INTRODUCTION TO MAGNETISM (II) : MAGNETISM TODAY

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The recent developments in Magnetism can, for the main part, be described under the general heading of Nanoscience and Nanotechnology. For example, the new permanent magnets owe much of their improved performance to the control of their microstructure and composition down to the scale of nanometric grains; as well as ultra-soft alloys that have become available. The sustained exponential progress that have been witnessed in magnetic recording have also encompassed a control of all sizes down to ever smaller values.

But there are also scientifically interesting issues that accompany, and in fact motivate, the technological challenge to "go nano". They justify that we speak now of Nanomagnetism.

J.F. Bobo, L. Gabillet and M. Bibes, J. Phys.: Condens. Matter **16**, S471-S496 (2004)
C. Chappert, A. Barthélémy in *Les Nanosciences : Nanotechnologies et nanophysique*, M. Lahmani, C. Dupas et P. Houdy Eds. (Belin, 2004, in french)

1) Surface anisotropy

As explained in the lecture by K.H. Müller, magnetism in bulk solids comes from the spin, as the orbital part of the moment that single atoms can possess is quenched by the crystalline electric field within the solid. However, at the surface of a solid for example, this field is reduced and its symmetry changes. As a result, an anisotropic orbital moment becomes allowed, that creates (via the spin-orbit coupling) a magnetic anisotropy with axis the surface normal. As this contribution is localized at the surface, it is called surface or interface anisotropy. The existence of this anisotropy had been predicted by Néel in the framework of an atomic pair interaction model of the anisotropy, with the right order of magnitude (1 mJ/m^2). For sufficiently thin samples (< 2 nm for Co/Au for example), the surface contribution is important and can even dominate over the bulk terms. Thus, by growing multilayers, new artificial magnetic materials can be prepared. The effect also occurs at the atomic steps on a surface, and becomes prominent for atomic clusters. Thus, we should expect generally that, at small sizes, the anisotropy differs markedly form the bulk.

The measurement of this anisotropy and the associated anisotropy of the orbital moment is one of the great applications of X ray spectroscopy (see the lectures of C. Vettier, S. Pizzini and M. Neumann).

P. Bruno, Phys. Rev. **B39** 865 (1989)

2) Molecular magnetism

Going further down we reach, when only a few atoms are left, the regime of molecular magnetism. It is indeed chemistry that allows building in a controlled way architectures of this size (molecules). The experiments on single crystals of such molecules, mainly conducted by W. Wernsdorfer in Grenoble, have revealed the quantum behaviour of theses small spins (S=10 typically), with non-classical phenomena among which of course the tunnel effect. This research tackles now larger molecules and the study of coupled spins.

W. Wernsdorfer, Adv. Chem. Phys. **118**, 99-190 (2001)

3) <u>Electronic effects</u>

As everyone knows, the spin is a property of the electrons. In metals, electrons are delocalized, and move under electric field or diffuse. The two aspects of the electrons, spin and charge schematically (magnetism and transport more precisely) could in bulk solids be considered as largely independent. Coupled effects, the main one being magnetoresistance (see the lecture by J.M. de Teresa) were small, of the order of the percent.

The situation changes radically in nanostructures, as sizes become comparable to the lengths over which the spin of an electron is conserved. The first phenomena discovered that showed the strong interplay between magnetism and transport in metallic multilayers were the interlayer exchange coupling and the giant magnetoresistance.

J. Kübler, *Theory of Itinerant Electron Magnetism* (Oxford, 2000)

a) interlayer exchange coupling

An exchange coupling can occur between two magnetic layers separated by a non magnetic metallic spacer, when of nanometric thickness. The coupling strength oscillates with spacer thickness, between ferromagnetic and antiferromagnetic signs, and is damped exponentially with increasing thickness. The effect being interfacial, thin magnetic layers are also required for having measurable effects. It has also been shown that the coupling oscillates depending on the thickness of the magnetic layers.

The interpretation of the effect rests on spin-dependent reflexion and transmission coefficients of the electrons at the spacer/magnetic layer interfaces. The oscillation periods that were measured could be interpreted from the geometry of the Fermi surface of the spacer. The full observation of the damped oscillations requires interfaces of the highest crystallographic quality.

