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Tunable Aharonov-Bohm effect in an electron interferometer

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The Aharonov-Bohm effect has been investigated in submicrometer-sized annuli fabricated from GaAs-$Al_xGa_{1-x}As$ heterostructures constructed with a narrow metal gate intercepting one branch of the rings. The gate locally alters the phase of the confined electron wave function, making these rings act as tunable electron interferometers. The amplitude and phase of the magnetoresistance oscillations were controlled over a ~ 1 V gate voltage range. Although the device can discriminate between a shift in Feynman trajectories and the electrostatic Aharonov-Bohm effect, no phenomena periodic in gate potential characteristic of the latter were resolved.

In optical interferometers it is possible to modulate the interference condition at the output port in a controllable fashion. Typically this involves modifying the optical path length of one of the interferometer's arms relative to the other. Is it possible to achieve similar results for an *electron* interference device? In this paper we discuss an experiment that demonstrates such behavior.

Over the last few years it has become feasible to construct electronic devices on a size scale sufficiently small that the nonsuperconducting electron wave maintains its phase coherence.[1] The magnetoresistance of such samples displays fluctuations due to Aharonov-Bohm[2] (AB) effects produced by the electron trajectories. Similarly, annular samples exhibit magnetoresistance oscillations with flux periodicity h/e. Since its inception, the solid-state AB effect has generated a wealth of information[3-8] regarding quantum transport in a wide range of materials. In this work we use AB rings as electron interferometers sensitive to externally induced changes in the phase of the wave function.

We have implemented a tunable electron interferometer[9] in annuli fabricated from high-mobility GaAs-$Al_xGa_{1-x}As$ heterostructures so that $W \simeq \lambda_f \ll l_e \lesssim L \simeq L_\phi$. Here $W = 90$–130 nm is the conducting width of the wire, $\lambda_f \simeq 60$ nm is the Fermi wavelength, $l_e \simeq 1.6$–2 μm is the momentum relaxation distance, $L = 5.9$ μm is the ring's mean circumference, and $L_\phi \gtrsim 5$ μm is the phase-breaking length. How these parameters were determined is discussed below. These electron waveguides have been extensively discussed in the literature.[10-13] Since only a few (2–3) one-dimensional subbands are occupied, the AB effect in these annuli gives rise to magnetoresistance oscillations whose low-field peak-to-peak amplitude is up to 10% of the total ring resistance. We alter the interference condition giving rise to the AB oscillations ("fringes") by constructing a metal gate over one branch of the ring (see insets to Fig. 1). According to one view, applying a negative gate bias locally depletes the confined electrons beneath the metal. This modifies the Fermi velocity there and modulates the phase acquired by the electron wave in that arm of the ring relative to the other. Alternatively, the local gate may be pictured as introducing a controllable scatterer, drawing up a potential barrier with a variable phase shift, or modifying the Feynman trajectories. Varying the gate voltage is analogous to changing the index of refraction in one branch of a photon interferometer.

Washburn *et al.*[14] have demonstrated a tunable AB effect in a normal metal (Sb) ring by employing an electric field in the plane of the ring produced by a capacitor. There the externally applied scalar potential presumably affected both branches of the annulus since the ring was entirely between the capacitor plates. This corresponds to a fringe shift caused by distributing the refractive index modification over both branches of an optical interferometer. These experiments, however, did not distinguish between a shift of Feynman trajectories and an electrostatic Aharonov-Bohm (EAB) effect arising from coupling of the unperturbed wave functions to an external scalar potential. In the electron interferometers discussed here the phase shifts are introduced into one branch. The gate couples to the electron gas over a distance of order 0.34 μm given by the sum of the gate width and twice the

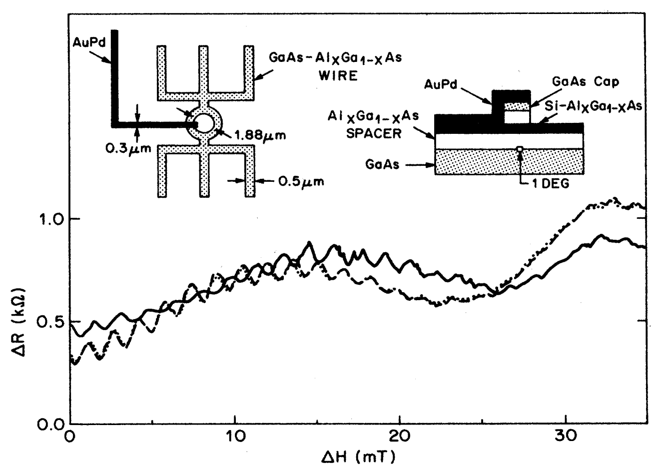

FIG. 1. Magnetoresistance of a gated 1.88-μm-diam ring. The dashed curve was recorded with $V_g = 0$ mV first. V_g was then swept to -300 mV, producing the solid trace. The dotted data refer to data obtained when V_g was then returned to its original value. The insets are schematics of the gated annuli and are not drawn to scale.

