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Study of electron charging effects in semi-conductor quantum dots

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Abstract
Single-electron charging effects have mostly been studied in granular films, metal tunnel junctions, and STM-grain junctions. More recently, it has become apparent that charging effects can strongly affect the transport properties of semiconductor submicron structures weakly coupled to the contact leads by tunnel barriers. The study of charging effects in semiconductor devices started with the observation of conductance oscillations in disordered wires, which were later explained to result from the confinement of electron charges between impurity potential barriers. This stimulated the work by Meirav et al. in which a lateral quantum dot with controllable potential barriers was used. Their device could change the number of electrons in the dot one-by-one, which was seen in the conductance by the appearance of oscillations, and they confirmed the explanation in terms of charging effects. Later work by McEuen et al. on the same kind of device nicely showed the interplay between charging effects and magnetically-induced zero dimensional (0D) energy states, which we will discuss in more detail below. These various experiments are reviewed. In this paper, we report experiments on lateral quantum dots. defined by split-gates in a two dimensional electron gas (2DEG). The split-gate geometry allows a detailed study of the conditions for observing charging effects, because of the ability to control the coupling of the quantum dot to the environment. In particular, we will emphasize the special properties and possibilities in which semiconductor quantum dots differ from metal structures; for example, the quantized conductance of a point contact and resonant tunneling in relation to single-electron charging, and different experimental ways to determine the charging energy.

Keywords: Various experiments, environment, particular

Introduction
To describe charging effects in quantum dots, we follow the recent literature [37-38] in which the charging theory for metal systems is generalized to include discrete energy states. Figure 3.1 a schematically shows the potential landscape of the quantum dot, which is induced by the gates. In Figure 3.1 b the equivalent circuit is shown.
At sufficiently large negative voltage applied to the QPCs, the induced potential barriers will strongly localize the electrons in the dot. The number of electrons in the dot is therefore determined being an integer and can only be changed by an integer. We write the electrostatic energy $E_{e,s}$ *of* the dot as:

$$E_{e-s}=\frac{(-en+Q_0)^2}{2C}$$

with: $n = N — N_0$

$$Q_0=C_l V_l+C_r V_r+\sum C_g V_g$$

$$C=C_l+C_r+\sum C_g\,. \qquad (1)$$

The integer part of the excess charge in the dot is $en = e(N — N_0)$, where N is the number of electrons in the dot, and the elementary charge e is taken positive. N_0 is the number of electrons at zero gate voltage and zero bias voltage (so $N_0>N$), which compensates the positive background charge originating from the donors. Q_0 represents the continuous part of the excess charge, which is induced by voltage differences V_t and V_r between the dot and the leads ($eV_t = \mu_l$, — $\mu_d(N)$, $eV_r = \mu_d(N)$—μ_r, where $\mu_d(N)$ is the electrochemical potential of the dot calculated below) [39], and by the gate voltages.

C is the total capacitance of the dot to ground, which consists of the capacitances C_t and C_r between the dot and the two leads, and the sum of the capacitances C_t and C_r between the dot and the two leads, and the sum of the capacitances ΣC_g between the dot and the gates.

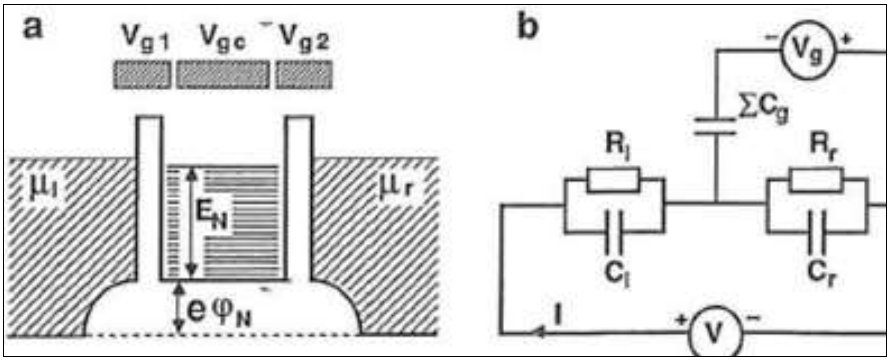

Fig 1a: Potential landscape in the 2 D E G induced by the gates *F, C,* 1, and 2. μ_t and μ_r are the electrochemical potentials of the wide 2 DEG reservoirs. φ_N is the electrostatic potential with N^{th} electrons in the dot. $E_N$is the energy level of the N^{th} electron in the dot, relative to the bottom of the conduction band, b Equivalent circuit of a, with a simplification of the different gate voltages by a single voltage source

Note that for $n=l$ and $Q_0 = 0$,(1) gives the charging energy $e^2/2C$ for a single electron.

The ground state energy for N electrons in the dót at zero temperature is the sum over the single particle energies E_p relative to the bottom of the conduction band, and the electrostatic energy:

$$U(N)=\sum_{p=1}^{N} E_p+\frac{(-en+C_g V_g)^2}{2C}. \qquad (2)$$

From (3.2) we calculate the electrochemical potential which by definition is the minimum energy necessary to add the N^{th}electron to the dot: $\mu_d(N)=U(N) -U(N-1)$,

$$\mu_d(N)=E_N+\frac{(n-1/2)\,e^2}{C}-e\frac{C_g}{C}V_g. \qquad (3)$$

In a more familiar form $\mu_d(N) = \mu_{ch}(N) + e\varphi_N$, i.e. the electrochemical potential is the sum of the chemical potential $\mu_{ch}(N) = E_N$and the electrosta.3tic potential $e\varphi_N$. When the number of electrons is changed by one, the resulting change in electrochemical potential is (at fixed gate voltage):

