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Anisotropic $1/f$ noise and motion of magnetic vortices in $YBa_2Cu_3O_{7-\delta}$

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Measurements of the $1/f$ noise have been performed on $YBa_2Cu_3O_{7-\delta}$ single crystals for currents in the *a-b* plane and along the *c* axis. In the normal state, the normalized noise spectral density S_v/V^2 in the *a-b* plane is comparable with that along the *c* axis. In the superconducting transition region, a large enhancement of S_v/V^2 is observed along the *c* axis while no such enhancement is observed in the *a-b* plane. Our experimental data suggest that while the $1/f$ noise in the normal state may be due to structural defects, a completely different noise source exists in the superconducting transition region. We discuss the $1/f$ noise behavior in the superconducting transition region in terms of the anisotropic nature of $YBa_2Cu_3O_{7-\delta}$ and the motion of magnetic vortices.

The behavior of $1/f$ noise in high-temperature superconductor materials can be studied in three different regions: (1) the normal state ($T_c \ll T \leq$ room temperature), (2) the superconducting transition region ($T \approx T_c$), and (3) the superconducting state ($T \ll T_c$). Here T_c is the superconducting transition temperature where the electrical resistance vanishes. At present, our knowledge is fragmented. *In the normal state,* experimental data on bulk and thin-film samples indicates that the magnitude of the normalized $1/f$ noise spectral density S_v/V^2 is very large when compared with metals.[1-3] Large $1/f$ noise is found even in the *a-b* plane of $YBa_2Cu_3O_{7-\delta}$ single crystals.[4] *In the superconducting transition region,* an anomalously enhanced peak of the $1/f$ noise power is observed in various bulk and thin-film samples.[1-3,5,6] *In the superconducting state* of thin-film samples, the magnitude of $1/f$ noise, attributed to magnetic flux motion, increases with increasing temperature and depends strongly on the microstructure of the samples.[5,7]

The work described in this paper is based on $1/f$ noise measurements in $YBa_2Cu_3O_{7-\delta}$ single crystals where the probing current was in the *a-b* plane for one set of crystals and parallel to the *c* axis for another set. The observed anisotropy in the $1/f$ noise power provides an explanation of the earlier observations of enhanced noise peaks in the superconducting transition region in bulk and film samples and also allows for a new interpretation of the $1/f$ noise that unifies the present results with those in the superconducting state and our earlier results in the normal state.

Our study was motivated by several important questions. Does the $1/f$ noise observed in the normal state depend on the orientation of the probing current? Why is there an enhanced peak of the $1/f$ noise in the superconducting transition region of many copper oxide materials? Why does the magnitude of the flux noise depend strongly on the microstructure of samples? To address these questions, we studied the temperature dependence of the $1/f$ noise on carefully prepared $YBa_2Cu_3O_{7-\delta}$ single crystals in both the normal state and the superconducting transition region, making the first measurements of the $1/f$ noise both in the *a-b* plane and along the *c* axis of the crystals. We find that in the normal state S_v/V^2 measured in the *a-b* plane is comparable with that along the *c* axis. In the superconducting transition region, however, a very large enhancement of S_v/V^2 is observed along the *c* axis while no such enhancement is observed in the *a-b* plane. These experimental results are interpreted in terms of the anisotropic nature of $YBa_2Cu_3O_{7-\delta}$ and the motion of magnetic vortices.

The $YBa_2Cu_3O_{7-\delta}$ single crystals were prepared by a flux-growth technique. The starting powder (nominal stoichiometry $YBa_9Cu_{23}O_x$) was prepared by thoroughly mixing precursor $BaCuO_2$, prereacted $YBa_2Cu_3O_{7-\delta}$, and excess CuO. This powder was loaded into a gold crucible, heated in air to 980 °C for 24 h, cooled (3 °C/h) to 870 °C, and cooled to room temperature (50 °C/h). The crystals were oxygen annealed at 600 °C for 12 h and subsequently at 450 °C for 6 days. The attachment of electrical leads has been described elsewhere.[4] Since it is extremely difficult to attach many electrical leads with low contact resistance to the same crystal, the *a-b* plane and the *c*-axis measurements were done on two different sets of samples, each set containing four crystals, respectively. The dc electrical resistivities in the *a-b* plane (ρ_{ab}) and along the *c* axis (ρ_c), measured by the four-probe technique, are shown in Figs. 1(a) and 1(b). The magnitudes and the temperature dependence of ρ_{ab}, for all the crystals that we have studied, are consistent and very similar to those reported by others in the literature.[8,9] On the other hand, we observe small variations in the temperature dependence of ρ_c. The metallic behavior (indicated by the positive temperature coefficient of resistivity) near the room temperature, as shown in Fig. 1(b), exists in some samples but not in others. Several explanations have been proposed for this variation: (1) an oxygen deficient interior of the sample;[9] (2) electrical shorting by the ρ_{ab} component due to imperfect crystallinity;[9] and (3) a small misalignment of electrical leads.[10]

