

Magnetism in Nanostructure

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Abstract

In this term paper I have tried to point at the main challenges faced by the scientists in this field. I have also tried to explain the physics of nanomagnets and their future applications in technology and medicine.

Introduction

It is becoming increasingly common to use the prefix “nano” to describe developments in science and technology in which nano-scale effects are of fleeting importance. Nanomagnetism, however, is different, because the fundamental properties of magnets are defined at nanometre length scales.

Permanent magnets play a critical role in technology and industry. Permanent magnets are used for all purposes, ranging from generation and distribution of electrical power to information processing. Permanent magnets are also widely used to store information. For long time, scientists are trying to increase information storage density. Nanomagnets hold some promising possibility to achieve this goal. Nanomagnets may also find applications that range from medical imaging and drug delivery to sensors technology and computing.

Nanomagnetism - What Is It?

Ferromagnetic materials consist of tiny individual domains in which the magnetic moments of all the component atoms or molecules point in the same direction. This direction varies from one domain to the next, but what makes ferromagnets useful is the

fact that all the domains remain aligned in an external magnetic field – even after the field has been switched off. A computer disk, for example, contains a 2D ferromagnetic thin film on which information is stored in sub-micron-sized “bits” made of hundreds of domains. The magnetic moments within different domains are forced to align with the magnetic field produced by the read head, which consists of a current-carrying coil wound round a magnetic yoke. Since the moments in the magnetic domains remain stable, the material “remembers” whatever information has been recorded.

Nanomagnetism basically involves studying how such ferromagnetic materials behave when they are geometrically restricted in at least one dimension. Apart from 2D thin films, such objects can be 1D “nanowires”, or zero-dimensional “magnetic islands”. Thanks to new high-resolution fabrication techniques, these objects are now relatively easy to make. Indeed, physicists have been able to create nanomagnets with structures that range from relatively large micron-sized domains to individual atomic chains.

Sizes and Shapes of Nanomagnets

Scientists have synthesized nano-magnets of different sizes, shapes and materials. Nanomagnets can measure anything from just under a micron to a few nanometers in size. They also come in many different shapes – dots, pillars, disks, rods, chains, etc. Nano dots are usually spherical/hemispherical and have a diameter of about 1 nm or more. For 1.4 nm diameter Fe nanodots, each dot may contain about 700 atoms or more if we assume a bcc structure. Dot profile analysis indicates that the average widths of the Fe dots are 1.4 nm and 3.5 nm, respectively [1].

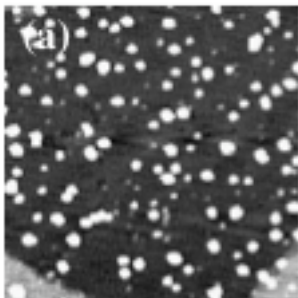


Fig 1: STM morphology of Fe nanodots on Cu(111) substrate.

The elliptical shaped nanopillars are grown on Si substrate and have dimensions about $70 \text{ nm} \times 130 \text{ nm}$. The samples consist of a thick Cu lower contact, the multilayer, and a thick Au top contact. The multilayer ($F1-N-F2$) is made of $\text{Fe}(\text{Cr})\text{-Cr-Fe}(\text{Cr})$ or $\text{Ni}(\text{Cr})\text{-Cu-Ni}_{84}\text{Fe}_{16}$ or $\text{Ni}_{84}\text{Fe}_{16}\text{-Cu-Cr-Fe}(\text{Cr})$. The N layer is made thick ($6 - 20 \text{ nm}$) to reduce exchange coupling between $F1$ and $F2$ layers [2]. To simplify the operation, samples are iron milled only through $F2$ and part of N , leaving $F1$ (fixed polarizer) to have a much larger area ($\sim \mu\text{m}^2$) and be much thicker than $F2$. The dipolar coupling between $F1$ and $F2$ is then minimal.

The Cobalt nanoplatelets are grown on $\text{Si}(111)$ substrate and has a edge length of 8.1 nm . Those are triangular in shape and have a thickness of few monolayers [3].

