Aharonov-Bohm oscillations in p-type GaAs quantum rings

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We have explored phase coherent transport of holes in two p-type GaAs quantum rings with orbital radii 420 nm and 160 nm fabricated with AFM oxidation lithography. Highly visible Aharonov-Bohm (AB) oscillations are measured in both rings, with an amplitude of the oscillations exceeding 10% of the total resistance in the case of the ring with a radius of 160 nm. Beside the h/e oscillations, we resolve the contributions from higher harmonics of the AB oscillations. The observation of a local resistance minimum at B=0 T in both rings is a signature of the destructive interference of the holes’ spins. We show that this minimum is related to the minimum in the h/2e oscillations.

The Aharonov-Bohm (AB) phase [1], represents the geometric phase acquired by the orbital wave function of the charged particle encircling a magnetic flux line. This phase is experimentally well established and manifests itself through oscillations in the resistance of mesoscopic rings as a function of an external magnetic field. The spin part of the particle’s wave-function can acquire an additional geometric phase in the systems with strong spin-orbit (SO) interactions [2, 3]. The SO induced phase additionally modulates the resistance oscillations in mesoscopic rings. This SO induced phase in solid-state systems has been recently the subject of a number of experimental investigations [4, 5, 6, 7, 8, 9, 10].

SO interactions are particularly strong in p-type GaAs heterostructures, due to the p-like symmetry of the states at the top of the valence band and the high effective mass of holes. The presence of exceptionally strong SO interactions in carbon doped GaAs heterostructure used for fabrication of rings investigated in this work, is demonstrated by the simultaneous observation of the beating in Shubnikov-de Haas (SdH) oscillations and weak anti-localization in the measured magnetoresistance. The hole density in an unpatterned sample is 3.8 × 10^{11} cm^{-2} and the mobility is 200 000 cm^{2}/Vs at a temperature of 60 mK. The strength of the Rashba spin-orbit interaction is estimated to be ∆_{SO} ≈ 0.8 meV, while the Fermi energy in the system is \(E_F = 2.5\) meV.

Here we study AB oscillations in two quantum rings with radii 420 nm and 160 nm realized in this 2DHG with strong SO interactions. In contrast to previous experiments on p-type GaAs rings, where the signature of the phase acquired by the hole’s spin was attributed to the splitting of the h/e peak in the Fourier spectrum [4, 5], we have recently reported the direct observation of beating in the measured resistance of the quantum ring with an orbital radius of 420 nm [10]. An example of the observed beating in the gate configuration \(V_{pg1} = -172\) mV and \(V_{pg2} = -188\) mV of the large ring is shown in Fig. 1(a), while the corresponding splitting of the h/e Fourier peak is shown in Fig. 1(c). In addition, we observe a resistance minimum at \(B = 0\) T in all gate configurations, and attribute its origin to the destructive interference of the hole spins propagating along time reversed paths [10].

We now focus on the magnetotransport measurements performed on the smaller ring with an orbital radius of 160 nm (Fig. 2(a)). Fig. 2(b) shows the magnetoresistance of the small ring (oscillating curve, blue online), together with a low-frequency background resistance composed of the low frequency Fourier components of the signal (smooth curve, red online) in the plunger gate configuration \(V_{pg1} = -78.5\) mV, \(V_{pg2} = -222\) mV. AB oscillations, obtained after subtraction of the low-frequency background from the raw data, with a peak-to-peak amplitude of \(\sim 4\) kΩ are clearly resolved (Fig. 2(c)). Therefore the visibility of the AB oscillations is larger than 10%. The Fourier transform of these oscillations reveals a split h/e peak, with side peaks at 12 T^{-1} and 17 T^{-1}. Besides, h/2e and h/3e peaks are clearly visible (Fig. 2(d)). The electronic radius of the holes’ orbit of 150 nm, obtained from the period of the oscillations of around 60 mT, agrees well with a lithographic mean radius of the
holes’ orbit.

Due to the large period of the AB oscillations, only up to 10 oscillations are present in the magnetic field range (-0.3 T, +0.3 T) where SdH oscillations do not obscure the data analysis and no beating can be seen in the raw data. Therefore, although the amplitude of the AB oscillations in the case of the small ring is quite large, a detailed analysis of the beating of the AB oscillations can not be performed for this sample as it was done in the case of the larger ring [10].

