Simple concepts of magnetization processes – From macrospins to materials

Olivier Fruchart
Institut Néel (CNRS and Université Joseph Fourier)
25 rue des Martyrs – 38042 Grenoble Cedex 9 – France

Olivier.Fruchart-at-grenoble.cnrs.fr
Slides and lecture notes online: http://perso.neel.cnrs.fr/olivier.fruchart/slides.html

Magnetic materials have various uses in applications, depending on how their magnetization reverses against applied fields or other stimuli. 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. Therefore understanding magnetization reversal, with a view to further engineering it, is a major task in applied magnetism.

Magnetization reversal is often 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 three parts.
The first part considers macrospins (single-domains), strictly speaking applicable only in the limit of very small sizes (circa 10nm), however also suitable to introduce many phenomena applicable to all materials
The second part deals with micromagnetism, considering well-defined elements at a mesoscale.
The third part considers magnetization processes at play in extended systems.
The fourth part is a practical guide on what to do with hysteresis loops in order to better understand the magnetization processes at play in your system.

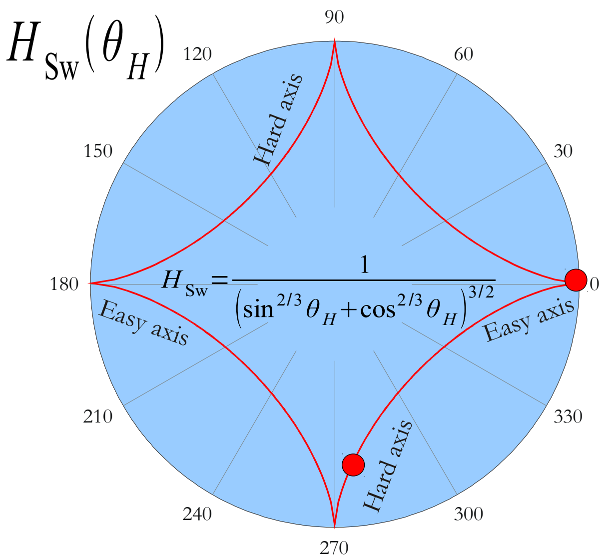

FIG.1 The Stoner-Wohlfarth astroid: the polar plot of the reversal field under the assumption of coherent reversal.

I. Single-domain concepts

The basic ingredients of magnetization reversal are magnetic anisotropy and Zeeman energies. The first one sets energy minima separated by energy barriers, responsible for metastability underlying coercivity, while the latter helps overcoming these energy barriers. Therefore the simplest and earliest models of magnetization

reversal consider these two ingredients only. Setting aside exchange 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.
In the past decade, 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).

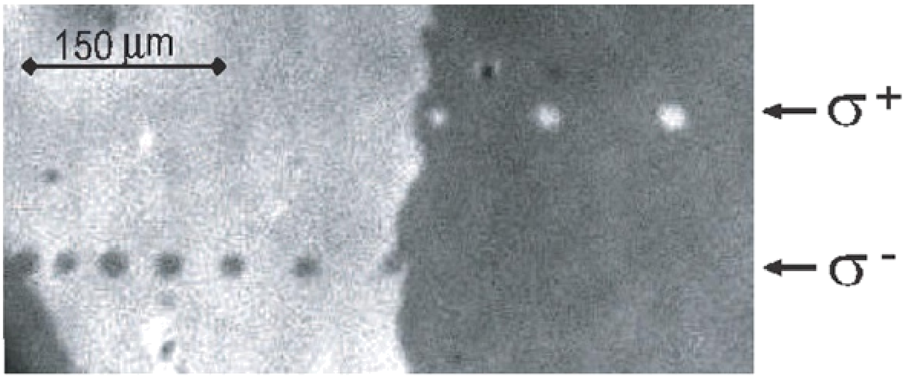

FIG.2. All-optical magntization reversal using the inverse Faraday effect [STA2007].

II. Micromagnetism

Micromagnetism describes magnetization arrangements and processes at the mesoscale, beyond macrospins however at a length scale where phenomena may still be described analytically or numerically, possibly based on suitable assumptions. It typically covers the range 10nm to one micrometer. Flat thin film magnetic elements patterned by e.g. lithography are model systems for micromagnetism, 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 micromagnetism on such elements. Characteristic length scales of nanomagnetism will be introduced: dipolar and anisotropy exchange length, quality factor. Well below these length scales systems are mostly uniformly-magnetized. Upon increasing their 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.
We will also introduce basics about domain walls: The Bloch domain wall, domain walls in thin films (Bloch versus Néel [NEE1955], energetics of domains versus their angle, its consequences such as cross-tie walls, domain walls and magnetic vortices [SHI2000] in stripes and wires.

