THERMAL ACTIVATED DISSIPATION IN Bi$_2$Sr$_2$Ca(Cu$_{1-x}$Co$_x$)$_2$O$_{d}$
EPITAXIAL THIN FILMS

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Abstract
The scaling behavior of the effective activation energy of high-quality epitaxial c-oriented Bi$_2$Sr$_2$Ca(Cu$_{1-x}$Co$_x$)$_2$O$_d$ thin films with 0 ≤ x ≥ 0.025 has been studied as a function of temperature and magnetic field. For all samples, the effective activation energy scales as $U(T, \mu_oH) = U_o(1 – T/T_c)^mH^n$ with exponent $m = 1.25 ± 0.03$, $n = - 1/2$ and the field scaling 1/$\mu_oH$ and $-U \mu_oH$ for thick films and ultra thin films, respectively. The results are discussed taking account of the influence of the Co substitution with a model in which $U(T, H)$ arises from plastic deformations of the viscous flux liquid above the vortex-glass transition temperature.

INTRODUCTION

The Bi-based system, mainly contains Bi:2201, Bi:2212 and Bi:2223 phases have single, double and triple layers of CuO$_2$ in the subunit cell, and more planes are believed to be associated with higher value of $T_c$ [1]. The effect of different dopants materials like transition metals and rare earth have been reported by different authors in the Bi-based superconductors [2-6]. Dopant play an important role on the properties of high- cuprates superconductors, characterize by a large number of anomalies in the “mixed and normal state” [1-9].

The systematic study of the influence of an external magnetic field on the resistive transition is an important source of information for the vortex dynamics in high temperature superconductors [3]. Much effort has been made to describe the complete shape of the resistive transition, but no evidence could be found for a unique mechanism for the whole transition curve. The high temperature part of the resistivity transition could be reasonably explained by taking into account the fluctuation of the superconducting order parameter [10], while in the low resistance part, i. e. at lower temperatures, the dissipation of is mainly due to the motion of the vortices within the samples [4-7, 11].
Due to the relatively high temperatures involved and the short coherence length in high-T$_c$ cuprates, thermally activated flux motion plays an important role in the study of the vortex motion just below the critical temperature.

In this paper, we study the field dependence of the activation energy for Bi$_2$Sr$_2$Ca(Cu$_{1-x}$Co$_x$)$_2$O$_{8+d}$ thin films, and the influence of the Co content of the resistivity near transition temperature on a wide variety of thin film samples as a function of their microstructure and morphology. This material was chosen because its high anisotropy and reliable in situ fabrication make it an ideal model system. The main results of this paper are that the resistive transitions of all samples can be approximated by the thermally activated form

$$\rho(T, H) = \rho_o \exp(- \frac{U}{k_B T})$$

where $U$ is the activation energy describing the average flux pinning strength, $k_B$ is the Boltzmann constant and $T$ is the temperature. Usually $U$ is a function of the magnetic field ($H$), of the current density ($j$) and of the temperature $U = U(H, j, T)$ or more explicitly

$$U(T, H) = U_0 (1 - t)^m H^n,$$

where $t = T/T_c$ is an important parameter for interpreting the flux motion with $m = 1.5 - 1.8$ and $n = - 1/2$ or the dependence of the magnetic field as $-\ln H$ of the activation energy $U$. There is no general agreement for the dependence of magnetic field on the precise value of the exponents $m$ and $n$ [7-12].

**EXPERIMENTAL DETAILS**

C-axis oriented epitaxial Bi$_2$Sr$_2$Ca(Cu$_{1-x}$Co$_x$)$_2$O$_{8+d}$ thin films were prepared from stoechiometric targets using a DC magnetron sputtering deposit at a 5 – 10 nm/min rate, onto polished MgO (100) single crystal substrates with the substrate temperature $T_s=780^\circ$C in a controlled atmosphere (0.3 mbar research grade Ar and 0.3 mbar O$_2$ partial pressure) yielding film thicknesses of about 3000 Å. In order to increase the oxygen content, the samples were annealed in situ for 40 minutes at $T_0 = 450^\circ$C in a 1 mbar oxygen atmosphere and cooled to room temperature at a 10 K/min rate. Structural characterizations were carried out by X-ray diffraction (XRD), energy dispersive X-ray analysis and optical microscopy revealing
almost a single phase with the impurity level being less than 1-2%. Magnetoresistivity measurements were performed by the standard DC method on microbars, obtained by the photolithography technique using a Keithley 220 programmable current source and a Keithley 182 sensitive digital voltmeter. The measured current direction was always perpendicular to the direction of the field and the current density was about 30 A/cm².

