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Measurements of anisotropic characteristic lengths in YBCO films at microwave frequencies

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We used microwave self-resonant and magnetically modulated microwave absorption techniques to measure the London penetration depth, λ, and coherence length, ξ, in the direction parallel and perpendicular to the *a–b* plane of YBCO films. We found that both λ and ξ were anisotropic; it appeared that the value of $\lambda_{\parallel}$ (0) was about 1800 Å and $\lambda_{\perp}$ (86.5) about 26 000 Å, where $\lambda_{\parallel}$ is the penetration depth for the applied microwave electric field parallel and $\lambda_{\perp}$ perpendicular to the film plane (*c*-axis is perpendicular to the film plane). We deduced $\xi_{\parallel}$ to be equal to 129 Å and $\xi_{\perp}$ 40 Å at 86.5 K. The anisotropy factor γ we determined to be about 3.

I. INTRODUCTION

The London penetration depth, λ, and coherence length, ξ, are important parameters in a superconductor. For example, the London penetration depth which measures the length over which magnetic fields are attenuated near the surface of a superconductor, is related to the effective mass and density of superconducting pairs. The coherence length measures the size of Cooper pairs, or equivalently the size of the vortex flux quantum core. They are referred to in the literature as the characteristic lengths of superconductors. One of the key reasons why high T_c superconductors are different from conventional superconductors is that the high T_c superconductors have small coherence lengths[1] ($\sim$10 Å) compared to nonoxide superconductors[2] ($\sim$1000 Å).

There are many techniques[3–9] for measuring the penetration depth, such as muon-spin-rotation (μ^+SR), small angle neutron scattering, polarized neutron reflectometry, kinetic inductance, ac susceptibility, dc magnetization, and microwave cavity techniques. The measured values of penetration depth varies from sample to sample and sometimes from method to method.

The coherence length usually is deduced from the measurement of the upper critical magnetic field,[1] H_{c2}. However, H_{c2} of YBCO is extremely high (>100 T at 4.2 K). Typically, critical fields near T_c are measured in order to deduce ξ. Then, $\xi(0)$ is usually extrapolated from the formula[2] $\xi(T)=\xi(0)[1-(T/T_c)]^{-1/2}$.

For isotropic material, the Ginzburg–Landau parameter is defined as $\kappa=\lambda/\xi$, and readers are referred to some newly developed theories.[10] For anisotropic superconductors,[11] $\xi=(\xi_a\xi_b\xi_c)^{1/3}$ and $\lambda=(\lambda_a\lambda_b\lambda_c)^{1/3}$. Since $\xi_a\simeq\xi_b$, $\lambda_a\simeq\lambda_b$ for YBCO, the following definitions are introduced.[11,12]

$$\kappa_{\perp}=\frac{\lambda_{\parallel}}{\xi_{\parallel}}, \tag{1}$$

and

$$\kappa_{\parallel}=\sqrt{\frac{\lambda_{\parallel}\,\lambda_{\perp}}{\xi_{\parallel}\,\xi_{\perp}}}. \tag{2}$$

The relationships between them are

$$\kappa_{\parallel}=\gamma\kappa_{\perp}, \tag{3}$$

$$\xi_{\parallel}=\gamma\xi_{\perp}, \tag{4}$$

and

$$\lambda_{\parallel}=\frac{1}{\gamma}\lambda_{\perp}. \tag{5}$$

where γ is the anisotropy factor.

YBCO is an anisotropic material, and both the London penetration depth and coherence length are anisotropic. Their values depend on the direction of the microwave electric field relative to the *c* axis. In this paper, we used microwave self-resonant (MSR)[11] and magnetically modulated microwave absorption (MMMA)[12] techniques to deduce the London penetration depth and coherence length of YBCO films where the electric microwave fields are parallel and perpendicular to the film plane, respectively.

II. LONDON PENETRATION DEPTH DEDUCED FROM SURFACE IMPEDANCE

The YBCO films in our measurements were laser ablated with transition temperature $T_c\simeq 90$ K and the critical current density was of the order of 10^6 A/cm^2 at 77 K. The *c* axis was normal to the film plane.

