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# Magnetically modulated microwave absorption measurement of the penetration depth in a polycrystalline $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ thin film

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In previous work, a magnetically modulated microwave absorption (MMMA) technique to measure the Ginzburg–Landau parameter  $\kappa = (\Lambda/\xi)$  in high- $T_c$  superconductors (bulk samples of YBCO) was described. In this work, how this technique can be applied to the measurement of the London penetration depth  $\Lambda$  is described. Data are reported for the temperature variation of  $\Lambda$  in a well-characterized  $c$ -axis-oriented polycrystalline thin film of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ , prepared by a pulsed laser deposition technique. For low temperatures,  $\Lambda(0) \simeq 3640 \text{ \AA}$  with the microwave electric field oriented parallel to the  $c$  axis. The temperature dependence of  $\Lambda(0)/\Lambda(T)$  can be well described by the two-fluid model. The data are also reasonably fit by a BCS model, however the MMMA technique (in the work here reported) does not have the resolution at low temperatures to obtain strong quantitative evidence for an energy gap  $\Delta$  (even if it exists).

## I. INTRODUCTION

Until such time as a generally accepted microscopic theory of high- $T_c$  superconductors is obtained, one can presently think about these superconductors from the viewpoint of the phenomenological Ginzburg–Landau model. In such a model, the parameters of importance are the London penetration depth  $\Lambda$  and the coherence length  $\xi$ . In previous work,<sup>1,2</sup> it was shown how the value of  $\kappa = (\Lambda/\xi)$  can be obtained from the hysteretic  $B$ - $H$  curves of the superconductor as measured by the magnetically modulated microwave absorption (MMMA) technique. The work is here extended in order to illustrate how this technique can be applied to measure the penetration depth  $\Lambda$  itself. The sample was a YBCO film fabricated by a pulsed laser deposition technique.<sup>3</sup>

From the temperature variations of  $\Lambda$  it is tempting to quote a BCS gap parameter  $\Delta$ , but the literature contains many conflicting results.<sup>4–11</sup> The problem with microwave determinations of  $\Delta$  from measured values of the London penetration depth is that resolution is often lost for small changes in  $\Lambda$  when the temperature  $T$  is appreciably below  $T_c$ . Although the data often has high resolution as  $T \rightarrow T_c$  the temperature dependence of  $\Delta$  then also becomes important in this regime yielding a difficulty in determining  $\Delta(0)$ . Furthermore, the temperature dependence of  $\Delta$  is not expected to be simple if the gap is anisotropic due to the intrinsic anisotropy of high- $T_c$  superconductors.

Unfortunately, these problems also exist in the present MMMA measurements. Thus, the positive features of the experimental technique are that the Ginzburg–Landau parameters  $\Lambda$  and  $\xi$  can be obtained as well as information on hysteretic  $B$ - $H$  curves. The negative feature (shared by other microwave measurement techniques) is that for  $T \ll T_c$  the temperature variations of these parameters are not well enough resolved to make definitive statements on

the nature (or existence) of an energy gap  $\Delta$ .

Data for the penetration depth will be presented for a well-characterized YBCO thin film with a  $c$ -axis orientation. The data is fit very well by a simple two-fluid model.

## II. THEORY

The magnetic equation of state of a superconducting sample can be computed from the thermodynamic law

$$\delta F = (1/4\pi) \int d^3r H \delta B, \quad (1)$$

where we choose the Ginzburg–Landau free energy (in terms of the complex pairing field  $\psi$ ) as

$$\begin{aligned} F = & (1/4\pi) \int d^3r |B|^2 + \int d^3r f(|\psi|^2, T) \\ & + (\hbar^2/2M) \int d^3r \{ \alpha |(\nabla_c - (iq/\hbar c)A_c)\psi|^2 \\ & + (1 - \alpha) |[\nabla_p - (iq/\hbar c)A_p]\psi|^2 \}, \end{aligned} \quad (2a)$$

where  $q = 2e$  is the electron-pair charge,  $M = 2m$  is the electron-pair mass, and  $\alpha$  is the anisotropy parameter which distinguishes the  $c$  direction (perpendicular to the easy-pair flow planes) from the  $p$  directions (parallel to the easy-pair flow planes). The free-energy density  $f$  defines the intrinsic correlation length  $\xi$  and penetration depth  $\lambda$  via

$$\begin{aligned} f(|\psi|^2, T) = & - (\hbar^2/4M\xi^2) |\psi|^2 \\ & + (\pi/2) (\hbar q \lambda / M c \xi)^2 |\psi|^4. \end{aligned} \quad (2b)$$

In the microwave cavity the electric field  $c$  direction for the experiment dictates a measurement of the penetration depth

