

MAGNETIC MATERIALS

5 This invention relates to magnetic materials and, in particular, to the use of rotational symmetry to tailor the magnetic properties of the materials.

10 The volume of information which can be stored on a computer hard disk has risen by a factor of 10^7 in the past 40 years and looks set to continue rising at an exponential rate in coming decades. Today's conventional magnetic materials will be unable to meet the demanding performance requirements of tomorrow's magnetic data storage industry. One option currently being considered is a synergy of nanotechnology and quantum mechanics to make nanometre scale magnetic particles called nanomagnets. These, by 15 virtue of their extremely small size, possess very different magnetic properties from their parent bulk material. Each nanomagnet is analogous to a giant atom of an artificial element, allowing new magnetic materials to be built up giant atom by giant atom. The rapidly growing field of nanomagnetism may provide among other things 20 advanced replacements for hard disk media and a new generation of high speed, low power, non-volatile computer memory chips.

25 The most important property of a naturally occurring magnetic element or alloy is its anisotropy. This refers to the presence of preferred magnetisation directions within the material and is ultimately responsible for determining the way in which a magnetic material behaves and the technological applications for which it is suitable. In a conventional magnetic material anisotropy 30 arises from the shape and symmetry of the electronic Fermi surface and so is intrinsic to the particular element or alloy and cannot easily be tailored. In nanomagnets, however, the anisotropy depends not only on the band structure of the parent material, but also on the shape of 35 the nanomagnet. One of the most attractive features of artificial magnetic materials is that their magnetic

properties can be engineered by the choice of the shape of the constituent nanomagnets.

According to one aspect of the present invention, a memory element comprises nanomagnets having a rotational symmetry selected in order to provide high remanence and a
5 suitable coercivity.

According to a second aspect of the present invention, a sensor element comprises nanomagnets having a rotational symmetry selected such that they are superparamagnetic and
10 exhibit substantially zero hysteresis so that a magnetisation of the nanomagnets depends only on the current value of applied field and not on the field history.

According to a third aspect of the present invention, a magnetic logic element comprises nanomagnets having a
15 rotational symmetry selected such that they are superparamagnetic and exhibit substantially zero hysteresis so that a magnetisation of the nanomagnets depends only on the current value of applied field and not on the field
20 history.

The devices of the invention are artificial magnetic materials formed on the surface of a substrate, such as a piece of silicon, using a technique such as electron beam lithography. The devices may be in the size range 40-500nm
25 and in the thickness range 3-10nm and may be, triangular, or pentagonal geometries which respectively correspond to rotational symmetries of order 3 and 5. The order may, however, be greater. The parent material may be Supermalloy ($\text{Ni}_{80}\text{Fe}_{14}\text{Mo}_6$), which is chosen for two reasons. Firstly, this
30 alloy is intrinsically almost isotropic and so any anisotropy in the nanomagnets must come from their shape. Secondly, Supermalloy and its molybdenum-free relative Permalloy are two of the ubiquitous soft magnetic alloys of industry and research and as such make an effective
35 demonstration of the new and varied properties which can be given to a simple material by nanometric structuring. As described below, we are able to make artificial magnetic

materials with an enormously wide range of magnetic properties simply by varying the symmetry of the constituent nanomagnets.

5 Examples relating to the present invention will now be described with reference to the accompanying drawings, in which:

Figure 1 shows scanning electron micrographs of some of the artificial magnetic materials;

10 Figure 2 shows hysteresis loops for nanomagnets of different size, thickness and geometric shape;

Figure 3 shows a hysteresis loop for a superparamagnetic triangular nanomagnet;

Figure 4 shows experimentally measured coercivities as a function of nanomagnet size;

15 Figure 5 shows the experimentally measured anisotropy field inside different nanomagnets;

Figure 6 shows the dominant anisotropy term of Figure 5 expressed as an anisotropy field (A) and as an anisotropy energy per nanomagnet (B) for different nanomagnets;

20 Figure 7 shows susceptibility as a function of nanomagnet size and symmetry; and

Figure 8 shows a schematic arrangement of a superparamagnetic nanomagnet in use as a magnetic field sensor or logic element.

