BASE TRANSIT TIME IN ABRUPT GaN/InGaN/GaN and AlGaN/GaN/AlGaN HBTs

Shean-Yih Chiu, A. F. M. Anwar and Shangli Wu

Electrical and Systems Engineering Department, University of Connecticut, CT 06269
anwara@engr.uconn.edu

MRS Internet J. Nitride Semicond. Res. 4S1, G6.7 (1999)

Abstract

Base transit time, t_b, in abrupt npn GaN/InGaN/GaN and AlGaN/GaN/AlGaN double heterojunction bipolar transistors (DHBTs) is reported. Base transit time strongly depends not only on the quasi-neutral base width, but also on the low field electron mobility, m_n, in the neutral base region and the effective electron velocity, S_c, at the edge of base-collector heterojunction. m_n and S_c are temperature-dependent parameters. A unity gain cut-off frequency of 10.6 GHz is obtained in AlGaN/GaN/AlGaN DHBTs and 19.1 GHz in GaN/InGaN/GaN DHBTs for a neutral base width of 0.05um. It is also shown that non-stationary transport is not required to study t_b for neutral base width in the range of 0.05um for GaN-based HBTs.

Introduction

Wide bandgap group III-nitride semiconductors are currently being pursued for possible high temperature and high power applications. Current gain as high as 10^5 is reported for GaN/SiC HBT [1]. In order to investigate high frequency performance the behavior of the base transit time, t_b, needs to be investigated. Mohammad et al. [2] has reported the dependence of t_b on base doping concentration in a graded GaN/InGaN HBT.

The double integral formulation of t_b by Kroemer [3] for HBTs is based upon the assumption that excess minority carrier concentration at the edge of base-collector depletion layer is negligible. Roulston [4] emphasized upon the use of a finite carrier velocity (saturation velocity) at the edge of the base-collector depletion region, thereby, introducing the component of base transit time due to velocity saturation. A more general formulation for carrier velocity at b-c heterojunction was used by Hafizi et al. [5]. Jahan et al. [6], based upon a self-consistent calculation of thermionic and tunneling components of the total current, proposed a tunneling factor for the determination of carrier velocity at the b-c junction. In this paper, the method formulated by Jahan et al. [7] is used in the determination of the effective electron velocity at base-collector junction which affects the electrons transport across base-collector junction.

In this paper, t_b in abrupt GaN/InGaN/GaN and AlGaN/GaN/AlGaN HBT is reported. The computation of t_b includes the effects of bandgap narrowing, carrier saturation and partitioning of the total current into thermionic and tunneling components. Results obtained from an ensemble Monte Carlo simulation are used in the determination of low field mobility, m_n.

Theory

Base transit time, t_b, can be expressed as a sum of $t_{b1} + t_{b2}$, where

$$\tau_{b1} = \int_0^{W_B} \frac{n_{ib}^2(x)}{N_{AB}(x)} \int_x^{W_B} \frac{1}{D_n(y)} \frac{N_{AB}(y)}{n_{ib}^2(y)} dydx \tag{1}$$

and

$$\tau_{b2} = \frac{1}{S_c} \frac{N_{AB}(W_B)}{n_{ib}^2(W_B)} \int_0^{W_B} \frac{n_{ib}^2(x)}{N_{AB}(x)} dx$$

where $N_{AB}(x)$ is the base doping concentration, $n_{ib}^2(x) = n_{ie}^2 \exp(\Delta_g / kT)$ is the effective intrinsic carrier concentration in base region. The effective bandgap narrowing across the emitter-base heterojunction, $\Delta_g(In_xGa_{1-x}N) = x \cdot E_g(InN) + (1-x) \cdot E_g(GaN) - x \cdot (1-x) E_{gb}$ (E_{gb}=1.0 eV)[8] where x is the In-mole fraction in $In_xGa_{1-x}N$ and n_{ie} is the effective intrinsic carrier concentration in emitter region. τ_{b1} is the component of the base transit time due to diffusion in the neutral base region and τ_{b2} accounts for the finite base-collector junction velocity, S_c. The effective minority carrier velocity, S_c, characterizing electron transport across the space-charge region at the base-collector junction is formulated as $S_c = v_{th} \cdot \gamma \cdot \exp[(qv_{jp} - \Delta E_c)/kT]$ [9], where ΔE_c is the conduction band discontinuity, v_{jp} is the applied voltage drop at the collector, γ is the tunneling transmission factor, and v_{th} is the thermal velocity. The factor γ is determined by invoking the proper partitioning of the total current into tunneling and thermionic components [7]. WKB method is used to compute the transmission probability required in calculating the tunneling component of the total current.

