Patterning nanostructures to study magnetization processes

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Abstract. Lithography techniques such as electron-beam lithography and focused-ion-beam milling are widely used to fabricate structures with dimensions well below 1 µm. These techniques have been used to produce planar magnetic structures with sub-micrometer dimensions and well controlled geometry. This has allowed the study of basic magnetic behaviour and the development of structures with potential for applications in magnetic recording and magnetic logic devices. The techniques of electron beam lithography and focused-ion-beam milling for the fabrication of magnetic nanostructures are outlined here. These techniques have been used to fabricate ribbon-like planar nanowires to study the behaviour of the individual magnetic domain walls which mediate the reversal process in such elongated structures. These methods allow the production of structures in which the location of domain wall formation and position can be controlled, allowing separation and study of the domain wall nucleation and propagation processes. Domain wall injection and domain wall propagation behaviour are investigated and shown to be stochastic processes.

1. Introduction

As lithographic fabrication technology pushes the critical dimensions of ferromagnetic structures deeper into the sub-micrometer regime of fine particle magnetism, the magnetic domain configurations of the structures are, in principle, simplified as the dimensions become comparable with the length scales of domain wall width and the exchange length. Understanding the magnetization processes in such magnetic structures is of fundamental interest and important for future device applications in magnetic memory, spintronics [1-3] and magnetic logic [4, 5]. The magnetization structure and reversal behaviour also depend on the intrinsic properties of the magnetic material and here Permalloy of nominal composition Ni$_{81}$Fe$_{19}$ was used.

2. Patterning Nanostructures

By fabricating magnetic nanostructures using techniques such as focused-ion-beam milling or electron-beam lithography a wide range of shapes can be defined in two dimensions, presenting the opportunity to control and explore magnetization behaviour in a systemic way. Electron beam lithography begins by adding a polymer layer (the ‘electron beam resist’) of several tens of nanometres thickness to a clean substrate (typically silicon). The polymer used here is poly(methylmethacrylate) known as PMMA which was deposited by spin coating a 2% solution of PMMA in anisole. Coated substrates were baked on a hot plate to evaporate the solvent. Pattern writing was undertaken in an electron microscope using lithography facilities that take control of beam movement and blanking. The electron beam is moved across the sample and the substrate is exposed to the electron beam following a computer generated pattern. With a sufficient dose of electrons a given area of electron resist becomes soluble in a developer solution and is removed from
the substrate. The requisite dose is determined by the polymer type, its molecular weight and the
development conditions. It can also depend on the geometry of structures being patterned and is
usually determined by dose testing the structures of interest. Here exposed substrates were
developed by immersion in standard developer for PMMA, i.e. methyl-isobutyl-ketone (MIBK)
mixed in the ratio 1:3 with isopropyl alcohol, typically for 30 seconds. After washing in isopropyl
alcohol and drying the substrate with the patterned resist was coated with a thin-film of magnetic
metal. Thin films were deposited by either thermal evaporation or sputtering using single targets of
the required composition. Nominal film thickness was typically 5 nm. After deposition the substrates
were bathed in acetone with ultrasonic assistance to ‘lift-off’ the patterned resist leaving the
magnetic nanostructures on the substrate.

Focused-ion-beam (FIB) milling has been developed more recently as a tool for the fabrication of
nanostructures. In contrast to electron beam lithography using lift-off where the magnetic material is
deposited onto a patterned substrate, with FIB milling the substrate is initially coated with a
magnetic thin-film using the techniques described. A focused beam of Ga+ ions is then directed at
the sample to remove material by locally sputtering material off the surface. By controlling the beam
movement and dwell-time, nanostructures are patterned by removal of unwanted material
surrounding the nanostructure [6]. The rate of milling depends on the material being milled and the
beam current. However, higher beam currents give poorer spatial resolution lithography. An
alternative method of patterning involves using a magnetic layer capped with a thin film a few
nanometres thick of another metal, such as aluminium. In this case the sample is irradiated with a
sufficient dose such that ion bombardment causes intermixing of the layers and destroys the
ferromagnetism of the magnetic layer leaving nanoscale ferromagnetic structures as designed. This
method works well for very thin films and is more rapid than milling material [7].