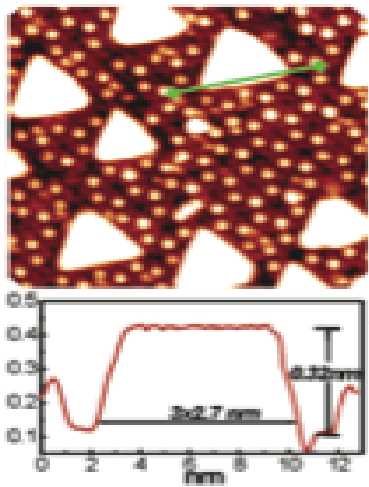


Fig 2: STM image of Co nanoplatelets.

The Co nanoparticles are grown on clean $\text{Pt}(111)$ surface by molecular beam epitaxy in UHV condition. The two dimensional, monolayer particles usually have one an average very few atoms of cobalt (1 to 5). And by controlled diffusing, one can increase the atom number per nanoparticle [4]. In Fig. 3, each nanoparticle has a size 85 \AA by 85 \AA .

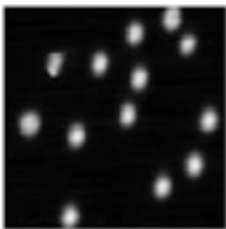


Fig. 3: STM image of Co nanoparticles on $\text{Pt}(111)$ surface.

Other groups have fabricated nanostructures (Fig. 4) and nanowires (Fig. 5) and nanocrystals (Fig. 6) of cobalt on different substrates [5, 7].

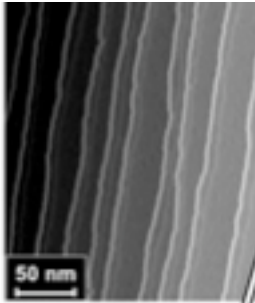


Fig. 4: STM image of Co nanostructures deposited on W(110) stepped single crystal.

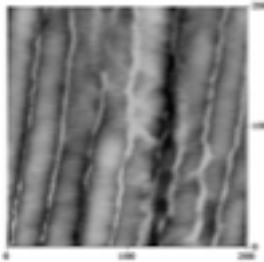


Fig. 5: STM image of Co nanowires on NiO surface.

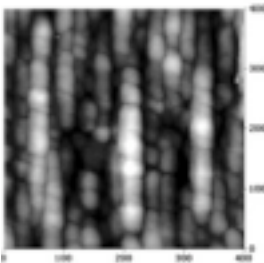


Fig. 6: STM image of Co nanocrystals on NiO surface.

Fabrication of Nanomagnets

Now I will briefly describe how to fabricate/grow some of these nanostructures. The Fe/Cu(111) nanodots are grown by the BLAG method (Fig. 1). Direct deposition of Fe onto Cu(111) does not lead to dot formation [1]. Therefore, the Fe/Cu(111) dot assemblies were synthesized by a novel method as buffer layer assisted growth (BLAG) in an ultrahigh vacuum (UHV) system with base pressures below 10^{-10} Torr. The Cu(111) single crystal surface was prepared by cycles of 1 KeV Ne ion sputtering and annealing to 800 K, before it was cooled to about 15 K. Inert Xe gas of 5N purity was then released

into the UHV chamber. Xenon exposures ranged from 0 to 600 L. Iron was then evaporated from a wire (5N purity) that was heated by electron bombardment. The deposition rate was independently calibrated by a combination of *in situ* scanning tunneling microscope (STM), reflection high-energy electron diffraction, and Auger electron spectroscopy. After Fe deposition, the sample was slowly warmed to 300 K to desorb the Xe buffer layer and allow the Fe dots to land on the Cu substrate.

The Co nanoplatelets fabrication experiments were performed in an ultrahigh vacuum system (base pressure $<5 \times 10^{-11}$ Torr) housing a molecular beam epitaxy (MBE) apparatus, and a scanning tunneling microscope (STM). All the STM images were recorded at room temperature with a tunneling current of 20 to 50 pA. Clean Si(111) substrates (p-doped, with a resistivity of 3~5 Ωcm) were prepared by well-established annealing procedures. Co deposition was carried out by direct-current heating of a tungsten filament coated with Co. The deposition rate was approximately 0.18 ML/min. To minimize silicide formation, before Co deposition, they have first prepared a template consisting of the Si(111) substrate covered by a spatially ordered and identically sized Al cluster array, utilizing a recently discovered self-assembly approach [3].

