Lateral Quantum Dots in High Mobility Heterostructures

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We have fabricated single lateral quantum dots in the two-dimensional electron gas (2DEG) of modulation doped GaAs/AlGaAs and Si/SiGe heterostructures, which are basic elements for more sophisticated devices. Electrical measurements were carried out at temperatures down to 30 mK. The technology of the GaAs structures has been adapted to Si/SiGe-based lateral quantum dots. We report Coulomb blockade measurements of lateral quantum dots formed by the split-gate technique on MBE grown modulation doped GaAs/AlGaAs and $Si/Si_{0.75}Ge_{0.25}$ heterostructures.

Introduction

In several recent proposals [1] – [3] lateral quantum dots were discussed as a promising option to realize the quantum entanglement necessary for quantum computation. As an approach to this topic we have chosen to fabricate single quantum dot devices in the two-dimensional electron gas (2DEG) of GaAs/AlGaAs and Si/SiGe heterojunctions. These dots are the basic building blocks of more complex structures (e.g. [4]), which we plan to investigate in the near future.

The technology of the GaAs structures has been adapted to Si/SiGe based lateral quantum dots. Recently, several lateral quantum dots in silicon/silicon-germanium heterostructures have been reported [5], [6]. However, none of these were achieved by the classical split-gate technique that is necessary for the coupling of quantum dots and for high integration.

Sample Preparation

GaAs/AlGaAs

High mobility modulation doped GaAs/AlGaAs heterostructures were grown by MBE at TU Vienna. The 2DEG in these samples is typically situated 70 – 100 nm below the surface. Further processing of the samples was done in the cleanroom in Linz. Hall bars were structured by optical lithography. Ohmic contacts to the 2DEG were made by depositing Cr, Au, Ge, Ni, Au and annealing at 450 °C. The mesa was wet chemically etched.

The electrical properties of the 2DEG were determined by quantum Hall effect and SdH measurements. Typical carrier densities were in the range from 2 to 4×10^{11} cm^{-2} with mobilities between 0.3 and 2×10^6 cm^2/Vs.

The area of the quantum dot is defined by Cr/Au gates on top of the Hall bar mesa, which were written by e-beam lithography. The top center gate electrode acts as a plunger gate. Gold connections from the bond pads to the small gates are structured by optical lithography.

Si/SiGe

High mobility modulation doped Si/SiGe heterostructures were grown by MBE in Linz. The 2DEG in these samples is situated about 85 nm below the surface. Hall bars were structured by optical lithography. Ohmic contacts were formed by deposition of Au/Sb and subsequent annealing at 350 ºC. A Hall bar structure was prepared by reactive ion etching (RIE) with SF_6.

Electrical measurements (SdH and QHE) at 1.5 K showed an electron mobility of 150,000 cm²/Vs at an electron density of 3.2×10^{11} cm^{-2}

The split gate structures were written by e-beam lithography and defined by lift-off of the Schottky-gate metal Pd. The top center gate electrode acts as a plunger gate. Connections from the bond pads to the small gates are made of Palladium.

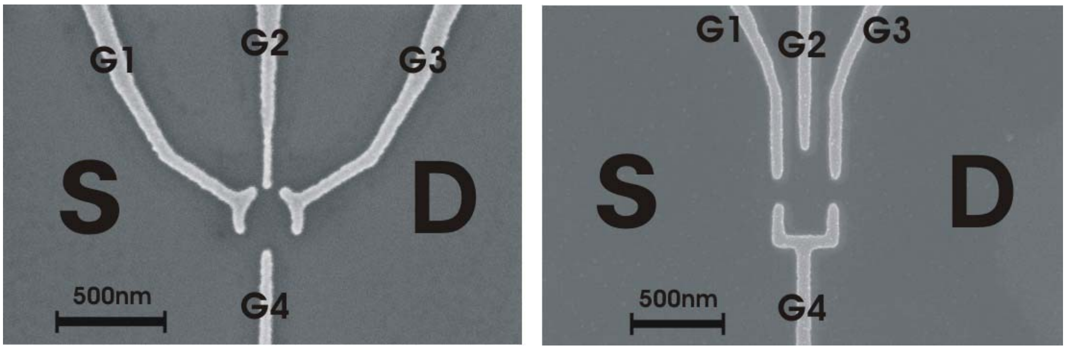

Fig. 1: Scanning electron micrograph of (a) the Cr/Au top gates on a GaAs/AlGaAs sample and (b) the Pd split gates on a Si/SiGe sample. The pitch between the upper gates is 185nm.