3. Magnetization Processes in Planar Nanostructures

For circular, square and near equi-dimensional planar magnetic nanostructures fabricated by electron
beam lithography systematic studies have elucidated the magnetization structure and shown that the
reversal processes depend on the magnetization configuration of the structure, in particular the
ability to support a vortex spin structure [8, 9] and the effects of interactions between structures [10].
For highly-elongated or ‘planar-wire’ structures the combination of the intrinsic magnetic properties
of Permalloy and the thin, elongated geometry leads to a simplified single, axial domain structure
with some magnetization deviation at the ends of the wires which is larger for wider structures. The
reversal process in the elongated structures takes place by propagation of domain walls along the
axis of the structure beginning at one or both ends. The initial reversed domains and the associated
head-to-head or tail-to-tail walls are formed at the ends of the structure.

Magnetization switching measurements here were undertaken on individual nanostructures using
a highly sensitive continuous wave laser magneto-optical Kerr effect (MOKE) magnetometer [11].
The normalised MOKE signal can be taken as indicative of the magnetization direction.

3.1. Effect of Edge Roughness of Structures on Magnetization Behaviour

Before considering the gross geometry dependent magnetization behaviour it should be noted that
the structural roughness at the edges of nanostructures can affect the switching behaviour.
Distributions in the switching fields of arrays of nominally identical nanomagnets may in part be due
to variations in edge profile arising from edge roughness resulting from the fabrication process.
This may be important in future device applications where uniform switching behaviour is required
in large arrays. The effect of edge roughness was investigated experimentally by varying the
exposure and development conditions during electron beam lithography patterning of rectangular
nanostructures [12]. The edge roughness was characterised using a scanning electron microscope
with ±2.5 nm resolution. For structures with widths ranging from 323 nm to 640 nm the switching
field increases linearly with the peak-to-peak edge roughness, see for example figure 1. For the
widest structures (lowest switching fields) large edge roughness more than doubled the switching
field. In contrast, for 200 nm wide structures no variation in switching field with edge roughness was observed.

The mechanism for enhancement of the switching field may be due to distortions of the spin structure arising from the edge roughness changing the energetics of the system and affecting the initiation of the magnetization reversal process. Alternatively, edge roughness may aid the initial stage of reversal, but then cause pinning of flux closure domains or newly nucleated domain walls, increasing the switching field by hindering domain wall propagation. For FIB milled nanostructures the edge definition is more complex. In addition to the milling resolution determined by the beam spot size and resolution of the beam movement, the incorporation of Ga+ ions at the edges of the magnetic nanostructure is likely to modify the magnetic properties and ultimately quench the ferromagnetism at the edges. As a result the effective magnetic width of FIB milled nanostructures may not correspond with the physically observed width.

3.2. Thickness/Width Dependence of Magnetization Switching
For elongated nanostructures the switching process involves the formation (nucleation) of a reverse domain at the ends of the structure followed by the rapid propagation of the wall(s) through the nanostructure. For simple rectangular nanostructures the switching field is observed to increase with the reciprocal of the width of the structure [13, 14]. This can be understood in terms of the self demagnetizing field which increases with the width of structure making wide structures easier to switch as the initial spin structure is more strongly distorted at the ends of the structures in response to the higher demagnetizing field. The switching field also depends on the thickness of the nanostructures as this too affects the demagnetization factor. For a given width the switching field increases as the thickness of the structure increases [13].

