Shape critical domain reversal in patterned nickel and permalloy stripes in Neel and Bloch regime

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We present a systematic study of shape controlled domain reversal phenomenon in patterned Nickel and Permalloy thin films for thickness lying in the Neel and Bloch regime. The films were patterned with continuous stripes of varying aspect ratios using photo-lithography. MOKE measurements and Kerr microscopy have been done in longitudinal arrangement for magnetic fields applied along the length and the width of the stripes. For magnetic fields applied along the length of the stripes, domain reversal phenomenon resulted in propagation of domains from one stripe to another for both Neel and Bloch regime of Ni and Py thin films. Similarly, for magnetic fields applied along the width of the stripes, stripe domains along with multiple domain walls were observed during the magnetization reversal in Neel as well as Bloch regime of Ni and Py thin films. We observed a decrease in domain width and an increase in domain wall density as one goes from Neel regime to Bloch regime for both Ni and Py films. The comparison of domain reversal in Ni and Py stripes shows that the domains switch gradually in Ni compared to Py thin films. Shape anisotropy was found to be the dominant factor to determine the domain reversal mechanism in all cases. It was noticed that the effect of shape anisotropy increases as the aspect ratio is increased. Micromagnetic OOMMF simulations were also done to support the experimental data. Furthermore, we have shown that the coercive fields can be tuned by varying the aspect ratios of the patterned structures. The ability to control the magnetization reversal and domain wall density in these patterned structures is a key to various applications of spintronics.

Keywords: Shape anisotropy, Neel domain wall, Bloch domain wall, domain reversal

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I. INTRODUCTION

Patterned magnetic thin films is a vast area of research from several perspectives. Two of them are: First, they are a good candidate to study the effect of lateral confinement on the spin re-arrangements and magnetization reversal processes\textsuperscript{[1-7]}; Second, they provide a basis to understand the new physical phenomena which are of fundamental interest and key to future applications in hard disk drives, magnetic random access memory (MRAM) and other spintronics devices\textsuperscript{[8,9]}. Moreover, it also offers a unique opportunity to attain a precise control over the local magnetic properties of patterned thin films. For example, the magnetization, $M$, distribution and reversal in thin films with restricted lateral size is mostly governed by the magneto-static fields localized on their edges\textsuperscript{[10]} which can be tuned by changing the shape of the patterned structures. In the context of superconducting spintronics, domain walls can be used with superconductors to generate the spin-polarized triplet supercurrent\textsuperscript{[11]}. The triplet Cooper-pairs can carry a net spin component and hence, offer the potential to eliminate the heating effects associated with spintronics devices. Domain wall superconductivity is another aspect of superconducting spintronics where the knowledge about domain reversal is important\textsuperscript{[12,13]}. Moreover, the magnetization reversal of one or more ferromagnetic components is the key functional aspect of spintronics devices. For example, lateral spin valves are one of the most widely utilized device structures in spintronics\textsuperscript{[14,15]}. For an effective implementation of the lateral spin valve experiments, the two ferromagnetic electrodes should possess different coercive fields which allows independent reversal of magnetization and realization of parallel and anti-parallel magnetic alignments. In this context, a systematic investigation of the variation in the coercive fields and the shape anisotropy constants of patterned Fe films on GaAs with geometry and thickness was done by Meng et al. and co-workers\textsuperscript{[16]}. Thus, it is vital to study the influence of shape and size on the magnetization dynamics of ferromagnetic components in patterned structures. Another study to look at the effect of shape on domain formation was done in permalloy patterns with a width of several micrometers\textsuperscript{[17]}. Domain observations using the longitudinal magneto-optical Kerr effect (MOKE) showed that pointed ends suppress the formation of end domains. Therefore, it increases the stability of the high-remanence state which is useful for sensor operation. These studies have considerably improved the basic understanding of magnetization processes in patterned magnetic structures. Smyth et al\textsuperscript{[18]} prepared an array of permalloy particles and
demonstrated the effect of particle size and aspect ratio on the hysteresis experimentally and numerically. They reported an increase in the coercive field with decrease in particle width. Gabois and Zhu\textsuperscript{19} demonstrated numerically the effect of edge roughness on the switching fields of nano-scale Ni bars. The field driven reversal processes have been mostly studied with a variety of theoretical and experimental techniques in permalloy and iron thin films patterned in different shapes and sizes. However, a systematic study of the influence of shape and size on the magnetization reversal and the coercive fields of Ni and Py films in Neel and Bloch domain wall regime is lacking.

