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Tailoring magnetism in artificially structured materials: the new frontier

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Abstract

The current standard of electronic devices and data storage media has reached a level such that magnetic materials have to be fabricated on a nanometer scale. In particular, the emerging concept of spintronics, which is based on fact that current carriers have not only charge but also spin, requires the assembling of nanometer-sized magnetic structures with desired magnetic properties. It is this background that motivates scientists and engineers to attempt to grow and characterize magnetic objects at smaller and smaller length scales, from 2D films and multilayers to 1D wires and eventually to 0D dots. In this article, some of the most significant progress in recent years in the effort of growing artificially structured magnetic materials are reviewed. The new structural and magnetic properties of these materials are discussed, with an emphasis on the correlation between structure and magnetism, which also serves as guidance for improving their magnetic properties. The emerging emphasis is on converting the existing knowledge into growing and studying low-dimensional complex materials, which promise to have considerably higher "tuning" ability for desired properties.

Keywords: Magnetic films; Magnetic interfaces; Metal–metal magnetic heterostructures; Epitaxy; Magnetic phenomena (cyclotron resonance, phase transitions, etc.); Electrical transport (conductivity, resistivity, mobility, etc.)

1. Introduction

In modern society, applications of magnetic materials can be found almost everywhere. From the familiar small magnets that hang our children's drawings on the refrigerators, to the almost as familiar industrial transformer cores, motor generators and microwave guides, our daily life is intimately tied to magnetism and magnetic materials. The most noteworthy impact of magnetism occurs via information transport and data storage devices, which mostly consist of artificially structured magnetic materials. Here artificially structured materials (ASM) refer to the materials which are either made into reduced dimensions such as two-dimensional (2D) ultrathin films, one-dimensional (1D) wires and zero-dimensional (0D) dots, or assemblies of these low-dimensional structures such as multilayers, wire and dot arrays. Magnetic ASM have been utilized in technologies with a large and growing economic impact. The magnetic

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recording industry alone exceeds $100 billion in annual sales. It is continuously pushing the technical envelope as evidenced by the fact that over the past decade, the density of information storage has been increasing at a compound annual rate exceeding 60% per year while the cost of storing information on a computer hard drive has been decreasing at the same rate [1].

This progress has been made possible by a series of scientific and technological advances, mostly marked by the synthesis of artificially structured magnetic materials. Consider, as an example, the read head of a disk drive. The technological challenge in this case is to sense the ever smaller magnetization of each "bit", whose size keeps decreasing with increasing density. The traditional inductive read sensors could no longer be scaled to the rapidly decreasing sizes required and a more sensitive sensor was clearly needed. In 1988, a phenomenon called giant magnetoresistance (GMR) effect was first observed by German and French scientists independently in a metallic multilayer system consisting of stacked thin films of magnetic and nonmagnetic materials [2,3]. Fig. 1 demonstrates the principle of GMR effect using a schematic view of a ferromagnetic Co/nonmagnetic Cu trilayer. Here both Co and Cu contain electrons with opposite spin directions, which are defined as "spin up" and "spin down". The difference is that the number of spin up and spin down electrons are equal in nonmagnetic Cu and unequal in ferromagnetic Co. If a voltage is applied between the two Co layers, both "up" and "down" electrons will sense the voltage and try to travel from one Co to the other Co layer through the Cu layer as well as the two Co/Cu interfaces. However, the electronic structures of Co and Cu are such that the up electrons of Co and Cu have matching potentials, and the Co down electrons are in a considerably lower potential than that of Cu. This means that the Co up electrons will have no difficulty to pass through the first Co/Cu interface and reach the second Co/Cu interface, while the Co down electrons will mostly be scattered back at the first Co/Cu interface. At the second Co/Cu interface, the Co up electrons can only pass through if there are "empty space" available for up electrons in the second Co layer.

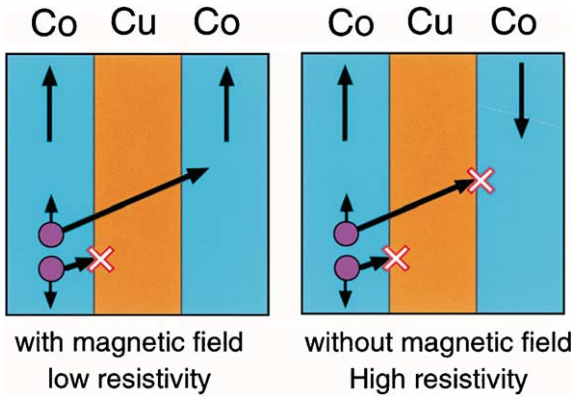

Fig. 1. Schematic view of a Co/Cu/Co trilayer which exhibits GMR effect. When a bias voltage is applied between Co(I) and Co(II) layers, the spin up and spin down electrons in Co(I) layer form two independent current channels to travel across the trilayer. Due to the potential barrier between the Co and Cu electrons, the spin down electrons are scattered back at the Co(I)/Cu interface independent of the relative magnetization orientations between the two Co layers. The spin up electrons in Co(I) have much less difficulty to reach Co(II) when the magnetization of the two Co layers are parallel as compared to the antiparallel case. As a result, the resistance of the trilayer is minimum (maximum) when the magnetization of the two Co layers are parallel (antiparallel).

From Co electronic structure we know that such "empty space" is created when the magnetization of the two Co layers are parallel. As a result, the electrical resistance of such a Co/Cu trilayer system reduces to the minimum when the magnetization of the two Co layers are parallel, and increases to maximum when the magnetization of the two Co layers are antiparallel. The change of the resistance with respect to the maximum resistance is often referred as magnetoresistance. The word "giant" is used for the multilayer system because its magnetoresistance is typically around 10–100%, which is one to two orders of magnitude larger than the conventional magnetoresistance in bulk ferromagnetic metals.

The key to have a large GMR effect is to make sure the two Co layers are absolutely antiparallel in the absence of an external field. This relies on an interaction called indirect exchange coupling between the two Co layers. The indirect exchange coupling has a oscillatory behavior which favors either parallel (ferromagnetic coupling) or

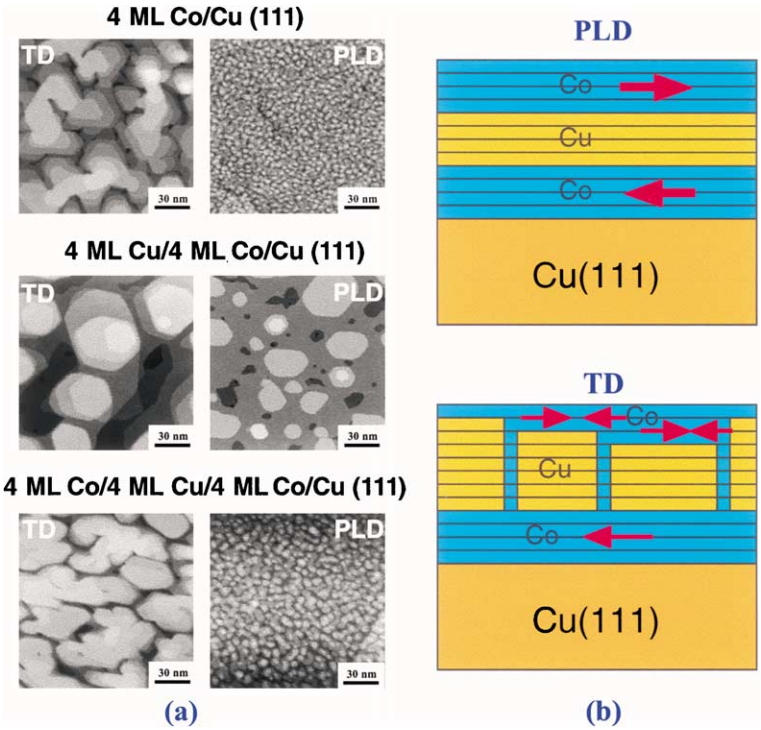

Fig. 2. (a) Surface morphology of a Co/Cu/Co trilayer grown on Cu(1 1 1) using MBE (left) and PLD. The images were taken as snapshots after the completion of each layer by STM. The roughness of the TD trilayer is much higher than that of the PLD trilayer. The Cu spacer layer does not completely separate the two Co layers in the TD trilayer. (b) Schematic views of the TD and PLD trilayer shown in (a). Magnetic measurements confirm that only the PLD trilayer has realized a complete antiferromagnetic coupling between the two Co layers.

antiparallel alignment (antiferromagnetic coupling) depending on the Cu interlayer thickness. For a complete antiferromagnetic coupling, the Cu interlayer has to be uniformly thick in space. In Fig. 2 we again use the example of Co/Cu trilayer to demonstrate that synthesis plays a key role to achieve desired magnetic properties of a GMR device. On a single crystal Cu with (1 1 1) surface orientation, Co/Cu/Co trilayers were grown by two techniques, i.e. molecular beam epitaxy (MBE or TD) and pulsed laser deposition (PLD). The major difference between these two growth techniques is the deposition rate, with PLD rate (during each pulse) being six orders of magnitude larger than that of the TD. From the surface topography images taken by scanning tunneling microscope (STM), as shown in Fig. 2(a), the TD grown Co/Cu trilayer is so rough that the Cu interlayer does not completely separates the two Co layers. The PLD trilayer, however, grows in a nearly ideal layer-by-layer manner and thus form a high quality trilayer with sharp Co/Cu interfaces. Consequently, the two Co layers are completely antiparallel aligned in the PLD trilayer, and only partially antiparallel aligned in the TD trilayer, as schematically shown in Fig. 2(b) [4]. This example clearly tells us that synthesis can make a real difference in magnetic properties of ASM.

