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Vortex pinning in electron-doped cuprate superconductor $La_{2-x}Ce_xCuO_4$

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We have measured the vortex pinning strength in thin films of the electron-doped cuprate $La_{2-x}Ce_xCuO_4$ for various doping x from $x = 0.075$ ($T_c = 25$ K) to $x = 0.15$ ($T_c = 12.5$ K). The optimal doping for this compound is $x \approx 0.11$, at which $T_c = 29$ K. Films were prepared by a molecular-beam epitaxy method. A structural XRD investigation revealed no doping-induced lattice strain. We use a two-coil technique at frequencies from 10 to 100 kHz. The superfluid density $n_s(0)$ grows rapidly with x on the underdoped side and decreases slowly on the overdoped side. The Labusch parameter κ, i.e. the spring constant for a pinned vortex, shows large variations as the doping changes. It increases with x rapidly to a maximum at slight underdoping and then it decreases on the overdoped side more rapidly than $n_s(0)$. Even at optimal doping $\kappa(0)$ is an order of magnitude lower than the highest values observed in YBCO.

Introduction Recently the electron-doped cuprate superconductors have become the object of the controversy concerning the symmetry of the order parameter and seeming change in that symmetry with doping ([1, 2] and references therein). In this paper we report the results of the measurements of magnetic penetration depth λ, its temperature and external magnetic field dependence, and the vortex pinning strength (Labusch parameter κ), derived from the penetration depth data, as well as changes in these parameters with doping. The study was performed on thin films of the electron-doped cuprate superconductor $La_{2-x}Ce_xCuO_4$. As far as the authors know, this is the first study of the vortex pinning in this compound, although there were previous reports on vortex physics in related cuprates $Pr_{2-x}Ce_xCuO_4$ [3] and $Nd_{2-x}Ce_xCuO_4$ [4–6]. The samples for this study were prepared in the range of Ce compositions from underdoped ($x = 0.075$) to overdoped ($x = 0.15$) by MBE technique. Details of the film deposition are given in Ref. [7]. Optimal doping for these films is $x \approx 0.11$. The composition was determined within 0.1% by inductively coupled plasma technique.

The magnetic penetration depth was measured using a two-coil mutual inductance technique, as described in Refs. [10, 11] at an excitation frequency of 50 kHz. The main source of uncertainty in our experiment (as large as 20%) is the film thickness. This affects only absolute values of the measured penetration depth, but not its temperature dependence. To obtain the Labusch parameter one has to calculate the vortex inductance by subtracting the inductance of the superfluid from the total inductance [8]. Then for the Labusch parameter one gets

$$\kappa = \frac{B\phi_0}{\mu_0(\lambda^2(T,B) - \lambda^2(T,0))} . \tag{1}$$

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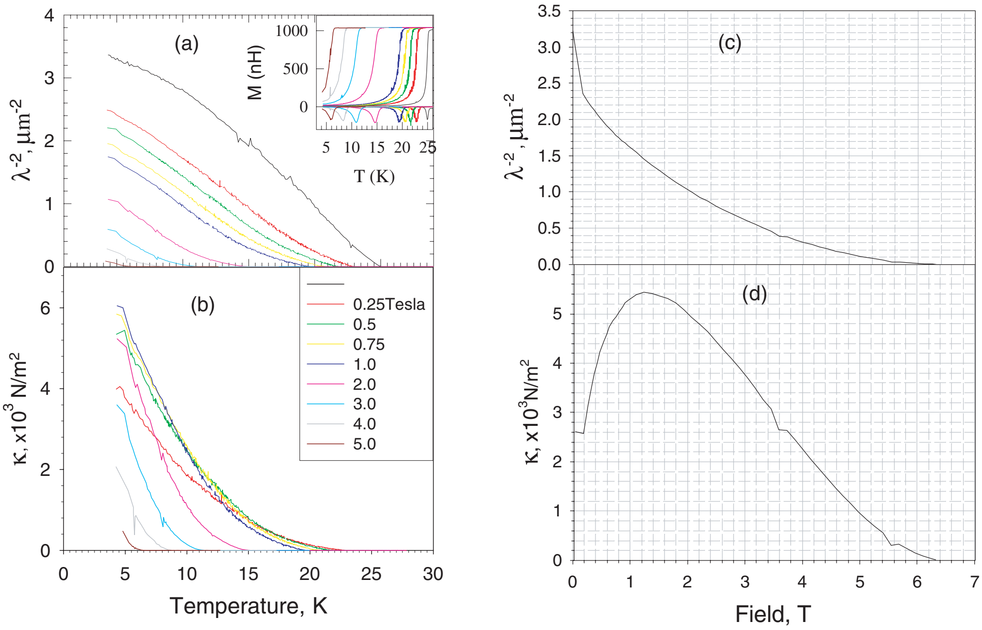

Fig. 1 (online colour at: www.interscience.wiley.com) Penetration depth and Labusch parameter as functions of temperature (a, b) and applied magnetic field (c, d) for an underdoped sample, x = 0.075.

