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Scaling of the flux pinning in $La_{1.45}Nd_{0.40}Sr_{0.15}CuO_4$ stripe phase superconductor

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Abstract

Magnetization measurements for $La_{1.45}Nd_{0.40}Sr_{0.15}CuO_4$ single crystal have been performed in order to investigate the effects of spin–charge ordering on pinning and scaling behavior of J_c and P_f. Despite the large differences in the irreversible fields along the *ab*-plane and the *c*-axis, the obtained values of H_c (hence the free energy) are basically similar. The maximum pinning forces obtained from the irreversible magnetization along *c* and in the *ab*-plane were found to scale with $(H_c)^\beta$ for both crystallographic directions. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Growing experimental evidences indicate that the charge carriers in some high-temperature superconductors (HTS) are lined up in rows in the CuO_2 planes, sandwiched between them are regions of copper atoms whose pins are aligned antiferromagnetically with nearest neighbors having opposite spins (for general review see Refs. [1–3]). This arrangement of charges and spins, known as stripes, was first inferred from X-ray absorption (XAS) and X-ray diffraction (XRD) experiments. Neutron scattering revealed that the period of spin is twice the period of charge carriers. The stripes In $La_{1.45}Nd_{0.4}Sr_{0.15}CuO_4$ are oriented parallel to [1 0 0] and [0 1 0] directions in successive planes of CuO_2 [4,5]. These stripes can be viewed as being one-dimensional superconducting quantum wires, representing superconductivity on a microscopic level. These stripes formed after doping with Nd and Sr are static (do not fluctuate with time or position). Dynamic stripes rather than static are thought to exist in other high-temperature superconductors (HTS) such as $YBa_2Cu_3O_7$ (For general review see) [1].

2. Experimental technique

The sample used in this work is a 140 mg single crystal ($T_c = 10.5$ K). It is a portion of the same sample used for neutron scattering, and earlier was for another study [2]. The magnetization curves were measured with a quantum designs SQUID magnetometer. The free-energy density was

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evaluated from the area under the reversible part of the magnetization. Critical currents (J_c) were determined in the irreversible part of the magnetization curves using Bean's model $J_c = 17\ \Delta M/r$, where r is the average dimension of the sample perpendicular to the applied magnetic field. The difference in magnetization (ΔM) is measured in emu/cm^3 and r in cm.

3. Results and discussion

Fig. 1a shows two hysteresis loops taken for fields applied parallel to the c-axis and along the ab-plane. The magnetization along the c-axis direction is about an order of magnitude larger than that along the ab-plane, indicating that the Nd^{3+} ion moments are along the c-axis. The hysteresis loops showed a wide span of the reversible magnetization that can be used to evaluate H_c with reasonable accuracy. The

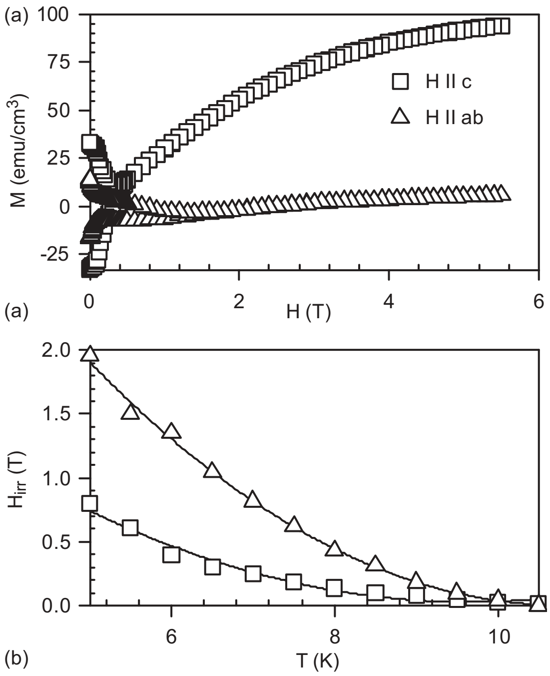

Fig. 1. (a) Hysteresis loops taken at 5 K for $H \| c$-axis and along ab-plane. (b) The irreversibility field H_{irr} vs. T obtained from hysteresis loops taken at various temperatures.

irreversible field (H_{irr}) value deduced from the hysteresis loops is presented in Fig. 1b. At a given temperature, the figure shows that the irreversibility field along the ab-plane is higher than that along the c-axis. In another words, the magnetization along the c-axis reveals a wider range of reversibility than ab-plane. However, the hysteresis loops below H_{irr} (hence higher pinning force) taken along the c-axis are wider than the loops taken when the field is applied along the ab-plane.

