Mechanisms for Conduction via Low-frequency Noise Measurements of High-Tc Thin-film Microbridges

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Abstract **– We have investigated possible mechanisms for conduction in high-Tc thin-film microbridges biased into the voltage state via the low-frequency noise properties. Measurements on thinned YBCO microbridges indicate that the voltage noise power spectral density $S_V(f)$ is proportional to the DC voltage $\overline{V}$ and displays a $f^{-\alpha}$ decay between 10 Hz and 10 kHz with $\alpha \simeq 1$. The featured near-linear dependence of $S_V(f)$ on the DC voltage $\overline{V}$ and the apparent decrease in the measured noise with increasing temperatures are consistent with a flux flow origin of the $1/f$ noise. In most samples, the presence of an applied magnetic field ($\leq$ 50 G) did not have a measurable effect on the noise. We also observed a strong increase in noise level after thinning in one sample. The features of the measured noise are thus consistent with the Habbal-Joiner model where flux lines (or bundles) transit a sample with their motion interrupted by interaction with pinning centers.**

I. INTRODUCTION

The appearance of a DC voltage when a transport current exceeding a critical value I_c is passed through a sample of type-II superconductor is generally accepted as the result of the motion of quantized flux vortices (or fluxons). In a recent study on HTS thin-film microbridges [1], Davidson et al. systematically reduced the critical current of the bridges by thinning the film and measured the dependence of the current-voltage characteristics on a small external magnetic field. They found no measurable increase in the magnetic field sensitivity due to film thinning in all films tested. However, in a series of publications, Martens et al. (see, for example, [2]) reported a substantial enhancement of the magnetic field sensitivity of their weakened HTS thin-film microbridges.

We have investigated possible mechanisms which give rise to the DC voltage in thinned (weakened) YBCO thin-film microbridges driven into the voltage state by a transport current using measurements of the low-frequency voltage noise as a tool.

Measurements of the voltage noise have been used as an investigative technique in past studies of flux flow in type-I and type-II materials (see the review of Clem [3] and references therein). Our approach in this work is to first establish the main features of the measured noise and then justify them using existing models. Results of our measurements on unthinned and thinned YBCO films are presented, compared, and discussed.

II. EXPERIMENTS

A. Sample Preparations and Processing

Four YBCO/LAO films from three different suppliers were characterized, processed and tested. Samples Y262L and Y674L are pulsed-laser-deposition films grown in our laboratory and are considered representative of high-J_c, high-pinned films. Sample Y1551S supplied by Hypres, Inc., was grown by an amorphous multi-layer sputter deposition procedure followed by a high-temperature post-anneal. Sample YBL-11A is a high-quality low-pinned film grown by the BaF_2 technique at AT&T Bell Laboratories [4].

Samples Y1551S and YBL-11A were patterned with arrays of 4 parallel 5 μm wide × 10 μm long links with 5 μm separation between links. Sample Y262L was patterned with a single bridge of dimensions 50 μm wide by 100 μm long. Sample Y674L was patterned with two different bridge geometries: one is a single link 20 μm wide and 50 μm long and the other an array of 4 parallel 5 μm wide × 50 μm links. The circuit pattern was defined with AZ1350J-SF photoresist and ion-beam etching. Metal contacts were thermally evaporated gold. Details of the processing have been described elsewhere [1].

Thinning of the microbridges was accomplished using a 1.7×10^{-3} M solution of ethylenediaminetetraacetic acid (EDTA) [1]. The solution was continuously stirred during the etching process with N_2 bubbling. The samples were immersed for the desired time and quenched in isopropyl. We have found that, in general, the decrease in the microbridge's critical current does not correspond to a simple reduction of the cross-sectional area.

B. Measurements

All electrical measurements (R vs. T, I vs. V, and dV/dI vs. V) were made using a standard four-point technique with the sample inside a test rig. The test rig was purged with

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a continuous flow of dry helium gas prior to and during cooling. Below 100 K, the rig was sealed off and an over-pressure of helium was maintained. Contacts to the sample were made using a fixture fitted with spring-loaded pins; contact resistance in the range of 1-10 Ω was typical. The temperature was controlled with a Lakeshore Model 330 controller; all voltages and currents were measured using two Fluke 8824 multimeters and an EG&G Princeton Applied Research (PAR) 5209 lock-in-amplifier. A uniform magnetic field up to 50 G was supplied by a wire-wound solenoid.

