Nonequilibrium electron transport in heterostructure bipolar transistors probed by magnetic field

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We show that the static current-voltage characteristics of a heterojunction bipolar transistor are dramatically influenced by application of a magnetic field. Nonequilibrium base transport has a strong influence on collector/emitter breakdown voltage, V_{CE_B}. With a magnetic field applied perpendicular to the direction of the injected emitter current V_{CE_B} increases from 2.6 V at 0 T to 8 V at 8 T. In the same device with a magnetic field applied parallel to the current flow, the current gain increases by a factor of 2 over the same magnetic field range. Transistors which exploit nonequilibrium base and collector transport have qualitatively different behavior compared to conventional devices which use diffusive and drift-diffusive transport.

Recent interest in high velocity nonequilibrium electron transport in compound semiconductor bipolar devices is partly driven by the desire to develop a new class of ultrahigh speed transistor. For example, using an *N-p-n* heterostructure bipolar transistor (HBT), an extreme nonequilibrium distribution of electrons with excess kinetic energy ΔE_C, can be injected from the wide band gap *N*-type emitter into the conduction band of the narrow band-gap *p*-type base (see Fig. 1). For a thin base width, $Z_B < \lambda$ (where λ is the nonequilibrium electron mean free path), a significant number of electrons can maintain a high velocity of $v \sim 10^8$ cm s^{-1} and traverse the base with little scattering. Experimentally, in the fastest bipolar transistors the measured average electron velocity through the base and collector is $v = 4 \times 10^7$ cm s^{-1} at a temperature of $T = 300$ K (Ref. 1) increasing to more than $v = 6 \times 10^7$ cm s^{-1} at $T = 80$ K. The practical realization of such transistors raises questions concerning the impact nonequilibrium transport has on device operation. In particular, differences, other than speed which exist between a device employing nonequilibrium transport and one which uses the more familiar, low velocity, diffusive and drift-diffusive transport, is of interest.

In this letter we report results of using a magnetic field to probe the effect of nonequilibrium charge transport on HBT performance. We show that a magnetic field applied parallel to the direction of the current injection can increase the current gain β of a HBT with nonequilibrium base charge transport in contrast to transistors with diffusive base transport in which β decreases. Importantly, and again in contrast to a diffusive device, our results show that nonequilibrium base transport can have a dramatic influence on collector transport.

A number of *N-p-n* $\mathrm{Al_{0.48}In_{0.52}As/In_{0.53}Ga_{0.47}As}$ HBT layer structures were grown using molecular beam epitaxy (MBE) on semi-insulating $\langle 100 \rangle$ oriented InP substrates. The substrates are polished with bromine methanol and then etched in $\mathrm{H_2SO_4{:}H_2O_2{:}H_2O}$ (4:1:1) solution for 10 min followed by 3 min in 0.3% bromine methanol.[2] Surface oxide on the InP substrate is desorbed in the MBE system at a temperature of 530 °C while an $\mathrm{As_4}$ beam is used to stabilize the surface. High-purity solid sources of As, Al, Ga, In, Si, and Be are used in the effusion cells, and during growth the substrate is maintained at 540 °C with a growth rate of 2 μm per hour. The base is doped to $p = 2 \times 10^{19}$ cm^{-3} with Be in all the HBT devices. Transistors with base width $Z_B = 500$, 800, 2000, and 4000 Å and a fixed collector depletion width $Z_C = 3000$ Å were investigated. A standard photolithographic process is used to produce transistors with intrinsic emitter stripe width $W = 0.5$, 1.0, 1.5, 2.5, and 3.5 μm (see Fig. 2) and a base to emitter electrode spacing of 0.5 μm. The magnetic field dependence of common emitter current gain β and breakdown voltage V_{CE_B} was measured in a superconducting magnet with the sample maintained at a temperature of $T = 4.2$ K.