We further analyze the dependence of the AB oscillations on plunger gates voltages. The evolution of the AB oscillations along the line \( V_{pg1} = 0.5 \cdot V_{pg2} - 20 \text{mV} \) in parameter space \( (V_{pg1}, V_{pg2}) \) is investigated in Fig. 3. Fig. 3(a) shows the raw data, while Fig. 3(b) and 3(c) show filtered h/e and h/2e oscillations, respectively. When \( V_{pg1} \) and \( V_{pg2} \) increase along the given line, both ring arms become narrower and the holes’ orbit inside the ring shrinks, causing the resistance of the ring to increase continuously from 20 – 50 kΩ.

We again observe a resistance minimum at \( B = 0 \text{T} \) in all gate configurations (Fig. 3(a)) and find that it is related to the minimum in the h/2e oscillations at \( B = 0 \text{T} \) (Fig. 3(c)), consistent with the results from the large ring sample [10, 11]. It should be emphasized that the observed minimum is not caused by weak-antilocalization in the ring leads, since the weak-antilocalization dip in bulk two-dimensional samples has a much smaller magnitude (less than 1Ω) than the minimum at \( B = 0 \text{T} \) in the rings [11]. The resistance minimum at \( B = 0 \text{T} \) is a result of the destructive interference of the holes’ spins in the ring.

The presence of phase jumps in the h/e oscillations (Fig. 3(b)) and their absence in the h/2e oscillations (Fig. 3(c)) is also observed. The fact that the phase of the AB oscillations can not change continuously, but only in discrete steps of \( \pi \) is a consequence of the Onsager relations \( G_{ij}(B) = G_{ji}(-B) \). For changes of the plunger gates along the line \( V_{pg1} = 0.5 \cdot V_{pg2} - 20 \text{mV} \) we indeed observe phase jumps of \( \pi \) in h/e oscillations at lower magnetic fields up to 0.2 T, but at the higher fields, above 0.2T, we find continuous monotonic shifts of the AB minima and maxima (Fig. 3(a) and 3(b)). We attribute these continuous shifts of the AB minima and maxima towards higher fields upon increasing plunger gate voltages \( V_{pg1} \) and \( V_{pg2} \) to an increase of the AB oscillation frequency upon continuous shrinking of the holes’ orbit within the ring. Continuous, but non-monotonic top-gate induced shifts of the AB minima and maxima were recently observed in HgTe quantum rings [7], and this behavior is interpreted as a manifestation of the Aharonov-Casher phase.

In conclusion, we have measured highly visible
Aharonov-Bohm oscillations in two quantum rings with radii 420 nm and 160 nm fabricated by AFM oxidation lithography on p-type GaAs heterostructure with strong spin-orbit interaction. The visibility of the AB oscillations exceeds 3% in the larger ring and 10% in the smaller ring. Beside the h/e oscillations, the higher harmonics of the AB oscillations are resolved in both rings. A resistance minimum at $B = 0$T, present in both rings, points to the signature of destructive interference of the holes’ spins propagating along time-reversed paths.

[1] Y. Aharonov and D. Bohm, Phys. Rev. 115, 485 (1959).
[2] H.A. Engel and D. Loss, Phys. Rev. B 62, 10238 (2000).
[3] A.G. Aronov and Y.B Lyanda-Geller, Phys. Rev. Lett. 70, 343 (1993).
[4] A. F. Morpurgo, J. P. Heida, T. M. Klapwijk, B. J. van Wees, and G. Borghs, Phys. Rev. Lett. 80, 1050 (1998).
[5] J.B. Yau, E.P. De Poortere and M. Shayegan, Phys. Rev. Lett. 88, 146801 (2002).
[6] M.J. Yang, C.H. Yang, Y.B. Lyanda-Geller, Europhys. Lett. 66, 826 (2004).
[7] M. König et al., Phys. Rev. Lett. 96, 076804 (2006)
[8] T. Bergsten, T. Kobayashi, Y. Sekine, and J. Nitta, Phys. Rev. Lett. 97, 196803 (2006)
[9] B. Habib, E. Tutuc, and M. Shayegan Appl. Phys. Lett. 90, 152104 (2007)
[10] B. Grbić, R. Leturcq, T. Ihn, K. Ensslin, D. Reuter, and A.D. Wieck Phys. Rev. Lett. 99, 176803 (2007)
[11] B. Grbić, PhD thesis No. 17248, ETH Zurich (2007).