Nanomagnetic Materials: A review

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ABSTRACT

Nanotechnology and nanostructured materials have the potential to significantly impact energy efficiency, storage, and production. Such applications can be used to monitor and remediate environmental problems; curb emissions from a wide range of sources; and develop new, "green" processing technologies that minimize the generation of undesirable by-product effluents. As well as being an excellent experimental means of studying fundamental magnetic phenomena, these low dimensionality magnets may in the future form the basis of technologies (information storage, permanent magnets, color printers, etc.). Highlighted areas include the quest for magneto-electronics and the importance of novel interfacial magnetic coupling phenomena. Nanomagnetism includes the artificial structuring of magnetic materials on a sub micron level and natural occurring magnetic entities such as molecules and clusters. Here the emphasis will be on the macroscopic behaviors found in single domains of quantum spins, quantum coherence, dissipation and tunneling of magnetization, and disorder and frustration effects. Nanometer-sized magnetic particles are situated at the frontier between classical and quantum magnetism.

Keywords: Nanomagnets, nanostructures, nanotechnology

1 INTRODUCTION

Magnetism is one of the oldest fields in science but it is also at the forefront of the nanotechnology revolution. The last 10 years have seen great interest in the magnetism of reduced dimensionality structures. Workers around the world have recently started to study 1-D and 0-D magnets by laterally structuring thin magnetic films into magnetic quantum wires and dots. As well as being an excellent experimental means of studying fundamental magnetic phenomena, these low dimensionality magnets may in the future form the basis of new data storage and computing technologies. Highlighted areas include the quest for magneto-electronics and the importance of novel interfacial magnetic coupling phenomena. Examples of how nanotechnology provides new strategies to realize composite magnetic materials with exceptional properties and interesting physics will be presented.

Nanometer-sized magnetic particles are situated at the frontier between classical and quantum magnetism. Detecting their magnetic properties is technologically very challenging (information storage, permanent magnets, color printers, etc.). Recently, three CNRS laboratories succeeded in measuring the magnetization of a 3 nm diameter single cobalt particle that contains about 1000 atoms only. These measurements provide the first verification of a theory of micromagnetism initially developed by Néel in 1948.

The Physics of Materials Department, Lyon produced monocrystalline cobalt particles by laser deposition and embedded a tiny concentration into a niobium film. The Photonics and Nanostructures Laboratory, Bagneux used electronic lithography to construct a Micro Superconducting Quantum Interference Device (micro-SQUID) from the niobium film. This was used to achieve a record sensitivity of the magnetization reversal of a few hundred magnetic moments, i.e., the magnetization reversal of a single 3 nm cobalt particle.

The trick consists of placing the cobalt particle in the vicinity of the micro-SQUID junctions. The magnetization flip can then easily be detected as a function of the orientation of the applied field and temperature. Nanomagnetism includes the artificial structuring of magnetic materials on a sub micron level and natural occurring magnetic entities such as molecules and clusters. Here the emphasis will be on the macroscopic behaviors found in single domains of quantum spins, quantum coherence,

dissipation and tunneling of magnetization, and disorder and frustration effects.

2 PROPERTIES OF MAGNETIC NANOSCALE OBJECTS

- Nanofabrication
- NanoMOKE probe
- Modulated Field Magnetic Anisotropy(MFMA)
- Circular Prisms

People developed a computer program which solves the so called "micromagnetic equations" and this allows to predict the magnetisation distribution inside any nanomagnet. Then we will be able to fabricate square and circular magnetic quantum dots of size 10-200nm and probe their magnetic properties in order to make a comparison with theory. The basic experimental techniques and apparatus required for studying the properties of magnetic nanoscale objects are: electron beam thin film deposition, high resolution electron beam lithography, spatially resolving magneto-optical Kerr effect (MOKE) magnetometry, B-H looping, Magnetic Force Microscopy (MFM) and atomic force microscope (AFM).

Shown below is an example of a micromagnetic simulation of a magnetic vortex inside a square nanomagnet and an electron micrograph of experimentally made 100nm nanomagnets

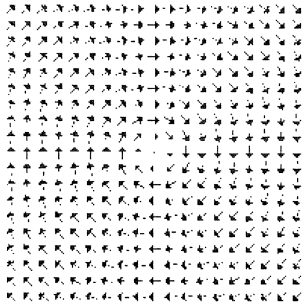


Figure 1: Micromagnetic simulation of magnetic vortex inside a square nanomagnet.

