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Thermally activated behavior of $1/f$ noise in $YBa_2Cu_3O_{7-\delta}$

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The $1/f$ resistance noise in $YBa_2Cu_3O_{7-\delta}$ single crystals has been measured in both the *a-b* plane and the *c* direction from room temperature to the superconducting transition. Evidence that $1/f$ noise in $YBa_2Cu_3O_{7-\delta}$ is thermally activated was obtained for both directions. We propose oxygen sites as possible fluctuation centers.

Fluctuations with a $1/f$-type power spectrum have been measured on almost all resistive materials, from semiconductors to metals. The mechanism of this $1/f$ noise is not nearly so simple as it may first appear. In the early years of study, many general theories were proposed to account for $1/f$ noise in all materials. At least by the time Hooge, Kleinpenning, and Vandamme wrote their review article,[1] they believed that the formula $S_R(f)/R^2=\gamma/N_c f^\alpha$ with $\gamma\approx 2\times 10^{-3}$ and $\alpha\approx 1$ was empirical in homogeneous samples. This implied the existence of some general theory. In the formula, N_c is the number of charge carriers, R is the resistance, and $S_R(f)$ is the power spectral density of the resistance fluctuations at a frequency f. Today, probably no one would believe that any unique mechanism of $1/f$ noise exists in all materials. However, it is still tempting to assume that the same kinetics can be used to describe most of the fluctuation processes. Of all kinetics pictures proposed, thermally activated kinetics[2] is one of the most plausible. In this picture, with some conditions, a so-called Dutta-Dimon-Horn relation is set up,

$$\alpha=1+\left[1-\frac{\partial \ln S_R(\omega,T)}{\partial \ln T}\right]\Big/\ln(\omega\tau_0)\ , \qquad (1)$$

for angular velocity ω. The attempt time τ_0 is a time constant determined by the nature of the fluctuation center. Experimental data on many metal films[2-4] and some other systems[5,6] generally fit the above relation, giving evidence to this thermally activated kinetics picture. Thermally activated kinetics does not predetermine any detailed mechanism, but it does give some insight, which helps us to understand the mechanism of $1/f$ noise for particular material.

$1/f$ noise in copper oxide superconductors has been found to be extraordinarily large.[7-13] In the normal state, the magnitude of the $1/f$-noise spectral can be 4–10 orders higher than that of conventional metals. This anomalously large $1/f$ noise is interesting theoretically. But, with some of the theories proposed, the mechanism of $1/f$ noise in copper oxide superconductors is far from being determined. As far as we know, the Dutta-Dimon-Horn relation has not been checked in those materials. In fact, data on the temperature dependence of α is very limited.

In our paper, we report the results of $1/f$-noise measurements along different axes of $YBa_2Cu_3O_{7-\delta}$ single crystals. The temperature dependence of both α and the noise spectral density have been measured in detail. We find that, by taking into account the resistive properties of our samples, our data fit the thermally activated kinetics picture. A possible mechanism is then suggested.

The $YBa_2Cu_3O_{7-\delta}$ single crystals were first prepared by a flux-growth technique.[14] They were then oxygen annealed at 550 °C for 1 h and subsequently at 400 °C for 4 days. We used four samples in our experiment, two for the *a-b* plane measurements, denoted as *A*1 and *A*2, and two for the *c* direction measurements, denoted as *C*1 and *C*2. Electrical leads of *C*1 and *C*2 were prepared by a gold contact technique.[12] Two gold pads were evaporated on each of the two *a-b* surfaces, followed by annealing in oxygen at 500 °C for 1 h. Thin platinum wires were attached to the gold pads by silver epoxy. For samples *A*1 and *A*2, four thin platinum wires were directly attached to the edges of each sample by silver epoxy, followed by annealing in oxygen at 600 °C for an hour. All electrical leads were connected to the samples quite well, with a contact resistance of less than 1Ω.

