Observation of Ballistic Holes

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We report the first direct observation of ballistic hole transport in semiconductors, via energy spectroscopy experiments. Light holes are preselected and injected via tunneling into 31-nm-thick p^+-GaAs layers. About 10% of the injected holes have been found to travel ballistically maintaining distributions $\simeq 35$ meV wide, with a mean free path of about 14 nm. Resonances in the injection currents, resulting from quantum interference effects of the ballistic holes, are used to support the light nature of the ballistic holes.

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Ballistic transport of carriers in solids was previously inferred via a variety of indirect techniques.[1-3] Recent energy spectroscopy experiments in GaAs have demonstrated directly the existence of ballistic electrons[4]; however, holes were never directly observed to be transported ballistically. In GaAs there are two valence bands[5]: a light-hole band containing about 5% of the total hole population, with a curvature effective mass $m_{\text{lh}} = 0.082 m_e$, where m_e is the free-electron mass, and a heavy-hole band with $m_{\text{hh}} = 0.51 m_e$. Since the mean free path (mfp) is approximately proportional to the inverse of the mass, ballistic transport of heavy holes is unlikely in practical structures. In order to look for ballistic hole transport we have used a tunnel barrier, which has large transmission for light holes, injecting $\simeq 30$-meV-wide energy distributions of light holes into heavily doped p^+-GaAs layers, 31 nm thick. With spectroscopy performed after traversal, we have measured similar distribution widths and peak energies, with about 10% of the holes being ballistic. The ballistic transport and the light nature of the holes are supported by the observation of resonances in the injection currents due to quantum interference effects of the ballistic light holes in the thin GaAs layers.[6]

Experiments were done with a novel three-terminal structure (hot-hole transistor) grown by molecular-beam epitaxy on a p^+ (100) GaAs substrate, described in Fig. 1. A tunnel injector, composed of a p^+-GaAs layer (called emitter), an intrinsic $Al_xGa_{1-x}As$ barrier layer with $x = 0.5$ (12 nm thick), and a p^+-GaAs layer (31 nm thick, called base), was used to select and inject light holes. When biased with V_{EB} it injected a quasimonoenergetic distribution of light hot holes ($\simeq 30$ meV wide), favored by the tunneling process (by a factor of $\simeq 10^7$), with most holes emerging into the base layer with excess energy near eV_{EB}. The 31-nm base layer was terminated with a spectrometer made of a relatively thick, intrinsic $Al_yGa_{1-y}As$ layer with $y = 0.31$ (47 nm thick, called collector barrier), followed by a thick p^+-GaAs layer (called collector). The AlAs mole fraction in the collector barrier was linearly graded down to $y = 0.17$ over 6 nm on the base side to minimize the quantum-mechanical reflections. The GaAs layers were doped with acceptors (Be) to a level of 1.6×10^{18} cm^{-3}. The structure was selectively etched to expose the base layer, and alloyed Ohmic contacts were made to the emitter, base, and collector layers.

Arriving hole distributions were analyzed by the thick AlGaAs spectrometer barrier. Upon the application of a potential difference, V_{CB}, the potential height of the collector barrier, Φ_C, changes, affecting the collected current density $J_C = e\int_{\Phi_C}^{\infty} n(E_\perp) v_\perp(E_\perp) dE_\perp$, where e is the electronic charge, and $n(E_\perp)$ is the number of holes per unit normal energy, an energy associated with the normal component of the velocity, $v_\perp(E_\perp)$. The normal energy distribution can be found from $ev_\perp(E_\perp)n(E_\perp) = dJ_C/d\Phi_C$, or

