FFFN35/FYST24
Transport characterization of double quantum dots
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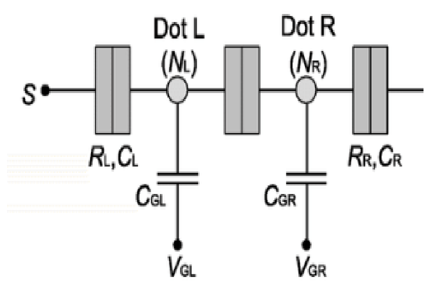
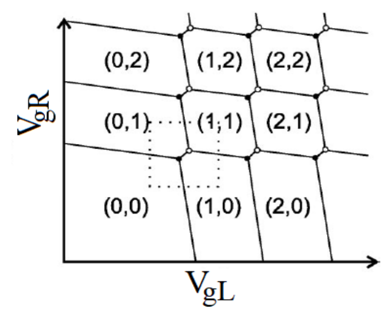
1 Introduction

This project considers charge transport through a double quantum dot, DQD. The nanowire used in the fabrication of this device is p-type so in this case the charge carriers will be holes. In contrast to a single quantum dot, QD, a DQD consists of two islands coupled in series with one another. That is a DQD consists of two single hole transistors, SHTs, coupled in series. This configuration can be used as a qubit, but can also be used for controlled study of charge transport and spin physics. In this report we will form and characterize a gate-defined p-type double quantum dot in GaSb nanowire.

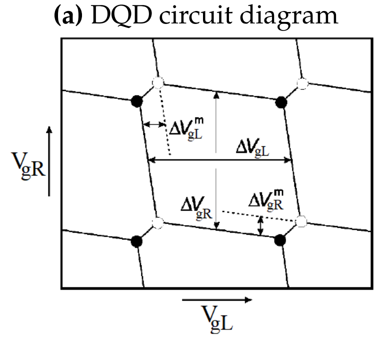
2 Theory



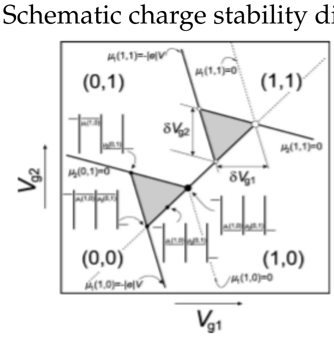
(a) DQD circuit diagram



(b) Schematic charge stability diagram



(c) Triple points



(d) Finite bias triangles

Figure 1: Schematic illustration of a DQD and its charge stability diagram. Figure a taken from [1]. b,c and d taken from reference [2].

Figure 1a shows the semiclassical equivalent circuit of a serial double quantum dot device. Two individual SHTs are connected by a tunnel barrier. Each SHT has a gate, allowing the energy levels on the left and right dot to be controlled individually. A schematic charge stability diagram of the DQD is obtained when a constant bias is applied across the DQD and the potential of each gate is varied, this is shown in figure 1b. Within each honeycomb cell the charge configuration, (N_L, N_R), on the two dots remains unchanged. A closer look at a honeycomb cell is shown in figure 1c. Here we see points in the middle of three honeycomb cells, these are the regions where current can flow.

The transport of holes through the device is represented by the white dots located at the corner of three honeycomb cells and represents the transition of the hole through the bordering honeycomb cells: $(N_L + 1, N_R + 1) \rightarrow (N_L + 1, N_R) \rightarrow (N_L, N_R + 1)$ $\rightarrow (N_L + 1, N_R + 1)$ which clearly indicates flow of a positive charge from right to left; that is a hole enters the left dot, moves to the right dot then exits to the drain at which point this repeats. The black dots represent the electron transition $(N_L, N_R) \rightarrow (N_L + 1, N_R) \rightarrow$ $(N_L, N_R + 1) \rightarrow (N_L, N_R)$ which indicates flow of negative charge from left to right.

The flow of current is governed by the relative potentials of the source, drain and the two gates, (plunger gates), with charge carrier transport requiring either $\mu_S \geq \mu_L \geq \mu_R \geq \mu_D$ where μ_L is the potential for the left plunger gate and μ_R is that of the right plunger gate, or $\mu_D \geq \mu_R \geq \mu_L \geq \mu_S$. These conditions result in triangular regions where current can flow as opposed to the points observed in figure 1c. These triangular regions are known as finite bias triangles and are illustrated in figure 1d.

