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Possible observation of transmission resonances in GaAs-$Al_xGa_{1-x}As$ transistors

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We have studied the effects of very narrow potential barriers on the transport through short one-dimensional GaAs-$Al_xGa_{1-x}As$ wires. The barrier is applied by a 45-nm-wide gate to a nominally 2-μm-wide two-dimensional electron gas. The measurements reveal reproducible fluctuations in the transconductance whose origin is unknown. It might be that the fluctuations are associated with the slight disorder in the devices. The possibility that the fluctuations result from transmission resonances is also discussed.

Much of the effort in transport experiments has been toward the study of quantum-mechanical effects in disordered metallic samples. The observed departures from the classical Drude conductivity result from superpostions of the carrier wave functions. Experiments on rather large samples—samples in which the resistance was measured at scale $L \gg L_\phi \gg l$ where L_ϕ is the distance over which the wave function retains phase information and l is the mean-free-path length—resulted in the studies of incipient localization.[1] Reducing the dimensions of the samples so that the measurements were at scale $L \simeq L_\phi \gg l$ produced the discovery of conductance fluctuations.[2-4] Progress is now being made toward study of the ballistic (or nearly ballistic) transport.[5-7] In particular, correlations between the voltage fluctuations measured by probes at different points along the wire indicate that the measurement scale is not very different from l.[6] It is clear from this work that there is considerable similarity between electronic conduction in coherent samples and the variety of effects known from the classical physics of waves and especially from optics. In fact, recently the flow of observations has run backwards with light scattering experiments taking their cue from results observed in disordered metals.[8] Corresponding experiments on acoustic waves have also shed light (or should we say sound) on the physics of conduction through disordered samples.[9]

In order to test for the transmission resonances which are familiar from optics, we have constructed devices comprising short wires (lithographically patterned length $L = 10\ \mu$m and width $w = 2\ \mu$m) connected to four probes and a narrow (45-nm-wide) cross gate [see Figs. 1(a) and 1(b)]. The wires were patterned by implanting ^{11}B into the two-dimensional electron gas formed at the interface

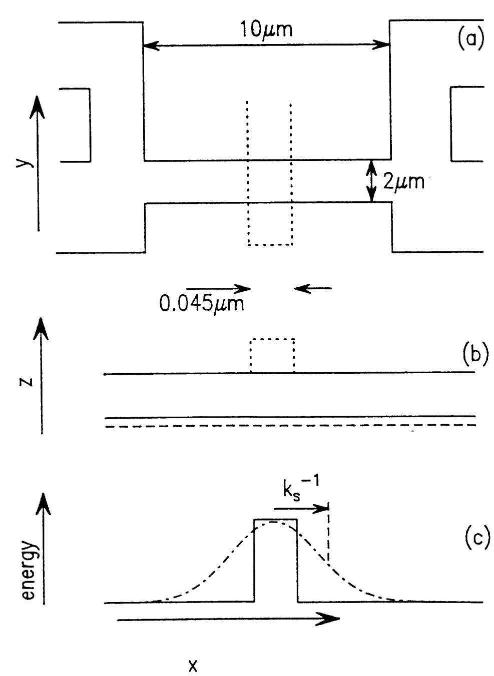

FIG. 1. (a) A plan view (*not* to scale) of the four-probe GaAs-$Al_xGa_{1-x}As$ wire with a narrow cross gate (dotted line). Dimensions are those patterend by lithography; the effective width is thought to be $\sim 1.5\ \mu$m. (b) Cross-sectional view of the device. The gate is formed on top of the $Al_xGa_{1-x}As$ and GaAs cap layer; it is about 60 nm above the two-dimensional gas (dashed line). (c) Sketch of the energy barrier provided by the gate for the idealized case of no screening (solid line) and for the more realistic case with screening (dash-dot line).

between GaAs and $Al_xGa_{1-x}As$ ($x=0.3$). From Shubnikov-de Haas measurements, the carrier concentration in the wires is known to be $n_s=(2.7\pm0.2)\times10^{15}/m^2$. From conductance measurements and the patterned channel width w, one estimates the mobility μ to be 10–20 m^2/V sec. The width of the conducting channel is certainly less than the patterned width (2 μm) of the wire. The amount of depletion from the sides (by pinning sites) is probably about 0.5 μm (Ref. 10) but this depletion is impossible to measure accurately. The assumption that the mobility is not degraded by processing leads to an effective width $w=1.5\pm0.1$ μm for sample 1 in this paper. (For other samples, this estimate varies from 0.02 to 1.5 μm.) Assuming that the conductance between the voltage probes can be described by a Drude formula, we find that the mean free path in the wires is about $l\sim3$ μm. This places these devices in the "nearly ballistic" regime where $L\gtrsim l$ and in the one-dimensional transport regime $w\lesssim l$. From the measured n_s, we obtain the Fermi wavelength of the electrons $\lambda_F=47$ nm so that there is a maximum of approximately 200 transverse channels (individual k_y modes) contributing to the conduction.

