$In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}/In_{0.27}Ga_{0.73}Sb$ double-heterojunction bipolar transistors with $InAs_{0.66}Sb_{0.34}$ contact layers

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Presented are the first DC and RF results for a double heterojunction bipolar transistor, at a 6.2 Å lattice constant, incorporating $InAs_{0.66}Sb_{0.34}$. These devices show excellent performance with a high collector current density of 1.9×10^5 A/cm^2, high breakdown voltage over 2.5 V, high short-circuit current gain cutoff frequency of 59 GHz, and maximum frequency of oscillation of 34 GHz.

Introduction: The 6.1 Å materials, and by extension the 6.2 Å materials, have shown great promise for low-power, high-speed performance owing to a large range of available bandgaps, band offsets, and high electron and hole mobilities [1–4]. Diodes fabricated in the 6.2 Å material system have shown high current densities at very low voltages, leading to devices that consume half the power of similar InP-based devices and a fifth the power of similar GaAs-based devices. In this Letter, the first $In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}/In_{0.27}Ga_{0.73}Sb$ double-heterojunction bipolar transistors (HBTs) incorporating $InAs_{0.66}Sb_{0.34}$ for use as the emitter contact and sub-collector layers is presented. Use of $InAs_{0.66}Sb_{0.34}$ results in a significant improvement in performance over the first reported HBTs in this material system [5]. These devices show excellent DC and RF performance with the highest measured short-circuit current gain cutoff frequency (f_τ) for an HBT fabricated in this material system.

Growth and fabrication: The HBTs were grown by solid-source molecular beam epitaxy (MBE) using As_2 and Sb_2 from valved cracking sources. From substrate to surface, the growth consisted of a semi-insulating (SI) GaAs substrate; a buffer of 3000 Å GaAs, 12 Å AlSb, 5000 Å $Al_{0.65}Ga_{0.35}Sb$, and 1 μm of $In_{0.21}Ga_{0.19}Al_{0.60}Sb$; a 5000 Å n^+ (Te: 4×10^{18} cm^{-3}) $InAs_{0.66}Sb_{0.34}$ sub-collector; a 1950 Å n $In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}$ collector consisting of a 400 Å doping grade (Te: $4 \times 10^{18} \sim 5 \times 10^{16}$ cm^{-3}) adjacent to the subcollector, a 1500 Å low doped (Te: 5×10^{16} cm^{-3}) region, and a 50 Å UID layer adjacent to the base; a 1000 Å p^+ (Be: 3×10^{19} cm^{-3}) $In_{0.27}Ga_{0.73}Sb$ base; a n $In_{0.69}Al_{0.31}As_{0.41}Sb_{0.59}$ emitter consisting of a 500 Å moderately doped (Te: 2×10^{17} cm^{-3}) layer adjacent to the base, a 90 Å doping grade (Te: $2 \times 10^{17} \sim 6.7 \times 10^{18}$ cm^{-3}), and a 210 Å highly doped (Te: 6.7×10^{18} cm^{-3}) layer adjacent to the emitter contact layer; and a 100 Å n^+ (Te: 9.6×10^{18} cm^{-3}) $InAs_{0.66}Sb_{0.34}$ emitter contact. $InAs_{0.66}Sb_{0.34}$ has been shown to have superb electron transport properties and offers extremely low contact resistance when used for n-type ohmic contacts, making it an excellent choice for the n-type emitter contact and sub-collector layers [6]. Alternatively, $In_{0.27}Ga_{0.73}Sb$ has been shown to have excellent hole transport properties and results in extremely low resistance, p-type contacts, making it an ideal choice for the p-type base layer [7].

The HBTs were fabricated using standard processing and e-beam lithography techniques. The emitter and collector n-type contacts consisted of an unannealed Ti:Pt:Au (100:50:2500 Å) stack [6]. The base p-type contact consisted of an unannealed Pd:Pt:Au (100:50:2500 Å) stack [7]. The emitter mesa was defined using a tartaric-based wet etch, with the base mesa defined by $SiCl_4$-based ICP RIE. The tartaric-based etch used for the emitter mesa etch is non-selective, requiring a thicker base layer ($t_{base} = 1000$ Å) to guarantee a good yield. After device isolation by a wet etch, co-planar ground-signal-ground waveguides were deposited onto the SI GaAs substrate with airbridges to the relevant HBT contacts.

Measurements, results, analysis: The Gummel plot and common-emitter collector characteristics for an HBT with a 2×10 μm^2 emitter contact area are shown in Figs. 1 and 2, respectively. The area of the base-emitter junction, measured by scanning electron microscopy (SEM), is approximately 1.4×9.4 μm^2, owing to undercutting during the emitter wet etch. The device shows excellent base and collector idealities of $\eta_B = 1.5$ and $\eta_C = 1.0$, respectively. The improvement of the base ideality (η_B) and high base-emitter voltage before the diodes become resistively limited, as compared to previous results [4, 5, 8], suggest that the inclusion of $InAs_{0.66}Sb_{0.34}$ for the emitter contact and sub-collector layers has reduced the relative series resistance seen by each junction, improving the overall performance of the device. The low current gain, $\beta = I_C/I_B = 2 - 3$, is believed to be due to Be diffusion into the emitter, removing the efficacy of the base-emitter heterojunction, as similar device structures have yielded current gains as high as $17 \sim 20$ [4, 5, 8]. As can be seen from the collector characteristic in Fig. 2, the HBT exhibits a high collector current density of $I_C = 1.9 \times 10^5$ A/cm^2. The high collector current at low base-emitter biases demonstrates the excellent low voltage operation of these devices. Relatively large breakdown voltages ($V_{CE,bkdn} > 2.5$ V) at low currents have been measured.

