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Nanomagnetic structures at surfaces

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Abstract

Magnetism on the nm scale is a new research field with high potential from the application point of view. Nowadays, the research is focused on the fabrication of ferromagnetic nanostructures. The manipulation of growth and structure known from the epitaxy of ultrathin films is increasingly being used to create magnetic structures with reduced dimensions. An important impact is expected from self-organizing phenomena appearing in films and at surfaces.

1. Introduction

Transfer times from basic research to device development shrink remarkably in the struggle for shares of the huge storage market. The trend is best illustrated by the six years that elapsed between the discovery of the giant magnetoresistance effect [1,2] and the realization of a prototype read-head [3]. Still, novel segments of the magnetic storage market can be explored if the price for the storage unit is reduced. Lower prices ask for higher density and cheaper fabrication. This situation stimulates activities in research and development simultaneously to evaluate new concepts for data storage. Concurrently industrial laboratories and basic research are pushing the frontiers of dimensions into the nm range. Triggered and guided by industry, nanomagnetic research is thus a steeply rising field of interest. Very precise ideas are developed for new storage concepts of non-volatile memory devices, i.e. the magnetic random access memory MRAM [4,5] based on magnetic structures of nm size. Ideas for active devices based on spin effects have been put forward [6].

Approaching the nm size in magnetic structures yields new effects and properties. The research field is very young and most activities focus on the fabrication of nanomagnets of well-defined shape, structure and reproducible properties. In this review we comment on different approaches and concepts of nanomagnet fabrication under the aspect of their potential for commercial application and mass production.

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2. Magnetic nanostructures at surfaces

Investigations of free clusters of 3D-metals have revealed that particles of a few hundred atoms, i.e. with a size of a few nm, behave like the bulk material [*7]. Hence, ultrathin structures with a thickness of one or two atoms should exhibit ferromagnetism with diameters in the range of 10 nm. This number is a kind of benchmark that points out the range of sizes that has to be tackled in basic research.

Structures on that scale, however, pose two basic questions: First, the ratio of surface- to volume-atoms is strongly enhanced, which means that the surface properties will dominate the properties of the nanostructures. Hence, surfaces and interfaces are of chief importance, and their quality must be controlled at least as well as the interior structure. Secondly, sufficiently small nanostructures may behave superparamagnetically, which destroys the desirable alignment of the magnetization and hence the stored information. To overcome this dilemma the blocking temperature has to be tuned. It is determined by the magnetic anisotropy energy of the particle, i.e. the product of the volume and the anisotropy energy. To obtain the smallest possible size one has to maximize the magnetic anisotropy of the ferromagnetic material. Tuning of the anisotropy can be achieved by manipulating the structure [8], the composition [9] and/or the interface properties of the ferromagnetic material.

Beyond those constraints the nanostructures should

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exhibit homogeneous shape, size, periodicity and well-defined orientational dependent properties. The latter means that crystal and/or magnetic axes of the individual structures should be perfectly aligned.

This demands sophisticated fabrication techniques which allow tuning of growth, structure, morphology and magnetic properties. This can only be achieved if perfect structures on the atomic scale are produced, utilizing epitaxy in combination with a template that determines the structure and the orientation of the deposited materials. The lateral patterning can only be realized either with perfect surfaces and epitaxial thin films which are structured afterwards, or with growth-determined morphologies on appropriate substrates. Generally speaking it is the path of the well-established and successful epitaxy of ultrathin ferromagnetic films that bears the highest potential to meet the prerequisites of both approaches.

3. Artificial patterning

The direct way to create nanostructures is by lithographical patterning. Structures of 15 nm width have been fabricated utilizing electron beam writing [10]. With special post-epitaxy processes [11] well-defined nanomagnets can be created giving the scientist quick access to investigate the magnetic properties of nanostructures with high flexibility regarding the shape, size and arrangement of the nanomagnets [12–15,**16–**18].

Combining a scanning tunneling microscope with chemical vapor deposition has also been used for serial patterning of films with nm resolution [19,20] providing the opportunity of positioning the nanomagnets exactly [19].

A new approach is the magnetic patterning of epitaxial films. The magnetic properties, e.g. the anisotropy or the Curie temperature [*21,**22], are altered by ion irradiation instead of removing the ferromagnetic material by some etching procedures.

The above serial techniques will be very time-consuming if large arrays of nanomagnets are produced. Consequently, they are not suited for commercial mass production. Parallel patterning by optical lithography is better suited for the fabrication of large arrays [23,24]. Structures with sizes in the range of 100 nm can be made by utilizing X-rays [25].