Here B is the externally applied magnetic field, $\lambda(T, B)$ and $\lambda(T, 0)$ are measured magnetic penetration depth in the field, and without the field, respectively, $\phi_0 = 2 \times 10^{-15}$ Wb is the magnetic flux quantum, and $\mu_0 = 1.26 \times 10^{-6}$ H/m is the magnetic permeability of vacuum. By using measured values of $\lambda(T, 0)$ in Eq. (1) instead of hypothetical λ, corresponding to the firmly pinned vortices, we effectively neglect a suppression of the superfluid density by the magnetic field, which occurs along with the insertion of vortices. The penetration depth $\lambda(T, B = 0)$ and superfluid density ρ_s are related through $\rho_s = m/\mu_0 \lambda^2 e^2$, where m and e are mass and charge of the electron.

Experimental results The data on three films will be presented here, underdoped ($x = 0.075$), near optimal doping ($x = 0.09$) and overdoped ($x = 0.135$). The Figs. 1a and 1b show the inverse square penetration depth and the Labusch parameter as a function of temperature in various magnetic fields for the underdoped film. The inset in subfigure (a) shows real and imaginary parts of the mutual inductance. As the field increases, the $\lambda - 2$ decreases monotonically, as does the critical temperature.

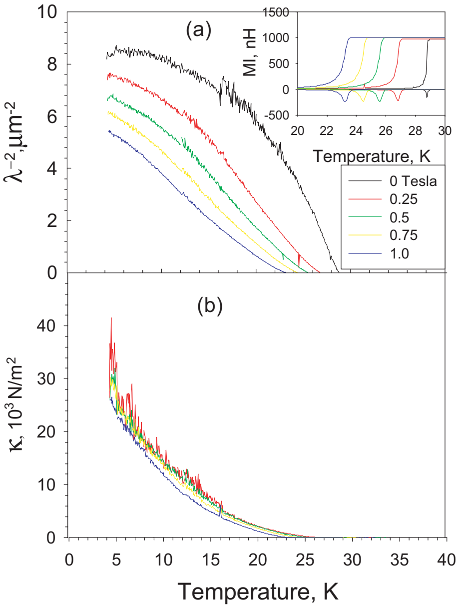

Fig. 2 (online colour at: www.interscience.wiley.com) Penetration depth (a) and Labusch parameter (b) as functions of temperature for an optimally doped sample, x = 0.09.

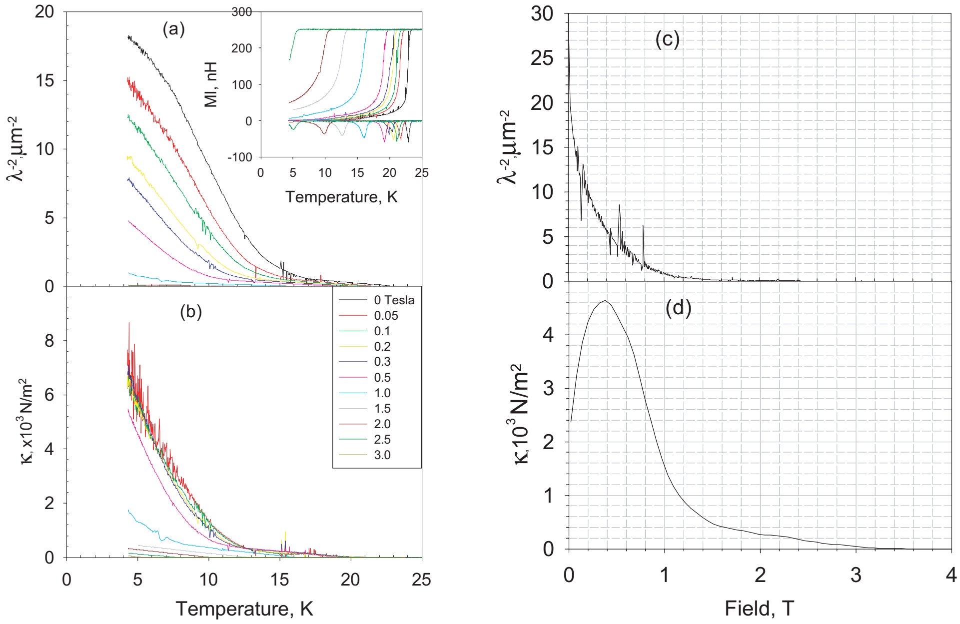

Fig. 3 (online colour at: www.interscience.wiley.com) Penetration depth and Labusch parameter as functions of temperature (a, b) and applied magnetic field (c, d) for an overdoped sample, $x = 0.135$.

