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## Stochastic domain wall depinning in permalloy nanowires with various types of notches

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## Stochastic domain wall depinning in permalloy nanowires with various types of notches

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Stochastic phenomena in magnetic nanowires based on domain wall (DW) motion is scientifically important thus to understand and control such behaviors are very meaningful. Here we report on the investigation of pinning and depinning of DWs in permalloy nanowires with six types of longitudinally asymmetric notches using focused magneto-optic Kerr effect (FMOKE) magnetometer and magnetic force microscopy (MFM). The hysteresis loops obtained by FMOKE indicate the generation of one or two distinct depinning fields by creating one notch close to the edge of the nanowires, in comparison multiple depinning processes occur in the nanowires with two identical notches symmetrically placed along the transverse direction, indicating more remarkable stochastic DW depinning phenomena. The MFM images verify the existence of DW in each type of nanowires and the DW sizes in the latter kind of nanowires are generally larger than those in the former ones. These observations can be explained by considering the thermal perturbation and edge or surface roughness effects in nanowires. © 2016 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>). [<http://dx.doi.org/10.1063/1.4973647>]

### INTRODUCTION

Precise and effective control of the domain wall (DW) motion in ferromagnetic nanostructures can have important impacts on developing next generation magnetic devices, including magnetic memory<sup>1</sup> and logic components.<sup>2,3</sup> Propagation and depinning of DW in magnetic nanowires can be achieved using external magnetic field<sup>4,5</sup> or spin-polarized current.<sup>6-8</sup> In these nanostructures, artificial defects, such as notches or protrusions<sup>9-12</sup> can become potential pinning sites for DW trapping. For soft magnetic nanowires, magnetic moments lie in-plane due to shape anisotropy. Thus two basic types of DWs<sup>13,14</sup> are identified, namely, the vortex and transverse DWs. The vortex DW (VDW) is energetically favored in the thicker and wider magnetic nanowires,<sup>2,4</sup> while the transverse DW (TDW) is preferred in thinner and narrower magnetic nanowires,<sup>3</sup> a result of the competition between the exchange energy and the demagnetizing energy. Configuration and chiralities of DWs

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will have a profound effect on DW dynamics, and influence the pinning and/or depinning behaviors of DWs in response to external magnetic fields and electric currents.<sup>15-18</sup>

However, these two types domain wall structure only describes the most simplified magnetic moment configurations. Even in well-defined magnetic nanowires or other nanostructures, there also exist stochastic DW motion during DW nucleation, propagation, pinning and depinning processes,<sup>5,17-19</sup> which greatly affects the exquisite control of DW dynamics and thus DW related spintronic devices. While the detailed mechanism of the stochastic phenomena still remains unknown, it is suspected that they are partially due to the intrinsic nature of the travelling DW at a non-zero temperature and partly due to the unavoidable defects in material, introduced during the nano-fabrication process,<sup>18,20,21</sup> and at surface and interface. Recently, many experimental attempts have been made to visualize the stochastic phenomena of DW pinning-depinning by direct characterization using magnetic transmission soft x-ray microscopy (MTXM) techniques and so on<sup>19,22,23</sup> or indirect probes such as hysteresis loops and/or magnetoresistance measurements.<sup>4,5,9-11,17,24</sup> In the literature, M. Y. Im *et al*<sup>19,23</sup> reported on the direct observation of stochastic DW depinning in permalloy nanowires with a symmetric triangular notch along the wire (longitudinal) direction using MTXM and found that the stochasticity depends on the wire width and the notch depth. Both W. W. Zhu *et al*<sup>17</sup> and J. Brandão *et al*<sup>5</sup> observed two distinct depinning fields with a random nature using focused magneto-optic Kerr effect (FMOKE) magnetometer in permalloy nanowires with an asymmetric triangular notch along the longitudinal direction. In addition, Brandão *et al*<sup>5</sup> further found that the occurrence probabilities of these two depinning fields depended strongly on the degree of notch asymmetry, which can be modified by the outgoing angle (see the definition in Ref. 5) of the notch, and one of the depinning field is found to dominate over the other when the notch shape becomes more asymmetric. These studies hint that purposely introducing notch shape asymmetry may reduce the selectivity of the DW pinned around the notch and thus effectively suppress the stochasticity of DW depinning.

In this work, we investigated the pinning and depinning processes of DWs in permalloy nanowires with pre-fabricated six different types of notches by FMOKE and magnetic force microscopy (MFM). All of the notches are asymmetric in the longitudinal direction, in addition half of them are also asymmetric in the transverse direction (perpendicular to the nanowire and in-plane as well). By comparing the FMOKE and MFM results in these nanowires, we show the influence of the transverse asymmetry of the notch on the DW depinning behavior and identify which type of notch is most suitable to suppress the stochasticity of DW depinning.

