PHYSICAL REVIEW B VOLUME 56, NUMBER 1 1 JULY 1997-I

Hall coefficients of $YBa_2Cu_3O_y/PrBa_2Cu_3O_y$ superlattices in the flux-flow regime

H. C. Yang and L. M. Wang
Department of Physics, National Taiwan University, Taipei 10746, Taiwan, Republic of China

H. E. Horng
Department of Physics, National Taiwan Normal University, Taipei 11718, Taiwan, Republic of China

(Received 6 February 1997; revised manuscript received 1 April 1997)

In this work, we measured the longitudinal ρ_{xx} and transverse ρ_{xy} resistivities as a function of the current density in the flux-flow regime in $YBa_2Cu_3O_y/PrBa_2Cu_3O_y$ superlattices. According to these measurements, the Hall electric field is a nonlinear function of the current density in the vicinity of the local minimum of negative Hall coefficient. Also, the Hall resistivity is independent of J in the low current density. Furthermore, the ρ_{xy} and ρ_{xx} are found to obey the power law $\rho_{xy}=A\rho_{xx}^{\beta}$ with $\beta=1.7\pm0.05$ over a wide current densities and temperatures. Above results are discussed in terms of the existing theories. [S0163-1829(97)03626-6]

INTRODUCTION

The study of longitudinal ρ_{xx} and transverse ρ_{xy} resistivities of high-T_c superconductors, especially in the mixed state, is important in the understanding of vortex dynamics. One striking feature of vortex dynamics is the sign reversal of ρ_{xy} caused by the vortex motion in mixed state. Another interesting issue that has attracted special attention is the scaling relationship between ρ_{xy} and ρ_{xx}, i.e., ρ_{xy} and ρ_{xx} follow $\rho_{xy}\sim\rho_{xx}^{\beta}$: in pinned regime as first observed by Luo *et al.*[1] The anomalous Hall effect is influenced by many factors, which include transport current density,[2] pinning force,[3,4] and magnetic-field strength. To investigate current-dependent anomalous Hall effect, Kunchur *et al.*[2] has measured the Hall coefficients of $YBa_2Cu_3O_y$ epitaxial films over an extended current-density range, where high current-density suppresses flux pinning. With increasing current density, they observed an enhancement of the sign reversal of the Hall angle $\alpha=\rho_{xy}/\rho_{xx}$. Li, Zhang, and Adrian[3] and Wang, Yang, and Horng[4] recently reported the effect of flux pinning on the mixed-state Hall coefficient in $YBa_2Cu_3O_y/PrBa_2Cu_3O_y$ superlattices, indicating that the Hall anomaly diminished or even disappeared with decreasing pinning strength. A scaling law $\rho_{xy}\sim\rho_{xx}^{\beta}$ holds good for all samples with some variation in the exponents. Among those factors affecting the ρ_{xy} and ρ_{xx}, the effects of transport current on the mixed-state Hall effects of $(YBa_2Cu_3O_y/PrBa_2Cu_3O_y)_n$ [$(YBCO/PBCO)_n$] are seldom examined; the superscript n is the number of modulation layer in $(YBCO/PBCO)_n$ superlattices. Herein, we report measurement of mixed-state Hall effects over a wide range of current density ($1\times10^3-1\times10^5$ A/cm^2) for $(YBCO/PBCO)_n$ superlattices in the flux-flow regime. In this regime, the Lorentz force exceeds the pinning force and the flux line moves in a viscous flow. Thus, Hall measurements with varied current density provide information on the anomalous Hall effect's evolution while the pinning force is systematically suppressed and the Lorentz force becomes larger. We observed that the ρ_{xy} is independent of J in the low current density and the Hall electric field is a nonlinear function of the current density in the vicinity of the local minimum of negative Hall coefficient. Furthermore, ρ_{xy} and ρ_{xx} obey $\rho_{xy}\sim\rho_{xx}^{\beta}$ with $\beta=1.7\pm0.05$ in a magnetic field over wide current densities and temperature ranges in YBCO/PBCO superlattices.

