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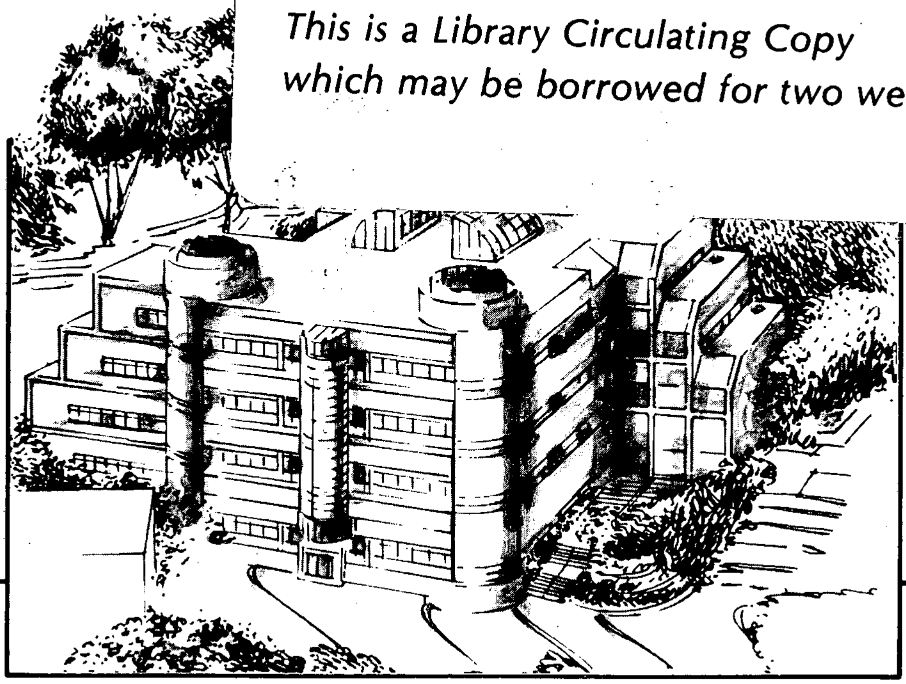

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Abstract

We have used a dc SQUID to measure the low-frequency magnetic flux noise produced by thin-film rings of $YBa_2Cu_3O_{7-\delta}$ (YBCO) with various microstructures. Below the transition temperature T_c of the YBCO, the spectral density of the noise scales as 1/f (f is the frequency) from 1 Hz to 1 kHz. This noise generally increases with temperature and vanishes abruptly at T_c. Improvements in crystalline microstructure dramatically reduce the magnitude of the noise, which was lowest for a highly oriented sample with its c-axis perpendicular to the substrate. Making a radial cut to interrupt current paths around the sample ring does not significantly affect the magnitude of the noise, demonstrating that the noise arises from a local mechanism such as the thermally activated hopping of flux bundles. Flux creep was observed in one sample cooled in a magnetic field of 1 mT, and the creep rate exhibited a sharp maximum near 80 K. We conclude that SQUIDs and flux transformers of YBCO must be fabricated from highly oriented films to obtain low noise at low frequencies.

Introduction

The first application of thin films of high-temperature superconductors has been dc Superconducting QUantum Interference Devices (SQUIDs). Several groups[1-4] have successfully operated such devices patterned on thin films of YBCO, but found high levels of low-frequency flux noise. Koch *et al.*[1,5] have described SQUIDs operating at 77 K that have achieved a noise energy $\varepsilon(f) = S_\Phi(f)/2L = 2 \times 10^{-25}$ JHz^{-1} at 1 Hz, where $S_\Phi(f)$ is the spectral density of the flux noise in the device at a frequency f and L is the inductance of the loop. The noise power scales as 1/f at low frequencies, and is at least five orders of magnitude greater than that of a conventional Nb or Pb SQUID in its 1/f region at 4.2 K. If inherent in the material, this noise would pose a significant obstacle to low-frequency applications of high-T_c SQUIDs.

We have studied magnetic flux noise and flux creep in thin-film rings of YBCO as functions of temperature, film microstructure, and applied magnetic field. Our noise measurements demonstrate that the low frequency noise decreases substantially as the microstructure is improved. We report an experiment indicating that the noise arises from a local mechanism, and an investigation of the temperature dependence of the flux creep rate. Both of these experiments have consequences for the design of YBCO flux transformers. Finally, we mention some preliminary results on the effect of field cooling on the noise.

