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Low-frequency excess noise in SQUIDS with $YBa_2Cu_3O_7$ step-edge junctions

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Abstract. We have fabricated RF and DC SQUIDS with step-edge Josephson junctions (SEJ) and $YBa_2Cu_3O_7$ thin films. The low-frequency noise of these SQUIDS has been investigated as a function of temperature, bias current and magnetic field. Typically, the energy resolution in the white noise region of the DC SQUIDS with an inductance of 45 pH was 3×10^{-30} J Hz^{-1} at 77.5 K. Depending on the bias current, the low-frequency spectrum could be of either $1/f$ type or Lorentzian type. The Lorentzian spectrum was generated by random telegraph signals (RTSS). An Arrhenius plot was obtained from the temperature dependence of the switching time of these RTSS. We have determined two barrier lengths of 0.23 eV and 1 eV of the two-level fluctuator (TLF) generating this RTS noise. From the magnetic-field dependence of the low-frequency noise we have found that the noise is periodic with the flux corresponding to the area of the SEJ. The results were discussed in terms of a model treating the SEJ as a multi-junction interferometer which forms a two-level fluctuator when the junction is placed inside a SQUID loop. The noise is generated by thermally activated switching of the SQUID between the two different states of the SQUID.

1. Introduction

SQUIDs with various grain-boundary Josephson junctions fabricated from $YBa_2Cu_3O_7$ (YBCO) epitaxial thin films exhibit substantial $1/f$ type noise [1–3]. The $1/f$ noise can arise either from critical current fluctuations or from flux motion. We have shown that the $1/f$ noise of DC and RF SQUIDs with step-edge junctions (SEJs) is determined by the noise properties of the junctions [3]. It was shown that each SEJ consists of two weak links connected in series and having different critical currents [3, 4]. In that study, we found that the low-frequency excess noise was generated by critical current fluctuations. Furthermore, we also observed random telegraph noise signals (RTNs). However, the origin of the low-frequency RTNs remained somewhat unclear. Here, we report some results of our investigation of RTNs in interferometers containing two SEJs.

2. Fabrication

The RF and DC SQUIDs consisted of epitaxial YBCO films pulsed-laser-deposited on $SrTiO_3$ substrates with ion-milled steep steps permitting the formation of the SEJ. The fabrication procedure was described in detail in [4, 5]. The films were patterned by Ar-ion milling. The step height to film thickness ratio was about 2/3. To obtain sufficiently large critical currents, the devices were post-annealed in oxygen plasma. All interferometers consisted of two SEJs. The SQUID inductances were 35 pH to 80 pH.

The noise measurements were performed using standard RF- and DC-flux-locked-loop read-out circuits. The measurements of the dependence of the noise on bias current and the random telegraph signal (RTS) measurements were made by a small signal read-out scheme using an Nb SQUID as a preamplifier. This circuit was described in more detail in [3].

3. Experimental results

The flux-noise spectral density below the crossover frequency scaled at some bias currents approximately as $1/f$, while at different bias conditions the $1/f$ spectrum changed to a Lorentzian type, as shown in figure 1 for a DC SQUID. The corresponding real-time voltage signals were RTNs. We have found an analogous behaviour in RF SQUIDs when varying the temperature [3]. In some RF and DC SQUIDs it was possible to find conditions under which no $1/f$ noise was found up to frequencies of 0.25 Hz. We have studied the influence of bias conditions on the excess noise in more detail. Figure 2 shows the dependence on bias current of the transfer function and the flux noise of a DC SQUID at 1 Hz at

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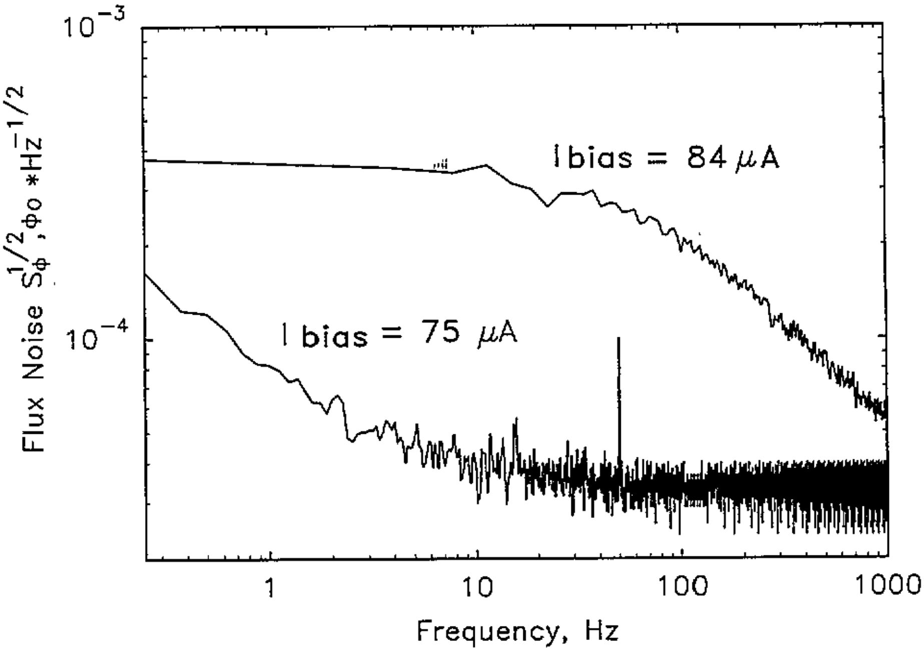