3.3. Magnetic Domain Wall Behaviour in Planar Nanowires
The variation of switching field arising from different widths can be used in the design of more complex nanostructures where a domain wall generated in the wider parts of a structures can be propagated into a narrower region (at lower fields than the nucleation field of the narrower section), allowing the behaviour of domain wall propagation in the narrower region of the structure to be studied. Figure 2 illustrates the reduction of the switching field observed by the addition of a wider section to one end of a 200 nm wide nanostructure. Care must be taken when using such ‘injection pad’ structures to provide domain walls for narrower sections as the switching field of the pad can be

![Figure 1](image-url). Electron micrographs of two structures with their corresponding magnetization loops for two planar nanowires with the same average width showing the effect of edge roughness. The structures have a peak-to-peak edge roughness of (a) 27 nm and (b) 60.5 nm. Average width 575 ± 2.5 nm.
Figure 2. Magnetic hysteresis loops comparing the switching fields of 200 nm wide planar nanowires with and without the presence of a 600 nm wide domain wall ‘injection pad’ at one end of the structure. The nanowire shapes are illustrated above the loops. 

Multi-modal and vary with temperature as a result of competing domain configurations [15]. Nonetheless such ‘injection pads’ are useful in the design of experimental structures for generating domain walls at specific locations.

Alternatively, domain walls can be introduced in a nanostructure by locally increasing the magnetic field at the end of the structure using a current carrying conductor fabricated on top or below the magnetic structure [16, 17], see for example figure 3a. Figure 3b shows the effect of adding localised pulses of magnetic field to an offset sinusoidally varying field. With no pulses the offset in field prevents the magnetization reversing. With the addition of pulses that approximately coincide with the negative peak of the sinusoidal field the magnetization of the nanostructure reverses. The use of current pulses with controlled amplitude and duration reveals the stochastic nature of the domain nucleation process in these nanostructures (see figure 3c). For potential device applications [e.g. 4] where successive domains of opposite polarity are required bipolar pulse switching has been demonstrated [17].

Domain walls can also be introduced by heating a structure to reduce the nucleation field. The reduction of the switching field can be achieved locally using Joule heating of similar conducting tracks fabricated onto the magnetic nanostructure but the effect is small [18].

Figure 3. (a) SEM image of a 200 nm wide Permalloy planar nanowire emerging from beneath a 30 nm thick aluminium conducting strip-line. (b) MOKE measurements showing a 400 nm wide nanowire that does not switch when subjected only to an asymmetric sinusoidal magnetic field but switches when a localised pulsed field is applied at the peak of the negative sinusoidal field. For the same 400 nm wide structure (c) shows the probability that switching occurs increases with both pulsed field amplitude and the pulse duration.
Using two dimensional nanostructures with orthogonal sections connected by corners the location of domain walls can be controlled by the application of orthogonal magnetic fields. A domain wall injected into one section of a nanostructure by a field in the x-direction will stop at a corner and only propagated further through the adjoining orthogonal section of the structure upon the application of a field in the y-direction. By controlling the applied field in two dimensions in the plane of the nanostructure the wall location can be controlled and the wall behaviour studied. Using L-shaped nanostructures the presence or absence of a domain wall at the corner can be observed via its effect on the switching field. If the two sections of an L-shaped structure are magnetized in opposition a domain wall exists at the corner. The application of a field along one of the sections will propagate the wall and switch the magnetization of the section. When the magnetization of the two sections is initially continuous the reversal of one section (by applying a field along its axis) requires the nucleation of a reverse domain and associated domain wall, so the switching field for this process is higher. Therefore, a magnetic hysteresis loop may be offset along the field axis when measured in such an L-shaped structure. This is the case when the corner is a simple sharp 90° connection where the wall may be pinned at the corner by the increased width of the structure at the corner [19]. However, when the corner is a curved structure of constant width the wall can move more easily through the structure. Figure 4 shows the magnetic hysteresis measured along the x-axis of a 200 nm wide, 5 nm thick, structure fabricated by electron beam lithography. When the magnetization lies in the negative x-direction a domain wall is present at the corner. The application of an increasing field in the positive x-direction causes the domain wall to move through the structure as a function of increasing field resulting in the upward curving magnetization until complete switching is observed. In contrast, once the magnetization is switched into the positive x-direction the magnetization through the structure is continuous and reversal proceeds by the nucleation and rapid propagation of a domain wall resulting in a sharp switching event to reverse the magnetization.

