Coupled Split Gate Quantum Dots in GaAs Heterostructures

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We report electrical investigations on a GaAs based double quantum dot structure at low temperatures. The split-gate structure forming the dots was fabricated by a combination of optical and electron beam lithography. The measurements were performed in a dilution refrigerator at temperatures down to 30 mK. We were able to observe a strong indication of a double dot with variable coupling in-between the dots.

Introduction

Split gate quantum dots are among the discussed options for realizing a split-gate quantum computer [1]. A single dot could be used as a qubit, forming a basic building block for quantum computation. However, at least two coupled dots are needed to create entanglement between electrons and perform more useful qubit operations. In the past we have successfully created single GaAs split-gate dots, followed by similar structures in the SiGe system [2]. We now have extended our design to double dots within the GaAs system with the prospect of using the gathered experience in measurements on coupled SiGe dots in the future, where the experimental situation is more difficult.

Sample Preparation

Our samples are based on a MBE grown GaAs/$Al_{0.3}Ga_{0.7}As$ heterostructure with a 2DEG situated approx. 70 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 at different magnifications. By applying a negative voltage to the split gates the dot potential is formed in the underlying 2DEG. This double dot design consists of six gate fingers, which define a quantum dot (see Fig.1 (d)). Three tunnel barriers are formed by gate 1 in conjunction with gates 2, 4 and 6. These barriers are supposed to separate the two dots from the surrounding 2DEG and from each other. Gates 3 and 5 are designed to be used as plunger gates to be able to vary the number of electrons on the two dots independently of each other. Gates 7 and 8 form quantum point contacts together with gates 2 and 6 respectively, which are intended for use as charge detectors. The size of the whole double dot structure is less than 500 nm, leaving roughly a size of 200 nm for each of the single dots.

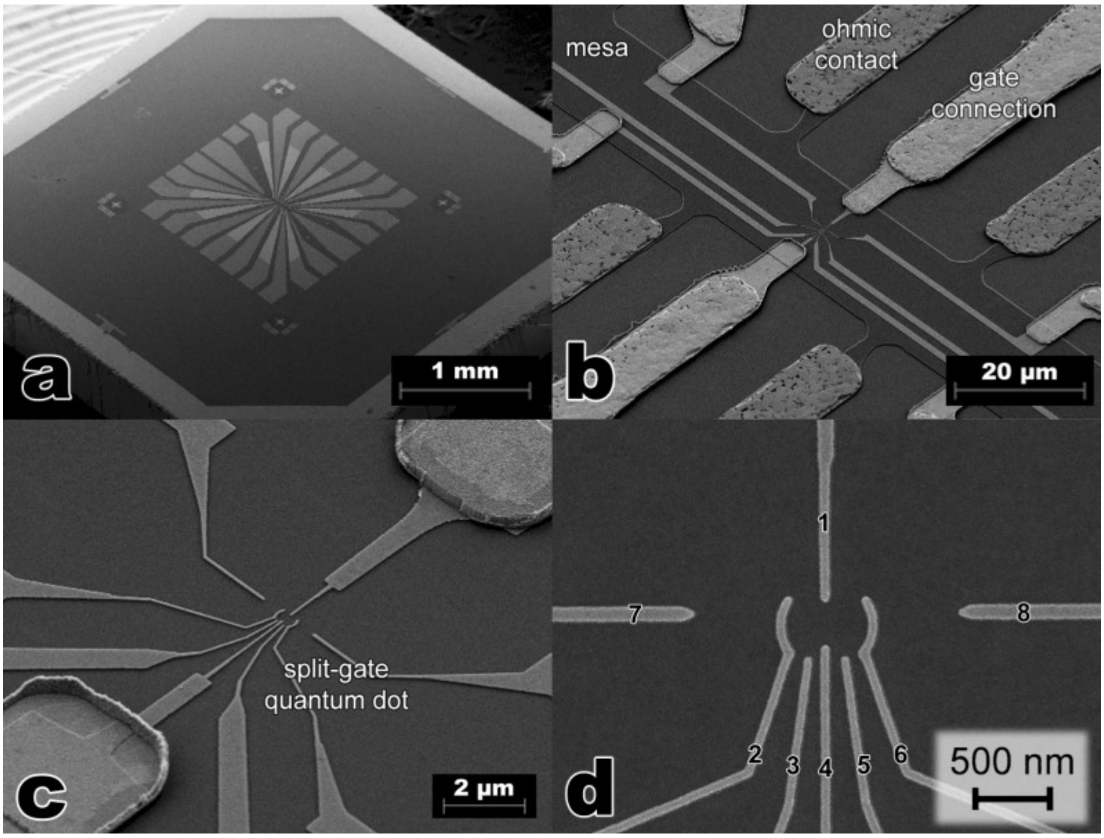

Fig. 1: SEM images of a double quantum dot split-gate structure fabricated by electron beam lithography. Pictures (a) – (d) show the sample at increasing magnifications.

