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An ultrasensitive radio-frequency single-electron transistor working up to 4.2 K

Henrik Brenning, Sergey Kafanov, Tim Duty, Sergey Kubatkin, and Per Delsing
Quantum Device Physics Laboratory, Chalmers University of Technology, S-412 96 Gothenburg, Sweden
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We present the measurement of a radio-frequency single-electron transistor that displays a very high charge sensitivity of $1.9 \mu eV/\sqrt{\text{Hz}}$ at 4.2 K. At 40 mK, the charge sensitivity is 0.9 and 1.0 $\mu eV/\sqrt{\text{Hz}}$ in the superconducting and normal state, respectively. The sensitivity was measured as a function of radio frequency amplitude at three different temperatures; 40 mK, 1.8, and 4.2 K. © 2006 American Institute of Physics. [DOI: 10.1063/1.2388134]

I. INTRODUCTION

The radio-frequency single-electron transistor (rf-SET) is the most sensitive detector of charge to date. Unlike the conventional SET, it is not bandwidth limited by the resistance-capacitance product of the SET resistance and the parasitic lead capacitance. Typically the rf-SET displays a high bandwidth, 10 MHz, in combination with a charge resolution of the order of $10^{-5} e/\sqrt{\text{Hz}}$. Although the conventional SET is theoretically more sensitive than the rf-SET, the rf-SET can operate at frequencies where $1/f$ noise is negligible, which makes the rf-SET more sensitive under experimental conditions. The improved bandwidth and charge sensitivity have made the rf-SET a good choice when measuring small state charge qubits, charging of quantum dots, and single electron transport. In rf measurements of the SET, the impedance of the SET is matched to the characteristic impedance of a coaxial cable by a resonance circuit. The difficulty of making a tank circuit with a high $Q$ value as well as a high operating frequency makes rf measurement of a SET practical only when the SET is relatively low ohmic. Hence, SET resistances in the range 20–200 kΩ are desirable. As the tunnel junctions are made smaller the charging energy ($E_C$) increases, which increases both the charge sensitivity of the SET and the maximum operating temperature. However, since the tunnel resistance is inversely proportional to the junction area, this also increases the resistance, and eventually the resistance becomes too large for rf-SET operation. With conventional aluminum angle evaporation, it has been difficult to make tunnel junctions smaller than $100 \times 100 \text{nm}^2$ ($E_C/k_B=1 \text{K}$) without increasing the device resistance too much. Hence, the operating temperature range of the rf-SET has been limited to roughly a few hundred millikelvin (mK). By using low oxidation pressure we show here that it is possible to combine high $E_C$ with rf operation. There are numerous experiments that require the bandwidth and sensitivity of the rf-SET and are therefore performed at mK temperatures. With a higher operating temperature of the rf-SET, many of these experiments could also be conducted at 4.2 K. Other experiments now use conventional SETs with a higher charging energy, and also resistance, to enable measurements at higher temperatures. By switching to a rf-SET operating at 4.2 K some of these experiments, such as electron counting and the scanning-SET, could gain in sensitivity and bandwidth. In this article, we describe the measurement of a rf-SET working from 40 mK to 4.2 K, with sensitivities of the order of $1 \mu eV/\sqrt{\text{Hz}}$.

II. SAMPLE FABRICATION AND EXPERIMENTAL SETUP

The SET was fabricated with two-angle evaporation of aluminum on SiO$_2$ and in situ oxidation. The details are described in Ref. 8. A very low oxidation pressure was used during fabrication, which resulted in very thin tunnel barriers. Since the tunnel resistance depends exponentially on the barrier thickness, this improved the conductance per unit area of the barriers without increasing the capacitance per unit area. The data presented here are taken on a device which had a high-bias-tunnel-resistance $R_S=25$ kΩ, in spite of its very small size (see Fig. 1). The relatively low resistance made cotunneling contributions sizable. The effect of this was twofold. First, the Coulomb diamonds were smeared due to cotunneling, even at low temperature, which made it difficult to fit asymptotes to the Coulomb diamond edges and, hence, to determine the charging energy ($E_C$). Second, the nominal $E_C$ (as determined of the total island capacitance) of the SET was lowered to an effective $E_C^{10}$. The charging energy of the SET was estimated by fitting asymptotes to the Coulomb diamond [see Fig. 3(b) (see later)], resulting in $E_C/k_B=18\pm2 \text{K}$, which corresponds to a total island capacitance $C_{\text{IS}}=58$ aF. One junction capacitance was slightly larger than the other, 33 aF compared to 25 aF, which indicates that the geometrical symmetry of the SET was good.

