論文の内容の要旨

論文題目　Emergent Low-Dimensional Quantum Phenomena in $SrTiO_3$

（$SrTiO_3$における低次元量子現象）

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Introduction

Historically low-dimensional superconductors and semiconductors have been separated into two distinctive regimes: ultra-thin superconductors have been limited by strong disorder, while low-dimensional semiconductors can be in the clean limit but not superconducting. While many experimental attempts have been performed to search for bulk superconductivity in well-known semiconductors, disorder at high density is problematic [1]. In this context, $SrTiO_3$ (STO) is a promising candidate, displaying versatile phenomena, in particular such as high electron mobility, and low-density superconductivity. Motivated by these properties, a variety of heterostructure implementations have been intensively studied out to explore novel two-dimensional (2D) electron physics in STO [2]. This poses several challenges: 1) structural control and cleanliness of electron layers are often restricted; 2) The lack of detailed information on the normal and superconducting properties, respectively, in both the three-dimensional (3D) and 2D limits. In order to address these questions, light is shed on the electronic structure, and superconductivity of STO in this Thesis, through control of the sample fabrication and low-temperature transport measurements. By *systematic* variation of the sample thickness and dopant density, we reveal 3D-2D dimensional crossovers in both the superconducting and normal states. Approaching the 2D limit, novel physics such as a change of the electron-phonon coupling and intrinsic spin-orbit interactions are unraveled, opening up new possibility of novel ground states in low dimensions.

Fabrication of high-quality δ-doped $SrTiO_3$ heterostructures

The first step necessary for investigating the transport properties is to fabricate a high-quality conducting sample. We realized atomic-scale-controlled *n*-type STO heterostructures by applying a δ-doping technique, where a

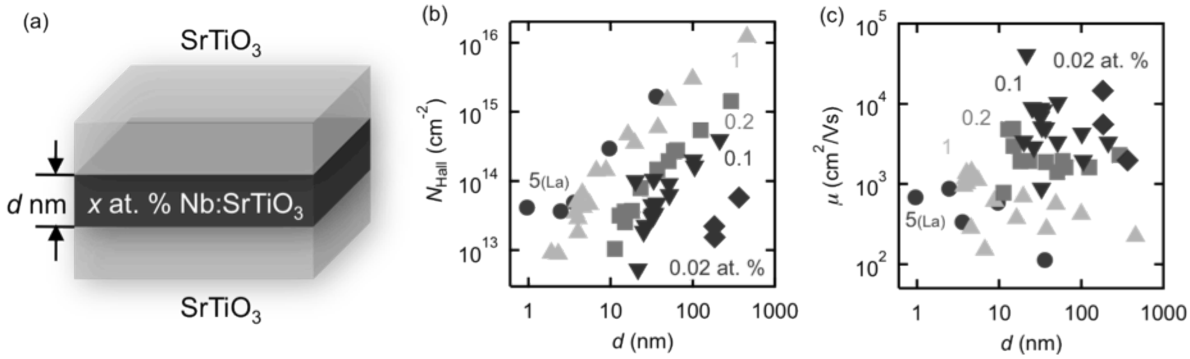

Fig. 1 (a) A schematic diagram of Nb δ-doped $SrTiO_3$ heterostructures. (b) Sheet carrier density N_{Hall}, and (c) Hall mobility μ estimated by the Hall measurement at temperature T = 2 K.

thin layer of Nb doped STO is sandwiched between 100 nm-thick undoped STO buffer and capping layers on a STO (001) substrate [Fig. 1 (a)]. The doped layer thickness d varied from a few to several hundred nanometers. The sheet carrier density N_{Hall} and Hall mobility μ could be varied over a range of three orders of magnitude [Fig. 1 (b,c)]. The advantage of this δ-doping structure is that we can investigate the intrinsic properties of STO in a symmetrically confined potential structure, in the absence of extrinsic effects such as interface or surface scattering, lattice mismatch, and broken inversion symmetry.

Electronic structure of $SrTiO_3$

Taking advantage of the high-mobility electrons, we determined the dimensionality of the Fermi surface of Nb doped STO heterostructures unambiguously, and discovered a 3D to 2D crossover in the normal state from Shubnikov-de Haas (SdH) oscillations at low temperatures. As the doped layer becomes thinner, a beating pattern of the quantum oscillations appeared due to the 2D confinement [Fig. 2 (a)]. From the fact that the multi-frequency components of thin samples [Fig. 2 (b)] could be scaled only with the perpendicular magnetic field, and have similar effective mass, it can be concluded that the observed electrons are the light electrons in the conduction band of STO, split by 2D subband quantization. Interestingly, the carrier density estimated from SdH oscillations is less than 20 % of N_{Hall}, indicating the existence of the heavy electrons that are not observed in the SdH oscillations [Fig. 2 (c,d)].

