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TOPICAL REVIEW

The effect of spatial confinement on magnetism: films, stripes and dots of Fe on Cu(111)

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Abstract
In this article, we review recent progress in the exploration of the complex magnetic phases of the fcc Fe/Cu(111) system. In particular, we emphasize the magnetic properties realized by the synthesis of novel nanostructures of Fe on Cu(111). These include monolayer films, one-dimensional stripe arrays and nanodot arrays. The effects of spatial confinement, together with strong spin–lattice correlations, result in dramatically different magnetic behaviour for the various manifestations of the Fe/Cu(111) system. Multi-scale theoretical calculations have been used to provide an understanding of the magnetic behaviour in each case.

(Some figures in this article are in colour only in the electronic version)

Contents

1. Introduction

In the last decade, basic science has had a remarkable impact on practical devices in the area of magnetic recording. In less than ten years, the discovery of giant magnetoresistance, a phenomenon that occurs in thin film sandwiches of magnetic and non-magnetic materials, developed into a $100 billion per year market for a new generation of hard disk drives. This amazingly rapid progress resulted from basic research that gave the community both the ability to grow these artificial structures and a basic understanding of their behaviour that allowed optimal tuning of their properties. The rich physics associated with these magnetic films [1, 2]—which are nanoscale in only one spatial dimension—provides ample testament that nanophase magnetic materials are not just smaller but also different! As efforts to reduce device size have continued, it has become imperative to investigate the magnetic properties of artificial structures on smaller length scales and in reduced dimensionality, as in nanowires [3–8], dots [9–12] and pillars [13]. These advances, coupled with emerging techniques for synthesizing magnetic nanowires [8, 14, 15], nanoparticles [16] and molecular magnets [17, 18], have established the research of spatially confined magnetic materials as a new frontier both in basic science and technology.

New properties that emerge at the nanoscale have at least four origins:

(1) As the surface-to-volume ratio increases, material properties are increasingly dominated by surface and interface effects—a 5 nm cube of bcc Fe contains ∼12 000 atoms, ∼2000 of which are on the surface.
(2) Spatial confinement results in new quantum phenomena. The oscillatory exchange coupling [19], GMR [20], spin-dependent tunnelling [21] and exchange bias [22–24] manifest in magnetic multilayers are linked with one or both of these factors.
(3) A contribution that can perhaps be called 'characteristic length effects'. The exotic effects seen in GMR spin valves, for example, would not be observed if the individual layers in the structure were thicker than the spin-diffusion length, which is the average distance that an electron will travel in a material before undergoing a scattering process that changes its spin.
(4) In many spin systems, like colossal magnetoresistance (CMR) materials [25] and magnetic semiconductors [26, 27], correlation effects are already important in the bulk spin structure, spin fluctuations and spin transport. In general, spatial confinement will significantly change these correlation effects.

Before the exotic magnetic and electronic properties of various nanostructures like ultrathin films, nanowires and nanodots can be explored, important strides must be made in controlling their synthesis. While state-of-the-art e-beam lithography may produce structures down to the nanometre scale, mass production of such structures by lithography or etching-based fabrication has proven to be exceptionally challenging [28, 29]. For this reason, in the past decade considerable effort has been devoted to investigating growth methods using self-assembly principles. Self-assembled magnetic nanowire and nanodot arrays have been achieved on various types of substrates.

In this paper we will review studies of the spatial confinement effect on magnetism in a highly interesting system, Fe on Cu(111). We pick this particular system because it provides a classic demonstration of the tremendous impact that novel synthesis techniques

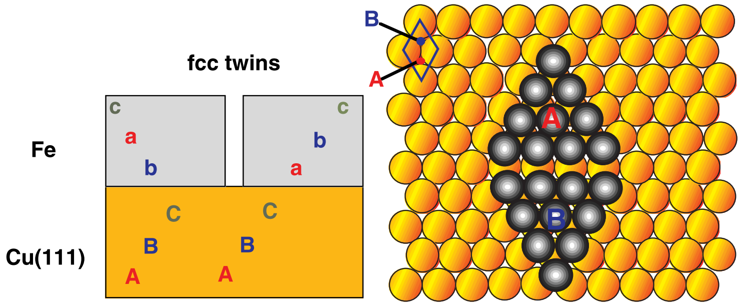

Figure 1. Schematics showing the phenomenon of twinning. The spacing between iron atoms on the Cu(111) surface is such that iron atoms in a particular island will either occupy 'A' sites only or 'B' sites only, depending on which of these two sites was settled upon by the atom that seeded the island. The image shows the fault line that forms when an A-type island tries to merge with a B-type island.

can have on the study of nanomagnetism. Ultrathin films, nanowires and nanodots of Fe have been successfully grown on the Cu(111) substrate, despite the fact that conventional growth techniques like thermal evaporation and sputter deposition do not support the growth of any of these nanostructures. The fact that these three types of nanostructures, which are spatially confined in different dimensions, can be grown on a common template allows direct observation of the effect of spatial confinement on magnetism.

