APPLIED PHYSICS LETTERS VOLUME 79, NUMBER 24 10 DECEMBER 2001

Radio-frequency single-electron transistor: Toward the shot-noise limit

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(Received 18 April 2001; accepted for publication 28 September 2001)

We have fabricated an aluminum single-electron transistor and characterized it at frequencies up to 10 MHz by measuring the reflected signal from a resonant tank in which the transistor is embedded. We measured the charge sensitivity of this radio-frequency single-electron transistor to be $3.2\times10^{-6}\ e/\sqrt{\mathrm{Hz}}$, which corresponds to the uncoupled energy sensitivity of 4.8 $\hbar$. Our measurements indicate that with further improvements, the radio-frequency single-electron transistor could reach the shot-noise limit estimated to be about 1 $\hbar$. *© 2001 American Institute of Physics.*
[DOI: 10.1063/1.1424477]

The single-electron transistor (SET) is known as a highly sensitive electrometer[1,2] based on the Coulomb blockade.[3,4] Electrons tunnel one by one through two small-capacitance tunnel junctions, with capacitances C_1 and C_2; the gate, with capacitance C_g, is used to modulate the generated current. The charging energy $[E_C=e^2/2(C_1+C_2+C_g)]$ associated with a single electron prevents sequential tunneling through the island at voltages below a threshold V_t, which can be controlled by applying a voltage V_g to the gate. This Coulomb blockade is effective at temperatures $T<E_C/k_B$ and for junction resistances larger than the resistance quantum $R_Q=6.45$ kΩ.[3,4]

The conventional SET, based on measuring either the current or voltage across the transistor, has suffered from the relatively large output resistance R of the transistor. For the typical resistance values of 100 kΩ and cable capacitance of $C\sim1$ nF, the corresponding RC time limits the bandwidth to a few kHz. With the invention of the radio-frequency SET (rf-SET),[5] the SET was made fast and very sensitive. Charge sensitivities of 1.2×10^{-5} and $6.3\times10^{-6}\ e/\sqrt{\mathrm{Hz}}$ have been reached for signal frequencies of 100 and 2 MHz, respectively.[5,6] The rf-SET can be used as a readout device in applications from very sensitive charge meters and current standards,[4] in which electrons are counted one by one, to read-out of quantum bits.[6–9]

The energy sensitivity should be limited by shot noise, and it has been estimated for a dc operated SET in the normal state to be 0.7 $\hbar$.[10] For the rf-SET in normal state, the sensitivity is expected to be a factor 1.4 worse.[11] The rf-SET can be operated in two different modes in which the SET is submitted to either (i) a large rf-amplitude and zero source-drain voltage (V_{dc}),[5,6] referred to here as the pure rf mode, or (ii) a small rf-amplitude and fixed V_{dc}, referred to as the rf+dc mode [see Fig. 1(a)]. In this letter, we present measurements on an rf-SET operated in the rf+dc mode which shows improved charge sensitivity. Both normal and superconducting states of the SET have been measured.

The measured SET transistor was fabricated by electron beam lithography and standard two-angle evaporation of aluminum, with oxidation between the first and second layers to create tunnel junctions. The sum capacitance was $C_{\mathrm{SET}}=267$ aF, corresponding to $E_C=3.5$ K, and the total resistance of the SET was 43 kΩ. The current–voltage ($I-V$) characteristics of the SET could be modulated with a gate voltage as shown in Fig. 1(a). The gate voltage period was $\Delta V_g=9$ mV, corresponding to a gate capacitance $C_g=18$ aF. The sample was mounted at the mixing chamber of a dilution refrigerator, which had a base temperature of about 20 mK.

In the rf-SET, the readout is done by monitoring either the reflected[5,6] or the transmitted signals[12] at the resonant frequency of a tank circuit composed of an inductor (L) connected to the SET and the parasitic capacitance (C_p) of the connection pad.

