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

Toshimasa Fujisawa and Yoshiro Hirayama^{*} NTT Basic Research Laboratories, *also at CREST 3-1, Morinosato-Wakamiya, Atsugi, 243-0198, JAPAN phone: +81-462-40-3449, fax: +81-462-40-4723, e-mail: fujisawa@will.brl.ntt.co.jp

1. Introduction

A single electron transistor (SET) is a high-sensitive electrometer and has been applied to logic circuits and memories based on single electron charging effect on a small-capacitance island. Quantum bits and quantum logic gates have also been proposed for quantum dots that represent superposition of charge states [1]. 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 most. This is much lower than the intrinsic RC cut-off frequency 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 [2]. As the LC resonator works as an impedance transformer, the frequency range can be wider than 100 MHz, which is useful for studying charge dynamics on quantum dots as well as for high frequency operation of the SET devices.

In this report, we propose and demonstrate a modified rf-SET technique, which measures the *transmission* through the resonator. The advantages of the 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 shows the circuits of the conventional reflection measurement of the rf-SET (a) and the transmission type rf-SET (b). The SET, the 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 (a), the rf carrier signal, $V_r e^{i\alpha x}$, is measured. This is the simplest rf-SET circuit demonstrated by Schoelkopf et al. [2]. It requires some external circuit, i.e.

a directional coupler or circulator, to separate the incident and reflected signal. The transmission type (b), however, is designed to measure the transmitted signal, $V_r e^{i\alpha t}$, through the other inductor. Two inductance of 2L have to be used to obtain the same resonant frequency but in principle external circuits are not required for the signal separation.

Differences also appear in the resonance characteristics (fig. 1c). 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 high 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_r behave the same way in the high resistance limit, i.e., $|V_r/V_i|^2 = |V_t/V_i|^2 = 1 - 4Q^2Z_0/R$ if $R >> Q^2Z_0$. Here Q is the quality factor of the resonator, i.e. $Q = \omega_0L/Z_0 = 1/\omega_0CZ_0$, and $Z_0 = 50 \Omega$ is the impedance of the rf source.



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

3. Experiments

We used a SET device fabricated in the AlGaAs/GaAs hetero-interface using ion implantation and Schottky gates [1]. 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 300mK, while the active circuits are operated at 300 K. The rf carrier signal at resonance (680MHz) is fed into the resonator (2L = 200 nH, C = 0.58 pF, and Q~10). The transmitted signal is amplified and rectified by a diode detector in the square law response regime, hence the output voltage is proportional to the transmitted power, $T \sim V_t^2$.

Fig. 2 shows the CB oscillation measured in a conventional dc current measurement (lowest trace) and by rf transmission measurement (upper traces). The decreased transmission power, T_0 -T, which should be proportional to the $4Q^2Z_0i$, is plotted with different incident amplitude. Here *i* is the ac current with related to the ac voltage amplitude across the sample $v = QV_i$. The CB peaks are broadened as the ac voltage increases, and maximum modulation is obtained at the amplitude equivalent to the charging energy.

To estimate the charge sensitivity, we modulate the gate voltage by a sinusoidal wave, $V_{mod} \sin(2\pi f_{mod}t)$, at $f_{mod}=10$ kHz, and detected the modulated amplitude of the rectified signal, $T_{mod} sin(2\pi f_{mod}t)$, using a spectrum analyzer. The gate voltage and the rf amplitude is chosen to give a highest sensitivity. The amplitude, T_{mod} , linearly increases with the square of the modulation amplitude, V_{mod} , in the low power regime as seen in fig. 3. 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 is a pure sinusoidal on the gate voltage. The noise level of the rectified power is limited by the noise of the preamplifier operated at 300 K. The charge sensitivity in our measurement is estimated to $5x10^{-4}$ e/ \sqrt{Hz} . A cooled preamplifier and higher Q of the resonator are needed to improve the sensitivity.

4. Summary

We have proposed the transmission type rf-SET operation using a quantum dot. Our demonstration is limited in a classical CB regime due to the low charge sensitivity, but this technique will explore dynamical study of single electron transport.

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References

[1] T. H. Oosterkamp et al., Nature 395, 873 (1998). T. Fujisawa et al., Science 282, 932 (1998).

[2] R. J. Schoelkopf et al., Science 280, 1238 (1998).



Fig. 2 Coulomb-blockade oscillation measured at 300mK. The lowest trace shows dc a current measurement at a drain voltage of $V_d = 200\mu V$. The upper traces show the change of the transmitted power, T_0 -T, with different microwave amplitude.



Fig. 3 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.