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Uniaxial pressure dependence of the dynamical properties of vortex lines in Bi-2212 single crystals

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Abstract

By applying uniaxial pressures on Bi-2212 single crystals we have changed their interplanar spacing in order to understand which is the influence of anisotropy on the dynamics of vortex lines. We have performed transport measurements using the DC flux transformer configuration, applying uniaxial pressures and a magnetic field parallel to the *c*-axis of the sample. Our results indicate that the correlation length in the *c* direction can be effectively increased with pressure, modifying the nature of vortices in the liquid state.

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Keywords: Uniaxial pressure; Anisotropy; Flux transformer; Superconductivity

1. Introduction

Although an extensive experimental and theoretical work has been done studying the static and dynamic properties of the mixed state of high-temperature superconductors, the role played by disorder and anisotropy is not completely understood. It is well established that when the temperature is decreased, the vortex liquid transforms into a vortex lattice at the melting line [1–4], $T_m(H)$. However, the problem of whether this transition coincides or not with the crossover from a regime with low dimensionality (entangled or 2D) to one with high dimensionality (disentangled or 3D) at a temperature $T_{CR}(H) \geqslant T_m(H)$ has not been solved yet. Several experiments with highly anistropic $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals (Bi-2212) reveal that both transitions take place at the same

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temperature [5,6]. Other authors, on the other hand, have found an intermediate liquid-3D phase for the same compound [7,8], as well as in experiments done in Bi-2212 with different oxygen content [9], and also with the less anisotropic $YBa_2Cu_3O_{7-\delta}$ optimally doped [10].

The purpose of this work is to study the effects produced on vortex dynamics when a variation of the anisotropy ($\gamma = (\rho_c/\rho_{ab})^{0.5}$) takes place by applying an uniaxial pressure along the *c*-axis into highly anisotropic single crystals of Bi-2212. Considering the large compressibility of Bi-2212 along the *c*-axis [11] a reduction in γ is effectively expected, as a consequence of the pressure-induced reduction of the distance between CuO_2 layers. We analyze the sensitivity to the anisotropy and disorder of multiterminal transport measurements on Bi-2212 single crystals, in the low magnetic field region of the phase diagram. Our study is focused on the possible dissipation mechanisms present in the vortex liquid state.

2. Experimental

In order to apply uniaxial stresses along the *c*-axis of slightly overdoped Bi-2212 single crystals we used a pressure cell which was designed to apply pressures up to 500 MPa. The value of the applied pressure was calculated considering the applied load over the cross-sectional area of the crystals. We have used good-quality Bi-2212 single crystals, grown by directional solidification [12], with typical dimensions of $1.5 \times 1.5 \times 0.015\,\mathrm{mm}^3$, with the smallest dimension along the *c* direction. The crystals were mounted in a multiterminal DC flux transformer configuration [13], which allows us to determine the dissipation on both *ab* planes and along the *c*-axis of the crystal. Considering that samples are placed between the two planar-sapphire anvils of the cell, we used copper strips injected in plastic to perform good electrical contacts ($<100\,\Omega$) by solely pressing them to the sample's surfaces. Small magnetic fields (up to 500 Oe) were applied parallel to the *c*-axis of the crystals.

3. Results and discussion

A typical result for the temperature dependence of the primary and secondary voltages (V_p, V_s), divided by the primary current is shown in Fig. 1 for different applied pressures and at zero magnetic field. We calculate the γ values using the algorithm proposed by Busch et al. [14].

The most important feature here is the marked decrease of γ, from a typical value of $\gamma \simeq 100$ at room pressure [15,16] to $\gamma \simeq 9$ at 80 MPa. We have obtained a linear relation $\gamma \simeq 117 - 1.4P$ (P expressed in MPa, for P in the 60–80 MPa range), which evidences the typical value at $P = 0$. A saturation of γ to 1 is expected for higher pressures. An increase of the normal state resistance with increasing pressure can also be noticed, probably related to the appearance of additional defects in the sample. We have also found a monotonic increase of the onset of the superconducting state (T_{co}) at a rate of $\mathrm{d}T_{co}/\mathrm{d}P \simeq 0.1\,\mathrm{K/MPa}$, similar to the one obtained for hydrostatic pressure experiments [17].

Another important feature showed in the lower panel of Fig. 1 is that when γ is decreased below a certain value, the appearance of a temperature T_{cut} is promoted, in which V_p and V_s become equal (within an experimental accuracy of 100 nV), indicating that the decrease in γ increases the vortex coupling along the *c*-axis, as occurs in less anisotropic compounds such as $YBa_2Cu_3O_{7-\delta}$ [10].

In Fig. 2 we have plotted the primary voltages for two pressures at several magnetic field values in the well-known Arrhenius form in order to study the activation energy $U_H(T,H)$ characteristic of the thermally assisted flux flow (TAFF) model [15], in which the TAFF resistivity is related with temperature through the expression $\rho(T,H) = \rho_0 \exp[-U_H(1/T - 1/T_c)]$.