Measurements

Measurements on this sample were performed in a dilution refrigerator capable of reaching temperatures of down to 30 mK. A low frequency lock-in technique was used for the measurements. A small AC voltage signal is applied on the sample and the resulting current through as well as the voltage drop across the device is measured by the lock-in amplifier. This gives the differential conductance $G=dI/dV_{SD}$. The applied voltage should not lead to additional heating of the sample, which means the condition $V_{SD} < kT/e$ should be fulfilled. At 30 mK this means the voltage should not exceed 2.5 µV. Additionally a larger DC voltage can be superimposed on the AC signal, which shifts the working point of the device, allowing to trace the nonlinear current voltage characteristics.

Single Quantum Dot

The double dot structure can of course also be used as a single dot, by adjusting the gates in corresponding fashion. Figure 2 shows a 2D plot of the differential conductance G of such a single dot depending on both the plunger gate voltage and on the source drain voltage. In the dark rhombic regions transport through the dot is blocked, whereas the lines around these regions mark transport through ground and excited states of the dot. From this plot the relevant basic data of the quantum dot can be easily extracted.

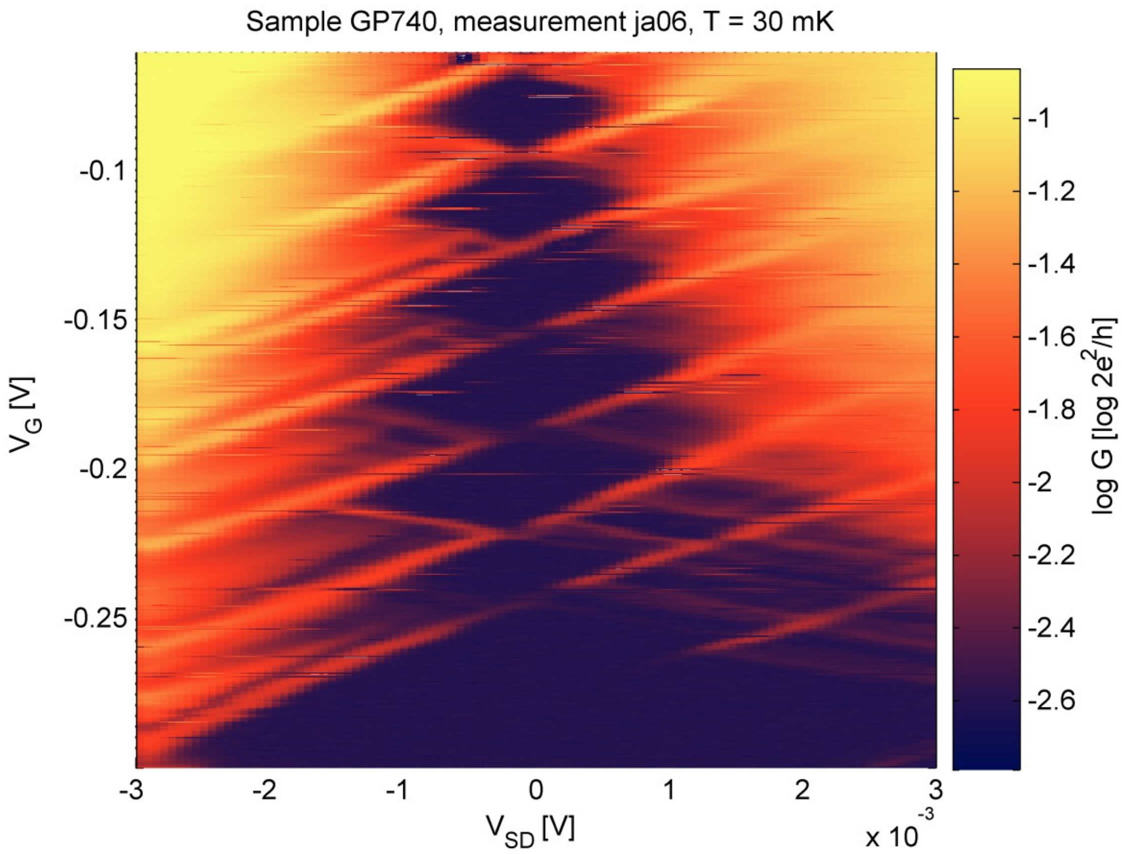

Fig. 2: Differential conductance G versus V_G and V_{SD} of a single quantum dot formed in our double dot structure. The dark rhombic regions mark where the Coulomb blockade is preventing transport through the dot. From the slope and distance of the diagonal lines we can evaluate the basic parameters of the dot.

In case of this dot we obtain a total capacitance C = 159 aF, a source capacitance C_S = 81.5 aF and a gate capacitance C_G =5.3 aF. The closely spaced lines outside the diamond regions correspond to excited states of the dot and their spacing can be used to roughly estimate the active size of the dot. In this case the average spacing ΔE is about 0.14 meV, giving an estimate of 182 nm for the diameter.