Results and Discussions

5×4 μm^2 single finger npn $GaN/In_xGa_{1-x}N$ and $Al_{0.2}Ga_{0.8}N$ HBTs are investigated. The material parameters used in the simulation are as follows: $m_e(GaN)=0.2m_0$, $m_h(GaN)=0.6m_0$ [10], $m_e(InN)=0.115m_0$ [11], $m_h(InN)=1.6m_0$ [12], $m_e(AlN)=0.314m_0$, $m_h(AlN)=0.71m_0$ [13], $E_{gGaN}(T)=3.503+5.08\times10^{-4}\times T^2/(T-996)$ eV, $E_{gInN}(T)=2.01-1.8\times10^{-4}\times T$ eV, $E_{gAlN}(T)=6.118-1.799\times10^{-3}T^2/(T+1462)$ eV [14], $\varepsilon_{GaN}=9.5\varepsilon_0$, $\varepsilon_{InN}=19.6\varepsilon_0$ and $\varepsilon_{AlN}=8.5\varepsilon_0$ [13] where ε is static dielectric constant, m_0 is electron rest mass, T is absolute temperature (K), and ε_0 is permittivity in vacuum. Emitter and collector doping concentrations equal 5×10^{17} cm^{-3}. The base is 0.05um wide and is doped uniformly 10^{19} cm^{-3}. The conduction band offset, ΔE_c, is assumed to be 75% of the difference in bandgaps of the constituting semiconductor alloys [15].

In Fig. 1(a) the low field mobility, μ_n, and the diffusion coefficient, D_n, are plotted as a function of temperature for $In_{0.2}Ga_{0.8}N$ and GaN at a doping concentration of 10^{19} cm^{-3}. The low field mobility data is obtained from an ensemble Monte Carlo simulation which accounts for piezoelectric, ionized impurity, alloy, intervalley, acoustic and polar optical phonon scattering [16]. The diffusion constant $D_n = kT/q \cdot \mu_n \cdot [F_{1/2}(\xi_n)/F_{-1/2}(\xi_n)]$ where $\xi_n = (E_{fn} - E_c)/kT$ is the reduced Fermi level for electrons and $F_{\pm1/2}(\xi_n)$ is the Fermi-Dirac integral. D_n initially increases followed by gradual decrease beyond T=200K. In Fig. 1(b) the base-collector electron junction velocity, S_c, is plotted as a function of base-collector bias, V_{bc}, for varying In-mole fraction with temperature as a parameter. Due to a smaller band offset at the b-c junction S_c approaches thermal velocity at lower V_{bc} for x=0.1 as compared to that at x=0.2. The behavior of S_c for AlGaN/GaN/AlGaN is similar to that of GaN/InGaN/GaN.

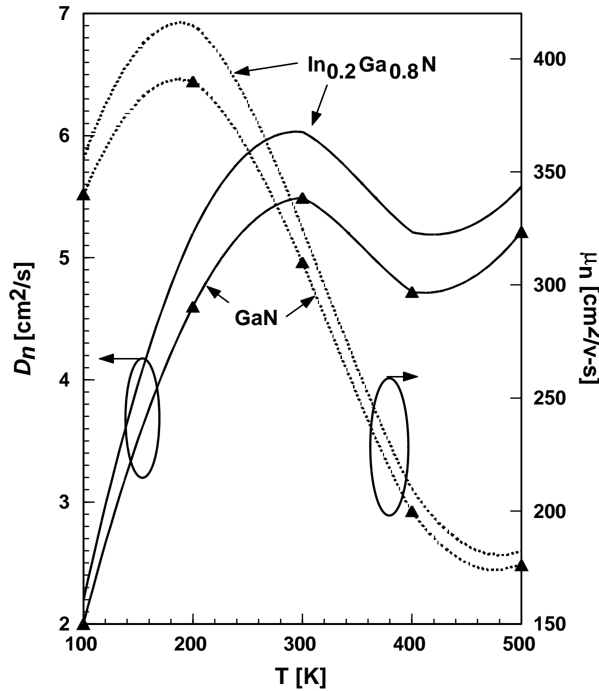

Fig. 1(a) Low field mobility $\boldsymbol{m}_n$ and diffusion coefficient D_n for $In_{0.2}Ga_{0.8}N$ and GaN as a function of temperature at a doping concentration of 10^{19} cm^{-3}. Solid triangles represent D_n and $\boldsymbol{m}_n$ for GaN.

