# InGaAs/InP DHBT's with > 370 GHz $f_t$ and $f_{max}$ using a Graded Carbon-Doped Base

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We report an InP/InGaAs/InP DHBT, fabricated using a conventional mesa structure, exhibiting a 370 GHz $f_t$ and 375 GHz $f_{max}$, which is to our knowledge the highest $f_t$ reported for a mesa InP DHBT—as well as highest simultaneous $f_t$ and $f_{max}$ for a mesa HBT . The device employs a 30 nm carbon-doped InGaAs base with graded base doping, and an InGaAs/InAlAs superlattice grade in the base-collector junction.

Development of analog and digital systems operating at clock speeds of 80-160 GHz require continued improvement in transistor performance [1]. Target HBT specifications for 160 Gb/s systems include an $f_t$ and $f_{max}$ higher than 440 GHz, a breakdown voltage exceeding 3 V, operating current density greater than 10 mA/μm$^2$ at 0.0 Volts $V_{cb}$, and low base-collector capacitance ($C_{cb}/I_c$ < 0.5 psec/V) [2]. The DHBTs presented here progress further toward that goal. Prior to this work, the highest $f_t$ reported for a DHBT was 351 GHz with an $f_{max}$ of 288 GHz at a current density of 6.7 mA/μm$^2$, $V_{ce}$ = 1.3 V, using an InGaAsP base-collector grade [3].

To achieve simultaneously high $f_t$ and $f_{max}$ in a mesa HBT, the base-collector capacitance must be minimized, while maintaining a low base resistance. Since contact resistance, $\rho_c$ , decreases exponentially as the inverse square root of semiconductor doping, we pursued low base $\rho_c$ by doping our InGaAs base with carbon at $8\cdot10^{19}$ cm$^{-3}$. At high base doping levels though, the current gain is reduced due to increased Auger recombination in the neutral base. To increase the current gain and decrease the base transit time, a 30 nm thin base was selected and a built-in drift field introduced by decreasing the doping linearly from $8\cdot10^{19}$ to $5\cdot10^{19}$ cm$^{-3}$. The active collector region is 150 nm thick and contacts to the subcollector are on 12.5 nm of n$^+$ InGaAs above the n$^+$ InP. The InGaAs portion of the subcollector acts as an etch stop layer and is needed to maintain low $\rho_c$. Of equal importance, the InGaAs is kept thin in order to minimize thermal resistance through the subcollector so that the devices can operate well at higher current densities. Compared to our previous DHBTs with a carbon doped graded base [4], these DHBTs have a higher $f_\tau$ and operating current density—the improvements mostly attributed to the thinner collector (150 nm vs 200 nm) and thinner InGaAs subcollector layer (12.5 nm vs 50.0 nm). The layer structure is shown in table 1.

The epitaxial material was grown by IQE Inc on a 3" SI-InP wafer and the HBTs were fabricated in an all wet etch, standard triple mesa process. Emitter contact widths vary from 0.4-2.0 μm and base contacts extend 0.3, 0.5, or 1 μm on each side of the emitter metal. A single layer of metal is used to form device interconnects—50 Ω CPW transmission-lines, along with the on-wafer microwave calibration structures.

TLM measurements show the base $\rho_s$ = 603 Ω/sq and $\rho_c \cong 20$ Ω·μm$^2$, collector $\rho_s$ = 12 Ω/sq and $\rho_c \cong 9$ Ω·μm$^2$, and the emitter $\rho_c \sim$ 10-15 Ω·μm$^2$. The base metal sheet resistance is 0.5 Ohm/sq. The HBTs have a DC current gain β of 8-11 and a maximum current density of 12 mA/μm$^2$ at $V_{ce}$ = 1.5 V. The common-emitter breakdown voltage $V_{BR,CEO}$ is 5 V, and at $J_c$ = 8 mA/μm$^2$ the maximum $V_{ce}$ is greater than 2.5 V.

5-40 GHz and 75-110 GHz RF measurements were performed using on wafer LRL calibration structures, as well as OSLT calibration in the 5-40 GHz band. The calibration resulted in a $|S_{21}|$ << 0.1 dB for a zero-effective length transmission line. The HBTs exhibited a maximum 370 GHz $f_t$ and 375 GHz $f_{max}$ (fig. 2) at $J_c$ = 7.2 mA/μm$^2$ and $V_{ce}$ = 1.3 V ($V_{cb}$ = 0.35 V). This device had a 0.6 by 7 μm$^2$ emitter and 0.5 μm base ohmic contact width—1.7 μm base mesa width. Peak $f_t$ is between $J_c$ = 7-10 mA/μm$^2$ at $V_{ce}$ = 1.3 V for different HBT's on the wafer. In addition, the maximum sustainable $J_c$ is > 10 mA/μm$^2$, at which $C_{cb}/I_c \cong 0.26$ psec/V.

InP/InGaAs/InP DHBTs with heavy carbon base doping have obtained very high bandwidths operating under high current densities. The record $f_t$ and high $f_{max}$ were acquired by achieving simultaneously low base and collector transit times, low emitter and base contact resistance, together with a non-current blocking base-collector grade.

