審査の結果の要旨

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The Doctoral thesis defense for Jiyeon Lee took place on July 14, 2020 at 10 a.m. in Kashiwa. The defense committee members, professors T. Okamoto, T. Kimura, K. Okazaki, S. Shin, and M. Lippmaa joined the defense hearing in a video conference.

In the introductory Chapter 1, oxide heterostructures are introduced that exhibit carrier accumulation in an interfacial quantum well. The motivation for the work is linked to well-known layered phases such as the high-temperature superconductors that can be viewed as natural superlattices in which separate perovskite-like blocks appear to take on specific functions, such as sustaining superconductivity, controlling the carrier density, enhancing the two-dimensional characteristics or adjusting the lattice parameter. In complex lattices with large unit cells, it can be difficult to separate these functional characteristics within a unit cell, but the functions can be studied in isolation in artificial interfaces. One such isolated system that has been studied in detail in recent years is the accumulation layer formed in $SrTiO_3$-based heterostructures. In particular, the nominally wide-gap insulating titanate can support metallic, superconducting, charge-ordered, and magnetically ordered states that either do not appear in bulk $SrTiO_3$ or are distinct from the bulk counterparts. In particular, a potential spintronic device structure is considered, where a titanate heterostructure may offer an intriguing possibility of utilizing gate-tunable spin-orbit coupling strength.

Chapter 2 of the thesis reviews possible strategies for creating confined carrier systems in $SrTiO_3$. A delta doped $SrTiO_3/LaTiO_3/SrTiO_3$ heterostructure was selected as the target for study in this thesis.

Chapter 3 of the thesis is devoted to the description of the experimental techniques. The heterostructures were grown by pulsed laser deposition. This relatively high-energy deposition technique offers two important advantages, namely the ability to grow epitaxial layers at very low temperatures and to control the point defect density and hence the dielectric permittivity of the film. These advantages were put to good use in the fabrication of the delta-doped heterostructures.

Chapter 4 presents the main results on the carrier density control in the heterostructures. Metallic heterostructures were obtained for sheet doping densities of 0.5 La atoms or more per titanate unit cell. The doping effect saturated for $LaTiO_3$ layer thicknesses of 5 unit cells. Most of the experiments were thus done with 2-unit-cell-thick delta-doping layers, corresponding to a maximum sheet charge transfer of one electron per titanate unit cell. Since the two-dimensional carriers accumulate in the surface layer of a $SrTiO_3$ single-crystal substrate, the preparation procedure of the substrate can have a large effect on carrier localization. High-temperature processing at >900 °C for more than a few minutes was found to lead to an order of magnitude change in the sheet resistance. Real-time reflection high-energy electron diffraction pattern monitoring was thus used to ensure that all substrate surfaces were structurally equivalent.

The carrier density analysis is described in Chapter 5, focusing on a two-carrier fitting model of Hall data to determine the number and mobility of itinerant carriers and to infer the depth distribution of carriers. It was found that carrier mobility in the interfacial quantum well part of the heterostructure was limited to about 500 cm^2/Vs due to structural disorder at the $SrTiO_3$ crystal surface but a second population of carriers, spread over a much larger depth, reached mobilities of over 10,000 cm^2/Vs. It was shown that the sheet carrier density and the depth distribution could be controlled by two structural parameters—the La doping layer thickness, and the thickness of the $SrTiO_3$ capping layer, which controls partial depletion of carriers from the interface. These results were published in Applied Physics Letters.

Several types of magnetotransport measurements were performed to probe the carrier behavior. In-plane magnetoresistance measurements with the magnetic field perpendicular to the current flow showed that for the heaviest doping levels, the depth distribution of the metallic layer can reach 100 nm, which corresponds to the high-mobility carrier population seen in the Hall analysis. Out-of-plane magnetoresistance measurements showed a linear field dependence that was inconsistent with the simple two-layer transport model used for Hall analysis. This discrepancy was explained by the presence of spatial inhomogeneity in the conducting layers, which may be related to the large fraction of localized carriers. Magnetoresistance measurements done with the magnetic field parallel to the current flow were used to probe the strength of the interfacial spin-orbit coupling. The spin-orbit coupling strength can be influenced by the asymmetry of the quantum well and the crossing of a Lifshitz point when the Fermi level height is changed. Measurements appeared to indicate a monotonic change of the spin-orbit coupling strength, which suggests that the carrier density of the heterostructures was still too high, even for a delta-doping layer consisting of just a single La oxide atomic layer.

Electrostatic gating experiments are described in Chapter 6, showing that fine-tuning the carrier density is possible. Reversible carrier depletion over a narrow range was achieved by applying a negative gate bias, modulating the sheet resistance by a factor of 10. Positive gate bias, which forces carriers deeper into the substrate, was found to exhibit a memory effect, related to carrier trapping in shallow trap states in the pristine $SrTiO_3$ substrate. Several possible trap mechanisms were considered and the trap depth was estimated from the temperature dependence and light illumination experiments. Significant detrapping appeared at around 100 K, suggesting that the trap state depth is <10 meV.

Chapter 7 of the thesis provides a summary and concludes that the delta-doped interfaces do offer sufficiently broad carrier density tuning by combining surface depletion and gating controls to explore novel types of spintronic devices.

Ms. Lee performed all the sample fabrication, device fabrication, and transport measurements. Prof. Osada provided access to a superconducting magnet for gating experiments. A part of the capping layer thickness data was obtained in collaboration with one of the co-authors of the Applied Physics Letter publication, Dr. Hou. Prof. Takahashi assisted with the electrode patterning.

By unanimous decision, the defense committee agreed that the candidate, Ms. Jiyeon Lee, should be awarded the degree of Doctor of Philosophy.

よって本論文は博士（科学）の学位請求論文として合格と認められる。

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