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Effect of anisotropy on the vortex liquid dissipation in $YBa_2Cu_3O_{7-\delta}$ thin films

Z. Sefrioui[a,*], D. Arias[a,1], M. Varela[b], C. León[a], J. Santamaría[a]

[a]*GFMC, Departamento de Física Aplicada III, Universidad Complutense de Madrid, 28040-Madrid, Spain*
[b]*Departamento de Física, Universidad Carlos III de Madrid, Avda de la Universidad 30, 28911 Leganés, Madrid, Spain*

Abstract

Transport measurements have been used to investigate the vortex dynamics in the mixed state on high quality deoxygenated $YBa_2Cu_3O_{7-\delta}$ thin films, in magnetic fields up to 8 T. Epitaxial $YBa_2Cu_3O_{7-\delta}$ thin films, grown by high pressure dc sputtering, were deoxygenated in situ following a stability line of the pressure–temperature phase diagram. We show that varying the oxygen content, the dynamics of the vortex liquid phase reveal a crossover from a densely entangled liquid to a decoupled state. At small oxygen deficiencies the activation energy for vortex motion is found to depend as $1/H$ on the applied magnetic field, suggesting a densely entangled liquid. Strongly deoxygenated samples however, show a crossover from an entangled liquid, with a $1/H^{0.5}$ dependence of the activation energy in magnetic fields up to 2 T, to a decoupled state, characterized by a logarithmic dependence for higher fields.

Keywords: High T_C superconductors; Thin films; Flux pinning and creep

1. Introduction

The combined effects of pinning, anisotropy and thermal fluctuations, is known to stabilize different vortex phases in high temperature superconductors, confirming the relatively complex phase diagram [1]. It is well established now that the nature of the melting transition separating vortex solid and liquid phases is strongly affected by disorder. While in clean systems the melting transition is first order [2,3], the introduction of disorder turns the melting transition into second order and the vortex solid becomes a glass [4–7]. Very recently, experimental evidence has been presented for the existence of the vortex glass phase in untwinned, proton irradiated YBCO [8]. In twinned crystals, however, the second order transition is consistent with a Bose glass transition [9]. While it is clear that the nature of defects (correlated or point like disorder) determines a specific response of the vortex system, the coexistence of both kinds of disorder in the same sample gives rise to a complicated scenario and may lead to novel vortex phases. The stability of various phases (entangled vortex solid [18], entangled vortex liquid [26,27], densely entangled liquid [23], decoupled vortex liquid [30], etc.) is determined by the competition between pinning and vortex–vortex and vortex–defect interactions controlled by magnetic field [10–14]. As a result, the response of the vortex system originates from this competition, leading to complex transition lines with multicritical points [15,16].

Contrary to most previous studies that focused their investigations on introducing disorder (both correlated and/or point like disorder [8,9,15,16], without significant changes in anisotropy parameter), we report on the evolution of the liquid phase with increasing anisotropy in deoxygenated YBCO thin films. We show that reducing the oxygen content, the dynamics of the vortex liquid phase reveals a crossover from a densely entangled liquid, with a $1/H$ dependence of the activation energy, to a decoupled state, characterized by a logarithmic dependence for higher fields.

2. Experimental

High quality epitaxial $YBa_2Cu_3O_{7-\delta}$ thin films were grown on (100) $SrTiO_3$ using a high pressure (3.6 mbar pure oxygen atmosphere) sputtering system. The substrate temperature was 900°C, and the oxygen content was adjusted in situ slowly following a stability line of the

*Corresponding author. Present address: Instituto de Microelectronica de Madrid, Isaac Newton 8, PTM, 28760 Tres Cantos Madrid, Spain.
[1]On leave from Universidad del Quindio, Armenia, Colombia.

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pressure–temperature phase diagram during sample cool down [17]. Film thickness was kept in the range of 500–700 Å to ensure a homogeneous oxygen distribution. Transport curves were measured on photolitographically patterned bridges with dimensions $30\times500\ \mu m^2$. Contacts were done on evaporated silver pads to ensure small contact resistance. Magnetic fields up to 8 T were applied parallel and perpendicular to *c* axis, and a temperature stability better than 50 mK was ensured prior to data acquisition.