Every nanostructure has been fabricated in its own way. However all of those processes are performed in UHV condition to minimize contamination. So I have only described two processes here.

Modelling Nanomagnets

Ferromagnets can be regarded as a collection of magnetic dipoles, which interact like tiny bar-magnets that are fixed in space yet are also free to rotate as they please. The resulting magnetostatic interaction between neighbouring dipoles makes each pair point in opposite directions. However, there is another magnetic interaction – the quantum-mechanical exchange interaction – that creates a net magnetization within each domain. This interaction is caused by the overlap between the wavefunctions describing the spins

of neighbouring electrons. The exchange interaction creates an effective torque on neighbouring magnetic dipoles that causes them to line up [6].

The overall orientation of the dipoles in a particular domain is therefore a balance between the (classical) dipole– dipole magnetostatic interaction and the quantum exchange interaction. At distances of about 10nm (depending on the material), the quantum interaction is the stronger of the two. However, the magnetostatic interaction decays more slowly with distance, so it has a greater impact at length scales of about 100nm and above. The overall orientation of the dipoles also depends on the specific structure of the material, which gives the magnetism an anisotropy that does not decay with distance.

So to determine the magnetization distribution in a nanomagnet of a particular shape and size, one has to take all three contributions into account. But attempting to calculate the precise electron wavefunctions at each atomic site in a material would take vast amounts of computer time. Instead, scientists ignore the atomic nature of the material and introduce an approximate phenomenological expression for the exchange interaction. This approximation lets scientists simulate the distributions of magnetization in complex lithographically fabricated structures ranging in size from 10 nm to 10 μm .

Magnetic Anisotropy Energy

The property that makes magnets so useful is the magnetic anisotropy energy (MAE), which describes the tendency of magnetization to align along specific spatial directions rather than randomly fluctuate over time. The MAE determines the stability of the magnetization in bulk as well as nanoparticle systems. With respect to bulk solids, surface- supported nanoparticles offer additional degrees of freedom to tune the MAE by ad hoc modifications of the particle size, shape, and coupling with the substrate, making nanosized systems attractive for basic investigations as well as for miniaturized data-storage applications [4].

The model can be refined by including the effects of temperature, which can make atomic spins to fluctuate. As a material gets warmer, the amount of magnetic order falls until it eventually loses all magnetization and becomes paramagnetic. Thermal effects are much stronger in low- dimensional materials than they are in the bulk. Figure 7 shows some experimental data to determine this temperature, also known as blocking temperature, at which a magnetic nanostructure will lose its preferred magnetization direction [8]. The ZFC curve has the peak at the blocking temperature. Above the blocking temperature, the magnetization direction of a nanostructure will fluctuate randomly in absence of any external magnetic field. This effect is called “superparamagnetism”. Also inset of Figure 7 shows that above the blocking temperature, nanomagnets lose their hysteresis property.

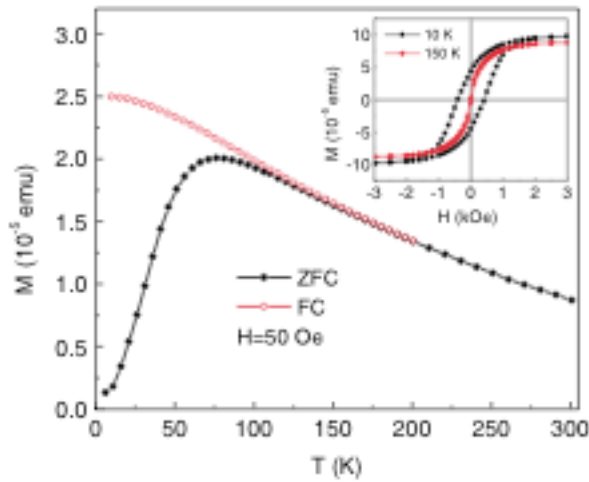


Fig. 7: Temperature dependence of the dc magnetization in a 50 Oe field for both ZFC and FC processes. Inset shows the M-H curves below and above the blocking temperature.

