Suppression of the Aharonov-Bohm effect in the quantized Hall regime

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We have examined the suppression of oscillations due to the Aharonov-Bohm effect in the magnetoresistance of annuli fabricated in high-mobility $Al_xGa_{1-x}As/GaAs$ heterostructure. The oscillations, with a periodicity near zero field corresponding to a flux of hc/e through the average area of the annulus, decrease dramatically in amplitude and shift to a lower frequency as the magnetic field increases, and vanish near the resistance minima associated with plateaus in the Hall effect. Our observations show that the net current is carried by edge states in the quantized Hall regime, and the suppression of the Aharonov-Bohm effect is due to the absence of backscattering.

The Aharonov-Bohm (AB) effect occurs because two electron trajectories which encircle a magnetic flux acquire a relative phase shift proportional to the flux. As the flux changes, the transmission probability of the electron oscillates with a periodicity of hc/e. Previously,[1,2] we reported the observation of oscillations due to the AB effect in the magnetoresistance of annuli (fabricated in high-mobility $Al_xGa_{1-x}As/GaAs$ heterostructure using a partial etch of $Al_xGa_{1-x}As$) with a period corresponding to a flux of hc/e through the average area of the annulus. Under the conditions of the experiment the magnetic field penetrated both the annulus and the quasi-one-dimensional (1D) wire of width W comprising the annulus. For magnetic fields where $W > 2r_c = 2\sqrt{\hbar c/eH}$, the oscillation amplitude was suppressed.[2,3]

Recently,[4] a Landauer-type formulation of transport in the quantum Hall regime has been developed which relates the resistance to the transmission coefficients associated with edge states. Following the Landauer approach, Jain and Büttiker[5] have subsequently proposed that the suppression of the AB effect is due to the absence of backscattering between edge states in the quantized Hall regime. For $W < 2r_c$, the current is carried in the bulk of the wire and the resistance is due to scattering from either the device geometry, the leads or impurities. However, for magnetic fields where the Hall resistance is quantized (i.e., where $W \gg 2r_c$, see Fig. 1), the driving force provided by the confining potential of the wire moves carriers along the edges of the wire with opposite edges carrying oppositely directed currents and, because of the absence of backscattering between the two edges, dissipationless transport results. Because of the magnetic field, a carrier is never scattered further than a few r_c from the edge and so a carrier cannot change direction or backscatter to the opposite edge if $W > 2-4r_c$. According to Jain and Buttiker, the AB effect is suppressed in the quantized Hall regime because the outer edge states, which are connected to the leads and determine the resistance, do not enclose a flux while the inner edge states which do enclose a flux are not coupled to the outer edge states.

This letter describes an experimental study of the suppression of the AB effect in the quantized Hall regime. We report further four-terminal measurements of the magnetoresistance of annuli fabricated in high-mobility $Al_xGa_{1-x}As/GaAs$ heterostructure where the wires comprising the annulus are only a few Fermi wavelengths wide. The oscillations observed in the magnetoresistance, with a periodicity near zero magnetic field corresponding to a flux of hc/e through the average area of the annulus, decrease exponentially in amplitude and shift to lower frequencies for magnetic fields beyond $W \approx 2r_c$. For $W \gg 2r_c$, the frequency of oscillation is identified with trajectories which encircle the inner edge of the annulus and we find that the oscillations vanish in resistance minima corresponding to plateaus in the Hall resistance, but reappear beyond the minima. Our observations demonstrate that edge states carry the net current in the quantized Hall regime and that the suppression of the AB effect is due to the exponential reduction of backscattering resulting from the exponentially decreasing

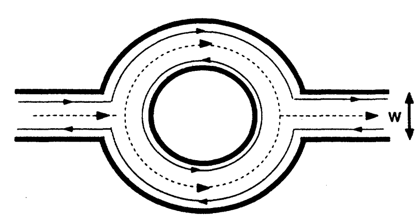

FIG. 1. A schematic representation of transport through an annulus near zero magnetic field, $W < 2r_c$ (dashed line) and in the quantum Hall regime $W \gg 2r_c$ (solid line). The arrows indicate the direction of current flow. In the quantized Hall regime a net current results from the difference between two oppositely directed currents associated with the edge states.

overlap between edge states with increasing magnetic field.