The test rig was placed inside a Faraday cage during noise measurements. The current bias circuit was powered by batteries and the noise signal from the sample is boosted using a PAR 5817 low-noise pre-amplifier. Since the source impedance is small, the voltage noise input of the amplifier is the dominant source of the system noise (about $1.2\mathrm{nV}/\sqrt{\mathrm{Hz}}$ at 1 kHz). The system noise was measured with the bias circuit shorted and subsequently subtracted. The noise spectral density was recorded with a Stanford Research Systems SRS760 FFT spectrum analyzer. A stable trace was obtained by averaging over several hundred readings.

III. RESULTS AND DISCUSSIONS

A. Results

Resistance-temperature and current-voltage measurements were made on all four samples. At least one microbridge was tested on each sample. Table I summarizes typical T_c and I_c at 77 K for the microbridges (primed quantities indicate values obtained after samples were thinned). Samples Y1551S and Y262L were thinned prior to noise characterizations. Noise measurements were made on samples YBL-11A and Y674L before and after thinning. Both were thinned to approximately half of their original thickness (about 1000 Å for YBL-11A and 400 Å for Y674L) as estimated from a simple four-point resistance measurement at room temperature.

TABLE I

SUMMARY OF PROPERTIES BEFORE AND AFTER THINNING

Sample	T_c(K)	T_c'(K)	I_c(mA)	I_c'(mA)
Y1551S	-	81	15	0.5
Y262L	-	76	> 280	0.5*
YBL-11A	89.5	88	50	10
Y674L	86	83	10	5

* At 64 K

Fig. 1 displays a typical low-frequency RMS noise voltage spectral density for thinned microbridges measured at a constant DC voltage. The shown power spectra S_V exhibit a $1/f^{\alpha}$ dependence with $\alpha \simeq 0.8$. In general, α varies within the range between 0.6 and 0.9 depending on samples, voltages, and temperatures. For a given microbridge, α tends to decrease at smaller voltages and higher temperatures. We have not observed any cut-off frequency in the noise spectrum up 100 kHz.

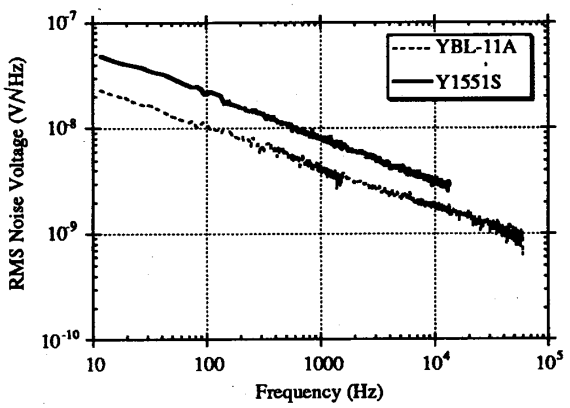

Fig. 1. RMS noise voltage spectral density measured at 77K for Y1551S Link F at 30 mV and YBL-11A Link A at 0.3mV.

Fig. 2 shows the measured noise voltage spectral density as the DC voltage is reduced in steps of one-half decade.

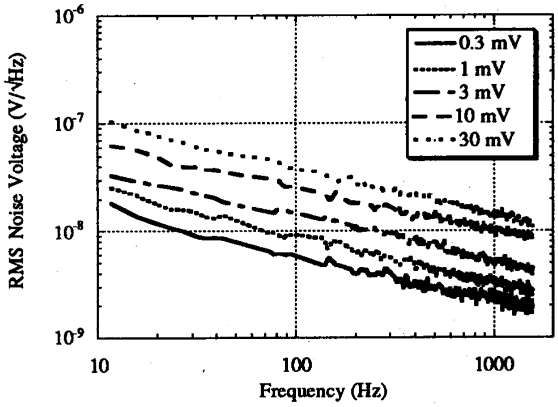

Fig. 2. RMS noise voltage spectral density measured at 64K for sample Y262L at several different biases.

