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Influence of structural disorder on low-temperature behavior of penetration depth in electron-doped high-T_C thin films

A.J.C. Lanfredi [a], S. Sergeenkov [b], F.M. Araujo-Moreira [a,*]

[a] Grupo de Materiais e Dispositivos, Centro Multidisciplinar para o Desenvolvimento de Materiais Cerâmicos – CMDMC, Departamento de Física, Universidade Federal de São Carlos – UFSCar, Caixa Postal 676, CEP 13565-905, São Carlos – São Paulo, Brazil
[b] Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russian Federation

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Abstract

To probe the influence of structural disorder on low-temperature behavior of magnetic penetration depth, $\lambda(T)$, in electron-doped high-T_C superconductors, a comparative study of high-quality $Pr_{1.85}Ce_{0.15}CuO_4$ (PCCO) and $Sm_{1.85}Ce_{0.15}CuO_4$ (SCCO) thin films is presented. The $\lambda(T)$ profiles are extracted from conductance-voltage data using a highly-sensitive home-made mutual-inductance technique. The obtained results confirm a d-wave pairing mechanism in both samples (with nodal gap parameter $\Delta_0/k_BT_C = 2.0$ and 2.1 for PCCO and SCCO films, respectively), substantially modified by impurity scattering (which is more noticeable in less homogeneous SCCO films) at the lowest temperatures. More precisely, $\Delta\lambda(T) = \lambda(T) - \lambda(0)$ is found to follow the Goldenfeld–Hirschfeld interpolation formulae $\Delta\lambda(T)/\lambda(0) = AT^2/(T + T_0)$ with $T_0 = \ln(2)k_B\Gamma^{1/2}\Delta_0^{1/2}$ being the crossover temperature which demarcates pure and impure scattering processes ($T_0/T_C = 0.13$ and 0.26 for PCCO and SCCO films, respectively). The value of the extracted impurity scattering rate Γ correlates with the quality of our samples and is found to be much higher in less homogeneous films with lower T_C.

Keywords: Electron-doped superconducting materials; Magnetic penetration depth; Pairing symmetry

1. Introduction

The accurate experimental determination of the temperature behavior of the magnetic penetration depth, $\lambda(T)$, has been of great interest to the scientific community since the very discovery of high-T_C superconductors. Since the effective value of $\lambda(T)$ is extremely sensitive to local inhomogeneities, a thorough analysis of its low-temperature profile gives probably one of the most reliable methods to determine the quality of a superconducting material (especially in the form of thin films), which is of utter importance for applications [1,2].

On the other hand, the magnetic penetration depth is strongly sensitive to the variations of the macroscopic superconducting order parameter and therefore its study can give important information about both the symmetry of the superconducting state and the pairing mechanisms.

It is well established that most of the conventional low-T_C superconductors have s-wave pairing symmetry. As for high-T_C cuprates, the study of pairing symmetry in these materials has been (and still remains) one of the most polemical and active fields of research over the last few years [2] and the experimental determination of the temperature dependence of λ has been one of the most common methods in these studies. In particular, a power-like dependence T^n of the penetration depth at low temperatures clearly points at a nodal structure of the superconducting gap (as expected for strongly correlated materials) where the exponent n depends on the type of the node in the k-space. Most phase-sensitive measurements [3,4] have revealed that hole-doped high-T_C cuprates with nearly optimal doping have predominantly $d_{x^2-y^2}$ pairing symmetry. Regarding the case of the hole-doped cuprate

* Corresponding author. Tel.: +55 16 33518222; fax: +55 16 33614835.
E-mail address: faraujo@df.ufscar.br (F.M. Araujo-Moreira).

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$YBa_2Cu_3O_{7-\Delta}$, some groups have reported experimental evidences for a pairing symmetry transition from pure $d_{x^2-y^2}$ (for under-doped compositions) to a mixed-type $d + id_{xy}$ (for over-doped compositions) [5]. At the same time, for electron-doped cuprates, which have composition of the form $Ln_{2-x}Ce_xCuO_4$ (where Ln corresponds to Pr, Nd, or Sm), the pairing mechanisms are not yet fully understood [6–10]. For example, using the point contact spectroscopy technique, Biswas et al. [7] have found strong evidences in favor of d-wave pairing symmetry in under-doped ($x \approx 0.13$) $Pr_{2-x}Ce_xCuO_4$ (PCCO). Further studies revealed [8] that the low temperature superfluid density of Ce-based magnetic superconductors varies quadratically with temperature in the whole range of doping, in agreement with the theoretical prediction for a d-wave superconductor with impurity scattering. In addition, remeasured [9] magnetic-field dependence of the low-temperature specific heat of optimally-doped ($x = 0.15$) PCCO give further evidence in favor of d-wave-like pairing symmetry in this material at all temperatures below 4.5 K. And finally, the recent penetration depth measurements on $Sm_{1.85}Ce_{0.15}CuO_4$ (SCCO) single crystals [10] have indicated that this magnetic superconductor exhibits a rather strong enhancement of diamagnetic screening below 4 K most probably driven by the Neel transition of Sm sublattice due to spin-freezing of Cu spins.

