Noise properties of direct current SQUIDs with quasiplanar $YBa_2Cu_3O_7$ Josephson junctions

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We describe the noise performance of dc SQUIDs fabricated with quasiplanar ramp-type Josephson junctions on the basis of *c*-axis-oriented $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ thin-film heterostructures. The noise spectrum of the dc SQUIDs was measured with dc- and ac-bias schemes at different temperatures and showed values below $10^{-5}\ \Phi_0/\mathrm{Hz}^{1/2}$ down to frequencies of about 1 Hz at 70 K. Up to now for the magnetic flux noise and the energy resolution obtained at 1 kHz and 77 K the best values were 2.5×10^{-6}, $\Phi_0/\mathrm{Hz}^{1/2}$ and 3×10^{-31} J/Hz, respectively. A study of the white and $1/f$ noises of the SQUIDs was performed. The influence of magnetic flux, bias current, high static magnetic fields, and aging on the SQUID noise were investigated. The junctions and devices do not degrade due to aging in air or thermal cycling.

The sensitivity of the dc SQUIDs on high-temperature superconductors is limited by noise, which usually consists of a white noise and a $1/f$ noise. The white voltage noise is proportional to the operating temperature. The $1/f$ noise can be produced by a large variety of different physical sources and can reach significant values in high-T_c SQUIDs at frequencies of about 1 Hz (see, e.g., Ref. 1). The quality of the films and Josephson junctions included in the SQUID, the ambient conditions like electromagnetic disturbances, and the measuring apparatus play a major role in the measured noise spectrum. To find out which type of Josephson junction has the lowest noise, to study and suppress different noise sources in SQUIDs are tasks that are important for applications.

Presently, for dc SQUIDs, e.g., on bicrystal Josephson junctions[2] measured in a shielded environment at 77 K, the achieved noise levels are already low enough for many conceivable applications. Often the devices have to operate without a magnetic shielding. They should not show a large increase of the noise in external magnetic fields up to a few gauss. Nearly all applications also require practical junctions, which could be fabricated in a reproducible fashion and have a long lifetime: they should be rugged enough to withstand long storage (aging), handling, and thermal cycling. Probably, these problems can at least be partially overcome when the coupling between the superconducting electrodes occurs through a normal conducting oxide by the proximity effect.[3,4]

Earlier[3] we developed a technique of deep-UV photolithography for $YBa_2Cu_3O_7$ and $PrBa_2Cu_3O_7$ heterostructures combined with a nonaqueous Br-ethanol etching and used it for the preparation and study of ramp-type Josephson junctions on the basis of gently sloping edges of the bottom electrode. The junctions showed low values of the ramp angle of about 3° (see Ref. 3) and could thus be considered as quasiplanar. This is advantageous for the operation of the junctions in dc SQUIDs,[4] where the influence of the external magnetic fields on the junctions should be suppressed. A spread of the critical currents and resistance of the junctions below 20% can be achieved.[3,5] This allows large modulation voltages to be obtained in dc SQUIDs,[4] but requires a very high-quality *c*-axis-oriented bottom electrode with a low density of precipitates and a delicate preparation procedure of the multilayer structure. The present report is devoted to the study of the noise properties in the SQUIDs with quasiplanar $YBa_2Cu_3O_7/PrBa_2Cu_3O_7/YBa_2Cu_3O_7$ thin films.

The high-oxygen pressure dc sputtering technique, which was used for the deposition of the $YBa_2Cu_3O_7$ and $PrBa_2Cu_3O_7$ films, has been discussed in detail elsewhere.[6] The *c*-oriented films of $YBa_2Cu_3O_7$ sputtered in a similar fashion have a typical critical current density above 5×10^6 A/cm^2 at 77 K and a zero-resistance transition temperature of about 91 K. The junctions optimized for the SQUIDs had a width of about 3 μm, a thickness of the $PrBa_2Cu_3O_7$ barrier of about 30 nm, and a critical current density of about 10^3 A/cm^2 at 77 K. The main details of the junction preparation procedure were described in previous publications (see, e.g., Refs. 3–5).

