Analysis of fluctuation conductivity of $YBa_2Cu_3O_{7-\delta}$-$PrBa_2Cu_3O_{7-\delta}$ superlattices

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The fluctuation-induced conductivity measured on $YBa_2Cu_3O_{7-\delta}$-$PrBa_2Cu_3O_{7-\delta}$ superlattices (SL) is analyzed using various theoretical models describing weak fluctuations in layered superconductors and considering both Aslamazov-Larkin (AL) and Maki-Thompson (MT) terms. From the analysis $\xi_c(0)=1.6\pm0.1$ Å and $\tau_\phi(100\ \mathrm{K})\simeq3\times10^{-13}$ s in clean limit are derived for the interlayer coherence length and temperature-dependent phase-relaxation time, respectively. Large τ_ϕ values and AL-MT crossover revealed for all samples studied are attributed to the two-dimensional electronic state nature of SL above the crossover temperature. Possible mechanisms of charge scattering in high-T_c superconductors are also discussed. [S0163-1829(97)04009-5]

I. INTRODUCTION

To account for the physical nature of high-T_c superconductivity different theoretical models covering strong correlation of charge carriers,[1] mixture of s-wave and d-wave pairing[2] and Fermi-liquid or non-Fermi-liquid behavior of high-T_c superconductors (HTSC's),[3] etc., have been widely discussed over the last few years. Nevertheless, the coupling mechanism related to this superconductivity still remains controversial. It is now quite clear, however, that proper understanding of the normal-state properties of HTSC's is of primary importance in deciphering their unique behavior in the superconducting state.[3–7] The investigation of the fluctuation-induced conductivity is regarded as one of the experimentally accessible methods just shedding light on the transport properties of high-T_c oxides in the normal state. Just above transition temperature T_c but outside of the critical region, resistivity $\rho(T)$ is affected by superconducting fluctuations resulting in noticeable deviation of $\rho(T)$ down from its linear dependence at higher temperatures. Thus there appears a fluctuation-induced conductivity,

$$\sigma'(T)=[\rho_N(T)-\rho(T)]/[\rho_N(T)\rho(T)], \tag{1}$$

where $\rho(T)$ is the actually measured resistivity and $\rho_N(T)=aT+b$ is the extrapolated normal resistivity. Unfortunately, this physically reasonable determination of $\rho_N(T)$ has not yet been theoretically justified.

Two forms of fluctuation contributions to $\sigma'(T)$ are usually considered. The direct Aslamazov-Larkin (AL) contribution arises from excess current carried by fluctuation-created Cooper pairs above T_c.[8] The additional, indirect Maki-Thompson (MT) contribution reflects the influence of superconducting fluctuations on the conductivity of normal electrons.[9] In layered structures such as high-T_c superconductors the AL term is described by a Lawrence-Doniach (LD) model[10] and predicts a crossover from three dimensional (3D) electronic state of the system to a two dimensional one (2D) with increasing temperature. The AL term dominates close to T_c whereas the MT term turns out to be dependent on phase-relaxation time τ_ϕ and gains importance in 2D fluctuation region in the case of moderate pair-breaking.[11] The crossover should occur at $\xi_c(T)\simeq d/2$, where ξ_c is the coherence length along the c axis and d is the distance between conducting layers. Consequently, measurements of fluctuation conductivity provide a sufficiently simple method of getting reliable information about $\xi_c(0)$, τ_ϕ, and dimensionality of the electronic system of the superconductor. In view of a very short Ginzburg-Landau coherence length $\xi_{\mathrm{GL}}(0)$ in high-T_c oxides $\sigma'(T)$ should be observed at temperatures well above T_c. Therefore, evaluating the fluctuation contribution the predominant scattering mechanism can also be investigated. The crossover phenomena analyzed in terms of the LD model have been reported by many research groups but the MT contribution was found to be uncertain[12,14–17] thus excluding the possibility to evaluate τ_ϕ.