In Fig. 3 we show results of measuring the common emitter current gain for a number of devices with different Z_B and for a fixed base current as a function of magnetic field applied perpendicular to the direction of injected emitter current $B_\perp$. In the simplest classical description of electron motion in a magnetic field, carriers of charge e, mass m^*, and velocity v describe part of the radius $r = m^* v / e B_\perp$ between collisions. Thus, for an electron transiting the base and initially moving perpendicular to the plane of the emitter heterojunction (in the z direction) the application of $B_\perp$ increases the effective path length for the

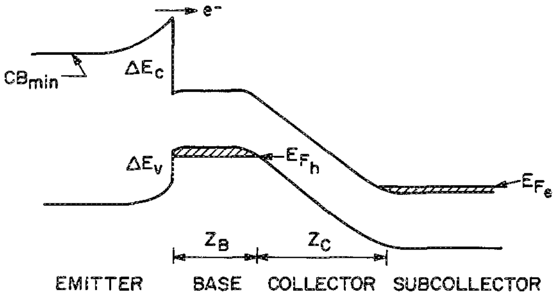

FIG. 1. Energy-band diagram for an AlInAs/InGaAs HBT with $\Delta E_C = 0.48$ eV, $\Delta E_V = 0.24$ eV, $Z_C = 3000$ Å, and Z_B as the base width.

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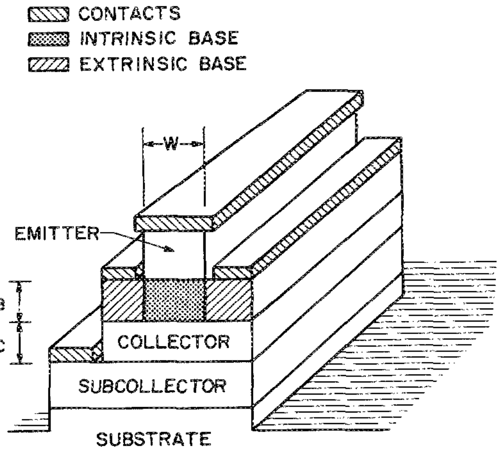

FIG. 2. Schematic representation of the processed device with W being the width of the intrinsic device (area under the emitter stripe).

charge carrier to traverse the base. The resulting increase in base transit time increases the probability of electron scattering so that by increasing $B_\perp$, it is possible to continuously change base transport dynamics from the nonequilibrium case ($Z_B<\lambda$, $B_\perp=0$ T) to the diffusive regime ($B_\perp \gtrsim m^*v/eZ_B$). In addition, for small emitter stripe width W, a significant number of injected electrons can be deflected into the extrinsic base region where they can recombine, degrading β by contributing to the base current I_B. The current gain of the transistor should decrease dramatically when the cyclotron radius r is the same as the base thickness Z_B, i.e., when $Z_B=m^*v/eB_\perp$. This decrease is expected because, when $r \lesssim Z_B$, injected electrons can only leave the base region and flow as collector current by scattering. Obviously, the more often an electron scatters the greater the chance it has of recombining with holes in either the extrinsic or intrinsic base (and contributing to the base current). For example, a magnetic field of 4.7 T is required to give $r=500$ Å (for $v=10^8$ cm s^{-1} and an effective electron mass $m^*=0.041m_0$). As may be seen in Fig. 3, for $Z_B=500$ Å and $B=4.7$ T β decreases to around 0.14 (approximately $1/\exp^2$) of its $B_\perp=0$ T value. In contrast, for $Z_B=4000$ Å the same decrease in β requires a much smaller value of $B_\perp=0.65$ T.