$$v_\perp(E_\perp)n(E_\perp) \propto e^{-2}\eta^{-1} dj_C/dv_{CB},$$

where $\eta = e^{-1} d\Phi_C/dV_{CB}$ is a proportionality factor. If

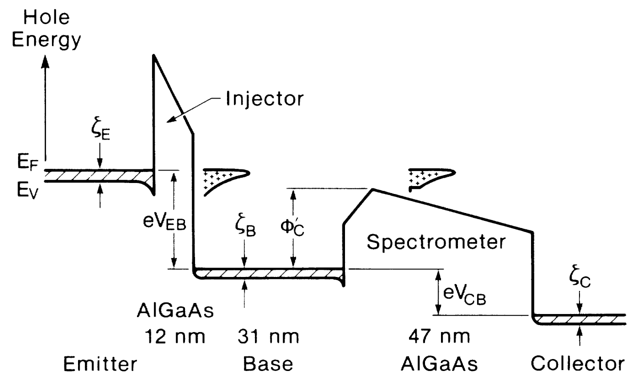

FIG. 1. Valence band in the hot-hole transistor with hole energy plotted upward. The tunnel injector and spectrometer barriers have AlAs mole fractions of 0.5 and 0.31, respectively. The collector is shown biased negatively. The emitter, base, and collector are p^+-GaAs doped to a level of 1.6×10^{18} cm^{-3}.

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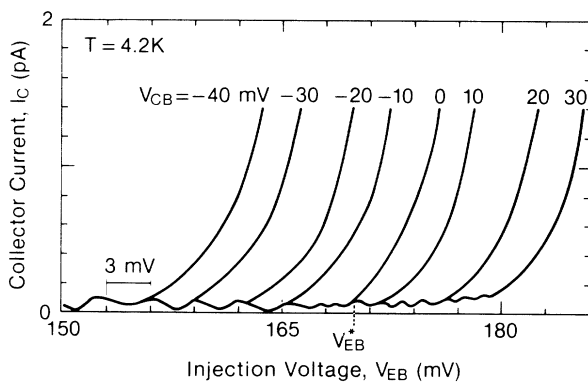
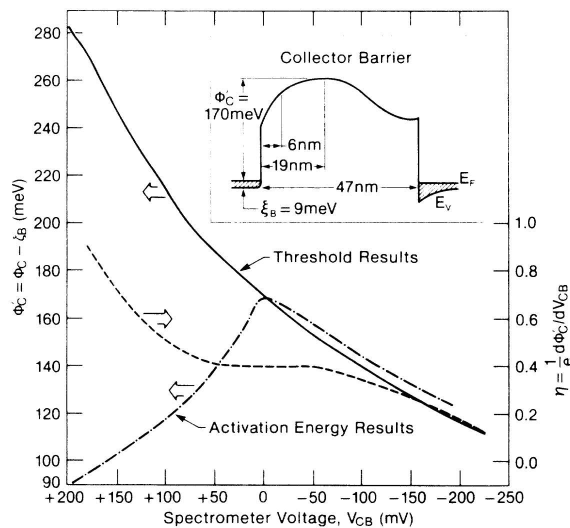
our graded barrier were ideal, for $V_{CB}>0$ we would have $\eta \simeq 1$ (with peak potential at collector side), and for $V_{CB}<0$, $\eta \simeq \frac{6}{47} \simeq 0.13$ (with peak 6 nm away from the base side). However, some barrier parameters such as the density of any unintentional charges,[7] of the extent of acceptor (Be) segregation from the collector,[8] are important and difficult to determine accurately. Thus, a study of the spectrometer barrier, leading to the actual Φ_C and η, has to be done.

This study is done, with our hot-hole transistor structure, by our finding a low-temperature threshold injection voltage, V_{EB}^*, for some V_{CB}, for which an onset in the collector current occurs. Then the Fermi level in the emitter is at the same height as the peak potential of the collector barrier, and some ballistic holes can graze and pass the top of the barrier.[9] More accurately, the collector-barrier height is $\Phi_C = eV_{EB}^* + \zeta_B + \delta$, where ζ_B is the Fermi energy in the base (Fig. 1), and $\delta \simeq 10$–20 meV is a correction due to holes tunneling somewhat below the barrier top. The results of such experiments, done at high current sensitivities, are seen in Fig. 2(a). From here, with neglect of δ, the collector-barrier height above the Fermi level in the base, $\Phi_C' = eV_{EB}'$, is plotted in Fig. 2(b). With no bias applied $\Phi_C' = 170$ meV and $\zeta_B \simeq 9$ meV for our doping, and thus $\Phi_C = 179$ meV$+\delta$, a value higher by at least 20 meV than the published band-discontinuity values.[10] This difference is most probably related to unintentional positive charges in the barrier, which we address below.