Measurements

When applying a negative voltage to the gates the underlying 2DEG is depleted and the dot area is defined in the center. By varying the plunger gate voltage, the energy levels inside the quantum dot can be moved into and out of resonance with the Fermi level in the leads. The conductance will increase whenever the energies are aligned and decrease in between, forming the so called Coulomb oscillations. If a large DC bias is applied at the source drain contacts the transport blockade can be overcome and excited energy states of the quantum dot can be probed.

GaAs Quantum Dots

By measuring the conductance versus both the plunger gate voltage V_G and the source drain voltage V_{SD}, we obtain the so-called quantum dot spectrum. It gives access to a lot of information about the quantum dot. Such a measurement is shown in Fig. 2 (a) below.

From the size and shape of the rhombic regions indicated by lines we obtain electrical properties such as capacitances of the gates and leads with respect to the dot. It is also possible to estimate the electrically active size of the dots from these data. This will differ from the actual geometrical size of the dot because of a depletion region, which extends around the gates. The difference between structural diameter and electrically active diameter indicates that the depletion region extends about 80 – 90 nm around the gates.

By changing the plunger gate voltage the tunnel barriers are also influenced, which limits the number of measurable Coulomb oscillations. Counteractive changing of the voltage on the outer gates allows us to stabilize the tunnel barriers and therefore increase the range of occupation numbers accessible by measurement.

In a few of the investigated samples we have observed conductance fluctuations superimposed upon the usual Coulomb oscillations. What at a first glance looked like random noise, turned out to be a reproducible fluctuation on a very small gate voltage scale, which was preserved over several sweeps in both directions (see Fig. 2 (b)).

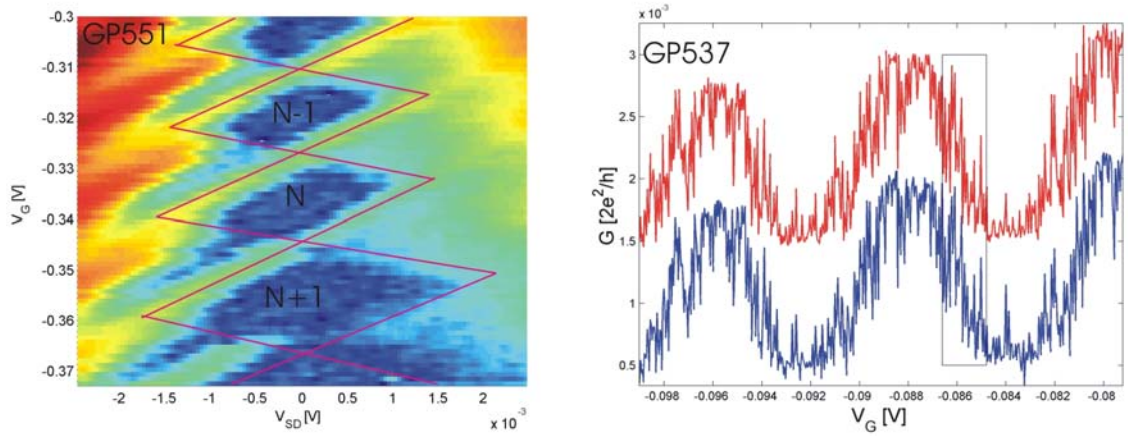

Fig. 2: (a) Differential Conductance of the AlGaAs quantum dot as a function of gate voltage and applied dc source-drain voltage; (b) reproducible conductance fluctuations.

