Manipulation of chiral spin structures by electric fields

Electric field effect on magnetic interactions in ultrathin transition-metal films

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In Short

- Application of local electric fields is a promising route in spintronic devices towards control of magnetic properties at low energy cost.
- Chiral spin structures such as domain walls and skyrmions are proposed in novel type of device concepts such as racetrack memories.
- Using a multiscale approach combining density functional theory, spin dynamics simulations, geodesic nudged elastic band method and transition-state theory we explore how the magnetic interactions and spin structures in ultrathin films can be manipulated by electric fields.

The discovery of the giant magnetoresistance (GMR) by Fert and Grünberg [1],[2] initiated the field of spintronics which aims at utilizing not only the charge but also the spin of the electron for transport and storage of information. The first application of the GMR has been in the read-heads used in hard-disk drives which were commercially available as early as 1997. Today, also the tunneling magnetoresistance (TMR) effect is being exploited and new devices such as magnetic random access memories (MRAMs) are emerging. In the magnetic tunnel junctions which store the data in MRAMs the magnetization of one of the electrodes can be switched with an electric current by the spin-transfer torque (STT) [3],[4].

A magnetic data storage concept suggested ten years ago by Stuart Parkin is the so-called racetrack memory [5] which is based on moving domain walls by the STT. One of the challenges of this approach lies in the high current densities which are needed for domain wall motion. Spin-orbit torques have more recently turned out to allow a much more efficient current-induced domain wall motion in particular for chiral domain walls which are stabilized by the Dzyaloshinskii-Moriya interaction [6],[7]. Recently, it has also been proposed by Fert et al. [8] to use skyrmions instead of domains as the magnetic bits in racetrack memories. Skyrmions are localized and topologically stabilized spin structures (see Figure 1) which occur in certain class of magnetic materials and which can be moved at current densities which are five orders of magnitude lower than those required for domain wall motion [9].

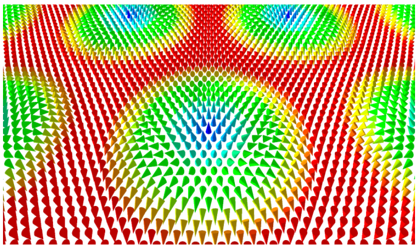

Figure 1: *Example of a magnetic skyrmion lattice in an ultrathin film. The arrows represent the magnetic moments single atoms where red (blue) arrows are pointing into (out of) the film. The color gradient shows the canting of the magnetic moments.*

An attractive route for the manipulation of chiral domain walls as well as skyrmions, e.g. writing and deleting, at low energy cost is the application of local electric fields. Due to the spin-dependent screening of electric fields there are changes in the electronic structure which can modify the magnetic interactions. While the variation of the magnetocrystalline anisotropy with electric field has been studied in the past [10], there is still very little known about the modification of the exchange and the Dzyaloshinskii-Moriya interaction due to external electric fields. However, their interplay is essential for the stabilization of chiral spin structures such as skyrmions.

Experimentally, it has been shown that domain wall motion can be controlled by applying electric fields, an effect that has been attributed to changes in the magnetocrystalline anisotropy [11],[12]. It has also been demonstrated that electric fields can be used to write or delete nanometer size skyrmions [13] (see Figure 2 for a sketch of the experimental setup) as well as micron-sized skyrmion bubbles [14].

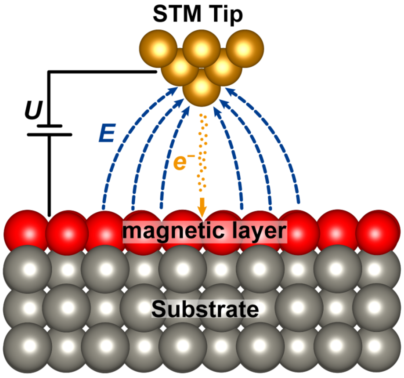

Figure 2: *Sketch of a junction comprised of the tip of a scanning tunneling microscope and an ultrathin film on a surface. A bias voltage is applied between tip and surface which leads to a small tunneling current and an electric field.*

It has been speculated that the modification of either the exchange interaction, the Dzyaloshinskii-Moriya interaction, the magnetocrystalline anisotropy or of the local atomic structure could explain this electric field manipulation of skyrmions [13],[14]. However, this issue has not been addressed by theoretical studies, yet.

In this project we use a multiscale approach combining density functional theory (DFT) and atomistic spin dynamics simulations to explore the possibility of manipulating localized spin structures at transition-metal interfaces by electric fields. Our focus will be ultrathin transition-metal films at surfaces with significant Dzyaloshinskii-Moriya interaction (DMI), which exhibit chiral domain walls or magnetic skyrmions. Based on DFT we will calculate the electric field dependence of the exchange and the DMI as well as the magnetocrystalline anisotropy energy. The electric field induced changes of the magnetic interactions in these systems may allow to write and/or to delete such localized spin structures.

We will explore this possibility by atomistic spin dynamics using the magnetic interactions as parametrized from our DFT calculations including the effect of the electric field. The local variation of the electric field on the surface e.g. due to the tip of a scanning tunneling microscope (Figure 2) can be included in these simulations. The energy barriers for the collapse or creation of localized spin structures such as skyrmions or antiskyrmions will be obtained by applying the geodesic nudged elastic band (GNEB) method. Harmonic transition-state theory is used to calculate the lifetimes which is a key property for any type of applications. This cutting-edge approach starting from first-principles calculations has only recently been developed and applied to study the annihilation of skyrmions in ultrathin films [15],[16],[17].

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More Information

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