Artificially structured magnetic materials are also critical to the future progress of the computer and electronics industries as they confront the fundamental barriers that stand in the way of continued exponential growth in integration density and circuit speed. Recently, a new breed of electronic devices has emerged, promising major breakthroughs in these areas. These new devices

are called spintronic or magnetoelectronic devices. They utilize the fact that the current carriers (either electrons or holes) in electronic devices carry not only charge but also spin [5]. An illustrative example is the so-called magnetic random access memory (MRAM). The MRAM, based on the GMR effect or spin-dependent tunneling effect, has the advantage of being nonvolatile, yet with faster speed, higher density and lower cost, compared to the current dynamic random access memory (DRAM) devices, which are based on charged capacitors. Several major recording industries are working intensively on the MRAM projects and it is highly hoped that in the next few years PCs will all be ''instant-on'' computers since the MRAM, with its nonvolatile nature, does not require any booting time!

As we show in Figs. 1 and 2, the promise of these technologies can only be attained to the extent that we learn how to fabricate high quality magnetic thin films, multilayers or even smaller objects. This has not always been an easy task despite the rapidly improved techniques and knowledge of thin film growth. The major difficulty comes from the fact that there are many parameters that influence growth quality, because the ASM are often grown under conditions that are far from thermodynamic equilibrium. The quality of thin films depends on both the thermodynamics and growth kinetics. The presence of substrate often adds to the complexity.

To gain a fundamental understanding of the magnetic behavior of the ASM is another great challenge. This is because these materials often have a very different dimensionality, symmetry, or crystallographic structure compared to the traditional bulk magnets which we have known for a long time. For example, the thin films or multilayers are usually 2D, and sometimes they can have a crystallographic structure which does not exist in bulk at similar temperatures. As we will see later, by properly controlling the growth, 1D wires or 0D dots can also be fabricated. For years theoretician have speculated that reduced dimensionality will strongly affect the magnetism of magnetic materials [6]. Now with real samples in hand, scientists can finally study what kind of new magnetic behavior they would show. With this background, since the early 1980s, there have been a large number of research groups in the world working on magnetism of low-dimensional materials, and the observation of the GMR effect is one of the examples reflecting the significance and success of the research. With the ever improved knowledge of low-dimensional magnetism, particularly the correlation between the magnetic properties, electronic properties and structural properties, we are achieving an ability to design and to fabricate low-dimensional materials with desired magnetic properties, or, as summarized in our title, to tailor magnetism in ASM.

In this paper, we review some of the most important progress and successes in this part of the magnetism research in the past two decades. This, of course, cannot be done without addressing the synthesis of these ASM. In Section 2 we will discuss current knowledge about how to grow 2D films, 1D wires and 0D dots. While these low-dimensional objects remain to be ASM themselves, they are also building blocks of more complex artificial materials. The magnetic properties of these building blocks are reviewed in Section 3, and some general conclusions or comments on the correlation between structure and magnetism of these systems are presented. In Section 4 we address the fabrication of more complex artificial structures composed of these building blocks, and demonstrate how to achieve desired magnetic properties by strategically stacking them. The final section, Section 5, we project the future of designer magnets in various research and application directions.

2. Growth of low-dimensional magnets

2.1. 2D: epitaxial growth of ultrathin films

From magnetism point of view, the word ''ultrathin'' refers to the thickness regime within which the ferromagnetic exchange coupling strength is large enough to hold the magnetic moments parallel across the film thickness. The ultrathin limit, when expressed in film thickness, is typically of the order of 20–30 atomic layers for most magnetic thin film systems [7]. Because of this low thickness limit, small surface and interface roughness can

have significant influence on the magnetic properties of the films. For this reason, it is highly desired to grow the films in a layer-by-layer manner.

The growth mode of the magnetic films, mostly 3d elements of Fe, Co, and Ni or their alloys, is determined by a number of key parameters. These include the lattice mismatch between the substrate and the film, the substrate temperature during growth, the growth rate, and the surface free energies of both the substrate and the film. Bauer has given a simple free energy argument, which includes a comparison of the surface free energy of the bare substrate (which exists before film growth) and the sum of the free energies of the film surface and film/substrate interface (which are created after film growth), to predict the growth mode of films [8]. The general trend is that the higher the surface free energy of the substrate compared to that of the film, the more the films tend to wet the substrate. Three typical growth modes have been classified, they are layer-by-layer growth (Frank van de Merve growth), 3D island growth (Vollmer–Webber growth), or monolayer growth followed by 3D island growth (Stranski–Kastanov growth).

Although Bauer's free energy argument is plausible and physically transparent, it is a rule for growth under equilibrium condition. In real world, more than often the films are grown under a condition that the substrate temperature is too low and (or) the deposition rate is too high for thin film systems to reach its thermodynamic equilibrium. The growth kinetics plays an important and sometimes a dominant role which generally makes the islands denser and smaller. This, provided the lattice mismatch between the film and the substrate is not too large, will assist some of the thin films to grow layer-by-layer which is otherwise not favored from the free energy consideration. Such kinetics-limited growth is particularly important for growing 2D magnetic films, since the magnetic elements such as Fe, Co and Ni all tend to have a higher surface free energy compared to the noble metals like copper, silver and gold, which are often used as templates.

Experimentally the most reliable way to verify the layer-by-layer growth mode is using electron diffraction technique such as reflection high energy electron diffraction (RHEED) or medium energy electron diffraction (MEED). In real experiments the diffraction geometry is set up in a way where the reflected electron beams from neighboring terraces separated by monolayer high steps diffract constructively (in-phase) or destructively (out-of-phase). Thus, the reflected beam intensity is directly related to the layer distribution of the films, and will oscillate with a periodicity of 1 ML. For example, in out-of-phase condition, the beam intensity will reach a minimum when the surface layer is half filled, and a maximum when the surface layer is fully filled. Fig. 3 shows the MEED intensity oscillations of Fe films grown on Cu(1 0 0) substrate at room temperature. As indicated in the figure, above 2 ML the MEED intensity starts to oscillate layer by layer. The lack of oscillation for the first layer is primarily due to the poor first layer growth [9]. The corresponding surface morphologies of the films at the arrow-marked points (3

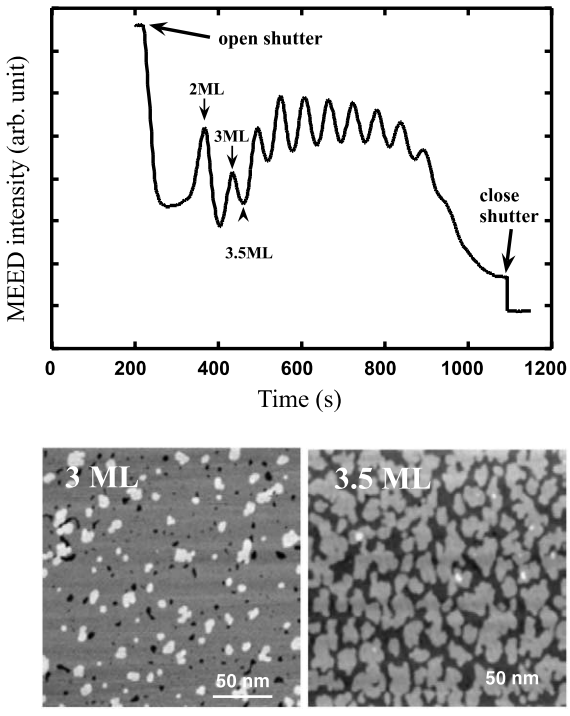

Fig. 3. Growth of Fe ultrathin films on Cu(1 0 0). Above 2 ML, Fe films grow layer by layer on Cu(1 0 0), as indicated by the periodic MEED oscillations (upper) and smooth STM surface morphology (lower).

and 3.5 ML) are shown by STM images below the MEED curve. Apparently the film grows layer by layer from 2 to 11 ML, as proved by both the MEED oscillations and the STM morphology, despite the fact that Fe has higher surface free energy than copper.