Applying a magnetic field **H**, the analysis of a fluctuation-induced magnetoresistance gives further information about the scattering mechanism in HTSC's. A general theory being valid both in absence and presence of applied magnetic field has been developed by Hikami and Larkin (HL).[11] Aronov, Hikami, and Larkin (AHL)[18] extended the theory to incorporate the Zeeman effect. Both MT-orbital and MT-Zeeman terms were found to be strongly dependent on τ_ϕ.[13,15]

The evaluation of τ_ϕ in comparison with transport relaxation time τ measured by electrical conductivity, is a principal contribution to understanding the physics of the transport properties. Whether $\tau_\phi>\tau$ or $\tau_\phi\approx\tau$ is important in view of the controversy over the Fermi-liquid or non-Fermi-liquid nature of the electronic state in HTSC's.[3,5,19,20] Matsuda *et al.*[13] were the first to analyze their magnetoresistance data on $YBa_2Cu_3O_{7-\delta}$ films in terms of AHL theory. Significant contribution of the MT mechanism was found assuming τ_ϕ to be temperature dependent, $\tau_\phi \sim 1/T$. From the fit the phase relaxation time was estimated as $\tau_\phi \approx 1\times10^{-13}$ s at 100 K suggesting that scattering rate $\hbar/\tau_\phi \approx \hbar/\tau \simeq 0.7k_BT$. On the other hand, $\tau_\phi = (1.2-1.4)\times10^{-13}$ s measured on single crystals was reported by Winzer and Kumm.[15] Bieri and Maki[21] and Bieri, Maki, and Thompson (BMT)[22] extended AHL theory taking the clean limit into account. They reanalyzed the data of Matsuda *et al.* both in dirty and clean limits, and found $t \equiv \tau_\phi/\tau = 4$ and $t = 2.7$, respectively. However, the issue has not been experimentally confirmed.[23]

As magnetic field might somehow affect results in the fluctuation region investigation of the fluctuation conductivity (with $\mathbf{H}=0$) has apparent advantages over the magnetoresistance approach but in previous measurements the MT term has never been distinctly observed neither on films nor in single crystals. Measuring of $\sigma'(T)$ on $YBa_2Cu_3O_{7-\delta}/PrBa_2Cu_3O_{7-\delta}$ (YBCO/PrBCO) superlattices[24] enabled us to reveal an evident MT contribution and to obtain information on τ_ϕ. But only preliminary results have been briefly reported.[24,37]

In this paper our further investigations of resistivity and $\sigma'(T)$ on high-quality YBCO/PrBCO superlattices with different periodicity are reported. Using measured τ_ϕ, found to be in a good agreement with BMT theory in the clean limit, possible scattering mechanisms in the normal state are discussed.

II. EXPERIMENTAL APPROACH

The electronic properties of high-T_c superconductors are usually attributed to their layered structure in which electrically conducting CuO planes are intercalated by various subunits acting as charge reservoirs. The layered structure is also believed to be responsible for a large anisotropy of their normal- and superconducting-state properties. Therefore, the investigation of the artificially layered superlattices such as $YBa_2Cu_3O_{7-\delta}/PrBa_2Cu_3O_{7-\delta}$ (YBCO-PrBCO) has the complementary advantages in offering the possibility to modify the anisotropy in a controlled way by successively modifying the individual thicknesses of the layers. Recent progress in thin film preparation technology[25,26,29] makes high-quality superlattice thin films available for detailed analysis. Different properties of SL are being widely investigated[27,30,28] although, no results concerning the fluctuation conductivity in SL have yet been reported by other groups.

In the present work, superlattices with 7Y×7Pr, 7Y ×14Pr, and 4Y×1Pr layer periodicity Λ (samples S1, S2, S3) have been analyzed. The total number of Λ is 20 for all samples. Only the YBCO layers were taken into account in calculating $\rho(T)$. X-ray and Raman-scattering analysis shows that all samples are excellent SL with the c axis perfectly oriented perpendicular to the layer planes. As a reference and to compare the fluctuation conductivity results with literature data a single layer YBCO film was also tested. All samples have been grown on $SrTiO_3$ (100) substrates by pulsed laser ablation, lithographically patterned and chemically etched into well-defined 1.68×0.2 mm^2 Hall-bar structures.[29] To get the resistivity data standard four-probe dc measurements have been performed using a fully computerized setup.

