Origin of 1/f noise peaks of $\text{YBa}_2\text{Cu}_3\text{O}_x$ films in a magnetic field*

W.N. Kang, D.H. Kim, J.H. Park, S.S. Yom, S.S. Choi

Applied Physics Group
Korea Institute of Science and Technology, Seoul 136-791, Korea

and

K.E. Gray

Materials Science Division
Argonne National Laboratory, Argonne, IL 60439

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*Work at KIST is supported by the Ministry of Science and Technology in Korea, at Argonne by the U.S. Department of Energy, Division of Basic Energy Sciences-Materials Sciences, under contract #W-31-109-ENG-38 (KEG) and by the NSF Office of Science and Technology Centers under contract #DMR 91-20000 (DHK).

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Applied Physics Group

Korea Institute of Science and Technology, Seoul 136-791, Korea

K. E. Gray

Materials Science Division

Argonne National Laboratory, Argonne, IL 60439, USA

Abstract

The temperature and magnetic field dependence of $1/f$ noise has been measured in epitaxial $\text{YBa}_2\text{Cu}_3\text{O}_x$ films. In a magnetic field, two noise peaks were observed as temperature decreases; one at higher temperature was found to match the thermal fluctuation of the sample resistance and the other near the foot of the transition was found to be magnetic-field dependent. The location of the latter was shifted toward low temperature and the peak height was decreased as a magnetic field increased. In a zero field only one peak from the resistance fluctuation was observed. We show that the field-dependent noises are due to flux motion interacting with the pinning potential. A classical model is used to explain the field-induced noise peaks. We interpret that the temperature dependences of the flux bundle size and the sample resistance are the reasons for the noise peaks, and a rough estimation of the temperature and field dependence of the flux bundle size is presented. Any possible relationship between the noise peaks and the flux-line-lattice phase transition is also discussed.

PACS number: 74.40.+k

Introduction

Low frequency (f) noise, mostly $1/f$ noise, of the high-temperature superconductors (HTS) near the superconducting transition temperature T_C has been studied by several groups. One of the interesting properties of $1/f$ noise in this region is the enhanced noise which was observed in various bulks and thin films of $\text{YBa}_2\text{Cu}_3\text{O}_x$ [1-5], Bi [6], and Tl based compounds [7]. Understanding the origin of $1/f$ noise is quite important in the application area, such as infrared bolometer and superconducting quantum interference device which are mostly operating at 77 K or near T_C . Number of models has been suggested to explain the origins of $1/f$ noise near T_C . Extremely large noise observed in the bulk samples of $\text{YBa}_2\text{Cu}_3\text{O}_x$ was explained as the noisy hopping processes across the inhomogeneous boundaries [1]. For polycrystalline thin films of $\text{YBa}_2\text{Cu}_3\text{O}_x$, Lee et al. [2] observed two noise peaks, one near the onset T_C and the other near the zero-resistance temperature. The noise peaks near the onset was magnetic field independent and well fitted to a thermal fluctuation effect, while the magnitude of the peak near the zero-resistance temperature decreased as applied field increased up to 50 gauss. They suggested the latter peaks due to flux flow. Rosenthal et al. [3] also observed enhanced noise near T_C in the polycrystalline films of $\text{YBa}_2\text{Cu}_3\text{O}_x$, but they concluded that this noise does not arise from thermal fluctuations. In addition, the spectral noise density S_V decreased markedly as the microstructure of the films were improved. The result of the noise dependence on the microstructure of the film was also reported by Ferrari et al. [4] in thin film rings of $\text{YBa}_2\text{Cu}_3\text{O}_x$. In these samples, similar noise peaks were observed near T_C . They [5] further analyzed S_V within the random fluctuation model of Dutta, Dimon, and Horn [8] to determine the density of activation energy at zero temperature. The importance of the sample morphology was also evidenced by Song et al. [9] who reported no enhanced $1/f$ noise near T_C in $\text{YBa}_2\text{Cu}_3\text{O}_x$ single crystals in a zero field. From this experimental result Song et al. suggested that the zero-field noise behavior near T_C is not an intrinsic property, but microstructure dependent.