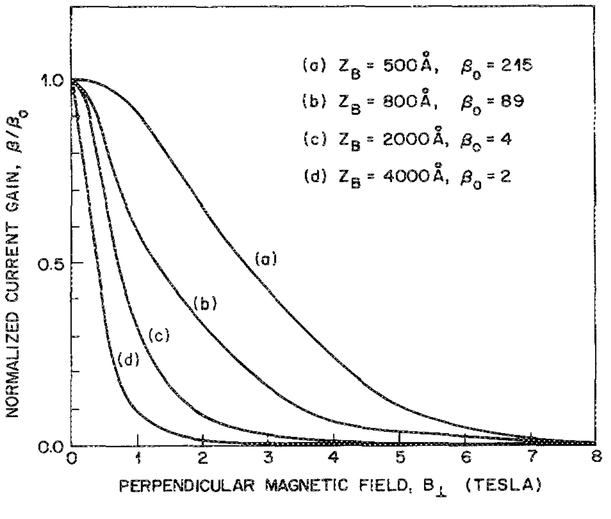

FIG. 3. Dependence of normalized common emitter current gain β/β_0 on magnetic field applied perpendicular to the direction of injected emitter current. Data obtained with the sample maintained at a temperature $T=4.2$ K, $W=2.5\,\mu$m, $V_{CE}=1$ V, and a fixed emitter current density of 2.5 A cm^{-2} at $B_\perp=0$ T.

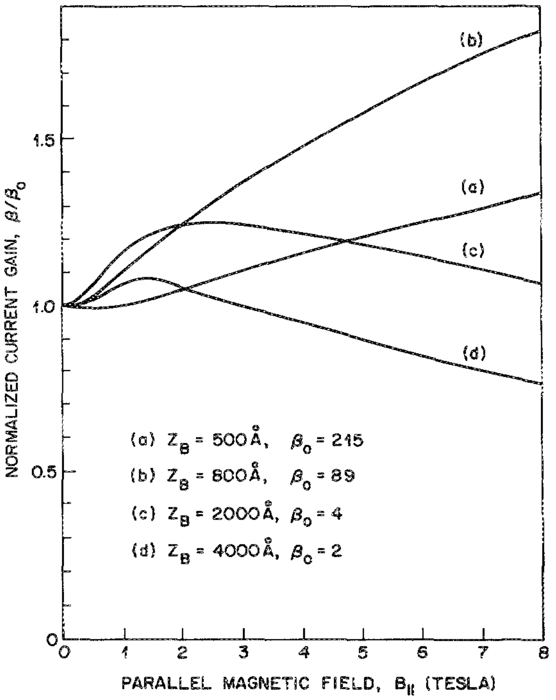

FIG. 4. Dependence of normalized common emitter current gain β/β_0 on magnetic field applied parallel to the direction of injected emitter current. Data obtained with the sample at $T=4.2$ K, $W=2.5\,\mu$m, $V_{CE}=1$ V, and a fixed emitter current density of 2.5 A cm^{-2} at $B_\parallel=0$ T.

In Fig. 4 we show the results of applying a magnetic field parallel to the direction of injected current ($B_\parallel$). For the narrowest base width ($Z_B=500$ Å and $W=2.5\,\mu$m), there is a modest increase in current gain with increasing magnetic field ($\beta=1.34\beta_0$ at $B_\parallel=8$ T). Since $Z_B<\lambda$, most electrons traverse the base very rapidly ($\sim$50 fs) without scattering and so $B_\parallel$ has little effect. However, there are also a small number that suffer angular scattering out of the forward z direction [average scattering angle $\theta \sim 30°$ (Ref. 3)]. These electrons have a finite probability of reducing β by recombining with holes in the extrinsic base. In this case, application of a magnetic field $B_\parallel$ results in an increase in β by causing electrons scattered by angle θ to describe a helical path of radius r about the z direction and thereby reduce the volume of extrinsic base into which electrons can move. This is confirmed experimentally by investigating β for different stripe widths W. For example, by decreasing the stripe width to $W=0.5\,\mu$m and keeping $Z_B=500$ Å fewer electrons traverse the *intrinsic* base and $B_\parallel$ has significantly more effect.

