

Few-electron quantum dot fabricated with layered scanning force microscope lithography

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Abstract

Few-electron quantum dots with integrated charge read-out have been fabricated by layered local anodic oxidation of a Ga[Al]As heterostructure and a thin Titanium top gate. The additional set of gates provided by the metallic film is used to tune the quantum dots into the few-electron regime. Current through the quantum dots and the quantum dot charge have been simultaneously measured for electron numbers varying between zero and two. The singlet–triplet splitting varies in two different samples between 0.5 and 1.5 meV. The Zeeman splitting of the first conductance resonance is observed in parallel magnetic field. The high tunability and straightforward implementation of these structures are promising for future nanostructure design.

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Transport experiments in few-electron quantum dots have shown many interesting results such as the energy spectra in artificial atoms [1–3] as well as related spin effects [4–8]. In addition, few-electron dots are considered as model systems in the Loss–DiVincenzo proposal [9,10] for quantum computing with electron spins. Sophisticated nanostructures can be fabricated by patterning two-dimensional electron gases with a scanning force microscope (SFM) [11]. However, to our knowledge, quantum dots which can be emptied down to the last electron have not been realized with this technique. A multiple layer local oxidation technique was developed in order to increase the tunability of the samples [12]. Here, we report the fabrication with this multiple-layer oxidation technique and present measurements on lateral few-electron quantum dots.

We show the results of two samples A and B based on different Ga[Al]As heterostructures with a two-dimensional electron gas (2DEG) 34 nm below the surface. Both samples are similar in lithographic design. Sample A is depicted in Fig. 1(a). In sample A (B), the electron density at 4.2 K is about $4.8 \times 10^{15} \text{ m}^{-2}$ ($5 \times 10^{15} \text{ m}^{-2}$) and the mobility about $45 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$ ($30 \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$). The nanostructures were fabricated by two-layer local oxidation using an atomic force microscope in tapping mode [12]: the GaAs cap layer is locally oxidized with a voltage-biased SFM-tip. The 2DEG is depleted below the oxide lines (bright lines in Fig. 1(a)) defining the quantum dot. A 6–7 nm thick Titanium film is then evaporated on top and cut by local oxidation (indicated by black lines) with the SFM into mutually isolated parts acting as top gates. This additional set of gates provides the high tunability of the quantum dot, which is necessary to reach the few-electron regime. In addition, these top gates tend to screen electron–electron interactions in the system and minimize the cross-talk between adjacent gates.

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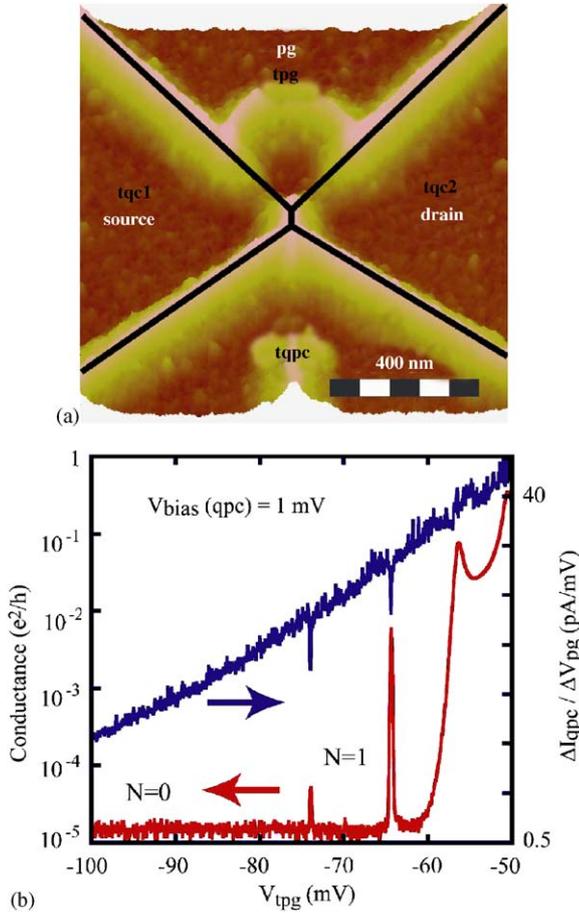


Fig. 1. (a) SFM-micrograph of the sample A. In-plane gates (white letters), Titanium oxide lines (black lines) and top gates (black letters) are indicated. (b) Conductance and detector signal as a function of top plunger gate voltage. Coulomb peaks in transport correspond to a dip in the detector signal.

