Crossover of pinning mechanism in $La_{1.85}Sr_{0.15}CuO_4$ crystals

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The pinning mechanism in $La_{1.85}Sr_{0.15}CuO_4$ (LaSCO) was investigated by analyzing the critical current dependence on field and temperature. Unlike other high temperature superconductors such as $YBa_2Cu_3O_7$, $DyBa_2Cu_3O_{7-\delta}$, and $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$, which exhibit a single pinning mechanism over wide temperature and magnetic field ranges, our data in LaSCO show a clear crossover from δl to δT_c pinning with temperature or field. While δl pinning is effective at low fields or low temperatures, δT_c pinning dominates at high fields or high temperatures. Implications of the pinning mechanism crossover on the unique behavior of the second magnetization peak in LaSCO are discussed. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1853171]

Flux pinning by point defects in superconductors are associated with two kinds of disorder:[1]

(1) "δT_c pinning" related to spatial fluctuations of the transition temperature T_c, leading to spatial modulation of the linear and quadratic terms in the Ginzburg–Landau (GL) free energy functional.
(2) "δl pinning" related to spatial fluctuations of the charge carrier mean free path near a lattice defect, affecting the term associated with the gradient of the order parameter in the GL functional.

In recent years, different methods were developed to find the dominant pinning mechanism in various superconductors. Griessen *et al.*[2,3] applied their "generalized inversion scheme" (GIS) to determine the temperature dependence of the critical current density j_c in $YBa_2Cu_3O_7$ (YBCO) and $DyBa_2Cu_3O_{7-\delta}$ (DBCO) films, and found good agreement with the theoretical predictions for δl pinning. Giller *et al.*[4] proposed a relatively simple, though indirect, method to determine the dominant pinning mechanism. This method is based on measuring the magnetization curves in the range of the second magnetization peak (SMP), and identifying the field B_{od}, which signifies the vortex disorder-induced phase transition. The temperature dependence of B_{od} determines the pinning mechanism: B_{od} increasing (decreasing) with T indicates δl pinning (δT_c pinning). Using this method they concluded that the pinning mechanism in $YBaCu_3O_{7-\delta}$ and $Nd_{1.85}Ce_{0.15}CuO_{4-\delta}$ crystals are δl pinning and δT_c pinning, respectively. In attempting to apply this method to $La_{1.85}Sr_{0.15}CuO_4$ (LaSCO), one encounters a fundamental difficulty: The temperature dependence of B_{od} in LaSCO exhibits a steep concave decrease with temperature,[5] corresponding to neither δl nor δT_c pinning. Determination of the dominant pinning mechanism in LaSCO is, therefore, a challenge. In this manuscript we apply the GIS method to find the temperature dependence of j_c in LaSCO. Our results reveal a crossover between δl and δT_c pinning mechanisms, occurring in the vicinity of the second magnetization peak. This unusual crossover in the pinning mechanism may be a clue for understanding the distinctive behavior of B_{od} vs T in LaSCO.

Measurements were performed on an optimally doped $La_{1.85}S_{0.15}CuO_4$ sample ($0.7\times1.8\times1.17$ mm^3, T_c=37 K), using a Quantum Design MPMSXL SQUID magnetometer. Magnetic field, applied perpendicular to the c axis, was raised to a constant field between 5 and 50 kOe, and 20 consecutive magnetic measurements were taken at intervals of 1 min. This procedure was repeated at different temperatures and fields. In addition, magnetization was measured at constant temperature as a function of the external field being swept up to 50 kOe and down to zero in steps of 200 Oe.

