SINGLE PARAMETER ANALYSIS OF HYSTERETIC MAGNETIC FLUX TRAPPING IN HIGH T_C SUPERCONDUCTOR RIBBON

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INTRODUCTION

Practical use of the new high transition temperature (T_C) superconductors demands that they be capable of carrying a large transport current. At the critical value (I_C) of current, the sample is full of flux; additional current creates additional flux and forces the flux line lattice, which was trapped in the material microstructure, to move continuously, which causes dissipation. The value of the magnetic field strength at the sample surface when full field penetration occurs is called H*. This paper describes noncontacting AC measurements of H* in ribbons of Pb-BiSrCaCuO coated with silver layers. The results can be described in terms of the single parameter H*, which is a function of both the ribbon thickness and sample temperature. The way in which these results can be used to develop a practical method of determining H* and I_C with spatial resolution is described.

THE CRITICAL STATE

The new high T_C materials are extreme type II superconductors where, in the presence of an external magnetic field and/or a transport current, magnetic flux exists in the material in the form of flux lines distributed on a lattice [1]. Individual flux lines are pinned at microstructural inhomogeneities such that only under a sufficiently high local current flows will they become depinned and flow throughout the material. The value of the local current density that causes depinning, the microscopic critical current density { J_C }, is directly proportional to the pinning force strength. The critical state model [2] describes the pinned flux line distribution within the material quasistatically, assuming that the equilibrium distribution is achieved at each value of the externally applied field on a time scale that is short compared to experimental times. Flux lines penetrate the material to a flux front boundary, which eventually penetrates the sample completely at a particular value of the external field {H*}. Ampere's law relates the full field penetration value at the surface to the critical current density and layer thickness by $H^*=J_C d/2$ for a layer superconducting geometry.

SUPERCONDUCTING TAPE AND AC PROBE GEOMETRY

Bismuth-based superconductor material (Pb-BiSrCaCuO, 2223 phase) was extruded within a silver tube to form a silver-coated flat tape approximately 1 cm wide by 3 cm long with thicknesses of about 0.06 mm each for the superconducting and silver layers.[1]

Magnetization was measured with small solenoidal coils. The drive field coil had a radius of 0.5 mm and was wound with 13 turns of #38 wire; the balanced pickup coils were wound over the drive coil with 5 turns each. The coil geometry is shown in Fig. 1 along with the pattern of the AC current the probe induced in the sample. For an excitation current of 100 mA, the calculated peak magnetic field strength parallel to and at the surface of the sample ranges from about 200 A/m, in the absence of a sample, to 400 A/m with a fully superconducting sample. The response of the induced current was recorded by a lock-in amplifier at a frequency of 1 kHz.

The measurement geometry and cryostat have been previously described [3,4]. The coil position was fixed over approximately the center of the sample

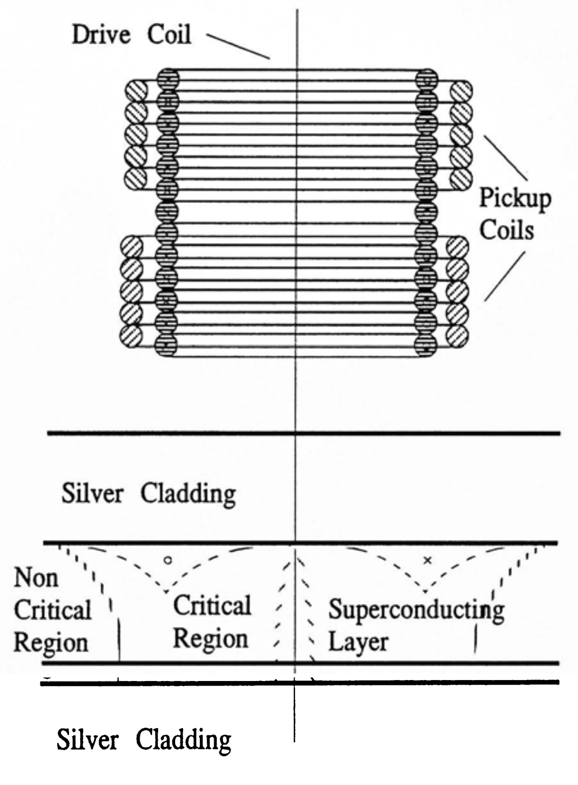

Fig. 1. Critical state generation and detection coil assembly above silver-sheathed Pb-BiSrCaCuO. Also shown are the expected critical state region boundaries for the applied field strength, H, at the layer surface, with values below and above H*.

