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# Phase coherence, interference, and conductance quantization in a confined two-dimensional hole gas

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A system of two parallel constrictions in a two-dimensional hole gas has been studied. At zero magnetic-field conductance quantization is observed through the individual constrictions. At high magnetic fields Aharonov-Bohm oscillations result from resonant tunneling through states encircling the repulsive potential between the constrictions. The oscillations demonstrate directly phase-coherent transport of holes.

The majority of transport measurements on low-dimensional systems have been performed on material where the charge carriers are electrons. A multiplicity of effects has been observed which demonstrate the quantum-mechanical nature of electrons, including the quantum Hall effect,[1] the quantization of the one-dimensional (1D) ballistic conductance,[2,3] and Aharonov-Bohm (AB) oscillations.[4] These effects are of a universal nature. Under the right conditions they should be observable in any low-dimensional system of charge carriers. The experimental study of low-dimensional hole systems is of interest in demonstrating this universality.[5,6] Furthermore, by directly studying quantum-mechanical effects in hole systems one may hope to confirm some of the aspects of the Fermi-liquid theory, in particular the equivalence of holes and electrons as single-particle-like excitations of many-body systems.[7]

In this paper we report a direct observation of phase-coherent transport and interference effects in a hole system. We also present evidence for ballistic transport of holes and 1D conductance quantization.

In a strong perpendicular magnetic field Landau levels (LL's) form in a two-dimensional hole gas (2DHG) and transport can be described using the concept of edge states. These form along the edges of the sample where the electrostatic potential drops below the Fermi energy $E_F$ (we adopt the convention of negative energy for holes). In a similar manner edge states encircle an obstacle in the 2DHG forming closed loops [Fig. 1(a)]. The phase accumulated by the edge-state wave functions that encircle the loop depends on the wavelength and the loop circumference. In addition the Aharnonv-Bohm effect causes a phase change of $2\pi$ whenever the magnetic flux through the loop changes by $h/e$. If phase coherence is preserved around the loop then constructive interference occurs whenever the combined phase change per revolution is an integer multiple of $2\pi$. A ladder of allowed states is thus formed. A set of these single-particle (SP) states is associated with each circulating edge state, which itself falls to larger negative energies as it approaches the edge [Fig. 1(b)]. SP states enclosing a smaller area therefore have a larger negative energy and a shorter wavelength. The precise structure of the ladder and the SP energy spacing thus depend on the particulars of the electrostatics of the edge states. The SP states have been described for cavities in two-dimensional electron gases[8–11] (2DEG's) and recently also around an obstacle.[12]

Changing the magnetic field $B$ changes the flux through the closed loop. This in turn changes the Aharonov-Bohm phase and hence shifts the SP states in energy. If extended states exist in the vicinity of the obstacle then each time $E_F$ aligns with a SP state resonant tunneling between the extended states occurs. This will happen each time the flux through the loop changes by $h/e$. Conductance oscillations due to these resonant tunneling events are therefore periodic in $B$. They have been first discussed in relation to the breakdown of the quantum Hall effect.[13,14] The period in flux of these AB oscillations is $h/e$.

To realize the system described above a Hall bar was fabricated along the $[\bar{2}33]$ direction of a silicon-doped GaAs-$Al_{0.3}Ga_{0.7}As$ heterostructure grown on a (311)$A$-oriented substrate. The mobility was 32 $m^2 V^{-1} s^{-1}$ and the hole concentration was $2.2\times10^{15}$ $m^{-2}$ at 50 mK. At such carrier concentrations only the heavy-hole subband in the valence band is occupied. The carriers' effective mass is about $0.45m_e$ where $m_e$ is the free electron mass.[15] Details of the wafer growth will be described elsewhere.[16]

Electron beam lithography was used to define an etch mask in *PMMA*. Two parallel constrictions of length 0.3 $\mu$m and width 0.4 $\mu$m, separated by a 0.3-$\mu$m-radius dot—the obstacle—were patterned by etching the 2DHG through the mask (Fig. 1). Self-aligned metal gates were evaporated into the etched trenches which define the constrictions and the dot. Electrical contacts were made to the gates recessed into the constriction arms but not to the dot. Applying a positive bias to these gates results in lateral depletion of the hole gas. The gates can therefore be used to vary the width of each constriction independently, from its maximum width to zero.

Measurements were performed in a dilution refrigerator at $T<50$ mK using standard phase-sensitive detection techniques. As is usual, the equivalent of the two-terminal resistance across the device is obtained by summing the four-terminal resistance and the Hall resistance.