We can see that the reduction of γ produced by the uniaxial pressure causes the emergence of the two characteristic regimes of samples with low anisotropy: low and high TAFF regimes, $TAFF_L$ and $TAFF_H$, respectively, as were found recently by Darminto et al. [18] in the same compound, highly overdoped with oxygen. The crossover temperature between the two states is

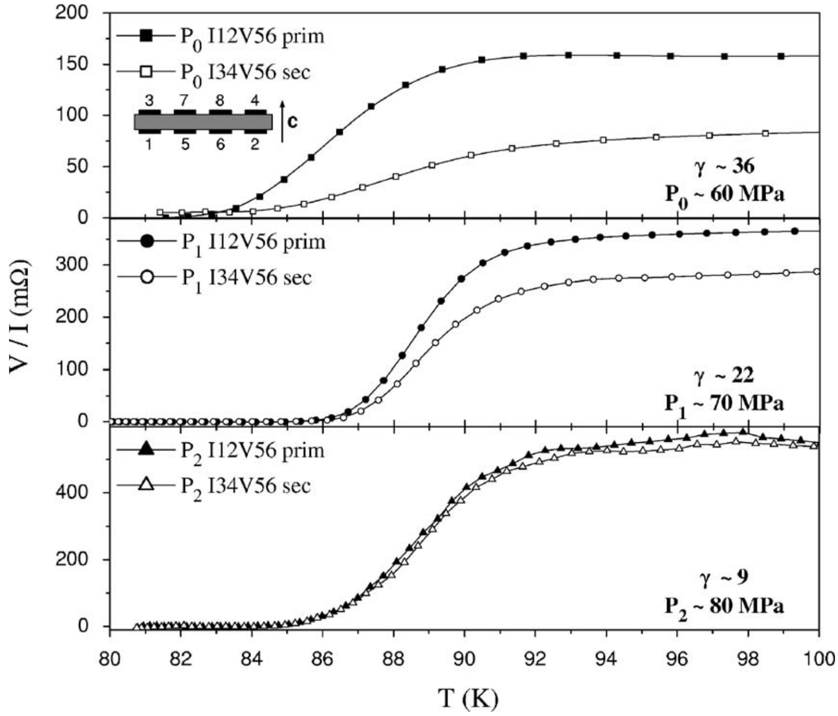

Fig. 1. Temperature dependence of the primary and secondary voltages, divided by the primary current, of a Bi-2212 single crystal, for different values of uniaxial pressure applied along the *c* crystallographic axis. The anisotropy γ is also indicated for each pressure. The inset in the upper graphic shows the contact geometry.

usually designated as T_{CR}, which takes values of 84 K ($H = 500$ Oe) and 87 K ($H = 160$ Oe). In Fig. 3, we have outlined the field-dependent energies U_H obtained from the previous figures for $\gamma \simeq 22$ and $\gamma \simeq 9$. Several theoretical and experimental works relate thermally activated processes with the dynamics of vortex matter through elastic and plastic dissipative regimes [19–22]. For $P_1 = 70$ MPa we have a sample with a high value of γ, and the activation energy is characterized by an exponent $\alpha \simeq -0.73$, intermediate between the plastic ($\alpha = -0.5$) and elastic ($\alpha = -1$) theoretical exponents. However, for the highest value of applied pressure and lowest γ, the separation in two regimes at T_{CR}, one with $\alpha \simeq -0.46$ and another with $\alpha \simeq -0.77$, makes us think that the decrease of γ produces the emergence of the new low-temperature regime, $TAFF_L$, associated with elastic dissipation of vortices.

Voltage–current measurements were performed at fixed temperatures with the transformer arrangement for several values of applied magnetic field between 0 and 500 Oe. On the one hand, for $\gamma > 22$, dissipation over primary and secondary configurations never reach equal values, in accordance with the results presented in Fig. 1. On the other hand, as far as uniaxial pressure decreases the anisotropy of the crystal, phase coherence along the *c*-axis was achieved ($\gamma \simeq 9$), making voltages coincide over both surfaces of the sample at a temperature and field-dependent current I_{cut}, as can be observed in low anisotropic YBCO (optimally doped).

