DC MAGNETIC FIELD DEPENDENCE OF THE SURFACE IMPEDANCE IN SUPERCONDUCTING PARALLEL PLATE TRANSMISSION LINE RESONATORS*

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Abstract--We have measured the real and imaginary parts of the surface impedance of cuprate superconducting films in the parallel plate resonator geometry at 11 GHz as a function of perpendicular DC magnetic field. The results are relevant for all applications of superconducting films in the presence of DC or RF magnetic fields. Above a temperature dependent crossover field, we see a linear increase of the surface resistance and reactance with field, up to 4 kG. We extract the microscopic vortex dynamical parameters: the viscosity and pinning-potential restoring force constant, along with their temperature dependences, using the low-temperature and low-field limit of the unified model of Coffey and Clem. We find that the pinning frequency is above 40 GHz for temperatures below 60K. Consequently, a complete understanding of the field dependence of the microwave surface impedance of the cuprates must include both vortex pinning and viscosity. The vortex viscosity is temperature dependent and, in the context of the Bardeen-Stephen model, consistent with a temperature dependent normal-state resistivity below T_c.

I. INTRODUCTION

Many high frequency applications of superconductivity require very low surface impedance in the presence of strong magnetic fields. Microwave devices, such as circulators and isolators, must perform in a DC magnetic field on the order of several kilogauss. Superconductive microwave devices such as filters, switches, phase shifters, antennas and attenuators, must also perform at high RF magnetic fields. The purpose of our research is to identify the microscopic mechanisms responsible for the DC and RF magnetic field dependence of the microwave surface impedance, especially as regards device applications.

The parallel plate resonator (PPR)[1] is ideally suited for measuring the properties of superconductors destined for device applications. It is essentially an all-superconducting parallel plate transmission line resonator, similar to the microstrip and stripline geometries used in microwave integrated circuits. No lithographic patterning is required to prepare the PPR, so the measurements are in no way influenced by lower quality material created by the patterning process. In addition, the PPR does not suffer from heating at high microwave power levels, as may be found in narrow patterned microstrip and stripline geometries [2]. Finally, the PPR affords a simple, direct measure of the absolute surface resistance and changes in the surface reactance of superconducting thin films, and is very sensitive to small changes in both quantities.

II. EXPERIMENT

Thin films of $YBa_2Cu_3O_{7-\delta}$ (YBCO) were prepared by pulsed laser deposition on $LaAlO_3$ substrates. During deposition, the substrates were held at 710°C in 200 mTorr of oxygen, and the laser energy density per pulse on the target was 2 J/cm^2. The films are approximately 1 μm thick, and had an ac-susceptibility T_c of approximately 89K. Because of their thickness, we expect both c-axis and a-axis grains to be present. The films were chosen to be representitive of those which are commercially available at present. Thick films were also chosen to avoid finite-film-thickness corrections to the penetration depth [3] and surface resistance [4] at low temperatures and fields.

The parallel plate resonators were made by sandwiching two superconducting films face-to-face around a 12.5 μm thick Teflon FEP dielectric spacer.[3] The device was placed in a copper chamber, and the resonant modes of the PPR were excited by coaxial cables terminated with 50 Ω microstrips [1]. The coupling into the PPR could be varied *in-situ* so that the appropriate coupling could be achieved. All measurements were performed in the undercoupled regime and at the lowest possible microwave power. Microwave field strengths parallel to the film surface were no greater than 10 Oe during the measurements, and were low enough to no longer influence the temperature and field dependence of the surface impedance. The effects of increasing the microwave power, both with and without a DC external field, will be discussed in later publications. The microwave measurements were performed with an HP 8510C vector network analyzer.

We measured the resonant frequency f_0 and quality factor Q of the PPR as a function of temperature and DC magnetic field. The surface resistance is found from the geometry coefficient: $R_s = \Gamma/Q$, where $\Gamma = \pi\mu_0 d f_0(T,H)$ and d is the dielectric spacer thickness.[1] Changes in the surface reactance at low temperatures can be obtained from: $\Delta X_s \equiv X_s(T,H)-X_s(4.2K,H=0)=2\Gamma[f_0(4.2K,H=0)-f_0(T,H)]/f_0(4.2K,H=0)$. Note that the Q to R_s and f_0 to ΔX_s transformations are independent of the particular mode excited in the PPR. All measurements discussed here were performed at 11 GHz.

A perpendicular DC magnetic field was provided by a Cryomagnetics 6-Tesla split-coil superconducting magnet. The field dependence of the surface impedance was measured from the zero-field-cooled state. Although the PPR is very sensitive to small changes in surface resistance and reactance, it is difficult to perform measurements in the vicinity of T_c or at high fields because of the very low Q values in those ranges.