$$\mu_d(N+1)-\mu_d(N)=E_{N+1}-E_N+e^2/C. \qquad (4)$$

Equation (3.4) implies that the electrochemical potential changes by a finite energy when an electron is added to the dot. $\mu d(N+l)-\mu d(N)$is large for large energy splitting between consecutive OD-states, and/or for a small capacitance. This energy gap can lead to a blockade for tunneling of electrons into and out of the dot, as shown schematically in Figure 3.1a, where N electrons are localized in the dot. The $N+l$ electron can not tunnel into the dot, because the resulting electrochemical potential $\mu_d(N+1)$ is higher than the electrochemical potentials of the reservoirs. So for $\mu_d(N)<\mu_l$, $\mu_r<\mu_d(N + 1)$ the electron transport is blocked, which is known as the Coulomb blockade. Transport is only possible by thermal activation or tunneling via virtual states. Note that the energy gap of (3.4) takes place at the Fermi energy, which determines the transport properties and the activation energy. Below $\mu_d(N)$, the energy states are separated by $E_{N+1} —E_N$, which in our case, are much smaller energy differences.

We get for the period of the oscillations in gate voltage ΔV_gcorresponding to a change of one electron:

$$\Delta V_g=\frac{C}{C_g}\left(\frac{E_{N+1}-E_N}{e}\right)+\frac{e}{C_g}. \qquad (5)$$

For vanishing energy splitting $E_{N+1}–E_N \approx O$, the usual voltage-capacitance relation for a single electron charge is obtained: $\Delta V_g = e/C_g$.

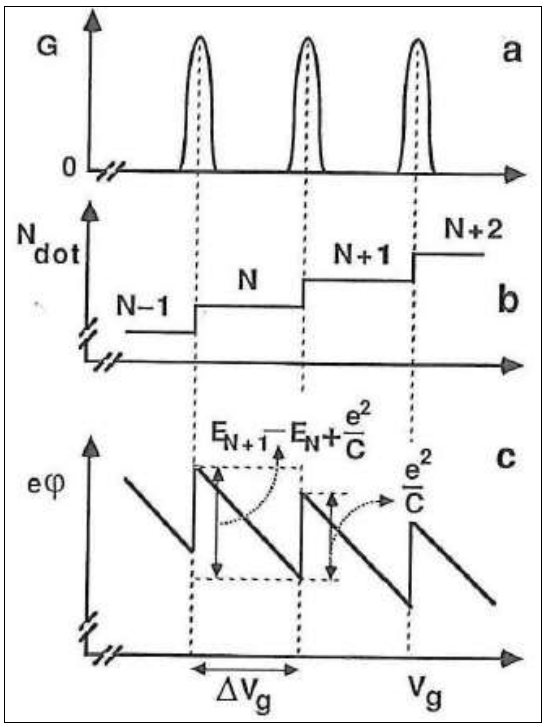

Fig 2: Comparison of the conductance G a, number of electrons N_{dot}, b. and electrostatic energy $e\varphi$c, of the dot versus gate voltage V_g. Between the Coulomb oscillations, N_{dot}, is fixed, which corresponds to the Coulomb blockade. A t the maximum of the oscillations, N_{dot} oscillates by one electron, and $e\varphi$oscillates by e^2/C. I n this case, the Coulomb blockade is removed, resulting in transport.

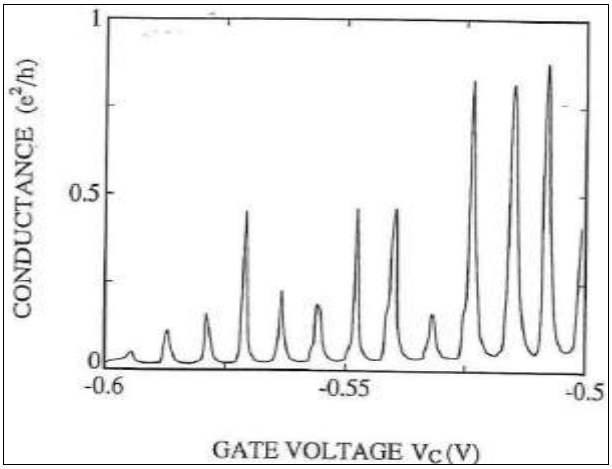

Fig 3: Conductance of the dot versus center gate voltage *Vc*for G_1, $G_2 << 2e^2/h$. The Coulomb oscillations appear as sharp peaks with an amplitude of about e^2/h

Figure 1.3 shows the oscillations, when both QPCs are put well in pinch-off $(G_1\ G_2 << 2e^2/h)$. Now, the oscillations appear as sharp peaks with an amplitude up to e^2/h.

Conclusions

In most aspects, the experiments performed on semiconductor devices, as reported in, and in this chapter, can be described by the theory developed for metal systems. The unique advantage of quantum dots defined by gates in a 2DEG, is that the conditions for the occurrence of charging effects can be studied by simply tuning the gate voltages. We showed that at zero magnetic field a sharp transition exists at QPC conductances G_1, $G_2 = 2e^2/h$ for charging effects to appear.

To apply these arguments to the metal junctions, we note that in this case the barriers are thin but much higher than the Fermi energy. Although the subbands have a small transmission probability $T_m << 1$, many subbands ($m \approx 10^6$ - 10^8) contribute incoherently to the conductance. The total fluctuation becomes of order 1 when $\sum_m T_m$ is of order 1.

Experimentally it is found that for tunnel junctions the charging effects occur much more gradually when the tunnel conductances become $G \approx 2e^2/h$ [40].

The experiments performed on quantum dots containing more than 100 electrons, show that although the Coulomb interaction between the electrons is included in the charging theory only as a constant capacitance parameter, this simplification nevertheless gives a good description.

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