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The effect of interlayer coupling on critical current density in Bi2212 system

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Abstract The dependences of critical current density J_c on the interlayer coupling strength and magnetic field in Bi2212 crystals were obtained by measuring the magnetic loop of the crystals with different interlayer coupling strengths. It was revealed that J_c decreases with the decrease in the interlayer coupling of the crystals. The relation of $J_c \propto \exp(-H^{\beta})$ was also found in the crystals, and further analysis indicated that it was the result of Zeldov pinning potential model.

Keywords superconductivity, critical current density, flux pinning, interlayer coupling

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1 Introduction

All high-temperature cuprate superconductors show a layered structure with the CuO_2 plane acting as the conductive channel between which the insulator or semiconductor reservoir layer is inserted; thus, they all show quasi-two-dimensional transport properties. In the structure, the CuO_2 plane interacts with each other by means of Josephson coupling and magnetic attraction of vortices, and

this interlayer coupling plays important roles in determining the critical current density of the materials and the vortex structure of the superconductors [1,2]. The Bi-based cuprates show the poorest interlayer coupling in all the cuprate systems; thus, the investigation in Bi-based cuprates can elucidate the relationship between the interlayer coupling strength and the transport properties in high-temperature superconductors, which may lead to finding an effective method in developing the practical properties of the materials. The Pb- and Pr-doped $\text{Bi}_2\text{Sr}_2\text{CaCuO}_{8+\delta}$ (Bi2212) system can adjust the interlayer coupling strength in a wide range, which is very suitable in investigating the influence of interlayer coupling on the practical properties of the Bi-based cuprates. In this paper, the relationship between interlayer coupling and critical current density was investigated in the Pb- and Pr-doped Bi2212 crystals using magnetic measurement.

2 Experimental

Pb- and Pr-doped Bi2212 single crystals were grown using a self-flux method with excess Bi_2O_3 included to act as a flux. Details for crystal growth have been described elsewhere [3]. The craved crystal sheets were annealed in air at 400°C for 50 h to improve homogeneity; the oxygen content increased in the anneal as well. X-ray diffraction (XRD) indicated that no extra peaks could be found from secondary phase in the annealed crystals. The cation stoichiometry of the single crystals was analyzed by energy dispersive X-ray (EDS) analysis using a scanning electron microscope (Stereoscan 440, Leica). The thickness of the crystal sheets was measured using a scanning electron microscope (Hatachi X650). The magnetization measurements were carried out at different temperatures using Maglab system (Oxford) in the applied magnetic field up to 8 T with field direction parallel to the c-axis of the crystal.

3 Experimental results and discussions

The magnetization at different temperatures of $\text{Bi}_{1.7}\text{Pb}_{0.36}$

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$\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$; $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$; $\text{Bi}_2\text{Sr}_2\text{Ca}_{0.83}\text{Pr}_{0.17}\text{Cu}_2\text{O}_{8+\delta}$, and $\text{Bi}_2\text{Sr}_2\text{Ca}_{0.72}\text{Pr}_{0.28}\text{Cu}_2\text{O}_{8+\delta}$ crystals were measured, respectively. Their interlayer coupling strength was decreased orderly based on the experimental results of the anisotropy factor in Pb- and Pr-doped Bi2212 systems [4,5]. The measured magnetization can be transferred in tesla by using the sample volume data. The magnetization loop at different temperatures of the $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ crystal was shown in Fig. 1.

The critical current density J_c of the sample can be expressed as

$$J_c = \frac{200\Delta M}{b(1-b/3a)} \quad (1)$$

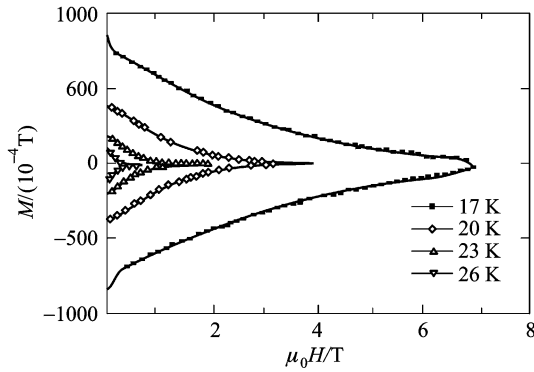


Fig. 1 The magnetization loop of the $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ crystal at different temperatures