In this work, we present a study of $1/f$ noise in c-axis oriented high-quality epitaxial films of $\text{YBa}_2\text{Cu}_3\text{O}_x$ in an attempt to understand the possible origin of flux-flow noise in a magnetic field up to 600 gauss. We choose epitaxial films since they can provide intrinsic properties as well as morphology dependent properties. The previous measurements reported in Refs. 2 and 3 had been performed on polycrystalline films where the role of the grain boundaries can not be neglected. Our results show that two noise peaks were observed in a magnetic field as temperature decreases; one at higher temperature was found to match the thermal fluctuation of the sample resistance and the other near the foot of the transition was found to be magnetic field dependent. In a zero field only one peak from the resistance fluctuation was observed. Our main focus lies on the field-dependent noise peaks. We show that the field-dependent noises are due to the thermally activated flux motion interacting with the pinning potential. The peaks occur mainly from the competing effect of the increase of the flux bundle size and the decrease of the sample resistance as temperature decreases.

Experiments

Films of $\text{YBa}_2\text{Cu}_3\text{O}_x$ are grown by dc-plasma assisted metalorganic chemical vapor deposition (MOCVD) on a (100) LaAlO_3 substrates, and detailed electrical and structural properties are reported elsewhere [10]. TEM showed that films are epitaxial and c-axis oriented. The samples were patterned to form a 6 μm wide and 500 μm long microstrip with conventional photolithography and wet chemical etching. Silver was evaporated on the voltage and current pads to reduce contact resistance. The thickness of the film was ~ 100 nm and vanishing resistance occurred around 87 K in a small current limit. The critical current density at 77 K was 2×10^6 A/cm². Noise spectral density S_V was measured by dc four-probe method. Direct currents were supplied by a battery with large ballast resistors connected in series with the sample. Voltage signal was first dc filtered by tantalum capacitors, then put into a low-noise transformer (Princeton Applied Research 1900) followed by a preamplifier (Stanford

Research 560) which is connected to a Fourier spectrum analyzer (Hewlett Packard 3562A). Resistances of the samples with the same bias currents were measured with a digital voltmeter (Keithley 181).

Results

All noise power showed $1/f$ -like behavior over the frequency range, 1 to 100 Hz. The temperature dependence of S_V shown below is obtained by averaging the signal over 10 - 11 Hz frequency span where the variation of the gain of the transformer on the input impedance is negligible. Figure 1 shows S_V as a function of temperature T in magnetic fields $H = 0, 200, 400, 600$ gauss applied parallel to the c -axis under a bias current I of $250 \mu\text{A}$ ($J = 4 \times 10^4 \text{ A/cm}^2$). In a zero field, only one peak at T_i was observed, while in a magnetic field additional peak at T_f near the foot of the superconducting transition appeared. The field dependence of two peaks is clearly different. The magnitude of T_f peak decreases and the peak position moves to lower T as applied field increases, while those at T_i remain unchanged. This field dependence of the noise peaks indicates that T_f peaks are field induced, while T_i peak is not related to magnetic fields. Figure 2 shows peaks at T_f after subtracting out the field-independent noise.

We have also measured the current dependence of S_V for a bias current varying from 125 to 500 μA . In this current range, we observed a linear dependence of noise on V_{dc} in the temperature range from 85 to 91 K. This linear dependence is somewhat different from the usually-observed current dependence of $1/f$ noise in various metals and semiconductors at room temperature which follow the empirical formula by Hooge [11], that is $S_V \sim V_{dc}^2/f$. Among the reported measurements of YBaCuO, $1/f$ noise of single crystals [9] and polycrystalline samples [3] showed V_{dc}^2 dependence, while Lee et al. [2] observed $S_V \sim V_{dc}$ similar to our results. The implication of the linear current dependence of present experiment will be discussed later.

