Measurements of noise spectral densities for a high-T_c superconductor: Single-crystal $Bi_2Sr_2CaCu_2O_x$

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The noise power spectral density for a $Bi_2Sr_2Ca_1Cu_2O_x$ single crystal has been examined as a function of magnetic field, temperature, and frequency. In the normal state, the normalized noise power spectral density $S_n(f)$ was observed to be several orders of magnitude greater than that of normal metals. Near the superconducting transition temperature, we observed a marked increase in $S_n(f)$ with and without an external magnetic field. Moreover, in this region, we observed an unusual frequency dependence of the noise power spectral density on the external magnetic field.

I. INTRODUCTION

Recently a great deal of attention has been paid to the investigation of $1/f$ noise in various high-T_c superconductors[1–9] (HTSC's). In both the normal and superconducting transition regions, the measured spectral density of the noise voltage $S_v(f)$ has been observed to be much larger than the usually accepted value of normal metals. Among several efforts[7–9] to describe such enhancement in the normal state HTSC's, Maeda *et al.*[7] found that neither the universal conductance fluctuation model[10] nor the local interference model[11,12] could explain the high enhancement of noise. Song and co-workers[8,9] used the tunneling model which is a direct application of McWhorter's potential-fluctuation mechanism.[13] They regarded the twin boundary of the $YBa_2Cu_3O_{7-x}$ (YBCO) single crystals as a potential-fluctuation source and quantitatively explained the large enhancement. However, contrary to other measurements,[1–4,7] they could not find the noise enhancement near a transition temperature (T_c).

One can conjecture various possible origins of the $1/f$ noise in association with the superconducting state. The first possible origin is thermal fluctuations.[14] However, the noise power calculated from this model is known to be much smaller than measurements.[2–4,7,8] The second possible mechanism is the effect of superconducting fluctuations;[15] however, there exists no theory to relate them directly to the observed $1/f$ noise spectra. The third origin could be magnetic flux noise.[5,16–19] This source is relevant to superconducting quantum interference device (SQUID) noise, but may or may not be directly related to the transport measurements of present interest.

In this paper, we examine the variation of $S_v(f)$ using high quality single crystals of $Bi_2Sr_2Ca_1Cu_2O_x$ (BSCCO) prepared by the well-known CuO flux method.[20,21] The most distinctive features observed from the present measurements are the following: (1) the enhancement of normalized noise power spectral density $S_n(f)$ [$=S_v(f)/V^2$, where V is the static voltage across the sample] in the normal state, including anomalously high enhancement near T_c, (2) the marked change of frequency dependence near T_c, and (3) the substantial increase of noise power spectral density $S_v(f)$ with magnetic field near T_c. These results will be compared to Hooge's empirical formula $S_n(f)=\gamma/N_c f^{\alpha}$,[22] where N_c is the total number of charge carriers in the sample, and to the Voss-Clarke thermal fluctuation formula,[14] $S_n(f)=\beta^2 k_B T^2/fC_v A$. Here $\beta=(1/R)dR/dT$, k_B is Boltzmann's constant, C_v, the heat capacity, and A, a geometric factor which is of the order of unity. For calculations of $S_n(f)$ we used published values of specific heat (43.2 J/K at 300 K and 1.44 J/K at 75 K) (Ref. 23) and our measured resistance data.

II. EXPERIMENTS

High quality BSCCO single crystals were prepared by the CuO flux method[20,21] with the starting composition of Bi:Sr:Ca:Cu = 4:3:3:6. From our extensive characterization of the single crystals with x-ray diffraction and the method of Laue and Auger,[21] we obtained the crystal structure of $Bi_2Sr_2Ca_1Cu_2O_x$, which resulted from highly aligned c-axis growth. The typical size of crystals is $3\times4\times0.02$ (mm^3).

Electrical contacts were attached to the sample by using indium soldering. The contact resistance was much less than 1 Ω and contact noise was shown to be negligible in our experiments. The standard four-probe method was used to measure both the electrical resistance and the noise power spectral density. The sample was located in a magnetically shielded Janis Research 10DT supervaritemp cryostat. For noise measurements, a battery generated current (10–30 mA) was passed through the a-b plane of the sample and magnetic fields up to 80 G were applied perpendicular to the direction of current. The resistance of the ballastic resistor in series with the sample was chosen to be at least 1000 times greater than that of the sample. At each temperature the noise spectrum was measured from 2 to 100 Hz. Other details of its experimental setup are similar to that of Testa *et al.*[2]