The inset to Fig. 1 shows isothermal magnetic loops at different temperatures. Three characteristic fields can be identified: The onset of the SMP (indicated by a square), the peak field (triangle), and the field corresponding to a kink (circle) located in between the onset and the peak.[5] As previously reported,[5] all these characteristic fields are strongly temperature dependent. Figure 1 shows the temperature dependence of the magnetic moment measured at different external fields. At low temperatures, all the curves corresponding to the different external fields show a similar strong decrease with temperature. However, at intermediate temperatures the curves split, exhibiting weak temperature dependence and then merge again at higher temperatures. The split at the low temperature regime starts at lower tempera-

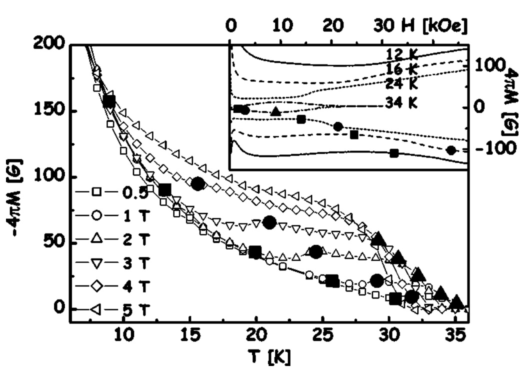

FIG. 1. Magnetic moment of $La_{1.85}Sr_{0.15}CuO_4$ as a function of temperature at the indicated fields. The onset, kink, and peak of the SMP are indicated by bold squares, circles, and triangles, respectively. Inset: Magnetization loops at the indicated temperatures. Symbols have the same meaning as in the figure.

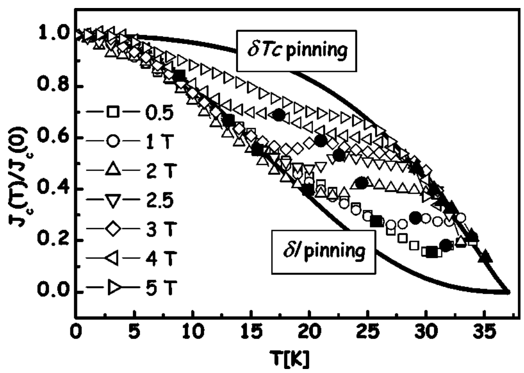

FIG. 2. Normalized critical current density of $La_{1.85}Sr_{0.15}CO_4$ as a function of temperature at the indicated external fields. Bold lines are theoretical predictions for j_c, corresponding to δl and δT_c pinning. Bold squares, circles, and triangles indicate the onset, kink, and peak inductions, respectively, taken from Fig. 1.

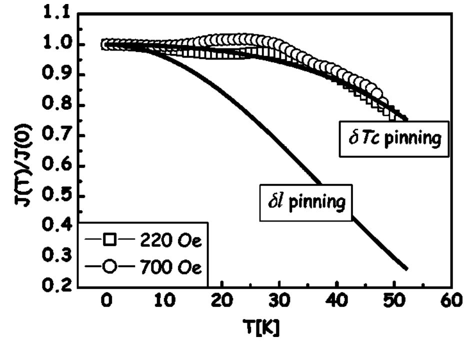

FIG. 3. Normalized critical current density of $Bi_2Sr_2CaCu_2O_{8+\delta}$ as a function of temperature at 270 Oe (squares) and 700 Oe (circles). Bold lines are theoretical predictions for j_c, corresponding to δl and δT_c pinning.

ture as the external field is larger. Similarly, the merging temperature is lower for larger external fields. The SMP characteristic fields (onset, kink, peak) are indicated in Fig. 1 by bold squares, circles, and triangles, respectively. The figure reveals that the low temperature split of the curves starts approximately at the onset of the SMP, the shallow peaks observed in the intermediate temperature regime are related to the kink, and the merging in the high temperature regime occurs near the peak of the SMP.

This unusual behavior of the irreversible magnetization points to a distinctive behavior of the pinning in LaSCO as a function of field and temperature. In order to explore this behavior, we employed the GIS method[2,3] to calculate the temperature dependence of j_c in LaSCO. This method enables model independent derivation of j_c from magnetic relaxation data. The method assumes variable separation for the collective pinning energy U_c,

$$U_c(T,H) \propto [j_c(T,H)/j_c(0,H)]^p G(T),$$

where $G(T)=[1+(T/T_c)^2]^l[1-(T/T_c)^2]^m$. The parameters p, l, and m are determined by the dimensionality of the vortices and the creep regime (single vortex, small bundle, large bundle). The critical current j_c can be expressed[2,3] by U_c, $G(T)$ and the measured $j(T,t)$:

$$j_c(T) = j_c(0)\exp\int_0^T \frac{CR(T')T\left(1-\dfrac{d\ln G}{d\ln T'}\right)+\dfrac{d\ln j}{d\ln T'}}{1+pCR(T')}\frac{dT'}{T'},$$

where $R=-d\ln j/d\ln t$ and $C=\lim_{T\to 0}(-1/R)\times(d\ln M/d\ln T)$ is a constant, experimentally determined as approximately 26 in our sample for all fields up to 50 kOe. In analyzing the data we consider three-dimensional vortices because anisotropy of LaSCO is relatively small ($\gamma\approx 10-30$) compared to BSCCO. This assumption of 3D vortices is also supported by recent muon spin rotation measurements.[6] In deciding upon the creep regime we note that assumption of small bundle regime leads to the unreasonable result of $j_c<j$ in a certain field and temperature ranges. Likewise, assumption of large bundles gives rise to a linear decrease of j with B, in contrast to the theoretical prediction of $j_c\propto B^{-3}$. Proceeding with the assumption of a single vortex regime, we calculated j_c assuming $\xi\propto[(1+t^2)/(1-t^2)]^{0.5}$ and $\lambda\propto(1-t^4)^{-0.5}$, where $t=T/T_c$. For more details of the procedure used for deriving the critical current from magnetic relaxation measurements the reader is referred to Appendix A of Ref. 3.

Figure 2 shows the calculated critical current density as a function of temperature for different external magnetic fields. The continuous bold curves in this figure show the theoretical predictions[2] $j_c\propto(1+t^2)^{5/6}(1-t^2)^{7/6}$ and $j_c\propto(1+t^2)^{-0.5}(1-t^2)^{2.5}$ for δT_c pinning and δl pinning, respectively. This figure reveals a crossover from δl pinning at low temperatures to δT_c pinning at high temperatures. This crossover occurs at lower temperatures as the external field is increased. Note that the calculated j_c begins to deviate from the theoretical δl curve at the onset of the second magnetization peak (bold squares) and it starts to follow the theoretical δT_c curve close to the second magnetization peak (bold triangles). Employing the same procedure to a $Bi_2Sr_2CaCu_2O_{8+\delta}$ sample ($0.05\times 9\times 2$ mm^3, $T_c=92$ K) yields the results depicted in Fig. 3 which clearly reflect a single pinning mechanism, namely a δT_c pinning, over the entire temperature range up to 55 K.

It is interesting to note that evidence for a similar crossover was found in $Bi_{2-x}Pb_xSr_2CaCu_2O_{8+\delta}$ (Ref. 7) using a different technique namely, by analyzing the field dependence of the pinning force. In $Bi_{2-x}Pb_xSr_2CaCu_2O_{8+\delta}$, as well as in LaSCO, the domination of δT_c pinning at high temperatures and fields is expected because local fluctuations in T_c are more effective as T_c is approached.

As was shown in Fig. 1, the crossover in the pinning mechanism in LaSCO occurs in close vicinity of the SMP. Assuming that the SMP signifies a phase transition in the vortex matter,[8] this crossover should affect the behavior of the transition line $B_{od}(T)$. The unusual concave decrease of $B_{od}(T)$ observed in LaSCO (Ref. 5) over a wide temperature range, may be related to the crossover in the pinning mechanism. Another possibility is that the SMP in LaSCO is not related to a vortex matter phase transition, and that it just originates from the pinning mechanism crossover. In this case, previous attempts to fit the experimentally measured $B_{od}(T)$ curve to theoretical predictions based on phase transition models are erroneous.[5]

In conclusion, in optimally doped LaSCO sample, a crossover from δl pinning to δT_c pinning is observed. This crossover occurs in the vicinity of the SMP and exhibits a strong dependence on temperature and magnetic field. The connection between this pinning mechanism crossover and the vortex order–disorder phase transition in LaSCO remains an interesting theoretical challenge.

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