Experimental Observation of Persistent Currents in a GaAs-AlGaAs Single Loop

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We report measurements of the magnetic response of a GaAlAs/GaAs mesoscopic ring. We have developed a dedicated SQUID technique where sample and SQUID are on the same chip. We have detected a periodic signal, with a period h/e, which is the signature of a persistent current with an amplitude 4 ± 2 nA, in good agreement with current theories.

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Quantum interferences lead to a number of new phenomena in the transport properties of mesoscopic systems [1]. However, conservation of the phase coherence of the electron wave functions in the whole sample can also affect the equilibrium properties of the system. Büttiker, Imry, and Landauer in 1983 [2] were the first to consider a one dimensional (1D) mesoscopic ring threaded by a magnetic field. They predicted, following earlier work of Byers and Yang [3], that because of the modification of the boundary conditions by the magnetic flux, the electron wave function and then any physical property of the ring is a periodic function of the magnetic flux with a fundamental period $\phi_0=h/e$. The flux dependence of the free energy F subsequently implies the existence of a thermodynamic, and therefore persistent, current $I(\phi) = -\partial F/\partial\phi$. The sign and the amplitude of this current depend on the number of electrons in the ring. An order of magnitude is given by the contribution of the last occupied level, i.e., $I_0=ev_F/L$, where v_F is the Fermi velocity and L the perimeter of the loop. Considerable theoretical work has since been devoted to a more realistic system, namely, a disordered 3D ring [4–8]. As for other mesoscopic phenomena, the current is sample specific and the measured current, in the case of a single loop experiment, corresponds to the typical current $I_{\rm typ}=\langle I^2\rangle^{1/2}$. In the case of a perfect 3D system, i.e., without disorder, one can take into account the additional transverse dimensions by adding the contribution of each channel. The total current is then given by $I=I_0\sqrt{M}$ since the $M=A/\lambda_F^2$ channels are not correlated (A is the section of the ring and λ_F^2 the Fermi wavelength). However, this result is only valid in the ballistic case.

Disorder will couple the channels and lead to a compensation between channels, which cancels this multiplicative factor [9]. The effect of weak disorder (in the diffusive regime) is also to smooth out the $F(\phi)$ dispersion curve and to open gaps at each crossing point. Theory predicts that the current is then reduced following a power law, i.e., $I=I_0 l/L$ where l is the elastic mean free path. This result can be understood by replacing the ballistic time, $\tau=L/v_F$, required to complete one turn, in the expression of I_0, by the diffusive one, $\tau_d=L^2/D$, where $D=v_F l$ is the diffusive constant.

Finite temperatures will affect the current through two different mechanisms. The first one is to mix contributions of levels in an energy interval k_BT. This mechanism reduces the current since adjacent levels give opposite contributions to the current and an exponential decay is predicted. The energy scale at which such a mixing occurs is given not by the level spacing Δ but by the Thouless energy E_c since this is the energy scale for energy correlations. The second effect of temperature is to reduce the phase coherence length L_ϕ and if $L>L_\phi$, the current vanishes exponentially with L/L_ϕ.

The first experimental evidence of the existence of such currents has been given by Lévy *et al.*, in 1990 [10]. The authors have investigated the magnetic response of an assembly of 10^7 copper rings using standard SQUID magnetometry. In this experiment, one measures the mean current for which only the even harmonics do not average to zero [11–13]. The current they have measured is higher than the predicted one by more than an order of magnitude. In 1991, Chandrasekhar *et al.* published the first experiment on a single loop [14]. Using a high sensitivity SQUID they reported the magnetic response of a gold loop. The value they obtained is higher than the theoretical value by more than 2 orders of magnitude. In this Letter we present the first experiment on a semiconductor single loop in the GaAs/GaAlAs system. We have developed a special SQUID technique to measure the magnetization of the sample, where the sample and the SQUID are made on the same chip. In contrast with the previous measurements, the result we have obtained is in good agreement with theoretical predictions.

