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Magnetic Penetration Depth Measurements in Low and High T_c Thin Film Superconductors at Microwave Frequencies

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The microstrip resonator technique can be used to measure the absolute value and temperature dependence of λ(T) in superconducting thin films. The zero temperature penetration depth is sensitive to the microstructure and orientation of the grains in the oxide superconducting films. The microstrip transmission line technique allows one to precisely measure the low temperature dependence of λ(T) and provides a means for extracting an energy gap Δ(0) of the superconducting films.

The value of the magnetic penetration depth λ at zero temperature is one of the fundamental length scales of superconductivity and is quite sensitive to the quality of the material near the surface. Materials with microstructure which impedes the flow of shielding currents will have penetration depths significantly larger than those of a perfect material. The temperature dependence of the penetration depth is sensitive to the microstructure of the material and the superconducting energy gap.[1]

Our measurement of the magnetic penetration depth in superconductors is achieved by measuring the characteristics of a superconducting transmission line operating at microwave frequencies.[2] The phase velocity for quasi-TEM modes propagating down a microstrip line is,[2,3]

$$v_{phase} = \frac{1}{\sqrt{LC}} = \frac{c/\sqrt{\varepsilon_r}}{\sqrt{1 + \frac{2\lambda \coth t/\lambda}{d}}} \qquad (1)$$

where t is the thickness of the (assumed identical) films, d is the dielectric thickness and ε_r is the relative effective dielectric constant of the microstrip. Hence by measuring the phase velocity as a function of temperature and knowing the microstrip parameters t, d and ε_r, one can determine the penetration depth using equation (1). Details of the data extraction procedure are given in ref. 2.

In practice, the superconducting microstrip transmission lines are made in a flip-chip geometry using two identically prepared films. The films are clamped together with a dielectric material in between. Thin films of Nb, 500Å thick, were deposited on 1-102 sapphire in a UHV electron beam evaporation system. Measurements of the magnetic penetration depth in Nb show a zero temperature value and temperature dependence comparable to those predicted by BCS theory.[2]

Oxide superconductor films of $YBa_2Cu_3O_{7-\delta}$ have been made by two techniques. Some films were electron beam co-evaporated from Y, BaF_2 and Cu targets onto (100) $LaAlO_3$ substrates and post-annealed at 850C in H_2O saturated oxygen.[4] These films showed c-axis orientation in x-ray diffraction. Films were also prepared by a single target *in-situ* off-axis sputtering technique.[5] These films were prepared on MgO and $LaAlO_3$ substrates and showed varying amounts of c-axis and a-axis oriented grains.

Results of the penetration depth measurements of these films are summarized in Table I. The temperature dependence of all films measured was

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approximated well by the empirical two-fluid dependence, $\lambda(T)=\lambda(0)/(1-(T/Tc)^4)^{1/2}$. Values of the zero temperature penetration depth scale roughly with the value of the resistivity at 100 K, ρ_{100}, and the abundance of a-axis oriented grains.

Table I Results of penetration depth measurements in $YBa_2Cu_3O_{7-\delta}$ thin films.

Film	a/c abundance	Tc(R=0) (K)	Tc(1/λ=0) (K)	ρ_{100} (μΩcm)	dρ/dT (μΩcm/K)	λ(0) Å
688126 post-annealed	c	86.5	86.3	150	1.4	3650
64 in-situ	c	80.6	80.6	150	1.1	2550
127 in-situ	10% a	74.0	72.0	175	1.6	5490
202 in-situ	70% a	77.0	75.5	350	1.5	6680

Measurements by others of the penetration depth in single crystal and very thin c-axis films of YBCO yield a value for $\lambda(T=0)\approx 1400$ Å.[6] The larger values for λ(0) measured here can be explained by several effects, including the presence of a-axis grains in the film (which increase in abundance as the film thickness increases) and grain boundary weak links that exist between grains in the YBCO thin films.[2,7]

In the BCS theory, λ(T) depends on a number of parameters, including the London penetration depth λ_L, coherence length ξ_0, mean free path ℓ, zero temperature energy gap Δ(0) and T_c. At low temperatures, in the local limit, the BCS penetration depth has a simple dependence,[1]

$$\frac{\lambda(T)}{\lambda(0)} - 1 \propto e^{-\Delta(0)/k_B T} \qquad (T < T_c/2) \qquad (2)$$

Measurements of the penetration depth in Nb between 2K and 4K when plotted to show the exponential relaxation of λ(T) to λ(0) (Eq. (2)), give a value for $2\Delta(0)/k_B T_c = 3.2$ (Fig. 1a). The value of the activation energy is not sensitive to the T_c chosen or the value of λ(0). Values of $2\Delta(0)/k_B T_c = 3.7$ for Nb have been reported by tunneling measurements.[8] Measurements of the low temperature dependence of λ(T) in YBCO films do not show a simple single exponential decay like that seen in Nb (Fig. 1b). If the data is forced to fit the dependence of Eq. (2), one finds values of $2\Delta(0)/k_B T_c < 2$.

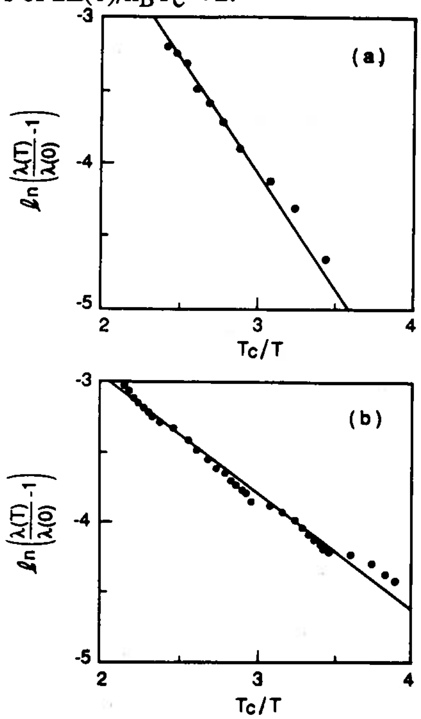

Fig. 1. Plot of $\ln(\lambda(T)/\lambda(0) - 1)$ versus T_c/T for a) Nb and b) YBCO (film 202) thin films.

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