Fabrication and Characterization of Lateral Quantum Dots in GaAs Heterostructures

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We have improved the design of our lateral quantum dots, which are fabricated from a two-dimensional GaAs/AlGaAs heterostructure by electron beam lithography. Our split gate geometry, which defines the dot electrostatically by metal gates, has been modified. The devices were characterized electrically in a ^{3}He cryostat at 300 mK. Due to improvements in device design and measurement conditions we can now control the number of electrons in the dot over a wider range. Additionally we have observed reproducible conductance fluctuations overlaid on the Coulomb oscillations.

Introduction

In several recent proposals [1], [2] lateral quantum dots were discussed as a promising option to realize the quantum entanglement necessary for doing quantum computation. We have fabricated quantum point contacts and single lateral quantum dots in the two dimensional electron gas (2DEG) of a GaAs/AlGaAs heterostructure, which are basic elements for more sophisticated devices. Already one year ago we have presented first working devices of this type, but the fabrication process was not very reliable then and measurement results were not reproducible from one device to the next. In the meantime we have improved both the fabrication process and the electrical measurements. In our present devices we have thus greater control over the number of electrons in the quantum dot. Now we can think of combining two or more lateral dots, which will allow us to investigate effects, in coupled dot systems.

Experimental

Our samples are based on a MBE grown GaAs/$Al_{0.3}Ga_{0.7}As$ heterostructure with a 2DEG situated approximately 100 nm below the sample surface. They have a carrier concentration of about 2×10^{11} cm^{-2} and a mobility of up to 1.4×10^{6} cm^2/Vs. Ohmic contacts were made from an Au/Ni/Ge alloy and Hall bar mesas were wet-etched with H_2SO_4:H_2O_2:H_2O (1:6:150). The quantum dot structure was defined by e-beam lithography and subsequent deposition of Cr/Au metal electrodes (i.e. the split gates) on top of the hall bar mesa. Figure 1 shows all important parts of the sample in different magnifications. By applying a negative voltage to the split gates the underlying 2DEG can be completely depleted. Our new dot design consists of four gate fingers, which define a quantum dot. The two outer gates in connection with the bottom gate define the tunnel barriers, which separate the quantum dot area from the surrounding 2DEG. The top center gate (the plunger gate) can be used to change the electrostatic potential of the dot. In comparison to our previous design the tunnel junctions are further away from the plunger gate, and are thus not so easily influenced by the plunger gate voltage, which has been one of the major problems with the former design. A SEM image of the new split gate geometry is shown in Fig. 1 (b), the old geometry is shown for comparison in the inset. The quantum dot area defined by the metal gates is approximately circle shaped with a diameter of roughly 400 nm in the investigated sample.

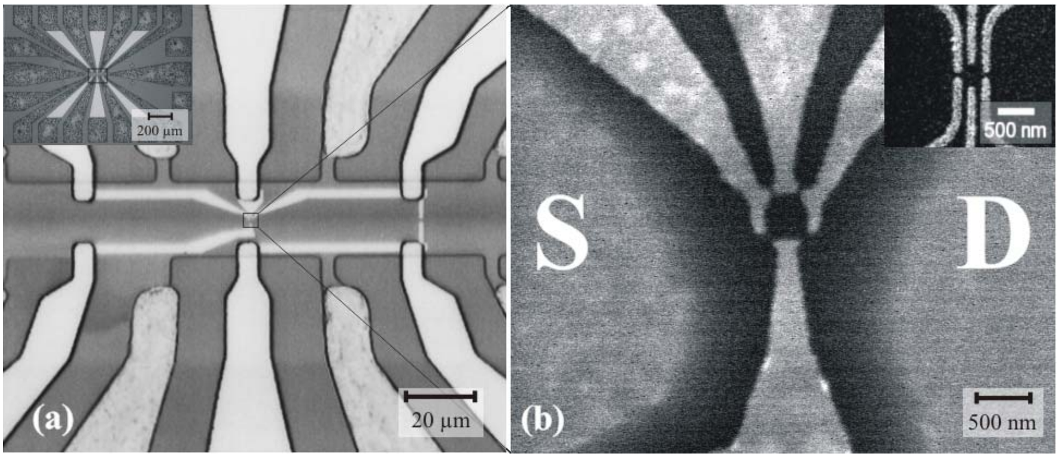

Fig. 1: (a) shows an SEM image of a part of the hall bar containing the split-gate structure. The inset shows the entire structure including the ohmic contacts.
(b) SEM image showing enlarged view of the center region marked in Fig. 1 (a). The inset shows the old gate geometry for comparison.