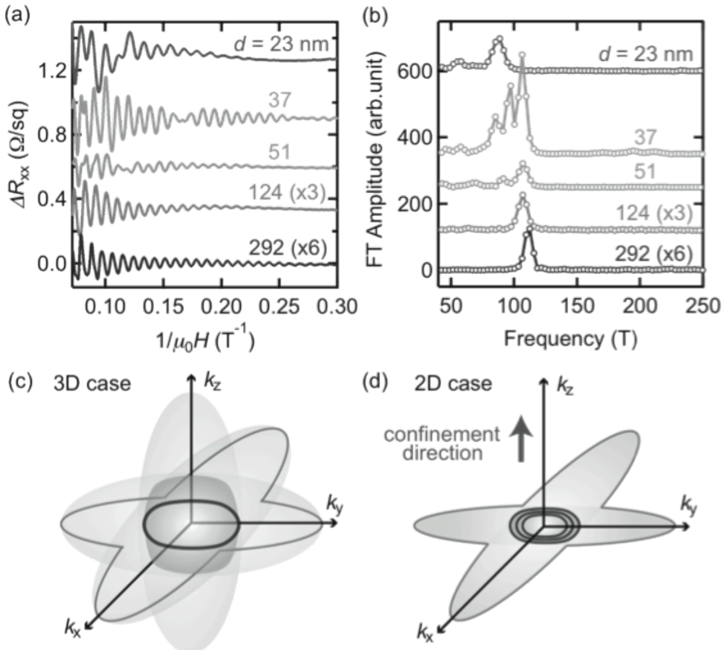

Fig. 2 (a) SdH oscillations measured at T = 100 mK in 0.2 at. % doped samples with various thickness d. (b) Fourier transformation (FT) spectra. (c,d) Schematic diagrams of the 3D and 2D Fermi surfaces based on the results.

Superconductivity of $SrTiO_3$

How does superconductivity change as d decreases? Firstly, superconducting transition was measured in a series of 1 at. % δ-doped STO samples, where an upturn in the transition temperature T_c was found in the thin limit, indicating possible change of the electron-phonon coupling [Fig. 3 (a,b)]. Secondly, the magnetic response of the samples gave vital information of dimensionality of a superconductor: We observed 1) anisotropy of the upper critical field, H_{c2}, developing as d becomes smaller

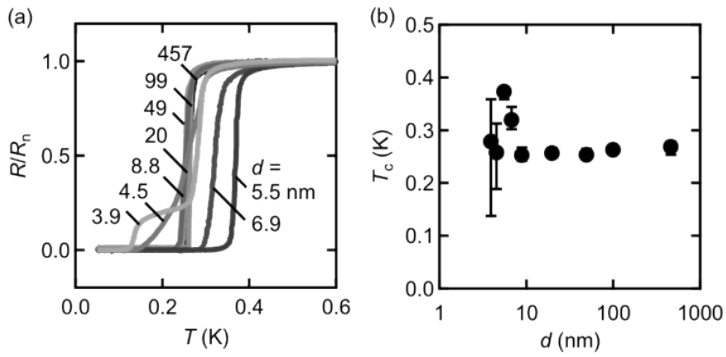

Fig. 3 (a) Normalized resistance plotted with temperature for 1 at. % doped samples with various thicknesses. (b) Superconducting transition temperature as a function of d. The error bar of data denotes the 10-90% width of the superconducting transition in (a).