The noise spectral density (S_v) was measured by the "cross-correlation" technique and details of such measurements have been described elsewhere[4]. In Fig. 2 we plot the typical results of the normalized spectral density S_v/V^2 as a function of temperature. Here V is the mean dc voltage across the sample. At each temperature the noise spectrum was measured from 0.1 to 100 Hz in incre-

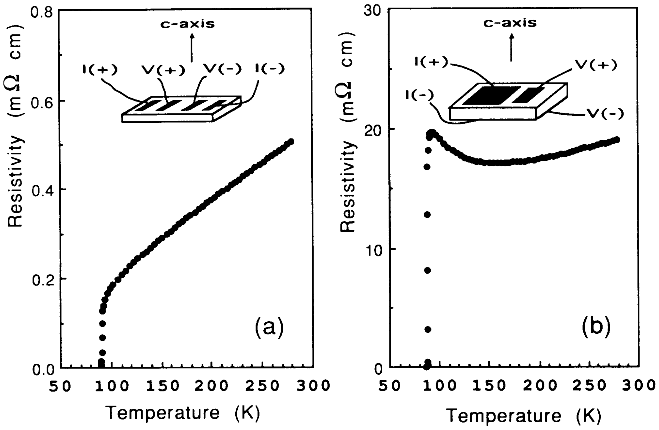

FIG. 1. The electrical resistivity of $YBa_2Cu_3O_{7-\delta}$ single crystals as a function of temperature. Inset: the configuration of electrical leads. The shaded areas are gold pads deposited on the crystal to reduce the contact resistance. (a) ρ_{ab} measured in the *a-b* plane of sample *A*. The superconducting transition starts at 91 K and zero resistance is reached at 90 K (T_c). (b) ρ_c measured along the *c* axis of sample *B*. The superconducting transition starts at 91 K and T_c is 87 K.

ments of 0.125 Hz. All noise spectra have characteristic $1/f$ behavior. Two features can be seen clearly from the data: (1) in the normal state, the magnitude of S_v/V^2 measured in the *a-b* plane [Fig. 2(a)] is comparable with that along the *c* axis [Fig. 2(b)]; and (2) there is no enhanced $1/f$ noise peak in the superconducting transition region in the *a-b* plane while the enhancement is very prominent along the *c* axis.

In the normal state, the temperature dependence of S_v/V^2 is similar for both orientations of the probing current. Theories, such as Voss-Clarke's temperature fluctuation model[11] and Handel's quantum noise model,[12] predict a noise spectral density that is several orders of magnitude smaller than our experimental results. Previously we suggested that the noisy behavior is mainly due to various structural defects in the copper oxide materials

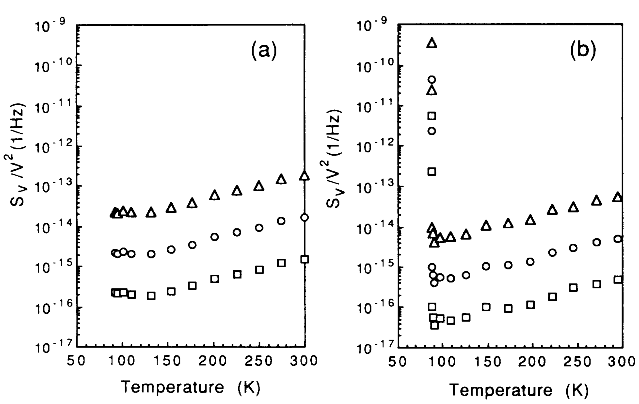

FIG. 2. Normalized $1/f$ noise spectral density S_v/V^2 as a function of temperature for sample *A* (measured in the *a-b* plane) and sample *B* (measuring along the *c* axis). The data are selected from 3 different frequencies: 0.7 Hz (triangles), 7 Hz (circles), and 70 Hz (squares).

(such as grain boundaries and twinning boundaries).[4] This point of view is supported by our recent $1/f$ noise measurements performed on high-quality $Tl_2Ba_2CaCu_2O_8$ thin films[13] in which we find that the magnitude of S_v/V^2 in the normal state is much lower than that previously observed in other copper oxide materials (some $Tl_2Ba_2CaCu_2O_8$ thin films have an S_v/V^2 that is as small as in conventional metals). The single crystals used in this study are known to have internal twinning boundaries[14] and the magnitude of S_v/V^2 measured in the *a-b* plane is in agreement with previous results.[4] The magnitude of S_v/V^2 measured along the *c* axis, as shown in Fig. 2(b), is about five times smaller than that in the *a-b* plane. Since the $1/f$ noise in copper oxide materials is a volume effect[2] and the sample volumes are similar (volume of sample $A = 7.9\times10^{-5}$ cm^3 and volume of sample $B = 7.6\times10^{-5}$ cm^3), it appears that the magnitudes of S_v/V^2 in the *a-b* plane and along the *c* axis are comparable and both are very large compared to metals. This behavior is observed in all the crystals that we have studied except one crystal measured in the *c* direction which has a large oxygen deficiency ($T_c = 32$ K) and its S_v/V^2 in the normal state is about 3 orders of magnitude higher than other crystals. This observation seems to suggest that oxygen deficiencies may also act as a source of large $1/f$ noise and it is consistent with our proposal that the noisy behavior of the copper oxides in their normal state is mainly due to various structural defects.[4]