In this work, we have studied shape controlled tuning of domain reversal in nickel and permalloy thin film stripes of different aspect ratios for the film thickness lying in the Neel and Bloch domain wall regime. Longitude Kerr microscope measurements have been performed in order to show the domain reversal in these micro-structures. For magnetic fields applied along the length of the stripes, a controlled propagation of domains was observed from one stripe to another. For magnetic fields applied along the width of the stripes, multiple stripe domains and domain walls were formed in the stripes. The variation of domain width and domain wall density is shown for different domain wall regime. Variation of coercive fields have been shown as a function of the aspect ratios of different stripes. Micromagnetic OOMMF simulations results agree with the experimental data.

II. EXPERIMENTAL DETAILS

Patterned Ni and Py thin films with thickness of 15 nm and 90 nm were prepared at room temperature using dc magnetron sputtering of high purity (99.999\%) Ni and Py ingots on cleaned Si-SiO\textsubscript{2} substrates. The films made in this work are isotropic, therefore, any anisotropy in the patterned magnetic structures should come from their shape. Prior to the deposition, substrates were cleaned through a sequence of ultra-sonification in acetone and isopropanol baths. The base pressure of the deposition system was $2 \times 10^{-8}$ mbar. No substrate heating was employed during the deposition. Ni and Py films were patterned using photo-lithography and ion-milling techniques as shown in Fig. 1(a). The magnetic domains were imaged by high resolution magneto-optical Kerr microscope supplied by M/s Evico Magnetics, Germany. All magneto-optical Kerr effect measurements were performed at room temperature. The magnetization (M-H) loops were measured simultaneously by deriving the
magnetization signal from the average domain image intensity in longitudinal mode for an in-plane magnetic field applied along the length and the width of the stripes. The magnetization configurations were also simulated using the OOMMF software code.

A. RESULTS AND DISCUSSIONS

Figure 1(a) show the FESEM image of the patterned Ni film with stripes of different widths varying from 5 µm to 50 µm and with a thickness of 15 nm (Neel regime). The length of all stripes was kept constant as 100 µm. Generally, the domain wall energy per unit area (the sum of anisotropy, exchange and stray field energy densities) gradually increases with increasing film thickness for Neel walls, whereas for Bloch walls, the domain wall energy decreases with increasing film thickness. Therefore, Neel walls are energetically favorable at lower thickness while Bloch walls are favorable at thickness beyond a certain threshold value. It has been predicted theoretically that the crossover thickness in nickel films is about 50 nm whereas it is 30 nm in case of Py thin films. Therefore, throughout the text, we will refer to Ni and Py films of 15 nm thickness as the Neel regime and the 90 nm thickness as Bloch wall regime.

In order to compare the magnetization reversal of stripes with different aspect ratios, MH loops along with simultaneous domain images were recorded for different stripes for an in-plane applied magnetic field along the length and the width of the stripes. Henceforth, keeping in mind that the magnetic field is always applied in the plane of the substrate, throughout the text, we will refer to these two field configurations as parallel and perpendicular field, respectively. Figure 1 shows the coercive fields ($H_c$) of Ni and Py stripes as a function of their width for Neel as well as Bloch regime of thickness in parallel and perpendicular configuration. For parallel configuration, we observe a decrease in ($H_c$) with increase in the width of the stripes. This shows that the sample geometry has a dramatic effect on the reversal of the magnetization. This is because demagnetizing fields come into picture on reducing the dimensions in patterned structures. The demagnetization field for a single stripe is proportional to $M_s t/w$, where $M_s$ is the saturation magnetization, $t$ is the thickness and $w$ is the width of the stripe. The demagnetization field, $H_d$, reduces the internal field of a stripe to $H_i = H_a - H_d$, where $H_a$ is the applied field. Therefore, the coercive field of stripe of width $w$ becomes:
\[ H_c = H_0 + A/w \]

