Normal-state $1/f$ noise in $YBa_2Cu_3O_{7-\delta}/PrBa_2Cu_3O_{7-\delta}$ superlattices with a two-unit-cell-thick $YBa_2Cu_3O_{7-\delta}$ layer in one period

Sangtian Liu,* Guijun Lian, Guoliang Liu, Min Wang, Guohong Li, Guangcheng Xiong, and Shousheng Yan
Department of Physics, Peking University, Beijing 100871, People's Republic of China
(Received 16 November 1994)

The experimental results of the normal-state $1/f$ resistance fluctuation of $YBa_2Cu_3O_{7-\delta}/PrBa_2Cu_3O_{7-\delta}$ (YBCO/PrBCO) superlattice samples with a two-unit-cell-thick YBCO layer in one period are reported. The noise power spectral densities at room temperature are 2 to 4 orders of magnitude lower than in YBCO single crystals and thin films. They are the lowest ones reported to our knowledge in the YBCO system. The results imply that the contribution of the interplane conduction processes or the dimension effect might be important to the $1/f$ noise level.

High-level $1/f$ noise power is one of the abnormal properties in the normal state of high-T_c cuprates. It has been studied by many groups in various sample forms.[1–8] For the $YBa_2Cu_3O_{7-\delta}$ (YBCO) system, $1/f$ noise has been investigated in bulk samples, epitaxial films, and single crystals.[1,5–8] The $1/f$ noise in these samples has different levels and even in a YBCO single crystal the noise level is still about five orders of magnitude larger than in clean metallic samples. In our earlier study, in order to investigate the relation of $1/f$ noise and microstructure in the YBCO system, we measured the normal-state $1/f$ noise in a $YBa_2Cu_3O_{7-\delta}/PrBa_2Cu_3O_{7-\delta}$ (YBCO/PrBCO) superlattice with a seven-unit-cell-thick (about 8.4 nm) YBCO layer and a three-unit-cell-thick (about 3.6 nm) PrBCO layer in one period.[9] The study showed that the noise power of the superlattice is about two orders of magnitude lower than that of the YBCO thin films, close to the reported noise level in YBCO single crystals. Furthermore, there are some models in which the dimension effect is important to the noise level.[1,10,11] All this encourages us to continue the study of $1/f$ noise in YBCO/PrBCO superlattices with a thinner YBCO layer. In this paper we present our measurements of $1/f$ noise in YBCO/PrBCO superlattices with a two-unit-cell-thick YBCO layer in one period. Our results show a tremendous decrease in the $1/f$ noise power in the superlattice sample with an ultrathin YBCO layer.

The superlattice samples were grown by laser ablation onto single-crystal $Zr(Y)O_2$ substrates under the conditions that are appropriate for YBCO thin films with T_c about 90 K. Layers of PrBCO and YBCO were deposited alternately with a total thickness of about 150–250 nm. X-ray diffraction measurement showed that the c axis is oriented perpendicular to the substrate surface and satellite peaks were clearly observed. We denote the samples by M/N, where $M(N)$ is the number of units cells along the c axis in the YBCO (PrBCO) layer per superlattice period. The $1/f$ noise of superlattice samples 2/2, 2/6, and 2/8 has been studied.

The $1/f$ noise spectra were measured from 1 to 100 Hz by standard four-terminal techniques.[6,9] Four gold leads were attached by silver paste to silver contacts deposited on the surface of the samples after a careful cleaning by ion beams. The area between the middle two voltage contacts is about 1.5 mm^2. The voltage signal was dc filtered, passed through a PAR 1900 low-noise transformer and a PAR 113 preamplifier, and was detected by a HP 35665A spectrum analyzer to obtain noise power spectra.

The typical temperature dependence of the resistivity in the superlattice samples 2/2, 2/6, 2/8 measured by the four-terminal method is shown in Fig. 1. The 2/2 sample has the midpoint transition temperature $T_c^{mid}=58$ K and the onset transition temperature $T_c^{onset}=83$ K, and above T_c^{onset} the resistivity increases linearly with temperature. These results are consistent with those reported by other groups.[12] For the 2/6 sample, $T_c^{mid}=33$ K and $T_c^{onset}=67$ K; above T_c^{onset} the resistivity decreases with increasing temperature. The 2/8 sample is nonsuperconducting and its resistivity decreases when temperature increases. From the above results, it can be seen that, under the conditions of our laser ablation, when the thickness of the Pr layers is increased, the transport properties of the samples change. This may result from modification of the YBCO layers by partial substitution