Figure 1. Flux noise spectrum of a DC SQUID operated in a flux-locked loop with an inductance $L = 150$ pH at different bias currents at 77.5 K.

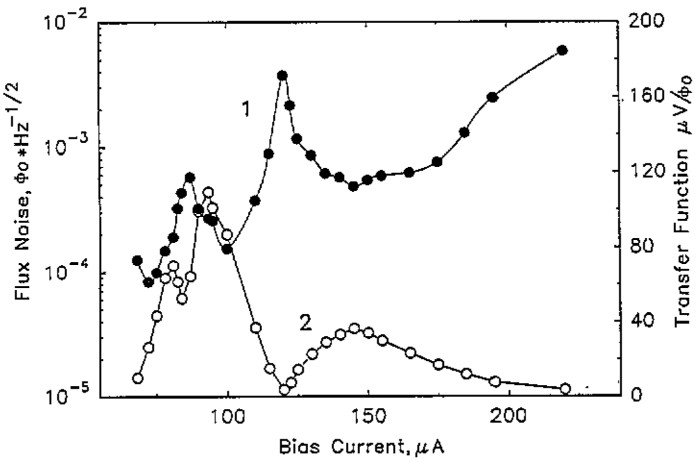

Figure 2. Dependence of the flux noise (1) at 1 Hz and the transfer function (2) on bias current of the DC SQUID shown in figure 1 at 77.5 K.

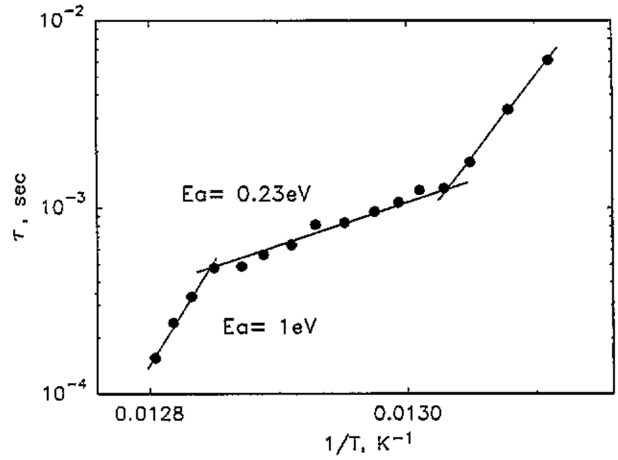

Figure 3. Temperature dependence of the switching time determined from the real-time signals of an RF SQUID with $L = 90$ pH.

77.5 K. The excess noise had a minimum at bias currents which were lower than that at which the peak of the transfer function occurred. Typically, the white noise of DC SQUIDs with $L = 45$ pH was $8 \times 10^{-6}\Phi_0\ \mathrm{Hz}^{-1/2}$ with a corresponding energy resolution of 3×10^{-30} J Hz^{-1} at frequencies above 30 Hz at $T = 77.5$ K. In some DC SQUIDs, we found two peaks in the transfer function occurring at different bias currents. Fortunately, in SQUIDs with SEJs having a large second critical current, the corresponding noise peak is shifted close to the corresponding bias current value, far above the bias for optimum SQUID operation.

We have studied the low-frequency excess noise near the maximum of the transfer function in more detail. In all studied RF and DC SQUIDs we found that the form of the Lorentzian spectra strongly depends on temperature, bias current and magnetic field. The Lorentzian spectra were caused by random telegraph switching. We have measured the real time output voltage and have determined the effective switching time τ_{eff} from the following formula: $\tau_{\mathrm{eff}}^{-1} = \tau_{\mathrm{d}}^{-1} + \tau_{\mathrm{u}}^{-1}$, where τ_{d} and τ_{u} are the corresponding switching times for down and up switching of the system. The temperature dependence of the effective switching time of a representative RF SQUID with $L_{\mathrm{s}} = 90$ pH could be plotted as an Arrhenius plot, as shown in figure 3. From this Arrhenius plot two activation energies of 0.23 eV and 1 eV were determined.