III. RESULTS AND DISCUSSION

Figure 1 displays the temperature dependence of resistance on magnetic field perpendicular to the basal (a,b) plane. In all cases, the superconducting transition started close to 85 K, but the onset of zero resistance depended on the value of the applied magnetic field. In the case of zero magnetic field with current $I=1$ mA, the transition temperature T_c was observed to be at 78.8 K. We note that even a weak magnetic field significantly alters resistance behavior. The rapid variation of slope in resistance suggests the influence of free vortices caused by the external magnetic fields.[24] In Fig. 2, the normalized noise

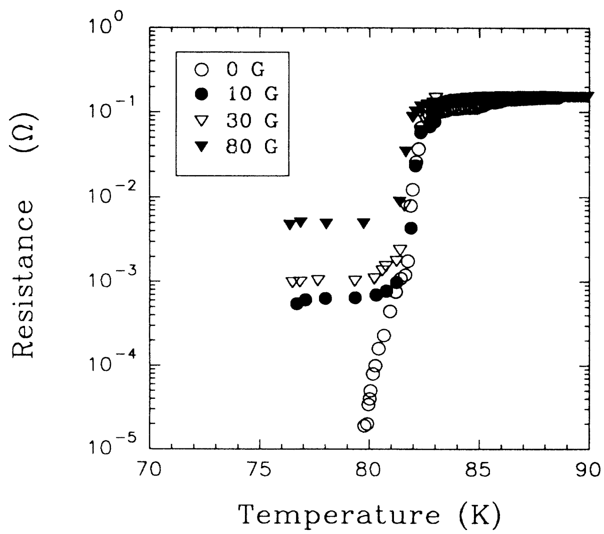

FIG. 1. Temperature dependence of resistance.

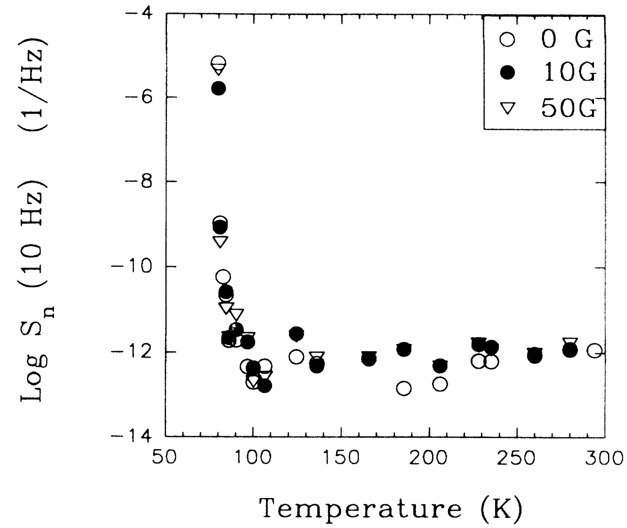

FIG. 2. Temperature dependence of normalized noise spectral density $S_n(f)$ at $f=10$ Hz for selected magnetic fields.

power spectral density $S_n(f)$ at $f=10$ Hz and at various magnetic fields is plotted as a function of temperature from $T=80$ to 300 K. In this measurement, the bias current was 18.5 mA and magnetic fields were applied parallel to the c axis. In the normal state, $S_n(f)$ has little variation with temperature at all applied magnetic fields. At $T=300$ K, we compared the magnitude of S_n (10 Hz) to Hooge's empirical formula. We found that $\gamma=7\times10^2$, which is five orders of magnitude greater than the value of $\gamma=2\times10^{-3}$ for conventional metals. It is noteworthy that comparably large values of $S_n(f)$ were also obtained from other HTSC's such as Tl-compound,[8] YBCO single crystals,[9] and YBCO thin film.[25]

By using the McWhorter's potential-fluctuation model,[13] Song and co-workers[8,9] made an attempt to explain the large enhancement of normal state noise power spectral density quantitatively. In their model calculation, they regarded twin boundaries in the single crystal as metal-insulator-metal and they assumed that there exists an energy barrier for charge carriers to overcome in the insulating layer. Moreover, in fitting the data, the two most important parameters of barrier thickness and barrier height were found to be highly sensitive in determining the magnitude of $S_n(f)$ and temperature dependence. However, it was known that there were no twin boundaries in the BSCCO single crystals[20] used in the present experiments. Although this model calculation attempted to analyze $1/f$ noise for normal state HTSC's quantitatively, we believe that it is not possible to apply the same model to our BSCCO sample.