Halperin[6,7] first attributed the net current in the quantized Hall regime to the difference in two oppositely directed currents carried by edge states, but experiments[8,9] on 2D samples with macroscopic (50-μm) inhomogeneities have since been interpreted as evidence of a current (which may be grossly inhomogeneous) distributed throughout the bulk of the 2D wire. On the contrary, our observations indicate that for high mobility devices fabricated on the scale of an electron wavelength, edge states carry the net current. Moreover, our observations indicate that the Landauer formulation for the resistance as developed by Jain and Buttiker is appropriate to the quantized Hall regime.

The fabrication of the devices is described elsewhere.[10] The devices are fabricated in both conventional modulation-doped and δ-doped $Al_xGa_{1-x}As/GaAs$ heterostructures.[11] The salient feature of the fabrication is a partial etch of the $Al_xGa_{1-x}As$ which laterally constrains the two-dimensional (2D) electron gas at the $Al_xGa_{1-x}As/GaAs$ interface to the region beneath an etch mask defined by electron beam lithography. The lithographic width of the etch mask used to define the wires comprising the annuli is approximately 500 nm, but the conducting width of the wire is estimated to be considerably narrower (usually $W < 25$ nm) due to depletion from the exposed edge of the device. Twelve devices were examined; four in great detail. The starting material for these devices ranged in mobility from 30–180 $m^2/V\,s$. We have not observed any degradation in mobility due to the fabrication technique, but the carrier density, estimated from the high field ($H > 2$ T) Shubnikov–de Haas (SdH) oscillations in the wire, typically decreases by approximately 30–50 % from the 2D value. For economy, we will focus on results obtained from devices with a starting mobility and carrier density of about 50 $m^2/V\,s$ and 4.4×10^{15} m^{-2}. The carrier density in the 1D wire deduced from SdH is approximately 3.0×10^{15} m^{-2}. We measured the four-terminal, transverse (to the field) magnetoresistance of nominally 2-μm-diam annuli like that shown in the inset to Fig. 2 using an ac resistance bridge operating at 14 Hz. The current excitation was typically less than 1 nA. If the same lead configuration was used, the measured resistance was correlated from day to day to better than 95%.

Figure 2 shows the magnetoresistance $R_{2,5;1,6}$ of a nominally 2-μm-diam (actually 1.82 ± 0.05 μm) annulus found for 70-mT intervals starting at magnetic fields of $H=0$ mT, 0.920 T, and 2.470 T, respectively. $R_{2,5;1,6}$ denotes a four-terminal resistance measurement in which leads 2 and 5 are used for current excitation, and 1 and 6 are used for voltage detection. The convention for numbering the leads is given in the inset of Fig. 2. We observe that the magnetoresistance oscillates near 0 mT with periodicity corresponding to a flux of hc/e through the area of the annulus defined by the average diameter. As the magnetic field increases, both the amplitude and frequency decrease dramatically, however. Background fluctuations, which have lower frequency aperiodic and periodic components,[2] are also seen superimposed upon