However, there do exist some magnetic thin film systems where layer-by-layer growth is extremely hard to achieve under usual growth conditions because of a rather large island edge diffusion barrier which hinders the necessary interlayer diffusion for the 2D growth. For example, Co has a 3D island growth mode on a Cu(1 1 1) substrate no matter what substrate temperature is used. The rough morphology of Co/Cu(1 1 1) films appears to be the main reason that MBE-grown {Co/Cu(1 1 1)} multilayers do not show the expected GMR effect [10,11]. To reduce the island edge diffusion barrier, one could either use surfactants such as Pb [12] or minimize the island size by ultrafast deposition [13], and in both cases good layer-by-layer growth of Co/Cu(1 1 1) films has obtained.

2.2. 1D: parallel atomic chains or stripes along the substrate steps

Magnetic 1D chains or stripes are distinguished from conventional magnetic nanowires by the fact that the former have a limited height and width which are less than few nanometers, while the latter can range from few to several hundred nanometers. As we pointed out earlier, for a ferromagnetic metal several nanometer is the length scale beyond which the individual magnetic moments are no longer all aligned in one direction. So far the growth of 1D magnetic chains or stripes has been mostly done using substrates with parallel aligned steps. The presence of steps can strongly alter the atomistic process of adatom diffusion. At a step edge the diffusion barrier tends to be higher than that on the terrace, hindering adatoms to cross over the steps. The local stress field around the step edges is also different from that on the regular terrace. In some cases the diffusion across the step edges is greatly suppressed resulting in a step decoration effect, i.e. deposited atoms stay in close vicinity to step edges. If the diffusion along the step edges is sufficiently active, 1D chains or stripes will be formed along the step edges. Fig. 4 shows the STM images of 1.0 ML Fe grown on flat (a) and vicinal with 1.2° miscut (b) Cu(1 1 1) substrates. On the flat substrate, Fe forms triangular-shaped islands with double- or triple-layer in height. On the vicinal surface, almost all Fe atoms are decorated along the step edges and form parallel stripes. The Fe stripes are typically 4 nm wide, 0.4 nm high and micrometer long along the step edges. The height and the width of the Fe stripes can be modified by

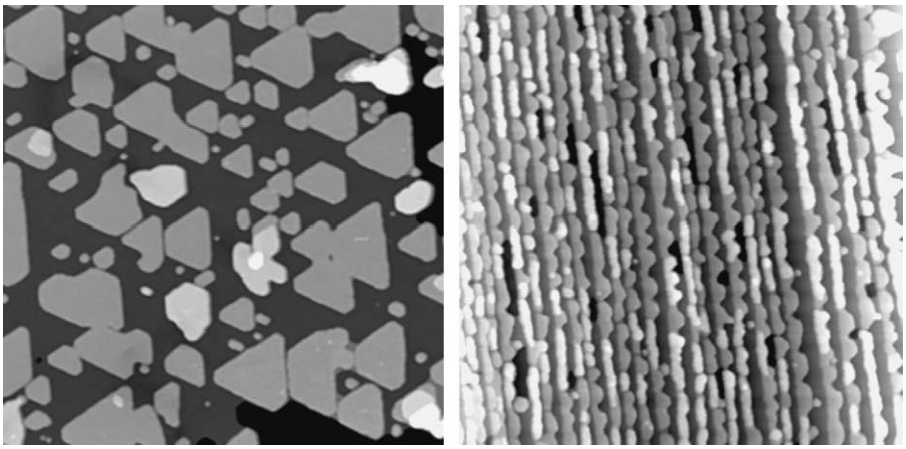

Fig. 4. Surface morphology of 1.0 ML Fe on flat (left) and vicinal (right) Cu(1 1 1) substrate. Scanning area is 200×200 nm^2. The Fe nanowires formed on the vicinal substrate are about 5 nm wide and 0.4 nm high.

changing the total dosage of Fe. Recently, 1D atomic chains of Co have been successfully grown on a high density stepped Pt(9 9 7) surface [14].

The step decoration effect is only applicable to a limited number of systems. If the substrates have a higher surface free energy than that of the film, a more general method can be used to grow 1D wires. This method is called step flow growth. The substrate should still be miscut to introduce parallel steps on the surface. The magnetic materials will then be deposited onto the substrate at a temperature which is high enough for the step-flow growth. If the dosage is a small fraction of a monolayer, parallel aligned stripes will be formed along the steps. 1D Fe stripes have been formed in this way on W(1 1 0) substrates [15].

While it is common to take advantage of step effect, there are alternative ways to grow 1D chains or stripes. The noteworthy ones include the formation of alternative 1D stripes of magnetic Co (or Fe) and nonmagnetic Ag on Mo(1 1 0) substrate [16], and deposition on grating NaCl(1 1 0) template at a glancing angle with respect to the surface [17]. Recently, it was observed that deposition at glancing angle on a flat substrate breaks the symmetry of islands [18], and can yield elongated islands with 1D appearance when the incident angle is close to 90° off surface normal at low temperatures [19].

2.3. 0D: ordered quantum dot arrays

Traditionally there are two ways to grow arrayed quantum dots (QDs), one is "serial" and the other is "parallel". The most typical serial way is using an STM tip to assist the deposition of magnetic clusters onto a chosen substrate. By precise control of the tip position, the QDs can be prepared one by one into any desired pattern [20,21]. Fig. 5 shows the morphology of Fe QD arrays prepared by STM-assisted chemical vapor deposition. After iron pentacarbonyl [Fe(CO)] gas is introduced into the UHV chamber, the STM tip had been moved into the location where the Fe QD is wished to be placed. A voltage pulse of about 10–20 V is applied between the tip and the sample. The local electric field dissociates the iron pentacarbonyl molecules. Iron clusters are deposited underneath the tip. The procedure is then repeated at all desired locations on the surface. A patterned QD array can be formed in this way.

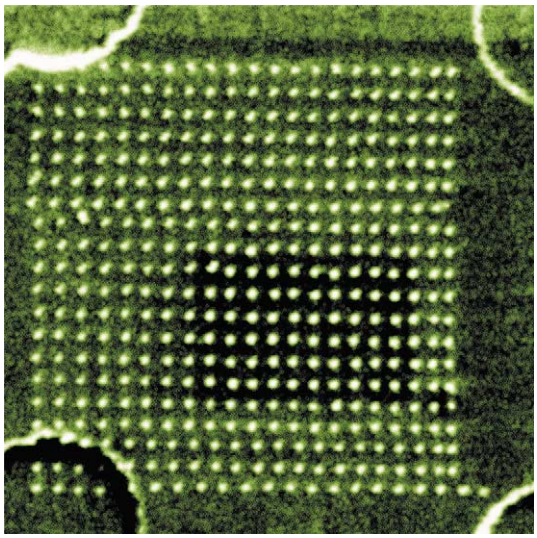

Fig. 5. Scanning electron microscope images (4.5×4.5 μm^2) of square Fe dot arrays grown by STM-assisted CVD onto a substrate of two-dimensional electron system (GaAs–$Ga_{0.7}Al_{0.3}As$) (image copied from Ref. [139]).

The major disadvantage of the serial method is its slowness. Although the time scale appears to be acceptable for laboratory research, it is virtually impossible to use such a method in manufacturing applications, where mass production of QD arrays needs to be done in a reasonably short time. Therefore, much of the recent research effort has gone to the parallel approach—self assembling the QD arrays. So far most of the self assembling of QD arrays have been done based on periodic stress effect. For example, in some thin film systems dislocations form a network with a particular symmetry. If growing magnetic material on top of such kind of films, the dislocations often repel adsorbed atoms diffusing over the surface, and so they serve as templates for the confined nucleation of nanostructures from adatoms. Fig. 6 shows the QD array of Fe nucleated on the dislocation network of a Cu bilayer on Pt(1 1 1) at 250 K [22]. The lateral dimension of the Fe islands and their distance are as small as about 2 nm, which means a density of the order of 10 Terabit/in.^{2}. Similar