25 A standard lift-off based electron beam lithography process can be employed to form devices according to the present invention. The sample substrate was oriented single crystal silicon. The spacing between each nanomagnet was always at least equal to the diameter of the nanomagnet, and for the smallest structures was as large as 30 3 times the diameter. The surface roughness of the nanomagnets was less than 0.5nm and the microstructure showed 5nm randomly oriented grains. The top surface of each nanomagnet was covered with a 5nm thick layer of gold 35 to prevent oxidation. The integrity of the geometric shape was found to be preserved in structures as small as 50nm in

size. Figure 1 shows Scanning Electron Microscopy images of some of the structures.

In order to determine the magnetic properties of these different artificial materials we measured their hysteresis loops (M-H loops) using a known high sensitivity magneto-optical method. The silicon surface can be viewed under an optical microscope while a laser spot (size $\approx 5\mu\text{m}$) is moved over the surface until focused on top of one of the patches of artificial material. The reflected laser beam is polarisation analysed in order to access the longitudinal Kerr effect, which serves as a probe of the component of magnetisation lying in the optical plane of incidence. This magnetisation is then recorded while a 27Hz alternating magnetic field of up to 1000 Oe strength is applied in the plane of the sample. All measurements were performed at room temperature.

Figures 2 and 3 show some of the hysteresis loops measured from nanomagnets of different size, thickness and geometric shape. One sees immediately that the loops are very different from each other and from that obtained from the conventional unstructured material. The variety of technological applications covered by the samples represented in this figure is considerable. The known small rectangles shown in Figure 2B could be suitable for making an artificial replacement for hard disk media: the nanomagnets used here could in principle achieve data storage densities in excess of 100 Gbits/inch², i.e. 10 times greater than today's state-of-the-art conventional media. The known larger rectangles in Figure 2D would be well suited to Magnetic Random Access Memory (MRAM), an emerging replacement for semiconductor memory: a memory chip using magnetic elements of this size could offer 1 Gbit of non-volatile high speed memory. What is surprising is that a wide range of magnetic properties are manifested by the triangular and pentagonal nanomagnets. The triangles in Figure 2E, which have a high remanence and a low coercivity, could be employed as a memory element

whereas the pentagons of Figure 2F and the superparamagnetic triangles of Figure 3 would make an excellent high sensitivity magnetic field sensor or hard disk read head, having an effective relative permeability of 3000 and zero hysteresis. These diverse applications are a direct result of varying the size, thickness and, most importantly, the symmetry of the nanomagnets which make up the artificial material.

In order to quantify this important effect, we have measured coercivity from the hysteresis loops as a function of size, thickness and symmetry order of the nanomagnets. Coercivity is a measure of the applied field necessary to reduce the magnetisation to zero (i.e. hysteresis loops have a central width of twice the Coercivity) and as such is a measure of how readily an external field can reverse the magnetisation direction of a nanomagnet. This is a key parameter in assessing the suitability of a given magnetic material for technological applications. Figure 4 shows the results, where, in order to be able to compare different geometries, we express the size of the nanomagnets by the square root of their area. We have confirmed the repeatability of certain of these experimental results on a second set of samples.

The first apparent feature from the data of Figure 4 is that the 2-fold and 4-fold symmetries display one class of behaviour while the 3-fold and 5-fold symmetries display another class: 2- /4- fold nanomagnets show high coercivities which at first rise with decreasing lengthscale; 3- /5- fold nanomagnets show low coercivities which fall to zero with decreasing lengthscale. The second observation which can be made about Figure 4 is that in all cases increasing the thickness leads to a strong rise in coercivity, which is not the case in unstructured magnetic films.

The behaviour of the 2-fold nanomagnets is very straightforward and is due to a well understood phenomenon called shape anisotropy. The magnetisation prefers to

"streamline" with the longest axis of the nanomagnet in order to minimise the surface area of the pole faces. The field driving this effect is the demagnetising field which passes between pole faces through the inside of the magnet.

5 The demagnetising field scales approximately with the ratio t/a where t is the thickness of the nanomagnet and a is its size and so one sees in Figure 4A a coercivity which rises with decreasing size.