In our experiment the detected critical temperature is the temperature where the vortices become unbound and therefore produce resistive, rather than inductive response, which shows as a disappearance of the superfluid. In other words, what we detect in case of a perpendicular magnetic field present is the irreversibility line on the phase diagram "magnetic field–temperature", rather than the actual $B_{c2}(T)$. The Figs. 1c and 1d show the penetration depth and the Labusch parameter at 4.2 K as a function of the applied magnetic field. The Labusch parameter at first increases with field up to ≈ 1.5 T and then falls off. The κ–B curve has a $b^{1/2}(1-b)^2$ shape ($b = B/B_{c2}$), often observed for bulk pinning force in type II superconductors (see e.g. [9] and references therein). From this observation we deduce $B_{c2} \approx 6$ T in this film. This number will be substantiated by other method later in this report. It is worth noticing that values of the pinning constant in this material are two orders of magnitude lower than in optimally doped films of YBCO obtained by pulsed laser deposition [13].

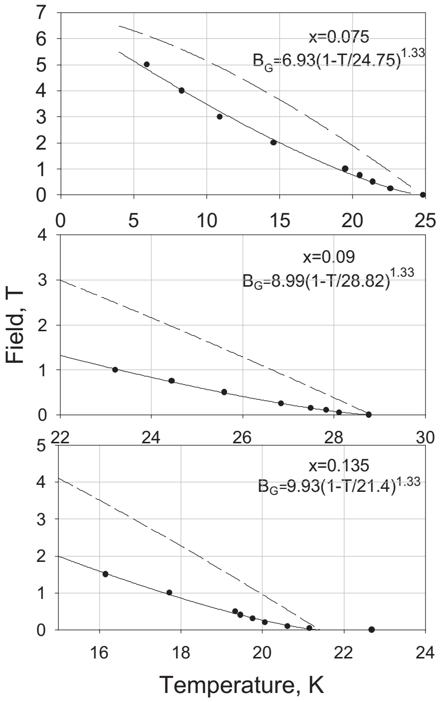

Fig. 4 T–B-phase diagram of underdoped, optimal and overdoped samples. For reference, dashed lines show the upper critical field $B_{c2}(T) = B_{c2}(0)[1-(T/T_c)^{3/2}]$.

Figure 2 shows the magnetic penetration depth and the Labusch parameter for the sample near the optimal doping,

$x = 0.09$. Unfortunately, the sample was destroyed in the process of experimentation and available data are limited to that in Fig. 2. One can see that the sample near the optimal doping has a higher superfluid density and the pinning constant is almost an order of magnitude higher than that in the underdoped sample.

Data from the overdoped sample ($x = 0.135$) are shown in Fig. 3. The inset in Fig. 3c shows a hysteresis in penetration depth, when the magnetic field is cycled from zero to ±1000 G.

The superfluid density is highest here, while the Labusch parameter drops down to the same low values as in the underdoped sample. The superfluid density vs. temperature data have a prominent tail at high temperature, and the vortex melting point does not decrease with magnetic field as fast as in the under- or optimally doped sample. The origin of this feature is unclear, but it is not due to the sample inhomogeneities, because the dissipative peaks in the imaginary mutual inductance data are narrow.

It is possible to estimate an upper critical field in these materials by plotting the field vs. the vortex melting temperature and then extrapolating the plot to zero, as shown in Fig. 4. We fit the data with a functional form $B_G = B_{c2}(0)(1 - T/T_c)^{4/3}$ [12]. For reference $B_{c2}(T)$ is also shown as dashed lines. They are drawn as $B_{c2}(0)[1 - (T/T_c)^{3/2}]$. Although an extrapolation from around 10–20 K down to 0 K is rather questionable, it is still possible by doing so to get an estimate of the upper critical field. They are 7, 9, and 10 T for the underdoped, optimal, and overdoped samples, respectively. The first of these numbers agrees well with B_{c2} obtained for the underdoped film earlier in this paper. These values are significantly smaller than B_{c2} for hole-doped cuprates such as YBCO, BSCCO, or LSCO. Thus the ab-plane coherence length $\xi_{ab} \approx 80$ Å.

Conclusion It is found that superfluid density in the electron-doped cuprate $La_{2-x}Ce_xCuO_4$ increases monotonically with Ce doping. The Labusch parameter κ shows large variations with doping: in an optimally doped sample it is an order of magnitude higher than in either an under- or overdoped sample. The vortex melting transition temperature is suppressed by a magnetic field in all samples, but less so in the overdoped one.

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