Like MAE, blocking temperature also depends on size, shape, material and substrate. Many researchers across the world are now trying to increase the blocking temperature of the nanomagnets. Blocking temperature usually increase with number of atoms. Shapes also matter. Nanorods usually have higher blocking temperature than nanodots of comparable volume.

M.H. Pan et al. have shown that their nanoplatelets have a blocking temperature of as high as 100 K [3]. Qualitatively, they attribute the unusually high values of TB observed in their systems to the extremely thin and planar geometry of the nanomagnets. For ultrathin films of only a few monolayers in thickness, the surface anisotropy often dominates, resulting in magnetization perpendicular to the surface. In their samples, hysteresis is observed only when the magnetic field is perpendicular to the surface, indicating the dominance of the surface anisotropy. Moreover, the observed anisotropy is even a factor of 2 higher than that observed for Co/Au(111).

The MAE also depends on material and substrate on which nanostructures are grown. Scientists found that cobalt atoms on a platinum substrate have a particularly large magnetic anisotropy energy, which describes the tendency of the magnetization to align along specific spatial directions rather than fluctuate randomly over time. According to Gambadella *et al.*, each cobalt atom had an anisotropy energy of about 9.3 meV, which is about 200 times larger than that of a bulk crystal. In comparison, samarium cobalt, which is a widely used permanent magnet, has a value of just 1.8 meV per cobalt atom [6, 9]. It can be concluded that the enhanced anisotropy in Co/Pt(111) system is due to the Co atoms along the island peripheries, which have lower coordination numbers than those in the substrate. As a result, the MAE per atom of nanostructures depends on its surface/volume ratio [4].

Prospects for data storage

Using nanomagnets one can design a new generation of magnetic hard disks. Due to advances in thin-film magnetism and magnetic sensors, the size of data bits has fallen from $10\ \mu\text{m} \times 0.7\ \mu\text{m}$ two decades ago to just $300\ \text{nm} \times 15\ \text{nm}$ in 2002. Unfortunately, the signal detected by the read head becomes more noisy as the data bits get smaller, and fewer grains fit into each bit. The obvious solution is to make the grains themselves smaller. But if the grains are too small, data are more likely to be lost because thermal

fluctuations can cause the magnetization in a grain to accidentally flip direction. So increasing MAE is one of the main goal of scientists doing research with nanomagnets.

Nanomagnets in Biology and Medicine

Nanomagnets are also being increasingly used in biomedicine. They can, for example, enhance the signal from magnetic resonance imaging (MRI). One way of boosting the MRI signal is to use contrast agents made of magnetic nanoparticles that vary in size from 10–500nm. These agents include superparamagnetic iron-oxide particles that have been coated with a suitable chemically neutral material to prevent them from reacting with body fluids. The particles – dubbed magnetic nanobeads – can be injected into the bloodstream and, depending on their size, travel to different organs. By selecting particles of particular sizes, researchers can then study specific parts of the body [6, 10].

Nanomagnets could also be used for drug-delivery. The magnetic nanobeads are first laced with drug molecules and then steered by external magnetic-field gradients until they reach the desired parts of the human body. This targeted drug delivery technique limits the amount of healthy tissue that is exposed to the drug and is one of the most active areas in cancer research, where it is currently the subject of clinical trials. It has also been reported that cancerous cells can be treated thermally, based on the fact that some cancer cells are more susceptible to high temperatures than normal cells. Therefore, by increasing the temperature of the tissue to more than 42°C, the cells could be selectively destroyed. To achieve this, a dose of magnetic nanoparticles could be injected into a region of malignant tissue, after which an alternating magnetic field could be applied to the particles. If the field is sufficiently strong and of optimum frequency, the particles would absorb energy and heat the surrounding tissue, thereby affecting only the infected cells.

Inference

Despite the many applications of nanomagnets in biomedicine, the field is still driven by the search for faster, cheaper and higher-density magnetic-storage devices and sensors. The three main challenges are to design new types of magnetic nanostructures, to increase the blocking temperature for such materials, and to ensure that such nanostructures can be made cheaply in large quantities. With nanomagnets promising to revolutionize both electronics and biomedicine, it is clear that they will play an increasingly large role in our lives.

References

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