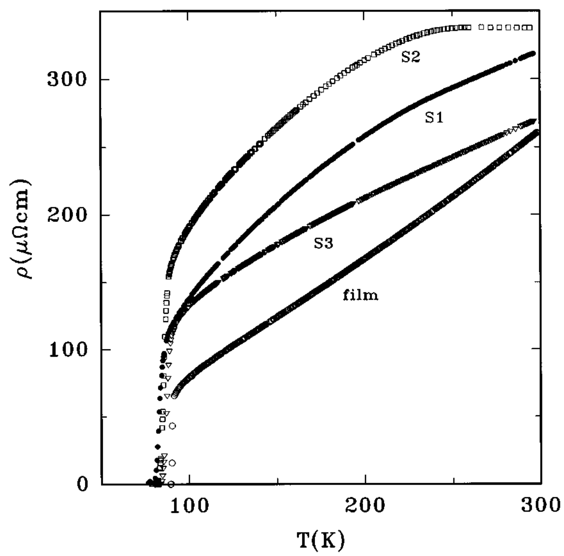

FIG. 1. Resistivity as a function of temperature for the samples S1 (solid circles), S2 (squares), S3 (triangles down), and reference film (circles). To clarify the picture the data for S3 are multiplied by 0.84.

III. RESULTS AND DISCUSSION

A total of nine superlattices with different layer composition were measured. Usual diminution of T_c with increasing the number of PrBCO layers[27,28] was found. Moreover, the significant reduction of T_c is always followed by nonmetallic resistivity temperature dependence. Naturally, to be analyzed in terms of fluctuation conductivity only samples with metallic $\rho(T)$ dependence were chosen. To obtain more information the samples with $\rho(T)$ close to the film resistivity curve (S3—4Y×1Pr), with $\rho(T)$ close to nonmetallic dependence (S2—7Y×14Pr) and the symmetrical one (S1—7Y ×7Pr) with $\rho(T)$ being almost in the middle between the film resistivity and nonmetallic region (Fig. 1), have been eventually analyzed. Figure 1 shows resistivity temperature dependence for all samples studied. The reference film exhibits almost linear $\rho(T)$ dependence typical for Y-123 systems in their optimal oxygen doping (i.e., maximum T_c) region.[20] In contrast with the film, resistivity curves of SL were found to have excessive resistivity and to show pronounced negative buckling below a representative temperature $T^* \sim 250$ K but to remain linear above T^* at least up to ~ 400 K (Fig. 1, samples S1 and S3).

This T-linear resistivity has attracted much attention as a possible indication of specific normal metallic state in this class of materials. However, the interpretation of the scattering mechanism causing the linearity is still controversial. In ordinary Fermi liquid theory electron-phonon scattering gives a T-linear resistivity $\rho(T) \sim \tau^{-1}(T)$, and assuming $k_BT \geqslant \hbar\omega_D$ the scattering rate can be described by[31]

$$\hbar\tau^{-1} = 2\pi\lambda k_BT, \tag{2}$$

where λ is the coupling constant and ω_D is the Debye frequency. At the same time scattering by electrons gives a T^2-dependence of the scattering rate and definitely requires some additional mechanism (d-wave pairing for example[32]) to transform this T^2 dependence into the linear one. Thus, at the first glance the phonon-limited resistivity in high-T_c oxides seems to be more appropriate. However, there are many doubts that solely phonons are able to provide the superconducting coupling at such high temperatures[20] and the problem remains questionable.

In metals, including conventional superconductors, where the electron-electron interaction is neglected, $\rho(T)$ is to be described by a Bloch-Gruneisen (BG) formula[33] giving approximately linear ρ vs T dependence down to $T\approx 0.25\Theta$. Here, $\Theta\approx 400$ K (for YBCO) denotes an effective ''transport'' Debye temperature.[20] However, Fig. 1 convincingly shows that the BG formula does not meet the case for superlattices at least as $T\leqslant T^*$. Appropriate derivatives, $d\rho/dT$, reveal sharp change of the slopes around T^* suggesting the change of the scattering mechanism at T^*.