Electrical measurements were mainly carried out at 77 K with the SQUIDs immersed in boiling nitrogen.[4,5] The cryostat was placed inside the concentric Cu, Al, and μ metal cylinders to shield the SQUIDs from external electromagnetic fields. This shielding provided a suppression of the static magnetic field down to about 1 nT and electromagnetic noise down to about 100 fT for 2 kHz bandwidth. The SQUIDs were operated in a flux-locked loop using a commercial dc SQUID electronics having a white noise voltage level of about 0.2 nV/Hz$^{1/2}$ relative to the input.

Modulation voltages V_{pp} (peak to peak) of about 20 μV ($\partial V/\partial\Phi\approx\pi V_{pp}\approx80\ \ \mu V/\Phi_0$) were observed at 77 K on dc SQUIDs with a loop inductance of $L\approx40$ pH. This corre-

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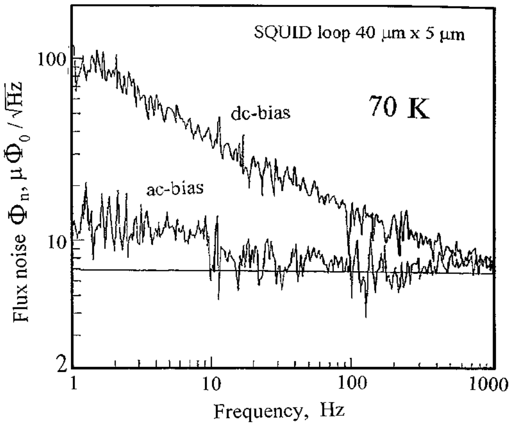

FIG. 1. Flux noise spectrum of a dc SQUID with a loop of 40 $\mu m \times 5$ μm at 70 K. The measurements were performed in a conventional flux-locked loop scheme with dc- and ac-bias current.

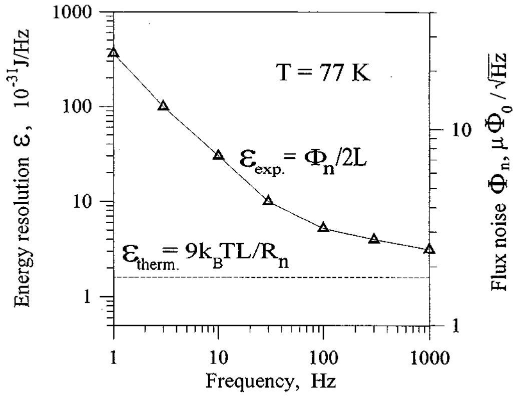

FIG. 2. Energy sensitivity $\epsilon_{\mathrm{exp}}=\Phi_n^2/2L$ of a dc SQUID having an inductance L of about 40 pH and a flux to voltage transfer coefficient of about 80 μV/Φ_0 at 77 K. The junctions included in this SQUID have a critical current of about 30 μA, $R_n \approx 3$ Ω, $d_{\mathrm{Pr}} \approx 30$ nm, and a width of about 5 μm.

sponds to the theoretical estimate for V_{pp} obtained by Enpuku *et al.*,[7] when we introduce our experimental values $I_c \approx 30$ μA and $R_n \approx 3$ Ω.

Due to the relatively high modulation voltages of the SQUIDs we were able to investigate the intrinsic noise properties of the SQUIDs. The spectral density of the white voltage noise for the dc SQUID is given by $S_V(f) \approx 16k_BTR_n \approx (0.23$ nV$)^2$/Hz for the Nyquis current noise, $T=77$ K, and the typical junction resistance $R_n \approx 3$ Ω.