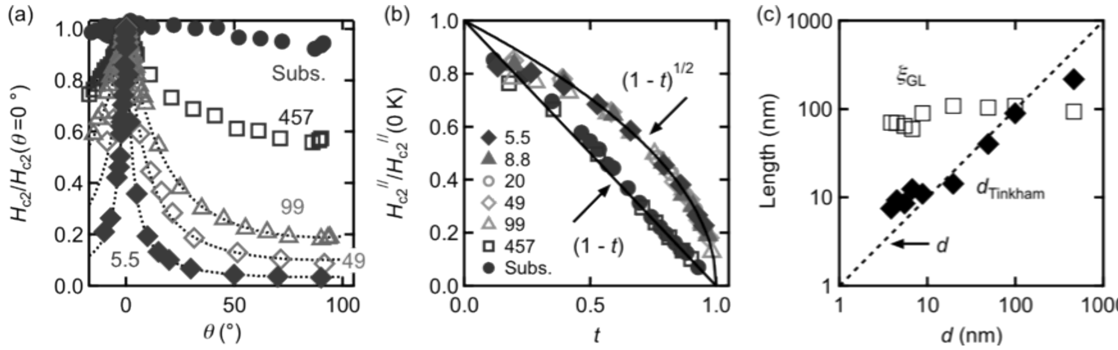

Fig. 4 (a) Normalized upper critical field H_{c2} vs angle θ of the 1% samples with various thickness. Dotted lines are the fits using 2D superconductivity theory [3]. (b) Normalized parallel upper critical field $H_{c2}^{//}$ vs the reduced temperature $t = T/T_c$. Solid lines are the theory curves. (c) Ginzburg-Landau coherence length ξ_{GL}, and the thickness of superconducting layer $d_{Tinkham}$ plotted with d.

[Fig. 4 (a)], 2) the T dependence of the parallel upper critical field, $H_c^{//}$, changed from linear to square root below d = 99 nm [Fig. 4 (b)]. These findings are consistent with linearized Ginzburg-Landau (GL) theory for 2D superconductors where the GL coherence length ξ_{GL} is smaller than the thickness of superconducting layer $d_{Tinkham}$ [3]. In our experiments, ξ_{GL} ~ 100 nm, whereas $d_{Tinkham}$ monotonically decreases with d, indicating that 3D-2D superconducting crossover occurs at d ~100 nm [Fig. 4 (c)].

An important point for these δ-doped samples is that $H_c^{//}$ exceeds the Pauli paramagnetic limit [Fig. 5 (a)], suggesting considerable SO scattering in the system. We performed a qualitative measure of SO scattering, using theoretical analysis [Fig. 5 (b,c)] of H_{c2} considering the effects of spin paramagnetism and SO scattering [4], and extracted the SO scattering times τ_{so} and the momentum scattering times τ_{tr} [Fig. 5 (d)]. Crucially, conventional SO scattering mechanisms cannot explain the scaling of the relationship between these two characteristic scattering times, indicating the novel role of intrinsic SO interactions. Notably, τ_{tr} estimated here was one order of magnitude smaller than the Drude scattering time τ_{drude}, indicating the different densities of superconducting and normal-state electrons, which is also suggested from the discrepancy between N_{Hall} and $N_{superfluid}$ estimated from scanning probe measurements [5].

