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Noise measurement near the transition region in $YBa_2Cu_3O_{7-\delta}$ thin-film superconductor

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We have measured the noise spectrum near the transition temperature of the high-T_c superconductor $YBa_2Cu_3O_{7-\delta}$ thin film which shows a rather broad transition temperature width with the onset transition temperature $T_{c,\text{onset}}=90$ K and the zero-resistance temperature $T_{c,\text{zero}}=30$ K. We observed two noise peaks, one near the onset transition temperature (81 K) and another one near the zero-resistance temperature (45 K). These two noise peaks show distinctively different dependences on the magnetic field and driving current. Furthermore, the frequency dependence of the noise spectrum at 81 K shows $1/f$ behavior while that of the noise spectrum at 45 K shows $1/f^{(1+\alpha)}$ behavior with α approaching 1, as the magnetic field is increased. The noise peak near the zero-resistance temperature region is believed to be due to the noise associated with the motion of free vortices.

I. INTRODUCTION

Since the discovery of the high-T_c superconductor La-Ba-Cu-O by Bednorz and Muller,[1] a considerable amount of interest has been focused on the fluctuation effect in the ceramic oxide superconductors. The high-T_c superconductors developed so far, in general, show a rather unusually broad transition temperature width compared to the conventional low-T_c superconductors, partly because of their short coherence length ξ of the order of 10 Å, and also because of the granular nature of the oxide ceramic superconductors.[2] Because of the short coherence length, only a few Cooper pairs are accommodated within the coherence volume; the fluctuation effect causes a rather strong paraconductivity.[3] Below T_c, there appears a resistance tail which was frequently observed in conventional low-T_c superconductors. Palstra *et al.*,[4] for example, interpreted the observed dissipation at a temperature below T_c in $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ subjected to a magnetic field in terms of thermally activated flux creep. On the other hand, Dubson *et al.*[5] interpreted the resistance tail observed in a bulk $Y_1Ba_2Cu_3O_{7-\delta}$ as a result of strong junction disorder in the granular high-T_c superconductor. Another possibility for the resistance tail is due to the free vortices. Within the Kosterlitz-Thouless picture,[6] vortex-antivortex pairs are created at a temperature above its dissociation temperature T_M. Existence of free vortices can cause a dissipation under a transport current even at a temperature below $T_{c,\text{BCS}}$, the Bardeen-Cooper-Schreiffer (BCS) critical temperature. Recently, Testa *et al.*[7] reported an $1/f$ noise measurement which has a single sharp noise peak near the transition temperature in a bulk copper oxide superconductor. Based on the unusually strong magnitude and temperature dependence of the noise power, they interpreted their result as the effect of thermal fluctuation, probably in the grain boundary. However, the earlier work by Voss *et al.*[8] in conventional low-T_c superconductors showed a noise peak which is possibly related to the flux motion. Therefore, it might be interesting to study the noise power in a high-T_c superconductor with a broad transition width for two reasons. First, one can study the adequacy of the thermal fluctuation model[9] to describe the noise by comparing the temperature dependence of the noise density $S(f)$ with the resistance change $(dR/dT)^2$ inside the transition region where there is a rather severe change of R. Second, one can study the possible origin of the noise, such as the thermal fluctuation or the flux motion, by comparing temperature dependences of the noise power and the sample resistance.

In this paper, we report a noise power measurement in thin-film $Y_1Ba_2Cu_3O_{7-\delta}$ which shows a broad transition width $\delta T=50$ K in the resistance measurement.

II. EXPERIMENT

The high-T_c $YBa_2Cu_3O_{7-\delta}$ thin films studied in this experiment were deposited onto the yttrium stabilized zirconia substrate by the rf sputtering method. Typical film thickness was around 3000 Å. A post-deposition annealing process in the oxygen environment is required to recover superconductivity in the film. X-ray diffraction measurement also indicates the formation of the "1:2:3" structure from the amorphous state after annealing at 850 °C for about one hour in the flowing oxygen gas. The onset superconductive transition temperature was around 90 K. The zero-resistance transition temperature, however, varied from 30 to 80 K depending on the duration and temperature of annealing. The resistance of the film with a broad transition width showed little dependence on the temperature between room temperature and the onset T_c, while those with a narrow transition width showed a metallic behavior.