P. Bruno, Phys. Rev. **B52**, 411 (1995)
M.D. Stiles, J. Magn. Magn. Mater. **200**, 322 (1999)

b) giant magnetoresistance

Giant magnetoresistance (GMR) is observed in the same kind of samples (although the requirements on the interface flatness do not apply), when a current is applied through the structure. A variation of resistance by a large amount is observed when applying a field : typically it can fall to half the value at zero field. See the lecture of J.M. de Teresa for details about this subject.

The explanation of the phenomenon invokes the big difference in resistivity between majority electrons (those having a spin polarized along the direction of the majority of the electrons, as the metal is magnetic) and minority electrons. When all magnetic layers are parallel, this results into a short-circuit effect that decreases the resistivity.

GMR, controlled by small fields in spin-valve structures, has enabled very sensitive field sensors to be developped, including those in the read heads of hard disks. It provides now the easiest method for detecting the magnetization orientation in an isolated magnetic nanostructure.

M. Baibich et al. Phys. Rev. Lett. **61**, 2472 (1988)

A. Barthélémy, F. Petroff and A. Fert, in *Handbook of Ferromagnetic Materials vol. 12*, K.H.J. Buschow Ed. (North Holland, 2002)

c) spin transfer

Shortly after the discovery of these phenomena, a "reciprocal" effect was predicted, by which a current crossing a magnetic multilayer exerts a torque on the layers' magnetizations. Depending on the current direction, one layer tends to become parallel or antiparallel to the adjacent layer. The effect arises from the reorientation of the current's spins when entering one layer, hence the name. Very large current densities are however needed (10^{11} A/m^2 is typical for usual magnetic metals, values are smaller for magnetic semiconductors).

The effect has been observed a few years after this prediction, and has since given rise to a tremendous activity. The torque being non-conservative (it does not derive from a magnetic energy), a rich magnetic static and dynamic behaviour appears : the magnetization of one layer can for example precess continuously with a large amplitude, or switch.

For spin transfer to dominate over the effect of the field created by the current (Oersted field), the sample needs to be small in lateral size, a value of 100 nm being typical for metals. Thus we reach 3d confined structures now.

J. Slonczewski, J. Magn. Magn. Mater. **159**, L1 (1996)
L. Berger, Phys. Rev. **B54**, 9353 (1996)
M.D Stiles and J. Miltat, in *Spin Dynamics in Confined Structures III* (Springer, to appear)

d) spin pumping

With no applied current, as electrons are delocalized and can diffuse, the spin transfer is analogous to the the interlayer exchange coupling mentioned above, and to another effect also discovered recently, called spin pumping.

It manifests itself in an increase of the damping coefficient of the spin precession due to the diffusion of the electrons, with their precessing spin, out of the magnetic layer and inside the non-magnetic layer where the spin is eventually reversed.

Y. Tserkovnyak, A. Brataas and G.E.W. Bauer, Phys. Rev. **B66** 224403 (2002)

4) Micromagnetics : past and future

Our description of the magnetization variations in space and time has thus to be modified so as to try to include the effects described above. That description, called micromagnetics, contains just a few phenomenological parameters that, up to now, only depended on the material considered. These are the spontaneous magnetization at the temperature considered, the exchange constant, the anisotropy, supplemented by dynamic parameters : the gyromagnetic ratio and the damping constant. The coupling to elasticity can be described by the magnetoelastic interaction, with one or a few parameters linked to the magnetostriction constants.

This theory has been very successful in understanding, quantitatively, the domain structures and their dynamics under field. With the predominance of microfabricated samples now, it has been applied more and more to the understanding of the magnetic behaviour of such objects. At the same time, a number of micromagnetic codes have become available. Recently, calculations have incorporated thermal fluctuations too, as they become very important at small sample volumes.

One obvious extension of micromagnetics consists in defining surface parameters, like for the case of the surface anisotropy. However, the electronic effects that involve the diffusion of electrons may prove too complex for such a simplification. For atomic size samples too, the basic assumption of this continuous theory fails and one may well need to resort to atomic modelling directly.

A. Hubert and R. Schäfer, *Magnetic Domains* (Springer, 1998)