**Title:** 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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In$_{0.65}$Al$_{0.35}$Sb, and 1

Measurements, results, analysis: the relevant HBT contacts.

guides were deposited onto the SI GaAs substrate with airbridges to device isolation by a wet etch, co-planar ground-signal-ground wave-
doped (Te: 5 $\times$ 10$^{18}$ cm$^{-3}$) 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 ($f_m$) 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 In$_{0.27}$Ga$_{0.73}$Sb, and 1 μm of In$_{0.71}$Ga$_{0.29}$As$_{0.41}$Sb$_{0.59}$ collector consisting of a 200 Å doping grade (Te: 9.6 $\times$ 10$^{18}$ cm$^{-3}$) adjacent to the sub-collector, a 1500 Å low doped (Te: 5 $\times$ 10$^{16}$ cm$^{-3}$) region, and a 50 Å UID layer adjacent to the base; a 1000 Å p$^+$ (Be: 3 $\times$ 10$^{19}$ cm$^{-3}$) In$_{0.27}$Ga$_{0.73}$Sb base; a n In$_{0.69}$Al$_{0.31}$As$_{0.41}$Sb$_{0.59}$ collector consisting of a 400 Å doping grade (Te: 6.7 $\times$ 10$^{18}$ cm$^{-3}$) adjacent to the sub-collector, a 1500 Å low doped (Te: 5 $\times$ 10$^{16}$ cm$^{-3}$) region, and a 50 Å UID layer adjacent to the base; a 1000 Å n$^+$ (Be: 3 $\times$ 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 500 Å lightly doped (Te: 2 $\times$ 10$^{17}$ cm$^{-3}$) adjacent to the emitter contact layer, and a 100 Å n$^+$ (Te: 9.6 $\times$ 10$^{17}$ cm$^{-3}$) In$_{0.66}$Sb$_{0.34}$ emitter contact. In$_{0.66}$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$_{0.71}$Ga$_{0.29}$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 Te$_{0.5}$Pt$_{0.5}$Au (100:50:2500 Å) stack [6]. The base p-type contact consisted of an unannealed Pd$_{0.6}$Pt$_{0.4}$Au (100:50:2500 Å) stack [7]. The emitter mesa was defined using a tartaric acid-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 of an HBT with a 2 $\times$ 10$^{-3}$ 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 $\times$ 9.4 μm$^2$, owing to undercutting during the emitter wet etch. The device shows excellent base and collector ideality of $n_B = 1.5$ and $n_C = 1.0$, respectively. The improvement of the base ideality ($n_B$) and high base-emitter voltage before the diodes become resistively limited, as compared to previous results [4, 5, 8], suggest that the inclusion of In$_{0.65}$Al$_{0.35}$Sb, 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 $\times$ 20 [4, 5, 8]. As can be seen from the collector characteristic in Fig. 2, the HBT exhibits a high collector current density of $I_C = 1.9 \times 10^4$ 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.

The measured 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$^2$ are shown in Fig. 3. The maximum measured short-circuit current gain cutoff frequency was $f_m = 59$ 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 \(\approx 1 \mu m\), base contact width of 2 \(\mu m\), collector thickness of 1550 \(\AA\)) resulting in an estimated base resistance of \(R_B = 12.3 \Omega\), base-collector capacitance of \(C_{BC} = 148.5 \text{ fF}\), and an associated \(f_{\text{max}}/f_t = 0.61\) (with \(f_t = 59 \text{ GHz}\)), very close to the measured ratio of \(f_{\text{max}}/f_t = 0.57\). \(f_{\text{max}}\) 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 \(f_t\).

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

**Conclusions:** \(\text{In}_{0.59}\text{Al}_{0.41}\text{Sb}_{0.59}/\text{In}_{0.27}\text{Ga}_{0.73}\text{Sb}\) double-heterojunction bipolar transistors incorporating \(\text{InAs}_{0.66}\text{Sb}_{0.34}\) 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 \((I_C = 1.9 \times 10^5 \text{ A/cm}^2)\), relatively large breakdown voltage \((V_{CE,\text{break}} > 2.5 \text{ V})\), a maximum \(f_t = 59 \text{ GHz}\) (the highest measured for this material system), and \(f_{\text{max}} = 34 \text{ GHz}\).