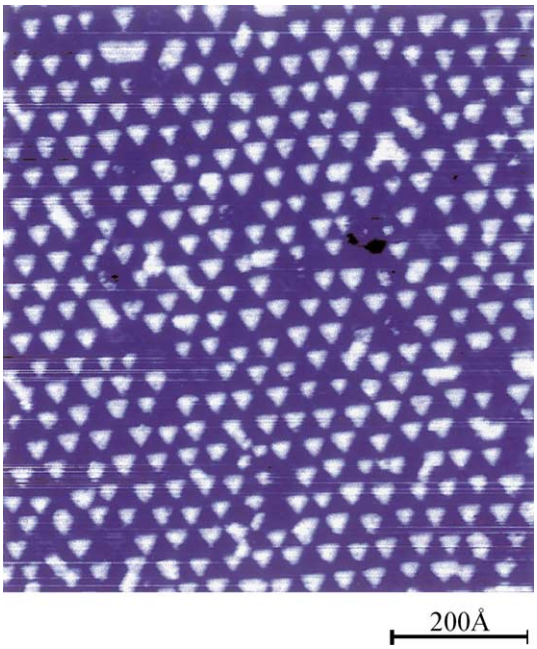

Fig. 6. STM image of a periodic array of Fe islands nucleated on the dislocation network of a Cu bilayer on Pt(1 1 1) at 250 K (image copied from Ref. [22]).

densities of magnetic dots has also been grown on a Au(1 1 1) $(23 \times \sqrt{3})$ reconstructed surface [23,24]. Teichert et al. have recently shown that it is possible to grow magnetic dot arrays by depositing magnetic materials at an glancing angle onto a semiconductor substrate with existing arrayed nanostructures, and an areal density of $0.25 \times 10^{12}/\text{in.}^2$ has been achieved [25].

The limitation of the parallel approach is that it is system specific and depends on whatever mother nature has offered to us. The key to creating a more general means to grow QD arrays is to eliminate the substrate effect. In the past, scientists have tried to use a cluster beam source to directly land QDs on substrates [26]. Another interesting approach is to adsorb inert gas elements (Xe, for example) on the substrate prior to deposition [27]. The adsorption temperature is kept low enough to have a solid phase on top of the substrate. The magnetic elements are subsequently deposited onto the inert buffer layer at cold temperature. The adatoms will have a very high mobility to easily form QDs on the buffer layer. The system is then gently warmed up to evaporate the buffer layer away, and the QDs will softly land on the real substrate. Very recently, it was suggested that the QDs will form a triangular lattice if they are electrically charged before the landing process [28].

3. Magnetism of low-dimensional materials

3.1. 2D ultrathin films

In the middle of the 1960s, Mermin and Wagner predicted that a 2D system would not exhibit long-range magnetic order at finite temperatures if the system is magnetically isotropic [29]. This prediction appeared to be confirmed by early experimental results on Ni thin films, where magnetic "dead layers" were claimed at the surface [30]. Although these results are now known to be an artifact due to the contamination in the film preparation process, they stimulated great interest in studying magnetic properties of surfaces and thin films. The follow-up experiments on various ultrathin films have provided overwhelming evidence to show that ferromagnetic order does exist even in monolayer films. The long-range order is now understood to be stabilized by either magnetic uniaxial anisotropy—an energy term which favors all magnetic moments aligned along one particular direction [31], or long-range dipolar interaction—an interaction between the magnetic moments similar to attraction or repulsion between two ordinary magnets [32]. Both the uniaxial anisotropy and the dipolar interaction suppress the long-wave length spin fluctuations at finite temperatures, which in turn stabilize the ferromagnetic order.

The existence of ferromagnetic order in ultrathin films obviously is great news for scientists who are interested in low-dimensional magnetism. In the past two decades, magnetic ultrathin films have been extensively studied and some striking differences between 2D ultrathin films and 3D bulk, as shown below, have been observed and understood. For ultrathin films, while the reduced dimensionality and the surface effect are the main reasons for their new magnetic properties, growth-linked

parameters such as roughness and stress can also significantly affect the magnetic properties. In the following, we mention a number of important and general magnetic properties associated with 2D ultrathin films.

3.1.1. Surface magnetic anisotropy and spin reorientation

In general the magnetization direction of 2D ultrathin films tends to be parallel to the surface plane. This is because for a slab-shaped ultrathin film, if all the magnetic moments are aligned parallel to the film plane, there are no exposed magnetic free poles (much similar to the south and north poles of a permanent magnet) throughout the sample except at the very ends of the film. The number of magnetic free poles increases when the moments are aligned along any other directions. By having the least exposed magnetic free poles, the magnetostatic energy reaches the minimum for the system. Therefore, if there are no any other energy terms involved, the magnetization direction of an ultrathin film always lies in the film plane. This tendency towards in-plane magnetization, since it is originated from the slab shape of the film, is termed as shape anisotropy. Besides the shape anisotropy, there exist other energy terms that favor certain orientations of the magnetization. For example, for a magnet with crystallographic symmetry, there exists an energy term called magnetocrystalline anisotropy, which favors magnetization direction along certain major crystal symmetry axes. At the surface of a magnet, as first pointed out by Néel [33], due to the missing neighbor atoms, the magnetocrystalline anisotropy is generally one to two orders of magnitude larger than that of the bulk. This new energy term is often referred to as surface anisotropy, which may favor magnetization direction either parallel or perpendicular to the film plane depending on the system. In case the surface anisotropy favors perpendicular magnetization and is large enough to overcome the in-plane shape anisotropy, the magnetization direction of the film will be perpendicular to the film plane. Such perpendicular magnetization has been observed in numerous magnetic ultrathin film and multilayer systems [34–36], which have attracted great attention because of their potential use as high density recording materials.

The competition between the surface, shape and some other anisotropy energies gives rise to a striking magnetic phenomenon called spin reorientation (SRT) which involves 90° rotation of the magnetization direction from perpendicular to in-plane or vice versa. Experimentally it has been observed that the SRT can be driven by film thickness, temperature [37,38], and film chemical composition [39]. As an example, we explain how SRT occurs via increasing film thickness in a system with perpendicular surface anisotropy. At low thickness, the ratio of the surface atoms to the atoms underneath is large enough that the surface anisotropy wins the competition against the shape anisotropy. The magnetization of the system is thus perpendicular to the film plane. With increasing thickness the ratio of the surface atoms to the atoms underneath decreases. At a certain critical thickness, the surface anisotropy becomes equal to the shape anisotropy. Above this thickness, the shape anisotropy dominates and the system becomes in-plane magnetized. In most systems, the SRT is from perpendicular (at low thickness or low temperature) to in-plane (at high thickness or high temperature), and the critical thickness or critical temperature defines the point where the surface anisotropy just compensates the shape anisotropy. However, reversed SRT from in-plane to perpendicular has also been observed in Ni/Cu(1 0 0) system [40,41], whose origin was attributed to the involvement of an additional anisotropy energy other than the surface and shape anisotropy. For interested readers, the description of the reversed SRT is referred to the original references listed above.

From a thermodynamic point of view SRT represents a phase transition [42]. Consider the perpendicular component of the magnetization, or the angle of the magnetization with respect to the film plane, their change with increasing thickness or temperature can be of first order, when it proceeds via abrupt rotation of magnetization, or of second order when the magnetization rotation is continuous. In real systems the former is characterized by the coexistence of perpendicular and in-plane magnetic domains [43,44], and the latter is

featured with a single domain with magnetization direction pointing at an angle between 0° and 90° with respect to the film plane. A recent study on ultrathin Fe/Gd(0 0 0 1) films has shown that both types of SRT occur in two steps with increasing temperature [45]. Comprehensive theoretical work has been carried out by Millev et al. [46].

3.1.2. Enhanced magnetic moment

The enhancement of the magnetic moment in a 2D system can be generally understood as a result of reduced nearest neighbor atoms. Take Fe as an example, the magnetic moment of an Fe atom is $4.0\mu_B$ in isolated form (no nearest neighbors), and is reduced to $2.2\mu_B$ in bulk crystal (eight nearest neighbors). A 2D Fe film, which has an intermediate number of nearest neighbors, should thus have a moment between that of the bulk and a free atom. Theoretical calculation of a free-standing Fe(1 0 0) single-atomic-layer (monolayer) thick film has indeed revealed a moment of $3.07\mu_B$ [47]. An Fe film has to be supported by a substrate. Since the electronic hybridization between film and substrate often counteract with the reduced dimensionality, the best substrates are those whose electronic structure is clearly separated from that of the substrate. In this respect Fe/MgO(1 0 0) serves as a good candidate since the Fe and Mg electronic structures are well separated. Indeed, the calculation performed on monolayer Fe on MgO(1 0 0) substrate yields magnetic moment of $3.04\mu_B$ [46], which is very close to that of the free-standing Fe(1 0 0) monolayer. Experimental measurements of magnetic moments of 2D films are generally very challenging, although torsion magnetometry and polarized neutron reflection have been applied successfully. Enhanced magnetic moments have been observed in ultrathin film systems such as Fe/W(1 1 0) [48] and Fe/Ag(1 0 0) [49].

