Growth and Transport Properties of [Rare Earth]TiO3/SrTiO3 Interfaces

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Introduction

The advent of electronics has transformed our society significantly. The principle of electronics is based on the ability to actively control the flow of electrons, which carry charge. The field received a great boost in its development from the study of semiconductor materials, which led to the invention of the transistor, a crucial device for control of the charge flow. There are two main classes of transistors, the bipolar transistor and the field effect transistor. The first is a series of semiconductors with different amount of charge carriers, where the voltage applied to a middle section controls the current through the device. The last type utilizes a semiconducting channel through which the current flows, which can be controlled capacitively by applied a voltage underneath the channel, the so-called gate voltage. In this thesis on the transport properties of a conducting channel at the interface between two oxide insulators, gating will play a prime role.

In the ongoing trend of the further miniaturization of electronic components, one bottleneck has started to occur, which is the dissipation of heat in the device, caused by the current flow. At the same time, as fundamental understanding of magnetic materials had deepened, it has become clear that not only the charge, but also the spin and the angular moment of the electron can be used. By controlling the amount of spin flow, electronic-like devices can be created. This new field is named spintronics similarly to electronics. The easiest materials to use for spintronics are metals with different magnetic states, controlled by magnetic fields. However, spin effects can also be found in semiconductor materials with broken inversion symmetry, because of the presence of (noticeable) spin-orbit coupling. Using semiconductors to create a two-dimensional electron gas is promising for the creation of operational devices because an applied gate voltage can now be used to vary the spin-orbit coupling and thereby the spin and charge currents between two ferromagnetic electrodes. Such a device, first proposed by Datta and Das, is called a spin transistor [1]. A spin-polarized charge current would be injected into the channel through one of the contacts, and applying an electric field via the gate voltage would induce spin precession. The amount of precession over the length of the channel controls how effective the electron can exit through the magnetic drain contact, leading to a variation in resistance. A low (high) resistance can be considered as an on (off) state.

To actually fabricate such a device is a challenging task which, for best results, requires the combination of a two-dimensional electron gas (a 2DEG; needed for high on/off ratio's) with ferromagnetic electrodes. Here transition metal oxides come into play. In 2004, Ohtomo and Hwang [2] discovered that a 2DEG can form at the interface interface between two insulating transition oxides, in their case between $SrTiO_3$ and $LaAlO_3$. Subsequently, superconductivity [3, 4] tunable spin-orbit coupling [5], and signatures of magnetism and even coexistence of superconductivity and magnetism [6–8] were been reported. Since then, many more of the subtleties of the band structure of the 2DEG and the effects of gating fields have been unraveled. Still, in particular the occurrence of magnetism is not yet well controlled or even understood. Using combinations of oxide insulators as a platform to realize prototypes for spintronics devices still requires more research.

The aim of this thesis is to investigate the possibilities to induce spin-polarization into oxide 2DEGs and their control by electric fields. The original $LaAlO_3/SrTiO_3$ interface contains one atom which can carry magnetism, the Ti atom. In $SrTiO_3$ it occurs in the form of TiO_2 sheets, has a valency 4+ and does not carry a magnetic moment. When oxide vacancies are introduced it can become Ti^{3+} and carry a moment based on one d electron. It is generally assumed that oxide vacancies are at the basis of the magnetism which has been reported at $LaAlO_3$/ $SrTiO_3$ interfaces. There are no magnetic moments on the $LaAlO_3$ side of the interface, and the question which led this research is what the influence on the 2DEG would be when introducing magnetism through that side. In the ABO_3 structure of $LaAlO_3$, this can be done by substituting Ti for Al, but also by substituting the non-magnetic rare earth element Lanthanum by magnetic ones such as Eu or Gd. This is not trivial, since structural issues, valency issues, but also the issue of ferromagnetism versus antiferromagnetism all come into play. The effect of 'δ-doping', meaning the insertion of one or two atomic layers of a different oxide, was also investigated.

For the research, a number of heterostructures was prepared, namely $LaAlO_3/SrTiO_3$, $LaTiO_3/SrTiO_3$, $LaAlO_3/GdTiO_3/SrTiO_3$, $LaAlO_3/EuTiO_3/SrTiO_3$ and $LaAlO_3/Eu_{1-x}La_xTiO_3/SrTiO_3$. They were all prepared using Pulsed Laser Deposition (PLD) at the University of Twente. Transport measurements, especially back gate experiments, were the main tool to investigate the possibly tunable properties of these systems. Special focus with respect to magnetotransport properties was on the behavior of the Anomalous Hall effect, which is often used as a signature for the occurrence of ferromagnetism in the conduction electron system. Chapter 1 introduces the parent system $LaAlO_3/SrTiO_3$ (or LAO / STO) and the most relevant experimental and theoretical results obtained thus far, the theory of the Anomalous Hall Effect and a review of (RE)TiO_3 (Re=La, Gd, Eu, $Eu_{1-x}La_x$) and called LTO, GTO, ETO and ELTO). Experimental techniques and protocols are described in Chapter 2. Chapter 3 describes the tunable Anomalous Hall Effect in strongly intermixed LAO/GTO/STO and point out a possible link between the enhancement of the Spin-Orbit Interaction and the appearance of the Anomalous Hall Effect. Chapter 4 focuses on signatures of non-uniformities in normal and superconducting state at interface between STO and amorphous LTO (a-LTO) studied by the magnetotransport measurements. Chapter 5 studies the Superconductor-Insulator transition and the magnetoresistance hysteresis in strongly intermixed LAO/GTO/STO and a-LTO/STO. The observed hysteresis is argued to be rather a signature of inhomogeneous superconducting state than a signature of the coexistence of superconductivity and magnetism. Chapter 6 is dedicated to LAO/STO δ-doped with ELTO. Special attention is paid to the AHE mechanism and the Kondo-like regime which is observed. Unlike what is inferred from most of literature, we argue that the Kondo-like regime which arises in back-voltage experiments at low carrier concentration, arises from the properties of $SrTiO_3$, and are not due to magnetic coupling.