RL-TR-92-179
Final Technical Report
June 1992



# EM PROPERTIES OF HIGH Tc SUPERCONDUCTORS

Northeastern University

S. Sridhar



*APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.*



Rome Laboratory
Air Force Systems Command
Griffiss Air Force Base, NY 13441-5700

This report has been reviewed by the Rome Laboratory Public Affairs Office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

RL-TR-92-179 has been reviewed and is approved for publication.

| Accession For | |
|---|---|
| NTIS GRA&I | ☑ |
| DTIC TAB | ☐ |
| Unannounced | ☐ |
| Justification | |
| By | |
| Distribution/ | |
| Availability Codes | |
| Dist | Avail and/or Special |
| A-1 | |

APPROVED:

JOHN S. DEROV
Project Engineer

FOR THE COMMANDER:

JOHN K. SCHINDLER, Director
Electromagnetics & Reliability Directorate

DTIC QUALITY INSPECTED 2

If your address has changed or if you wish to be removed from the Rome Laboratory mailing list, or if the addressee is no longer employed by your organization, please notify RL( ERAC) Hanscom AFB MA 01731-5000. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document require that it be returned.

# REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188



| 1. AGENCY USE ONLY (Leave Blank) | 2. REPORT DATE | 3. REPORT TYPE AND DATES COVERED |
|---|---|---|
| | June 1992 | Final Jun 90 - Jun 91 |

**4. TITLE AND SUBTITLE**
EM PROPERTIES OF HIGH $T_c$ SUPERCONDUCTORS

**5. FUNDING NUMBERS**
C - F30602-88-D-0028, Task E-0-7080
PE - 61102F
PR - 2305
TA - J5
WU - P6

**6. AUTHOR(S)**
S. Sridhar

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Northeastern University
110 Forsyth Street
Boston MA 02115

**8. PERFORMING ORGANIZATION REPORT NUMBER**
N/A

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
Rome Laboratory (ERAC)
Hanscom AFB MA 01731-5000

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
RL-TR-92-179

**11. SUPPLEMENTARY NOTES**
Rome Laboratory Project Engineer: John S. Derov/ERAC/(617) 377-2638

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Approved for public release; distribution unlimited.

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** (Maximum 200 words)
The aim of this contract was to study the factors influencing microwave properties of high $T_c$ superconductors, via fundamental measurements on high quality thin film and single crystal materials. Two principal lines of investigation were pursued: In single crystals of $Y_1Ba_2Cu_3O_{7-\delta}$ ($T_c$=93K) ultrasensitive rf methods were used to study the penetration depth $\lambda$, lower critical fields $H_{c1}$ and vortex pinning forces. The penetration depth and surface resistance were found to obey temperature dependences in good agreement with BCS calculations. The anisotropy and temperature dependence of $H_{c1}$ were measured and also found to be in good agreement with BCS theory. The pinning forces were measured, and the results imply that in good quality single crystals, the pinning is due to core pinning by defects, and implies intrinsic critical currents $2x10^7 A/cm^2$.

**14. SUBJECT TERMS**
Anisotropy and temperature dependence, Microwave properties of high Tc superconductors, BCS calculations

**15. NUMBER OF PAGES** 16

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| UNCLASSIFIED | UNCLASSIFIED | UNCLASSIFIED | UL |

EM PROPERTIES OF HIGH Tc SUPERCONDUCTORS

Contract No. F30602-88-D-0028 (Task E-0-7080)
Subcontract No. 93928-43/RI-70438X

PRINCIPAL INVESTIGATOR:
PROFESSOR S.SRIDHAR

Department of Physics, Northeastern University, Boston, MA 02130.

FINAL REPORT

The aim of this contract was to study the factors influencing microwave properties of high $T_c$ superconductors, via fundamental measurements on high quality thin film and single crystal materials. Two principal lines of investigation were pursued:

- In single crystals of $Y_1Ba_2Cu_3O_{7-\delta}$ ($T_c$ = 93K), ultrasensitive rf methods were used to study the penetration depth $\lambda$, lower critical fields $H_{c1}$ and vortex pinning forces,

- In epitaxial thin films of $Y_1Ba_2Cu_3O_{7-\delta}$, the influence of processing techniques on the microwave surface resistance was studied.

SINGLE CRYSTALS OF YBCO

Very sensitive measurements of the penetration depth and the surface resistance were analyzed to elucidate the phenomenology of the Meissner and mixed states in $Y_1Ba_2Cu_3O_{7-\delta}$ single crystals. The experiments were carried out in a Nb superconducting cavity at 10 GHz, and an ultrastable tunnel diode oscillator at 6 MHz. The temperature T- and magnetic field H- dependence of the parameters $\lambda$ and $R_s$ were studied.

The Meissner state temperature dependence of $\lambda$ and $R_s$ were found to be in good agreement with BCS calculations, and yield parameters $\lambda(0)$ = 1400 Å and a gap ratio $2\Delta(0)/kT_c = 4.3$.

The experiments yield the sharpest known signature of the lower critical field $H_{c1}$, which is observed as a sharp break in the $\lambda(H)$ data at fixed T as the magnetic field H is varied. The critical field $H_{c1}(T)$ was measured both parallel and perpendicular to the c-axis. Its temperature dependence was found to be in excellent agreement with BCS calculations. The data yield an anisotropy ratio of 3.4, which is independent of temperature and underscores the validity of Ginzburg Landau theory.