(a)



(b)

FIG. 2. (a) Collector-current onsets for different V_{CB}, and an example of determining the threshold eV_{EB}^* for $V_{CB}=0$. Note the very small currents rising from the noise line. (b) Φ_C' and the derivative η as functions of V_{CB}. Also plotted are the barrier heights from separate measurements of activation energy for thermionic emission [for $V_{CB}>0$ (<0) the barrier is that for holes in the collector (base)]. Inset: A probable collector-barrier shape.

Figure 2(b) also gives the calculated η, which together with Φ_C' is sufficient for the analysis of our spectroscopy experiments; however, the study of Φ_C and η in some detail gives us a physical insight of the barrier shape, as related to actual barrier parameters. In the range -50 mV $< V_{CB} < 50$ mV, $\eta = 0.4$, suggesting a barrier peak at some 0.4×47 nm $= 19$ nm away from the base side. This, and the increase in the barrier height from the value given in Ref. 10 (seen above), can result from unintentional positive charges in the barrier, charges which we independently measured.[11] One can also see that η approaches unity only at large positive V_{CB}, an effect that can be attributed to barrier lowering on the collector side, most probably due to Be segregation into the barrier during growth.[8] This was verified by measurement of activation energies for thermionic emission, with results given in Fig. 2(b).[10] The method proved credible as seen from the good agreement between the activation energy results for $V_{CB} \leq 0$, and Φ_C' determined from the threshold measurements. For large positive V_{CB} we find a rather low barrier height on the collector side, $\Phi_C - \zeta_C \simeq 90$ meV. From these results a more realistic shape of the collector barrier is shown in the inset in Fig. 2(b). This barrier has a potential peak that moves from near the base side to the collector side as V_{CB} increases.

Spectroscopy was done by the measurement, at 4.2 K, of the collector current I_C versus the collector voltage V_{CB}, at different injection voltages V_{EB} [Fig. 3(a)]. The current rises steeply up to a knee where the slope clearly changes. The hole energy distributions, shown in Fig. 3(b), are derived by the division of the dI_C/dV_{CB} curves by the η determined above, and the conversion of the horizontal scale to excess normal energy above ζ_B [with use of Fig. 2(b)]. A few interesting features can be noticed. For injection energies in the range 190–210 meV, a clear ballistic behavior is observed. The distributions are extremely sharp with widths at half maximum of $\simeq 35$ meV, and peaks tracking exactly the injection energy, eV_{EB} (10 meV apart). At the lower-energy end, decaying tails of distributions, peaking somewhere closer to

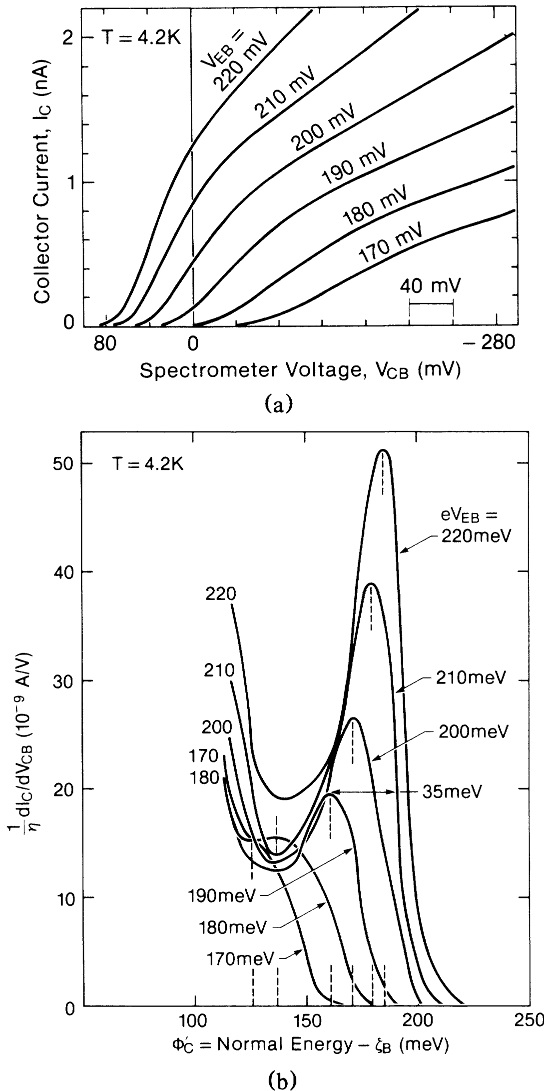


FIG. 3. (a) Collector current I_C vs spectrometer voltage V_{CB}, for different injection voltages V_{EB}. (b) Hole energy distributions deduced from the above I_C-V_{CB} curves and the η given in Fig. 2(b). Ballistic peaks are seen for $V_{EB}=190$, 200, and 210 mV. For lower V_{EB}, upper energy tails of nonballistic hole distributions are dominant.