In Fig. 4, those currents are plotted for different temperatures, and for applied magnetic fields of 160 and 500 Oe perpendicular to the *ab* planes. A difference between V_p and V_s of 10 μV was considered in order to define the values of I_{cut}. We also point out for each field the temperatures

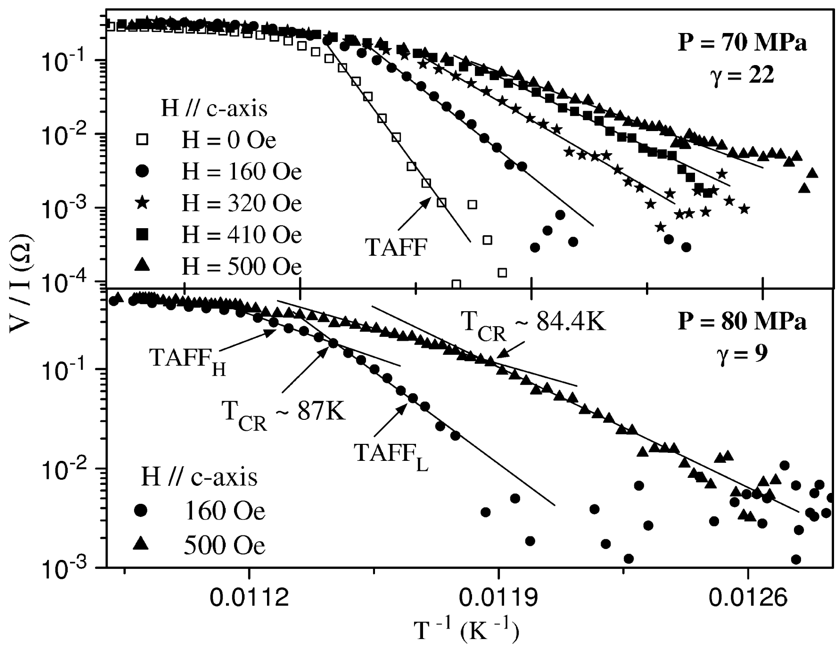

Fig. 2. V/I vs. $1/T$ at different applied magnetic fields for the sample with $\gamma = 22$ and $\gamma = 9$. Straight lines are drawn to highlight the TAFF zones. In the lower graphic are indicated the crossover temperatures T_{CR} that separates the high and low TAFF regimes.

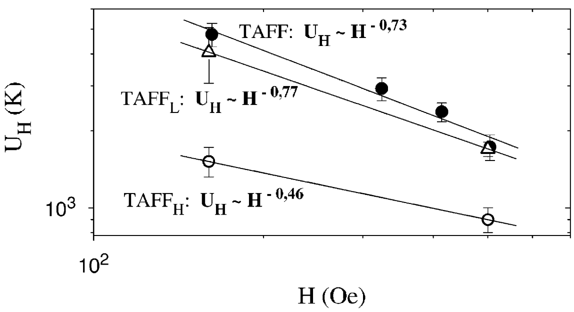

Fig. 3. TAFF activation energy plotted as a function of magnetic field. Solid symbols correspond to $P_1 = 70\,\mathrm{MPa}$ (higher γ), while open symbols correspond to $P_2 = 80\,\mathrm{MPa}$ (lowest γ). For each case, functional dependencies of U_H are shown too.

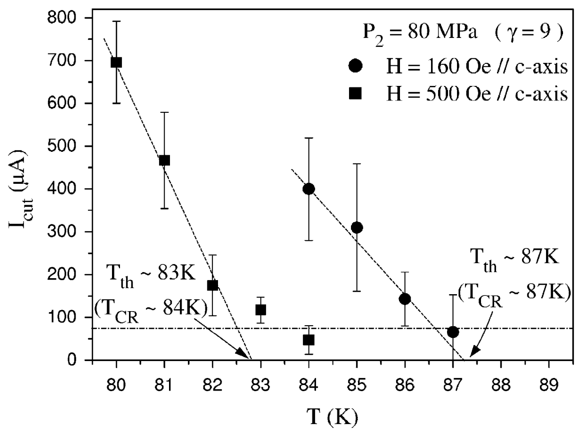

Fig. 4. I_{cut} vs. temperature, obtained from V–I measurements for the most isotropic case ($\gamma \simeq 9$). The dashed line indicates the bias current level used in TAFF measurement (80 μA).

T_{th} in which vortex cutting along the thickness of the crystal is achieved with an applied current tending to zero. Comparing with the TAFF measurements carried out over one side of the sample, we can see that values of T_{CR} and T_{th} essentially coincide, keeping in mind that TAFF measurements were performed with a bias current greater than I_{cut} (T_{th}) $\simeq 0$. Taking this coincidence into account we can associate T_{CR} to a passage from a low to a high correlated system along the

c-axis, or, considering the obtained $U_{\mathrm{H}}(H)$ dependencies, from an entangled to a disentangled vortex system.

4. Conclusions

In conclusion, we have presented in this report interesting effects produced by the application of uniaxial pressure over high anisotropic superconducting samples. We have shown that, in the region of low magnetic fields, a uniaxial effort along the c crystallographic direction produces the reduction of the anisotropy of the crystal, which has important implications in the dynamics of vortex matter, making the system shift to a state that involves entangled or disentangled regimes.

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