Vertical scaling in heterojunction bipolar transistors with nonequilibrium base transport

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We experimentally measure a departure from conventional scaling of current gain β with base thickness x_B in abrupt junction *n-p-n* heterojunction bipolar transistors. It is empirically established that extreme nonequilibrium electron transport in the base causes β to vary as approximately $1/x_B$. In our AlInAs/InGaAs transistors this new behavior occurs for base thickness $x_B \lesssim 1000$ Å.

For the first time, we show a departure from the conventional dependence of β on base thickness x_B in abrupt junction *n-p-n* heterojunction bipolar transistors (HBTs). This is to be contrasted with the familiar $\beta \propto 1/x_B^2$ found in homojunction bipolar transistors where current gain is limited by diffusive base transport. Our data, combined with high frequency and collector breakdown measurements, confirm the fact that, in the regime where extreme nonequilibrium electron transport in the base dominates, β scales as $1/x_B$. In addition, there exists another regime where current gain scales approximately as $1/x_B^2$, but base transport cannot be described using the commonly accepted notion of diffusive electron transport.

In a classical *n-p-n* homojunction (and graded-junction) bipolar transistor, electrons introduced from the emitter diffuse across the base. If the current gain is base recombination limited, base current $I_B = Q_B/\tau_n$, where Q_B is the electron charge in the base and $1/\tau_n$ is the electron recomibination rate. Because base thickness is typically much less than the minority carrier diffusion length, but more than the electron mean free path, $Q_B \propto x_B$, the base current scales as $I_B \propto x_B$. The collector current I_C is limited by electron diffusion across the base with an effective electron velocity $V_{\text{eff}} \propto D/x_B$, where D is the diffusion constant. Therefore, common emitter current gain $\beta = I_C/I_B \propto 1/x_B^2$. In an abrupt heterojunction bipolar transistor collector, current is limited by injection at the emitter-base conduction band spike ΔE_c when $v_{\text{therm}} \exp(-\Delta E_c/k_BT) \ll D/x_B$. In this expression, $v_{\text{therm}} \lesssim 1 \times 10^7$ cm s^{-1} is the x-directed average thermal velocity in the emitter and $k_BT = 0.025$ eV is the thermal energy at room temperature. Thus, for example, the *collector current* in an abrupt junction HBT with $\Delta E_c > 0.2$ eV, $x_B > 100$ Å and $D = 25$ cm^2 s^{-1} does not directly depend on base thickness x_B even if base transport is diffusive.[1] In such a transistor, the base thickness dependence of β arises solely from the x_B dependence of base current, I_E. In our experiments, we observe a changeover from a $1/x_B$ dependence for $x_B \lesssim 1000$ Å to a $1/x_B^2$ dependence for $x_B \gtrsim 1000$ Å. Using high frequency and collector breakdown measurements, we establish that this behavior is related to nondiffusive electron transport in the base.

Single crystal, $Al_{0.48}In_{0.52}As/In_{0.53}Ga_{0.47}As$ layer structures were grown on semi-insulating ⟨100⟩ InP substrates by solid source molecular beam epitaxy.[2] Base thicknesses are in the range 200 Å$\leqslant x_B \leqslant$4000 Å, base doping level is $p = 1.5 \times 10^{19}$ cm^{-3}, and the collector space charge region is $x_C = 3000$ Å thick for all samples except the device with $x_B = 1500$ Å for which $x_C = 5000$ Å. By proper control of growth rate and substrate temperature, we are able to ensure the appropriate superposition of the metallurgical junction with the emitter-base junction. Following crystal growth, HBTs similar to those described in Ref. 3 were fabricated. Since emitter size effect is negligible in these devices,[3] small area devices with emitter stripe widths of 2.5 μm were chosen to eliminate emitter-current crowding. It is also important to establish that current gain is not limited by nonideal $2k_BT$ current components, particularly in thin base transistors where the neutral base recombination is is small. Figure 1(a) shows the Gummel plot for a HBT with $x_B = 200$ Å. Note, the base current ideality factor is essentially identical to that for the collector current indicating negligible $2k_BT$ effects.