where \( H_0 \) is the coercive field of a stripe with infinite width (thin film) and \( A \) is a constant parameter which depends on the thickness, finite length shape anisotropy factor and saturation magnetization of the stripe. The fitting model assumes that a small part of the stripe reverses magnetization coherently and propagates along the stripe. Here, \( H_0 \) and \( A \) are free fitting parameters. The fitting results gave a value of 65 Oe and 20 Oe for \( H_0 \) of Ni film of 15 nm and 90 nm thickness while \( H_0 \) was 25 Oe and 2 Oe for Py film of 15 nm and 90 nm thickness. The values of \( H_0 \) show the soft magnetic nature of Ni and Py thin films and are consistent with the literature\(^{30,31}\). The stripe with lower width (higher aspect ratio) has a larger shape anisotropy and therefore, requires a larger energy to switch, resulting into higher \( H_c \). On the other hand, in perpendicular configuration, we observe an increase in \( H_c \) with increase in width of stripes. Due to the shape anisotropy, the short axis of the stripes tends to be the hard axis in these patterned structures. Therefore, the stripe with lower width (higher aspect ratio) will have more tendency to act like hard axis, resulting into lower \( H_c \). Similar results were reported in previous literature for magnetic fields applied along the easy axis and hard axis of Co nanowires\(^{35}\).

Figure 2(a), (b), (c), (d), (e) show the hysteresis loop along with simultaneous images recorded with Kerr microscope from a local region consisting of three stripes with aspect ratios of 2, 2.5 and 3.33 (marked as \( R_4, R_5, R_6 \) in Fig. 1(a)) in the Neel regime of Ni thin film for parallel configuration. We observe that the magnetization reversal starts from the stripe with lower aspect ratio due to its low coercivity. A monotonic decrease in the coercivity of alternate stripes results in a propagation of domains from one stripe to other as shown in Fig. 2(c), (d). Since the growth of domains happens in a particular direction, we propose that a 180° domain wall propagates from wider stripes to narrower stripes of the patterned geometry. R.H.Wade\(^{36}\) in 1962 showed that the polycrystalline nickel thin film of 16 nm thickness comprises of 180° domain walls with a domain wall thickness of 55±0.5 nm. Although it is difficult to find the width of domain walls in our study but the kind of domain walls observed are similar to that in the literature. In Fig. 2(f), (g), (h), (i), (j), (k), we show the MH loop along with the Kerr microscope images of stripes with aspect ratios of 2.5 and 3.33 (marked as \( R_4, R_5 \) in Fig. 1(a)) in the Neel regime of Ni thin film for perpendicular configuration. We observe that domain nucleation initiates in the lower width region, at some nucleation points as shown in Fig. 2(h). Then, domains started to
grow around the nucleation points and stripe domains were formed giving rise to multiple domain walls throughout the structure. We notice that the sequence in which the domain nucleation starts in different stripes, follows the variation of co-ercive fields as a function of width as shown in Fig. 1(f).

Figure 3(a), (b), (c), (d), (e) show the hysteresis loops along with the Kerr microscope images from a local region consisting of inner stripes with aspect ratios of 10 and 19 (marked as $R_1$, $R_2$ in Fig. 1(a)) in the Bloch regime of nickel thin film for parallel configuration. Note that the Kerr images shown in this manuscript have been taken from particular stripes for representation purpose. We observed a propagation of domains in the parallel configuration as shown in Fig. 3(b) and (d). In Fig. 3(f), (g), we show the MH loop and the Kerr image for stripes with aspect ratio of 2.5 and 3.33 (marked as $R_4$, $R_5$ in Fig. 1(a)) in perpendicular configuration. The domain reversal resulted in a growth of stripe domains as shown in Fig. 3(g). The comparison of Kerr images shown in Fig. 2(i) and 3(g) suggests that the domain width decreases in Bloch regime for the patterned Ni film. Therefore, the domain wall density increases in Bloch regime compared to Neel regime.

