ELSEVIER

Physica E 12 (2002) 774–777

PHYSICA E

www.elsevier.com/locate/physe

Aharonov–Bohm oscillations for charge transport through two parallel quantum dots

A.W. Holleitner[a,*], H. Qin[a], R.H. Blick[a], K. Eberl[b], J.P. Kotthaus[a]

[a] *Center for NanoScience and Sektion Physik, Ludwig-Maximilians-Universität, Geschwister-Scholl-Platz 1, 80539 München, Germany*

[b] *Max-Planck-Institut für Festkörperforschung, Heisenbergstr. 1, 70569 Stuttgart, Germany*

Abstract

We observe Aharonov–Bohm oscillations in an interferometer containing one quantum dot in each arm. The two quantum dots are laterally defined in a two-dimensional electron gas and are both brought to the few electron limit. By the results we verify that at least part of the charge transport is coherent in such a mesosopic system. © 2002 Elsevier Science B.V. All rights reserved.

PACS: 73.63.K; 72.15.R; 03.65.−w

Keywords: Quantum dots; Aharonov–Bohm interferometer

As proposed in 1959, the Aharonov–Bohm (AB) effect allows to probe the wave nature of electrons [1]. Two conducting arms enclose an area which is penetrated by a magnetic flux. An electron in the upper arm acquires an additional phase due to the vector potential **A** in comparison with the electron in the lower arm. If the magnetic field is varied, the conductance of the whole mesoscopic system will be modulated with a periodicity of $\Phi_0 = h/e$ which yields to the AB-oscillations. In solids, these were observed in metallic loops [2], and later on in semiconductor heterojunctions [3]. The appearance of AB-oscillations in an experiment, where a single quantum dot was integrated into one of the arms demonstrated that charge transport through the quantum dot is coherent [4].

In this work we show measurements of AB-oscillations for the case of one ultra small quantum dot incorporated in each interferometer arm, respectively. The two quantum dots are laterally defined within a two-dimensional electron gas (2DEG) where the conductance is measured in a two-terminal manner. The presented results are obtained in the case that both dots are only weakly coupled to each other, but as reported recently [5], the device also allows to vary the coherent coupling between the two quantum dots. Hereby, it is a promising candidate for measuring the non-locality and entanglement of singlet- and triplet-states within a double dot system, as it was proposed theoretically [6].

Starting with a 2DEG which is located 90 nm below the surface of an AlGaAs/GaAs heterostructure, two lateral quantum dots are defined by applying negative voltages to Schottky-gates which are evaporated onto the surface. In addition to this technique, we first define insulating areas of Calixarene and then the structure of the above gates (see Fig. 1(a)) [5]. Since the

* Corresponding author. Fax: +49-89-2180-3182.
E-mail address: alex.holleitner@physik.uni-muenchen.de (A.W. Holleitner).

PII: S1386-9477(01)00418-0

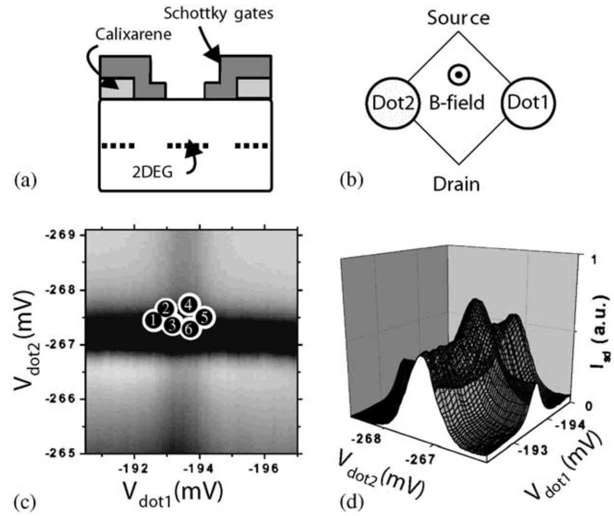

Fig. 1. (a) In addition to Schottky-gates, layers of *Calixarene* are defined on top of an AlGaAs/GaAs heterostructure. By applying appropriate voltages to the gates the regions of the 2DEG below the resist films are not depleted. (b) With this technique a parallel double quantum dot is formed in a way that both dots are equally connected to source and drain. The two transport channels enclose an area which is penetrated with a magnetic flux Φ, if we apply a perpendicular magnetic field. Thus, the structure operates as an Aharonov–Bohm interferometer containing two quantum dots [5]. (c) Part of the charging diagram of the double quantum dot which shows intersecting Coulomb resonances. Charge transport simultaneously takes place via both quantum dots. (d) The currents through both quantum dots are added to each other.

dielectric constant of Calixarene is about $\varepsilon \sim 7.1$ and the layers have a thickness of approximately 45 nm [7], the regions of the 2DEG which are below the Calixarene are not depleted if the voltages are applied appropriately. [1] This provides experimental access to charge transport through parallel devices, e.g. several quantum point contacts [8] or as here, through two parallel quantum points (see Fig. 1(b)) [5].

