Observation of quantum asymmetry in an Aharonov-Bohm ring

S. Pedersen, A. E. Hansen, A. Kristensen, C. B. Sørensen, and P. E. Lindelof
The Niels Bohr Institute, University of Copenhagen, Universitetsparken 5, DK-2100 Copenhagen, Denmark
(Received 12 April 1999)

We have investigated the Aharonov-Bohm effect in a one-dimensional GaAs/Ga0.7Al0.3As ring at low-magnetic fields. The oscillatory magnetoconductance of these systems is systematically studied as a function of density. We observe phase shifts of $\pi$ in the magnetoconductance oscillations, and halving of the fundamental $h/e$ period, as the density is varied. Theoretically we find agreement with the experiment, by introducing an asymmetry between the two arms of the ring.

I. INTRODUCTION

The Aharonov-Bohm effect, first proposed in 1959, was experimentally realized in a normal metal cylinder in 1982 as an oscillatory magnetoresistance with period $h/2e$ (Ref. 2), a periodicity originating from the interference between an electron path and its time-reversed path.3 The fundamental $h/e$ period was later observed in normal metal loops4 and soon after in mesoscopic semiconductor loops.5 The Aharonov-Bohm effect quickly became a very fruitful research area in experimental mesoscopic semiconductor physics.6–8 All these early investigations, except one,9 however focus their attention on the Aharonov-Bohm effect at relatively high-magnetic fields ($\omega, \tau \sim 1$). From a theoretical point of view the behavior of these high-field investigations has been treated in Refs. 10 and 11.

Recently, due to the perfection of device fabrication, the Aharonov-Bohm effect has gained renewed interest. Aharonov-Bohm rings are now used to perform phase sensitive measurement on, e.g., quantum dots.12 Theoretically this experiment has attracted much interest13,14—see also references therein. Also experiments where a local gate only affects the properties in one of the branches of the Aharonov-Bohm device have been performed.15 Both these reports use the idea, that by locally changing the properties of one of the arms of the ring, and studying the Aharonov-Bohm effect as a function of this perturbation, information about the changes in the phase can be extracted from the measurements. Furthermore, a realization of the electronic double-slit interference experiment presented surprising results,16 which has recently been considered from a theoretical point of view.17 Especially the observation of a period halving from $h/e$ to $h/2e$ and phase shifts of $\pi$ has attracted large interest in these reports.

All these investigations, are as in contrast to the prior ones, performed at relative low magnetic fields and the perturbation enforced on the ring is regarded as local. Furthermore, they are all performed in the multimode regime. Hence, we find it of importance to study the Aharonov-Bohm effect in the single-mode regime at low-magnetic fields and as a function of a global perturbation.

II. EXPERIMENT

Our starting point in the fabrication of the Aharonov-Bohm structures is a standard two-dimensional electron gas (2DEG) realized in a GaAs/Ga0.7Al0.3As heterostructure. The two-dimensional electron density is $n = 2.0 \times 10^{15}$ m$^{-2}$ and the mobility of the heterostructure is $\mu = 90$ T$^{-1}$. This corresponds to a mean free path of approximately 6 $\mu$m. The 2DEG is made by conventional molecular-beam epitaxy and is situated 90 nm below the surface of the wafer. For further details regarding the heterostructure, contacts, etc., we refer to Ref. 18.

Using standard e-beam lithography (EBL) a 100-nm-thick PMMA etch mask is defined on the surface of the heterostructure. The pattern written in the PMMA was transferred to the 2DEG by a 50-nm shallow wet etch in H$_3$PO$_4$:H$_2$O$_2$:H$_2$O. The dimensions of the etched Aharonov-Bohm structure is given by a ring radius $r = 0.65$ $\mu$m and a width of the arms $w = 200$ nm as can be seen on Fig. 1. In a second EBL step we define a PMMA lift-off mask for a 50-nm-thick and 30-$\mu$m-wide gold gate, which covers the entire Aharonov-Bohm ring. This allows us to globally control the electron density in the Aharonov-Bohm ring during the measurements. Due to depletion from the edges, the structure is initially pinched off. By applying a positive voltage $V_g$ on the global gate, electrons are accumulated in the structure and the structure begins to conduct.