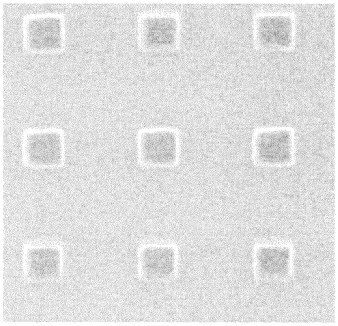


Figure 2: Electron Micrograph of 100nm Nanomagnets.

3 NANOFABRICATION

The nanostructures are prepared using a technique called electron beam lithography. This is a photographic process which uses a scanning electron microscope to project an image of the required structures onto a silicon substrate coated with a photosensitive resist layer. Development removes only the resist which has been exposed to the electron beam. A magnetic metal is then deposited, followed by lift-off of the unwanted metal. This technique can make structures with a lateral size as small as 7nm. The steps to produce a structure by EBL are shown below: The sample is covered with a thin layer of PMMA, then the desired structure is exposed with a certain dose of electrons. The exposed PMMA changes its solubility towards certain chemicals. This can be used to produce a trench in the thin layer. If one wants to produce a metallic structure, a metall film is evaporated onto the sample and after dissolving the unexposed PMMA with its cover (lift-off) the desired metallic nanostructure remains on the substrate.

4 NANOMOKE PROBE

Experimental techniques capable of measuring magnetic properties of magnetic structures on a nanometer scale form two classes. The first class are microscopic probes such as Lorentz microscopy, electron holography, and magnetic force microscopy (MFM) These probes can spatially resolve the magnetization distribution within a single magnetic element and so provide valuable information on the microscopic origin of magnetic behaviour. They are not, however, able to determine

quantitative hysteresis loops. Furthermore, in the case of MFM, questions still remain over the extent to which the magnetic field coming from the magnetically charged tip is able to influence the sample.

The second class are spatially averaging probes such as vibrating sample magnetometry (VSM) or alternating gradient field magnetometry (AGFM), which measure the total magnetic flux emanating from the sample. These are able to determine

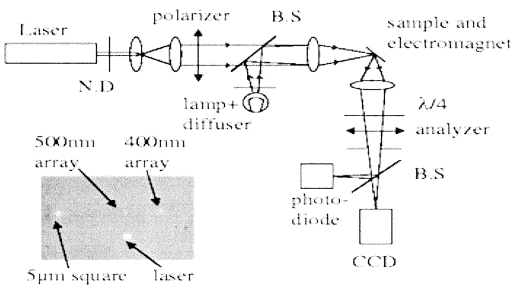


Figure 3: The design of new type of magnetic probe

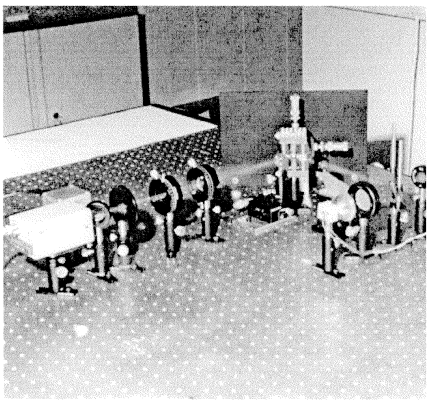


Figure 4: The experimental set up of new nanomagnetic probe

quantitative hysteresis loops, but because they are not local probes, very large arrays comprising, typically, $10^{6}-10^{7}$ particles are required. The fabrication of such large arrays is both slow and, in the case of electron-beam lithography, limiting to the resolution available. In addition, statistical smearing of the results can occur because of the size of the ensemble.

The design of a new type of nanomagnetic probe and set up which combines features of both of these classes are shown in Figures 3 and 4. The probe uses the Magneto Optical Kerr Effect (MOKE), the phenomenon by which the polarisation of light is rotated when it is reflected from the surface of a magnetic material. Our NanoMOKR probe can determine quantitative hysteresis loops from small arrays of nanomagnets or from individual nanomagnets. The technique is non-invasive, highly flexible, very rapid and does not require special sample preparation. It is therefore an ideal probe for studying fundamental problems in experimental nanomagnetism.

