Mixed-state Hall-effect studies in high-T_c-superconducting $(YBa_2Cu_3O_{7-\delta})_n/(PrBa_2Cu_3O_{7-\delta})_m$ superlattices

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The mixed-state Hall conductivity behavior has been studied systematically on a series of superconducting $(YBa_2Cu_3O_7)_n/(PrBa_2Cu_3O_7)_8$ (here $n=3,8,16,24,45,60$) superlattices in three magnetic fields with $H\|c$ axis and $H\perp J$. It was found that the Hall sign anomaly diminishes and even disappears with the decreasing of the YBCO layer thickness, i.e., the increase of the anisotropy parameter ϵ, and the decrease of the pinning strength. The scaling relationship between the Hall resistivity ρ_{xy} and the longitudinal resistivity ρ_{xx}, i.e., $\rho_{xy}\propto\rho_{xx}^{\alpha}$ holds for all of the samples with various ϵ. This indicates that the anomalous Hall sign reversal is independent of the scaling law between ρ_{xy} and ρ_{xx}. The present work supports the Wang, Dong, and Ting theory which suggested that the mixed-state Hall sign anomaly originated from the backflow current due to the pinning force and the thermal fluctuations.

The study of the Hall effect, especially in the mixed state, plays an important role for the understanding of some aspects of superconductivity and vortex motion in type-II superconductors. The Hall resistivity in the mixed state has two evident properties. One is the sign reversal of the Hall resistivity when the temperature is decreased below T_{c0}, and the other is the pronounced scaling relationship between the Hall resistivity ρ_{xy} and the longitudinal resistivity ρ_{xx}, i.e., $\rho_{xy}\propto\rho_{xx}^{\alpha}$, here the theoretical value of the exponent α is about 2. The anomalous behavior of the Hall sign near T_{c0} has been observed widely in ceramics, single crystals as well as in epitaxial thin films of high-T_c superconductors[1–5] and even in some conventional low-T_c superconductors.[6–8] The scaling law has been found not only in YBCO,[9] but also in strongly anisotropic superconductors such as $Tl_2Ba_2Ca_2Cu_3O_{10}$.[10]

In response to this anomalous behavior of the Hall conductivity, various kinds of theoretical interpretation have been proposed. Freimuth, Hohn, and Galffy[11] attributed the sign reversal to the large thermomagnetic effect in the mixed state. Harris, Ong, and Yan[12] suggested that the sign reversal is a unique feature of vortices parallel to the *ab* plane, but, in fact, it can also be explained by anisotropic time-dependent Ginzburg-Landau (TDGL) theory.[13,14] Hagen *et al.*[15] argued that the sign reversal is due to the general properties of vortex motion. Moreover, Luo *et al.*[9] proposed that the scaling law of $\rho_{xy}\propto\rho_{xx}^{\alpha}$ is a result of vortex-glass transition. Several theoretical explanations have also been put forward. Ferrell[16] considered the effect of the opposing drift of thermal excited quasiparticles which collide quasiclassically with the hydrodynamic superfluid velocity field. His calculated Hall angle has sign opposite to that in the normal state. Dorsey[17] and Kopnin, Ivlev, and Kalatsky[18] showed that the Hall anomaly could be a consequence of the time-dependent Ginzburg-Landau (TDGL) theory. Meilikhov and Farzetdinova[19] interpreted the anomalous Hall effect based on the models of Bardeen and Stephen (BS) and Noziéres and Vinen (NV) models by considering Andreev reflection at the interface between the normal core and the superconducting periphery. Recently, Wang, Dong, and Ting[20] (WDT) have developed a unified theory for the flux motion, particularly for the mixed-state Hall effect in type-II superconductors based upon the normal core model of BS and by taking into account both the backflow effect and thermal fluctuations of the vortex. To explain the Hall sign reversal, the pinning force still plays an essential role, although the thermal fluctuations of the vortex have been taken into account in WDT theory. Budhani, Liou, and Cai[21] have studied the mixed-state Hall effect for different pinning strengths in $Tl_2Ba_2Ca_2Cu_3O_{10}$ samples by creating linear defects through irradiation of high-energy silver ions, and they argued that the sign reversal in ρ_{xy} at low magnetic field diminishes with increasing defect concentration, contrary to the theory of Wang and Ting (WT).[22]

However, in recent experiments of Samoilov *et al.*[23] where the authors investigated the mixed-state Hall effect in epitaxial $Tl_2Ba_2CaCu_2O_8$ thin films and $YBa_2Cu_3O_7$ single crystals before and after irradiation with high-energy Pb ions, the irradiation-induced columnar defects do not modify the behavior of the Hall conductivity, which is contrary to the result of Budhani, Liou, and Cai. In order to clarify the role of the pinning force acting in the interpretation of Hall sign anomaly in high-T_c superconductors, we have selected the $(YBCO)_n/(PrBCO)_m$ multilayer as candidates in which the pinning strength can be modified easily by

TABLE I. Transport properties of $(YBCO)_n/(PrBCO)_8$ multilayers. In calculation of ρ_{xy}, only the thickness of YBCO layers has been taken into consideration.