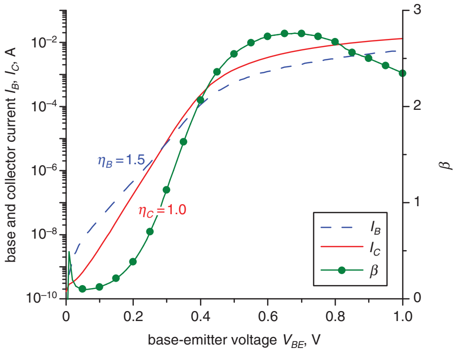

Fig. 1 *Gummel plot of 2×10 μm^2 HBT showing base current (I_B), collector current (I_C), and current gain (β)*

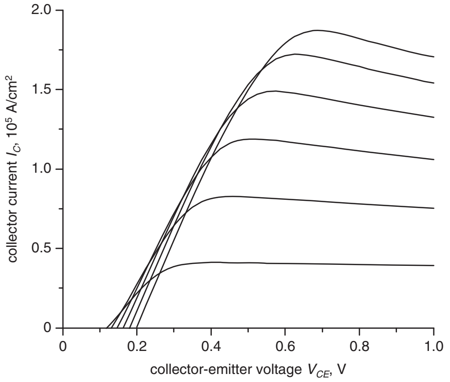

Fig. 2 *Common-emitter collector characteristics of 2×10 μm^2 HBT*
Base current (I_B) stepped from 0 to 12 mA with 2 mA steps

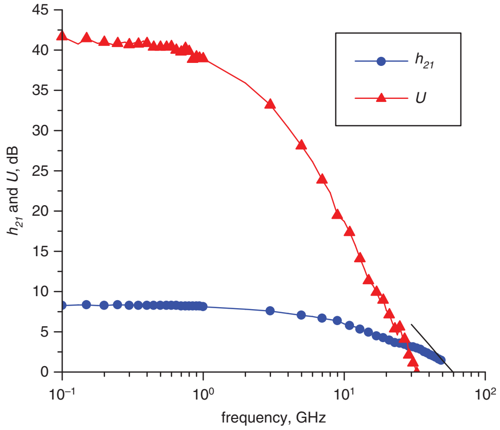

Fig. 3 *Plot of short-circuit current gain (h_{21}) and Mason's unilateral gain (U) at $V_{CE} = 1$ V and $I_C = 7.6 \times 10^4$ A/cm^2*

The measured short-circuit current gain (h_{21}) and Mason's unilateral gain (U) for $V_{CE} = 1$ V and $I_C = 7.6 \times 10^4$ A/cm^2 are shown in Fig. 3. The maximum measured short-circuit current gain cutoff frequency was $f_\tau = 59$ GHz with an associated maximum frequency of oscillation of $f_{max} = 34$ GHz ($V_{CE} = 1$ V, $I_C = 7.6 \times 10^4$ A/cm^2; Fig. 4). f_{max} in these devices is limited by the device geometry (base-emitter contact spacing of ∼1 μm, base contact width of 2 μm, collector thickness of 1550 Å) resulting in an estimated base resistance of $R_B = 12.3\ \Omega$, base-collector capacitance of $C_{BC} = 148.5$ fF, and an associated f_{max}/f_τ ratio of 0.61 (with $f_\tau = 59$ GHz), very close to the measured ratio of $f_{max}/f_\tau = 0.57$. f_{max} is expected to improve by nearly a factor of 2.5 simply through proper device scaling. Additionally, a selective etch for the emitter mesa definition would facilitate the use of a thinner base [8], which should improve f_τ.

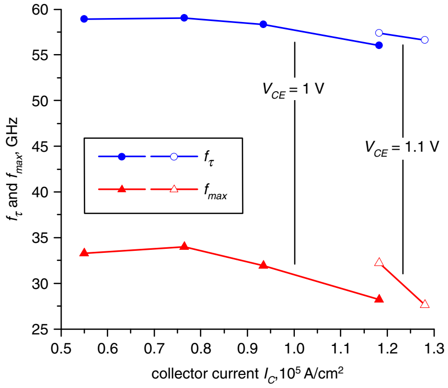

Fig. 4 *Plot of short-circuit current gain cutoff frequency (f_τ) and maximum frequency of oscillation (f_{max}) against collector current (I_C) and collector-emitter voltage (V_{CE})*

Conclusions: $In_{0.59}Al_{0.31}As_{0.41}Sb_{0.59}/In_{0.27}Ga_{0.73}Sb$ double-heterojunction bipolar transistors incorporating $InAs_{0.66}Sb_{0.34}$ in the emitter contact and sub-collector layers have been demonstrated. These HBTs show excellent DC performance and RF performance with a high collector current density ($I_C = 1.9 \times 10^5$ A/cm^2), relatively large breakdown voltage ($V_{CE,bkdn} > 2.5$ V), a maximum $f_\tau = 59$ GHz (the highest measured for this material system), and $f_{max} = 34$ GHz.

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One or more of the Figures in this Letter are available in colour online.

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