In our measurement setup [see Fig. 1(b)], the drain of the SET was connected to a chip inductor while the source was grounded. The value of the inductor (620 nH) was chosen so that it formed a resonant circuit with the capacitance C_p of the substrate pad at a frequency $f_0\approx332$ MHz. The carrier signal was supplied by a rf-signal generator and launched to the tank circuit via a directional coupler and a number of attenuators.

A cold amplifier with a 24 dB gain was situated in the helium bath. Two more amplifiers with a total gain of 68 dB were placed at room temperature. The reflected and amplified signals were measured with a spectrum analyzer.

The tank circuit is characterized mainly by its resonance frequency and the loaded quality factor $Q=(Z_{\mathrm{LC}}/R_d+Z_0/Z_{\mathrm{LC}})^{-1}$, where $Z_0=50\ \Omega$ is the cable impedance, $Z_{\mathrm{LC}}=\sqrt{L/C_p}$, and R_d is the dynamic resistance of the SET. To evaluate the loaded Q value, we applied a large dc current through the SET and measured the resulting shot noise with the spectrum analyzer. The inset of Fig. 1(a) shows good agreement between the calculated and measured noise power. We estimate the quality factor of the tank circuit at

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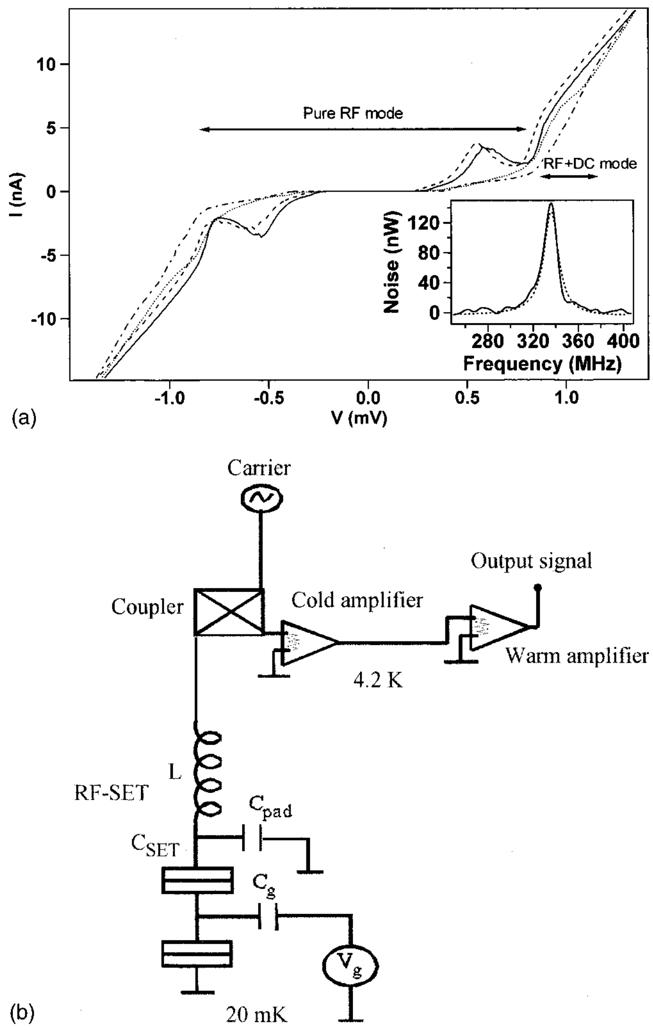

FIG. 1. (a) $I-V$ characteristics of the SET in the superconducting state for different gate voltages. The two operating modes of the rf-SET are shown. The inset shows measured and calculated shot noise from the SET. The curve was obtained by subtracting the noise for a current of 50 nA from the noise of 60 nA. (b) The measurement scheme of the radio-frequency single-electron transistor.

$Q\approx 24$ for $R_d = R_{\rm SET} = 43$ kΩ, and the bandwidth of the system to be about 7 MHz.