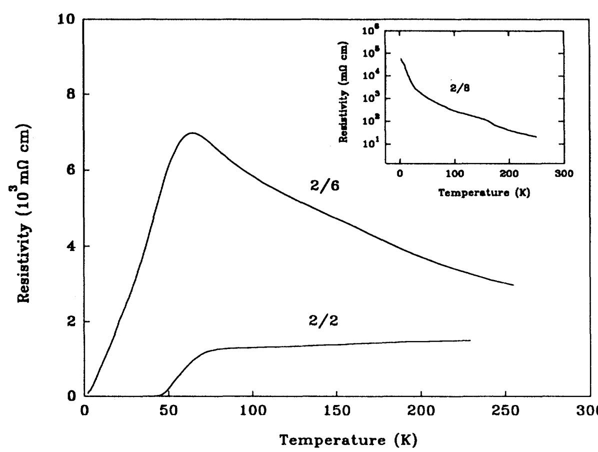

FIG. 1. Temperature dependence of resistivity in the superlattice samples 2/2, 2/6, and 2/8.

0163-1829/95/51(10)/6751(3)/$06.00

of Pr for Y, the less sharp border between YBCO and PrBCO layers, or charge transfer.[13–17] The details will be published elsewhere.[18] So the $1/f$ noise in the superlattice samples with thicker Pr layers might not reflect the behavior of the ultrathin YBCO film. However, the $1/f$ noise measurement in this sample may be a help to establish the reliability of the noise measurement of the 2/2 sample.

The normalized noise power spectral densities (PSD's) S_V/V^2 of the 2/2, 2/6, and 2/8 samples at room temperature are shown in Fig. 2, in which $S_V/V^2 \propto f^{-\gamma}$, and γ is about 1.1, within the range of $1/f$ noise.[19] The PSD increases as the thickness of the Pr layers increases.

In Fig. 3, we plot the PSD (S_V) of sample 2/2 as a function of the square of the dc voltage (V^2) over it. The linear behavior indicates that the noise we measured results from conductance fluctuation, and the heating effect is negligible.[5]

The 10-Hz normalized PSD's of the 2/2 sample in a temperature range of 100 to 300 K are shown in Fig. 4. The noise level varies weakly with temperature.

Since the ratio of the sample thickness to its length is extremely small, only about 10^{-5}, and the voltage contacts, near the middle of the sample, are far away from the current contacts at the edge, the YBCO and PrBCO layers in the superlattice can be considered electrically parallel connected.[17] If we assume the Y layers and Pr layers are independent parallel noise sources, because the conductivity of the Pr layers is at least two orders of magnitude lower than that of the Y layers, the $1/f$ noise of the superlattice is dominated by the Y layers.[9]

The $1/f$ noise power of a material is usually expressed by the empirical formula of Hooge, Kleinpenning, and Vandamme:[19] $S_V(f)=\alpha V^2/(n\Omega f)$, where n is the carrier density, Ω is the sample volume, and the dimensionless constant α has a value of the order of 10^{-2}–10^{-4} in clean metals.[7,19] The reported experimental data displayed high $1/f$ noise level in high-temperature superconductors, indicated by a very large α value when compared with metals: 10^5–10^7 for YBCO bulk samples[1] and 10^3–10^4 in YBCO single crystals.[8] For YBCO thin film, the α value is of order 10^3–10^5.[4,6] The YBCO/PrBCO superlattice 7/3 had an α value of 10^3.[9] The lowest α value in the YBCO system, reported by Liu *et al.* in fine-quality YBCO thin films,[7] is about 14.

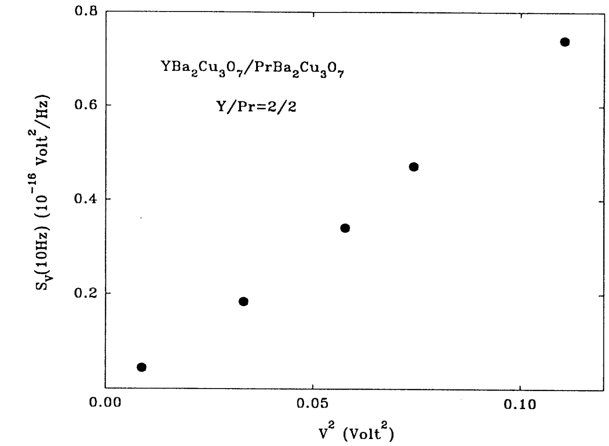

FIG. 3. Noise power spectral density S_V (at 10 Hz) of the 2/2 sample at room temperature as a function of the square of the dc voltage (V^2) over the sample. The linear relation means that the voltage fluctuation results from the fluctuation of the conductance and the heating effect is negligible.

