Thermally-Activated Vortex Motion and Electrical Dissipation in a $Bi_2Sr_2CaCu_2O_\delta$ Thin Film

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ABSTRACT

The magnetoresistance, obtained from resistivity measurements with external magnetic fields up to 0.5*T*, was used to directly measure and investigate the electrical dissipation properties of a c-axis oriented $Bi_2Sr_2CaCu_2O_{8+\delta}$ thin film. An activation-related "peaked" profile below T_c was observed in the magnetoresistance. In increasing applied magnetic field, the peak shifts to lower temperatures, broadens, and becomes more asymmetric. The analysis, made based on an Arrhenius-type activation mechanism, shows that the activation energy decreased with increasing applied magnetic field, as predicted by the Anderson-Kim Thermally-Activated Flux Creep Theory. Therefore, in these low magnetic fields and temperatures, the vortex motion predominant in the films is thermally activated and contributes largely to the dissipation in these films.

INTRODUCTION

Transport properties of high-temperature superconductors (HTSC), particularly of thin films, have been intensively studied to derive valuable information on critical currents, vortex pinning, electrical dissipation mechanisms, I-V characteristics and phase transitions, to name a few. In particular, the study of electrical dissipation in HTSCs proves to be of great significance for its envisioned technological application. In this paper, the behavior of the electrical dissipation due to an applied transport current in varying applied magnetic field and temperature regimes is studied.

Electrical dissipation because of the presence of an applied magnetic field and transport current is referred to as the magnetoresistance due to flux motion (Poole et al., 1995). Flux motion results from the Lorentz force induced by the applied transport current and is the mechanism leading to power dissipation and flux-flow resistance in the superconducting mixed state. Aside from the Lorentz force, thermal activation or fluctuations may also cause flux motion (Tamegai et al., 1998; Zhang et al., 2001).

Several models have been proposed to explain the dissipative behavior of HTSCs in a magnetic field (Tamegai et al., 1998). One of these models is the theory of thermally activated flux creep developed by P.W. Anderson. The theory assumes that flux creep occurs by bundles of flux lines jumping between adjacent pinning points and that the movement of these flux lines is an activation process directed by thermal energy (Anderson & Kim, 1964; Anderson, 1962).

Thermally-activated flux motion causes the broadening of the transition region of the resistance curves when a

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magnetic field is applied (Kucera et al., 1992). The smooth power law behavior of the voltage-current (VI) curves is also attributed to this motion of magnetic flux lines.

METHODOLOGY

The sample used was a $Bi_2Sr_2CaCu_2O_\delta$ thin film grown via Liquid Phase Epitaxy in the Condensed Matter Physics Laboratory of the National Institute of Physics. X-ray diffraction (XRD) shows a preferential growth along the c-axis. Transport measurements were made using the in-line contact configuration. Four contacts were placed on the surface of the film using annealed silver pastes and gold wires. A current of 1 mA was supplied to the outer two contacts while voltage measurement was done across the inner two. The film was attached to a cold head that could be cooled down to approximately 10 K. For magnetoresistivity measurement, a magnetic field was applied along the film's *c*-axis.

The temperature dependence of the resistance was then determined, with and without applied magnetic fields. Magnetic fields used were less than 0.6*T* and the magnetoresistance profile against varying temperature was obtained using the equation:

$$R_M = \frac{\Delta R}{R(0)} = \left[\frac{R(B) - R(0)}{R(0)} \right] \qquad (1)$$

RESULTS AND DISCUSSION

From the resistivity measurements, the critical temperature of the sample was found to be ~87 K. In the presence of an increasing magnetic field applied along the film's *c*-axis, it is observed that the transition region broadens (Fig. 1). This is due to the increasing number of thermally activated mobile vortices (Anderson & Kim, 1964).

An activation-related peaked behavior was observed in the magnetoresistance profile shown in Fig. 2. Thus, the behavior was analyzed using the Arrhenius relation so that a magnetic field-dependent energy scale may be correlated to the activation mechanism behind the "peaked" nature of the magnetoresistance profile. The magneto resistance may then be expressed as:

$$R_M(T) = R_{M\,\max} \exp \frac{-E_a}{k_B T} \qquad (2)$$

where E_a is a magnetic field-dependent energy scale.