The noise contribution from the cold amplifier depends on the dynamic resistance of the SET because the amplifier sees different source impedance. The amplifier noise is high for maximum conductance, as seen in the inset of Fig. 2, for the normal state and the superconducting state of the SET. To evaluate the noise temperature T_n of the system, i.e., tank circuit plus amplifiers, we measured the noise power as a function of the dc current through the SET (see Fig. 2) and compared it with the simulated noise power P_c given by

$$P_c = GB(k_B T_n + 2e\eta I), \tag{1}$$

where $B=1$ MHz is the measurement bandwidth, $\eta=0.5$ for dc bias higher than the threshold voltage V_t (Refs. 13 and 14) and I is the dc current through the SET.

Fitting the experimental data of Fig. 2 with Eq. (1), we found the gain G of about 92 and the noise temperature T_n, extracted from the crossing point of the linear asymptotes, of about 6.3 K. The warm amplifier's contribution to the noise temperature is about 0.3 K, and the loss in the connecting line between the sample and the cold amplifier, estimated to about 1.3 dB, contributes by ~1.5 K.

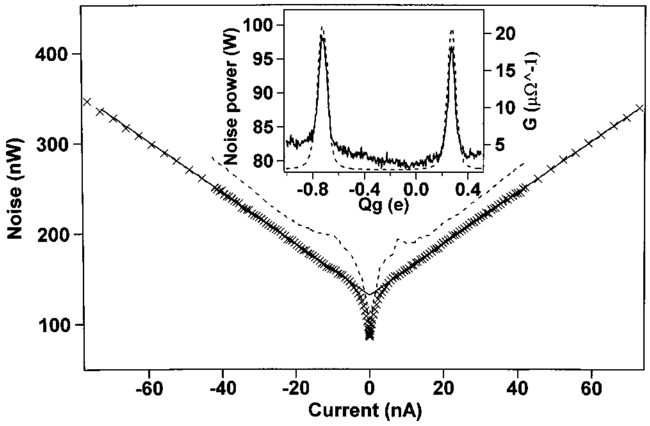

FIG. 2. The noise power of the system as a function of current through the SET in the normal (cross) and superconducting (dashed line) states. In the normal state, the crossing point of the calculated noise P_c (continuous line) corresponds to a noise temperature of ~6 K. The inset shows the output noise power (continuous line) and the conductance (dashed line) of the SET vs the gate charge. The data were taken simultaneously in the normal state.

Figure 3 shows the two side bands of the amplitude modulation of the carrier for a gate signal with amplitude of 0.05 $e_{\rm rms}$ (electrons root mean square), and a frequency of 2 MHz. Since the phase noise of the carrier generator is low, about −130 dBc at 10 kHz, the noise floor near the main peak is low compared to our previous results.[8]

The charge sensitivity is evaluated for a measured signal-to-noise ratio (SNR) of the side bands and for the input signal, with amplitude Δq in $e_{\rm rms}$, as

$$\delta q = \frac{\Delta q}{\sqrt{B}\cdot 10^{\rm SNR/20}}\,(e/\sqrt{\rm Hz}), \tag{2}$$

where B is the resolution bandwidth of the spectrum analyzer.

In the superconducting state, the maximum SNR for an rf-SET should occur at a power where the sum of the ac

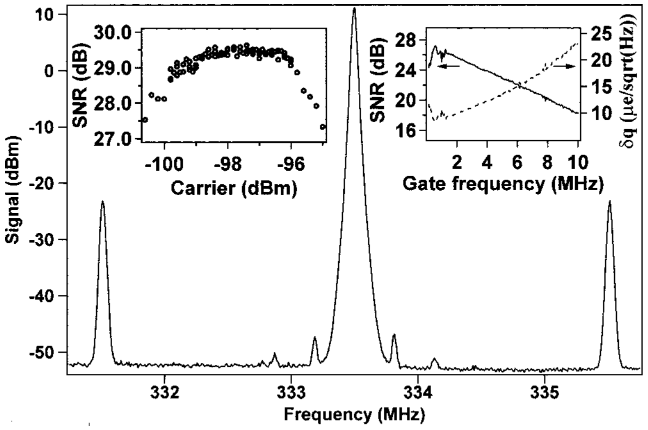

FIG. 3. The reflected power vs the carrier frequency. The carrier is amplitude modulated by the SET, generating two side bands, for a signal at gate of 0.038 $e_{\rm rms}$ and 2 MHz. The left inset shows the signal to noise as a function of the carrier amplitude with a gate signal corresponding to 0.0095 $e_{\rm rms}$. The SET was in superconducting state and the drain-source bias was 0.856 mV. The right inset shows the charge sensitivity vs the gate frequency for signal of 0.02 $e_{\rm rms}$, when the SET was in the normal state.