In order to investigate the relation between noise and resistance tail in the transition region, we chose films which show a long resistance tail. After scribing the film to make a narrow line shape of 10×0.8 mm^2, Ohmic contact was made by indium soldering onto a four-terminal probe. The room-temperature sheet resistance $R_{\square}$ of the film we studied is about 18.5 $\Omega/\square$. Noise spectra were measured by the conventional four-terminal method to eliminate any contact-related complication in the spectral range 0.5–10 Hz. During the measurement, the sample was shielded by a μ-metal box to reduce external noise interference.

The noise signal was amplified using a Stanford Research preamplifier SR 550 coupled to a line-notch filter and a band-pass filter, if necessary. Noise power at fixed frequency was measured by a lock-in technique, while the noise power spectral density was obtained by a fast Fourier transformation of the discretely sampled data from an analog-to-digital converter. The excess noise spectrum $S_{\rm exc}(f)$ in the sample was obtained by subtracting background noise from the measured noise.

III. RESULTS

Figure 1 shows a typical noise power measured at 15 Hz together with the resistance and the resistance derivative of the sample. The superconductive onset transition temperature T_c is 90 K. The zero-dissipation temperature T_M which turns out to be strongly dependent on the magnitude of the testing current is 30 K for the testing current of 500 μA. With testing currents of 1 and 0.1 μA, the zero-dissipation temperature increases to 43 and 52 K, respectively. Unexpectedly, there appears two noise peaks, one near the onset temperature of the resistance transition and another one near the tail region of the resistance. The noise peak at around 81 K appears to be associated with the change of the resistance in the film implying a thermal fluctuation associated noise mechanism. The large noise peak observed at a lower temperature, however, cannot be explained by the thermal fluctuation in the film because, in that temperature range, R and dR/dT both approach zero. Thermoelectric power (TEP) measurement for a film from the same batch shows a tail similar to the resistance tail without any "anomalous" peak near the zero-dissipation temperature as shown in Fig. 2. The value of the TEP reduces to zero at around 50 K which is quite close to the zero-dissipation temperature 52 K in the zero testing current limit. Moreover, the TEP does not show any noticeable effect of the applied magnetic field, unlike the resistance which shows a noticeable decrease in T_M upon applying magnetic field. To clarify the origin of the noise peak near the resistance tail, we have measured the driving current, magnetic field, and frequency dependences of the noise. Driving current dependence of the noise power is shown in Fig. 3 with the current ranging from 0.05 to 1 mA. For a current less than 0.02 mA, the noise power from the sample became less than the preamplifier noise level. As can be seen from Fig. 3, the noise peak at a higher temperature and the noise peak at a lower temperature show different current dependence. As the driving current is increased, the magnitude of the noise peak at a higher temperature increases but the position of the noise peak temperature remains almost unchanged at 81 K. However, the noise peak at a lower temperature shifts toward a lower temperature as the current increases. A similar shift was observed in the resistance measurement for the sample. The onset T_c around 90 K in the resistance measurement did not change for the current range tested, but the zero-dissipation temperature T_M decreased upon increasing the testing current. The decrease of 10 K in the zero-dissipation temperature for an increase of 1 mA in the driving current in the low current limit is in good agreement with the resistance measurement.[10] The magnitude of both noise peaks shows somewhat unexpected current dependence with $S(15\ {\rm Hz}) \propto I^{1.3}$ at low temperature and $S(15\ {\rm Hz}) \propto I^{1.3}$ at 81 K. It is quite puzzling why the noise power in the high-T_c superconducting film shows a deviation from the expected $S(f) \propto I^2$ behavior, unless the origin of the noise in the high-T_c superconductor involves a shot noise nature which will show $S(f) \propto I$ behavior. Furthermore,