The experimental setup is depicted in Fig. 1. Various filters are not shown to simplify the figure. The rf signal is transmitted from room temperature via a directional coupler at 4.2 K, and is reflected at the combined SET/tank circuit. At resonance, the reflected power depends on the resistance of the SET and the tank circuit parameters, i.e., $P_R=P_A(1-4Q_L^2Z_0/R_{\text{SET}})^3$, where $P_R$, $P_A$, and $Q_L$ are the reflected rf power, the applied rf power, and the loaded $Q$ value of the tank circuit. $Z_0$ and $R_{\text{SET}}$ denote the characteristic impedance.

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4Electronic mail: henrik.brenning@mc2.chalmers.se
The sensitivity can be seen in the upper inset in Fig. 2. The sensitivity of the sideband peak with the noise floor, i.e., the signal to noise ratio. The sensitivity was 0.9±0.1 nA/mV in the normal state of the SET, respectively.

![Diagram](https://example.com/diagram.png)

**FIG. 1.** The schematics of the rf measurement. Filters are not shown. The inset in the top right corner shows a scanning electron microscope image of the SET, with the exception of the gate electrode. I, S, and D stand for island, source, and drain, respectively. The scale bar is 100 nm. The dashed rectangle enclose the SET and the tank circuit, where the L denotes the inductance and C denotes the pad capacitance.

III. RESULTS AND DISCUSSION

We measured the sensitivity for different rf amplitudes, and for each rf amplitude we varied $V_{SD}$ and $V_g$ to find the optimum bias point. This procedure was repeated at the temperatures 4.2, 1.8 K, and 40 mK. At 4.2 K, the best SNR was 22.9 dB, $\Delta q_{rms}=0.0044e_{rms}$, and $B$ was 15 kHz, which results in a sensitivity of $1.9±0.1 \mu e$/VHz. The current voltage characteristics shown in Fig. 2 display a large modulation of approximately 20 nA of the source drain current ($I_{SD}$) with respect to the gate voltage ($V_g$), despite the relatively high temperature. In the lower inset of Fig. 2, the SNR is plotted as a function of $V_g$ and $V_{SD}$, where the highest signal to noise ratio is achieved close to zero bias. A closer inspection shows that this maximum was achieved with $V_{SD}=−0.05$ mV, i.e., near a pure rf mode measurement. The optimum sensitivity in the pure rf mode has been calculated by Korotkov and Paalanen,

$$\delta q = 2.65 \frac{e(R_2 C_2)^{1/2}}{(2B/10^{SNR/20})},$$

where $k_B$ and $T$ stand for the Boltzmann constant and absolute temperature. If the total capacitance and resistance of the measured SET is used, this formula results in a maximum theoretical sensitivity of $1.2 \mu e$/VHz at 4.2 K. The charge sensitivity is therefore approximately 1.6 times worse than the theoretical limit.

At 40 mK (see Fig. 3), the sensitivity improved approximately by factor of 2. In the superconducting case, the sensitivity was 0.9±0.1 $\mu e$/VHz. Several factors contribute to the uncertainty of the charge sensitivity. The spectrum analyzer has an accuracy better than 0.01 dB, and calibrating the voltage necessary to induce $V_{rms}$ on the gate has an uncertainty of $\sim 4\%$. In addition to these systematic errors, the gate bias points can vary due to fluctuating charges in the vicinity of the SET island. Two consecutive measurements separated by 24 h resulted in two nearly equal best sensitivities (0.85 and 0.88 $\mu e$/VHz in the superconducting state). The combined uncertainty is $\sim 7\%$. The sensitivity in the normal state was $1.0±0.1 \mu e$/VHz, and in both the superconducting and the normal state the $V_{SD}$ was small at the optimum bias point, 0.1 mV. At this temperature, however, the...
the booster clearly contributes.

The higher energy and lower tunnel resistance of the amplifier compared to Ref. 13 has been taken into account, and hence, a better charge sensitivity. Using the modified sensitivity formula (1), the sensitivity of the previously best reported result \(13\) is 2.3 \(\mu\)e/\(\sqrt{H}\), which should be compared to our values: 1.9 \(\mu\)e/\(\sqrt{H}\) (at 4.2 K), 1.0 \(\mu\)e/\(\sqrt{H}\) (at 40 mK, normal state SET), and 0.9 \(\mu\)e/\(\sqrt{H}\) (at 40 mK, superconducting SET).

In summary, we have measured a charge sensitivity for a rf-SET that is better than the previously best reported value at 40 mK and at 4.2 K. This is due to high charging energy and low tunnel resistance. The higher operating temperature of this device makes it possible to perform rf-SET measurements at 4.2 K rather than at mK temperatures.

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