 

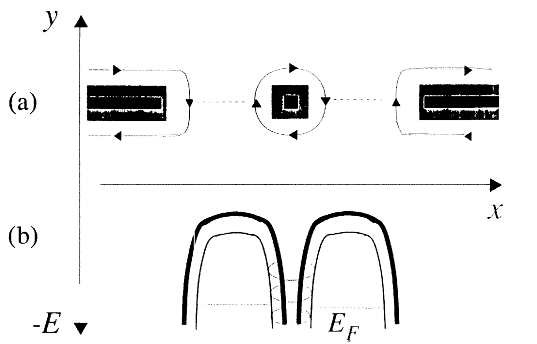


FIG. 1. (a) Two restrictions in parallel. The shaded regions represent the etched trenches. The dark regions at the trenches' centers are the recessed gates. A single edge state is represented by a solid line. The dashed line represents resonant tunneling from one edge of the sample to the other via the confined edge state. (b) Schematic energy diagram. The thick lines represent the electrostatic potential in the constrictions. A single Landau level, falling towards the edge to form an edge state, is represented by the thin lines. The circular lines are some of the associated SP states. $E_F$ is represented by the dashed line.

The inverse of the two-terminal resistance, expressed in units of $e^2/h$, gives the number of spin-polarized edge states transmitted through the device.

Pinching off one of the constrictions enables measurement of conductance vs gate voltage characteristics of the second constriction. Figure 2 shows these characteristics for one of the constrictions, at $B=0$ and 3 T. The 2DHG series resistance was subtracted from the data prior to inverting it. To reduce noise resulting from random telegraph signals (RTS's) each curve in Fig. 2 is the average of forty gate voltage sweeps. At $B=0$ rounded steps at integer multiples of $2e^2/h$ can be seen. This quantization of the 1D conduction demonstrates that the holes are traveling ballistically through the constriction. The zero-field steps wash out at about 400 mK. This value may be compared with a typical temperature of 4 K, at which quantization steps in the conduction of 1D constrictions in 2DEG's wash out.[17] Since the hole-electron effective mass ratio in GaAs is about 8 and the subband spacing is inversely proportional to to the mass, a maximum temperature of 400 mK for observation of steps is reasonable. A direct determination of the 1D subband spacing in the constriction by applying a dc source drain bias was, however, prevented by RTS's switching events. At the required levels of dc bias these became very fast and rendered averaging impractical.

At $B=3$ T the filling factor $\nu$ in the bulk of the 2DHG, far away from the constriction, is just greater than 3. Three conductance plateaus are observed at multiples of $e^2/h$ as the Landau levels at this field are spin polarized. The plateaus are now much clearer. They represent successive reflections of edge states at the constriction as the top of the valence band is lowered.

The constrictions were next individually tuned to transmit two edge states at a field corresponding to $2<\nu<3$ in the bulk. Upon sweeping the magnetic field AB oscillations were observed (Fig. 3). The period of the oscillations is approximately 6 mT, corresponding to the addition of $h/e$ of flux to an edge-state loop of radius $r=0.46$ $\mu$m. As the etched dot radius is 0.3 $\mu$m this indicates a depletion width of 0.15 $\mu$m which is reasonable.[18]

In the ideal case of symmetric tunneling probabilities and weak coupling between the SP and extended states, sharp periodic resonances with a modulation of nearly 100% are expected. The Fourier transform of such resonant peaks contains a large number of harmonics. The $n$th harmonic corresponds to the $n$th revolution of a charge carrier around the loop and all the harmonics have similar strengths. If the coupling is not weak higher harmonics have smaller amplitudes, resulting from a hole leaving the orbit at either constriction. In addition, in a real case phase randomizing events occur. This is also manifested by the attenuation of higher harmonics in the Fourier transform. An exponential decay of the amplitude with distance is usually assumed. Applied to an

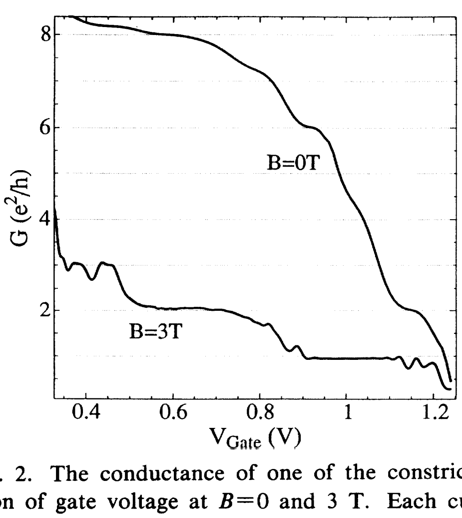


FIG. 2. The conductance of one of the constrictions as a function of gate voltage at $B=0$ and 3 T. Each curve is the average of forty gate voltage sweeps to eliminate the effect of the RTS's. Note that at $B=0$ the higher steps do not fit the right quantized values. This is due to a change of a few hundred ohms in the series resistance as a function of gate voltage.

