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Interlayer magnetotransport study in electron-doped $Sm_{2-x}Ce_xCuO_{4-\delta}$

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Abstract. Vortex and pseudogap states in electron-doped $Sm_{2-x}Ce_xCuO_{4-\delta}$ ($x \sim 0.14$) are investigated by the interlayer transport in magnetic fields up to 45 T. To extract intrinsic properties, we fabricated small 30 nm-high mesa structures, sufficiently thin to be free of the recently reported partial decomposition problems. On cooling, the c-axis resistivity ρ_c of the mesa structures reveals a semiconductive upturn above T_c, followed by a sharp superconducting transition at 20 K. When the magnetic field H is applied along the c-axis, $\rho_c(T)$ shows a parallel shift without significant broadening, as also observed in the hole-doped underdoped cuprates. Above the transition we observe negative magnetoresistance (MR), which can be attributed to the field suppression of the pseudogap, whose magnitude is as small as 38 K. Our results in the $x \sim 0.14$ samples closely correspond to the interlayer transport behavior in the 'overdoped' regime of hole-doped $Bi_2Sr_2CaCu_2O_{8+y}$.

Keywords. Electron-doped cuprate; mesa structure; high-field magnetoresistance; pseudogap.

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1. Introduction

Magnetotransport has been widely used for the studies of the vortex states in high-T_c cuprate superconductors [1]. In particular, the observed resistive broadening of the superconducting transition under magnetic fields in underdoped hole-doped cuprates highlights the importance of the fluctuations near the upper critical field H_{c2}. More recently, because of the layered structure which forms intrinsic tunnel junctions, the interlayer tunneling transport in the highly anisotropic high-T_c cuprates has been used as a powerful probe for both the density of states in the CuO_2 planes [2,3], as well as the vortex phase diagram at high fields [4,5].

Such interlayer magnetotransport studies have been mostly focused on hole-doped $Bi_2Sr_2CaCu_2O_{8+y}$ (BSCCO), whose anisotropy parameter γ exceeds 100.

Recent normal-state studies in electron-doped systems indicate that the two sides of the doping divide in cuprates seemingly display various aspects of particle–hole asymmetry. In addition to the lower transition temperatures, T_c, in electron-doped (n-type) cuprates ($L_{2-x}Ce_xCuO_{4-\delta}$, where L = Nd, Pr, Eu, or Sm) the antiferromagnetic phase persists to much higher doping levels, while superconductivity is observed in a narrower doping range $0.14 \lesssim x \lesssim 0.18$ [6,7]. A number of questions remains unresolved as to the differences in properties of the superconducting and the normal-state pseudogap [8] states in n- and p-type cuprates. In the superconducting n-type cuprates, experimental situation regarding the pseudogap is far less clear and often contradictory [9–11]. Thus, a useful information may be gained from a study of the interlayer transport properties in electron-doped systems with values of γ large, comparable to BSCCO [12].

In the electron-doped cuprates, however, there is a known materials issue that first needs to be addressed. It has been recently reported [13] that the annealing process required for oxygen reduction produces a partial decomposition, and the secondary phase forms an oriented quasi-two-dimensional long-range epitaxial structure parallel to the CuO_2 sheets. Such chemical 'inhomogeneity' may obscure intrinsic features in the transport measurements. In this study we report the interlayer transport measurements on 30 nm-thin mesa structures in the n-type superconducting single crystals of $Sm_{2-x}Ce_xCuO_{4-\delta}$ (SCCO) with the Ce content $x \sim 0.14$ – structures much thinner than typical separation of the secondary phase. This enables us to probe the *intrinsic* behavior of the interlayer magnetoresistance and compare it to the bulk behavior in fields up to 45 T. The results highlight striking similarities to the overdoped cuprates of p-type.

