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Pseudo-symmetric bias and correct estimation of Coulomb/confinement energy for an unintentional quantum dot in MOSFET channel

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Abstract

We describe a simple measurement method, a pseudo-symmetric bias, which enables the correct estimation of a charging energy of an unintentional quantum dot (QD) in MOSFET channel. If the channel has a single dominant QD with large charging energy, and also has, due to a potential fluctuation, an array of stray QDs with much smaller charging energies. Regarding the array of stray QDs as series resisters for the dominant QD, this method correctly estimates the charging energy of the dominant QD, which may be, due to the series resistances, over estimated by the conventional measure of the size of the Coulomb diamond in the source-drain voltage. We apply this method for a short-channel MOSFET, and find that the charging energy of dominant QD is indeed smaller than the size of the Coulomb diamond.

1. Introduction

In quantum dot (QD) device, where a QD is weakly tunnel couples to both of the source and drain electrode and capacitively couples to the gate electrode, measurement of a drain current I_D as a function of a source voltage V_S and a gate voltage V_G define a series of the diamond-shaped region where I_D is strongly suppressed. The size of this Coulomb diamond measured in V_S is the energy of the Coulomb charging and/or quantum confinement energy for the dot (here after we refer this the charging energy). This Coulomb diamond measurement has been used as a powerful method for characterizing the single electron transport of QD devices [1].

Recently a QD-like transport via a single trap site in silicon MOSFETs has been paid much attentions [2-4]. If a single trap site, by chance, exists in a short-channel MOSFET, a QD-like single electron transport via the trap site is possible in a sub-threshold region of V_G at low temperature. The sub-threshold region here satisfies following three conditions. 1) Direct transport or tunneling between source to drain is negligible, *i.e.* the channel is closed in a usual manner. 2) The energy level of the trap site, that is in the band gap of silicon, is comparable with the Fermi energies of source and drain electrodes. 3) The channel length is short enough to allow tunneling between the trap site and source or drain. QD-like transports via a single donor are reported in the sub-threshold region of MOSFETs [2-4]. Clear Coulomb diamonds are observed and the changing energies of the donors are discussed based on the size of the Coulomb diamonds.

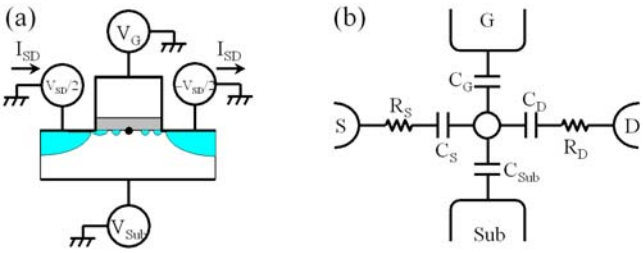

Fig. 1 (a) Schematic of MOSFET with a single trap site (a dominant QD) marked as a black dot at the center of the channel, and some stray QDs caused by potential fluctuation of the channel. Measurement electronics shows a symmetric bias condition. (b) Effective equivalent circuit of the system. The dominant QD capacitively couple to the gate and substrate with C_G and C_{Sub} respectively. Stray QDs are modeled as series resistor, R_S (R_D), connecting source (drain) electrode with tunnel junction capacitance C_S (C_D) to the dominant QD. Note any other capacitances are assumed to be negligible.

In an actual condition it is likely that, in addition to the single trap site (a dominant QD, that has large charging energy and limit I_D), a potential fluctuation near the dominant QD act as a series of stray QDs that is distributed around the dominant QD (Fig. 1(a)). Those stray QDs will have much smaller charging energies. Thus at the temperatures whose thermal energy is comparable or larger than the charging energies of the stray QDs, The array of stray QDs will behave as an effective series resisters that is located between the dominant QD and the source (or drain) electrode (Fig. 1 (b)). The series resistors cause additional voltages drop of the source-drain voltage V_{SD}, as well as the usual voltage drops due to the dominant QD. Due to this series resistance, only a fraction α ($0 \le \alpha \le 1$) of V_{SD} is applied to the dominant QD, and the size of the Coulomb diamond, measured in V_{SD}, will appeared to be larger than the actual charging energy of the dominant QD.

In this paper we show a measurement method, a pseudo-symmetric bias, which enables the correct estimation of α. We apply this method to a short-channel MOSFET and evaluate α.

2. Pseudo-symmetric bias

In a bias condition as in Fig. 1 (a), the MOSFET channel is symmetrically biased with two identical electronics for source and drain electrodes. This symmetric bias condition can be mimicked using more conventional measurement electronics as in Fig. 2 (a). Instead of using two identical electronics, suppose that we shift the ground only for source and drain electronics as in Fig. 2(b). Then the source

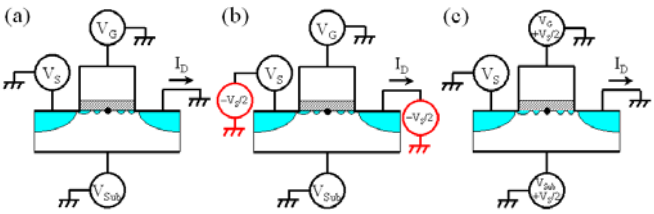

Fig. 2 (a) Measurement condition for a usual asymmetric bias condition. (b) A pseudo-symmetric bias condition that replacing the ground for V_S and I_D measurement electronics by amount of $-V_S/2$, and (c) its equivalent condition where V_G and V_{Sub} are replaced with $V_G + V_S/2$ and $V_{Sub} + V_{Sub}/2$ respectively.

and drain electrode are biased with $+V_S/2$ and $-V_S/2$ respectively. More easy set up is shown in Fig. 2(c) that is equivalent with Fig. 2(b), *i.e.*, shifting all ground by amount of $+V_S/2$, which we call a pseudo-symmetric bias. Hence when we sweep V_S, voltages for the gate and substrate electrodes should be simultaneously changed.