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[1]Samples were prepared by M. Lanagan at Argonne National Laboratory.

surface with 0.7 mm between the sample and the lowest winding. The probe was used by increasing the AC excitation field until full penetration of the critical state region through the tape was achieved locally under the coil, see Fig. 1 and references [3,4]. The eddy currents induced in the silver coating were subtracted by an external signal dividing circuit balanced at 120 K, well above the onset of superconductivity (112 K) for this material.

MEASUREMENT RESULTS AND ANALYSIS

Figure 2 shows the AC signal magnitude as a function of the excitation coil current. The applied field has been subtracted by the balanced coils, so only the net sample magnetization is shown. At a sufficiently low temperature, chosen to be 19.9K, the response is that of a completely shielded sample, i.e., the basic probe response (the results are independent of the sample since at this low temperature the fields applied are much less than the critical fields). The rest of Fig. 2 shows the response for the penetrations of the flux line lattice into the sample that occur as the temperature is varied. To compare data at different temperatures, the basic probe response was eliminated by dividing the results by the data for T=19.9 K. The normalized results for the temperatures where the sample was superconducting are shown in Fig. 3.

The critical state model prediction for flux penetration is a geometric calculation based on one parameter: the full field penetration value, H*. For the given probe/sample geometry, there should be a well-defined H*(T,d) that depends only on temperature and layer thickness. In principle it can be calculated directly; however, this calculation has proved amenable only in situations where the

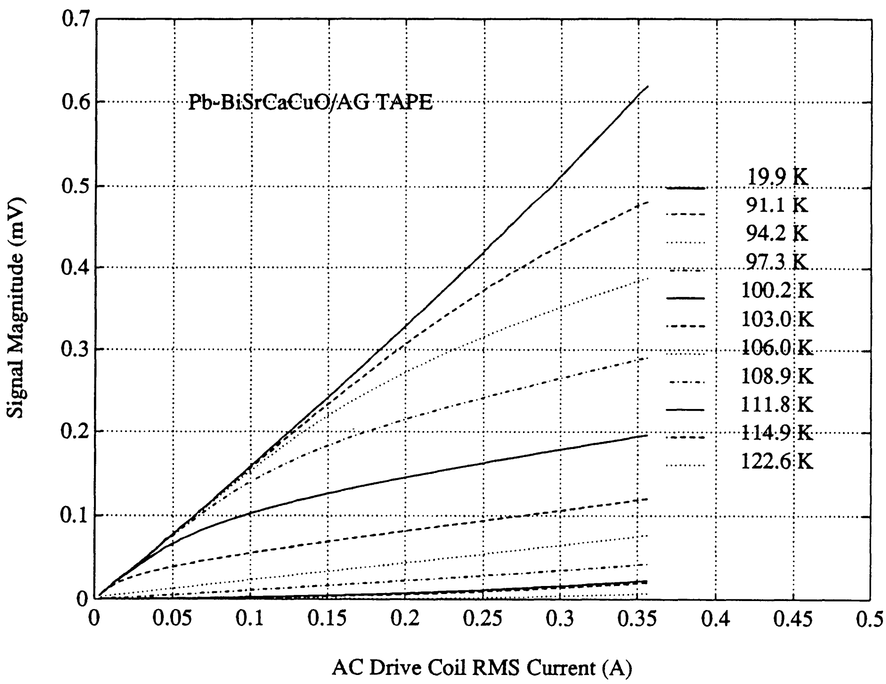


Fig. 2. Sample magnetization as a function of external field at 1 kHz for different temperatures.