Another major attraction of the Fe/Cu(111) system is that iron initially grows on this surface in the face-centred cubic structure, which is well known for its rich magnetic phases and strong spin–lattice coupling [30]. In general, a small variation of the lattice constant or lattice distortion can result in drastic changes of magnetic phases that range from low-moment ferromagnetic phase, antiferromagnetic phase, ferrimagnetic phase and high-moment ferromagnetic phases. For the very same reason, ultrathin films of fcc Fe on the Cu(100) surface have been extensively studied in the last ten years, and many exciting magnetic phase transitions [31, 32] and strong spin–lattice correlations [33, 34] have been identified. The fcc Fe/Cu(111) system, as we will soon show below, is just as exciting and its degree of complexity is just as high. Combining the results for both crystallographic orientations of fcc Fe will also lead to a better overall understanding of the material.

In order to emphasize the critical role of novel synthesis techniques in the study of low-dimensional magnetism, we organize this review as follows. In section 2 we will point out that conventional molecular beam epitaxy (thermal MBE) fails to yield any of the low-dimensional magnetic nanostructures. The structure and magnetism of the thermal MBE grown Fe/Cu(111) will be, nevertheless, discussed in that section to provide the readers with a reference point. In the following sections we discuss the growth, structure and magnetism of well ordered Fe/Cu(111) nanostructures. Ultrathin films, stripe arrays and dot assemblies of Fe on Cu(111) are described in sections 3–5, respectively. In section 6, we make a direct comparison of the magnetic properties of these manifestations of Fe on Cu(111). The final section provides a summary and an outlook on future research.

2. Thermal MBE growth of Fe on Cu(111): rough and discontinuous films

2.1. Morphology and structure

When prepared with a conventional growth technique like thermal evaporation in ultrahigh vacuum, Fe has a strong tendency to form multilayer islands on Cu(111) due, in part, to an effect called twinning. Twin structures are common features of epitaxial growth on fcc(111)

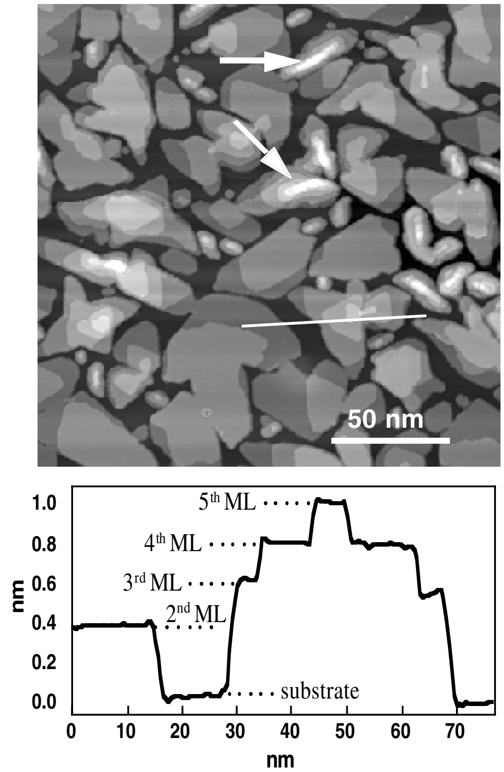

Figure 2. STM image of the rough morphology that results when two atomic layers of Fe are deposited via thermal evaporation on the Cu(111) surface at 220 K. The line scan below the image shows that this morphology is far from that of an ideal 2.0 ML film. The white arrows indicate the locations of ridge-like bcc(110) structures.

surfaces [35]. As shown in figure 1, the rhombic surface unit cell of the fcc(111) surface provides two possible sites, A and B, for adatom nucleation. Since the difference between the nucleation energies of the two sites is generally very small, an adatom has essentially no preference for one site over the other. Those that nucleate at A sites seed the growth of A-type islands, and those that nucleate at B sites lead to B-type islands. These two types of islands cannot merge to form a smooth film because a fault line, as shown in figure 1, always exists at the boundary between them.

A second feature that leads to roughness is low interlayer mass transport [36]. Because there is a high energy barrier for Fe atoms to overcome when moving from one atomic layer to the next, the thermal motion of the atoms is unable to 'heal' pits and peaks in the morphology. The consequences of fcc twinning and low interlayer mass transport can be seen in the scanning tunnelling microscope (STM) image of an Fe/Cu(111) film shown in figure 2. The film was prepared by MBE at a substrate temperature of 220 K, with the nominal Fe dosage of 2 monolayers (ML). The marked line profile shows that the typical island height is about 5 ML, and that a considerable fraction of the copper surface (darkest contrast) remains uncovered after two atomic layers of Fe are deposited.

In figure 2, another noticeable feature is the appearance of some ridge-like islands (marked by white arrows). These ridge-like structures represent the typical morphology of bcc(110) structures, which are elongated due to one-dimensional lattice matching with the fcc Cu(111)

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