Effect of Reduced Temperature on the f_T of AlGaAs/GaAs Heterojunction Bipolar Transistors

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Abstract—**The high-frequency and dc performance of single-heterojunction $Al_{0.25}Ga_{0.75}As$/GaAs HBT's have been measured at temperatures between 300 and 110 K. We have found that the maximum unity-current-gain cutoff frequency f_T increases from 26 GHz at 300 K to 34 GHz at 110 K. The results at 110 K are not adequately described by the simple estimate for base transit time, $\tau_B = W_B^2/2D_n$, at least until corrections for degeneracy and minority-carrier mobility enhancement are included. Reasonable agreement can also be obtained assuming that base transport is limited by the thermal velocity of electrons at reduced temperatures.**

CONSIDERABLE work has been conducted over the past 30 years on the temperature dependence of various bipolar transistor parameters. The most frequently observed parameter has been the common-emitter current gain β, which typically decreases quasi-exponentially with decreasing temperature. This is generally associated with the difference in apparent bandgap narrowing in the emitter and base regions of homojunction devices [1]. However, very little work has been conducted on the temperature dependence of the high-frequency performance of heterojunction bipolar transistors [2], [3]. To investigate the temperature dependence of carrier transit times in these devices, we have performed a series of high-frequency and dc measurements on AlGaAs/GaAs HBT's at cryogenic temperatures. The variation in unity-current-gain cutoff frequency f_T with temperature indicates that the predominant transport mechanism through the neutral base of the device is not purely diffusive.

The epitaxial device structures were grown by low-pressure MOCVD in an EMCORE GS3100 reactor. The growth parameters are similar to those previously reported elsewhere [4]. The subcollector was 600 nm thick and doped to $n = 5 \times 10^{18}$ cm^{-3}. The collector was 500 nm thick and doped to $n = 5 \times 10^{16}$ cm^{-3}. The base was 100 nm thick and doped to $p = 1 \times 10^{19}$ cm^{-3} and was followed by a 10-nm-thick unintentionally doped setback layer. The $Al_xGa_{1-x}As$ emitter was 120 nm thick and doped to $n = 5 \times 10^{17}$ cm^{-3}. The composition was linearly graded from $x = 0.0$ to 0.25 over 30 nm on both sides of the emitter to eliminate the formation of a potential spike barrier ΔE. The ΔE is less than 3 meV at 300 K as determined by the technique outlined in [5]. The emitter contact layer was 100 nm and doped to $n = 5 \times 10^{18}$ cm^{-3}. The devices studied were fabricated using a non-self-aligned process, with emitter dimensions of 3.5×10 μm^2 and collector dimensions approximately four times larger.

Direct current and microwave measurements were made from 300 to 90 K. S parameters were measured from 0.5 to 20 GHz with an HP 8510B network analyzer and a vacuum cryogenic probe station equipped with Cascade Microtech probes, the details of which have been outlined elsewhere [6]. The measurement system was calibrated off-wafer using a Cascade Microtech impedance standard. The microwave results reported here are based on the extrinsic measurements. The measured S parameters were converted to H parameters and extrapolated versus frequency following a 6-dB/octave rolloff to determine the f_T. Typical H_{21} versus frequency curves at 300 and 110 K are shown in Fig. 1. The peak value of f_T at each temperature monotonically increases from 300 to 110 K as shown in Fig. 2.

The f_T of an HBT is related to the total response delay time by

$$\frac{1}{2\pi f_T} = \tau_{EC} = \tau_E + \tau_{CC} + \tau_F \tag{1}$$

where the total emitter–collector transit time τ_{EC} is the sum of the individual delays encountered in the device: τ_E = emitter base charging time, τ_{CC} = collector charging time, and τ_F = intrinsic transit time = $\tau_\beta + \tau_{SCL}$, where τ_B = neutral base transit time and τ_{SCL} = base–collector depletion-width transit time. The collector charging time has been determined from low-frequency s-parameter data [7]. The emitter charging time was calculated from material and geometrical data. Small-signal element values have been calculated from the measured s parameters and verified by fitting

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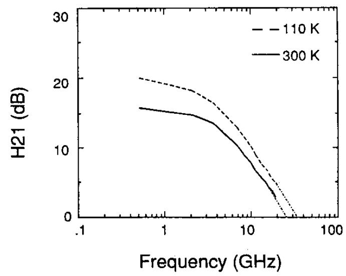

Fig. 1. H_{21} versus frequency for $T = 300$ K ($f_T = 26$ GHz) and for 110 K ($f_T = 34$ GHz).

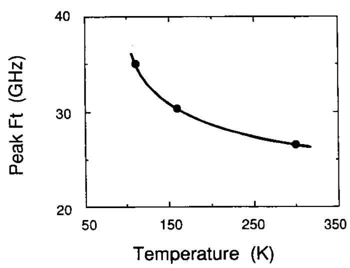

Fig. 2. Peak unity-current-gain cutoff frequency f_T (GHz) versus T (K) for a single 3.5 × 10-μm^2 emitter-finger HBT device.

TABLE I
VARIOUS MEASURED AND CALCULATED HBT DEVICE PARAMETERS

Parameter	$T = 300$ K	$T = 110$ K
I_C (mA)	14	23
V_{BE} (V)	2.0	2.1
V_{CE} (V)	1.3	1.6
R_E (Ω)	2.6	0.7
R_{EE} (Ω)	1.5	1.4
R_B (Ω)	100	55
R_{BB} (Ω)	2.25	1.36
R_C (Ω)	26	20
R_{FB} (kΩ)	12	10.5
C_{je} (fF)	125	221
C_{jc} (fF)	81	109
C_{FB} (fF)	5.23	5.03
β	4.0	8.5
τ_F (ps)	3.2	2.1
f_T (GHz)	26	34

to a small-signal equivalent circuit as in [8]. Table I gives the values of small-signal element values and other important device parameters extracted from the data.