The abruptness of the emitter-base heterojunction is confirmed by carefully measuring the temperature dependence of the collector current $I_C = I_S[\exp(eV_{BE}/nk_BT) - 1]$ for $V_{CB} = 0$ V. Typical results of measured $I_S|_{V_{CB}=0\ V}$ are shown in Fig. 1(b). From these data, we are able to determine an effective barrier energy for electrons of $\phi \sim 1.23$ eV. This corresponds to $\sim (E_{gb} + \Delta E_c)$, where $E_{gb} = 0.76$ eV is the bandgap of the $In_{0.53}Ga_{0.47}As$ base and $\Delta E_c = 0.47$ eV, the energy of the conduction band offset, is the excess kinetic energy with which electrons are injected from the emitter into the base. By way of contrast, in a transistor with graded emitter-base junction, we would obtain $\phi \sim E_{gb}$ and only low energy electrons in thermal equilibrium with the lattice could be introduced into the base. An increase in the excess initial kinetic energy of electrons injected into the base of an abrupt HBT extends the region over which nonequilibrium electron transport is important and potentially increases device speed.[4]

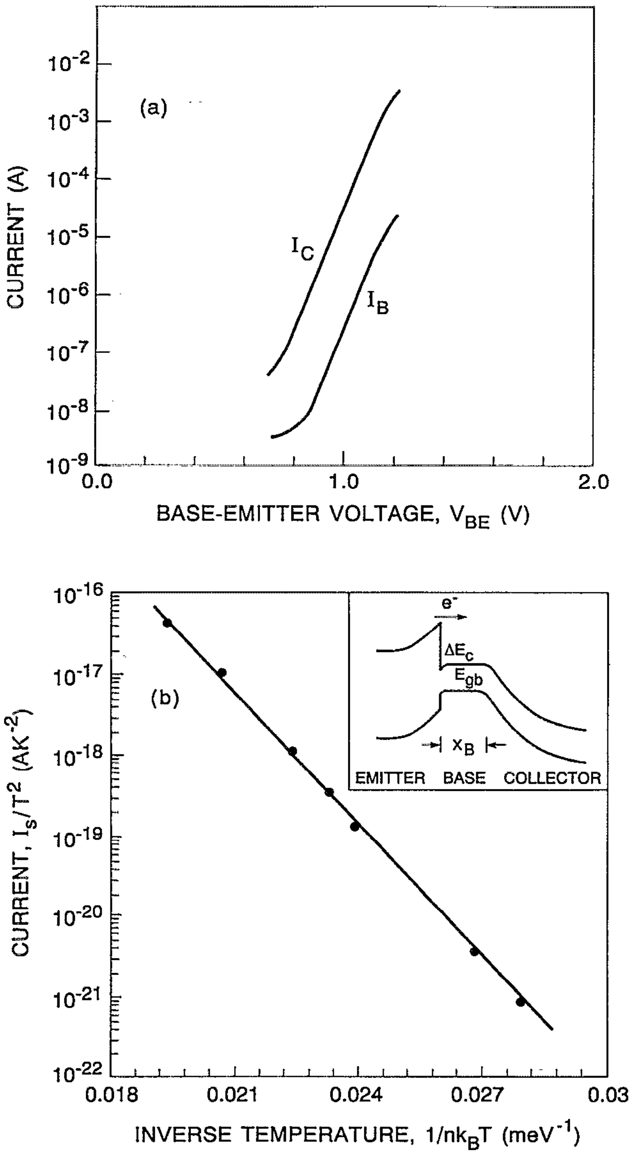

FIG. 1. (a) Measured room temperature Gummel plot for an $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ HBT with $x_B = 200$ Å. (b) Measured temperature dependence of current I_S for $V_{BC} = 0$ V. The inset shows a schematic of the band diagram of an abrupt $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ *n-p-n* HBT under bias.