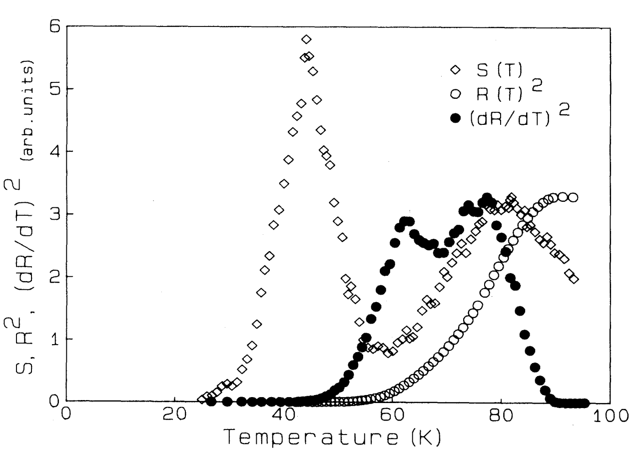

FIG. 1. Typical temperature dependence of the noise power $S(15\ {\rm Hz})$ (◇), $R^2(T)$ (open circle), and $(dR/dT)^2$ (solid circle) in $YBa_2Cu_3O_{7-\delta}$ thin film. The driving current for both resistance and noise measurements is 500 μA.

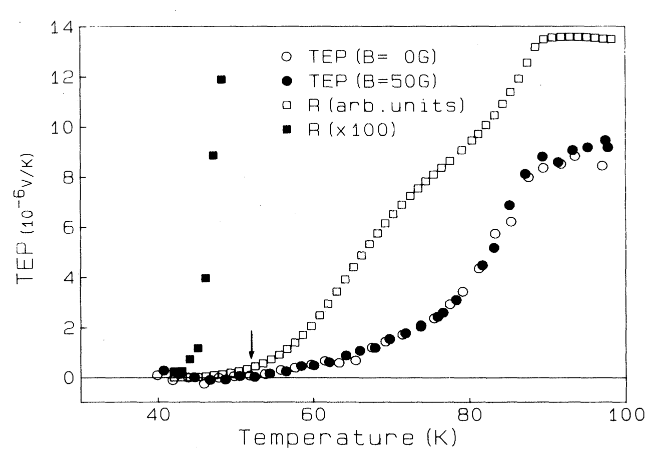

FIG. 2. Thermoelectric power also showing tail similar to the resistance measurement. The zero-dissipation temperature T_M from the resistance measurement with a testing current 1 μA is 43 K. Within the experimental error, the TEP reduces to zero at around 50 K regardless of the magnetic field up to 50 G.

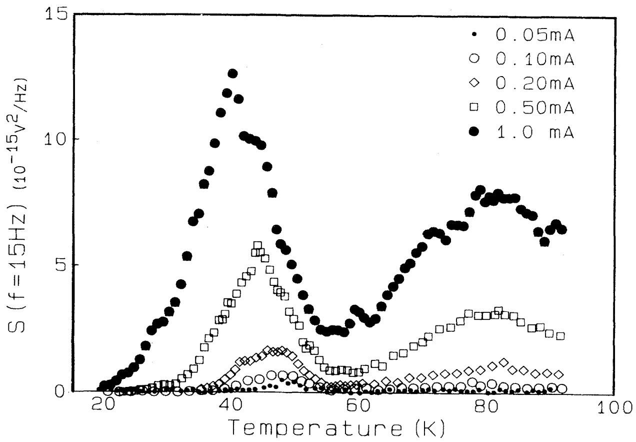

FIG. 3. Driving current dependence of the noise power at 15 Hz. The temperature of the noise peak near onset T_c remains unchanged, while that near the zero-dissipation temperature shifts toward low temperature as the current increases. Magnitude of S shows approximately $I^{1.3}$ dependence.

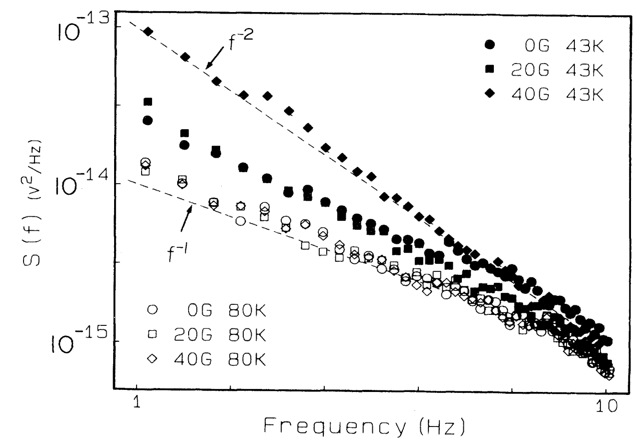

FIG. 5. Noise spectral density measured at 80 K shows $1/f$ behavior regardless of the magnetic field up to 40 G. However, $S(f)$ at 43 K shows almost $1/f^2$ behavior.

