Extreme nonequilibrium electron transport in heterojunction bipolar transistors

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We use hot-electron spectroscopy to demonstrate the existence of extreme nonequilibrium electron transport in the base of *n-p-n* heterojunction bipolar transistors. In the device, electrons are tunnel injected into a thin (~ 300 Å wide), degenerately doped, *p*-type GaAs base.

Extreme nonequilibrium (or quasiballistic) electron transport can dominate transistor performance when device geometries have length scales similar to a characteristic mean free path λ of charge carriers. In the base of a typical GaAs/AlGaAs *n-p-n* double-heterojunction bipolar transistor (DHBT), the relevant value of λ is around 350 Å.[1] However, until now, no evidence has been found for quasiballistic base transport in DHBT's.[2,3]

In this letter we demonstrate, for the first time, the existence of quasiballistic electron transport over 300 Å length scales in GaAs/AlGaAs bipolar transistors using a tunnel injector as the emitter.[4] The device turn-on characteristics are shown to be modified by the presence of extreme nonequilibrium electron transport in the base. In addition, the use of a tunnel emitter allows tuning of the injection energy as a function of applied emitter bias voltage V_{be}, giving further useful information on transport dynamics.

Transistor structures were grown by molecular beam epitaxy on semi-insulating ⟨100⟩ oriented GaAs substrates. Figure 1 shows a schematic band diagram of the structure under bias. Electrons in the *n*-type (1×10^{18} cm^{-3} Si impurity) GaAs emitter can tunnel through an intrinsic 80-Å-thick, AlAs barrier into a 260-Å-wide *p*-type (3×10^{18} cm^{-3} Be impurity) GaAs base. After traversing the base, electrons impinge upon the GaAs/Al$_x$ Ga$_{1-x}$As base/collector barrier, which consists of a 110-Å-thick layer in which the Al concentration x increases from $x=0$ to 0.48. This analog grading[5] was necessary to reduce quantum mechanical reflection of hot electrons arriving at the base/collector junction. The remainder of the collector arm is a 3000-Å-thick layer of *n*-type (8×10^{16} cm^{-3} Si impurity) $\text{Al}_{0.48}\text{Ga}_{0.52}\text{As}$ and an 8000-Å-thick n^+ layer of GaAs which serves as the collector contact.

The wafers were fabricated into two level mesa structures using standard photolithographic and wet chemical etching techniques, allowing separate electrical contact to emitter, base, and collector. Ohmic contacts to emitter and collector were fabricated by rapid thermal annealing an AuSn alloy, and the base contact was achieved using a AuBe alloy. The completed transistor structures had an emitter area of 6×10^{-6} cm^{-2}.

In this letter we focus on base transport dynamics in our device. When the emitter is forward biased, minority carriers are injected into the base with an excess energy E_i, above the conduction-band minimum of GaAs. Here we only consider $E_i < E_{\Gamma L}$, where $E_{\Gamma L} = 330$ meV is the energy of the subsidiary L minimum in GaAs. Therefore, only Γ-valley transport need be considered. While traversing the base, the injected electrons may suffer elastic collisions with ionized impurities and inelastic collisions by exciting the majority, *p*-type, carriers. Elastic scattering rates are low because heavy holes are very effective at screening static impurities. In fact, it has been shown that, for the case of interest, inelastic scattering rates are an order of magnitude larger than elastic scattering rates. Therefore, we expect inelastic scattering to dominate base transport dynamics.[1]

In Fig. 2 we show typical common base current gain α and common emitter current gain β characteristics for the device sketched in Fig. 1. Measurements were taken at a temperature $T = 4.2$ K to avoid thermal effects, although we note that qualitatively similar results were also obtained at $T = 77$ K. As may be seen in Fig. 2(b) the value of β increases from $\beta = 90$ at $I_c = 90\,\mu$A (corresponding to a current density $j = 15$ A cm^{-2}) up to $\beta = 150$ at $I_c = 420\,\mu$A. There is good agreement between the α and β characteristics, and the current gain increases up to $\beta = 250$ for $j = 10^3$ A cm^{-2}. The common base current gain α, shown in Fig. 2(a), increases strongly at $V_{\text{bc}} \simeq -1$ V and saturates at $V_{\text{bc}} \simeq +1$ V. This behavior in the device turn-on characteristics is a direct consequence of lowering the base/collector barrier energy ϕ_{bc}, shown schematically in Fig. 1.