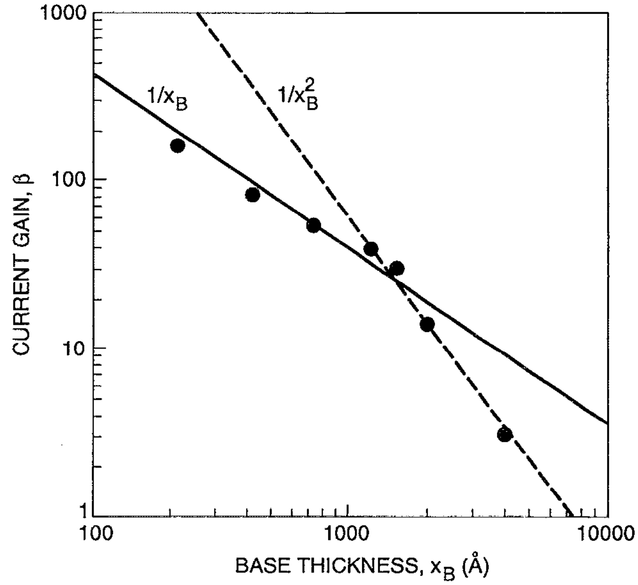

FIG. 2. Plot of measured room temperature common emitter current gain, β, as a function of base thickness, x_B, for $I_C = 100$ μA and $V_{BC} = 0$ V. The broken line is the behavior expected for $\beta \propto 1/x_B^2$ and the solid line is for $\beta \propto 1/x_B$.

Measured room temperature current gain, β for $I_C = 100$ μA and $V_{BC} = 0$ V as a function of base thickness x_B, is shown in Fig. 2. It is clear from the data that for $x_B < 1000$ Å the current gain β scales as $1/x_B$, whereas for $x_B > 1000$ Å β varies approximately as $1/x_B^2$. Naively, we expect a $1/x_B$ dependence when charge transport in the base is dominated by extreme nonequilibrium electron motion. In this simplistic picture the collector current, I_C, is independent of base thickness but the base current, I_B, is proportional to the volume of the neutral base. As expected, we observe that, for a given base-emitter bias V_{BE}, the difference in current gain for devices with $x_B = 200$ Å and $x_B = 400$ Å is solely determined by changes in base current.

The presence of extreme nonequilibrium electron transport at the base-collector junction should enhance avalanche multiplication in the collector. This has been verified and, thereby, independently confirms the existence of extreme nonequilibrium transport in our devices. Figure 3 shows the measured avalanche multiplication constant γ as a function of base thickness, x_B.[5] Here, $\gamma = I_{av}/(I_C - I_{av})$ where $I_{av} = \Delta I_C - \Delta I_B$ is the avalanche current. As may be seen in Fig. 3, extreme nonequilibrium electron transport in the base enhances γ when $x_B \leqslant 1000$ Å. This observation correlates remarably well with the measured dependence of current gain on base thickenss shown in Fig. 2, indicating that the $1/x_B$ behavior of β is related to the presence of extreme nonequilibrium electron transport at the base-collector junction.

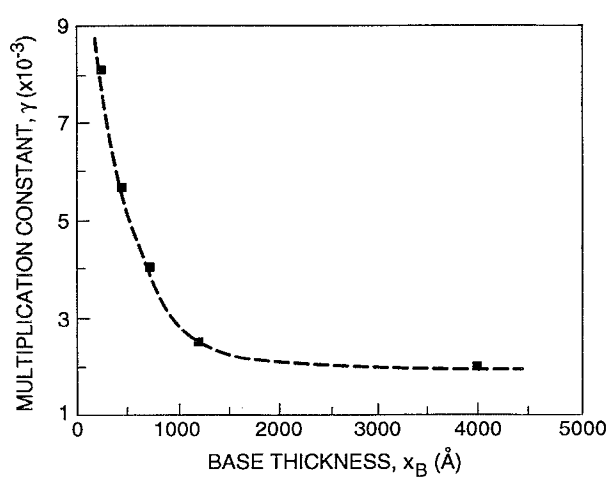

FIG. 3. Measured room temperature value of multiplication constant γ vs base thickness x_B for abrupt junction $In_{0.52}Al_{0.48}As/In_{0.53}Ga_{0.47}As$ HBTs. γ was obtained by measuring the variation in current from $V_{CB} = 0.2$ to 1.0 V.