We have made an attempt to attribute revealed ρ vs T behavior to additional scattering of the charge carriers between YBCO and PrBCO stacks due to size-effect.[24] A good qualitative agreement of $\rho(T)$ dependence with Fuchs-Sondheimer theory for size-effect contribution to the resistivity[34] was found for S1 taking into account the multiple connected PrBCO layers certainly affecting the conductivity above ~150 K. However, more detailed analysis of other samples has clearly shown that more elaborate theory is required to describe a size-effect in HTSC's.

Thus, considering the ρ vs T linearity at high temperatures to be the intrinsic normal-state property of high-T_c YBCO superconductors we have computed $\sigma'(T)$ as mentioned above [see Eq. (1)]. The experimental $\sigma'(T)$ data were analyzed using the HL theory[11] including both AL and MT contributions. In absence of the magnetic field

$$\sigma'_{\mathrm{AL}}=\{e^2/[16\hbar d\epsilon]\}\{1+[2\xi_c(0)/d]^2\epsilon^{-1}\}^{-1/2} \qquad (3)$$

and

$$\sigma'_{\mathrm{MT}}=\{e^2/[8\hbar d(1-\alpha/\delta)]\}\ln\{(\delta/\alpha)[1+\alpha+(1+2\alpha)^{1/2}]/[1+\delta+(1+2\delta)^{1/2}\}\epsilon^{-1}, \qquad (4)$$

where $d=11.7$ Å is the interlayer periodicity, $\alpha=[2(\xi_c(0)/d)^2]\epsilon^{-1}$ is a coupling parameter and $\delta_{\mathrm{HL}}=(16/\pi\hbar)[\xi_c(0)/d)]^2k_BT\tau_\phi$. Outside the critical region $\sigma'(T)$ is the function of $\epsilon(T)=(T-T_c)/T_c$ which denotes the reduced temperature and T_c is the mean-field transition temperature. Here T_c is defined as the temperature at which $d\rho/dT$ versus T shows a maximum or ρ versus T has its inflection point.[16]

Equation (3) reproduces result of the LD model[10] considering the presence of Josephson-like interaction between the conducting layers since $\xi_c(T)>d$ close to T_c (3D region), whereas the MT term gains importance in the case of $k(T-T_c)\gg\hbar/\tau_\phi$, where $\xi_c(T)<d$ (2D region).[11] Thus the HL theory predicts both 3D-2D and AL-MT crossovers as temperature increases but the last one has never been observed before. The 3D-2D crossover should occur at the temperature

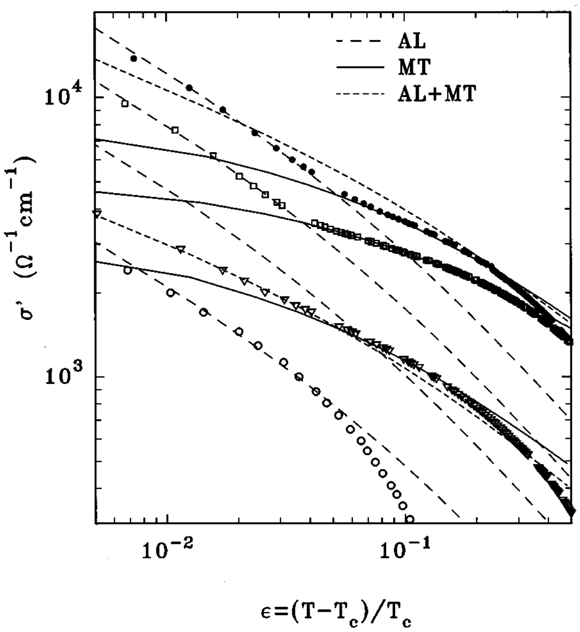

FIG. 2. Fluctuation conductivity as a function of reduced temperature for the samples S1 (solid circles), S2 (squares), S3 (triangles down), and reference film (circles) compared with appropriate terms of the HL theory in the clean limit.

