Abstract

A spin-based electronics, also known as *spintronics*, is a rapidly evolving field of research which exploits the spin degree of freedom of the electron to develop a new generation of electronic devices. The advantages of such devices lie in the areas of speed, densities, volatility and electric power consumption, compared to conventional charge-based electronics.

The development of random access memory (MRAM) is one of the pivotal challenges in the spintronics field. This goal requires the ability to manipulate the magnetization of a nanometric layer. Until recently, this manipulation has been done by magnetic fields which are generated by electric currents. This method has two main drawbacks that limit the ability to minimize and compress the data cells: first, the applied fields are not localized, and second, they are not scalable with the cell size. The search for more effective methods has led to much interest in the interaction between spin-polarized current and magnetization, an interaction which can yield current-induced magnetization dynamics. Domain wall motion and magnetization switching in heterostructures are remarkable examples of these dynamics.

The interaction between current and magnetization via spin torque, or angular momentum transfer mechanism, can be found in the case of non-homogeneous magnetization. In the domain wall, or in the interface between layers, this non-homogeneity

is clear. Thus, one might expect that far from a boundary layer such interaction would not occur. However, theoretical models show that small magnetic variations due to thermal fluctuations can cause current-induced magnetic instability in a homogeneous layer. The amplitude of the threshold current that generates this instability is system-dependent.

Itinerant ferromagnets are common sources of spin current, as they exhibit a spontaneous unbalanced spin occupation in the Fermi surface. In this research I used thin layers of $SrRuO_3$. $SrRuO_3$ is an itinerant ferromagnet with uniaxial magnetic anisotropy and a Fermi surface dominated by the $4d$ energy levels of the Ru. Compared to the $3d$ transition metal, as Fe, the spin polarity is high and reaches 50 %. The domain walls are very thin, $\sim$ 3 nm, organized in a stripe pattern and were demonstrated to exhibit highly efficient domain wall motion.

In the main section of this work I investigate the induction of magnetization reversal in a uniformly magnetized layer of $SrRuO_3$ by injection of an electric current. We identify that the current affects the magnetization reversal while excluding effects of joule-heating or Oersted field. We extract the temperature and field-dependence of the threshold current. We show that at low temperatures, the current-induced magnetization reversal has weak field dependence, and magnetization reversal events occur also in the presence of magnetic fields which oppose reversal. This study was published in "Current-induced magnetization reversal in $SrRuO_3$", Y. Shperber, D. Bedau, J. W. Reiner, and L. Klein, Phys. Rev. B **86**, 085102 (2012).

Examining the influence of a lower-than-threshold current on the magnetization yields that there is a regime where current-induced magnetization reversal occurs with the assistance of thermal activation. We observe that for a given temperature, the average waiting time for reversal ($\overline{\tau}$) depends exponentially on the current amplitude, and, for a given current, $\overline{\tau}$ depends exponentially on the inverse temperature. This behavior of the average time can be described by a modified Néel Brown formula where the energy barrier decreases linearly with the current. This study was published in "Thermally assisted current-induced magnetization reversal in $SrRuO_3$", Y. Shperber, O. Sinwani, N. Naftalis, D. Bedau, J. W. Reiner, and L. Klein, Phys. Rev. B **87**, 115118 (2013).

The interplay between spin-polarized current and magnetization also results in magnetization-dependent resistivity. This dependence is crucial to the development of novel spintronics devices, and it is the basis for most current memory and sensor technologies. In this study we focused on the anisotropic magnetoresistance effect (AMR) and the planar Hall effect (PHE).

AMR is a spin-orbit effect, where the scattering of the charge carriers depends on the current orientation with respect to the magnetization. The induced scattering has a transverse "Hall-like" component, called the PHE. In amorphous or polycrystalline magnetic film, where the current $\mathbf{J}$ is in the x direction and the magnetization is in the $x-y$ plane, the generated electric field due to AMR and PHE has both a longitudinal component $E_x = \rho_\perp J_x + (\rho_\parallel - \rho_\perp) J_x \cos^2\varphi$, and a transverse component $E_y = (\rho_\parallel - \rho_\perp) J_x \sin\varphi \cos\varphi$, where φ is the angle between the current and the magnetization.

Another source of anisotropic resistivity may appear in epitaxial films which consist of non-cubic crystalline structure. The electric field in this case can be determined by the above equations, where φ is the angle between the current and one of the crystal axes.

Expressions for the electric fields in the case of crystal films in the presence of magnetization can be more complex, and generally contain both the angle between the current and the magnetization, and the angle between the current and one of the crystal axes.

In this section of the work I explore changes in the anisotropic resistivity of epitaxial $SrRuO_3$ films due to induced magnetization in the paramagnetic state by using the PHE. We find that the in-plane anisotropy is proportional to M^2 and that it depends on the magnetization direction. We provide a full description of this behavior at 160 K for induced magnetization in the (001) plane. This study was published in "Field induced resistivity anisotropy in $SrRuO_3$ films", Y. Shperber, I. Genish, J. W. Reiner, and L. Klein, J. Appl. Phys. **105**, 07B106 (2009).

This work was expanded into the ferromagnetic phase for several current directions, with respect to the crystal. We observed that the AMR and the PHE are well-described by a combination of the magnetization and crystal sources, without need of more complex terms. This study was published in "Low-temperature anisotropic magnetoresistance and planar Hall effect in $SrRuO_3$", N. Haham, Y. Shperber, J. W. Reiner, and L. Klein, Phys. Rev. B **87**, 144407 (2013).

In summary, the thesis addresses effects which originate from the interplay between spin-polarized current and magnetization of a ferromagnetic layer and are crucial to the development of novel spintronics devices. We observed, on the one hand, the effect of current on the magnetization, where in a uniformly magnetized layer of $SrRuO_3$ the reversal energy barrier is reduced by a current, and when the current exceeds a threshold magnitude a magnetization instability appears, and, on the other hand, the effect of magnetization on the current as expressed in the dependence of longitudinal and transverse resistivities on the magnetization vector in the paramagnetic and ferromagnetic phase.