InAlAsSb/InGaSb double heterojunction bipolar transistor

R. Magno, J.B. Boos, P.M. Campbell, B.R. Bennett, E.R. Glaser, B.P. Tinkham, M.G. Ancona, K.D. Hobart, D. Park and N.A. Papanicolaou

An *npn* double heterojunction bipolar transistor has been made using $In_{0.27}Ga_{0.73}Sb$ for the base and two different $In_xAl_{1-x}As_ySb_{1-y}$ alloys for the emitter and collector. It has a common emitter current gain of 25. The emitter-base voltages required for a given collector current are smaller than those of InP-based HBTs.

Introduction: Minimising the power dissipation in heterojunction bipolar transistors (HBTs) while maintaining high-frequency operation is an important goal particularly for electronic devices to be used in battery powered systems. The use of a narrow bandgap semiconductor for the base reduces the size of the emitter-base voltage required for a given collector current, which is an important factor in obtaining low power dissipation. In this work, we used $In_{0.27}Ga_{0.73}Sb$ with a bandgap near 0.5 eV for the base layer, compared to the 0.6–0.75 eV for the base layers in state-of-the-art InGaAs/InP or Si/SiGe HBTs. The two different $In_xAl_{1-x}As_ySb_{1-y}$ alloys used for the emitter and collector along with the $In_zGa_{1-z}Sb$ base constitute a new group of semiconductors for making an *npn* double heterojunction bipolar transistor (DHBT). The group of alloys reported here has a lattice constant of 6.2 Å [1]. Even higher performance is expected for similar alloys with a lattice constant nearer to 6.3 Å as the InGaSb base would have an even narrower bandgap of ~0.3 eV. In related work, several groups have recently reported the development of low-power *npn* HBTs with an InAs base [2–5].

The emitter-base and base-collector conduction band offsets are important parameters in determining the performance of a DHBT. Interpolation methods developed for the III–V alloys indicate that a large range of conduction band offsets are available for $In_xAl_{1-x}As_ySb_{1-y}$ relative to $In_zGa_{1-z}Sb$ at a fixed lattice constant while maintaining a large valence band offset [6]. The conduction band offset tuning is accomplished by varying the In/Al and As/Sb ratios of the InAlAsSb. A large valence band offset is also important as it prevents parasitic hole currents from flowing from the base into the emitter. For the 6.2 Å lattice constant alloys, the models predict that the $In_{0.27}Ga_{0.73}Sb$ base valence band is about 350 meV above the valence band of $In_xAl_{1-x}As_ySb_{1-y}$ layers almost independent of x and y [6].

High-frequency operation also requires a base layer with a small parasitic resistance. We have measured a mobility of 160 cm^2/V s with a hole concentration of 3×10^{19} cm^{-3} for 1 µm-thick Be-doped $In_{0.27}Ga_{0.73}Sb$ layers in our laboratory. With this we project a sheet resistance of 325 Ω/square for a 40 nm-thick base which is small compared to the sheet resistances ~500–1000 Ω/square for the InGaAs and GaAsSb used in DHBTs lattice matched to InP. Low resistance ohmic contacts to *p*-type InGaSb can also be readily achieved [7].

Experimental details: The samples used in this work were grown by solid source molecular beam epitaxy with valved sources for As_2 and Sb_2. Te is used for the *n*-type dopant in the InAlAsSb alloys and Be is used for the *p*-type dopant in the InGaSb. A growth rate of one monolayer per second was used for each layer. The group III sources were calibrated using RHEED oscillations on test structures. Flux measurements were used to set the valves of the group V sources. Many test layers were prepared to determine the required group V fluxes and the optimum growth temperature [1].

The alloy composition and doping concentrations of the emitter-base-collector structure are illustrated in Fig. 1. As there are no commercially available substrates with a 6.2 Å lattice constant, GaSb with a 6.0954 Å lattice constant was used along with a 1.0 µm AlSb buffer layer (lattice constant of 6.135 Å) to help accommodate the lattice mismatch between the GaSb and DHBT material. The collector alloy composition was grown to a thickness of 1.2 µm to accommodate the remaining lattice mismatch in order to have a 6.2 Å lattice constant near the base. The bottom 0.2 µm of the collector layer was heavily doped to aid in obtaining a low resistance contact. A 100 nm-thick base with a *p*-type doping of 5×1018 cm^{-3} was chosen for this first device to minimise the possibility of Be segregation into the emitter layer. A relatively thick base has been used to minimise difficulties in etching through the emitter to the base. The emitter contains 250 nm of $In_{0.52}Al_{0.48}As_{0.25}Sb_{0.75}$ with a 200 nm layer doped at 3×10^{17} cm^{-3} and an additional 50 nm heavily doped layer designed to aid in obtaining a low-resistance contact. The final part of the emitter consists of 30 nm of the narrow-bandgap collector alloy and a thin InAs top layer to aid in obtaining a low-resistance ohmic contact.