Naturally, increasing Z_B increases the number of electrons which suffer a collision while traversing the base and so, for a $W = 2.5$ μm, β_0 decreases from $\beta_0 = 215$ for $Z_B = 500$ Å to $\beta_0 = 89$ for $Z_B = 800$ Å (see Fig. 4). Since comparatively more electrons are scattered into the extrinsic base volume, the enhancement in current gain with increasing $B_{\parallel}$ is more dramatic. The situation changes qualitatively for very large values of Z_B. For $Z_B = 4000$ Å electrons spend a long time (a few ps) and suffer a large number of collisions while traversing the base in an essentially diffusive manner. Current gain β_0 is small mainly because of radiative recombination in the intrinsic base. In this case application of a magnetic field $B_{\parallel}$ causes current gain to decrease. The decrease occurs because, as is well known, the presence of a magnetic field increases radiative recombination between electrons and holes due to wave function shrinkage.[4]

Application of a perpendicular magnetic field $B_{\perp}$ allows one to measure from a regime in which nonequilibrium transport dominates to one in which diffusive transport describes carrier motion. We have used this fact to explore the influence nonequilibrium base transport has on transistor breakdown voltage, V_{CE_B} for a fixed saturated collector current $I_C = 10$ μA. As may be seen in Fig. 5, $B_{\perp}$ has little influence on the breakdown voltage for a sample in which base transport is always diffusive, i.e., $Z_B = 4000$ Å. However, for a HBT with $Z_B = 800$ Å in which nonequilibrium electron base transport is important, V_{CE_B} is relatively small ($V_{\mathrm{CE}_B} \simeq 2.6$ V) in zero magnetic field.[5] This is because, in a device where $Z_B \lesssim \lambda$ collector transport depends on base transport dynamics[3] (in contrast to conventional diffusive transistors). Electrons arrive at the base/collector junction with considerable average excess kinetic energy and these electrons are rapidly accelerated in the electric field of the collector to energies above threshold for impact ionization (and breakdown). As discussed above, application of $B_{\perp}$ increases scattering in the base and has the effect of reducing the average excess kinetic energy of electrons arriving at the base/collector junction. In this situation electrons have to be accelerated from a lower energy before reaching the threshold for breakdown and so V_{CE_B} increases. For $B_{\perp} = 8$ T base transport is essentially diffusive and the breakdown voltage for the device, $V_{\mathrm{CE}_B} \simeq 8$ V, is almost the same as the case with $Z_B = 4000$ Å.

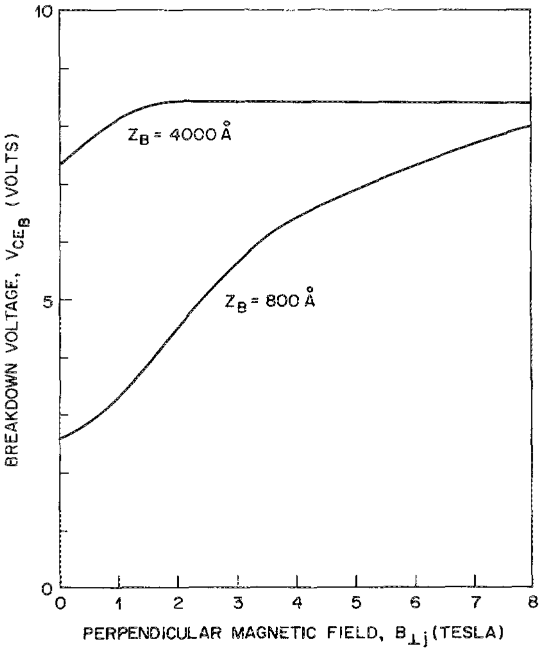

FIG. 5. Measured collector/emitter breakdown voltage V_{CE_B} for a sample with $Z_B = 4000$ Å and $Z_B = 800$ Å as a function of perpendicular magnetic field $B_{\perp}$. Data obtained with the sample at $T = 4.2$ K. The saturated collector current is $I_C = 10$ μA and breakdown is defined to occur for $I_C = 30$ μA. The devices have an emitter area of 30 μm^2.

In conclusion, we have used a magnetic field to probe the dynamics of electron transport in HBTs. Devices which make use of nonequilibrium base and collector transport have qualitatively different behavior compared to structures which use diffusive and drift-diffusive transport. Nonequilibrium electron transport is shown to improve current gain but necessarily reduces collector/emitter breakdown voltage.

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