2. Experimental

We used a self-flux method [14,15] with the crucible turn-over technique [16] to get plate-like single crystals with surfaces flux-free and shiny. The as-grown crystals were post-annealed under Ar flow for 20 h at 950°C. Ce concentration x was determined as ∼0.14 by energy dispersive X-ray spectroscopy (EDS). Mesa structures with typical dimensions of 8 μm × 12 μm × 30 nm were fabricated using the photolithography and ion milling techniques [17]. Au/Ag bilayer was evaporated on the 'natural' surface of the annealed crystals, with two contacts on top of the mesa (see figure 1a) enabling four-terminal measurements of the c-axis resistivity ρ_c of the mesa alone. With the thickness of the secondary phase layer in the range 4–8 nm and with the volume fraction of 1–3% [13], the height (30 nm) of our mesas is much smaller than typical separation between the neighboring secondary-phase layers.

For high-field experiments, we measured ρ_c of bulk single crystals by using the 45 T hybrid DC magnet at NHMFL, Florida. The hybrid magnet comprises 11.5 T superconducting outsert and 33.5 T resistive insert magnets, and so some of the data presented here are restricted to a field range between 11.5 and 45 T. A capacitance sensor was used for temperature control.

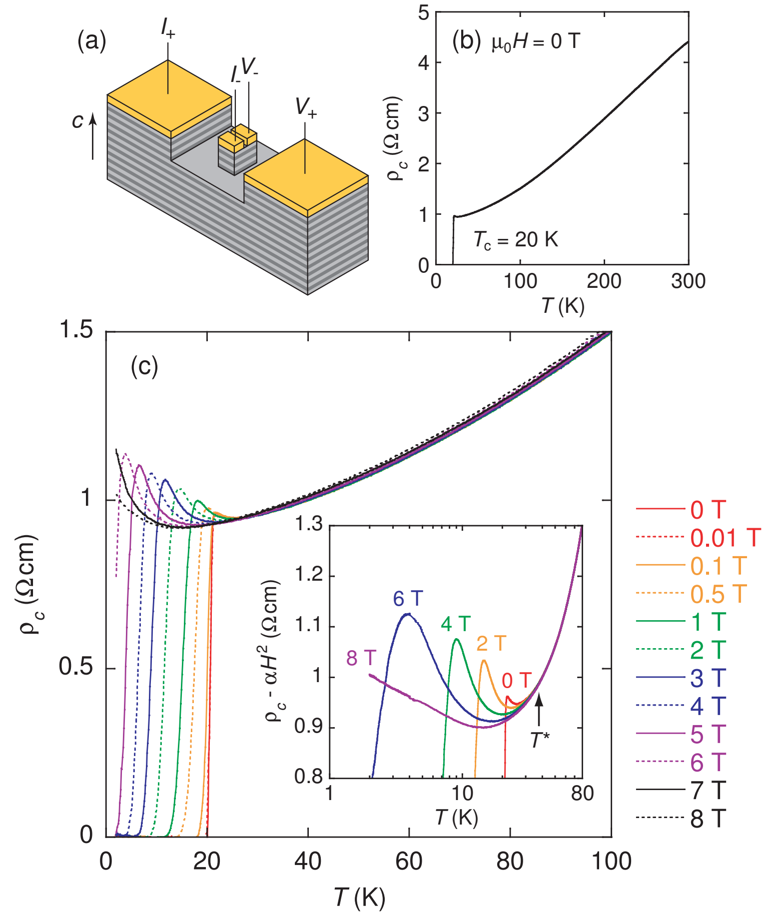

Figure 1. (**a**) Schematic illustration of our mesa structure (not to scale). (**b**) Temperature dependence of ρ_c in zero field for a mesa sample. (**c**) $\rho_c(T)$ curves in magnetic fields applied along the c-axis. A slight field spread of the curves at high T is due to a small positive MR $\propto H^2$. After subtracting this MR all high-T data follow a single curve (inset). Negative MR is observed below $T^\star \approx 38$ K.

3. Results

Figure 1 shows the temperature dependence of ρ_c in a mesa sample. Eleven mesas measured showed consistently reproducible values of ρ_c, giving us confidence in null effect of the secondary phase. At zero field, on cooling $\rho_c(T)$ shows a semiconductive upturn above T_c followed by a sharp superconducting transition at 20 K. The sharpness of the transition is a reflection of high homogeneity in the measured mesa region.

