An equivalent circuit for quantum point contact together with quantum dot

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Abstract

Detection of current flow through quantum dot (QD) is one application of quantum point contact (QPC). An equivalent circuit is introduced to simulate current flow through QD as well as QPC. The resistance and capacitance of components are defined to be voltage dependent. Their relations for voltage dependence of components are defined in such a way that the results of simulation and measurement are close to each other. It is shown that the flow of current through the QD will change its voltage as well as the QPC voltage and by this change the flow of current through QD will be detected.

Key words: Quantum Dot; Quantum Point Contact; Simulation; Equivalent Circuit.

1. Introduction

Quantum point contacts (QPCs) have been used for many applications. Detection of tunneling behavior in quantum dots (QDs) or between the dots of Double quantum dots (DQDs), in some cases where direct measurement is impossible, can be done by QPCs. Measurement of QD charge in a high applied magnetic field is another application of QPC [1]. This measurement can be used to detect landau level and spin blockade effects in QD. Tunneling rate between QD and source and drain (Γ_s, Γ_d) in single electron transistor can be measured using QPC [2]. This measurement can be used to investigate effects that arise from interaction of QD and source/drain contacts (e.g., Kondo and Fano effects). Also, QPC can be used as a large bandwidth detector for statistical counting of single electron tunneling through QD [3]. Generally, QPC can be used to detect very low and immeasurable currents through QD [4].

One way of investigating charge detection in combination of QD and QPC is using circuit modeling. Parallel combination of Resistor and Capacitor is usually used for modeling tunneling junction. In this paper, a new circuit model will be introduced for the device fabricated and presented in reference [5]. In the next section measurement results of the device are presented and then a circuit model is introduced. The values of the circuit elements are given in section 3.

2. Conductance-Voltage characteristics and the new circuit model

Figure 1 shows image of the device made on top of GaAs/AlGaAs heterostructure with two dimensional electron gas [5].

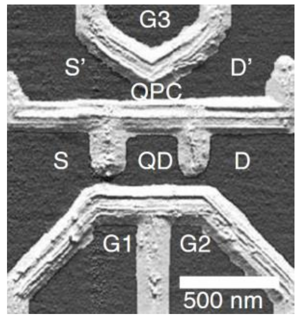

Fig. 1. AFM image of the device; oxide lines are in bright color and the dark color displays 2D gas [5].

Bright color displays the oxide lines where the 2D gas below it is depleted. Source and drain are connected to the QD by the two tunneling junctions and tunneling rate through these junctions is controlled by the gates G1 and G2. QPC together with its source and drain (S' and D') is located near the QD to detect the current through it and gate G3 is used to tune this detection. Figure 2 shows QD conductance as well as QPC conductance as a function of gate voltage measured at 40 mK [5].

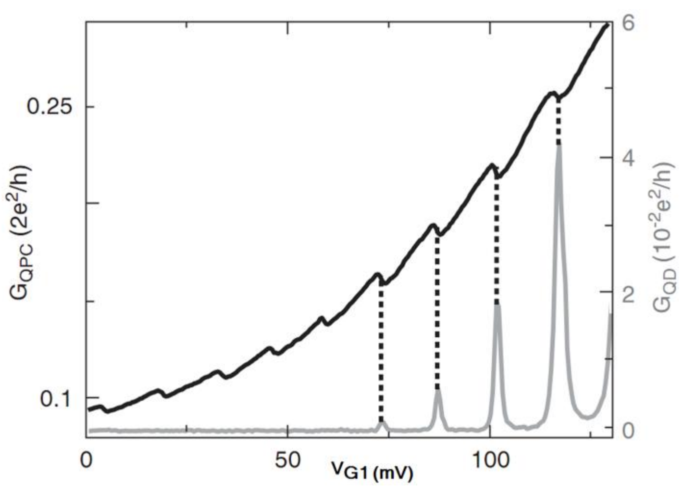

Fig. 2. Measurement of QD conductance (G_{QD}) and QPC conductance (G_{QPC}) as a function of the gate voltage.