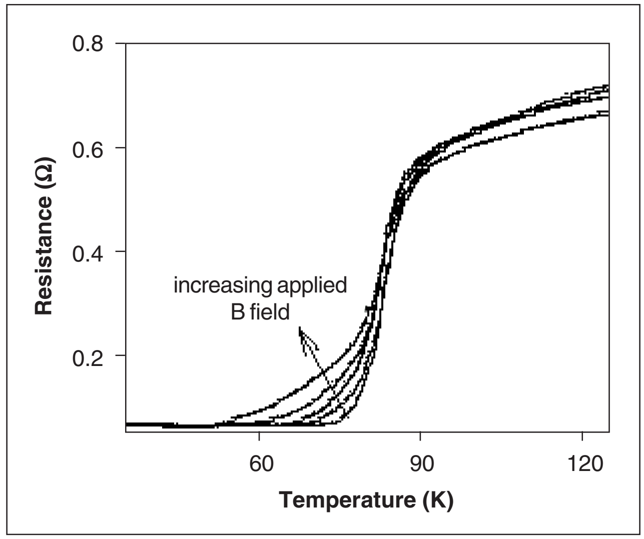

Fig. 1. The broadening of the transition region with increasing applied magnetic field is attributed to thermally-activated flux flow.

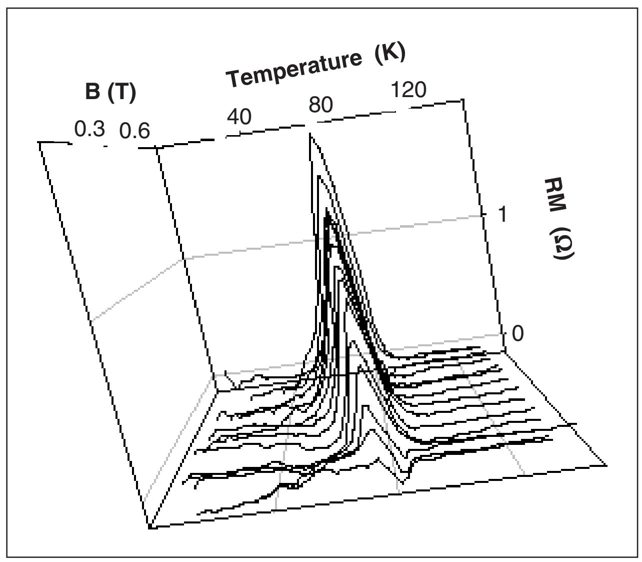

Fig. 2. Normalized magnetoresistance (R_M) profile at applied magnetic fields from 0T to 0.6T.

This activation-related model of the magnetoresistance profile is comparable in form to the thermally activated behavior of the vortex creep velocity from the Anderson-Kim Flux Creep Theory, given by the equation (Anderson & Kim, 1964; Anderson, 1962):

$$v = v_o \exp\left(\frac{-F(T)}{k_B T}\right) \qquad (3)$$

where F(T) is a temperature-dependent energy scale.

This suggests that the two are correlated and have an activation type behavior. This is supported by the fact that the drift velocity of the vortices induces an electric field with a component that retards the applied transport current and leads to electrical dissipation or magnetoresistance (Yeshurun et al., 1996).

