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Abstract—A non-contacting method of determining the critical current of a superconducting film has proven useful in several laboratories as a routine indicator of HTS film quality. It consists of a small coil pressed against the film surface and driven with an audio frequency sine wave current (I_{drive}). The onset of a significant third harmonic voltage component (V_{3f}) across the coil indicates that the screening currents in the film have exceeded their critical value. We show in this paper that the quantity V_{3f}/(f I_{drive}) should be a universal function of I_{drive}/I_{sc} if the Bean critical state model is applicable. Here I_{sc} is a scaling current that is proportional to J_c d (J_c=critical current density in the film, d is its thickness) and f is the frequency. By varying the temperature of a thin YBCO film between 4.2 K and its transition, this scaling was observed to apply over a range of J_c’s covering two decades and drive frequencies covering more than three decades. The frequency dependent measurements revealed a logarithmic dependence of the critical current on frequency that can be interpreted as a manifestation of flux creep. This data was used to infer the pinning energy within the collective pinning model.

I. INTRODUCTION

Inductive measurements of the critical current are now made by numerous groups as part of the standard array of measurements to characterize HTS films. Most commonly, the magnetization of a sample in an applied magnetic field is measured, from which shielding currents in the film may be deduced. We have developed [1] an alternative technique that makes use of a small flat coil pressed against the film surface, and driven with an ac current (sine wave) to induce shielding currents in the film. For low enough currents, the inductive reactance of the coil is reduced by the proximity of the film but is linear. If the current in the coil is large enough, the screening current density in the film will reach its critical value (J_c). When this occurs, the coil impedance is no longer linear. A sensitive way to monitor the onset of nonlinear response is to measure the third harmonic voltage (V_{3f}) component across the coil. A sharp onset of V_{3f} at a particular coil current amplitude indicates that the shielding current has reached the critical value in some parts of the film. The relationship between coil current and screening current density may be easily calculated for a given coil and spacing from the film.

There are obvious advantages of this method compared to magnetization measurements. It may be used with large area films, which are increasingly used to fabricate devices. The sample may be pressed against a copper block simplifying temperature control and measurement. Furthermore, the measurement electronics are relatively simple and inexpensive.

Up to now this measurement has primarily been used to rapidly screen YBCO films at a convenient temperature (78 K). In this role, it is sufficient to estimate a point where V_{3f} drops to zero using a more or less arbitrary criterion. As such, the measurement seems to correlate well with other measures of film quality, such as transition temperature and surface resistance. In the work reported here the YBCO film was carefully studied by the single coil technique as a function of temperature and frequency to evaluate its utility in determining fundamental physical properties of films such as the temperature dependence of the critical current and the pinning energy.

II. MEASUREMENTS

A YBCO film grown by laser ablation on a STO substrate by the University of Md. group was used. Since the coil current is proportional to J_c d, it is desirable to use a small film thickness d if large J_c values are to be encountered, as is the case when data are to be taken at low temperature. By using a thickness d~50 nm, the coil current required at the lowest temperature, ~100 mA, is low enough to avoid heating of the film. The critical current at 4.2 K is approximately 4\times10^7 A/cm².

The copper wire coil used for the work reported here has dimensions ID=2mm, OD=4.5 mm, thickness=0.5 mm, 300 turns. It is desirable that the coil be smaller than the smallest sample to be measured and that all of the turns couple as strongly as possible to the film (hence a thin coil). A large number of turns enhances the signal/noise of the measurement and reduces the coil current necessary to induce the critical state in the film.

A convenient way to extract the harmonic component of the coil voltage, which is much smaller than the fundamental frequency component, is to use a digital processing lock-in amplifier (Stanford Research Systems model SR850). One advantage of digital processing is that it is quite easy to vary the drive frequency used. We
find generally the system can be used from below 100 Hz (where signal/noise becomes an issue) to 30 KHz, set by the maximum frequency that the amplifier can detect. To verify that there is no intrinsic instrumental frequency effect, a nonlinear circuit involving semiconductor diodes was substituted for the coil, and no discernable frequency dependence was observed.

III. DATA ANALYSIS

Fig. 1 shows the dependence of $V_{3f}$ on coil current for three different temperatures. It can be seen than the onset of a finite $V_{3f}$ is not abrupt, but is somewhat rounded. To clarify the significance of the shape of the curve, it would be desirable to calculate the film response using for instance the Bean critical state model. In fact, the currents flowing in the film can become quite complicated when there are large excursions of the drive coil current, involving concentric rings of oppositely flowing current. Without delving into such a calculation, it can be seen immediately that the spatial pattern of currents in the film depends only on $I_{drive}/I_{sc}$, where $I_{sc}$ is the coil current that just drives the film into the critical state. The magnitude of the film currents must be proportional to $J_{cd}$, which in turn is proportional to $I_{sc}$. Thus the third harmonic voltage across the coil (ultimately arising from the mutual inductance between the coil and currents in the film) should be proportional to $I_{sc}$ and be a function only of $I_{drive}/I_{sc}$. Finally we find that $V_{3f}/I_{drive}$ should be a universal function of $I_{drive}/I_{sc}$. Additionally $V_{3f}$ must be proportional to frequency $f$; thus we expect $M_3=V_{3f}/(fI_{drive})$ should be a universal function of $I_{drive}/I_{sc}$, with $I_{sc}$ proportional to $J_{cd}$. This is clearly the case, as can be seen in Fig. 2, where we plot $M_3$ against the log of the drive current for a series of sample temperatures. As the critical current ($I_{sc}$) varies over more than two decades, the shape of the curve remains identical.