$$T_0=T_c\{1+[2(\xi_c(0)/d)]^2\} \qquad (5)$$

at which $\alpha=1/2$, i.e, $\xi_c(0)=(d/2)\sqrt{\epsilon_0}$. The crossover from AL to MT contribution should occur at $\delta\simeq\alpha$. It leads to the crossover temperature

$$\epsilon_0=(\pi\hbar)/(8T\tau_\phi). \qquad (6)$$

No significant difference between both crossover temperatures is predicted.[11] As mentioned above, Bieri, Maki, and Thompson[22] extended the theory to incorporate the clean limit approach. But when $\mathbf{H}=0$ the only difference with the HL theory is that $\delta_{\mathrm{BMT}}=1.203(l/\xi_{ab})\delta_{\mathrm{HL}}$, assuming nonlocal effects[22] can be ignored.

Figure 2 shows experimental data of $\sigma'(\epsilon)$ for all SL and reference film compared with the MT (solid lines) and the AL (long dashed lines) terms of HL theory extended to the clean limit. Close to T_c the data for S1 (solid circles) and S2 (squares) fit the AL terms fairly well, whereas S3 (triangles down) can be fitted only by the summary AL+MT curve (dashed line) being typical for twinned films[17] and single crystals.[15] But above T_0 all the data for SL fit the MT terms extremely well. Thus, as predicted by the theory, an evident AL-MT crossover is revealed for S1 and S2 as temperature increases. S3 exhibits somehow other behavior, being intermediate between films and SL, and suggesting a presence of interlayer interaction between YBCO via thin PrBCO layers but the AL-MT crossover is quite discernible on the plot. The result is found to be different from that observed in the film showing an ordinary $\sigma'(\epsilon)$ dependence (Fig. 2, circles) with usual divergence of the data down from the theoretical curve at $\epsilon\simeq 0.06$.[15,17]

Apart from other motives, observation of the crossover offers a possibility to determine T_0 and using Eq. (6) independently obtain credible values of $\xi_c(0)$, in this way no-

TABLE I. Characteristics of the samples.

Sample	ΔT_c (K)	T_c (K)	$\rho(100\ \text{K})$ ($\mu\Omega$ cm)	$d\rho/dT^{a}$ ($\mu\Omega$ cm K^{-1})	$n(100\ \text{K})$ ($10^{21}\ \text{cm}^{-3}$)	l(100 K) (Å)	$\mu(100\ \text{K})$ (cm^2/V s)
S1(7Y×7Pr)	3.8	82.4	118	0.48	1.9	120	50
S2(7Y×14Pr)	7.5	85	172	~0	2.8	90	38
S3(4Y×1Pr)	8.0	87.9	156	0.68			
Film (Ref. 13)	1.4	86.2	96	0.71	4.43	90	25

[a]For SL $d\rho/dT$ are measured in T-linear region above T^*.

ticeably reducing the number of fitting parameters. Actually, in AL fit only scaling C factors reflecting inhomogeneous current distribution in the samples[14] have been used. To provide MT fit only C factors and appropriate values of $\tau_\phi(T)\sim T^{-1}$ should be put into consideration as fitting parameters. As result, from the MT fit $C=1.8$, $\tau_\phi(100\ \text{K})=2.7\times10^{-13}$ s ($t=2.5$)—S1; $C=2.9$, $\tau_\phi(100\ \text{K})=0.6\times10^{-13}$ s ($t=0.6$)—S2; and $C=0.4$, $\tau_\phi(100\ \text{K})=7\times10^{-13}$ s ($t=6.4$)—S3 are derived in the clean limit with $\tau=(1-1.1)\times10^{-13}$ s and $\xi_c(0)=1.6\pm0.1$ Å for all samples studied. The samples parameters compared with parameters of Matsuda *et al.*'s film[13] are listed in Tables I and II.

