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# Summary

This thesis explores interfacial conductance and electric field-effects in $LaAlO_3/SrTiO_3$ heterostructures. High quality epitaxial $LaAlO_3$ films were grown on $SrTiO_3$ substrates by 90° off-axis sputter deposition. The conductance properties of the interfaces were modulated by applying external electric fields in different geometries, namely back-gating (applying an electric field to the back side of the substrate) and ionic liquid gating (which applies an electric field on the side of the $LaAlO_3$).

**Controlling the interfacial conductance in $LaAlO_3/SrTiO_3$ heterostructures**

In Chapter 3 we study the fabrication of conducting interfaces between $LaAlO_3$ and $SrTiO_3$ by 90° off-axis sputtering in an Ar atmosphere. At a growth pressure of 0.04 mbar the interface was metallic, with a carrier density of the order of $1 \times 10^{13}\,cm^{-2}$ at a temperature of 3 K. By increasing the growth pressure, we observed an increase of the out-of-plane lattice constants of the $LaAlO_3$ films while the in-plane lattice constants did not change. Also, the low-temperature sheet resistance increased with increasing growth pressure, leading to an insulating interface when the growth pressure reached 0.10 mbar. We attributed the structural variations to an increase of the La/Al ratio, which also explains the transition from metallic behavior to insulating behavior of the interfaces. Our research emphasizes the key role of the cation stoichiometry of $LaAlO_3$ in the formation of the conducting interface, and shows that the control which is furnished by the Ar pressure makes sputtering as versatile a process as pulsed laser deposition. Compared to the latter technique, the main disadvantage of the sputtering process is that it lacks *in situ* tools to precisely control the film thickness.

**Electron trapping mechanism in $LaAlO_3/SrTiO_3$ heterostructures**

In $LaAlO_3/SrTiO_3$ heterostructures, a commonly observed but poorly understood phenomenon is that of electron trapping in back-gating experiments. This basically means that not all charges induced by the gate are free to move and contribute to the conductance, but that some are trapped in, presumably, defects in the $SrTiO_3$. In Chapter 4, by combining magnetotransport measurements and self-consistent Schrödinger-Poisson (S-P) calculations, we obtained an empirical relation between the number of trapped electrons and the gate voltage. We found that the trapped electrons follow an exponentially decaying spatial distribution away from the interface. However, contrary to earlier observations, we found that the Fermi level of the conduction band in the quantum well

remains quite far below the top of the well. The enhanced trapping of electrons induced by the gate voltage can therefore not be explained by a thermal escape mechanism, in which conduction electrons further diffuse into the substrate and get trapped. Additional gate sweeping experiments strengthened our conclusion that the thermal escape mechanism is not valid. We therefore propose a new mechanism which involves the electromigration and clustering of oxygen vacancies in $SrTiO_3$. Our work indicates that such electron trapping is a universal phenomenon in $SrTiO_3$-based two-dimensional electron systems. In the S-P calculation, an important ingredient is the empirical formula for the permittivity of $SrTiO_3$, which depends on temperature and electric field. A thorough study of this question was performed nearly 50 years ago, but we could not obtain any reasonable description of our results using the proposed formula. Our recent study was only performed at room temperature and liquid He temperature. Therefore, it is necessary to revisit this question.

**Tuning Rashba spin-orbit coupling in $LaAlO_3/SrTiO_3$ heterostructures by band filling**
The electric-field tunable Rashba spin-orbit coupling at the conducting $LaAlO_3/SrTiO_3$ interface has potential applications in spintronic devices, in which the electrical functions (partly) depend on the spin of the electron. However, different gate-voltage dependence of the coupling strength has been reported in experiments. On the theoretical side, it has been predicted that the largest Rashba effect appears when the Fermi level lies around the crossing point of the $d_{xy}$ and $d_{xz,yz}$ orbitals or bands. In Chapter 5, we studied the tunability of the Rashba effect in $LaAlO_3/SrTiO_3$ by means of back-gating. By changing the back-gate voltage we can cross from a single band ($d_{xy}$ only) to a two-band situation, which is called a Lifshitz transition. We trigger the Lifshitz transition multiple times by tuning the gate voltage so that the Fermi energy is varied to go across the band crossing between the $d_{xy}$ and $d_{xz,yz}$ bands. By analyzing the observed weak antilocalization of the magnetoresistance, we are able to show that the maximum spin-orbit coupling effect occurs when the Fermi energy was near the Lifshitz point. Moreover, we found strong evidence for a single spin winding over the Fermi surface. Currently, the theoretical models for analyzing weak antilocalization are all based on single-band conduction. Therefore, it is very important that theorists develop new models which take multi-band conduction into account.

**Tunable magnetic interactions in $LaAlO_3/SrTiO_3$ heterostructures by ionic liquid gating**
An electric dipole layer effect using ionic liquids is able to achieve a charge transfer orders of magnitude larger than conventional field-effect transistors. However, the large ions at the liquid-solid interface inevitably cause Coulomb scattering, which limits the carrier mobility enhancement. In Chapter 6, we study the effect of $LaAlO_3$ thickness on

the electrical transport properties in $LaAlO_3/SrTiO_3$ heterostructures by ionic liquid gating. We find that, in our case of not too high mobilities, the interface conductance is dominated by the strong interfacial interactions rather than by the ions of the liquid. We observe a Kondo effect, which is enhanced while increasing the gate voltage. We also observe a gate-tunable and temperature-dependent anomalous Hall effect, which emerges near the Kondo temperature. Our experiments pave a way to manipulate the novel magnetic interactions in $LaAlO_3/SrTiO_3$ heterostructures.