When we apply magnetic field H along the c-axis, $\rho_c(T)$ shows a parallel shift of the transition (see figure 1c), which is in contrast to the significant broadening

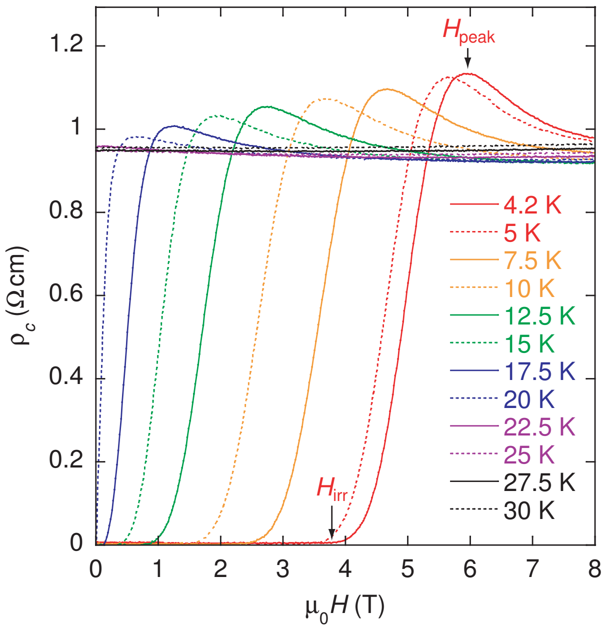

Figure 2. Field dependencies of ρ_c for a set of temperatures for the SCCO mesa sample. Negative MR above $H_{\rm peak}$ is a consistent signature of the pseudogap.

observed in the underdoped cuprates of *p*-type and is rather similar to the behavior in the overdoped regime [18]. Above the transition, ρ_c has a small standard positive magnetoresistance (MR) proportional to H^2. When we subtract this positive H^2 term, distinct negative MR term is found below $T^\star \sim 38$ K, as shown in the inset of figure 1c.

The field dependence of ρ_c is shown in figure 2. Above the irreversibility field $H_{\rm irr}$, ρ_c becomes non-zero, and it shows a peak at $H_{\rm peak}$, in close correspondence to that observed in BSCCO. The peak behavior is explained by a competition of the Josephson (vortex) and quasi-particle contributions in the interlayer tunneling conductivity [4]. Above the peak we observe negative MR term again, which can be attributed to the field suppression of the gap as discussed in the interlayer transport studies in BSCCO [2,5].

For comparison, we also measured the *c*-axis MR for bulk single crystals of SCCO. We find that in the bulk crystals the ρ_c values are higher and the upturn is enhanced (see inset of figure 3a). Some of this enhancement must originate from the chemical inhomogeneity we discussed earlier: since the secondary phase is reported to have long-range epitaxial structure parallel to the *ab*-plane, ρ_c in a bulk crystal may be expressed as a sum of the contributions from both phases. However, the relative MR reveals behavior quantitatively consistent with the intrinsic mesa data. The consistency of the relative changes in mesa and bulk MRs suggests that the observed negative MR is of the same origin in both, namely it comes intrinsically from the field suppression of the pseudogap. The intrinsic negative MR in the mesas and