Using a four-probe technique the temperature dependence of the resistance of each sample was measured. Samples *A*1 and *A*2 (in the *a-b* plane) display a decrease in resistance with decreasing temperature. Samples *C*1 and *C*2 (*c* direction) show an increase in resistance with decreasing temperature from room temperature to the beginning of the superconducting transition (Fig. 1). The superconducting transition starts at a temperature above 90 K for all samples, with a width of 5–8 K. A resistive "step" was observed in the transition region of the *a-b*

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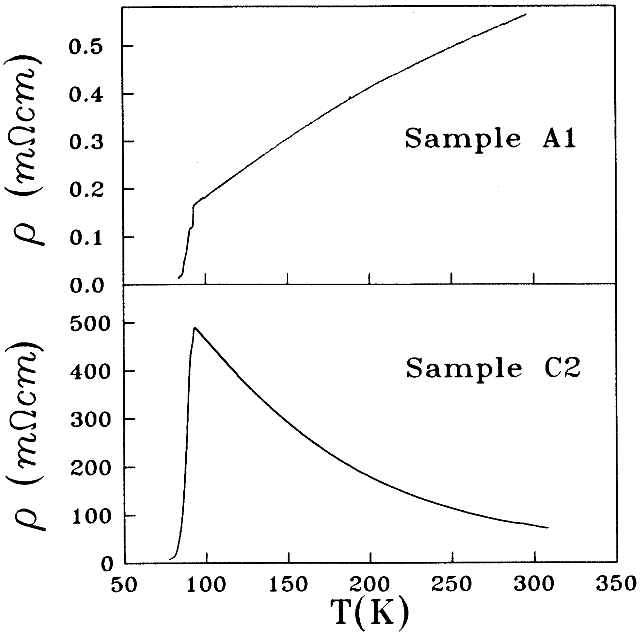

FIG. 1. The electrical resistivities of samples $A1$ (in the a-b plane) and C2 (in the c direction). A step can be seen clearly in the transition region of sample $A1$.

plane samples (Fig. 1). This step probably indicates some resistively different phases are connected in series in those samples.

The $1/f$-noise spectrum was measured using an *ac* bridge method. A sinusoidal current is applied to the sample through a ballast resistor of resistance at least 100 times larger than that of sample. Voltage across the sample is first amplified about 1200 times by a home-made low-noise amplifier. The amplified voltage is subsequently balanced by a signal from a parallel route, yielding the amplified voltage fluctuation. This signal is then amplified by a lock-in amplifier (EG&G PARC model No. 5302). The 5302 has two output channels, X and Y, with 90 degrees of phase difference. We set the X channel in phase with the voltage of the sample, so that the Y channel reads the out-of-phase signal. In such a setup, only the X channel contains the resistance noise of the sample. Output of both channels are then fast Fourier transformed in a dynamical analyzer (Hewlett-Packard model No. 35665A). The noise spectral density of the X channel is subsequently subtracted from that of the Y channel, followed by averaging over groups of data. Since the white noise is phase independent with the current, the white noise of the X channel is the same as that of the Y channel after enough averaging. Subtraction of the spectral density of the X channel from that of the Y channel substantially increases the sensitivity of the measurement. A careful check of our experimental setup has been carried out to make sure that the noise from the electrical contacts is negligible.

