Base transport dynamics in a heterojunction bipolar transistor

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We have used hot-electron spectroscopy to study nonequilibrium electron transport in the base of a heterojunction bipolar transistor. Electrons injected from an *n*-type AlGaAs emitter into a *p*-type GaAs base were found to be strongly scattered such that they could be characterized by an effective electron temperature after traversing several hundred angstroms. The effective electron temperature, measured at 4.2 K, was found to be 150 K for a sample having a 900-Å base region and 500 K for a sample having a 450-Å base region.

Heterojunction bipolar transistors (HBT's) are being investigated for future high-speed digital, optical, and microwave applications. Because serious consideration is being given to such structures, it is important that the physics of carrier dynamics in HBT's be understood to a level sufficient to ensure realistic device modeling. Electron transport in a heterojunction bipolar transistor having an abrupt injector differs from that of a homojunction bipolar transistor in allowing one to inject an extreme nonequilibrium charge carrier distribution into the base over the heterojunction emitter. In an *n*-*p*-*n* HBT the injected electron momentum distribution, which is peaked normal to the plane of the emitter, enters the base where electrons scatter, altering the distribution. The amount by which electrons scatter determines whether the initial distribution thermalizes (strong scattering) or emerges with a peaked momentum distribution (weak scattering).

To investigate the physics of injected hot-electron transport in an HBT we have applied to the technique of "hot-electron spectroscopy" used to explore nonequilibrium electron transport in unipolar structures.[1-3] Our study utilizes a double heterojunction bipolar transistor grown by molecular beam epitaxy on ⟨100⟩ oriented semi-insulating GaAs substrates at 650 °C. The transistor consisted of an *n*-type (2×10^{17} cm^{-3}) AlGaAs emitter from which electrons could be injected into a Be-doped *p*-type (2×10^{18} cm^{-3}) base and collected with an *n*-type (2×10^{17} cm^{-3}) AlGaAs collector. A schematic diagram of the grown layers is shown in Fig. 1. As may be seen, some compositional grading adjacent to the base/collector heterojunction was incorporated in the structure to reduce quantum mechanical reflection of the hot electrons arriving at the collector. Not shown in the figure is a small base doping set back to prevent outdiffusion of *p*-type dopant into either the collector or emitter during growth. Transistors were fabricated from the grown crystals by etching two level mesas to reveal the base and collector. Ohmic contact was made by rapidly annealing an Au-Sn alloy to emitter and collector and an Au-Be alloy to the base. Results of measurements on the two HBT's reported here have the same base doping ($P_b = 2\times10^{18}$ cm^{-3}), similar Al concentration in the emitter and collector, but different base widths: $W_b = 900$ and 450 Å. When the emitter is forward biased, electrons are injected into the base with an excess energy above the conduction-band edge of $\phi_{be} = 0.2$ eV (sample with the 900-Å base widths) and $\phi_{be} = 0.15$ eV (sample with the 450-Å base width). These injected electrons scatter in the base and impinge on the base/collector

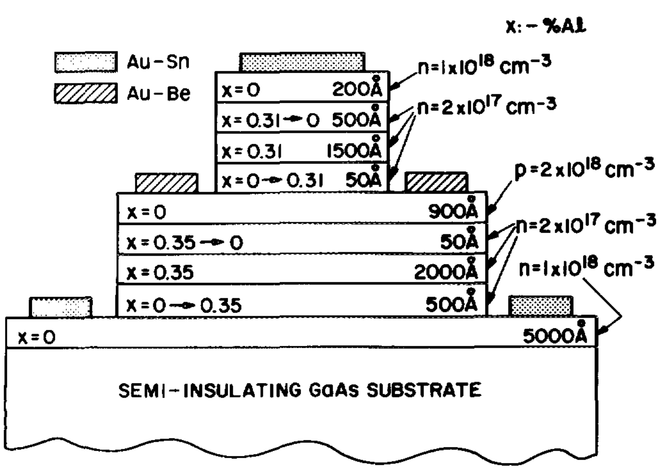

FIG. 1. Schematic diagram of the layer structure comprising the double heterojunction bipolar transistor having the 900-Å base region. The fraction of Al present in each layer is given by *x*.

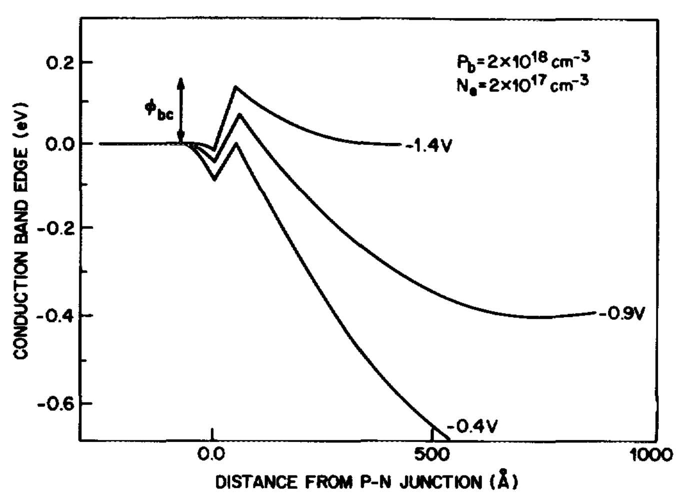

FIG. 2. Calculated variation of the base/collector conduction-band edge with distance at indicated values of forward bias.