In analogy to the charge stability diagram of a single quantum dot, the dimensions of the finite bias triangles as well as a honeycomb region of constant charge can be related to the characteristic capacitances, lever arms and charging energies. As illustrated in figure 1c, the horizontal dimension of the honeycomb corresponds to the voltage change required on V_{gL} to add a single hole to the left dot. Similiarly, the vertical dimension corresponds to the voltage change on V_{gR} in order to add a single hole to the right dot [2]. Thus the capacitance $C_{gR(L)}$ of the right(left) plunger gate can be found using :

$$C_{gR(L)} = \frac{e}{\Delta V_{gR(L)}}[2]. \tag{1}$$

The vertical and horizontal separation between the electron and hole triple points represent the change in the potential of the right dot from adding a single charge to the left dot and the change in the potential of the left dot from adding charge to the right dot. This information allows us to find the capacitance on the tunnel barrier, C_m, using:

$$C_m = \frac{\Delta V^m_{gR(L)}}{\Delta V_{gR(L)}} C_{L(R)}[2]. \tag{2}$$

The finite bias triangles in figure 1d, similar to the Coulomb diamonds observed with a single quantum dot, can be used to extract the lever arms, $\alpha_{R(L)}$, of each of the quantum dot by comparing the energy difference over which current flows to the bias applied:

$$\alpha_{R(L)}\delta V_{gR(L)} = \frac{C_{gR(L)}}{C_{R(L)}}|e|\delta V_{g_R(L)} = |eV|[2] \tag{3}$$

where V is the bias applied over the source and drain.

The capacitances can then be used to find the charging energies, $E_{CR(L)}$, for each quantum dot:

$$E_{CR(L)} = \frac{e^2}{C_{R(L)}} \frac{1}{(1 - \frac{C_m^2}{C_R C_L})} [2]. \tag{4}$$

An interesting feature of the double dots is that the presence of a charge carrier on one dot not only impacts the potential of that dot, but the potential of the other dot as well. This energy is known as the electrostatic coupling energy, E_{Cm}, and is responsible for the energy separation between the electron transport process and the hole transport process and is given by:

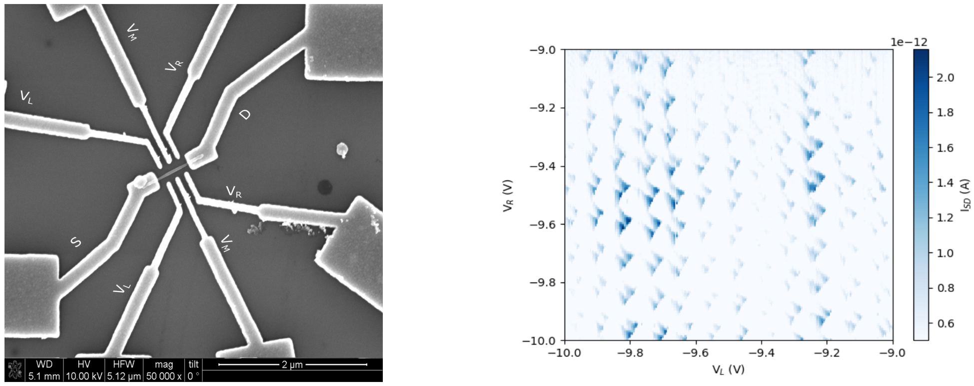
$$E_{Cm} = \frac{e^2}{C_m} \frac{1}{(\frac{C_R C_L}{C_m^2}) - 1} [2] \tag{5}$$

3 Experimental method

Figure 2a is a scanning electron microscope, SEM, image of the device used in this experiment. This device was fabricated with GaSb nanowire set between Ni/Au contacts at the source and the drain. The contacts form Schottky barriers with the nanowire which serve as tunnel barriers to the DQD [3]. Symmetric side-gates are placed along the nanowire with the two outer sets serving as the plunger gates in order to control the potentials of each dot individually and the middle set is used to induce a barrier between the two sides [4].

It is important to note that our material is p-type, so all voltages were tuned for the transport of holes. In order to form the DQD first the potential of the back-gate, which for our sample is just the substrate, was adjusted until the nanowire was near a conductive regime, (-10V). At this point the barrier gate was set to a positive value thus inhibiting hole transport through the region between the two dots. This induces a tunnel barrier between the two sides of the wire which is what makes them two separate quantum dots.