The charging energies of both dots are $E_C^{\text{dot1}} = e^2/2C_\Sigma^{\text{dot1}} = 6.5$ meV and $E_C^{\text{dot2}} = 3.0$ meV, respectively. Thus, we can evaluate the total capacitance of each dot to be of $C_\Sigma^{\text{dot1}} \cong 12$ aF and $C_\Sigma^{\text{dot2}} \cong 27$ aF. Approximating the capacitances C_Σ^{dots} as for classical conducting discs $C_\Sigma = 8\varepsilon_0\varepsilon_r r_e^{\text{dot}}$ ($\varepsilon_r \cong 12.8$ in GaAs), we estimate the electronic radii $r_e^{\text{dot1}} \cong 14$ nm and $r_e^{\text{dot2}} \cong 30$ nm, respectively. At a bath temperature of 4.2 K the sheet density is found to be $n_s = 1.7 \times 10^{15}\ \text{m}^{-2}$. By this, we can estimate the number of electrons in each dot to be smaller than $N_{\text{dot1}} \sim 2$ and $N_{\text{dot2}} \sim 5$, i.e., both dots are in the few electron limit. From the electron mobility $\mu = 80\ \text{m}^2/\text{V s}$ (at 4.2 K) we deduce that the elastic mean free length $l_e \sim 5.44\ \mu$m is larger than the typical lengths of the device ($\sim$ 500 nm). As can be seen in Fig. 1(c), the charging diagram of the double dot shows intersecting Coulomb resonances. At the crossing point the current through the mesoscopic structure is added of the contributions of each quantum dot (see Fig. 1(d)). This verifies that both dots are equally connected to source and drain as marked in Fig. 1(b) [9]. With the electronic temperature T_e similar to the ^{3}He/^{4}He bath temperature $T_b \cong 100$ mK $\sim 9\ \mu\text{eV}/k_B$ (k_B denotes the Boltzmann constant), the charge transport through each quantum dot is dominated by tunneling through one single quantum level.

Threading a magnetic flux through the area which is given by the two transport paths and measuring the charge transport at a small source–drain voltage V_{sd} yields AB-oscillations as can be seen in Fig. 2. At different positions of the charging diagram (as marked by circles $1, \ldots, 6$ in Fig. 1(c)) we detect oscillations with a period of $\Phi_0 = h/e$. The dominant component

[1] The regions of the 2DEG below the Calixarene are pinched off at an applied voltage of ~ -690 mV. The shown measurements, however, are performed at smaller voltages.

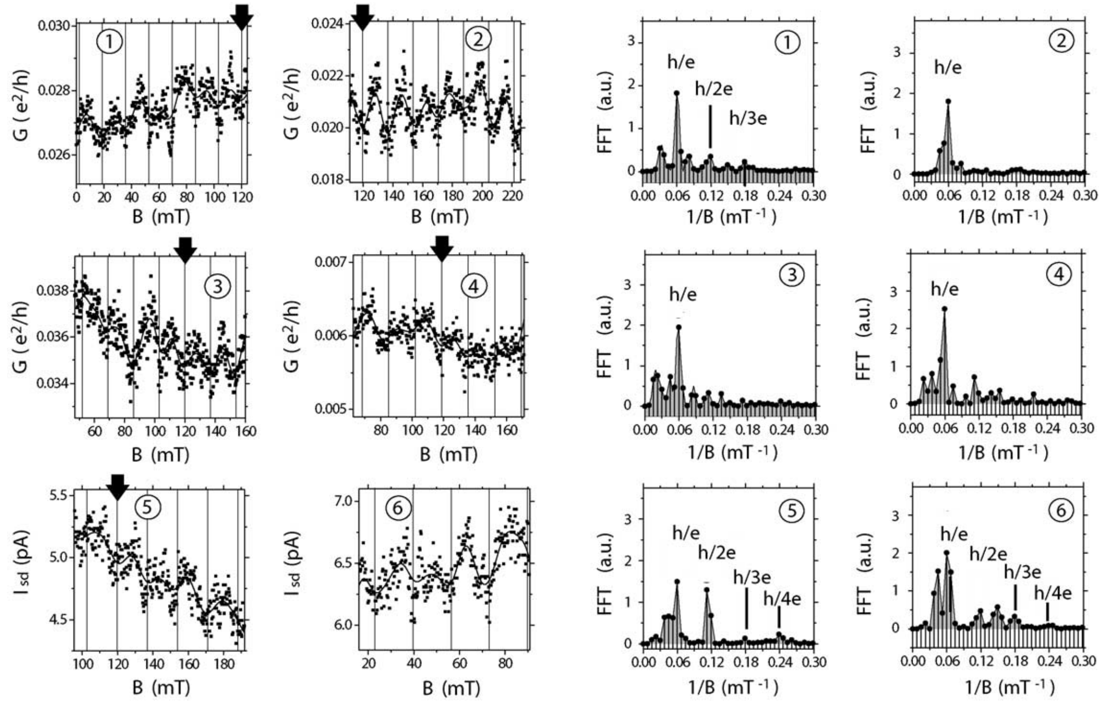

Fig. 2. (a) Magnetic field dependence of the conductance at different positions 1, … , 6 within the charging diagram of the double quantum dot (see Fig. 1).[2] The black lines are averaged curves demonstrating the oscillatory behavior. (b) Fast fourier transformations (FFT) of the left data after subtraction of an offset.

can be deduced from the fast Fourier transformations (FFT) which are shown on the right side of Fig. 2. The plots of the FFT exhibit a clear resonance at $1/B \sim 0.0596$ m T^{-1} which corresponds to a period of $B = 16.8$ m T. This value fits to an expected enclosed area of 2.5×10^{-13} m^2 and is in good agreement with measurements on a similar sample [5]. Higher harmonics of the base frequency can be detected but have a reduced amplitude.