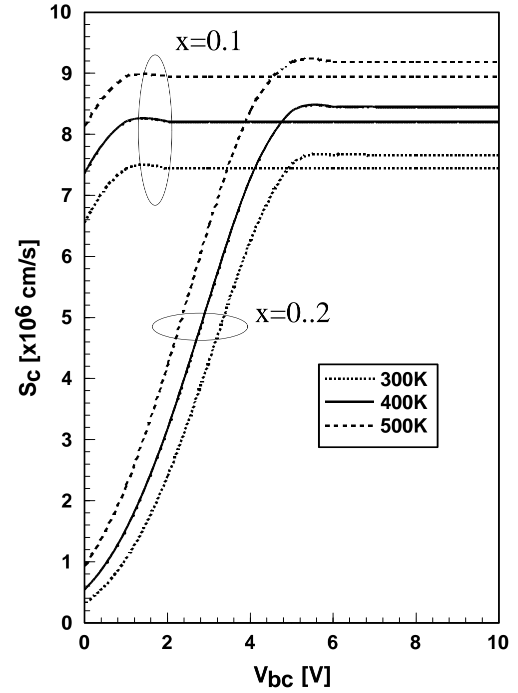

Fig. 1(b) The effective electron velocity at base-collector junction, S_c , versus V_{bc} for $In_xGa_{1-x}N$/GaN.

In Fig. 2(a) the base transit time τ_b is plotted as a function of V_{be} for V_{bc} =3.0 V. τ_b decreases with increasing In-mole fraction in GaN/$In_xGa_{1-x}N$/GaN HBTs, irrespective of temperature and this behavior can be explained with the aid of Fig. 1. A higher S_C at x=0.1 results in a lower τ_{b2} as compared to that at x=0.2 for V_{bc} = 3V. The magnitude of τ_{b1} at x=0.1 is slightly greater than that at x=0.2. This may be attributed to a slightly higher low field mobility at x=0.1 that results in a lower diffusion constant as compared to that at x=0.2. The relative magnitudes of τ_{b1} and τ_{b2} reflects the role of the transport processes namely drift-diffusion versus thermionic field emission. As seen from Fig 2(b), the diffusion controlled component of the base transit time τ_{b1} is always the dominating time constant at elevated temperatures. However, at higher D_n at 300K results in a lower τ_{b1} and a higher τ_{b2}. Or in other words, at 300K the contribution of thermionic field emission related component of the base transit time τ_{b2} becomes significant. τ_b for $Al_{.2}Ga_{.8}N$/GaN HBTs at V_{bc} =3.0 V is controlled by τ_{b2} and is due to the small electron effective velocity.

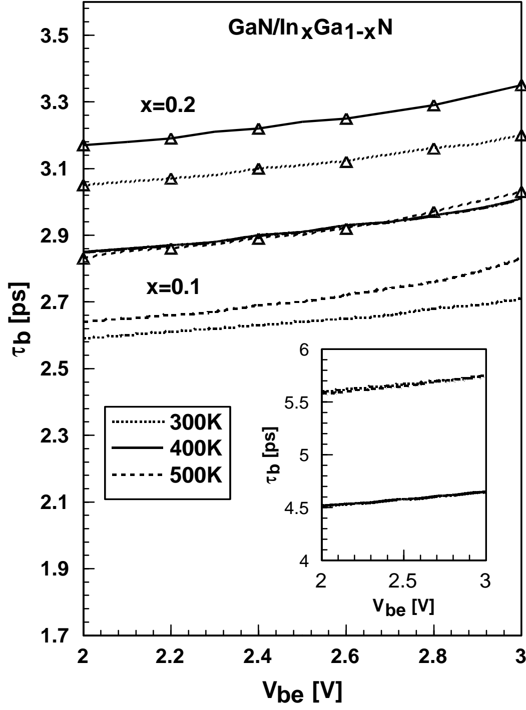

Fig. 2(a) τ_b is plotted as a function of V_{be} at various temperature for GaN/In$_x$Ga$_{1-x}$N HBTs with base doping concentration of 10^{19} cm^{-3}, V_{bc}=3V. Base width equals 0.05um. The inset shows τ_b for Al$_{0.2}$Ga$_{0.8}$N/GaN DHBT. Lines represent x=0.1 and lines with open triangles represent x=0.2.