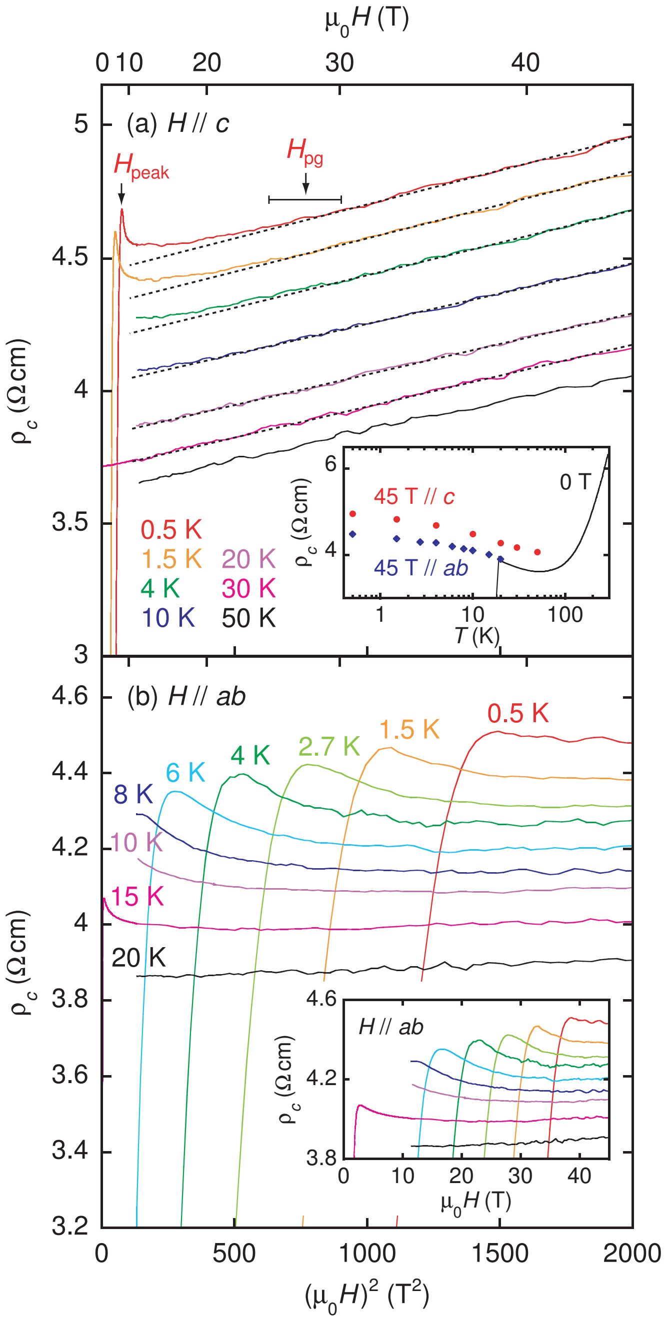

Figure 3. ρ_c vs. H^2 at various temperatures in a SCCO bulk sample for (**a**) $H \| c$ and (**b**) $H \| ab$. Dashed lines are high-field fits to H^2 dependence. The inset in (a) shows T-dependencies of ρ_c of the bulk sample without field (solid line) and in 45 T (filled symbols). The inset in (b) shows $\rho_c(H)$ for $H \| ab$ in a linear scale.

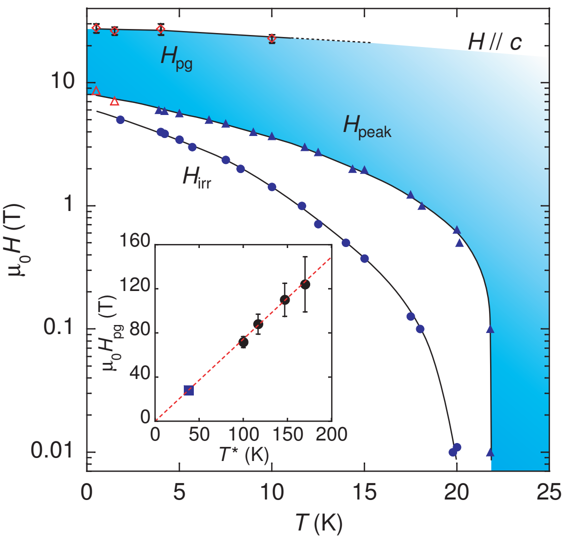

Figure 4. H–T diagram for the SCCO mesa (closed symbols) and the bulk sample (open symbols). Error bars in $H_{\rm pg}$ and $H_{\rm peak}$ are close to the size of symbols. Lines are guides to the eye. Negative MR term (in the shaded region) goes to zero at the $H_{\rm pg}(T)$ boundary. Inset: $H_{\rm pg}$ (at low T) vs. $T^\star$ (at 0 T) in SCCO (square) and BSCCO (circles). Dotted line is the Zeeman scaling line with $g = 2$.

in the bulk is consistently observed below $T^\star \sim 38$ K, above which the pseudogap vanishes. High-field MR data in the bulk up to 45 T clearly indicate a cross-over from a negative slope to a standard positive H^2 MR, from which we evaluate the pseudogap closing field $\mu_0 H_{\rm pg} \sim 28$ T. This pseudogap energy scale is considerably smaller than that of BSCCO [2], which will be discussed later. We note that here the field scales are such that for the first time the disappearance of negative interlayer MR can be observed without requiring further assumptions and extrapolations.

