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Angular Dependence of Critical Currents on $YBa_2Cu_3O_{7-y}/Pr_{0.5}Y_{0.5}Ba_2Cu_3O_{7-y}$ Superlattices†

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We measured the angular dependence of critical currents on $YBa_2Cu_3O_{7-y}/Pr_xY_{1-x}Ba_2Cu_3O_{7-y}$ superlattices at various applied magnetic fields and temperatures to investigate the effect of layer coupling on the dimensionality of the superlattices. The applied magnetic field was up to 6 Tesla and the temperatures varied from T_c to about 50 K. The angie between 'he applied magnetic field and the c-axis of superlattices were from 0° to 180°. The current was always perpendicular to the applied magnetic field. The Kes model was introduced to fit our data to study the dimensionality of the superlattices. For sample where the coupling is weak, the 2D Kes model has better fitting. These results will be discussed.

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Due to the layered crystal structure, the high-T_c superconducting oxides show highly anisotropic in superconducting transport properties. Moreover, the c-axis coherence length ξ, which is about 3 Å for $YBa_2Cu_3O_{7-y}$ and 1 Å for $Bi_2Sr_2CaCu_2O_8$ at OK, is significantly shorter than the lattice constant c. Thus, the order parameters are large in the $Cu\text{-}O_2$ planes, but almost uniformly zero between the layers. This implies that, at low temperature, a 2D layered model is more suitable for high-?; superconductors then a 3D anisotropic, spatially homogeneous model [1]. The interlayers can act as strong intrinsic pinning centers if the fiux lines are injected parallel to the layers [2]. Furthermore, P. H. Kes et *al.* [3] suggested that the superconducting properties should be independent on the field component parallel to the layers. However, at temperatures near T_c, due to the comparability of $\xi_c(t)$ and lattice constant c of $YBa_2Cu_3O_{7-y}$, the coupling between superconducting layers is much larger and the superconducting properties deviate from the 2D behavior. It is expected to observe a dimension crossover from 3D to 2D on YBCO by lowering down

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the temperature. Since the superlattices can artificially change the distance between superconducting layers. Therefore, in this work, we grew the superlattices with alternating sheets of $YBa_2Cu_3O_{7-y}$ (YBCO) and $Pr_{1-x}Y_xBa_2Cu_3O_{7-y}$ (PYBCO) where x = 0 or 0.5, and measured the critical current density J_c. Since the coupling between superconducting layers can be artificially varied by the PYBCO thickness and concentration of Y, we can investigate the dimensionality transition of the superlattices.

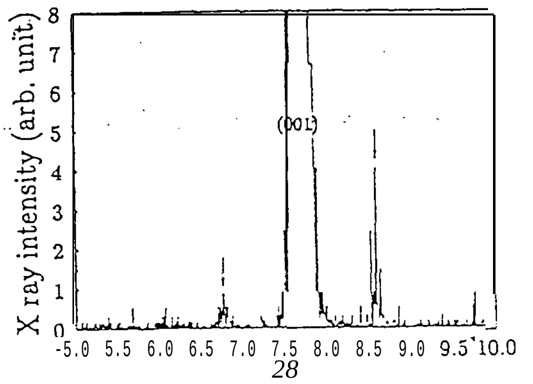
There are two kinds of superlattice studied in this work, one is $YBa_2Cu_3O_{7-y}/PrBa_2Cu_3O_{7-y}$ (YBCO/PBCO), another one is $YBa_2Cu_3O_{7-y}/PrBa_2Cu_3O_{7-y}$ (YBCO/PYBCO). The superlattices were deposited by a dual target RF sputtering system with an off axis configuration. The two targets are stoichiometric $YBa_2Cu_3O_{7-y}$ and $(Pr_{1-x}Y_x)Ba_2Cu_3O_{7-y}$ with $x=$ 0 or 0.5. The films were epitaxially grown on 650-700 °C $SrTiO_3(100)$ substrates. The sputtering gas was a mixture of Ar and O_2. After deposition, one atmosphere of oxygen was introduced to the chamber and the film was dwelt one hour at 600 °C, then the film was cooled down to room temperature at rate of 5 °C/min. The X-ray diffraction peaks demonstrated a preierred orientation with the crystal c axis perpendicular to the substrate surface. Fig. 1 shows the XRD pattern in the vicinity of (001) peak from a YBCO/PYBCO (48Å/48Å) film. The arrows indicate the satellite peaks due to the superiattice modulation. The modulation wavelength estimated from the position of satellite peaks is 96 Å, which is consistent with desired thickness calibrated from Dektak surface profile. In order to study the J_c dependence of the angle θ, θ is the angle between the magnetic field H and the c axis of superlattices. The samples were mounted on a rotatable sample holder with the magnetic filed perpendicular to the rotation axis. J_c was determined using the voltage drop criterion Of 5 μV/mm. In this experiments, the current flew along the ab plane and the parallel to rotation axis. Since the Lorentz force acts on the flux line is F_L = J x H/c. In the situation J parallel to rotation axis, the Lorentz force can express by two components along c-axis and ab-plane:

$$F_{L,c} = \frac{1}{c} JH \sin\theta$$

$$F_{L,ab} = \frac{1}{c} JH \cos\theta$$

the absolute value of Lorentz force is independent on the angle θ.

Since, P. H. Kes *etal.*[3] point out that the critical current density J_c of a 2D layered superconductor will be determined by the c-axis component of magnetic field only. Hence, in order to probe the 2D property, a theoretic curve suggested by P. H. Kes *etal.* was calculated as $J_c(H,\theta) = J_c(H\cos\theta, 0°)$ from the data of J_c versus H at θ = 0°. Fig. 2 shows the J_c-θ dependence of a 960 Å YBCO film. We can not fit the data to the 2D Kes model. Because the criterion of 3D-2D transition $\Gamma(1-t) = 2[\xi_{ab}(0)/d]^2$ [4] is not satisfied in our sample, where Γ is the effective mass ratio m_c/m_{ab}, t is the relative temperature T/T,, ξ_{c} is the Ginzburg-Landau (GL) coherence length along ab-plane and d is the distance between the superconducting layers. In other words, it predicts that if $d > \sqrt{2}\xi_c(t)$, the superconductor will become a 2D system. For YBCO system, d is 8.3 Å and ξ_c is about 12 Å at $t=$ 0.94. Thus, for observing the dimension crossover, it is necessary either to lower the temperature or to increase the d value. However, we can introduce PYBCO to increase



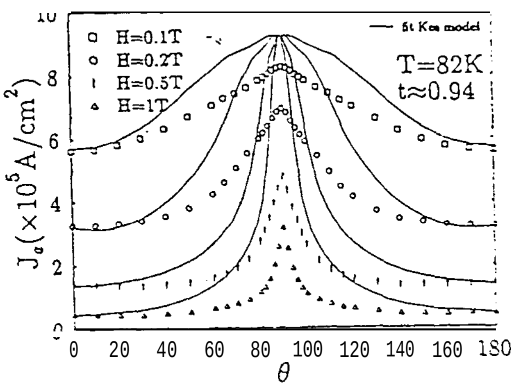
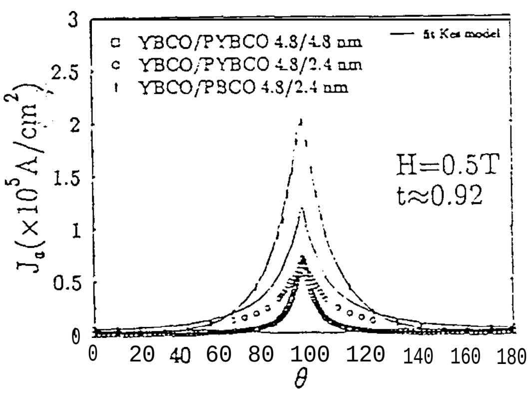


FIG. 1. X-ray diffraction pattern for a $YBa_2Cu_3O_{7-y}/Pr_{0.5}Y_{0.5}Ba_2Cu_3O_{7-y}$ (48Å/48Å) x 16 superlattice, the arrows indicate the positions of the satellite peaks.

FIG. 2. J_c as a function of θ under magnetic fields of $H = 0.1, 0.2$, 0.5, and 1 T for a $YBa_2Cu_3O_{7-y}$ thin film. The thickness of thin film is 960 Å. The solid line are obtained using the 2D Kes model.



