Measurement of Base Transit Time and Minority Electron Mobility in GaAsSb-Base InP DHBTs

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Abstract
Measurements are presented showing an extraction of base transit time and minority carrier electron mobility in GaAsSb-Base Indium-Phosphide Double Heterojunction Bipolar Transistors. For p-doped GaAsSb with doping value 6E19 cm−3, the electron diffusion constant was found to be 61 cm2/sec. The junction temperature Tj was also characterized at the bias point IC = 6 mA, VCB = 0.55V and determined to be 85 °C, which corresponds to an electron mobility of 1970 cm2/(V-s).

INTRODUCTION
GaAsSb/InP Type-II DHBTs are used extensively in a variety of instrument products from mmWave network analyzers to high performance oscilloscopes. The underlying DHBT IC technology requires a favorable combination of high current gain and bandwidth, low turn-on voltage, and high breakdown voltage [1], which are controlled mostly by epitaxial design. To achieve even higher performance DHBT ICs, the epi design must be further optimized.

In order to optimize the base epi for future devices, it is useful to determine the minority electron mobility in p+GaAsSb. Rather than extracting electron mobility from bulk material or large area devices, this work extracts mobility specifically from an RF discrete device operating at a nominal bias point. By varying the base epi thickness and measuring RF data on discrete devices, it is possible to extract the minority carrier diffusion constant in the base. Knowing the junction temperature, it is then possible to extract the electron mobility in the base at a nominal operating point.

In this work, an experimental method is presented for the characterization of minority carrier mobility in the base region of bipolar transistors. Also presented are measured RF data on discrete DHBT devices, measurement of DHBT junction temperature, and the extracted mobility of p+GaAsSb in GaAsSb/InP DHBTs.

MEASUREMENT OF DIFFUSION COEFFICIENT AND BASE TRANSIT TIME
A lot of seven wafers (“Lot A”) was grown and processed identically. The epi structures used in “Lot A” all had lattice matched, p-doped, GaAsSb bases, but the base thickness was varied from Wb = 250-750 Å. Small-signal microwave measurements were performed on devices from each wafer, and the emitter-collector delay time τEC = 1/2πfT was extracted from a single-pole approximation of h21(f) for each device operating in the forward-active mode at constant VCB = 0.55V and multiple collector currents IC = 1.5-8 mA.

Using a single-pole approximation of h21(f) of a small-signal T-model, the total delay time τEC is estimated as a sum of internal delay times:

\[ \tau_{EC} = \tau_T + \left( C_{JE} + C_{JC} \right) \frac{\eta kT}{q I_C} \]  

Where

\[ \tau_T = \tau_B + \tau_C + \left( R_C + R_E \right) C_{JC} \]

The delay time τT was extracted for each epi design by extrapolating τEC vs. 1/IC to 1/IC = 0 using data from IC = 1-6
mA, as shown in Fig. 1 [2]. The delay times $\tau_T$ followed a quadratic relationship versus base thickness $W_B$, as shown in Fig. 2. This quadratic dependence can be understood because the delays $\tau_C$ and $(R_C+R_E)C_{IE}$ remain the same for all the wafers, while the base delay varies quadratically with base thickness as $\tau_B = W_B^2/2D_{eb} + W_B/v_{exit}$ [3]. There is currently no estimate for exit velocity $v_{exit}$ of electrons in GaAsSb/InP transistors during nonequilibrium transport, but the value of $5.5E7$ cm/s, which was extracted for InGaAs/InP DHBTs by Monte Carlo simulation, is a viable approximation and was used to enhance the quadratic fit shown in Fig. 2. The quadratic fit in Fig. 2 shows the value $D_{eb}$ of 61 cm$^2$/s, with a 392 fs residual delay corresponding to the delay terms $\tau_C + (R_C + R_E)C_{IE}$ in Equation 2.

