Experimental project in course “The Physics of Low-Dimensional Structures”

Quantum Dot Spectroscopy

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Introduction

With decreasing size of electronic devices a lot of research has been carried out to understand the fundamental phenomenon governing charge carrier transport in electrical conductors. Some of the most known phenomena in nanoscale electron transport experiments are quantized conductance, charge carrier tunneling and quantum confinement. Perhaps the most famous example where those effects together with electron-electron interaction manifest them self is Coulomb blockade.

Coulomb blockade

One way in which the Coulomb blockade manifests itself is as an increased resistance of small electrical conductor islands, called quantum dots (QD), at small electrical bias voltages. Well-known experimental device geometry for observing Coulomb blockade is shown in Figure 1. It consists of a quantum dot that is tunnel-coupled to two contacts and capacitively coupled to a gate electrode.

![Figure 1: The two contacts, source (S) and drain (D), that can be used to apply electrical bias are tunnel-coupled to a quantum dot (QD). An additional gate electrode (G) can be used to manipulate an electrostatic potential of electrons on the QD independently of the S and D contacts. C_L, C_R and C_g are corresponding two terminal coupling capacitances.](image)

Electron transport through the QD is only possible if electrons tunnel through the tunnel-barriers. If we assume elastic tunneling process during which electron energy does not change, for electron to tunnel into the QD there need to be available states at the same energy. However, due to Coulomb repulsion between electrons and quantum confinement effects there is a finite energy cost for adding a single electron to the QD. For smaller conductors such as QD at low temperatures $T$ the addition energy can become comparable to characteristic thermal excitation energy $k_B T$ and then electrons no longer can receive this energy form thermal fluctuations. This leads to a situation where electron transport through the QD is blocked due to lack of electron energy. This effect is called Coulomb blockade.

In the geometry shown in Figure 1 there are two ways of enabling electrons to tunnel into the QD. First, one can provide electrons with additional potential energy by applying a source-drain bias $V_{sd}$. Second, one can apply a positive bias $V_g$ to the gate electrode thus reducing the amount of energy that electrons lack for entering a QD state.

One of the simplest approximation in which one can calculate current through a quantum dot is given by Landauer formula

$$I(V_{sd}, V_g, T) = \frac{e}{h} \int \tau(\epsilon, V_g)[f_2(\epsilon, V_{sd}, T) - f_1(\epsilon, V_{sd}, T)] d\epsilon$$

where $\tau$ is the transmission function describing the QD, but $f_1$ and $f_2$ are the Fermi distributions of electrons in source and drain contacts. Even though Landauer formula is in principle for ballistic electron transport, it provides with basic insides in what can be expected from I-V characteristics and gate voltage dependence.
For example, it predicts that a current from source (S) to drain (D) is present only when there is an energy state within a source-drain bias window as shown in Figure 2.

![Figure 2: Schematic representation of a quantum dot (QD) tunnel-coupled to source (S) and drain (D) contacts. Energy of electrons $\varepsilon$ on vertical axis. A voltage is applied between S and D. The QD has a state available for electron transport within a S-D bias window. Resulting current density depending on energy $\varepsilon$ is represented with a green plot on the very left.]

If we assume that by varying the gate voltage $V_g$ we shift the QD state energies with respect to electrochemical potentials of the contacts, then by sweeping the $V_g$ while a small source-drain bias $V_{sd}$ is applied will result in a series in peaks. This series of peaks are called Coulomb oscillations.

A two dimensional diagram showing current as a function of the $V_g$ and $V_{sd}$ is called bias spectra or stability diagram. In this diagram a typical Coulomb blockade pattern shows a series of diamond-like regions where current is blocked. In a real device bias spectroscopy provides with information about the device parameters such the addition energy and coupling capacitances as well as about other features. Examples that can introduce signatures in bias spectroscopy are co-tunneling, absorption and emission of photons or phonons, or electron energy spectra quantization in contacts.
Experimental devices

Experiments were performed on two devices that were intended to have the same characteristics. They were supposed to be InAs nanowires with two higher band gap (InP) segments serving as potential barriers. InAs segment between the barriers forms a quantum dot (QD). The devices were fabricated on a Si substrate also acting as a back-gate. Two metallic leads are connected to the nanowire to serve as source and drain contacts.

The device can be imaged in a scanning electron microscope (SEM). Figure 4 below shows a nanowire connected to the source and drain contacts and a bare nanowire in which InP barriers are apparent.

Figure 3: (a) InAs/InP nanowire on a SiO₂-Si substrate connected to source and drain contacts. (b) InP barriers in the InAs nanowire defining a quantum dot (QD).

Figure 4: SEM images. (a) Nanowire connected to source and drain contacts. (b) InP tunnel barriers in a bare nanowire defining the QD.
Experiments and results

Experiments are done using two voltage sources to apply the source-drain voltage $V_{sd}$ and the gate voltage $V_g$. These voltages are controlled by computer software which also reads the current and plots the acquired data. All measurements are carried out in liquid He temperatures (4.2 K).