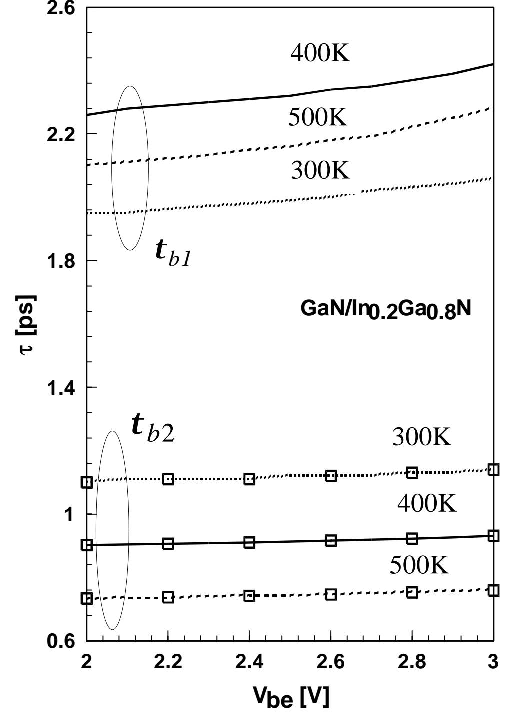

Fig. 2(b) Shows τ_{b1} and τ_{b2} for GaN/In$_{0.2}$Ga$_{0.8}$N DHBT. Lines represent τ_{b1} and lines with open squares represent τ_{b2}.

The dependence of τ_b upon base width for a base doping concentration of 10^{19} cm^{-3} at room temperature is shown in Fig.3. V_{be}=2V and V_{bc}=3V are assumed. As expected, τ_b increases with increasing base width. For extremely narrow base widths, the dominant component of τ_b is $\tau_{b2.}$ As compared to In$_x$Ga$_{1-x}$N-based HBTs, GaN-based HBTs have higher τ_b due to lower low field mobility and lower effective electron velocity at base-collector junction. The above calculation is performed using stationary transport. The validity of the above approximation is shown in Fig. 4, where the average velocity is plotted as a function of distance. As noted, the average velocity remains constant over a base width variation from 0.02µm to 0.8µm for both GaN and In$_{.2}$Ga$_{.8}$N in the presence of an applied field of 500KV/cm. For comparison a similar plot for GaAs is also shown where the applied electric field is 10KV/cm. For GaAs the effect of non-stationary transport is clear and for base widths less than 1µm assuming stationary transport data becomes questionable.

In Fig. 5, the unity gain cutoff frequency $f_T = 1/(2\cdot\pi\cdot\tau_{ec})$ is plotted as a function of collector current density, J_c, where $\tau_{ec} = \tau_e + \tau_b + \tau_c$ is the total transit time from emitter to the collector. τ_e is emitter charging time, expressed as $\tau_e = r_e \cdot C_{je}$ where r_e is the dynamic resistance and C_{je} is the base-emitter junction capacitance. $\tau_c = R_c \cdot C_{jc}$ is the collector

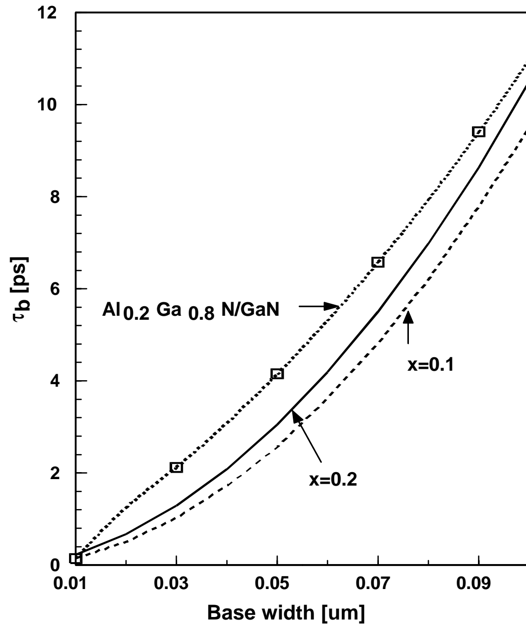

Fig. 3 t_b is plotted as a function of base width with In-mole fraction as a parameter for GaN/$In_xGa_{1-x}N$ and $Al_{0.2}Ga_{0.8}N$/GaN HBTs (solid triangles). A base doping of 10^{19} cm^{-3}, T=300K, V_{be}=2.0V and V_{bc}=3.0V are considered.

