SEMICONDUCTOR QUANTUM DOTS

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ABSTRACT

This work discuss problem of quantum dots and electron density, 2DEG density and coulomb blockade in quantum dots. The schematic diagram of a quantum dot in a lateral geometry is shown. The fabrication procedure for evaporating metal gate eletrodes and dry etching is demonstated.

1 INTRODUCTION

Quantum dots are suitable devices to study the interplay of classical charging effect and quantum confinement. The quantum dots discussed in this thesis are defined in a 2-dimensional electron gas (2DEG) formed within a heterostructure of semiconductor materials. The 2DEG has a high electron mobility and low electron density (typically 10^5 – 10^6 cm^2/Vs and ~10^{15} m^{-2}, respectively). The low electron density results in a large Fermi wawe lenght, and a largescreening lenght,enabling to vary the 2DEG density with an electric field. Lithographically defined semiconductor quantum dots have the shape of a disk with a diameter as small as 50-100 nm, becoming of the same order of magnitude as the Fermi wawelenght.

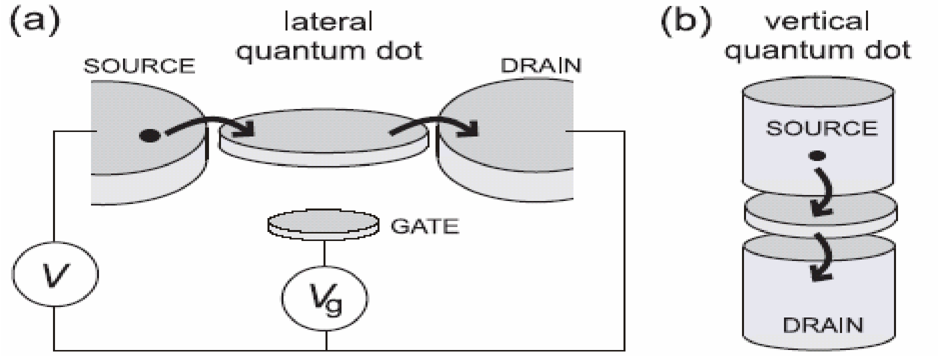

Fig. 1: *Schematic diagram of a quantum dot in a lateral geometry (a) and a vertical geometry (b). The quantum dot is represented by a disk, connected to source and drain contacts by tunnel junctions. For the lateral geometry the gate electrode is indicated, as well as theexternal voltage sources supplying the source drain voltage, V, and the gate voltage, Vg.*

By attaching current and voltage probes to a quantum dot, it is possible to measure its electronic properties. In Fig. 1 two quantum dot geometries are shown schematically. The lateral dot in Fig. 1a is coupled to three terminals. Particle exchange can only occur with two of the terminals, as indicated by the arrows. These source and drain contacts connect the dot to the macroscopic world. The third terminal serves as a gate electrode and is used to change the dot's electrostatic energy. Whereas in the lateral geometry transport takes place in the plane of the 2DEG, in the vertical geometry of Fig. 1 b transport occurs perpendicularly to that plane.

In the following discussion, two important assumptions are made. First, the Coulomb interactions among electrons in the dot, and between electrons in the dot and those in the environment, are parameterized by a single, constant capacitance, C. This capacitance can be thought of as the sum of the capacitances between the dot and the left lead (source), C_L, the right lead (drain), C_R, and the gate, C_g: $C = C_L + C_R + C_g$. Second, the discrete energy spectrum can be described independently of the number of electrons on the dot. On the fig. 2 is schematic diagrams of the potential landscape of a quantum dot. The minimum energy needed to add an electron to the left (right) lead equals the electrochemical potential µL(R). The electrochemical potentials of the leads are related to the bias voltage, V , by −|e|V = µL −µR. (a) The electrochemical potential for adding the Nth electron to the dot, µdot(N), lies below the lowest electrochemical potential of the leads (i.c. µR). The electrochemical potential for adding the next electron, µdot(N +1), is separated from µdot(N) by the addition energy, EC +ΔE, which is higher than µL so that the (N+1)th electron cannot enter the dot. In this configuration the number of electrons on the dot, N, is fixed and transport through the dot is blocked (Coulomb blockade). The electrostatic potential of the dot is –|e|ψN. (b) The addition of the (N +1)th electron is allowed, since µdot(N +1) lies within the applied bias window. In this configuration the number of electrons on the dot alternates between N and N +1, resulting in electron transport through the dot.