Application of a negative voltage to the gate acts to deplete the region under the gate, and to provide a barrier in the potential seen by electrons traveling along the wire. If there were no screening, then a square barrier of width 45 nm would be drawn up from the bottom of the conduction band [as illustrated by the solid line in Fig. 1(c)]. In this situation (λ_F comparable to the barrier width) transmission resonances[11] should appear in the transconductance. Both common sense and numerical modeling[12] demonstrate that a barrier with sharp walls cannot exist; screening will smear the edge of the barrier on length scales of order $l_s=k_s^{-1}\sim40$ nm. The effective barrier will then be roughly Gaussian shaped (illustrated by the dash-dot line), and the amplitude of the transmission resonances will be considerably reduced.[11,12]

The devices were mounted in the mixing chamber of a dilution refrigerator and connected to room-temperature electronics through a series of filters. The conductances of several wires were measured as a function of gate voltage by standard audio-frequency lock-in techniques in both two- and four-probe configurations. From the conductances at $V_g=0$, large statistical variations in the mobility (or width) of the wires were discovered. We judge, however, that the carrier concentrations were approximately equal since the threshold voltages did not vary widely ($\Delta V_T\lesssim20\%$). The threshold tended to be about $V_T=-0.6$ V in agreement with numerical modeling of the devices.[12]

In Fig. 2 we plot the conductance of two wires near the threshold. In each case, $G(V_g)$ is composed of monotonic part and a fluctuating part. The monotonic part represents the increase of the average conductance as the barrier is lowered. Far from threshold, the conductance of sample 1 approaches 4 m$\Omega^{-1}\simeq90e^2/h$ which is reasonably consistent with the estimate of the number of channels made earlier. The fluctuations, which are present at $T=4$ K and change little as temperature falls to $T<0.1$ K, have an rms amplitude $\Delta G\simeq2.3$ e^2/h. The widths of the conductance peaks are $\Delta V_g\sim5$–10 mV. Fluctuations

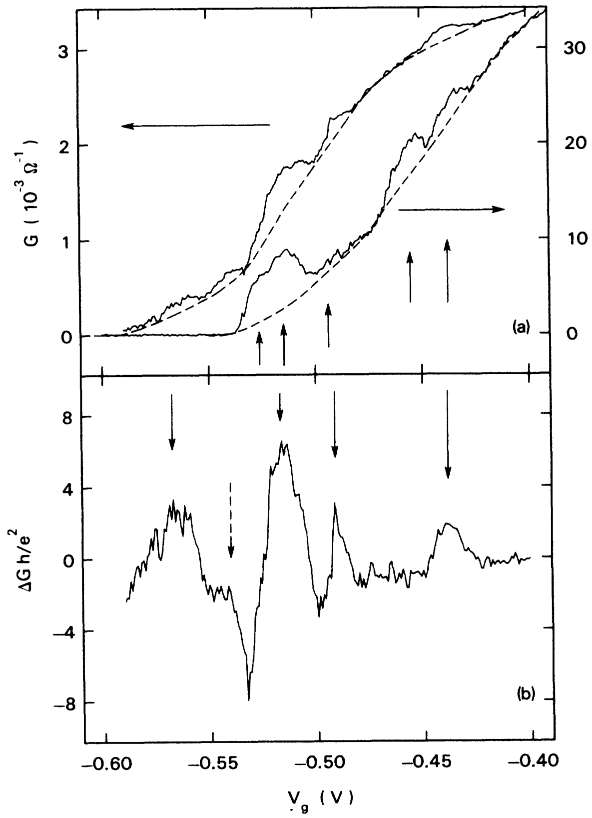

FIG. 2. The dependence of the conductance $G(V_g)$ on gate voltage near threshold at 0.02 K for sample 1 (left axis) and sample 2 (right axis). The arrows mark the positions of the peaks in the conductance of sample 2. The dashed lines are *ad hoc* estimates of the classical $G(V_g)$ described in the text. (b) The fluctuations in the $G(V_g)$ from sample 1. The arrows mark the positions of the peaks in $G(V_g)$.