Sample specification	N	T_{c0} (K)	ρ_{xx} (300 K) $\mu\Omega$ cm	ρ_{xx}(300 K)/ρ_{xx} (100 K)	ρ_{xy} (95 K)/H $\mu\Omega$ cm T^{-1}	dn_H/dT 10^{19} cm^{-3} K^{-1}	ϵ^2
3:8	13	70	491.7	2.56	0.29	1.51	6400
8:8	11	75	430.5	2.76	0.30	2.12	144
16:8	9	88.5	673.2	2.2	0.31	1.32	44
24:8	8	89	427.8	2.26	0.10	5.58	28
45:8	5	90.5	586.3	2.19	0.20	2.29	25
60:8	4	90	515.2	2.23	0.16	3.95	25

adjusting the interplanar coupling between YBCO layers, i.e., by varying the modulation ratio $n:m$. The mixed-state Hall resistivity behavior has been studied systematically on a series of superconducting $(YBCO)_n/(PrBCO)_8$ ($n=3,8,16,24,45,60$) multilayers. One result is that the Hall sign anomaly changes (diminishes or even disappears) systematically with increasing anisotropy ϵ which corresponds to the decreasing of the pinning strength in $(YBCO)_n/(PrBCO)_8$ multilayers. The scaling law $\rho_{xy}\propto\rho_{xx}^{\alpha}$ holds always for all of the samples with various ϵ.

A series of high-quality c-oriented high-T_c superconducting $[(YBCO)_n/(PrBCO)_8]_N$ superlattices were prepared by sequential continuous high pressure d.c. sputtering onto heated (100)$SrTiO_3$ substrates in pure oxygen atmosphere ($P_{O_2}\approx 3$ mbar) from planar, stoichiometric $YBa_2Cu_3O_{7-\delta}$ and $PrBa_2Cu_3O_{7-\delta}$ targets as reported elsewhere.[24] The thicknesses of the films range between 200 and 300 nm. The repeated periods N have been summarized in Table I for each sample. All of the samples were characterized by x-ray diffraction (XRD) with good modulation structure. Other detailed superconducting properties as well as structural characteristics can be seen in Refs. 25 and 26.

The measurements of the longitudinal voltage V_{xx} and the Hall voltage V_{xy} as function of T in three magnetic fields ($H=1$, 3, and 5 T) were performed on six selected superlattices with modulation ratio 3:8, 8:8, 16:8, 24:8, 45:8, and 60:8, respectively. In our measurements, $H\|c$ axis and the current density J of about 500 A/cm^2, with $H\perp J$, was applied to the samples. The Hall voltage V_{xy} was obtained from the antisymmetric part of the transverse voltage under magnetic-field reversal.

In Table I we have given the critical transition temperature of zero resistance T_{c0} for each sample at zero field. T_{c0} was suppressed by decreasing the thickness of the superconducting YBCO layer. The resistivity at room temperature (about 300 K), ρ_{xx}(300 K) and the ratio of ρ_{xx}(300 K)/ρ_{xx}(100 K) are also given in Table I. There was no evident systematic change of these values related to the thickness of the YBCO layer. For all of the samples, ρ_{xx}(300 K)/ρ_{xx}(100 K) exceeds 2, which is larger than that reported by Affronte *et al.* and is very close to that of YBCO.[27] This very good metallic conductivity of ρ-T curves in the normal state indicates that the scatter by the interface is much less important in our multilayers.

The sharpness of the interface and its higher T_{c0} show that the samples which are investigated in our experiments do not consist of the $Y_{1-x}Pr_xBa_2Cu_3O_7$ alloy. Even if a little of $Y_{1-x}Pr_xBa_2Cu_3O_7$ is present in the interface, the Pr concentration x will not exceed 15%. This can be shown by the XRD studies[28] and TEM investigations[29] in YBCO/PrBCO superlattices. Therefore, what we will discuss below is different from the mixed-state Hall effect in $Y_{1-x}Pr_xBa_2Cu_3O_7$,[30,31] or the result of $Y_{0.5}Pr_{0.5}Ba_2Cu_3O_7$ reported by Affronte *et al.*,[27] since T_{c0} and ρ_{xx}(300 K)/ρ_{xx}(100 K) in our samples are far larger than that of $Y_{0.5}Pr_{0.5}Ba_2Cu_3O_7$.

