論文内容の要旨

論文題目　Photoemission Study of Single-Layer Cuprate High-Temperature Superconductors

（1 層型銅酸化物高温超伝導体の光電子分光による研究）

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Understanding the nature of the correlated electron systems has been the most challenging issue in condensed matter physics due to the difficulties inherent in the many-body character of electron correlations. Unconventional behaviors of highly correlated electron system, in particular transition-metal oxides, have been extensively investigated in recent years [1]. The cuprate systems show not only high-T_c superconductivity but also show various unusual behaviors in the vicinity of the filling-control Mott metal-insulator transition, and drastically change their behaviors depending on the electron density in the two-dimensional CuO_2 planes, which is the stage of the high-T_c superconductivity. Therefore, since the discovery of the high-T_c superconductors, enormous number of studies has been performed to understand the mechanism of high-T_c superconductivity beyond the conventional BCS theory.

Angle-resolved photoemission spectroscopy (ARPES) is a powerful tool to probe the electronic structure through the measurements of band dispersions directly. Recent development of the ARPES method has enabled us to observe fine structures near the chemical potential (μ). Indeed, ARPES studies on the cuprate superconductors have been performed extensively [2]. Particularly, those ARPES work for high-T_c cuprates have clarified significant characteristic feature such as the observation of d-wave superconducting gap anisotropy and the pseudogap above T_c.

The relationship between the pseudogap and the superconductivity has been extensively studied to clarify whether the pseudogap is a precursor for the superconductivity or is not directly related to the superconductivity. The evolution of the electronic structure with hole doping, from the Mott insulator to the superconductor and how $T_{c,max}$ is determined have been long-standing issues. Recently the importance of out-of-CuO_2 plane disorder effects has been pointed out. In order to study above critical issues on the high-T_c superconductivity, we have investigated the electronic structure of the single-layer cuprates $La_{2-x}Sr_xCuO_4$ (LSCO) and $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (Bi2201) systems using photoemission spectroscopy.

The single-layer cuprates such as LSCO and Bi2201 have single CuO_2 planes, and therefore no multilayer splitting, and the sample synthesis is possible in a wide doping range (LSCO: $0 < p < 0.30$, Bi2201: $0.05 < p < 0.18$), while the $T_{c,max}$ is relatively low. Furthermore, in single-layer cuprates, $T_{c,max}$ can be controlled widely by systematically introducing disorder, such as *Ln*-Bi2201 where La is substituted by other lanthanoids (*Ln* = La, Nd, Eu, Gd) and Zn or Ni-LSCO where Cu is substituted by Zn or Ni. In this thesis, we present detailed electronic structure of Bi2201 and LSCO from lightly-doped to optimally-doped region and disorder controlled Bi2201 by photoemission spectroscopy.

Angle-integrated photoemission study of LSCO

We have performed an angle-integrated photoemission study of LSCO covering from lightly-doped to heavily-overdoped regions. The superconducting gap energy Δ_{sc} was found to remain small for decreasing hole concentration while the pseudogap energy Δ^* and the pseudogap temperature T^* increase as shown in Fig 1. The different behaviors of the superconducting gap and the pseudogap can be explained if the superconducting gap opens only on the Fermi arc around the nodal (0,0)-(π π) direction while the pseudogap opens around (π,0). The results suggest that the pseudogap and the superconducting gap have different microscopic origins. We have also deduced the doping dependence of the coherence temperature T_{coh} below which the Fermi-Dirac statistics of electron/holes is manifest in the spectra. The T_{coh} rapidly increased with doping. This indicates that the superconducting dome appears below both T_{coh} and T^*, suggesting that the superconductivity emerges out of the Fermi liquid (on the Fermi arc) in hole-doped La_2CuO_4.

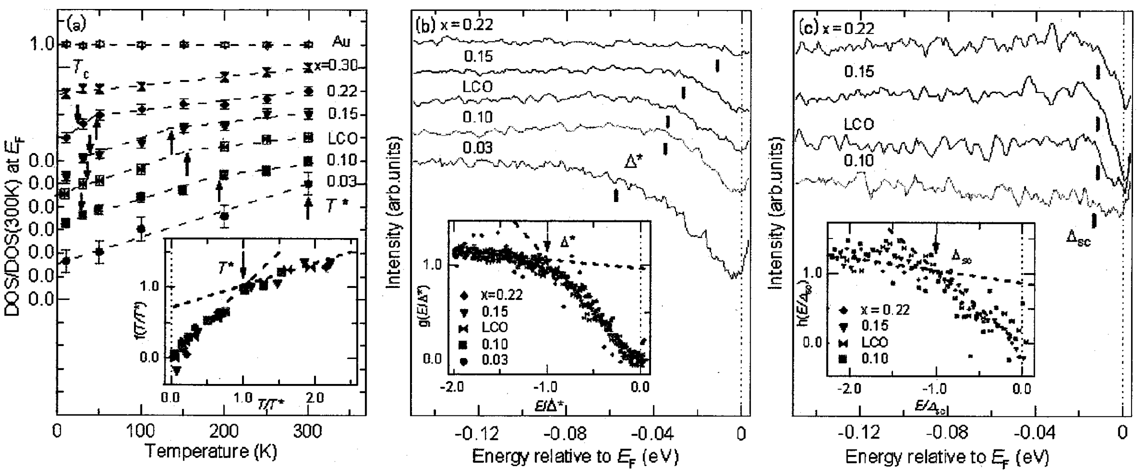

Fig. 1: Temperature and doping dependences of the pseudogap and the superconducting gap in LSCO. (a) Normalized density of states (DOS) at Fermi energy (E_F) as a function of temperature. Inset shows a scaling plot. (b) Difference normalized DOS between $T > T^*$ and $T^* > T > T_c$. Inset shows a scaling plot. (c) Difference normalized DOS between $T^* > T > T_c$ and $T < T_c$. Inset shows a scaling plot.