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| Thickness (Å) | Material | Doping $cm^{-3}$ | Description |
|---|---|---|---|
| 400 | $In_{0.53}Ga_{0.47}$ As | 3E19 : Si | Emitter Cap |
| 800 | InP | 3E19 : Si | Emitter |
| 100 | InP | 8E17 : Si | Emitter |
| 300 | InP | 3E17 : Si | Emitter |
| 300 | InGaAs | 8E19-5E19:C | Base |
| 200 | $In_{0.53}Ga_{0.47}$ As | 3E16:Si | Setback |
| 240 | InGaAlAs | 3E16 : Si | Base-Collector Grade |
| 30 | InP | 3.0E18 : Si | Delta doping |
| 1000 | InP | 3E16 : Si | Collector |
| 250 | InP | 1.5E19:Si | Sub Collector |
| 125 | $In_{0.53}Ga_{0.47}$ As | 2E19 : Si | Sub Collector |
| 3000 | InP | 2E19 : Si | Sub Collector |
| Substrate | SI : InP | | |

*Table 1: DHBT layer composition*

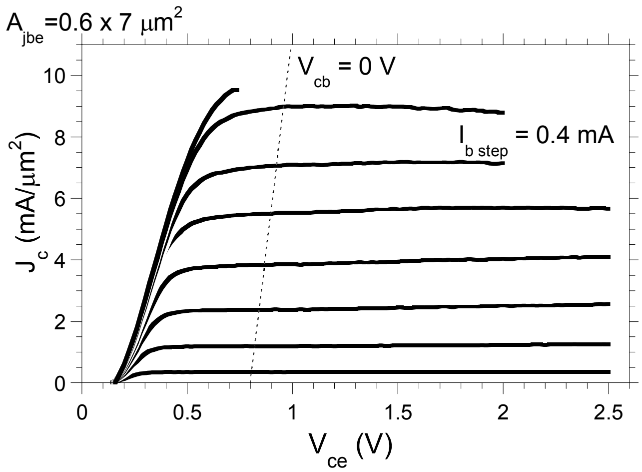


*Figure 1: Common emitter I-V characteristics*

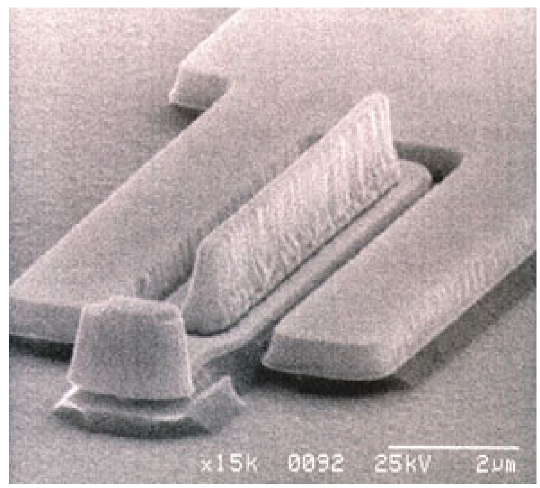


*Figure 3: SEM of fabricated HBT before pasivation*

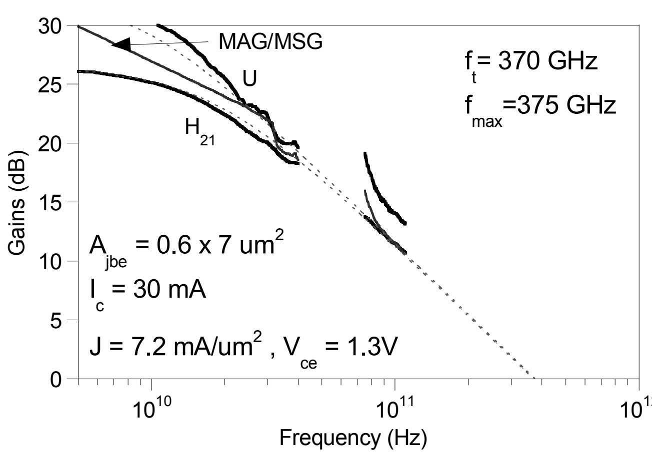


*Figure 2: Measured microwave gains*

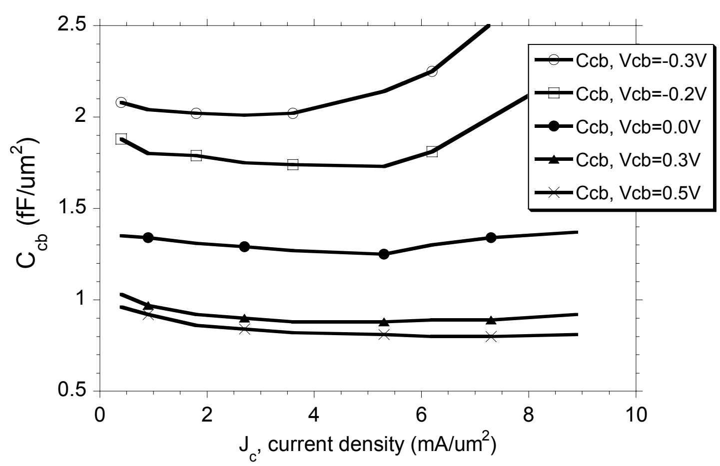


*Figure 4: $C_{cb}$ variation with different bias conditions*