The normal-state Hall resistivity ρ_{xy}/H as function of T for six samples is shown in Fig. 1. As the conductivity of $PrBa_2Cu_3O_7$ is much lower than that of $YBa_2Cu_3O_7$, here in the calculation of ρ_{xy}/H for the multilayer, only the thickness of $YBa_2Cu_3O_7$ layer has been taken into consideration. No evident systematic variation of ρ_{xy}/H related to the thickness of YBCO layers can be obtained from this figure. But the magnitude of ρ_{xy}/H for 3:8, 8:8, and 16:8 is obviously larger than that in 24:8, 45:8, and 60:8. The value of ρ_{xy}/H at 95 K was also shown in Table I. It is about 0.3 $\mu\Omega$ cm T^{-1} for these samples with a thinner YBCO layer, while it is in the range of 0.1 to 0.2 $\mu\Omega$ cm T^{-1} for those with a thicker YBCO layer. The increase of ρ_{xy}/H with the decreasing YBCO-layer thickness in YBCO/PrBCO superlat-

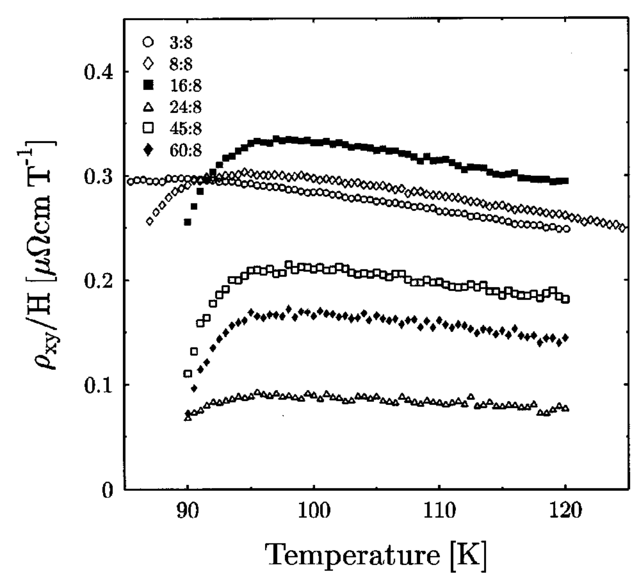

FIG. 1. Normal-state Hall resistivity as a function of temperature for six superlattices with different modulation ratio, there is no systematic change of ρ_{xy}/H related to the thickness of the YBCO layer.