5 MODULATED FIELD MAGNETO-OPTICAL ANISOTROPY (MFMA) MEASUREMENTS

The flexibility of nanoMOKE means that different types of measurement can be made with the same apparatus. Modulated Field Magneto-Optical Anisometry (MFMA) is a particularly useful measurement which allows the magnetic anisotropy surface of a nanomagnet to be mapped directly. This allows the magnitude, symmetry and orientation of any anisotropy present in the nanomagnet to be determined. Figures 5, 6 and 7 show the experimentally measured anisotropy fields from triangular, square and pentagonal nanomagnets. The magnetic fields corresponding to different colours in Figures 5, 6 and 7 are as shown in Figure 7. These polar plots are to be read in the following way: the direction in the plot gives the direction in the nanomagnet, the radius in the plot gives the size of nanomagnet being considered and the colour gives the anisotropy field. These plots show results from nanomagnets in the size range 50nm-500nm. One sees that the triangular nanomagnets show a 6-fold symmetric anisotropy, the square nanomagnets a 4-fold anisotropy and the pentagonal nanomagnets a remarkable 10-fold anisotropy. All of these anisotropies come from the shape of the

nanomagnet and not from the basic material properties. This shows how fundmental magnetic properties such as anisotropy can be controlled and engineered in a precise fashion by nanometre scale structuring.

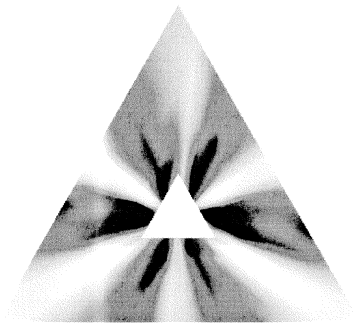


Figure 5: Triangular nanomagnet shows 6-fold symmetric anisotropy

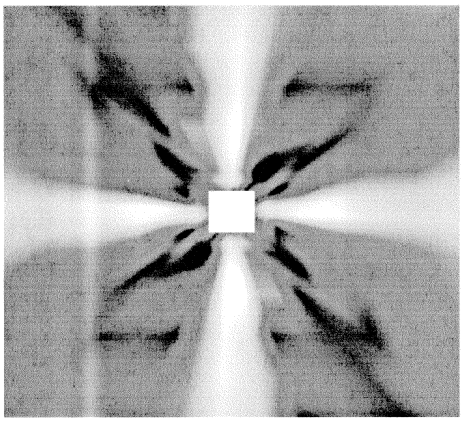


Figure 6: Square nanomagnet shows 4-fold symmetry in anisotropy

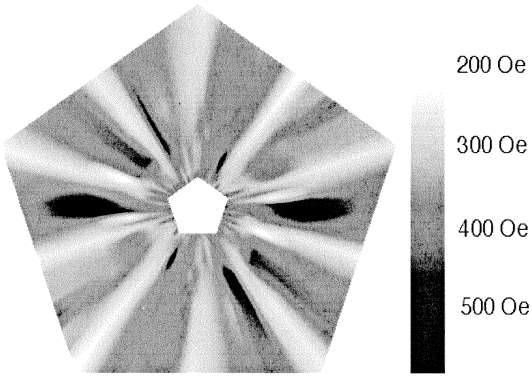
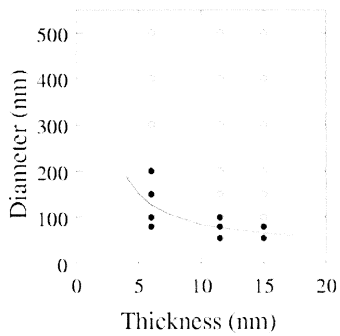


Figure 7: Pentagonal nanomagnet shows remarkable 10-fold symmetry in anisotropy.

