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Low-Dimensional Electronic Properties of Oxide Heterostructures

Department of Advanced Materials Science, 86017, Minu Kim
Supervisor: Professor Harold Y. Hwang

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INTRODUCTION

The low-dimensional electronic properties of oxide heterostructures are one of the central interests of emerging research in materials for post-silicon science and technology. Oxides have *versatile* physical properties, such as Mott insulators, colossal magnetoresistance, and high-T_c superconductors, which do not exist in semiconductors. The representative oxide material, $SrTiO_3$, becoming metallic by chemical doping of Nb atoms, is one of the target materials of this study because of its low carrier density and the high electron mobility in bulk. However, it has been difficult to control the structural and physical properties of oxide thin films due to their low crystallinity. Here, we investigate the low-dimensional electronic states in oxide heterostructures studied by precise interface-termination control and delta doping technique. We examine the exotic electronic states in low-dimensional systems with various physical phenomena: photoconductivity, superconductivity, and normal-state transport.

EXPERIMENTAL

The $LaAlO_3/SrTiO_3$ (LAO/STO) interfaces and the $SrTiO_3$/1% at. Nb:$SrTiO_3/SrTiO_3$ (STO/Nb:STO/STO) heterostructures were fabricated by pulsed laser deposition, where the film thickness was calibrated by reflection high-energy electron diffraction and a stylus profilometer. The photoconductivity measurement was carried out in a Physical Properties Measurement System (PPMS) with Halogen and Xenon lamps. The intensity of the incident light was from 1-10 μW. The low-temperature transport measurements were made with a 16-Hz a.c. resistance bridge in a dilution refrigerator and ^{3}He option of the PPMS.

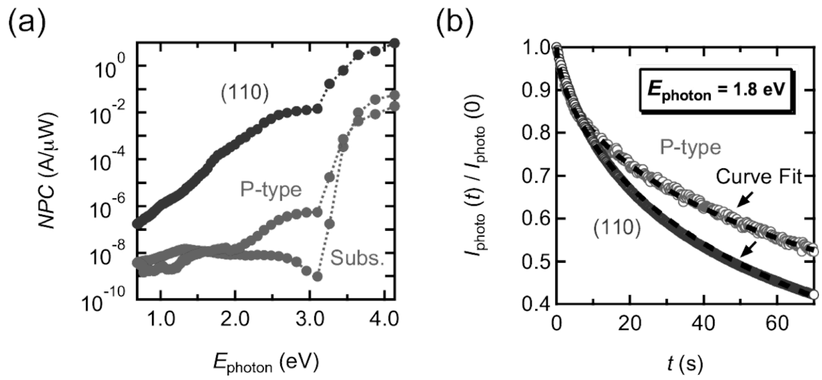

Fig. 1 The Photoconductivity effect at the LAO/STO interface. (a) Normalized photocurrent (NPC) for the P-type and (110) interfaces, and an annealed (100) STO substrate. (c) Non-exponential decay of photo-carriers at the two interfaces under the illumination of 1.8 eV photons.

RESULTS AND DISCUSSIONS

Photoconductivity effect on various LAO/STO Interfaces

Interfacial engineering, an essential topic for device applications, is based on studies of the electronic states at the interface. The LAO/STO interface has three kinds of interfaces, N-type, P-type, and (110) interface, depending on the crystal orientation and the interface termination layer [1]. In this study, the physical properties of two insulating P-type and (110) LAO/STO interfaces were investigated using the photoconductivity effect (Figure 1). Photocurrent spectroscopy revealed the existence of interface states with broadened energy levels positioned around ~2.3 eV from the top of the conduction band of STO. The long lifetime and non-exponential relaxation of the photo-induced carriers were observed at the two interfaces, in contrast to the fast decay in annealed (100) STO substrate.

Superconducting properties of STO/Nb:STO/STO heterostructures

Electron-doped STO has invoked many attractions due to its low carrier density among superconductors [2]. While the research of nano-scale $SrTiO_3$ superconducting film has been rather limited, we investigated the superconducting properties of the STO/Nb:STO/STO heterostructures with various doped-layer thicknesses (Figure 2) down to a few nm. As the theory of two-dimensional (2D) superconductivity [3] predicts, the 3D to 2D superconductivity crossover was observed as the doped layer becomes thinner than the superconducting coherence length ~ 100 nm. The 2D superconductors with a few nm of thicknesses showed the novel superconducting properties such as an increase of the transition temperature and the mean-free path, and violation of the Pauli paramagnetic limit.