The expression for the surface impedance is[11]

$$Z_s=\frac{i4\pi\omega\lambda}{c^2}\left(1-i\frac{c^2\rho}{4\pi\omega\lambda^2}\right)^{1/2}. \tag{6}$$

We can solve for the London penetration depth and obtain

$$\lambda=\frac{c^2}{4\pi\omega}\sqrt{X_s^2-R_s^2}, \tag{7}$$

where

$$R_s=\frac{4\pi\omega\lambda}{\sqrt{2}c^2}\left(\sqrt{1+\left(\frac{c^2\rho}{4\pi\omega\lambda^2}\right)^2}-1\right)^{1/2}, \tag{8}$$

and

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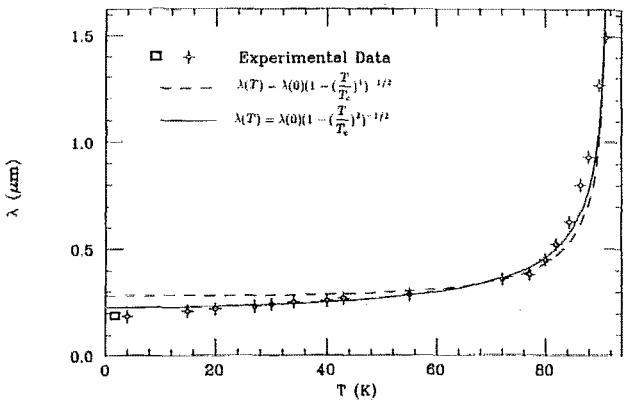

FIG. 1. London penetration depth as a function of temperature deduced from MSR and CPW techniques; the stars are from MSR and the square is from CPW. Dashed line is fitting with two fluid model, solid line is with $\lambda=\lambda(0)[1-(T/T_c)^2]^{-1/2}$.

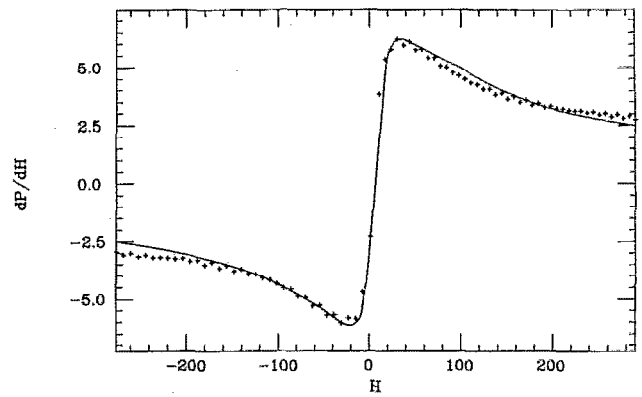

FIG. 2. dP/dH as a function of H by using MMMA technique. The points are experimental data and the curve is fitting with fluxoid model. From the curve fitting, $\lambda_\perp$ and $\xi_\perp$ can be obtained.

$$X_s=\frac{4\pi\omega\lambda}{\sqrt{2}c^2}\left(\sqrt{1+\left(\frac{c^2\rho}{4\pi\omega\lambda^2}\right)^2}+1\right)^{1/2}. \tag{9}$$

At low temperatures, the surface reactance is dominant; $X_s \gg R_s$; therefore,

$$\lambda=\frac{c^2}{4\pi\omega}X_s=\frac{c^2}{4\pi}L_s, \quad T\ll T_c. \tag{10}$$

We used (7) to calculate the London penetration depth by using the surface resistance and surface reactance values deduced from our MSR measurement,[11] where the electric microwave field was parallel to the film plane. We denoted the penetration depth from this MSR technique as $\lambda_\parallel$. Typical values of $\lambda_\parallel$ were 1800 Å at 4 K and 8000 Å at 86.5 K, for example. In Fig. 1 we have plotted λ values deduced from MSR data. We also have superimposed the value of $\lambda(0)$ obtained from the shift in the resonant frequency with temperature using a CPW resonator.[7] We have fitted λ to the Gorter–Casimir two fluid model,[2]

$$\lambda(T)=\lambda(0)\left[1-\left(\frac{T}{T_c}\right)^4\right]^{-1/2}. \tag{11}$$

The results are shown in Fig. 1 with a dashed line. If we change the power factor in (11) from 4 to 2,

$$\lambda(T)=\lambda(0)\left[1-\left(\frac{T}{T_c}\right)^2\right]^{-1/2}, \tag{12}$$

we obtain a better fitting curve (see solid line in Fig. 1).