Due to the increase of the dynamic resistance R_d the white noise should diverge when the bias current I approaches I_c. With a dc-bias measuring scheme this effect is covered by $1/f$ noise, which was found to be proportional to the transfer function $\partial V/\partial\Phi$ and is maximal at $I \approx I_c$. An increase of the bias current well above I_c leads to a proportional increase of the white voltage noise level up to about 1 nV/Hz$^{1/2}$ at $I \approx 10I_c$. This corresponds to the results obtained by Kawasaki *et al.*,[8] but contrary to Ref. 8 the noise appearing at high bias currents does not show a $1/f$-like behavior. At such bias currents the transfer function $\partial V/\partial\Phi$ vanishes and the $1/f$ voltage noise associated with the flux fluctuations must thus be negligible.

At low frequencies of $f < 100$ Hz the observed noise spectrum of the dc SQUIDs follows the $1/f$ dependence leading to an increase of the noise up to about 10^{-4} Φ_0/Hz$^{1/2}$ at 1 Hz. The low-frequency $1/f$ noise of the SQUIDs could appear due to fluctuations of the critical current and in this case can be significantly reduced by performing the measurements with an ac-bias technique.[1,9] The effect of the ac bias showed a maximum effect at 70 K, where it helped to suppress the $1/f$ noise nearly 10 times at 1 Hz (see Fig. 1). This indicates that for this temperature the $1/f$ noise is mainly generated by the fluctuations of the critical current in the junctions. The flux noise Φ_n was reduced down to about 10^{-5} Φ_0/Hz$^{1/2}$ at 1 Hz at 70 K. This corresponds to a voltage noise level of about 0.6 nV/Hz$^{1/2}$, which only slightly exceeds the noise of the electronics. Above 80 K due to the increased thermally activated vortex motion in the electrodes the application of the bias reversal was not profitable any more. Below 65 K the SQUID showed switching effects, which also led to an increase of the $1/f$ noise level.

Up to now for the flux noise at 77 K a best value of about $\Phi_n \approx 2.5 \times 10^{-6}$ Φ_0/Hz$^{1/2}$ at 1 kHz was achieved for a SQUID having an inductance of $L \approx 40$ pH and a junction resistance of $R_n \approx 3$ Ω. The corresponding energy sensitivity of the SQUID is about $\epsilon(1$ kHz$) \approx \Phi_n^2/2L \approx 3 \times 10^{-31}$ J/Hz (see Fig. 2). With the Nyquist current noise the estimate of the energy resolution in the white noise region is $\epsilon_{th} \approx 9k_BTL/R_n \approx 1.5 \times 10^{-31}$ J/Hz.

The transfer function $\partial V/\partial\Phi$ and $1/f$ noise have similar maxima for the dependence on bias current or applied flux. For SQUIDs containing junctions with an area of $S > 5$ μm^2 we observed two maxima of the transfer function $\partial V/\partial\Phi$. This is related to a high frequency resonance in the SQUID loop at a voltage $V_{\mathrm{res}} = \Phi_0/2\pi(LC/2)^{1/2}$. For the given SQUID inductance and the measured value of V_{res} the estimated specific junction capacitance C/S was about 0.04 F/m^2 and the effective dielectric constant of $PrBa_2Cu_3O_7$ was about 30. For junctions with an area $S < 5$ μm^2 the resonance was shifted to higher voltages and did not significantly influence the operation of the SQUIDs.

An increase of the barrier thickness leads to an increase of R_n and a decrease of C and I_cR_n. The junctions with $R_n > 10$ Ω nominally have critical currents comparable with the thermal noise current $I_{\mathrm{th}} = 2\pi k_BT/\Phi_0 \approx 3.4$ μA. The thermal noise current is generated by thermally activated phase slippage[10] and causes a rounding of the $I-V$ characteristics. For an I_cR_n product of the junctions used in the investigated SQUIDs of about 100 μV at 77 K the increase of the junction resistance above about 20 Ω resulted in a reduction of the voltage modulation V_{pp}.