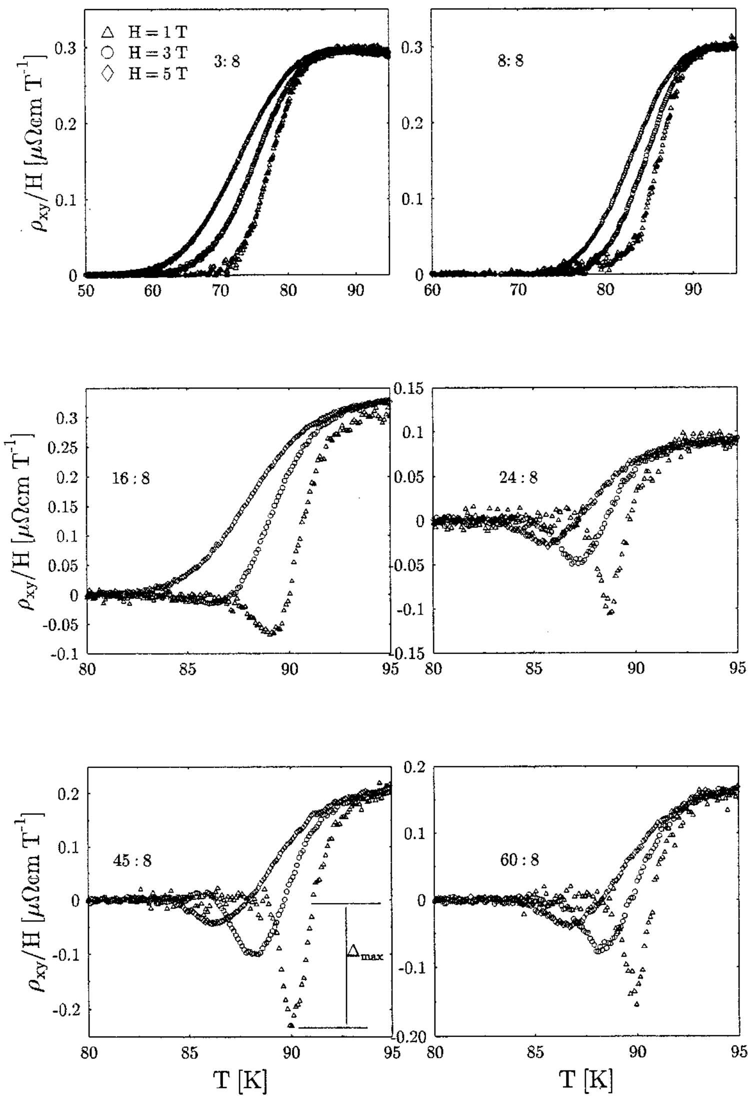

FIG. 2. ρ_{xy}/H vs T in three magnetic fields for six $(YBCO)_n/(PrBCO)_8$ superlattices with different unit cells of YBCO layer. No sign reversal in ρ_{xy} has been observed in samples 3:8 and 8:8. For 16:8 there is no Hall sign anomaly at $H=5$ T, but at $B=1$ and 3 T there is sign reversal present in ρ_{xy}. In other samples with a YBCO layer thicker than 24 u.c., their Hall resistivity behavior are just like that in pure YBCO thin films.

tices has also been reported by Affronte *et al.* Our results support the point of view proposed by Affronte *et al.* The increase of ρ_{xy}/H is related to the fact that the layer undergoes a mechanical strain that is only weakly thickness dependent for thin layers. This strain arises from the mismatch between the $YBa_2Cu_3O_7$ and $PrBa_2Cu_3O_7$ lattices. This strain may have an influence on the oxygen ordering in the $YBa_2Cu_3O_7$ layers and this may lead to a slightly different carrier concentration between multilayers with different modulation lengths. If we assume that $n_H=1/eR_H$ holds in the YBCO/PrBCO multilayer system, too, we find that the linearity of n_H-T is still valid for all of the samples. The slopes of the n_H-T curves are, however, different from sample to sample. The dn_H/dT values are also given in Table I. They are about 1.5 (10^{19} cm^{-3} K^{-1}) for the 3:8, 8:8, and 16:8 samples, while dn_H/dT is larger than 1.5 (10^{19} cm^{-3} K^{-1}) for 24:8, 45:8, and 60:8. However, there is no evident systematic change in them, either. We admit that T_{c0} might be related to n_H, but there is no certain connection between them, since ρ_{xy}/H and dn_H/dT differ from one sample to another, but their T_{c0} are almost the same (about 90 K) at least for those samples with the thicker YBCO layer.

However, the mixed-state Hall resistivity changes more systematically in relation to the layer thickness and they are shown comparatively in Fig. 2 at the three magnetic fields. Clearly, for samples 24:8, 45:8, and 60:8, when T is decreased below their individual T_{c0}, ρ_{xy} changes from positive to negative, i.e., there exists a so-called sign reversal of ρ_{xy}. For 16:8, there also exists a sign reversal at low magnetic fields ($H=1$ and 3 T) but the Hall sign anomaly is diminished compared with that in 24:8, 45:8, and 60:8, i.e., the maximum magnitude of the negative ρ_{xy},$\Delta_{\max}$, defined as that shown in Fig. 2, becomes smaller. At $H=5$ T, the Hall sign anomaly has simply disappeared. In 3:8 and 8:8, no sign reversal has been observed at three magnetic fields within the experimental accuracy. Therefore, this systematic change of Hall sign related to the layer thickness of YBCO must reflect some important features in the mixed state, and therefore gives some information on the origin of Hall sign reversal in the high-T_c superconductors.

Li *et al.*[32] found that the characteristics of the magnetic field and angular dependence of the critical current density crosses from three dimensions to two dimensions by increasing the temperature from below to above the T_c^{in} of the intercalating $Pr_xY_{1-x}Ba_2Cu_3O_{7-\delta}$ layer in $YBa_2Cu_3O_{7-\delta}$/$Pr_xY_{1-x}Ba_2Cu_3O_{7-\delta}$ superlattices. This result demonstrates that the interplanar coupling is a very important parameter in determining the flux motion in high-T_c superconductors. When $x=1$, $Pr_xY_{1-x}Ba_2Cu_3O_{7-\delta}$ is replaced by $PrBa_2Cu_3O_{7-\delta}$. Fu *et al.*[26] argued that the magnetoresistance in $(YBCO)_1/(PrBCO)_3$ and $(YBCO)_1/(PrBCO)_5$ has a strong anisotropy. They estimated that the anisotropy parameter ϵ is about 50 and ∞, for a 1:3 and a 1:5 superlattice, respectively. In those samples, which are investigated in our experiment, the superconducting layer YBCO is not a one unit cell, but the PrBCO layer is thick enough to weaken the interplanar coupling between YBCO layers, so that the anisotropy parameter ϵ will change systematically related to decreasing YBCO layer thickness. Generally, we could not get $\epsilon=H_{c2}^{\parallel}/H_{c2}^{\perp}$ because it is very difficult to measure the upper critical field $H_{c2}^{\parallel}$ and $H_{c2}^{\perp}$, directly. However, if one defines the depinning field as the field at which the magnetoresistance is about 10% of the normal resistance, i.e., $\rho(T,H_{\rm CR})=0.1\rho_{\rm normal}(T_{c0})$,[33] in the flux-flow region, the depinning field is directly proportional to the upper critical field, so $\epsilon=H_{c2}^{\parallel}/H_{c2}^{\perp}\approx H_{\rm CR}^{\parallel}/H_{\rm CR}^{\perp}$. The depinning field $H_{\rm CR}^{\parallel}$ and $H_{\rm CR}^{\perp}$, for magnetic field parallel and perpendicular to the *ab* plane, can be obtained from the magnetoresistance curves which correspond to $H||ab$ plane, and $H||c$ axis, respectively. In terms of this method, we have estimated $\epsilon^2\approx 6400$, 144, 44, and 28 in Table I for the 3:8, 8:8, 16:8, and 24:8 samples, respectively. For other samples, ϵ^2 is about 25 which is very similar to that in the pure YBCO thin film.[34]