3. Results and discussion

Samples with different oxygen contents ($7-\delta=7$, 6.48, 6.4) were analyzed to investigate the vortex dynamics in the liquid state. Resistive transitions with magnetic field applied parallel and perpendicular to the *c* axis were used to investigate the vortex motion in the liquid phase. Fig. 1 shows the Arrhenius plots of the resistivity for a deoxygenated $YBa_2Cu_3O_{6.48}$ thin film in magnetic fields up to 6 T applied parallel to the *c* axis.

The irreversibility line defined by the onset of non linearity in *I–V* curves [15] for both field orientations, can be used to get an estimate of the anisotropy parameter γ in our oxygen-depleted samples. The corresponding irreversibility line for $YBa_2Cu_3O_{6.48}$ sample with magnetic field applied parallel and perpendicular to the *c* axis is shown in Fig. 2. For both orientations, the irreversibility line could be fitted to an equation of the form $H=H_0(1-T/T_{c0})^{\alpha}$, where T_{c0} is the zero field transition temperature and H_0 and α are fitting parameters. We obtain $H_{0ab}=345\pm10$ T, $\alpha_{ab}=1.9\pm0.05$, $H_{0c}=13\pm0.5$ T, $\alpha_c=1.25\pm0.05$ for both

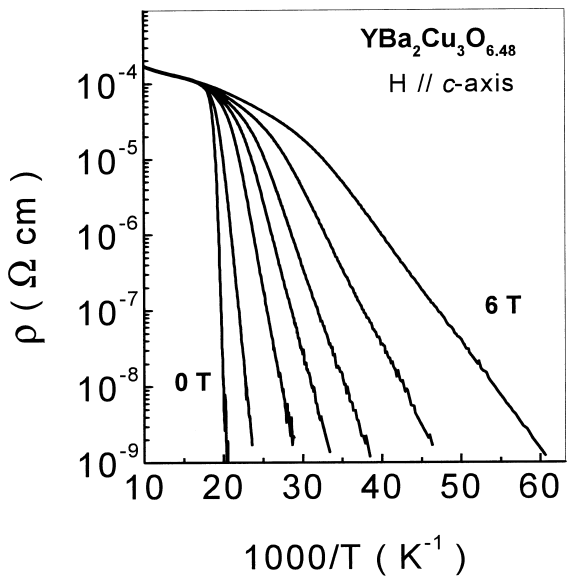

Fig. 1. (a) Electrical resistivity vs. $1000/T$ for deoxygenated $YBa_2Cu_3O_{6.48}$ thin film in magnetic fields applied parallel to the *c* axis.

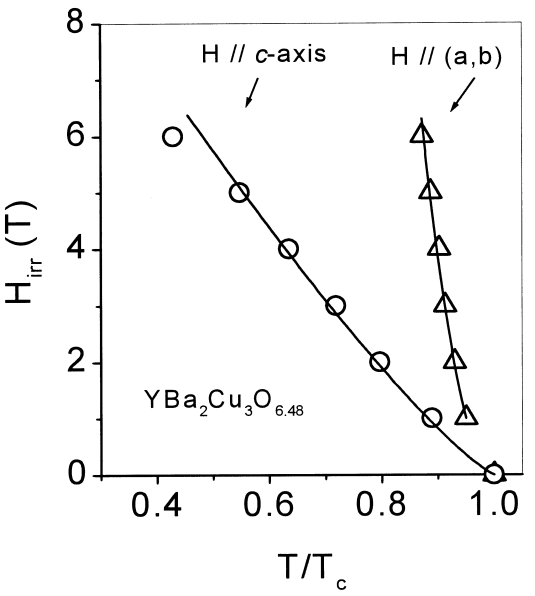

Fig. 2. Irreversibility line for deoxygenated $YBa_2Cu_3O_{6.48}$ thin film in magnetic fields parallel and perpendicular to the *c* axis. The solid lines are fits to the equation $H=H_0(1-T/T_{c0})^{\alpha}$.

