Coherent coupling of two quantum dots embedded in an Aharonov-Bohm ring

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Abstract

We define two laterally gated small quantum dots ($\sim$ 15 electrons) in an Aharonov-Bohm geometry in which the coupling between the two dots can be broadly changed. For weakly coupled quantum dots we find Aharonov-Bohm oscillations. In an intermediate coupling regime we concentrate on the molecular states of the double dot and extract the magnetic field dependence of the coherent coupling.

85.30.Vw, 03.65.Bz, 73.40.Gk
Quantum dots are the perfect experimental tool for investigating phase coherence processes in mesoscopic devices [1,2]. One of the questions which can be considered is the entanglement of fermionic particles, e.g. electrons in a solid state environment. In this work we present an experimental approach allowing to coherently couple two quantum dots by a tunneling barrier embedded in an Aharonov-Bohm (AB) ring [3]. For such a system it is expected that singlet and triplet states have distinct AB-phases [4]. Therefore, this setup is a promising candidate for realizing a quantum bit in a solid state device [5]. The fundamental question being addressed is whether the coherent coupling of two quantum dots in the few electron limit can be understood in terms of only two excess electrons, one in each quantum dot, or whether the whole shell structure has to be taken into account. First, we characterize the double quantum dot and demonstrate that the coupling between the two quantum dots, containing about 15 electrons each, can be varied in a wide range. For the case of weak coupling we detect AB-oscillations. Secondly, we concentrate on the molecular states of the double quantum dot, first evidence of which has been found in transport [6] and microwave spectroscopy [7]. We extract the magnetic field dependence of the coherent coupling of the two quantum dots and compare it to recent theoretical models [8,9].

The device we used is realized within a two-dimensional electron gas (2DEG) being 90 nm below the surface of an AlGaAs/GaAs heterostructure (see Fig. 1). At a bath temperature of 35 mK the electron mobility and density are found to be \( \mu = 80 \, \text{m}^2/\text{Vs} \) and \( n_s = 1.7 \times 10^{15} \, \text{m}^{-2} \), respectively. By electron beam writing and Au-evaporation Schottky-gates are defined. Under appropriate voltage bias these form two quantum dots. As seen in the scanning electron microscope micrograph of Fig. 1(a) the two gates gate\(_1\) and gate\(_2\), which define the center tunneling barrier between the two quantum dots, are patterned on an additional resist layer. This 45 nm thick layer is fabricated from negative resist Calixarene (hexaacetate \( p \)-methycalix[6]arene) [10]. Since the dielectric constant of Calixarene is about \( \epsilon_{\text{Cax}} \approx 7.1 \) [11] there is no depletion below gate\(_1\) and gate\(_2\) [12,13]. By aligning these ‘carbon-bridges’ to a precision of \( \delta x \leq 15 \, \text{nm} \) we obtain an experimental setup in which one electron can either tunnel through dot\(_1\) or dot\(_2\) (see Fig. 1(b)).

By setting the lead-dot coupling of one of the quantum dots to be \( \Gamma_{lj} = \Gamma_{rj} \approx 0 \, \text{\mu eV} \) (\( j = 1, 2 \) as in Fig. 1(b)), we first characterize each dot individually. From transport spectroscopy we find the following charging energies for each dot \( E_{\text{Cdot1}}^\ast = e^2/2C_{\text{dot1}} = 1.68 \, \text{meV} \) and \( E_{\text{Cdot2}}^\ast = 1.71 \, \text{meV} \) [14] which correspond to total capacitances of about \( C_{\Sigma} \approx 47 \, \text{aF} \).

Taking into account the electron density, the number of electrons in the dots is estimated to be \( 15 \pm 1 \) with dot radii of about \( r_e \approx 54 \, \text{nm} \). This is in good agreement with the lithographic dimensions seen in Fig. 1(a). For the energies of the excited states we obtain the following values: \( \epsilon_{\text{dot1}}^\ast \approx 110 \, \text{\mu eV} \) and \( \epsilon_{\text{dot2}}^\ast \approx 117 \, \text{\mu eV} \). Generally, all experiments are carried out at a cryogenic bath temperature of \( T_b = 50 \, \text{mK} \). In temperature dependent measurements, however, the electronic temperature saturates at a value of \( T_e \approx 110 - 125 \, \text{mK} \). Furthermore, we determine the total intrinsic width of the resonances to be \( \Gamma = \Gamma_{lj} + \Gamma_{rj} \approx 108 \, \text{\mu eV} \) (\( j = 1, 2 \) as in Fig. 1(b)). Summarizing the results so far, the mesoscopic system can be tuned into a regime \( 2E_C = U > \epsilon_{\text{dots}}^\ast \sim \Gamma > k_BT_e \) in which charge transport is dominated by tunneling through single particle levels.