The GaAlAs/GaAs heterojunction is grown using molecular beam epitaxy. The structure of the epilayers is the following: 720 nm GaAs buffer layer, 24 nm undoped GaAlAs spacer layer, 48 nm Si doped GaAlAs, and 10 nm of undoped GaAs cap layer. When cooled down to liquid helium temperature in the dark the two dimensional electron gas (2DEG) at the heterointerface has an electron density of 3.6×10^{11} cm^{-2} and a mobility of 1.14×10^{6} cm^2/Vs. This yields a Fermi velocity $v_F = 2.6\times10^{5}$ m s^{-1}, a Fermi wavelength $\lambda_F = 42$ nm, and an elastic mean free path $l = 11$ μm. All the lightographic operations required to fabricate the loop and the measuring system are performed using electron beam lithography on PMMA (polymethyl methacrylate) resist with a JEOL 5DIIU electron beam writer. We first pattern a titanium mask of the loop. Then by ion milling with 250 V argon ions we etch 10 nm of the GaAs cap layer. This is sufficient to deplete the underlying 2DEG. The ring (internal diameter 2 μm and external diameter 3.4 μm) is connected to AuGeNi contacts in a conventional four-probe geometry. With a similar technique we have fabricated 80 μm long wires of different widths to characterize the sample after etching. For wires of similar width, we have measured a phase coherence length of 25 μm using weak localization theory [15] (no spin-orbit scattering is observable). The mean free path and the density measured by conductance and Shubnikov–de Haas oscillations are not significantly modified compared with the original 2DEG. These measurements give a depletion length of the order of 0.27 μm on each side due to the etching process. Therefore the real width of our loop is $W = 0.16$ μm. Two Schottky gates are then deposited, which allow, by application of negative bias, depletion of the 2DEG underneath. The first one is deposited on the two outgoing wires and makes possible the insulation of the ring from the measuring wires. The second, placed on one branch of the ring, allows the suppression of all interference effects, i.e., Aharonov-Bohm oscillations and persistent currents. A coil with the same radius as the GaAlAs/GaAs ring is also patterned next to it for SQUID calibration. Gates and calibration coil are obtained by liftoff of 20 nm thick titanium and 60 nm thick gold films. The device is then covered with a 150 nm insulating layer (AZ 1350 resist baked at 200 °C). The next step is the fabrication of the SQUID. We chose to fabricate the SQUID in a flat gradiometer configuration with two counter-wound loops to compensate the external magnetic field. The first level consists of two half loops, one on top of the GaAlAs/GaAs ring and the second on top of the calibration coil. The latter contains the two microbridge Josephson junctions [16]. Figure 1 shows the device at that point of fabrication. Then another insulating layer is spun (100 nm AZ 1350) and the circuit is closed with the two opposite half loops. The contact between the two aluminum layers is ensured by recovering them with aluminum pads deposited after an ion bombardment clean. Each layer is made of 50 nm thick aluminum.

In order to maintain sensitivity on the SQUID, we have to limit the magnetic field modulation because of the residual geometrical dissymmetry due to the finite accuracy of the lithography. In our sample, this dissymmetry is about 4% and we can sweep a magnetic field up to ±2.1 mT, corresponding to $4\phi_0$ in the ring. This flux modulation is much larger than in previous experiments with noncompensated SQUID where the limitation was due to flux jump in the superconducting aluminum film used as field coil [17]. The modulation is a triangular wave with 0.1 Hz frequency to avoid heating by eddy currents. In these conditions, the resolution of the SQUID is about $10^{-5}\phi_0/\sqrt{\text{Hz}}$. The sensitivity to the current in the ring is calibrated using the calibration coil. A complete description of the SQUID measurement technique has been given elsewhere [16].