The n value can be evaluated from the Hall number per unit-cell volume $V/(R_H e)$. For YBCO in the fully oxygenated state, $V/(R_H e)$ is close to 1, or $n=5.75\times10^{21}/\mathrm{cm}^3$.[7] For the superlattice YBCO/PrBCO, Matsuda *et al.*[20] have found that, in 1/1, 1/2, and 1/4 samples in temperature range of 100 to 300 K, $V/(R_H e)=0.5$–1.2, or $n=(2.8$–$6)\times10^{21}/\mathrm{cm}^3$. Affront *et al.*[21] studied 8/8, 3/3, 2/2, and 1/1 samples and obtained n values of $(4$–$10)\times10^{21}/\mathrm{cm}^3$. In the study of the $1/f$ noise of single-crystal YBCO, Song *et al.*[8] chose $n=2\times10^{21}/\mathrm{cm}^3$. We selected the n value to be $2.8\times10^{21}/\mathrm{cm}^3$ in the YBCO/PrBCO superlattice 7/3.[9]

For the 2/6 and 2/8 samples, as we mentioned above, the $1/f$ noise behavior cannot be regarded simply as that of the YBCO layer and it is difficult to chose the n and Ω values in the formula of Hooge, Kleinpenning, and Van-

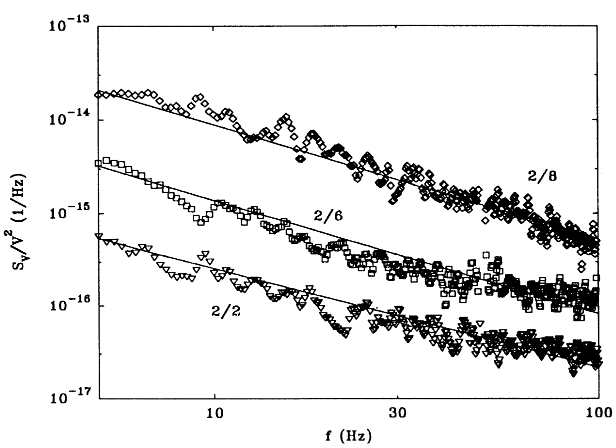

FIG. 2. $1/f$ noise power spectra of the 2/2, 2/6, and 2/8 samples at room temperature.

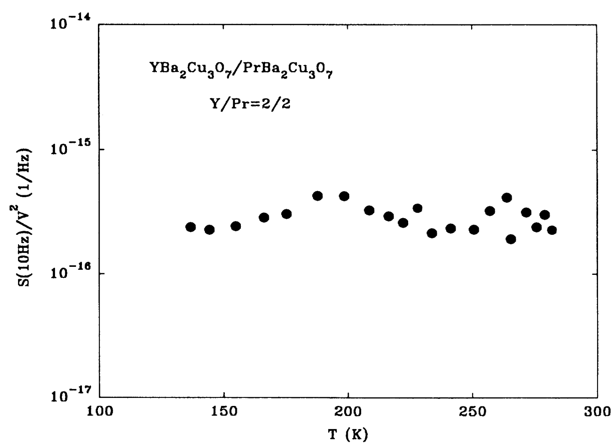

FIG. 4. Normalized noise power spectral densities of sample 2/2 at different temperatures.

damme, so we only estimate the α value of the 2/2 sample here. If we choose $n=5.75\times10^{21}/\text{cm}^3$, the α value at room temperature will be 1.4. If we consider the charge-transfer effect and the T_c depression in the sample, and choose $n=2\times10^{21}/\text{cm}^3$, then the estimated α value of the samples will be 0.5. This result is the lowest one reported in the normal state of the YBCO system to our knowledge, only two orders of magnitude greater than in metal films and semiconductors.[19]

Liu *et al.*[7] have studied the normal-state $1/f$ noise in YBCO films as a function of oxygen content x, and found that the normalized noise power has a sharp minimum at $x=6.5$. They attribute this behavior to vacancy creation in the Cu-O chains and suggest that the chains are the primary source of resistance fluctuations. Their model can also explain the significantly lower normal-state $1/f$ noise magnitude in $Tl_2Ba_2CaCu_2O_8$ films. Our 2/2 sample, as mentioned above, was prepared under the conditions for oxygen-rich YBCO and, furthermore, a study on the thermoelectric power (TEP) of the same sample[18] shows that the TEP has a slightly positive slope $dS(T)/dT$, like that in oxygen-rich YBCO samples.[17,18] All this suggests that the Cu-O chains in the YBCO layers of our sample are most likely fully oxygen occupied. Moreover, according to the Cu-O chain model, merely reducing the thickness of the Y layer cannot cause obvious decrease of the noise level. So vacancy creation in the Cu-O chains might not be the main reason for the tremendous decrease in noise level in the 2/2 sample.

In order to explain the abnormally large $1/f$ noise in YBCO and $ErBa_2Cu_3O_{7-\delta}$ (ErBCO) bulk samples, Testa *et al.*[1] proposed a possible model that the noise comes from the large anisotropy of conduction in copper oxide and a reduced number of charge carriers involved in the interplane conduction process causes an enhanced contribution to the noise. In our 2/2 superlattice, the ultrathin Y layer reduces the contribution of the interplane conduction processes to the noise; this might be one of the reasons that its $1/f$ noise level is much lower than in YBCO thin films and superlattices with thicker YBCO layers.