Brunner *et al.*[35] have pointed out that the flux-creep activation energy is proportional to the thickness of the YBCO layer in (YBCO)/(PrBCO) superlattices, so that the flux-creep activation energy decreases with the decreasing YBCO-layer thickness. That means the flux-creep activation energy decreases with increasing anisotropy in (YBCO)/(PrBCO) multilayers. If one assumes that the activation energy is determined by the pinning of the vortices, then the pinning strength changes systematically with the increasing anisotropy in these multilayers. Therefore, we argue that the interesting mixed-state Hall sign behavior arises from the systematic change of the pinning strength in a series of $(YBCO)_n/(PRBCO)_8$ multilayers with thinner YBCO layers. It will be discussed in the frame of Wang, Dong, and Ting (WDT) theory as follows in detail.

Wang and Ting,[22] based upon the Bardeen and Stephen normal-core model for flux lines and by taking into account the backflow current due to pinning force, demonstrated that the anomalous Hall effect could be explained in terms of the existence of pinning forces in the samples. Recently, Wang, Dong, and Ting[20] developed the WT theory by taking into consideration both the backflow effect and thermal fluctuations. They analytically derived the relationship between the longitudinal resistivity ρ_{xx} and the Hall resistivity ρ_{xy} written as follows:

$$\rho_{xy}=\frac{\beta_0\rho_{xx}^2}{\Phi_0 H}[\eta(1-\bar{\gamma})-2\bar{\gamma}\Gamma(v_L)], \qquad (1)$$

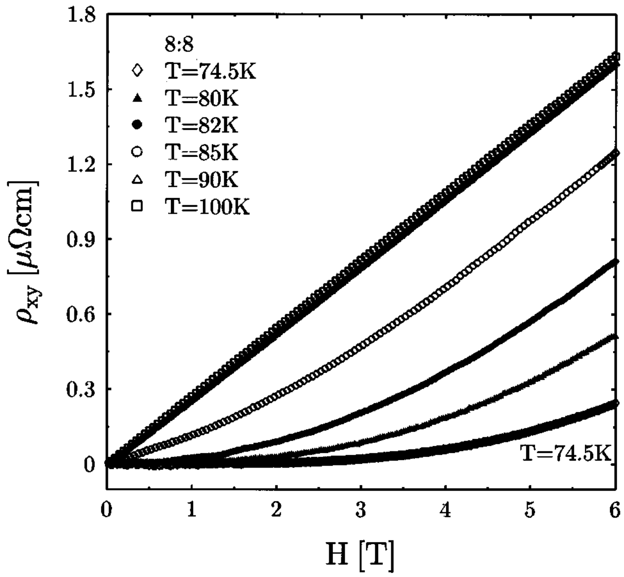

FIG. 3. ρ_{xy} as function of H at several temperatures for 8:8 superlattice. No evident sign reversal in $\rho_{xy}(H)$ has been observed even in very low magnetic field at the temperature 74.5 K which is slightly below its $T_{c0}=75$ K.

where $\beta_0=\mu_m H_{c2}$ with $\mu_m=\tau e/m$, the mobility of the charge carriers and where τ is the Drude relaxation time, $H_{c2}=\Phi_0/2\pi\xi^2$ being the usual upper critical field with ξ the superconducting coherence length, and $\eta=Ne\Phi_0\beta_0=\Phi_0H_{c2}/\rho_n$ is the usual viscous coefficient with $\rho_n=(Ne^2\tau/m)^{-1}$ the resistivity of the normal state. $\bar{\gamma}=\gamma(1-\bar{H}/H_{c2})$ with $\bar{H}$ the average magnetic field over the core and γ the parameter describing the contact force on the surface of the core, which depends on T in the following way:[22] $\gamma\sim 0$ (NV limit) for $\xi/l\ll 1$ and $\gamma\sim 1$ (BS limit) for $\xi/l\gg 1$ with l as the mean free path of the carrier. $\Gamma(v_L)$ is determined by the equation $\langle F_p\rangle_t=-\Gamma(v_L)v_L$, where

