Few-Electron Quantum Dot Circuit with Integrated Charge Read-Out

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We report on the realization of a few-electron double quantum dot defined in a two-dimensional electron gas by means of surface gates on top of a GaAs/AlGaAs heterostructure. Two quantum point contacts (QPCs) are placed in the vicinity of the double quantum dot and serve as charge detectors. These enable determination of the number of conduction electrons on each dot. This number can be reduced to zero while still allowing transport measurements through the double dot. Microwave radiation is used to pump an electron from one dot to the other by absorption of a single photon. The experiments demonstrate that this quantum dot circuit can serve as a good starting point for a scalable spin-qubit system.

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The experimental development of a quantum computer is at present at the stage of realizing few-qubit circuits. In the solid state, particular success has been achieved with superconducting devices in which macroscopic quantum states are used to define two-level qubit states (see [1] and references therein). The opposite alternative would be the use of two-level systems defined by microscopic variables, as realized for instance by single electrons confined in semiconductor quantum dots [2]. For the control of one-electron quantum states by electrical voltages, the challenge at the moment is to realize an appropriate quantum dot circuit containing just a single conduction electron.

Few-electron quantum dots have been realized in self-assembled structures [3] and also in small vertical pillars defined by etching [4]. The disadvantage of these types of quantum dots is that they are hard to integrate into circuits with a controllable coupling between the elements, although integration of vertical quantum dot structures is currently being pursued [5]. An alternative candidate is a system of lateral quantum dots defined in a two-dimensional electron gas (2DEG) by surface gates on top of a semiconductor heterostructure [2]. Here, integration of multiple dots is straightforward by simply increasing the number of gate electrodes. In addition, the coupling between the dots can be controlled, since it is set by gate voltages. The challenge is to reduce the number of electrons to one per quantum dot. This has long been impossible, since reducing the electron number decreases at the same time the tunnel coupling, resulting in a current too small to be measured [6].

In this report we demonstrate a double quantum dot device containing a voltage-controllable number of electrons down to a single electron. We have integrated it with charge detectors that can read-out the charge state of the double quantum dot with a sensitivity better than a single electron charge. The importance of the present circuit is that it can serve as a fully tunable two-qubit quantum system, following the proposal by Loss and DiVincenzo [7], which describes an optimal combination of the single-electron charge degree of freedom (for manipulation with electrical voltages) and the spin degree of freedom (to obtain a long coherence time).

Our device, shown in Fig. 1a, is made from a GaAs/AlGaAs heterostructure, containing a 2DEG 90 nm below the surface with an electron density, \( n_s = 2.9 \times 10^{11} \text{ cm}^{-2} \). This small circuit consists of a double quantum dot and two quantum point contacts (QPCs). The layout is an extension of previously reported single quantum dot devices [2]. The double quantum dot is defined by applying negative voltages to the 6 gates in the middle of the figure. Gate \( T \) in combination with the left (right) gate, \( L \) (\( R \)), defines the tunnel barrier from the left (right) dot to drain 1 (source 2). Gate \( T \) in combination with the middle, bottom gate, \( M \), defines the tunnel barrier between the two dots. The narrow "plunger" gate, \( P_L \) (\( P_R \)), on the left (right) is used to change the electrostatic potential of the left (right) dot. The left plunger, \( P_L \), is connected to a coaxial cable so that we can apply high-frequency signals. In the present experiments we do not apply dc voltages to \( P_L \). In order to control the number of electrons on the double dot, we use gate \( L \) for the left dot and \( P_R \) for the right dot. All data shown are taken at zero magnetic field and at a temperature of 10 mK.

We first characterize the individual dots. From standard Coulomb blockade experiments [6] we find that the energy cost for adding a second electron to a one-electron dot is 3.7 meV. The excitation energy (i.e. the difference between the first excited state and the ground state) is 1.8 meV at zero magnetic field. For a two-electron dot the energy difference between the singlet ground state...
and the triplet excited state is 1.0 meV at zero magnetic field. Increasing the field (perpendicular to the 2DEG) leads to a transition from a singlet to a triplet ground state at about 1.7 Tesla.

In addition to current flowing through the quantum dot, we can measure the charge on the dot using one of the QPCs. We define only the left dot (by grounding gates $R$ and $P_R$) and use the left QPC as a charge detector. The QPC is formed by applying negative voltages to QPC-L and $L$. This creates a narrow constriction in the 2DEG, with a conductance, $G$, that is quantized when sweeping the gate voltage $V_{QPC-L}$. The plateau at $G = e^2/h$ and the transition to complete pinch-off (i.e. $G = 0$) are shown in Fig. 1b. At the steepest point, where $G \approx e^2/h$, the QPC-conductance has a maximum sensitivity to changes in the electrostatic environment, including changes in the charge of the nearby quantum dot. As can be seen in Fig. 1b, the QPC-current, $I_{QPC}$, decreases when we make the left-dot gate voltage, $V_M$, more negative. Periodically this changing gate voltage pushes an electron out of the left dot. The associated sudden change in charge increases the electrostatic potential in the QPC, resulting in a step-like structure in $I_{QPC}$ (see expansion in Fig. 1b, where the linear background is subtracted). So, even without passing current through the dot, $I_{QPC}$ provides information about the charge on the dot. To enhance the charge sensitivity we apply a small modulation (0.3 mV at 17.7 Hz) to $V_M$ and use lock-in detection to measure $dI_{QPC}/dV_M$. Figure 1c shows the resulting dips, as well as the corresponding Coulomb peaks measured in the current through the dot. The coincidence of the two signals demonstrates that the QPC indeed functions as a charge detector. From the height of the step in Fig. 1b (50 pA, typically 1-2 percent of the total current), compared to the noise (5 pA for a measurement time of 100 ms), we can estimate the sensitivity of the charge detector to be about 0.1e, with $e$ being the single electron charge. The important advantage of QPC charge detection is that it provides a signal even when the tunnel barriers of the dot are so opaque that $I_{QPC}$ is too small to measure. This allows us to study quantum dots even while they are virtually isolated from the leads.