The magnitude of the noise shown in Fig. 2 is now plotted against the DC voltage on log-log scales in Fig. 3. Fitting the data to $S_V = aV^b$ where a and b are constants results in a value of b close to 1 (about 0.8 for all three frequencies shown). The same fit on Y1551S and YBL-11A data (at 77K) yields $b \simeq 1$ and 0.5, respectively. In all samples tested, the square law fit of S_V on V is always worse than the linear fit.

The noise was also measured for various temperatures below and above T_c. In all four samples, the magnitude of the noise decreased as the temperature was increased until it became comparable to the system noise. It is not immediately obvious that thinning of the film should contribute to an increase in the (excess) voltage noise. This is indeed the case as we observed a considerably larger level of noise after YBL-11A was thinned (roughly an order of magnitude larger, see Fig. 5). A smaller but measurable increase in the noise was also seen in Y674L.

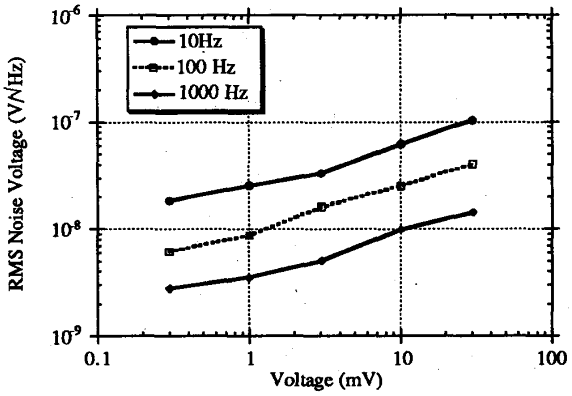

Fig. 3. Dependence of the noise magnitude on the DC voltage at several frequencies. Sample Y262L was measured at 64 K.

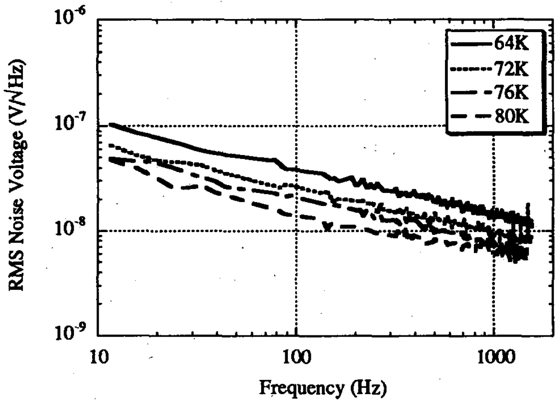

Fig. 4. Temperature dependence of the noise in sample Y262L at 30 mV.

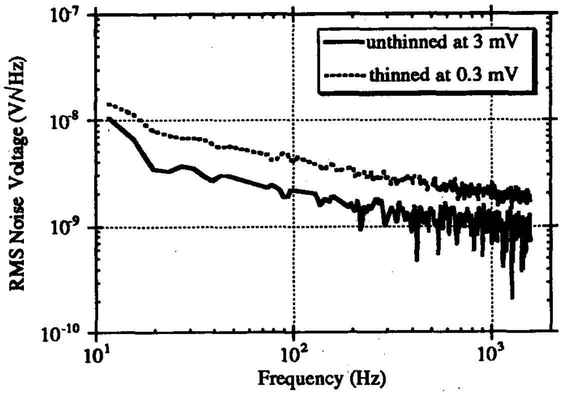

Fig. 5. RMS noise votage spectral density measured at 86 K for YBL-11A Link A before and after thinning. Note the difference in bias.

The presence of external magnetic fields of 25 G and 50 G did not produce a measurable change in the noise of two samples (Y1551S and Y262L) and only a small but reproducible increase (< 1 nV/$\sqrt{\text{Hz}}$ between 10 Hz and 1 kHz) was detected in one (YBL-11A).