EXPERIMENT

YBCO/PBCO superlattices were prepared in a high-vacuum radio-frequency (RF) magnetron sputtering system. The RF magnetron sputtering system's detailed description and the sample's characterization have been previously[5] reported. The I-V curves were measured by sending a pulsed dc current to the current leads of the five-leads Hall pattern with a duration time of about 1–2 sec and the Hall voltage was measured by a nanovoltmeter. The temperature was controlled by a temperature controller and the temperature in measurements became stable at around 0.05 K. The current density of Hall and resistivity measurements varied from 0.5 to 1×10^5 A/cm^2. To avoid the cumulative heating in the Hall measurement, the interval between two adjacent current pulses was set as long as 15 sec. All samples were patterned to a five-lead Hall geometry in the transport Hall and resistivity measurements. Gold pads were evaporated onto the Hall and resistivity leads. Current leads had a negligible contact resistance.

RESULTS AND DISCUSSION

Figures 1(a) and 1(b) reveal the double-logarithm plots of ρ_{xx} versus J and ρ_{xy} versus J for a YBCO/PBCO (60 Å/48 Å)$_{16}$ superlattice at a fixed magnetic field of 2 T and temperature range of 75–84 K. The resistivity ρ_{xx} increases steadily as J is increased and has an Ohmic behavior in the limit of high current density. The ρ_{xy}-versus-J curves show sign reversal when the current density is increased at each fixed temperature range of 75–84 K. Furthermore, the ρ_{xy}-versus-J curves show two plateaus; one plateau is located at low current density while the other is located at high current density. The ρ_{xy} is J independent at low current den-

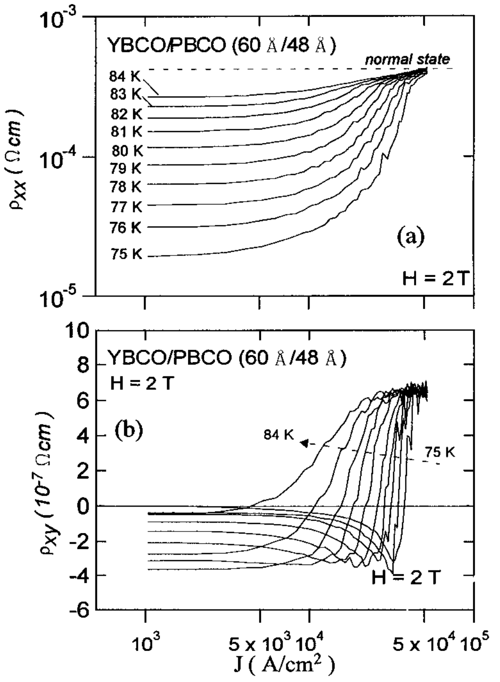

FIG. 1. (a) The double-logarithm plot of ρ_{xx}-vs-J and (b) ρ_{xy}-vs-J curves for a YBCO/PBCO (60 Å/48 Å) superlattice at a fixed magnetic field of 2 T and temperature range of 75–84 K. The increment of the temperature in each curve is 1 K.

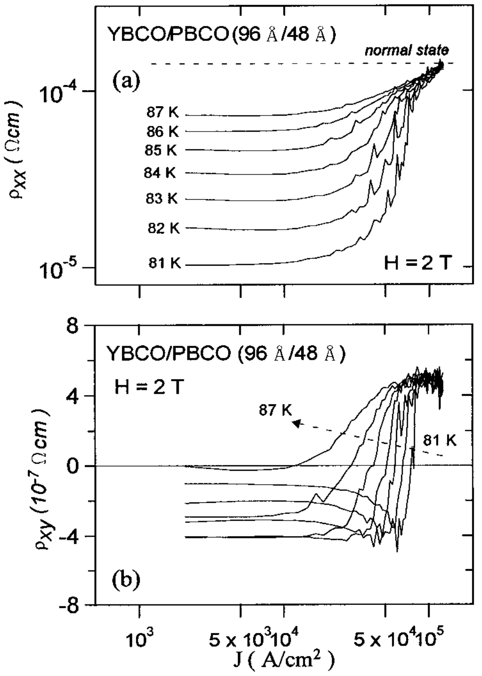

FIG. 2. (a) The double-logarithm plot of ρ_{xx}-vs-J and (b) ρ_{xy}-vs-J curves for a YBCO/PBCO (96 Å/48 Å) superlattice at a fixed magnetic field of 2 T and temperature range of 81–87 K.

sity whereas the ρ_{xy} at high current-density plateau is emerged to a value of 7×10^{-7} Ω cm. The current density at which sign reversal occurred shifts to a lower current density with increasing temperature. Notably, the sign-reversal density J_{sr} (the current density at which ρ_{xy} equals zero) is close to the plateau region of the $J_{xx}(J)$-versus-J curve. This finding suggests that the sign reversal of ρ_{xy} occurs near the free flux-flow regime.

