An ultra sensitive radio frequency single electron transistor working up to 4.2 K

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December 23, 2021

Abstract

We present the fabrication and measurement of a radio frequency single electron transistor (rf-SET), that displays a very high charge sensitivity of 1.9 $\mu$e/$\sqrt{Hz}$ at 4.2 K. At 40 mK, the charge sensitivity is 0.9 and 1.0 $\mu$e/$\sqrt{Hz}$ 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 K and 4.2 K.
The radio frequency single electron transistor (rf-SET) is the most sensitive detector of charge to date. Unlike the conventional single electron transistor (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 high bandwidth, 10 MHz, in combination with a charge resolution of the order of $10^{-5} \text{e}/\sqrt{Hz}$. Although the conventional SET is theoretically more sensitive than the rf-SET [1], the rf-SET can operate at frequencies where $1/f$ noise is negligible, which makes the rf-SET more sensitive in experimental conditions. The improved bandwidth and charge sensitivity have made the rf-SET a good choice when measuring solid state charge qubits [2] [3], charging of quantum dots [4] and single electron transport [5] [6]. In rf measurements of the SET, the impedance of the SET is matched to the characteristic impedance of a co-axial 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. Therefore, SET resistances in the range 20 to 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 $100 \times 100 \text{ nm}^2$ ($E_C \approx 1K$) without increasing the device resistance too much. Hence, the operating temperature range of the rf-SET has been limited to roughly a few hundred mK. By using low oxidation pressure [7] we here show 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 millikelvin 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 [6] and the scanning-SET [8], could gain in sensitivity and bandwidth.

In this letter, we describe the measurement of a rf-SET working from 40 mK to 4.2 K of the order of \(1 \mu e/\sqrt{Hz}\).

The SET was fabricated with 2-angle evaporation of aluminum on \(\text{SiO}_2\) and in situ oxidation. The details are described in [7]. In the fabrication a very low oxidation pressure was used, which resulted in very thin tunnel barriers. Since the tunnel resistance depends exponentially on the barrier thickness, this improved the specific conductance of the barriers without increasing the specific capacitance. The data presented here are taken on a device which had an asymptotic serial tunnel resistance \(R_\Sigma = 25 \text{k}\Omega\), in spite of its very small size (see figure 1). The relatively low resistance made strong tunneling contributions sizable. The effect of this was two fold. First, the Coulomb diamonds were smeared due to strong tunneling, 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 \(E_C\) [9]. The charging energy of the SET was estimated by fitting asymptotes to the coulomb diamond (see figure 3b) and the resulting charging energy was \(E_C = 18 \pm 2 \text{ K}\), which corresponds to a total island capacitance \(C_\Sigma = 58 \text{ aF}\). 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 SET up 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, \(i.e. P_R = P_A \left(1 - 4Q^2 \frac{Z_0}{R_d} \right) [10] \), where \(P_R, P_A, Q\) are the reflected rf power, the applied rf power and the Q-value of the tank circuit. \(Z_0\) and \(R_d\) denote the characteristic impedance of coaxial cable connected to
the tank circuit and the resistance of the SET respectively. In our set up, the Q-value was approximately 11.6 and the characteristic impedance was 50Ω. To measure the charge sensitivity of the SET, we proceeded as in [11]. The SET was excited with a 1.5 MHz gate voltage which amplitude modulates the carrier frequency (345 MHz) and produces sidebands in the frequency spectrum of the reflected rf signal. The sidebands and main frequency can be seen in the upper inset in figure 2. The sensitivity of the SET is then calculated by comparing the height of the side band peak with the noise floor, i.e. the signal to noise ratio. The sensitivity \( \delta Q \), is:

\[
\delta Q = \frac{\Delta q_{\text{rms}}}{\left(\sqrt{2}B \times 10^{-\text{SNR}}\right)}
\]

Here, \( \Delta q_{\text{rms}} \) is the applied root mean square gate charge, \( B \) is the resolution bandwidth and SNR is the signal to noise ratio in dB. The additional factor \( \sqrt{2} \) in the denominator as compared to [11], includes the contributions from both sidebands since information can be extracted by homodyne mixing from both sidebands. 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 and 40 mK.

At 4.2 K, the best SNR was 22.88 dB, \( \Delta q_{\text{rms}} \) 0.0044 e\(_{\text{rms}}\) and \( B \) was 15 kHz, which results in a sensitivity of 1.9 ± 0.1 \( \mu e/\sqrt{Hz} \). The current voltage characteristics shown in figure 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. It is clear that rf operation of the SET should be possible. In the lower inset of figure 2, the reflected power 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 [11] measurement. The optimum sensitivity in the pure rf mode has been calculated by Korotkov and Paalanen [1]:

\[
\delta Q = 2.65e \left( R_{\Sigma} C_{\Sigma} \right)^{1/2} \left( k_B T C_{\Sigma} / e^2 \right)^{1/2}
\]
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 \( 1.2 \, \mu e/\sqrt{Hz} \) at 4.2 K. The charge sensitivity is therefore approximately 1.6 times worse than the theoretical minimum.