Electrical measurements were carried out in a ^{3}He cryostat at a temperature of 300 mK using a low frequency lock-in technique (f = 10 Hz). To avoid heating of the electrons it is important to keep the excitation voltage lower than the thermal energy, which corresponds to 25 µV at 300 mK, thus excitation voltages of 10 µV or below have been used. In order to define the quantum dot in the 2DEG, negative voltages have to be applied to the split-gates. By sweeping the plunger gate voltage the number of electrons in the dot is changed. Such a measurement is shown in Fig. 2 (a), where the conductance through the dot is plotted versus the plunger gate voltage. From the period of the conductance peaks a gate capacitance of $C_G = 8.9\times10^{-18}$ F can be calculated. Because the plunger gate voltage also has an influence on the tunnel barriers, the peak conductance decreases towards more negative voltages, until it is finally totally pinched off at about $V_G = -0.2$ V.

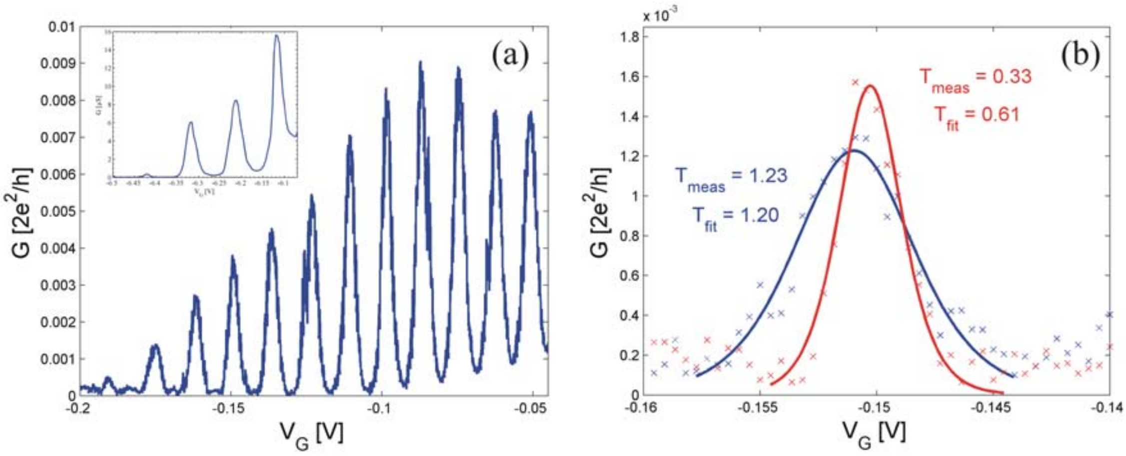

Fig. 2: (a) Coulomb oscillations observed in the conductance G versus plunger gate voltage V_g. The spacing of the peaks gives an estimate of the gate capacitance $C_g = 8.9$ aF.
(b) Fit of Coulomb peak lineshape at two different temperatures.

When compared to measurements in our first samples, where only very few for two temperatures are shown in Fig. 2 (b), while at the higher temperature (1.2 K) the fitted temperature is in good agreement with the measured temperature value, at a measured temperature of 0.3 K the fit indicates that the electron gas is heated up to 0.6 K. Therefore we have to further improve our measurement equipment by installation of additional filters, which eliminate any disturbing signals.

Closely looking at the data shown in Fig. 2 (a), one can see that there is a fluctuation superimposed upon the Coulomb oscillations (Fig. 3 (a)). So far we observed these fluctuations in two samples, where the fluctuations have been bigger for the larger dot with a diameter of 900 nm. Figure 3 (b) shows a measurement in the larger dot where the gate voltage was swept up and down (curves are offset for clarity), from which it is obvious that the fluctuation is not some random noise but a reproducible effect. The origin of these fluctuations is not yet clear to us. Oscillations could be seen, the improvement is clearly visible. One of our goals is now to design the gate geometry in a way that transport is possible until only one electron remains in the dot.

The Coulomb peaks have a thermally broadened lineshape and can thus be used to determine the temperature of the electron gas, which may be heated up with respect to the crystal lattice by stray pick-up of RF signals. A fit of the lineshape