Recently, neutral atom lithography has been proposed and realized [26–*28]. The field gradients in standing waves of intense laser light exerts forces on atoms which are used to transfer the periodicity of the interference pattern into the lateral arrangement of the deposited atoms. The clue is that a direct pattern transfer is achieved in non-contact mode that prevents any chemical processing commonly used in lithography. The deficiency of the technique is that only certain atoms can be deposited so far. This obstacle has been mastered utilizing the shadow deposition technique [29] in combination with a pattern produced by atom lithography [*30].

A real breakthrough in the light of mass production comes from the imprint technique that allows parallel patterning of nanostructures with dimensions below 10 nm [**31].

In spite of its drawbacks, e-beam lithography has a big advantage: its flexibility to create complex structures. Special devices in the μm and/or nm scale range have been fabricated which are successfully used to study properties of nanomagnets with high sensitivity and without the need for spatially high-resolution analyzing techniques [*32,33,**34–**36].

4. Self-organized structures at surfaces

A relatively new route to create nanostructure arrays is to use self-organization phenomena at surfaces. Arrays can be obtained either by utilizing a preexisting periodic structure at the surface where the deposited material nucleates or by using self-organization of the deposited material into a periodic array.

Surfaces with periodic structure or morphology are produced due to minimization of the surface free energy. Depending on macroscopic surface orientation facets [**37] or steps can appear, or strain relief creates self-organized pattern [38]. The structures are stable and can be used as a template to create nanomagnet arrays. On vicinal surfaces wires are obtained by step-edge flow in equilibrium growth [*39,40] or in kinetically controlled growth [41,42]. The periodicity is determined by the miscut angle.

A very well known example for a superstructure on a clean metal surface due to strain relief is observed on the Au(111) surface (Fig. 1). A mesoscopic, chevron or herringbone, structure is obtained due to a $22\times\sqrt{3}$ reconstruction along ⟨110⟩. The chevron structure is built as the reconstruction appears along two adjacent ⟨110⟩ directions to attain strain relief in two directions. The elbow sides are nucleation points for material with a large lattice mismatch, like Co [43]. A two-dimensional array of hcp Co islands with a height of two atoms is achieved (see Fig. 1). At coverages of 0.7/1.5 monolayers the islands start to coalesce along the ⟨120⟩/⟨110⟩ directions, respectively [44]. Hence, the nanostructures consist of ~1700 atoms before coalescence. Cobalt structures of that size revealed superparamagnetic behavior [*45,46].

Self-assembled nanostructures have also been produced by strain relief mechanisms in thin films or adsorbed gases on single crystal surfaces [**47,**48]. The dislocation network in a Cu-film deposited on Pt(111) was successfully used as a template to create an array of Fe nanostructures [**47]. A strain relief pattern was also found in nitrogen adsorbed on Cu(001) [**48] serving as a template for iron deposition. Very stable Fe or Co stripes have been obtained utilizing self-organization by strain relief in the

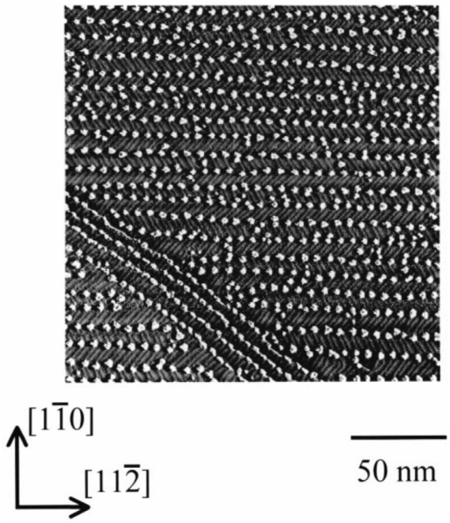

Fig. 1. Co islands on Au(111). Scanning tunneling microscope image of hcp cobalt bilayer islands on Au(111). The Co coverage is 0.24 monolayers. The islands nucleate at the elbows of the herringbone structure of the clean Au(111) surface. The herringbone or chevron structure is visible in the background. Double-lines built the zigzag pattern. Perpendicular to the double-lines the surface strain is relieved by arranging 23 surface atoms on the position of 22 bulk atoms. A hcp-stacking fault is created within the double-lines. The spacing between the islands along [11$\bar{2}$] is 73 Å. On the lower left terraces separated by steps can be seen. The steps are decorated by Co islands. (Courtesy of M. Klaua.)

deposited film [**49]. Co-evaporation of two immiscible materials with different lattice parameters causes an arrangement of the two materials in rows.

