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Investigation of current noise in underdamped Josephson devices by switching current measurements

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Abstract

Experimental measurements on critical current noise in underdamped niobium based Josephson devices by a technique based on the switching current measurements is reported. By sweeping the junction with a current ramp we measure the critical current switching as a function of the time using the standard time of flight technique. In such a way it is possible to obtain the critical current fluctuations $\Delta I_c = I_c(t) - \langle I_c(t) \rangle$ and the relative standard deviations which corresponds to the root square of the current fluctuation power. Pointing at the white noise fluctuations (above few Hz) and taking into account the physical frequency of the device, it is possible to evaluate the power spectral density of the critical current. The analysis has involved high quality underdamped Josephson junctions having an area ranging from (4x4) μm^2 to (40x40) μm^2 in the temperature range from 4.2 K to few tenth of mK. These measurement provide very useful information about the intrinsic noise of Josephson devices involving SQUIDs and qubits.

Keywords: Current noise, Josephson junction, SQUID, Power Spectral Density (PSD).

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1. Introduction

The effect of noise on the dynamics of the Josephson devices has received considerable theoretical and experimental attention. In particular, due to their interest for the applications, great attention has been devoted to overdamped Josephson devices (junctions and SQUIDs). In fact, exhaustive analytic theories

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and numerical simulations have been developed for non-hysteretic Josephson junctions and SQUIDs where the Nyquist noise in the shunt resistors is considered the main noise source [1-5]. In these cases, both analytic approach based on the Fokker-Plank equation [1,5] and direct numerical solution of Langevin equation have been developed [2-4]. Such theories have been widely supported by numerous experimental measurements. Furthermore, it has also been showed that the limiting noise as the temperature tends to zero is set by the zero-point current fluctuations (quantum noise) in the shunt resistors [6-8]. In the recent years, there is a renewed interest for the study of noise in underdamped devices due to the their employments for the quantum computation [9]. It is well known that the critical current of a Josephson device fluctuates causing a current, a voltage or a magnetic flux noise. The low frequency fluctuations of the critical current due essentially to the presence of the trapping center in the junction tunnel barrier together with the flux vortices hopping between pinning sites in superconducting films (mainly in the SQUID loop) produce a low frequency noise in the Josephson devices. Such a noise plays an important role for several applications as Biomagnetism, Geophysics and in particular for quantum computation application because the decoherence time in Josephson qubits is related to the low frequency noise [10]. Therefore a deep understanding of its nature is very useful. Recently, several theoretical interpretations and experimental works concerning this important issue have been developed [11-16]. For frequency above few Hz, the LT_c (low critical temperature) underdamped Josephson devices still exhibit critical current fluctuations due to thermal activation processes. Due to the random nature of these fluctuations, it is reasonable to expect that this noise is independent on the frequency (white noise). Even if, many studied have been devoted to the thermal escape processes in underdamped junction and SQUID, at our knowledge, there are not explicit studies of the intrinsic critical current noise in underdamped Josephson devices showing the link with the power spectral density of the critical current fluctuations in the white region and its dependence on the temperature and the junctions size.
In this paper, we report an experimental investigation of the critical current noise in underdamped niobium based Josephson junctions and SQUIDs by using switching current measurements.

2. Measurement method

The total noise of a stochastic physical signal is assumed as the root square of the power of the signal fluctuation around its mean value. In the case of the critical current I_c of a Josephson junction, the critical current fluctuation is $\Delta I_c = I_c(t) - \langle I_c \rangle$, hence the total intrinsic noise is given by:

$$\left\langle \Delta I_c^2(t) \right\rangle^{1/2} = \sigma = \left[\left\langle I_c^2(t) \right\rangle - \left\langle I_c(t) \right\rangle^2 \right]^{1/2} \qquad (1)$$

where σ is the standard deviation of the current fluctuations. By using the well know relation between the power of a signal and its power spectral density (PSD) it is possible to obtain the following equation which links the square current noise with its PSD ($S_{\Delta Ic}(\omega)$):