Figures 2(a) and 2(b) reveal double-logarithm plot of ρ_{xx} versus J and ρ_{xy} versus J for a YBCO/PBCO (96 Å/48 Å)$_{10}$ superlattice at a fixed magnetic field of 2 T and temperature range of 81–87 K. The behavior of ρ_{xx} versus J and ρ_{xy} versus J resembles that of Figs. 1(a) and 1(b), demonstrating that the behavior of $\rho_{xx}(J)$ and $\rho_{xy}(J)$ in a magnetic field is a universal characteristic of YBCO/PBCO superlattices.

Based on the normal core model of Bardeen and Stephen[6] and by considering both the backflow effect and thermal fluctuation, Wang, Dong, and Ting[7] (WDT) developed a unified theory on flux motion and derived the following equation:

$$\rho_{xy}=(\beta_0\rho_{xx}^2/\Phi_0 B)\{\eta(1-\overline{\gamma})-2\overline{\gamma}\Gamma(V_L)\},\tag{1}$$

where β_0 denotes $(\tau e/m)H_{c2}$, η represents $\Phi_0 H_{c2}/\rho_n$ and is the viscosity coefficient, $\overline{\gamma}=\gamma(1-H/H_{c2})$ with H the average magnetic field over the core, γ denotes the parameter describing the contact force on the core's surface, $\Gamma(V_L)$ represents a scaling function which depends on V_L. Equation (1) can be rewritten in terms of E_{xx} and E_{xy}, yielding

$$E_{xy}=(\beta_0 E_{xx}^2/J\Phi_0 B)\{\eta(1-\overline{\gamma})-2\overline{\gamma}\Gamma(V_L)\}.\tag{2}$$

We discuss the behavior of ρ_{xx} versus J and ρ_{xy} versus J for a YBCO/PBCO (60 Å/48 Å)$_{16}$ superlattice with the model proposed by WDT. For fixed temperatures and magnetic fields, in the regime of $\gamma\sim0$ or $\eta\gg\Gamma(V_L)$ and $\gamma\sim0$ the relation $E_{xy}=(\beta_0E_{xx}^2/J\Phi_0B)$ holds. In the low current-density regime ($J\leqslant5\times10^3$ A/cm^2 and $J\leqslant1\times10^4$ A/cm^2) for YBCO/PBCO for (60 Å/48 Å)$_{16}$ and (96 Å/48 Å)$_{10}$ superlattices, respectively (Figs. 1 and 2), E_{xx} is linearly proportional to J, i.e., $E_{xx}=J\rho_{xx}$. Inserting $E_{xx}=J\rho_{xx}$ into Eq. (2) reveals that E_{xy} is proportional to J. Therefore, ρ_{xy} is independent of current density in the low-J regime. The J-independent behavior of ρ_{xy} is indeed experimentally observed, as shown in Figs. 1(b) and 2(b). Furthermore, in the high current-density regime [$J\geqslant3\times10^4$ and $J\geqslant8\times10^4$ A/cm^2) for (60 Å/48 Å)$_{16}$ and (96 Å/48 Å)$_{10}$ superlattices, respectively], the ρ_{xx} is independent of current density. In the middle range current density around $J_{\min}$ [$J_{\min}$ is the current density at which ρ_{xy} has a maximum negative value (in the vicinity of the glass transition)], the E_y is a strongly nonlinear function of the current density. This regime reveals the vortex moving in a viscous flow and a sign reversal of Hall coefficient.

Figure 3 reveals the double-logarithm plot of ρ_{xy} versus ρ_{xy} for a YBCO/PBCO (60 Å/48 Å)$_{16}$ superlattice in a magnetic field of 2 T and at fixed temperature range of 75–77 K. Regarding the current dependence of ρ_{xx} and ρ_{xy}, the important finding is that ρ_{xx} and ρ_{xy} form straight lines for all temperatures considered, i.e., ρ_{xy} relies on ρ_{xx} according to $\rho_{xy}=A\rho_{xx}^{\beta}$ all the way into the nonlinear range. The exponent is around 1.7±0.05 in a magnetic field of 2 T at all temperature ranges near the vortex glass transition. We

