

Direct Observation of Ballistic Transport in GaAs

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We present the first direct evidence of hot electrons traversing ballistically a thin GaAs layer. The energy distribution of the hot electrons associated with the momentum in the direction of the current was measured with the use of a tunneling-hot-electron-transfer amplifier as an electron spectrometer. The width of the ballistic peak was found to be about 60 meV for hot electrons with excess energy of some 300 meV above the thermal electrons. Those values are close to the expected initial injection values.

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As the dimensions of semiconductor devices get smaller, the probability that electrons can traverse them without scattering at all, i.e., ballistically, increases. Under these conditions the transport of electrons in the solid resembles that in vacuum, but with the effective mass and group velocity of the electrons in the semiconductor. A purely ballistic transport model was first calculated by Shur and Eastman.¹ In a diode structure composed of $n^+ - n^- - n^+$ layers, with the ballistic transport occurring in the n^- layer, a dc current-voltage characteristic at high injection levels was shown to obey the Child-Langmuir law $I \sim V^{3/2}$ of a vacuum-tube diode if ideal boundary conditions were assumed. However, more realistic boundary conditions (due to carrier spillover from the n^+ layers into the n^- layer) led to a different $I-V$ characteristic,² which made the ballistic effect difficult to prove. Note also that most test structures suffered from inherent difficulties. Typical examples were large series resistances due to the Ohmic contacts and transport regions which could not be made short enough for the observation of the effect.³ Three-terminal structures have been used as electron spectrometers and have demonstrated that hot electrons traverse thin semiconductor layers,⁴⁻⁷ but no evidence for ballistic transport has been reported. We have measured the energy distribution of hot electrons at low temperatures, after they have traversed a thin n^- -GaAs layer and were collected by a heterojunction collector. As we will show, about 50% of the injected hot electrons reached the collector without any measurable loss of energy, which proves for the first time the existence of ballistic transport in semiconductors.⁸

The energy diagram of the device used for this experiment is shown schematically in Fig. 1. The thin $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layer on the left (120 Å, undoped, $x = 0.3$) is placed between two n^+ -GaAs layers, both doped to $1 \times 10^{18} \text{ cm}^{-3}$. Because of the band discontinuity between AlGaAs and GaAs, a tunneling barrier for the electrons is formed. The potential barrier height, Φ_C , is related to the Al mole fraction x by the relation $\Phi(\text{meV}) = (750 \pm 50)x$, for $x < 0.4$.⁹ We call the left GaAs layer the emitter (E) and the next GaAs

layer the base (B). Biasing the base positive with respect to the emitter will cause electrons to tunnel from the emitter and emerge into the base with an excess energy approximately equal to eV_{BE} . The base is made very thin, 310 Å thick, to allow the injected electrons to cross it with minimum chance for collisions. The collector (C , the n^+ -GaAs layer on the far right, doped to $1 \times 10^{18} \text{ cm}^{-3}$) is separated from the base by another $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layer which is made relatively thick (1000 Å, undoped, $x = 0.3$). This AlGaAs layer prevents the equilibrium electrons in the base from entering the collector even when there is a substantial collector bias V_{CB} . However, it allows the injected hot electrons which transverse the base to surmount the collector barrier, provided that their energy E_n associated with their momentum normal to the barrier exceeds the collector barrier height (Φ_C). To reduce the quantum mechanical reflections that the hot electrons might suffer at the $B-C$ interface, the Al concentration in the collector is graded over about 60 Å over

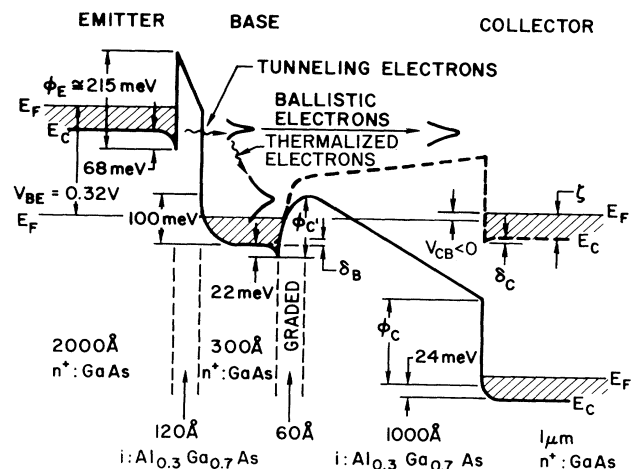


FIG. 1. An energy vs distance diagram of the heterojunction device for the Γ electrons. Typical voltages for normal operating conditions are applied. The dashed line describes the potential distribution in the collector region for negative V_{CB} . The device parameters are noted.

the base side; thus an abrupt potential step is avoided.