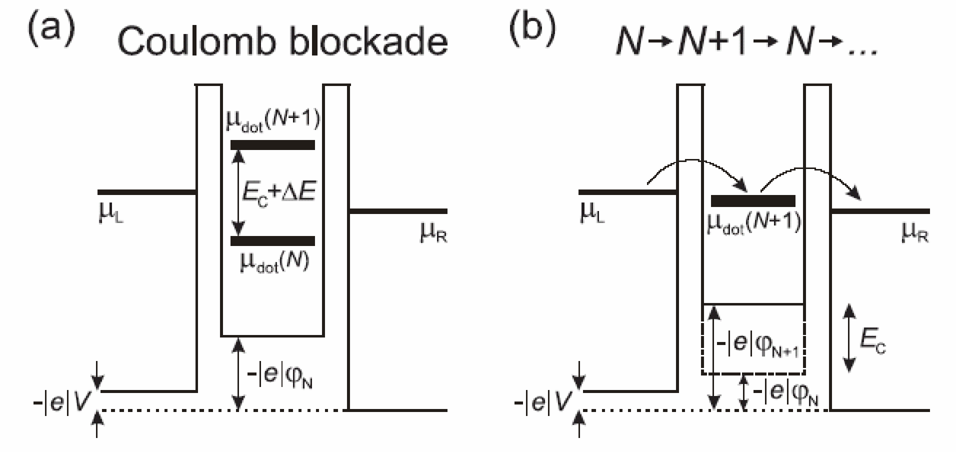

Fig. 2: *Schematic diagrams of the potential landscape of a quantum dot.*

2 FABRICATION PROCESS

For the devices discussed in this thesis use is made of GaAs/AlGaAs heterostructures. A typical example of such a heterostructure is shown in Fig. 3 The 2-dimensional electron gas is situated at the interface of GaAs and AlGaAs, typically 100 nm below the surface. The electron density of the 2DEG is determined by the n-type doping (Si) in the n-AlGaAs layer. In order to confine electrons laterally, the 2DEG can be locally depleted, using metal gate electrodes on top of the heterostructure or using etched trenches.

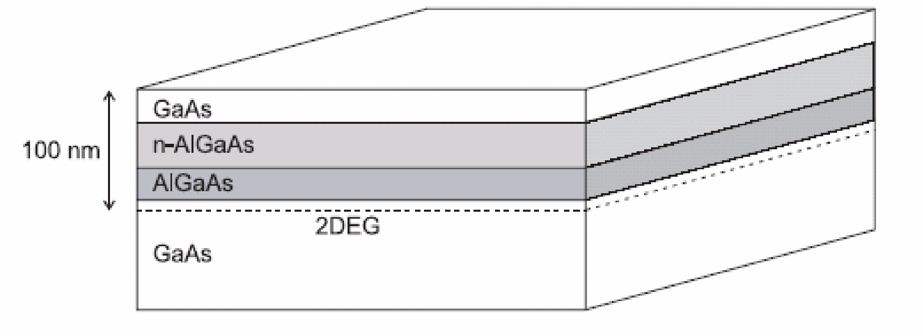

Fig. 3: *Schematic pictureof a GaAs/AlGaAs heterostructure. The position of the 2-dimensional electron gas (2DEG) in indicated by the dashed line.*

The fabrication procedure for evaporating metal gates is schematically depicted in Fig. 4 a-d. First, a layer of organic resist (poly-methyl-methacrylate, PMMA) is spun on top of the heterostructure. The gate pattern is defined by electron beam writing in the electron-sensitive resist (Fig. 4a). At the places where the resist is exposed, the polymers are broken. The exposed parts are removed by a developer (solution of methyl isobutyl ketone, MIBK, and iso-propyl alcohol, IPA), as shown in Fig. 4b. Note that there is some undercut of the PMMA layer. This undercut is caused by the significant electron scattering at the interface between GaAs and PMMA during the electron beam exposure. In the next step, metal is evaporated, which only makes contact to the heterostructure at the places where the resist has been exposed and removed (Fig. 4c). In our devices, the metal gates are fabricated by evaporating a layer of Ti and a layer of Au consecutively. The Ti layer serves as a ‘sticking’ layer. The last step is the removal of the remaining resist by acetone. Thus the metal on top of the resist is removed as well, the so-called ‘lift-off’ (Fig. 4d). The lift-off process is facilitated by the undercut in the resist layer. The first two fabrication steps for defining an etched pattern are identical to the first two steps of the metal evaporation (Fig. 4 e,f). In Fig. 4g dry etching is illustrated. The dry etching of the devices discussed in this thesis, is done by focused ion beam (FIB) and electron cyclotron resonance (ECR) etching. The last step is again the removal of the remaining resist by acetone (Fig. 4h). For measuring electron transport through the 2DEG, ohmic contacts are connected to it by evaporating AuGeNi and annealing at ~ 400 degrees Celsius for 60 seconds.

