Size effect of $1/f$ noise in the normal state of $YBa_2Cu_3O_{7-\delta}$

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The $1/f$ noise power spectral density in the normal state of two series of $YBa_2Cu_3O_{7-\delta}$ samples—microbridges of width 4–200 μm and ultrathin films of thickness 2.4–10.8 nm—are measured at temperatures from 80 to 300 K. Two characteristic lengths—one in the ab plane with a magnitude of about 10^1 μm and another along the c axis with a magnitude of about 10^0 nm — are discovered. The noise level decreases sharply below the characteristic lengths. The lowest noise level observed is in the range of that of normal metals. The experimental data can be described reasonably well by the Dutta-Horn thermally activated model. Some possible mechanisms are also discussed.

Abnormally high levels of $1/f$ noise in the normal state of high-T_c superconductors (HTSC) have been observed.[1–9] The question as to whether this is an intrinsic property of HTSC, however, still needs to be answered experimentally. The $1/f$ noise power spectral density (PSD) $S_V(f)$ is empirically described by Hooge's formula:

$$S_V(f)=V^2\frac{\gamma}{f^{\alpha}n\Omega}, \tag{1}$$

where V is the dc voltage across the sample, n the charge carrier density, and Ω the sample volume. α is typically between 0.8 and 1.4, and γ is the specific Hooge parameter that characterizes the noise level of the system being measured. γ is typically between $10^{-5}-10^{-1}$ in metals and about 10^{-3} in semiconductors. $YBa_2Cu_3O_{7-\delta}$ (YBCO) has an abnormally large γ value: 10^5-10^7 for bulk and 10^3-10^4 for thin films and single crystals, which is more than 4 orders of magnitude larger than the γ value of metals. Recently, however, low noise levels have been reported in HTSC samples of small sizes. Liu *et al.* found that a YBCO/$PrBa_2Cu_3O_{7-\delta}$ (PrBCO) superlattice sample with YBCO layers of 2-unit-cells thickness yielded a γ value of 1.4.[10] Scouten *et al.*, measuring γ value for a 2-μm wide YBCO microbridge, reported a value close to that of metals.[11] Dong *et al.* also observed that film size greatly influenced the noise level.[12] These reports motivated us to systematically study the size dependence of $1/f$ noise in the normal state of YBCO. We studied samples of various sizes both in the ab plane and along the c axis. The results show that the noise level decreases as the sample size is reduced. The characteristic length for noise reduction in the ab plane differs from that along the c axis. The experimental data are also compared with the Dutta-Horn thermally activated model. Some possible explanations are presented at the end of this paper.

The microbridges were prepared by first depositing a high-quality, c-axis-oriented YBCO thin film of 200 nm thickness onto a (100) $SrTiO_3$ substrate using pulsed laser ablation. Then microbridges of width 4, 10, 20, 50, 100, and 200 μm and a typical length-to-width ratio of 2.5-to-1 were patterned using standard photolithography. This allowed sample size variation in the ab plane. To obtain sample size variation along the c axis, ultrathin films of YBCO in a sandwich form were prepared on (100) $SrTiO_3$ substrates using the same deposition technique. In order to lessen lattice mismatch and to protect the ultrathin YBCO layer, a 20-nm-thick layer of PrBCO was grown first, followed by the YBCO layer, and finally by another 20-nm-thick layer of PrBCO on the top. The substrate temperature was kept at 785 °C, optimized for the YBCO layers. The thickness of the YBCO layers was 2.4 nm [2 unit cells (U.C.)], 3.6 nm (3 U.C.), 4.8 nm (4 U.C.), 6.0 nm (5 U.C.), 8.4 nm (7 U.C.), and 10.8 nm (9 U.C.). Details of the sample preparation techniques have been published elsewhere.[13]

The spectra of the $1/f$ noise in the voltage fluctuation were measured between 1 and 100 Hz using a standard four-probe dc technique. Four gold wires were cold-pressed with indium to silver pads, which were evaporated onto the samples through a mechanical mask. The voltage signal was dc filtered by a large capacitance, passing through a PAR1900 low-noise transformer and a PAR113 preamplifier, and was finally received by an HP35665A spectrum analyzer, which generated the noise power spectra.