To determine the origin of this thermal activation process, we investigated the influence of an external magnetic field on the noise properties of the RF and DC SQUIDs. By applying a magnetic field up to 0.5 G,

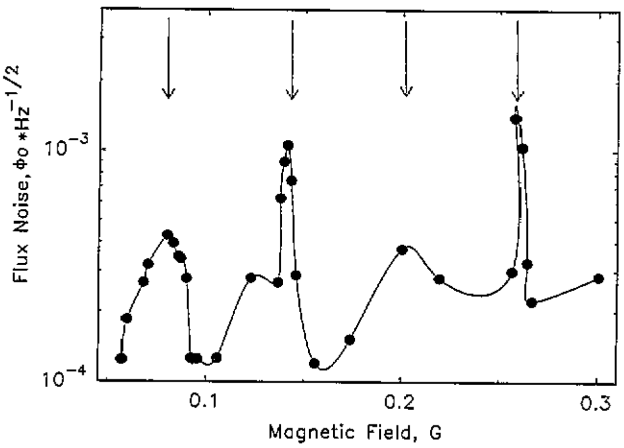

Figure 4. Magnetic-field dependence of the flux noise of the RF SQUID shown in figure 3 at 1 Hz and 77.5 K. The noise peaks, shown by arrows, have a period of 56 mG.

we found a periodic dependence of the excess noise on the magnetic field, with a period of 56 mG (figure 4). The field period of the SQUID loop corresponding to Φ_0 was 0.23 mG. Operating the SQUID with an RF read-out circuit in a bias mode, where a quantum interference of the main SQUID-loop did not occur, we found a quantum interference pattern from the Josephson junction with a field period of 112 mG. We also found, qualitatively, the same behaviour in several RF and DC SQUIDs.

4. Discussion

It was shown that under different bias conditions the noise spectrum can either be of $1/f$ or of Lorentzian type. At different bias currents we found two peaks in the transfer function which were correlated with peaks in the low-frequency noise. That noise was of the Lorentzian type. The two peaks can be explained by the fact that an SEJ consists of two weak links at the two grain boundaries [3,4]. The presence of more than two weak links in a DC SQUID loop generates, at certain bias currents, additional noise, as shown in figure 2 and discussed in [6].

The random telegraph signals could be explained by a model of a two-level fluctuator (TLF) and a thermally activated switching of the system between the two minima of the potential energy of the TLF. We assumed a TLF model, and, using the standard expression: $S_\Phi \propto \tau_{\text{eff}}[8\pi[1 + (0.5\omega\tau_{\text{eff}})^2]]^{-1}$, determined from the Lorentzian spectra $S_\Phi(f)$ the effective switching time between two different states, τ_{eff}. Using these data we have reconstructed the real-time signals $V(t)$ as discussed in section 3. There are three possible sources for the RTSs generated by a TLF: first, critical current fluctuations caused by charge transfer through localized states in the weak link [7], second, the flux motion [8], and third, the presence of additional metastable states in the interferometer caused by intrinsic quantization loops and additional weak links in the interferometer [6].The temperature dependence of the excess noise could not be explained by resonant tunnelling or hopping through localized states. Also, since the noise did not scale linearly with an applied magnetic field, the motion of vortices could not be the source of the RTNs.

As shown before, the excess noise was periodic with the flux period of the SEJ. We concluded that the observed periodic noise maxima originate from the additional flux quantization in internal interferometers of the SEJ. Calculating the potential energy $E_k = \Phi_0^2/2L_k$, where L_k is the inductance of different loops, of an interferometer with an inductance of the SQUID loop of 90 pH and of the internal loop of the SEJ of 5 pH, we obtained 0.15 eV and 2.71 eV respectively. In this model the dependence of the potential energy on the flux of the small interferometer is modulated with the periodic potential of the large interferometer. This results in a two-level fluctuator with barrier heights close to the values which were determined from the Arrhenius plot of effective switching times of the RTNs. Since the thermal energy at 77 K is about 7 meV, the different energy states of this interferometer are well defined. However, thermal noise may induce switching between the difference states. Transitions between these states may be stimulated not only by temperature but also by changing the bias current and the magnetic field, which is consistent with the obtained results. They are the consequence of at least one of the weak links, the SEJ being an interferometer with two (or more) Josephson junctions.

Acknowledgments

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