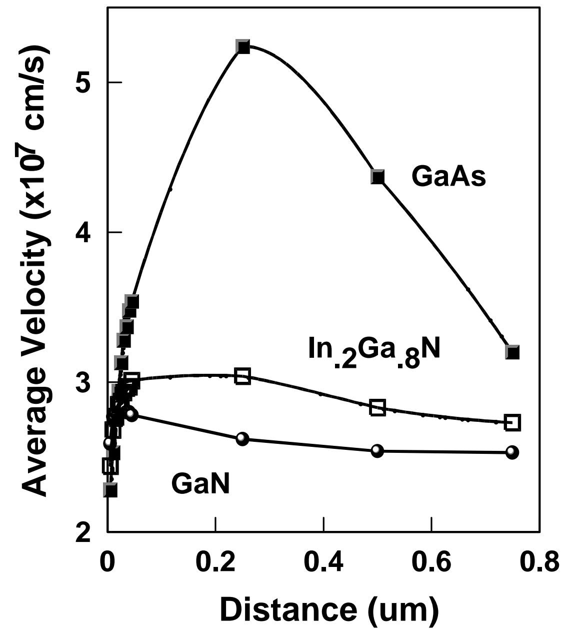

Fig.4 Average velocity is a function of distance at high electric field for GaAs, GaN, and $In_{0.2}Ga_{0.8}N$.

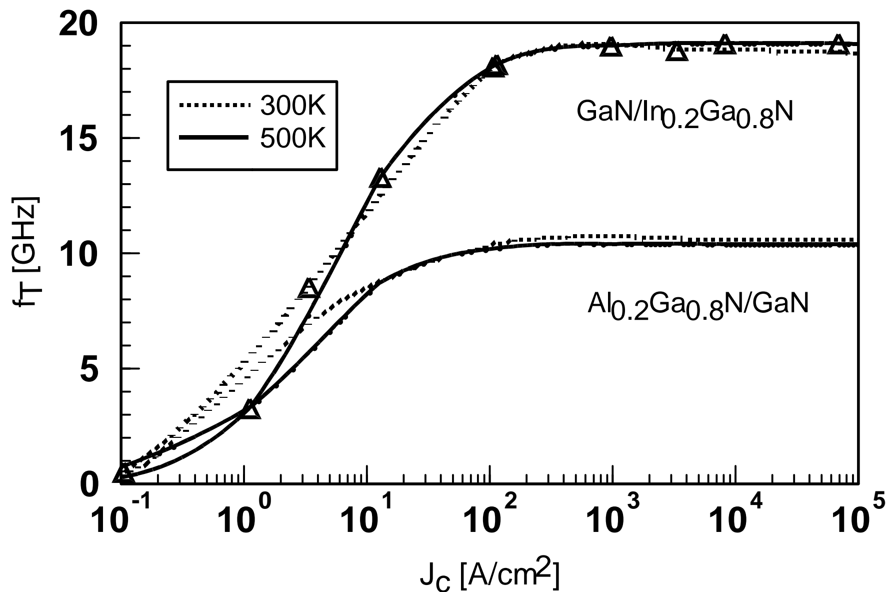

Fig. 5 f_T is shown as a function of collector current density at various temperatures for GaN/$In_{0.2}Ga_{0.8}N$ and $Al_{0.2}Ga_{0.8}N$/GaN HBTs. Base width equals 0.05um with $N_{AB}=10^{19}$ cm^{-3}. Solid lines represent T=500K and dashed lines represent T=300K

charging time where R_c is the collector resistance and C_{jc} is the collector junction capacitance. For collector current densities below 100 A/cm^2 τ_e dominant time constant, however for current densities above 100 A/cm^2 τ_b dominates. An f_T of 19.1 GHz is obtained at 500K for GaN/$In_{.2}Ga_{.8}N$/GaN DHBT. A higher low field mobility and b-c junction velocity in $Al_{0.2}Ga_{0.8}N$/GaN DHBT produce a f_T of 10.6 GHz at 300K .

Conclusion

Base transit time in abrupt GaN/InGaN/GaN and AlGaN/GaN/AlGaN HBTs are determined by accounting for bandgap narrowing, carrier degeneracy and the proper low field mobility. A narrow base width with a consequently large base resistance is recommended along with a lower In-mole fraction to realize superior unity gain current cut-off frequency, f_T. f_T=10.6 GHz at T=500K for $Al_{0.2}Ga_{0.8}N$/GaN HBT and f_T= 19.1 GHz at T=300K for GaN/$In_{0.2}Ga_{0.8}N$ have been demonstrated.

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