Experimental Details

A detailed description of the apparatus and the samples has appeared elsewhere.[6] Briefly, a $Nb\text{-}NbO_x\text{-}PbIn$ SQUID in the form of a 1 mm square washer is mounted in a vacuum can and thermally grounded to the liquid ^4He bath. A film of YBCO approximately 200 nm thick, patterned to the same dimensions as the SQUID, is supported on a thermally isolated stage about 100 μm from the SQUID. The sample can be maintained at temperatures up to 125 K without impairing the performance of the SQUID. A small modulation and feedback coil enables us to operate the SQUID in a flux-locked loop, while a field coil 13 mm in diameter, centered just below the SQUID, allows us to apply magnetic fields of a few mT.

Table I summarizes the important material parameters of the three YBCO films we have measured. All were deposited on $SrTiO_3$ substrates, samples 1 and 2 by coevaporation and sample 3 by cosputtering, and then annealed.[7] The samples are numbered in order of increasing degree of crystallographic orientation: sample 1 is polycrystalline with some oriented grains, sample 2, mixed a- and c-axis oriented, and sample 3, predominantly c-axis oriented.

In order to refer our SQUID noise measurements to noise in the sample, we need to determine the mutual inductance $M_\ell = \alpha(LL_\ell)^{1/2}$ between the SQUID and the YBCO loop of inductance L_ℓ. We define ΔI_c to be the difference between the maximum and minimum critical currents observed when the flux applied to the SQUID is varied. Since the effective inductance L_e of the SQUID is reduced to $L(1-\alpha^2)$ when the YBCO is superconducting and ΔI_c scales approximately as $1/L_e$, we can extract the coupling coefficient α from the change in ΔI_c as the sample is heated through T_c.[6] The dependence of ΔI_c on temperature for sample 3 is shown in Fig. 1. The spectral density of the flux noise in the loop is given by $S_\Phi(f) = S_\Phi{}^s(f)/\alpha^2$, where $S_\Phi{}^s(f)$ is the noise observed in the SQUID.

To determine the temperature dependence of the

Table I. Properties of three YBCO samples. Values of J_c are from magnetization measurements prior to patterning.

Sample #	$SrTiO_3$ orientation	YBCO orientation	T_c K	J_c(4.2K) A/cm^2
1	18° from (100)	polycrystalline	47	—
2	(100)	mixed a- and c-axis	85	2×10^4
3	(100)	> 90% c-axis	85	5×10^6

screening of the YBCO more accurately, we also measured the current in the modulation coil required to produce one flux quantum in the SQUID. The inferred value of the mutual inductance M between the modulation coil and the SQUID for sample 3 is shown vs. temperature in Fig 1. Below T_c, the mutual inductance is reduced by the screening effect of the YBCO. We define T_c as the greatest temperature at which M is depressed below its constant high-temperature value. The small jump near 60 K is reproducible, and likely represents the presence of a small amount of oxygen-deficient phase of YBCO with $T_c \approx 60$ K.

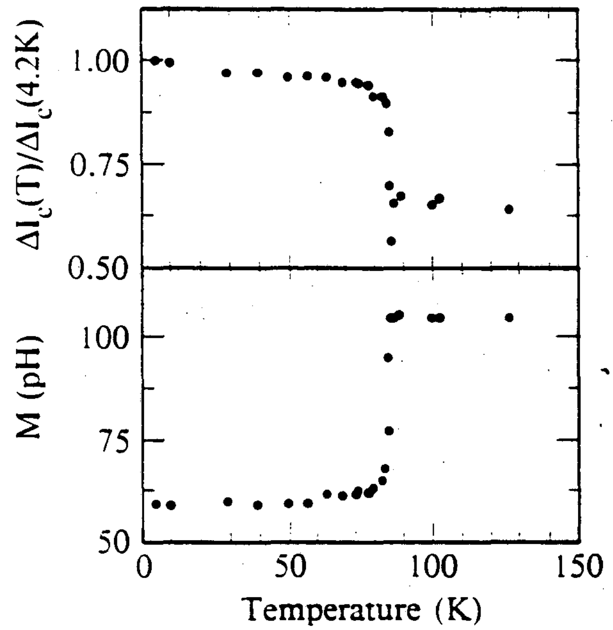

Figure 1. Normalized modulation amplitude of the critical current of the SQUID, $\Delta I_c(T)/\Delta I_c(4.2K)$, and mutual inductance M between the SQUID and the modulation coil, as functions of temperature for sample 3.