The temperature dependence of the resistances of all microbridges shows standard R-T behavior like that of bulk YBCO films. The resistance decreases linearly with decreasing temperature at all temperatures. The superconducting transition temperature is about 90 K. For the ultrathin films, the temperature dependence of the normalized resistance is shown in Fig. 1. The zero-resistance temperature, T_{c0}, decreases from 81 K in a 9-U.C.-thick YBCO film to 16 K in a 2-U.C.-thick film. It can be seen that at temperature T'_{c0} there is a maximum in the resistance-versus-temperature curves for films with YBCO layers thinner than 6.0 nm (5 U.C.). The resistance increases with decreasing temperature above T'_{c0} for these films, while the resistance changes only slightly and metallically for films with thicker YBCO layers. Below T'_{c0}, resistivity decreases quickly with decreasing temperature for all films, indicating that although T_{c0} is quite low in films with thinner YBCO layers, the onset of the superconducting transition occurs at comparable temperatures for all film thicknesses.

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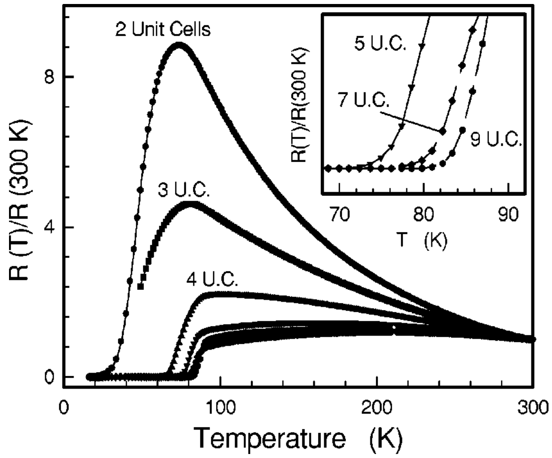

FIG. 1. The temperature dependence of resistance in PrBCO/YBCO/PrBCO sample. The thickness of YBCO layer is given near curve. All the data are normalized by each sample's resistance at 300 K.

We have found that all samples produce clean $f^{-\alpha}$ spectra in the frequency range 1–100 Hz at temperatures from 80 to 300 K, with the exponent α ranging from 0.8 to 1.3. The noise spectra $S_V(f)$ always scale with V^2, indicating that the measured noise spectra result solely from the fluctuation of conductance, and self-heating due to the current flow is negligible. The charge carrier density n can be estimated from the Hall number R_H. For YBCO, n is approximately 1 per cell, or $\sim 5.75\times 10^{21}$ cm^{-3}.[14] Affonte *et al.* studied YBCO/PrBCO superlattice samples and obtained an n value of $(4-10)\times 10^{21}$ cm^{-3}.[15] In their study of $1/f$ noise in YBCO single crystals, Song *et al.* chose $n=2\times 10^{21}$ cm^{-3}.[5] In our work, we selected n to be 5.75×10^{21} cm^{-3} for microbridges and 2.0×10^{21} cm^{-3} for ultrathin films with consideration for charge transfer and reduction in T_c in the sandwich samples.[16–19] In fact, the values of n chosen above do not affect the noise level of the samples.

The parameter γ for three microbridges as a function of temperature is shown in Fig. 2. The values of γ decrease as the sample width decreases. γ is about 10^{-1} for the 4-μm microbridge, 4 orders of magnitude lower than for the 50-μm microbridge. The γ value decreases slightly with decreasing temperature, which is consistent with previously reported results.[11,12] In Fig. 3, we plot γ value at room temperature as a function of microbridge width. Scouten *et al.*'s data, represented by two triangle symbols, are also presented for comparison. The square symbol shows the γ value of a bulk YBCO film. The values of γ for the three larger microbridges are on the order of 10^3-10^4, the same as for the bulk YBCO film. As the sample width decreases, however, the γ value decreases rapidly. It seems that there is a characteristic length on the order of $10^1\,\mu$m. When the width of a microbridge is less than this characteristic length, the noise level drops from an abnormally high level of 10^3-10^4, as in bulk films, to 10^{-2} in the 2-μm microbridge, falling within the range of γ for normal metals.

