Simple concepts of magnetization reversal – from materials to nanostructures

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Magnetic materials have various uses in applications, depending on how their magnetization reverses against applied fields. This behavior may be grasped in the form of hysteresis loops, from which global quantities are extracted such as coercivity, remanence, susceptibility, losses; and the thermal and frequency dependence of these quantities. For example permanent magnets and data storage rely on remanence and coercivity, sensors and shielding on susceptibility, transformers on susceptibility and low losses, etc. Therefore understanding magnetization reversal, with a view to further engineering it, is a central task in applied magnetism.

Magnetization reversal is a complex process as a huge number of degrees of freedom is at play with multiscale and non-linear effects, not speaking of microscopic details (microstructure and defects) of real systems which often are not known precisely. Real systems can therefore be handled analytically only at the expense of simplifying assumptions. Grasping the essential aspects of magnetization reversal is crucial for selecting the assumptions to be made and retaining only the parameters most relevant in a given situation. Only this allows one to deliver accurate understanding and predictions using simple models.

Magnetization reversal is determined by the several sources of energy characterizing magnetic materials: exchange, anisotropy, Zeeman, dipolar. As always in physics, the competition between different energies yields characteristic length scales. Nanomagnetism may have been called mesomagnetism, i.e. the scale where macroscopic (schematically magnetic domains) and microscopic (schematically sizes of a few nanometers where exchange dominates) scales meet. Following this idea the lecture will be divided in two part. The first part deals with concepts based on macrospins (single-domains), and their application to macroscopic samples through models. The second part is an introduction to a more detailed description of nanomagnetism, explicitly handling non-uniform magnetization configurations in nanostructures, with application to coercivity and manipulation of domain walls in patterned elements.

I. SINGLE-DOMAIN CONCEPTS AND THEIR RELEVANCE IN MATERIALS

I.1 Macrospin models for coercivity

The basic ingredients of magnetization reversal are anisotropy and Zeeman energies. The first one sets energy minima separated by energy barriers, responsible for metastability underlying coercivity, while the latter helps overcome these energy barriers. Therefore the simplest and earliest models of magnetization reversal consider these two ingredients only. Setting aside exchange
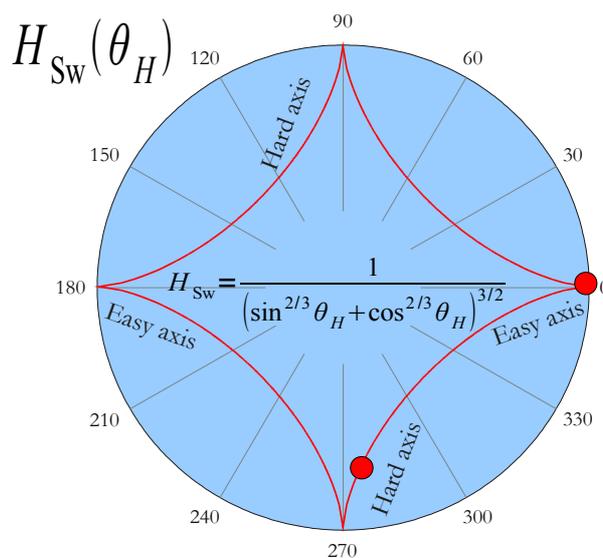

$$H_{Sw}(\theta_H)$$

$$H_{Sw} = \frac{1}{\left(\sin^{2/3}\theta_H + \cos^{2/3}\theta_H\right)^{3/2}}$$

FIG.1 The Stoner-Wohlfarth astroid: the polar plot of the reversal field under the assumption of coherent reversal.

energy implies that magnetization is assumed to be uniform in the systems considered. This yields so-called *coherent rotation models*, as first outlined by Stoner and Wohlfarth [STO48], and the famous astroid first drawn and geometrical constructions discussed to infer various informations by Slonczewski [SLO56]. In a simple case we will derive energy barriers preventing magnetization reversal, and infer the dependence of coercivity on temperature and time scales, and introduce the effect of superparamagnetism. Relevance for real small magnetic elements will be discussed based on examples.