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*Work supported by the State of Maryland and by an NSF NYI grant. Manuscript received August 24, 1992.

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III. RESULTS

Shown in Figures 1 and 2 are the measured surface resistance, and changes in the surface reactance, of a pair of YBCO films as a function of temperature, for a variety of fixed perpendicular fields. The surface resistance increases linearly with temperature up to a point at which a much stronger dependence dominates. All of the R_S data, independent of external field, extrapolates to approximately 50 μΩ at zero temperature, somewhat higher than the best values obtained to date on YBCO [5], although similar to values obtained for a-axis films [6]. The surface reactance data appears to maintain the same temperature dependence with field, changing only the zero-temperature residual reactance. The zero-field temperature dependence of the penetration depth and surface resistance of YBCO films have been discussed extensively in previous publications [5,7,8]. The inset in Figure 2 shows the low-temperature residual reactance as a function of DC field strength.

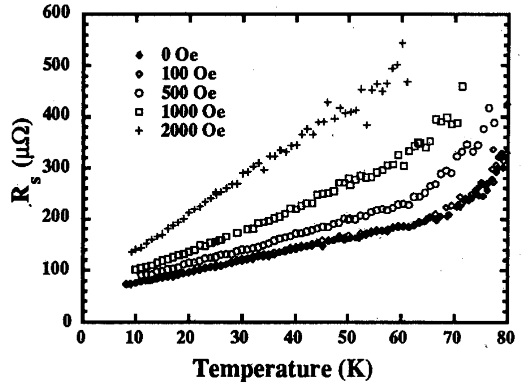

Fig. 1. Surface resistance at approximately 11 GHz versus temperature for a YBCO parallel plate resonator at five fixed perpendicular DC magnetic fields.

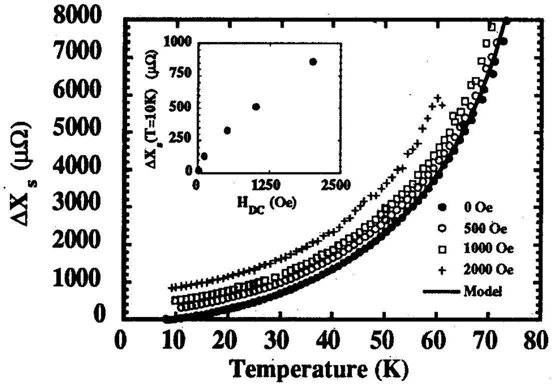

Fig. 2. Changes in surface reactance at 11 GHz (measured from 4.2K, zero external field) versus temperature for a YBCO parallel plate resonator at several fixed perpendicular DC magnetic fields. The solid line represents the change in reactance for the approximate model: $\lambda(T) = 1300\text{Å}/(1-(T/T_c)^2)^{1/2}$, with T_c=90K. The inset shows the residual ΔX_S at 10K versus field.

Figures 3 and 4 show the surface resistance and change in surface reactance as a function of applied perpendicular DC magnetic field at a series of fixed temperatures. Most of the data shows a general linear dependence on field, with some hint of a different field dependence at the lowest fields and temperatures (see the inset of Fig. 2).

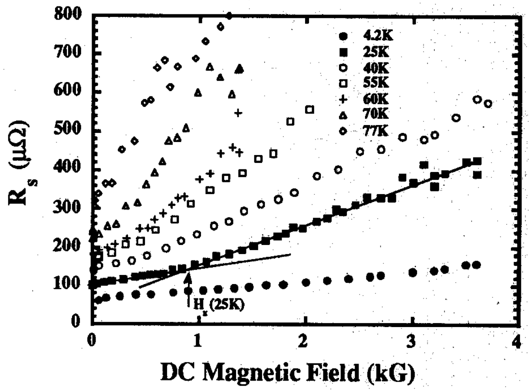

Fig. 3. Surface resistance at 11 GHz versus perpendicular DC magnetic field for a YBCO parallel plate transmission line resonator at several fixed temperatures. Shown is the construction used to determine H_X.

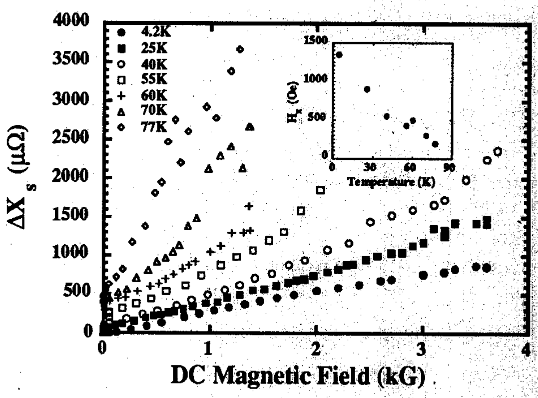

Fig. 4. Changes in surface reactance at 11 GHz versus perpendicular DC magnetic field for a YBCO parallel plate transmission line resonator at several fixed temperatures. The inset shows the crossover field, H_X, versus temperature as obtained from the data in Fig. 3.