In their study of the $1/f$ noise in InO_x, Cohen, Ovadhayu, and Rokni[22] found that high noise level occurs in materials near the metal-insulator transition region. With the percolation picture of variable-range hopping in the Mott regime, Feng, Pichard, and Zeng[10,11] estimated the α value due to moving impurities to be $(\xi_p/a)^3$, where a is the lattice constant, which is of the order of a few angstroms, and ξ_p is a percolation correlation length, which can be much greater than the lattice constant. When the thickness of the sample is reduced to less than ξ_p, $\alpha\sim(\xi_p/a)^2$ and, as a result, the noise level will decrease tremendously. Since the YBCO material is close to a metal-insulator transition by virtue of correlation,[10,11] this dimension effect might be one of the possible reasons for the very low noise level in the 2/2 sample.

In summary, we have studied the normal-state $1/f$ noise in YBCO/PrBCO superlattices with an only two-unit-cell-thick YBCO layer in one period. The noise level we obtained is the lowest one in the YBCO system to our knowledge. Possible mechanisms were discussed. It might be helpful to understand the origin of the high $1/f$ noise level in high-T_c oxide superconductors.

The authors gratefully acknowledge discussions with Professor Shechao Feng in UCLA. This work is supported by the Doctoral Foundation of the Chinese Education Commission and the National Center for R&D on Superconductivity of China.

*Present address: Department of Applied Physics, Nanjing University of Science and Technology, Nanjing, 210014, P. R. China.

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

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

[3]A. Maeda, H. Watanabe, I. Tsukada, and K. Uchinokura, Physica C **185**, 1301 (1991).

[4]A. Misra, Y. Song, P. O. Crooker, J. R. Gaines, and A. H. Cardona, Appl. Phys. Lett. **59**, 863 (1991).

[5]Y. Song, A. Misra, Y. Cao, A. Querubin, Jr., X. D. Chen, P. P. Crooker, and J. R. Gaines, Physica C **172**, 1 (1990).

[6]Liu Sangtian, Yu Qishan, Xiong Guangcheng, Lian Guijun, Li Jie, Li Guohong, and Yan Shousheng, Chin. J. Low Temp. Phys. **16**, 138 (1994).

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

[8]Y. Song, A. Misra, P. P. Crooker, and J. R. Gaines, Phys. Rev. Lett. **66**, 825 (1991).

[9]Sangtian Liu, Guangcheng Xiong, Guoliang Liu, Guijun Lian, Guohong Li, and Shousheng Yan, Solid State Commun. **89**, 507 (1994).

[10]S. Feng and J.-L. Pichard, Phys. Rev. Lett. **67**, 753 (1991).

[11]S. Feng, J.-L. Pichard, and F. Zeng, Phys. Rev. B **48**, 2529 (1993).

[12]Q. Li, X. X. Xi, D. Wu, A. Inam, S. Vadlamannati, W. L. McLean, T. Venkatesan, R. Ramesh, D. M. Hwang, J. A. Martinez, and L. Nazar, Phys. Rev. Lett. **64**, 3086 (1990).

[13]Eric E. Fullerton, J. Guimpel, O. Nakamura, and Ivan K. Schuller, Phys. Rev. Lett. **69**, 2859 (1992).

[14]R. F. Wood, Phys. Rev. Lett. **66**, 829 (1991).

[15]M. Rasolt, T. Edis, and Z. Tesanovic, Phys. Rev. Lett. **66**, 2927 (1991).

[16]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).

[17]Guoliang Liu, Guangcheng Xiong, Guohong Li, Guijun Lian, Ke Wu, Sangtian Liu, Jie Li, and Shousheng Yan, Phys. Rev. B **49**, 15 287 (1994).

[18]Guoliang Liu, Min Wang, Guijun Lian, Guohong Li, Sangtian Liu, Guangcheng Xiong, and Shousheng Yan (unpublished).

[19]F. N. Hooge, T. G. M. Kleinpenning, and L. K. J. Vandamme, Rep. Prog. Phys. **44**, 31 (1981).

[20]Y. Matsuda, S. Komiyama, T. Terashima, K. Shimura, and Y. Bando, Phys. Rev. Lett. **69**, 3228 (1992).

[21]M. Affronte, J.-M. Friscone, O. Brunner, L. Antognazza, L. Miéville, M. Decronex, and Ø. Fischer, Phys. Rev. B **43**, 11 484 (1991).

[22]O. Cohen, Z. Ovadyahu, and M. Rokni, Phys. Rev. Lett. **69**, 3555 (1992).