Time-Resolved Detection of Individual Electrons in a Quantum Dot

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We present measurements on a quantum dot and a nearby, capacitively coupled, quantum point contact used as a charge detector. With the dot being weakly coupled to only a single reservoir, the transfer of individual electrons onto and off the dot can be observed in real time in the current signal from the quantum point contact. From these time-dependent traces, the quantum mechanical coupling between dot and reservoir can be extracted quantitatively. A similar analysis allows the determination of the occupation probability of the dot states.

The electronic occupation in semiconductor quantum dots can be read out using a quantum point contact (QPC) [1]. Quantum dots are proposed as scalable spin qubits in a future quantum information processor [2] and the read-out could be implemented by a QPC detector. Experiments using a radio-frequency single-electron transistor resulted in a high bandwidth real-time read-out of a quantum dot’s charge state [3]. Theoretical considerations on dephasing [4, 5] have given evidence that a higher quantum measurement efficiency can be obtained using a detector without any internal degrees of freedom, such as, e.g., QPC containing a single mode. Recent investigations using QPCs as charge detectors were performed on double [6, 7] and single [8, 9] quantum dots, all using DC lock-in techniques that average over many electrons passing through the dot. Very recently, real-time charge read-out measurements on a split-gate defined structure were reported [10].

In this paper, we present measurements detecting single electrons in real time using a QPC charge detector, in a circuit created entirely by surface probe lithography [11, 12, 13]. The structure consists of a quantum dot and a nearby, electrostatically coupled QPC (see Fig. 1(a)). It is written on a GaAs/Al0.3Ga0.7As heterostructure, containing a 2-dimensional electron gas (2DEG) 34 nm below the surface as well as a backgate 1400 nm below the 2DEG, isolated from it by a layer of LT-GaAs. Negative voltages were applied to the surrounding gates (G1, G2, S_{QPC}, D_{QPC}, the latter two also containing the charge detection circuit), and to the back gate, to reduce the charge on the dot and close its tunnel barriers. A voltage applied to gate P was used to tune the detector QPC to a regime where it is sensitive to the charge on the dot.

All measurements were performed in a dilution refrigerator with a base temperature of 80 mK. A small bias voltage $V_{\text{bias, dot}} = 10 \mu V$ was symmetrically applied across the dot between source ($S_{\text{QD}}$) and drain ($D_{\text{QD}}$). In a regime where both barriers are open and a transport current through the dot is measurable, the example traces in Fig. 1(b) and 1(c) were measured, showing the correlation between the Coulomb peaks in the transport current (b) and the corresponding kinks in the conduc-

FIG. 1: (a) AFM micrograph of the structure with designations of gates: source (S) and drain (D) of the quantum dot (QD) and the quantum point contact (QPC) used as a charge detector; lateral gates G1 and G2 to control the coupling of the dots to the reservoirs; Plunger gate (P) to tune the QPC detector. (b) Example measurement of the current through the dot. (c) Simultaneous measurement of the conductance through the QPC, where each step corresponds to a change of the dot’s charge by one electron.

tance vs. gate voltage curve of the QPC (c). For later measurements, a compensation voltage $V_P = a V_{G1} + b V_{G2}$ was applied to the gate P, with constants $a$ and $b$ chosen such as to keep the charge detection circuit in a regime of almost constant sensitivity. The sensitivity of our AFM-defined circuit is comparable to similar set-ups realized by electron beam lithography defined split-gate devices [14, 15].

The following measurements were performed with one tunnel barrier (the one near the drain contact) completely closed and the other one tuned to a very low electron transition rate, of the order of only a few electrons per second.

Figure 2(a) shows a section of a measurement of the QPC detector’s conductance versus two different gate voltages, where each vertical or horizontal trace can be thought of as being similar to Fig. 1(c). Each step corresponds to an electron being transferred onto the dot. Towards lower values of $V_{G2}$ (see marked region), the smooth behavior of the step transforms to a discrete appearance where only two possible values for the QPC conductance are observed.

In the following, we present time-dependent traces of
FIG. 2: (a) Measurement of the QPC’s conductance versus \( V_{G1} \) and \( V_{G2} \). Towards lower values of \( V_{G2} \) (see e.g. inside the black ellipse), the smooth, washed out appearance of the step in conductance is replaced by a discrete switching behavior with only two possible states. The time between individual measured points was about 2 seconds, the integration time of the (DC) measurement 0.2 seconds. (b) Single oscilloscope trace of the QPC’s conductance versus time. The dot was tuned to a point near a step in the QPC’s conductance. (c) Histogram of the data in plot (b) and 19 similar sweeps. (d) The upper graph shows an example for the distribution of times the system spends in both states. The lower graph shows the integrated, normalized distribution representing the probability that after a certain time the system has changed its state at least once. Exponential fits \( \exp(-t/\tau) \) agree well with the data and suggest that (1) the behavior of the system does not depend on its history and (2) that a single energy level in the dot contributes to charging.