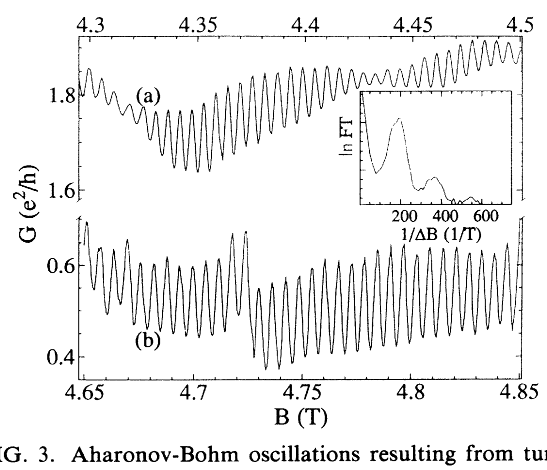


FIG. 3. Aharonov-Bohm oscillations resulting from tunneling through SP states. (a) Two edge states going through the constrictions, (b) a single edge state with the gates optimized for maximum amplitude. The inset shows the logarithm of the Fourier transform of the oscillations in (b).

edge state encircling the dot the amplitudes $A_n$ of the Fourier components therefore obey a relation $A_{n+1} = (1-t)^{4n} A_1 \exp(-np/l_\phi)$, where $n$ is the order of the harmonic, $p$ is the circumference of the dot, and $t$ is the amplitude of the tunneling probability into and out of the bound state. A comparison of the relative strengths of the harmonics may then be used to obtain the characteristic length for the decay—the phase-coherence length $l_\phi$.

Figure 3(b) shows that by carefully adjusting the gates, the modulation of the oscillations can be increased to a maximum of about 50%, when there is only a single edge state in each constriction. A Fourier transform of these oscillations reveals a first harmonic, a much weakened second harmonic, and traces of the third harmonic (inset of Fig. 3). The peaks are broad, the width representing the uncertainty in the area of the loop. To compare the strength of the harmonics one has to consider the area under the peaks. The amplitude of the tunneling probability across a constriction and into the SP states is estimated as $t = 1 - G_i^{1/2}$ where $G_i$ are the conductances of the individual constrictions. Use of the above relation then yields values for $l_\phi$ for the hole edge-state wave function of 2–5 $\mu$m. Since thermal averaging may also contribute slightly even at base temperature this estimate may be only a lower bound for $l_\phi$. It is interesting to note that comparable values were obtained for the electron $l_\phi$ in similar systems.[4,12,19]

Upon raising the temperature the higher harmonics vanish almost immediately, making a determination of the temperature dependence of $l_\phi$ impractical. The AB oscillations themselves die out at around 300 mK, due to the thermal smearing of the SP states which are therefore of the order of 25 $\mu$eV apart. Assuming parabolic potential in the constrictions of width 0.2 $\mu$m at $E_F \sim \hbar\omega_c \sim 1$ meV at $B = 4$ T, the slope of the potential is approximately 40 $\mu$eV/nm at $E_F$. The flux enclosed by adjacent SP states differs by $h/e$ so that $B\delta(\pi r^2) = h/e$ where $r$ is the radius of the dot. The difference in radius of consecutive SP states is therefore $\delta r \sim h/(2\pi r e B) \sim 1$ nm, which gives a SP energy separation $\sim (dE/dr)\delta r = 40$ $\mu$eV. Despite the crude approximation this estimate is in rough agreement with the temperature dependence results.

For given gate voltages the AB oscillations persist over a range of a few tesla. As the field is increased the number of edge states in the bulk and in the constrictions decreases. We have observed oscillations for filling factors in the constrictions ranging from just over two at low fields, down to well below one in high fields. Throughout this field range only very small changes in the period of the oscillations are observed. We attribute these to a change in the area enclosed by the edge states as a result of changes in $E_F$ and in the magnetic length. In contrast, recent results in a similar 2DEG system showed a doubling of the frequency of the oscillations as the number of edge states encircling the dot increases from one to two.[11,12] Charging of an isolated edge state around the dot has been suggested as an explanation for this observation. We note that as yet no such effect has been seen in our hole system. Further work designed to ascertain the reason for this apparent difference between the hole and electron systems is planned.