The structure which is described in Fig. 1 was grown in a molecular-beam epitaxy system on a n^+ (100)-oriented GaAs substrate. Except for the AlGaAs of the collector, which was grown at a substrate temperature of 700 °C, the structure was grown at 600 °C, and the n -type dopant was Si. The layered structure was then processed into a three-terminal device. Reactive ion etching to reach the base layer, AuGe-based Ohmic contacts, and boron implantation for isolation were used. Further details have been given elsewhere.⁶

At room temperature thermionic currents above the barriers are dominant. As the device is cooled down, the thermal currents get smaller and tunneling dominates. Figure 2 gives a set of the device characteristics measured at 4.2 K showing the collected current I_C as a function of V_{CB} for several values of I_E from 0 to 100 μA . Without injection, I_C is negligibly small for $V_{CB} < 1$ V; thereafter it rises because of Fowler-Nordheim tunneling of the base thermal electrons through the resultant triangular barrier of height Φ'_C . At a given injection current and $V_{CB} > 0$, the collector current is related to the emitter current by $I_C = \alpha I_E$, where α is the transfer ratio. As V_{CB} increases from 0 to 1 V, Φ'_C decreases from approximately 215 to about 165 meV as a result of the interface grading and the applied field. This causes α to increase from 0.5 to 0.75. When V_{CB} is made negative, I_C decreases slightly, until some threshold voltage is reached below which I_C drops sharply to zero. As I_E and consequently V_{BE} increase, the threshold voltage increases too.

For negative collector voltage (as shown by the dashed line in Fig. 1) the effective barrier height Φ'_C for electrons in the base depends linearly on V_{CB} . The derivative of I_C with respect to Φ'_C (or V_{CB}) in this range (defined as G_C) is proportional to the number of electrons as a function of E_n . A family of these curves, where I_E is the parameter, is plotted in Fig. 3. The main peak is the ballistic peak. As the injection

energy into the base increases, the main peaks shift to the left, and the number of electrons per unit energy increases, but the full width at half maximum stays about 60 meV. In Table I we summarize the most important parameters. V_{BE} is measured for each injection-current level I_E . The energy eV_{BE} determines the maximum excess kinetic energy of the hot electrons at 0 K with respect to the Fermi level in the base. It can be shown that the number of injected hot electrons at an energy E_n is $\sim (E_F - E_n)D(E_n)$ for $E_n < E_F$ at 0 K, where $D(E_n)$ is the one-dimensional tunneling probability through the emitter barrier. Using a simple WKB approximation for $D(E_n)$ we derive an asymmetric energy distribution with a peak which is displaced by $\Delta \approx 15$ meV below the Fermi level of the emitter and has a total width at half maximum of 40–60 meV. Both peak position and width are only weakly dependent on V_{BE} . The maximum energy of ballistic electrons is eV_{BE} above the Fermi level in the base upon injection. This energy should be equal, at the threshold condition for current collection, to $\Phi_C - \zeta + eV_p - \delta_C + \Delta$ (the "ballistic condition"). As shown in Fig. 1, ζ is the Fermi-level position with respect to the conduction-band edge in the n^+ -GaAs, δ_C is a measure of the band bending of the accumulation layer in the collector, and V_p is the $|V_{CB}|$ which corresponds to the peak position of the distribution in E_n . When $-V_{CB}$ approaches V_p , tunneling of the hot electrons through the resultant triangular collector barrier top, and quantum mechanical reflections, can be appreciable, and vary with V_{CB} . Thus the apparent collected energy distribution tends to broaden and shift toward lower energies, and appears to be more symmetric.

The values of Φ_C which satisfy the ballistic condition for our data are given in Table I. They have an average of 213 meV. Values of Φ_C reported in the literature⁹ range from 200 to 250 meV, with the assumption that our x is accurate to about $\pm 5\%$, name-

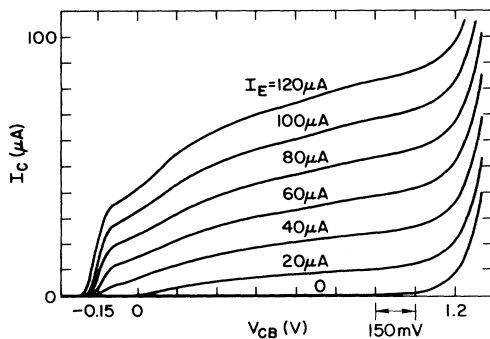


FIG. 2. The collector current of the device as a function of V_{CB} at 4.2 K, where I_E is the parameter for the different curves. The transfer coefficient α was deduced from these curves.

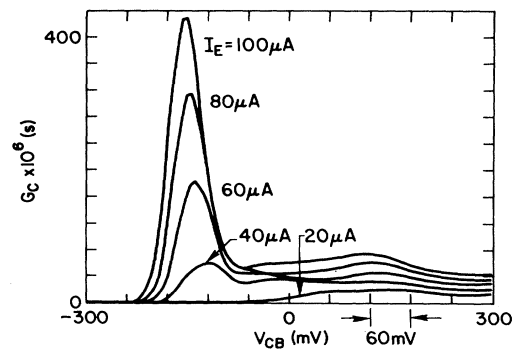


FIG. 3. The energy distributions of the collected hot electrons, G_C , where the injection current I_E is the parameter for the different curves. As I_E increases, the peak of the distribution V_p increases too.

