Characterization of Lateral Quantum Dots Fabricated by E-Beam Lithography

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Small lateral quantum dots were fabricated from a two-dimensional GaAs/AlGaAs heterostructure by electron beam lithography using a split gate technique, where the geometry of the dot is defined electrostatically by metal gates. The devices were characterized electrically in a ^{3}He cryostat at 300 mK. The measurements show conductance oscillations typical for Coulomb blockade. From the experimental data, the diameter of the dots was estimated to be approximately 125 nm.

Introduction

Artificial semiconductor quantum dots are among the presently discussed options for realizing the quantum entanglement necessary for doing quantum computation [1] and are also a suitable system for possible spintronics devices [2]. Since we are still at the beginning of our research in this field, we have chosen to fabricate single lateral quantum dots in a 2D GaAs/AlGaAs system as an entry point, which acts as a basis for more complicated devices.

A quantum dot can be shortly described as a mesoscopic electronic system coupled weakly to two electronic reservoirs (Fig. 1(a)). Electronic transport through such a structure is inhibited if the energy necessary to add an electron to the dot exceeds the electrochemical potential of the reservoirs and the thermal energy $k_B T$. This phenomenon is known as the Coulomb blockade. The addition of one electron to a quantum dot of total capacitance C requires the charging energy $E_C = e^2/C$.

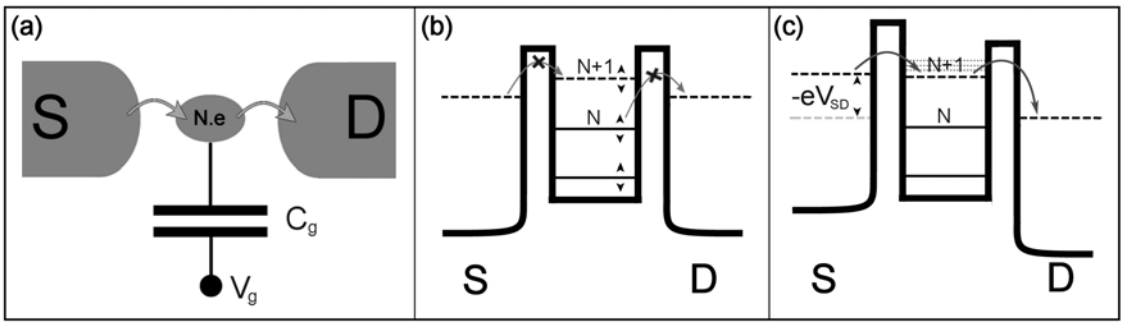

Fig. 1: (a) Schematic representation of a quantum dot. The area in the center is only coupled via tunneling to the source and drain leads. The charge on the dot can only be varied in quantized steps of e. (b) Schematic band diagram of the blocked state; by changing $V_{G,}$ the energy levels inside the dot can be shifted. (c) A large source-drain voltage allows transport via the N+1 state (dashed line), or its excited states (dotted lines).

By applying a voltage to a gate coupled capacitively to the quantum dot the energy levels inside the dot are shifted with respect to the reservoirs (Fig. 1(b)), which allows changing the number of electrons on the dot one by one. The variation in energy levels amounts to $\Delta E = e\Delta V_G(C_G/C)$, when changing V_G by ΔV_G. Whenever an energy level inside the dot is aligned with the chemical potential in the leads, current flows via sequential tunneling of single electrons into and out of the dot, resulting in periodic peaks in the conductance trace, which are referred to as Coulomb oscillations. The period corresponds to the charging energy E_C, which is equivalent to a period of $\Delta V_G = e/C_G$ in gate voltage units. Transport through the structure can also be achieved by applying a large DC source-drain bias (Fig. 1(c)). Whenever the Fermi level in the biased lead is aligned with one of the dot levels, the conductance increases. When the bias is raised further, the excited states of the dot energy levels also contribute to transport. The I-V characteristic of such a device is thus strongly non-linear.

Experimental

The investigated samples are based on a MBE grown $GaAs/Al_{0.3}Ga_{0.7}As$ heterostructure with a two dimensional electron gas (2DEG), which is situated 70 nm below the sample surface and has a carrier concentration of 2.73×10^{11} cm^{-2} and a mobility of 250000 cm^2/Vs. Using standard optical lithography, Hall bar mesas were wet-etched and ohmic contacts were made from an Au/Ni/Ge alloy. The actual quantum dot was defined by e-beam lithography and subsequent deposition of metal electrodes (i.e. the split gates) on top of the hall bars. The optical microscope image in Fig. 2(a) shows the ohmic contacts, the mesa, and the gate electrodes. By applying a negative voltage to the split gates, the 2DEG can be completely depleted. Using three pairs of gate fingers, a quantum dot can be easily defined. The outer pairs of gates define the tunnel barriers, which separate the quantum dot area from the surrounding 2DEG. Besides of defining the dot geometry, the inner gates can be used to change the electrostatic potential of the dot. Usually only one of the inner gates is varied and is then referred to as the plunger gate. A SEM image of this split gate geometry is shown in Fig. 2(b). The quantum dot area defined by the metal gates is approximately circle shaped with a diameter of roughly 260 nm in the investigated sample.