At 40 mK (see figure 3), the sensitivity improved approximately by factor of two. In the superconducting case, the sensitivity was \( 0.9 \mu e \pm 0.1 \mu e/\sqrt{Hz} \). Several factors contribute to the uncertainty. The spectrum analyzer has an accuracy better than 0.01 dB, and calibrating the voltage necessary to induce 1 \( e_{\text{rms}} \) on the gate has an uncertainty of approximately 4\%. In addition to these systematic errors, the gate bias points can vary due to fluctuating charges in the vicinity of the SET. Two consecutive measurements separated by 24 hours resulted in two nearly equal maximum sensitivities (0.85 and 0.88 \( \mu e/\sqrt{Hz} \) in the superconducting state). The combined uncertainty is \( \sim 7\% \). The sensitivity in the normal case was \( 1.0 \pm 0.1 \, \mu e/\sqrt{Hz} \), and in both the superconducting and the normal state case the \( V_{SD} \) was small at the optimum bias point; 0.1 mV. At this temperature, however, the theoretical maximum sensitivity is roughly five times better than what we measured. A plot of the shot noise of the SET as a function of current (see figure 3a) with the SET at 40 mK and in the normal state, shows that the noise temperature (\( T_n \)) of the amplifier clearly contributes. \( T_n \) is approximately 10 K referred to the tank circuit, \( i.e. \) substantially higher than the nominal noise temperature of the amplifier alone, which is 2 K. In the charge sensitivity measurements we used a resolution bandwidth of 15 kHz, which translates the noise temperature to a \(-92\) dBm noise floor. This level co-insides with the noise floor of the 40 mK sensitivity measurements, \( i.e. \) the sensitivity is degraded by the amplifier noise. Self heating of the SET, which grows larger with a smaller SET, could also limit the performance of the SET in the 40 mK measurements. Since the applied voltage is large and the island is very small (see figure 1), the electron temperature may well be of the order of 1 K.
In figure 4, we see how the charge sensitivity depends on the applied rf signal for the measurements at 40 mK, 1.8 K and 4.2 K. For each of these rf amplitudes, \( V_{SD} \) and \( V_g \) has been optimized to find the best sensitivity. As seen in figure 4, the maximum sensitivity is found at rf amplitudes $-82.5$ dBm (40 mK, superconducting state), $-77.5$ dBm (40 mK, normal state), $-80.5$ dBm (1.8 K, normal state) and $-72.5$ dBm (4.2 K).

The SET reported here had a 5–6 times larger \( E_C \) compared to the sample in [11], but lower tunnel resistance. As shown by Korotkov and Paalanen, the size of the optimum rf signal increases with increasing \( E_C \) [1]. Therefore, we could apply a larger rf signal and still cover a part of the coulomb diamond where \( dI_{SD}/dV_g \) was large. The applied rf signal was between 12.5 (at 40 mK, superconducting state) and 17.5 (4.2 K) dB larger than in [11]. This yielded a better signal to noise ratio, even when the higher noise temperature of the amplifier compared to [11] 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 [11] is $2.3 \ \mu e/\sqrt{Hz}$, which should be compared to our sensitivities: $1.9 \ \mu e/\sqrt{Hz}$ (at 4.2 K), $1.0 \ \mu e/\sqrt{Hz}$ (40 mK, normal state SET) and $0.9 \ \mu e/\sqrt{Hz}$ (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 both 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.

We were supported by the Swedish VR and SSF, and by the Wallenberg foundation.
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Caption figure 1

The schematics of the rf-measurement. Filters are not shown. The inset in the top right corner shows an 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

Caption figure 2

(Color online). Measurements at 4.2 K. The current-voltage characteristics, I_{SD} as a function of V_{SD} for various V_{g} voltages. In the upper left inset, the reflected power (RP) as a function of frequency is shown. The two sidebands are situated 1.5 MHz to the left and right of the main frequency. The lower right inset is a color plot of the signal to noise ratio of the side bands as a function of V_{SD} and V_{g}.

Caption figure 3

(Color online). Measurements at 40 mK with the SET in the superconducting state. a). The current-voltage characteristics, for various V_{g}. In the upper left inset, the shot noise of the SET as a function of I_{SD} where the noise is collected in a 8 MHz span at the output of the cold amplifiers. The two asymptotes intersect at the amplifier noise contribution, which is estimated to 10 K. In the lower right inset the signal to noise ratio of the sideband, measured in dB, is plotted as a function of V_{SD} and V_{g}. The mark “x” shows the optimum bias point for P_{i} = -102.5 dBm, and the dotted circle marks the optimum bias point for P_{i} = -82.5dBm. P_{i} signifies the power of the incident rf signal at the tank circuit. b) The reflected power of the tank circuit as a function of V_{SD} and V_{g}. The dotted red lines show a fit to coulomb blockade diamond, with $E_{C} = 18 \pm 2K$
Caption figure 4

(Color online). The sensitivities as a function of the applied rf power at the tank circuit for three different temperatures.
Figure 1, author H. Brenning
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