In brief, the virtue of using self-assembly is that inherently a large array of highly periodic nanostructures is created which have a narrow size distribution, are epitaxially grown and perfectly aligned with respect to their crystallographic structure. The disadvantage is that only a limited size range is achievable [see Co/Au(111)] and that no multilayered nanostructures can be produced so far.

A much higher flexibility is found in our last example for self-assembled templates, i.e. macroscopic surfaces with facets. Such a surface can be created if unstable single crystal surfaces decompose into facets of stable surfaces shown recently for a NaCl(110) surface [**37]. A large variety of surface morphologies with different facets can be produced in the heteroepitaxy of semiconductors [*50]. An example for the SiGe epitaxy on Si(001) is given in Fig. 2 [**51]. A square pattern of fourfold pyramids is obtained in the growth of $Si_{0.25}Ge_{0.75}$/Si. The side planes are four {105} facets. The structure is created due to strain relief in the initial growth of $Si_{0.25}Ge_{0.75}$ on Si(001). The Si layers in the multilayer stack mediate the strain and cause nucleation of the following SiGe layers preferentially on top of the buried islands [*50,**51]. Fig. 2 reveals the three-dimensional structure of such a surface. The clue is that the orientation of the facets allows us to select facets of one orientation which can be covered with

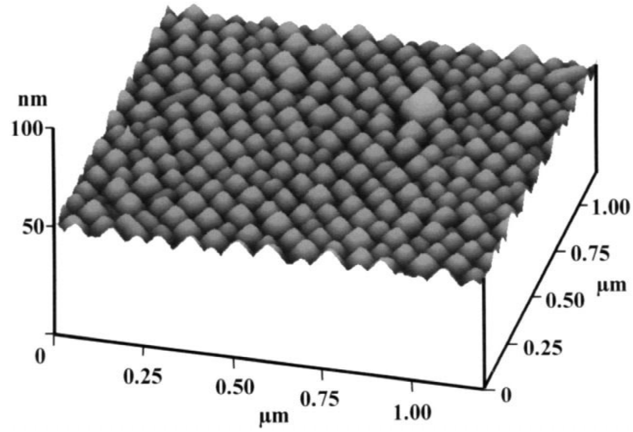

Fig. 2. Strain relief pattern of SiGe/Si(001). Atomic force microscopy image of $Si_{0.25}Ge_{0.75}$/Si multilayer grown on Si(001) with a miscut of 0.4°. The surface consists of uniform, {105} faceted pyramids with square base of 85±12.25 nm. The facets are tilted against the (001) surface by 11.3°. (Reprinted with permission from [**51].)

any material by shadow deposition. The periodicity and size of the resulting nanostructures is given by the facet array.

From the very general point of view nanostructures are obtained because the template consists of surfaces of very small size arranged periodically. Hence, with such surfaces nanostructures are always created. It depends on the geometry of deposition whether they are isolated or connected. The nanosurfaces of one orientation appear within a very limited range of azimuthal and polar deposition angle. The whole flexibility of tuning and manipulating of structure and morphology is at the disposal of the scientist, equivalent to the situation using macroscopic surfaces. Single- as well as multi-layers can be deposited without changing size and periodicity. By selecting the appropriate geometry different facets can be covered with the same or different material. An array of four different nanostructures, i.e. consisting of four different materials, can thus be fabricated on one template. The field that is opened by such templates is just beginning to be explored. Ferromagnetic nanostructures ($25\times35\times5$ nm^3) have been realized by pulsed laser deposition under grazing incidence utilizing such a template [52].

5. Conclusion

The actual concepts for fabricating nanostructures have been introduced. The activities in the basic research are split up into two branches. The first approach is to use conventional lithography to obtain quick access to nanostructures for studying their magnetic properties. E-beam lithography is utilized to build miniaturized tools for the analysis of nanoparticles which have been created simultaneously on the same substrate. A few experiments using such devices have been successfully performed. The second approach uses self-assembled structures at surfaces and in thin films to fabricate large arrays of nanostructures. The goal of this research is to find new and easy methods for producing arrays of high periodicity with nanomagnets of perfect structure and narrow size distribution. While self-organizing phenomena have several advantages over the serial process mainly used in lithography, they are still far from being of use for industrial applications.

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