Discussion

The upper peak at T_i has been observed in polycrystalline samples by many groups, while their interpretations vary. In our case, T_i peak shows a good agreement with either dR/dT or $(dR/dT)^2$, thermal fluctuations of the resistance [12]. The usual resistance fluctuation $(dR/dT)^2$ also fits the data, but we find dR/dT fits slightly better and this fit is plotted as a solid line in Fig. 1.

The main focus of this paper is to understand a possible origin of the noise peak at T_f in a magnetic field and its field dependence. The qualitative explanation of the noise peak T_f can be given in terms of flux motions. The details of flux motion under current flow are not simple [13], but main components of the forces exerting on the moving flux lines consist of the Lorentz force, the pinning force, and the viscous force etc. If the Lorentz force on a given flux line or bundle exceeds the pinning force, flux lines start to move. Thermal activation also can help flux lines out of their pinning centers. When they are out, flux lines move with a constant flux-flow velocity due to the viscous force. Moving flux lines can be pinned at different locations or they keep moving to the edge of the sample and leave. Pinned ones can get in motion again some time later by the Lorentz force and thermal activation, repeating the same sequence until they reach the edge of the sample. During these processes, voltage pulses with various heights and duration arise. At sufficiently low temperatures where pinning is strong, most flux lines are pinned, thus flux-motion noise will vanish. Noise is also small when the pinning is negligible at high temperatures since flux lines drift without being disturbed by pinning potential. Between these two limiting regions of pinning, individual voltage pulses during the flux migration result in a noise peak.

The first quantitative approach of the flux-motion noise in HTS were done by Ferrari et al. [5] within the picture of the random fluctuation model, which was first introduced by Dutta et al. [8] to explain the temperature dependence of the noise from metal films. Ferrari et al. [5] showed that the noise below T_C is well explained by the random fluctuation model and determined the density of activation energy at $T = 0$. However, this model was not successful to explain excess noise peaks near T_C [5].

Instead we start with the simple flux flow model [14,15], which is generalized later by Habbal and Joiner [16].

If flux transports across the superconductor, a voltage pulse arise corresponding to the amount of flux and its duration. The actual voltage we measure is made of all kinds of voltage pulses with different heights and lifetimes. For simplicity, we begin with a noise from identical pulses and later sum over all possible configurations to obtain a full noise spectrm. For randomly occurring identical rectangular pulses of constant height ΔV and lifetime τ , the noise spectrum is shot-noise like and given by [14,15]

$$S_v = 2V_{dc}\Delta V\tau \frac{\sin^2(\pi f\tau)}{(\pi f\tau)^2} \quad (1).$$

When flux moves across the superconductor, the pulse height is given as

$$\Delta V = \frac{\Phi}{\tau},$$

where Φ is total flux of a moving bundle. Generally, if a moving flux bundle is pinned after moving a distance l , the phase change due to the motion is no longer a multiple of 2π , but should be reduced by a factor of l/L where L is the width of the strip [16]. If a flux bundle moves with a velocity $v = l/\tau$, then

$$\Delta V = \Phi \frac{v}{L} \quad (2).$$

To obtain a full noise spectrum, we have to average over all possible individual spectra (subpulses) with an appropriate distribution function. During the process, we assume that ΔV and τ are independent each other and all bundles move with the same flux-flow velocity given by Bardeen-Stephen model [17], and, furthermore, since V_{dc} in Eq. 1 already has a meaning of the average of a particular stream of pulses, we separately do the average process on V_{dc} . Then a full noise power spectrum at a given temperature T is

$$S_v(f, T) = \frac{2}{L} \langle V_{dc} \rangle \langle \Phi \rangle v \int \frac{\sin^2(\pi f\tau)}{(\pi f\tau)^2} \tau D(\tau) d\tau \quad (3),$$

where $D(\tau)$ is a distribution function of the lifetime and the brackets indicate an average over all subpulses. Exact functional form of $D(\tau)$ is not known, but the integration should give rise to $1/f$ dependence in order to match the experimental results. For instance, set $D(\tau) = 1/\tau$ and the integration interval to be from 0 to 1 provides $1/f$ dependence for $f > 1$ Hz.

