Superconductivity in NCCO thin films and effect of Gd and Ni doping

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Abstract

Thin films of electron-doped superconductor $Nd_{2-x}Ce_xCuO_{4-y}$ (NCCO), $Nd_{1.8-x}Gd_{0.2}Ce_xCuO_{4-y}$ and $Nd_{2-x}Ce_xCu_{0.998}Ni_{0.002}O_{4-y}$ were fabricated for Ce concentration range of $0.09 \leq x \leq 0.14$. Superconducting critical temperature, T_c decreases continuously as Ce concentration decreases and the superconductor-insulator transition is found below Ce concentration of 0.11, which is lower than in bulk material. This fact suggests the presence of underdoped region in NCCO thin films.

Key words: NCCO; S-I transition; thin films

In the electron-hole doped symmetry picture of cuprate-oxide superconductors [1], the electron-doped system should have similar phase diagram as found in the hole-doped system. However, in the electron-doped system of $Nd_{2-x}Ce_xCuO_{4-y}$ (NCCO), superconductivity is found in doping concentration of $0.14 \leq x \leq 0.18$ [2], where the superconducting-insulator transition is close to the optimum doped concentration of x = 0.15. This raises a question that the underdoped region might be absent in the electron-doped system, which contradicts with the electron-hole doped symmetry picture.

The occurrence of superconductivity in the electron-doped system is extremely sensitive to the oxygen stoichiometry and oxygen reduction is a necessary process after sample preparation. The diffusion coefficient of oxygen in Nd_2CuO_4 [3] is low and it is difficult to remove oxygen in bulk NCCO crystals. Therefore, thin film samples, which have large surface to volume ratio, is suitable to study some of the properties of electron-doped system.

In this study, we have fabricated thin film samples of NCCO with Ce concentration of $0.09 \leq x \leq 0.14$ and measured resistivity and superconducting critical temperature. The superconducting-insulator (S-I) transition point for thin films sample is determined. In the two-dimensional system, the onset of superconductivity is correlated to the two-dimensional universal critical residual sheet resistance of $h/4e^2$ [4]. Therefore, defects and impurities, which govern the residual resistivity, should affect the S-I transition point assuming that they do not change the dimensionality of the system. Along this purpose, we study the effect of the defects and the impurities using two types of substitution. First, Gd atoms were substituted for Nd atoms in the composition of $Nd_{1.8-x}Gd_{0.2}Ce_xCuO_{4-y}$ (NGCCO) and second, Ni atoms were substituted for the electronically active site of CuO_2 layer, $Nd_{2-x}Ce_xCu_{0.998}Ni_{0.002}O_{4-y}$ (NCCNO).

We prepared stoichiometric ceramic targets of NCCO, NGCCO and NCCNO with Ce concentration of $0.09 \leq x \leq 0.14$ by standard solid-state reaction method. Targets were annealed at 1050^{o}C for about 36 hours with several intermediate grindings. The c-axis oriented thin films were fabricated by pulsed laser deposition technique on $SrTiO_3$ (100) substrates that were kept at temperature of 820^{o}C. The detail of the fabrication process is given elsewhere [5]. After deposition, thin films samples with thickness of 800 Åwere subsequently annealed at 750^{o}C in vacuum ($\sim 10^{-5}$

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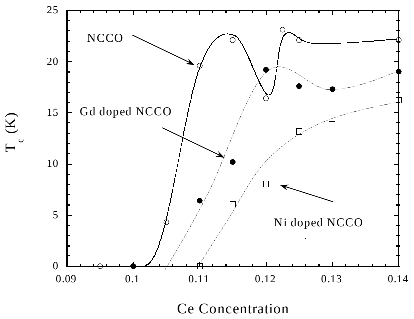

Fig. 1. Superconducting critical temperature, T_c vs Ce concentration for NCCO, NGCCO and NCCNO thin films. The lines are the guide for the eyes only.

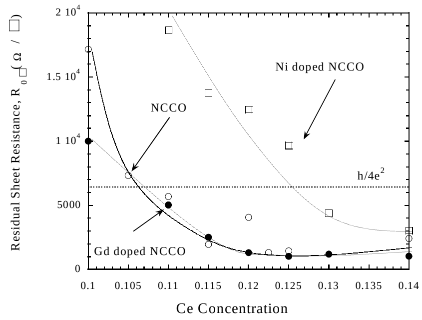

Fig. 2. The normal state residual sheet resistance vs Ce concentration for NCCO, NGCCO and NCCNO thin films. The lines are the guide for the eyes only.

Torr) for 30 minutes. The samples were characterized by XRD to determine the c-axis lattice parameter and atomic force microscopy (AFM). Standard four-probe resistivity measurement were performed in the temperature range of 2-300 K to measured the normal-state resistivity and superconducting critical temperature of the samples.

In figure 1, T_c data of NCCO, NGCCO and NCCNO thin films are plotted against Ce concentration. For all compounds, T_c decreases as Ce concentration decreases. In general, NGCCO and NCCNO have lower T_c than NCCO if the Ce concentration is the same. We found that the S-I transition points in NCCO, NGCCO and NCCNO were below Ce concentration of $x = 0.11$, which is far below the reported value of bulk NCCO [2]. This fact suggests the presence of underdoped region in the electron-doped system of NCCO thin films. The substitution of 0.2% Ni on CuO_2 layer and substitution of 20% Gd at Nd site lower T_c and shift the S-I transition point. This effect is larger in the NCCNO sample, since the Ni impurities reside in the electronically active site. Moreover, we observed a dip in the T_c data of NCCO thin films. However, a similar effect did not appear in the NGCCO and NCCNO data and we could not confirm the presence of 1/8 anomaly in NCCO system in the substitution experiment.

To obtain further information, we calculate the residual sheet resistance from resistivity data with the assumption that the normal-state resistivities of NCCO, NGCCO and NCCNO thin films follow the relation of $\rho_{\mathrm{ab}}(\mathrm{T}) = \rho_{\mathrm{ab},0} + \mathrm{AT}^{\mathrm{n}}$, where $\mathrm{n} = 2$ and A is a constant. The sheet resistance is calculated with the relation of $\mathrm{R}_{\mathrm{s}0} = \rho_{\mathrm{ab},0}/\mathrm{d}$, where d is the distance between CuO_2 layers taken from the XRD data. Figure 2 shows the residual sheet resistance data plotted against Ce concentration. For NCCO and NGCCO, the data coincide with each other especially in the superconducting region. In these samples, the substitution of Gd in the Nd site do not significantly change the residual resistivity although T_c values in NGCCO are lower than those in NCCO. The S-I transition in both compounds occurs near the Ce concentration of 0.105, at which the residual sheet resistance reaches the universal value of $\mathrm{h}/4\mathrm{e}^2 = 6.45\mathrm{k}\Omega$. Meanwhile, for the NCCNO thin films, the residual sheet resistance rapidly increases as Ce concentration decreases. The R_{s0} value where the S-I transition occurs is found to be 3 times larger than the universal value. This inconsistency may be caused by the morphology and bad contacts between grains, since the AFM topography reveals the grain size of the NCCNO much smaller than that in NCCO or NGCCO.

In summary, we have prepared the NCCO, NGCCO and NCCNO thin films with Ce concentration $0.09 \leq x \leq 0.14$ and measured T_c and residual sheet resistance. The T_c data suggest the presence of the underdoped region in the NCCO thin films. The onset of S-I transition point for NCCO and NGCCO coincides with the universal critical value of two dimensional system.

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