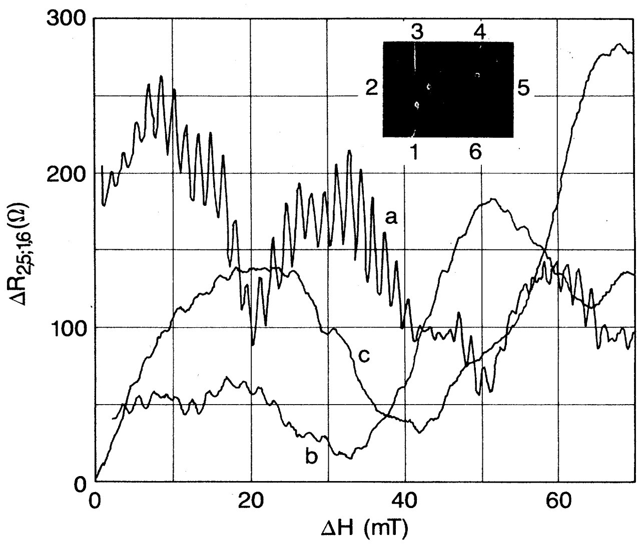

FIG. 2. The typical magnetoresistance $R_{2,5;1,6}$ of a nominally 2-μm-diam annulus obtained for $T=280$ mK observed near (a) 0 mT, (b) 0.92 T, and (c) 2.47 T. An electron micrograph of the device is shown in the inset and the convention for numbering the leads is indicated there.

these oscillations. The background fluctuations beat with the oscillations so that in short intervals of magnetic field the amplitude is reduced.

Figure 3 exhibits the change observed in the Fourier power as a function of magnetic field. To obviate any complications to the interpretation of the suppression associated with the beating phenomenon mentioned above, the Fourier transforms were taken using a window approximately 220 mT wide; much larger than the typical periodicity associated with a beat (approximately 20 mT). Not only do we observe the hc/e fundamental, but the $hc/2e$ harmonic is routinely found as well.[2,3] We can obtain a lower bound on the phase coherence length, L_ϕ, using the ratio of the amplitudes of the hc/e and $hc/2e$ Fourier components and we typically find that $L_\phi > 3$ μm.

If we assume that the width of the hc/e peak in the Fourier spectrum obtained near 0 mT is given approximately by $(\Delta H)^{-1}=2\pi rW/(hc/e)$, where r is the radius and W is a lower bound on the conducting width of the wire, then $W > 150$–190 nm. We notice that for $R_{2,5;1,6}$ the Fourier intensity in the hc/e band beyond approximately $H=120$ mT is below 10% of the peak value observed near $H=0$ mT for the device of Fig. 3. Generally, we find that $W\approx(2-4)r_c$ for magnetic fields near the 10% attentuation of the AB effect. As shown in Fig. 3(j), the peak in the Fourier power obtained from $R_{2,5;1,6}$ decays exponentially with magnetic field for 200 mT $< H < 1.6$ T according to $P \propto \exp(-L_0^2/4r_c^2)$, where P is the Fourier power and L_0 is a characteristic length. For the device of Fig. 3, the fit to the data (indicated by the dashed line) yields $L_0=95\pm7$ nm, but typically, $82 < L_0 < 160$ nm. The hc/e power spectra obtained from $R_{2,5;4,6}$ and the $hc/2e$ spectra obtained from

$R_{2,5;1,6}$ decay with a similar L_0 which, respectively, indicates that the suppression of the AB effect is not due to the leads used for the measurement or to degradation of L_ϕ with field.

In Fig. 3 the Fourier power is shown to decrease dramatically between $H=0$ and 215 mT indicative of the suppression of the *AB* effect. As the field increases, the centroid of the power spectrum shifts monotonically from 630 T^{-1} to lower frequency, eventually reaching approximately 420 T^{-1} near 1 T. The Fourier power in the band between 500–750 T^{-1}, the bandwidth previously associated with the width of the wire, is below the noise beyond this field, and no power above the noise is observed on the corresponding upper edge of the zero-field bandwidth beyond $H=800$ mT for the device of Fig. 3. The dramatic shift found in both the amplitude and frequency is apparent in a comparison of the Fourier spectra Figs. 3(a) and 3(i) and is summarized in Fig. 3(j). The peak in the Fourier spectra found at high magnetic fields is shifted monotonically to the edge of the bandwidth associated with the Fourier spectrum observed near $H=0$ mT. This is a general feature of the suppression of the AB effect in each of the 12 devices examined, independent of the radius of the annulus ($r=0.5-1$ μm *nominally*), the mobility of the starting material, and the width of the *hc/e* peak in the Fourier spectra at zero field.