10 The effects of the 3-, 4- and 5-fold symmetries are, in contrast, not so easily understood. This is because the demagnetising field of any structure is described by a second rank Cartesian tensor and so can only exhibit uniaxial (2-fold) symmetry. There is therefore no shape anisotropy present, at least in the conventional sense, in
15 the plane of these higher order symmetry structures. Nevertheless, the square nanomagnets clearly experience some reasonably strong impediment to changing the direction of the magnetisation and so there must be some anisotropy present. The fact that this anisotropy is clearly weaker
20 in the triangular magnets shows that although it is not classical shape anisotropy, it is still linked to the shape of the nanomagnet.

There is a recently discovered feature in square nanomagnets called configurational anisotropy. This comes
25 about because of the very small deviations from uniform magnetisation which occur in nearly all nanomagnets. To date it has not been made clear to what extent this new anisotropy is important in defining the magnetic properties of nanomagnets. In order to test the hypothesis that the
30 varied behaviour which one sees in Figures 2 to 4 is due to configurational anisotropy, we have performed a direct measurement of the anisotropy in the nanomagnets using a technique which we call Modulated Field Magneto-optical Anisometry. A strong static magnetic field H (≈ 350 Oe) is
35 applied in the plane of the nanomagnets and a weaker oscillating field H_t (14 Oe amplitude) is applied in the plane of the nanomagnets, perpendicularly to H . The

amplitude of the resulting oscillation of the magnetisation is recorded by the same magneto-optical technique used to obtain the hysteresis loops of Figures 2 and 3 and is directly related to the amplitude and symmetry of any anisotropy present in the nanomagnet. We have measured experimentally the anisotropy for triangular, square and pentagonal nanomagnets in the size range 50-500nm at a thickness of 5nm and present the results in Figure 5. In these polar plots, the angle gives the in-plane direction ϕ within the nanomagnet, the radius gives the radius of the nanomagnet in that direction and the colour gives the

experimentally measured quantity $H_a = \frac{1}{M_s} \frac{\partial^2 E}{\partial \phi^2}$ for a

nanomagnet of that size where M_s is the saturation magnetisation (800 emu cm⁻³) and $E(\phi)$ is the average magnetic energy density of the nanomagnet when magnetised in the direction ϕ . Although H_a is not the usual definition of anisotropy field, it can be shown that any oscillations in H_a have the same symmetry order as the underlying anisotropy and an amplitude equal to the magnitude of the anisotropy field. Figure 5 shows experimental data from 22 different samples of artificial magnetic material (8 sizes of triangles, 8 sizes of squares and 6 sizes of pentagons), each measured in either 19 or 37 different directions ϕ (0-180° in 10° steps for triangles and squares, 0-180° in 5° steps for pentagons) making a total of 526 measurements.

It is immediately clear from Figure 5 that there are strong anisotropy fields present in all of the nanomagnets studied. The triangular nanomagnets exhibit anisotropy with 6-fold symmetry, the square nanomagnets show a 4-fold symmetric anisotropy and the pentagonal nanomagnets possess a remarkable 10-fold anisotropy. Frequency doubling occurs in the triangular and pentagonal structures because energy is always quadratic in the magnetisation and so odd symmetry orders cannot be supported.

We have applied a Fourier analysis to the plots of Figure 5 in order to obtain the magnitude of the anisotropy fields as a function of nanomagnet size and symmetry and show the results in two different forms in Figure 6. In Figure 6A we plot the anisotropy fields directly, whereas in Figure 6B we have plotted the anisotropy energy of a single nanomagnet (in units of kT where k is the Boltzmann constant and T is 298K) using the theoretical relationship

$$U_a = 2M_s H_a V / n^2$$

In this equation U_a is the anisotropy energy of a single nanomagnet (in ergs), H_a is the anisotropy field (in Oe), n is the symmetry order of the anisotropy (4 for squares, 6 for triangles, 10 for pentagons) and V is the volume (in cm^3) of the nanomagnet. An important element in our understanding of the influence of symmetry order on magnetic properties is provided by the n^2 term in this equation. It means that although all of the geometries show approximately similar anisotropy fields in Figure 6A, they show very different anisotropy energies in Figure 6B.

