Noise performance of the radio-frequency single-electron transistor

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Abstract

We have operated a Single Electron Transistor (SET) in the radio frequency mode. In this way both the bandwidth and the sensitivity of the traditional SET can be increased several orders of magnitude. By optimizing the system we reached a best sensitivity of $3.2 * 10^{-6} e/\sqrt{Hz}$. We use this system to study charge noise up to 1MHz and to demonstrate pulsed, short-time measurements of charge.

Key words: Shot noise; single-electron transistor; 1/f-noise; pulsed measurement

1. Introduction

The single-electron transistor (SET) is the most sensitive electrometer available today allowing even for fractions of an electron to be detected [1]. In traditional transistors the bandwidth is limited to a few kHz by an RC time-constant where R is the resistance of the transistor ($R \approx 100k\Omega$) and C is the cabling capacitance ($C \approx 1nF$). By coupling the SET to a resonant RF circuit the impedance of the SET can be transformed to close to 50Ω and will hence not suffer from the RC cut-off and the bandwidth is increased dramatically [2]. In our measurement set-up microwaves are sent into the cryostat to a directional coupler with a -27dB coupling ratio, continues to a bias-tee where a DC-bias voltage for the SET is added and then reaches the tank-circuit and the SET. The drain of the SET is connected to a microwave inductor that together with the parasitic capacitance C_p of the on-chip connection pad forms a resonant microwave circuit with a frequency $f = 1/(2\pi\sqrt{LC_p}) \approx 330 - 380MHz$, where $C_p \approx 330fF$ and $L \approx 530 - 700nF$ has been used. The Q-value of the resonator is 20-25. The reflected signal passes through the bias-tee and directional coupler and reaches an NRAO cryogenic HEMT amplifier with a nominal noise temperature $T_N = 2.5K$ and 24dB gain. Two more amplifiers are used at room-temperature with a total gain of 68dB. The reflected signal is then analyzed in a spectrum analyzer or mixed with the microwave source and the DC-output is recorded on an oscilloscope. The HEMT amplifier and directional coupler is placed at 4.2K and the bias-tee and sample holder with tank circuit at the $\sim 20mK$, base temperature of the cryostat.

2. Noise performance

The best sensitivity was found in the superconducting state with a sample having a charging energy $E_c/k_B = 3.5K$, resistance $R = 43k\Omega$ and a gate capacitance $C_g = 18aF$. By applying a 2MHz gate signal of $0.0095e_{rms}$, a DC-bias voltage of 0.85mV and a microwave power level of -97.4dBm a charge sensitivity $\delta q = 3.2 * 10^{-6} e/\sqrt{Hz}$ was achieved (Fig 1). This corresponds to an uncoupled energy sensi-

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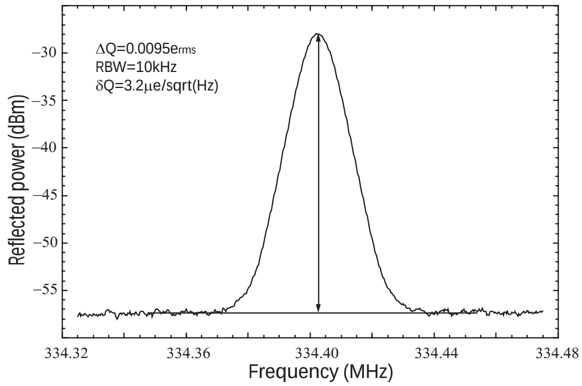

Fig. 1. The picture shows in detail one of the side peaks that results from amplitude modulation of the 332.4MHz microwave carrier by a 2MHz gate signal of $0.0095e_{rms}$. Note the large signal to noise ratio. The bandwidth of the RF-SET was 7MHz and the resolution bandwidth 10kHz.

tivity $\delta\varepsilon = (\delta q)^2/2C_\Sigma = 4.8\hbar$. The sensitivity should be limited by shot-noise and has been estimated to $\approx 1\hbar$ for a superconducting RF-SET [3]. From noise measurements we find that the cryogenic amplifier is responsible for 60% of the added noise and represents thus the main noise source. To improve the RF-SET read-out and possibly make a quantum limited amplifier one could use a cryogenic SQUID amplifier that have much lower noise temperature.