Various reviews are available on micromagnetism: [HUB1999], [MAR2003], [SLO2003], [FRU2005], [FRU2012].

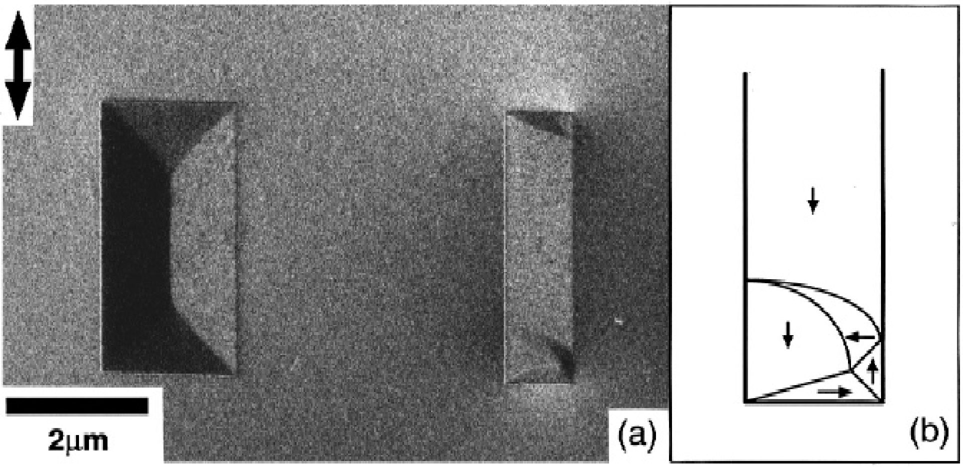

FIG.3. Flux-closure (so-called Landau state, left) and essentially single-domain state with end domains (right) [KIR1997].

III. 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 microscopic models such as the Kondorski model for pinning [KON1937], and phenomenological ones such as the Fatuzzo-Labrune [FAT1962,LAB1989] model relevant for thin films.

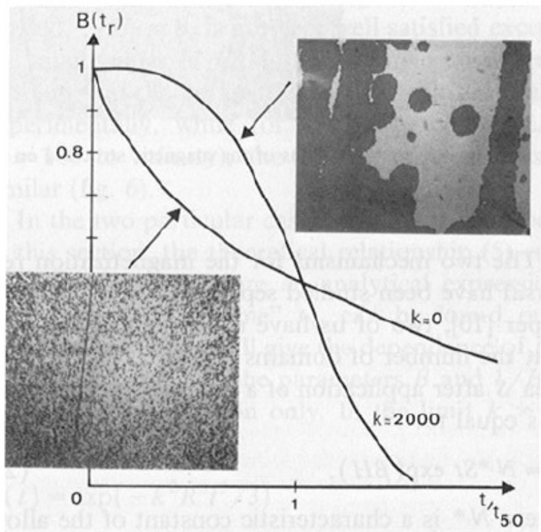

Fig. 4. Magnetization versus reduced time t_R for a GdFe sample ($k \approx 2000$) and a TbCo one ($k \approx 0$), corresponding domain structure observed by Kerr effect.

FIG.4. Nucleation (lower-left) versus propagation (upper-right) extreme schemes for magnetization reversal, taken from the historical paper of [LAB1989].

III. What to learn from hysteresis loops?

Hysteresis loops, also called magnetization curves, are the most widespread means of characterizing a magnetic material. We will present a practical guide on what to do with hysteresis loop to gain knowledge on your system. Some issues covered will be: extract magnetic moments, magnetic anisotropy, consider interactions and distributions such as with FORC diagrams [PIK1999], signatures for various magnetization processes (eg nucleation versus propagation), temperature effects.

References

[BAC1999] C. H. Back, R. Allenspach, W. Weber, S. S. P. Parkin, D. Weller, E. L. Garwin & H. C. Siegmann, Minimum Field Strength in Precessional Magnetization Reversal, Science 285, 864-867 (1999)

[BEL2003] M. Beleggia & M. D. Graef, On the computation of the demagnetization tensor field for an arbitrary particle shape using a Fourier space approach, J. Magn. Magn. Mater. 263, L1-9 (2003)

[BER1996] L. Berger, Emission of spin waves by a magnetic multilayer traversed by a current, Phys. Rev. B 54, 9353 (1996)

[COW1998] R. P. Cowburn & M. E. Welland, Phase transitions in planar magnetic nanostructures, Appl. Phys. Lett. 72, 2041-2043 (1998)

[FAT1962] E. Fatuzzo, Theoretical considerations on the switching transient in ferroelectrics, Phys. Rev. 127, 1999-2005 (1962)

[FRU2005] O. Fruchart & A. Thiaville, Magnetism in reduced dimensions, C. R. Physique 6, 921 (2005) [Topical issue, Spintronics].

