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Determination of the microscopic pinning mechanism in high-temperature superconductors

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Abstract

We report on a new, relatively simple, magnetic method to determine the dominant pinning mechanism: Spatial fluctuations of the transition temperature T_c ("δT_c-pinning") or of the charge carrier mean free path ℓ ("$\delta\ell$-pinning"). The method is based on measuring the magnetization curves in the range of the second anomalous peak, identifying the field B_{ss} which signifies the vortex solid–solid transition. The qualitative temperature dependence of B_{ss} determines the pinning mechanism: B_{ss} increasing (decreasing) with T indicates $\delta\ell$-pinning (δT_c-pinning). Using this method we have determined the pinning mechanism in $YBa_2Cu_3O_{7-\delta}$ and $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ crystals to be δl-pinning and δT_c-pinning, respectively. © 2000 Elsevier Science B.V. All rights reserved.

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Flux pinning in superconductors may be caused by spatial fluctuations of the transition temperature T_c ("δT_c-pinning") or of the charge carrier mean free path ("$\delta\ell$-pinning") near a lattice defect [1]. Spatial variations of T_c lead to spatial modulation of the linear and quadratic terms in the Ginzburg–Landau (GL) free energy functional, whereas variations of the mean free path affect the term associated with the gradient of the order parameter in the GL functional. Griessen et al. [2,3] utilized dynamic relaxation measurements to deduce the pinning mechanism in $YBa_2Cu_3O_{7-\delta}$ (YBCO) films. In their method, the temperature dependence of the critical current j_c and the collective pinning energy U_c are determined, and by fitting the results to the theoretical predictions they infer $\delta\ell$-pinning for $T < 80$ K and $B < 2$ T. In this paper we report on a new, relatively simple magnetic technique to determine the pinning mechanism. The technique is based on measuring the magnetization curves at various temperatures, in the field range of the anomalous second peak, identifying the field B_{ss} which signifies the vortex solid–solid transition [4–10]. The transition field, B_{ss}, in $Bi_2Sr_2CaCu_2O_{8+\delta}$ (BSCCO) [4] and $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ (NCCO) [5] has been associated with the sharp onset of the second magnetization peak. In untwinned YBCO B_{ss} has been associated with a sharp kink in the magnetization curves in between the onset and the peak fields [6]. Experimentally, the temperature dependence of B_{ss} in these three systems differs markedly: $B_{ss}(T)$ is approximately constant in BSCCO, it decreases monotonically with temperature in NCCO, and it increases with temperature in the untwinned YBCO. These differences can be explained quantitatively within the framework of a recent theory [7–10] describing a mechanism for a disorder-induced phase transition, from a relatively ordered vortex lattice, to a highly disordered vortex solid. The essence of this theory is that the vortex solid–solid phase transition is determined by the interplay between the vortex elastic energy E_{el} and the pinning energy E_{pin}. The transition line B_{ss}, as defined by $E_{el}(B,T) = E_{pin}(B,T)$, depends strongly on the specific microscopic pinning mechanism. Detailed calculations show that for δT_c-pinning B_{ss} decreases monotonically with T, whereas for $\delta\ell$-pinning B_{ss} increases with T.

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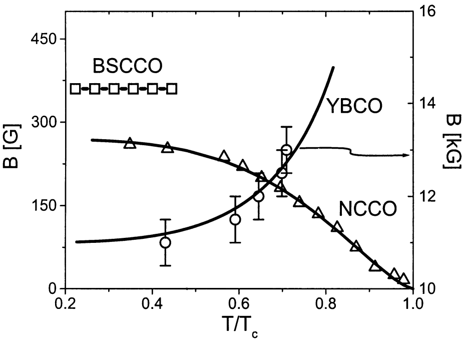

Fig. 1. The vortex solid–solid transition line in BSCCO, NCCO, and YBCO crystals. Solid lines are theoretical fits.

Thus, the two pinning mechanisms are borne out in the experiment in the behavior of $B_{ss}(T)$.

Fig. 1 shows the experimental data for $B_{ss}(T)$ in BSCCO, NCCO, and untwinned YBCO crystals. The solid lines show fit to the theory (see Refs. [5,6] for details). The increase of B_{ss} with temperature observed in YBCO indicates a $\delta\ell$-pinning mechanism, in agreement with the conclusions of Griessen et al. [2]. The decrease of B_{ss} with temperature observed in NCCO indicates a δT_c-pinning mechanism. For BSCCO B_{ss} is found only at relatively low temperatures, over a small range of T/T_c, and therefore it shows no temperature dependence. In this particular case the data is inconclusive regarding the pinning mechanism as one may fit the data with either mechanism. We note that in some BSCCO samples, e.g. oxygen-doped and electron-irradiated BSCCO [11–13], B_{ss} initially increases with temperature, suggesting a $\delta\ell$-pinning mechanism at low temperatures in these samples.

In summary, the markedly different temperature dependence of the vortex solid–solid phase transition lines in BSCCO, NCCO and YBCO is directly related to the different pinning mechanisms in these systems. Using this method we have determined the dominant pinning mechanisms in YBCO and NCCO crystals to be $\delta\ell$-pinning and δT_c-pinning mechanisms, respectively. The low-temperature data for oxygen-doped BSCCO also indicate $\delta\ell$-pinning mechanism.

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