The measurements are performed in a two-terminal geometry for which the phase of the AB-oscillations is supposed to be locked [10]. As marked by black arrows in Fig. 2, the curves 1, … , 5 have a distinctive minimum at around $B \sim 118$ m T which means that the phase of the measurements is constant over the range of these positions within the charging diagram of Fig. 1(c). On top of the Coulomb resonance, however, (which is covered by number 6) we see indications that the AB-oscillations undergo a phase change [4,10]. As in Ref. [4], the noise level is enhanced when both quantum dots are in resonance. This effect can either be attributed to phase-switching or to charging effects between the two quantum dots.

Generally, the AB-oscillations demonstrate that at least part of the charge transport is coherent. For the coherent part of the conductance through one quantum dot we can write $G_{\mathrm{coh}} \sim e^2/\tau_{\mathrm{D}} k_{\mathrm{B}} T_{\mathrm{e}}$, where τ_{D} denotes the dwell time of an electron in the structure. Hereby, we can estimate the decoherence time of the mesoscopic device to be larger than $\tau_{\mathrm{D}} \sim 2$ ns [4]. The circumference U of the area which is enclosed by the two transport arms gives a lower limit for the coherence length in our device $l_{\Phi} \geqslant U \sim 1.8$ μm.

To summarize, we define a parallel double quantum dot, where charge transport takes place via both quantum dots simultaneously. Applying a

[2]Figs. 3(5) and 3(6) correspond to measurements where no source and drain voltage V_{sd} is applied. Mesoscopic noise, i.e., pumping due to absorption of photons, drives the current I_{sd}.

perpendicular magnetic field to the device threads magnetic flux into the area which is enclosed by the two transport arms. For both quantum dots are only weakly coupled to each other we see AB-oscillations of the conductance in this few electron system. As expected for a two-terminal measurement the AB-oscillations are phase locked. On top of the Coulomb resonances, however, we see indications of a phase change.

Funds from the Deutsche Forschungsgemeinschaft (DFG) within the Sonderforschungsbereich SFB 348 and from the Bundesministerium für Forschung und Technologie (BMBF) are gratefully acknowledged. H. Qin thankfully receives financial support from the Volkswagen Stiftung.

References

[1] Y. Aharonov, D. Bohm, Phys. Rev. 115 (1959) 485.
[2] R.A. Webb, S. Washburn, C.P. Umbach, R.B. Laibovitz, Phys. Rev. Lett. 54 (1985) 2696.
[3] G. Timp, A.M. Chang, J.E. Cunningham, T.Y. Chang, P. Mankiewich, R. Behringer, R.E. Howard, Phys. Rev. Lett. 58 (1987) 2814.;
K.Y. Lee, W. Hansen, III T.P. Smith, C.M. Knoedler, J.M. Hong, D.P. Kern, J. Vac. Sci. Technol. B 7 (1989) 1819.
[4] A. Yacoby, M. Heiblum, D. Mahalu, Hadas Shtrikman, Phys. Rev. Lett. 74 (1995) 4047.;
E. Buks, R. Schuster, M. Heiblum, D. Mahalu, V. Umansky, Nature 391 (1998) 871.
[5] A.W. Holleitner, C.R. Decker, H. Qin, K. Eberl, R.H. Blick, Phys. Rev. Lett. 87 (2001) 256802.
[6] D. Loss, E.V. Sukhorukov, Phys. Rev. Lett. 84 (2000) 1035.
[7] J. Fujita, Y. Ochiai, S. Matsui, Appl. Phys. Lett. 68 (1996) 1297.;
A. Tilke, M. Vogel, F. Simmel, A. Kriele, R.H. Blick, H. Lorenz, D.A. Wharam, J.P. Kotthaus, J. Vac. Sci. Technol. B 17 (4) (1999) 1594–1597.
[8] A.G.C. Haubrich, D.A. Wharam, H. Kriegelstein, S. Manus, A. Lorke, J.P. Kotthaus, A.C. Gossard, Appl. Phys. Lett. 70 (1997) 3251.
[9] F. Hofmann, T. Heinzel, D.A. Wharam, J.P. Kotthaus, G. Böhm, W. Klein, G. Tränkle, G. Weimann, Phys. Rev. B 51 (1995) 13872.
[10] L. Onsager, Nuovo Cimento 6, suppl. 2 (1949) 249.;
A. Ley Yeyati, M. Büttiker, Phys. Rev. B 52 (1995) R14360.