I.2 Coercivity in materials

In real extended systems the assumption of uniform magnetization is obviously not valid, and coherent rotation models usually fail. In particular the experimental value of coercivity is often much smaller than the one expected from the value of anisotropy. This discrepancy has long been known as Brown paradox. This 'paradox' is lifted by the fact that in reality magnetization reversal instead proceeds via nucleation of small reversed domains, and possibly the propagation of the associated domain walls [GIV2003]. This stresses that the engineering of microstructure is of particular importance to hinder or ease these processes to yield application-oriented materials, such as highly-coercive materials (permanent magnets). Simple models to account for these processes will be presented, including the Fatuzzo-Labrune [FAT1962,LAB1989] model relevant for thin films.

I.3 Novel ways for magnetization reversal

In the past decade, along with knowledge and

Fig. 4. Magnetization versus reduced time t_R for a GdFe sample ($k \approx 2000$) and a TbCo one ($k \approx 0$), corresponding domain structure observed by Kerr effect.

FIG.2. Nucleation (lower-left) versus propagation (upper-right) extreme schemes for magnetization reversal, taken from the historical paper of [LAB1989].

technological progresses accompanying the field of spintronics, new ways of reversing magnetization have emerged. These open new fundamental fields, as well as potential applications. We will shortly discuss thermally-assisted reversal (decrease the coercivity with heating), precessional dynamics and switching [BAC1999] (typical time scale 1ns), spin transfer torque [SLO1996,BER1996] (reversal using spin-polarized currents as a mean to bring the momentum required to reverse magnetization), electric fields [WEI2007] (direct through charge transfer, or through induced stress), all-optics [STA2007] (so-called inverse Faraday and Kerr effects).
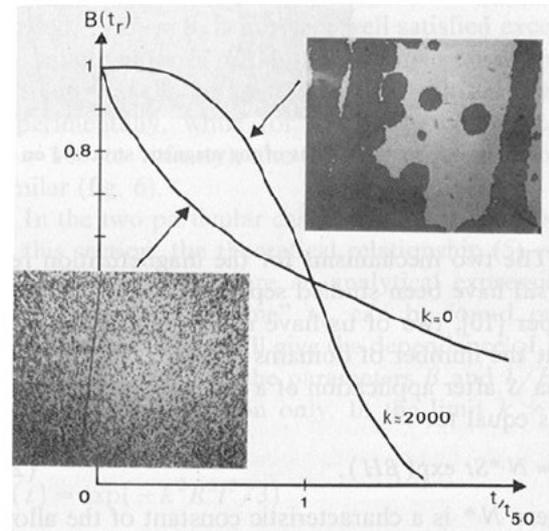
FIG.3. All-optical magntization reversal using the inverse Faraday effect [STA2007].

II. Non-single-domain effects

II.1 Dipolar energy

Dipolar energy is often the core of problems and wealth of behaviors in nanomagnetism, owing to its non-local character. It is therefore important to review the different ways it can be handled, and its basic consequences on magnetization reversal. We will introduce the concepts of volume and surface charges, dipolar field and potential, demagnetizing coefficients [BEL2003] (calculation, hypothesis, examples, relevance and use). Textbook consequences on hysteresis loops will be given: hard axis loops, correction of internal fields etc. finally, ways to infer collective effects (often dipolar-related) from more elaborate loops will be described, such as irreversible versus reversible contributions to hysteresis loops, Henkel plots, Preisach models.

II.2 Nanomagnetism – Coercivity in patterned elements

Flat thin film magnetic elements patterned by e.g. lithography are model systems for nanomagnetism, owing to their relative simplicity (two-dimensional magnetization configurations), and our ability to essentially characterize them fully using plane view magnetic microscopies. There are also obviously objects of prime importance for technology. As a consequence their study is extremely well documented, and we will base our description of nanomagnetism on such elements. Characteristic length scales of nanomagnetism will be introduced: Bloch wall width, exchange length, quality factor. Well below these length scales systems are mostly uniformly-magnetized. Upon increasing this size deviations from strictly-speaking single-domain appear (e.g. flower and leaf states associated with configurational anisotropy [SCH1988,COW1998]). Above these sizes flat elements may retain an essentially single-domain magnetization configuration owing to the shorter range of dipolar field in two dimensions. Then end domains may occur leading to so-called C and S states; engineering of the coercivity with end geometries (e. g. flat or pointed) will be outlined. Non-single-domain states will finally be described, with the vortex state, and more generally the Van den Berg construction [VAN1984], and Bryant and Suhl model for flux-closure domains.

