Electronic Homogeneity in the Overdoped Regime of the Electron-Doped High-$T_c$ Superconductors

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Abstract. In order to investigate the electronic homogeneity in electron-doped high-$T_c$ cuprates, magnetization and specific heat measurements have been performed for Pr$_{1-x}$La$_x$Ce$_x$CuO$_4$ single crystals with $x = 0.13 - 0.17$. It has been found from the magnetization curve that the hysteresis is relatively small and that the so-called second magnetization peak is absent for every $x$. Moreover, the Sommerfeld constant in the ground state has shown $H^{lnH}$ dependence on magnetic field $H$ for every $x$, suggesting that the superconductivity is not pure but dirty. These results are in contrast to those observed in the overdoped regime of hole-doped La$_{2-x}$Sr$_x$CuO$_4$ where an inhomogeneous superconducting state is formed in spite of the superconductivity being pure. Therefore, it has been concluded that a rather homogeneous electronic state is realized in the electron-doped cuprates, suggesting different electronic states between hole- and electron-doped cuprates.

1. Introduction

Recently, the study of microscopic electronic inhomogeneity of the superconductivity in high-$T_c$ cuprates has attracted interest. For hole-doped La$_{2-x}$Sr$_x$CuO$_4$ (LSCO), it has been suggested from the magnetic susceptibility measurements that both the superconducting (SC) transition temperature, $T_c$, and the SC volume fraction decrease markedly with increasing $x$ in the overdoped regime [1]. The low-temperature specific heat measurements have revealed the existence of a finite value of the Sommerfeld constant in the SC ground state [2]. In addition, from the magnetization-hysteresis-loop measurements, a so-called second magnetization peak has been observed in the overdoped regime, indicating the enhancement of the vortex pinning [3]. These results suggest that the electronic state in overdoped LSCO is so inhomogeneous as to be composed of normal and SC states.

As for the electron-doped cuprates, the situation is rather complicated due to the reduction process of excess oxygen which is essential for the appearance of superconductivity. Therefore, in order to investigate whether the electronic state is inhomogeneous or not, we have carried out magnetization and specific heat measurements in electron-doped single crystals of Pr$_{1-x}$La$_x$Ce$_x$CuO$_4$ (PLCCO) with $x = 0.13 - 0.17$. 
2. Experimental

Single crystals of PLCCO with $x = 0.13 - 0.17$ were grown by the travelling-solvent floating-zone method. The quality of the grown crystals was checked by the x-ray back-Laue photography to be good. The composition of the crystals was checked by the inductively coupled plasma analysis. The reduction annealing was performed in vacuum at various temperatures for various hours to obtain SC crystals. Magnetization and specific heat measurements were performed in magnetic fields up to 7 and 9 T parallel to the c-axis using a SC quantum interference device (SQUID) magnetometer and a commercial apparatus (Quantum Design, PPMS), respectively.

3. Results and Discussion

Figure 1 shows the dependence on magnetic field $H$ of the hysteresis in the magnetization curve, $\Delta M$, for fully reduced crystals of PLCCO with $x = 0.13 – 0.17$. The $T_s$’s of crystals with $x = 0.13, 0.15$ and 0.17 are 20.5 K, 12.2 K and 5.1 K, respectively. It is found that, compared with $\Delta M$ of overdoped LSCO with $x = 0.198$ [3], the hysteresis is quite small and no second magnetization peak is observed in PLCCO. These results suggest that the vortex pinning is relatively weak in PLCCO, implying a rather homogeneous electronic state in contrast to the inhomogeneous one in overdoped LSCO.

Figure 2(a) shows the temperature dependence of the specific heat, $C$, plotted as $C/T$ vs. $T^2$ for fully reduced crystals of PLCCO with $x = 0.13 – 0.17$. It is found that $C$ at low temperatures is expressed as $C/T = \gamma_0 + \beta T^2$, where $\gamma_0$ is the residual Sommerfeld-constant in the ground state and $\beta$ is the coefficient of the specific heat of phonons. For every $x$, $\gamma_0$ is not zero but has a finite value even in the SC state, which is consistent with the results in the former report [4]. It is noted that $C/T$ shows no upturn due to a Schottky anomaly, suggesting that the crystals are free of any measurable magnetic impurities.

It is well known for $d$-wave superconductors that $\gamma_0$ exhibits $H^{1/2}$ dependence [5], which has been observed in overdoped LSCO in spite of the existence of a finite value of $\gamma_0$ in zero field. Therefore, it has been concluded that the superconductivity in overdoped LSCO is pure and that the electronic state is inhomogeneous [2]. For dirty $d$-wave superconductors, on the other hand, $\gamma_0$ is proportional to $HlnH$ [6]. As shown in Fig. 2(b), the magnetic-field dependence of $\Delta\gamma_0 = \gamma_0(H) - \gamma_0(0)$ for PLCCO with $x = 0.15$ is well reproduced by $HlnH$ rather than $H^0$. These results suggest that the observed finite value of $\gamma_0$ in zero field is not due to the inhomogeneous superconductivity but due to the

![Figure 1](image1.png)

**Figure 1.** Magnetic-field dependence of the magnitude of the hysteresis in the magnetization curve, $\Delta M$, for Pr$_{1-x}$LaCe$_x$CuO$_4$ with $x = 0.13 – 0.17$. $\Delta M$ for La$_{2-x}$Sr$_x$CuO$_4$ with $x = 0.198$ is also shown for comparison [3].
homogeneous dirty superconductivity where probably the scattering by the residual excess oxygen is frequent.

The present results of magnetization and specific heat have revealed that a rather homogeneous SC state is formed in the electron-doped cuprates, in contrast to the inhomogeneous SC state observed in the hole-doped cuprates. One possible explanation for the different electronic states is related to the so-called non-Ce-doped superconductivity in the parent compounds of the electron-doped cuprates such as La$_{2-x}$RE$_x$CuO$_4$ (RE: rare-earth elements) with the Nd$_2$CuO$_4$-type structure [7,8]. Very recently, we have suggested that the electronic state of the electron-doped cuprates including the parent SC compounds is able to be understood in terms of a band structure taking into account the strong electron correlation [9]. In order to clarify whether or not the novel electronic state leads to the homogeneous SC state in the electron-doped cuprates, further experiments to unveil the detailed electronic state of PLCCO are necessary.

4. Summary

We have investigated the electronic homogeneity in PLCCO with $x = 0.13 - 0.17$ from the magnetization and specific heat measurements. It has been found that the magnetization curve exhibits a relatively small hysteresis and that the residual Sommerfeld constant in the ground state shows $H\ln H$ dependence. These results suggest that a rather homogeneous SC state is realized in the electron-doped cuprates, in contrast to the inhomogeneous SC state in the overdoped regime of hole-doped LSCO.

References

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Figure 2. (a) Temperature dependence of the specific heat, $C$, plotted as $C/T$ vs. $T^2$ in zero field for fully reduced crystals of Pr$_{1-x}$LaCe$_x$CuO$_4$ with $x = 0.13 - 0.17$. (b) Magnetic-field dependence of $\Delta\gamma_0 = \gamma_0(H) - \gamma_0(0)$ for the fully reduced crystal of Pr$_{1-x}$LaCe$_x$CuO$_4$ with $x = 0.15$. 