Strong Aharonov-Bohm oscillations in GaAs two-dimensional holes

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We measured Aharonov-Bohm resistance oscillations in a shallow two-dimensional GaAs hole ring structure, defined by local anodic surface oxidation. The amplitude of the oscillations is about 10% of the ring resistance, the strongest seen in a hole system. In addition we observe resistance oscillations as a function of front gate bias at zero magnetic field. We discuss the results in light of spin interference in the ring and possible applications to spintronics.

The Aharonov-Bohm (AB) effect and related phenomenon in mesoscopic semiconductor structures have attracted much attention over the last years. The AB effect reflects the fact that when magnetic flux pierces through a ring structure, a phase difference develops between the electron wavefunctions traveling in the ring’s two arms. This phase difference is $2\pi (\Phi/\Phi_0)$, where $\Phi = \pi r^2 B$ is the magnetic flux through the ring, $r$ is the ring radius, $B$ is the applied magnetic field in the perpendicular direction, and $\Phi_0 = h/e$ is the flux quantum. Hence the resistance of the ring exhibits oscillations periodic in $B$ with a period equal to $\pi r^2/(h/e)$.

In semiconductors, the AB effect has been seen in rings made from two-dimensional (2D) electron systems in various materials but has been difficult to observe in 2D hole systems (2DHSs). Recently, AB oscillations with an amplitude of about 0.1% (of the total ring resistance) were observed by Yau et al. in a 500 nm radius ring structure patterned via electron-beam lithography in GaAs 2D holes. In the present work we aimed to increase the amplitude of the AB oscillations in this system by fabricating smaller rings. For this purpose we employed the local anodic oxidation (LAO) technique using an atomic force microscope (AFM). Here we present our measurements of AB oscillations in a GaAs 2D hole sample with $r \approx 160 \text{ nm}$. The observed AB oscillation amplitude is about 100 times larger than in Ref. 3. A further motivation for our experiments is the fact that the 2DHS in GaAs exhibits strong spin-orbit interaction which is tunable with gate bias. Nitta et al. highlighted that the resistance in a ring structure in such a system can be modulated by changing the gate bias even at $B = 0$ and proposed it as a spin interference device. In our ring structure, we do indeed observe oscillations as a function of gate bias at $B = 0$; however, the origin of these oscillations is unclear.

Our sample was grown on a GaAs (311)A substrate by molecular beam epitaxy and contains a modulation-doped 2DHS confined to a GaAs/Al$_{0.3}$Ga$_{0.7}$As interface. The interface is separated from an 11 nm-thick Si-doped Al$_{0.3}$Ga$_{0.7}$As layer (Si concentration of $1.64 \times 10^{19}$ cm$^{-3}$) by a 15 nm Al$_{0.3}$Ga$_{0.7}$As spacer layer. A 5 nm GaAs layer caps the structure resulting in the 2D hole layer residing $\approx 31 \text{ nm}$ below the surface. We fabricated Hall bar samples via optical lithography and used alloyed In/Zn for the ohmic contacts. Metal gates were deposited on the sample’s front and back to control the 2D hole density ($p$). Before patterning the surface using an AFM and depositing the gates, we characterized the 2DHS at $T \approx 300 \text{ mK}$ and determined its mobility to be $1 \times 10^5 \text{ cm}^2/\text{Vs}$ in the [011] direction at $p = 2.8 \times 10^{11} \text{ cm}^{-2}$. The resistance measurements through the ring were made at $T \approx 30 \text{ mK}$ in a dilution refrigerator with standard low frequency lock-in technique.

We fabricated the ring structure via the LAO technique using an AFM. A shallow 2D electron gas confined to a GaAs/AlGaAs heterostructure is depleted when the surface of the sample is oxidized using a negative bias on an AFM tip. The extent of the depletion depends critically on the depth of the 2D gas and hence the need to grow very shallow 2D samples as described above. Recently, this technique was used to pattern mesoscopic structures in GaAs 2DHSs. Similar to these techniques, in order to deplete the carriers in our structures, we used a tip voltage of $-27.5 \text{ V}$, a humidity level of $\approx 50\%$ and a scanning speed of 0.05 $\mu \text{m/s}$.

An AFM micrograph of one of our ring structures is shown in Fig. 1(a). The light areas indicate the oxide grown with the LAO technique. The drawn inner radius of the ring used for the measurements is 100 nm [Fig. 1(b)]. With the oxidation parameters stated above, we expect an oxide height of 10-12 nm. The lower graph in Fig. 1(b) shows the height profile along the dashed line in the top picture and indicates a well-formed, 10 nm-high profile. In order to demonstrate that the oxide lines do indeed deplete the 2D gas underneath, we applied voltage ($V$) across one side of such a line and measured the current leaking through the barrier. There is negligible leakage for $-0.5 \lesssim V \lesssim 0.3 \text{ V}$ [Fig. 1(c)].

Figures 2(a) and (b) show the measured ring resistance as a function of $B$ and the change in resistance after subtracting a fourth order polynomial. The amplitude depends on the front ($V_F$) and back ($V_B$) gate voltages, and the largest we have seen is $\approx 10\%$ (at $V_F = -5 \text{ mV}$, $V_B = -143 \text{ V}$). In fact, the resistance oscillations are very sensitive to the gate biases and for a particular $V_B$, are only observed within a 2-3 mV range of $V_F$. However, within this range the oscillations are very robust and reproducible. The Fourier transform spectrum of one of the traces, obtained by zero padding the data and Hamming window, is shown in Fig. 2(c). The strong peak at $19.3 \text{ T}^{-1}$ is observed in the Fourier transforms of all the
traces and corresponds to $r = 160$ nm which agrees with the drawn dimensions of the ring [see dashed circle in Fig. 1(b)]. The origin of the other peaks is less clear; the two side peaks at 13.3 T$^{-1}$ and 24.8 T$^{-1}$ may be related to spin-orbit coupling in the system of HgTe [3, 12]. However, in our case, the number of oscillations in the range of ±0.2 T is small and it is difficult to draw definitive conclusions.