Various reviews are available on nanomagnetism: [HUB1999], [MAR2003], [SLO2003], [FRU2005]...
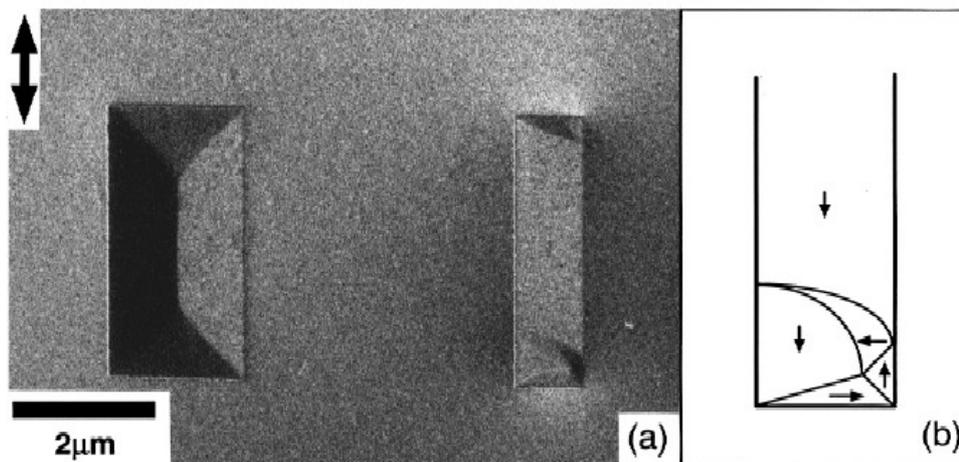

FIG.4. Flux-closure (so-called Landau state, left) and essentially single-domain state with end domains (right) [KIR1997].

II.3 Manipulation of magnetic domain walls

We will start with a reminder about domain walls in thin films (Bloch versus Néel [NEE1955], energetics of domains versus their angle, and its consequences such as cross-tie walls, perpendicular media). Nowadays a very active field of research is concerned with the study and propagation of domain walls in nanostripes (typically 100nm wide). In this framework we will describe usual

concept of reservoirs and nucleation for injecting domain walls in stripes, pinning domain walls. Beyond their mere location, inner details of the domain walls will be discussed, such as head-to-head domain walls (vortex versus transverse), and magnetization processes inside domain walls (FRU2009] and magnetic vortices [SHI2000,WAE2007].
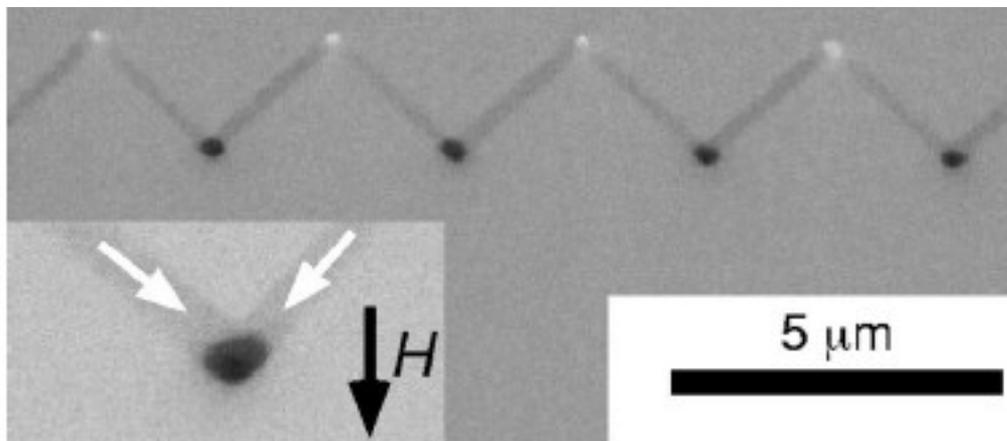

FIG.5. Illustration of the nucleation of head-to-head domain walls in zig-zag stripe patterns [TAN2000].

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