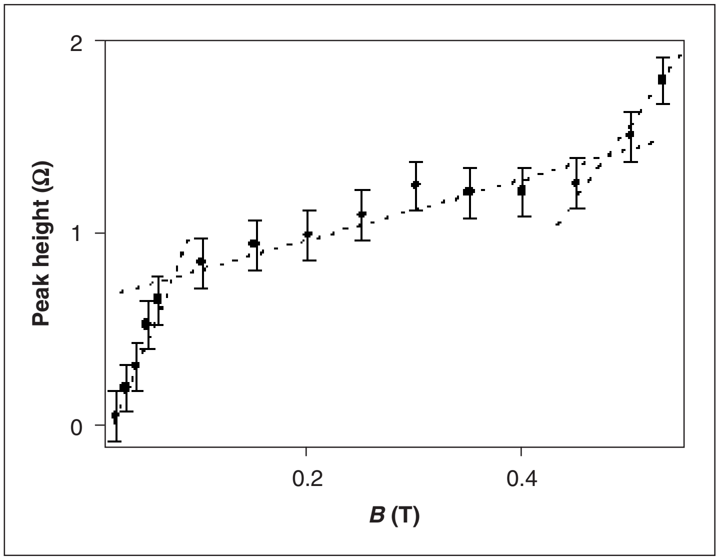

Fig. 3. The non-linear increase in the peak height of the magnetoresistance profile as B_{app} is increased.

From the Arrhenius plot of the normalized resistance, the activation energy was observed to decrease non-linearly with increasing applied magnetic field. This typical result is explained by the fact that vortices increase in number as the applied magnetic field increases. In turn, the interaction between vortices increases in magnitude as well, so that the propensity for these vortices to move increases too, leading to a decrease in the activation energy and an increase in the measured resistance of the system.

Fig. 3 shows that the R_{Mmax} changes as the applied field (B_{app}) is increased. From the plot, three separate regimes can be discerned. These regimes are differentiated by the rate at which the peak height increases with increasing B_{app}(dR_{Mmax}/dB_{app}). This rate at extremely low fields ($B_{app} < 0.1T$) and at relatively high fields ($B_{app} > 0.45T$) is greater than at intermediate values of the applied magnetic field ($0.1T < B_{app} < 0.45T$).

At low fields, only a small number of vortices exist. Thus, in this regime, dR_{Mmax}/dB_{app} is high because the vortices are more mobile. Increasing the field increases the number of vortices in the system. At intermediate field strengths, an ordering in the vortex system takes place so that the mobility of the flux lines decreases. Hence, dR_{Mmax}/dB_{app} is smaller. Further increasing B_{app} leads to an enhanced cooperative motion of the vortices, leading to a high dR_{Mmax}/dB_{app}.

Fig. 4 shows a plot of the temperature position of the magnetoresistance peak as the applied field is varied. The figure shows that the peak of the magnetoresistance profile shifts to lower temperature as B_{app} is increased. This peak shift is related to the decrease in the activation energy as B_{app} is increased. Note that as B_{app} is increased, more vortices are introduced into the system. At temperature $T = T_{peak}$, all these vortices must be fully thermally activated. Therefore, as B_{app} is increased, thermal activation of the vortices happens more readily. Hence, the peak (where complete thermal activation occurs) will shift to lower temperatures.

It can be observed from Fig. 2 that the R_M profile is inherently asymmetric even at extremely low fields. Fig. 5 emphasizes this increase in the peak asymmetry as B_{app} is increased. The shifting of the low-temperature edge of the magnetoresistance profile to lower temperatures causes the asymmetry. Note that the low-temperature edge marks the melting point when the phase transition from the vortex solid state to the vortex liquid state takes place. With a consequent decrease in activation energy as B_{app} increases, the flux melting

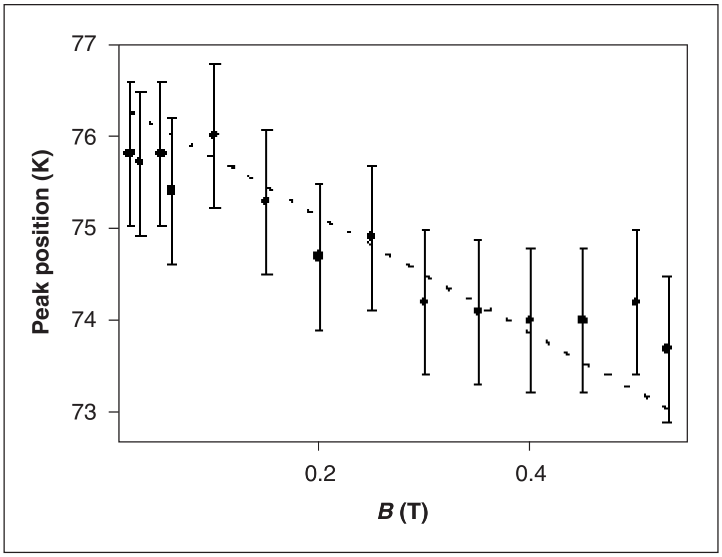

Fig. 4. Variation of R_M peak position with applied magnetic field. The peak is observed to shift to lower temperatures with increasing applied magnetic field. The dotted line indicates the general trend of the decrease.

