# Electrical Investigations on Quantum Point Contacts

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Quantum point contacts were fabricated from a two-dimensional AlGaAs structure by electron beam lithography in different techniques. Best electrical characteristics were achieved in split gate geometry. The resistance steps due to lateral quantization of the electron gas were observed. In addition conductance peaks in the high ohmic region due to Coulomb blockade of a random quantum dot appeared in the same samples. The diameter of the random quantum dot was estimated to be about 80 nm.

## 1. Introduction

In order to raise the skills in fabrication and investigation of quantum nanostructures, two diploma works were performed at the Institute for Semiconductor Physics in Linz. The main subject of the first work was the preparation of the structures, whereas the goal of the second work was its electrical characterization at low temperatures. The final goal of the project is to contribute to the upcoming quantum information technology.

## 2. Experimental

Quantum point contacts were prepared on high-mobility GaAs/AlGaAs Hall bars grown by MBE. The Hall bars were defined by conventional optical lithography and prepared by wet chemical etching [1]. For the point contacts different techniques were compared. Point contacts with deep etched sidewalls are sometimes not conducting due to the depletion layer along the damaged surfaces. Quantum point contacts which were defined by split gates on top of the Hall bars showed a better controllability and reproducibility. Images of such structures are shown in Fig. 1. The lateral opening of the point contacts is about 300 nm.

The structures were investigated at low temperatures of 1.4 K ($^4$He cryostat) and of 300 mK ($^3$He cryostat) with and without magnetic fields. When a negative gate voltage $V_g$ is applied to the split gate fingers, the two-dimensional (2D) electron gas layer is depleted just below. This can be seen for sample BT-482 in Fig. 2 (a), where the resistance increases from region “a” to region “b”. The current which flows along the Hall bar then can pass the gated region only through the narrow constriction in the 2D layer. Inside the quantum point contact, the electron wave is quantized in lateral modes. When the negative gate voltage is further increased, the lateral opening of the point contact is reduced and the number of occupied modes below the Fermi energy decreases. This is visible in a stepwise increase of the resistance of the quantum point contact in region “c” of Fig. 2 (a).

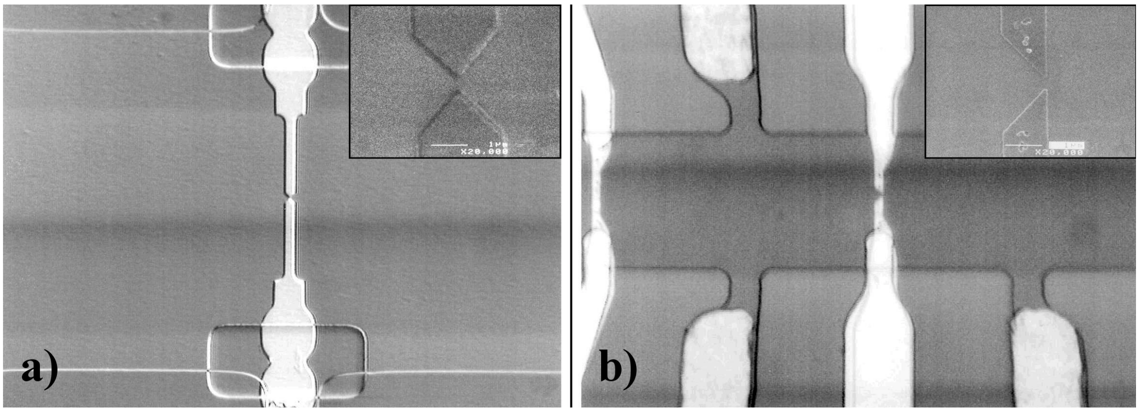
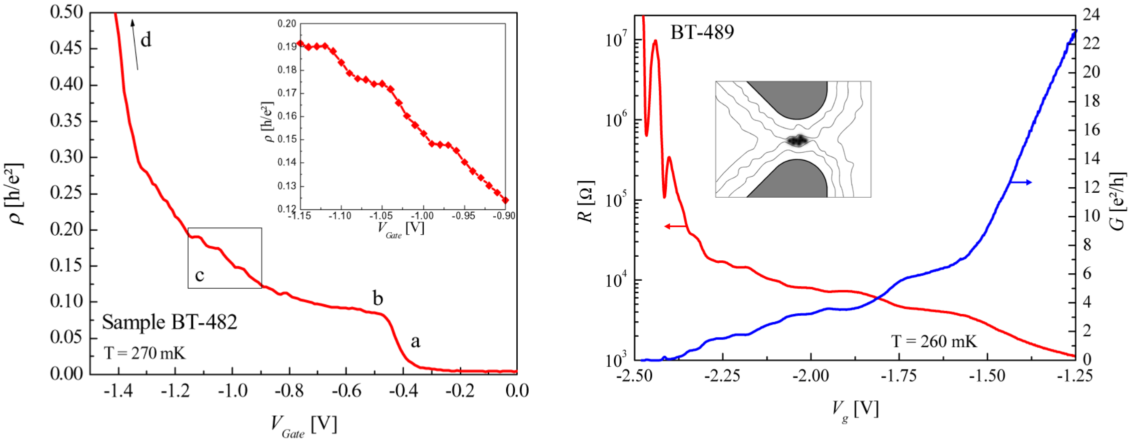