field orientations, which are in agreement with the values previously reported for single crystals [18]. The ratio H_{0ab}/H_{0c} supplies an estimate of the anisotropy parameter $\gamma\approx30$, similar to the value obtained for deoxygenated single crystals with the same doping level [19]. Following the same procedure, anisotropy parameters of 6 and 60 were obtained for fully oxygenated samples and for $YBa_2Cu_3O_{6.4}$, respectively. The ratio H_{0ab}/H_{0c} only allows determination of γ when the irreversibility line follows the scaling law expected from the anisotropic Ginsburg Landau theory [25]. YBCO in plane lattice parameters are very close, domains rotated 90° frequently appear in thin epitaxial films grown on $SrTiO_3$, which may give rise to dense arrays of twin boundaries (correlated disorder). In this respect, the irreversibility line determined for $H//c$ axis could be shifted by twin boundary pinning as demonstrated by Puig et al. [28,29] and hence the determination of γ from the ratio H_{0ab}/H_{0c} would be incorrect. In contrast, a downward shift in the irreversibility line was observed in our samples (see Fig. 2), suggesting that the dynamics of vortices is dominated by point disorder. Moreover, the scaling of the angular dependence of the magnetoresistance according to the anisotropic Ginzburg Landau theory, see Ref. [25], was checked to hold over the whole oxygen stoichiometry range of this experiment.

The temperature dependence of resistivity data (see Fig. 1) can be described by the thermally activated form $\rho(H,T)=\rho_0\exp\ [-U(H,T)/k_BT]$, where $U(H,T)$ is the activation energy for vortex motion. It is clear that all curves remain linear over more than three orders of magnitude in resistivity, which confirms the linear temperature dependence of the activation energy [20] i.e.

$U(H,T) = U_0(H)[1 - T/T_{c0}]$. This dependence was double checked from the derivative $[\partial(\ln \rho)/\partial(T^{-1})]$ in resistivity plots, which displayed a clear plateau. It is worth to note that the resistivity data used to determine the activation process in the liquid state do not overlap with the critical region for which critical scaling was obtained [17,21]. Fig. 3a shows the activation energy as a function of applied magnetic field for samples with different oxygen contents ($7-\delta=7$, 6.48, 6.4). For samples with $7-\delta=7$, 6.48, the activation energy for vortex motion is found to depend as $1/H$ on the applied magnetic field. Strongly deoxygenated samples ($7-\delta=6.4$), however, show a crossover from a $1/H^{0.5}$ dependence of the activation energy in magnetic fields up to 2 T, to a logarithmic dependence for higher fields.

The $1/H$ dependence of U_0 has been found in YBCO crystals in presence of correlated disorder [22,23]. Although correlated disorder has been proposed to stabilize a disentangled liquid state, as demonstrated by flux transformer measurements [24]. However, our measurements [25] of the angle dependent resistivity did not show the presence of the cusp like features characteristics of the Bose glass phase [9], which appears only if correlated disorder dominates the dynamics of vortices. Interestingly, this dependence has been found in crystals with splayed defects and has been interpreted in terms of a densely entangled liquid state [23]. While the $1/H$ dependence actually suggests a densely entangled liquid in our samples, the $1/H^{0.5}$ dependence of activation energy for $YBa_2C_3O_{6.4}$ (when the anisotropy parameter is enhanced $\gamma\sim60$ [17]) in magnetic fields up to 2 T is consistent with plastic motion of vortices, which strongly indicates vortex entanglement [26,27]. Similar dependence has been observed by López et al. [18] for proton irradiated YBCO single crystals and by Puig et al. [28,29] for YBCO in presence of quenched disorder, in which anisotropy parameter was not modified.

In case that only oxygen vacancies promote vortex entanglement in our oxygen depleted YBCO thin films, one would expect that point like disorder introduced by deoxygenation should enhance pinning thus increasing the activation energy as observed very recently in proton irradiated YBCO single crystals by Paulius et el. [16]. However, a decrease of the activation energy is observed in our films when the oxygen content is reduced (see Fig. 3a). A possible explanation may be in connection with the the reduced T_C of oxygen depleted samples. Consequently, the reduced condensation energy will lower the pinning energy at those defects, resulting in a weaker pinning. This interesting result suggests a complicated scenario in which point like disorder and anisotropy may compete to raise or lower activation energy. In this respect, an enhanced anisotropy parameter result in a softening of the vortex system which favors vortex entanglement and the melting transition shift to low temperatures. This can be understood looking at the size of the plastic barriers $U_{pl} \sim \epsilon_0 a_0/\gamma$ [26,27], which shows that magnetic field and anisotropy act in the same direction to enhance plastic motion of vortices.

