Title:

TRANSPORT PROPERTIES OF $Tl(2)Ba(2)CaCu(2)O(8)$ MEANDER LINES

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Transport Properties of $\text{Ti}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ Meander Lines

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Abstract---We have measured the electrical transport properties of 10 cm long $\text{Ti}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ thin film meander lines in magnetic fields up to 18T. The large resistance of the meander line effectively increased the electric field, or equivalently, resistivity sensitivity by two orders of magnitude. In moderate magnetic fields the critical current density is found to depend only on the component of the magnetic field normal to the ab planes owing to the highly anisotropic nature of the system. The resistivity versus temperature was measured as a function of magnetic field up to 18T. The linear resistivity is found to vanish in a manner consistent with the occurrence of a second order phase transition. The critical exponent $\nu(z-1)$ is virtually field independent with a value 5.3 ± 1 consistent with previous measurements of a three dimensional vortex glass transition in $\text{YBa}_2\text{Cu}_3\text{O}_7$ and $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$. The critical regime is 10-15K wide in agreement with values for $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ at high magnetic field.

I. INTRODUCTION

The nature of the onset of dissipation in high temperature superconductors has been a topic of extensive research. For the $\text{YBa}_2\text{Cu}_3\text{O}_7$ (YBCO) system vortices extend over large longitudinal ranges, that is, they behave as vortex lines over most of the phase diagram; and it is expected that three-dimensional correlations play a major role in the formation a low temperature ordered phase. In clean single crystals of YBCO evidence for a first order melting transition of the Abrikosov lattice, and an associated weakening of the pinning due to the loss of a finite shear modulus in the vortex liquid state, is believed to destroy the "resistanceless state" [1,2]. In thin films, which inherently possess a larger number of defects, the transition to the low temperature zero resistance state has been shown to have the characteristics of a second order phase transition [3] in agreement with the theoretical prediction of a vortex glass phase [4].

In more anisotropic systems, such as the Bi and Tl based superconductors, the situation becomes more complicated as the weak coupling between adjacent superconducting layers can lead to quasi-two-dimensional behavior [5] and the existence of pancake vortices [6]. At high temperatures

thermal fluctuations deter any ordering processes in the vortex arrangement from occurring. However, when the temperature is low enough such that the relevant coupling energy (Josephson or magnetic) dominates the thermal energy, correlations along the c axis should become strong enough that segments of vortex lines form. It is then expected that pinning becomes more effective due the finite line tension of these segments and a resistanceless state possible.

Measurements of the vanishing of the linear resistivity of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ (BSCCO) single crystals provided evidence that a second order phase transition into a resistanceless state does occur in such systems at low temperature [7]. The critical exponents obtained from the analysis were consistent with those obtained for YBCO thin films and it was concluded that a transition was associated with three dimensional effects. In the following paper we investigate both the low and high current density transport properties of $\text{Ti}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ thin films. First, we demonstrate that the angular dependence of the critical current of this system obeys that of other highly anisotropic systems in moderate magnetic fields. We then focus on the temperature dependence of the linear resistivity in the region where it vanishes in high magnetic field and discuss our results in terms of the vortex glass context.

II. EXPERIMENT

The meander lines studied were prepared from 1cm by 1cm $\text{Ti}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ thin films manufactured by DuPont [8]. The virgin films were patterned by a standard photolithography method and ion milled with 250V Ar^+ ions. A two-by-two array of meander lines was produced on each thin film. A shadow mask was used to evaporate silver on the contact pads, and the films were subsequently annealed at 400°C in flowing oxygen to establish a low contact resistance. Each meander line array was then diced into four individual patterned samples with a photoresist protective coating to prevent damage to the film surface, which was removed with acetone after cutting was completed. Wires were attached to the contact pads with silver epoxy and the samples were annealed at 250°C in flowing oxygen yielding contact resistances of approximately 1Ω .

The meander line pattern has a noninductive geometry which was originally designed to avoid pick-up in pulsed magnetic fields (see figure 1). Adjacent line segments carry current of opposite polarity. In the present study we take advantage of the enhanced length of the meander lines to extend the electric field sensitivity typical of thin film microbridges. The width of the line is 60 μm , with a 60 μm spacing between adjacent current carrying segments and a

thickness of $\sim 0.5 \mu\text{m}$. The length of the meander line is $\sim 10 \text{ cm}$, which is at least two orders of magnitude larger than typical microbridge lengths used to measure transport properties of thin films yielding two additional orders of magnitude in electric field sensitivity.

The transport measurements were made with a four probe measurement technique although the current and voltage taps did not have the standard in-line configuration (see figure 1). Critical current measurements for magnetic fields less than 1 T were made in a transverse iron core magnet, which allowed for axial rotation with angular resolution of 0.5° . The samples were immersed in a liquid cryogen either nitrogen or neon. Resistance versus temperature and current-voltage characteristics in magnetic fields up to 18 T were measured at the National High Magnetic Field Laboratory at Los Alamos National Laboratory. We present data for which the current-voltage characteristic was ohmic in the limit of vanishing current. The resistive transition in zero magnetic field had an onset at $T=105 \text{ K}$ and the resistivity dropped five orders of magnitude within 7 K of the onset point. Two samples were mounted simultaneously to enable consistency

Fig. 1 The meander line pattern with a $60 \mu\text{m}$ line width and $60 \mu\text{m}$ spacing is shown. The meander line pattern is noninductive since adjacent lines carry current in opposite directions. The contact pads are visible in (b) on which two silver strips are evaporated to establish current and voltage taps on each end of the meander line.

checks. The two samples exhibited nearly identical resistive transitions in zero magnetic field, and I-V curves taken on both samples in succession at several temperatures in 6T were found to overlay without any renormalization. Thus the results presented here are representative of the meander lines. Resistance versus temperature was taken in the field cooled mode with a current density of 3 A/cm^2 . The resistivity resolution with this low current density was approximately $3 \times 10^{-11} \Omega \cdot \text{cm}$ with an associated electric field sensitivity of $1 \times 10^{-10} \text{ V/cm}$.