Fig. 1: Optical microscope pictures of split gate point contacts for samples a) BT-482 and b) BT-489. Details of the point contacts are shown in SEM-images as insets at the upper right corners.

In sample BT-489, in addition to the steps also peaks in the resistance are visible (see Fig. 2 (b)). These peaks in the resistance correspond to minimums in the conductance. It will be shown in the following that the conductance minimums correspond to the Coulomb-blockade regime of a random quantum dot inside the point contact [2]. Such a quantum dot can easily be formed by the potential fluctuations due to the remote doping centers and is illustrated in an inset in Fig. 2 (b).



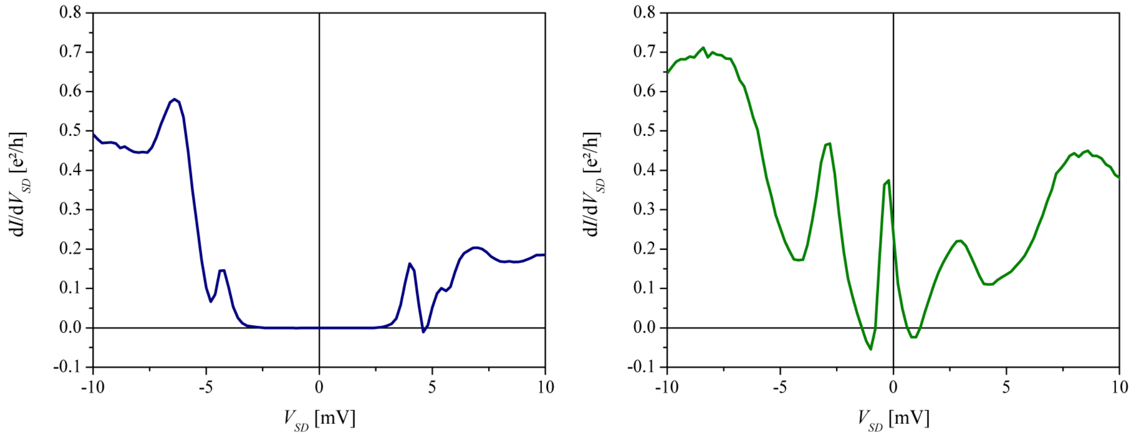
(a)

(b)

Fig. 2: (a) Resistance of sample BT-482 versus split gate voltage. Different regions of the 2D electron gas depletion and channel narrowing are visible. (b) Peaks in the resistance of sample BT-489 due to Coulomb blockade in a random quantum dot. The inset shows schematically how such a random dot could appear.