In the mixed state for fields $H > H_{c1}$, the $\lambda(H)$ data obey a $\sqrt{H}$ dependence. We have developed a model which describes this behavior quantitatively. Start from the equation of motion for the displacement x of a single vortex : $\eta\, \dot{x} + \alpha\, x = \phi_0 J_\omega e^{i\omega t}$, where $\eta$ and $\alpha$ are the viscosity and pinning force constants. From the electric field $E_\omega = B(H)\, \dot{x}$, one can show that the oscillatory vortex response leads to a constitutive relation $J_\omega = [(\alpha - i\omega\eta)/(-i\omega\phi_0\ B)]\ E_\omega$, from which one obtains for the penetration depth :

$$\lambda^2(H,T) = [\phi_0/\mu_0\, \alpha(T)]\ B(H).$$

The above equation predicts that the penetration depth measurements yield B(H), and further that $\lambda \propto \sqrt{H}$, since at high fields $B(H) \approx H$. Also from the slope of $\lambda^2(H)$ vs. H at high fields, the pinning force constants can be obtained. Our measurements are the first to yield a direct experimental B(H) vs. H curve, which is only presented in textbooks as theoretical curves. Also we obtain the pinning force constants $\alpha(T)$ for both $H \parallel \hat{c}$ and $H \perp \hat{c}$. This quantity is found to have a $\alpha(0)(1-t^2)^2$ temperature dependence, which is consistent with core pinning. The magnitudes of $\alpha$ are $\alpha(0) = 2\times10^5\ N/m^2$ for $H \parallel \hat{c}$ and $2\times10^4\ N/m^2$ for $H \perp \hat{c}$.

The pinning force constants are consistent with intrinsic critical currents which are $J_c(0) \sim 2 \times 10^7\ A/cm^2$. These values should be regarded as the upper limit to critical currents achievable in single crystals. Our measurements imply that pinning is due to defects, most likely O vacancies, which pin the cores of vortices. In polycrystals, the pinning force constants are $\sim 4\ N/m^2$, which implies critical currents of $\sim 10^3\ A/cm^2$.

## EPITAXIAL THIN FILMS OF YBCO

The following issues regarding microwave properties of films were addressed:

• *Thickness effects on the surface impedance of YBCO thin films.* Measurements were carried out on high quality YBCO films provided by Bellcore-Rutgers. These films made by laser ablation techniques are the highest quality available. The results indicate a substantial increase in $R_s$ and $\lambda$ with decreasing thickness. An analysis of electrodynamic effects due to small thickness was carried out. The analysis shows that the opposite should occur, viz. that both $R_s$ and $\lambda$ with decreasing thickness. An analysis of electrodynamic effects due to small thickness was carried out. The analysis shows that the measurement configuration employed along with the ability to vary thickness, enables direct measurement of a fundamental parameter, the complex conductivity. Our data presently imply that a peak which is predicted to occur in $\sigma_1$ is absent. This very important result is being pursued further. The thickness studies also have important implications for device applications.

• *Comparison of deposition processes.* We have carried out a comparison of various thin film deposition processes by measuring $R_s$ and $\lambda$ of YBCO films made by laser ablation, MOCVD and sputtering. The laser ablated films yield the highest quality films, with extremely sharp transitions (3 orders of magnitude drop in $R_s$ within 2K below $T_c$). The sputtered films are rapidly approaching the quality of laser ablated films. The MOCVD data are the first on good quality films obtained by this method.

• *Effect of PBCO barrier layer.* PBCO barrier layers provide good lattice match for YBCO films. We have found that YBCO films with a 500Å PBCO layer have essentially the same $R_s$ and $\lambda$ as films without a barrier layer. This implies that the barrier layers can be successfully used, and is important in device applications.

## PUBLICATIONS AND PRESENTATIONS

"Pinning Forces and Lower critical fields in $Y_1Ba_2Cu_3O_y$ crystals : Temperature dependence and anisotropy", Dong-Ho Wu and S.Sridhar, Phys. Rev. Lett., 65 , 2074 (1990)

"Microwave properties of $Y_1Ba_2Cu_3O_y$ Crystals and Films", J.Owliaei and S.Sridhar, MRS Meeting, Boston, Nov.30, 1990.

"Pinning parameters and lower critical fields in $Y_1Ba_2Cu_3O_y$", Dong-Ho Wu and S.Sridhar, MRS Meeting, Boston, MA, Nov. 28, 1990.

"Anisotropies of lower critical fields and flux pinning force densities in $Y_1Ba_2Cu_3O_{7-\delta}$", Dong-Ho Wu and S.Sridhar, March APS meeting, Cincinatti, March, 1991.

"Microwave properties of high $T_c$ superconducting films and crystals", J.Owliaei and S.Sridhar, March APS meeting, Cincinatti, March, 1991.

"Flux dynamics and lower critical fields in the organic superconductor $\kappa$-[BEDT-TTF]$_2$Cu[NCS]$_2$, B.Maheswaran, B.Willemsen, Dong Ho Wu, S.Sridhar and R.C.Haddon, March APS meeting, Cincinatti, March, 1991.