III. RESULTS AND DISCUSSION

Figure 2 shows the critical current density of the meander line as a function of the magnetic field angle (measured relative to the ab plane) for a moderate magnetic field amplitude of 0.5T at $T=26 \text{ K}$ using the standard $1 \mu\text{V/cm}$ criterion. The critical current density decreases when the magnetic field is oriented off the crystallographic ab planes diminishing by approximately an order of magnitude when the field is parallel to the c axis. In figure 3 we replot the angular dependent data versus the component of the magnetic field perpendicular to the ab plane ($H \sin \theta$) with that for values taken with the field applied parallel to the c axis. In addition, similar data from an angular scan with a magnetic field of 0.03 T at 75 K is also displayed. The collapsing of the data onto the same curve for a given temperature confirms that the critical current density depends only on the component of the magnetic field normal to the CuO_2 planes and that these films exemplify behavior typical of highly anisotropic superconductors [9,10]. The self-field critical current density of 2 MA/cm^2 at 75 K is similar to that previously reported on films of the same origin [8], indicating that the patterning process did not degrade the film quality. We note that the critical current density as a function of magnetic field showed negligible hysteresis upon increasing and decreasing field ramps at $T=26 \text{ K}$ implying that the film is strongly linked at this temperature. This is important because much of the vortex glass analysis which will be discussed next covers this temperature regime.

Fig. 2 The angular dependence of the critical current is displayed for a 0.5T magnetic field magnitude when the sample is immersed in liquid neon.

Fig. 3 The angular dependent critical current densities obtained as in fig.2 plotted versus $H \sin \theta$ along with data taken with the magnetic field applied strictly along the c axis.

In the three dimensional vortex glass formulation the linear resistivity vanishes as $\rho \sim (T - T_g)^{v(z-1)}$. If this model is applicable then the quantity $[d \ln \rho / dT]^{-1}$ should be linear in temperature with a magnetic field independent slope determined by the scaling exponent $[v(z-1)]^{-1}$ and a temperature intercept given by the vortex glass transition temperature T_g . Figure 4 confirms that the linear resistivity approaches zero in a manner consistent with the vortex glass model. The quantity $[d \ln \rho / dT]^{-1}$ is linear in temperature over an interval of ~ 12 - 15 K with a slope $[v(z-1)]^{-1} = 0.198 \pm 0.15$ and a temperature intercept of $T_g = 16.8 \pm 0.7$ K. This type of behavior was observed for all magnetic fields studied ($4 \text{ T} \leq H \leq 18 \text{ T}$). Similar behavior has been observed in thin films of the same origin in magnetic fields up to $H = 5 \text{ T}$ [11]. The scaling regime ranges from approximately 10 K to 15 K over the entire magnetic field range investigated and no significant magnetic field dependence is observed within the

Fig. 4 The inverse logarithmic derivative of the linear resistivity exhibits a linear temperature dependence over a large temperature range of approximately 15 K. The extrapolated temperature-axis intercept gives the vortex glass transition temperature $T_g = 16.8 \pm 0.7$ K and the slope yields the critical exponent $[v(z-1)]^{-1} = 0.198 \pm 0.15$.

Fig. 5 The scaling exponent $[n(z-1)]^{-1}$ shows negligible magnetic field dependence over 14 T with an average value of 0.19 corresponding to value of $n(z-1)$ equal to 5.3 ± 1 .

scatter of the data. These characteristics of the scaling regime are consistent with observations made in reference [7] on single crystal BSCCO, in which the scaling regime shows little magnetic field dependence above $H = 4 \text{ T}$ and has approximately the same extent as reported here. The relative width of the scaling region reported for YBCO single crystals $\Delta T / T_g = 0.05$ [12] is significantly less than those obtained for BSCCO and $\text{Ti}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ in high magnetic field which is ~ 1 . Thus, a large critical regime appears to be manifest to more two-dimensional-like systems.

In figure 5 the approximate independence of the critical exponent on magnetic field is displayed. The exponent $[v(z-1)]^{-1}$ varies from 0.17 to 0.21 yielding an average value of $v(z-1) = 5.3$ in reasonable agreement with the values of 6.5 ± 1.5 , 7 ± 1 , and 7.1 ± 1.1 found for YBCO thin films [3], BSCCO single crystals [7], and similar thin films at lower magnetic fields [11], respectively. The values of T_g obtained over the magnetic field range from 4 T to 18 T are displayed in figure 6. The local slope of the phase line at the highest magnetic fields is 3 T/K.

Fig. 6 The vortex glass transition temperature T_g as a function of magnetic field

III. CONCLUSION

The transport properties of long $\text{Ti}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ thin film meander lines have been measured in both the low and high current regime. The critical current density for a given temperature is found to depend solely on the component of the magnetic field normal to the ab planes indicating quasi-two-dimensional behavior for this system. However, as the current density is reduced we find evidence at low temperature that a second order phase transition into a three-dimensional vortex glass occurs with a critical exponent $\nu(z-1)=5.3\pm 1$. The width of the critical region is $\sim 15\text{K}$ and virtually independent of magnetic field. This value is unconventionally large for classical systems but is in agreement with values obtained for BSCCO single crystals. More investigation into the nature of the width of the phase transition is required.

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