As seen in Fig. 3, even for a thin film system with good layer-by-layer growth, the exposed surface layer is not ideally flat due to the presence of some islands. Since a reduced number of nearest neighbors tend to increase the magnetic moment of surface atoms, the moment of magnetic atoms at the edges of islands would be even larger because their nearest neighbors are further reduced. Albrecht et al. have compared the magnetic moments of Fe/W(1 1 0) films with rough surface (more step edge atoms) and smooth surface (less step edge atoms), and concluded that the moment enhancement at the step edge has a upper limit of about $1.1\mu_B$ [50]. Similar results have been obtained by nonlinear magneto-optical Kerr effect measurements on Co/Cu(1 0 0) films [51], where one monolayer oscillation period of the surface magnetization was observed due to variation of roughness with the same periodicity.

3.1.3. Curie temperature and critical behavior

The temperature dependence of magnetic order also depends upon the dimensionality of a magnet. The Curie temperature, which separates the ferromagnetic and paramagnetic phases, is determined by the strength of magnetic anisotropy and dipolar interaction because the aforementioned Mermin–Wagner theorem shows that isotropic exchange interaction gives no long-range order. Because the strength of both magnetic anisotropy and dipolar interaction are often smaller than the strength of exchange coupling, the Curie temperature is, not surprisingly, reduced for a 2D film. However, as pointed out by Erickson and Mills [52], the Curie temperature of the films increases with thickness and will be close to that of the bulk when the films reach several monolayer thickness. The thickness dependence of the Curie temperature is most properly expressed by finite-size scaling theories [53], which were backed by various experimental results on ultrathin films of Fe [54], Co [55], and Ni [56].

The temperature dependence of spontaneous magnetization near the Curie temperature is called the critical behavior, which is often characterized by the exponent of a phenomenological power-law fitting of the magnetization vs. temperature data. The smaller the power-law exponent, the faster the magnetization falls to zero when approaching the Curie temperature. The amplitude of the power-law exponent depends on the anisotropy and the dimensionality of the magnetic system, generally the lower the dimensionality, the smaller the power-law exponent. Huang et al. [57] have reported the values of the power-law exponents for various ultrathin films and their cross-over from 2D to 3D when increasing the film thickness.

3.1.4. Correlation between structure and magnetism

The magnetic properties and the structural properties of 2D ultrathin films are strongly correlated. Magnetic quantities such as magnetic moment, magnetic anisotropy and Curie temperature are closely linked to structural parameters such as lattice constant, strain, roughness etc. A good example to illustrate the magnetic moment–lattice constant correlation is the fcc Fe ultrathin films on Cu(1 1 1) substrate. Fig. 7 shows the thickness dependence of magnetic moment of Fe/Cu(1 1 1) films measured by the magneto-optical Kerr effect. The linear slope for films above 3 ML is about three times smaller than that of the films below 3 ML, indicating that the magnetic moment of the Fe films drops by a factor of 3 at about 3 ML or above. Detailed structural analysis by RHEED shows that the lattice constant of the films happens to become smaller also at 3 ML or above, which is the likely origin of the reduction of the moment [58].

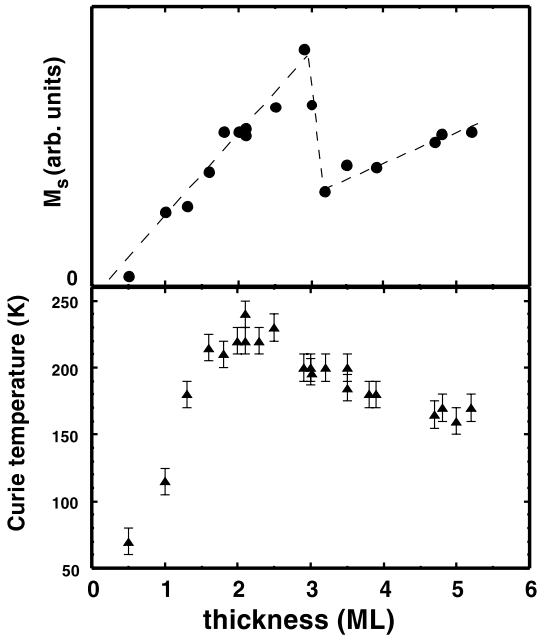

Fig. 7. Saturation magnetization along the surface normal (upper panel) and Curie temperature (lower panel) as a function of the thickness of the Fe/Cu(1 1 1) films prepared by PLD M_s increases linearly with thickness reaching its maximum at about 3 ML, and then drops to a smaller value. At higher thickness M_s again linearly increases but with a smaller slope. The change of the slope reflects a magnetic phase transition from a high moment ferromagnetic phase to a low moment ferromagnetic phase. The Curie temperature reaches a maximum at 2 ML, and then gradually decreases with increasing thickness.

The magnetic anisotropy in 2D films is affected by a number of structural parameters including the strain, roughness and intermixing between film and substrate. Epitaxially grown films, if they have a lattice mismatch with the substrate, their lattice constant will be stretched or compressed to match the substrate lattice in the lateral directions, which will result in a contraction or an expansion of the film lattice in the vertical direction (tetragonal distortion), respectively. This tetragonal distortion essentially breaks the crystallographic symmetry of the films. As a result, the strain-induced magnetic anisotropy shows up similarly to surface anisotropy. The strain-induced anisotropy can contribute significantly to the magnetization orientation in films, depending on both the sign and the amplitude of the lattice mismatch between the film and the substrate. We use an unusual SRT in Ni/Cu(1 0 0) ultrathin films to demonstrate the importance of the strain-induced anisotropy. As mentioned, the conventional SRT in ultrathin films involves 90° spin rotation from perpendicular to in-plane direction with growing film thickness. The Ni/Cu(1 0 0) films, however, have an interesting reversed SRT which goes from in-plane to perpendicular. It is now understood that the Ni/Cu(1 0 0) films have an in-plane surface anisotropy and a perpendicular strain-induced anisotropy [59]. The contribution of surface anisotropy is inversely proportional to the film thickness. Therefore above a critical thickness the perpendicular strain-induced anisotropy takes over despite of the in-plane shape anisotropy. This explains the reversed SRT and shows how significant the strain-induced anisotropy can be in an ultrathin film system.

The surface roughness has its influence on magnetic anisotropy by changing the effective surface symmetry or shape of the films. The surface symmetry is broken at step edges, whose density is directly associated with the surface roughness. Using a simple model, Bruno has argued that the existence of the step edge atoms would cause the reduction of the effective surface anisotropy [60]. The surface roughness also reduces the in-plane

shape anisotropy [61]. In an extreme case, the shape anisotropy could favor perpendicular magnetization if the roughness is high enough to show columnar islands [62]. For ordinary 2D films, the effect of roughness is generally too small to change the direction of magnetization, although it does appear to have some influence on the magnetization direction at the critical thickness of the SRT where other anisotropies of the film cancel out [63].

In some magnetic ultrathin film systems, the correlation between structure and magnetism can be complex. No other system shows such complexity better than the Fe/Cu(1 0 0) ultrathin film system. Initially this system attracted attention because at room temperature Fe grows on Cu in fcc structure [64], a high temperature phase which has been predicted to have rich magnetic phases by theories [65–67]. Early experimental results indeed indicated signs that more than one magnetic state exists in this system [68–70]. It was later found out, as seen in Fig. 8, that the system can be divided into three regions based on their magnetic states [71]. In region I (below 4 ML), the films have a uniform high moment ($\sim 2.5\mu_B$) ferromagnetic phase as shown by the linear increase of magnetic moments as a function of thickness and proved by other experimental measurement [72,73]. The high moment ferromagnetic phase was understood to be linked with increased atomic volume of Fe due to the tetragonal expansion [74]. In region II (4–11 ML), the magnetic moment of the film is nearly a factor of two smaller than that of the 4 ML film, and kept nearly constant for all thicknesses in region II. More careful experimental measurements indicates that the moment of the film actually oscillates with increasing thickness. The current understanding of such interesting magnetic behavior is that the top one or two layers of the films have a high-moment ferromagnetic phase, and the layers underneath have some sort of antiferromagnetic structure [75,76]. The structural origin of the coexistence of the ferromagnetic and antiferromagnetic phases have been discussed mainly based on the fact that the films undergo a structural transition from fct (tetragonally distorted fcc) to fcc for all layers except the top two in region II, although the real structure of the films is more complex due to a fcc to bcc Martensitic structural phase transformation [77,78]. In region III (>11 ML), the fcc to bcc structural transformation completes and as a result, the bcc films become again uniformly magnetized with an easy magnetization being parallel to the film plane. The precise location of the transition regions on the thickness scale is in addition influenced by adsorbates, e.g. carbon monoxide [79] and hydrogen [80].