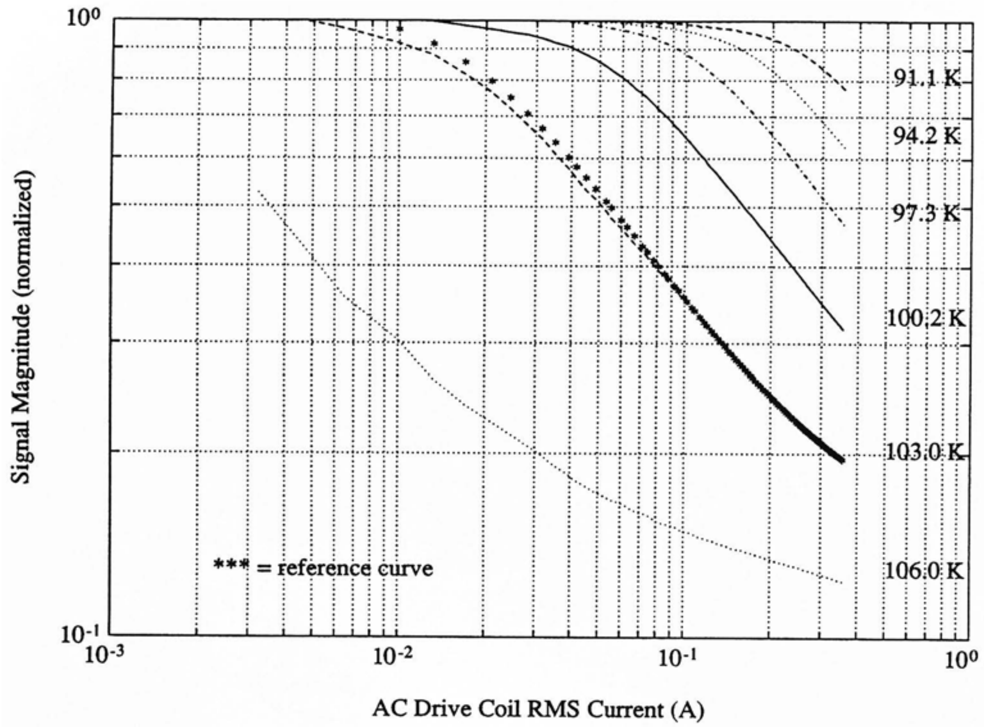
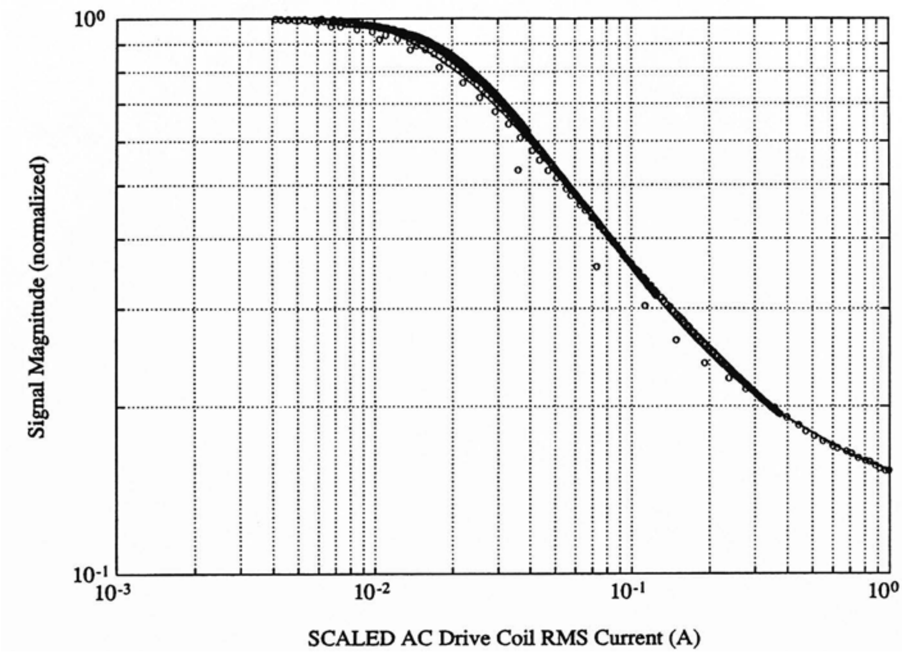


Fig. 3. Sample magnetization as a function of external field normalized by the low temperature (19.9 K) probe response. The reference curve compiled from all the data for this probe geometry is also shown {***}.

externally applied field is uniform and the sample shape is sufficiently simple that no demagnetization effects are present [5,6]. The calculations of references 5 and 6 are for a slab geometry in a parallel field where the demagnetizing factor is zero and the local critical current is proportional to $1/|H_{local}|$. The results reported here are very similar to these, even though the geometry is more complicated.

Recently, a successful calculation was achieved for sample shapes exhibiting demagnetization effects, a sphere and a cylinder in a uniform field [5]. The geometry used here is the most practical for actual measurements on tapes, but uses a source coil producing a non-uniform field throughout the sample, which consequently exhibits demagnetizing effects also. Therefore, an exact calculation of the expected response is not available. An empirical approach was taken to provide the required normalization. Since the critical state model suggests the response should be a function of only one intrinsic parameter, H*, all the results should scale with this value as a function of temperature for a given sample thickness. Figure 4 shows the data of Fig. 3 redrawn at scaled drive current values such that all the data overlaps on one curve. The data nearest to that for T_R=103 K was chosen as the reference. The reference curve obtained using all the data is plotted in Figs. 3 and 4. This curve accounts for the probe/sample geometry and provides a reference to which data for other temperatures and other samples can be compared in a quantitative manner. The scaling factors for the current, which align the data, are shown in Fig. 5. They depict the ratio between the full field penetration values at a given temperature and the reference.