Quantum oscillations of the delta-doped STO heterostructure

When the Nb:STO layer in the STO/Nb:STO/STO heterostructures is reduced to a few atomic planes, it can be treated as the delta-doped structure where the enhancement of mobility can be connected to quantum transport phenomena. While the sample with 5.5 nm of doped layer showed 2D characteristics in the superconducting state, Shubnikov-de Haas (SdH) oscillations that scaled with the perpendicular magnetic field (Figure 3) appeared in the normal state. This is the first manifestation of 2D electronic states in a 2D superconductor.

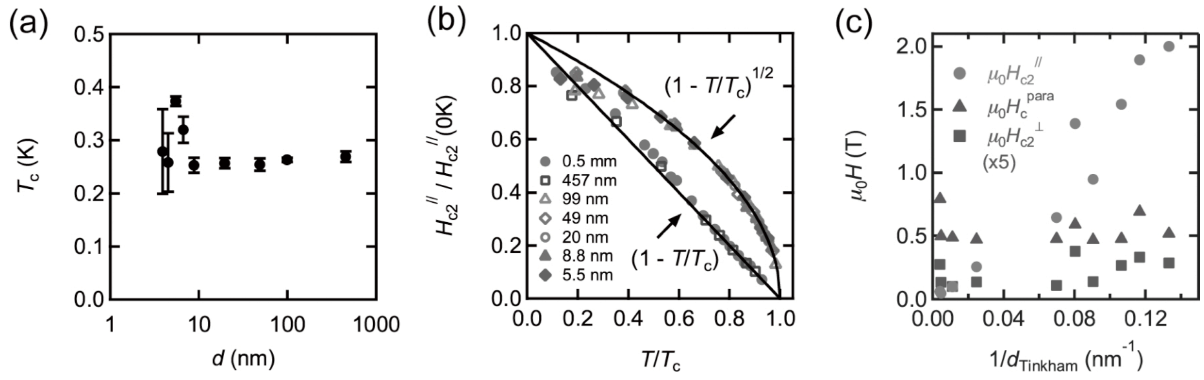

Fig. 2 Superconducting properties of the STO/Nb:STO/STO heterostructures. (a) Transition temperature with 10-90 % width. (b) Temperature dependence of the parallel upper critical field. (c) Upper critical fields in perpendicular and parallel field geometry and Pauli paramagnetic limiting field as a function of inverse superconducting thickness.

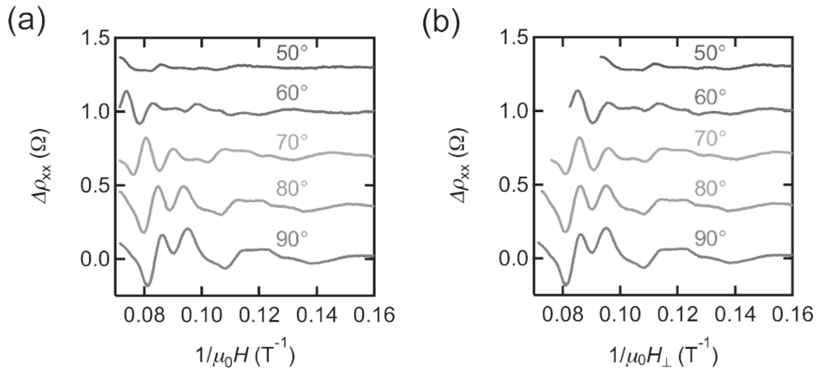

Fig. 3 The SdH oscillations in the delta-doped STO heterostructure. The sheet resistance of the oscillating component in various angles plotted against (b) the total magnetic field and (c) the perpendicular magnetic field.

We also compared a theoretical subband calculation and the experimental data.

CONCLUSIONS AND PERSPECTIVES

In this study, we explored the low-dimensional electronic properties of oxide heterostructures via various physical phenomena. At the LAO/STO interfaces, the presence of the interface states and their effects on photo-carriers was revealed, which will be a basis for the interface engineering in oxides. The novel superconducting properties and normal-state 2D SdH oscillations were found in the STO/Nb:STO/STO heterostructure, showing the successful application of delta-doping growth techniques in oxides. This makes possible the design of further complex oxide heterostructures, such as the superconductor superlattice with analogy to the layered superconducting cuprates. Further reducing defects and enhancing electron mobility may give rise to the emergence of the quantum Hall effect, and even a possibility to study the interplay of superconductivity and quantum oscillations [4]. These results elucidate the versatile physical properties of oxide heterostructures, which can be connected to potential oxide devices operated based on conceptually new mechanisms.

REFRENCES

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PRESENTATIONS

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