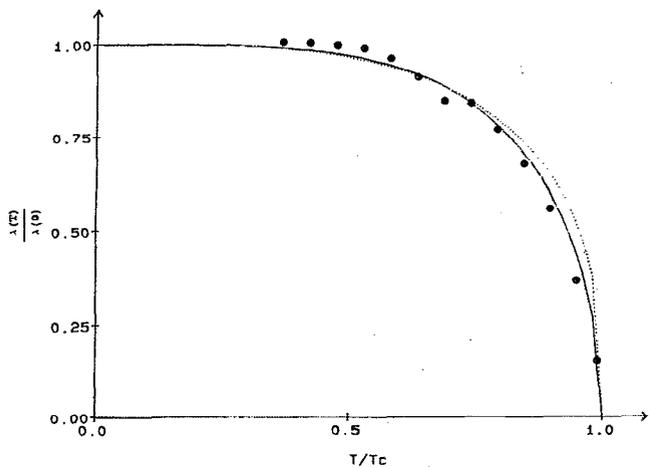


FIG. 1. The MMMA signal is shown for various various temperatures as a function of  $H$ .

$$\Lambda = (\lambda/\alpha^{1/2}), \quad (3)$$

which is presumably larger than that which would be measured for electric fields in the  $p$  directions. As  $H \rightarrow H_{c1} + 0^+$  the equation of state is well known to be

$$B \rightarrow (2\phi_0/3^{1/2}\Lambda^2) (\ln\{3\phi_0/[4\pi(H - H_{c1})]\})^{-2}. \quad (4)$$

For the magnetic-field-induced resistivity of the superconductor we follow the Bardeen-Stevens theory, i.e.,

$$\rho_n = (AB/\phi_0\sigma), \quad (5)$$

where  $A$  is the effective cross sectional area of a normal region at the center of a vortex,  $\phi_0$  is the magnetic flux

quantum carried by the vortex, and  $\sigma$  is the conductivity of the normal region. Equation (5) is equivalent to a surface impedance of

$$Z = - (4\pi\omega/c^2) [\Lambda^2 + i(c^2\rho_n/4\pi\omega)]^{1/2} = R - iX. \quad (6)$$

The MMMA technique directly probes the differential absorption

$$\left(\frac{\partial R}{\partial H}\right) = \left(\frac{\partial B}{\partial H}\right) \left(\frac{\partial R}{\partial B}\right). \quad (7)$$

From Eqs. (5), (6), and (7), information concerning magnetic equations of state  $\mu = (\partial B/\partial H)$  and  $\Lambda$  (via  $\partial R/\partial B$ ) are obtained from the experimental  $(\partial R/\partial H)$ .

### III. EXPERIMENT

Thin-film polycrystalline samples of  $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$  were prepared (using the pulsed laser deposition technique) with a thickness of  $\sim 5000 \text{ \AA}$ . Typical film samples (having an area of  $\sim 1 \text{ cm}^2$ ) were deposited on polished  $\text{MgO} \langle 100 \rangle$  substrates at  $T = 775 \text{ }^\circ\text{C}$  and then quenched *in situ*. X-ray diffraction measurements indicate the sample to be  $c$ -axis oriented with the  $c$  direction perpendicular to the substrate plane. Room-temperature resistivity (using four-probe measurements) was found to be  $\sim 360 \mu\Omega \text{ cm}$ . The critical current density at  $T = 77 \text{ K}$  was found to be  $1.5 \times 10^6 \text{ A/cm}^2$ . The critical temperature was  $T_c = 95 \text{ K}$ .

The MMMA measurements were performed using a standard Varian E-line EPR spectrometer operating in the x band. The sample, 2 mm wide and 1 cm long, was placed in the center of the  $\text{TE}_{102}$  cavity, where the microwave magnetic field is a maximum. The dc field and the modulating field were oriented normal to the film (i.e., along the  $c$  axis). The sample was cooled through  $T_c$  after