As it is expected, the figure shows that at specific values of gate voltage, where tunneling occurs, the current through the QD increases. The period of these peaks should be $e/2C_g$ [6],

but the period of this measurement is not a constant value and it increases with increase of gate voltage. Therefore the capacitance of the gate capacitor should be reduced. Change of concentration of electron as a result of applying gate voltage is the reason for change of the gate capacitance. The figure also shows that the peak of conductance increases with increase of the gate voltage which is result of reduction of tunneling barrier as a result of change of electron concentration.
Figure 2 shows that the peak of QPC conductance occurs about at the same gate voltages that the peak of QD conductance occurs. Therefore it will be assumed that QPC is a resistor that is connected to the QD by a capacitance. Also, the figure shows that the QPC conductance increases with increase of the gate voltage. Therefore the QPC resistance should be a function of the gate voltage. The proposed equivalent circuit is shown in figure 3.

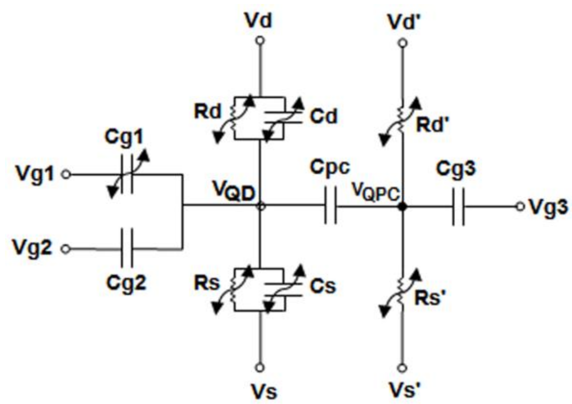

Fig.3. Proposed equivalent circuit of the device.

The value of the capacitance and resistance of components of this circuit is calculated in the next section.

3. Relations for components of the equivalent circuit

The values of conductance peaks will be used to calculate value of capacitance and resistance of the components of equivalent circuit. Then a relation will be introduced which is function of applied gate voltage.
First, gate value at peaks will be used to calculate the first and second gate capacitance. The gate voltage difference between peaks should be $e/2C_g$ [6] where Cg is the gate capacitance. It can be seen from table 1 that the value of the first gate capacitance changes with applied gate voltage.

Vg_1 (mV)	60	74	88	102	117
Cg_1 (aF)	11.62	11.60	11.57	11.52	11.45

Table 1. Gate voltage at the peaks and corresponding first gate capacitance.

The relation for the first gate capacitance is

$$C_{g1} = 11.52 + 3.9 \times V_{g1} - 39 \times V_{g1}^2 \quad aF \qquad (1)$$

The voltage or capacitance of the second gate (G2) shifts the voltage of QD conductance curve versus the first gate voltage. For a fixed value of second gate voltage, a small change of its capacitance will shift the curve. The calculated values for the second gate voltage and its capacitance are given in table 2.

Vg_2 (mV)	27
Cg_2 (aF)	1.03

Table 2. Second gate voltage and capacitance.

The values of source and drain resistance (R_s and R_d) will be chosen in such a way that the conductance between source and drain becomes exactly the values in figure 2. Their values for the peak points are given in table 3.

Vg_1 (mV)	74	88	102	117
R_s (=R_d) M Ω	9.50	1.30	0.35	0.16

Table 3. Fist gate voltage at the QD peaks and corresponding source/drain resistance.

These values vary with gate voltage. The relation for fitting the curve through these points is

$$R_s(=R_d) = 0.134 + 10^{-6} \times \exp\left(-125 \times \left(Vg1 - 0.2\right)\right) \quad M\Omega \tag{2}$$

The junction capacitance of QD (Cd or Cs) has effects on the minimum current, but the measurement is done at low temperature and the minimum QD current at low temperature is about zero. Change of QD voltage is another effect of junction capacitance which has effects on the QPC conductance. The capacitance of junction capacitor is chosen in such a way that to set the difference of peak and valley for each step of QPC conductance. The value of this capacitance is given in table 4.

