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TEMPERATURE DEPENDENCE OF THE MAGNETIC PENETRATION DEPTH IN Nb, NbCN AND $YBa_2Cu_3O_{7-\delta}$ THIN FILMS

S. M. Anlage*, B. W. Langley*, G. Deutscher+, R. W. Simon#, J. M. Murduck#, C.-B. Eom*, M. R. Beasley* and T. H. Geballe*

* Department of Applied Physics, Stanford University, Stanford, California, 94305 USA; + School of Physics and Astronomy, Tel Aviv University, Tel Aviv, 69978, Israel; # TRW Space & Technology Group, Redondo Beach, CA, USA

We utilize the microstrip resonator technique to measure with very high sensitivity the magnetic penetration depth in thin film samples of Nb, NbCN and $YBa_2Cu_3O_{7-\delta}$. The penetration depth data for the low-T_c superconductors can be fit very well to a single-gap BCS temperature dependence using measured parameters. The temperature dependence of the $YBa_2Cu_3O_{7-\delta}$ data cannot be fit to a single-gap BCS temperature dependence, but may require a multiple gap fit.

A simple way to determine the magnetic penetration depth λ of a superconductor is to measure the inductance of the material in the thin film geometry. Since the film thickness can be adjusted to be on the order of λ, the changes in inductance associated with a change in temperature can be quite large. The total inductance is the sum of two parts, magnetic and kinetic. The magnetic inductance is associated with magnetic fields created in the region around and inside the film when a current passes through the film. This part of the inductance depends on the distance to nearby conductors and other irrelevant geometrical parameters, but also depends on λ through the amount of flux stored in the superconducting film. The kinetic inductance (for a film of thickness small compared to λ) is proportional to λ^2 divided by the cross sectional area of the film (1,2). Hence for suitable thin film geometries, this part of the inductance can be made large and very sensitive to the magnetic penetration depth.

A common technique to measure the inductance is to put the film into an electrical circuit and measure a property of that circuit which depends on the inductance. The phase velocity per unit length for a signal propagating on a lossless transmission line is simply $v_{Ph} = 1/(LC)^{1/2}$, where L is the series inductance and C is the shunt capacitance per unit length. For a wide superconducting microstrip transmission line made up of two identical films of thickness t and penetration depth $\lambda(T)$ separated by a dielectric of thickness d, this becomes (3),

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

This phase velocity can be measured more easily as the resonant frequency of a finite section of transmission line, terminated by large impedance mismatches (4). Resonant frequencies are typically in the range 1 to 5 GHz and resonator Q's are in the range of several hundred to over 10,000.

To determine $\lambda(T)$ from Eq. (1), one needs to know the film and dielectric thicknesses t and d, and the relative dielectric constant ε_r. In practice, the dielectric constant proves to be difficult to measure at microwave

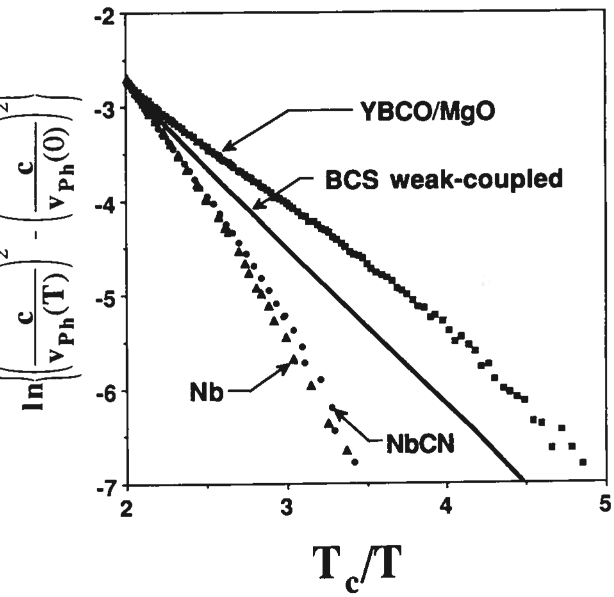

FIGURE 1
Measured phase velocity data presented as suggested by Eq. (2) vs. T_c/T for Nb, NbCN, *in-situ* sputtered $YBa_2Cu_3O_{7-\delta}$ films, as well as the BCS weak-coupling temperature dependence.

frequencies and low temperatures. This in turn makes it difficult to accurately invert Eq. (1) and solve for the penetration depth exactly. One can avoid all these problems by examining just the low temperature dependence of $\lambda(T)$ directly in a way which is independent of geometry, dielectric properties, and any assumption for the form of $\lambda(T)$. Re-writing Eq. (1) in the low temperature limit, for thick and thin films, one has (5),

$$\ln\left\{\left(\frac{c}{v_{Ph}(T)}\right)^2-\left(\frac{c}{v_{Ph}(0)}\right)^2\right\}=\ln\left(\frac{\lambda(T)}{\lambda(0)}-1\right)+\text{const.}\left(T<\frac{T_c}{2}\quad \begin{matrix} t<\frac{\lambda}{2} \\ t>\frac{3\lambda}{2}\end{matrix}\right) \qquad (2)$$