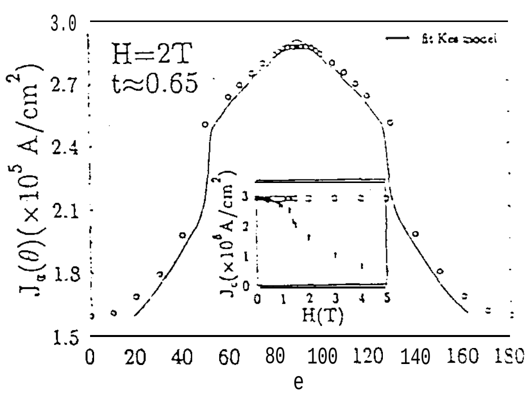


FIG. 3. J_c as a function of θ under magnetic fields $H = 0.5$ T at $t \approx 0.92$ for the superlattices YBCO/PYBCO(48Å/48Å), YBCO/PYBCO(48Å/24Å), and YBCO/PBCO (48Å/24Å). The solid lines are obtained using the 2D Kes model.

FIG. 4. J_c as a function of θ under magnetic fields $H = 2$ T at $t \approx 0.65$ for the superlattice YBCO/PYBCO (48Å/24Å) x 20. The solid line are obtained using the 2D Kes model. The inset shows the field dependence of J_c at $\theta = 0°$ (†) and 90° (□).

the distance d. In Fig. 3 the J_c versus θ for three superlattice samples YBCO/PYBCO (48Å/48Å) (sample A), YBCO/PYBCO (48Å/24Å) (sample B) and YBCO/PBCO(48Å/24Å) (sample C) under $H = 0.5$ Tesla and $t \approx 0.92$ are shown. Since the T_c of the PYBCO film was about 8 K, it behaves as normal layers in the higher temperature range. Therefore, the d values for each sample can be estimated to be 56.3 Å, 32.3 Å and 32.3 Å. Using the

GL coherence length of a YBCO film, $\sqrt{2}\xi_c(t)$ is about 15 Å at $t = 0.92$. As d is greater than $\sqrt{2}\xi_c$ for all three samples, one can expect that all three samples behave as 2D system. However, we observed that the angular dependence of J_c can be scaled well by the 2D Kes model in the sample A and the sample C, but the data of the sample B deviate conspicuously from the theoretic curve. These results show that, the coupling between the YBCO layer is stronger for a PYBCO normal layer than for a PBCO normal layer. This is because the PYBCO is a superconductor and the PBCO is a semiconductor at low temperature, thus the order parameter decreases slower in the PYBCO layer than in the PBCO layer. As a result, the intrinsic pinning should be weaker in the sample B and the Lorentz force component $F_{L,c}$ can move the flux along c direction. So, the $J_c(\theta)$ data of sample B are lower than the theoretic curve. When the temperature decreased to $t \approx 0.65$, as shown in Fig. 4, the $J_c(\theta)$ data of sample B become well described by the 2D Kes model. This means that the coupling between the YBCO layers are reduced due to the decrease of $\xi_c(t)$ at low temperature. It is noticeable that there is a shoulder on the $J_c(\theta)$ curve. In the inset of Fig. 4, this feature can also be seen on the $J_c(H)$ curve at $\theta = 0°$, but it is flat at $\theta = 90°$. This indicates that the shoulder is correlated to the extrinsic pinning only.

In conclusion, the angular dependence of J_c was investigated to examine the dimensionality of superconducting superlattice. We observed the 3D-2D transition by varying the temperature or varying the normal layer thickness. These results show that the dimensionality is determined by the coupling strength between superconducting layers. The coupling strength depends on the effective separation distance of superconducting layers and the GL coherence length along c-axis.

References

[1] John R. Clem, Phys. Rev. B43, 7837 (1991).
[2] M. Tachiki and S. Takahashi, solid state communication! 72, 1083 (1989).
[3] P. H. Kes, J. Aarts, V. M. Vinokur, and C. J. van der Beek, Phys. Rev. Lett. 64, 1063 (1990).
[4] W. E. Lawrence and S. Doniach, in *Proceedings of the Twelfth Infernal Conference on Low Temperature Physics, Kyoto, 1970,* ed. by E. Kanda ed. (Keigaku, Tokyo, 1971), p. 361.