InAs 20 nm $n^+ = 3e18\ cm^{-3}$
$In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}$ 30 nm $n = 3e18\ cm^{-3}$
$In_{0.52}Al_{0.48}As_{0.25}Sb_{0.75}$ 20 nm $n^+ = 3e18\ cm^{-3}$
30 nm grade $n = 3e17$ to $3e18\ cm^{-3}$
200 nm $n = 3e17\ cm^{-3}$
$In_{0.27}Ga_{0.73}Sb$ 100 nm $p^+ = 5e18\ cm^{-3}$
$In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}$ 1 µm $n = 3e16\ cm^{-3}$
0.1 µm grade $n = 3e18$ to $3e16\ cm^{-3}$
0.1 µm n^+ $3e18\ cm^{-3}$

Fig. 1 *Layer structure for 6.2 Å lattice constant InAlAsSb/InGaSb DHBT (GaSb substrate and AlSb buffer not shown)*

Devices were fabricated using optical lithography and wet etching to define the mesas and ohmic contact areas. Defining the 2.8 × 20 µm emitter stripe required several steps of etching and testing to determine when the base layer had been reached. Thinner base layers will be used in the future now that processing techniques have been established. A Pd/Pt/Au unalloyed ohmic contact was used for the base and unalloyed Cr/Au was used to contact the emitter and collector.

Results: The common-emitter I-V curves for the DHBT shown in Fig. 2 indicate a DC current gain of 25. The maximum collector current, I_c, in Fig. 2 corresponds to a density of 1.8×10^4 A/cm^2. The low collector-emitter offset voltage of 220 mV in Fig. 2 supports the possibility of low power dissipation. The Gummel plot presented in Fig. 3 demonstrates the small emitter-base voltages, V_{BE}, required to have collector currents to 9 mA or 1.6 × 104 A/cm^2. The difference between this DHBT and an InP DHBT with an $In_{0.53}Ga_{0.47}As$ base can be seen by comparing the emitter-base voltages needed for a collector current density of 100 A/cm^2. In Fig. 3, this corresponds to $I_C = 5.5 \times 10^{-5}$ A which occurs at $V_{BE} = 260$ mV. This is smaller than the 500 mV needed for an InP DHBT with an $In_{0.53}Ga_{0.47}As$ base [8].

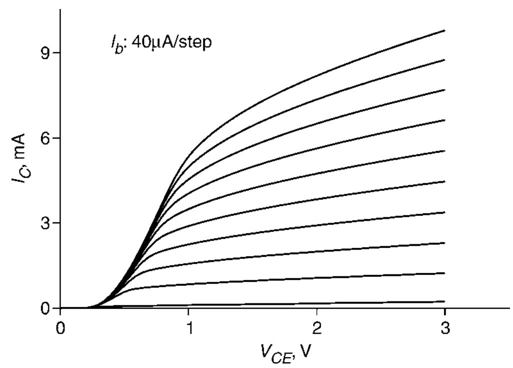

Fig. 2 *Common-emitter I–V data for DHBT with 2.8 × 20 µm emitter area*

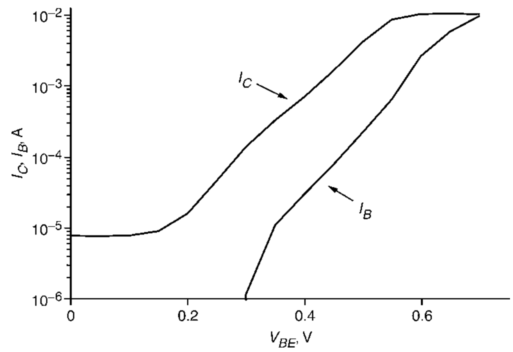

Fig. 3 *Gummel plot for DHBT*

Discussion: In summary, a DHBT made of InAlAsSb/InGaSb alloys has been developed. The results presented here illustrate a number of properties that indicate low power dissipation is possible. For a given current density the emitter-base voltage is about one half that required for an InP DHBT, and the collector-emitter offset voltage is a low 220 mV. The device presented here was designed using conservative rules to obtain a first device to act as a benchmark to judge future improvements. As mentioned above, it is possible to reduce the base sheet resistance by close to a factor of 6 by increasing the Be concentration. A substantial reduction in collector resistance can also be obtained by using an InAsSb subcollector layer. InAsSb layers with a 6.2 Å lattice constant with a mobility of $6000\ cm^2/V s$ at a carrier concentration of $2 \times 10^{18}\ cm^{-3}$ have already been grown in our laboratory. In addition the InAsSb alloy has a bandgap ~ 0.2 eV, which should result in much lower contact resistance to the collector. Grading the composition of the $In_{0.27}Ga_{0.73}Sb$ base is expected to enhance the operating frequency. The output power may be optimised for specific applications by adjusting the collector bandgap through choosing the appropriate composition for the $In_xAl_{1-x}As_ySb_{1-y}$ collector. Work is also under way to grow these layers on SI-GaAs substrates, which will allow high-frequency RF testing.

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E-mail: magno@bloch.nrl.navy.mil

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