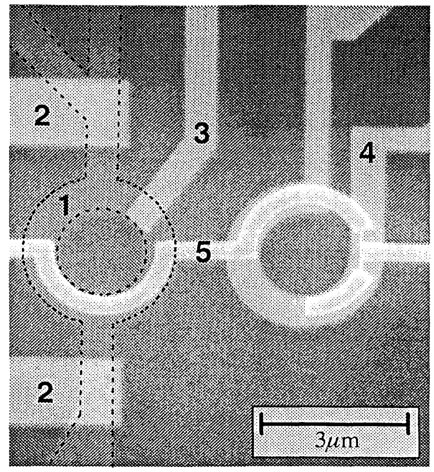

FIG. 1. Electron micrograph of the experimental device. On the left is the ring etched in GaAs 2DEG (labeled 1) (the dashed line has been added because of the poor contrast) with the two gates, (2) and (3). On the right is the calibration coil (4). On the top is the first level of the SQUID fabrication (5) with the two microbridge junctions on the right. The picture has been taken before the second level of the SQUID fabrication.

To measure the conductance of the ring, a dc current of 1.5 nA is injected. The mean resistance is about 1 kΩ. If one assumes ballistic transport this value implies six channels of conduction, each one with an e^2/h contribution to the conductance, in good agreement with the calculated channel number. The values of the voltage on the ring and magnetization are stored at the same time in an array of 256 points during each period of field modulation. These simultaneous measurements allow us to check the electronic temperature and coherence of the ring, by the observation of the Aharonov-Bohm oscillations. In particular, no perturbation due to Josephson oscillations in the SQUID, which is well coupled to the ring, was observed.

For noise cancellation, we perform periodic measurements (≈ 4 h) with the ring open or closed using the second Schottky gate (-330 mV for open ring and $+40$ mV for closed ring). The signal is then extracted by Fourier transform of the difference between a closed and an open ring, while the noise is evaluated from the difference between measurements with the ring open. Typical results for signal and noise at $T=15$ mK are depicted in Fig. 2 for the resistance signal and in Fig. 3 for the magnetic response. The separation between each point in the Fourier transform is directly related to the amplitude of the flux modulation. Our modulation of $4\phi_0$ gives a pitch of $\frac{1}{4}\phi_0$ for the horizontal scale. The vertical scale is the square root of the spectrum power and is directly expressed in ohms in Fig. 2 and in nA in Fig. 3.

The resistance signal (Fig. 2) clearly shows the Aharonov-Bohm oscillations with the period h/e and its first harmonic $(h/2e)$. The extension of the signal of one point around the h/e and $h/2e$ values is due to the aspect ratio of the ring [1]. This measurement allows us to control the amplitude of the modulation. In most of our data we have observed an h/e frequency component on the magnetization signal, whereas such a component is never present in the noise spectrum (Fig. 3). The randomness of the persistent current explains why we do not observe the h/e signal on all measurements. However, the absence of the h/e component in the noise is a clear indication of the mesoscopic nature of this signal. Averaging our different measurements and subtracting the noise, we find a typical current amplitude of 4 ± 2 nA, comparable to the value $I_0=ev_F/L=5$ nA computed using our experimental parameters.

The increase of signal at the origin of the spectrum is the signature of the aperiodic fluctuations for the Aharonov-Bohm signal [1] (which are not suppressed by the opening of the ring) whereas for the magnetization signal it is probably due to low frequency fluctuations of the SQUID response. It is important to note that the mesoscopic state of the ring is not completely stable. We observe random modifications of the Aharonov-Bohm oscillations on a time scale of 10 to 40 h. These fluctuations are attributed to some slow relaxation process of the impurities in the semiconductor, inducing changes in the scattering potential or in the Fermi level [18]. As persistent currents are sample specific, this effect prevents data accumulation over a long period without averaging to zero. Indeed we obtain a larger signal when averaging only the magnetization data recorded when the Aharonov-Bohm signal is stable. The randomness of the sign of the current has also been observed during these microscopic configuration changes. However, the sensitivity is not high enough for testing the signal averaging with these microscopic changes. In particular, we are not able to observe the $h/2e$ oscillations. Preliminary measurements performed with the ring completely isolated with the help of the first gate yield a similar result for the magnitude of the typical current.