of about the same *relative* amplitude $\Delta G/G$ and width ΔV_g have been observed in three other devices having the same geometry. The results of simulations of the device characteristics (self-consistently including the classical effects of screening)[12] can be used to obtain the chemical potential beneath the gate as a function of V_g. This analysis indicates that in terms of the chemical potential, the width of the peaks is $\Delta\mu\simeq0.2$ K, so the peaks are probably not smeared too drastically by the temperature $T<0.1$ K. Sample 2, which has much lower conductance, exhibits fluctuations of approximately the same *relative* amplitude and spacing. The fluctuations are somewhat more pronounced in this wire. In fact, the transconductance is negative in several places.

The obvious choice is to attribute the fluctuations to disorder, i.e., to proclaim them conductance fluctuations of the kind discussed by Al'tshuler and co-workers[13] and Lee *et al.*[14] This hypothesis immediately runs aground on the problem of the gate-voltage scale of the fluctuations. According to the predictions for conductance fluctuations in the case of diffusive motion of the carriers, the scale is $E_c/e=V_c=\pi^2\hbar D/eL_\phi^2$. Taking $L_\phi\gtrsim l\simeq3$ μm in sample 1, we find $E_c<0.23$ meV for diffusive motion. If we make a simple estimate for nearly ballistic motion by replacing

L_ϕ^2/D by L_ϕ/v_F (v_F is the Fermi speed), the result is even smaller: $E_c \lesssim 0.05$ meV. On the other hand, the typical separation ΔV_g of the peaks in Fig. 2(b) is $\Delta V_g \gtrsim 30$ mV which amounts to $\Delta\mu \gtrsim 1$ meV—a factor of 4 or more larger than these estimates. If the reduced conductance of sample 2 results entirely from decreased width, then the above analysis holds. It is more likely that the mobility has been degraded somewhat in this wire; if this has happened, then the estimates from the conductance fluctuations theory could be consistent with the spacing of the peaks in sample 2. Figure 2(b) contains "dead" regions (e.g., $-0.48 < V_g < -0.45$ V) where no fluctuations appear. This contradicts the wealth of phenomenology on the conductance fluctuations from other experiments,[3,4] wherein the chemical potential or magnetic field maps a dense fluctuation spectrum. These dead regions are rather more reminiscent of the fluctuations in the localized regime where conductance proceeds by transmission through resonant levels or percolating paths in the hopping regime. For these reasons, along with the expectations based on the sample geometry, we doubt that the fluctuations result from simple conductance fluctuations.

If the fluctuations were associated with transmission resonances, then, naively speaking, we would have expected a regular dependence on V_g. For a square barrier the resonance peaks are spaced[11] as $k_F \propto (V_g)^{1/2}$. Unfortunately, there are so few peaks in the conductance that no solid conclusions may be drawn about the agreement of the data with this prediction. Simply mapping the positions of the major peaks (marked by arrows in Fig. 2) is not very encouraging. These data (o) are displayed in Fig. 3, and they do not convincingly support a $(\Delta V_g)^{1/2}$ power law (dashed line).

From the transmission resonance model, it is plausible that, in the absence of the fluctuations, $G(V_g)$ might lie generally below [e.g., the dashed lines in Fig. 2(a)] the experimental curve so that some of the peaks in the data are disguised by our method of extracting the fluctuations. [We simply subtracted a best-fit polynomial of the fifth order from the raw data to obtain the curve in Fig. 2(b).] For instance, the peak marked by the dashed arrow appears. If $\Delta G > 0$, then the peaks in the conductance are rather large: up to $10e^2/h$ in amplitude. In Fig. 3 we also plot the positions of the peaks obtained from this latter assumption for sample 1 (∇) and sample 2 (+). The slope of the experimental data is dependent on the choice of threshold voltage V_T. We have simply used $V_T = -0.59$ V for sample 1 and $V_T = -0.54$ for sample 2, which are extracted by eye from the $G(V_g)$ data. If we were to fit a power law from these few data it would be steeper than $V_g^{1/2}$; more precisely, the data (∇ and o) yield the power $p = 0.73 \pm 0.15$. If these fluctuations represent transmission resonances, then the large value of p probably reflects the distortion of the ideal square barrier by screening. A parabolic barrier leads to $p = 1$, so that the experimental value implies that the potential is rounded as we suspected from our initial considerations about screening.