Device 1

First we set the source to drain voltage $V_{sd}$ to 50 $\mu$V and sweep the gate voltage $V_g$ from 0 to 30 V. Current through the device as a function of gate voltage is shown in Figure 5. Data shows oscillations in current due to Coulomb blockade.

![Figure 5: Source-drain current as a function of gate voltage when $V_{sd} = 50$ $\mu$V (Coulomb oscillations).](image)

Then we performed a bias spectroscopy by varying the source-drain bias from -20 to +20 mV in steps of 0.5 mV. We repeated source-drain bias sweeps for a range of $V_g$. As a result we were able to obtain a two dimensional plot for differential conductance depending on $V_{sd}$ and $V_g$. Results are shown in stability diagram in Figure 6a. We then repeated the bias spectroscopy for certain gate voltage ranges with smaller voltage step sizes. This allowed resolving finer details in the spectra.
Figure 6: Stability diagrams. (a) Data from all bias range that was scanned during bias spectroscopy measurements. (b) and (c) are better resolved measurement data containing information about electron transport in the lowest laying states in the QD.
Device 2

Just as we did before with the first device we started by a back gate voltage sweep. The source to drain voltage $V_{sd}$ was set at 50 μV and the gate voltage $V_g$ was varied from 0 to 32 V. The results are shown in Figure 7. Data shows no Coulomb oscillations.

![Figure 7: Source-drain current as a function of gate voltage when $V_{sd} = 50$ μV.](image)

Figure 8 shows current-voltage characteristics for the second device at different gate voltages.

![Figure 8: I-V characteristics showing linear relation between current and voltage (Ohm's law).](image)
Discussion

*Device 1*

In Figure 5 one can see a series of maxima in current as the gate voltage $V_g$ is varied. This is a clear signature of Coulomb blockade. The charge carrier transport through the QD onsets at around $V_g = 7$ V. The current peaks are not equally spaced and vary in intensity which is most probably a combination of different effects. Figure 6a is a bias spectroscopy diagram and gives more information about its characteristics. Figures 6b and 6c are separate measurement results that were carried out in a narrower gate voltage range with better resolution.

There is a number of features one can spot in Figure 6a. First, comparing it with data in Figure 5 one can see that the electron transport through the devices onsets at a different gate voltage. This is a commonly seen property of QDs and can be explained by nearby charge reorganization that can be different from measurement to measurement. Second, in Figure 6a is possible to see that there are several sizes of Coulomb diamonds. Size of the small Coulomb diamonds throughout data suggests that charging energy of the QD is 10 meV, but the fact that addition energy varies 8 to over 20 meV from $N_{th}$ to $N_{th} + 1$ electron suggests that quantum confinement effects play an important role in this device. Third, Figure 6a also shows a pattern that is not that often seen in transport measurements; on top of the diamond pattern around zero source-drain bias there is an additional pattern of three bigger diamonds between gate voltages 21 and 29 V. Such characteristic in bias spectroscopy is something that has previously been identified as double-dot like behavior. The explanation is that there are effectively two different size QDs which influence the transport characteristics.

Once we take a closer look on bias spectra in Figures 6b and 6c we notice that most of the diamonds in the diagrams have a set of brighter lines parallel to their side facets. These lines represent increased conductance regions and are often referred to as excited states. One common cause of such features in QD stability diagrams is electron transport through “orbitally” excited states. However, from Figure 6a we already concluded that quantum confinement effects in the device energetically are comparable to the charging energy, whereas the lines parallel to the diamonds in the diagrams 6b and 6c are spaced around 2 meV apart and are too close to originate from such orbital excitations. According to C. C. Escott 2010 such features in bias spectroscopy can also appear due to distinct features in density of states in the source and drain contacts, or from phonon/photon absorption and emission in the QD. Indeed, 2 meV might be consistent with charging energy of a 100 nm long segment of InAs that is effectively a source or drain contact. If we assume phonon velocity in InAs to be 4000 m/s, 2 meV would also correspond to phonons with wavelength of 8 nm, which is of the order of QD size (15 to 20 nm). Generally, to discriminate between these two possibilities either a magnetic field dependent or temperature dependent measurements need to be performed. Additionally one should consider the fact that in our case the source and drain contacts effectively are InAs nanowire segments that are exposed to influence of the back gate, which is often not considered in theoretical models.

*Device 2*

The second device that we measured did not show any signs of Coulomb blockade. Figure 7 shows how current through the device depends on the gate voltage. No current blockade can be seen. In fact the behavior of the device is more similar to a point-contact-like circuit element. Figure 8 confirms that the device obeys Ohms law at different gate voltages. This suggests that there are either no continues InP barriers in the nanowire or, if there are any, they might have “holes” in them.
Summary

Device one shows a pronounced Coulomb blockade and quantum confinement effects in the quantum dot. It also shows double dot-like behavior and excited states that cannot be due to orbital excitations.

Device two shows no Coulomb blockade. It rather acts like a point contact and obeys Ohms law in the conductive gate voltage region.