[FRU2012] Lecture note on nanomagnetism (http://perso.neel.cnrs.fr/olivier.fruchart/publications/index.html).

[GIV2003] D. Givord, M. Rossignol & V. M. T. S. Barthem, The physics of coercivity, J. Magn. Magn. Mater. 258-259, 1-5 (2003)

[HUB1999] A. Hubert & R. Schäfer, Magnetic domains, Springer (1999).

[KIR1997] K. J. Kirk, J. N. Chapman & C. D. W. Wilkinson, Switching fields and magnetostatic interactions of thin film magnetic nanoelements, Appl. Phys. Lett. 71, 539-541 (1997)

[KON1937] E. Kondorski, On the nature of coercive force and irreversible changes in magnetisation, Phys. Z. Sowjetunion 11, 597 (1937)

[LAB1989] M. Labrune, S. Andrieu, F. Rio & P. Bernstein, Time dependence of the magnetization process of RE-TM alloys, J. Magn. Magn. Mater. 80, 211-218 (1989)

[MAR2003] J.I. Martin et coll., Ordered magnetic nanostructures: fabrication and properties, J. Magn. Magn. Mater. 256, 449-501 (2003).

[NEE1955] L. Néel, Énergie des parois de Bloch dans les couches minces, C. R. Acad. Sci. 241, 533-536 (1955)

[PIK1999] C. Pike & A. Fernandez, An investigation of magnetic reversal in submicron-scale Co dots using first order reversal curve diagrams, J. Appl. Phys. 85, 6668 (1999)

[SCH1988] M. A. Schabes & H. N. Bertram, Magnetization processes in ferromagnetic cubes, J. Appl. Phys. 64, 1347-1357 (1988)

[SHI2000] T. Shinjo, T. Okuno, R. Hassdorf, K. Shigeto & T. Ono, Magnetic vortex core observation in circular dots of permalloy, Science 289, 930 (2000)

[SKO2003] R. Skomski, Nanomagnetics, J. Phys.: Cond. Mat. 15, R841–896 (2003).

[SLO1956] J. C. Slonczewski, Theory of magnetic hysteresis in films and its applications to computers, Research Memo RM 003.111.224, IBM Research Center, Poughkeepsie, NY (1956)

[SLO1996] J. C. Slonczewski, Current-driven excitation of magnetic multilayers, J. Magn. Magn. Mater. 159, L1-L7 (1996)

[STA2007] C. D. Stanciu, F. Hansteen, A. Kimel, A. Kirilyuk, A. Tsukamoto, A. Itoh & T. Rasing, All-Optical Magnetic Recording with Circularly Polarized Light, Phys. Rev. Lett. 99, 047601 (2007)

[STO1948] E. C. Stoner & E. P. Wohlfarth, A Mechanism of Magnetic Hysteresis in Heterogeneous Alloys, Phil. Trans. Roy. Soc. Lond. A 240, 599-642 (1948). Reprinted: E. C. Stoner & E. P. Wohlfarth, reprint of 1948 'A Mechanism of Magnetic Hysteresis in Heterogeneous Alloys', IEEE Trans. Magn. 27, 3469-3518

(1991).
[TAN2000] T. Taniyama, I. Nakatani, T. Yakabe & Y. Yamazaki, Control of domain structures and magnetotransport properties in patterned ferromagnetic wires, Appl. Phys. Lett. 76, 613 (2000)
[VAN1984] H. A. M. Van den Berg, A micromagnetic approach to the constitutive equation of soft-ferromagnetic media, J. Magn. Magn. Mater 44, 207-215 (1984)
[WAE2007] B. V. Waeyenberge, A. Puzic, H. Stoll, K. W. Chou, T. Tyliszczak, R. Hertel, M. Fähnle, H. Brückl, K. Rott, G. Reiss, I. Neudecker, D. Weiss, C. H. Back & G. Schütz, Magnetic vortex core reversal by excitation with short bursts of an alternating field, Nature 444, 461-464 (2006)
[WEI2007] M. Weisheit, S. Fähler, A. Marty, Y. Souche, C. Poinsignon & D. Givord, Electric Field–Induced Modification of Magnetism in Thin-Film Ferromagnets, Science 315, 349 (2007)