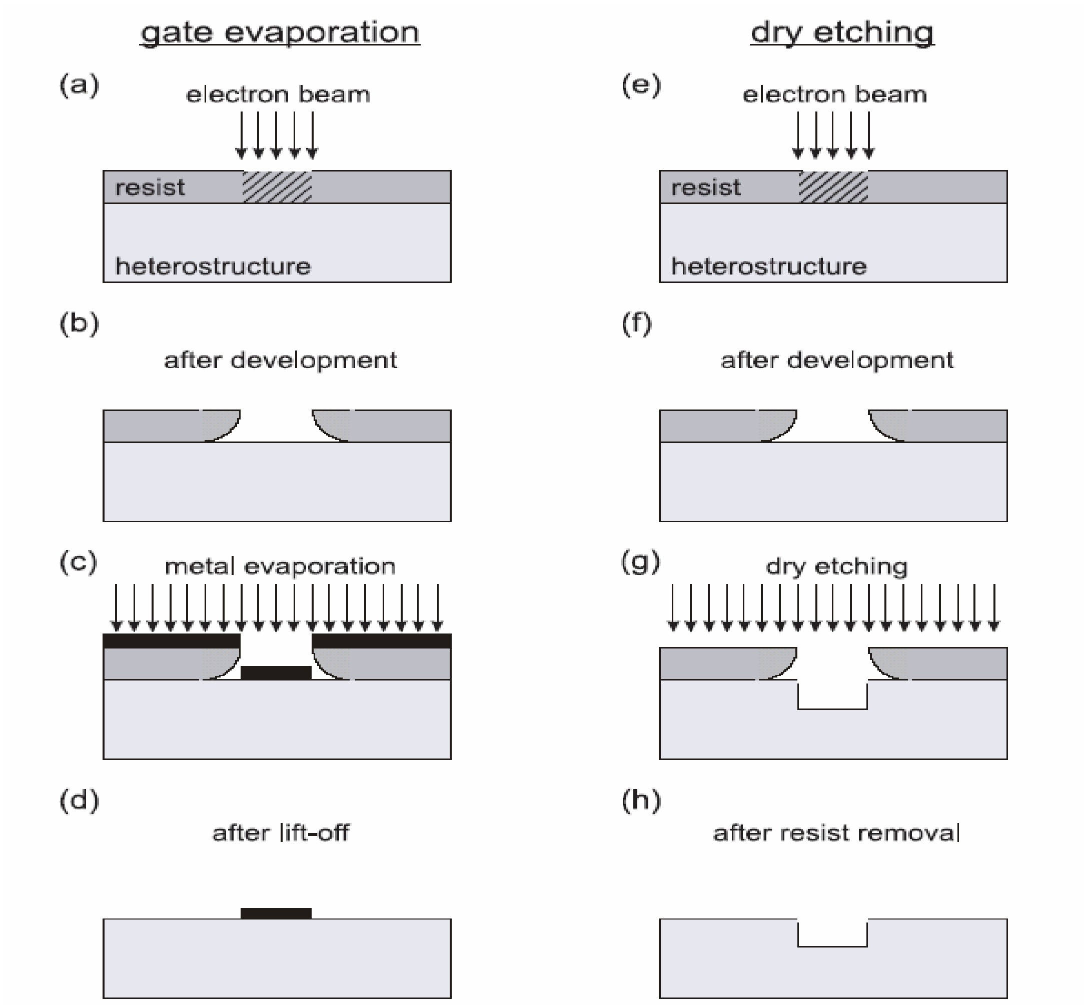

Fig. 4: *Schematic pictures showing the fabrication procedure for evaporating metal gate electrodes (a-d) and dry etching (e-h).*

3 CONCLUSSION

The vertical quantum dots are sub – micron pillars fabricated in an In/Al/GaAs double-barrier heterostructure. A metal gate electrode is deposited around them. The lateral quantum dot and ring devices are defined in the two-dimensional electron gas (2DEG) ofGaAs/AlGaAs heterostructure by means etched hed trenches and metal gate electrodes fabricated on top of the heterostructure.

The quantum dots are weakly coupled to source and drain contacts by tunnel barriers. The addition of single electron to the dot change on the dot by the elementary charge $-/e/$. The charging energy is given by e^2/C, where C is the total capacitance between the dot and its environment. At low temperature, this charging energy can block electron transport through the quantum dot, known as ‘Coulomb blockade’. By varying the voltage applied to one or more of the gate electrodes, the electrostatic potential of the dot can be changed. For certain gate voltages, two charge states are degenerate and single – electron tunneling is possible. The alternation of Coulomb blockade and single – electron tunneling as the gate voltage is varied, leads to so – called ‘Coulomb oscillations’ in the conductance through the dot.

REFERENCES

[1] Van Der Wiel, W., G.: Electron transport and coherence in semiconductor quantum dots and rings. DUP Science. 2005