Hole transport in p-type GaAs quantum dots and point contacts

B. Grubić*, R. Leturcq*, T. Ihn*, K. Ensslin*, D. Reuter +, and A. D. Wieck+

*Solid State Physics Laboratory, ETH Zurich, 8093 Zurich, Switzerland
+Angewandte Festkörperphysik, Ruhr-Universität Bochum, 44780 Bochum, Germany

Strong spin-orbit interaction characteristic for p-type GaAs systems, makes such systems promising for the realization of spintronic devices. Here we report on transport measurements in nanostructures fabricated on p-type, C-doped GaAs heterostructures by scanning probe oxidation lithography. We observe conductance quantization in a quantum point contact, as well as pronounced Coulomb resonances in two quantum dots with different geometries. Charging energies for both dots, extracted from Coulomb diamond measurements are in agreement with the lithographic dimensions of the dots. The absence of excited states in Coulomb diamond measurements indicates that the dots are in the multi-level transport regime.

The interest in low dimensional hole-doped GaAs systems arises primarily from the fact that spin-orbit [1] as well as carrier-carrier Coulomb interaction effects are more pronounced in such systems compared to the more established electron doped systems, due to the fact that holes have approximately 6 times larger effective mass than electrons [2]. However, the investigation of electronic transport in low-dimensional p-type GaAs systems was mainly limited to two-dimensional bulk samples, due to difficulties to fabricate stable p-type nanodevices with conventional split-gate technique. The main problems we encountered in measurements on split-gate devices tested on several different p-type heterostructures are strong hysteresis effects in gate sweeps, as well as significant gate instabilities and charge fluctuations.

In order to overcome these problems with metallic gates, we employ a different lithography technique, namely, Atomic Force Microscope (AFM) oxidation lithography [3, 4] to define nanostructures on two-dimensional hole gases (2DHG). We demonstrate that for a 2DHG 45 nm below the sample surface the AFM written oxide lines with a height of 15-18 nm completely deplete the 2DHG beneath at low temperatures [5]. Density and mobility of the unpatented sample at 4.2 K are: \( p = 4 \times 10^{11} \text{cm}^{-2} \), \( \mu = 120000 \text{cm}^2/\text{Vs} \).

We fabricated a quantum point contact (QPC) with a lithographic width of 165 nm and tested its electronic functionality by measuring its conductance at low temperatures (Fig. 1). At the temperature of 500 mK quantized conductance plateaus are observed corresponding to transmission of one and two modes through the QPC. In addition, a plateau-like structure is observed corresponding to transmission of one and two modes through the quantized conductance plateaus are observed corresponding to transmission of one and two modes through the QPC. Inset: AFM micrograph of the QPC.

![FIG. 1: Two-terminal QPC conductance measurement at T=500 mK (black curve) and T=70 mK (gray curve). The trace corresponding to T=70 mK is shifted upwards by one conductance unit for clarity. A bias of 10 \( \mu \)V is applied symmetrically across the QPC. Inset: AFM micrograph of the QPC.](image)

We report on transport measurements of the dots close when the value of the plunger-gate voltage increases, as this is a clear indication that we measure hole transport. Coulomb resonances in two quantum dots with different geometries. Charging energies for both dots, extracted from Coulomb diamond measurements are in agreement with the lithographic dimensions of the dots. The absence of excited states in Coulomb diamond measurements indicates that the dots are in the multi-level transport regime.
FIG. 2: (a) Differential conductance of the rectangular dot in the configuration $V_{qpc1} = -213$ mV, $V_{qpc2} = -236$ mV as a function of plunger gate voltage. (b) AFM micrograph of the rectangular quantum dot with designations of the gates. (c) Coulomb diamonds in differential conductance for the rectangular dot in the configuration $V_{qpc1} = -225$ mV, $V_{qpc2} = -235$ mV, represented in a logarithmic gray scale plot (white regions represent low conductance). (d) AFM micrograph of the circular quantum dot. (e) Coulomb diamonds in differential conductance for the circular dot in the configuration: $V_{pg2} = -32$ mV, $V_3 = 72$ mV, $V_4 = 120$ mV, $V_5 = 310$ mV, $V_6 = 200$ mV represented in a logarithmic gray scale plot.

are fitted both with an expression for a thermally broadened Coulomb blockade peak in the multi-level transport regime and a coupling broadened Lorentzian peak. In all cases the thermally broadened resonance fits better to the data than a coupling broadened resonance, indicating that the dots are in the weak coupling regime. The electronic temperature extracted from the fitting is $\sim 130$ mK.

Coulomb diamond measurements are performed in the weak coupling regime for both dots, and the results are shown in Fig. 2. The uniform size of the diamonds indicates that all confined holes reside in one single potential minimum rather than occupying several disconnected or tunnel-coupled potential minima. From the extent of the diamonds in bias direction we estimate a charging energy of the rectangular dot to be $E_{C,rect} \approx 1.5$ meV, while the lever-arm of the plunger gate is $\alpha_{rect} \approx 0.26$. In case of the circular dot we obtain $E_{C,circle} \approx 0.5$ meV and $\alpha_{circle} \approx 0.14$. Assuming a disk-like shape of the dots allows us to estimate electronic radius of the dots from the values of their charging energies. The obtained value for the rectangular dot is $r_{rect} \approx 115$ nm, and for the circular $r_{circle} \approx 340$ nm, which is consistent with the lithographic dimensions of the dots and indicates that the dots are really formed in the regions encircled by the oxide lines.

Due to the large effective mass of holes, the single-particle level spacing in case of hole quantum dots is significantly smaller compared to electron quantum dots with similar size. The estimated mean single-particle level spacing in the rectangular dot is $\Delta_{rect} \leq 15$ $\mu$eV, and in the circular dot is $\Delta_{circle} \leq 2$ $\mu$eV. Therefore we were not able to resolve excited states in Coulomb diamond measurements in neither of the two dots. This fact, together with the observed temperature dependence of Coulomb peak heights [5] indicates that both dots are in the multi-level transport regime. In order to be able to investigate the single-particle level spectrum in hole quantum dots, one has to significantly reduce the lateral dimensions of the dot as well as the hole temperature.

In conclusion, we fabricated tunable nanodevices on p-type GaAs heterostructures by AFM oxidation lithography. By using this fabrication technique we were able to overcome the problems with large hysteresis effects present in gate sweeps in conventional split-gate defined nanostructures on p-type GaAs, and the stability of the structures improved as well. Electronic functionality of these structures was demonstrated by observing conductance quantization in a QPC, and Coulomb blockade in two quantum dots with different geometries. Further reduction in size of the p-type quantum dots is necessary in order to explore the influence of spin-orbit and carrier-carrier interactions on single-particle level spectra.

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