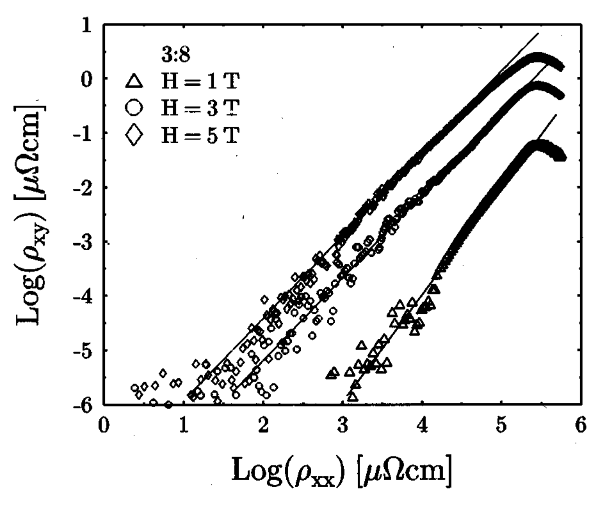

FIG. 4. $\ln(|\rho_{xy}|)$ vs $\ln(|\rho_{xx}|)$ plot for YP144 at $H=1$ T (triangle), 3 T (square), and 5 T (circle). The base of logarithm in this figure is e. Solid lines represent a fit to the power-law dependence $\rho_{xy}\propto\rho_{xx}^2$ (for $H=1$ T); $\rho_{xy}\propto\rho_{xx}^{1.6}$ (for $H=3$ and 5 T).

$v_L = \langle v_\phi(i) \rangle_t$ is the time average drift velocity for ith flux vortex, and $\langle F_p \rangle_t$ time averaged pinning force in which the thermal fluctuations have been considered.

First, let us discuss the sign reversal. For fixed J and magnetic field H, the sign of ρ_{xy} is simply determined by the sign of $\eta(1-\bar{\gamma}) - 2\bar{\gamma}\bar{\Gamma}(v_L)$. If the pinning is relatively strong, i.e., $\Gamma(v_L) > \eta(H/H_{c2})$, when the magnetic field H is within the intermediate region, ρ_{xy} will change its sign from positive to negative by decreasing the temperature below T_{c0}. This predication is in agreement with the experimental result for 24:8, 45:8, and 60:8.

It has already been mentioned above that when the superconducting layer YBCO becomes thinner, due to the decrease of the flux-creep activation energy, i.e., the interplanar coupling between YBCO layers becomes weaker and subsequently the superconductivity in the multilayer is suppressed. It leads to an enhancement of the thermal fluctuations and consequently it enhances the flux motion, therefore the friction due to the pinning decreases with decreasing YBCO-layer thickness. As a result of that, the condition that the friction due to the pinning is much smaller than the Bardeen-Stephen friction, i.e., $\Gamma(v_L) \ll \eta(\bar{H}/H_{c2})$ can be satisfied in this case in the intermediate field. The condition for the disappearance of the negative Hall in Eq. (1) is simply $\eta(1-\bar{\gamma}) > 2\bar{\gamma}\Gamma(v_L)$, which leads to the following expression if we insert $\bar{\gamma} = \gamma(1-\bar{H}/H_{c2})$ into the above formula:

$$\bar{H} > H_{c2}\left(1 - \frac{\eta}{\gamma[2\Gamma(v_L) + \eta]}\right). \tag{2}$$

Provided that $\bar{H}/H_{c2} \leq 1$ (for $\bar{H}/H_{c2} \geq 1, \rho_{xy}$ is always positive), then $\Gamma(v_L) \ll (H/H_{c2}) < \eta$, which leads to

$$\bar{H} > H_{c2}\left(1 - \frac{\eta}{\gamma[2\Gamma(v_L) + \eta]}\right) \approx H_{c2}\left(1 - \frac{1}{\gamma}\right). \tag{3}$$

Since γ lies between 0 (lower temperature limit) and 1 (higher temperature limit), Eq. (3) can be always satisfied in the whole temperature range even in very smaller external magnetic field, ρ_{xy} is therefore always positive. Actually, no Hall sign reversal has been observed at very small magnetic field in the 8:8 sample. The ρ_{xy} as a function of the magnetic field H at several temperatures for the 8:8 is shown in Fig. 3. Within the experimental accuracy, no evident negative $\rho_{xy}(H)$ has been observed even at the temperature ($T \approx 74.5$ K) slightly below its $T_{c0} = 75$ K.

