Low dimensional magnetism – Experiments

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1 Introduction

A brief overview of fundamental phenomena occurring in magnetic systems of low dimensionality will be proposed. The phenomena under study and its associated dimensionality may concern an entire magnetic system (*e.g.* a thin film) or a restricted part of it of lower dimensionality (*e.g.* 1D atomic steps on 2D continuous film). This will cover thin films and their surfaces/interfaces ; atomic steps ; thin stripes and wires ; clusters and atoms.

All the phenomena described here occur in thin films, although they are modified (often enhanced) for still lower dimensionality. The analysis of these phenomena is often performed for thin films because the translational symmetry allows one for easier modelling and quicker calculation, and the fabrication is better controlled than for lower dimensionality.

As the field is very broad, only review references are provided in this abstract. More focused articles will be referred to during the lecture.

2 Ferromagnetic order

2.1 Methods

The methods that have proved best suited for the study of fundamental properties of low-dimensional magnetic systems are Nuclear Magnetic Resonance (NMR), Mossbauer spectroscopy, Ferromagnetic resonance (FMR), Xray Magnetic Circular Dichroism (XMCD), Torque Oscillatory Magnetometry (TOM), the Magneto-Optical Kerr Effect (MOKE). Microscopies include MOKE microscopes, Spin-Polarized Scanning Electron Microscope (sp-SEM, or SEMPA), the Photo-Electron Emission Microscope (PEEM), Spin-Polarized STM (sp-STM).

2.2 Metastable phases

Epitaxial constraints such as symmetry and lattice mismatch can be exploited to stabilize a material's structure that do not occur in the bulk, and whose magnetic state might be original. Examples will include $\gamma - \mathrm{Fe}$ from films to dots, cubic Co, Hexagonal Pd, etc.

2.3 Ordering temperature

It will be shown how thermal excitations become important in low dimensions, reducing ordering temperatures, altering critical exponents, inducing nonhomogeneities of magnetization at finite temperature.

2.4 Surface polarization

The ground state magnetization is not homogeneous in low-dimensional systems because of the hybridization with surrounding non-magnetic materials. The magnetization value of magnetic atoms is changed at interfaces, and some evanescent magnetization is induced in the non-magnetic material. Examples will be given, along with care that must be taken to derive experimentally ground state properties.

3 Magnetic anisotropy

3.1 Methods

Methods include MOKE, XMCD, FMR, Mossbauer, NMR.

3.2 Different microscopic origins of magnetic anisotropy energy (MAE)

Apart from dipolar energy, MAE in low-dimensional systems is often overwhelmingly larger that the bulk materials. This MAE arises from both magneto-elastic contribution (the materials can be highly strained due to epitaxial mismatch, surface stress, etc) and surface/interface anisotropy (related to hybridization at interfaces).

3.3 Can one disentangle magnetoelastic from surface anisotropy ?

Beyond theory, that can address each phenomenon separately, it is still an experimental challenge to separate magneto-elastic MAE from interface MAE in thin films. We will review the approaches followed during the last decades, from surface anisotropy determination using $1/t$ plots, to the outlining of significant non-linearities of magneto-elastic coupling coefficients.

3.4 From surfaces to atoms

Beyond thin films, we will address the case of lower dimensionality : steps on vicinal surfaces, edges of flat self-assembled clusters, self-assembled wires, down to single supported atoms. The role of the increased orbital moment will be outlined (Bruno's and van der Laan's models ; methods and care for measurements).

3.5 Temperature dependance of anisotropy in low dimensions

Temperature dependence will be shortly discussed.

4 Layered systems : from concepts to functional building bricks

New phenomena occur when several layers of magnetic materials are assembled, directly or via non-magnetic layers. I will give a very brief theoretical and experimental overview of such phenomena, and show how they can be of use in devices.

4.1 Oscillatory exchange coupling

Oscillatory exchange coupling is now considered a well understood phenomena, with good agreement between theory and experiments. The application to synthetic (or artificial) antiferromagnet will be given.

4.2 Antiferromagnetic exchange coupling

Exchange coupling and bias has been known since the 50's. Several models based on different physical explanations have been proposed to account for these phenomena. Progress in the understanding of their relevance has been made recently and will be presented. Exchange bias can be applied to harden materials or increase the blocking temperature of superparamagnetic systems (see below).

4.3 Orange-peel and dipolar coupling

Reminder about the existing orange-peel coupling models ; dipolar coupling in layered dots. Application to decrease of demagnetizing effects of grains in recording media.

5 Superparamagnetism

5.1 Theoretical description

When thermal energy becomes comparable to the anisotropy energy preventing magnetization reversal, the mean magnetization vector of a system fluctuates randomly in space over time, its time-average being zero. In analogy with the paramagnetic state for atomic spins, this phenomenon is called superparamagnetism, and occurs above a temperature T_B called the *blocking temperature*. In a macrospin description $T_\mathrm{B} \sim KV/25k_\mathrm{B}$ where V is the sample volume (or activation volume) and K its anisotropy per unit volume. Superparamagnetism is a severe concern for low-dimensional systems, for which V and therefore the total anisotropy energy KV preventing magnetization reversal is small. I will try to clarify the semantic debate sometimes occurring, whether a *superparamagnetic* system may be called *ferromagnetic*.

5.2 Experimental examples

Superparamagnetism can occur in thin films, dots fabricated by lithography, self-organized systems, etc. Information about a system can be gained from the analysis of magnetization curves in the superparamagnetic regime. Examples will be given, and the care needed in selecting models to fit experimental data will be stressed.

5.3 How can one overcome superparamagnetism ?

Superparamagnetism at room temperature can limit down-scaling of magnetic devices, explaining why trying to increase T_B at constant V is an active field of research. The energy barrier preventing the occurrence of superparamagnetism is roughly KV. Therefore two routes can be followed to increase T_B, either increase V and K.

- The increase of V can be achieved by polycrystalline or epitaxial columnar growth at constant lateral density.
- The increase of K motivates the microscopic understanding of MAE for tailoring it, as was outlined in partie 3. Ways to increase K include : fabrication of high-K materials (FePt etc), decrease of dimensionality while keeping volume unchanged, exchange bias, etc.

References

Methods : 1-7.
Fundamentals properties of single layers : 8-12.
Quantum well effects and interlayer exchange interactions : 13-16.
Exchange bias : 17-20.
Nanomagnetics in general : 21.

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