The ratio of thickness to length for the PrBCO/YBCO/PrBCO sandwich samples is about 10^{-5}. Since the two voltage contacts are near the middle of the samples and far away from the current contacts at the edge, the YBCO and PrBCO

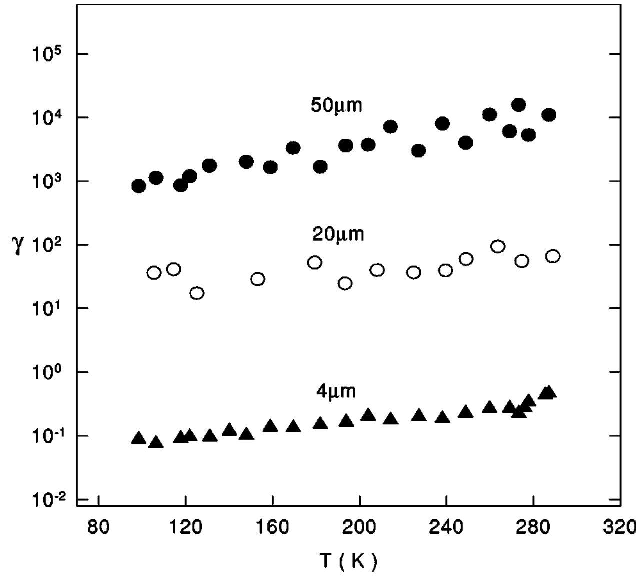

FIG. 2. The parameter γ of three microbridges with width of 4, 20, and 50 μm as a function of temperature.

layers can be considered as having parallel electric connections. If we assume that the YBCO and PrBCO layers are relatively independent, the noise PSD of the whole film can be estimated using a simplified parallel-noise-source model.

The $1/f$ noise spectra can be expressed in terms of voltage (V) fluctuation, resistance (R) fluctuation or conductance ($G=1/R$) fluctuation as follows:

$$\frac{S_V}{V^2}=\frac{S_R}{R^2}=\frac{S_G}{G^2}=\frac{k}{f}, \tag{2}$$

where k is a constant equal to $\gamma/n\Omega$ in Hooge's formula. Assuming that there are two independent parallel noise sources, then

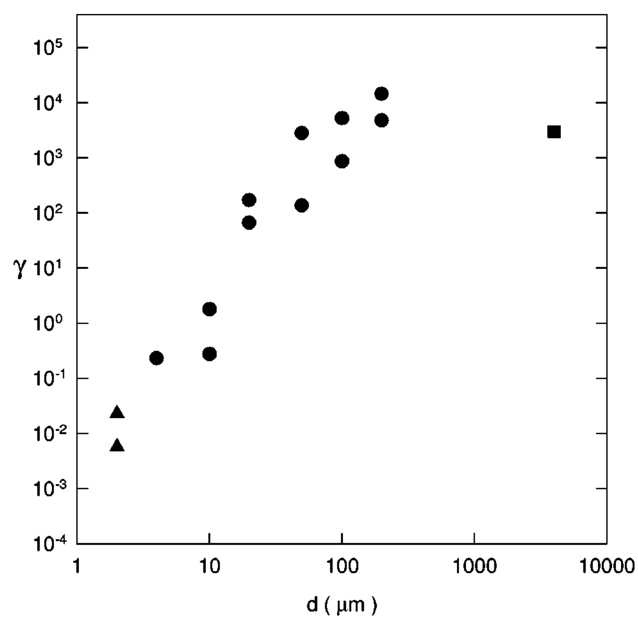

FIG. 3. The room-temperature noise level γ as a function of microbridge width. The data of Scouten *et al.* (triangles) and the present authors (circles) are shown together. The square point shows the γ value of a bulk YBCO thin film.