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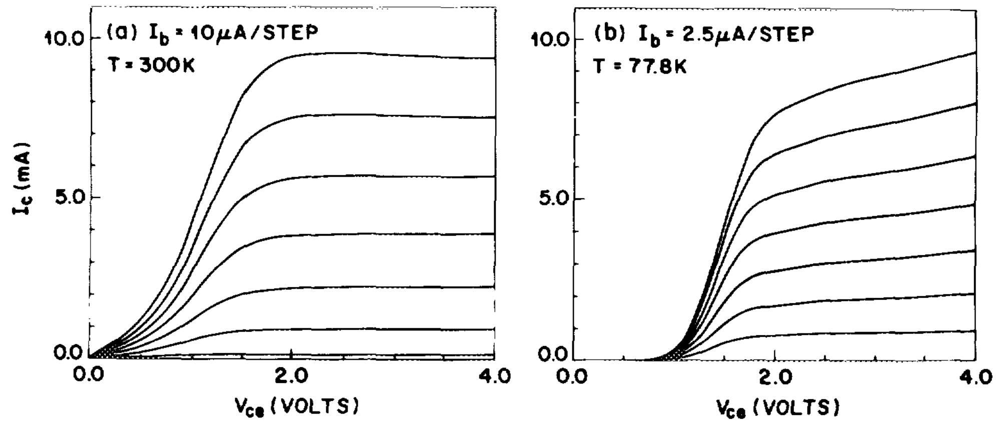

FIG. 3. Common emitter characteristics of the double heterojunction bipolar transistor having a 900-Å transit region measured at (a) 300 K and (b) 77.8 K. The emitter mesa diameter is 100 μm.

junction with a momentum distribution characteristic of the strength of scattering that occurred in the base. By applying a forward bias to the base/collector junction, the GaAs/AlGaAs heterojunction barrier may be used as a hot-electron analyzer giving direct information on the hot-electron momentum distribution arriving at the collector. For a given collector barrier energy, ϕ_{bc}, only those hot electrons with a component of momentum perpendicular to the plane of the barrier, $p_\perp$, such that $p_\perp > \sqrt{2m_e \phi_{bc}}$, where m_e is the effective electron mass, can surmount the barrier and flow as collector current, j_c.

The calculated variation of the base/collector conduction-band edge with applied bias is shown in Fig. 2. It was obtained by summing the variation of built-in potential and electron affinity across the graded heterojunction[4] for a device structure similar to that sketched in Fig. 1. When a forward bias of $V_{bc} \simeq -0.4$ V is applied, one just begins to analyze the distribution. With increasing forward bias (more negative V_{bc}), fewer electrons surmount the increasing base/collector barrier energy, ϕ_{bc}, until finally at $V_{bc} \simeq -1.6$ V $\phi_{bc} > \phi_{be}$ and no electrons are collected. Our calculations indicate that ϕ_{bc} varies almost linearly with V_{bc}.

This variation in collector band edge with applied bias manifests itself in both the common emitter and common base transistor characteristics. Typically, transistors with the 900-Å- (450-Å-)wide base have common emitter current gains β of over 50 (100) at a temperature of 300 K increasing to greater than $\beta = 500$ (10 000) at 100 K. Figure 3 shows the common emitter characteristics of a transistor with a 900-Å base width measured at 300 and 78 K. Note that at room temperature there is some departure from an ideal saturation characteristic. A collector/emitter bias V_{ce} of 1.5 V is required before saturation occurs. This effect, which is a direct result of lowering ϕ_{bc} (Ref. 5) (the base/collector junction barrier), is enhanced by reducing the sample temperature to 78 K. Low temperatures reduce thermal smearing effects allowing one to observe an appreciable emitter/collector offset voltage. Figure 4 shows the common base characteristic at 300 and 78 K for the same sample used to obtain Fig. 3. Again current saturation is nonideal, occurring between $V_{bc} = -0.4$ and -1.6 V.