IV. ANALYSIS

The first approach to all surface impedance data on short-coherence length cuprates like YBCO, is to assume that weak links dominate the electrodynamic response, particularly at low temperatures. A great variety of microwave surface resistance [5], magnetic penetration depth [7], and infrared absorbtion data [9] on YBCO films are consistent with the weak-link model. Briefly, the model describes the surface impedance as arising from a combination of intrinsic contributions in the superconducting grains, along with extrinsic contributions from RF currents which flow through weak links created at planar defects such as grain or twin boundaries. These weak links serve to increase the measured penetration depth, enhance the surface resistance, and give the surface impedance an additional temperature dependence associated with the weak link tunneling critical current density.[10] These enhancements may also be accompanied by an ω^2 frequency dependence (at least for microwave and millimeter-wave frequencies) which is similar to that of intrinsic BCS superconductors.

We divide the field dependence data into low- and high-field regimes. At very low fields, vortex entry will proceed through weak links between the grains. Quantitative analysis of the low-field data, and the RF-field dependence, will be presented in later publications. However, we do note here the existence of a temperature dependent crossover field, $H_x(T)$. Above this field most of the $R_S(H)$ and $X_S(H)$ data are well described by straight lines, whereas below $H_x(T)$ those data are either linear, but with a different slope, sublinear, or quadratic. The crossover field may denote the crossover from the penetration of Josephson vortices at low fields to Abrikosov vortices at high fields [10]. One notes that $H_x(T)$, shown as an inset in Fig. 4, falls as $1-(T/T_c)$, typical of a weak-link tunneling critical current density.[10] We believe the data below $H_x(T)$ to be dominated by weak links, while that above reflects the influence of pinning and vortex viscosity in the grains, but may also be influenced by the weak links.

The data at high fields is not consistent with simple flux flow resistivity $R_S(H)$, $X_S(H) \sim (H/H_{c2})^{1/2}$, or with a weak link model $R_S(H)$, $X_S(H) \sim H/H_{c2J}$ [10] because the resulting values for H_{c2} and H_{c2J} are unreasonably small, and the data does not have a $H^{1/2}$ dependence in the high-field range. Clearly a more sophisticated model is required.

We proceed with an analysis of the high-field data beginning with the unified model of Coffey and Clem [11]. In the limit of low temperatures, there is no thermally assisted flux motion, and also $(\lambda/\delta_{nf})^2 << 1$, where λ is the London penetration depth and δ_{nf} is the normal-fluid skin depth. If, in addition, we consider the low field limit, $2B_{c1} < B << B_{c2}$, we can expand the Coffey and Clem result for the surface impedance [11] to obtain;

$$R_s(B,T) = R_s(0,T) + \frac{\omega\, \phi_0 B}{2\, \lambda(B,T)\, \kappa_p(B,T)}\; \frac{\omega\tau}{1 + (\omega\tau)^2},$$

$$X_s(B,T) = \mu_0\, \omega \lambda\, (B,T) \left[1 + \frac{\phi_0 B}{2\, \mu_0\, \lambda(B,T)^2\, \kappa_p(B,T)}\; \frac{1}{1 + (\omega\tau)^2} \right]$$

(valid for low temperatures and $B << B_{c2}$), where κ_p is the pinning potential restoring force constant, η is the viscosity, and $\tau \equiv \eta/\kappa_p$ is the vortex relaxation time in the low-temperature limit.

Note that the ratio of the slopes, $(dX_S/dB)/(dR_S/dB) = 1/\omega\tau$ in this model,[12] and gives directly the relaxation time, τ, of a plucked vortex in the low-temperature, low-field limit. From the data in Figs. 3 and 4, we find that $\omega\tau \sim 0.25$ over most of the temperature range of the measurement (see Fig. 6). Thus our measurements are in the low-frequency limit, $\omega < \omega_{pin} = 1/\tau$, and one must treat both the viscosity and pinning potential on an equal footing [13].

In addition, if $\lambda(B,T)$ and $\omega\tau$ are known, one can use the above expressions to find κ_p and η directly from our measurements of dR_S/dB and $d\Delta X_S/dB$. We have used a computationally simple approximation to the penetration depth in zero field: $\lambda(T) = 1300Å/(1-(T/T_c)^2)^{1/2}$ (shown in Fig. 2), and the results for $\kappa_p(T)$ and $\eta(T)$ in the low-field limit [9] are shown in Figure 5.