The anisotropy energy is particularly interesting because of a phenomenon called superparamagnetism, which is the process by which anisotropy energy barriers can be overcome by the kT thermal energy fluctuations in nanometre scale magnets. As an approximate guide, a barrier can be overcome on the timescale of our measurements once it is less than 10kT in height. This means that once the anisotropy energy is less than 10kT, one would expect the coercivity to fall rapidly to zero. According to Figure 6B this should occur once the element size is less than approximately 150nm, the squares being last to fall as the size is reduced. Conversely, once the anisotropy energy is greater than 10kT, the coercivity should approximately follow the anisotropy field. This explains the difference in behaviour which one observes in Figure 4 between the squares on the one hand and the triangles and pentagons on the other. The anisotropy field of the squares (Figure 6A)

shows a peak as the element size is reduced and this peak is reflected directly in the square coercivity data (Figure 4C). The pentagon anisotropy field shows no peak, and this is also reflected directly in the coercivity data (Figure 4D), although the fall to zero occurs at a slightly larger size in the coercivity data than in the anisotropy field because of thermal activation. Finally, the triangle anisotropy field does show a peak just like the square, but because the anisotropy energies are lower in the triangle, thermal activation sets in at a larger size and prevents the peak from being seen in the coercivity data (Figure 4B). We can thus explain the experimentally determined coercivity data as being due to a combination of configurational anisotropy and thermal activation.

High remanence materials possessing finite coercivity (and therefore a memory function) are not the only technologically important magnetic materials. Equally important are the zero remanence, zero coercivity materials which find applications in magnetic sensors and logic elements and in this case it is the susceptibility, χ , which is the key parameter. χ is defined as $4\pi\partial M/\partial H$ where M is the magnetisation of a nanomagnet and H is the applied magnetic field. χ is thus directly proportional to the zero field slope of hysteresis loops such as that shown in Figure 2F. We have measured χ using our magneto-optical experiment (at a frequency of 27 Hz) as a function of nanomagnet size and symmetry at a constant thickness of 3.7 ± 0.5 nm and present the results in Figure 7. χ is only meaningful when the coercivity is zero and so we have restricted ourselves to this case. For comparison, we have also plotted in this figure the theoretical susceptibility derived from the Langevin function. This is a statistical thermodynamic concept which would apply to a single giant spin in free space. Three observations can be made from Figure 7. Firstly, the experimentally determined susceptibilities of the smallest nanomagnets are all close to the free space Langevin model even though no fitting

parameters were used, showing our experimental system to be well controlled. Secondly, the deviations from the Langevin model are greatest for the square symmetry nanomagnets. This is consistent with these possessing the strongest configurational anisotropy energy, meaning that the giant spin contained in a square nanomagnet looks least like a giant spin in free space. It is configurational anisotropy which eventually causes all of the symmetries to fall away from the Langevin model with increasing size. Thirdly, the susceptibilities measured here are two orders of magnitude greater than would have been obtained from magnetic particles of the same shape and aspect ratio but made on a larger than nanometre lengthscale (i.e. micrometers and above, as most conventional magnetic field sensors use). In this latter case, susceptibility comes from the motion of domain walls against the internal demagnetising field, which can be very strong. The unique role of nanometre scale structuring is thus clearly demonstrated.

Figure 4 and Figure 5 illustrate well the way in which nanometric structuring really does emulate the creation of new magnetic materials. Supermalloy grows with f.c.c. crystallography which usually results in 2- or 4-fold anisotropy. Nevertheless, Figure 5A exhibits 6-fold symmetry which is usually reserved for materials with h.c.p. crystallography. In this case the symmetry of the nanomagnet shape (triangular) can be used to emulate a change in crystallographic phase. Similarly, the relatively high coercivities of square and rectangular nanomagnets (Figure 4A and Figure 4C) would usually only be found in magnetic materials with a high anisotropy and a weakly coupled microstructure. In this case a careful choice of nanomagnet symmetry emulates a change in element and a change in microstructure. Finally, elementary crystallography dictates that a crystalline lattice cannot possess 10-fold symmetry and so we should not expect to find a naturally occurring crystalline element or alloy

with a 10-fold magnetic anisotropy. Figure 5C, however, shows that we have succeeded in creating one artificially using nanostructuring. In this case nanometric shaping has been used to give a crystalline material a property which is usually reserved for quasi-crystals.