each of the noise peaks shows quite a different magnetic field dependence as shown in Fig. 4. Noise power S(15 Hz) at 81 K does not show any noticeable dependence on the magnetic field applied. On the other hand, the magnitude of S(15 Hz) at 45 K decreases as the applied magnetic field increases. This behavior is similar to the magnetic field effect on the conventional thin-film superconductor.[8] This behavior is further confirmed by the spectral density measurements at 81 and 45 K with the magnetic field applied as shown in Fig. 5. The frequency dependence of $S(f)$ at 81 K follows roughly $1/f$ regardless of the magnetic field intensity up to 40 G. At 45 K, however, the applied magnetic field has a strong influence over the frequency dependence of the noise spectrum. $S(f)$ shows $1/f^{(1+\alpha)}$ with $\alpha=0.2$, 0.35, and 1.0 for the magnetic field of 0, 20, and 40 G, respectively. Incidentally, magnitudes of $S(f)$ under different magnetic fields are equal at $f=10$ Hz. Therefore at 15 Hz, S(15 Hz) will show a decreasing trend as one increases the applied magnetic field, a fact which is already shown in Fig. 4.

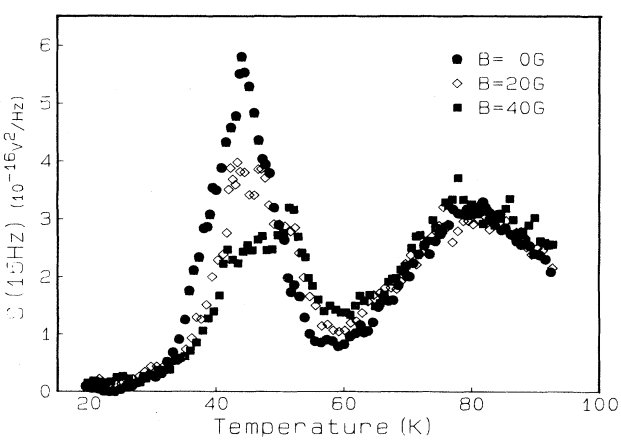

FIG. 4. Magnetic field dependence of noise power S(15 Hz) measured with a driving current $I=500$ μA. The noise peak near the onset T_c does not show any noticeable change. The magnitude of the peak near the zero-dissipation temperature decreases as the field increases.

IV. DISCUSSION

In a high-T_c superconducting film of $YBa_2Cu_3O_{7-\delta}$ which shows a wide transition width, we have observed two different types of noise peaks, one at a temperature just below the superconductive onset temperature and another one at a temperature just above the zero-dissipation temperature as shown in Fig. 1. Below the zero-dissipation temperature, there was no detectable noise. The general shape and position of the noise density S(15 Hz) at 81 K is quite different from that of R^2 or $(dR/dT)^2T^2$, unlike the earlier report.[7] Thus it seems that the thermal fluctuation model[9] of Voss and Clarke alone cannot adequately describe the noise spectrum observed in the transition temperature region of the granular superconductor. Our separate I-V measurement showed a linear Ohmic relation at this temperature. Application of a magnetic field had little effect on the I-V characteristics at this temperature, being similar to the behavior of the noise spectrum at 81 K, which did not show any noticeable effect of the magnetic field applied. Therefore a flux-flow related origin for this noise is excluded. A heuristic approach of calculating the noise spectrum by including a resistance fluctuation effect by the Hooge formula[11] and a thermal fluctuation effect[9] by Voss and Clarke

$$S(f)=S_{\mathrm{Hooge}}+S_{\mathrm{VC}}$$
$$=a[IR(T)]^2+b[I(dR/dT)T]^2 , \quad (1)$$

shows a rather good agreement with the experimental result as shown in Fig. 6. Although there is no microscopic base for the above heuristic approach, the good agreement is interpreted as evidence supporting the notion that, in the granular superconductor, the noise near the