Temperature-dependent ARPES study of LSCO

We have measured the temperature and momentum dependences of the ARPES spectra from the lightly-doped to optimally-doped LSCO. We have observed a different temperature dependence of the momentum distribution curve (MDC) width in the nodal region ~(π/2,π/2) from that in the antinodal region ~(π,0). The MDC width is strongly affected by the pseudogap opening in the antinodal region, and the in-plane resistivity is reproduced better by taking into account the temperature dependence of the Fermi arc length. We have also observed the anisotropic temperature dependence of the inelastic scattering rate above the pseudogap temperature ~150 K. For the lightly-doped LSCO (x=0.03) we have observed little temperature dependence in the width of the momentum distribution curves and dispersions. However, with decreasing temperature, the spectra show a gap opening, corresponding to the localization behavior observed in the transport properties. The observed gap may be due to a Coulomb gap in the Anderson localization or the polaronic behavior of doped holes with strong electron-lattice coupling.

Doping dependence of the electronic structure in Bi2201

We have performed ARPES and core-level x-ray photoemission studies of the single-layer cuprate Bi2201 and revealed the doping evolution of the electronic structure from the lightly-doped to optimally-doped regions. We have observed the formation of the dispersive quasi-particle band, evolution of the Fermi "arc" into the

Fermi surface (as shown in Fig. 2) and the shift of the chemical potential with hole doping as in other cuprates. The doping evolution in Bi2201 is similar to that in $Ca_{2-x}Na_xCuO_2Cl_2$ (Na-CCOC), where a rapid chemical potential shift toward the lower Hubbard band of the parent insulator has been observed, but is quite different from that in LSCO, where the chemical potential does not shift, yet the dispersive band and the Fermi arc/surface are formed around the Fermi level already in the lightly-doped region. The (underlying) Fermi surface shape and band dispersions are quantitatively analyzed using tight-binding fit, and the deduced next-nearest-neighbor hopping integral t' also confirm the similarity to Na-CCOC and the difference from LSCO.

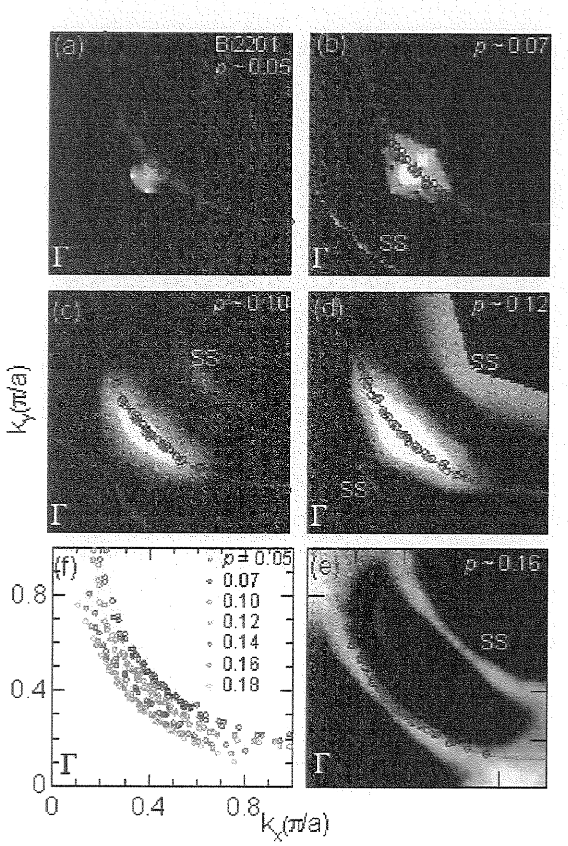

Fig. 2: Doping dependence of the Fermi surface and "underlying" Fermi surface in Bi2201. (a)-(e) *k*-space mapping of spectral weight at E_F. (f) Doping dependence of the (underlying) Fermi surface.

<u>Effects of the out-of-plane disorder on the nodal quasiparticle and superconductivity</u>

How the out-of-plane disorder affects the electronic structure has been investigated for Ln-Bi2201 (Ln = La, Nd, Eu, Gd) by ARPES. We have observed that, with increasing disorder, 1) the quasi-particle mean-free path decreases, 2) the pseudogap is enhanced, and 3) the superconducting gap is depressed, while the Fermi surface shape as well as the band dispersions are not changed. The results indicate that out-of-plane disorder acts as a weak scatterer and it depresses remarkably the superconductivity realized on the Fermi arc.

[1] M. Imada, A. Fujimori and Y. Tokura, Rev. Mod. Phys. **70**, 1039 (1998).

[2] A. Damascelli, Z. Hussain and Z.-X. Shen, Rev. Mod. Phys. **75**, 473 (2003).