To define $J_c$ a criterion must be chosen; in the case of transport measurements it is a specified value of electric field. Fig. 2 suggests that in the case of inductive measurements a specified value of $M_3$ should be chosen. The choice of a suitable criterion is somewhat arbitrary. We find that there is more variability among films in the shape of the curve near the onset than higher along the curve. The curve at low $M_3$ is presumably sensitive to degraded regions of the film small compared to the coil diameter, while the higher $M_3$ portion of the curve characterizes an average of film properties over roughly the coil diameter. Thus to avoid excessive sensitivity to fine scale inhomogeneities one should not use too small a criterion for $M_3$. The $J_c$ data given in this paper all used a criterion $M_3=30$ $\mu$H. Note that for a coil of the same dimensions but different number of turns $N$, $M_3$ would scale as $N^2$.

The current density, $J$, in the film resulting from a given coil current may be calculated using a method outlined in [2]. In the case of our coil, the calculation yields

$$J = 2.3 \times 10^{11} \text{ A/cm}^2 \left( \frac{I_{drive}}{A} \right) \left( \frac{d}{\AA} \right)$$

IV. EXPERIMENTAL RESULTS

In Fig. 3 we show a plot of $J_c$ versus temperature using the above $M_3$ criterion, with a drive frequency of 1 KHz. Near the transition $J_c$ varies as $(T_c-T)^{1.4}$. We can also stabilize the temperature and vary the drive coil frequency. In the Bean critical state model the critical...
Fig. 3. A plot of inferred critical current density as a function of temperature for a 50 nm thick film, where a criterion \( M_3 = 30 \) \( \mu H \) was used. The frequency was 1 KHz.

Fig. 4. The apparent critical current using a criterion \( M_3 = 30 \) \( nH \) as a function of frequency.


current should be independent of frequency. In fact there is a weak logarithmic dependence on frequency; an example is shown in Fig. 4.

V. DISCUSSION OF FREQUENCY DEPENDENCE

The dependence of \( J_c \) on \( \ln(f) \) seen in Fig. 4 suggests that a flux creep phenomenon is applicable. Consider the expression [3]

\[
J_c = J_{c0} - \frac{kT}{(dU/dJ)} \ln(t_0)
\]  

(2)

for the relaxation of screening current \( J_c \) a time \( t \) after the critical state is established. Here \( U(J) \) is the energy barrier to vortex flow, \( J_{c0} \) is the critical current in the absence of thermal fluctuations, and \( t_0 \) depends on geometry and initial creep rate and is assumed small compared to \( t \). In our ac measurement, the critical state is reestablished twice each cycle, and it is reasonable to associate the time \( t \) with \( 1/f \). Thus the relaxation rate \( Q = d\ln(J_c)/d\ln(f) \), which is plotted as a function of temperature in Fig. 5, should vary as

\[
Q = kT/(J_c (dU/dJ))
\]  

(3)

This expression clearly does not account for the data as the temperature approaches zero, since the denominator remains finite. Presumably at low temperature (3) no longer applies and the process of thermally assisted quantum creep [4,5] becomes operative. In [5] it is shown that if \( U \) is independent of temperature and \( U(J) \) has the dependence predicted by collective pinning theory [3], we should have

\[
kT/Q = U_c + \text{const.} \times T
\]  

(4)

for temperatures high enough that (2) is valid. Here \( U_c \) is the characteristic pinning energy of the system. In Fig. 6 we see that there is a substantial region where (4) is apparently followed by our data, with \( U_c \approx 700 \) K. The transition to thermally assisted quantum creep occurs at approximately 10 K, similar to the observation in [5].

This value for \( U_c \) is 2-3 times greater than found in [5]. The explanation may lie in the unusually low magnetic fields used in these measurements (.03 T, the field generated by the coil and film currents). Also, we have used an unusually thin film, 50 nm, which may have stronger pinning.

Fig. 5. The relaxation rate \( d\ln(J_c)/d\ln(f) \) as a function of temperature.
VI. CONCLUSIONS

The single coil method has been shown to give meaningful results over more than two decades of $J_c$ values. For thin enough films the entire temperature range may be covered. By varying frequency, flux creep data comparable to that obtained by other methods is obtained. To date, data have been taken with no external field. In this case, the measurement probes an unusual regime, where flux diffusion is occurring only along the c direction of the material. This may account for an unusually high value of the pinning energy inferred. Measurements with an applied field parallel to c should also be possible.

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REFERENCES