In our sample, the disorder is very weak: $l/L\approx1.3$ and the typical value of persistent current must be close to the value for a perfect system: $I_0=ev_F/L$. The second correction comes from the finite number of channels. The channel number $M=W/\lambda_F$ is very low in our sample: $M\approx4$. Therefore the maximum correction expected is $\sqrt{M}=2$ and the predicted current should be in the range 5 to 10 nA. The difference with experimental value (4 nA) is not significant since we are dealing with typical values.

In the GaAlAs/GaAs system, the carrier density is very low and therefore the electron-electron interaction is more important than in metals [19]. The possibility that this interaction can increase the persistent current by 1 or 2 orders of magnitude has been proposed to explain the previous experiments [20,21]. This is ruled out by our result, which shows that electron-electron interactions do not significantly change the value of the persistent current. All previous experiments were performed on metallic systems with large disorder, $l/L\approx10^{-3}$, and large number of channels, $M\approx10^4$. Comparison between all

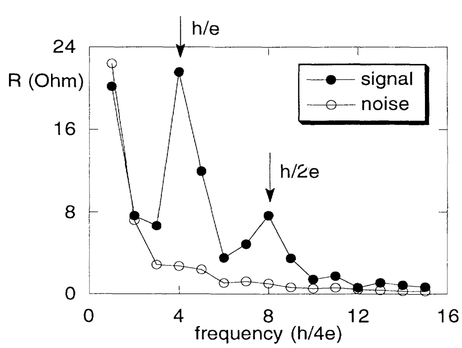

FIG. 2. Square root of spectrum power of the resistance fluctuations of the ring (mean resistance ≈ 1 kΩ). Open circles correspond to experimental noise, i.e., differences between measurements with ring open. Solid circles correspond to experimental signal, i.e., differences between measurements with ring closed and ring open. The two arrows indicate the position of period h/e and $h/2e$.

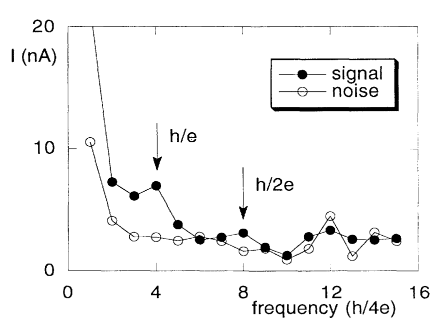

FIG. 3. Square root of spectrum power of magnetization of the ring. The values are converted into the equivalent current in the ring using the calibration coil. Open circles correspond to experimental noise, i.e., differences between measurements with ring open. Solid circles correspond to experimental signal, i.e., differences between measurements with ring closed and ring open. The two arrows indicate the position of period h/e and $h/2e$.

experiments strongly suggests that disorder and/or channel number are not correctly taken into account in the theories.

In conclusion, we have used a single chip experimental setup to measure persistent currents in a GaAlAs/GaAs system. Our result shows that, in contrast with previous experiments, the measured persistent current corresponds to the theoretical predictions in the case where the disorder is very weak and the channel number is small. Our original experimental method, which enables us to suppress *in situ* interference effects by opening the ring, gives us confidence with this result.

More detailed measurements are needed for the understanding of the effect of disorder, geometrical dimensions, temperature, and averaging processes. Improvement of our SQUID performance with a better compensation and the addition of shunting resistors to the Josephson junctions should allow such measurements.

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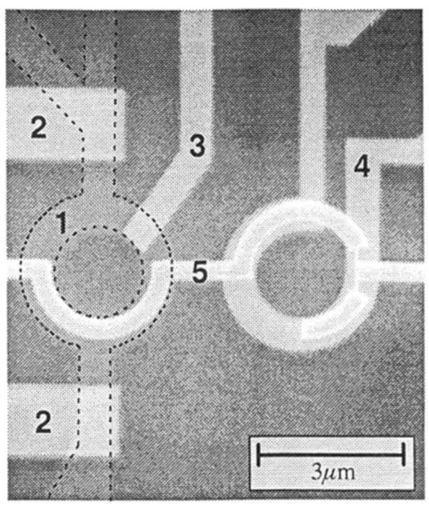

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