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# Noise in the single electron transistor and controlled Josephson current in ballistic three terminal devices

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## Abstract

Two separate research topics are discussed. We discuss noise measurements of single electron transistors and the gain dependence of the noise. We will also describe the fabrication and preliminary measurements on several different superconductor/two-dimensional electron gas/superconductor structures. © 2001 Elsevier Science B.V. All rights reserved.

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## 1. Gain dependent noise in the single electron transistor

An extensive investigation of low frequency noise in single electron transistors [1] as a function of gain is presented. Comparing the output noise with gain for a large number of bias points, it is found that the noise is dominated by external charge noise. For low gains we find an additional noise contribution which is compared to a model including resistance fluctuations. We conclude that this excess noise is not only due to resistance fluctuations. For one sample, we find a low minimum charge noise of $q_n \approx 2 \times 10^{-5}$ e/$\sqrt{\text{Hz}}$ at a frequency of 4.4 kHz.

The samples were fabricated on oxidized Si substrates using electron beam lithography and the standard double-angle evaporation technique. The resistance of the SET directly after fabrication was $R_T = R_1 + R_2 \approx 3.5$ kΩ, which after a storage for six months, had increased to $R_T \approx 45$ kΩ. Due to its relatively low resistance, the SET had a very high maximum gain of $\partial I/\partial Q_g = 12$ and 34 nA/e in the normal (N) and superconducting (S) states, respectively, see Fig. 1.

We used a symmetric, current sensitive amplifier which voltage biased the SET [2]. To optimize the preamplifier noise performance low noise operational amplifiers with low $1/f$ noise were used.

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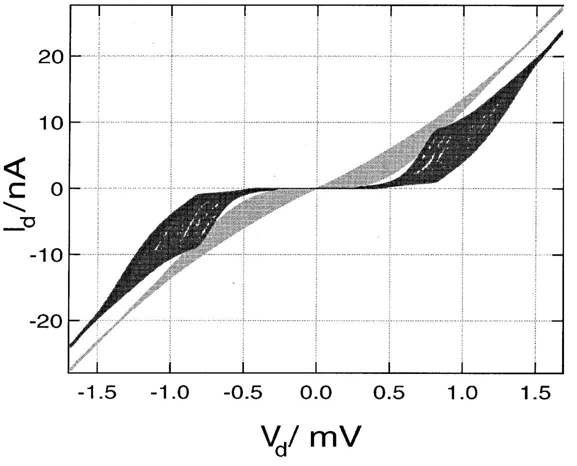

Fig. 1. The current voltage characteristics of a SET transistor for several values of gate voltage. Black curves are for the superconducting state and gray curves are for the normal state.

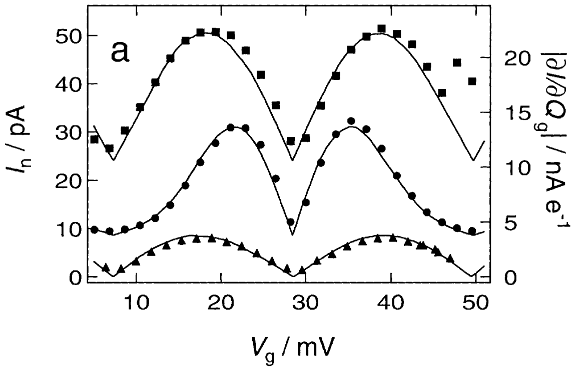

Fig. 3. Current noise (symbols) and gain (curves) of the single electron transistor. As can be seen the noise follows the gain almost perfectly demonstrating that the dominating noise source acts at the input of the SET.

Furthermore, the bias (feedback) resistors were chosen to $R_F = 10\ \mathrm{M\Omega}$ to lower the amplifier noise floor at low frequencies.

Noise spectra for the normal and superconducting states of the SET are shown in Fig. 2. Each spectrum has been referred to the input of the SET by dividing by the frequency dependent gain. The spectra N and S were measured at the bias points which gave maximum gain. For reference, a spectrum with no SET connected, R, is also shown and is divided by the same gain as in the normal state to obtain the input referred noise floor set by the amplifier. A minimum charge noise of $q_n \approx 2\times 10^{-5}\ e/\sqrt{\mathrm{Hz}}$ at a frequency of 4.4 kHz was found both in the superconducting and the normal state.

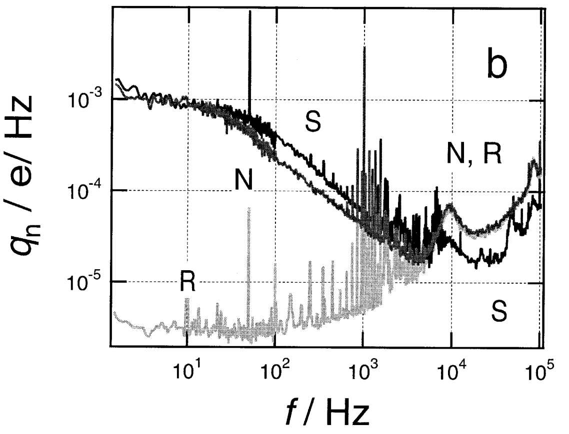

Fig. 2. Charge noise spectra for the SET transistor both in the superconducting (black) and normal (dark gray) state.