From the exponential fits, two mean dwell times \( \tau_{on} \) (electron on dot) and \( \tau_{off} \) (no electron on dot) can be obtained. The same numbers can be extracted by counting the transitions per time interval \( f_{\text{trans}} \) during a time sweep and determining the fractions \( p_{\text{on}} \) and \( p_{\text{off}} \) of the total time the system spends in each of the two states (see histogram in Fig. 2(c)). It follows that \( \tau_{\text{on}} = \tau_{\text{off}} \). To reduce the statistical error, 20 time sweeps have been analyzed for every data point shown.

In a regime where only one tunnel barrier is open, no finite bias transport measurements are possible which would allow the determination of the exact value of \( \alpha_{G1} \). Its value is therefore obtained from the peak spacing by assuming a charging energy of the dot \( E_c = 2 \text{ mV} \), determined from finite bias transport measurements performed in a more open regime of the dot. This method yields \( \alpha_{G1} = 0.075 \text{ eV/V} \), a value that was used in Fig. 2(f) and 3(c). Considering that, at lower electron numbers, \( E_c \) tends to increase due to the reduction in size of the dot, the energy and temperature values to be determined below (see Figs. 2(f) and 3(c)) are to be considered an upper bound.

Motivated by the experimental findings and their statistical properties, we interpret our results using the model depicted in Fig. 3(a), which shows a single energy level in a quantum dot which can be aligned with respect to the Fermi level of the reservoir, from which it is separated by a tunable tunnel barrier. The lower conductance in the QPC (see Fig. 2(b)) corresponds to the state where an electron is on the dot, due to the capacitive coupling of the dot to the QPC. A similar scheme was used in an experiment using an SET as a detector. A more sophisticated analysis considering more than one level in the dot can be performed using the theory by Beenakker.

Assuming that an electron is on the dot, the mean rate values corresponds to the observed step height in Fig. 2(a) in the parameter range featuring a smooth transition. This allows a discrimination between charging events on the dot and other possible sources of switching events.
FIG. 3: (a) Model for the transfer of individual electrons between a single reservoir and a quantum dot. The tunnel coupling is assumed to depend on the single-level state $N$ and can be tuned via the voltage $V_{G2}$. (b) Greyscale plot of the relative occupancy $\gamma_{on}$ of the dot. Each point is calculated from 20 oscilloscope traces, each 9 seconds long, via the method described in the text. The section corresponds roughly to the marked range of Fig. 2(a). Due to a minor charge rearrangement, however, the voltage ranges are not exactly the same. The ellipse marks the point where the statistical analysis of dwell times (Fig. 2(d)) was applied. This measurement was performed with the QPC containing more than one mode. (c) Temperature extracted from the data in (a) using a fit of the Fermi function (see Fig. 3(c)) for every value of the gate voltage $V_{G2}$. (d) Coupling strength $\Gamma$ to the leads extracted from the same set of data as (a) and (b). As expected, $\Gamma$ increases with $V_{G2}$.

at which it will leave the dot is $\tau_{off}^{-1} = \Gamma \times (1 - f(\mu_N))$, where $\tau_{off}$ is the average time interval the dot stays in the $(N+1)$ electron state, $\mu_N$ is the electrochemical potential for the addition of the $N$th electron, $f(E)$ is the distribution function in the reservoir, and $\Gamma$ is the coupling between the level and the reservoir. Physically, the value of $\Gamma$ accounts for the strength of tunnel barriers, wave function overlap and the lead’s density of states (assumed to be constant over the relevant energy interval). Correspondingly, the rate for electrons to tunnel on an (initially empty) dot is $\tau_{on}^{-1} = \Gamma \times f(\mu_N)$. It follows that $\Gamma = \tau_{off}^{-1} + \tau_{on}^{-1}$ and $f(\mu_N) = \tau_{off}/(\tau_{off} + \tau_{on})$.

This means that we are able to determine the tunnel coupling $\Gamma_N$ of an individual energy level to a single reservoir as well as the energy distribution $f(E)$ of the lead.

In Fig. 2(f), the solid line represents a fit using the Fermi distribution $f(E) = 1/(1 + \exp(-E/k_B T))$, from which a temperature $T \approx 150$ mK can be extracted.

In the following we present data in a more extended parameter regime. Figure 3(b) shows a plot of the extracted distribution function $f(E)$ versus the two gate voltages $V_{G1}$ and $V_{G2}$. For each scan in the direction of $V_{G1}$, a fit using the Fermi distribution was made. The resulting temperature values are represented in Fig. 3(c), the mean value being slightly above 200 mK. The origin of the scattering of $T$ values in Fig. 3(c) remains to be investigated, since it cannot be assigned entirely to uncertainties in the fitting procedure or lack of data points.

The numerical extraction of the parameter $\Gamma$ is most reliable near the transition. $\Gamma$ was therefore determined where $f(E)$ was closest to $1/2$. The resulting curve is shown in Fig. 3(d). Over the range presented, $\Gamma$ changes by roughly one order of magnitude. Further reducing $V_{G2}$ by only a few ten mV leads to a further increase of the observed times between switching events (of the order of minutes and more). This is in accordance with recent observations of long dwell times of electrons on a single or double dot.

We have reported on the real-time charge read-out of a quantum dot using a quantum point contact, both defined by AFM Lithography. We estimate that amplifier and cabling bandwidth as well as the sensitivity can be improved to reach read-out frequencies in the MHz range (see also [10]).

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