# Pinning Forces and Lower Critical Fields in $YBa_2Cu_3O_y$ Crystals: Temperature Dependence and Anisotropy

Dong-Ho Wu and S. Sridhar
*Department of Physics, Northeastern University, Boston, Massachusetts 02115*
(Received 20 July 1990)

Measurements of the field-dependent radio-frequency penetration depth $\lambda(H,T)$ are used to delineate the lower-critical-field $H_{c1}$-$T$ phase boundary, and to study flux dynamics, in $YBa_2Cu_3O_y$ crystals. For both H $\parallel \hat{c}$ and H $\perp \hat{c}$, $H_{c1}$ obeys a BCS temperature dependence, with a temperature-independent anisotropy of $3.4 \pm 0.3$. In the mixed state, the data obey $\lambda^2(H) = [\phi_0/\mu_0\alpha(T)]B(H)$, and yield both the functional dependence $B(H)$ and the pinning force constant $\alpha(T)$. The latter is anisotropic, obeys an approximately $(1-t^2)^2$ temperature dependence, and vanishes slightly below the bulk transition temperature.

PACS numbers: 74.30.Ci, 74.60.Ec, 74.60.Ge, 74.70.Vy

The high-$T_c$ superconductors display some unusual properties in the presence of magnetic fields. Despite extensive research[1] during the last three years, most of which has focused on dissipative effects at high fields, important parameters which define the mixed state, such as the lower critical field $H_{c1}$ and pinning force constants, are still poorly determined. In this work, we present direct measurements of these parameters, via sensitive measurements of the field-dependent penetration depth in $YBa_2Cu_3O_y$ crystals.

The penetration depth is a probe of the condensate fraction of order parameter, and is particularly sensitive to changes induced by external magnetic fields. In the Meissner state, the external field causes homogeneous changes of the order parameter, while it induces spatially inhomogeneous excitations (i.e., vortices) in the mixed state. These effects are probed in the present experiment by radio-frequency (6 MHz) currents induced by small rf fields $H_\omega$ applied perpendicularly to the $\hat{c}$ axis. The sample is placed in a small 20-turn tightly wound coil, which forms part of the tank circuit of an ultrastable tunnel diode oscillator. Changes $\Delta\lambda$ in the penetration depth due to a static magnetic field H are measured as resonant frequency shifts $\Delta f(H)$, by $\Delta\lambda(H) \equiv \lambda(H) - \lambda(0) = -G\Delta f(H)$, where $G$ (typically $\sim 10$ Å/Hz) is a geometric factor. The very high stability of the oscillator (1 Hz in $6\times10^6$ Hz) enables a resolution of $\sim 10$ Å, which is essential to observe the effects reported here. In all the experiments discussed here, $H_\omega \perp \hat{c}$ always, while H is oriented perpendicularly or parallel to $\hat{c}$. The rf response is determined by the dc flux density in the sample (as we show below), and the data directly yield $H_{c1}(T)$, the functional dependence $B(H)$, and the pinning force constant $\alpha(T)$, in both orientations and over the entire temperature range 4.2 K to $T_c$.

High-quality $YBa_2Cu_3O_y$ crystals were fabricated as discussed in Ref. 2. Detailed measurements of several electrodynamic parameters, viz., $\lambda_{ab}(T)$, $R_s(T)$, the pair-breaking parameter $k(T)$, and also the lower critical field $H_{c1\perp}(T)$, have been reported earlier,[3] and are found to obey temperature dependences in good agreement with BCS calculations. Thus these crystals, which have extremely sharp transitions, are well characterized as regards their electrodynamic properties in the Meissner state.

Typical results for $\Delta\lambda$ vs H ($\parallel\hat{c}$) are shown in Fig. 1 at $T = 9.7$ K. $\Delta\lambda = 0$ in the Meissner state, until the critical field $H^0_{c1\parallel}$ is reached signaling the entry of flux. Here $H^0_{c1\parallel} = H_{c1\parallel}/\mathfrak{N}$ is the bulk critical field reduced by the demagnetization factor $\mathfrak{N}$. For $H > H^0_{c1\parallel}$, $\Delta\lambda$ increases with a field dependence which is *sublinear*.

In Fig. 1 *the break at $H^0_{c1\parallel}$ is sharp and unambiguous.* In general, the rf measurements appear to yield much cleaner signatures for $H_{c1}$ compared to magnetization data—we believe this to be due to the very high sensitivity of the rf technique. The resolution limit of $\Delta\lambda = 10$ Å corresponds to $\Delta M/M \sim 2\times10^{-5}$ for a sample 50 μm thick, when H $\perp \hat{c}$.

Combining the parallel and perpendicular measurements (the latter are shown in Fig. 2), the temperature dependence of $H_{c1}$ both parallel and perpendicular to $\hat{c}$,

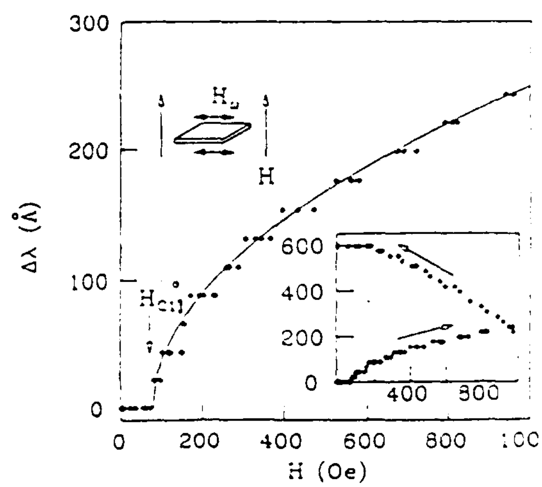


FIG. 1. $\Delta\lambda(H) \equiv \lambda(H) - \lambda(0)$ vs H ($\parallel\hat{c}$) at $T = 9.7$ K. Note the sharp break at $H^0_{c1\parallel}$, and the sublinear dependence for large fields (the line is a guide to the eye). Top inset: Field configuration. Bottom inset: Complete behavior for field cycling