The plunger gates are then varied across negative voltages in order to create islands of conductivity between the Schottky diodes and the barrier. The successful creation of a double quantum dot depends on the relative values of the voltages applied to the plunger gates, as explained in the previous section.



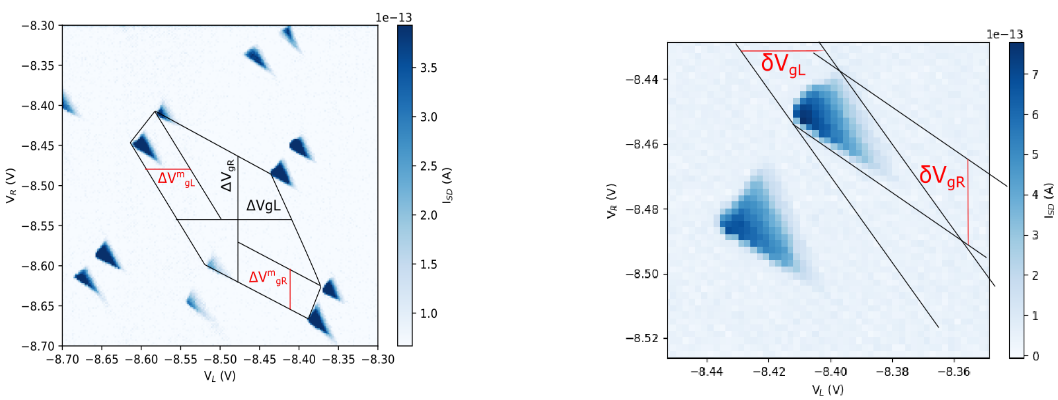
(a) SEM image of the device used in this experiment.

(b) Long range charge stability diagram from our device with a bias of 4mV

Figure 2: In a; a picture of the device used in this experiment. In b; long range stability diagram from this device obtained during measurements.

4 Result and discussion

In the charge stability diagram of this device shown in figure 2b we can see the expected triangles and honeycomb pattern which are used to extract important device characteristics such as the capacitances, lever arms, charging energy and electrostatic coupling energy. However, the resolution of the triangles from our device makes it more difficult to examine these characteristics. In order to more clearly explain how these parameters are extracted from the data we will be using the charge stability diagram from a similar device. The honeycomb cell and finite bias triangles depicted from this device are shown in figures 3a and 3b.



(a) Honeycomb cell obtained from the other device.

(b) Finite bias triangle

Figure 3: In a; sketch of the honeycomb from charge stability diagram. In b; zoom in of a, sketch of how to get the dimensions of the triangles bias is 1 mV.

The dimensions of the honeycomb and the finite bias triangles were estimated from figures 3a and 3b. The equations described in section 2 were then used to calculate the capacitances, lever arms, charging energies and electrostatic coupling energy. The result for the DQD device are listed in table 1.

	value	**unit**			**value**	**unit**
ΔV_{gR}^{m}	0.052	V		C_{gR}	1.53	aF
ΔV_{gL}^{m}	0.054	V		C_{gL}	1.14	aF
ΔV_{gR}	0.14	V		C_m *	12	aF
ΔV_{gL}	0.14	V		C_R	31	aF
δV_{gR}	0.027	V		C_L	33	aF
δV_{gL}	0.029	V		E_{cR}	6.0	meV
α_R	0.038	eV/V		E_{cL}	5.8	meV
α_L	0.035	eV/V		E_{cm} **	2.2	meV

Table 1: Table of the estimated values of the dimensions of the triangles and the Coulomb spacings obtained from figures 3a and 3b, as well as calculated capacitances and charging eneriges.
* mean value of C_{mR} and C_{mL}. ** calculated from mean of C_{mR} and C_{mL}.

As we can see the data extracted from this device matches closely with theory with the expected honeycomb pattern between devices and the triple points expressed as finite bias triangles. In addition the calculated value for E_{cm} corresponds closely with the observed distance between the triple points. These results confirm the creation of a double quantum dot as a single dot would not have separate finite bias triangles on the corners of the honeycomb cell, but would instead be connected current. If we had additional time to work on the project we could have eliminated the noise from our device in order to obtain better resolution and provide device characterization from those results.

References

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