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ABSTRACT

Thesis by Jakub Pawlak:

„Multiferroic Tunnel Junctions based on BTO/LSMO operated by spin current"

The PhD thesis describes research on the multiferroic tunnel junctions (MFTJs). These junctions consist of two ferromagnetic electrodes separated by a ferroelectric layer. MFTJs exhibit both the Tunnel Magnetoresistance (TMR) and Tunnel Electroresistance (TER) effects. They can be used in new type of RAM (Random Access Memory) – non-volatile, switched faster and with less power consumption. The ability to operate at room temperature and to control magnetization directions of the electrodes without an external magnetic field is crucial for their application. The magnetization direction can be altered through two spin current effects: Spin-Transfer Torque (STT) and Spin-Orbit Torque (SOT). The former involves a high-density current flowing through the junction, while the latter with current flowing only through the electrode, thereby reducing junction wear and power consumption. The main goal of the research was to achieve significant TMR and TER effects at the room temperature and to control the junction using current or voltage.

To fabricate these junctions, the following materials were selected: ferromagnetic $La_{0.67}Sr_{0.33}MnO_3$ (LSMO) with high spin polarization at Fermi level (allowing theoretically large TMR), ferroelectric $BaTiO_3$ (BTO), and $SrTiO_3$ (STO) as a substrate. It should be noted, that ferroelectric properties can be sustained in nanometer-thick layers for only a small group of materials. These materials require well-ordered crystalline structures to maintain their properties. Therefore, the selection of materials needs to be considered holistically, taking into account the necessity of their epitaxial growth.

Given the sensitivity of LSMO properties to parameters such as strain, stoichiometry, temperature, etc., the initial stage of the research focused on optimizing the process of preparing atomically smooth substrates and analyzing their surfaces using the Reflection High-Energy Electron Diffraction (RHEED) technique. Special attention was also given to the process of multilayers fabrication, which aimed to preserve the crystalline structure and sharp interfaces. The influence of the substrate preparation and the deposition conditions on the magnetic properties of LSMO was investigated. Subsequently, the magnetic and transport properties of LSMO in multilayer structures were studied, which are important for their application in tunnel junctions. The phenomena occurring in LSMO have not yet been fully understood due to its complex electronic structure. Therefore, a wide range of experimental research techniques such as RHEED, Vibrating Sample Magnetometry (VSM), Ferromagnetic Resonance (FMR), X-ray Diffraction (XRD), X-ray Reflectivity (XRR), Atomic Force Microscopy (AFM), Transmission Electron Microscopy (TEM), as well as theoretical and phenomenological models and DFT (Density Functional Theory) calculations were employed to analyze and interpret the results. The research revealed significant increase in resistance and coercive magnetoresistance in LSMO on a thin MgO buffer, which may be related to the strain.

Subsequently, the multilayer structures were nanostructured to create micrometer-scale junctions. Initially, two types of junctions were planned: LSMO/BTO/LSMO, which theoretically could achieve a large TMR due to high spin polarization of electrodes, and LSMO/BTO/MgO/LSMO, where the additional MgO layer in the buffer allows for an increased TER. However, the research revealed high instability of these devices, caused by the destructive effects of ion etching on the

LSMO, BTO, and STO layers. The solution was to use junctions with a metal/BTO/LSMO architecture, where the bottom electrode and tunnel barrier were left as a continuous layer. Moreover, the metal top electrode deposited at room temperature did not require etching, and instead employed the lift-off technique. The asymmetric architecture of the junction enables a high TER, while the preserved structure of the oxide layers enables a higher TMR. Research on Fe/BTO/LSMO junctions revealed some of the highest TMR and TER values at room temperature. Additionally, measurements of the spin diode effect demonstrated the potential utilization of the STT effect. In the next step, the top Fe electrode was replaced by a Pt/Co bilayer, enabling the use of the SOT effect. Measurements of SOT-FMR (Spin-Orbit Torque Ferromagnetic Resonance) revealed an interesting effect – an additional signal originating from the bottom electrode, despite measurement performed on only the top layer of the junction. This effect may be related to the spin pumping in LSMO induced by the Oersted field and the occurrence of the inverse spin Hall effect in the upper electrode.