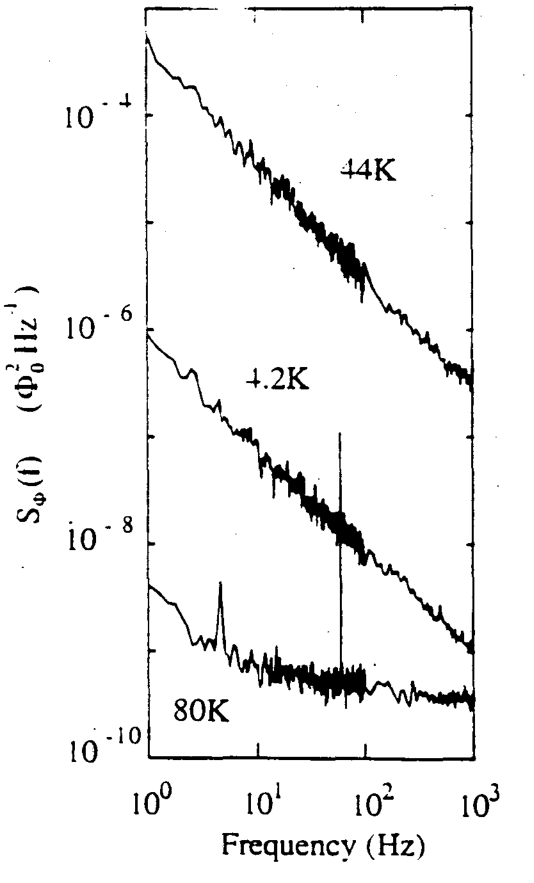

Figure 2. Power spectra of observed flux noise for sample 1 at three different temperatures. At 80K, the spectrum is that of the SQUID, divided by α^2.

Flux Noise

Noise spectra for sample 1 at three temperatures are shown in Fig. 2. Below T_c, $S_\Phi(f)$ varies approximately as 1/f from 1 Hz to 1 kHz. Since the transition temperature for sample 1 was only 47 K (most probably due to underannealing), the spectrum at 80 K reveals just the intrinsic noise of the SQUID, with no evident contribution from the sample.

Figure 3 is a plot of the spectral density of the noise at 1 Hz vs. temperature for the three samples. The 1/f noise generally increases with temperature, peaks at T_c, and then falls off quite rapidly. At sufficiently high temperatures, the noise from the YBCO is below the noise of the SQUID. From Fig. 3 it is evident that better-oriented films with higher critical current densities produce less noise. The lowest noise was obtained for sample 3. If we assume $L_\ell \approx 400$ pH, we find noise energies $\varepsilon(1Hz) \approx 7 \times 10^{-29}$ JHz^{-1} at 28K and $\varepsilon(1Hz) \approx 1 \times 10^{-27}$ JHz^{-1} near 77 K. If one could achieve the former value in a SQUID with the same dimensions as the square washer of YBCO, it would be roughly two orders of magnitude greater than typical conventional dc SQUIDs.[8] Nonetheless, this performance in a high-T_c SQUID operated in liquid Ne at 27 K would be adequate for many of the less demanding applications.

Local Mechanism

A plausible source of flux noise is the thermally activated hopping of flux quanta or bundles of flux quanta among pinning sites in the film. An appropriate distribution of many such hopping processes, each with its characteristic frequency and corresponding Lorentzian spectrum, would produce the

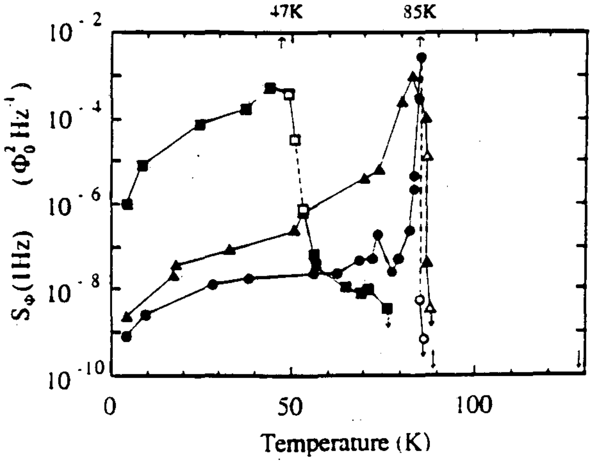

Figure 3. Spectral density of flux noise at 1 Hz for three samples: squares, sample 1; triangles, sample 2; circles, sample 3. The spectral density of the SQUID noise has been subtracted. Solid symbols imply that the spectral density is 1/f at 1 Hz, open symbols that it is white or nearly white. Dashed lines are drawn where white noise from the sample prevented flux-locked operation of the SQUID. Downward arrows above T_c indicate upper limits on the noise.