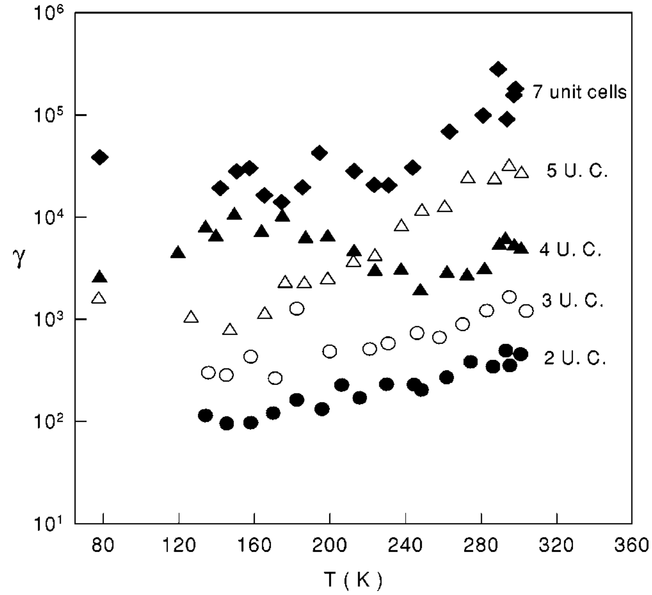

FIG. 4. The temperature dependence of γ in five PrBCO/YBCO/PrBCO samples. The thickness shown in the plot is that of YBCO layer.

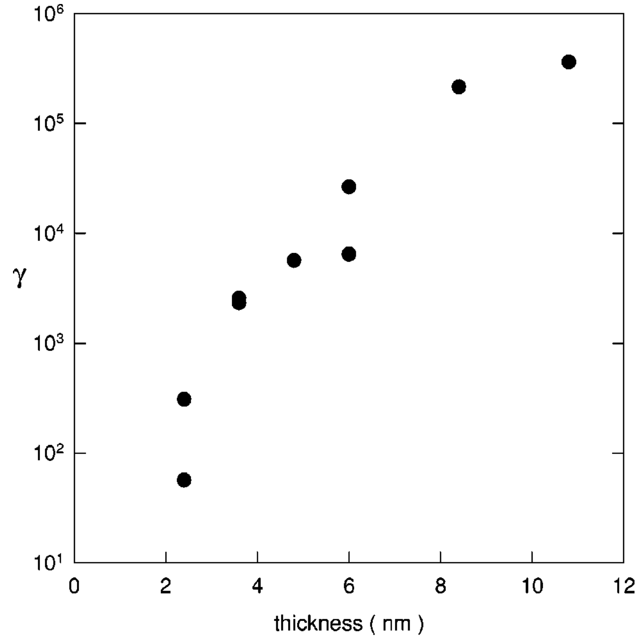

FIG. 5. The noise level γ as a function of thickness of YBCO layer in PrBCO/YBCO/PrBCO samples at room temperature.

$$\frac{S_{G_1}}{G_1^2}=\frac{k_1}{f} \quad \text{and} \quad \frac{S_{G_2}}{G_2^2}=\frac{k_2}{f}, \tag{3}$$

where the indices 1 and 2 correspond to the YBCO and PrBCO layers, respectively. The $1/f$ noise PSD of the whole film is

$$S_V(f)=\frac{k_1G_1^2+k_2G_2^2}{(G_1+G_2)^2}\frac{V^2}{f}. \tag{4}$$

If the thickness of a YBCO layer is about 10^0 nm, as that in our case, we get $G_2/G_1<10^{-2}$ and $k_1/k_2=10^{-1}-10^0$. Therefore, $S_V(f)\approx k_1V^2/f$. In other words, the $1/f$ noise of the whole sample is determined mainly by the YBCO layer, and the PrBCO layers provide only mechanical protection for the YBCO layer.