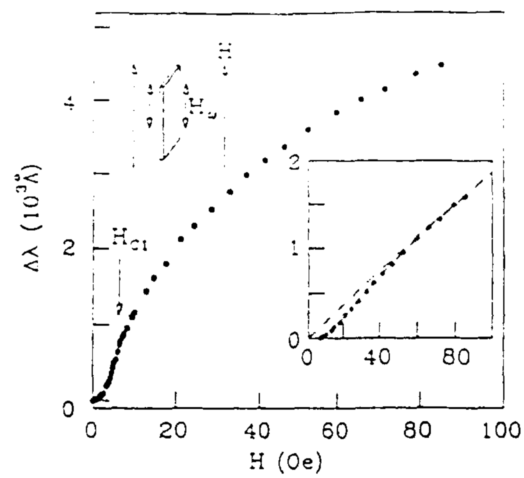


FIG. 2. $\Delta\lambda(H)$ vs H ($\perp\hat{c}$) at $T=84.5$ K. Top inset: Field configuration. Bottom inset: $[\Delta\lambda(H)-\Delta\lambda(H_{c1})]^2$ ($10^7$ Å) vs H.

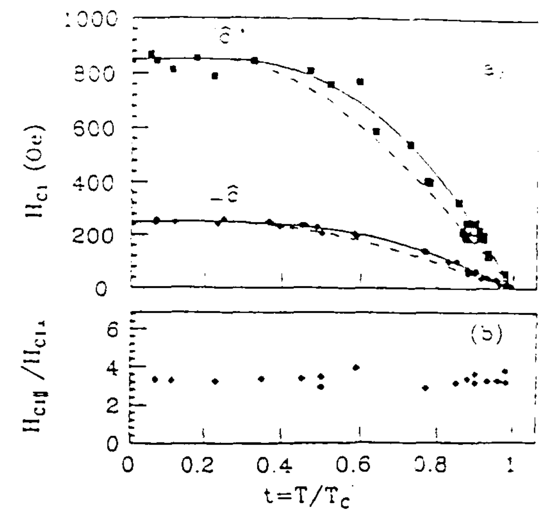


FIG. 3. (a) Temperature dependence of $H_{c1}$ in both the $\parallel\hat{c}$ and $\perp\hat{c}$ configurations. The lines represent BCS calculations, with gap ratios $2\Delta/kT_c=4.3$ (solid) and 3.5 (dashed). (b) Temperature dependence of the anisotropy ratio $H_{c1\parallel}/H_{c1\perp}$.

measured for the *same sample* ($T_c=88.2$ K), is displayed in Fig. 3. For $\mathbf{H}\parallel\hat{c}$, $H_{c1\parallel}=\mathfrak{N}H^0_{c1\parallel}$ with $\mathfrak{N}=11$ (and temperature independent) for this sample, estimated assuming an ellipsoidal shape (dimensions $1\times1$ mm$^2\times50$ $\mu$m). The $\mathbf{H}\perp\hat{c}$ data (here $H_{c1\perp}=H^0_{c1\perp}$) are identical to those reported[3] earlier using the same technique on another sample. (As shown in Fig. 2 of Ref. 3, the $H_{c1}$ signature in this configuration is also sharp and unambiguous.) The demagnetization effects were carefully checked with calibrations using Nb platelets of approximately the same dimensions as the $YBa_2Cu_3O_y$ samples. These calibration measurements confirm the demagnetization calculations and the magnitudes reported here.

The *BCS-like character of $H_{c1}$ in both configurations* is evident. We find $H_{c1\parallel}(0)=850\pm40$ Oe, and $H_{c1\perp}(0)=250\pm20$ Oe. These values lead to an anisotropy of $3.4\pm0.3$, which within the uncertainty in the measurement, appears to be temperature independent [Fig. 3(b)]. The $H_{c1}$ anisotropy may be compared with other results,[4] which typically range from 2.9 to 5.8.

For an *anisotropic superconductor*,[5] in the present notation, $H_{c1\parallel,\perp}=[\phi_0/4\pi\lambda_\parallel\lambda_{\parallel,\perp}][\ln(\sqrt{\lambda_\parallel\lambda_{\parallel,\perp}/\xi_\parallel\xi_{\parallel,\perp}})+0.5]$. Ignoring the logarithmic term, the field anisotropy can be used to deduce a mass anisotropy of

$$m_\parallel/m_\perp\propto\lambda_\parallel^2/\lambda_\perp^2\propto(H_{c1\parallel}/H_{c1\perp})^2=11.6$$

at 4.2 K. It appears that torque magnetometry[6] and magnetic anisotropy[7] measurements tend to yield higher values $\sim25$ to 64, while as noted above, $H_{c1}$ measurements tend to give lower values. To our knowledge the present work is the first complete and direct determination of the anisotropy temperature dependence. The mean-field behavior of $H_{c1}$ and the absence of any temperature dependence in the anisotropy validates the use of anisotropic Ginzburg-Landau theory.