The schematic of Figure 8 shows a possible arrangement using a superparamagnetic nanomagnet as part of a sensor or logic element. A trilayer spin valve 12 is joined at both sides to connector lines 14. The valve 12 comprises a magnetic bottom layer 16, a non-magnetic spacer layer 18 and one or more nanomagnets 20 in a superparamagnetic state as a top layer. Arrows 22 indicate the passage of current across the valve 12 and arrow 24 indicates the magnetisation in the magnetic bottom layer 16.

In conclusion, we have determined the relevance of the symmetry of the shape of nanomagnets on their magnetic properties and have applied it to practical applications. We find that symmetry plays a vital role, allowing magnetic properties to be controlled over a very wide range. We have shown that the key effect linking symmetry to the magnetic properties is configurational anisotropy. This provides new artificial magnetic materials where the magnetic properties can be tailored to a particular application with a very high degree of precision.

The first new idea is the use of configurational anisotropy via the symmetry of the element to tailor magnetic properties. To date, people in the art have only considered rectangular, square or circular elements. We have determined that the configurational anisotropy induced by other shapes such as triangles, pentagons and hexagons can be used to control the magnetic properties of the element. The second new idea is the use of superparamagnetism in nanostructures to remove hysteresis. In conventional materials, superaparamagnetism leads to very high saturation fields, and as such is no use for magnetic sensors. We show here, however, that in nanostructures superparamagnetism can lead to very low

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saturation fields (a few Oe - see Figure 2F). By itself this would be very suitable for a sensor or logic element. Even more interesting, however, is the fact that superparamagnetism guarantees a near-zero hysteresis which is a prerequisite for a good sensor (see Figure 3). The greatest problem facing the current use of nanostructures as sensors is the fact that generally hysteresis becomes greater as the lateral dimensions of the device are reduced.

These two ideas can be combined by setting the configurational anisotropy to a low value by the choice of a suitable shape (triangular, pentagonal or circle) which then allows the nanostructure to become superparamagnetic and hence act as a good sensor or logic element.

CLAIMS

1. A memory element comprising nanomagnets having a rotational symmetry selected in order to provide high remanence and a suitable coercivity and wherein the element has rotational symmetry of order 3 or 5.
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2. An element according to claim 1, formed from an artificial magnetic material formed on the surface of a substrate.
- 10 3. An element according to claim 1 or 2, formed from Superalloy ($\text{Ni}_{80}\text{Fe}_{14}\text{Mo}_5$).
4. An element according to claim 1, 2 or 3 the size range 40-500nm per side and in the thickness range 3-10nm.
- 15 5. A sensor element comprising nanomagnets having a geometric rotational symmetry around an axis selected such that they are superparamagnetic and exhibit substantially zero hysteresis so that a magnetisation of the nanomagnets depends only on the current value of applied field and not on the field history.
- 20 6. A sensor element according to claim 5, formed from an artificial magnetic material formed on the surface of a substrate the axis being substantially perpendicular to the surface.
7. A sensor element according to claim 5 or 6, formed from Superalloy
25 ($\text{Ni}_{80}\text{Fe}_{14}\text{Mo}_5$).
8. A sensor element according to any of claims 5, 6 or 7 in the size range 40-500nm per side and in the thickness range 3-10nm.
- 30 9. A sensor element according to any of claims 5 to 8, having rotational symmetries to the order 3 or 5.
10. A magnetic logic element comprising nanomagnets having a geometric rotational symmetry around the axis selected such that they are superparamagnetic

and exhibit substantially zero hysteresis so that a magnetisation of the nanomagnets depends only on the current value of applied field and not on the field history.

5 11. A logic element according to claim 10, formed from an artificial magnetic material formed on the surface of a substrate, the axis being substantially perpendicular to the surface.

12. A logic element according to claim 10 or 11, formed from Superalloy
10 ($\text{Ni}_{80}\text{Fe}_{14}\text{Mo}_5$)

13. A logic element according to any of claims 10, 11 or 12 the size range 40-500nm per side and in the thickness range 3-10nm.

14. A logic element according to any of claims 10 to 13, having rotational
15 symmetries to the order 3 or 5..