In Fig. 4, we plot the temperature dependence of γ for five ultrathin films. Except for the film with a 4-U.C. YBCO layer, all values of γ increase with increasing T. This behavior is consistent with that of microbridges and with other works.[11,12] The nonmonotonic behavior of the sample with a 4-U.C. YBCO layer may be caused by a high-angle grain boundary in the sample. A peak in the noise level at about 150 K is consistent with a peak reported in Ref. 11. In the range of 80–300 K, the noise level drops as the thickness of the YBCO layer decreases.

The room-temperature value of γ as a function of the thickness of the YBCO layer is shown in Fig. 5. The noise level is on the order of 10^5 in the two thicker films. As the YBCO thickness decreases to 2.4 nm (2 U.C.), the γ value decreases to 10^1-10^2, about 3–4 orders of magnitude lower than that in the thicker films. Along the c axis, the characteristic length below which fluctuations decrease rapidly is on the order of 10^0 nm, which is far less than that in the ab plane. In the study of $1/f$ noise in 2/2 YBCO/PrBCO superlattice, Liu *et al.* reported a γ value of 1.4,[10] less than the value we obtained in the 2-U.C. YBCO film here. The difference probably arises from the difference in structure. Liu's superlattice films are about 150–250 nm thick and are composed of many YBCO layers. According to Eq. (4), as long as a few layers of YBCO grow well, the noise level of the whole film will be mainly determined by them.

In their paper, Scouten *et al.*[11] applied the Dutta-Horn thermally activated model[20] to analyze the $1/f$ noise source in the normal state of YBCO microbridges. They believe that $1/f$ noise arises from thermally activated processes with a broad distribution of activation energies with respect to k_BT and that the noise is caused by hopping and reordering of basal plane oxygen vacancies. The characteristic feature is that the $\gamma(T)$ values increase with increasing temperature, as also observed in this work. We will further compare our experimental value of the frequency exponent $\alpha(T)$ with the thermally activated model.

Under certain conditions, Dutta *et al.*[21] deduced the following relation for $\alpha(T)$:

$$\alpha=1-\frac{1}{\ln(\omega\tau_0)}\left[\frac{\partial \ln S_V(\omega,T)}{\partial \ln T}-1\right], \tag{5}$$

where $\omega=2\pi f$, and the attempt time constant τ_0 is determined by the nature of the fluctuation center, with values around $10^{-14}-10^{-13}$ s. Figure 6(a) is a plot of $\ln S_V(f)$ as a function of temperature for a 20-μm microbridge and a 2-U.C. YBCO film. The two solid lines are polynomial fits to two sets of experimental data represented by circles and triangles. The temperature dependence of α is shown in Fig. 6(b). The lines in the figure are calculated using Eq. (5) with $\tau_0=10^{-13}$ s. Our experimental data for most samples fit Eq. (5) reasonably well, similar to the behavior of the 2-U.C. YBCO film. There are, however, a few samples, for example the 20-μm microbridge, showing some deviation, although their $\gamma-\text{vs}-T$ dependence is not abnormal. The $1/f$ noise is usually very sensitive to sample's strain fields, structure de-