When the thickness of the YBCO layer increases, the flux-creep activation energy increases, and the thermal fluctuations decrease, which leads to the increase of the friction due to the pinning, e.g., in the 16:8 sample, the magnitude of $\Gamma(v_L)$ may be comparable with Bardeen-Stephen friction $\eta(H/H_{c2})$ in the intermediate field ($H=1$ and 3 T), so that there is a Hall sign reversal, but at higher field ($H=5$ T), no sign anomaly can be observed. Moreover, the maximum of the negative ρ_{xy}, i.e., $\Delta_{\max}$ (defined as that shown in Fig. 2) at $H=1$ and 3 T was suppressed. This indicates that $\Delta_{\max}$ reflects the magnitude of $\eta(1-\bar{\gamma}) - 2\bar{\gamma}\Gamma(v_L)$, and should be determined by $\Gamma(v_L)$ and $\eta(\bar{H}/H_{c2})$ quantitatively, which is beyond our discussion in this paper.

Now let us turn to discuss the scaling law of $\rho_{xy} \propto \rho_{xx}^{\alpha}$. In 24:8, 45:8, and 60:8, $\rho_{xy} \propto \rho_{xx}^{q}$, here $q \approx 1.7$, holds in the temperature region where ρ_{xy} is negative. In 3:8 and 8:8, the sign anomaly has disappeared, but the scaling relationship $\rho_{xy} \propto \rho_{xx}^{q}$ is still valid in a very large temperature range where ρ_{xy} is always positive. However, the exponent q depends slightly on sample characteristics and magnetic field. Figure 4 shows $\ln(|\rho_{xy}|)$ vs $\ln(|\rho_{xx}|)$ for 3:8 in three magnetic fields. When $H=1$ T, $q \approx 2$, and $H=3$ and 5 T, $q \approx 1.6$. In 8:8, it was found that the scaling law $\rho_{xy} \propto \rho_{xx}^{1.7}$ almost holds, in three different magnetic fields. These results demonstrate that the anomalous behavior of the Hall voltage sign is independent of the scaling relationship between ρ_{xy} and ρ_{xx}. A similar result has been obtained by Samoilov *et al.*[23]

We tacitly admit that there exists the redistribution of charge carriers in the YBCO/PrBCO multilayer system. But we think with reservation that our experimental results could not be explained by Ferrell theory.[16] The essential reason is that there is no systematic change of ρ_{xy}/H and dn_H/dT (shown in Table I) at normal state related to the thickness of YBCO in our samples. Very recently, Liu *et al.*,[36] based upon the perturbation approach of Schmid and Larkin with a frictional force of the form proposed by Vinen and Warren under the influence of randomly distributed weak point pinning centers, have calculated the mixed-state longitudinal and Hall resistivity of superconductors. They have pointed out that in the weak collective-pinning case, for sample thickness much smaller than the penetration depth, no sign anomaly in ρ_{xy} is predicted, which is in good agreement with our experimental results. In terms of the value of $\Delta_{\max}$ shown in Fig. 2 and its corresponding thickness of YBCO layer for different samples in three magnetic fields, we estimated that the upper limits of the sample thickness below which will lead to no reversal in ρ_{xy}, mentioned by Liu *et al.*, are 10, 14, and 18 nm for $H=1$, 3, and 5 T, respectively.

In conclusion, according to the systematic measurements of the mixed-state Hall effect in a series of $(\mathrm{YBCO})_n/(\mathrm{PrBCO})_8$ superlattices, we found that the Hall sign anomaly is diminishing or even disappears with increasing anisotropic parameter and decreasing pinning strength in the samples. The scaling law $\rho_{xy} \propto \rho_{xx}^{\alpha}$ always holds for all of the samples with a somewhat different value of the exponent α. This indicates that the sign reversal is independent of the scaling relationship. Our experimental results are in good agreement with WDT theory, and finally we have estimated the upper limit of the thickness of the YBCO layer below which yields no Hall sign reversal in ρ_{xy} based on the collective weak pinning mixed-state Hall-effect theory proposed by Liu *et al.*