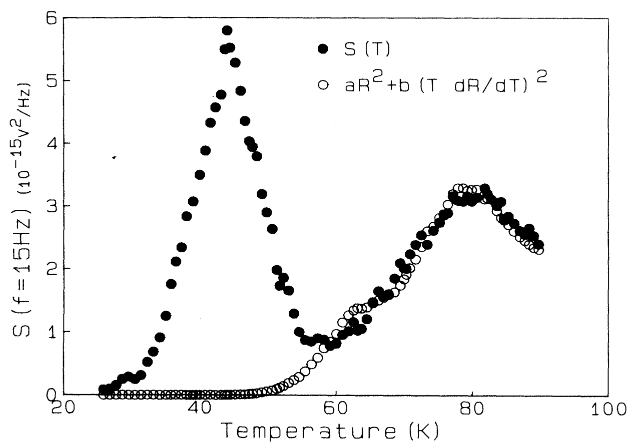

FIG. 6. Comparison between experimental (solid circle) and calculated (open circle) noise power at 15 Hz.

onset transition temperature is caused by the resistance fluctuation via the fluctuation in the number of Cooper pairs due to its extremely short coherence length and also by the thermal fluctuation in the sample. Since our sample showed a nearly temperature-independent resistance behavior between 300 and 100 K, we used best fitting parameters

$$b(=k_B/C_v[3+2\ln(1_1/1_2)]f^{\alpha})$$

of the noise power simulation and the reported specific-heat value[12] $C_v=6$ J/Kg atom for the estimate of the charge carrier number in the sample N_c and Hooge parameter γ instead of employing the free-electron model. This procedure gives $N_c=2.6\times10^{12}$ (or the carrier concentration $n_c=2.1\times10^{18}/\text{cm}^3$) and $\gamma=1.73$, the value which is quite contrasting to the typical metallic value[13] of $\gamma=2\times10^{-3}$ or to the reported $\gamma=10^5-10^7$ of Testa *et al.*[7] The low charge carries concentration $n_c=2.1\times10^{18}/\text{cm}^3$ together with the large value of γ may reflect the fact that the origin of the noise near the onset transition temperature is from the grain boundary.

The noise peak at low temperature showed quite different characteristics compared to the noise peak at higher temperature. Comparison to the resistance measurement indicated that the noise peak is located just above the zero-dissipation temperature T_M, where the resistance of the film at that temperature is typically less than 0.2% of the room-temperature value. Moreover, the noise peak shifts toward lower temperature as one increases the driving current. The zero-dissipation temperature T_M in the resistance measurement showed a similar behavior and was interpreted as a result of the dissipation due to the flux flow.[10] The decreasing trend of noise power $S(15\text{ Hz})$ at 45 K upon applying a magnetic field is similar to the result observed in the conventional superconductor[6] by Voss *et al.*, who interpreted their result in terms of the vortex motion. The unusual current dependence of noise power and the reduction of noise, while the resistance increases in the presence of a magnetic field, can be understood if there involves a correlated interaction between vortices as a result of the increased free-vortices number due to an external magnetic field or driving current. The observed $1/f^2$ dependence in $S(f)$ at 45 K under a magnetic field is in striking contrast to the $1/f$ behavior of $S(f)$ at 81 K. Although there is no clear explanation[14] for the observed $1/f^2$ behavior of $S(f)$ at 45 K under a magnetic field, the observed unusual driving current dependence ($S\propto I^{1.3}$ or $\langle V\rangle^{1.3}$), and the field dependence for the noise peak at a lower temperature are suggestive of the flux-flow related mechanism.

In conclusion, we have observed two different types of noise peaks in a thin-film high-T_c superconductor with a rather broad transition width. The noise peak near the onset T_c appears to be associated with the thermal fluctuation and possibly with the fluctuation in the number of Cooper pairs due to its extremely short coherence length, while the stronger noise peak near the zero-dissipation temperature is related to the flux flow in the sample.

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