The penetration depth was also measured by using the MMMA technique, where the microwave electric field was perpendicular to the film plane. The microwave power absorbed by the film was

$$P=C_1|B|\left[1-\left(\frac{\delta_1 D}{\xi^2}+\frac{\delta_1^2}{2\xi^2}\right)\exp(-2D/\delta_1)+\left(\frac{\delta_1}{\xi}+\frac{\delta_1^2}{2\xi^2}\right)\exp(-2\xi/\delta_1)\right], \tag{13}$$

where C_1 is a microwave e-field dependent parameter, B is the magnetic flux density, D is the flux lattice constant evaluated as $1/D^2=|B|/\phi_0$, and

$$\frac{1}{\delta_1^2}=\frac{1}{\delta_0^2}+\frac{1}{\lambda^2}, \tag{14}$$

where δ_0 is the normal skin depth. In the MMMA experiment we measured dP/dH or

$$\frac{dP}{dH}=\frac{dP}{dB}\frac{dB}{dH}. \tag{15}$$

dP/dB was calculated from Eq. (13), and dB/dH was obtained from vibrating-sample magnetometer (VSM) measurement of M vs H. Figure 2 shows measured and calculated dP/dH as a function of H. In this fit, we determined $\lambda_\perp \simeq 26000$ Å at 86.5 K.

III. DETERMINATION OF COHERENCE LENGTH

We have measured the coherence length of YBCO films by means of the MSR technique. From the surface impedance given in (8) and (9), we can calculate the normal resistivity of the superconducting film and it yields

$$\rho=\frac{c^2}{2\pi\omega}X_sR_s=\frac{c^2}{2\pi}L_sR_s. \tag{16}$$

In deducing $\xi_\parallel$ from the MSR technique we needed to apply a magnetic field, H, parallel to the c axis or perpendicular to the film plane. From the microwave transmission coefficient data, we measured only the peak values at resonance. The surface resistance R_s changed as H was varied. The surface inductance L_s, remained constant for fields up to 3 KG, since f_0 remained constant with H. Hence, the change of resistivity due to the applied magnetic field may be expressed as follows:

$$\Delta\rho=\frac{c^2}{2\pi}L_s\Delta R_s. \tag{17}$$

Using this equation, we can calculate the change of resistivity of the superconducting film through the measured

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TABLE I. Summary of λ, ξ, and κ.

T (K)	$\lambda_{\parallel}$ (Å)	$\xi_{\parallel}$ (Å)	$\kappa_{\perp}$	$\lambda_{\perp}$ (Å)	$\xi_{\perp}$ (Å)	$\lambda_{\perp}/\xi_{\perp}$	$\kappa_{\parallel}$
86.5	8000[a]	129[a]	62	26000[b]	40[b]	650	200
0	1800[a]	25[a,c]	72		8[b,c]		

[a]MSR result.
[b]MMMA result.
[c]Extrapolated from 86.5 K with $\xi(T)=\xi(0)[1-(T/T_c)]^{-1/2}$. The accuracy of our measurement was within $\pm 5\%$.

values of surface resistance changes due to the applied external magnetic fields. Using the Bardeen–Stephens relationship

$$\Delta\rho=\frac{\pi\xi^2 B}{\phi_0\sigma_n} \tag{18}$$

and (17), we determined $\xi_{\parallel}=129$ Å at 86.5 K, where we treated B as approximately equal to H. Below 77 K, we were not able to measure significant changes in R_s with respect to the application of a magnetic field, hence, no estimate of $\xi_{\parallel}$ was obtained. We extrapolated our results to $T\rightarrow 0$ K by using the relation

$$\xi=\xi(0)\left(1-\frac{T}{T_c}\right)^{-1/2}, \tag{19}$$

and found that $\xi_{\parallel}$ (0) to be 25 Å. The coherence length in the c-axis direction was deduced from MMMA measurement, where the microwave induced electric field was along the c axis. From the fitting curve in Fig. 2, we obtained $\xi_{\perp}$ (86.5 K)=40 Å, and therefore, $\xi_{\perp}$ (0)=8 Å. Together with the London penetration depths deduced from surface impedance, we calculated the Ginzburg–Landau parameters, and $\kappa_{\perp}$ was in the range of 62–72 while $\kappa_{\parallel}$ was about 200. In Table I we report our deduced values of $\xi_{\parallel}$, $\xi_{\perp}$, $\lambda_{\parallel}$, $\lambda_{\perp}$, $\kappa_{\parallel}$, and $\kappa_{\perp}$ from our MSR and MMMA measurements.

