Transmission Type rf Single Electron Transistor Operation of a Semiconductor Quantum Dot

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A single electron transistor is a highly sensitive electrometer, and can be operated at a high speed using the radio-frequency single electron transistor (RF-SET) technique. In this paper, we propose a modified RF-SET technique, which measures the transmission of the RF signal. It has some advantages, such as simpler circuits and clear frequency resonance as compared with the reflection measurement by RF-SET. We have tested the transmission-type RF-SET operation for a quantum dot in an AlGaAs/GaAs heterostructure.

KEYWORDS: single electron transistor, RF-SET, Coulomb blockade, transmission, quantum dot

1. Introduction

A single electron transistor (SET) is a highly sensitive electrometer and has been applied to logic circuits and memories based on the single electron charging effect on a small-capacitance island.(1) Quantum bits and quantum logic gates have also been proposed for quantum dots that represent a superposition of charge states.(2, 3) The typical charge sensitivity (or charge noise) is about 10^{-2} - 10^{-3} e/√Hz at 10-100 Hz due to background charge fluctuation, and can be ~10^{-5} e/√Hz above 1 kHz.(4) These values are not as low as the quantum limit of the SET, but much better than in any FET electrometer. The conventional electron transport experiments, however, are restricted to dc or low-frequency current measurements through the device, since the high impedance of SET devices and the large capacitance of the cables determine the highest frequency, typically 10-100Hz, or a few kHz at the most, which is much lower than the intrinsic RC cutoff frequency (~ 1GHz) of the small junctions. Recently radio-frequency (rf) SET operation has been proposed and demonstrated using a metal island, which measures the reflection of the rf signal from the SET device placed in a LC resonator(5). As the LC resonator works as an impedance transformer, the frequency range can be greater than 100 MHz, which is useful for studying charge dynamics on quantum dots as well as for the high-frequency operation of SET devices.

In this paper, we propose and demonstrate a modified RF-SET technique, which measures the *transmission* through the resonator. The advantages of a simplified circuit and clear resonance are tested on a semiconductor quantum dot whose single particle energy states are well defined.

2. Operation Principle

Figure 1 schematically show the circuit for the conventional reflection measurement of a rf-SET (a) and that for the transmission-type rf-SET (b). The SET, a variable resistor highly sensitive to the electron charge, q, on the island, is considered as a classical resistance, $R(q)$, in the analysis. In the reflection-type shown in Fig. 1(a), the rf carrier signal, $V_i e^{i\omega t}$ is supplied to the resonator and the reflected signal, $V_r e^{i\omega t}$, is measured. This is the simplest rf-SET circuit, demonstrated by Schoelkopf et al.(5). It requires some external circuit, e.g., a directional coupler, to separate the reflected from the incident signal. The transmission-type rf-SET is, however, designed to measure the transmitted signal, $V_t e^{i\omega t}$, through the other inductor. Two inductances of $2L$ have to be used to obtain the same resonance frequency, but in principle external circuits are not required for the signal separation.

Differences also appear in the resonance characteristics (Fig. 1(c)). The resonance appears as a small dip in the reflection measurements, while the peak in the transmission is always clear even when the SET is highly resistive in the Coulomb blockade (CB) regime. When the frequency is fixed at resonance $\omega_0=1/\sqrt{LC}$, the signals, V_r and V_t are sensitive to the sample resistance, R, as shown in Fig. 1(d). The transmission signal is a monotonous function of R, while the reflection is not. Note that the turning point in the reflection is at $R_t = Q^2 Z_0$. Here, Q is the quality factor of the resonator, i.e. $Q = \omega_0 L/Z_0 = 1/\omega_0 C Z_0$, and $Z_0 = 50\ \Omega$ is the impedance of the rf cable. Above this resistance, both signals behave almost similarly and can be approximated to $|V_r/V_i|^2 = |V_t/V_i|^2 = 1 - 4Q^2Z_0/R$ if $R >> Q^2Z_0$. It should be noted that the voltage across the SET is QV_i for both circuits.

3. Experiments

We have tested the transmission-type RF-SET, shown schematically in Fig. 2. A quantum dot as a SET device is fabricated in the AlGaAs/GaAs hetero-interface using ion implantation and Schottky gates [1]. The device is designed to have a double-dot geometry, but we apply negative voltages only to the two gates to form a single dot (see the inset). The typical addition energy is 1 meV and the discrete energy spacing is about 0.5 meV. Throughout this work, discreteness of the density of states in the dot is not essential and the results can be understood based on the classical Coulomb blockade effect.

The resonator (2L = 200 nH, C = 0.58 pF) has a central frequency f_{res} = 680 MHz and a quality factor Q ~ 10. The rf signal is applied to the resonator and the transmission signal is multiplied by the amplifier operated at room temperature. The signal is then rectified by a diode detector in the square law response regime, hence the output voltage is proportional to the transmitted power, ~ V_t^2. In addition to the resonator, some passive elements are used to allow dc measurements at the same time. The SET device and the passive circuits are cooled at 300 mK in a He3 cryostat, while the active circuits are operated at 300 K.