If anisotropy is further increased, the vortex system can be decoupled for moderated magnetic fields. In fact, in a previous paper [21] we have demonstrated that $YBa_2C_3O_{6.4}$ turns into 2D (with $T_g = 0$ K) for magnetic fields higher than 2 T. As a matter of fact, this sample, for $H > 2$ T shows a crossover of the dissipation mechanism into a logarithmic field dependence of the activation

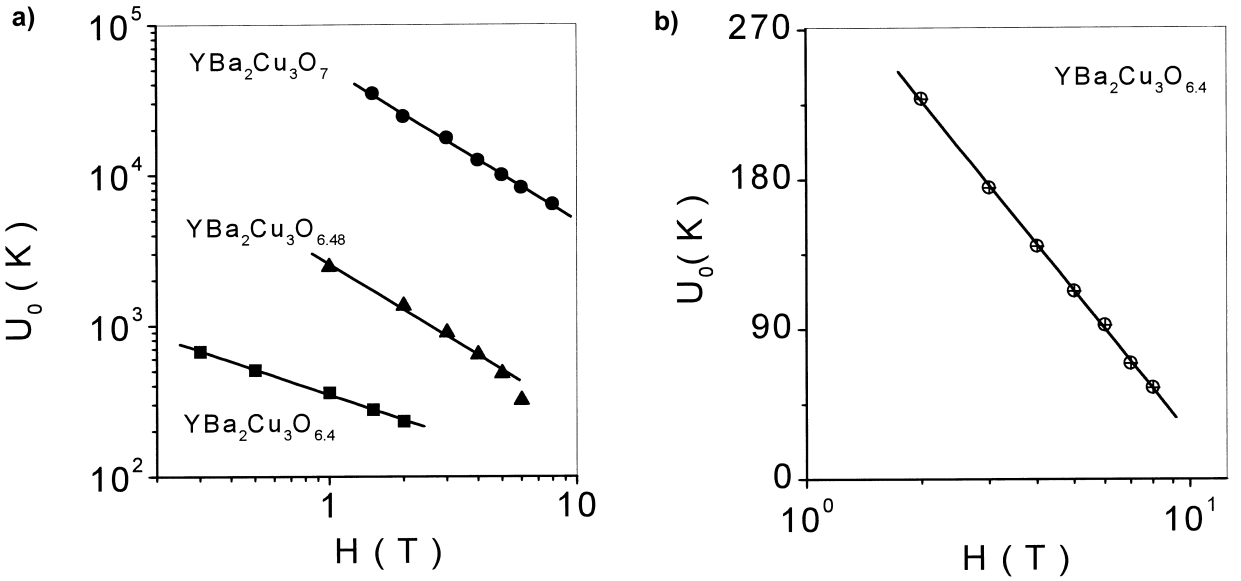

Fig. 3. (a) Magnetic field dependence of the activation energy for $YBa_2Cu_3O_7$ (solid circles), $YBa_2Cu_3O_{6.48}$ (solid triangles) and $YBa_2Cu_3O_{6.4}$ (solid squares) thin films. The solid line is a fit to $U_0 \propto H^{-\alpha}$ with $\alpha=1$ for $YBa_2Cu_3O_7$ and $YBa_2Cu_3O_{6.48}$ samples and $\alpha=0.5$ for $YBa_2Cu_3O_{6.4}$ sample. (b) Magnetic field dependence of the activation energy for $YBa_2Cu_3O_{6.4}$ in magnetic fields higher thin 1 T. The solid line is a fit to a logarithmic dependence.

energy (see Fig. 3b) characteristic of bidimensional systems [30].

4. Conclusions

In summary, we have studied the evolution of the liquid phase with increasing anisotropy in deoxygenated YBCO thin films. We have shown that reducing the oxygen content, the dynamics of the vortex liquid phase reveals a crossover from a densely entangled liquid, with a $1/H$ dependence of the activation energy, into an entangled state, with a $1/H^{0.5}$ dependence of the activation energy. At oxygen contents as low as $7-\delta=6.4$, increasing magnetic field above 2T results in a decoupling of the vortex system in the c direction, characterized by a logarithmic dependence of the activation energy on magnetic field.

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