**Measurement of Junction Temperature**

In order to calculate electron mobility in the base, it was necessary to estimate the junction temperature of the discrete devices operating at a nominal bias point. Junction temperature was estimated using the experimental method outlined in [4]. This method assumes that the base-emitter voltage is an invertible function of junction temperature when emitter current is constant. A map of $V_{BE}(I_E,T_J)$ is formed by measuring $V_{BE}$ vs. $I_E$ at multiple ambient temperatures and multiple values of $V_{CE}$. For constant $(I_E, T_{ambient})$, $V_{BE}$ vs. $V_{CE}$ is measured and extrapolated to $V_{CE} = 0$, which corresponds to a junction temperature $T_J = T_{ambient}$ (no power dissipation). This is performed over a grid of $(I_E, T_{ambient})$ and interpolation is used to estimate intermediate values of $T_J(I_E,V_{BE})$. Figure 3 shows the interpolated map of $T_J$ vs $I_E$ and $V_{BE}$. Figure 3 shows the estimated junction temperature as a function of $I_E$ and $V_{BE}$ for the measured discrete device. Thus, for a given emitter current, a decreasing base-emitter voltage indicates increasing junction temperature.

This interpolated map is also used to estimate junction temperature vs. power dissipation, as shown in Figure 4. Figure 4 was generated by measuring $V_{BE}$ vs. $V_{CE}$ for multiple emitter currents and at different ambient temperatures, and determining the junction temperature associated with each bias point using the interpolated map shown in Figure 3. The lowest curve corresponds to measurements taken at 25C ambient temperature, the same conditions as the small signal measurements described previously. The small signal measurements of the previous section were taken around a bias point with 8.5 mW power dissipation, which, according to Figure 3, corresponds to 85C junction temperature. By the Einstein relation, the electron mobility of GaAsSb with the same base thickness of 336 Å and with base concentration, a $\mu_n = 1970$ cm$^2$/V-s and a $\mu_p = 354$ cm$^2$/V-s was measured. Extrapolated delay time was estimated using the experimental method outlined in [3], fitted to $\tau = W_B^2/1216 + W_B^5.5 + 392$. This is performed over a grid of $(I_E, T_{ambient})$ and determining the junction temperature $T_J$ vs power dissipation in a sample device. Each curve shows different ambient temperatures.

**Measurement of Electron Diffusion Constant and Base Transit Time For Varied Base Doping**

In order to characterize mobility as a function of dopant concentration, a second lot (“Lot B”) was grown and processed in the same way as “Lot A,” but with a variety of base doping levels. All “Lot B” wafers were lattice matched with a variety of base thickness of 336 Å and with base doping levels. All “Lot B” wafers were lattice matched with the same base thickness of 336 Å and with base doping levels.
Electron diffusion coefficient $D_n$ versus base doping concentration for wafers in Lot A and Lot B. The base transit times $\tau_B$ were extracted for each wafer by finding $\tau_T$ as before, then subtracting the delay times $\tau_C$ and $(R_C + R_E)C_J$ from the residual delay time 392 fs. Once the base transit time was known, the diffusion constant was calculated from $\tau_B = W_B^2/(2D_n) + W_B/v_{exit}$ using $v_{exit} = 5.5 \times 10^7$ cm/s as before [3]. Error bars were calculated by estimating error sources (measurement errors, model assumptions, etc.) and calculating error propagation to the $D_n$ calculation [9].

Figure 5 shows a significant decrease in $D_n$ for doping levels $N_A$ above $6 \times 10^{19}$ cm$^{-3}$ and approximately constant $D_n$ value of 36 cm$^2$/s for higher values of $N_A$ (corresponding to a mobility of 1160 cm$^2$/s). The Lot B base transit times are about 215 fs for the 336A base widths, longer than the 154 fs from Lot A devices with $W_B = 336A$. The significant reduction in diffusion constant and mobility may be due to a strong dependence on doping concentration above values of $6 \times 10^{19}$ cm$^{-3}$, but growth reproducibility is also being investigated as a potential cause of this significant decrease.

**CONCLUSIONS**

This work has described an experimental method for extraction of the minority carrier diffusion constant and mobility in high speed bipolar transistors, including estimation of the junction temperature. This method can be used for any bipolar process. In this work the method was used to calculate the mobility of electrons in the p+GaAsSb base of high speed InP DBHTs, manufactured by Agilent Technologies. The experimental results of this work can be used to advance the design of the base region in p+GaAsSb base InP DHBTs.

**REFERENCES**


**ACRONYMS**

DHBT: Double Heterojunction Bipolar Transistor