the base Fermi level, are seen, masking the corresponding lower energy ballistic peaks. These tails are likely to originate from holes excited up from the equilibrium hole population in the base.[12] For $eV_{EB}>220$ meV, peaks do not shift in energy any more, as the spectrometer potential peak moves rapidly toward the collector side. Then holes, most probably, cannot traverse ballistically the full width of the AlGaAs barrier against a relatively strong retarding electric field, resulting in a drop of the collector current and in an artificial peak in dI_C/dV_{CB}.

The observed hole distributions are narrower by a factor of 2 compared with those of ballistic electrons measured by a similar technique.[4] This is due to the narrower supply function in the emitter being determined by the heavy holes: ζ_E + band bending (calculated classically) $\simeq 27$ meV for $V_{EB}=200$ mV. The small displacement in the peak positions below the Fermi level in the emitter is fully accounted for when we note that the injected distribution $n(E_\perp)\sim(E_F-E_\perp)D(E_\perp)$ at 0 K, where $D(E_\perp)$ is the one-dimensional tunneling probability, peaks some 15 meV below E_F,[4,13] and that the actual Φ_C' is higher by δ than the one used in Fig. 3(b). The above results are consistent with ballistic transport of the narrow distributions. Integrating the area under the distributions, we find that 8%–11% of the injected hole current is ballistic, with a calculated mfp $\simeq 14$ nm [by use of $0.1\simeq\exp(-31/\text{mfp})$].

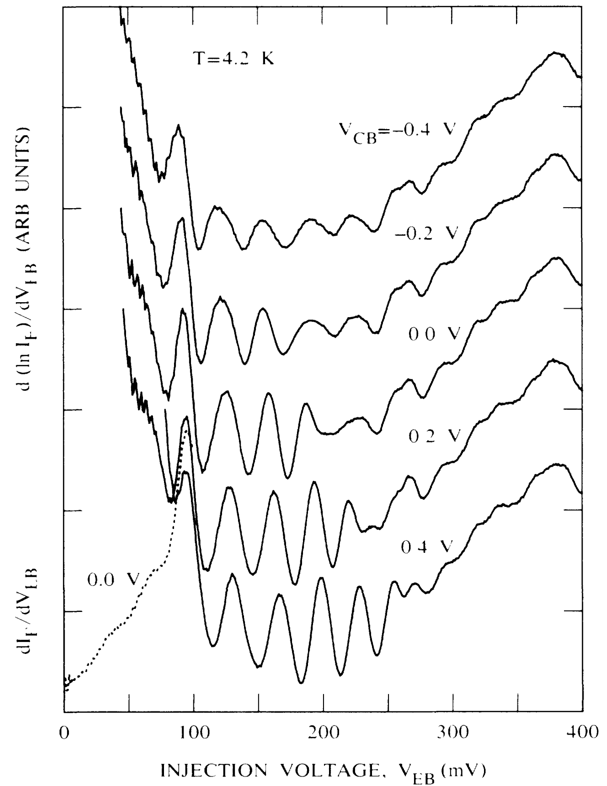


FIG. 4. Solid curves are the derivative of the logarithm of the injected current (high-frequency oscillations at the low V_{EB} are due to noise). As the collector voltages changes from positive to negative, fewer bound states are visible. The dotted line is dI_E/dV_{EB} for $V_{CB}=0$, showing the lower-energy resonances.

Even though it is highly likely that the observed ballistic holes are light, the spectroscopy measurements described above are not sufficient to prove it. Confirmation is provided by the analysis of strong resonances resulting from hole interference effects, observed in the injection tunneling currents, at certain energies that are particularly sensitive to the effective mass of the holes.[6] These resonances are due to a faster increase in the injection current whenever the Fermi level in the emitter crosses

the bottom of a quasi-2D hole band formed in the base. Figure 4 shows the derivatives $d(\ln I_E)/dV_{EB}-V_{EB}$, for different V_{CB}. As long as $eV_{EB}\leq\Phi_C'$, strong oscillations in the derivative are observed because the participating 2D states are strongly bound. However, when $eV_{EB}>\Phi_C'$, the oscillations are due to the less confined (virtual) states, and thus weaker. As seen in Fig. 4, when the collector voltage changes from positive (high Φ_C) to negative (low Φ_C) values, the topmost bound states gradually become virtual, and the corresponding oscillations get weaker.[6] The observation of the peaks due to interference effects confirm the ballistic transport of the holes.