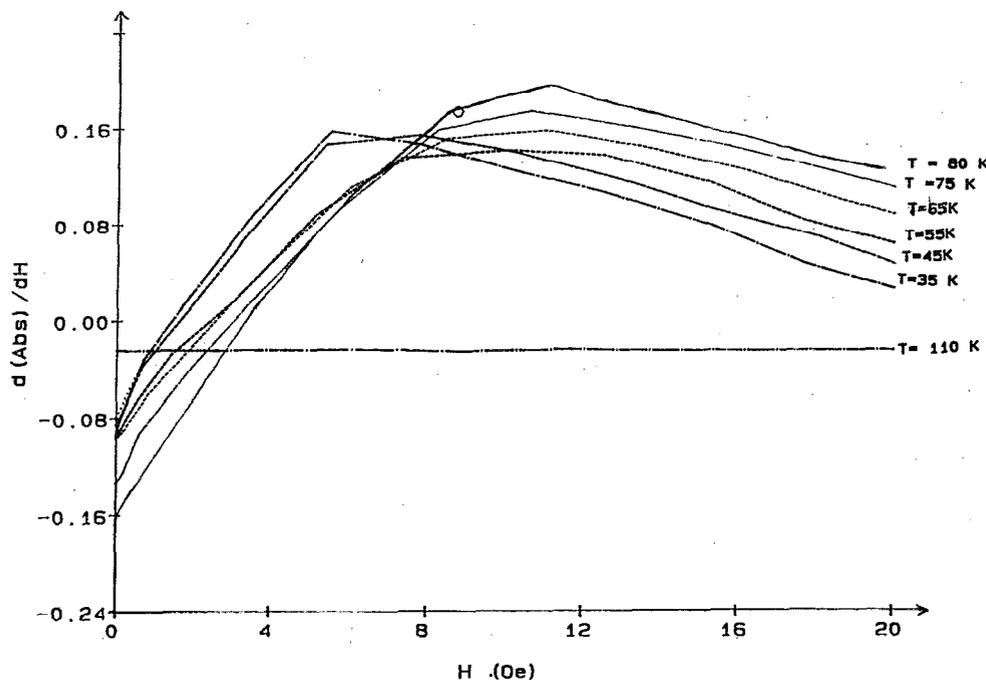


FIG. 2. The temperature dependence of the London penetration depth is compared with the two-fluid model (solid curve) and the BCS model (dotted curve).  $\Lambda(0) \approx 3640 \text{ \AA}$ .

which the temperature was held fixed, while the field-swept runs were performed. The derivative of the MMMA absorption signal [i.e., magnetically modulated microwave absorption  $\propto (\partial R/\partial H)$ ] was recorded as a function of dc magnetic intensity  $H$ , beginning each run at  $H=0$ . The 100-kHz modulating field was held at an amplitude of 2 G (peak to peak) for all measurements. In addition to the MMMA signal, the automatic (AFC) voltage was also monitored. The AFC voltage is proportional to the frequency shift in the cavity, and is a measure of the dispersion.

#### IV. RESULTS

In deducing  $\Lambda(T)$  from the measurement of  $\partial R/\partial H$  as a function of magnetic field at a given temperature  $T$ , it is only necessary to make use of data points  $(\partial R/\partial H)_1$  and  $(\partial R/\partial H)_2$  measured at  $H_1$  and  $H_2$ , respectively. For convenience we choose  $H_1$  and  $H_2$  to be slightly above  $H_{1c}$ , the lower critical field. At  $H \simeq H_{1c}$ ,  $(\partial R/\partial H)$  is at maximum, as in Fig. 1. The functional dependencies between  $\Lambda$  and  $(\partial R/\partial H)$  are as follows:

$$\Lambda^{2(\beta-1)} = (1/Q) [3\phi_0/4\pi(H_2 - H_{c1})]^{(\beta-1)}, \quad (8a)$$

$$Q = (H_2 - H_{c1}) / (H_1 - H_{c1}), \quad (8b)$$

$$\beta = (1/Q) (B_1/B_2)^2 \left[ \left( \frac{\partial R}{\partial H} \right)_1 / \left( \frac{\partial R}{\partial H} \right)_2 \right], \quad (8c)$$

$$B_i = (2\phi_0/3^{1/2}\Lambda^2) (\ln\{3\phi_0/[4\pi\Lambda^2(H_i - H_{c1})]\})^{-2}, \quad (8d)$$

for  $i=1$  and  $2$  as in Eq. (4). Eqs. (8) are solved for  $\Lambda$  in terms of the experimental parameters by an iterative procedure.

In Fig. 2 the experimental result for  $[\Lambda(0)/\Lambda(T)]$  are

shown, and compared with a simple two-fluid model,

$$[\Lambda(0)/\Lambda(T)] = [1 - (T/T_c)^4]^{1/2}. \quad (9)$$

The two-fluid model fits the data somewhat better than the BCS model (also shown in Fig. 2),

$$[\Lambda(0)/\Lambda(T)] \simeq \{[\Delta(0)/\Delta(T)] \times \tanh[0.88T_c\Delta(T)/(T_c - T)\Delta(0)]\}^{-1/3}, \quad (10)$$

but for reasons discussed in Sec. I we do not take seriously the comparison as a strong test for the existence, nonexistence, or the particular values of the energy gap. Such a statement would require more experimental resolution for  $T \ll T_c$  than is presently available using our MMMA method.

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