In this paper, we study the influence of local inhomogeneities on low-temperature dependence of the magnetic penetration depth $\lambda(T)$ in high-quality optimally-doped $Pr_{1.85}Ce_{0.15}CuO_4$ (PCCO) and $Sm_{1.85}Ce_{0.15}CuO_4$ (SCCO) thin films grown by the pulsed laser deposition (PLD) technique. The $\lambda(T)$ profiles have been extracted from conductance-voltage data by using a highly-sensitive home-made mutual-inductance bridge.

2. Samples characterization and experimental procedure

The structural quality of our samples was verified through X-ray diffraction (XRD) and scanning electron microscopy (SEM) together with energy dispersive spectroscopy (EDS) technique. Both XRD spectra and SEM data reveal that PCCO film is of higher structural quality than SCCO film (see Figs. 1 and 2).

The experimental bridge used in this work is based on the mutual-inductance method. To measure samples in the shape of thin films, the so-called *screening method* has been developed [11]. It involves the use of primary and secondary coils, with diameters smaller than the dimension of the sample. When these coils are located near the surface of the film, the response (i.e., the complex voltage output V_{AC}) does not depend on the radius of the film or its properties near the edges. In the reflection technique [12], an excitation (primary) coil coaxially surrounds a pair of counter-wound (secondary) pick-up coils. If we take the current in the primary coil as a reference, V_{AC} can be expressed via two orthogonal components, i.e., $V_{AC} = V_L + iV_R$. The first one is the inductive component, V_L (which is in phase with the time-derivative of the reference current) and the second one is the quadrature resistive component, V_R (which is in phase with the reference current). It can be easily demonstrated that V_L and V_R are directly related to the average magnetic moment and the energy losses of the sample, respectively [13]. When there is no sample in the system, the net output from the secondary coils is close to zero because the pick-up coils are identical in shape but are wound in opposite directions. The sample is positioned as close as possible to the set of coils, to maximize the induced signal in the pick-up coils.

An alternate current sufficient to create a magnetic field of amplitude h_{AC} and frequency f is applied to the primary coil by an alternating voltage source, V_{in}. The output voltage of the secondary coils V_{AC} is measured through the usual lock-in technique [14]. Fig. 3 shows the sketch of the experimental bridge used in our study based on the mutual-inductance screening method.

3. Results and discussion

To extract the profile of the penetration depth within the discussed here method, one should resolve the following

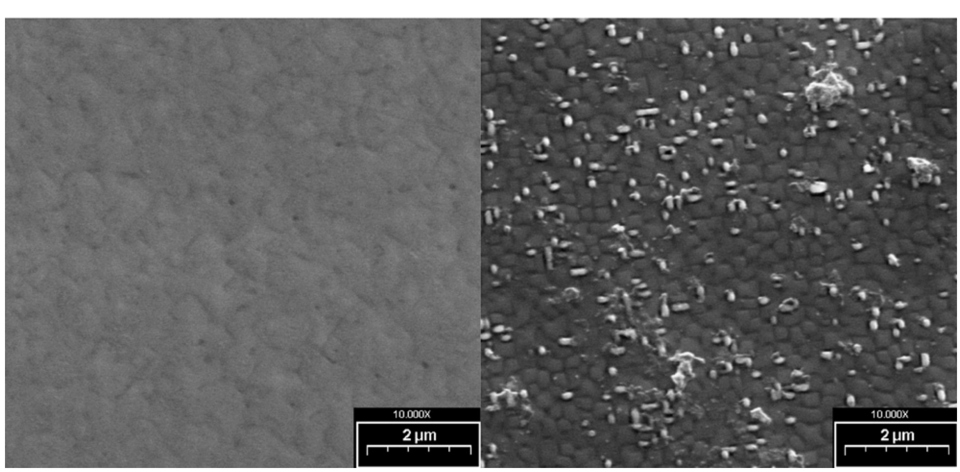

Fig. 1. SEM scan photography of PCCO (left) and SCCO (right) samples (magnification 10,000 times).