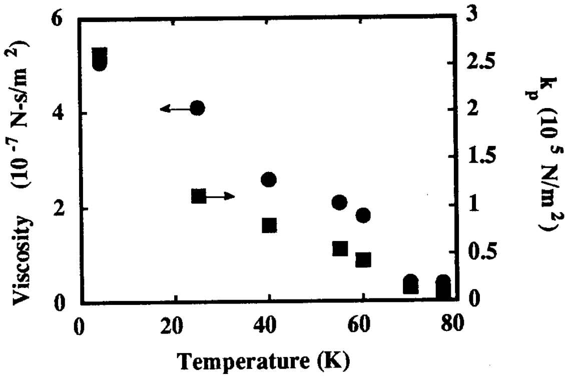

Fig. 5. Temperature dependence of vortex viscosity η and pinning potential restoring force constant κ_p (both per unit length of vortex), obtained within the context of the Coffey and Clem model in the limit of low temperatures and low magnetic fields.

The values for $\kappa_p(T)$ at low temperatures are quantitatively similar to those found by Wu and Sridhar for a magnetic field oriented parallel to the c-axis of a YBCO crystal,[14] although the temperature dependence is quite different. This difference may be due to the complicated microstructure of our films. There is some indication that the films consist of a base layer of c-axis material 2000 to 3000Å thick, with a-axis grains on top.[15] We speculate that the strongest pinning may come from the base layer, and the temperature dependence may be that of weak-link junctions between the a-axis grains.

As suggested by Morgan *et al.*,[16] one can also determine the temperature dependence of the normal-state resitivity below T_c in the context of the Bardeen-Stephen model [17]: $\rho_n(T) = \Phi_0\mu_0 H_{c2}(T)/\eta(T)$. Taking $\mu_0 H_{c2}(T) = 70T[1-(T/T_c)^2]$ at low temperatures for this film, we find the normal-state resistivity shown in Fig. 6. The results can be roughly fit to $\rho_n(T) \approx (30 + 0.3T(K))$ μΩcm, for T<60K, although it would be equally valid to say $\rho_n(T) = 40\ \mu\Omega\text{cm}$ and constant. These values for the intercept $\rho_n(0)$ are somewhat higher than those found from extrapolating the normal-state resistivity of c-axis films from above T_c,[15] and probably represents residual scattering due to quenched-in disorder. Above 60K, $\rho_n(T)$ increases sharply, consistent with analysis of surface resistance measurements on YBCO crystals.[18]

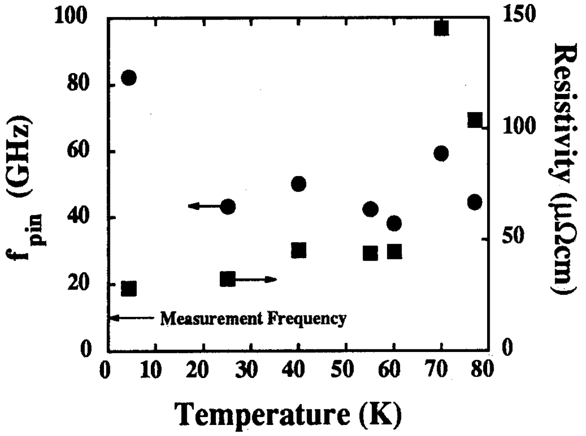

Fig. 6. Temperature dependence of the pinning frequency $f_{pin} = 1/(2\pi\tau)$ as obtained from the data in Figs. 3 and 4, and the normal-state resistivity obtained from the vortex viscosity in the context of the Bardeen-Stephen model.

V. SUMMARY

We have measured the surface impedance of a commercially available YBCO film in the device-like parallel-plate resonator geometry over the technologically interesting field range up to 4 kG. Below the crossover field $H_x(T)$, the surface impedance is dominated by Josephson (inter-granular) vortices. Above this crossover field, pinning and viscosity inside the grains influences the surface impedance. The pinning frequency is in the 40 to 50 GHz range, or above, for temperatures below 77K. Thus a full treatment of pinning and viscosity is required to understand the surface impedance of the cuprates in the microwave range. The pinning frequency and vortex pinning force-constant are in agreement with those obtained previously on YBCO crystals [14]. The vortex viscosity is consistent with a defect dominated normal-state residual resistance at low temperatures, and a rapidly increasing resistivity as T_c is approached from below.

VI. ACKNOWLEDGEMENTS

The authors would like to thank G. Harry for his assistance in these measurements, and J. Booth, A. Findikoglu, J. Halbritter, C. Lobb, R. Greene and A. J. Berlinsky for fruitful discussions.

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