Non-Blocking Collector InP/$GaAs_{0.51}Sb_{0.49}$/InP Double Heterojunction Bipolar Transistors with a Staggered Lineup Base–Collector Junction

C. R. Bolognesi, N. Matine, M. W. Dvorak, X. G. Xu, J. Hu, and S. P. Watkins

***Abstract*— We have developed lattice-matched InP/$GaAs_{0.51}$-$Sb_{0.49}$/InP NpN double heterojunction bipolar transistors (DHBT's) which take advantage of the staggered ("type II") band lineup at InP/$GaAs_{0.51}Sb_{0.49}$ interfaces: in this system the $GaAs_{0.51}Sb_{0.49}$ base conduction band edge lies ~0.18 eV above the InP collector conduction band, thus enabling the implementation of InP collectors free of the current blocking effect encountered in conventional $Ga_{0.47}In_{0.53}$As base DHBT's. The structure results in very low collector current offset voltages, low emitter-base turn-on voltages, and very nearly ideal base and collector current characteristics with junction ideality factors of $n_B = 1.05$ and $n_C = 1.00$. InP/$GaAs_{0.51}Sb_{0.49}$/InP DHBT's appear well-suited to low-power applications, but can also be used in power applications by virtue of their InP collector. The symmetry of the transistor band structure also lends itself to the potential integration of collector-up and emitter-up devices.**

***Index Terms*—DHBT, heterojunction, InP, transistor.**

InP/GaInAs-based heterojunction bipolar transistors (HBT's) have demonstrated excellent microwave characteristics [1], [2], but suffer from low breakdown voltages because of the narrow $Ga_{0.47}In_{0.53}$As collector energy gap of 0.75 eV. The use of an $Al_{0.48}In_{0.52}$As or InP collector in double heterojunction bipolar transistors (DHBT's) enhances breakdown voltages by reducing impact ionization in the collector, but it complicates the transistor design and fabrication because of the collector current blocking effect resulting from the positive conduction band discontinuity between $Ga_{0.47}In_{0.53}$As and $Al_{0.48}In_{0.52}$As or InP. In practice, various doping [3] and/or compositional grading schemes [4], [5] have been developed to minimize the blocking effect. Tiwari and Frank have shown that the specifics of the grading and doping schemes at the base/collector junction need to be carefully considered because they have a significant impact on DHBT performance [6], [7]. The availability of a blocking-free heterojunction system with a good etch selectivity would greatly simplify both device design and fabrication.

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We demonstrate lattice-matched, *nominally* abrupt interface NpN InP/$GaAs_{0.51}Sb_{0.49}$/InP double heterojunction bipolar transistors (DHBT's) in which the $GaAs_{0.51}Sb_{0.49}$ base conduction band edge is ~0.18 eV higher than the InP collector conduction band level [8] (a value consistent with other reports for the related GaInAs/GaAsSb system [9]): the resulting staggered ("type II") band lineup eliminates any collector current blocking and electron pile-up at the base–collector junction—electrons reaching the junction are ballistically *launched* into the InP collector, as indicated in Fig. 1. Optical transmission measurements on our MOCVD-grown undoped $GaAs_{0.51}Sb_{0.49}$ layers reveal a 300-K bandgap of 0.72 ± 0.01 eV (0.813 eV at 4 K [8]) in agreement with Klem *et al*. and Sugiyama *et al*. who also reported a value of 0.72 eV at 300 K [9], [10]. This lineup results in a large valence band discontinuity $\Delta E_V \approx 0.81$ eV at InP/$GaAs_{0.51}Sb_{0.49}$ heterojunctions—such a large ΔE_V suppresses hole back-injection into the InP emitter. The emitter/collector symmetry of InP/$GaAs_{0.51}Sb_{0.49}$/InP DHBT's is also well-suited for the potential integration of collector-up and emitter-up HBT's. We report DHBT's with near-ideal DC characteristics and a very low collector offset voltage $V_{\mathrm{CE,OFF}}$. A fundamental benefit of InP/$GaAs_{0.51}Sb_{0.49}$/InP DHBT's is that they can be implemented without compositional grading and with nominally abrupt interfaces: the turn-on and offset voltages are determined by the band lineups, doping levels, and junction areas. They are not affected by the effectiveness, or lack thereof, of compositional grading or pulse doping schemes that are intended to eliminate conduction-band spikes and barriers.