Near T_c, we found a substantial enhancement in $S_n(f)$ as shown in Fig. 2. In this transition region $S_n(f)$ is about seven orders of magnitude greater than that of the normal state. The substantial noise increment is worthy of comparison with the Voss-Clarke thermal fluctuation model.[14] We observed some similarity in increasing tendency of $S_n(f)$, but not in its absolute magnitude, which is greater by at least 13 orders of magnitude than the computed result. This observation is similar to the measurements of others.[2–4,7,8] Even though there exists some similarity in trend, the thermal fluctuation model completely fails to predict the observed anomalous enhancement of the normalized noise power spectral density near T_c.[1–5]

In Fig. 3, we present noise power spectral densities $S_v(f)$ measured at 228, 79.7, and 75.5 K with selected magnetic fields from 0 to 80 G. In the normal state at $T=228$ K [Fig. 3(a)] and zero magnetic field, $S_v(f)$ has the typical characteristics of $1/f$ behavior except at low-frequency range. Moreover, this behavior and amplitude of $S_v(f)$ are not changed with magnetic fields up to 50 G, within the range of experimental error. However, we found a very interesting behavior in $S_v(f)$ near T_c ($=78.8$ K) as shown in Fig. 3(b). At $T=79.7$ K, the log-log plot of $S_v(f)$ vs frequency does not display a linearity. The computed value of α is close to 0 for $2<f<6$ Hz, around 2 for $6<f<30$ Hz, and nearly 4 for $30<f<100$ Hz. At all the applied magnetic fields up to 80 G, similar behavior persisted. However, the magnitude of $S_v(f)$ increased with magnetic field in the noise frequency range from 2 to 30 Hz. Interestingly, above $f=30$ Hz $S_v(f)$ did not appreciably change with the applied magnetic fields. An additional unusual feature is observed at $T=75.5$ K as shown in Fig. 3(c). For $f>30$ Hz all of the $S_v(f)$ showed similar behavior, but for $f<30$ Hz the field dependence of $S_v(f)$ was marked. For $B<10$ G, $S_v(f)$ did not change appreciably while for $B>10$ G it showed a rapid increase with external magnetic field. For $f>30$ Hz, there was no increase of $S_v(f)$ with external magnetic fields up to 80 G. This is probably because magnetic flux effects may not play a significant role above the relatively high frequency of $f=30$ Hz. As shown in this figure, we observed the increase of $S_v(f)$ with the applied magnetic field. However, similar magnetic field dependence was observed in other magnetic flux noise measurements,[17,18] in which the magnetic flux noise spectral density $S_\Phi(f)$ was also seen to increase with external magnetic field. From this we suggest that the increment of $S_v(f)$ with magnetic field is related to external magnetic flux.

In Fig. 4, the temperature dependence of $S_v(f)$ at $f=2.4$ Hz with various values of magnetic field is presented for a temperature range below 80 K. In this figure, the noise power spectral density is seen to increase rapidly with both magnetic field and temperature until T_c is reached. However, above T_c $S_v(f)$ drops very rapidly with temperature while it does not vary strongly with the applied magnetic field as shown in Fig. 2.