IV. DISCUSSION AND CONCLUSION

Based upon our measurements of surface impedance using a microwave self-resonant technique, we have deduced the London penetration depth in the a–b plane of a superconducting YBCO film. Application of a magnetic field allowed us to deduce the coherence length in the a–b plane as well. MMMA results provided the London penetration depth and coherence length in the c-axis direction. The values of λ and ξ are anisotropic and depend on the direction of electric field or current relative to the c axis. At 86.5 K, $\xi_{\parallel}=129$ Å and $\lambda_{\parallel}=8000$ Å while $\xi_{\perp}=40$ Å and $\lambda_{\perp}=26\,000$ Å. At 0 K, $\xi_{\parallel}$ (0)=25 Å and $\lambda_{\parallel}$ (0)=1800 Å while $\xi_{\perp}$ (0)=8 Å. The Ginzburg–Landau parameters are $\kappa_{\parallel}$ about 200 and $\kappa_{\perp}$ in the range of 62–72, respectively. These yield an anisotropy factor of γ about 3.

We do not believe that the above values of ξ's represent their intrinsic limit. For example, we measured $\lambda_{\parallel}\simeq 1800$ Å at 4 K. However, others[9] have reported $\lambda_{\parallel}$ (0) as low as 1400 Å. If we assume the latter value of $\lambda_{\parallel}$ to be intrinsic, we extrapolate the following values for $\xi_{\parallel}$ and $\xi_{\perp}$, respectively, at 0 K: 19 and 6 Å.

[1] U. Welp, W. Kwok, G. Crabtree, K. Vandervoort, and J. Liu, Phys. Rev. Lett. **62**, 1908 (1989).
[2] A. C. Rose-Innes and E. H. Rhoderick, *Introduction to Superconductivity* (Pergamon, Oxford, 1978).
[3] G. Aeppli, R. J. Cava, E. J. Anasaldo, J. H. Brewer, S. R. Kreitzman, G. M. Luke, D. R. Noakes, and R. F. Kiefl, Phys. Rev. B **35**, 7129 (1987).
[4] D. W. Cooke, R. L. Hutson, R. S. Kwok, M. Maez, H. Rempp, M. E. Schillace, J. L. Smith, J. O. Willis, R. L. Lichti, K-C. B. Chan, C. Boekema, S. P. Weathersby, J. A. Flint, and J. Oostens, Phys. Rev. B **37**, 9401 (1988).
[5] E. M. Jackson, S. B. Liao, J. Silvis, A. H. Swihart, S. M. Bhagat, R. Crittenden, and R. E. Glover, Physica C **152**, 125, (1988).
[6] A. Fiory, A. Hebard, P. Mankiewich, and R. Howard, Phys. Rev. Lett. **61**, 1419 (1988).
[7] H. How, R. Seed, C. Vittoria, D. Chrisey, J. Horwitz, C. Carosella, and V. Folen, IEEE MTT **40**, 1668 (1992).
[8] D. Wu, W. Kennedy, C. Zahopoulos, and S. Sridhar, Appl. Phys. Lett. **55**, 698 (1989).
[9] L. Krusin-Elbaum, R. Greene, F. Holtzberg, A. Malozemoff, and Y. Yeshurun, Phys. Rev. Lett. **62**, 217 (1989).
[10] M. W. Coffey and J. R. Clem, Phys. Rev. Lett. **67**, 386 (1991); Phys. Rev. B. **45**, 9872 (1992); **45**, 10527 (1992); **46**, 11757 (1992).
[11] J. R. Clem, Supercond. Sci. Tech. **5**, S33 (1992).
[12] P. de Trey and Suso Gygax, J. Low Temp. Phys. **11**, 421 (1973).
[13] H. Jiang, T. Yuan, H. How, A. Widom, and C. Vittoria, *Layered Superconductors: Fabrication, Property, and Applications*, edited by D. T. Shau, C. C. Tsuei, T. R. Schmeider, and Y. Shiohara, MRS, 1992, p. 407; H. Jiang, Doctoral dissertation, Northeastern University, 1992.
[14] R. Karim, C. Vittoria, A. Widom, D. Chrisey, and J. Horwitz, J. Appl. Phys. **69**, 4891 (1991).

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