As far as the C factor is concerned, in previous studies on sintered samples[35] and thin films,[14] factors of $C<1$ were usually observed. In the case of single crystals[15] and high-quality epitaxial films,[13] however, $\sigma'(T)$ data are above the theory and to provide a fit factor $C\simeq1-1.6$ attributed to the high quality of the samples has to be used. In spite of good expected conducting quality of our samples the C factor in SL has to arise from obvious ambiguity of current distribution between the conducting layers leading to uncertainty in measured $\rho(T)$. Nevertheless, our symmetrical sample, S1, requires approximately the same factor, $C=1.8$, as the Matsuda *et al.*'s film. It also maintains $d\rho/dT\simeq0.48$ $\mu\Omega$ cm/K which is designated as an intrinsic property of Y-123 systems.[14,15] This is why we believe it to be the best sample to compare results on SL with those obtained from films and single crystals. As sample S2 shows, the more complicated is the scattering mechanism, resulting in enhanced resistivity, the larger is C factor and the smaller is τ_ϕ. Measured τ_ϕ, however, is comparable with that obtained by Sugawara *et al.*[23] using $C=3.5$ for the fit. As sample S3 is concerned, we think there is no essential physics behind observed high τ_ϕ and attribute it to the influence of additional interaction via thin PrBCO stacks. As pointed out by Triscone *et al.*[30] the conducting layers in SL can be considered well separated only when thickness of intermediate PrBCO layers $d_n\geqslant48$ Å.

TABLE II. Characteristics of the samples.

Sample	ξ_c (Å)	$\tau_\phi(100\ \text{K})$ (10^{-13} s)	C	λ_{ep}	m_{ab}/m_0
S1	1.7±0.1	2.7±0.1	1.8	0.11	3.5
S2	1.6±0.1	0.7±0.1	2.9	0.2	4.3
S3	1.5±0.1	6.0±0.1	0.4		
Film (Ref. 13)	1.6±0.3	1.0±0.1	1.6	0.12	4.8

Taking all these considerations into account and based on the experiment, $t=2.5$ is derived for S1 in the clean limit. The result is very close to the designated above theoretical estimation, $t=2.7$.[22] Moreover, the measured values of $\xi_c(0)=1.6\pm0.1$ Å are in good agreement with the results of Matsuda *et al.*[13] and Winzer and Kumm.[15] Thus, 7Y×7Pr SL provides an extremely good fit with both HL and BMT theories and $\tau_\phi\simeq2.7\times10^{-13}$ s, which is approximately 3 times larger than that observed on films and single crystals, has been experimentally confirmed in the clean limit. This implies that

$$k_BT\simeq4\hbar/\tau_\phi \tag{7}$$

which indicates the absence of significant pair breaking in homogeneous YBCO, in the clean limit, and yields $\lambda_{\text{cor}}\simeq0.04$ within weak-coupling theory [Eq. (2)]. Here the coupling constant is considered to reflect specific superconducting correlation in HTSC's, as will be discussed below.

Before proceeding with the consequences of a small λ value let us discuss the observed crossover (Fig. 2) in terms of dimensionality of the samples electronic system. Below the crossover temperature T_0 the $\sigma'(T)$ data (Fig. 2) are found to follow the LD model considering the conducting layers to be coupled by means of Josephson-like tunneling interaction. In this temperature region $\xi_c(T)>d$ and observed $\sigma'_{\text{AL}}(T)$ dependence, with slope close to 0.5 being typical for this kind of measurements,[14,15,35] can be taken as evidence for 3D conductivity. No clear influence of the MT fluctuation mechanism in this temperature range is observed. At the same time above T_0 the $\sigma'(T)$ is reproduced quite well by the HL (BMT) theory considering the MT term only. No presence of the AL contribution is observed as well. We have also failed with attempts to fit the data with summary AL+MT curve (Fig. 2, dashed line). This is surprising as the basic AL fluctuation mechanism is expected to be always present. That is why we consider the crossover only to reflect the significant change of interlayer interaction at $\xi_c(0)\simeq d$ resulting in the samples electronic system modification.