using Bean's critical model [6,7], here a and b are the length and width of the sample in centimeters, respectively, and J_c is in kA/m^2 . $\Delta M = M^+ - M^-$; here, M^+ and M^- are the magnetization of the sample in 10^{-4} T with increasing and decreasing applied fields, respectively. Several J_c data in the low-field region were omitted due to the original magnetization and the second peak effect. The magnetic field dependence of the critical current density J_c at different temperatures in the $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ crystal is shown in Fig. 2. It was found that J_c decreases monotonically with increasing magnetic field at constant temperature. At low temperatures, J_c shows a plateau in the low-field region and J_c decreases rapidly with a further field increase. However, the J_c plateau is distinguished at high temperatures. Meanwhile, J_c decreases rapidly with an increase in temperature when the field is constant. It was found that if the low-field J_c plateau is excluded, the field dependence of J_c could be fitted by

$$J_c(H) = J_c(0) \exp(-\beta H^\alpha) \quad (2)$$

where α and β are field-independent fitting parameters. The fitting results were shown as solid lines in Fig. 2, which accord well with the experimental results. For the $\text{Bi}_{1.7}\text{Pb}_{0.36}\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ and $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$, the parameter α was about 1.5 and almost temperature independent, while it showed weak temperature dependence for $\text{Bi}_2\text{Sr}_2\text{Ca}_{0.83}\text{Pr}_{0.17}\text{Cu}_2\text{O}_{8+\delta}$ and $\text{Bi}_2\text{Sr}_2\text{Ca}_{0.72}\text{Pr}_{0.28}\text{Cu}_2\text{O}_{8+\delta}$ crystals. For all samples, it was found that a tends to decrease when the

interlayer coupling strength is decreased, which may imply that the field dependence of the critical current density becomes a little weaker when the interlayer coupling strength is decreased. For parameter β , it increased rapidly with an increase in temperature; thus, the temperature dependence of J_c is mainly determined by the relationship between β and temperature in Eq. (2). This result can well interpret the J_c plateau in Fig. 2, for β was very small in low temperature, which made $\beta H^\alpha \ll 1$ and led to a weaker field dependence of J_c . In the fitting process, it was found that the fitting results in high field became poor if the J_c plateau data were included; thus, the plateau was excluded in the fitting. The field dependence of J_c for all the four crystals at 17 K was shown in Fig. 3. It was revealed that J_c decreased obviously with the decrease in interlayer coupling strength, which indicates that the interlayer coupling has an important influence on the critical current density of the cuprates. Although the difference of critical temperature T_c has some influence on J_c , the experimental results in Fig. 3 should be mainly attributed to the changes of the interlayer coupling of the sample. It was concluded that

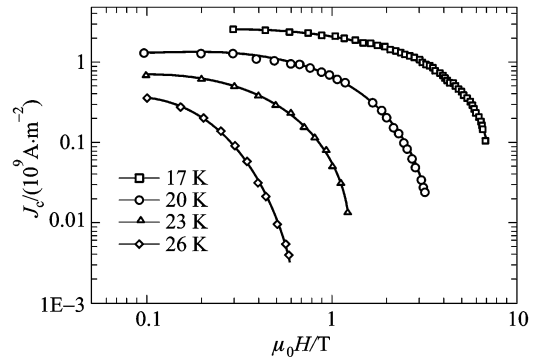


Fig. 2 The field dependence of critical current density for the $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ crystal at different temperatures. The solid line represents the fitting lines using Eq. (2)

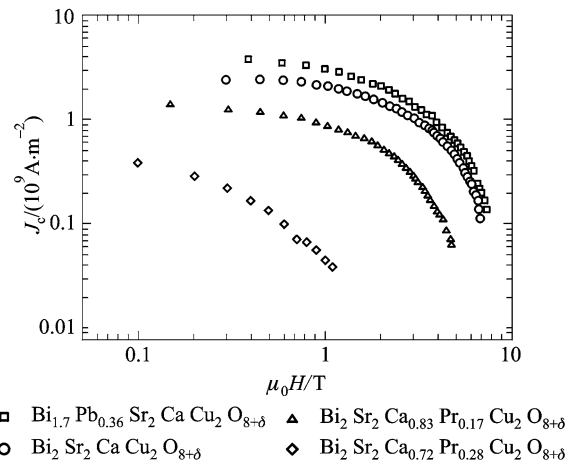


Fig. 3 The field dependence of critical current density for four crystals with different interlayer coupling strengths at 17 K

enhancing the interlayer coupling of the layer cuprates was an effective method in developing the critical current density of the superconductors.