SCALED AC Drive Coil RMS Current (A)

Fig. 4. Data of Fig. 3 scaled with respect to drive current so as to lie on a single curve. A least squares fit to this curve forms the reference curve shown in Fig. 3.

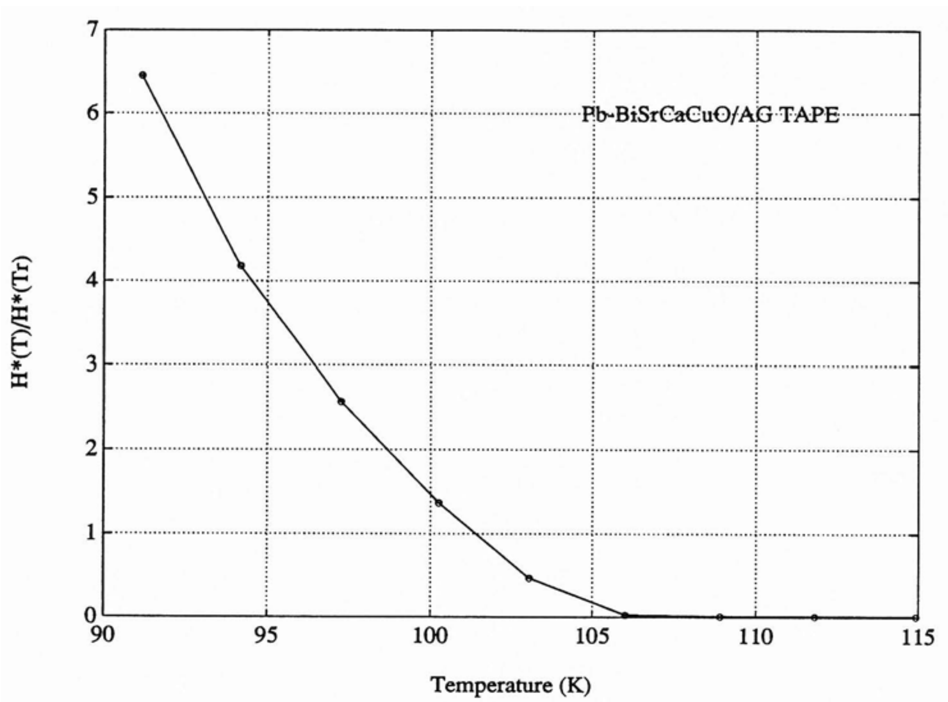


Fig. 5. Full field penetration values measured for the Pb-BiSrCaCuO layer normalized to its value at T_R = 103 K by the reference curve of Fig. 3.

In order to obtain the critical current value for any other sample, the relationship between H* and $J_C d$ must be known quantitatively. This can be obtained through measuring critical current and layer thickness { J_{C0} and d_0 } for one sample at some known temperature { T_0 } by the four-point probe technique and comparing AC probe measurements to the reference curve as before { $H^*(T_0)/H^*(T_R)$ }. The critical current for the unknown sample is then given by:

$$\frac{J_C(T)d}{J_{C0}(T_0)d_0} = \frac{\dfrac{H^*(T)}{H^*(T_R)}}{\dfrac{H^*(T_0)}{H^*(T_R)}} \tag{1}$$

The results for the measured sample of Fig. 2 show H* dropping to zero at about 106 K, which is well below the transition temperature of about 112 K for this Pb-BiSrCaCuO material. This is consistent with the conventional measurements and those of other researchers and delineates the point at which the flux line lattice becomes unstable even with no applied current flow.

CONCLUSIONS

This paper described the application of an AC surface probe, similar to presently used eddy current probes, to the measurement of DC transport critical currents and critical state dissipation in high T_C superconductors. It has been shown that the probe can provide quantitative measurement of the full field penetration in superconducting samples by measuring the response of AC induced screening currents for superconducting materials in the form of tapes with overlayers of silver. In this manner, the AC probe can be used to replace the contact DC probe for determining critical currents in a noncontacting and local manner suitable for scanning over or along the sample.

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