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 cm^2/sec. The junction temperature T_j was also characterized at the bias point I_C = 6 mA, V_{CB} = 0.55V and determined to be 85^o C, which corresponds to an electron mobility of 1970 cm^2/(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.

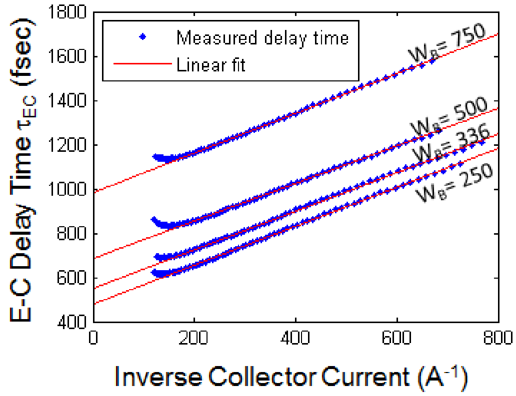

Fig. 1. Extrapolation of $\tau_{EC} = 1/2\pi f_T$ to determine the delay time τ_T according to the method in ref [2].

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 W_B = 250-750 Å. Small-signal microwave measurements were performed on devices from each wafer, and the emitter-collector delay time $\tau_{EC} = 1/2\pi f_T$ was extracted from a single-pole approximation of $h_{21}(f)$ for each device operating in the forward-active mode at constant V_{CB} = 0.55V and multiple collector currents I_C = 1.5-8 mA.

Using a single-pole approximation of $h_{21}(f)$ of a small-signal T-model, the total delay time τ_{EC} is estimated as a sum of internal delay times:

$$\tau_{EC} = \tau_T + \left(C_{JE} + C_{JC}\right)\frac{\eta kT}{qI_C} \qquad (1)$$

Where

$$\tau_T = \tau_B + \tau_C + (R_C + R_E)C_{JC} \qquad (2)$$

The delay time τ_T was extracted for each epi design by extrapolating τ_{EC} vs. $1/I_C$ to $1/I_C = 0$ using data from I_C = 1-6

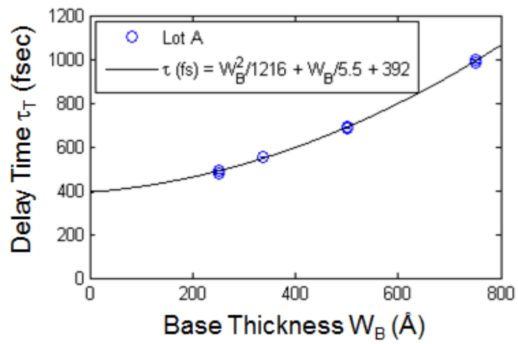

Fig. 2. Extrapolated delay time τ_T versus base thickness W_B, fitted to the quadratic function that is expected from refs [2] and [3].

mA, as shown in Fig. 1 [2]. The delay times τ_T followed a quadratic relationship versus base thickness W_B, as shown in Fig. 2. This quadratic dependence can be understood because the delays τ_C and $(R_C+R_E)C_{JC}$ remain the same for all the wafers, while the base delay varies quadratically with base thickness as $\tau_B = W_B^2/2D_{nB} + W_B/v_{exit}$ [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_n of 61 cm^2/s, with a 392 fs residual delay corresponding to the delay terms τ_C + $(R_C + R_E)C_{JC}$ 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

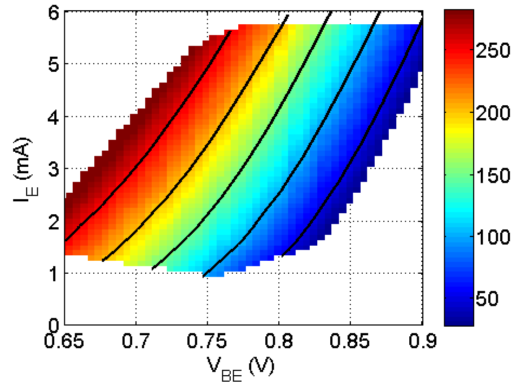

Fig. 3. Heat map of junction temperature T_j vs. I_E and V_{BE}. Solid black lines show constant-T_j contours from 50°C-250°C at increments of 50°C.

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, this results in an electron mobility of 1970 $cm^2/(V\text{-}s)$. For comparison, the value quoted for p-InGaAs in InGaAs/InP DHBTs at the same doping value was about 1500 $cm^2/(V\text{-}s)$ [5].

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 GaAsSb with the same base thickness of 336 Å and with base

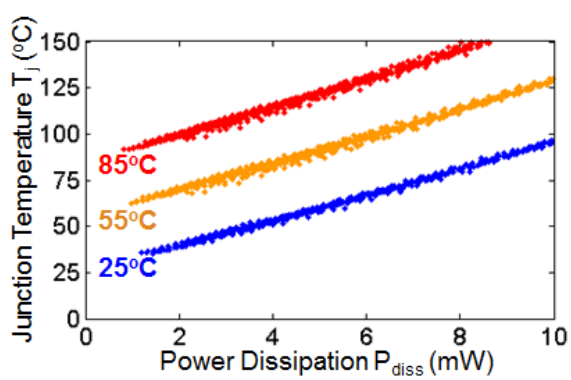

Fig. 4. Extracted junction temperature T_j vs. power dissipation in a sample device. Each curve shows different ambient temperatures.

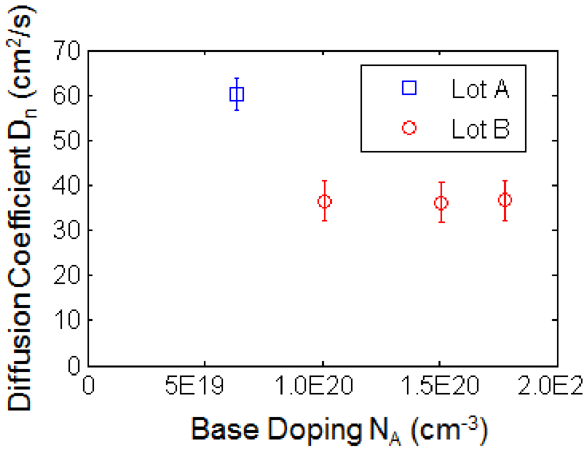

Fig. 5. Electron diffusion coefficient D_n versus base doping concentration for wafers in Lot A and Lot B.

doping values of 1.04, 1.30, and 1.60E20 cm^{-3}. The base transit times τ_B were extracted for each wafer by finding τ_T as before, then subtracting the delay times τ_C and $(R_C + R_E)C_{JC}$. The values of C_{JC}, R_C, and R_E for each Lot B device were estimated from microwave measurements according to the methods in [6-8]. The value of τ_C was found from "Lot A" data by extracting C_{JC}, R_C, and R_E using microwave measurements, and then subtracting $(R_C + R_E)C_{JC}$ from the residual delay time 392 fs. Once the base transit time was known, the diffusion constant was calculated from $\tau_B = W_B^2/2D_{nB} + W_B/v_{exit}$, using v_{exit} = 5.5E7 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 Na above 6E19 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 6E19 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.

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Acronyms

DHBT: Double Heterojunction Bipolar Transistor