RESULTS AND DISCUSSIONS

Figure 1 show the plot of the resistivity at various magnetic fields plotted on a semilogarithmic scale for samples with x = 0.02 Co. This plot displays over five orders of magnitude in resistivity and emphasizes the lowest temperature position of the transition where $\rho \ll \rho_0$. The qualitative shapes of the resistive transitions of all the samples studied were similar to those depicted in Fig. 1 despite the wide variety of surfaces morphologies.

Figure 1. Arrhenius plot of the resistive transition at various magnetic field applied parallel to the c-axis of the films.
As shown in Fig. 1, resistivity in a magnetic field decreases exponentially and the straight lines for low resistivity indicate that the dissipation mechanism is thermally activated. At finite temperatures, thermally activated flux creep produces dissipation as in relation (1) where $U$ is the effective activation energy which generally depends on the temperature and the applied field at a fixed current density such that

$$U(T, H) = U_0 f(T)g(H),$$

where $U_0$ is the unperturbed activation energy and the functions $f$ and $g$ incorporate the temperature and the magnetic field dependence.

In order to determine the field dependence of $U$, the resistivity of the samples is plotted as a function of inversed magnetic field at several temperatures in the range 50-85 K in Fig. 2.

In the $\log \rho_{xx}$ versus $\mu_0 H$ plot, the curves are rather linear indicating that $U \sim 1/\sqrt{\mu_0 H}$, so $n = -1/2$ (Fig. 2). With this extracted field dependence, we illustrated in Fig. 3, the derivated temperature dependence of the pinning energy.

![Fig. 2. Field dependence of log\(\rho_{xx}\) at several temperatures in the range 55-70 K.](image-url)
The temperature dependence of $U$ at fixed fields is not universal in the whole temperature range below $T_c$. At temperatures much lower than $T_c$, the temperature dependence of $U$ is approximately $(1 - t)$, which is the linear part of the slope of the Arrhenius plot of Fig. 1. If we assume a general power law for the temperature dependence of $U(T) \sim (1 - t)^m$, the temperature dependence can be extracted by plotting the product $U\mu_0H$ versus the standard high temperature thermal factor $(1 - t)$, and $m = 1.25 \pm 0.03$ is obtained for a temperature range of $0.95T_c - 0.60T_c$ on thick films of about 3000 Å with $x = 0.02$ Co as shown in Fig. 3.

We have found $U(\mu_0H)$ to be a power law over three orders of magnitude in magnetic field. The strong field dependence of the activation energy suggests some form of collective pinning. In agreement with an intuitive model proposed by Tinkham [13],

$$U \sim \frac{1}{2}\mu_0H_c^2\xi^n\alpha^m,$$

where $1/2\mu_0H_c^2$ is the condensation energy per unit volume and $\alpha = \sqrt{\Phi_0/\mu_0H}$. The activation energy, in Tinkham’s model, is the energy required for a correlated volume of flux to shear past neighboring vortices, and the exponent for the activation energy is expected to be $\alpha = (3 - m)/2$ where $m = 0-3$.

![Graph](image)

Fig. 3. The temperature dependence of product $\mu_0HU$ versus $1-t$, where $t = T/T_c$. 

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Fig. 4. The field dependence of the activation energy of the films is well approximated by $U(\mu_0 H) \sim 1/\sqrt{\mu_0 H}$.

The observed values of $\alpha$ are closer to 1/2. We approximate the activation energy by $U \sim 1/\sqrt{\mu_0 H}$ as can be seen in Fig. 4. Our results are roughly in agreement with the data from literature [8-12, 14] and with models by Geshkenbein et al. [15] and Vinokur et al. [16].

**CONCLUSIONS**

We have investigated the influence of the substitution of Cu by Co in high quality epitaxial Bi$_2$Sr$_2$Ca(Cu$_{1-x}$Co$_x$)$_2$O$_{8+d}$ thin films on the magnetoresistivity measured in magnetic field up to 5 T. We have found that the effective activation energy can be described by the scaling law

$$U(T, H) = U_0(1 - T/T_c)^m H^n$$

with $m = 1.25 \pm 0.03$ and $n = -1/2$ for the samples investigated in this work.

The magnitude and field dependence of the activation energy is much better predicted by 3D anisotropic Ginsburg-Landau theory than by 2D “pancake” vortices, which considers the possibility of a vortex glass in a system that was thought to be two-dimensional. Our results suggests that the
temperature dependence of U is not necessarily correlated with field
dependence and the field dependence might not be directly correlated with
the dimensionality of the materials.

REFERENCES