Our InP/$GaAs_{0.51}Sb_{0.49}$/InP DHBT structures were grown on exactly-oriented (001) InP:Fe SUMITOMO substrates in a horizontal Thomas-Swan MOCVD system at a pressure of 100 torr. Pd-diffused H_2 served as the carrier gas and TMIn, TEGa, TMSb, TBA's and TBP were the precursors. H_2S and CCl_4 were used for n- and p-type doping. The susceptor temperature was maintained at 560 ° during $GaAs_{0.51}Sb_{0.49}$ growth. The growth rate was ~1.0 μm/h for both InP and GaAsSb, and the V/III ratio for GaAsSb was ~2. A detailed study of the growth parameters and material properties will be presented separately. Device layers consist of a 3000-Å $Ga_{0.47}In_{0.53}$As subcollector (S: 1×10^{19} cm^{-3}), a 3000-Å InP collector (S: 2×10^{16} cm^{-3}; nominally), a 400-Å $GaAs_{0.51}Sb_{0.49}$ base (C: 4×10^{19} cm^{-3}), a 1500-Å InP emitter (S: 3×10^{17} cm^{-3}), a 500-Å InP layer (S: 3×10^{19} cm^{-3}), and a 2000-Å

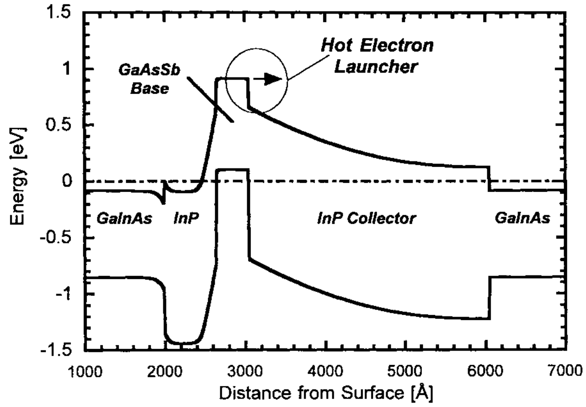

Fig. 1. Equilibrium InP/GaAsSb DHBT band diagram. The staggered band lineup at the InP/$GaAs_{0.51}Sb_{0.49}$ interface eliminates the current blocking effect at the base collector junction.

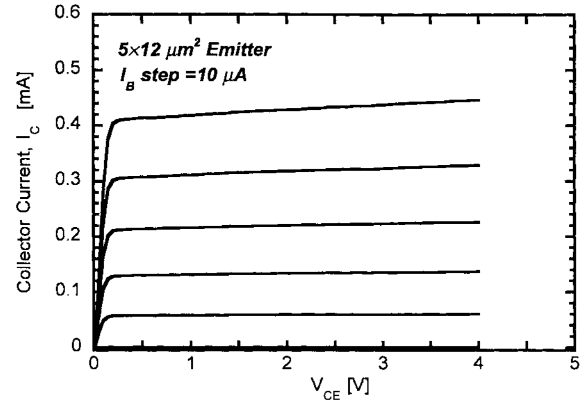

Fig. 2. Room temperature common-emitter $I-V$ characteristics for a 5×12 μm^2 InP/$GaAs_{0.51}Sb_{0.49}$/InP DHBT. The collector offset voltage is $V_{\mathrm{CE,OFF}} = 12$–14 mV, and $BV_{\mathrm{CEO}} = 6$–8 V. The collector–base junction area is $\sim 7 \times 17$ μm^2.

$Ga_{0.47}In_{0.53}As$ Ohmic contact layer (S: 1×10^{19} cm^{-3}). Fully self-aligned DHBT's were fabricated using the process previously described in [11]. Polaron and SIMS profiling reveal that a sulfur doping tail of $\sim$2–3×10^{17} cm^{-3} is present in the 3000-Å InP collector layer due to a memory effect following the growth of the heavily doped subcollector layer: it is shown below that this tail limits the RF performance of our devices (see Fig. 4). The growth conditions have not been optimized for base transport, and result in a base sheet resistance of $\rho_B = 1400$ Ω/sq. as determined by TLM measurements. Hall effect data confirm this result with $\mu_p = 25$–30 cm^2/Vs for a hole concentration of $p = 4 \times 10^{19}$ cm^{-3}, corresponding to $\rho_B = 1300$–1560 Ω/sq. Conventional Pt/Ti/Pt/Au and Ge/Au/Ni/Au were e-beam evaporated to form the base, and emitter/collector Ohmic contacts, respectively. The emitter contact was annealed at 300 °C for 1 min., and the base and collector contacts were simultaneously annealed at 215 °C for 1 min. Base contact resistances as low as 5×10^{-7} Ω-cm^2 were measured on TLM patterns. The devices were mesa-isolated and did not receive any surface passivation treatment.