screening length 200 Å. One may differentiate an EAB effect from an alteration of the Feynman paths because the former yields effects periodic in the potential experienced by the electrons, while the latter leads to aperiodic phenomena in general. Although the Sb and heterostructure rings possess comparable disorder [the perimeters are 3-4l_e (Ref. 15)], they differ in some important aspects with regard to this qualitative distinction. Most significantly, the metallic samples are wide: $W = 260\lambda_f$.[16] The resulting metal interferometer is then characterized by ballistic transport involving thousands of channels. The EAB periodicity will be washed out due to the variation of the contact time between the external potential and the wave function over the many channels.[17] By contrast, the semiconductor rings are narrow $W \sim 2\text{-}3\lambda_f$ electron waveguides. Also, the applied electrostatic potential is well screened in Sb where the screening length is ~2 Å, making resistance changes difficult. Field-effect phenomena are readily obtained in narrow heterostructure wires where screening lengths are about 200 Å.

The narrow, gated annuli were constructed using electron beam lithography in conjunction with reactive ion etching. The details of processing steps have been published elsewhere.[18] Briefly, the lithographic width of the etch mask above the selectively doped molecular-beam epitaxy GaAs-$Al_xGa_{1-x}As$ heterostructure was 0.5 μm and the mean ring diameter was 1.88 μm. The heterostructures were dry etched only down to the dopant layer, removing the two-dimensional electron gas (2D EG) everywhere except beneath the mask. Lateral depletion further reduced the conducting width W to 90–130 nm (see below). To construct a gate over one branch of the ring, the etch mask was removed, and metal alignment marks were applied using electron beam lithography and lift-off techniques. A second such step defined the 0.3-μm-wide AuPd gate. Two schematic views of the resulting device are shown in Fig. 1.

For the data displayed below we manufactured gated rings starting from material with a 2D EG sheet density of 3.9×10^{11} cm^{-2} and a zero-field mobility of 3×10^5 cm^2/V sec, as determined by Hall and Shubnikov–de Haas measurements on a 300-μm-wide specimen. These implied a momentum relaxation distance $l_e = 1.6\text{-}2$ μm. All measurements were performed at 280 mK using standard four-probe ac techniques and drive currents below 3 nA. The parameters $L_\phi \gtrsim 5$ μm and $W \simeq 90$ nm were obtained from Fourier spectra of the AB oscillations.[19] Gate leakage currents were immeasurably small at all applied gate potentials, corresponding to resistances in excess of 1 GΩ between the AuPd gate and the confined electron gas.

Figure 1 illustrates the effects of small excursions of gate voltage V_g on the AB oscillations. One can readily observe that the phase of the oscillations change as V_g is varied from 0 to −300 mV. On returning V_g to its initial value, the magnetoresistance retraces the original curve. This indicates that we are able to controllably tune the interference condition using V_g. Extreme care was required to achieve such reproducibility as there are only about 100 electrons confined beneath the metal gate. The magnetoresistance is then exquisitely sensitive to shifts in the depletion charge distribution responsible for confining the electrons in the conducting channel. A change in occupancy of one trap on cycling V_g could then easily degrade the reproducibility. Roughly 20% of the collected data were rendered useless by such effects and were discarded. However, the magnetoresistance reproducibility upon such cycling was better than 97% if the cryostat was not disturbed.

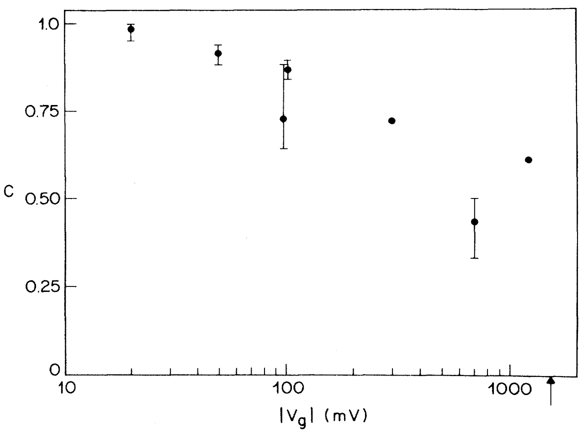

FIG. 2. The correlation coefficient of the AB magnetoresistance oscillations as a function of change in gate voltage from zero-bias conditions. The error bars correspond to the correlations found over shorter ranges of magnetic field. The arrow denotes the pinch-off voltage.

Figure 2 illustrates how the AB oscillations decorrelate with increasing $|V_g|$. The correlation coefficient C in Fig. 2 was computed between two digitally filtered magnetoresistance traces involving at least 45 cycles measured at the indicated gate voltages and zero bias. The filter eliminated all Fourier components except those in a passband around the h/e oscillations. The error bars indicate that in some field regions the oscillations are phase or amplitude modulated more or less than the average.

