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Magneto-microwave absorption observation of vortex creep-to-flow transitions in thin films of $Tl_2Ba_2Ca_2Cu_3O_x$

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Abstract. The temperature dependence of the microwave absorption due to a constant magnetic field in thin films of $Tl_2Ba_2Ca_2Cu_3O_x$ on single-crystal MgO substrates shows two temperature regions between 77 K and 120 K in which the absorption has a different dependence on temperature. The temperature at which the crossover occurs depends on the magnetic field, increasing as the field decreases, and is identified as the temperature at which the vortices become depinned and undergo flux flow. A measurement of the transition temperature versus magnetic field allows a determination of the irreversibility line for the film.

1. Introduction

Because of their higher transition temperatures and smaller coherence lengths, the copper oxide superconductors display considerable flux flow or creep. This movement of flux causes dissipation of current flow and manifests itself as a magnetic field-dependent increase in the resistance of the material in the superconducting state. Thus field-dependent resistance measurements are the traditional method of studying flux flow or creep. However, because the surface resistance also increases when there is flux movement there will be an increase in the absorption of microwave energy when a DC magnetic field is applied. Field-dependent microwave absorption has been used to measure flux movement in the low-temperature metallic superconductors such as $Ti_{0.7}V_{0.3}$ [1]. Some field-dependent microwave absorption studies have been reported for the high-temperature copper oxide superconductors and attempts have been made to use the measurements to understand the dynamics of flux flow in the materials [2–4]. A limitation of the microwave method in studying flux dynamics is that the microwaves only probe the surface regions of the material and the dynamics determined from such data may reflect the surface behaviour of the fluxons rather than the bulk behaviour. The microwave absorption method may, however, be useful in studying flux dynamics in thin films of the superconductors where the film thickness is in the order of the microwave penetration depth. In this work we have, therefore, chosen to use field-dependent microwave absorption to study flux dynamics in thin films rather than crystals or bulk materials.

The copper oxide superconductors have large H–T regions in which the flux solid has melted and in which the magnetic properties are reversible [5–7]. It is observed

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that there is an H–T line that separates reversible magnetic behaviour from irreversible behaviour. Below this H–T line the magnetic-field-dependent properties are irreversible and display magnetic-field-dependent hysteretic properties. In this region the vortices form a solid—either a lattice or a glass—and move by thermally activated hopping from pinning site to pinning site. Above the irreversibility line the flux solid has melted and the motion of the vortices may be described as viscous flow. However, the distinction between the H–T irreversibility line and the H–T line for melting of the vortex solid is unclear. Nevertheless, the dynamics of flux movement in the two regions should be different and a change in the dynamics should be observed as the H–T irreversibility line is traversed, which should be evident in the field-dependent microwave absorption data. This work reports the first observation of the depinning-to-fluid transition of the vortices in a thin film of a high-temperature superconductor, $Tl_2Ba_2Ca_2Cu_3O_x$, using a magnetic-field-dependent microwave absorption technique.

By measuring the temperature dependence of the microwave absorption at small temperature intervals in different magnetic fields a change in kinetics from flux flow to flux creep can be observed. Because the temperature of the crossover depends on the magnetic field strength, the H–T irreversibility line of the thin film of the superconductor can be determined.

2. Experimental details

The experiment measures the reflection coefficient, $\Gamma(H,T)$, of a resonant cavity containing the sample cooled below T_c. Near-optimal coupling changes in $\Gamma(H,T)$ are proportional to changes in the surface resistance $R_s(H,T)$. In order to measure the field-dependent flux flow, $\Gamma(H,T) - \Gamma(0,T)$—which is proportional to $R_s(H,T) - R_s(0,T)$—is measured. The experimental arrangement is shown in figure 1. The sample is located in a double-walled quartz glass finger-type Dewar through which cold nitrogen or helium gas can flow. A heater and a Scientific Instruments regulator control the temperature to within ± 0.1 degrees. The temperature is measured using a semiconductor diode sensor. The finger of the Dewar is inserted through a hole on the microwave cavity such that the tube and sample are at the centre of the cavity which operates in the TE_{102} mode. The microwave frequency is 9.2 GHz. The cavity is located between the poles of an electromagnet. The Klystron is tuned to the resonant frequency of the cavity. Absorption by the sample in the cavity changes the reflected power from the cavity to the arm of the bridge containing the diode detector. The change in the DC current in the detector measures the amount of microwave power absorbed by the sample and, for the range of power used in this measurement, is linearly related to the microwave power sensed by the detector.