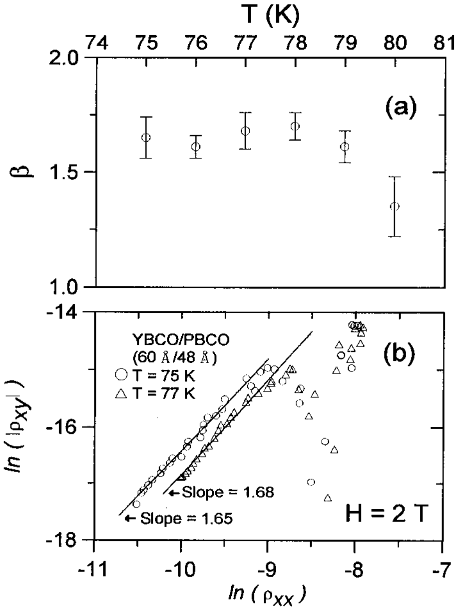

FIG. 3. (a) The exponent β as a function of temperature near the vortex glass transition. (b) The double-logarithm plot of ρ_{xy} vs ρ_{xy} for a YBCO/PBCO (60 Å/48 Å$)_{16}$ superlattice in a magnetic field of 2 T and at fixed temperatures of 75 and 77 K.

also measured ρ_{xx} and ρ_{xy} in a magnetic field of 2 T for a (60 Å/48 Å$)_{16}$ superlattice at fixed current density $J=1\times10^4$ A/cm^2. The ρ_{xy} and ρ_{xx} obey the power law $\rho_{xy}=A\rho_{xx}^{\beta}$ with β=1.7±0.05 in a magnetic field of 2 T. From Fig. 3, we can infer that the current and temperature dependence of ρ_{xy} and ρ_{xx}, over a wide range, obey the scaling relation

$$\rho_{xy}(J_x,T)=C[\rho_{xx}(J_x,T)]^{\beta},$$

with β=1.7±0.05 in a magnetic field of 2 T, where C is a constant for YBCO/PBCO (60 Å/48 Å$)_{16}$ superlattices.

The scaling behavior of the Hall resistivity has been attributed to the vortex flux pinning while the origin of the sign reversal generated a variety of possible explanations.[7–15]

First, inspired by the results of Luo *et al.*[1] for epitaxial $YBa_2Cu_3O_y$ film (β=1.7±0.2), Dorsey and Fischer[16] (DF) proposed interesting concepts to account for the power law $\rho_{xy}=A\rho_{xx}^{\beta}$ near the vortex glass transition. Furthermore, DF made an explicit prediction that the nonlinear Hall electric field should scale with a universal scale law at the vortex glass transition. The prediction correlates well with the experimental results of Wöltgens, Dekker, and de Wijn[17] in YBCO film. Wöltgens, Dekker, and de Wijn measured the nonlinear Hall resistivity in $YBa_2Cu_3O_y$ films near the vortex glass transition. According to their results, the Hall electric field E_y is a strongly nonlinear function of current density J_x. Furthermore, ρ_{xy} and ρ_{xx} obey the scaling behavior $\rho_{xy}=A\rho_{xx}^{\beta}$ with β=1.7 over wide current densities and temperatures. An alternative model for the scaling law of $\rho_{xy}=A\rho_{xx}^{\beta}$ with β=2.0 has been put forward by Vinokur, Geshkenbein, and Feigel'man, and Blatter (VGFB).[18] They indicated that the scaling of ρ_{xy} and ρ_{xx} is a general feature of any vortex state. The prediction is consistent with experimental results of Somoilov[19] in $Bi_2Sr_2CaCu_2O_y$ single crystal.

Recently, Li, Zhang, and Adrian[3] reported the effect of flux pinning on the mixed-state Hall coefficient, indicating that the Hall anomaly diminished or even disappeared with increasing anisotropy parameter and decreasing pinning strength. A scaling law in ρ_{xy} and ρ_{xx} was observed and the power law $\rho_{xy}=A\rho_{xx}^{\beta}$ holds good for all samples with some variation in the exponents β=1.6–2. Their results are consistent with the WDT theory and are similar to our recent work[3] on the scaling behavior of YBCO/PBCO superlattices in magnetic fields. The present work examines the J dependence of ρ_{xy} and ρ_{xx}. The ρ_{xy} and ρ_{xx} obey the power law $\rho_{xy}=A\rho_{xx}^{\beta}$ with β=1.7±0.05 over a wide range of current densities and temperatures. The Hall electric field is a nonlinear function of the current density in the vicinity of the local minimum of negative Hall coefficient which is consistent with the prediction of the DF model. Meanwhile, ρ_{xy} is independent of J in the low current density where the behavior of ρ_{xy} is Ohmic.