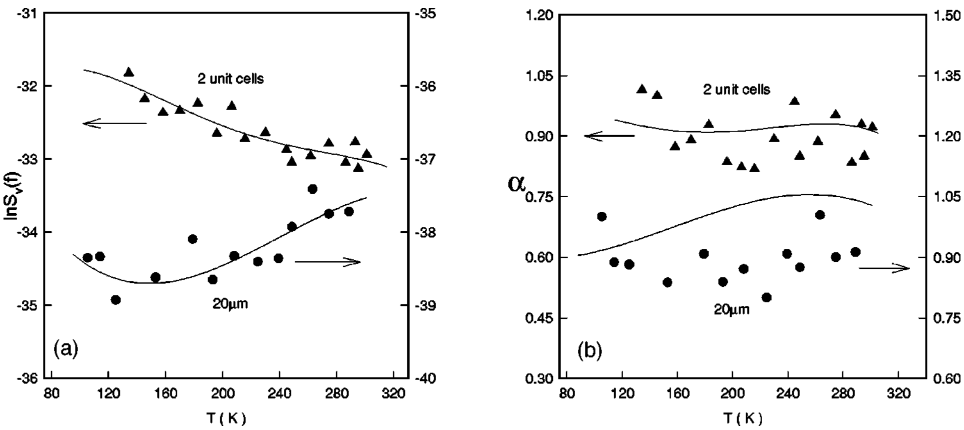

FIG. 6. A comparison between Dutta-Horn's thermally activated model and the data in this work. (a) A plot of $\ln S_V(f)$ as a function of temperature. The solid lines are polynomial fits of the experimental data (round points for bridges and triangluar ones for PrBCO/YBCO/PrBCO samples). (b) The temperature dependence of α value. The solid lines are calculated from Dutta-Horn relation Eq. (5) using the fitting results of $\ln S_V(f)$ in (a).

fects, and oxygen content. It is also inevitable that data fitting should have some errors. This is mostly because the measured $S_V(T)$ is disperse, causing different fitting results in the measured temperature range. This kind of error, however, is not large enough to account for the difference between the predicted behavior [calculated using Eq. (5)] and the experimental results, and consequently the reason of the deviation is not very clear.

To obtain an expression for the $1/f$ noise in HTSC, Song *et al.* proposed a metal-insulator-metal (MIM) model.[4] Based on the existence of many defects in HTSC — such as planar faults, line defects, and twin boundaries — they suggested that the energy barriers resulting from abundant defects should cause fluctuations in the number of charge carriers, which would lead to an abnormally high level of $1/f$ noise. They used percolation theory to estimate the noise in YBCO when $L>\xi$, where L is the sample's length and ξ is the percolation correlation length, which is usually the average distance between defects, ranging from 10^0 to 10^1 μm.[22] In their work, the theoretical results fit the experimental data reasonably well. Our results with microbridges can probably be explained by this model. In our case, when a sample is large enough, the $L>\xi$ condition is met, and the fluctuations caused by defects are much larger than the sample's intrinsic noise. Therefore, the $1/f$ noise level of samples with large widths is as abnormally high as normal films. When the width is reduced to the order of $10^0\mu$m, $L\leqslant\xi$, and the MIM model is no longer suitable for our films. For these samples, the noise level decreases in proportion to the reduction in sample size, which is in turn proportional to the number of MIM junctions in the sample. The measured fluctuations in a small microbridge are therefore much closer to the intrinsic behavior of YBCO material.

Feng *et al.* used a percolation model of Mott variable-range hopping to estimate the $1/f$ noise caused by moving impurities.[23,24] They obtained $\gamma\propto(\xi_p/a)^D$, where D is the number of dimensions, a the lattice constant, and ξ_p the percolation correlation length, which can be much greater than the lattice constant a. For our sandwich films, the thinnest was 2 U.C. YBCO layer can be regarded as a quasi-two-dimensional plane because the thickness of the YBCO layer is less than ξ_p. As a result, there will be a sharp drop in the noise level. In order to explain the abnormally high $1/f$ noise level in bulk YBCO samples, Testa *et al.* proposed a possible model in which the noise comes from the conduction process along the c axis and the low density of charge carriers in that direction results in a large fluctuation.[1] In our work, decreasing the thickness of YBCO layers lessened the number of CuO_2 planes. Consequently, the possibility of interplane coupling was reduced, which may have led to the clear drop in the noise level.

In conclusion, we have prepared two kinds of YBCO films with various sizes in the ab plane and along the c axis. The $1/f$ noise PSD's for the normal state of the films has been measured. It seems as if there are two characteristic lengths relating to fluctuation in these two directions. The characteristic length is on the order of 10^1 μm in the ab plane, and 10^0 nm along the c axis. When the sample size is less than the characteristic length, the noise level drops significantly. We have also compared our experimental data with the Dutta-Horn thermally activated model. The $\gamma(T)$ and $\alpha(T)$ dependence for most samples can be described reasonably well by this model. The results reported here imply that the intrinsic $1/f$ noise level in normal states of HTSC may not be abnormally high and the interplane conduction process does contribute to the $1/f$ noise.