The spectral position of the peak does not depend on magnetic field for $1\ T < H < 2.5$ T for the device of Fig. 3. This characteristic was clearly observed in three of the four devices examined in detail. As the magnetic field increases, the peak in the spectra near 420 T^{-1} observed for $H > 800$ mT vanishes near the resistance minima observed in $R_{2,5;1,6}$ beginning near $H=1.632$ T and $H=2.057$ T, but reappear beyond the minima. The resistance minima observed in $R_{2,5;1,6}$ correspond to plateaus seen in $R_{2,5;4,6}$ [see Fig. 3(k)]. The resistance $R_{2,5;4,6}$ is

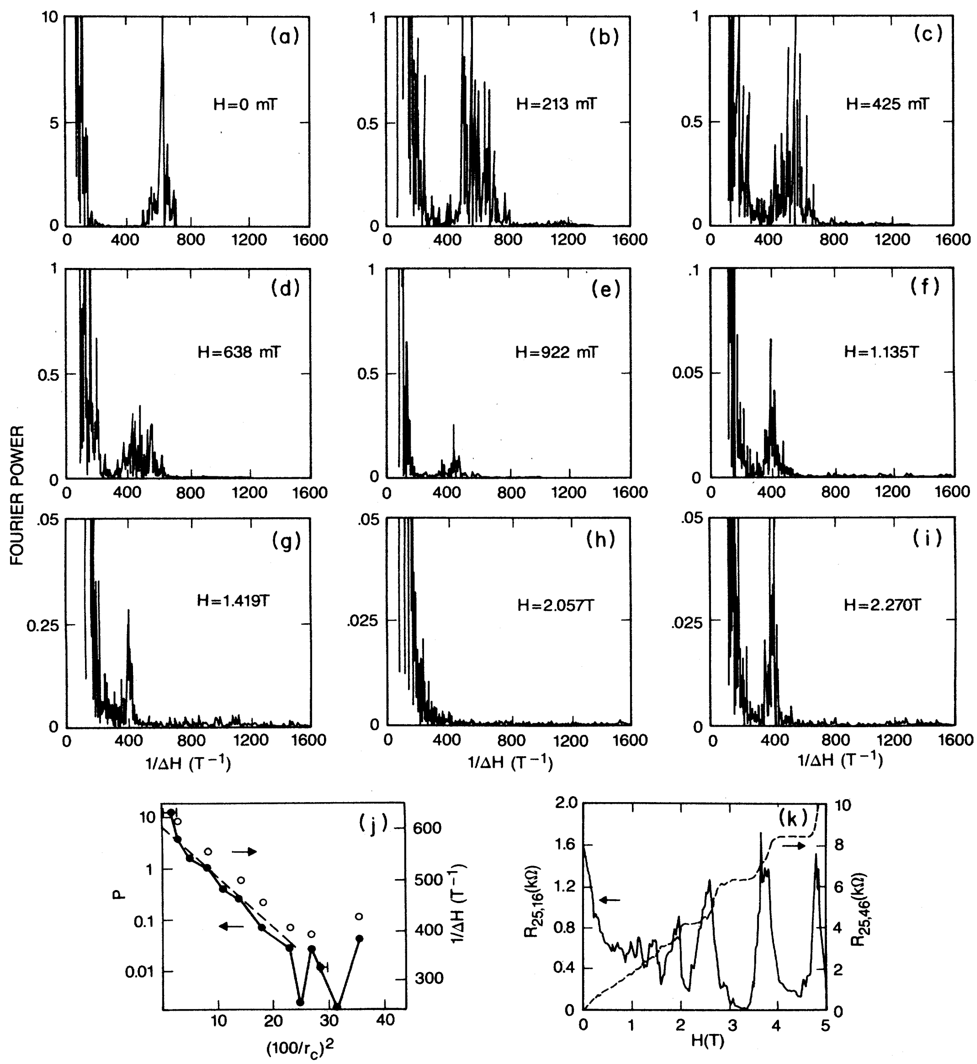

FIG. 3. (a)–(i) depict the Fourier power spectra found in $R_{2,5;1,6}$ as a function of magnetic field obtained over a 220-mT field range beginning at the field indicated. (j) summarizes the dependence of the power (solid points) and centroid (open circles) position on the magnetic length measured in nanometers; the dashed line represents the fit to the data. (k) shows the magnetoresistances $R_{2,5;1,6}$ and $R_{2,5;4,6}$.