observed 1/f spectrum.[9] Alternatively, it is possible that the various flux bundles contain the required distribution of flux quanta.[10] Hopping mechanisms of this kind have been proposed previously to account for flux noise in conventional SQUIDs.[8] It would appear that the hopping of flux could produce noise in the SQUID detector in two different ways. In the first, the motion of the flux bundles couples flux directly into the SQUID, while in the second the flux motion produces a circulating current around the loop that fluctuates in magnitude or spatial distribution. To distinguish between these two possibilities, we made a narrow radial slit in sample 2 so that there was no closed conducting path encircling the central hole. The results of repeating our noise measurements on the slit sample are shown in Fig. 4. We plot the spectral density of the flux noise at 1 Hz vs. temperature, measured before and after the ring was slit. No marked difference is evident. The noise does not involve currents circulating around the loop, implying that it arises from a local mechanism.

Our method for determining α^2 from the change in the modulation depth of the critical current of the SQUID is not applicable when the sample is slit. In this case, we had to assume a value of α^2 to calculate $S_\Phi = S_\Phi{}^s/\alpha^2$ for Fig. 4. Our conservative estimate is $\alpha^2 = 0.5$, equal to the measured value when sample 2 was intact and the maximum obtained for any sample. If instead we had taken $\alpha^2 = 0.35$, the minimum value for any sample, the solid symbols in Fig. 4 would have been raised slightly and their agreement with the open symbols would be slightly improved. Compared to the orders-of-magnitude variation in the noise spectral density with temperature, the uncertainty in α^2 introduces only minor corrections.

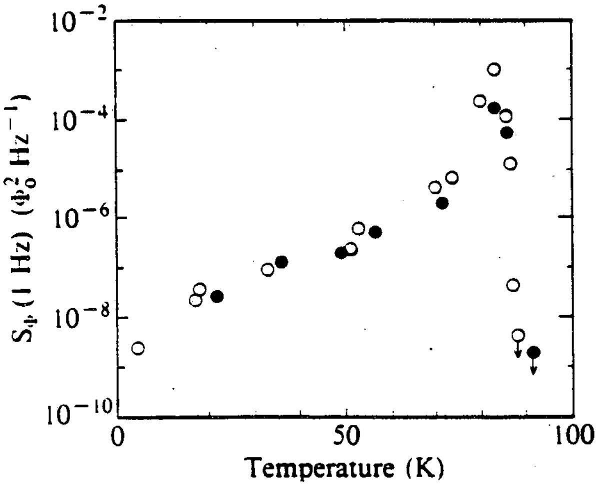

Figure 4. Spectral density of the flux noise at 1 Hz vs. temperature for sample 2, showing that currents circulating in the loop play no role in generating the noise. The open symbols represent measurements made with the ring intact, the solid symbols with the ring slit. At 4.2 K, the open and solid symbols coincide.

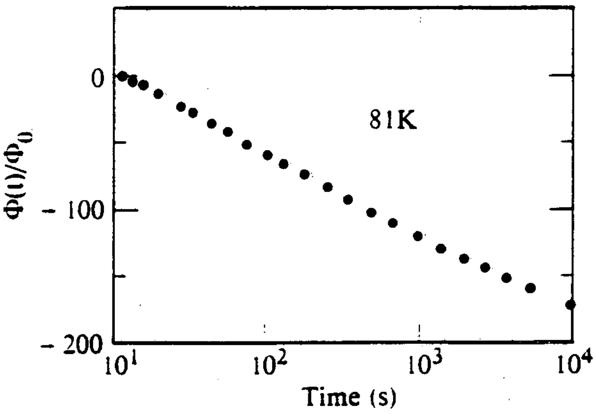

Figure 5. Change in the flux linking the SQUID in units of the flux quantum, $\Phi(t)/\Phi_0$, vs. time for sample 3 at 81 K. The sample was cooled through T_c in a magnetic field of 1 mT. The measurement was made with zero applied field, and t = 0 is the time at which the field was removed.