$$\left\langle [\Delta I_c(t)]^2 \right\rangle = \sigma^2 = \frac{1}{2\pi} \int_0^{\omega_f} S_{\Delta I_c}(\omega)\, d\omega \qquad (2)$$

where $\omega_f/2\pi$ is the physical bandwidth of the system. A reasonable assumption is that the physical bandwidth is equal to the plasma frequency of the junction $\omega_{p0} = 2\pi f_p = (2\pi I_c / C\Phi_0)^{1/2}$, where C is the junction capacitance and Φ_0 is the flux quantum. From the equation 2, we note that, if the noise is white, the PSD of the critical current noise is given by $S_{\Delta Ic} = 2\pi\sigma^2/\omega_{p0}$. Therefore if we are able to measure the standard deviation of the critical current and to evaluate the plasma frequency, we can obtain a direct measurement of the PSD of the critical current of a underdamped Josephson device. An effective way to perform a measurement of the critical current fluctuations is provided by the switching current technique.

The time critical current function (I_c (t)) can be obtained by sweeping the junction with a current ramp out of the superconducting state and measuring the critical current by using the standard time of flight technique. Note that, in this case the plasma frequency above reported has to be multiplied by a correction factor depending on the bias current I ($\omega_p(I)=\omega_{p0}[1-(I/I_c)^2]^{1/4}$). This method allows a direct measure of the critical current oscillations, whereas in other techniques the underdamped junction is biased above the gap voltage and it is placed as one arm of a Wheastone bridge having a SQUID as a null detector [11]. It is worth noting that the switching current technique described above corresponds to make a digital sampling of the critical current time oscillation. In fact, the time critical current function (Ic (t)) is digitally sampled with a sampling frequency f_s given by the ramp (sweeping) frequency. The total number of samples is $N=f_s \cdot \Delta t$, where Δt is the acquisition time. The current fluctuation is $\Delta I_c^k = I_c^k - < I_c >$, where k is an index which varies from 0 to N-1 and $<I_c>=(I_0+I_1+\ldots I_N-1)/N$ is mean value of the critical current. In the discrete case, the PSD of the critical current fluctuation $S_{\Delta Ic}$ (f) is given by the square module of the Fast Fourier Transform X_q divided the total number of samples:

$$S_{\Delta I_c}(q) = \frac{X_q \cdot X_q^*}{N}; \qquad X_q = \sum_{k=0}^{N-1} \left[\Delta I_c^k \left(f_s/2f_p\right)^{1/2}\right] \; e^{-j\frac{2\pi}{N}k_q}; \qquad q = 0,1,\ldots.N-1 \qquad (3)$$

The normalization term $(f_s/2f_p)^{1/2}$ takes into account the physical bandwidth of the system. As for the continuous case, it is reasonable to identify the plasma frequency as the physical bandwidth of the system. In fact the sampling (sweeping) frequency is different from the physical bandwidth, otherwise the total intrinsic noise σ (which is related to the width the P(I)) should strongly depend on the sampling frequency. Furthermore the PSD cannot depend by the bandwidth frequency. The computation of the discrete PSD is based on the Welch method.

The experimental set up is shown in Fig. 1. The junction was biased with a triangular-shaped waveform at a frequency of 100 Hz. A pulse generator was triggered by the waveform and it generated a TTL signal when the bias current pass through zero. The TTL signal was sent as a start to an acquisition board with a clock at 80 MHz (12.5 ns resolution). The stop signal is provided by a discriminator that detects the switching of the junction out of the zero voltage state [17]. The critical current values are obtained multiplying the measured current ramp slope dI/dt by the acquired interval time Δt. The estimated measurement resolution of the critical current is about 1 part in 10^4, which is essentially limited by the stability of the start signal. All the electrical connections to room temperature went through manganine wires. The measurements were performed, in a pumped liquid ^4He cryostat with two copper and three µ-metal coaxial shielding cans.