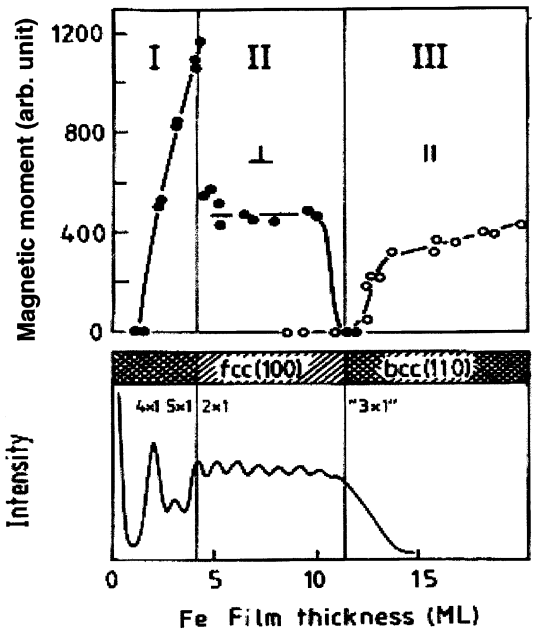

Fig. 8. Correlation between magnetism, structure and growth of Fe/Cu(1 0 0) ultrathin films. In the upper portion the measured magnetic moment at $T = 0$ K are depicted as a function of film thickness. Filled and open circles represent data recorded when external field is applied perpendicular ($\perp$) and parallel ($\|$) to the film plane, respectively. In the first two regions the magnetization is perpendicular to the film surface and parallel in region III. In the lower portion the intensity of the (0 0) MEED beam is depicted during Fe deposition showing the three different regions. The corresponding surface reconstructures for each region (4×1, 5×1 in region I, 2×1 in region II, and 3×1 in region III) are denoted as well. Between 4 and 11 ML in region II, the film is in fcc structure with (1 0 0) orientation (fcc(1 0 0)). Above 11 ML the films transform from the fcc(1 0 0) structure to a bcc structure (bcc(1 1 0)). (Figure copied from Ref. [140]).

3.2. 1D stripes

As mentioned, in two dimensions the magnetic anisotropy or even dipolar interaction can

suppress magnetic fluctuations and stabilize long-range ferromagnetic order. By contrast, in a 1D magnetic system, theoretical arguments show that even a highly anisotropic system does not yield a zero-field equilibrium spontaneous magnetization [81]. The prototype model is the Ising chain of localized spins or spin blocks with nearest-neighbor exchange interaction, which has no long-range order at nonzero temperatures [82]. However, it was also realized that an Ising chain could show the usual characteristics of a ferromagnet at low temperatures, because of the separation of the two ground states (spin up and spin down) and that thermal activation is needed for spin rotation [83]. Experimentally a large number of work on 1D magnetism were performed on organic or inorganic compounds with chains of 3d ions. The large intra-chain interaction (on the order of 10–100 K) and a much weaker inter-chain interaction (typically 100 or 1000 times smaller) have made these compounds quasi-1D magnetic systems. These compound materials have provided a large playground to study some fundamental magnetism issues such as 1D magnetic excitations and correlation between magnetic order and chain–chain interactions [84–86]. In this article we discuss 1D stripes formed by 3d magnetic metals such as Fe, Co and Ni, which are potentially important for future spin electronic devices.

So far only a limited amount of work has been done on 1D magnetic stripes. The magnetic measurements were pioneered by Elmers et al. on Fe stripes grown on W(1 1 0) substrate [87]. These Fe stripes showed a strong in-plane anisotropy perpendicular to the stripe axis and a magnetic behavior similar to that of a 2D film with uniaxial anisotropy, despite their quasi-1D appearance. It was later argued by the same authors, based on a Monte Carlo simulation, that a inter-stripe dipolar interaction has helped to stabilize the long-range order, which was consequently termed as "dipolar superferromagnetism" [88]. Fig. 9 shows the morphology (a) and the sharp magnetic phase transition (b) of the Fe/W(1 1 0) stripes. Magnetic domain imaging has been recently performed on such Fe stripes [89].

Distinctly different magnetic behavior has been observed in 1D Fe stripes grown on a Cu(1 1 1)

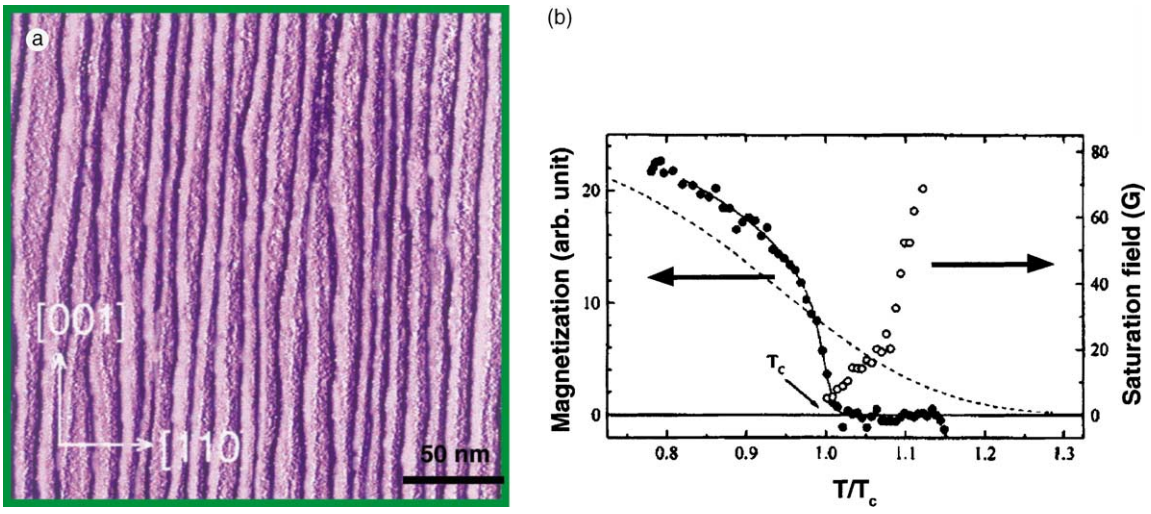

Fig. 9. (a) Differentiated STM image (250×250 nm^2) of a vicinal W(1 1 0) surface with steps along [0 0 1], covered by 0.8 ML of Fe. Note that the lighter colored stripes adjacent to the step edges are the Fe 1D stripes. (b) Remanent magnetization (•) and saturation field (○) as a function of temperature ($T_c = 179$ K). The full line represents a fit by a power law of exponent $\beta = 0.32$, convoluted with a Gaussian distribution of mean value $T_c = 179$ K and width of $\Delta T_c = 1.7$ K. The dashed line shows the same function but with a broader distribution of width $\Delta T_c = 15$ K, as would be expected for noninteracting stripes. (Figure copied from Ref. [88]).

substrate [90]. Since the Fe/Cu(1 1 1) stripes have an easy magnetization axis perpendicular to the substrate surface, dipolar interaction between the wires would not favor ferromagnetic ordering in this case. Although the wires do show hysteresis loops at low temperatures, their magnetization, in the absence of external field, is not stable with respect to time. The differences between the Fe/W(1 1 0) and the Fe/Cu(1 1 1) stripes indicate that the interaction between the stripes can affect significantly the overall magnetism of 1D stripes.

Besides magnetic ordering, several other magnetic properties of 1D wires have been discussed in the literature. A theoretical calculation has shown very interesting magnetic anisotropic behavior for 1D chains [91]. Not only does the magnetic anisotropy energy appear to be one order of magnitude larger than that of the 2D film, the anisotropy direction could even oscillate from along the chain to perpendicular to the chain depending on the chain width. For thicker wires (on the order of micrometer scale in width), the presence of domain walls appear to be significant for both magnetization reversal [92] and the transport properties [93] of the wires.

3.3. 0D particles and dot arrays

A small magnetic particle is a quasi-0D object which has different magnetic properties compared to their 2D or 3D counterparts. With decreasing size, magnetic particles first become single domain when the gain in magnetostatic energy (by forming domains) is overcompensated by the energy required to form a domain wall. As a rule of thumb, this occurs when the size is smaller than the 3D domain wall width (0.1–1 μm). At even smaller size, the particle approaches the superparamagnetic limit (10–20 nm) where the thermal energy activates the spontaneous spin flip at room temperature. For such nanometer-sized particles, spin flip can occur even at very low temperatures (<10 K), at which the thermal activation may be completely suppressed, by means of magnetic quantum tunneling [94–97]. The stability of the magnetization of a particle with respect to magnetization direction becomes one of the major concerns for applications in high-density magnetic recording.