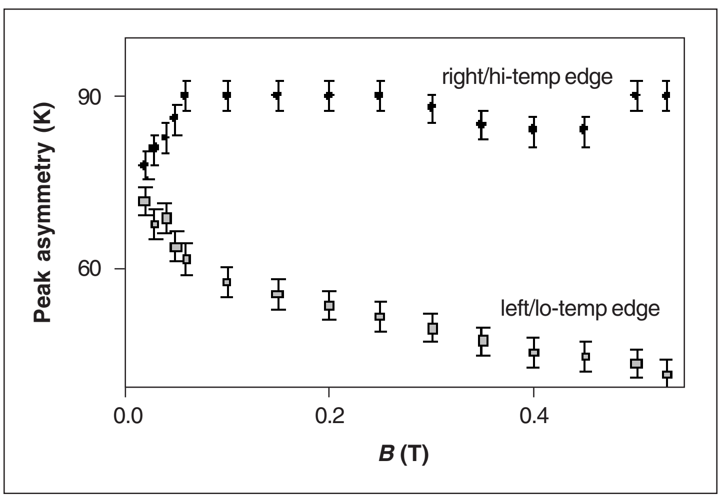

Fig. 5. Increasing asymmetry with increasing applied magnetic field.

effectively shifts to lower temperatures. This shifts the edge to lower temperatures, thus increasing the asymmetry.

CONCLUSIONS

The magnetoresistance profile for a Bi-2212 thin film was obtained for applied magnetic fields less than 0.6*T*. The magnetoresistance profile was found to have an activation-related peaked behavior. In the temperature range of $T_{peak} < T < T_c$, the expression for the magnetoresistance profile has the same form as the vortex creep velocity predicted by the Anderson-Kim Flux Creep Theory. Therefore, the mechanism of electrical dissipation must be via the thermally-activated motion of the vortices. Also, further analyses of the behavior of the magnetoresistance profile show: (i) a non-linear increase in the R_M peak height; (ii) a shift to lower temperatures of the R_M peak; and (iii) an increasing peak asymmetry of the R_M profile as the applied magnetic field was increased. These were explained in terms of flux ordering and energy considerations.

REFERENCES

Anderson, P.W., 1962. Theory of flux creep in hard superconductors. *Phys. Rev. Lett*. 9: 309-311.

Anderson, P.W. & Y.B. Kim, 1964. Hard superconductivity: Theory of the motion of Abrikosov flux lines. *Rev. Mod. Phys*. 36: 39-43.

Kucera, J.T., T.P. Orlando, G. Virshup, & J.N. Eckstein, 1992. Magnetic field and temperature dependence of the thermally activated dissipation in thin films of $Bi_2Sr_2CaCu_2O_{8+\delta}$. *Phys. Rev. B*. 46: 11004-11013.

Poole, C.P., et al., 1995. Superconductivity. San Diego, Academic Press.

Tamegai, T., H. Enriquez, Y. De Wilde, & N. Bontemps, 1998. Vortex-lattice melting, phase slips, and decoupling studied by microwave dissipation in $Bi_2Sr_2CaCu_2O_{8+\delta}$. *Phys. Rev. B*. 58: R14745-R14748.

Yeshurun, Y., A.P. Malozemoff, & A. Shaulov, 1996. Magnetic relaxation in high-temperature superconductors. *Rev. Mod. Phys*. 68: 911.

Zhang, Y.H., H. Luo, X.F. Wu, & S.Y. Ding, 2001. Effect of flux creep on Ic measurement of electric transport. *Supercond. Sci. Technol*. 14(6): 346-352.