3. Pulsed read-out

During continuous measurements with the RF-SET the voltage fluctuations on the island will necessarily back-act on the measurement object [4]. Thus in

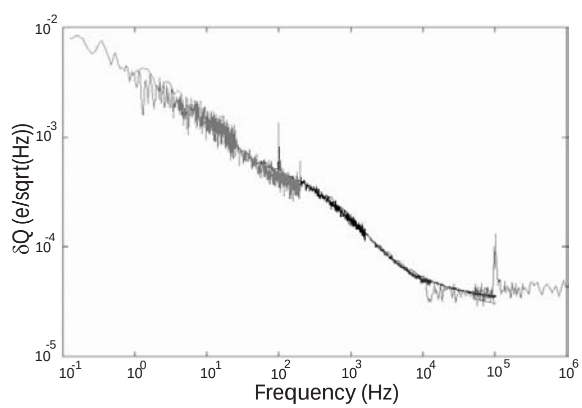

Fig. 2. The large bandwidth of the RF-SET makes it possible to measure the 1/f background charge noise up to 1MHz. The noise follows a $1/f^{0.9}$-dependence up to $\approx 10kHz$ where the amplifier noise starts to dominate.

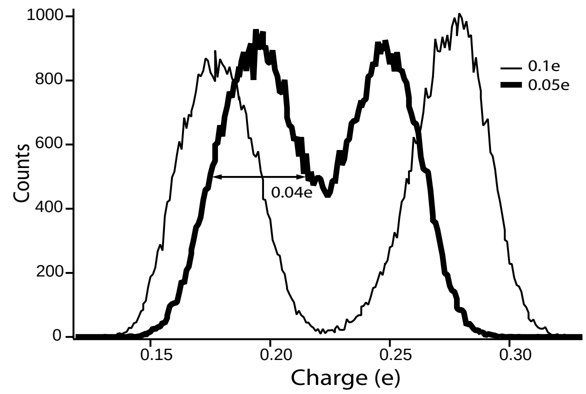

Fig. 3. The horizontal axis shows the induced gate charge and the vertical axis the number of counts collected in the multi-channel analyzer.

sensitive measurements it would be desirable to turn the measurement on only at times when a measurement is needed and keep the read-out device silent otherwise. We have implemented a low-back-action, RF-SET read-out, by pulsing the RF and the DC-bias of the SET on and off during operation. An arbitrary waveform generator creates $6\mu s$ RF-pulses in a 50Ω GaAs microwave switch (40dB on/off ratio) and also pulses the DC-bias. The amplitude of the reflected signal is collected in a multi-channel analyzer to make histograms.

Fig. 3 shows the pulsed response of the RF-SET when a 0.1 and 0.05 electron difference is induced by the gate. The sensitivity of this particular RF-SET in continuous measurements was determined to be $5.5 * 10^{-5} e/\sqrt{Hz}$. The sharpness of the peaks in relation to the measurement bandwidth determines the sensitivity. From the 0.05e trace we extract a half width at half maximum of 0.02e that divided by the square root of the measurement bandwidth 100kHz gives a charge sensitivity of $6.3 * 10^{-5} e/\sqrt{Hz}$ which is only slightly worse than the continuous case (Fig. 2). Thus we have demonstrated that it is possible to make short-time, accurate measurements of charge with maintained sensitivity.

References

[1] "Single Charge Tunneling, Coulomb Blockade Phenomena in Nanostructures" eds. H. Grabert, and M. H. Devoret **294** Plenum Press, New York (1992).

[2] R. J. Schoelkopf, P. Wahlgren, A. A. Kozhevnikov, P. Delsing, and D. E. Prober, Science **280** (1998) 1238.

[3] A. N. Korotkov and M. A. Paalanen, Appl. Phys. Lett. **74** (1999) 4052.

[4] A. Aassime, G. Johansson, G. Wendin, R. Schoelkopf and P. Delsing, Phys. Rev. Lett. **86** (2001) 3376.