[1] Y. Iye, S. Nakamura, and T. Tamegai, Physica **159**, 616 (1989).
[2] K. C. Woo, K. E. Gray, R. T. Kampwisrth, and J. H. Kang, Physica C **162-164**, 1011 (1989).
[3] T. R. Chien, T. W. Jing, N. P. Ong, and Z. Z. Wang, Phys. Rev. Lett. **66**, 3075 (1991).
[4] S. J. Hagen, C. J. Lobb, R. L. Greene, M. G. Forrester, and J. H. Kang, Phys. Rev. B **41**, 11 630 (1990).
[5] S. J. Hagen, C. J. Lobb, R. L. Greene, and M. Eddy, Phys. Rev. B **43**, 6246 (1991).
[6] J. Luo, T. P. Orlando, J. M. Graybeal, W. R. White, and M. R. Beasley, Bull. Am. Phys. Soc. **37**, 698 (1992).
[7] C. H. Weijsenfeld, Phys. Lett. **28A**, 362 (1968).
[8] A. W. Smith, T. W. Clinton, C. C. Tsuei, and C. J. Lobb, Phys. Rev. B **49**, 12 927 (1994).
[9] J. Luo, T. P. Orlando, J. M. Graybeal, X. D. Wu, and R. Muenchausen, Phys. Rev. Lett. **68**, 690 (1992).
[10] R. C. Budhani, S. H. Liou, and Z. X. Cai, Phys. Rev. Lett. **71**, 621 (1993).
[11] A. Freimuth, C. Hohn, and M. Galffy, Phys. Rev. B **44**, 10 396 (1991).
[12] J. M. Harris, N. P. Ong, and Y. F. Yan, Phys. Rev. Lett. **71**, 1455 (1993).
[13] V. B. Geshkenbein and A. I. Larkin, Phys. Rev. Lett. **73**, 609 (1994).
[14] J. M. Harris, N. P. Ong, and Y. F. Yan, Phys. Rev. Lett. **73**, 610 (1994).
[15] S. J. Hagen, A. W. Smith, M. Rajeswari, J. L. Peng, Z. Y. Li, R. L. Greene, S. N. Mao, X. X. Xi, S. Bhattacharya, Qi Li, and C. J. Lobb, Phys. Rev. B **47**, 1064 (1993).
[16] Richard A. Ferrell, Phys. Rev. Lett. **68**, 2524 (1992).
[17] A. T. Dorsey, Phys. Rev. B **46**, 8376 (1992).
[18] N. B. Kopnin, B. I. Ivlev, and V. A. Kalatsky, Sov. Phys. JETP Lett. **55**, 750 (1992); J. Low. Temp. Phys. **90**, 1 (1993).
[19] E. Z. Meilikhov and R. M. Farzetdinova, Physica C **210**, 473 (1993).
[20] Z. D. Wang, Jinming Dong, and C. S. Ting, Phys. Rev. Lett. **72**, 3875 (1994).
[21] R. C. Budhani, S. H. Liou, and Z. X. Cai, Phys. Rev. Lett. **71**, 621 (1993).
[22] Z. D. Wang and C. S. Ting, Phys. Rev. Lett. **67**, 3618 (1991).
[23] A. V. Samoilov, A. Legris, F. Rullier-Albenque, P. Lejay, S. Bouffard, Z. Ivanov, and L. G. Johansson, Phys. Rev. Lett. **74**, 2351 (1995).
[24] G. Jakob *et al.*, Europhys. Lett. **19**(2), 135 (1992).
[25] G. Jakob *et al.*, Appl. Phys. Lett. **59**, 1626 (1992).
[26] C. M. Fu *et al.*, Physica C **205**, 111 (1993).
[27] M. Affronte, J.-M. Triscone, O. Brunner, L. Antognazza, L. Miéville, M. Decroux, and Ø. Fischer, Phys. Rev. B **43**, 11 484 (1991).
[28] G. Jakob, Ph.D. thesis, Technical University of Darmstadt, 1993.
[29] C. L. Jia, H. Soltner, G. Jakob, Th. Hahn, H. Adrian, and K. Urban, Physica C **210**, 1 (1993).
[30] Y. X. Jia, Z. Z. Liu, M. D. Lan, and R. N. Shelton, Phys. Rev. B **47**, 6043 (1993).
[31] C. C. Almasan, S. H. Han, K. Yoshiara, M. Buchgeister, D. A. Gajewski, L. M. Paulius, J. Herrmann, M. B. Maple, A. P. Paulikas, Chun Gu, and B. W. Veal, Phys. Rev. B **51**, 3981 (1995).
[32] Qi Li, C. Kwon, X. X. Xi, S. Bhattacharya, A. Walkenhorst, T. Venkatesan, S. J. Hagen, W. Jiang, and R. L. Greene, Phys. Rev. Lett. **69**, 2713 (1992).
[33] G. Jakob, Ph.D. thesis, Technical University of Darmstadt, 1993.
[34] D. E. Farrell, C. M. Williams, S. A. Wolf, N. P. Bansal, and V. G. Kogan, Phys. Rev. Lett. **61**, 2805 (1988).
[35] O. Brunner *et al.*, Phys. Rev. Lett. **67**, 1354 (1991).
[36] Wu Liu, T. W. Clinton, and C. J. Lobb, Phys. Rev. B **52**, 7482 (1995).