In the following section we demonstrate that the coupling of the two quantum dots can be tuned into different regimes. For this purpose we connect gate\(_3\) and gate\(_4\) to each other and detect the charging diagram of the double dot at a small source drain bias of
\[ V_{sd} = -(\mu_{source} - \mu_{drain})/e = -20 \mu V. \]

Having set the voltage for the inner tunneling barrier to be \( V_{g1} = -317 \text{ mV} \) and \( V_{g2} = -349 \text{ mV} \), we find strong coupling of the two quantum dots (see Fig. 2(a)). In contrast to previous measurements on parallel double quantum dots, we detect the whole rhombic pattern in the charging diagram, since both dots are equally connected to the leads. For the electrostatic coupling strengths of the two dots we find \( C_{12}/C_{\Sigma}^{\text{dot1}} \approx C_{12}/C_{\Sigma}^{\text{dot2}} = 0.43 \pm 0.08 \), where \( C_{12} \) is the interdot capacitance. As seen in Fig. 2(b) the charging diagram for the weak coupling regime, i.e. \( V_{g1} = -537 \text{ mV} \) and \( V_{g2} = -594 \text{ mV} \), shows resonances intersecting, i.e. the two dots form an AB-ring. Measuring the variation of the amplitude at the crossing points of Fig. 2(b) by sweeping a perpendicular magnetic field, we detect AB-oscillations with a periodicity of \( \Delta B \approx 16.4 \text{ mT} \) (see inset of Fig. 2(b)). This corresponds to an area of \( A = 2.52 \times 10^{-13} \text{ m}^2 \) in good accordance with the lithographic size of the two-path dot system.

The fundamental question now arising is to what extent the excess electrons which contribute dominantly to the current through the whole system are independent of the core shell structure of the artificial atoms. For this purpose a different pair of gate voltages is employed to detect charging diagrams similar to Fig. 2, i.e. \( V_{g3} \) and \( V_{g4} \). Hereby, we are able to verify the transition from strong to weak coupling of the two dots in a more sensitive way. For an intermediate coupling regime Fig. 3(a) shows such a charging diagram. The voltage for the inner tunneling barrier is set to be \( V_{g1} = -448 \text{ mV} \) and \( V_{g2} = -453 \text{ mV} \) while the voltage for the two tunneling barriers which define \( \text{dot2} \) is tuned to be \( V_{g5} = -854 \text{ mV} \). From the charging diagram we can extract the regions with fixed electron numbers for \( \text{dot1} \) and \( \text{dot2} \), which is depicted by black lines in Fig. 3(b). Naturally, the charging diagram is interpreted in terms of capacitances between the dots and the electrostatic environment, respectively. In Fig. 3(a) the black line confined by two circles represents the electrostatic coupling of the two quantum dots. We obtain electrostatic coupling strengths of about \( C_{12}/C_{\Sigma}^{d\text{dot1}} \approx C_{12}/C_{\Sigma}^{d\text{dot2}} = 0.37 \pm 0.08 \).

Apart from the boundaries defined by the orthodox electrostatic model, we observe resonances which follow in parallel to the main resonances (sketched by dotted lines in Fig. 3(b)). Furthermore, we find resonances which are leaking from a ground state into the Coulomb blockade regions of the phase diagram, e.g. the resonance line between the compartments \((N_1 - 2, N_2)\) and \((N_1 - 1, N_2)\) can be traced into the \((N_1 - 1, N_2 - 1)\)-region (dotted-dashed line in Fig. 3(b)). For two very large quantum dots similar effects have been observed in a sample geometry in which the two quantum dots were connected to different drain/source contacts. As was shown in Ref. this corresponds to higher order tunneling events, indicating strong wave function coupling of the dots even at low-bias voltages.

In the following we will focus on the tunnel split resonances at the triple points in the phase diagram marked by the circles in Fig. 3(b) at \( A, B, C, D, \) and \( E \), where the wavefunction coupling is maximum. We recorded charging diagrams similar to the one in Fig. 3(a) applying a perpendicular magnetic field in the range \( B = 0 \text{ T} \) to \( 2 \text{ T} \). Subsequently, conductance traces crossing the split resonances are fitted by derivatives of the Fermi-Dirac distribution function with respect to \( V_{g4} \) (see Fig. 4(a)). Fitting the curves in accordance with the maximum tunnel splitting results in a magnetic field dependence of the splitting which is depicted in Fig. 4(b).
Starting with a maximum value at \( B = 0 \) T all curves follow a characteristic signature: a minimum around \( 0.12 - 0.4 \) T and a second maximum at \( \sim 0.78 - 1.05 \) T. For \( B > 1.4 \) T we find the saturation value of the splittings to be \( \Delta \epsilon_s = 100 - 110 \) µeV. We assume that both an interdot capacitance and an effective overlap of the wavefunctions have to be taken into account at the same time [9]. At zero magnetic field both contributions are superimposed. Increasing the magnetic field the two wavefunctions in the quantum dots are compressed and thus their overlap reduced. In this model the pure capacitive coupling results in an offset of about \( \Delta \epsilon_s \approx 110 \) µeV. Below \( B = 2 \) T the curves resemble the magnetic field dependence of the Heisenberg exchange energy \( J \) for two excess electrons, one in each quantum dot [8]. Although the main characteristics of all curves in Fig. 4(b) are similar, the magnitude of the splitting seems to be dependent on the specific electron number. Furthermore, the trace which corresponds to the triplepoint \( B \) lacks a second maximum. Accordingly, we infer that the coherent coupling of the two quantum dots not only depends on the shape of the total wavefunction of two coupled excess electrons as assumed so far, but on the specific spin and orbital electron configuration of the whole artificial molecule. For magnetic fields larger than \( B \geq B_0 = 0.6 \) T the Zeeman energy exceeds \( \Delta \epsilon_s (\epsilon_Z = (g\mu_B B)/2, \text{where } g = -0.44 \) in GaAs and \( \mu_B \) the Bohr magneton). Hence, we conclude that the coherent coupling of the magnetic field to the electron spins and its effect on the wavefunction overlap has also to be taken into account in a full theoretical description.

