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Electric field effect on magnetic interface phenomena

Understanding the principles governing the electrical manipulation of magnetization properties in materials is crucial for the advancement of magnetic memory devices. This dissertation investigates the direct and indirect effects of electric fields on magnetic interface phenomena, spanning scales from the atomistic to the micromagnetic level.

In order to have a solid starting place to understand the results of this dissertation, we spend some time to establish a theoretical background both on the microscopic (atomistic) scale as well as on the micrometer scale.

Special attention is given to the pivotal role of spin-orbit coupling in contemporary magnetism research landscape, with special emphasis on magneto-crystalline anisotropy and chiral exchange interactions such as the Dzyaloshinskii-Moriya interaction. We also discuss current research into innovative electrical methods for altering these crucial aspects of magnetism. After having laid the theoretical foundations of magnetism on these different length scales, we discuss some of the main aspects of 2 pillars of modern computational material science, namely density functional theory and micromagnetism.

In the result section, we start by discussing some experimental observations on the multilayer $Ta/Co_{20}Fe_{60}B_{20}/HfO_2$ and the discovery of so called “multiple magneto-ionic regimes”, i.e., different reversibility regimes of the magnetization reversal process in response to the application of an electric field at this particular ferromagnet/oxide interface. We follow up by showing ab initio calculations delving deeper in the microscopic mechanism governing this behavior. We discuss a plausible explanation for this behavior by thoroughly inspecting the different effects oxygen can have on the magneto-crystalline anisotropy of the material depending on its precise positioning and penetration depth. In these systems, the geometry of the oxygen-ferromagnet interaction seems to be of crucial importance for the reversibility characteristics of magneto-ionic switching.

Departing from the atomistic realm, the use of gauge theories (a tool borrowed from field theories) led to the development of a formalism for compactly describing interactions in continuum theories of magnetism taking in account arbitrary crystallographic point groups. This formalism was successfully translated into computational tools by adapting the open source micromagnetic code MuMax3, enabling the study of static and dynamic properties of magnetic materials in the presence of arbitrary chiral interaction.

In the final part of the thesis, we implement the matrix notation of the DMI tensors in collective coordinate models to efficiently describe the static and dynamic properties of magnetic domain walls in nanowires with perpendicular magnetic anisotropy. The numerical implementation mentioned in the previous paragraph serves as a basis to confirm our analytical prediction. This study of arbitrary chiral interactions reveals a highly nontrivial interplay of the different DMI tensor components (diagonal, antisymmetric and symmetric traceless) in the canting angle response of the domain wall to an in-plane field. We also discover a non-linear enhancement of the Walker breakdown field in the presence of some combinations of Dzyaloshinskii-Moriya tensor components and propose systems with S_4 symmetry as

promising candidates to experimentally display our theoretically formulated predictions. The analytical predictions show very good agreement with the numerical results.