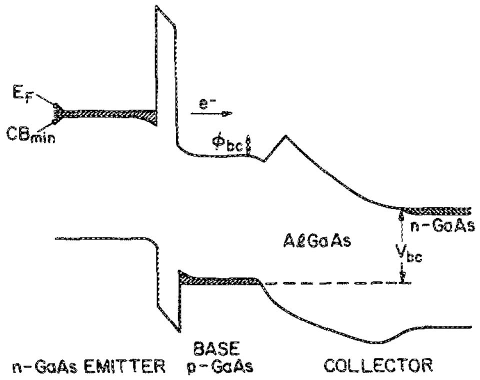

FIG. 1. Schematic band diagram of an *n-p-n* tunnel injection heterojunction bipolar transistor structure under bias. The conduction-band minimum CB$_{\text{min}}$, the electron quasi-Fermi level E_F, the base collector bias voltage V_{bc}, and the base collector barrier energy ϕ_{bc} are indicated.

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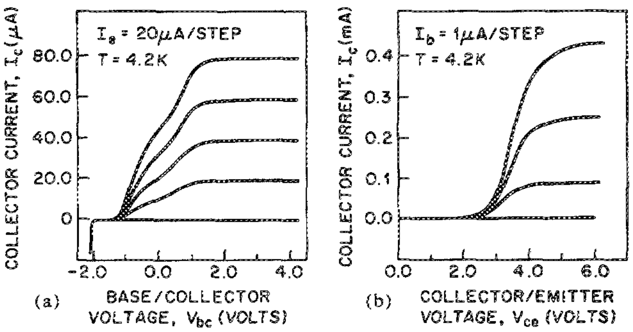

FIG. 2. (a) Common base and common emitter current gain characteristics at $T = 4.2$ K of the device shown schematically in Fig. 1. Emitter area is 6×10^{-6} cm^{-2}. Curves (a) were taken in steps of $I_e = 20\,\mu$A/step, beginning with an injected emitter current of zero. Curves (b) were taken in steps of 1 μA/step, beginning with an injected base current of zero.

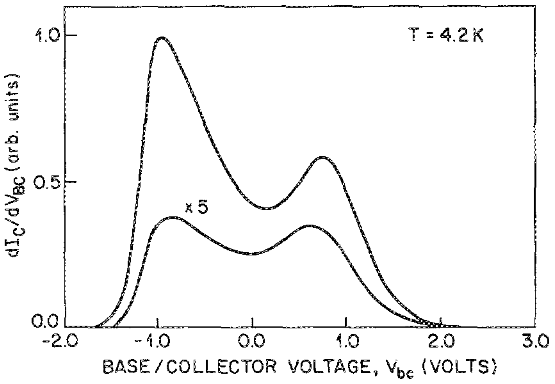

FIG. 3. Derivative of the collector current, dI_c/dV_{bc} with collector voltage V_{bc} for the bipolar transistor sketched in Fig. 1. The lower curve ($5\times$ scale) is for an injection current $I_e = 20\,\mu$A and injection energy $E_i = 170$ meV. The upper curve is for an injection current $I_e = 200\,\mu$A and injection energy $E_i = 220$ meV. The high-energy electron peaks are centered at around $V_{bc} = -1.0$ V. Measurements were taken with $T = 4.2$ K.