Fig. 2 shows room temperature current–voltage ($I-V$) characteristics for a fully self-aligned airbridge DHBT with a 5×12 μm^2 emitter completely surrounded by the base contact, and a 7×17 μm^2 collector base junction: the common-emitter current gain is 30–40 at $J_C = 2 \times 10^4$ A/cm^2, the collector current offset voltage $V_{\mathrm{CE,OFF}} = 12$–14 mV, and $BV_{\mathrm{CEO}} = 6$–8 V. The current gain is comparable to that found in other InP-based HBT's [1], [2] and significantly higher than previously reported for InP/GaAsSb HBT's [12], [13]: gain values in InP-based HBT's with narrow bandgap heavily doped bases are limited by short Auger recombination lifetimes [14] which reduce the maximum possible gain in comparison to GaAs. Fig. 3 shows Gummel characteristics with ideality coefficients of $n_B = 1.05$ and $n_C = 1.00$. For comparison, a Gummel plot for a 80×80 μm^2 emitter device is also shown, but offset to the right for clarity. In reverse-mode operation (electrons injected *up* from the collector *into* the emitter, with collector forward-biased and emitter reverse-biased), the emitter current I_{ER} exactly overlaps with I_{CF}: the overlap proves the equivalence of the

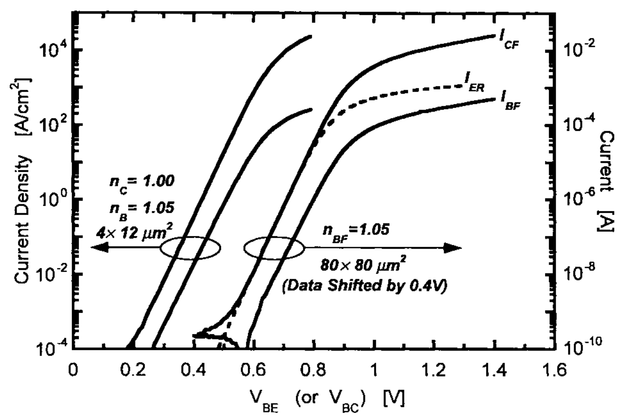

Fig. 3. Gummel characteristics for a 4×12 μm^2 InP/$GaAs_{0.51}Sb_{0.49}$/InP DHBT. The forward turn-on voltage at 1 A/cm^2 is $V_{\mathrm{BE}} = 0.4$ V. The collector and base junction ideality factors are $n_B = 1.05$ and $n_C = 1.00$. A large area 80×80 μm^2 device is also shown for comparison (offset for clarity), also showing the reverse mode emitter current I_{ER} (V_{BC}) (dashed line). The overlap of I_{CF} (V_{BE}) in forward mode and I_{ER} (V_{CB}) in reverse mode indicates the equivalence of the E/B and B/C heterojunctions (the difference at high currents is due to Ohmic losses). In reverse mode, the gain $I_{\mathrm{ER}}/I_{\mathrm{BR}}$ is <1 because the C/B junction area (350×350 μm^2) is much larger than the E/B junction area (I_{BR} not shown for clarity).

emitter/base and base/collector junctions. The absence of a conduction band spike at the junctions ensures that electrons are thermally injected into the base and results in $n_C = 1.00$; the low base current ideality factor n_B indicates that little recombination takes place in the emitter-base space charge region and suggests that $GaAs_{0.51}Sb_{0.49}$ may have a low surface recombination velocity. The hole mobilities in our GaAsSb bases are lower than those reported in [12], [13] and may suggest a somewhat poorer crystal quality for our bulk GaAsSb layers: basic transistor theory however shows that additional recombination in the quasineutral base region does not affect the junction ideality factors [15]—clearly, the excellent ideality factors reported here indicate the superior quality of our InP/$GaAs_{0.51}As_{0.49}$ heterointerfaces. As seen in Fig. 3, the present DHBT's do not exhibit size effects: devices with emitter sizes ranging from 80×80 μm^2 down to 4×12 μm^2 (smallest device fabricated in this work)