TABLE I. Summary of the energy distribution results. Φ_C is calculated with the assumption of $\zeta = 54$ meV for $1 \times 10^{18} \text{ cm}^{-3} n^+ \text{-GaAs}$.

I_E (μA)	V_{BE} (mV)	Δ (meV)	δ_C (meV)	V_p (mV)	Φ_C (meV)
40	278	12	5	120	205
60	302	16	6	139	217
80	317	17	6	148	212
100	329	17	7	154	219

ly, $x = 0.3 \pm 0.015$. Thus our results calculated for the ballistic condition are in good agreement with independent data. The experimentally observed 60-meV width of the main peak is also in good agreement with the width of the electron distribution that we calculate for our tunnel emitter. Since the energy loss associated with an optical-phonon scattering event is 36 meV, some scattering events could be occurring within the width of the peak or contributing to the lower tail of the distribution. However, the majority of the electrons in the peak could not suffer a scattering event; otherwise the resultant peak would be some 36 meV lower, leading to a Φ_C below 200 meV. Thus our results lead to the conclusion that the electrons in the main peak of Fig. 3 traverse the base and the collector barrier ballistically.

For positive V_{CB} , the collector barrier height Φ_C depends on V_{CB} in a complex way (since the exact grading profile of the collector barrier is not known). In this range the features which are observed in the energy distributions of Fig. 3 have to be scaled in their heights and widths by the same factor that relates Φ_C to V_{CB} . Thus it is difficult to interpret the features in this region.

The device characteristics were measured at different temperatures. As the temperature increases, the height of the peak of the energy distribution increases by about 10% at 80 K. Upon further increase (up to 140 K), the magnitude decreases (by some 10%), and the distribution shifts to lower energies and broadens (both by about 40 meV from the 4.2-K values). This trend can be explained by the enhanced tunneling probability of the electrons which are thermally excited into the Fermi tail, followed by an increase in scattering at higher temperatures. Optical-phonon emission is a likely loss mechanism. The optical-mode population increases from a negligible amount at 4.2 K to 0.05 phonon per mode at 140 K. The phonon energy is roughly equal to the shift in V_p and to the energy broadening. The phonons also redirect the electrons (by some 5° – 10°),¹⁰ which reduces V_p further. Although we do not see any phonon replicas, they could be smeared out by the initial broad energy distribution of the ballistic electrons.

There is some additional evidence, which is indirect, for ballistic transport. If intravalley electron-phonon scattering events do take place at the lowest temperatures, one would expect intervalley scattering to occur when $eV_{BE} + \zeta$ exceeds the intervalley energy difference between the Γ and L valleys (0.36 eV) by at least a phonon energy. This transfer would lead to enhanced scattering, and the electron velocities would randomize very quickly at the bottom of the L band. One would then expect a small transfer ratio and a peak energy position independent of eV_{BE} . This effect was not observed as V_{BE} was varied from 250 meV to 420 mV. We suggest that the very short transit time of the ballistic electrons in the base (~ 0.03 ps under the assumption of an electron velocity of $\sim 1 \times 10^8$ cm/s) compared to the phonon scattering time for hot electrons (about 0.16 ps)¹¹ precludes phonon emission and intervalley scattering.¹⁰ In the AlGaAs collector barrier the transit time is longer (~ 0.15 ps under a flat-band condition, and maybe 0.25 ps when a retarding field is applied), but apparently not long enough for a measurable intravalley scattering. Note that the energy of the hot electrons in the AlGaAs is not sufficiently high to allow scattering into the L valley.

A puzzling aspect of the results is the fact that only about 50% of the electrons are ballistic. A few possibilities come to mind. Multiple quantum mechanical reflections might prolong the net transfer time of the electrons and allow collisions. However, the expected reflections of electrons with excess energy of ~ 150 meV above the top of the collector barrier are too small to account for the small α . Also, there may be some inelastic tunneling processes in the emitter which would result in a fraction of the electrons emerging into the base with lower energies. This could occur because of some deep-lying impurities or defect centers in the barrier. It is also possible that scattering events like electron-plasmon in the n^+ base cause large energy losses, which lead to a partial thermalization. In the collector barrier, alloy scattering can redirect some of the hot electrons away from the collector and prevent collection.

In summary, we have used a tunneling-hot-electron-transfer amplifier to give direct evidence of

ballistic transport of hot electrons in GaAs. About 50% of the injected electrons traverse the base ballistically. The loss mechanism which prevents a complete ballistic transport has not been identified.

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