For the case of a base/collector barrier energy ϕ_{bc} which varies linearly with applied bias V_{bc}, it is known that dI_c/dV_{bc} is proportional to $n(p_\perp)$, the projection of the nonequilibrium momentum distribution at the collector barrier.[2,3] Thus direct spectroscopic information about the momentum distribution of nonequilibrium electrons arriving at the collector barrier is obtained electrically by measuring the derivative of the collector current as a function of the base/collector voltage in the common base configuration.

Results of measuring hot-electron spectra with the device maintained at $T = 4.2$ K are presented in Fig. 3. The lower curve represents the spectrum for a constant injection current $I_e = 20\,\mu$A and injection energy $E_i = 170$ meV. The upper curve is for $I_e = 200\,\mu$A and $E_i = 220$ meV. These measurements clearly show two maxima. For the upper curve, a high-energy peak, containing electrons from the initial injected distribution with energy $E_i = 220$ meV above the conduction-band minimum of the GaAs base, appears at a base/collector bias of around $V_{bc} = -1$ V. A low-energy peak (for which ϕ_{bc} is close to the conduction-band minimum) appears at a base/collector bias of around $V_{bc} = +1$ V and corresponds to that part of the electron distribution which has been heavily scattered. It is evident from Fig. 3 that the number of electrons contributing to the high-energy peak increases with increasing injection energy E_i. This is not unexpected since λ should also increase with E_i. It is interesting to note that the current gain β also increases with E_i [see Fig. 2(b)]. In part, this may be related to an increase in current density and subsequent saturation of traps in the device. However, it seems likely that the increase in λ also plays a role.

To confirm that the high-energy peak is due to nonequilibrium electron transport, we investigated the magnetic field dependence of the spectra. There was no effect on the spectra when a magnetic field $B_\parallel = 8$ T was applied parallel to the injection current. However, a perpendicular magnetic field of $B_\perp = 8$ T caused a 65% reduction of the high-energy peak and a corresponding increase of the low-energy peak. These results are consistent with the simplest description of nonequilibrium electron transport in a magnetic field using a classical kinematical model in which an electron injected into the base describes part of a circular orbit between scattering events.[6]

Hot-electron spectroscopy requires the use of a potential barrier between the base and the collector. The barrier used in our experiments was graded to reduce the influence of quantum mechanical reflections from ϕ_{bc}. However, we explored the role quantum reflection of nonequilibrium electrons at ϕ_{bc} has on the hot-electron spectrum by replacing the 110-Å-thick $Al_xGa_{1-x}As$ analog grade in ϕ_{bc} with an abrupt GaAs/$Al_xGa_{1-x}As$ heterojunction. Because electrons are efficiently reflected from an abrupt change in potential, one would expect the number of electrons in the high-energy peak to decrease. This is indeed what we observe. For an abrupt ϕ_{bc} the intensity of the high-energy peak decreases by a factor of 10 compared to the analog-graded case. Clearly, quantum mechanical reflections from ϕ_{bc} can dramatically change the transistor device characteristics. We note that removal of the base/collector barrier minimizes quantum reflections.

As mentioned above, previous work[2,3] using hot-electron spectroscopy failed to find any evidence of quasiballistic base transport in DHBT's. However, in these studies the collector arm was fabricated with chop-graded AlGaAs,[7] which we believe results in significant additional scattering due to inhomogeneities in alloy composition compared to analog-graded[5] structures.

In conclusion, we report the first observation of extreme nonequilibrium electron transport in a heterojunction bipolar transistor. The device turn-on characteristics are significantly influenced by base transport dynamics and quantum mechanical reflection at the base/collector heterojunction. We anticipate it will be possible to fabricate high-performance heterojunction bipolar transistors which are designed to utilize nonequilibrium transport. It is obvious that our findings will force a critical reassessment of present-day device modeling algorithms which, in general, fail to incorporate a description of quasiballistic electron transport in devices.

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