Next, we study the charge configuration of the double dot, using the QPC on the right as a charge detector. We measure $dI_{QPC}/dV_L$ versus $V_L$, and repeat this for many values of $V_{PR}$. The resulting two-dimensional plot is shown in Fig. 2a. Blue lines signify a negative dip in $dI_{QPC}/dV_L$, corresponding to a change in the total number of electrons on the double dot. Together these lines form the well-known "honeycomb diagram." The almost-horizontal lines correspond to a change in the electron number in the left dot, whereas almost-vertical lines indicate a change of one electron in the right dot. In the upper left region the "horizontal" lines are not present, even though the QPC can still detect changes.
FIG. 2: (a) Charge stability diagram ("honeycomb") of the double quantum dot, measured with QPC-R. A modulation (0.3 mV at 17.77 Hz) is applied to gate $L$, and $dI_{QPC}/dV_L$ is measured with a lock-in amplifier and plotted in color scale versus $V_L$ and $V_{PR}$. The bias voltages are: $V_{SD2} = 100 \mu V$ and $V_{DOT} = V_{SD1} = 0$. The label "00" indicates the region where the double dot is completely empty. (b) Zoom-in of Fig. 2a, showing the honeycomb pattern for the first few electrons in the double dot. The white labels indicate the number of electrons in the left and right dot.

in the charge, as demonstrated by the presence of the "vertical" lines. We conclude that in this region the left dot contains zero electrons. Similarly, a disappearance of the "vertical" lines occurs in the lower right region, showing that here the right dot is empty. In the upper right region, the absence of lines shows that here the double dot is completely empty.

We are now able to count the absolute number of electrons. Figure 2b shows a zoom-in of the few-electron region. Starting from the "00" region, we can label all regions in the honeycomb diagram, e.g. the label "21" means two electrons in the left dot and one in the right. Besides the blue lines, also short yellow lines are visible, signifying a positive peak in $dI_{QPC}/dV_L$. These yellow lines correspond to a charge transition between the dots while the total electron number remains the same. (The positive sign of $dI_{QPC}/dV_L$ can be understood if we note that crossing the yellow lines by making $V_L$ a little more positive means moving an electron from the right to the left dot, which increases $I_{QPC}$. Therefore the differential quantity $dI_{QPC}/dV_L$ displays a positive peak.) The QPC is thus sufficiently sensitive to detect inter-dot transitions.

In measurements of transport through lateral double quantum dots, the few-electron regime has never been reached [11]. The problem is that the gates, used to deplete the dots, also strongly influence the tunnel barriers. Reducing the electron number would always lead to the Coulomb peaks becoming unmeasurably small, but not necessarily due to an empty double dot. The QPC detectors now permit us to compare charge and transport measurements. Figure 3 shows $I_{DOT}$ versus $V_L$ and $V_{PR}$, with the dotted lines extracted from the measured charge lines in Fig. 2b. In the bottom left region the gates are not very negative, hence the tunnel barriers are quite open. Here the resonant current at the charge transition points is quite high ($\sim 100$ pA, dark gray), and also lines due to cotunneling are visible [20]. Towards the top right corner the gate voltages become more negative, thereby closing off the barriers and reducing the current peaks (lighter gray). The last Coulomb peaks (in the dashed circle) are faintly visible ($\sim 1$ pA). They can be increased

FIG. 3: Transport through the double dot in the same region as Fig. 2b. Plotted in logarithmic grayscale is $I_{DOT}$ versus $V_L$ and $V_{PR}$, with $V_{DOT} = 100 \mu V$ and $V_{SD1} = V_{SD2} = 0$. The dotted lines are extracted from Fig. 2b. In the light regions current is zero due to Coulomb blockade. Dark gray indicates current, with the darkest regions (in the bottom left corner) corresponding to $\sim 100$ pA. Inside the dashed circle, the last Coulomb peaks are visible ($\sim 1$ pA). (A smoothly varying background current due to a small leakage from a gate to the 2DEG has been subtracted from all traces.)
can become single-shot, with the charge detection started after the coherent manipulation of the double dot quantum states. This procedure maximally reduces backaction effects from the detector. Present experiments focus on increasing the speed of the read-out such that the determination of the charge state is faster than the mixing time, i.e. the time in which the measurement introduces transitions between the charge states [13].

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