To further check the domain reversal phenomenon in these patterned structures, we have performed 3D micro-magnetic OOMMF simulations on patterned Nickel films with 90 nm thickness in parallel and perpendicular field configurations as shown in Fig. 3, respectively. Here, x axis refers to the direction along the length of stripes, y axis refers to the direction along the width of the stripes and z axis refers to the axis transverse to the sample plane. The z dimension was kept as 90 nm whereas x and y dimensions were kept as 7 $\mu$m and 1 $\mu$m, respectively. The cell size for the simulation was kept as (10, 10, 10) nm$^3$ in (x, y, z) directions. The values of saturation moment and the exchange constant were taken from the literature as $4.9 \times 10^5$ A/m, $9 \times 10^{-12}$ J/m. The value of anisotropy constant was taken as 0 J/m$^3$ due to the polycrystalline nature of these films. The simulations show that the reversal of domains start from the edges of the pattern as shown in Fig. 3(c). This is in agreement with the experimental result shown in Fig. 3(b). The edges of the pattern act as the nucleation center for domain reversal in patterned structures, as reported earlier. On increasing the field in opposite direction, a part of the stripe reverses magnetization and propagates along the stripe as shown in Fig. 3(e). Similarly, we observed two domain walls propagating along the center of pattern as shown in Fig. 3(d). These results agree with the model used to fit the coercive field versus width curves shown in Fig. 1(b), (c), (d), (e). For
perpendicular configuration, simulations give stripe domains as shown in Fig. 3(h) which are similar to the experimental result shown in Fig. 3(g).

Figure 4 shows the hysteresis loop along with Kerr microscope images for the 15 nm permalloy stripes for parallel and perpendicular field configurations. Similar to the case of Ni, domain reversal starts from the stripe with lower aspect ratio in case of Py film in the Neel regime. Then, it proceeds towards the stripe with higher aspect ratio resulting in a propagation of domains along the direction of field as shown in Fig. 4(b) and (c). Stripe domains were observed for perpendicular configuration as shown in Fig. 4(e), (f), (g). The domain reversal Mechanism of these films is same as that of Ni films discussed previously.

Figure 5 shows the hysteresis loop along with Kerr microscope images for stripes with aspect ratios of 10 and 19 in the Py thin film in Bloch regime for parallel and perpendicular configuration. We observe a propagation of domains from low aspect ratio region to high aspect ratio region as shown in Fig. 5(b), (c). In Fig. 5(e), (f), we show the MH loop and Kerr images for stripes with aspect ratio of 3.3 and 2.5 in perpendicular configuration. The domains started to grow around the nucleation points resulting into stripe domains and finally merged to saturate in the opposite direction. We notice that the domain width is less and hence, the domain wall density is higher in Bloch regime of Fig. 5(f) compared to Neel regime of Fig. 4(g). The comparison of domain reversal of Py of Fig. 5(c) with Ni of Fig. 3(b) shows that the domain dynamics is more gradual in Ni compared to Py. Similar can be seen from the comparison of Fig. 5(a) and Fig. 3(a). Moreover, domain reversal mechanism was found to be same in Ni and Py films in the Neel and Bloch regime and therefore, the shape anisotropy is the dominant factor to determine the domain reversal mechanism in all cases.

1. **SUMMARY**

In summary, we have studied the propagation of domains in Ni and Py thin films patterned with continuous stripes of varying aspect ratio in both Neel as well as Bloch regime of thickness. For the Neel regime, Longitudinal Kerr microscope measurements reveal that there is a continuous variation of switching fields for magnetic fields applied along the length of the stripes. This results in a continuous propagation of domains along a specific direction. This has been explained due to the dominant shape anisotropy with increase in aspect ratio.
of the stripes. For magnetic fields applied along the width of the stripes, multiple stripe like domains were observed. For the Bloch regime also, a controlled propagation of domains was observed irrespective of higher thickness for parallel field configuration. A controlled propagation of domains has also been shown using OOMMF simulations. Similar results were obtained for Py stripes in Neel and Bloch regime. The domain reversal happens more gradually in Ni compared to Py. For the perpendicular configuration, multiple stripe domains were formed during the magnetization reversal of both Ni and Py films in Neel as well as Bloch regime. This shows that the shape anisotropy is the dominant factor to determine the domain reversal mechanism in all cases. From the comparison of Kerr images in Neel and Bloch regime, we observe that the domain wall density is higher in Bloch case compared to Neel case. Therefore, we conclude that it is better to use Bloch domain wall based devices to study the domain state based phenomena such as domain wall magnetoresistance, spin polarized supercurrent generation, domain wall switching etc. in spintronics. Furthermore, we have shown that it is possible to control the direction of motion of domains by making micro-structures using photo-lithography. The domain velocities can be studied in the same structure by doing careful measurements as a function of time.