The temperature dependence of $H_{c1}$ in both directions is in good agreement with BCS calculations, as shown in Fig. 3 as the solid lines. Here we have used $H_{c1}\propto1/\lambda^2(T)$, and employed detailed numerical BCS calculations[3] with a variable gap parameter $2\Delta/kT_c$. As Fig. 3 shows, best fits are obtained for $2\Delta/kT_c=4.3$, with less satisfying fits for 3.5, in agreement with our earlier findings[3] on the temperature dependence of electrodynamic properties.

We now turn to understanding the features of the $\Delta\lambda(H)$ data in Figs. 1 and 2. In the Meissner state ($H<H^0_{c1}$), $\Delta\lambda(H)=0$ for $\mathbf{H}\parallel\hat{c}$, and $\Delta\lambda(H)=k(T)H^2$ for $\mathbf{H}\perp\hat{c}$. The quadratic dependence in the latter case is well understood to be due to pair breaking by the applied static field, and the temperature dependence of $k(T)$ is very well described[3] by a Ginzburg-Landau model. This is not observed when $\mathbf{H}\parallel\hat{c}$ and $\mathbf{H}_\omega\perp\hat{c}$ because the dc and rf currents only superpose over a periphery of width $\lambda$ of the sample, and hence the pair-breaking quadratic dependence (determined by an overlap integral $\int H^2H_\omega dS$ over the sample area $S$) is very small and unobservable.

We next turn to the data for $H>H^0_{c1\parallel}$ when $\mathbf{H}\parallel\hat{c}$. In the mixed state, the rf induced current of density $J_\omega$ creates an oscillating Lorentz force which acts on the vortices, causing them to oscillate about their equilibrium positions. Start from the equation of motion for the displacement $x_\omega$: $\eta\dot{x}_\omega+\alpha x_\omega=f_L=\phi_0J_\omega$, where $\eta$ and $\alpha$ are the damping coefficient and the pinning force constant, respectively. From the electric field $E_\omega=B\dot{x}_\omega$, it is easy to show that the oscillatory vortex response leads to a constitutive relation $J_\omega=[(\alpha-i\omega\eta)/(-i\omega\phi_0B)]E_\omega$, from which we obtain for the penetration depth

$$\lambda^2(H,T)=[\phi_0/\mu_0\alpha(T)]B(H) \qquad (1)$$

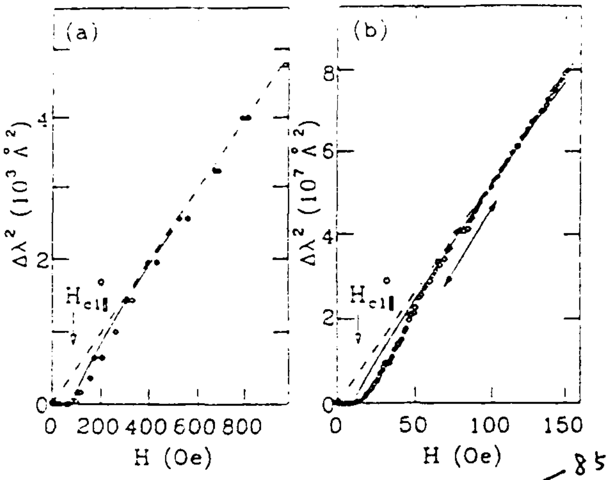


FIG. 4. $\Delta\lambda^2(H)$ vs H ($\parallel\hat{c}$) for (a) 9.7 K and (b) 84 K (including field-reversed data). Note that the $H \gg H_{c1\parallel}^0$ behavior linearly extrapolates through the origin. The solid lines represent calculations based on Ref. 10.

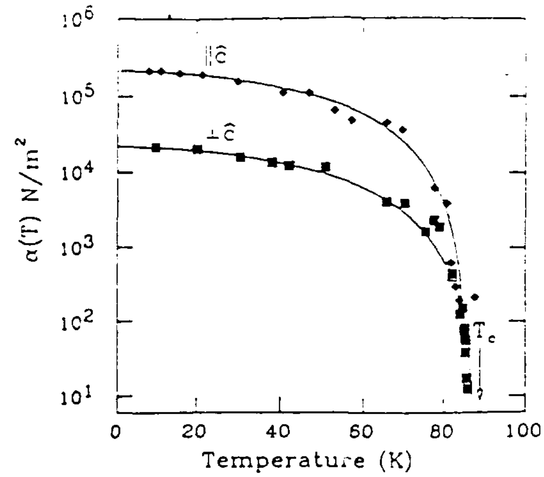


FIG. 5. Temperature dependence of the pinning force constant $\alpha(T)$. The lines represent a $[1-(T/T_c')^2]^2$ dependence.