Both in the symmetric and the pseudo-symmetric bias condition, the MOSFET channel is symmetrically biased with source and drain electrodes. But this does not necessarily means that the dominant QD itself is symmetrically biased due to the series resistances in Fig. 1(b). We first consider the case for negligible series resistances and the dominant QD is symmetrically biased. Suppose we measure the Coulomb diamond data with (pseudo-) symmetric bias condition and name it data 1. And then, we swap the two measurement electronics that is connected to the source electrode with that for the drain electrode, and measure the Coulomb diamond again (data 2). Obviously data 2 should be identical with the data 1 except the sign of V_{SD} (V_S).

In case of non-negligible series resistances, the Coulomb diamond data 1 and 2 will not be identical as in the above manner because the effective bias voltage for the dominant QD is attenuated by a factor of α. Thus instead of the pseudo-symmetric bias as Fig. 2(c), V_G and V_{Sub} should be replaced with $V_G + \alpha V_S/2$ and $V_{Sub} + \alpha V_{Sub}/2$ respectively. Or in other word, α can be correctly estimated by finding the identical data set 1 and 2 taken for an appropriate α.

3. Results and discussion

We measure a p-channel MOSFET with a channel length of 135 nm and a width of 0.22μm with silicon oxynitride gate dielectric, fabricated with standard 130nm CMOS technologies. The Coulomb diamond measurements are done in a ^{4}He pumped cryostat at temperature 1.6 K using the pseudo-symmetric bias conditions with various α.

Figure 3 (a)-(f) shows a series of Coulomb diamond data taken for various α's. A large Coulomb diamond, recognized as a blight region, is seen near $V_G = -0.84$ V. The size of this diamond measured in V_S is ~ 40 mV. After swapping source and drain electronics, data shown in Fig (g)-(l) are taken with the same α's as (a)-(f) respectively. Note the lateral axis for (g)-(l) is reversed for clear identification of two series of the data sets. It is clearly shown that the two data with α = 0.68, (d) and (j), are nearly identical. Thus the actual charging energy of the dominant QD defining this diamond is about 40 × 0.68 = 27 meV.

3. Conclusions

We described the pseudo-symmetric bias method for correctly estimate the charging energy of dominant QD in MOSFET channel. The result of the p-MOSFET shows the charging energy is 68% of the one simply measured from the size of the Coulomb diamond in V_S.

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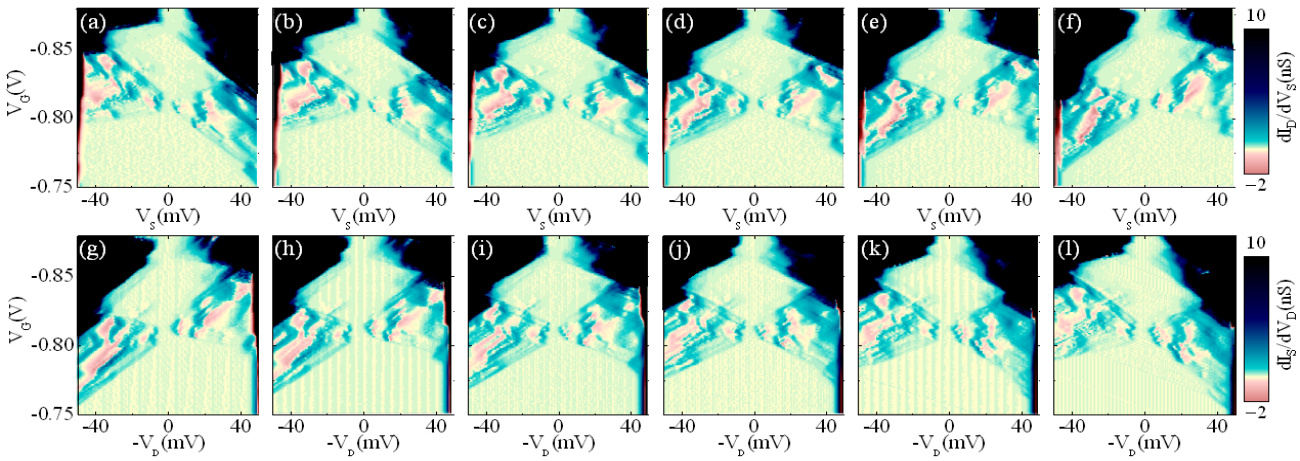

Fig. 3 (a)-(f); intensity plots of a differential conductance dI_D/dV_S as a function of V_S and V_G by the pseudo-symmetric bias condition for (a) α = 0.20, (b) 0.36, (c) 0.52, (d) 0.68, (e) 0.84 and (f) 1.00. (g)-(l); results of similar measurements with same α's for (a)-(f) respectively, but here applying drain voltage V_D and measure source current I_S, and plot dI_S/dV_D for $-V_D$ and V_G. V_{Sub} is kept to 0 V though out these measurements, *i.e.*, $\alpha V_S/2$ is applied to the substrate electrode.