To obtain the temperature dependence of the noise, we now consider the temperature dependence of each term in Eq. 3. $\langle V_{dc} \rangle$ is determined experimentally, which is steeply increasing function of temperature, and $\langle \Phi \rangle$ is generally a decreasing function of temperature [14] approaching a single flux quantum Φ_0 near T_c . According to the Bardeen-Stephen model, $v = \rho_n J / B_{c2}$, where the normal state resistivity ρ_n at a given T can be scaled to the normal state resistivity at T_c , ρ_{nc} , by $\rho_n = \rho_{nc} t$ with $t = T/T_c$, the upper critical field is given as $B_{c2} = B_{c2}(0)(1-t^2)$ in the clean limit, and J is the bias current density. Thus, $v \propto t/(1-t^2)$, a slowly increasing function of temperature. The integration term is also temperature dependent. Since voltage pulses with the longer τ dominate near T_c compared to the low temperature regime where those with the short τ dominates, and since $\sin^2(\pi f \tau) / (\pi f \tau)^2$ decreases with τ , the integration at low temperature is greater than that near T_c . We can simply define the integration as $A(t)/f$, where $A(t)$ is a decreasing function of temperature. Then Eq. 3 becomes

$$S_v(f, T) \propto \frac{2}{L} \langle V_{dc} \rangle \langle \Phi \rangle \frac{t}{(1-t^2)} \frac{A(t)}{f}. \quad (4).$$

Equation 4 is the main result to understand the noise peak at T_f . It means that S_v is proportional to the multiplication of a decreasing function of temperature $\langle \Phi \rangle A(t)$ and an increasing function $\langle V_{dc} \rangle t / (1-t^2)$, so we can expect a peak in S_v . In other words, the occurrence of the noise peak due to flux motion is mainly from the combined effect of the decrease of the flux bundle size and the increase of the resistance as temperature increases.

From Eq. 4, we can estimate the temperature dependence of $\langle\Phi\rangle A(t)$ by dividing S_V by $\langle V_{dc}\rangle t/(1-t^2)$. The resulting $\langle\Phi\rangle A(t)$ in various magnetic fields are shown in Fig. 3. We arbitrary set $\langle\Phi\rangle A(t) = 1$ where peak vanishes, so the y-axis scale provides an upper limit of the flux bundle size. Since the exact form of $A(t)$ is not known, only a rough estimation of the temperature and field dependence of the flux bundle size can be discussed. As mentioned above, $\langle\Phi\rangle A(t)$ increase as temperature decreases, and, furthermore, they tend to saturate at low temperature. The saturation values range from ~ 70 to ~ 700 depending on applied field. This saturation behavior of $\langle\Phi\rangle A(t)$ at low temperatures is partially due to the fact that the bundle size can not grow indefinitely, but should be limited by the sample dimension or defect structures. Also can be seen is a magnetic field dependence of $\langle\Phi\rangle A(t)$, which decreases with increasing field at a given temperature. If we consider the magnetic field dependence of the pinning energy [18], it is evident that $\langle\Phi\rangle$ should decrease with increasing field. Although there is no exact knowledge about the field dependence of $A(t)$, it can be roughly estimated that $A(t)$ also decreases with field because in higher field major contribution comes from the voltage pulses with the longer τ due to the smaller pinning energy. Thus the field dependence of $\langle\Phi\rangle$ would be weaker than that of $\langle\Phi\rangle A(t)$. Overall, the temperature and field dependence of $\langle\Phi\rangle A(t)$ is a consequence of the shift and reduction of the noise peaks with magnetic field shown in Fig. 2.