Double Quantum Dot

By varying gates 3 and 5 independently of each other one can check for the existence of coupled dots in the structure. In a single dot both gates couple to the same dot and one will observe a series of parallel lines in the conductance. For two dots each gate will mainly have an effect on its associated dot. That means the energy levels in the two dots are shifted more or less independently, leading to a pattern of crossed lines. In the extreme case of no coupling between the dots these lines would theoretically cross at right angle. The more strongly the dots are coupled the smaller the angle between the lines becomes. The extreme case of very large coupling corresponds to a single dot again. In between one observes a so-called honeycomb pattern. Figure 3 shows four such plots of the differential conductance G versus $V_{G,3}$ and $V_{G,5}$ for various settings of the other gates. In Fig. 3(a) the resulting conductance peak lines clearly cross, at a relatively small angle indicating the presence of a rather strongly coupled double dot. For the subsequent Figs. 3(b) – (d) the coupling is further increased to the extreme limit of a single dot (parallel lines) in Fig. 3(d).

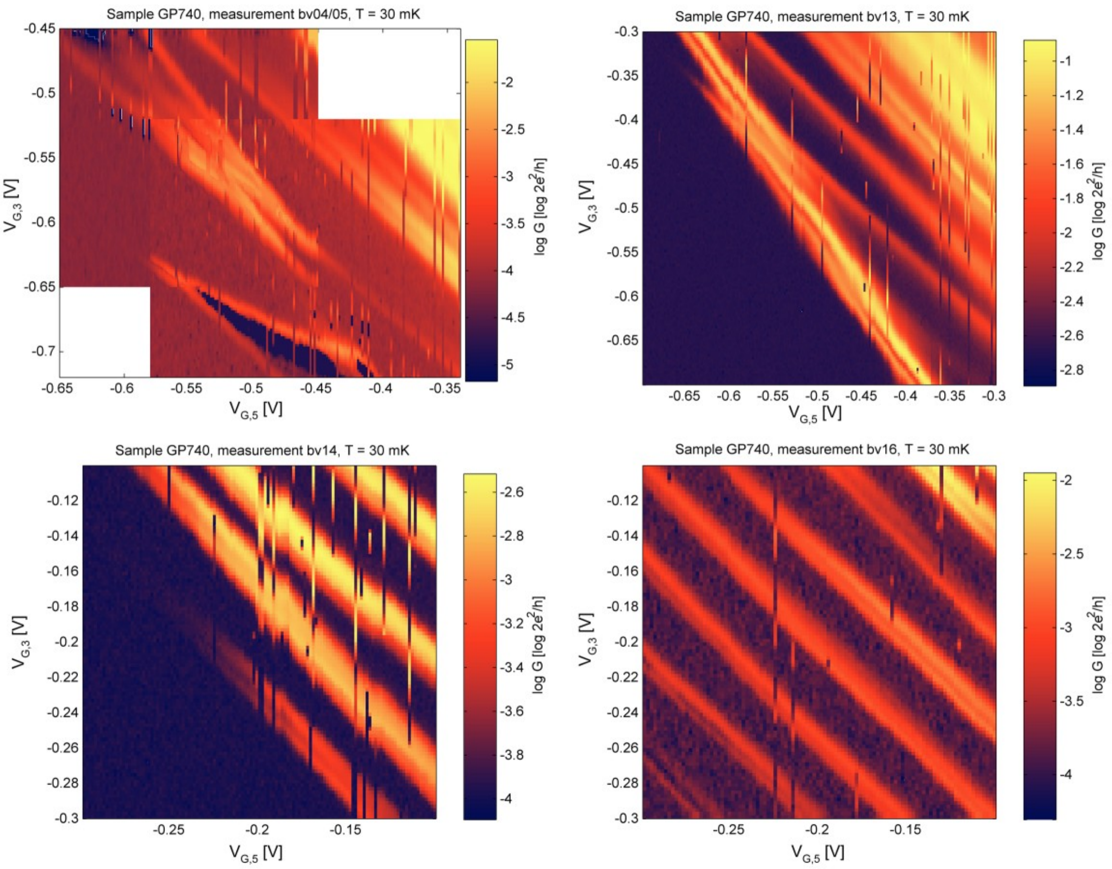

Fig. 2: 2D plots of the differential conductance G versus gate voltage on gate 3 and 5. (a) the crossed lines are a clear indication of having two rather strongly coupled dots. (b) – (d) with increasing coupling the lines become more parallel, finally indicating a large single dot in (d).

Conclusion

We have fabricated and electrically investigated a split-gate double quantum dot structure equipped with quantum point contacts for charge read-out. A single dot created in this structure had an estimated diameter of 180 nm. We could also observe the signature of variable coupling between two dots created in this structure.

Acknowledgements

FWF (P16160)

References

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