performance of the InAs-inserted-channel HEMT with a sub-0.1 µm gate length prepared using the T-gate fabrication process. The Letter examines the high-frequency performance of a sub-0.1 µm gate InAlAs/InGaAs HEMT with a thin InAs layer inserted into the InGaAs channel. The transconductance is 2.1 S/µm and the current-gain cutoff frequency is 264 GHz using a 0.08 µm-long gate.

InAlAs/InGaAs HEMT with a thin InAs layer inserted into the InGaAs channel. The transconductance is 2.1 S/µm and the current-gain cutoff frequency is 264 GHz using a 0.08 µm-long gate.

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