well quantized to the values $h/e^2 i$ only for values of $i=1$, 2, 3, 4, and 6. The resistance minima below 3 T are nonzero for the temperature range examined. The peak Fourier power is at most a factor of 200 lower (between the minima) at high field than that observed at zero field. The observation that the Fourier spectra vanishes in the resistance minima was made on only 2 of 12 annuli. All of the other devices were narrower using the criterion defined above, and the definition of the plateaus in a measurement such as $R_{2,5;4,6}$ was poorer below 3 T.

We interpret our results to be indicative of the absence of backscattering in the quantized Hall regime. For fields beyond $W \approx 2r_c$, the net current is carried by edge states, and the AB effect is suppressed in the field range of the Hall plateaus because in that range the current carried along the inner edge of the annulus (see Fig. 1) backscatters only weakly to the outlying edge involved in the voltage measurement since they are separated by more than $2r_c$. The peak amplitude depends upon the backscattered intensity and we presume that the backscattering depends upon the overlap between edge states. Thus, the exponential decay of the Fourier power with $r_c^{-2} \propto H$ between 200 mT and 1.6 T is indicative of the decreasing overlap as the magnetic field increases. The expected form for the overlap in a high magnetic field is proportional to $\exp(-\alpha W^2/4r_c^2)$,[12] where α is a constant of order unity and depends upon the shape of the confining potential, and is consistent with the data. We associate the peak in the Fourier spectra observed at high field, on the lower edge of the hole frequency band obtained near zero field, with the area circumscribed by inner edge states. Realistically, the outer edge states are coupled to areas enclosed by localized states throughout the bulk of the wire as well as states about the inner edge, but the latter states are more prominent presumeably because that area does not change appreciably with magnetic field. In the field range beyond the resistance minima and between the quantized Hall plateaus, we assume that the edge states along the inner edge of the annulus cannot tunnel directly to the outer edge, but rather scatter via potential fluctuations within the bulk of the wire.

Our interpretation is further supported by numerical simulations of the two probe magnetoresistance of a ballistic annuli described by a tight-binding Hamiltonian which confines electrons within hard walls. The calculation, which uses a recursive Green's-function technique to determine the resistance as a function of magnetic field, shows a shift in the hc/e period to a lower frequency with increasing magnetic field and reveals that the high-field period is uniquely associated with the area embraced by the inner edge.

The radius corresponding to the 420 T^{-1} frequency is $r \approx 0.75$ μm. It is greater than the inside lithographic radius by about 70 nm and corresponds to $W \approx 360$ nm assuming that half of the channel width is given by the difference between the radii associated with the centroid of the hc/e peak in the Fourier spectra for $H=0$ mT (640 T^{-1}) and 1.2 T (420 T^{-1}), respectively. Our estimate of W, deduced from the width of the hc/e fundamental at zero field, is not unequivocal and represents only a lower bound on the width of the conducting wire, especially in the limit where only a few 1D subbands carry the current. The width deduced from the zero-field Fourier spectra is not generally in agreement with that deduced from deviations of the SdH oscillations from $1/H$ periodcity either,[3] typically being approximately a factor of 2 smaller.

Finally, we notice that the suppression of backscattering affects the average resistance as well as the oscillatory component. It has already been shown that the *average* four-terminal magnetoresistance in a ballistic device is due predominately to scattering from junctions or bends in the wire only for H where $W<2r_c$.[13,14] This observation is also consistent with the suppression of backscattering from junctions or bends in a ballistic wire for H beyond $W \approx 2r_c$.

Note added in proof. Following the submission of this article for publication, we became aware of work by Ford and his collaborators at Cavendish Laboratory, University of Cambridge, which also reports the observation of a decrease in the frequency of the AB oscillations with increasing magnetic field.

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