An effective velocity across the neutral base and the base–collector depletion region can be determined from τ_F by

$$\nu_{\mathrm{eff}} = \frac{W_{BC} + W_B}{2\tau_F} \tag{2}$$

where W_{BC} is the base–collector depletion width and W_B is the neutral base width. We find that the ν_{eff} increases from 3.8×10^6 to 5.9×10^6 cm/s, a 55% increase, when the device is cooled from 300 to 110 K. The extent of velocity enhancement through the base–collector depletion width can be determined from (1) if a τ_B can be determined. A value for τ_B can be directly calculated based on diffusive transport using the expression $\tau_B = W_B^2/2D_n$, where D_n is the diffusion coefficient for minority-carrier electrons in the base region of the device. A value for D_n is usually approximated by applying the Einstein relation to the majority-carrier mobility μ_n, with the understanding that this is an upper limit approximation to the minority-carrier mobility $\mu_{n|\min}$ at 300 K. Using 1650 cm^2/V · s for μ_n [9], however, yields a τ_B greater than the τ_F measured for the device at 110 K, implying unphysical (negative) values for τ_{SCL} and the base–collector depletion-width velocity v_{SCL}.

Both theoretical and experimental work on the minority-carrier mobility temperature dependence in p$^+$ GaAs has shown that $\mu_{n|\min}$ actually surpasses μ_n at low temperatures [10], [11]. Although previously published results have not included calculations for N_A as high as 1×10^{19} cm^{-3}, Monte Carlo calculations for $\mu_{n|\min}$ at $N_A = 1 \times 10^{18}$ cm^{-3} increase by a factor of about 1.6 from 300 to 110 K [10]. Experimentally, $\mu_{n|\min}$ at 77 K and $N_A = 4 \times 10^{18}$ cm^{-3} has been shown to increase by as much as a factor of 5 [11]. In addition, the effective minority-carrier concentration n in the base region is high at the values of collector current densities required to obtain maximum f_T, especially at 110 K. In fact, the value of n exceeds the effective conduction band density of states N_c at 110 K, and this calls into question the validity of the Einstein relation under these conditions. This effect can be accounted for by using an approximation presented by Kroemer [12]. We estimate a factor of 3.5 increase in the minority-carrier mobility based on the experimental results at 77 K and the temperature dependence detailed in [10]. Applying both of these corrections to our estimate of τ_B yields a corrected τ_B' of 0.88 ps and a corresponding v_{SCL}' of 5.8×10^6 cm/s, an increase of 53% over the room-temperature value. This agrees quite well with changes in high-field electron velocity as a function of temperature measured by independent, microwave, time-of-flight measurements [13]. Table II summarizes these calculated results. (The single prime on τ_B' and v_{SCL}' designates correction for both degeneracy and the temperature dependence of minority-carrier mobility.)

Theoretical calculations have shown that in the limit of a thin uniformly doped base, the base transport will be limited by the thermal velocity of minority electrons across the base [14]. We can estimate τ_B and τ_{SCL} using the thermal velocity v_T calculated as

$$v_T = \left[\frac{2k_BT}{\pi m^*}\right]^{1/2} \tag{3}$$

where m^* is the electron effective mass in GaAs. We find that for $T = 110$ K, $v_T = 1.3 \times 10^7$ cm/s resulting in a velocity through the base–collector depletion width $v_{SCL\,\mathrm{therm}} = 5.7 \times 10^6$ cm/s, which also agrees with microwave time-of-flight results. This agreement in the percentage change suggests that transport through the neutral base of an HBT may not be purely diffusive at cryogenic temperatures.

In summary, we have measured a 31% increase in f_T when cooling AlGaAs/GaAs HBT's from 300 to 110 K. Velocity enhancement through the base–collector depletion width is responsible for improved device operation at cryo-

TABLE II
HBT BASE TRANSIT TIMES AND COLLECTOR VELOCITIES

τ_B (ps)	1.4	3.9
τ'_B (ps)	1.3	0.88
$\tau_{B\,\mathrm{therm}}$ (ps)	0.5	0.87
v_{SCL} (cm/s)	3.8×10^6	N.A.
v'_{SCL} (cm/s)	3.7×10^6	5.8×10^6
$v_{SCL\,\mathrm{therm}}$ (cm/s)	2.6×10^6	5.7×10^6

τ_B and v_{SCL} are based on simple diffusion theory.
τ'_B and v'_{SCL} are based on simple diffusion theory, but including corrections for both degeneracy and minority-carrier mobility temperature dependence.
$\tau_{B\,\mathrm{therm}}$ and $v_{SCL\,\mathrm{therm}}$ are based on thermal velocity limit.

genic temperatures. Based on the extracted values of τ_F, we show that electron diffusion as determined from the majority-carrier mobility does not accurately estimate the base transit time τ_B. By accounting for high-level injection and an increase in the minority-carrier mobility in the base, v'_{SCL} values of 3.7×10^6 and 5.8×10^6 cm/s are calculated at 300 and 110 K, respectively. We can also calculate v_{SCL} based on a thermal velocity limit through the base region yielding $v_{SCL\,\mathrm{therm}}$ of 2.6×10^6 and 5.7×10^6 cm/s at 300 and 110 K, respectively. Further work is necessary to fully understand the minority-carrier transport mechanism in thin highly doped base and collector space-charge regions at cryogenic temperatures.

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