INDUCTIVE MEASUREMENTS OF CRITICAL CURRENT DENSITY IN SUPERCONDUCTING THIN FILMS

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Abstract

A noncontacting method of probing the current-induced breakdown of superconductivity (i.e., " J_c ") in thin films is described, which makes use of a single pancake coil pressed against the film surface. The technique has a sensitivity that is approximately 100 times greater than direct transport measurements using room temperature electronics, and it eliminates many of the attendant difficulties of the latter. Preliminary results on Nb and Y-Ba-Cu-O films at 4.2 K reveal an exponential voltage-current dependence, as expected from the activated flux creep model. It is noted that, this being the case, no unique critical current density can be defined. In the case of the oxide superconductors the flux pinning parameters are such that even a "practical" J_c definition is probably not useful.

Introduction

With the appearance of a new class of superconducting materials, the high T_c oxides, has come a revived interest in techniques of measuring the critical current density. Determination of this parameter, which is of prime importance in technological applications, is anything but straightforward. The standard measurement approach consists of attaching leads to a sample and passing a current through it until a voltage is detected. To avoid self-heating due to contact resistance it is generally necessary to subject the sample to additional processing steps (to reduce contact resistance) and reduce its cross sectional area significantly (to reduce the current needed). These steps may degrade the material, and are certainly time consuming and inappropriate as a routine diagnostic tool. In this paper we discuss a non-contacting method of probing the current-induced destruction of superconductivity that has clear applicability as a routine screening analysis of thin film samples and may provide useful information about bulk samples as well. It has significantly improved sensitivity in comparison to direct transport measurements, and appears to yield information of greater physical insight than is contained in the somewhat ill-conceived concept of a unique critical current density.

Experiment

In their attempts to measure the "intrinsic" critical current density of Type 1 superconductors, Mercereau and Crane¹ first realized that many of the uncertainties associated with direct transport measurements are eliminated by using an inductive method to generate supercurrents in cylindrical

thin film samples. Their method was extended to planar thin films by Scharnhorst². A somewhat related technique to determine the penetration depth of thin films has been developed by Fiori and Hebard³. In all of these cases the film sample is positioned between a primary coil that induces supercurrents in the film and a secondary coil that monitors flux penetration.

We discuss here the use of a single "pancake" coil pressed against a film surface that performs both functions. A sinewave current is applied to the coil, inducing shielding supercurrents in the film. These supercurrents have the effect of reducing the magnetic flux linking the coil to a value less than it would have in the absence of a film. The system remains linear in coil current until the current density exceeds the critical value somewhere in the film. Above this level the film currents will redistribute themselves and the flux induced in the coil will no longer be proportional to coil current. To detect the onset of this nonlinear response we monitor the third harmonic voltage component across the coil. (The nonlinearity is symmetric in current, so only odd harmonics will appear.) This is done using the tuned amplifier section of a Princeton Applied Research Model 124A amplifier with $Q=100$ in the ACVM mode. It is necessary to insert a passive twin-tee filter at the amplifier input to remove most of the fundamental frequency component, both to avoid saturating the amplifier and to minimize a contribution due to the finite transmission of the amplifier bandpass filter at the fundamental.

Results

The data shown here were obtained with a 290 turn coil 0.9 mm thick, inner diameter = 3.0 mm, outer diameter = 6.2 mm, at a drive frequency of 1.6 kHz. Figure 1 shows the results of a measurement as discussed above on a 6000 Å thick high quality Nb film at 4.2 K. The initial linear slope is primarily due to harmonic distortion present in the drive current oscillator. There is an abrupt increase in third harmonic content at a drive current of 48 mA which could be interpreted as the point when J_c is exceeded somewhere in the film. To quantitatively interpret these observations we must relate the currents induced in the film to the coil current. In Ref. 4 a method for doing this for an infinite film is given that starts with the assumption that the back side of the film is completely shielded, that is, $B=0$. The magnetic fields on the coil side of the film can be simulated by replacing the film with a second (image) coil. One can then calculate $B_{||}$, the parallel component of field at the film surface. (The perpendicular component is zero.) Maxwell's equation gives,

$$K = \int_0^d J dx = B_{||} / \mu_0 \quad (1)$$

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Figure 1. Dependence of the third harmonic voltage across a coil coupled to a 6000 Å Nb film at 4.2 K as a function of current at the fundamental frequency (1.6 kHz) in the coil.