Excess noise spectra for all samples, at every temperature measured, have a characteristic $1/f$ behavior with an α value between 0.9 and 1.3. The normalized spectral density magnitude γ could have a difference of about four orders from sample to sample. The smallest room-temperature value of γ measured is about 7.1×10^3 (A2), which is about the same order as that of Song *et al.*,[10] while the largest is more than 10^7 ($C1$), which is almost the same order as those reported for polycrystals. No correlation was observed between the value of γ and the resistivity of the sample or the direction of the applied current. Where the temperature dependence of γ and α is concerned, a few interesting phenomena arise. γ decreases with decreasing temperature from room temperature to about 200 K for all samples. At lower temperatures, the γ of $C1$ and $C2$ becomes almost independent of temperature, while the γ of $A1$ and $A2$ increases with decreasing temperature. Interestingly, α's of all samples have a similar temperature dependence, i.e., α decreases from about 1.3 at room temperature to about 0.9 near the transition (Figs. 2 and 3). A comparison of our data with that of the thermally activated kinetics picture is also shown in Figs. 2 and 3. For $\tau_0=10^{-13}$ sec, the c direction data agree with Eq. (1), while those of the a-b plane deviate at lower temperatures. We believe that resistance fluctuations in the c direction are thermally activated. Agreement of the data for the a-b plane with Eq. (1) at upper temperatures and the similarity of the $\alpha-T$ relationship between the c direction and the a-b plane suggests that fluctuations in the a-b plane are also thermally activated. To explain the deviation of the a-b plane at lower temperatures, we have to see the conditions under which Eq. (1) holds.

Scofield, Mantese, and Webb[15] pointed out that S_R in

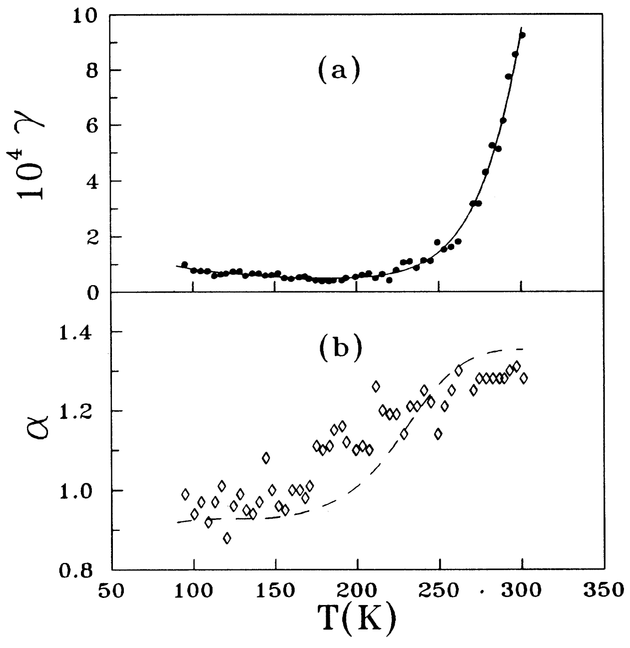

FIG. 2. The temperature dependence of $1/f$ noise in the c direction of a $YBa_2Cu_3O_{7-\delta}$ single crystal. (a) The temperature dependence of γ. The solid line is a polynomial fit of the experimental data (●). (b) The temperature dependence of α. The dashed line is calculated from Eq. (1) using the fitted line of (a). The measured α value (◇) agrees with the calculation.