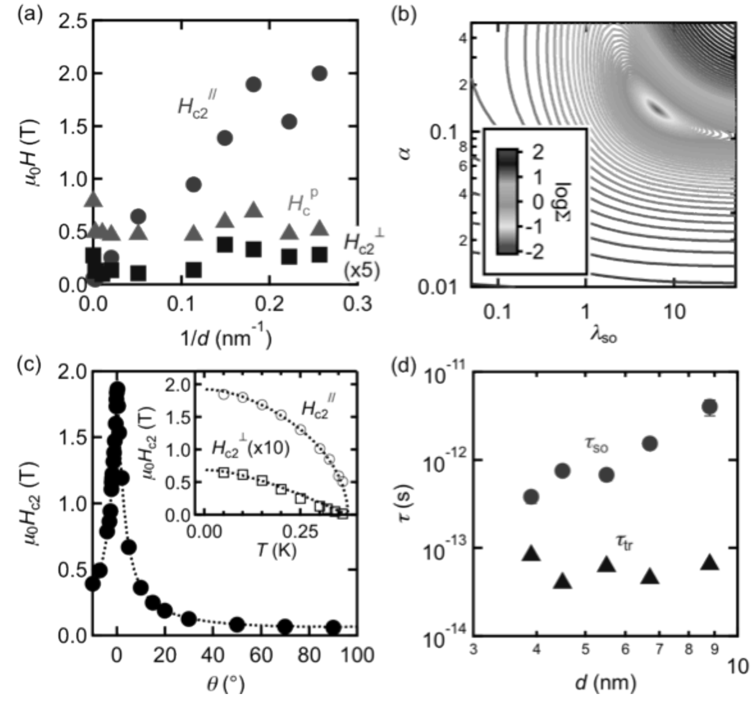

Fig. 5 (a) Upper critical field in the parallel geometry $H_{c2}^{//}$, in the perpendicular geometry $H_{c2}^{\perp}$, and the Pauli limiting field H_c^p, plotted against 1/d. (b) Simulation result using the WHH theory [4]. Σ is [(experimental data) - (theory)]^2, α is the orbital depairing parameter, and λ_{so} is the spin-orbit scattering rate. (c) Anisotropy and T dependence of H_{c2} of d = 5.5 nm sample. Dotted lines are the theory fit. (d) Spin-orbit scattering time τ_{so} and momentum scattering time τ_{tr} as a function of d.

Spin-orbit interaction of $SrTiO_3$

As a confirmation of the presence of SO scattering suggested from the superconducting data, the weak antilocalization (WAL) effect was also studied, exploiting the manifestation of SO coupling in the electron

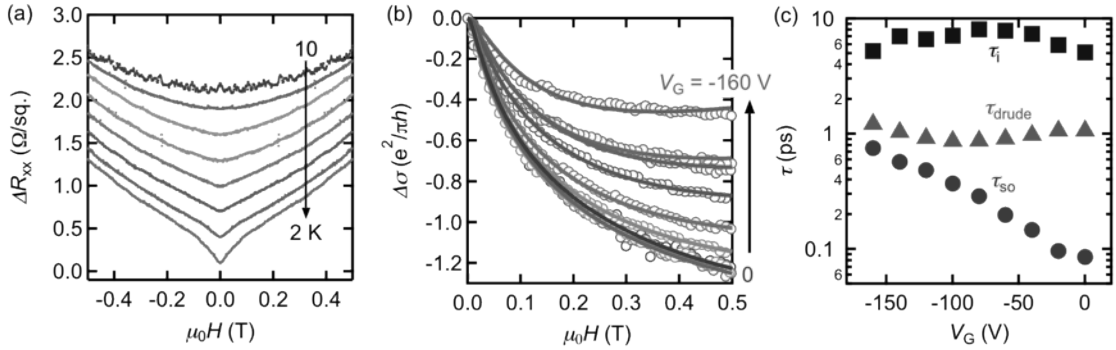

Fig. 6 (a) Magnetoresistance of a 1 at. % sample (*d* = 3.9 nm) at low temperatures. (b) Gate voltage (V_G) dependence of weak antilocalization correction to conductivity at *T* = 2 K. (c) Estimated inelastic scattering time τ_i, SO scattering times τ_{so} from the Hikami-Larkin-Nagaoka fits [6]. The Drude scattering times τ_{drude} are estimated from Hall measurements.

dephasing process in the normal state. As *T* decreases, we found a dip structure in the magnetoresistance near zero field caused by WAL [Fig. 6 (a)]. Fitting the result with Hikami-Larkin-Nagaoka theory [6], the inelastic scattering time τ_i and SO scattering times τ_{so} were successfully extracted. From the *T* dependence of τ_i, we revealed that the dephasing mechanism by inelastic scattering changes as the samples becomes thinner, suggesting that the electron-phonon coupling has been altered in thin samples. We also demonstrated that SO scattering times could be controlled by back gating [Fig. 6 (b,c)], indicating SO interaction changes as the confining potential structure is tuned from symmetric to asymmetric.

Conclusion & Outlooks

We investigated the physical properties of Nb doped STO heterostructures, by fabricating high-quality STO samples with wide controllability of the structure and cleanliness by the δ-doping technique. We could reveal 1) the precise information on the electronic structure and superconducting properties in 3D and 2D, and the dimensional crossover between them; 2) Novel 2D physics of STO unraveled from both the normal and superconducting states such as the change of electron-phonon coupling, and intrinsic SO interaction which can be controlled by back gating. Furthermore, these results suggest several key future steps toward searching for novel electronic phases in low dimensions: the sample cleanliness achieved in this study suggests the demonstration of the quantum Hall effect in the presence of *d*-electron correlation effects in the low-density limit, which has been only observed in *s*-*p* hybridized systems until now. Another novel possibility is the realization of unconventional superconductivity such as multi-gap superconductivity expected from the presence of the heavy and light electrons that are sub-band split in the 2D limit. Novel pairing state can also be expected where the distinction between spin-triplet and spin-singlet Cooper pairs is removed due to the strong SO interaction.

References

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