As mentioned before, we observed a linear dependence of S_V on V_{dc} in a limited current range and over all the transition region. This linear dependence is different from the usual current dependence of $1/f$ noise, that is $S_V \sim V_{dc}^2/f$, especially for the resistance fluctuation case. However, as derived in Eq. 4, a flux-flow noise should depend linearly on V_{dc} , thus it is nothing unusual to observe such a dependence experimentally. If the resistance near T_t is mostly due to flux motion, linear dependence on V_{dc} is not unreasonable even for the resistance fluctuation case. Linear dependence on V_{dc} is also observed by Voss et al. [19] at the superconducting transition in very thin, high-resistivity films of aluminum and tin. They observed a

similar noise peak, although an experimental detail differs, near the foot of the superconducting transition. The experiment was performed in an ambient field less than 1.7×10^{-4} gauss, so the current-induced noise was interpreted due to the independent motion of individual flux. If phase slips $\Delta\theta$ due to flux motion occur randomly, according to Voss et al., $S_v \sim \Delta\theta V_{dc}$, similar to Eq. 1. In our case of applied magnetic field, flux bundle rather than a single flux moves, so a voltage pulse ΔV replaces an individual phase slip while retaining the linear dependence on V_{dc} . However, Voss et al. [19] neglected any possible dependence of $\Delta\theta$ on temperature. In our work the temperature dependence of ΔV plays an important role to understand the origin of the noise peaks.

There has been an attempt to explain the noise peaks by the structural changes of the flux line lattice (FLL) [6]. Recently experimental evidences for a first-order FLL melting have been reported in high quality untwinned YBaCuO single crystals [20], in which the resistive transitions in a magnetic field showed hysteretic behavior upon heating and cooling. However, no such transition is observed in films where abundant defects destroy the long-range positional correlations, instead a number of vortex glass transitions were reported [21]. At the vortex glass transition temperature, it is known that the voltage exhibits cubic dependence on the current [21]. In our case, just slightly nonlinear current-voltage characteristics were observed at the peak locations, which is inconsistent with the vortex glass transition model. So far there is no evidence that there is any direct relationship between the noise peaks and FLL phase transition. But we note that the relative positions of the noise peaks in the superconducting transition region, i.e., near the foot of the transition, are closely located to those of the melting transitions [20, 22]. More detailed measurements in high magnetic fields including the transport properties are needed to clarify possible relation between the noise peaks and FLL structural changes.

Summary

The temperature and magnetic field dependence of $1/f$ noise in epitaxial $\text{YBa}_2\text{Cu}_3\text{O}_x$ films exhibited two noise peaks. One at higher temperature was found to match the thermal fluctuation of the sample resistance and the other near the foot of the transition was found to be magnetic-field dependent. We showed that the field-dependent noises are due to the thermally activated flux motion interacting with the pinning potential, and the peaks arise mainly from the competing effect of the increase of the flux bundle size and the decrease of the resistance as temperature decreases. Any possible relation between the noise peaks and FLL phase transition is also discussed.

Acknowledgments

The authors thanks T.S. Hahn, Y.H. Kim for helpful discussion. The work at KIST is supported by the Ministry of Science and Technology in Korea, and the work at ANL is supported by the U.S. Department of Energy, Basic Energy Sciences-Materials Sciences, under contract #W-31-109-ENG-38 (KEG), by the NSF Office of Science and Technology Centers under contract #DMR 91-20000 (DHK).