Hence by plotting the measured phase velocity data in the way suggested by Eq. (2), one has a direct measure of the deviation of the penetration depth from its zero temperature value, $(\lambda(T)/\lambda(0) - 1)$. An exponential dependence of the penetration depth at low temperatures, $(\lambda(T)/\lambda(0)-1) \propto T^{-1/2}\, e^{-\Delta(0)/k_BT}$, will show up roughly as a straight line of slope $-\Delta(0)/k_BT_c$ when the data is plotted against T_c/T (see Figure 1; note that only the slopes of the lines have physical meaning on this plot). The data for Nb and NbCN films (6) show straight lines for $T_c/T>2$ (as well as the BCS weak-coupled theoretical temperature dependence (7)) with low-temperature slopes $2\Delta(0)/k_BT_c< 5.1\pm1.5$ and $< 4.6\pm0.8$ respectively. These estimates of $2\Delta(0)/k_BT_c$ are large because the

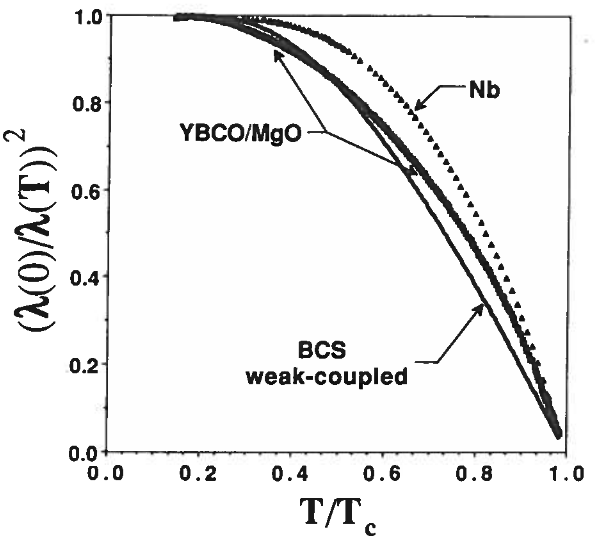

FIGURE 2
Plot of self-consistently calculated penetration depth data $(\lambda(0)/\lambda(T))^2$ vs. T/T_c for for Nb, *in-situ* sputtered $YBa_2Cu_3O_{7-\delta}$ films, and the BCS weak-coupling temperature dependence.

resolution limit is reached at low temperatures (4), hence the slopes are not evaluated entirely in the range $T<T_c/2$. The data for a representative $YBa_2Cu_3O_{7-\delta}$ film on MgO (8) has a low-temperature slope of $2\Delta(0)/k_BT_c= 2.5\pm0.3$.

The high temperature data is best examined by plotting $(\lambda(0)/\lambda(T))^2$ vs T/T_c. We have developed a method to convert the measured $v_{Ph}(T)$ data into $\lambda(T)$ (4,5). The results are shown in Fig. 2. We find that the best fits to the Nb and NbCN data come from a BCS temperature dependence with a single gap of $2\Delta(0)/k_BT_c$ = 4.25 and 4.75 respectively (9). However, the $YBa_2Cu_3O_{7-\delta}$ data cannot be fit over the entire temperature range with a single gap BCS temperature dependence. We are currently investigating ways of fitting the $YBa_2Cu_3O_{7-\delta}$ data with composite temperature dependences. The existence of two or more energy gaps in the temperature dependence of $\lambda(T)$ in $YBa_2Cu_3O_{7-\delta}$, and their physical meaning, will be addressed in future publications.

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REFERENCES

(1) R. Meservey and P. M. Tedrow, J. Appl. Phys. 40, 2028 (1969).
(2) S. M. Anlage, H. J. Snortland and M. R. Beasley, IEEE Trans. Magn. MAG-25, 1388 (1989).
(3) R. E. Matick, Transmission Lines for Digital and Communication Networks, (McGraw-Hill, New York, 1969), p. 243.
(4) S. M. Anlage, et al. Appl. Phys. Lett. 54, 2710 (1989); S. M. Anlage, B. W. Langley and M. R. Beasley, to be submitted to Rev. Sci. Instrum.
(5) S. M. Anlage, et al. Proceedings of Symposium S, Spring MRS Meeting, San Francisco, 1990; S. M. Anlage, et al. J. Supercond. 3, 311 (1990).
(6) The Nb and NbCN films were sputtered at TRW from Nb targets in Ar and $Ar/N_2/CH_4$ atmospheres, respectively.
(7) B. Mühlschlegel, Z. Phys. 155, 313 (1959).
(8) C. B. Eom, et al., Appl. Phys. Lett. 55, 595 (1989); C. B. Eom, et al., Physica C 171, 354 (1990).
(9) The program of J. Halbritter (Z. Phys. 266, 209 (1974)) was used to calculate the scaled weak-coupled isotropic BCS temperature dependence of $\lambda(T)$. Values of ℓ_{MFP}=130Å, λ_L=390Å, $\xi_F=(\pi/2)\xi_0$=380Å, and T_c=9.0K were taken for Nb and ℓ_{MFP}=300Å, λ_L=2300Å, ξ_F =50Å, and T_c=18K for NbCN.