TABLE I. Device parameters.

Parameter	Device 1	Device 2
x_B (Å)	700	4000
x_C (Å)	3000	3000
τ_F (ps)	0.47	6.5
f_T (GHz)	70	17

In addition to the $1/x_B$ scaling for $x_B < 1000$ Å, there exists another regime 1000 Å $\lesssim x_B \lesssim$ 4000 Å where β might be characterized by a $1/x_B^2$ dependence (see Fig. 2). However, as we will demonstrate, electron dynamics in the base cannot be ascribed to purely diffusive charge transport. This is to be distinguished from the above mentioned classical homojunction transistor scaling behavior in which a single minority carrier diffusion constant describes devices of differing x_B and consequently $I_C \propto 1/x_B$ and $I_B \propto x_B$ giving the familiar $\beta = I_C/I_B \propto 1/x_B^2$.

To obtain a more complete understanding of device operation, we also measured the high frequency response of our transistors. In Table I we show results from *s*-parameter measurements on two representative samples with the same geometry and collector thickness. In the table $\tau_F = \tau_B + \tau_C$ where τ_B and τ_C are the base and collector transit delays, respectively. For $x_B = 700$ Å, we have $\tau_F = 0.47$ ps and for $x_B = 4000$ Å $\tau_F = 6.5$ ps. Because electron velocity in the collector cannot exceed a group velocity of $\sim 1 \times 10^8$ cm s^{-1}, the minimum collector delay in both devices, for which $x_C = 3000$ Å, is $\tau_C = 0.15$ ps. Therefore, the maximum base transit delay in the $x_B = 4000$ Å device is $\tau_B = 6.35$ ps corresponding to a minimum average electron velocity of 6.3×10^6 cm s^{-1}. If it were possible to explain electron transport in the base using diffusive motion, this would imply a minority carrier mobility of around 5000 cm^2 V^{-1} s^{-1} and a diffusion constant of 125 cm^2 s^{-1}. Both of these values are unreasonably high (by almost an order of magnitude) for a majority carrier *p*-type doping level of 1.5×10^{19} cm^{-3}.[6] Therefore, even in an abrupt HBT with $x_B = 4000$ Å, in which current gain appears to scale as $1/x_B^2$ (see Fig. 2), electron motion in the base cannot be described by pure diffusion. Another approach might be to invoke the possibility of hot carrier diffusion in which electrons are presumed to be described by an effective electron temperature that is greater than the lattice temperature. Unfortunately, such a situation does not exist when electron injection energy is high [e.g., $\Delta E_c \gtrsim 0.2$ eV (Ref. 7)]. The reason for this is that, in abrupt junction HBTs with high injection energy ($\Delta E_c \gtrsim 0.2$ eV), the distribution of electrons launched into the base is always substantially nonthermal. In addition, the electron momentum distribution varies spatially across the base. In this situation, finding an analytic expression for the steady-state electron momentum distribuion (needed to determine current gain) is a rather subtle problem.

However, it is worth mentioning that the results presented here may be generalized. Numerical simulations using methods similar to those outlined in Ref. 8 indicate that, for these transistors, our results apply to devices with base doping levels from around $p = 1 \times 10^{19}$ cm^{-3} to well beyond $p = 1 \times 10^{20}$ cm^{-3}. The physical reason for this may be traced to the fact that total nonequilibrium electron scattering rate in these HBTs is insensitive to base doping in this range.[9]

In conclusion, we demonstrate that extreme nonequilibrium electron transport in the base of abrupt junction *n-p-n* HBTs causes current gain to vary with base thickness as $1/x_B$. In addition, there exists another regime where current gain scales approximately as $1/x_B^2$ but the physics of electron transport in the base cannot be described using diffusion.

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