where d is the film thickness. We are of course interested in the maximum current density induced in the film for a given coil current. Analysis of the coil used for the data of Fig. 1 resulted in the calibration $K_{\max} \approx (1000/\text{cm})I$, where I is the coil current. For a thick film ($d > \lambda$) we have $J_{\max} \approx K_{\max} / \lambda$, where λ is the penetration depth of the superconductor. Using $\lambda = 500$ Å for Nb we infer $J_{\max} \approx 1.4 \times 10^7$ A/cm² for the 6000 Å Nb film.

As long as $d > \lambda$, the assumption that $B=0$ behind the film is certainly valid. We have two pieces of experimental evidence that this assumption remains true to lowest order even in the opposite limit $d < \lambda$. The first is reported in Ref. 4, where fields at the back side were monitored with a SQUID. The apparent magnetic field observed behind a 200 Å Nb film was considerably reduced from its value with no film present, and could have been explained as stray coupling. A second line of evidence comes from our measurements of the inductance of the coil as modified by proximity to a superconducting film. We find it to be independent of Nb film thickness down to ~ 150 Å. This is a rather sensitive measure of the relative magnitudes of the shielding currents induced in the films, as these currents have the effect of

reducing the inductance by almost a factor 4 of the free-standing value of the coil. Both of these observations imply that, contrary to a naive interpretation of the London equation, a film with thickness less than the penetration depth (> 500 Å in Nb) fully shields magnetic fields. The method outlined in Ref. 4 for determining K is thus assumed to be approximately valid even when $d < \lambda$.

In the appendix we show that the dependence of the coil voltage on current in the region above the break point is simply related to the voltage-current relationship that would be measured in a direct transport measurement on the film. The noncontacting approach, however, has the additional advantage of having as much as 100 times greater voltage sensitivity. Moreover the chances of sample heating affecting the data are greatly reduced since the sample is in a dissipative state only during a fraction of each cycle.

To display the full range of the voltage data from the Nb sample shown in Fig. 1, we use a logarithmic scale in Fig. 2. Over several decades the film voltage depends approximately exponentially on current. The apparently abrupt change in slope seen in Fig. 1 is best interpreted as the point

Figure 2. Same as Fig. 1, but with the voltage axis plotted logarithmically.

where instrumental background intersects the rapidly rising term due to the film. As such it cannot have the fundamental significance that the linear plot suggests. Fig. 3 shows the data taken at 4.2 K from a 6000 Å "1-2-3" film of reasonably high quality as judged by other means. It is slightly off composition (Y(21)Ba(29)Cu(50)), the superconducting transition is complete at 85 K, and the resistivity at 100 K is 400 $\mu\Omega\text{-cm}$. In this sample the exponential dependence of the film voltage on drive current is again observed, in this case exceeding the instrumental contribution over the entire range. Thus one cannot uniquely define a critical current density.

Discussion

Our 1-2-3 film data particularly underscore the futility of attempting to characterize a sample with a single J_c parameter. Taking this film as an example, we note that a transport measurement using conventional electronics with a 1 μV criterion would correspond roughly to the 100 μV level in Fig. 3, yielding a respectable $J_c \approx 10^6 \text{ A/cm}^2$. At the other extreme a sensitive measurement using a SQUID could easily detect an estimated residual resistivity in the film $\approx 10^{-13} \Omega\text{-cm}$ at zero current, leading to the conclusion that there is no true supercurrent. (This estimate of resistivity follows if we assume a form $E = E_0 \sinh(J/J_0)$ and extrapolate the data of Fig. 3 to low current.) Clearly it is inappropriate to represent the quality of such a film by this poorly-defined parameter. Rather some attempt should be made to characterize the

voltage-current relationship over a wide enough range to permit extrapolation to the region of interest in a potential application.

The exponential form of our data is exactly what would be predicted by the "flux creep" phenomenon found in Type II superconductors in the critical state.⁵ The slope $d(\ln E)/dJ$ is proportional to the ratio of the depth U of the potential wells in which the flux vortices are trapped to the thermal energy kT . Yeshurun and Malozemoff⁶ have recently pointed out that U/kT_c for the high T_c oxides is probably at least an order of magnitude less than in usual superconductors. Among the ramifications of this fact is the probability that " J_c " is no longer well-defined even in a practical sense.