Figure 3 shows the CB oscillation measured in a conventional dc current measurement (lowest trace) and by rf transmission measurement (upper traces). The decrease in the transmission power, ~ V_0^2-V_t^2, which should be proportional to $4Q^2Z_0/i$, is plotted for different incident signal amplitudes. V_0 is defined as the transmission power at a sufficiently negative gate voltage (no conductance though the sample), and i is the ac current with respect to the ac voltage amplitude across the sample; $v = QV_i$. The extent of decrease in the transmission power increases with the ac voltage, and maximum modulation is obtained approximately at the ac amplitude across the SET equivalent to the charging energy, i.e. $eQV_i \sim E_c$.

To test high-speed operation of the RF-SET, we modulate the gate voltage by a sinusoidal signal, $V_{mod}\sin(2\pi f_{mod}t)$, to induce charge modulation on the island. We were required to fix the frequency f_{mod} at 10 kHz, due to the poor gate-voltage connection (not a coax). This frequency is not as high as the limit of the RF-SET operation, but much higher than the frequency range for normal current measurements. The modulation technique also allows us to estimate the charge sensitivity. We used a spectrum analyzer to measure the modulation amplitude on the transmission power. The gate voltage and the rf amplitude are chosen to give the highest sensitivity, where the gate voltages considered are at the maximum transconductance and the rf amplitude is equivalent to the charging energy. The modulation amplitude on the transmission linearly increases with the square of the modulation amplitude, V_{mod}, in the low-power regime as seen in Fig. 4. It has a maximum at the modulation amplitude equivalent to the half period of CB oscillation. The solid curve is the fitting curve to the data, if the CB oscillation has a $\cosh^{-2}(q/\delta)$ lineshape (δ = 0.2e is assumed) on the induced charge, q. The fitting gives the correct modulation amplitude in the unit of charge on the island, which is scaled in the upper part of Fig. 4. The noise level at the spectrum analyzer by the bandwidth of 30 Hz is also indicated in the Figure, which is limited by the noise in the preamplifier operated at 300 K. The charge sensitivity in our measurement is estimated to be 5×10^{-4} e/$\sqrt{\text{Hz}}$ at 10 kHz. A cooled preamplifier is needed to improve the sensitivity.

4. Summary

We have demonstrated a transmission-type rf-SET operation using a quantum dot. The simple circuit can be adapted to most measurement systems. Our demonstration is limited in a classical CB regime due to the low charge sensitivity, but this technique could be used for the dynamic study of single electron transport.

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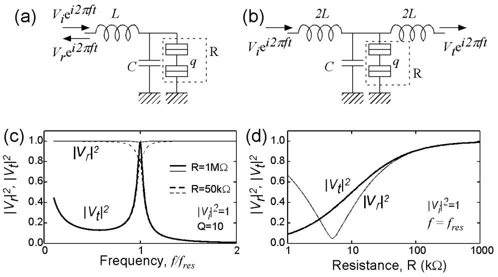

Fig. 1 Circuit diagrams for (a) reflection-type and (b) transmission-type rf-SET. (c) Expected frequency dependence of the reflected amplitude, V_r, and transmitted amplitude, V_t,.

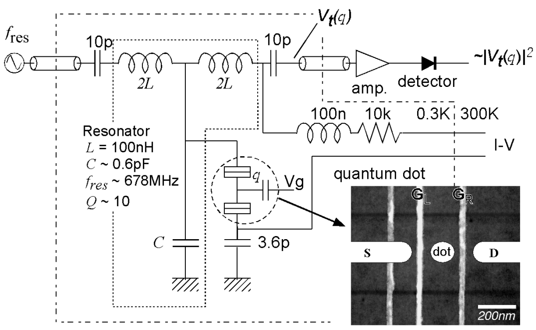

Fig. 2 Schematic circuit diagram of the transmission-type RF-SET. The SEM image shows a quantum dot device used in the experiment.

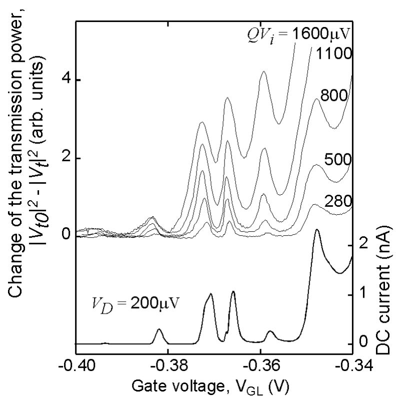

Fig. 3 Coulomb-blockade oscillation measured at 300 mK. The lowest trace shows the dc current measurement at a drain voltage of V_d = 200μV. The upper traces show the change in the transmitted power, T_0-T, for different microwave amplitudes.

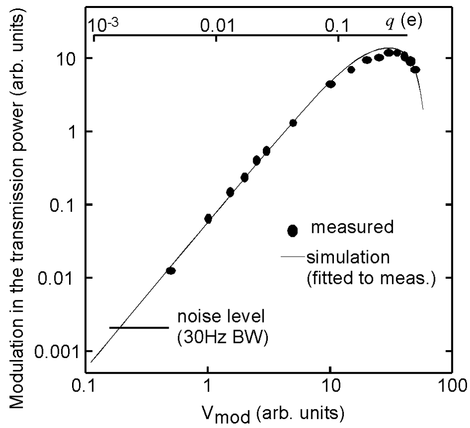

Fig. 4 The signal amplitude measured by the change of the transmitted power. The noise level is the power at the bandwidth of 30 Hz. The solid curve is the fitting curve if the CB oscillation is a pure sinusoidal one

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