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FIG. 1. a) FESEM image of the Ni stripes with thickness of 15 nm and widths varying from 5 \( \mu m \) to 50 \( \mu m \); Variation of coercive fields with respect to width of Ni and Py stripes have been shown along with the fitting, coercive fields have been taken from the hysteresis loops recorded using MOKE measurements of these stripes. \( H_{c||} \) represents the coercive field for magnetic fields applied along the length of stripes of Ni films with thickness of b) 15 nm, c) 90 nm and for Py films with thickness of d) 15 nm, e) 90 nm; \( H_{c\perp} \) represents the coercive field for magnetic field applied along the width of the stripes for Ni films with thickness of f) 15 nm, g) 90 nm and for Py films with thickness of h) 15 nm, i) 90 nm
FIG. 2. (a) Hysteresis loop measured by longitudinal Kerr microscope for three stripes of 15 nm nickel film with aspect ratio of 2, 2.5 and 3.33 for parallel configuration; (b) to (e) are the Kerr images corresponding to the field points marked A-D in (a), respectively, (f) Hysteresis loop for magnetic fields applied along the width of the stripes; (g) to (k) are the Kerr images corresponding to the field points marked A-E in (f); Black arrows in (b) and (g) represent the direction of applied magnetic field for the initial saturated state. The scale bar shown in (b) is valid for images (b),(c),(d) and (e). The scale bar shown in (g) is valid for (g),(h),(i), (j) and (k). Red arrows represent the direction of magnetization for the bright and dark portions of the image.
FIG. 3. (a) Hysteresis loop measured by longitudinal Kerr microscope for two stripes of 90 nm nickel thin film with aspect ratios of 10 and 19 for parallel configuration; (b), (d) are the Kerr images corresponding to the field points marked A, B in (a); (c), (e) show the corresponding OOMMF simulation images representing the propagation of domains; (f) Hysteresis loop for perpendicular configuration; (g) represents the Kerr image corresponding to the field point marked A in (f); (h) shows the corresponding OOMMF simulation image; the red color in simulation presents the moments in one direction whereas the blue color represents the moments aligned in other direction, the white color represents the region of changing moments i.e. domain walls. Black arrows in (b), (g) represent the direction of applied magnetic field. The scale bar shown in (b) is valid for all the images. Red arrows represent the direction of magnetization for the bright and dark portions of the image.
FIG. 4. (a) Hysteresis loop measured by longitudinal Kerr microscope for the stripes of 15 nm permalloy film with aspect ratio of 10 and 19 for parallel configuration; (b), (c) are the Kerr images corresponding to the field points marked A, B in (a), respectively, (d) Hysteresis loop for magnetic fields applied along the width of the stripes; (e) to (g) are the Kerr images corresponding to the field points marked A, B, C in (d); Black arrows in (b) and (e) represent the direction of applied magnetic field for the initial saturated state. The scale bar shown in (b) is valid for all the images. Red arrows represent the direction of magnetization for the bright and dark portions of the image.
FIG. 5. (a) Hysteresis loop measured by longitudinal Kerr microscope for the stripes of 90 nm permalloy sample with aspect ratio of 10 and 19 for parallel configuration; (b), (c) are the Kerr images corresponding to the field points marked A, B in (a), respectively, (d) Hysteresis loop for perpendicular configuration; (e), (f) are the Kerr images corresponding to the field points marked A, B in (d); Black arrows in (b) and (e) represent the direction of applied magnetic field. The scale bar shown in (b) is valid for all the images. Red arrows represent the direction of magnetization for the bright and dark portions of the image.