The thin films of $Tl_2Ba_2Ca_2Cu_3O_x$ were grown by electrochemical deposition of the constituent metals on a single-crystal MgO substrate and subsequent oxidation. The details of the fabrication of the films have been previously described [8]. The onset temperature of the superconducting state in the films is 120 K as measured by four-probe resistivity methods. X-ray diffraction measurements of the films indicate that there is preferential alignment of crystals on the substrate such that the c axis of the orthorhombic unit cell is perpendicular to the film surface. However, there is some misalignment of the crystallites of the film about the c axis.

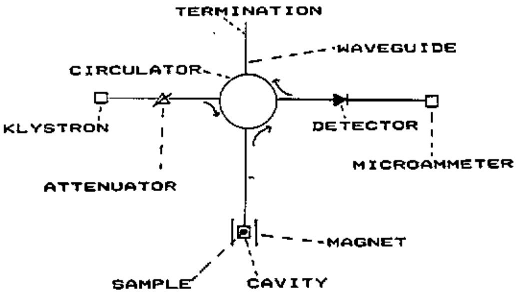

Figure 1. The microwave bridge arrangement used to measure the microwave absorption induced by a DC magnetic field in a superconducting sample.

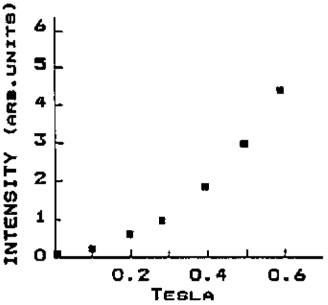

Figure 2. The increase in microwave energy absorbed versus DC magnetic field at 77 K in a thin film of $Tl_2Ba_2Ca_2Cu_3O_x$ for the DC magnetic field parallel to the c axis.

3. Results and discussion

The application of a DC magnetic field to the film of $Tl_2Ba_2Ca_2Cu_3O_x$ in the superconducting state increases the microwave energy absorbed over the zero-magnetic-field value because of the increase of the surface resistance due to the motion of the flux. Figure 2 gives plot of the increase in the absorption versus DC magnetic field at 77 K for the magnetic field parallel to the c axis of the film. The functional dependence of the increase of the absorption on the DC magnetic field is different to that reported in other high-temperature superconductors where the increase in the absorption usually has the form B^α with α generally less than one [2, 3]. It is also not in agreement with recent theoretical analysis which predicts a $\sqrt{B}$ dependence [9]. This discrepancy may be due to the magnetic field dependence of the pinning barrier. The surface resistance and thus the microwave absorption can be approximated as proportional to $\sqrt{\rho}$ where ρ is the bulk resistivity [10, 11]. At 77 K where the flux motion is creep, the bulk resistivity has the form [12]

$$\rho = CB\exp(-U/kT) \tag{1}$$

where C is a constant and U the pinning barrier. The microwave absorption will depend on $\sqrt{B}$ only if U is independent of B in the range of magnetic fields of the measurement. Typically U has been shown to depend on B as B^{-C_3} where C_3 is usually less than one [7]. Thus from equation (1) the field dependence of the surface resistance will be given by

$$R_s = [C_1 B\exp(C_2 B^{-C_3}/kT)]^{1/2} \tag{2}$$

where C_1, C_2 and C_3 are constants. This equation describes well the field dependence of the absorption shown in figure 2. It should be noted that equations (1) and (2) are appropriate to hopping in a vortex lattice. The nature of the motional dynamics in a vortex glass is not entirely understood but, as will be discussed below, the field-dependent microwave data for this film do not show evidence for a glass phase.

At constant magnetic field the absorption increases as the temperature approaches T_c. A plot of the log of the intensity versus the reciprocal of the absolute temperature for a constant magnetic field shown in figure 3 gives straight lines but indicates that there are two temperature regions in which the lines have different slopes. It is also observed, as shown in figure 3, that the temperature at which the slopes of the lines change depends on the magnitude of the applied magnetic field. The temperature of the change is higher in lower magnetic fields. By measuring the temperature dependence at different magnetic field strengths, the crossover temperature can be obtained versus DC magnetic field strength as shown in figure 4.