Further analysis of Eq. (2) revealed that the resulting field dependence of J_c was the direct result of logarithm current dependence pinning potential. Considering the interaction among the vortex, Zeldov et al. [8,9] suggested that the vortex pinning potential can be expressed as

$$U(H, T, J) = F(T)H^{-\alpha} \ln\left(\frac{J_0}{J}\right) \quad (3)$$

where J_0 is the critical current density when the pinning potential U is zero, α is the parameter, and $F(T)$ expresses the temperature dependence of the pinning potential. The pinning potential decreased with an increase in temperature; obviously, $F(T)$ decreased when the temperature increased. Generally, J_0 is field and temperature dependent, and it can be approximately treated as constant considering that U is proportional to the logarithm of J_0 . The electric field E caused by vortex creep can be expressed as

$$E = E_0 \exp\left[-\frac{U(H, T, J)}{k_B T}\right] \quad (4)$$

When E is increased to the effective electric field criterion E_c , the resulting critical current density will be

$$J_c(H, T) = J_0 \exp\left[-\frac{k_B T}{F(T)} \ln\left(\frac{E_0}{E_c}\right) H^\alpha\right] \quad (5)$$

Equations (5) and (2) give identical field dependence of the critical current density, which implies that Eq. (3) expressed the relationship between the pinning potential and current density in our Bi2212 system. Compared Eq. (5) with Eq. (2), it can be found that $\beta = \frac{k_B T}{F(T)} \ln \frac{E_0}{E_c}$ making it

easy to understand the fact that the fitting parameter β decreased rapidly with the increase in temperature. It was noted that in the fitting results, α was almost temperature independent for Bi_{1.7}Pb_{0.36}Sr₂CaCu₂O_{8+ δ} and Bi₂Sr₂CaCu₂O_{8+ δ} samples, which indicates that the pinning potential expressed as production of temperature function and field function was practicable. Although α showed very weak temperature dependence for Bi₂Sr₂Ca_{0.83}Pr_{0.17}Cu₂O_{8+ δ} and Bi₂Sr₂Ca_{0.72}Pr_{0.28}Cu₂O_{8+ δ} crystals, compared with the temperature dependence of β , α can be approximately treated as a constant, and thus, Eq. (3) was applicable to those samples, which indicates that the previous discussions were consistent.

4 Conclusions

The critical magnetization current was investigated in

strengths. It was found that the interlayer coupling strength of cuprates was the determining factor for the critical current density of superconductors. The experimental results revealed that the critical current density was the exponential function of the applied field, indicating that there existed logarithm current-dependent pinning potential in Bi2212 crystals.

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References

1. Jung C.-U., Kim J.-Y., Kim M.-S., Park M.-S., Kim H.-J., Yao Y.-S., Lee S.-Y. and Lee S.-I., Synthesis and pinning properties of the infinite-layer superconductor Sr_{0.9}La_{0.1}CuO₂, *Physica. C*, 2001, 366: 299–305
2. Sun Y.-Q., Feng S.-J., Li G., Shi L. and Li X.-G., Investigation of the relationship between magnetic relaxation and CuO₂ interlayer coupling in high temperature superconductors, *Chin. Low Temp. Phys.*, 2002, 24: 87–90
3. Chong I., Hiroi Z., Izumi M., Shimoyama J., Nakayama Y., Kishio K., Terashima T., Bendo Y. and Takano M., High critical-current density in the heavily Pb-doped Bi₂Sr₂CaCu₂O_{8+ δ} superconductor: generation of efficient pinning centers, *Science*, 1997, 276: 770–773
4. Li X.-G., Sun X.-F., Fan X.-J., Zhao X. and Wu W.-B., Pr-doping effect on the depinning of vortices in Bi₂Sr₂Ca_{1-x}Pr_xCu₂O_y single crystals, *J. Appl. Phys.*, 2000, 87: 5567–5570
5. Sun X.-F., Zhao X., Wu W.-B., Fan X.-J. and Li X.-G., Growth of Bi₂Sr₂Ca_{1-x}Pr_xCu₂O_y single crystals from Bi-rich melts, *Physica. C*, 1998, 305: 227–232
6. Bean C.-P., Magnetization of high field superconductors, *Rev. Mod. Phys.*, 1964, 36: 31–37
7. Umezawa A., Crabtree G.-W., Liu J.-Z., Weber H.-W., Kwok W.-K., Nurez L.-H., Morun T. J., Sowers C.-H. and Claus H., Enhanced critical magnetization currents due to fast neutron irradiation in single-crystal YBa₂Cu₃O_{7+ δ} , *Phys. Rev.*, B, 1987, 36: 7151–7153
8. Zeldov E., Amer N.-M., Koren G., Gupta A., McElfresh M.-W. and Gambino R.-J., Flux creep characteristics in high-temperature superconductors, *Appl. Phys. Lett.*, 1990, 56: 680–682
9. Zeldov E., Amer N.-M., Koren G. and Gupta A., Flux creep in Bi₂Sr₂CaCu₂O_{8+ δ} epitaxial films, *Appl. Phys. Lett.*, 1990, 56: 1700–1702