In the superconducting transition region, we observe very different results depending on the orientation of the excitation current (I) with respect to the *c* axis. *There is a prominent enhancement* of S_v/V^2 (typically 3 to 5 orders of magnitude) above the normal-state level when I is parallel to the *c* axis and there is *no enhancement* of S_v/V^2 when I is in the *a-b* plane (perpendicular to the *c* axis). This behavior is consistently observed in all the crystals that we have studied. Compared to the normal state, the anisotropic behavior of the $1/f$ noise in the superconducting transition region strongly suggests that a completely different noise source exists in this region.

Vortices of magnetic flux are formed in the superconducting transition region and they move transverse to the electric current density $\mathbf{J}$ because of the Lorentz force:[15] $\mathbf{f} = \mathbf{J}\times\mathbf{\Phi}_0/c$ where Φ_0 is the flux quantum and c the speed of light. The movement of the flux vortices induces an electric field of magnitude $\mathbf{E} = \mathbf{B}\times\mathbf{v}/c$ which is parallel to $\mathbf{J}$ ($\mathbf{B}$ is the magnetic field intensity and $\mathbf{v}$ is the velocity of the flux vortices). This electric field in turn generates a fluctuating voltage because of fluctuations in $\mathbf{v}$. Presently, there are many models to describe the motion of flux vortices in copper oxide superconductors. For instance, both thermally assisted flux creep[16] and thermally assisted flux flow[17] have been postulated. In the flux creep picture, $1/f$ noise is generated as individual vortices or sections of the vortex lattice (known as "bundles") come free from pinning centers and hop with characteristic time $\tau(T)$ at a given temperature T. Notice that the hopping motion of these bundles along the *c* axis results from the electric current in the *a-b* plane and the hopping in the *a-b* plane results from the current along the *c* axis. Assuming that the hopping is a Markov process leads to a Lorentz spectral density for a given activation energy U. A broad, featureless distribution of activation energies $D(U)$ has been invoked to explain the origin of $1/f$ noise in these instances.[7,18] The superposition of Lorentzian spectra can be used to calculate the $1/f$ noise spectrum if the distributions of U and the flux hopping time $\tau(T)$ are known [$\tau=\tau_0\exp(U(T)/k_BT)$, with k_B being the Boltzmann constant]. The noise spectrum is proportional to $\int dU\,D(U)\tau/[1+(\omega\tau)^2]$, where $D(U)$ is the density of activation energy[7,18] and ω is the angular frequency. The enhancement in the superconducting transition region suggests that the flux motion freezes out producing a peak in the factor $\tau/[1+(\omega\tau)^2]$ at $\omega\tau=1$. Although the technique we use for measurement cannot be extended into the superconducting state, the measurements by Ferrari *et al.* on thin films in the superconducting state[7] seemingly support the idea that the flux motion freezes out as T passes T_c leaving the vortices pinned in the superconducting state.

In order to explain why the enhancement occurs preferentially along the c axis, we need to consider the anisotropic nature of the $YBa_2Cu_3O_{7-\delta}$ system. It has been proposed that due to the large anisotropy in $YBa_2Cu_3O_{7-\delta}$ the flux line lattice is segmented in the c direction.[19] Similarly, Kes *et al.*[20] suggested that for arbitrary magnetic-field orientations, the field component parallel to the c direction creates a lattice of two-dimensional (2D) vortices which is virtually uncoupled to the field component parallel to the a-b plane. Independent of which description is more realistic, superconducting layers coupled by 2D Josephson junctions or an anisotropic 3D Ginzburg-Landau model,[21] the remarkably anisotropic nature of $YBa_2Cu_3O_{7-\delta}$ is well established. Experimentally it has been shown that the activation energies are much greater when the applied magnetic field is parallel to the a-b plane than when the field is parallel to the c axis.[16,22] If the activation energy was infinitely large, then all the vortices would be pinned and there would be no flux creep or flow, and consequently there would be no flux noise. Physically, the quasi-2D vortex lattice structure tends to limit the motion of vortices to the a-b plane and hopping between the planes is difficult. Therefore, when the probing current I is along the c axis, the motion of vortices is not hampered and the associated flux noise can be large. The opposite is true when I is perpendicular to the c axis and vortices are localized in the plane. As a result, the enhancement of the noise does not occur. In terms of the hopping motion, our data suggests that the activation energy U is very anisotropic: U is finite for hopping in the a-b planes and it is much larger for hopping parallel to the c axis.[23]