The sample was emerged in a 3He cryostat equipped with a copper electromagnet. All measurements were performed at $T = 0.3$ K if nothing else is mentioned. The measurements were done by conventional voltage biased lock-in techniques with an excitation voltage of $V_{pp} = 7.7$ $\mu$V at a frequency of 131Hz. In this paper, we focus on measurements performed on one device, almost identical results have been obtained with another device in a total of six different cool downs.

III. RESULTS AND DISCUSSION

Figure 1 presents a measurement of the magnetoconductance of the device displayed in the left insert. As expected the magnetoconductance show large Aharonov-Bohm oscillations. Due to the long distance between the voltage probes, the measurement is an effective two-terminal measurement; hence the Aharonov-Bohm magnetoconductance is as observed forced to be symmetrical as a consequence of the Onsager relations.

A Fourier transform of the magnetoconductance displays a large peak corresponding to a period of 33 Gs. This is in full agreement with the dimensions of the ring obtained from the scanning electron microscopy (SEM) picture.
The right inset in Fig. 1 displays the conductance as function of gate voltage at $T=4.2$ K. Steps are observed at approximate integer values of $e^2/h$. Five steps are seen as the voltage is increased with 0.18 V from pinch-off. Such steps have previously been reported in Aharonov-Bohm rings and can be interpreted using classical addition of conductance, which is reasonable at these relatively high temperatures.

In any case, this indicates that our system, in the gate-voltage regime used here, only has a few propagating modes. When the temperature is lowered a fluctuating signal is superposed on the conductance curve. At $T=0.3$ K the steps becomes completely washed out by these fluctuations. The fluctuations, which we ascribe to resonance’s, appear at the same temperatures where the Aharonov-Bohm magnetoconductance oscillations become visible and are the signature of a phase coherent device.

Figure 2 shows two contour plots; the left one displays the measured conductance $G(\Phi, V_g) - G(0, V_g)$ as a function of gate voltage and magnetic flux through the ring. The fluctuating zero-magnetic field conductance $G(0, V_g)$ has been subtracted from the measured conductance to enhance the contours of the Aharonov-Bohm oscillations. This figure clearly displays the Aharonov-Bohm oscillations as a periodic pattern in the horizontal direction. In the vertical direction the gate voltage is changed between 0.43 and 0.50 V. The studied systems begins to conduct at 0.33 V. The data clearly shows that, by changing the gate voltage, that is changing the density, it is possible to change the sign of the magnetoconductance—or stated differently, change the phase of the Aharonov-Bohm signal by $\pi$. This is quite surprising since a negative magnetoconductance is always expected in a symmetrical Aharonov-Bohm structure. However in the case of an asymmetrical structure this is no longer the case. In order to compare our measurements with theory, we need to estimate the electron density $n$ in the device. From a simple capacitor based estimate a voltage of 0.5 V corresponds to a electron density of $n = \epsilon(0.50 \text{ V} - 0.33 \text{ V})/ae = 1.36 \times 10^{15} \text{ m}^{-2}$. Here, $a = 90 \text{ nm}$ is the distance from the wafer surface to the 2DEG. At high magnetic fields, we observe the so called camel-back structure. An analysis of this structure yields a density of $n = 0.95 \times 10^{15} \text{ m}^{-2}$ at the gate voltage $V_g = 0.50 \text{ V}$. We, therefore,
estimate the electron density at 0.50 V to be $1 \times 10^{15} \text{ m}^{-2}$ and to be zero at 0.33 V. The characteristic dimensionless number $k_fL$ is found to be approximately 160 at $V_g = 0.50 \text{ V}$, where $L$ is half the circumference of the ring and $k_f = \sqrt{2}\pi n$ is the Fermi wave vector.

