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Current-induced domain wall motion in nanoscale ferromagnetic elements

O. Boulle [a], G. Malinowski [b], M. Kläui [c,*]

[a] SPINTEC, CEA/CNRS/UJF/INPG, INAC, 38054 Grenoble Cedex 9, France
[b] Laboratoire de Physique des Solides, CNRS, Université Paris-sud 11, 91405 Orsay Cedex, France
[c] Laboratory of Nanomagnetism and Spin Dynamics, Ecole Polytechnique Fédérale de Lausanne (EPFL), 1015 Lausanne, Switzerland; SwissFEL, Paul Scherrer Institut, 5232 Villigen PSI, Switzerland

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ABSTRACT

The manipulation of a magnetic domain wall (DW) by a spin polarized current in ferromagnetic nanowires has attracted tremendous interest during the last years due to fundamental questions in the fields of spin dependent transport phenomena and magnetization dynamics but also due to promising applications, such as DW based magnetic memory concepts and logic devices. We comprehensively review recent developments in the field of geometrically confined domain walls and in particular current induced DW dynamics. We focus on the influence of the magnetic and electronic transport properties of the materials on the spin transfer effect in DWs. After considering the different DW structures in ferromagnetic nanowires, the theory of magnetization dynamics induced by a spin polarized current is presented. We first discuss the different current induced torques and their origin in the light of recent theories based on a simple s-d exchange model and beyond. This leads to a modified Landau-Lifshitz-Gilbert equation of motion where the different spin transfer torques are included and we discuss their influence on the DW dynamics on the basis of simple 1D models and recent micromagnetic simulations studies. Experimental results illustrating the effects of spin transfer in different ferromagnetic materials and geometries constitute the body of the review. The case of soft in-plane magnetized nanowires is described first, as it is the most widely studied class of ferromagnetic materials in this field. By direct imaging we show how confined domain walls in nanowires can be displaced using currents in in-plane soft magnetic materials and that using short pulses, fast velocities can be attained. While a spin polarized current can trigger DW depinning or displacement, it can also lead to a modification of the DW structure, which is described in detail as it allows one to deduce information about the underlying spin torque terms. High perpendicular anisotropy materials characterized by narrow domain walls have also raised considerable interest. These materials with only a few nanometer wide DWs combined several key advantages over soft magnetic materials such as higher non-adiabatic effects leading to lower critical current densities and high domain wall velocities. We review recent experimental results obtained in this class of materials and discuss the important implications they entail for the nature of the spin torque effect acting on DWs.

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* Corresponding author at: Fachbereich Physik, Universität Konstanz, Universitätsstr. 10, D-78457 Konstanz, Germany.
E-mail address: mathias.klaeui@magnetism.ch (M. Kläui).

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1. Introduction

The physics of surfaces, interfaces and nanostructures has become one of the main areas of research, due to the trend in science and technology towards miniaturisation of physical systems into the nano-scale. From the scientific viewpoint, such systems pose a whole new set of problems, both theoretical and experimental. Fundamentally, novel properties emerge in magnetic elements as the lateral structure dimensions become comparable to or smaller than certain characteristic length scales, such as spin diffusion length, carrier mean free path, magnetic exchange length, domain wall width, etc. The effects of the governing energy terms determine the interplay between the relevant physical length scales and the sizes of the structured materials.

But not only from a basic physics point of view, have magnetic nanostructures moved into the research focus, but they have also been at the heart of a multitude of devices ranging from sensing applications to data storage. Probably the best known storage device is the magnetic disc drive [1], which was pioneered in the 1950s by IBM with the RAMAC and since then the storage density has seen a gigantic exponential increase. While hard drives continue to excel in the high capacity market, they entail nonetheless disadvantages, which have led to other memory concepts replacing them for applications, such as lower density mobile storage. A well-known example are MRAMs where the information is stored in the magnetization direction of a magnetic nanoelement. Novel storage class memory devices have also been put forward such as the magnetic shift register [2–5], based on nanoscale magnetic wires with domains delineated by domain walls representing the bits.

While the existence of domains in bulk materials and in continuous films could often be attributed to defects (at least for soft magnetic materials), the situation is radically different when structures are patterned into nanoscale elements. Here a magnetization configuration that constitutes the lowest energy state is often a multidomain state with domain walls, since the dipolar interaction (stray field) leads to the magnetization being parallel to the element edges, which then results in a spatially inhomogeneous magnetization distribution (domains). These domains and domain walls occur, when the geometry changes from the bulk to the nanoscale, since then the magnetic properties of ferromagnetic elements start to be governed by the element geometry and not only by the intrinsic materials properties. Such behaviour and in particular the magnetization configurations and reversal in small magnetic elements have been reviewed in detail for instance in Refs. [6,7]. Such a strong dependence on the geometry allows one then to tailor the magnetization configuration and spin switching by appropriately engineering the geometry. The magnetization configuration that constitutes the lowest energy state in a small magnetic structure can for instance be set to a multidomain state with domain walls, since the dipolar interaction (stray field) leads to the magnetization being parallel to the element edges. This results in a very reproducible and controllable spatially inhomogeneous magnetization distribution (domain configuration) [6].

The presence of useful spin structures is though not sufficient, since one needs to manipulate these. Conventionally this is done by applying magnetic fields and different reversal modes can be triggered [6]. Field-induced switching though exhibits poor scaling as the necessary current densities to generate the switching fields increase with decreasing design rule of the structure size. An alternative approach that has recently become available is to employ spin-polarized currents to manipulate the magnetization. This approach is not only exciting from the point of view of applications, but entails significant novel physics, which has only recently started to be explored. Its principle is based on the spin transfer effect which occurs when the direction of the current spin polarisation traversing a media is not aligned with the local magnetization. The alignement of the current spin polarisation along the magnetization induced by the exchange interaction then leads to a transfer of the current spin angular momentum to the magnetization which thus feels a torque. This torque can generate dynamical states of magnetization and in particular reverse its direction. The spin transfer effect was thus shown to be able to reverse the soft layer of a giant-magnetoresistive multi-layer structure [8] or excite steady precession state [9]. As recently demonstrated, spin-transfer effects can also be used to displace a magnetic domain wall by injecting current, which is at the heart of this review. This effect shows potential for novel memory and logic devices based on domain-wall propagation as it could simplify designs by eliminating magnetic field-generating circuits. While field-induced domain-wall motion is well established, current-induced domain-wall motion is now starting to be more and more understood and the field is now sufficiently mature to

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