The measurements for sample A were performed at 350 mK electronic temperature. Both quantum point contacts (QPCs) coupling the dot to the leads are tuned into the tunneling regime via the top gates tqc1 and tqc2. Negative voltage is applied to the top plunger gate in order to reduce the number of electrons on the dot. This metallic gate is positioned directly on top of the quantum dot. We measured the lever arm of this top gate on the dot to about 0.65. This is a big number compared to the remaining lever arm of 0.35 of all other gates together on the dot. This allows a very selective tuning of the quantum dot. The charge read-out point contact is tuned into the sensitive regime by the top gate tqpc. The conductance through the dot in the few-electron regime as a function of the top plunger gate is plotted on a logarithmic scale in Fig. 1(b). A conductance offset of 10 fA has been added. The charge on the dot is simultaneously observed by modulating in-plane gate pg, applying a DC-bias to the read-out QPC and measuring current through this QPC with AC lock-in technique at the pg-modulation frequency (upper trace of Fig. 1(b)). Coulomb resonances in transport correspond to a dip in the detector signal if the charge is quantized on the

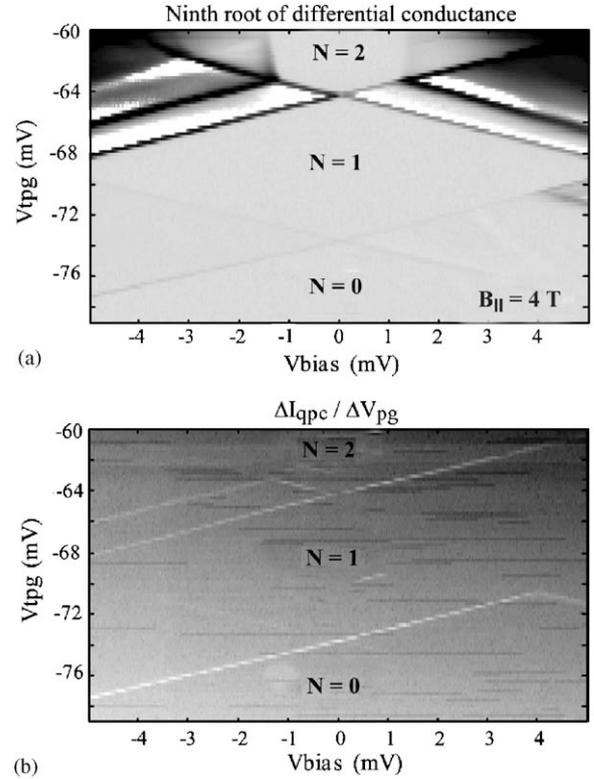


Fig. 2. (a) Differential conductance as a function of DC-bias and top plunger gate voltage. The excited states and inelastic cotunneling can be observed for $N=2$ electrons in the dot. (b) Detector signal is simultaneously measured. A strong asymmetry in the tunnel barriers is observed.

dot. The detector signal-to-noise ratio is small compared to split-gate defined systems because an additional electron on the quantum dot is screened by the metallic film on top. Regions of constant electron number N on the quantum dot are indicated in this and further figures.

A finite DC-bias voltage up to 5 mV is applied to source and drain symmetrically in order to investigate the level spectrum of the quantum dot in the few-electron regime. The differential conductance is measured as a function of DC-bias and top plunger gate voltage. The ninth root of the differential conductance is plotted in Fig. 2(a) in order to enhance the small conductance values. The results are qualitatively similar to earlier experimental data of vertical and split-gate defined few-electron dots [2,5,8]. The charging energy for the second electron is about 5.5 meV. This is larger than that measured in other lateral few-electron dots. This number is even more surprising since screening effects from the Titanium film on top are present. This indicates that the quantum dot is very small. A singlet (S)-triplet (T) splitting of about 1.4 meV is observed depending on the gate configuration. The triplet state leads to a cotunneling edge in the $N=2$ blocked region [8]. In a different cooldown with similar results, the S–T crossing [4] for two electrons in the quantum dot is observed above 6 T perpendicular magnetic field (data not shown here), again consistent with a very small quantum dot.

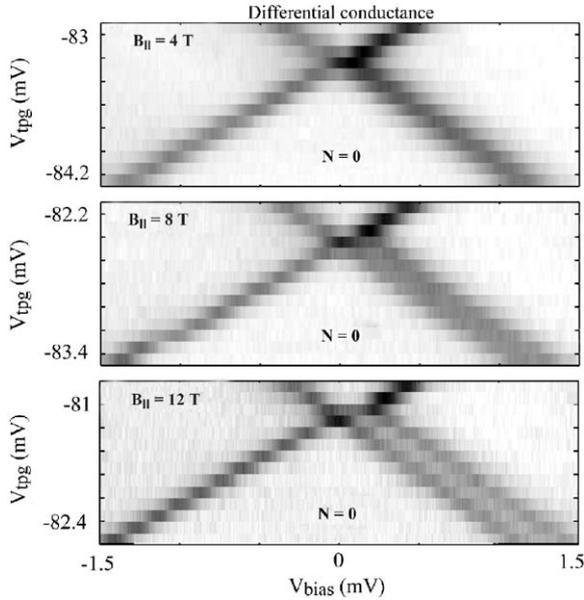


Fig. 3. Differential conductance as a function of DC-bias and top plunger gate voltage for fixed parallel magnetic field. The Zeeman splitting for the first electron ground state is observed at 12 T.