Finally, we compare the results derived with the VGFB, DF, and WDT theories. These theories are self-evidently of an entirely different nature. The DF theory predicts that a nonlinear Hall field E_y should scale with a universal power of the current density at the vortex glass transition, while the WDT theory predicts that, in the regime of $\gamma\sim0$ or $\eta\geqslant\gamma\Gamma(V_L)$ and $\gamma\sim0$, $E_{xy}=(\beta_0E_{xx}^2/J\Phi_0B)$ holds even in the nonlinear E_{xy} regime for fixed temperatures and magnetic fields, and varied current. The fact that β predicted by the VGFB theory is retrieved from the DF critical scaling analysis, leads to the conclusion that the DF and VGFB theories are mutually comparable in the sense that the specific combination of the critical components $(z+\gamma-1)/(z-1)$ of the scaling law $\rho_{xy}\alpha\rho_{xx}{}^{(z+\gamma-1)/(z-1)}$ in the DF theory is equal to β. Notably, neither the DF nor the VGFB can explain the sign reversal of the ρ_{xy} in type-II superconductors while the WDT theory predicts a sign reversal.

CONCLUSION

In summary, this study measures longitudinal ρ_{xx} and Hall ρ_{xy} resistivities as a function of current density under different currents and temperature regimes for YBCO/PBCO superlattices. According to those results, the Hall electric field is a nonlinear function of the current density in the vicinity of the local minimum of negative Hall coefficient. The Hall resistivity is independent of J in the low current density where ρ_{xx} is Ohmic. Furthermore, ρ_{xy} and ρ_{xx} obey $\rho_{xy}=A\rho_{xx}^{\beta}$ with β=1.7±0.05 over a wide range of current densities and temperatures in a magnetic field of 2 T.

ACKNOWLEDGMENT

The authors would like to thank the National Science Council of Republic of China for financial support under Grants Nos. NSC86-2112-M002-033 and NSC86-2112-M003-012.

[1] J. Luo, T. P. Orlando, J. M. Graybeal, X. D. Wu, and R. Muenchausen, Phys. Rev. Lett. **68**, 690 (1992).

[2] M. N. Kunchur, D. K. Christen, C. E. Klabunde, and J. M. Phillips, Phys. Rev. Lett. **72**, 2259 (1994).

[3] Kebin Li, Y. Zhang, and H. Adrian, Phys. Rev. B **53**, 8608 (1996).

[4] L. M. Wang, H. C. Yang, and H. E. Horng, Phys. Rev. Lett. **78**, 527 (1997).

[5] L. M. Wang, H. W. Yu, H. C. Yang, and H. E. Horng, Physica C **256**, 57 (1996).

[6] J. Bardeen and M. J. Stephen, Phys. Rev. A **140**, 1197 (1965); M. J. Stephen and J. Bardeen, Phys. Rev. Lett. **14**, 112 (1965).

[7] Z. D. Wang, J. Dong, and C. S. Ting, Phys. Rev. Lett. **72**, 3875 (1994); Z. D. Wang and C. S. Ding, *ibid.* **67**, 3616 (1991).

[8] E. Z. Meilihov and R. M. Farzetdinova, Physica C **210**, 473 (1993).

[9] A. Freimuth, C. Hohn, and M. Gaffy, Phys. Rev. B **44**, 10 396 (1991).

[10] R. A. Ferrel, Phys. Rev. Lett. **68**, 2524 (1992).

[11] H. E. Horng, H. H. Sung, L. M. Wang, and H. C. Yang, Solid State Commun. **93**, 537 (1995).

[12] J. L. Chen and T. J. Yang, Phys. Rev. B **50**, 4064 (1994).

[13] A. G. Arrov and S. H. Kami, Phys. Rev. B **41**, 9548 (1990).

[14] Y. X. Jis, J. T. Liu, M. D. Lau, and R. N. Shelton, Phys. Rev. B **47**, 6043 (1993).

[15] S. J. Hagen *et al.*, Phys. Rev. B **42**, 6777 (1990).

[16] A. T. Dorsey and M. P. Fisher, Phys. Rev. Lett. **68**, 694 (1992).

[17] P. J. M. Wöltgens, C. Dekker, and H. W. de Wijn, Phys. Rev. Lett. **71**, 3858 (1993).

[18] V. M. Vinokur *et al.*, Phys. Rev. Lett. **71**, 1242 (1993).

[19] A. V. Somoilov, Phys. Rev. Lett. **71**, 617 (1993).