In summary, we have found that the $1/f$ noise in $YBa_2Cu_3O_{7-\delta}$ single crystals is very anisotropic in the superconducting transition region even though in the normal state the magnitude of the $1/f$ noise measured in the a-b plane is comparable with that along the c axis. The observed large enhancement of the $1/f$ noise in the superconducting transition region occurs when the probing current is along the c axis but not in the a-b plane. Our experimental data suggest that while the $1/f$ noise in the normal state may be due to various structural defects, a completely different noise source exists in the superconducting transition region. These results are tentatively explained based on the anisotropic nature of $YBa_2Cu_3O_{7-\delta}$ and the motion of magnetic vortices. Our data suggest that the magnetic flux lattice is highly anisotropic, if not completely two dimensional. Our experimental observations also imply that highly oriented thin films are required for practical applications if the high level of $1/f$ noise is to be avoided.

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[1] J. A. Testa *et al.*, Phys. Rev. B **38**, 2922 (1988).
[2] A. Maeda *et al.*, Physica C **160**, 443 (1989).
[3] Y. Song *et al.*, Physica C **172**, 1 (1990).
[4] Y. Song *et al.*, Phys. Rev. Lett. **66**, 825 (1991).
[5] M. J. Ferrari *et al.*, Appl. Phys. Lett. **53**, 695 (1988).
[6] P. Rosenthal *et al.*, IEEE Trans. Magn. **MAG-25**, 973 (1989).
[7] M. J. Ferrari *et al.*, Phys. Rev. Lett. **64**, 72 (1990).
[8] S. W. Tozer *et al.*, Phys. Rev. Lett. **59**, 1768 (1987).
[9] Y. Iye, *Mechanisms of High Temperature Superconductivity*, edited by H. Kamimura and A. Oshiyama (Springer-Verlag, New York, 1989).
[10] P. W. Anderson and Z. Zou, Phys. Rev. Lett. **60**, 132 (1988).
[11] R. F. Voss and J. Clarke, Phys. Rev. B **13**, 556 (1976).
[12] P. H. Handel, Phys. Rev. Lett. **34**, 1492 (1975); P. H. Handel, Phys. Rev. A **22**, 745 (1980).
[13] A. Misra *et al.*, Appl. Phys. Lett. **59**, 863 (1991).
[14] J. C. Phillips, *Physics of High-T_c Superconductors* (Academic, New York, 1989).
[15] M. Tinkham, *Introduction to Superconductivity* (McGraw-Hill, New York, 1975), p. 158.
[16] J. Z. Sun *et al.*, Appl. Phys. Lett. **54**, 663 (1989).
[17] V. M. Vinokur *et al.*, Phys. Rev. Lett. **65**, 259 (1990).
[18] P. Dutta and P. M. Horn, Rev. Mod. Phys. **53**, 497 (1981).
[19] R. Wordenweber *et al.*, Physica C **171**, 1 (1990).
[20] P. H. Kes *et al.*, Phys. Rev. Lett. **64**, 1063 (1990).
[21] L. Krusin-Elbaum *et al.*, Physica C **163**, 125 (1990); H. Raffy *et al.*, Phys. Rev. Lett. **66**, 2515 (1991).
[22] D. Wu and S. Sridhar, Phys. Rev. Lett. **65**, 2074 (1990).

[23] We can make a crude estimate of U for hopping in the a-b plane by setting $\omega\tau=1$ so that the function $\tau/[1+(\omega\tau)^2]$ is maximum while $D(U)$ is flat, producing the enhancement at T_c. Since $\tau=\tau_0\exp(U(T)/k_BT)$, we obtain an expression for the pinning energy barrier $U=-k_BT_c\ln(\omega\tau_0)$. U near T_c is found to range from 0.14 to 0.19 eV, using the following parameters: $T_c=90$ K, $f=0.7$ to 70 Hz, $\tau_0=10^{-11}$ s. The value of τ_0 is obtained from T. T. M. Palstra *et al.*, Phys. Rev. Lett. **61**, 1662 (1988) and C. W. Hagen and R. Griessen, Phys. Rev. Lett. **62**, 2857 (1989). Compared with the result by Ferrari *et al.* obtained on the $YBa_2Cu_3O_{7-\delta}$ films (Ref. 7, in which they find a zero-temperature pinning energy of 0.1 eV), our estimate is about an order of magnitude larger since their result should be scaled by a temperature dependence of $1-(T/T_c)^4$ (see Ref. 7).