Conclusions

Our measurement method suggests that an exponential relationship between the electric field and current density exists in films of both conventional superconductors (Nb) and oxide superconductors. In the latter case the dependence is so weak as to render the concept of critical current density meaningless. Much more work remains to be done to determine whether conventional flux creep theory can account for these effects.

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Appendix

A simple circuit approach to analyzing this experiment helps make connection with the more conventional transport measurements. We consider a coil of rectangular cross section: b =dimension along the axial direction and c =dimension in the radial direction. With this coil in contact with the film surface the maximum in K (which is flowing in the opposite direction from the coil current) occurs at approximately the mean radius a of the coil windings. K falls off to roughly half its maximum value at the radial positions $a+c/2$ and $a-c/2$. We suppose that nothing fundamental is lost by modelling the extended film as a thin annular ring of inner radius $a-c/2$ and outer radius $a+c/2$ carrying a uniform current density K_{ave}/d , total current $i = K_{\text{ave}} c$. The destruction of superconductivity by a current can be represented by a function $v(i)$ describing the development of a dissipative voltage that would be measured in a transport measurement if the patterned stripe had a length/width ratio $= 2\pi a/c$ and the stripe carried current i . In our experiment the voltage V and current I in the coil are related by the coupled equations (neglecting coil resistance):

$$V = L_0 di/dt + M di/dt. \quad (1A)$$

$$v(i) = L di/dt + M di/dt \quad (2A)$$

Here L_0 is the self-inductance of the coil, L is the self-inductance of the ring, and M is the mutual inductance between the two. If the ring is fully superconducting ($v = 0$) we find $K_{\text{ave}} = i/c = -(M/Lc)I$ from (2). Using the method of Ref. 4 for

Figure 3. Same as Fig. 2, but with a 6000 Å Y-Ba-Cu-O film at 4.2 K coupled to the coil.

the coil used in this experiment it is found that $K_{ave} \approx (1000/\text{cm}) I$. Thus converting to the circuit model we find $M/L \approx 160$. In the general case the relationship between v and V is found by eliminating di/dt in (1) and (2):

$$V = (L_0 - M^2/L) di/dt + (M/L) v(i). \quad (3A)$$

The first term is the self-inductance of the coil, modified as explained earlier by proximity to a superconducting film. The second term is the one of interest. As long as $v \propto L di/dt$ (true for all our data) the time dependence of i in (3) is well approximated by $i(t) = -(M/L) I(t)$. Note that the voltage v that would be measured in a transport measurement is amplified here by the factor M/L . The amplification factor has no fundamental limit, since M is proportional to the number of turns in the coil. A plausible guess of a form for $v(i)$ that would yield the data of Figs. 2 and 3 is $v = v_0 \sinh(i/i_0)$. This predicts an rms voltage at the third harmonic across the coil: $V_{rms} \approx (M/L)(v_0/10) \exp(I_{rms}/I_0)$ for $I_{rms} > 3I_0$, in agreement with the dependences seen in our data. Here $I_0 = i_0/\sqrt{2}(M/L)$. In terms of intensive parameters of the material, we might have $E = E_0 \sinh(J/J_0)$; then $E_0 = v_0/2\pi a$, and $J_0 = I_0 \sqrt{2}(M/L)/(cd)$.

This analysis makes it clear that the inductive measurement described here is essentially a transport measurement with impedance transformation. Since it is the very low resistivity region of the superconductor-normal transition that is of primary interest, an impedance transformation would seem to be the most suitable approach to this measurement problem given the use of room-temperature amplifiers. We believe that for our coil the improvement in sensitivity over the most careful direct transport measurement is of order 100. This estimate tries to account for, on the one hand, the loss of signal power that occurs by focussing only on the third harmonic of $v(t)$. On the other hand we are able to make use of a frequency region where the amplifier noise contribution is minimal. It can be pointed out that according to (3A) there is no frequency dependence to the voltage generated in the coil by a nonlinear resistance in the film. However the "background" first harmonic term arising from the self-inductance can be reduced by using a low frequency.

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