The high structural quality of the whole heteroepitaxial multilayer device is very essential for the low noise properties of the junctions and SQUIDs. At an early stage of the optimization of the SQUID preparation procedure we observed significant telegraphlike noise increasing with the bias current above $I \approx I_c$. The telegraphlike noise becomes negligible in SNS junctions which have no carrier trapping at the interfaces and in the barrier.[11] This seems to be realized now

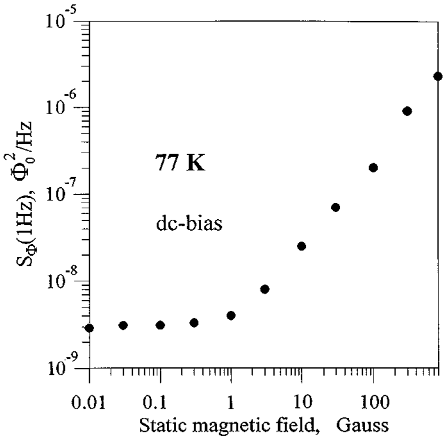

FIG. 3. Noise behavior of a dc SQUID (filled circles) cooled in high static magnetic fields at 1 Hz.

for the investigated junctions, because presently even with the bias current up to about $10I_c$ the $1/f$ noise including the telegraphlike noise is not observable any more.

Many near future applications of high-T_c. SQUIDs will require an operation in a magnetically unshielded environment. A static magnetic field can degrade the noise performance of the SQUIDs.[12] We have tested the performance of a dc SQUID cooled in static magnetic fields up to about 1000 G. The SQUID was immersed in liquid nitrogen together with a $SmCo_5$ permanent magnet. The magnet was fixed at different distances from the SQUID. The corresponding magnetic fields were separately calibrated by a Hall sensor.

The results of the noise study at 1 Hz in high static magnetic fields are presented in Fig. 3. In comparison with the results of Miklich *et al.*[12] obtained on bicrystal junctions, SQUIDs with quasiplanar junctions even without ac bias exhibit less noise while operating in static fields above about 0.1 G. External magnetic fields up to about 1 G did not influence the noise of the dc SQUIDs with quasiplanar junctions. This fact can be attributed to the geometry of the Josephson junctions. The junctions are intrinsically shielded from external magnetic fields by the Meissner effect in the top electrode.

The noise observed at higher fields was telegraphlike and can be associated with the flux motion in the $YBa_2Cu_3O_7$ films forming the SQUID. The application of constant magnetic fields up to about 10 G did not significantly degrade the noise and signal properties of the SQUIDs. The transfer function was reduced to 60 $\mu V/\Phi_0$ at 10 G and to about 25 $\mu V/\Phi_0$ at 100 G. In high magnetic fields of about 100 G an observed microphonic effect was drastically increasing. Additionally, at this field significant telegraphlike noise appeared, which is probably a result of continuous flux motion in the SQUID body. Liquid nitrogen often contains a certain amount of paramagnetic liquid oxygen, which has a relatively large magnetic susceptibility of about 8×10^{-3}. This could change the high static amplitude of the magnetic environment during the cooling of the sample and therefore produce a nonequilibrium flux distribution in the SQUID, which could partially lead to the observed telegraphlike noise.

Effects due to aging or thermal cyclings on the properties of the junctions and SQUIDs were investigated. The presence of moisture can corrode the involved films particularly by an electrochemical process on oxide-metal contacts. Also, electrical pulses can destroy the samples due to a concentration of electrical power on the junctions. Avoiding this the $I-V$ characteristics and noise spectra of the dc SQUIDs were not changed even after one year of storage in silica gel at room temperature and more than 50 thermal cycling operations between room and liquid nitrogen temperatures. The reason for such long-time stability of the junctions seems to be related to their structure: the junction characteristics are mainly determined by the relatively thick barrier layer, which is protected from the ambient atmosphere by a thick high-quality c-axis-oriented top electrode.

In conclusion, we have fabricated dc SQUIDs with quasiplanar $YBa_2Cu_3O_7$ Josephson junctions and investigated their noise properties. A study of the white and $1/f$ noises of the SQUIDs was performed. The influence of magnetic flux, bias current, high static magnetic fields, and aging on the SQUID noise was investigated. The obtained values of the energy resolution are already sufficient for many applications provided that an integrated or flip-chip flux antenna can be added without considerably increasing the noise.

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