Finally, we remark briefly on our measurements of the low-frequency noise in unthinned samples. Noise measurements were made on samples Y674L and YBL-11A before they were thinned. In both films, the excess noise was very small. The uncorrected noise which includes sample and system noise was typically 2-3 nV/$\sqrt{\text{Hz}}$ between 10 Hz and 1 kHz. Since these noise levels were comparable to the system noise, we did not attempt a quantitative characterization.

In summary, whenever a reliable noise measurement can be made, the following features of the measured noise on thinned microbridges can be established: 1) at most a linear dependence of S_V on the DC voltage $\overline{V}$, 2) a $f^{-\alpha}$ noise spectrum with $0.6 < \alpha < 0.9$, 3) an apparent decrease in noise magnitude with increasing temperatures below T_c, and 4) an apparent increase in noise magnitude due to film thinning.

B. Discussions

We propose that the apparent features, in particular 1) and 2), of the voltage noise measured in our weakened samples are consistent with a flux-flow noise model developed by Thompson and Joiner [5] and later extended by Habbal and Joiner [6]. These authors modified Van Gurp's shot-noise model [7] to include the effects of pinnings.

Van Gurp assumed that the time-dependent voltage V consists of a sequence of random, overlapping rectangular pulses produced by the moving fluxons (or bundles of fluxons) at a constant speed v. The resultant low-frequency shot-noise spectrum is proportional to the DC voltage $\overline{V}$.

Habbal and Joiner later observed that the noise power measured in type-II foils of PbIn alloys [6] is independent of f at low frequencies and varies as $1/f$ at higher frequencies. They explained such behavior by assuming a distribution of lifetimes for the individual voltage pulses: the vortices are temporarily held up for brief periods because of interactions with local pinning centers during their transit across the sample so that the voltage pulses originally proposed by Van Gurp are divided into sub-pulses. Their model predicts that $S_V \propto \overline{V}\langle\Phi^2\rangle\langle l_p^2\rangle/\langle\Phi\rangle\langle l_p\rangle$ where Φ is the flux in a bundle, l_p is the distance between pinning centers, and $\langle\rangle$ denoted statiscal average. A linear dependence of S_V on $\overline{V}$ is possible as long as $\langle\Phi^2\rangle\langle l_p^2\rangle/\langle\Phi\rangle\langle l_p\rangle$ is independent of the applied bias. Deviations from strict linearity can result from a dependence of this term on bias.

In most of the microbridges that displayed strong $1/f$ noise after thinning, the noise spectral density S_V depends almost linearly on the DC voltage in agreement with the predictions of Habbal and Joiner. The temperature dependence of S_V in thinned microbridges and the effect of thinning on the measured noise, in fact, support this model. As the temperature increases, increased thermal activations reduce the interactions of the fluxons with local pinnings, thus reducing the noise. Thinning, on the other hand, introduces additional, possibly substrate-induced, defects to the film which may act as pinning sites. The fluxons during their transit encounter more pinning sites resulting in an increase in noise. Correlations between pinning strength and flux-flow noise have been reported by Habbal and Joiner [8]. Recently, studies of the flux noise properties of HTS thin films [9] have also established a strong dependence of the level of $1/f$ noise on the microstructure of the film.

Finally, we comment briefly on the lack of effect of an external magnetic field on the noise measured in our samples. It is plausible that several different mechanisms are responsible for producing the noise. The negligible effect of the magnetic field although unsettling is not necessarily in contradiction with our suggestion that the noise is of flux-flow origin. It points to the possibility that in our weakened microbridges, the source of noise is predominantly fluctuations caused by interactions with pinning sites. Velocity fluctuations as a source of flux-flow noise have been suggested by Heiden [10] and Dirks and Heiden [11], and recently supported by Yeh and Kao [12].