By combining domain wall injection pads and corners in nanostructures the behaviour of individual domain walls can be studied. Such structures have been fabricated for experiments including the velocity of domain wall propagation [20, 21], the effect of spin-polarised current on the domain wall propagation [22, 23] and the pinning of domain walls by deliberately imposed defects [24].

Domain wall dynamics in a rectangular sub-micron width structure were first reported by Koch et al. [25] for the magnetization reversal of a 5 nm thick Ni$_{80}$Fe$_{40}$ 800 nm wide and 1.6 µm long patterned element using tunnelling magnetoresistance. In this case the switching was described as thermally assisted domain wall motion and an effective domain wall mobility of 16 (ms$^{-1}$)Oe$^{-1}$ was obtained. Ono et al. studied magnetization switching in a rectangular 500 nm wide, 40 nm thick Ni$_{80}$Fe$_{20}$ layer (forming part of a trilayer giant magnetoresistive structure) and measured the domain wall velocity at temperatures between 100 and 160 K [26]. The velocities obtained range between

![Figure 4](image_url). The switching behaviour of the horizontal arm of a 200 nm nanostructure (fabricated by electron beam lithography) showing the influence of the presence of a pre-existing domain wall on the switching behaviour. The magnetic field is applied along the x-axis only.
100-300 m/s. The domain wall mobility was 2.6 (ms\(^{-1}\))Oe\(^{-1}\) and found to be constant over the temperature range investigated. This mobility is much lower than that obtained from micromagnetic modelling and thin film measurements, and was attributed to a significantly higher gyromagnetic damping due to edge and surface defects [16]. Using the complex shaped single layer 200 nm wide 5 nm thick Permalloy nanowire illustrated in figure 5 the domain velocity was determined using the magnetooptic Kerr effect to detect magnetization switching [20, 21]. This structure separates the domain wall nucleation (injection) process from the domain wall propagation allowing the domain wall velocity to be determined at fields well below the nucleation field of the equivalent rectangular nanostructure. After domain wall injection and propagation to the first corner domain wall velocities were obtained from the time required for the wall to travel along a known length of the wire between the corners. The transit time was obtained from the duration of the pulsed field. Figure 5b shows examples of the switching data obtained using this method. The switching behaviour was found to be stochastic with the probability of switching increasing with the amplitude and duration of the pulsed fields used to propagate the domain wall. Figure 5c shows the field dependence of the domain wall velocity. Domain walls propagated very slowly at low fields (12 Oe) and the velocity increased rapidly with field to over 1 km/s above 45 Oe. The field dependence of the velocity is consistent with thermally activated wall motion and a limiting case analysis of the intrinsic gyromagnetic damping indicates a damping factor similar to that for continuous thin films [21]. The high velocities obtained have also been explained with micromagnetic modelling in term of the influence edge roughness which can aid the rapid propagation of domain walls in such narrow structures [27].

4. Summary

The nanolithography methods used to fabricate planar magnetic nanostructures have been briefly described. These methods have been applied to produce magnetic structures that allow control over the reversal process and hence allow the study of magnetization processes. Domain walls can be introduced into narrower wires from wider ‘nucleation pads’ or by localised field enhancement. The location of domain walls can be controlled using structures with corners and by applying orthogonal fields. The separation of domain wall nucleation and propagation allows the study of domain wall propagation behaviour with magnetic fields below the level required for direct nucleation. Such behaviour includes the velocity of propagation, domain wall pinning and current induced domain wall motion.

Figure 5. (a) An image of a 200 nm wide Permalloy nanostructure fabricated by FIB milling to study domain wall velocity. (b) Examples of the probability of non-switching observed in the domain wall velocity experiments. (c) The magnetic field dependence of domain wall velocity of a 200 nm wide, 5 nm thick Permalloy nanostructure.
5. References

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