As pointed out by Xie,[5] when $\xi_c(0)\ll d$ above T_0, confined in CuO planes 2D conductivity characterized by enhanced anisotropy of electronic properties is realized. In this case the tunneling of the correlated pairs between conducting layers is incoherent and the Josephson current vanishes along the c direction. As a result, only the single-particle tunneling processes are available whereas the superconducting correlation enhances the conductivity in the ab plane. This consideration would imply that the observed $\sigma'_{\text{MT}}(T)$ dependence above T_0 can be taken as evidence for pronounced 2D conductivity affected by the superconducting correlation which is characterized by the phase-relaxation time, τ_ϕ. In SL this 2D fluctuation region is found to range over at least 20 K suggesting the presence of fluctuating pairs well above T_c, most likely due to enhanced electron-electron correlation in high-T_c oxides,[7] resulting in large observed τ_ϕ. That is why according to Eliashberg[7] the appropriate coupling constant, being determined by τ_ϕ, has been designated above as λ_{cor}.

Thus, predicted by the HL theory AL-MT crossover is found to be followed by change of the interlayer interaction type resulting in 3D-2D crossover also predicted by the theory. As a result, either fluctuation mechanism below and above T_0 appears to be quite different, in this way reflecting the intrinsic properties of high-T_c superconductors. We also believe the absence of evident AL contribution above T_0 definitely shows that usual fluctuation approach fails in this temperature region suggesting the necessity of additional theoretical consideration in the case of specific 2D conductivity in HTSC's. We would also like to emphasize that distinct observation of that 2D behavior is believed to be due to pronounced layered structure of measured SL offering an opportunity for very thin but homogeneous YBCO layers to be studied.

The implications of the short coherence length and the effective two dimensionality of the conductivity in $YBa_2Cu_3O_{7-\delta}/PrBa_2Cu_3O_{7-\delta}$ superlattices can now be examined. From the Hall-effect measurements the hole density per unit sell was found to be 0.33 (S1) which implies $n=0.33/V_0=1.9\times10^{21}$ cm^{-3}. With the corrected resistivity $\rho'=\rho/C\sim66$ $\mu\Omega$ cm at $T=100$ K for our best sample we obtain $\mu\approx50$ cm^2/Vs for the mobility of holes. From the relation $l=(\hbar\mu/e)(2\pi n_s)^2$ with $n_s=nd\approx2.22\times10^{14}$ cm^{-2} the mean-free path $l=v_F\tau$ of holes at 100 K is estimated to be $l\approx120$ Å. Thus, the expected inequality $l(100\text{ K})\gg\xi_{ab}(0)$ is to verify the above clean limit approach. Using the Fermi velocity of $v_F=1.1\times10^7$ cm/s estimated on single crystals[15] we have the transport scattering time of $\tau(100\text{ K})=l/v_F\approx1.1\times10^{-13}$ s and an effective hole mass of $m^*/m_0=e\tau/\mu m_0\approx3.5$ which both commonly occur.[13,15] For S2 $\tau(100\text{ K})\approx1.0\times10^{-13}$ s and $m^*/m_0\approx4.3$ are found. Both values of τ have been used in above analysis. The result implies that (S1)

$$k_BT\simeq1.44\hbar/\tau \tag{8}$$

and yields $\lambda_{ep}\simeq0.11$ within weak coupling theory [Eq. (2)] which is approximately a factor of two smaller than that obtained from resistivity and optical measurements on YBCO films and single crystals.[38]

Nevertheless, the result seems to be reasonable as τ^{-1} due to phonons is linear in temperature only if kT exceeds a characteristic energy scale of the phonons[20] as mentioned above. As was pointed out by Gorkov and Kopnin (GK),[4] in Y-123 systems T-linear resistivity could be well described by electron-phonon scattering with characteristic energy $\Theta_D\sim400$ K. On the other hand, it seems somehow unlikely because at $T\sim\Theta_D$ and $\lambda\sim1$ the electron-phonon scattering is to be highly inelastic and should give rise to resistivity saturation at these temperatures. But it is not the case for HTSC's suggesting weak electron-phonon coupling.[39] As a result an inequality $\lambda\leqslant\lambda_{eff}$ was found[4] where λ_{eff} denotes the slope of resistivity $d\rho/dT$, and can be written as