Vg_1 (mV)	5	20	34	47	60	74	88	102	117
C_s (=C_d) aF	0.4	1.0	2.0	3.0	4.0	5.2	6.4	7.6	9.2

Table 4. First gate voltage at the QD peaks and corresponding source/drain capacitance.

The relation for this capacitance as a function of gate voltage becomes

$$C_s\left(=C_d\right) = 0.1 + 53 \times V_{g1} + 218 \times V_{g1}^2 \quad aF \tag{3}$$

In the figure of equivalent circuit (fig.3) it is assumed that the QPC is connected to its source and drain by resistor. The QPC voltage is $V_{QPC} = \left(V_{d'} + V_{s'}\right)/2$ and its current is given by

$$I_{QPC} = \left(V_{d'} - V_{QPC}\right)/R_{d'} \tag{4}$$

Where Rd' is its resistance. It can be seen from fig.2 that the QPC conductance increases with increase of the gate voltage. The QPC conductance decreases at the QD conductance peak where the current flow through QD occurs and causes it voltage to drop. Therefore, the QPC resistance should be a function of gate voltage as well as the QD voltage. The conductance at the peaks of QPC conductance is given in table 5.

Vg_1 (mV)	4	19	33	46	59	73	87	101	116
G_{QPC} (μS)	7.41	8.13	8.85	9.78	10.85	12.5	14.5	17.0	20.0

Table 5. First gate voltage at the QPC peaks and corresponding QPC conductance.

The relation between QPC resistance and gate voltage is given as

$$R_{s'}(=R_{d'}) = 2 - 1.92 \times \exp\left[0.2 \times \left(V_{g1} - 1.4V_{QD}\right)\right] \quad M\Omega \tag{5}$$

Figure 4 shows simulated results of QPC and QD conductance versus gate voltage using the equivalent circuit of fig.3. Also, the figure shows the measurement results and it can be seen that each two curves are very close to each other.

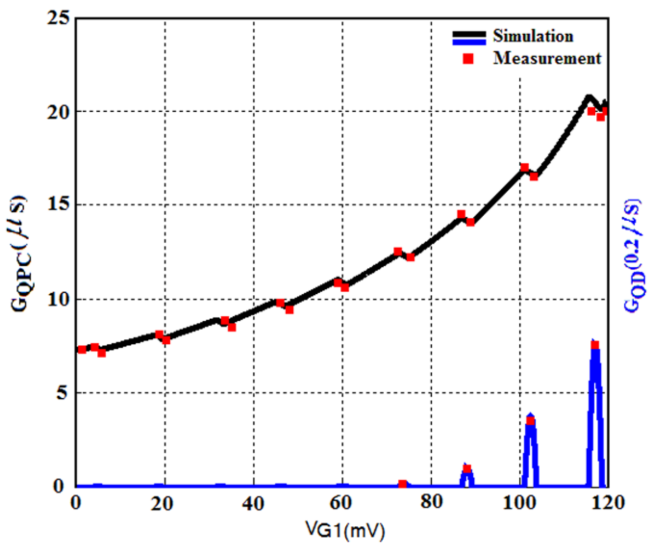

Fig.4. Simulated QD and QPC conductance as a function of gate voltage in comparison with measurement results.

4. Conclusions

One way of measurement of current through QD is use of QPC. In this paper a new equivalent circuit is introduced with which flow current through QD as well as QPC can be simulated. It was seen that the resistance and capacitance of components of the equivalent circuit are voltage dependent. In fact, applied voltage will change electron concentration which causes change of depletion and as a result change of capacitances. Also, this change of concentration will change the tunnel barrier and as a result the junction resistance.

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