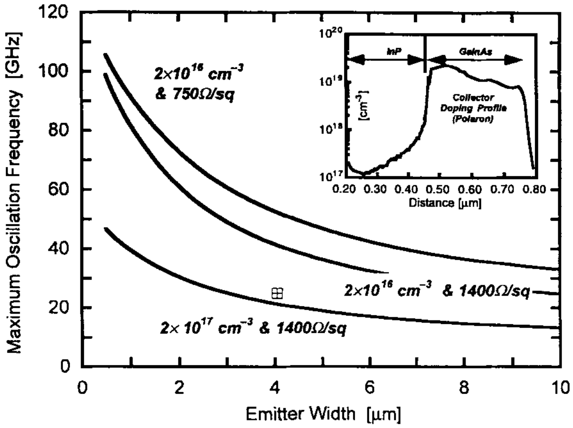

Fig. 4. Effect of the InP collector doping level and emitter geometry on the maximum frequency of oscillation, assuming $f_T = 70$ GHz. Inset: polaron profiling data through the InP collector layer revealing the subcollector doping tail.

showed identical current gains and ideality factors at a low current density of $J_C = 100$ A/cm^2. This observation also suggests that surface recombination does not play a dominant role in InP/$GaAs_{0.51}Sb_{0.49}$/InP DHBT's. In contrast, InP/$Ga_{0.47}In_{0.53}As$ HBT's fabricated in our laboratory with the same process [11] show a stronger size dependence with an increase in n_B from 1.10 to 1.35 when the emitter size is reduced from 80×80 μm^2 down to 4×12 μm^2.

The 300-K on-wafer microwave performance of the InP/$GaAs_{0.51}Sb_{0.49}$/InP DHBT's was measured between DC-40 GHz with an HP8510 network analyzer and GGB PicoProbe 40 A coplanar probes. A peak current gain cutoff frequency f_T = 70–77 GHz and a maximum oscillation frequency $f_{\rm MAX}$ = 25 GHz were extracted from the S-parameter data. In this staggered lineup system the lack of a conduction band spike at the emitter–base junction does not allow hot electron injection into the base (as with a GaInAs base), and this likely increases the base transit time when compared to conventional InP/$Ga_{0.47}In_{0.53}As$ HBT's. Two factors associated with the current lack of maturity of the InP/$GaAs_{0.51}Sb_{0.49}$ technology contribute to the low $f_{\rm MAX}$ value for the present devices: a) the large doping tail from the subcollector layer results in a collector doping of $\sim$2–3×10^{17} cm^{-3} which contributes a high collector-base capacitance $C_{\rm CB}$ (see Fig. 4); and b) the $GaAs_{0.51}Sb_{0.49}$ base 1400 Ω/sq. sheet resistance leads to a significant base resistance R_B with the 4–5 μm wide emitter stripes used here. Both factors reduce the maximum oscillation frequency through the relation $f_{\rm MAX} \approx \sqrt{f_T/8\pi R_B C_{\rm CB}}$. The collector doping tail and the base sheet resistance can be reduced by optimizing the growth protocol, and R_B can further be reduced by using narrower emitter stripes to enhance $f_{\rm MAX}$. Fig. 4 shows the calculated dependence of $f_{\rm MAX}$ on collector doping and emitter stripe width, assuming that in the first order f_T remains fixed at 70 GHz. Clearly, reducing the collector doping to its 2×10^{16} cm^{-3} nominal value and using a 1 μm emitter will result in $f_{\rm MAX} \geq f_T$.

Base sheet resistances of 700–1000 Ω/sq. should in principle be achievable in this system by increasing the base thickness and doping levels, and/or by improving the hole mobility by optimizing the base layer growth conditions: this is supported by McDermott *et al*. who reported mobilities of 40–45 cm^2/Vs for C-doped $GaAs_{0.51}Sb_{0.49}$ at $\sim 4 \times 10^{19}$ cm^{-3} [12], and by Bhat *et al*. who reported mobilities of 50 cm^2/Vs for C-doped $GaAs_{0.51}Sb_{0.49}$ at $\sim 7 \times 10^{19}$ cm^{-3} [13]. Such mobilities are still roughly 50% lower than those found in GaInAs, and will force the utilization of a narrow emitter stripe geometry to keep R_B low. Despite this limitation, InP/$GaAs_{0.51}Sb_{0.49}$/InP DHBT's appear to be promising for both low-voltage wireless applications and high-power applications because of the good thermal conductivity and low impact ionization rates in InP.

We have demonstrated near-ideal HBT characteristics based on the InP/$GaAs_{0.51}Sb_{0.49}$ system. Work is under way to optimize material properties to improve the RF performance.

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