Equation (1) shows that the rf $\lambda(H)$ measurements can be interpreted to yield, first, the dc magnetic flux density $B(H)$ inside the sample, and also the pinning parameter $\alpha(T)$. In Figs. 4(a) and 4(b), we plot $\Delta\lambda^2(H)$ vs $H$ for two temperatures, 9.7 and 85 K. The functional dependence is remarkably similar to the classic[8] $B(H)$ dependence expected for type-II superconductors. For $H \gg H_{c1\parallel}^0$, the data clearly coincide with a linear $H$ dependence[9] at all temperatures [Figs. 4(a) and 4(b)] passing through the origin, as $B(H)$ should. We have attempted to compare the data with detailed predictions for $B(H)$ at lower fields near $H_{c1}$. In Figs. 4(a) and 4(b), the solid lines represent Nelson's[10] form $B(H) \propto (H-H_{c1\parallel}^0)\ln[H'/(H-H_{c1\parallel}^0)]$, which is in reasonable agreement at low temperatures. For $H \gtrsim H_{c1\parallel}^0$ the data show an increasing rounding with increasing temperature at the onset of flux entry. Thus a functional form $B(H) \propto (H-H_{c1\parallel}^0)^{\beta(T)}$ appears to best describe the data in the intermediate-field range $H_{c1}^0 < H < 4H_{c1}^0$, with $\beta = 1$ at low temperatures [Fig. 4(a)] and $\beta > 1$ with increasing temperature [$\beta \approx 1.5$ at 85 K in Fig. 4(b)]. This is consistent with some calculations[10,11] of $B(H)$ near $H_{c1}$, and the temperature dependence suggests that line wandering increases with increasing temperature.

In the configuration H $\perp\hat{c}$, the behavior of $\Delta\lambda$ vs $H$ is qualitatively similar for $H > H_{c1\perp}$, in that a sublinear field dependence is also observed. Here the driving force arises from the flux density gradient $dB/dx$, and an analysis similar to that of Campbell and Evetts[12] again yields Eq. (1). This is confirmed experimentally in the plot of $[\Delta\lambda(H)-\Delta\lambda(H_{c1})]^2$ vs $H$ shown in the inset to Fig. 2. Again at high fields a linear behavior is observed, extrapolating to the origin. [The condensate effects appear to be adequately accounted for by the subtraction of the pair-breaking contribution evaluated at $H_{c1}$, i.e., $\Delta\lambda(H_{c1})$. It should be noted that this does not affect the high-field behavior, which is discussed next.]

From the data shown in Figs. 2 and 4, we extract a high-field ($H \gtrsim 4H_{c1}^0$) limiting slope, and from it obtain the pinning force constants $\alpha_\parallel$ and $\alpha_\perp$ in both directions. The temperature dependence of $\alpha$ is shown in Fig. 5. The pinning force depends on field orientation, with $\alpha_\parallel(0) = 2.2\times10^5$ N/m$^2$ and $\alpha_\perp(0) = 2.1\times10^4$ N/m$^2$. Elementary vortex-core-pinning considerations suggest that $\alpha \approx B_c^2/2\mu_0$. This yields $B_{c\parallel}(0) = 0.8$ T and $B_{c\perp}(0) = 0.25$ T. These values are in excellent agreement with other estimates.[13] The relation between $\alpha$ and $B_c$ also suggests a $(1-t^2)^2$ dependence. Indeed this is exactly what the data seem to obey, as shown by the solid lines representing $[1-(T/T_c')^2]^2$ in Fig. 5. Interestingly, $T_c' = 87$ K (H $\perp\hat{c}$) and $\sim 86.2$ K (H $\parallel\hat{c}$), both below the bulk $T_c = 88.2$ K, which is defined as the (sharp) peak in the temperature derivative $[d\Delta\lambda(T)/dT]$ of the $\lambda(T,H=0)$ data. This implies that the pinning forces vanish slightly below the mean-field transition temperature. Between $T_c'$ and $T_c$, the exact behavior is not clear, with $\alpha_\parallel$ appearing to increase again. A detailed study of this region is the subject of future work.

A comparison with results on polycrystals is interesting. The data are similar to the H $\perp\hat{c}$ results of Fig. 2; however, the field dependence is enormous. We obtain $\alpha(0) = 4.2$ N/m$^2$, which is $10^3$–$10^4$ smaller than for the single crystals. This is understandable because of the extremely weak pinning of the intergranular vortices.[14,15]

We next explore the relationship of our experiments to others on high-$T_c$ superconductors. Note that our measurements are *reactive* (nondissipative), and measure the in-phase ac response at the fundamental driving frequency. This necessarily requires a flux response proportional to displacement, i.e., a restoring force $-\alpha x$. Since $H_\omega \sim 10$ mOe, the probe current $J_\omega \sim 10^{-3}$ A/cm$^2$, which is much lower than in resistivity measurements. The vortices are taken to execute reversible oscillations, which are of amplitude $\ll 1$ Å. We have tested and found the results to be independent of the ac field over a small range of the rf field (the tunnel-diode-oscillator circuit allows current variations only by a factor of 2). The analysis is based on the reasonable assumption that $\alpha$ is field independent, at least at the low fields studied here. A very high fields, $\alpha$ may be expected to decrease — indeed high-field studies, which is the subject of future work, might be expected to distinguish between various theories of flux behavior (e.g., flux lattice melting, flux creep, vortex glass, etc.).