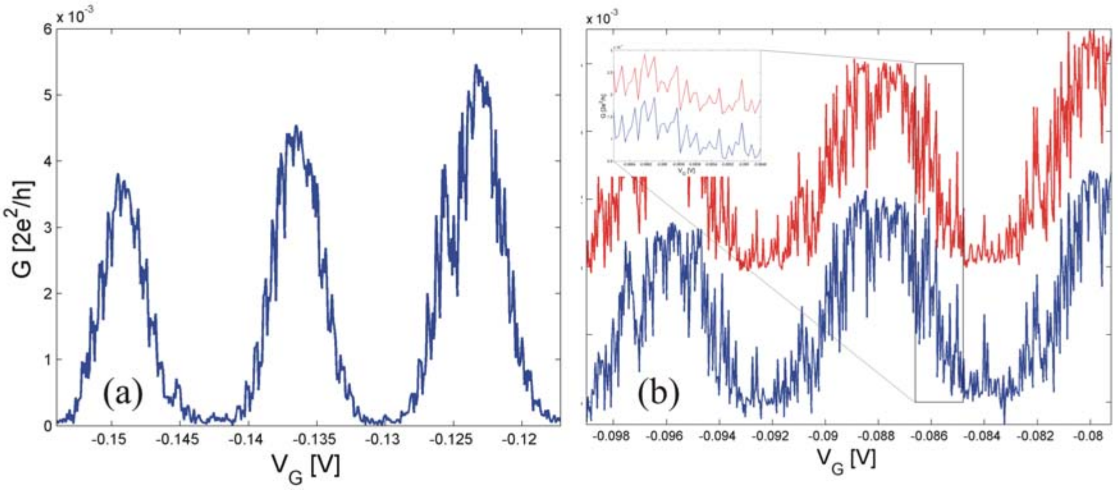

Fig. 3: Conductance fluctuations superimposed on Coulomb oscillations for two dots: (a) 400 nm dot; (b) 900 nm dot: the fluctuations are reproducible on a very small voltage scale.

In addition to changing the plunger gate voltage, we may apply a large DC source drain bias, superimposed by a small AC signal, which is detected by lock-in amplifiers. By doing so we measure the differential conductance dependent on both V_G and V_{SD}. With such a measurement the basic properties of the quantum dot are obtained, including total and source capacitance as well as an estimate of the actual size of the quantum dot. Figure 4 shows a grayscale plot of such a measurement. The horizontal axis corresponds to the plunger gate voltage V_G, the vertical axis to the source-drain voltage V_{SD}. The dark (bright) areas correspond to low (high) G. In the dark parallelogram-shaped regions marked by lines the number of electrons is fixed and no transport is possible due to Coulomb blockade.

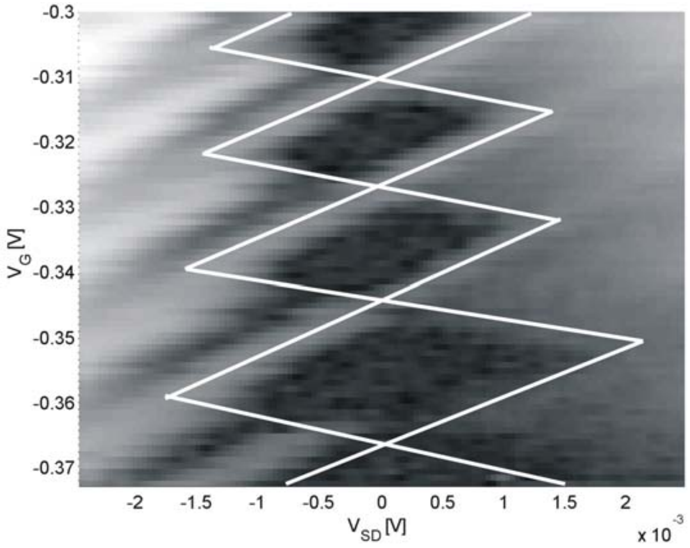

Fig. 4: Differential conductance *G* versus source-drain voltage V_{SD} and plunger gate voltage V_G. The dark (bright) areas correspond to low (high) *G*. Coulomb blockaded regions are enclosed by the lines.

From the conductance peak spacing ΔV_G at zero source drain voltage the capacitance C_G of the plunger gate can be calculated to be 8.9 aF. From the slopes of the peak lines we obtained the total and the source capacitance to be C = 103.8 aF and C_S = 27.2 aF. Via the known relation for the charging energy $E_C = e^2/C$ we related the gate voltage scale to an energy scale. From the capacitance of a 2D disk $C = 4\varepsilon_0\varepsilon_r d$ (for GaAs ε_r = 12.9) we estimated the diameter of the electron island to be about 225 nm. Considering that the depletion region will extend around the contours of the split-gates (by a length comparable to the depth of the 2DEG, which is ~100 nm), this is in good agreement with the structural diameter of 400 nm.

Conclusion

We have refined the processing our split-gate quantum dot devices and our results confirm that their electrical properties have improved. Further measurements will be performed on these structures to investigate the origin of the observed conductance fluctuations. Because the optimized fabrication process now gives very reproducible results and a good yield, as a next step we will integrate two or more dots into a quantum dot circuit, which may be combined with quantum point contacts for charge readout [3]. A dilution refrigerator, which is currently being installed in our lab, will allow us to reach lower temperature and increase the resolution in upcoming measurements.

References

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