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Impedance analysis of a radio-frequency single electron transistor

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1. Introduction

A radio-frequency single electron transistor (rf-SET) is a high-sensitivity and fast-response electrometer, which allows us to measure dynamical response of single electron [1,2]. Another interesting feature is the rf transport characteristics at high frequency, f, of the ~GHz domain. The rf-SET measurement provides information about the impedance of the device. An SET can be described by using two tunnel junctions characterized by tunneling resistance, R_t, and capacitance, C_t. Usually, C_t is so small that it cannot be measured directly by dc or low-frequency measurement. However, the impedance of the tunneling capacitance is $(j\omega C_t)^{-1} \sim 1\ \mathrm{M\Omega}$ at $f = \omega/2\pi = 1$ GHz for $C_t = 0.1$ fF, and it can be comparable to the tunneling resistance. This paper presents an SET impedance analysis and describes the interplay between the resistive and capacitive components of SET impedance.

2. Transmission-type rf-SET

We use a novel rf-SET circuit design, as shown in Fig. 1(a). An input signal, $v_i e^{i\omega t}$, passes through a device and an LC resonator (L_0 = 100 nH, C_0 ~ 0.6 pF, the resonant frequency of f = 643 MHz, and the quality factor Q ~ 8), and the transmitted signal, $v_t e^{i\omega t}$, is investigated. Compared with reflection measurement, originally demonstrated by R. Schoelkopf [1], and the transmission measurement with two inductors reported by us [2], the present rf-SET circuit is very simple. Moreover, the transmission coefficient, T, can be simplified as

$$T = v_t/v_i = -jQZ_0Y_X, \qquad (1)$$

which is proportional to the admittance (the inverse of the impedance) of the investigated device, Y_X, and is suitable for the impedance analysis. Here, $Z_0 = 50\ \Omega$ is the impedance of the rf lines.

In order to analyze T, the transmission signal is amplified and detected with a mixer [2], as shown in Fig. 1(b). The detection signal (a dc voltage), V_{det}, shows a sinusoidal dependence on the delay time, t_d, of the reference signal. We can obtain a complex value of T, and thus Y_X, from this dependence.

We use an SET fabricated in AlGaAs/GaAs two-dimensional electron system. The gate voltages, V_L and V_R, control the two tunneling barriers, and V_C is used to change the potential of the dot. For simplicity, we approximate this SET by a simple circuit that consists of two tunneling junctions (characterized by R_{t1}, C_{t1}, R_{t2}, C_{t2}), other capacitance to ground (C_g, including gate capacitances), and stray capacitance (C_s) [3], as shown in Fig. 1(c). The charging energy of the dot is defined by $E_c = e^2/C_\Sigma$, where $C_\Sigma = C_{t1} + C_{t2} + C_g$. The conventional dc measurements can be performed simultaneously with extra circuits (not shown in Fig. 1). The dot shows clear Coulomb blockade (CB) oscillations with E_c = 1 - 2 meV (corresponding to C_Σ = 0.08 - 0.16 fF), and single-particle excitation spectra with the level spacing of Δ = 0.1 - 0.3 meV. We apply $|v_i|$ = 0.2 - 0.7 mV, which is almost the same as the rf voltage across the SET, so discrete energy levels are partially smeared out. In this paper, we restrict ourselves to the classical Coulomb blockade regime to demonstrate the feasibility of impedance analysis using the rf-SET technique.

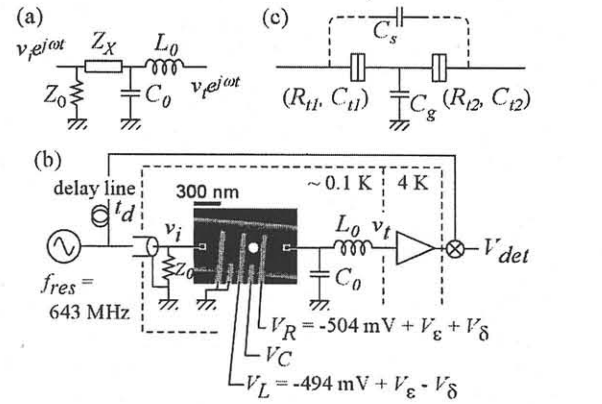

Fig. 1. (a) Circuit diagram of the transmission type rf-SET. (b) Schematic diagram of the measurement setup. The sample shown in the scanning electron micrograph contains a GaAs quantum dot (white circle) made by a dry etching (Upper and lower dark regions are etched) and five Schottky gates (vertical bright lines). The measurement was done in a dilution refrigerator (~0.1 K). (c) A simple model that describes a SET device.

3. Impedance analysis of an SET

Typical CB oscillations in the rf-SET measurements are shown in Fig. 2(a). The spectrum is qualitatively the same as that in dc current measurements. However, even in the CB

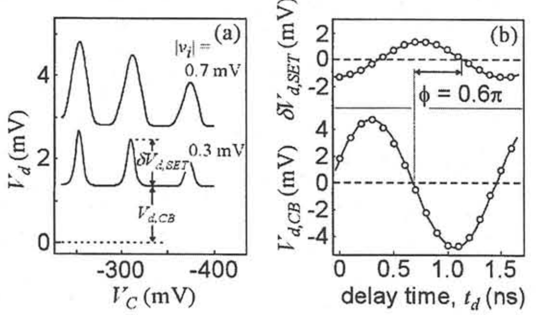

Fig. 2 (a) Typical CB oscillations detected by the rf transmission signal. We analyze the detector amplitude in the CB region, $V_{d,CB}$, and the peak height, $\delta V_{d,SET}$. (b) Phase analysis of the transmission signal. The amplitude and phase of $\delta V_{d,SET}$ provide information about the SET impedance.

region, V_{det} is a non-zero value, $V_{d,CB}$, which is almost constant for different CB regions. $V_{d,CB}$ changes sinusoidally with t_d as shown in Fig. 2(b). Since no electron tunneling is expected in the CB region ($R_{t1} = R_{t2} = \infty$), the admittance is approximately given by $Y_{X,CB} = j\omega(C_s + C_{t1}C_{t2}/C_\Sigma) \sim j\omega C_s$. We can deduce this transmission coefficient $|T_{CB}| = 7\times10^{-3}$ and $C_s \sim 2$ fF. Note that the phase of $V_{d,CB}$ can be considered as a reference phase for capacitive impedance.