The interplay between elastic and viscous forces determines the crossover frequency $f_0 = \alpha/\eta = \alpha\rho_n/\phi_0 B_{c2}$, where $\rho_n$ ($\approx 50\ \mu\Omega\,\mathrm{cm}$) is the normal-state resistivity, and $B_{c2}$ is the upper critical field. Assuming[16] $B_{c2} = 26$ T at 77 K, we get $f_0 \sim 9.6\times10^{10}$ Hz at 77 K. This may be compared to $\sim 10^8$ Hz for low-$T_c$ superconductors.[17]

It is possible to estimate a single-vortex depinning critical current if one assumes, for example, a sinusoidal potential well $U(x) = (-U_0/2)\cos(\pi x/L)$, where $L$ is the well dimension. Our measurements yield the curvature at low $x$ through the relation $\alpha = \pi^2 U_0/2L^3$. Equating the maximum pinning force to a maximum Lorentz force, one gets $J_{c0} = L\alpha/\pi\phi_0$. Using[16] $L \sim 70$ Å, we get $J_{c0\parallel} \sim 2.5\times10^7$ A/cm$^2$ and $J_{c0\perp} \sim 2.3\times10^6$ A/cm$^2$, from the measured values of $\alpha$ at low temperatures. These values should be regarded as upper limits to achievable critical currents in single crystals. (The polycrystalline data naturally imply much smaller values, $J_{c0} \sim 10^3$ A/cm$^2$). Furthermore, the observed magnitude of $\alpha$ is consistent with a barrier height of $U_0 \sim 10^3$ K and a well volume of $L^3 \sim 3.5\times10^5$ Å$^3$, which may be compared with the observed thermal activation energies in critical-current experiments.[16,18] From $\alpha \sim F_p L$, we deduce pinning force densities of $3.1\times10^{13}$ N/m$^3$ ($\parallel\hat{c}$) and $3.0\times10^{12}$ N/m$^3$ ($\perp\hat{c}$), which appear to be larger than those calculated by Kes and van den Berg[19] for pinning by twin boundaries. Our interpretation of the data is consistent with densely populated pinning centers,[20] and pinning due to twin boundaries is unlikely to be the dominant cause in our crystals.[21]

Our results are significant for several reasons. First, they provide the *complete* low-field $H$-$T$ phase diagram in $YBa_2Cu_3O_y$ crystals, particularly the $H_{c1}$ phase boundary and its anisotropy. Further, the $\lambda(H)$ measurements are a probe of the constitutive relations governing the superconductor. In the Meissner state, the $\lambda(H)$ data test the nonlinear London relation $J = -Q_1 A - Q_2 A$,[3] wherein pair-breaking effects manifest themselves as $\Delta\lambda = kH^2$, and are measured via the pair-breaking parameter $k$ ($\equiv d\Delta\lambda/dH^2$) which is $\propto Q_2$. In the mixed state, the $\lambda(H)$ data yield the $B(H)$ constitutive relation for the first time, and the derivative $\alpha \equiv (d\Delta\lambda^2/dH)^{-1}$ is a measure of the pinning forces. The pinning parameter $\alpha$ (also known as the Labusch parameter) determined in this work is an important parameter which enters into the analysis of other experiments, and in theories of the flux state. In contrast to dissipative (e.g., resistivity) measurements, the *reactive* measurements carried out here probe the thermodynamic, quasiequilibrium properties of the superconductor in the presence of a magnetic field.

This work was supported by NSF-ECS-8811254 and by the U.S. Air Force Systems Command, Rome Air Development Center. We thank J. R. Clem and R. S. Markiewicz for useful discussions.

[1] *Physical Properties of High $T_c$ Superconductors*, edited by D. M. Ginzberg (World Scientific, Singapore, 1989).

[2] Dong Ho Wu, W. Kennedy, C. Zahopoulos, and S. Sridhar, Appl. Phys. Lett. 56, 696 (1989).

[3] S. Sridhar, Dong-Ho Wu, and W. Kennedy, Phys. Rev. Lett. 63, 1873 (1989).

[4] L. Krusin-Elbaum *et al.*, Phys. Rev. B 39, 2936 (1989); A. Umezawa *et al.*, Phys. Rev. B 38, 2843 (1988).

[5] R. A. Klemm and J. R. Clem, Phys. Rev. B 21, 1868 (1980).

[6] D. Farrel *et al.*, Phys. Rev. Lett. 64, 1573 (1990); 61, 2805 (1988).

[7] M. Tuominen, A. M. Goldman, Y. Z. Chiang, and P. Z. Jiang, Phys. Rev. B 42, 412 (1990).

[8] M. Tinkham, *Introduction to Superconductivity* (McGraw-Hill, New York, 1979).

[9] A. F. Hebard, P. L. Gammel, C. E. Rice, and A. F. J. Levi, Phys. Rev. B 40, 5243 (1989). In this work, a $\sqrt{H}$ dependence of $\lambda(H)$ has been observed in mutual-inductance measurements on thin films at high fields. The reported magnitudes of $d\lambda/d\sqrt{H}$ are in excellent agreement with our data for H $\parallel$ ĉ.

[10] D. R. Nelson, Phys. Rev. Lett. 60, 1973 (1988).

[11] T. Natterman and R. Lipowsky, Phys. Rev. Lett. 61, 2508 (1988).

[12] A. M. Campbell and J. Evetts, Adv. Phys. 21, 199 (1972).

[13] M. B. Salomon and J. Bardeen, Phys. Rev. Lett. 59, 2615 (1987).

[14] J. Clem, in *Proceedings of the International Conference on Superconductivity, Stanford, CA 1989* [Physica (Amsterdam) 162-164, 1137 (1989)].