When the magnetic field is applied parallel to the ab-planes, the peak field is shifted to higher fields as shown in figure 3b. This is naturally explained by strong superconducting anisotropy in layered cuprates [4,19]. At high fields, the positive MR term for $H \| ab$ is smaller than for $H \| c$ [20], and the negative part dominates. The peak in $\rho_c(H)$ is less pronounced at lower temperatures, and, indeed, at 0.5 K the peak is barely discerned. This indicates that the pseudogap closing field in this configuration is not more than 40 T, which gives the $H_{\rm pg}$ anisotropy less than 1.4. This small anisotropy is in stark contrast with the huge anisotropy of superconducting parameters (e.g., $H_{\rm peak}$) and is in good agreement with the value 1.35 obtained in BSCCO, corresponding to the small anisotropy of the g-factor [19,21].

The temperature dependence of $H_{\rm irr}$, $H_{\rm peak}$, and $H_{\rm pg}$ are plotted in figure 4 for the $H \| c$ configuration. Consistently, the $H_{\rm peak}(T)$ data for the mesa and the crystal follow a single curve. At high temperatures, $H_{\rm pg}$ is not easily determined since $\Delta\rho_c$ becomes quite small, in agreement with the smallness of the pseudogap energy scale. At low temperatures ($T \lesssim 10$ K), $H_{\rm pg}$ is nearly 'flat' in temperature

– a characteristic T-dependence also found in BSCCO [2,19]. We also found nearly exponential dependence of $H_{\rm peak}$ at low temperatures, which can be understood by the two channel contributions in the interlayer tunneling conductivity [4,22].

4. Discussion

The obtained pseudogap temperature $T^\star \sim 38$ K and its closing field $H_{\rm pg} \sim 28$ T obey a simple Zeeman energy relation $k_{\rm B}T^\star = g\mu_{\rm B}\mu_0 H_{\rm pg}$ with $g \sim 2$ ($k_{\rm B}$ is the Boltzmann constant and $\mu_{\rm B}$ is the Bohr magneton), as shown in the inset of figure 4. This result is consistent with the previous reports in BSCCO [2,19], and suggests the pre-eminent role of spin correlations over the orbital effects in forming the pseudogap in both BSCCO and SCCO.

The energy scale $T^\star \approx 38$ K at zero field in our $x \sim 0.14$ SCCO samples is considerably smaller than $T^* > 300$ K in underdoped BSCCO for $p \sim 0.14$ [2]. This begs an intriguing question as to the real doping level in the electron-doped cuprates. If, as has been suggested [7,23], we take into account oxygen deficiency $\delta \sim 0.04$–0.045, then electron concentration in the crystals should be counted as $n = x + 2\delta \sim 0.22$–$0.23$. With this uncertainty of n, the smallness of the pseudogap energy scale in SCCO may be simply due to an undercount of the doping level. The absence of significant resistive broadening of the superconducting transition under magnetic fields also points to its 'overdoped' nature.

5. Summary

We have elucidated the intrinsic behavior of the interlayer magnetotransport in SCCO by using thin mesa-structured samples. The intrinsic negative MR term can be consistently explained by the pseudogap in the density of states. While the energy scale of the pseudogap $T^\star \sim 38$ K in SCCO is considerably smaller than that in BSCCO with $p \sim 0.14$, all observed intrinsic features in our n-type SCCO ($x \sim 0.14$) reveal remarkable similarities to the overdoped p-type BSCCO, among them the Zeeman relation between the pseudogap temperature and its closing field, and the apparent parallel shift of the superconducting transition.

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