We have shown previously for the case of a base/collector barrier energy, ϕ_{bc}, which varies linearly with applied voltage bias, V_{bc}, that dj_c/dV_{bc} is proportional to $n(p_\perp)$, a projection of the hot-electron momentum distribution at the collector barrier.[3] Thus, measuring the hot-electron spectrum, dj_c/dV_{bc}, as a function of V_{bc} in the common base configuration, gives direct information on the hot-electron momentum distribution. Figure 5 shows the hot-electron spectrum for two samples placed at 4.2 K having base widths of (a) 450 Å and (b) 900 Å. The injection energy ϕ_{be} and the conduction-band minimum in the base E_c are indicated in the figure. There is no evidence in either spectra of the initial injected distribution with most of the spectral weight occur-

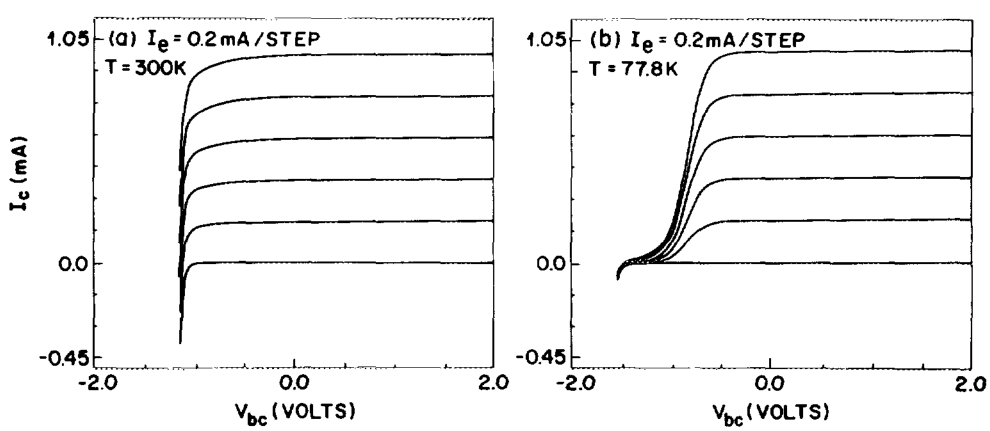

FIG. 4. Common base characteristics of the double heterojunction bipolar transistor having a 900-Å base region measured at (a) 300 K and (b) 77.8 K.

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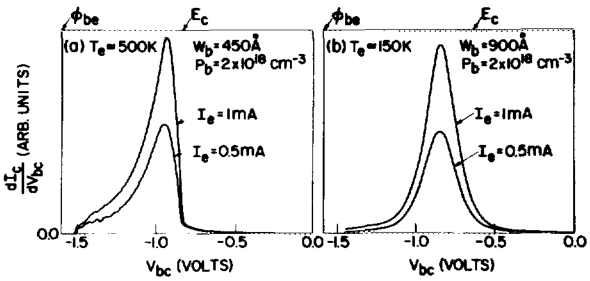

FIG. 5. Hot-electron spectra, measured at 4.2 K, for a double heterojunction bipolar transistor having (a) a 900-Å base width and (b) a 450-Å base width. The inferred electron temperature is indicated in the figures.

ring close to E_c (the conduction-band edge). This indicates that the initial injected distribution has been strongly scattered while traversing the transistor base. In fact, the distribution has been scattered sufficiently that we may infer an "effective electron temperature" T_e with which to describe the electron distribution arriving at the collector. For the sample with the 900-Å base width we found $T_e \sim 150$ K and for the 450-Å sample $T_e \sim 500$ K. It should be noted that the base conduction-band edge (E_c) is not at the same position on each spectrum due to the different Al concentrations used in the collector of each sample.

In order to confirm that the observed spectra were due to hot-electron transport, the magnetic field dependence of the spectra was measured. We found the results of these measurements to be consistent with those expected for hot-electron transport. When the magnetic field was applied parallel to the direction of current injection, little change was observed in the spectra for fields as high as 5 T. With the field in this direction electrons, classically, follow a helical path between collisions, and the effective base width remains constant. When the magnetic field was applied perpendicular to the direction of current injection, the spectra became more sharply peaked at lower energies closer to E_c.

The structure used in our study models a realistic device by having a high p-type base doping level ($P_b \simeq 2\times 10^{18}$ cm^{-3}) to reduce the base resistance so that high-frequency performance may be realized. At these impurity levels elastic ionized impurity scattering plays an important role in randomizing the momentum of hot electrons traversing the base. Also important are inelastic collisions involving the excitation of the coupled optic-phonon/p-type majority-carrier system in the base. These processes include intervalence-band scattering in which, for example, a light hole is activated into the heavy-hole band.

In conclusion, the results of our hot-electron spectroscopy measurements show that the scattering rate for electrons in p-type GaAs is at least as strong as in n-type GaAs. The observed strong scattering of hot electrons in the p-type base of an HBT suggests that previous claims of near "ballistic" base transport were premature.[6,7] Due to the high scattering rate in a necessarily heavily doped base a proposed resonant tunneling transistor[8] will not function in the originally intended manner utilizing, as it does, ballistic electron base transport. Of course this does not preclude the possibility that a resonant tunneling transistor with diffusion limited base transport will have some of the proposed device's low-frequency characteristics.

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