Local magnetic properties of high-T_c superconductors probed by scanning SQUID microscopy

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Abstract

We have performed scanning SQUID (Superconducting QUantum Interference Device) microscopy (SSM) on the ac-surfaces of heavily Pb-doped Bi2212, $Bi_{1.6}Pb_{0.6}Sr_{1.8}CaCu_2O_y$, single crystals at low temperatures. The observed images demonstrated interlayer Josephson vortices below T_c. The value of c-axis penetration depth, λ_c, evaluated from the SSM images was 11.2 ± 0.7 μm, which is approximately one order of magnitude smaller than that of pure Bi2212 in the optimal doping regime. This clearly indicates that Pb doping substantially reduces the anisotropy of Bi2212.

Key words: High-T_c superconductivity; Scanning SQUID microscopy; Josephson vortex

1. Introduction

It is well known that high-T_c superconducting cuprates (HTSCs) consist of alternate stacking of superconducting CuO_2 and insulating blocking layers. The strength of interlayer coupling, which is a characteristic parameter used in the interlayer tunneling model, strongly affects the superconducting properties of HTSCs. The c-axis penetration depth, λ_c, and the Josephson plasma frequency, $\omega_p = c\lambda_c^{-1}\epsilon^{-1/2}$, where ϵ is the dielectric constant of interlayer medium and c is the speed of light, reflect this coupling. Scanning SQUID microscopy (SSM) is a powerful to visualize vortices trapped in superconducting materials [1,2]. In particular, it is possible to evaluated λ_c from an SSM image of Josephson vortices generated between CuO_2 sheets of HTSCs [3].

In this study, we have directly measured the c-axis penetration depth in Pb-doped Bi2212 using SSM. By controlling external magnetic fields, we succeeded in observing well-isolated Josephson vortices, from which we estimated λ_c as 11.2 ± 0.7 μm.

2. Experimental

Pb-doped Bi2212 single crystals were grown by the floating zone technique. The crystals were heat-treated at 400 °C for 72 hours in a quartz tube sealed with pure oxygen gas of effective pressure $P = 2.1$ atm. Magnetization measurements using a conventional SQUID magnetometer showed T_c(midpoint) = 65 K with $\Delta T_c < 5$ K. The prepared crystals were molded in an epoxy resin and then cut to expose cross-sectional edge surfaces (ac-plane).

The SSM employed in this experiment was basically same as that used in ref. [4]. The spatial resolution and

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the magnetic-flux sensitivity are 5 μm and 5 $\mu\Phi_0$ / $\sqrt{Hz}$, respectively, where Φ_0 is the flux quantum (2.07 $\times$ 10^{-15} Wb). The distance between pick-up coil and sample surface, z, was maintained at $\sim$ 5 μm.

3. Results and discussion

Fig. 1 shows a SSM image (300 μm $\times$ 60 μm) of Pb-doped Bi2212 crystal observed at 3 K, where brighter and darker contrasts denote positive and zero field perpendicular to the SQUID sensor plane, B_z. To investigate well-isolated Josephson vortices, the sample was field-cooled under $B = +\ 0.5\ \mu$T perpendicular to the surface, which almost cancels out the environmental field. By integrating observed B_z values around a vortex, it was confirmed that each one is a single vortex carrying $\Phi_0 = hc/2e$.

Then, we quantitatively analyze the magnetic-field distribution around a vortex in detail [3]. Fig. 2 plots a cross-sectional B_z profile along a line shown in Fig. 1 (solid line). Two parameters λ_c and z were obtained by fitting theoretical function described in ref. [3], where λ_a was assumed to be 0.2 μm [5]. Fig. 2 also includes a fitting curve with $\lambda_c = 12.5\ \mu$m and $z = 6.7\ \mu$m (dotted line). As can be seen, both curves coincide with each other very well. Statistical analysis of four B_z profiles yields $\lambda_c = 11.2 \pm 0.7\ \mu$m. This value is in good agreement with the reported data, $\lambda_c = 12.6\ \mu$m, estimated from the Josephson plasma frequency [6], and is approximately one order of magnitude smaller than that of pure Bi2212 in the optimal doping regime, reflecting that Pb doping substantially reduces the anisotropy of Bi2212.

4. Summary

We have successfully imaged well-isolated interlayer Josephson vortices in Pb-doped Bi2212 for the first time. The B_z profiles across vortices were well described by the theoretical function including λ_c and z parameters. The λ_c value deduced by the curve-fitting procedure is 11.2 $\pm$ 0.7 μm, which is almost identical to the literature data, 12.6 μm, estimated from the Josephson plasma frequency.

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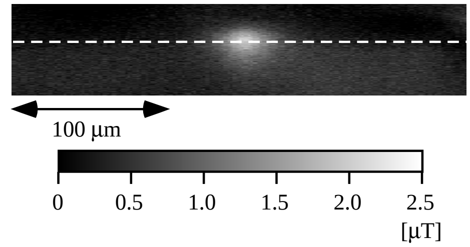

Fig. 1. SSM image of Pb-doped Bi2212 at 3 K. The external field is 0.5 μT. The scanning area is 300 μm $\times$ 60 μm.

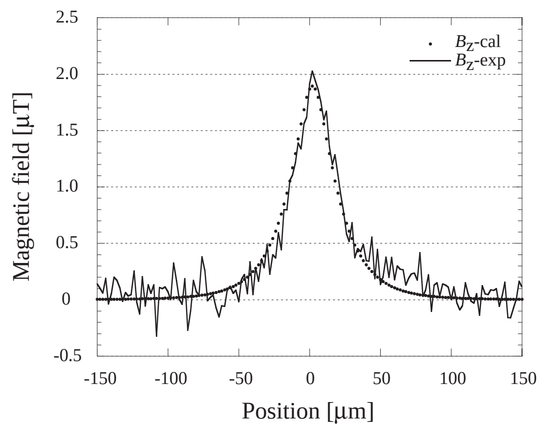

Fig. 2. Comparison of experimental and calculated B_z profiles around a vortex. The experimental one is a cross section along the line in Fig. 1. The penetration depth λ_c and the effective height z are assumed to be 12.5 μm, and 6.7 μm, respectively.

References

[1] K. A. Moler, J. R. Kirtley, D. G. Hinks, T. W. Li, M. Xu, Science**279** (1998) 1193-1196.

[2] J. R. Kirtley, K. A. Moler, G. Villard, A. Maignan, Phys. Rev. Lett.**81** (1998) 2140-2143.

[3] J. R. Kirtley, V. G. Kogan, J. R. Clem, K. A. Moler, Phys. Rev. B**59** (1999) 4343-4348.

[4] T. Morooka, S. Nakayama, A. Odawara, K. Chinone, Jpn. J. Appl. Phys.**38** (1999) L119-L121.

[5] O. Waldmann, F. Steinmeyer, P. Müller, J. J. Neumeier, F. X. Régi, H. Savary, J. Schneck, Phys. Rev. B**53** (1996) 11 825-11 830.

[6] T. Motohashi, J. Shimoyama, K. Kitazawa, K. Kishio, Phys. Rev. B**61** (2000) R9269-9272.