As mentioned above our device exhibited a number of RTS's. Figure 4 shows the conductance of the device changing dramatically as a result of an RTS switching between states.[20] The positions in magnetic field where the switches occur are designated by arrows with numbers to distinguish the two different RTS's. The RTS designated as no. 1 causes the conductance to change from a value between 1 and 2, in units of $e^2/h$, to a value less than 1, and vice versa. This means that the number of edge states transmitted through the device changes from one fully and one partially transmitted edge state to only one partially transmitted edge state. The period and phase of the oscillations however do not change. This is readily seen with the aid of the vertical dotted lines in Fig. 4. The lines are equidistant and follow the conductance peaks. To within the accuracy of the measurement no phase change is observed. This is the case for RTS no. 1 as well as for the smaller RTS no. 2. It should be mentioned however that within the data collected, more RTS's can be identified, some of which change the period of the oscillations by a few percent and naturally upset the phase (not shown). These RTS's are probably due to charging of defects in the vicinity of the dot, affecting its size.

If the effect of the "phase-conserving" RTS's were confined to merely changing the series resistance close to the device, one would expect the amplitude of the oscillations in a resistance measurement not to change. This is not the case. The amplitude of the oscillations as well as the modulation depth on either side of the RTS's are different. This suggests that the phase-conserving RTS changes the tunneling probability across at least one of the constrictions. In doing so the symmetry of the two tunneling probabilities may be enhanced or diminished thus affecting the height of the resonances.

As already observed, RTS no. 1 switches the conductance between $\nu > 1$ and $\nu < 1$ without affecting the phase

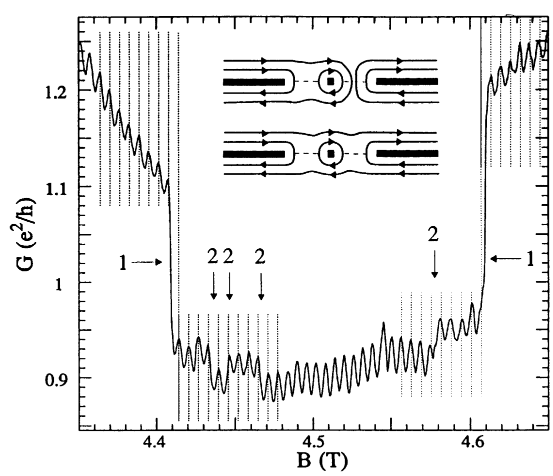


FIG. 4. RTS switching events affect the conductance but not the period and phase of the AB oscillations. The arrows identify RTS no. 1 and RTS no. 2 (see text). The dotted vertical lines are equidistant and mark the conductance peaks. The diagrams in the inset schematically represent the proposed effect of RTS no. 1.

or period of the oscillations. It may therefore be inferred that the oscillations for $\nu<1$ as well as for $\nu>1$ are entirely due to one confined edge state. Even in the case of $\nu>1$, when more than one edge state goes through the device, the partially transmitted outer edge state cannot be affecting the oscillations. If it did, some change in the oscillations would have been expected when, after the RTS, this edge state becomes totally reflected. We explain this as follows. In the case of RTS no. 1, and for $\nu>1$, the outer edge state is partially transmitted only through one of the constrictions and is totally reflected by the other. The situation is depicted in the top schematic diagram in Fig. 4. The only state encircling the dot is due to the inner edge state, giving rise to AB oscillations. The main effect of the RTS is to turn off the transmission of the outer edge state causing it to be totally reflected. This is depicted in the lower diagram in Fig. 4. The conductance of the device drops but the inner edge state encircling the dot is not affected. The AB oscillations are unperturbed except for a change in amplitude as already discussed. It is therefore reasonable to deduce that the different RTS's observed in our device originate from independent defects. These affect the device's behavior in different manners which may indicate their approximate location.

In conclusion, we have presented direct demonstration of phase-coherent transport of holes, in the form of interference and Aharonov-Bohm oscillations. We have estimated the phase-coherence length of the hole edge-state wave function and found it to be close to that obtained in similar systems for electrons. The effects of different RTS's on the device's conduction have been presented and used to deduce the approximate location of the RTS's. We also report the observation of ballistic transport of holes and 1D conductance quantization at zero magnetic field.

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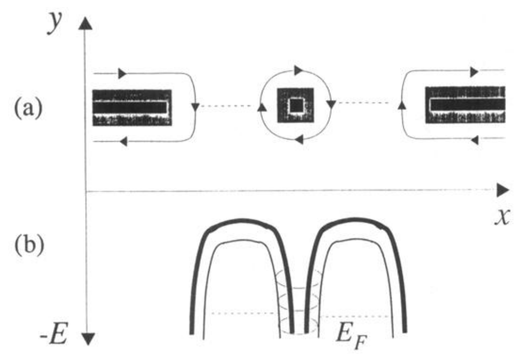


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