In summary we have realized an experimental setup by which electrons can tunnel through two quantum dots in an Aharonov-Bohm geometry, while the coupling \( J \) between the dots can be broadly tuned. We demonstrate for weakly coupled dots that the setup allows to probe Aharonov-Bohm oscillations. In an intermediate coupling regime we determine the coherent coupling of the two quantum dots and extract the magnetic field dependence of the tunnel splitting. We conclude that in addition to the coupling of the electron spins to an applied magnetic field the whole shell structure has to be taken into account to describe the coherent coupling of the two artificial atoms.

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[13] The pinch-off voltage for the ‘carbon-bridges‘ is found to be $V_{g1} = V_{g2} \cong -685 \text{ mV}$, whereas the presented measurements are performed at voltages of $V_{g1} = V_{g2} \leq -600 \text{ mV}$.
[14] In this section all given values for dot$_1$ were obtained at $V_{g1} = -520 \text{ mV}$ and $V_{g2} = -580 \text{ mV}$, whereas for dot$_2$ $V_{g1} = -530 \text{ mV}$ and $V_{g2} = -600 \text{ mV}$.
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[19] A triplepoint is the point where three charge configurations of the double quantum dot are degenerate.
[20] Compressing of the wave functions also results in lowering of the conductance. For $B > 2 \text{ T}$ the conductance amplitudes of the Coulomb oscillations vanish.
[21] The triple points $A$ to $E$ are defined in Fig. 3(b) – point $F$ corresponds to the triple point of the two phase boundaries $(N_1, N_2 + 1) / (N_1 + 1, N_2 + 1)$ and $(N_1, N_2 + 1) / (N_1, N_2 + 2)$. 

5
FIGURES

FIG. 1. (a) The device is defined by electron-beam writing in a two step process. In addition to the conventional Schottky gates defining the quantum dots, two regions are covered with the resist Calixarene (see text for details). (b) By applying appropriate negative voltages to the gates, a two-path quantum dot system is realized. An electron in the source contact can tunnel via both dots into the drain contact. Furthermore, the coupling between the two dots can be tuned by voltages which are applied to gate$_1$ and gate$_2$.

FIG. 2. The grayscale plots of the charging diagram of the double dot reveal that the coupling between the two dots can be tuned into different regimes: (a) As a characteristic of strong electrostatic coupling we find a rhombic pattern in the charging diagram. Here, the molecular states are spread over the whole double dot. (white $\leq I = 0$ pA $< \text{black} < I = 16$ pA $\leq \text{white}$). (b) In the case of weak coupling we find resonances of the double dot intersecting (only part of the total charging diagram is shown). The device operates as an Aharonov-Bohm (AB) interferometer (white $\leq I = 0$ pA; black $\geq I = 9$ pA). If a magnetic field is applied perpendicular to the quantum dots, the amplitude of the crossing points produces AB-oscillations as shown in the inset.

FIG. 3. (a) Charging diagram spanned by $V_{g3}$ and $V_{g4}$ in a coupling regime with strong wavefunction overlap in a logarithmic gray scale plot (white $\leq I = 0$ pA$<\text{black}< I = 18$ pA$\leq \text{white}$). The black line confined by two circles denotes the electrostatic coupling of the two quantum dots. As an indication of the coherent coupling the triplepoints [19] are split into two resonances (exemplarily indicated by two arrows). (b) The different compartments in the charging diagram are labeled by possible electron configurations of the double quantum dot ($N_1,N_2$). Excited states are sketched by dashed and dotted lines, while the crossing points where the tunnel splitting occurs are marked by A, B, C, D, and E (see text for details).

FIG. 4. (a) The logarithmic line plot shows the single trace which is indicated in Fig. 3(a) by two black arrows. The tunnel split resonances of point A with respect to $V_{g4}$ can clearly be seen (open boxes). The black lines are fits obtained with derivatives of the Fermi-Dirac distribution – the splitting $\delta V_{g4}$ is denoted by a black arrow. (b) Magnetic field dependence of $\delta V_{g4}$: Points A to F (F out of range in Fig. 3) are the crossing points in Fig. 3(b) [21]. The overall error bar is indicated by $\pm \delta \epsilon = 13 \mu eV$ (see text for details).
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