References

1. J.A. Testa, Y. Song, X.D. Chen, J. Golben, S.I. Lee, B.R. Patton, and R. Gaines, *Phys. Rev.* **B38**, 2922 (1988).
2. J.H. Lee, S.C. Lee, and Z.G. Khim, *Phys. Rev.* **B40**, 6806 (1989).
3. P.A. Rosenthal, R.H. Hammond, M.R. Beasley, R. Leoni, Ph. Lerch, and J. Clarke, *IEEE Trans. on Magnetism*, **25**, 973 (1989).
4. M.J. Ferrari, M. Johnson, F.C. Wellstood, J. Clarke, P.A. Rosenthal, R.H. Hammond, and M.R. Beasley, *Appl. Phys. Lett.* **53**, 695 (1988).
5. M.J. Ferrari, M. Johnson, F.C. Wellstood, J. Clarke, D. Mitzi, P.A. Rosenthal, C.B. Eom, T.H. Geballe, A. Kapitulnik, and M.R. Beasley, *Phys. Rev. Lett.* **64**, 72 (1989).
6. A. Maeda, Y. Kato, H. Watanabe, I. Terasaki, and K. Uchinokura, *Physica* **B165&166**, 1363 (1990).
7. Y. Song, A. Misra, Y. Cao, A. Querubin Jr., X. Chen, P.P. Crooker, and J.R. Gaines, *Physica* **C172**, 1 (1990).
8. P. Dutta, P. Dimon, and P.M. Horn, *Phys. Rev. Lett.* **43**, 646 (1979); P. Dutta and P.M. Horn, *Rev. Mod. Phys.* **53**, 497 (1981).
9. Y. Song, A. Misra, P.P. Crooker, and J.R. Gaines, *Phys. Rev. Lett.* **66**, 825 (1991).
10. W.N. Kang, H.S. Shin, Y.S. Yoon, S.S. Choi, and S.S. Yom, (unpublished).
11. F.N. Hooge, *Phys. Lett.* **29A**, 139 (1969); F.N. Hooge, T.G.M. Kleinpenning, and L.K.J. Vandamme, *Rep. Prog. Phys.* **44**, 479 (1981).
12. R.F. Voss and J. Clarke, *Phys. Rev.* **B13**, 556 (1976).
13. for example, V.M. Vinokur, V.B. Geshkenbein, M.V. Feigel'man, and G. Blatter, *Phys. Rev. Lett.* **71**, 1242 (1993).
14. G.J. van Gorp, *Phys. Rev.* **166**, 436 (1968).
15. D.K.C. MacDonald, "Noise and fluctuations", John Wiley & Sons, New York (1962).
16. F. Habbal and W.C.H. Joiner, *J. Low Temp. Phys.* **28**, 83 (1977).
17. J. Bardeen and M.J. Stephen, *Phys. Rev.* **140**, A1197 (1965).

18. M. Tinkham, Phys. Rev. Lett. **61**, 1658 (1988).
19. R.F. Voss, C.M. Knoedler, and P.M. Horn, Phys. Rev. Lett. **45**, 1523 (1980).
20. H. Safar, P.L. Gammel, D.A. Huse, D.J. Bishop, J.P. Rice, and D.M. Ginsberg, Phys. Rev. Lett. **69**, 824 (1992).
21. R.H. Koch, V. Foglietti, W.J. Gallagher, G. Koren, A. Gupta, and M.P.A. Fisher, Phys. Rev. Lett. **63**, 1511 (1989).
22. D.E. Farrell, J.P. Rice, and D.M. Ginsberg, Phys. Rev. Lett. **67**, 1165 (1991).

Figure Captions

Fig. 1. The temperature dependence of S_v at 10.5 Hz in MOCVD grown YBCO films in various magnetic fields, 0 (open circle), 200 (triangle), 400 (square), and 600 (solid circle) gauss. Two peak are observed in a magnetic field, while only one peak was observed in zero field. The solid line is a scaled dR/dT curve measured with the same bias current of 250 μA .

Fig. 2. Magnetic-field dependent noise peaks after subtracting out the field-independent noise. The symbols are the same as those in Fig. 1.

Fig. 3. The temperature dependence of $\langle \Phi \rangle A(t)$ in various magnetic fields. We arbitrary set $\langle \Phi \rangle A(t) = 1$ where peak vanishes.