In contrast, the admittance of the SET is a complex value, $Y_{X,SET}$, when the SET is conductive. For experimental convenience, we analyzed the peak height, $\delta V_{d,SET}$, rather than the absolute value. $\delta V_{d,SET}$ also changes with t_d, accompanying a phase shift, ϕ, from the $V_{d,CB}$ trace [see Fig. 2(b)]. We can determine $\delta T = T - T_{CB}$ and $\delta Y_{X,SET} = Y_{X,SET} - Y_{X,CB}$ from this measurement. $\delta Y_{X,SET}$ is a complicated function of the parameters of the model shown in Fig. 1(c), but can be written in a simple form in some cases. If the SET is made with two identical tunneling junctions ($R_{t1} = R_{t2}$ and $C_{t1} = C_{t2}$), $\delta Y_{X,SET} \sim (R_{t1} + R_{t2})^{-1}$. And, if the two junctions are largely asymmetric ($\omega C_{t1}R_{t1} << 1 << \omega C_{t2}R_{t2}$), $\delta Y_{X,SET} \sim j\omega C_{t2}(1 - C_{t1}/C_\Sigma)$.

In our device, we can control tunneling resistances, R_{t1} and R_{t2}, almost independently with V_L and V_R, respectively, while C_{t1} and C_{t2} are expected to be almost constant. We introduce two voltages, V_ε and V_δ, to change R_{t1} and R_{t2} simultaneously in the same direction (V_ε) or in the opposite direction (V_δ). They are correctly given by $V_L = -494$ mV $+ V_\varepsilon - V_\delta$ and $V_R = -504$ mV $+ V_\varepsilon + V_\delta$. Figure 3(a) shows V_ε dependence at $V_\delta \sim 0$, where the tunneling resistances are kept symmetric ($R_{t1} \sim R_{t2}$). $|\delta T|$ changes with V_ε in accordance with the dc conductance, $G_{dc} = (R_{t1} + R_{t2})^{-1}$ [See lines in the middle panel of Fig. 3(a)]. The phase shift, ϕ, is kept almost constant ~0.6 π, which is close to $\pi/2$. These behaviors are consistent with the simple model. The tunneling barriers can be approximated well by simple tunneling resistances even at this frequency.

Figure 3(b) shows V_δ dependence, where the ratio R_{t1}/R_{t2}

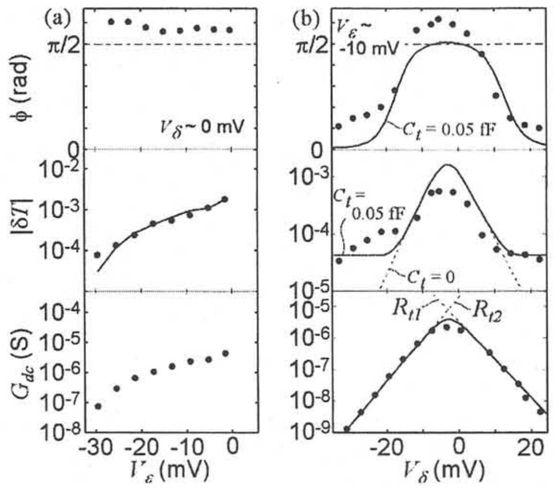

Fig. 3. The phase shift, ϕ, (upper panel), transmission coefficient, $|\delta T|$, (middle panel), and the dc conductance, G_{dc}, (lower panel). The two gate voltages are swept simultaneously (a) in the same direction by V_ε, and (b) in the opposite direction by V_δ. The solid line in the middle panel of (a) is the transmission coefficient calculated from G_{dc}. The solid lines in (b) are obtained by a fitting using R_{t1} and R_{t2} shown by the dashed lines in the lower panel, $C_{t1} = C_{t2} = C_t = 0.05$ fF, and $C_g = 0$. The dotted line in the middle panel of (b) is the case using $C_{t1} = C_{t2} = C_t = 0$.

is largely changed. ϕ changes from ~0.6 π ($V_\delta \sim 0$) to ~0.1 π ($|V_\delta| \sim 30$ mV), indicating a transition from resistive to capacitive impedance. $|\delta T|$ decreases when $|V_\delta|$ is changed from 0 to 20 mV, but becomes almost constant for $|V_\delta| > 20$ mV. In this constant regime, $|\delta T|$ depends only on the tunneling capacitances. The solid line in Fig. 3(b) is a fitting curve obtained with $C_{t1} = C_{t2} = 0.05$ fF, which qualitatively reproduces the V_δ dependence. Since we know $C_\Sigma \sim 0.1$ fF from the charging energy ($E_C = 1.7$ meV) for this condition, the tunneling capacitance dominates the total capacitance and the charging energy.

4. Conclusion

We have successfully demonstrated an impedance (admittance) analysis of an SET using rf transport. The transmission characteristics can be understood on the basis of a simple resistance and capacitance model.

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