IV. CONCLUSION

We have presented a study of the voltage noise in thinned YBCO microbridges driven into the voltage state by a transport current. In all samples tested the following features were observed whenever a reliable noise characterization can be made. The noise spectral density $S_V(f)$ exhibits a $1/f$ dependence and is linearly proportional to the DC voltage $\overline{V}$. The noise decreases with increasing temperatures and increases after thinning of the sample. A small but reproducible increase in the noise due to the presence of an external magnetic field ($\leq$ 50 G) was observed in one sample. The same field, however, did not produce a measurable effect on two others. The linear dependence of the spectral density S_V on $\overline{V}$ and the noise's temperature dependence suggest that the noise is of flux-flow origin. The overall trends of the measured noise are consistent with a flux-flow model developed by Habbal and Joiner. We interpret the lack of effect of small applied magnetic fields to suggest that fluctuations caused by local pinning interactions may be the dominant source of noise. A systematic study of the magnetic field dependence of the noise is clearly needed and is the subject of ongoing research. A highly irregular flux motion is consistent with all apparent features of the measured noise.

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REFERENCES

[1] B.A. Davidson, R.D. Redwing, T. Nguyen, J.M. O'Callaghan, F. Raissi, J.U. Lee, J.P. Burke, G.K.G. Hohenwarter, J.E. Nordman, J.B. Beyer, S.H. Liou, J. Eckstein, M.P. Siegal, S.Y. Hou, and J.M. Phillips, "Magnetic field sensitivity of variable thickness microbridges in TBCCO, BSCCO, and YBCO," *IEEE Trans. on Appl. Superc.*, vol. 4, no. 4, pp. 228–235, Dec. 1994.

[2] J.S. Martens, V.M. Hietala, T.A. Plut, D.S. Ginley, G.A. Vawter, C.P. Tiggs, M.P. Siegal, J.M. Phillips, and S.Y. Hou, "Flux flow microelectronics," *IEEE Trans. on Appl. Superc.*, vol. 3, no. 1, pp. 2295–2314, March 1993.

[3] J.R. Clem, "Flux-flow noise in superconductors," *Physics Reports*, 75, No. 1, 1981.

[4] M.P. Siegal, J.M. Phillip, R.B. Van Dover, T.H. Tiefel, and J.H. Marshall, "Optimization of annealing parameters for the growth of epitaxial YBCO films on LAO (100)," *J. Appl. Phys.*, vol. 68, pp. 6353-6360, Dec. 1991.

[5] J. Thompson and W.C. Joiner, "Flux flow noise spectra of type II superconductors," *Solid State Comm.*, vol. 16, pp. 849-851, 1975.

[6] F. Habbal and W.C.H. Joiner, "Flux flow noise spectra in the presence of local pinning interactions," *J. Low Temp. Phys.*, vol. 28, nos. 1/2, pp. 83-93, 1977.

[7] G.J. Van Gurp, "Flux-transport noise in type-II superconductors," *Phys. Rev.*, vol. 166, no. 2, pp. 436-446, 1968.

[8] F. Habbal and W.C.H. Joiner, "Correlations between changes in pinning strength and flux-flow noise in type-II superconductors," *Phys. Lett.*, vol. 60A, no. 5, pp. 434-436, March 1977.

[9] M.J. Ferrari, M. Johnson, F.C. Wellstood, J. Clark, P.A. Rosenthal, R.H. Hammond, and M.R. Beasley, "Magnetic flux noise in thin-film rings of YBCO," *Appl. Phys. Lett.*, vol. 53, pp. 650-656, 1988.

[10] C. Heiden, "On the nature of flux transport noise," Proc. Thirteenth Int'l. Conf. Low Temp. Phys., ed. K.D. Timmerhaus, W.J. Sullivan and E.F. Hammel, vol. 3. New York: Plenum, 1974.

[11] H. Dirks and C. Heiden, "On the time behavior of local flux-flow noise in Niobium and Vanadium," in *Noise in Physical Systems*, ed. D. Wolf. Berlin: Spinger-Verlag, 1978.

[12] W.J. Yeh and Y.H. Kao, "Flux-flow noise in type-II superconductors," *Phys. Rev. B*, vol. 44, no. 1, pp. 360-373, 1991.