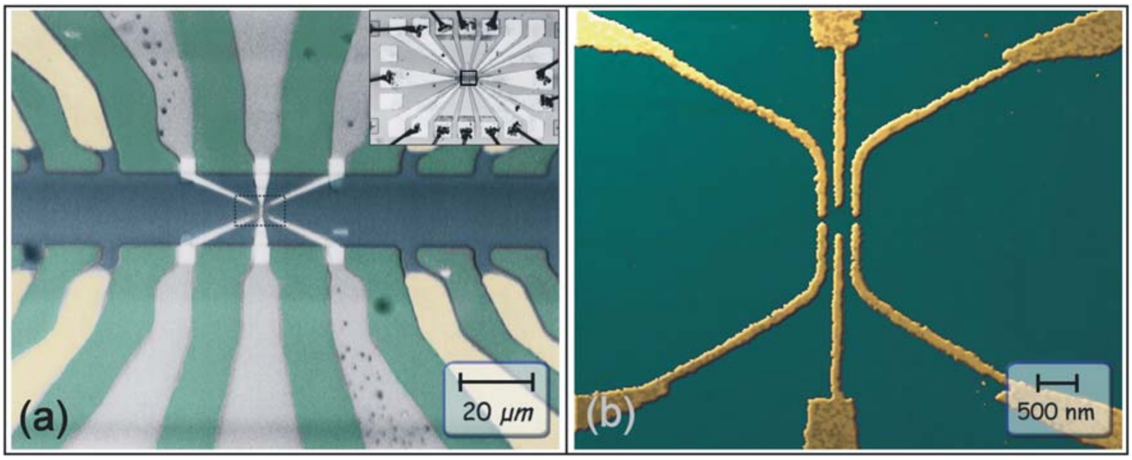

Fig. 2: (a) Shows a part of the hall bar containing the split-gate structure viewed in an optical microscope. The inset shows the entire structure including the bond pads. (b) This image was taken with the electron microscope and shows an enlargement of the center region marked in Fig. 2(a).

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.

The voltages on the split-gates were set to a negative value to ensure that the quantum dot is well defined and that the transport occurs via tunneling through the barriers. Then the plunger gate voltage was swept in order to change the number of electrons in the dot. Such a measurement is shown in Fig. 3(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 $C_G = 1.6\times10^{-18}$ F can be calculated. Because the plunger gate voltage also has an influence on the tunnel barriers, the conductance is totally pinched off at about –6.45 V. On the other hand, as V_G increases, conduction also occurs between the peaks (e.g. at –6.17 V), because the tunneling barriers become more transparent. In order to observe more oscillation periods, another split-gate geometry is required, where the plunger gate does not couple so strongly to the tunnel barriers.

By applying a large DC source drain bias, superimposed by a small AC signal, we measured the differential conductance dependent on V_{SD}. This measurement (Fig. 3(b)) clearly demonstrates the nonlinear *I-V* characteristics of the device. The differential conductance can even become negative, if an excited state has a long lifetime inside the dot and thus blocks transport as long as it is occupied.