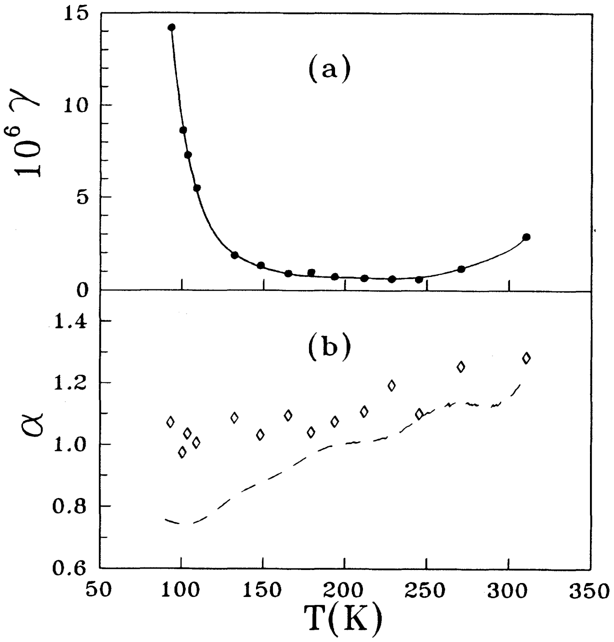

FIG. 3. The temperature dependence of $1/f$ noise in the *a*-*b* plane of a $YBa_2Cu_3O_{7-\delta}$ single crystal. (a) The temperature dependence of γ. The solid line is a polynomial fit of the experimental data (●). (b) The temperature dependence of α. The dashed line is calculated from Eq. (1) using the fitted line of (a). The structure of the calculated line should not be taken too literally. The measured *a*-*b* plane data (◇) deviate from the calculation at lower temperatures.

Eq. (1) should be substituted with

$$S(\omega,T)=S_R(\omega,T)/\langle\delta R^2(T)\rangle \ ,$$

where

$$\langle\delta R^2(T)\rangle\propto\langle\delta r^2(T)\rangle/R_0^2(T) \ ,$$

δr is the resistance change of each fluctuation, and $R_0(T)$ is the resistance of the sample. Only those with $\langle\delta R^2(T)\rangle\approx$const will fit Eq. (1). It should be noted that, generally, δr is not the local resistance change of a fluctuation δr_1. But if all fluctuation centers are connected in series, δr is equal to the local resistance change of each fluctuating center. Since the resistance of our samples show a step in the superconducting transition of the *a*-*b* plane samples, we believe that fluctuation in our *a*-*b* plane samples are connected in a series, or almost so. Further, R_0 for the *a*-*b* plane decreases with decreasing temperature. So if δr_1 increases with decreasing temperature rapidly, $\langle\delta R^2(T)\rangle$ for the *a*-*b* plane will increase rapidly with decreasing temperature. This explains why γ of the *a*-*b* plane increases at lower temperatures, while α does not drop significantly. Such a deviation from Eq. (1) will not occur for the *c* direction. Since R_0 for the *c* direction also increases rapidly at lower temperatures, $\langle\delta R^2(T)\rangle\approx$const for this direction.

Fluctuations with δr_1 following such a temperature dependence are possible in high-T_c superconductors. Oxygen fluctuation is a good candidate for this picture. We know that the temperature dependence of resistivity for a high-T_c superconductor changes with oxygen content.[16,17] It seems that there are some oxygen-dependent phases that show very different resistive behavior. Poulsen *et al.*[18,19] proposed a microscopic model of oxygen ordering recently. They argued that domains as small as a few cells could be formed with some oxygen ordering. In this picture, one oxygen fluctuation may change the local resistivity behavior, which gives rise to a local resistance difference with semiconductorlike resistive behavior. This lattice-atom fluctuation picture is also consistent with $\tau_0=10^{-13}$ sec, which is about equal to the inverse of the Debye frequency.

The present data cannot locate the exact peak position of the activation energies of the fluctuators. To know this one needs to extend the measurements to higher temperatures. However, from our results we estimate that the characteristic activation energy should be higher than $\sim$0.8 eV, which is quite insensitive to the choice of τ_0.[2] The estimation is not inconsistent with the activation energy of oxygen diffusion, which is around 1 eV, obtained by different authors.[20]

In conclusion, the temperature dependence of $1/f$ noise in $YBa_2Cu_3O_{7-\delta}$ single crystals has been measured in both the *a*-*b* plane and the *c* direction. The *c* direction noise fits the Dutta-Dimon-Horn relation in the whole temperature measured, while the *a*-*b* plane noise deviates from the relation at lower temperatures. This deviation of the *a*-*b* plane data is explained by considering the magnitude of resistance change of each fluctuator to be temperature dependent. As a result, fluctuations of $1/f$ noise in $YBa_2Cu_3O_{7-\delta}$ single crystals are thermally activated in both directions. Oxygen sites are proposed as possible fluctuation centers.

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