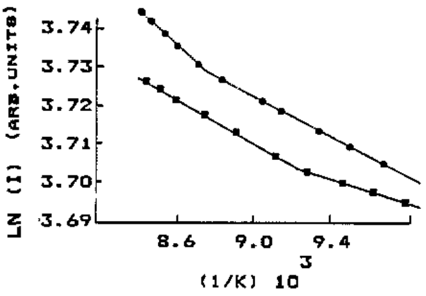

Figure 3. A plot of the log of the absorbed microwave energy versus the reciprocal of absolute temperature at 0.2 T (●) and 0.5 T (■) showing a change in slope of linear data depending on the magnetic strength.

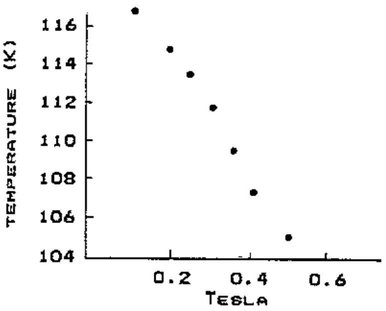

Figure 4. A plot of the transition temperature between two linear regions versus magnetic field.

The change in the slope of the log of the absorption versus the reciprocal of the absolute temperature is suggested to be a result of the change in the functional dependence of the microwave absorption on temperature due to the transition from the reversible to the irreversible regime. Further evidence for this interpretation comes from a measurement of the hysteresis of the absorption. It is found that below T', the transition temperature, the absorption is not reversible, with the direction of the magnetic field sweep showing a somewhat larger absorption on the down-sweep compared to the up-sweep. Above T' it is reversible. In the irreversible phase, vortices can be pinned, and the temperature dependence at a constant magnetic field should be determined by a thermally activated process giving the straight-line dependence as observed on the plot of the log of the absorption versus $1/K$. Kes *et al* [13] have described the motion of vortices in the flow region by solving a simple diffusion equation giving a thermally activated flux flow as observed here in the microwave absorption.

The plot in figure 4 represents the H–T irreversibility line for the film and can be described by the equation [5, 6]

$$(1 - T/T_c) = AH^Q \qquad (3)$$

for $Q = 0.97$.

Recently it has been proposed that the solid vortex phase is a glass rather than a lattice [14]. The order parameter of a glass-to-liquid transition would display a second-order dependence on the temperature. The data in figure 3, which have been measured at two-degree intervals, show that the transition is abrupt and first order. Thus within the limit of the two-degree separation of the data points the temperature dependence of the microwave absorption in a DC magnetic field does not provide evidence for a glass phase in the film of $Tl_2Ba_2Ca_2Cu_3O_x$.

While clearly a reversible-to-irreversible transition has been observed in the microwave data presented here, the question of the nature of the vortex state in granular films needs to be considered. The x-ray diffraction data on these films indicate that the film is a collection of crystallites oriented with their c axis perpendicular to the film but with misorientation about the c axis and thus some degree of granularity. At zero or low magnetic field, less than about 60 G or so, the microwave absorption will be dominated by weak links between the grains. However, the magnetic fields of these experiments are far in excess of the upper critical fields for weak links, and the grains in such fields are not coupled by links between them. The field-dependent microwave absorption observed here is due to vortex motion. The fact that the films are granular does not preclude the formation of a pinned vortex state. Pinning-to-depinning transitions (irreversible-to-reversible transitions) have been observed in a number of granular materials such as $Bi_{22}Sr_2Ca_{0.8}Cu_2O_y$ and $Tl_2Ca_2Ba_2Cu_3O_{10}$ by DC magnetization methods [15, 16].

These results imply the existence of a pinned vortex state in granular materials. Tinkham [17] has considered the nature of the vortex state in granular materials and pointed out that there are really two kinds of vortices in such materials—one called grain boundary vortices which do not pass through the grains, and the other called grain-pinned vortices which pass through the grains. In effect, in a granular material there may be two kinds of vortex solids.

In summary, it is shown that the temperature dependence of the magnetic-field-dependent microwave absorption shows two temperature regions distinguished by a different functional dependence of the absorption on temperature. The crossover temperature depends on the magnetic field and measures the irreversibility line of the film. Magnetic-field-dependent microwave absorption therefore provides a relatively straightforward method for determining the H–T phase line dividing the reversible and irreversible regions in thin films of the high-temperature superconductors. The data do not show any evidence of a second-order dependence of the absorption on temperature near the transition temperature.

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