voltage, i.e. amplitude of the rf signal, and the dc voltage across the SET roughly corresponds to the gap voltage in the $I-V$ curve. The optimum power is given by

$$P_{\mathrm{opt}} \approx \frac{1}{(Z_0 Q^2)} (4\Delta/e + V_t/2 - V_{\mathrm{dc}})^2, \tag{3}$$

where $\Delta/e \sim 0.2$ mV is the superconducting gap of Al. The optimum power occurs at -95 dBm for a quality factor of 24 and $V_t = 0.3$ mV. This value is in fair agreement with the experimental value of -97.4 dBm.

The best SNR of 29.6 dB with a resolution bandwidth of 10 kHz was obtained in the superconducting state. The left inset of Fig. 3 shows the response to a 9.5×10^{-3} e_{rms} gate signal at 2 MHz as a function of rf amplitude and for a fixed $V_{\mathrm{dc}} = 0.85$ mV. This gives a charge sensitivity $\delta q = 3.2\times10^{-6}$ $e/\sqrt{\mathrm{Hz}}$, which corresponds to an uncoupled energy sensitivity $\delta\epsilon = (\delta q)^2/(2C_{\mathrm{SET}}) = 4.8\,\hbar$. In normal state, however, the best SNR was 27.5 dB for a 10^{-2} e_{rms} gate signal at 2 MHz which corresponds to a charge sensitivity of about 9×10^{-6} $e/\sqrt{\mathrm{Hz}}$. The right inset of Fig. 3 illustrates the bandwidth of the rf-SET. At ~8 MHz, the electrometer in the normal state is still very sensitive with $\delta q = 2\times10^{-5}$ $e/\sqrt{\mathrm{Hz}}$.

From the noise measurements in the superconducting state (see Fig. 2) we can estimate the shot noise and the cold amplifier noise contributions. At the rms current of 10 nA (including the dc current) and dc bias of 0.85 mV, which corresponds to the optimum sensitivity, we find a total noise of approximately 200 nW, referred to the output of the system and for a resolution bandwidth of 1 MHz. This should be compared to the noise from the amplifier, which is about 80 nW depending on the dynamic resistance of the SET. Summarizing, we find that 60% of the noise comes from the shot noise and that the rest comes from the amplifier. This indicates that the shot noise contributes $\sim 3\,\hbar$, and that the amplifier contributes $\sim 2\,\hbar$ to the uncoupled energy sensitivity.

Comparing the charge sensitivity in this paper with our previous results,[6] we have managed to decrease the amplifier noise substantially, mainly by decreasing the attenuation between the sample holder and the cold amplifier through the use of niobium coax. To further decrease the amplifier noise contribution, we can either improve the amplifier system or increase the signal. The latter can be done by increasing both the charging energy and the superconducting gap Δ of the SET. On the other hand, the shot noise contribution is roughly the same as in Ref. 6. This contribution should be minimized as a function of the SET parameters R, E_C and Δ.

In conclusion, we have shown that the rf-SET can achieve a charge sensitivity of $\delta q = 3.2\times10^{-6}$ $e/\sqrt{\mathrm{Hz}}$. The best sensitivity was obtained when the SET was submitted to a small rf amplitude and fixed source-drain voltage. We found that the cold amplifier limits the sensitivity, and that the rf-SET can approach the quantum limit set by the shot noise of the single-electron transistor.

The samples were made in the Swedish Nanometer Laboratory. The authors were supported by Swedish NFR, TFR, SSF, and the Wallenberg Foundation as well as the European Union under the IST and TMR programs.

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