As a first-order approximation we use a linear relation between the Fermi wave vector and the gate voltage,

$$k_fL = 160 \frac{V_g - 0.33V}{0.50V - 0.33V}.$$  

(1)

In the case of asymmetrical structures the conductance is given by$^{22}$

$$g(\theta, \phi) = \frac{2\epsilon}{\cos^2 \theta + (1 - \epsilon)\cos 2\phi}.$$  

(3)

where $a_\perp = (1/2)(\sqrt{1 - 2\epsilon} \pm 1)$.

The right part of Fig. 2 shows a plot of Eq. (2), where the value of the phase due to asymmetry is set to vary as $\delta = 0.15 \times k_fL$ and the coupling parameter $\epsilon$ is set to 1/2. The scale on the $k_fL$ axis is determined by using Eq. (1), hence when the voltage is changed between 0.50 and 0.43 V the value of $k_fL$ changes between 160 and 94. It is seen in Fig. 2 that even though a perfect fit is not possible, it is indeed possible to reproduce the general features of the measurement by the theoretical expression (2). Figure 3 shows traces taken from the contour plots of Fig. 2. The figure on the left shows nine equidistantly spaced measurements ($\Delta V_g = 2.2 \text{ mV}$). According to Eq. (1) this corresponds to a equidistant spacing of 2.0 in units of $k_fL$. On the figure to the right, nine successive theoretical magnetoconductance curves are presented, the distance in $k_fL$ is also 2.0. The amplitude of all nine curves has been scaled by a factor of 0.1. Such a decrease of the Aharonov-Bohm amplitude could be explained by the fact, that the experiments were performed at finite temperatures and hence the phase coherence length is limited. Furthermore, it is known that in case of a multiple-mode system the amplitude of the Aharonov-Bohm signal is diminished.$^{22}$ Both these effects are in favor of a reduction of the amplitude of the oscillations. From the comparison of the theoretical expression and the measured magnetoconductance curves it is seen, that with the assumption of a linear relation between gate voltage and $k_f$ [see Eq. (1)], a direct comparison between single traces is possible in a limited voltage regime. With such a simple assumption, it is however not possible to describe the measurements in the whole gate voltage range from $V_g = 0.43 \text{ V}$ to $V_g = 0.50 \text{ V}$. One should also note, that when changing $V_g$ with 0.07 V new sublevels will get populated, as can be seen on the insert of Fig. 1. However, the period halving, and the changes of $\pi$ in the phase of the Aharonov-Bohm signal are observed for both theory and experiment.

IV. CONCLUSION

We have measured the Aharonov-Bohm effect in a one-dimensional GaAs/Ga$_{0.7}$Al$_{0.3}$As ring. The effect was studied as a function of the electron density in the ring. We find that the standard theoretical expressions for a symmetrical ring are not applicable. To reproduce the essential features of the measurements, i.e., the phase shifts and period halving, it is necessary to introduce a build-in asymmetry in the ring - i.e., different average densities or path lengths of the two arms in the ring.

The results presented above demonstrate the influence of asymmetry in an Aharonov-Bohm ring, and it gives insight to the recent observations of phase shifts and period halving in other related systems.
ACKNOWLEDGMENTS

We wish to thank Dr. David Cobden and Dr. Per Hede-gård for very useful discussions. This work was financially supported by Velux Fonden, Ib Henriksen Foundation, Novo Nordisk Foundation, The Danish Research Council (Grants Nos. 9502937, 9601677, and 9800243) and the Danish Technical Research Council (Grant No. 9701490).

19 The total conductance of a loop consisting of two ports and two ring arms, which are attributed with a conductance of $2e^2/h$ each, is given by $G = \frac{i}{2}e^2/h = e^2/h$ when classical addition of conductances is valid.