[15] J. Halbritter, J. Appl. Phys. (to be published).

[16] A. P. Malozemoff *et al.*, in *Strong Correlations and Superconductivity*, edited by H. Fukuyama *et al.* (Springer-Verlag, Heidelberg, 1989).

[17] J. Gittleman and B. Rosenblum, Phys. Rev. Lett. 16, 734 (1966).

[18] T. T. M. Palstra, B. Batlogg, R. B. van Dover, L. F. Schneemeyer, and J. V. Waszczak, Appl. Phys. Lett. 54, 763 (1989).

[19] P. Kes and J. van den Berg, in "Studies of High Temperature Superconductors," edited by A. V. Narlikar (Nova Science, New York, to be published).

[20] M. Inui, P. B. Littlewood, and S. N. Coppersmith, Phys. Rev. Lett. 63, 2421 (1989).

[21] Good quality samples such as those studied here generally show a low twin density.

16:30 **Monday Afternoon**
C26 11

ANISOTROPIES OF LOWER CRITICAL FIELDS AND FLUX PINNING FORCE DENSITIES IN $Y_1Ba_2Cu_3O_y$.*

Dong-Ho Wu and S. Sridhar, Physics Department, Northeastern University, Boston, MA 02115.

The field dependent rf penetration depth, $\lambda(H)$, was measured[1] on single crystals and polycrystals of $Y_1Ba_2Cu_3O_y$ with two different field configurations, viz. $H \parallel H_{rf} \perp \hat{c}$ and $H \perp H_{rf} \perp \hat{c}$. The experiments enabled the measurements of anisotropies of lower critical fields, $H_{c1}$, and pinning force densities, $\alpha$, throughout the whole temperature range, namely from $T_c$ to 4.2 K. The anisotropy of $H_{c1}$ is found to be $3.4 \pm 0.3$ and is temperature independent. From the above results, we also estimated the anisotropy of the effective mass. The critical current densities, $J_{c\parallel}(0)$ and $J_{c\perp}(0)$, for single crystals, estimated from $\alpha$, are $2 \times 10^7$ A/cm$^2$ and $2 \times 10^6$ A/cm$^2$, respectively. The results are consistent with direct measurements of $J_c$ for $\parallel$ and $\perp \hat{c}$. The role of anisotropy in flux dynamics with fields up to 7 T, the field dependence of $\alpha$, and the implication of temperature dependence of the anisotropy will be discussed in detail.

[1]Dong-Ho Wu and S. Sridhar, Phys. Rev. Lett., 65, 2074 (1990), S.Sridhar, Dong-Ho Wu and W.Kennedy, Phys. Rev. Lett., 63, 1873 (1989).

*Supported by USAF/RADC

9.00
I24 6 **Wednesday Morning**

MICROWAVE PROPERTIES OF HIGH $T_c$ SUPERCONDUCTING FILMS AND CRYSTALS*,

J. Owliaei and S.Sridhar, Physics Department, Northeastern University, Boston, MA 02115.

We have studied the microwave surface resistance of cystals and thin films of high $T_c$ superconductors as functions of temperature and also magnetic field. Absolute measurements of $R_s$ at zero field were carried out to explore several issues concerning the nature of the superconducting state. Earlier measurements[1] of $R_s$ and $\lambda$ have shown good agreement with BCS calculations. We discuss the comparison in light of recent data on films and crystals. In very thin films for rf fields applied on both sides should directly yield the complex conductivities. Results for $\sigma_1$ and $\sigma_2$ in this configuration are discussed. The high field measurements of $R_s$ and $\lambda$ yield information on the pinning forces and the interplay between pinning flux flow. We discuss these parameters via an analysis of the experiments in terms of a vortex oscillation model.

[1]S.Sridhar, Dong-Ho Wu and W.Kennedy, Phys. Rev. Lett., 63, 1873 (1989).

*Supported by USAF/RADC

9:24
Q23 8 **Friday Morning**

FLUX DYNAMICS AND LOWER CRITICAL FIELDS IN THE ORGANIC SUPERCONDUCTOR $\kappa$-BEDT $(CuSN)_2$*,

B. Maheswaran, B. Willemsen, Dong Ho Wu and S.Sridhar, Physics Department, Northeastern University, Boston, MA 02115, and R.C. Haddon, AT&T Bell Laboratories, Murray Hill, NJ 07974.

We have studied the electromagnetic response in the Meissner and mixed states of crystals of the organic superconductor $\kappa$-$[BEDT\text{-}TTF]_2Cu[NCS]_2$. The experiments utilise a resonant coil method, which has been extensively used for measuring $H_{c1}$ and penetration depths of high $T_c$ superconductors[1]. In the organic, the zero-field penetration depth $\lambda(T,H=0)$ only approximately obeys a two-fluid temperature dependence. $\lambda$ is strongly field dependent, with flux entry occuring at modest fields $\sim$ 100 Oe. In the mixed state, we deduce pinning forces which are strongly field-dependent, and the data indicate a crossover behaviour from flux pinning to flux flow.

[1]S.Sridhar, Dong-Ho Wu and W.Kennedy, Phys. Rev. Lett., 63, 1873 (1989), Dong-Ho Wu and S.Sridhar, Phys. Rev. Lett., 65, 2074 (1990).

*Supported by USAF/RADC