In Fig. 3, the output current noise (integrated over the frequency range 51–99 Hz), $I_N$ and gain $\partial I/\partial Q_g$ are shown versus gate bias voltage. As can be seen we find that the current noise directly follows the gain of the device, which can be expressed in the following way

$$S_I(f) = \left(\frac{\partial I}{\partial Q_g}\right)^2 S_{Q_g}(f). \tag{1}$$

The noise at the output closely follows the gain. This shows that low frequency noise in the SET is mainly due to external charge noise.

## 2. Modulation of the super current in a Josephson interference transistor

We have fabricated a three terminal superconductor–two-dimensional electron gas–superconductor (S–2DEG–S) junction with an ohmic injector contact to the normal region (i.e. the 2DEG). Using the third lead we can inject electrons, which have a controllable energy, into the junction. In this paper we show that the critical current $I_c$ can be modulated by the injection current.

Transport in mesoscopic superconductor–normal-conductor–superconductor (SNS) junction has been studied in a vast number of different systems [3]. Most of these systems were either two terminal devices or three terminal field effect devices.

We have fabricated a three terminal SNS device in which the third lead is an ohmic contact to the normal-conducting region inside the junction. This configuration allows us to inject electrons with a controllable energy into the junction and thereby to modulate the supercurrent [4,5].

The active part is a 4 nm InAs 2DEG layer embedded in an inverted modulation doped $In_{0.52}Al_{0.48}As/\ In_{0.53}Ga_{0.47}As$ heterostructure grown by molecular beam epitaxy, see Fig. 4.

The 2DEG is dry and wet etched and two superconducting niobium electrodes are angle evaporated to yield the highest possible interface transparency. The distance between the superconductors is $L = 0.6$ µm and the physical width of the 2DEG is $W_N = 0.6$ µm. The width of the point injector is $W_I = 70$ nm. Fig. 5 shows a SEM picture of a sample which was similar to the measured one.

All measurements have been carried out at temperatures below $T = 50$ mK. The $I$–$V$ curves show a finite resistance even around zero bias and the transition to the purely resistive branch is relatively smooth.

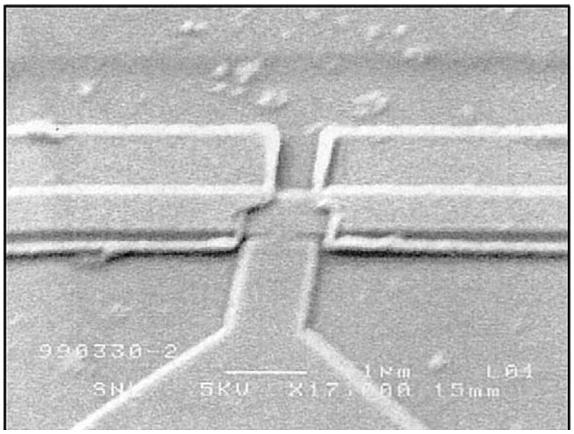

Fig. 5. Scanning electron micrograph of the sample.

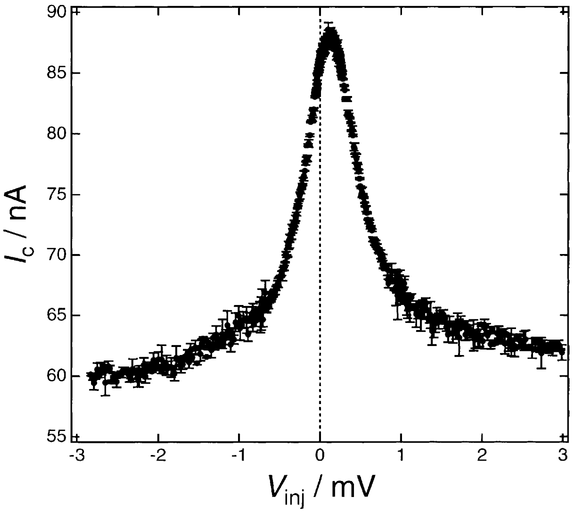

Fig. 6. Critical current as a function of the injector voltage.

We define our critical current $I_c$ as the current corresponding to the point of highest differential resistance, i.e. minimum slope in the $I$–$V$ curve. The junction is biased symmetrically and the injector voltage is applied relative to the symmetry point. Fig. 6 shows the modulation of the critical current as a function of the injector voltage. The leveling off of the $I_c$ around 60 nA depends on our definition of $I_c$.

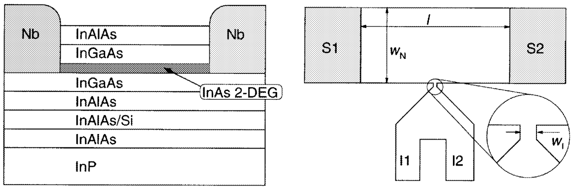

Fig. 4. Schematic illustration of the sample. (a) Cross-section through the sample showing the semiconductor heterostructure. (b) Top view of the sample showing the point injector connected to the middle of the normal-conductor region.

We note a monotonic decrease of the critical current as the injector voltage in increased from zero volt. Note that the injector voltage is less than the superconducting gap equivalent, $V_{\mathrm{inj}} < \Delta/e$. The shift toward positive injector voltage and the higher values of $I_c$ on the positive side could be due to sample asymmetry.

We show that the critical current can be modulated by applying a voltage to the normal part of the junction. The current gain in the present design is 0.4 but we believe that a gain larger than one is possible, making it more suitable for amplification applications.

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