Flux Creep

We have observed flux creep in sample 3 and measured the temperature dependence of the creep rate. Measurements of this effect in YBCO single crystals in larger applied fields have been reported by workers at IBM.[11] Before each flux creep measurement, we raise the temperature of the sample above 100 K, apply a magnetic field of 1 mT, and then cool to the temperature of interest. After waiting for temperature stabilization, we switch off the current in the field coil, place the SQUID in feedback, and record the change in the flux linking the SQUID over several hours. Figure 5 shows the results of one such measurement made with the sample at 81 K. The flux change Φ in the SQUID is expressed in units of the flux quantum $\Phi_0 \equiv h/2e$, and the negative sign corresponds to a decreasing magnetization of the sample. The signal is nearly linear on a logarithmic time axis, as expected for thermally activated flux creep. In all cases, the temperature drift during the measurement was less than 35 mK/h.

The drift in the flux measured by the SQUID was fitted to the usual creep equation[12]

$$\Phi = -\Phi_1 \ln(t/t_0),$$

where Φ_1 is the temperature-dependent creep rate and t_0 is the time at which we define $\Phi = 0$. A plot of Φ_1 as a function of temperature for sample 3 is shown in Fig. 6. It exhibits a sharp peak near 80 K. This is similar to the IBM result, although their peak is much broader. It is also similar to the behavior observed in conventional superconductors, where the flux creep rate has generally been observed to peak near the superconducting-normal phase boundary.[13] As shown in ref. 13, the flux creep rate Φ_1 is proportional to

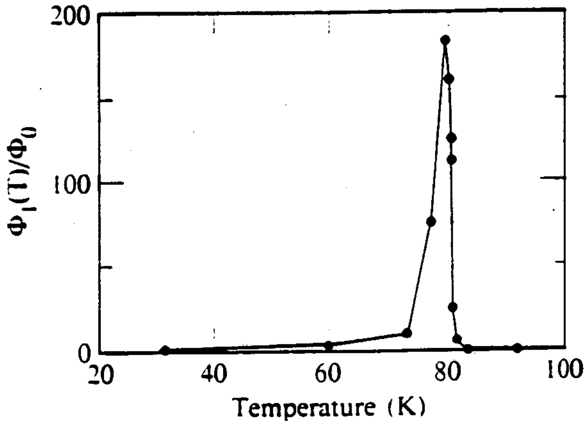

Figure 6. Flux creep rate Φ_1 in units of the flux quantum vs. temperature for sample 3, with T_c = 85 K. The greatest creep rate was measured at 79 K. The curve is a guide for the eye.

$k_BT(J_c/U_0)$, where J_c is the critical current density and U_0 the pinning energy. Thus the temperature dependence of Φ_1 reflects an interplay between thermal activation and the temperature dependence of the ratio J_c/U_0. The peak in Φ_1 as $T \rightarrow T_c$ observed in all flux creep studies suggests that the ratio J_c/U_0 goes through a maximum in superconductors as T approaches T_c, although both J_c and U_0 individually tend to zero. The detailed physics of this phenomenon is not known.

Field Dependence of Noise

We have also measured the power spectrum of the flux noise for sample 3 in zero magnetic field, after cooling through T_c in an applied field of 0 to 1 mT. For fields up to 100 μT, there is no apparent effect on the noise over the measured frequency range (1 Hz to 1 kHz). After cooling the sample in 1 mT, we found the noise power spectrum increased by roughly an order of magnitude. Furthermore, there was an additional low-frequency component with a slope steeper than 1/f that decayed on a time scale of hours. We identify this component with flux creep, noting also that a signal decaying monotonically with time produces a $1/f^2$ power spectrum. The interpretation of the excess 1/f noise that does not decay with time is more problematical, since the application of a field as large as 1 mT traps flux not only in the sample but also in other parts of the apparatus, most notably in the SQUID itself. We are currently attempting to disentangle the various sources of the observed noise.

Conclusion

Our observations of low-frequency 1/f flux noise in YBCO rings suggest that the high levels of 1/f noise observed in high-T_c thin film dc SQUIDs originate from flux noise in the loops rather than from noise associated with the Josephson weak links. The level of the 1/f noise decreases dramatically as the microstructure of the films is improved. From our observations on the noise in the slit loop, we believe that the noise mechanism is local in origin, rather than involving currents circulating around the ring. Thus, not only SQUIDs but also flux transformers must be fabricated from high-quality films to obtain a reasonably low level of 1/f noise. Of course, there is no reason to believe that the levels of noise measured on our best sample to date represent the lowest level attainable, and there is every reason to hope for further reductions in noise as the microstructure of the films is improved. Finally, we note that the operation of flux transformers or SQUIDs at liquid nitrogen temperatures in magnetic fields much over 100 μT may be subject to a substantial rate of drift.

Acknowledgments

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