$$\lambda_{eff}=(\hbar\omega_p^2/8\pi^2)d\rho/dT. \tag{9}$$

Using the observed $d\rho/dT\simeq0.48$ $\mu\Omega$ cm/K for S1 and plasma frequency $\omega_p=2.3$ eV for Y-123 (Ref. 4) we obtain $\lambda_{eff}\simeq0.6$ from Eq. (10) in a good agreement with above analysis. On the other hand, in an electron-scattering-based model developed by Lee and Read[32] $\hbar/\tau$ several times kT was found implying $\lambda>1$ and yields a short inelastic lifetime which is attributed to pair breaking. Consequently, we believe the obtained results show the prevalence of phonon-scattering-based interaction in high-T_c YBCO oxides in the clean limit. But the coupling constant turns out to be rather small.

Taking all above results into account it seems rather attractive to make an assertion that in our best 7Y×7Pr SL (S1) rather homogeneous structure, resulting in observed enhancement of τ_ϕ due to presence of additional moderate electron-electron correlation, is realized. If this is really the case, estimated values of τ_ϕ and λ can be taken as intrinsic for pure YBCO. Actually, when structure inhomogeneity gives rise to some additional scattering (S2), $\tau_\phi=0.7\times10^{-13}$ and $\lambda_{ep}\approx0.2$, which both are common occurrences,[17,23] are immediately obtained. As $\tau_\phi<\tau$ no correlation contribution can be distinctly estimated in this case.

Thus, the above analysis evidently shows that, on the one hand, usual phonon-scattering-based Fermi liquid approach does not contradict with the experimental results but the coupling constant λ_{ep} turns out to be small. On the other hand, as pointed out by Iye,[20] if phonons are the only excitations coupled to electrons in any significant way, electron pairing at such high temperatures seems to be rather questionable. Moreover, it should be also noted that the above mentioned Xie's model is the electron-scattering-based one. Thus, measured small λ_{ep} evidently requires some modification of the electron-phonon coupling in HTSC's. As it has been recently pointed out by Eliashberg[7] the additional electron-electron correlation is to be certainly taken into consideration in this case and an effective coupling constant λ is to be written as $\lambda=\lambda_{ep}+\lambda_{cor}$. Using above estimates for S1, $\lambda\simeq0.15$ is found to be still rather small. But, as have been pointed out by Kulic̑ and Zeyher,[40] if electronic correlation in high-T_c oxides is taken into account, a significant reduction of the effective coupling constant is expected. If this is really the case, our results reflect enhanced electron-electron correlation in HTSC's. Eventually, it seems reasonable to conclude that electron-phonon coupling added by moderate electron-electron correlations should be taken into account to explain high-T_c superconductivity.

In conclusion, it was found that up to ~110 K $\rho(T)$ of high-quality YBCO-PrBCO SL is strongly affected by superconducting fluctuations. At higher temperatures the rearrangement of the weight of different scattering mechanisms is believed to be responsible for the shape of the resistivity curves until the sample becomes normal above T^*. From measurements of the fluctuation-induced conductivity $\sigma'(T)$, the AL-MT crossover attributed to enhanced 2D conductivity in SL above the crossover temperature has been observed. The observation enables us to determine

$\tau_\phi(100\ \text{K})\approx 2.7\times 10^{-13}$ s which is about $3\times\tau$, in good agreement with the clean limit theory, and thus to evaluate the correlation contribution to the scattering mechanism resulting in $\lambda_{\text{cor}}\simeq 0.04$. From transport measurements $k_B T\simeq 1.44\hbar/\tau$ is found giving $\lambda_{ep}\simeq 0.11$ and indicating the priority of phonon-scattering-based interaction in homogeneous Y-123 oxides. Nevertheless, in accordance with Eliashberg[7] both electron-phonon and electron-electron interaction do play a role in resulting scattering mechanism and the effective coupling constant should be written as $\lambda=\lambda_{ep}+\lambda_{\text{cor}}$. Summarizing the results we may conclude that electron-phonon coupling added by moderate electron-electron correlation should be taken into account to explain high-T_c superconductivity.

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