3. Experimental result

The analysis has involved high quality niobium underdamped Josephson junctions [18] having an area ranging from (4x4) μm^2 to (40x40) μm^2 in the temperature range from 4.2 K to 1.2 K. In the figure 2a, we report the critical current fluctuation ΔI_c (t) as a function of the time of a (10x10) μm^2-junction measured at T=4.2 K, with the technique described above, by using a biasing waveform frequency of 100 Hz. Each measurement includes 100000 samples corresponding to an acquisition time of 1000 s. For clarity only a time window of a 1 s is depicted in the figure so that it is possible to see the single points. The inset shows the current current switching distribution P(I) (red dots in the onset of the figure 2a).

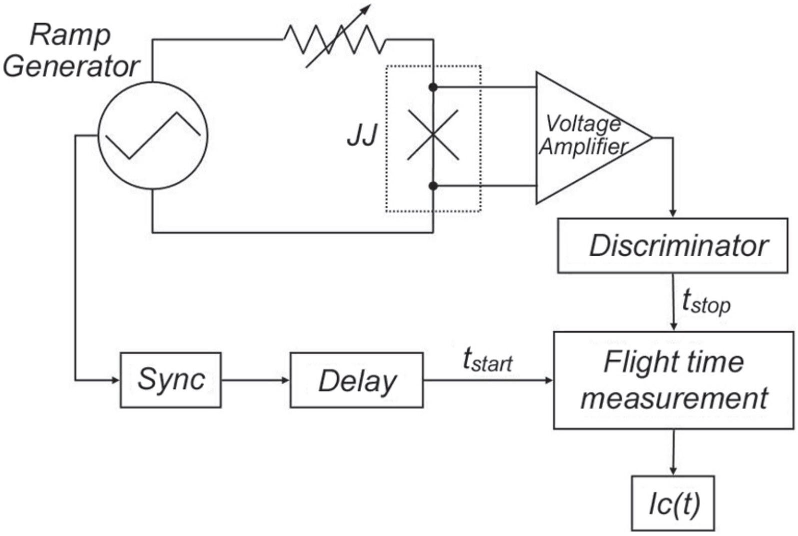

Fig. 1 a) . Experimental set up for the switching current measurements based on a time of flight technique. The resolution of the critical current measurements is about 1 part in 10^4.

In order to verify the reliability of the measurements, the current switching distributions have been compared with the predictions of the Buttiker, Harris and Landau (BHL) theory [19] (black line in the inset of the figure 2a). Spectral density of the critical currents relative to three underdamped Josephson junctions having an area of (4x4) µm^2, (20x20) µm^2 and (40x40) µm^2 measured at T = 4.2 K are reported in figure 2b. The white current noise S_{Ic} ranges from 2.0×10^{-24} A^2/Hz for the smallest junction to 0.7×10^{-22} A^2/Hz for the greatest one. Such values are consistent with the data recently reported in the literature [11].