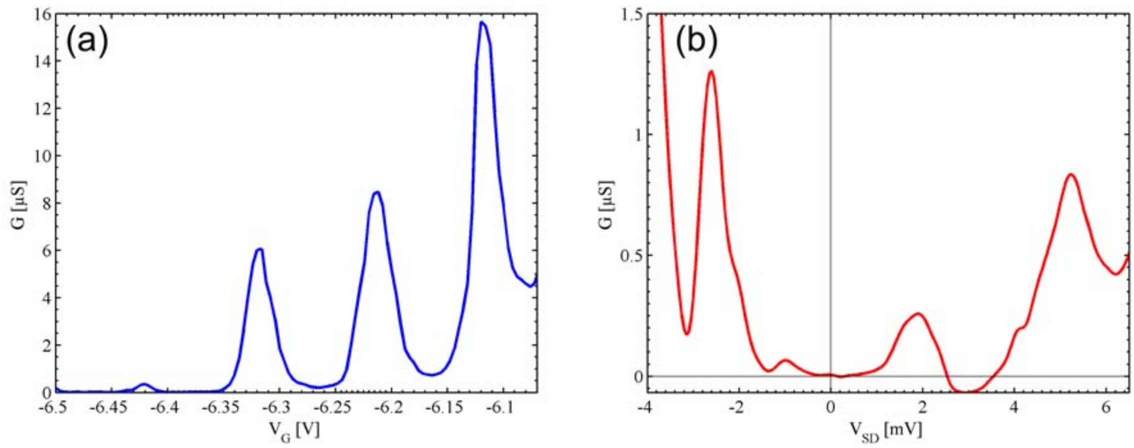

Fig. 3: (a) Coulomb oscillations observed in the conductance *G* versus plunger gate voltage V_g. The spacing of the peaks gives an estimate of the gate capacitance $C_g = 1.6\times10^{-18}$ aF. (b) Differential conductance *G* of a large bias V_{SD} measurement, showing nonlinear behaviour.

By combining both of the above measurements, most of the basic properties of the quantum dot can be obtained, including total and source capacitance as well as an estimate of the actual size of the quantum dot. Figure 4 shows a 3D plot of the differential conductance dependent on V_{SD} and V_G viewed from the top. The horizontal axis corresponds to the plunger gate voltage V_G, the vertical axis to the source-drain voltage V_{SD}. The blue (red) areas correspond to low (high) *G*. In the dark parallelogram-shaped regions, the number of electrons is fixed and no transport is possible due to Coulomb blockade. The features, from which important properties can be obtained, are marked by dotted lines.

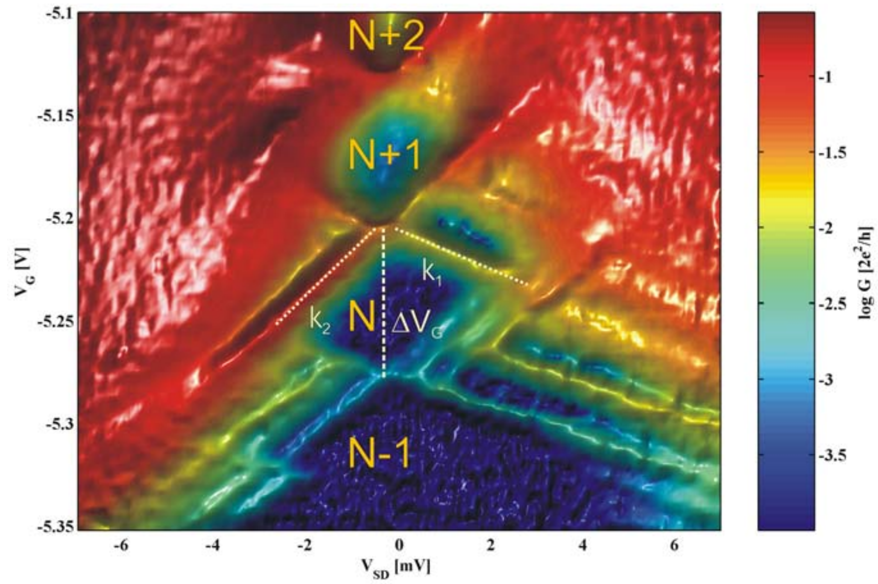

Fig. 4: Differential conductance *G* versus source-drain voltage V_{SD} and plunger gate voltage V_G. The blue (red) areas correspond to low (high) *G*. Coulomb blockaded regions are indicated by *N*–1, *N*, etc. Dotted lines mark some of the features used for evaluation. A light source illuminates the figure from the bottom to make the contours of peaks more clearly visible.

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 2.2×10^{-18} F. From the slopes of the peak lines (k_1, k_2) we obtained the total and the source capacitance to be $C = 71\times10^{-18}$ F and $C_S = 24\times10^{-18}$ F. 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 average vertical spacing of peak lines, corresponding to excited single electron states, we roughly estimated the diameter of the electron island to be about 125 nm. Considering that the depletion region will extend about 70 nm (i.e. the distance of the 2DEG from the surface) around the contours of the split-gates, this is in very good agreement with the structure diameter of 260 nm.

Conclusion

We have successfully fabricated split-gate quantum dots using 2D GaAs/AlGaAs heterostructures and our measurements of the Coulomb diamond demonstrate that they work as intended. Further measurements on these structures will be made to investigate their possible use for quantum information technology or for spintronics devices. Now that we have established this technology in our workgroup, we can further improve our device design and we will be able to fabricate more sophisticated structures such as coupled quantum dots, quantum dot arrays, etc. in the future.

References

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