A reasonable assumption is that the resonances in the barrier have been dressed by the disorder in the sample. This is certainly going to occur in any device which is not completely ballistic; our samples with $l \lesssim 3$ μm and $L = 10$ μm are certainly not completely ballistic. This may enter in either of two ways. Disorder will affect the wave function of the electrons which, instead of being plane waves with well-defined energy, are eigenfunctions of the random potential whose energy is not constant along the barrier. The disorder along the barrier has been proposed as a partial explanation of our data. This model[15] states that the fluctuations in $G(V_g)$ arise because, near threshold, the transmission over the barrier varies along the length of the gate (transverse to the wire). So far, however, this model cannot predict the regions of negative transconductance, so we do not know how much of our results it really explains. Also, the gate potential itself has dispersion resulting from width variations (< 10%) in the gate, which causes the resonance condition to differ along the barrier. The disorder will presumably instill some random factors in the amplitudes and positions of the resonances. This is the reason that our devices do not behave as simple one-dimensional scattering transmitters. It may also be part of the reason that the resonances are observable at all. From simple WKB arguments, one expects that a smooth barrier, such as a Gaussian which decays on length scale $\sim\lambda_F$, is not expected to yield resonances for plane waves impinging on it.[11] A solution of the Schrödinger equation based on a classical solution for the potential in the device also suggests that the resonances should be too small to observe.[12]

One further possibility remains; the fluctuations might indicate fluctuations in the density of states resulting from the subbands in the one-dimensional potential well formed by the edges of the wire. The regular series of oscillations associated with the density of states has been observed in

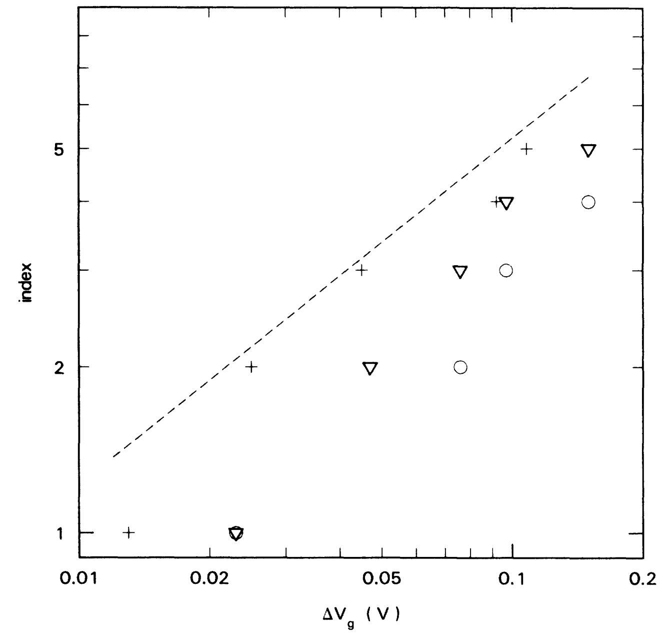

FIG. 3. Relative positions $V_{peak} - V_T$ of the peaks (o) in ΔG as a function of V_g, and positions of the peaks from sample 1 (∇) and sample 2 (+) derived by assuming that ΔG is never less than zero. The dashed line illustrates the slope of the prediction for the resonances from a square barrier.

parallel arrays of narrow wires by several methods.[16] Signatures of the one-dimensional density of state have also been sought for some time now in the transport of single wires,[17,18] but such searches have always been thwarted by disorder in the samples. Since the wire is narrower than the elastic mean free path, the carrier states might be quantized in the direction transverse to the wire. For a smooth, one-dimensional wire (square well) of width $w = 1.5$ μm, the separation in energy of the lowest subbands is of order 10^{-5} eV which is much smaller than the spacing observed in our sample. In order for the fluctuations in the conductance to be commensurate with splittings in the density of states, the width of the channel would have to be of order 150 nm which possibility can be immediately excluded. The wires having a patterned $w = 1$ μm also conduct[10] which indicates that the true channel width in the patterned 2 μm wire is larger than 1 μm. It seems, therefore, that the fluctuations do not mark fluctuations in the density of states of the wire.

We conclude by remarking that although the phenomenology of the fluctuations in the conductance of these narrow-gate devices is different from that in the ungated or homogeneously gated samples,[3] we cannot rule out the possibility that the observed fluctuations are the result of "universal conductance fluctuations."[13] Based on an analogy of the device geometry with optical scattering from a sharp barrier, we speculate that the fluctuations in G might result from resonant transmission through the localized potential barrier drawn up by the cross gate. The weak disorder in the sample adds a random character to the resonances.

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