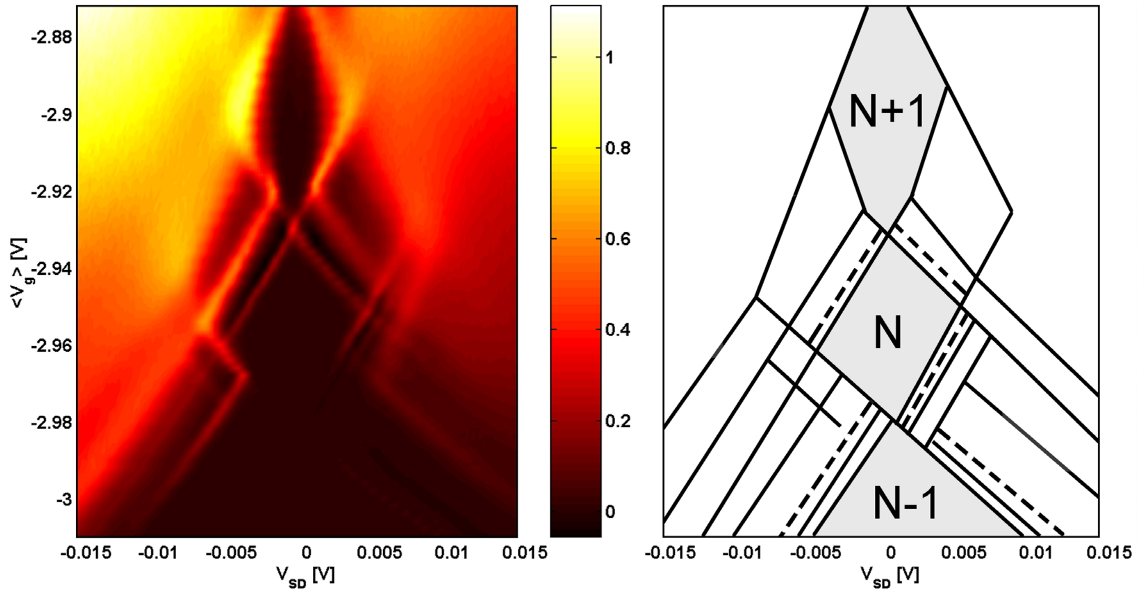
It is well known that due to the small size of a quantum dot, an additional single electron increases the potential of the dot so strongly that no further electron can enter. This is the Coulomb blockade regime. In order to test this behavior, a large source-drain voltage $V_{sd}$ across the quantum dot can be applied. If the voltage is large enough that it shifts the next electronic level below the Fermi energy at one side, an additional electron can enter the dot and leave at the lower Fermi energy side. Thus the conductivity increases.

Fig. 3 (a) shows the differential conductance versus $V_{sd}$ for the case that the Fermi energy is about in the center of the Coulomb gap. In comparison, Fig. 3 (b) shows the situation where the total energy of the n and the n+1 electron states are equal and the Coulomb gap is not effective. The conductance is than high at zero source-drain voltage.



(a) (b)

Fig. 3: Differential conductance as a function of the source-drain voltage (a) in the Coulomb blockade regime and (b) in the conducting regime of a random quantum dot inside the point contacts of sample BT-489.



(a) (b)

Fig. 4: Conductance spectrum of the quantum dot in sample BT-489. (a) Two-dimensional grayscale plot of the differential conductance G = dI/d$V_{SD}$ measured versus source-drain voltage $V_{SD}$ and gate voltage $V_g$. (b) Schematic diagram of the same data showing only the main features.

Figure 4 (a) shows the grayscale plot of the differential conductance. The horizontal axis corresponds to the source-drain voltage, the vertical axis to the split gate potential. The lighter areas correspond to higher conductance values. The same information is shown in Fig. 4 (b) in a schematic diagram. In Fig. 4 (b) one can see that the Coulomb blockade regimes form diamond-like shapes. At certain gate voltages, the necessary source-drain voltage in order to get conductivity through the quantum dot vanishes whereas at other source-drain voltages it is quite large. The solid lines in Fig. 4 (b) correspond to maximums in the differential conductance whereas the dashed lines mark regions of negative differential conductance. Such a decrease in the conductance with increasing source-drain voltage appears when an additional excited states opens up which has a slow transfer rate and thus blocks the quantum dot partly.

A detailed analysis of the different voltages reveals the most important dot parameters. From the vertical separation $\Delta V_g$ = 48 meV of the conductance peaks in Fig. 4, a gate capacitance of $3.3 \times 10^{-18}$ F can be estimated. The slopes of the conductance peaks lead to a total capacitance of $32 \times 10^{-18}$ F, which determines an absolute energy scale of the quantum dot. The Coulomb gap thus corresponds to a relative large energy of $E_C$ = 5 meV. The additional lines parallel to the Coulomb diamonds in Fig. 4 correspond to conduction through excited states of the quantum dot. From the energetic separation of the excited states in the energy spectrum the density of states can be estimated which gives a rough hint about the size of a small two-dimensional object. According to that, the dot has a diameter of about 80 nm, which is quite small.

## 3. Conclusion

Quantum point contacts were fabricated in 2D-AlGaAs heterostructures by electron beam lithography. The point contact structures showed the expected quantization steps in the resistance. In addition, a random quantum dot inside a quantum point contact could be characterized as well. With the acquired know-how in the fabrication of nanostructures it is planned to continue the work on quantum dots and to prepare especially coupled dot structures in order to investigate the elementary processes for quantum information.

## References

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