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[1] J. A. Testa, Y. Song, X. D. Chen, J. Golben, S. I. Lee, B. R. Patton, and J. R. Gains, Phys. Rev. B **38**, 2922 (1988).

[2] L. Liu, K. Zhang, H. M. Jaeger, D. B. Buchholz, and R. P. H. Chang, Phys. Rev. B **49**, 3679 (1994).

[3] J. H. Lee, S. C. Lee, and Z. G. Khim, Phys. Rev. B **40**, 6806 (1989).

[4] Y. Song, A. Misra, P. P. Crooker, and J. R. Gaines, Phys. Rev. Lett. **66**, 825 (1999).

[5] Y. Song, A. Misra, P. P. Crooker, and J. R. Gaines, Phys. Rev. B **45**, 7574 (1992).

[6] A. Misra, Y. Nakayama, S. Takebayashi, and K. Uchinokura, Physica C **160**, 443 (1989).

[7] A. Misra, Y. Song, P. P. Crooker, J. R. Gaines, and A. Cardona, Appl. Phys. Lett. **59**, 863 (1991).
[8] Y. Song, A. Misra, Y. Cao, A. Querubin Jr., X. D. Chen, P. P. Crooker, and J. R. Gaines, Physica C **172**, 1 (1990).
[9] H. Y. Dong, J. D. Guo, X. L. Xu, T. Zhang, and S. S. Yan, Physica C **282-287**, 1431 (1997).
[10] S. T. Liu, G. J. Lian, M. Wang, G. H. Li, G. C. Xiong, and S. S. Yan, Phys. Rev. B **51**, 6751 (1995).
[11] S. Scouten, Y. Xu, B. H. Moeckly, and R. A. Buhr, Phys. Rev. B **50**, 16 121 (1994).
[12] H. Y. Dong, X. D. Hu, Y. J. Bei, R. J. Nie, T. Zhang, and S. S. Yan, Physica C **282-287**, 1439 (1997).
[13] G. J. Lian, Z. H. Wang, J. F. Kang, and G. C. Xiong, Chin. J. Low Temp. Phys. **20**, 41 (1998).
[14] A. Matsuda, K. Kinoshita, T. Ishii, H. Shibata, T. Watanabe, and T. Yamada, Phys. Rev. B **38**, 2910 (1988).
[15] M. Affronte, J. M. Triscone, O. Brunner, L. Antognazza, L. Miéville, M. Decronex, and Ø. Fischer, Phys. Rev. B **43**, 11 484 (1991).
[16] M. Rosolt, T. Edis, and Z. Tesanovic, Phys. Rev. Lett. **66**, 2927 (1991).
[17] R. F. Wood, Phys. Rev. Lett. **66**, 829 (1991).
[18] J. Z. Wu, C. S. Ting, W. K. Chu, and X. X. Yao, Phys. Rev. B **44**, 411 (1991); H. L. Stormer, A. F. Levi, K. W. Baldwin, M. Anzlowar, and G. S. Boebinger, *ibid.* **38**, 2472 (1988).
[19] G. L. Liu, G. C. Xiong, G. H. Li, G. J. Lian, K. Wu, S. T. Liu, J. Li, and S. S. Yan, Phys. Rev. B **49**, 15 287 (1994).
[20] P. Dutta and P. M. Horn, Rev. Mod. Phys. **53**, 497 (1981).
[21] P. Dutta, P. Dimon, and P. M. Horn, Phys. Rev. Lett. **43**, 646 (1979).
[22] J. C. Phillips, *Physics of High-*T_c *Superconductors* (Academic, New York, 1989).
[23] S. C. Feng, J. L. Pichard, and F. Zeng, Phys. Rev. B **48**, 2529 (1993).
[24] S. C. Feng and J. L. Pichard, Phys. Rev. Lett. **67**, 753 (1991).