Interestingly, these fluctuations still occur on an energy scale smaller than 3 µeV, which is an order of magnitude smaller than the thermal energy at 300 mK (k_{BT} = 26 µeV), and would therefore be assumed to be smeared out.

Further measurements will be required to investigate the exact origin of these fluctuations.

Si/SiGe Quantum Dots

A lateral quantum dot formed by a split-gate technique was realized on a modulation doped $Si/Si_{0.75}Ge_{0.25}$ heterostructure and Coulomb blockade was measured up to 1 K. Figure 3 shows the quantum dot spectrum ("Coulomb diamond") taken at 30 mK and 1 K.

By analyzing the measured Coulomb diamonds we estimated the gate and the source capacity to be 6.4 aF and 30 aF respectively and the total dot capacity to be 65 aF. Therefore the dot diameter is approximately 160 nm resulting in less than 70 electrons in the dot.

These results show that SET functionality can be achieved in modulation-doped Si/SiGe heterostructures with a standard split-gate approach that can easily be integrated into an array of coupled SETs as suggested in Ref. [3].

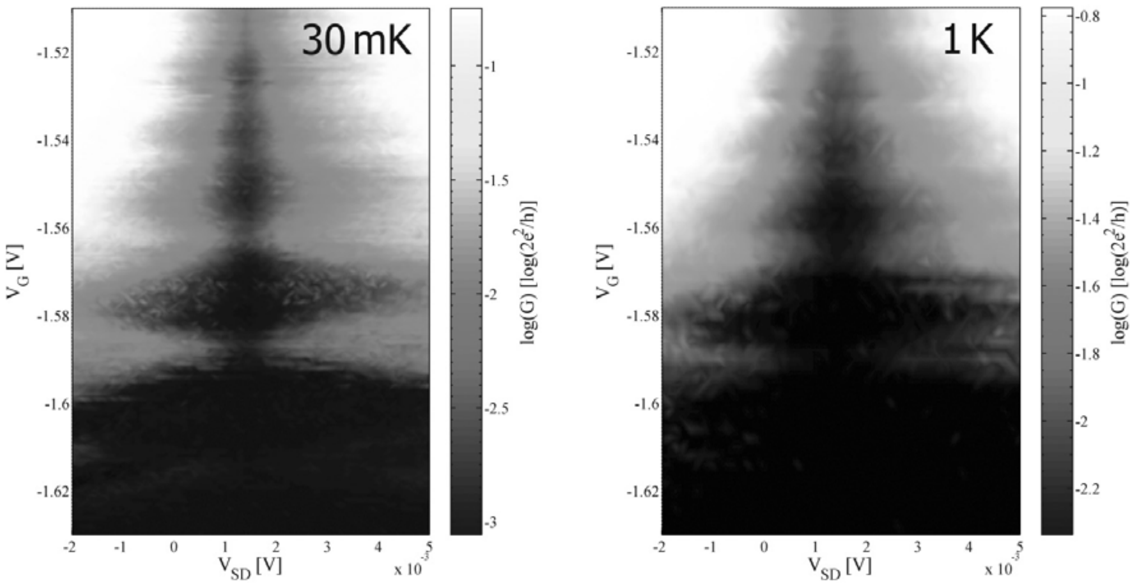

Fig. 3: Differential Conductance of the Si/SiGe quantum dot as a function of gate voltage and applied dc source-drain voltage at a) 30mK and b) 1K. Coulomb blockade diamonds are clearly visible.

Conclusion and Outlook

Single lateral quantum dots in the 2DEG of modulation doped GaAs/AlGaAs and Si/SiGe heterostructures have been realized with a split-gate technique. Coulomb blockade measurements, which prove the functionality of our devices, were performed down to a temperature of 30 mK. Based on these results we will fabricate quantum dot circuits consisting of two or more dots, which may be combined with quantum point contacts for charge readout.

Acknowledgements

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