Figure 3 demonstrates the results of wider sweeps in gate voltage on the AB effect. For $V_g = -700$ mV the oscillations are partially suppressed as well as being shifted in phase. At $V_g = -2000$ mV the AB interference has

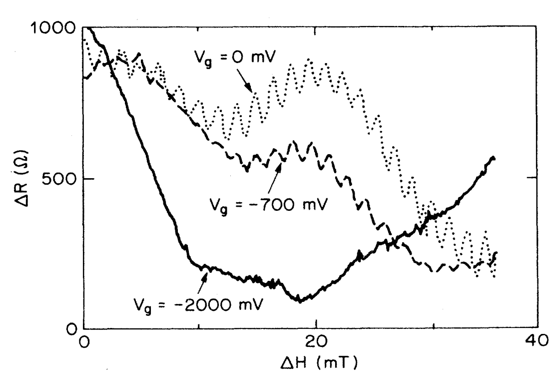

FIG. 3. Magnetoresistance traces taken on the same sample as Fig. 1 over a wider range of gate voltage.

vanished. This occurs because the branch of the ring with the gate has been pinched off. Evidence for this interpretation may be found by examining the resistance of the ring as a function of V_g at fixed magnetic field. Such a trace is presented in Fig. 4. At $V_g = -1500$ mV the resistance has roughly doubled, in accord with what one would classically expect if one branch of the ring were no longer conducting.

The inset to Fig. 4 shows the flux dependence of the relative phase between two filtered magnetoresistance traces taken at different gate potentials. Since the average phase shift over 90 cycles is an order of magnitude smaller than the rms phase fluctuation about the average, one cannot define a cycle-averaged phase modulation as a function of gate voltage. Similar to metals, one does not find a global shift of the h/e oscillations with an externally applied potential, instead the shifts seem to be grouped into regions of length $\sim 10h/e$.

Other features of Fig. 4 are noteworthy. In a ring of this type one might expect the EAB effect[14] to play a role. In this variation, the wave function acquires a phase shift by coupling to the scalar potential under the gate rather than to the flux through the hole. This implies a phase shift on the wave function linear in the applied potential and oscillations of the ring resistance as a function of gate voltage. One way to search for the EAB effect is via the magnetoresistance oscillations. However, the above-mentioned lack of a well-defined cycle-averaged *magnetoresistance* phase shift indicates the absence of a systematic flux-averaged wave-function phase shift linear in V_g. Alternatively, measurements of ring resistance as a function of V_g at *fixed* field, such as in Fig. 4, revealed no clear periodic structure on any scale within the 100-ppm experimental resolution. This indicates that the phase shifts introduced by the gate are not due to the EAB effect, rather they reflect a change in the Feynman trajectories.

In retrospect, the lack of an observable EAB effect in these devices may be explained from two points of view. First, one may crudely estimate the change in potential experienced by the electrons necessary to generate one EAB period from $\Delta V \sim 2\pi\hbar/e\tau_g \lesssim 2$ mV, where τ_g is the contact time of the wave function and the external potential. τ_g has been taken to be $\tau_g \sim L_g/v_F$ where $L_g = 0.34$ μm is an effective gate width and v_f is the Fermi velocity. This value for ΔV is about the same as that required to depopulate transverse subbands in these devices, so the wave function will be grossly changed by the gate before even one EAB period. The change in potential seen by the electron cannot then be taken as the simple adiabatic phase change implicit in the EAB effect. The second point is that an EAB cycle corresponds to having one less wavelength under the gate. Since there are only 5–6 wavelengths under the gate at zero V_g, the periodic effects will be at best elusive.

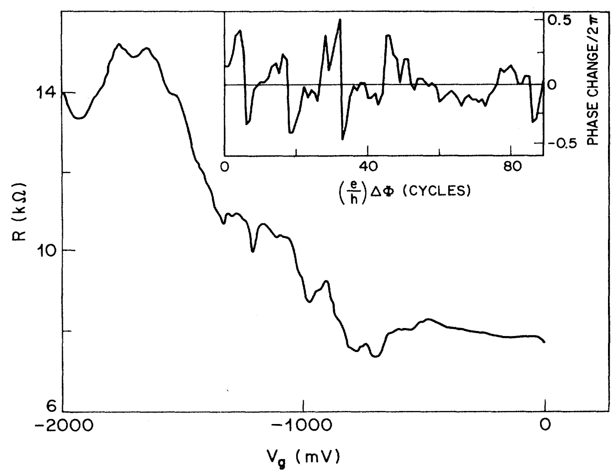

FIG. 4. Ring resistance as a function of gate voltage at zero magnetic field. Inset: The flux dependence of the phase shift of the $V_g = -1200$ mV oscillations relative to $V_g = 0$ mV over 90 cycles. The average shift is 0.008 cycles but the rms variation about this is 0.039 cycles.

In summary, we have demonstrated a tunable electron interferometer that operates by locally modifying the phase of the electron wave function. This may be viewed as arising from three physically equivalent local mechanisms: a change in density, modification of scattering, or perturbation of the Feynman trajectories under the gate. No clear signature of the EAB effect was resolved in the gated ring.

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