The reversible magnetization is used to evaluate the free energy, which has been used to obtain H_c. Therefore, we expect more accurate determination of the H_c values from the c-axis data than that for the ab-plane. Prior to evaluating the free-energy density, the normal state magnetization is subtracted from the total magnetization. For a given applied field direction, the normal state magnetization is obtained by fitting the reversible magnetization "paramagnetic" at high fields and temperatures using the extended Brillouin function. The area under the reversible magnetization represents the free energy which is proportional to $(H_c)^2$. The H_c values obtained at temperatures below T_c are shown in Fig. 2a for both field directions. Despite the different irreversibility fields for $H \| c$ and $H \| ab$-planes, the area under the two reversible curves is basically the same, indicating that the condensation energy is independent of direction of the applied magnetic field. However, we observe little difference between H_c values for both directions at low temperatures. At low temperatures close to the ordering temperature of Gd-ions (~ 3 K), the extended Brillouin function is not applicable. As a result, the subtraction procedure of the normal state magnetization is not precise. Moreover, at low temperatures the reversible part of the magnetization curve extends over a small range, hence the error in the calculated H_c increases.

The obtained H_c values shown in Fig. 2a agrees with the values obtained earlier by Ostenson et al. which they have used Curie–Weiss-like approach to subtract the normal state magnetization [2].

The pinning force has been evaluated from the width of the hysteresis loops (Fig. 1a) for both field directions. To illustrate the dependence of the pinning force (P_f) on the thermodynamic critical

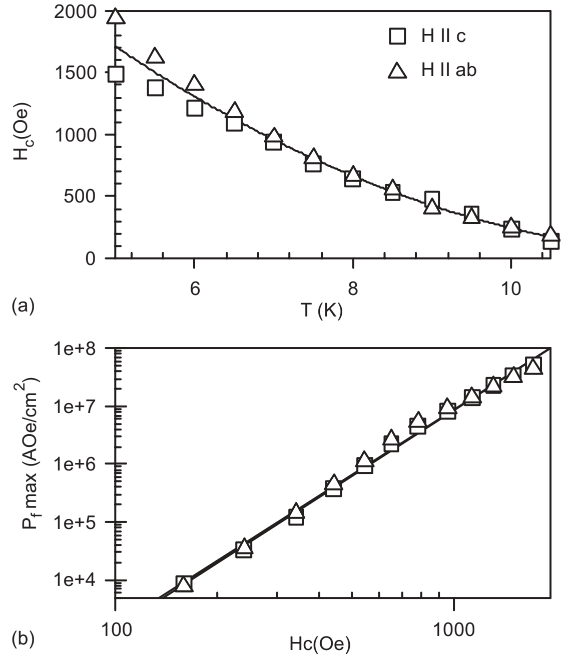

Fig. 2. (a) Variations of the thermodynamic critical field with temperature. (b) The maximum value of the pinning force for $H\|c$ and $H\|ab$ presented as $P_{f(max)}$ vs. H_c on a log–log scale.

field H_c, we present the maximum value of the volume pinning force $P_{f(max)}$ vs. H_c on a log–log scale as shown in Fig. 2b for both field directions $H\|c$ and $H\|ab$. The slope (β) of the line is ~ 3.7 indicating that pinning force scales roughly as $(H_c)^{3.7}$. It is interesting to notice that the line energy of vortex is proportional to $(H_c)^2$. The exponent is substantially higher than what we have found ($\beta = 2$) in $GdBa_2Cu_3O_7$ [3] and borocarbide superconductors: $LuNi_2B_2C$ and $Lu_{1-x}Gd_x$-Ni_2B_2C [6]. This implies that H_c and hence the free energy may not be the only factor contributing to the strength of flux pinning.

In conclusion, we were able to calculate the thermodynamic critical field H_c for the stripe phase superconductor with applied fields along two different directions. We showed that the thermodynamic critical field could be used as a single scaling parameter to scale the pinning force at various temperatures.

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