3.3.1. Isolated particles

The equilibrium of isolated single-domain particles at nonzero temperatures is generally described by well-established superparamagnetic theory [98–101]. Under this theory, the magnetic moments within each magnetic particle move coherently and can be treated as a single giant moment. The giant magnetic moment is coupled to magnetic anisotropy, which provides several equivalent equilibrium states depending on the actual type of the anisotropy. For an assembly of such kind of particles, the giant moments will have a balanced distribution in those equivalent states, leaving zero net magnetization of the system. An important concept associated with superparamagnetism is the blocking temperature, below which the thermal energy is not large enough to flip the giant moment within the measuring time. An operational definition of blocking temperature includes at least two requirements. First, above this temperature the magnetization curve must show no hysteresis loop. Second, the magnetization curves taken at different temperatures above the blocking temperature must superimpose when plotted against the magnetic field normalized by temperature after correction for the temperature dependence of the spontaneous magnetization. The particles can be considered as ferromagnetic particles below the blocking temperature, which is determined by the competition between the magnetic anisotropy barrier and thermal activation.

One of the characteristic features of a 0D particle is its large surface to volume ratio. It has been speculated that the large surface to volume ratio would give rise to enhanced magnetic moment and anisotropy. Early experiments on isolated Fe [102] and Co [103] particles embedded in nonmagnetic metals indicated only small changes of 0 K saturation magnetization as a function of the particle size. The measured results, however, are not necessarily connected with the intrinsic properties of 0D free clusters, since the electronic hybridization at particle/host interface could largely affect the surface magnetic moment. In the 1990s, there is growing interest of re-examining the magnetic moment of 0D clusters. These are free clusters made by cluster beam sources and their magnetic moments were measured by a conventional

Stern–Gerlach apparatus. Enhanced magnetic moments were reported for Fe [104], Co [105] and Ni [106] free clusters which typically contain several ten to several hundred atoms. Even Rh, which is nonmagnetic in the bulk, exhibits a sizable moment in cluster form [107]. In most cases the magnetic moment oscillates with the number of atoms contained in the cluster, reaching maxima or minima for open or close geometric shell, respectively. Since the open and close shells represent the largest and the smallest surface/volume ratio, respectively, this is a clear demonstration of the significance of the surface effect on the moment enhancement [108].

3.3.2. Magnetic dot arrays

While the fundamental 0D magnetic behavior can be addressed in studying the magnetic properties of isolated particles or free clusters, magnetic dot arrays attract the most attention due to their potential application in high density recording media. Various methods have been introduced to study the magnetization reversal process of the arrayed particles under external field and changing temperature [109,110]. When the dot arrays are dense enough, the interaction between the dots appears to have its influence on the magnetic properties. For example, the simplest dipolar interaction was found to increase the blocking temperature by effectively increasing the energy barrier between adjacent low energy states [111,112].

Since high blocking temperature is crucial for converting magnetic dot arrays into magnetic recording devices, it is necessary to increase the anisotropic barrier of the dots by all possible means. Fruchart et al. have recently further extended the idea of Co/Au(1 1 1) dot arrays to grow arrayed Co pillars on Au(1 1 1) substrate [113]. The principle is to deposit sequentially a fraction x of an atomic layer of Co and $1-x$ atomic layers of Au on the Au(1 1 1) substrate, which yielded arrayed pillars with 2:1 vertical aspect ratio. Because of the large number of Co atoms per pillar, the Co pillars have a much higher superparamagnetic blocking temperature (300 K) than that of the double layer-high Co/Au(1 1 1) dots ($\sim$20 K). In another approach, Sun et al. have used a chemical process to grow arrayed FePt dots, and were able to increase the blocking temperature from 20 to 30 K to higher than room temperature by thermal annealing. These authors have shown that the dot arrays support the magnetic reversal transition after a magnetic read–write process had been performed.

Besides magnetic recording, magnetic dot arrays have also been studied in terms magneto-optical response [114], vortex pinning in superconducting materials [115], and even possible application in magnetic refrigeration materials [116].

4. Tailoring magnetism in artificially structured materials

As shown above, the 2D, 1D and 0D objects all have interesting magnetic properties. The accumulated knowledge of their structural and electronic origins opens the route to modify their magnetic properties in a controllable and desired way. With such a capability to produce magnet design principles, low-dimensional magnetism has found itself right on the frontier of modern science and technology.

4.1. Spin engineering

The orientation of magnetization is one of the key features for a magnet. Magnetic properties of 2D magnetic thin films are often closely tied to their actual magnetization direction. If the magnetization direction can be oriented into any desired direction with high accuracy, i.e. spin engineering, magnetic thin films can be used with much higher efficiency in data storage and sensor devices.

Since the magnetization direction depends on the sign of the effective magnetic anisotropy constant, it is natural to control the spin direction by modifying the magnetic anisotropy. So far most attempts emphasized the modification of the surface anisotropy, which can be done by means of capping films with typically a fraction of a monolayer of magnetic [117] or nonmagnetic layers [118], or gas adsorption on the film surface [119]. In both cases the surface anisotropy constant can be changed controllably by controlling the coverage of the capping layers or absorbing gases. For

example, Webber et al. have reported that three hundredths of a monolayer of copper capping layer is sufficient to rotate spins of a 20 ML thick Co/Cu(1 0 0) film by 90° [118]. This means that one nonmagnetic Cu atom can switch the spin direction of 500 Co atoms. This seemingly large effect of Cu atoms is understood as a result of Cu atoms preferentially locate at the step edges of Co surface, which affects the magnetic anisotropy in a most efficient way. The spin direction of the Co film can be finely tuned by further adding copper atoms, which eventually comes back to its original direction after 1 ML of copper has been deposited. Hope et al. have combined the effects of CO adsorption and Cu capping on Co/Cu(1 1 0) films, which make it possible to direct rotation of spins in a fine step between two perpendicular directions of [1 −1 0] and [0 0 1] [119].

4.2. Spin electronic devices

The field of spin electronics has been growing dramatically in recent years. The central idea of spin electronics is centered around the fact that conduction electrons (or holes) carry not only charge, but also spin. According to Mott's observation of electrical conduction in a ferromagnetic material [120], the current is carried by two distinct channels which consist of electrons with antiparallel and nonequal spins. Depending on the magnetization direction, electrons of one spin polarization are more heavily scattered than those with the other polarization. The recognition of this distinction is the key which promises to unlock a new generation of spin electronics devices whose operation relies on differential manipulation of independent families of current carriers with opposite spin polarization.

The simplest demonstration of a spin electronic device is a magnetic multilayer system which shows GMR. Due to the differential spin scattering at the ferromagnetic/nonmagnetic interface [121], the electrical resistance of a GMR multilayer is the smallest (largest) when two magnetic layers are parallel (antiparallel) magnetized. The change of the magnetoresistance can be more than 100% [122], making the GMR multilayers an excellent candidate to construct magnetic field sensors. In real applications, instead of using the normal GMR multilayers, a multilayer system called spin valve has been introduced to increase the field sensitivity. Fig. 10 shows the fundamental structure of a spin valve multilayer. A nonmagnetic (Cu) layer separates two ferromagnetic layers. The magnetization of one of the ferromagnetic layers (Py) is pinned by an uni-directional anisotropy, which is provided by the uni-directional exchange bias between a ferromagnetic/antiferromagnetic (Py/FeMn) interface. The other ferromagnetic layer is free to rotate under a small external field. The resistance of this device varies depending on the external field direction, i.e. a field sensor. The GMR spin valve so far has already been successfully used in commercial magnetic disk readheads as shown in Fig. 10, and is being considered as one of the top candidates for building nonvolatile MRAM.

An important concept associated with spin-dependent transport is called "spin accumulation", which is simply an excess of the number density of up-spins over down-spins and can, thus, be viewed as a divergence in the electrochemical potentials of the two spin channels. Using this effect, Johnson [123] has constructed a three-terminal spin transistor, which includes a nonmagnetic base layer sandwiched by a ferromagnetic emitter layer and a ferromagnetic collector layer. The spin accumulation effect makes the base layer to have a different chemical potential than the collector layer, and will either pump the current into or out of the collector, depending on the magnetization direction of the collector layer. Later a more sophisticated spin valve transistor, which uses two Si layers as emitter and collector, and a GMR multilayer as the base, also, has been demonstrated [124].