In order to find the corresponding ballistic-hole mass, we have estimated the positions of the bound light-hole states in a symmetric square well, 31 nm wide and 200 meV deep. Obviously this is a gross simplification since it ignores the exact potential distribution in the base and the nonparabolicity effects of the hole band; however, it distinctly shows the nature of the ballistic holes. For $m_{lh}=0.082m_e$, we find bound levels at 3, 15, 35, 62, 97, 138, and 182 meV.[14] From Fig. 4, for $V_{CB}=0$, the observed bound peak positions including ζ_B are at 41, 72, 102, 133, and 168 meV, agreeing well with the calculations (the first two calculated levels are not seen since they are just at or below the Fermi level). Note that at energies higher than 100 meV the well widens and nonparabolicity increases the light-hole effective mass,[5] causing the last two observed peaks to be at somewhat lower energies. For comparison, heavy holes with $m_{hh}=0.51m_e$ would have sixteen bound states in the base, excluding them from the observed transport.

In summary, our results show, for the first time, unambiguous spectroscopic observation of ballistic light-hole transport in GaAs. Ballistic hole distributions, 35 meV wide, with a mean free path of about 14 nm, have been measured. Lower energy distributions, that might be due to excited holes from the Fermi bath, are observed too. Quantum interference effects in the thin transport regions provide added evidence for the ballistic transport.

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[1] R. J. von Gutfeld and A. H. Nethercot, Jr., Phys. Rev. Lett. **18**, 855 (1967).

[2] L. F. Eastman, R. Stall, D. Woodard, N. Dandekar, C. E. C. Wood, M. Shur, and K. Board, Electron. Lett. **16**, 525 (1980).

[3] R. Trzcinski, E. Gmelin, and H. J. Queisser, Phys. Rev. B **35**, 6373 (1987).

[4] M. Heiblum, M. I. Nathan, D. C. Thomas, and C. M. Knoedler, Phys. Rev. Lett. **55**, 2200 (1985); M. Heiblum, I. M. Anderson, and C. M. Knoedler, Appl. Phys. Lett. **49**, 207 (1986).

[5] J. C. Blakemore, J. Appl. Phys. **53**, R123 (1982).

[6] M. Heiblum, M. V. Fischetti, W. P. Dumke, D. J. Frank, I. M. Anderson, C. M. Knoedler, and L. Osterling, Phys. Rev. Lett. **58**, 816 (1987).

[7] T. W. Hickmott, P. M. Solomon, R. Fischer, and H. Morkoç, J. Appl. Phys. **57**, 2844 (1985).

[8] D. L. Miller and P. M. Asbeck, J. Appl. Phys. **57**, 1816 (1985).

[9] We may assume that some ballistic holes, few as they may be, always exist in the structure. We later prove their existence and find their number from spectroscopy measurements.

[10] J. Batey and S. L. Wright, J. Appl. Phys. **59**, 200 (1986). The valence-band discontinuity $\Delta E_V=5.5x$, where x is the AlAs mole percentage. For our AlGaAs collector barrier, $x=31\%$ and $\Delta E_V=171$ meV.

[11] Capacitance measurements done on separate p^+-intrinsic AlGaAs-p^- structures show a voltage shift in the flat-band condition consistent with positive charges in the barrier in the low 10^{16}-cm^{-3} range.

[12] Similar low-energy electron distributions had been reported by A. F. J. Levi, J. R. Hayes, P. M. Platzman, and W. Wiegmann, Phys. Rev. Lett. **55**, 2071 (1985).

[13] M. Heiblum, Solid-State Electron. **24**, 343 (1981).

[14] For 31-nm base thickness, light- and heavy-band mixing at $\mathbf{k}=0$ is insignificant. See, for example, S. Brand and D. T. Hughes, Semicond. Sci. Technol. **2**, 1607 (1987).