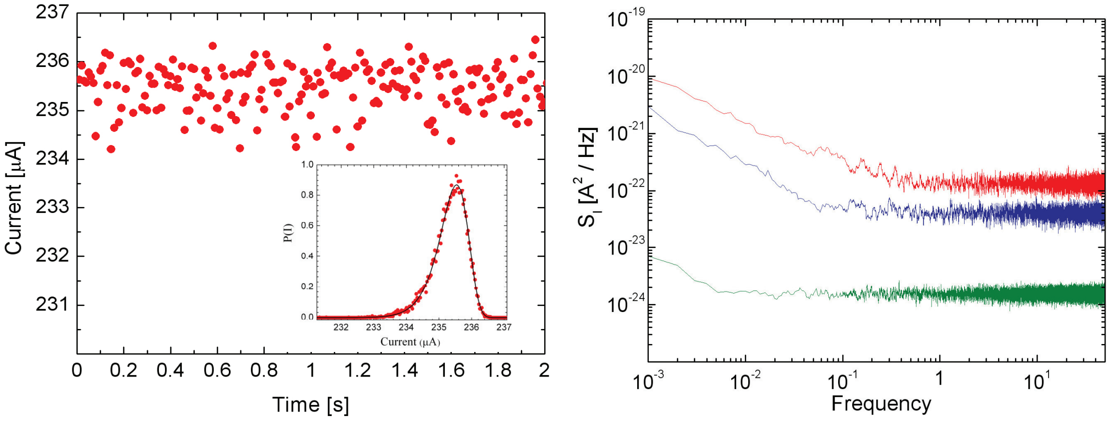

Fig. 2 *a)* The critical current fluctuation ΔI_c (t) as a function of time for a (10x10) µm^2-junction measured, at T=4.2 K. The inset shows the switching current distribution (red dots) compared with the theoretical prediction (black line). *b)* Spectral density of the critical currents relative to three underdamped Josephson junctions measured at T = 4.2 K. The junction areas are 16 µm^2 (green), 400 µm^2 (blue), and 1600 µm^2 (red). Each curve has been obtained by averaging the spectral density of 30 different measurements.

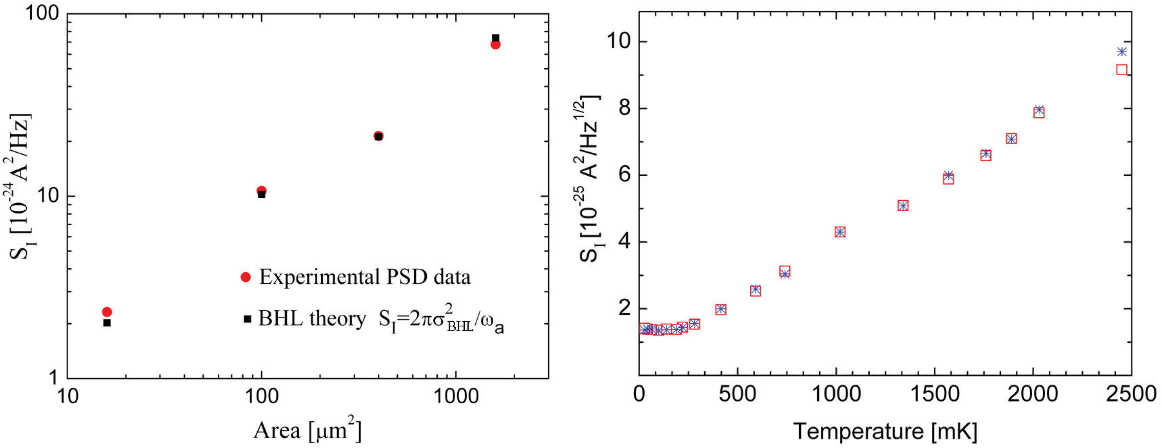

Fig. 3 *a)* White critical current noise of the Josephson junction as a function of its area (red dots) measured at T = 4.2 K compared with the values predicted by the Buttiker, Harris and Landau (BHL) theory (black squares). *b)* White critical current noise of a Josephson junction (5×5 μm^2) measured in the millikelvin regime (empty red square) compared with the values predicted by the BHL theory (blue asterisk). Note the presence of the saturation due to the quantum noise.

Figure 3a reports the PSD of the white current noise of four junction as a function of junction area; they have been compared with the values predicted by the BHL theory (black squares), obtained by dividing the σ_{BHL}^2 by the plasma frequency $\omega_p/2\pi$. The σ_{BHL} values have been obtained by fitting the current switching distributions with the BHL theory [19,20] as performed in the inset of figure 2a. Figure 3b shows the white critical current noise of a Josephson junction (25 μm^2) as a function of the temperature (empty red square) compared with the values predicted by the BHL theory (blue asterisk). It is possible to observe a saturation for temperatures less than 500 mK essentially due to a saturation of the σ values related to the macroscopic quantum tunneling effect.

4. Conclusion

In conclusion, measurements of power spectral density of the critical current noise in underdamped niobium based Josephson device have been performed by making the PSD of the critical current time fluctuations. The reported investigations can be useful for Josephson devices including underdamped junction like SQUID triggers, phase or flux qubits.

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