6 CIRCULAR PRISMS

Circular nanomagnets are particularly intersting because they have no preferential in-plane directions. Consequently, the magnetisation ought to be able to change direction very easily. Circular nanomagnets could form the basis of new high sensitivity magnetic field sensors or hard-disk drive read heads. The experimentally measured magnetic properties of a circular nanomagnets as a function of size and thickness are shown in Figure 8, 9 and 10. Two distinct types of behaviour is marked onto a phase diagram (Figure 8). The first type of behaviour is called Vortex behaviour. In these region of the phase diagram the magnetisation collapses into a giant whirlpool or vortex. Once this has occurred, large fields are required to destroy the vortex. The second class of behaviour is called Single Domain behaviour. In this region of the phase diagram quantum mechanical exchange energy is strong enough (even at room temperature) to keep all of the spins tightly locked together. These nanomagnets reverse under very small applied fields and may have great technological significance as field sensors and as magnetic logic devices.



• = Single Domain

o = Vortex

Figure 8: Magnetic properties of circular nanomagnet as a function of size and thickness

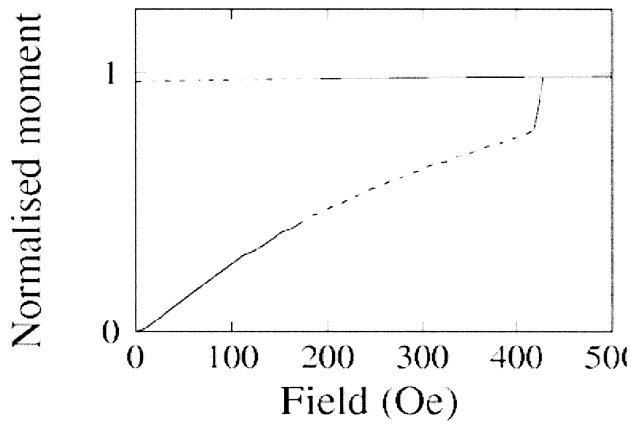


Figure 9: Magnetic field vs normalized moment in circular nanomagnets

7 CONCLUSIONS

Two state-of-the-art techniques, namely molecular beam epitaxy and advanced e-beam lithography are brought together to define the structures and control the properties in nanometer scale. The merits of ferromagnetic materials and semiconductors are combined in the novel next generation spin-electronic devices. This is believed to be significant and possibly revolutionary for both the magnetic information storage and the microelectronics industries. Nanoscale magnetism plays an increasingly important role in information technology. Computer hard disk drives store information in nanometer size magnetic bits; next generation computers may use a new type of magnetic memory chip (MRAM), which retains its memory after shut down. Scientists are trying to make nanometer-size magnetic logic devices for future microprocessors

The prediction of micromagnetic models, that a particle's magnetism has two equilibrium positions separated by an energy barrier, and that magnetism can move between the states by applying a magnetic field and by thermal activation, has been confirmed for the first time on a single isolated magnetic nanoparticle. Exciting new results are expected to demonstrate the quantum character of such particles.

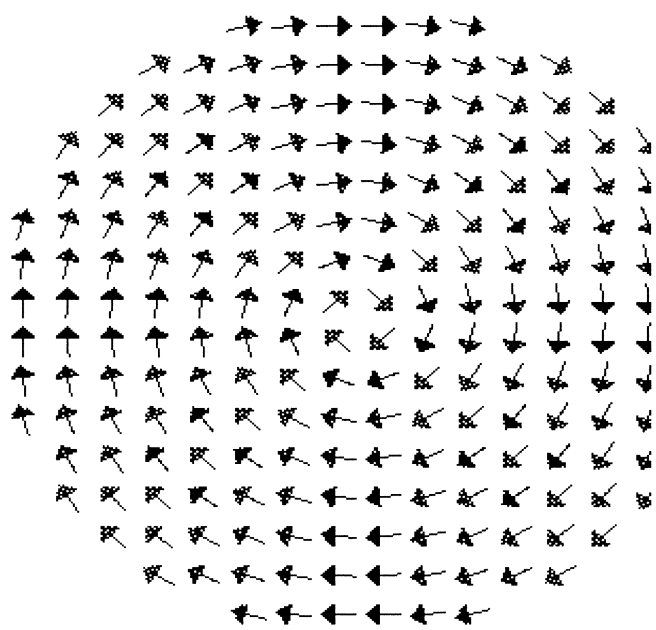


Figure 10: No preferential in-plane directions showing in circular nanomagnets