The detector signal as a function of DC-bias and top plunger gate voltage is shown in Fig. 2(b). It was measured simultaneously with the differential conductance through the dot. The dip in the detector signal occurs at the edge of the Coulomb blocked region on one side. The first excited state as well as the triplet state of two electrons can be followed also in the detector signal. An asymmetry in the tunnel barriers leads to the observed strong V_{bias} -asymmetry in the detector signal. The charging process in the detector is only observed when the dot level is aligned with the strong coupling lead. This asymmetry is set by the lithographic process defining the QPCs. We were not able to remove this asymmetry completely due to voltage limits of the top gates for this sample. This problem can be avoided by defining QPCs in a more open regime with the SFM-lithography.

The differential conductance for filling the first electron into the dot is measured for three fixed parallel magnetic field values as a function of DC-bias and top plunger gate voltage (see Fig. 3).

The expected Zeeman splitting of the first electron ground state (1eGS) as reported previously (e.g. Ref. [5]) is measured for finite in-plane fields. A g -factor of about $|g| = 0.2$ is estimated at 12 T. This value is smaller than the expected bulk value $|g| = 0.44$ due to the incomplete splitting of the temperature-broadened peaks. The splitting is only observed for one current direction because of the asymmetric tunnel barriers.

We performed measurements on sample B at 100 mK with similar results. The charging energy for the second electron of about 5 meV is comparable to sample A. The S–T splitting energies of about 0.7 meV at zero magnetic field are somewhat smaller (Fig. 4(a)). A perpendicular magnetic field of 3.5 T is applied to sample B (Fig. 4(b)).

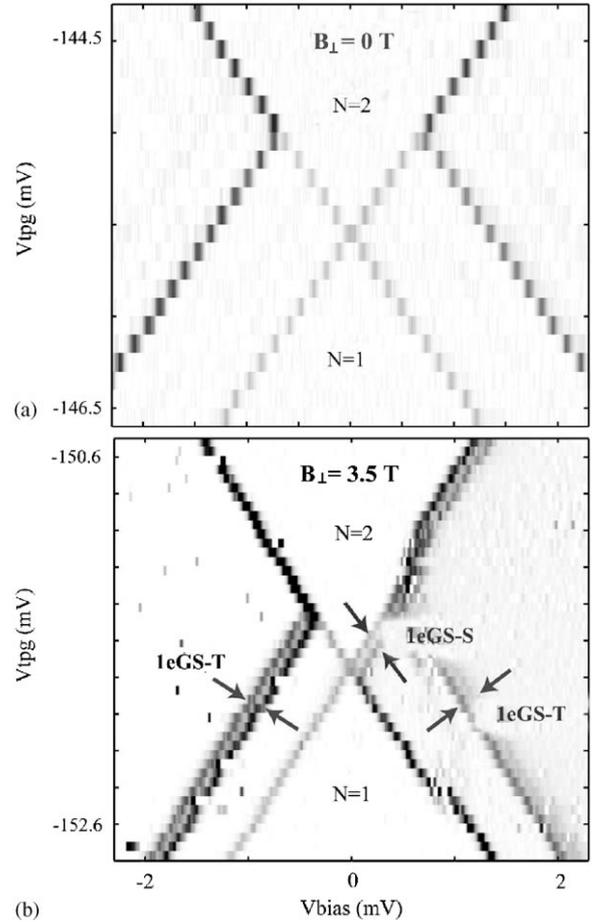


Fig. 4. Differential conductance as a function of DC-bias and top plunger gate voltage for fixed perpendicular magnetic field. (a) S–T splitting of about 0.7 meV observed at zero magnetic field. (b) S–T splitting reduced to 0.4 meV at 3.5 T perpendicular field. Zeeman splitting is measured for the 1eGS–S transition and the 1eGS–T transition.

The S–T splitting is reduced to 0.4 meV. Additionally, a Zeeman splitting is observed for 1eGS–S transition and the 1eGS–T transition as described in Ref. [6]. A g -factor of 0.4 can be extracted in agreement with previous measurements [5,8].

All experimental results, in particular Zeeman splitting and singlet–triplet transition, are in qualitative agreement with previous experiments for few-electron quantum dots. The energy scales (charging energy and singlet–triplet splitting) are bigger compared to other lateral few-electron dot systems. High tunability is achieved with the additional layer of Titanium top gates. The integration of these lateral few-electron dots into more complex structures is achievable with this layered SFM-lithography and promising for future nanostructure design.

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