We now discuss resistance oscillations in a ring device as a function of $V_F$ at $B = 0$. In a symmetric ring with spin-orbit coupling, even in the absence of $B$, the carrier wavefunction acquires a phase difference when traversing the two arms of the ring [6]. This results in a constructive or destructive interference at the other end of the ring. The phase difference is proportional to $r\Delta k_d$, where $k_d$ is the difference of the Fermi wavevectors ($k_{\pm}$) of the two spin-subbands which are split because of the spin-orbit interaction. If we assume isotropic Fermi contours, then $k_{\pm} = \sqrt{4\pi p_{\pm}}$, where $p_{\pm}$ are the densities of the two spin-subbands. In 2D systems with spin-orbit coupling, $k_d$ can be changed by tuning the electric field via front and back gate biases [6, 13]. Using this fact, Nitta et al. [6] showed that the ring resistance should oscillate as a function of the gate bias with the period given by the condition $r\Delta k_d \approx 1$, where $\Delta k_d$ is the change in $k_d$ with the gate bias [14]. A ring structure in these systems can hence be used as a spin interference device.

Figure 3 shows the resistance of our ring measured as a function of $V_F$ at different $V_B$. The traces indeed exhibit oscillations which are approximately periodic (e.g., with a period $\approx 7$ mV for $V_B = -146$ V). These oscillations were very robust over many cool-downs of the sample.

A quantitative understanding of Fig. 3 data, however, poses a problem. In order to check whether $r\Delta k_d \approx 1$ for an oscillation period in $R_{xx}$ vs $V_F$, we measured Shubnikov-de Haas (SdH) oscillations in an unpatterned region of the sample for different $V_F$. From the Fourier spectra of the SdH oscillations, we deduce $\Delta k_d$ (Fig. 3 inset) [3]. Based on this data, we expect $r\Delta k_d \approx 6 \times 10^5$ m$^{-1}$ for a 7 mV change in $V_F$. For $r = 160$ nm, this gives $r\Delta k_d = 0.1 \lessgtr 1$. We would like to point out that in similar experiments, König et al. [15] measured the ring resistance as a function of $V_F$ in a HgTe/HgCdTe quantum well sample and they too, find a very small value of $r\Delta k_d \approx 0.08$ for a full oscillation of ring resistance. It should be noted that electrons in the conduction band of HgTe are a spin-3/2 system, similar to holes in GaAs. The spin orientation and spin precession of a spin-3/2 system are quite subtle [16] and it is possible that it is this complexity that leads to the anomalous oscillations.

In the discussion above we have ignored two aspects of the ring device. First, the device is initially pinched off and a negative $V_F$ has to be applied to populate the ring with holes. This implies that the 2D hole density in the ring is much smaller than in the unpatterned region. Second, it is apparent in Fig. 1(b) that the ring structure is asymmetric. This asymmetry could also lead to resistance oscillations at $B = 0$ [17]. The resistance modulation would then be a consequence of the difference in the wavevectors in the right and left arms of the ring, $k_{rl}$. If we assume an initial density in the range of $1 \times 10^9$ cm$^{-2}$ to $1 \times 10^{10}$ cm$^{-2}$ in the right arm and 5 times this density range in the left arm, a plausible assumption given that the right arm is more pinched than the left arm, we find $r\Delta k_{rl} \approx 0.7$, where $\Delta k_{rl}$ is the change in $k_{rl}$ with $V_F$. Hence, low density and asymmetry in the ring could possibly explain the oscillations observed in our ring structure as a function of $V_F$ [18]. Note that this conjecture implies that the holes’ phase coherence is maintained in the drawn dimensions of the ring [see dashed circle in Fig. 1(b)]. The origin of the other peaks is less clear; the two side peaks at 13.3 T$^{-1}$ and 24.8 T$^{-1}$ may be related to spin-orbit coupling in the system of HgTe [3, 12]. However, in our case, the number of oscillations in the range of ±0.2 T is small and it is difficult to draw definitive conclusions.

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FIG. 2: (Color on-line) (a) Measured AB oscillations in the ring structure. The top four traces were measured at $V_B = -140$ V and at $V_F = -12, -13, -14$ and -15 mV respectively, starting from the top. The lowest trace was measured at $V_B = -143$ V and $V_F = -5$ mV. The fourth trace from the top is shifted down by $\sim 1$ kΩ for clarity. (b) Same data as in (a) for bottom four traces after subtracting the background resistance; traces are shifted vertically for clarity. (c) The Fourier transform spectrum of the measured oscillations, in the range ±0.2 T, at $V_B = -140$ V, $V_F = -13$ mV. The peak at 19.3 T$^{-1}$ corresponds to a ring radius of 160 nm, consistent with the geometry of the ring (see Fig. 1(b)).

FIG. 3: (Color on-line) Ring resistance measured at zero magnetic field, as a function of $V_F$ for $V_B = -140, -143, -146,$ and -149 V (from top to bottom). The grey boxes indicate the values of $V_F$ at which AB oscillations are observed. No AB oscillations were observed for $V_B = -149$ V. Inset: The change in $k_d$ as a function of $V_F$ in the unpatterned region.

In conclusion, we measured AB oscillations in GaAs 2D holes in a ring structure fabricated via the LAO technique. The observed oscillations have the highest amplitude seen in this system and are about 100 times larger than previously measured in rings fabricated via electron-beam lithography. We also observe oscillations with front gate bias whose origin remains a puzzle.

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