Datta and Das have proposed another spin electronic device called spin-injection high electron mobility transistor [125]. In their design, as seen in Fig. 11, the spin-polarized electrons are injected from a ferromagnetic metal pad into a 2D electron (2DEG) gas layer, which would be an inversion layer formed at the heterojunction between InAlAs and InGaAs. The 2DEG layer provides a high mobility channel, free of spin flip scattering. The spin-polarized electrons, when passing through the

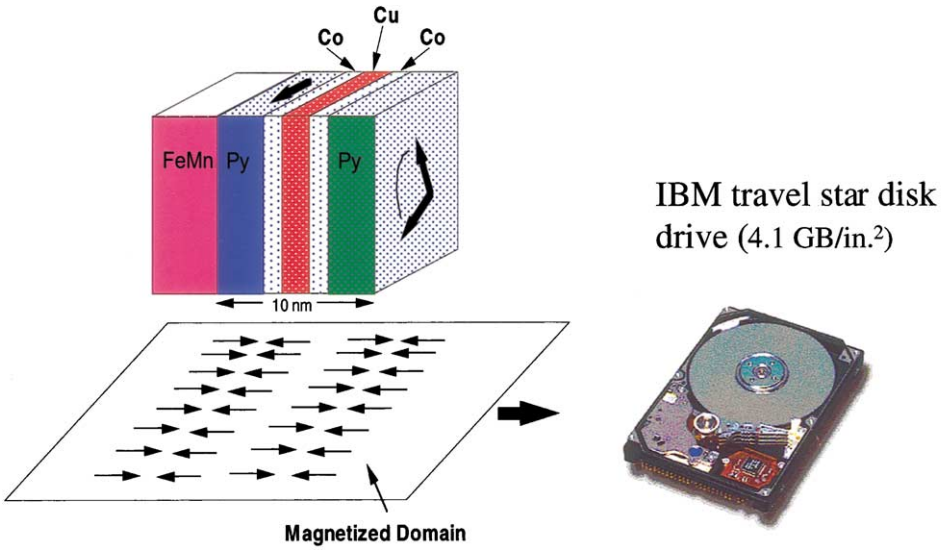

Fig. 10. GMR read sensor. Two magnetic layers (here each layer consists of a $Ni_{0.81}Fe_{0.19}$ alloy (Py) plus a few angstroms of Co) are separated by a Cu spacer layer. The moments of one of the magnetic layers is pinned by an FeMn antiferromagnetic layer. The other layer is free to rotate under the influence of the fringing fields from the magnetized domains on the spinning disk. As the magnetic moments of the free layer rotate, the resistance of the film changes allowing the information recorded in the magnetized domains to be read.

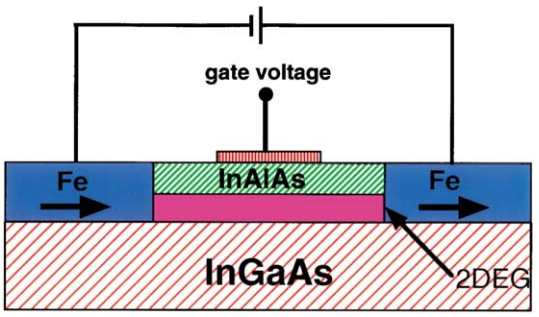

Fig. 11. Spin-polarized field-effect transistor scheme. A biased voltage applied between two ferromagnetic Fe pads (parallel magnetization) drives a spin-polarized electronic current through an interface layer (pink) between InAlAs and InGaAs. This interface layer is called a 2D electron gas layer, which does not flip electron spin directions of the current carriers. The spin direction of the current carriers can be tuned, however, by a gate voltage as shown in the figure. Similar to what has been described in Fig. 1, the resistivity varies depending on the relative orientation between the spin direction of the current carriers and the Fe pad (on the right hand side). A proof-of-principle experiment has been done by Hammar et al. (see Ref. [126]).

2DEG, would sense an effective magnetic field due to the electric field between the heterojunction, and hence will precess. This precession turns the spin direction somewhat off the magnetization direction of the spin injector, with the offset angle tunable by an external bias voltage applied to the heterojunction. Another ferromagnetic metal pad will be used as a detector located at the other end of the 2DEG layer. In this way the current passing through the 2DEG can be modulated by the bias voltage applied to the heterojunction, which is virtually a spin-polarized field-effect transistor. The most challenging part to realize this device is to successfully inject spin-polarized electrons from the ferromagnetic metal into the semiconductor, and good progress has been made recently [126].

4.3. Artificially ordered alloys

Low-dimensional magnetic alloys are attractive because these materials have, via composition, an additional adjustable parameter for tailoring materials with desired properties. The development of thin film growth techniques in ultrahigh vacuum has made it possible to fabricate artificial ordered alloys which may or may not exist in bulk equilibrium. New alloy phases can be achieved in thin

film growth due to factors such as enhanced surface diffusion, symmetry and strain influence by the substrate, and the low dimensionality effect. For example, it has been demonstrated that the strain effect could result in compositionally modulated alloy structures in bimetallic system which are immiscible in bulk [127,128].

The fact that 2D films can be made atomically smooth is particularly useful to grow artificial layered alloys, by alternatively stacking nanometer-thick layers of magnetic and nonmagnetic metals. Striking magnetic properties such as perpendicular GMR [129] in Fe/Cr multilayers and large magneto-optical effect [130] in Fe/Pt alloys have been reported. The ultimate limit of such kind of layered alloys are the monoatomic stacked $L1_0$ structure, which exists in nature for some bulk alloys such as FePt. In bulk synthesis the disadvantage is that one has to live with the phase diagram nature has provided, so only a very limited kinds of magnetic $L1_0$ alloys can be produced. Using epitaxial growth, a variety of $L1_0$ alloys, which do not exist in nature, can be artificially made by stacking monoatomic metal layers alternatively. Magnetic $L1_0$ alloys such as Fe/Cu [131] and Fe/Au [132] have been successfully fabricated in this way.

5. Outlook

The emergence of low-dimensional magnetic materials in the last two decades of the 20th century has already had a tremendous impact on modern technology. Moving into the 21st century, major efforts will be spent to make devices based on these artificial magnetic materials even smaller in size and function at a faster speed. Meanwhile scientists will keep looking for new low-dimensional magnetic properties and constructing better artificial magnetic materials. With this in mind, we foresee that the following directions will likely generate new excitement.

5.1. Magnetic imaging with atomic resolution

Since the dimensions of magnetic materials is being made smaller and smaller, the current nanometer resolution of magnetic imaging techniques are becoming more and more dissatisfying for research. For most people spin-polarized STM (SPSTM) holds the most promise to solve this problem. The operating principle of SPSTM is close to that of the STM. In both cases a sharp tip is scanning across the surface and record the magnetic (SPSTM) or topographic (STM) signal. Since STM is well know to have atomic spatial resolution, SPSTM is highly expected to show similar capability. The major challenges for developing the SPSTM include the very small signal and the tip–sample interaction. The spin-polarized tunneling current is usually several percent or less of the total tunneling current, and thus can be easily hidden by the noise. Adapting the lock-in technique appears to be able to improve the signal-to-noise ratio, and some initial success has been achieved [133]. The tip–sample interaction is due to the high magnetic stray field induced by the magnetic tip, which is on the order of about 0.1 T. Under such a large field, the local magnetic moment direction will be disturbed or even flipped for many magnetic thin films. In order to suppress the tip–sample interaction, instead of using ferromagnetic tips, people have tried other kinds of tips such as nonmagnetic tips coated with a magnetic thin film [134], or a GaAs tip pumped by circularly polarized light [135,136]. These tips seem to affect the sample considerably less, and have been applied to image magnetic domain structures of ultrathin films. There are also discussions about using antiferromagnetic or superconducting materials as a STM tip probe, and a new concept of using a two-terminal nonmagnetic tip [137]. Despite the technical difficulties, the SPSTM research is currently being hotly pursued. A first report on atomic resolution has been given recently [88].

5.2. New artificially structured magnetic materials

Searching for new magnetic materials with a desired function has always been a major topic in the history of magnetism research. In most cases, a single magnetic element falls short to simultaneously match all aspects of technical demands. As a result, these days the best performed hard and soft magnetic materials are alloys or compounds

[138]. The traditional bulk synthesis of magnetic alloys or compounds are limited by the bulk phase diagram. The ASM, constructed layer by layer, row by row, or even atom by atom, can be made of elements which are immiscible in the bulk. For this reason the ASM could have a much better tunability. In addition, the ASM are low-dimensional materials whose size can be made small and their response time fast. Following the trend of modern technology to make devices smaller and faster, ASM is perfectly suited for the future development of magnetic and electronic devices. For example, spin electronic devices are anticipated to become a new generation of electronic devices in the near future [5]. The new materials also will cross-fertilize fundamental research. As suggested by history, new exciting physics are often linked to new materials.

Materials science will be a major thrust for technology in the 21st century. Magnetic materials will play a major role. Artificially structured magnetic materials are a new frontier of fundamental and applied research in magnetism.

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