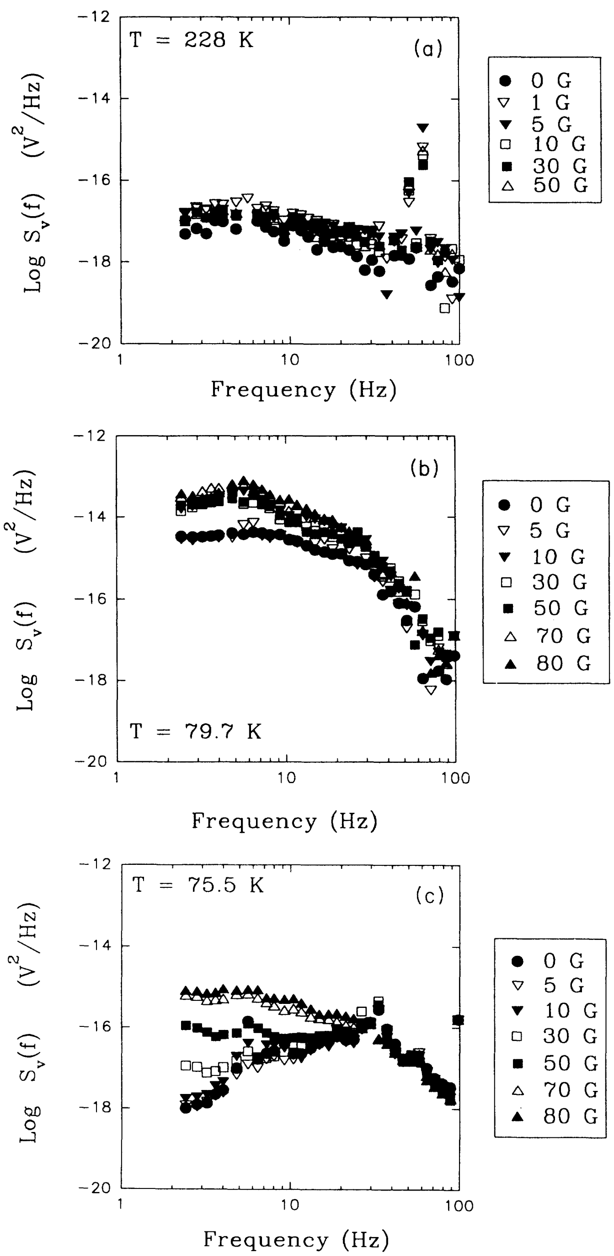

FIG. 3. Noise spectral density $S_v(f)$ vs frequency at (a) $T=228$ K, (b) $T=79.7$ K, and (c) $T=75.5$ K for selected magnetic fields.

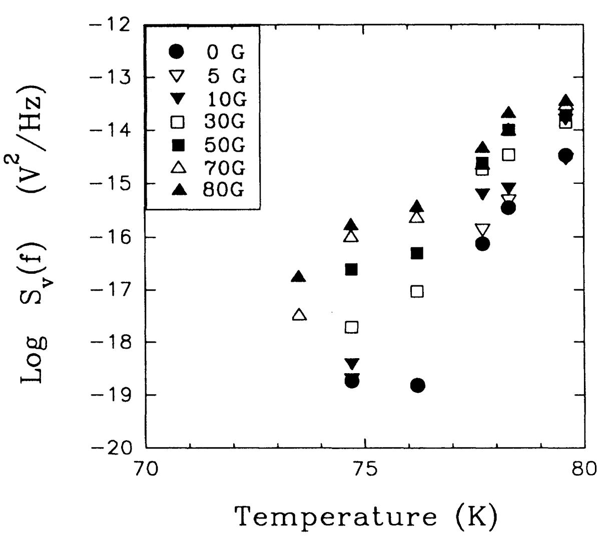

FIG. 4. Temperature dependence of noise spectral density $S_v(f)$ at 2.4 Hz showing the variation with magnetic field for temperature range below 80 K.

It was reported that in HTSC's the measured spectral density of the flux noise $S_\Phi(f)$ increases with temperature below T_c and then drops very rapidly just above T_c.[5,17–19] Moreover, it was observed that $S_\Phi(f)$ increases monotonically with magnetic field. Although their measurement technique is different from our measurement of voltage noise spectral density, a similar trend is also found in our measurement of $S_v(f)$ with the application of external magnetic field, as displayed in Fig. 4. Another point of interest is that the value of $fS_v(f)$ with $f=2.4$ Hz at temperatures near T_c is almost linear in the applied magnetic field. In the measurement of magnetic flux noise, $fS_\Phi(f)$ is also linear in magnetic field. Judging from this common observed linearity, we are led to believe that the unusually high noise enhancement for both cases is caused by the same mechanism. The rapid increase of $S_v(f)$ with magnetic field below T_c might have arisen from the motion of individual magnetic vortices.[18]

In our previous measurements of $1/f$ noise in micropatterned YBCO thin films,[25] we observed a similar behavior, i.e., the anomalous enhancement of $S_n(f)$ with external magnetic field and variation of α in $1/f^\alpha$ from 1 to 2 close to T_c. We tentatively concluded that this feature may not be related to a simple function of the number of vortices alone but may be a magnetic vortex as a result of the external magnetic field.

From the evidence discussed above, we believe that the anomalous enhancement of noise power spectral density near T_c without magnetic field may not come from the extrinsic properties of sample quality but from the intrinsic nature of HTSC's. Judging from excellent qualitative agreement with the results of magnetic flux noise measured by SQUID's, we are inclined to believe that the anomalously high enhancement of noise generated in the present HTSC's near T_c is related to the fluctuation of magnetic vortices.

IV. SUMMARY

We have measured the temperature and magnetic field dependence of $S_v(f)$ using high quality single crystals of $Bi_2Sr_2Ca_1Cu_2O_x$. We observed that $S_n(f)$ in the normal state is greater by four or five orders of magnitude than that of the normal metals predicted by Hooge's formula, and found an anomalously enhanced noise peak near T_c. Our finding is that $S_v(f)$ in the normal state region shows roughly a $1/f$ noise behavior regardless of variation in the external magnetic field, while below T_c, $S_v(f)$ increases with magnetic field and temperature. In particular, we observed an unusual frequency dependence of $S_v(f)$ with the variation of magnetic field near T_c. From our observation, we suggest that the anomalous increase of $S_v(f)$ near T_c is caused by the presence of vortex-antivortex pairs which are subject to the motions of individual magnetic vortices.

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