## EXPERIMENTS

A series of permalloy nanowires with various types of inward notches were fabricated on the thermally oxidized Si substrates by electron-beam lithography followed by dc magnetron sputtering and lift-off. The stacking structure of these nanowires is Ta(2 nm)/Fe<sub>19</sub>Ni<sub>81</sub>(25 nm)/Ta(3 nm). The bottom Ta film is the seed layer to improve the permalloy crystalline quality and the top Ta film is protective capping layer. Figure 1(a) show the scanning electron microscope (SEM) image of a representative nanowire with a triangular notch roughly situated in the middle of the nanowire. The length of the nanowire is about 23  $\mu\text{m}$ . The elliptic part located at the left end of the nanowire is for DW nucleation and injection, and the tip part located at the right end is used to prevent the formation of undesired DWs.<sup>17</sup> The widths of the left and right arms are 1  $\mu\text{m}$  and 0.6  $\mu\text{m}$ , respectively. The other five nanowires were designed with identical nucleation pad, notch length, left and right arms but different notches. All six types of nanowires were fabricated under identical conditions. Figure 1(b) shows the enlarged pictures of all these six types of notches used in this experiment. Left column contains the triangular, trapezoidal and irregularly-quadrangular notch patterned on one side of the nanowire and close to the edge, while in right column each contains two identical notches patterned on both sides of a nanowire and is transversely symmetric. Note that for the two patterns in the same row as shown in Fig. 1(b), the notches have similar shape but the right one has smaller depth than the left one. For simplicity, these notch types are denoted as type *a*, *b* and *c* for the left column, and *a'*, *b'* and *c'* for the right column, respectively. It should also be noted that the lateral length and width of the narrowest part for each type of notch are designed identically to be 2  $\mu\text{m}$  and 0.2  $\mu\text{m}$ , respectively. Therefore, along the longitudinal direction, all the six types of notches are asymmetric

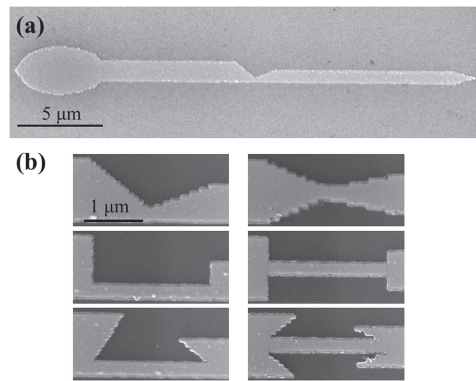


FIG. 1. SEM images of (a) Entire permalloy nanowire with one triangular inward notch, and (b) enlarged six types of notch structures.

in shape. Nevertheless, in the transverse direction, type *a*, *b* and *c* notches are asymmetric while type *a'*, *b'* and *c'* notches are symmetric. These different shaped notches will have significant influences on the pinning and depinning behaviors of DWs in the nanowires, which will be addressed in the following.

Magnetic hysteresis (*M-H*) loops of all the nanowire samples were recorded at room temperature by a high sensitive FMOKE (NanoMOKE III, Durham Magneto Optics Ltd.) with a focused laser spot of 30 μm in diameter, which can cover the entire region of a single nanowire. During the loop measurement, the magnetic field was applied in the film plane and parallel to the longitudinal direction. Each loop is obtained by averaging over 100~150 single-shot measurements to assure a high signal-to-noise ratio. To confirm that the DW does exist in the nanowire and can be pinned at notches, magnetic force microscopy (MFM, Bruker Dimension Icon) was operated at room temperature on all the nanowires. Detailed description on the FMOKE and MFM measurements can be referred to our previous reports.<sup>24</sup>

## RESULTS AND DISCUSSION

Figure 2 are the measured *M-H* loops for all six nanowire samples with different types of notches imaged as shown in Fig. 1(b). The loops match their notch type notations shown in Fig. 2. From general comparison one can easily find out that the three hysteresis loops in the left column have obvious jumps at the ascending or descending branch, while those in the right column have more gradual changing branches. These contrastive results are originated from distinctly different reversal processes in the nanowires with different types of notches, which will be explained in the following.

The *M-H* loop for a nanowire with 'type *a*' notch is shown in Fig. 2(a), in which two abrupt jumps can be seen clearly in the ascending or the descending branch. Next we will use the descending branch as example to discuss how the loop is formed. Firstly, all the magnetic moments in the nanowire align in the positive direction under a saturation field of  $H_a = 320$  Oe. Here  $H_a$  denotes the applied magnetic field during the *M-H* loop measurement. When  $H_a$  decreases from maximum to zero and then increases in magnitude along the negative direction, a DW initially nucleated at the elliptic portion propagates along the left arm and then is pinned at the notch to create the first jump at  $H_a = -68$  Oe. With increasing  $H_a$  in the negative direction, the DW can remain being pinned close to notch until  $H_a$  reaches -153 Oe, where the DW got depinned from the notch, displaying the second abrupt jump in the loop descending branch. Similar reversal process can be also observed in the ascending branch with slightly different pinning or depinning fields, which may be caused by artificial effects been discussed in our previous report.<sup>24</sup> It is worth noting that the *M-H* loop is obtained by averaging over 100~150 single-shot loops, so the drastic jumps indicate that the pinning or depinning fields achieved by single-shots have good repeatability. For this nanowire with the width of the right arm around 600 nm, there is only one depinning field in the reversal process. When the width of right

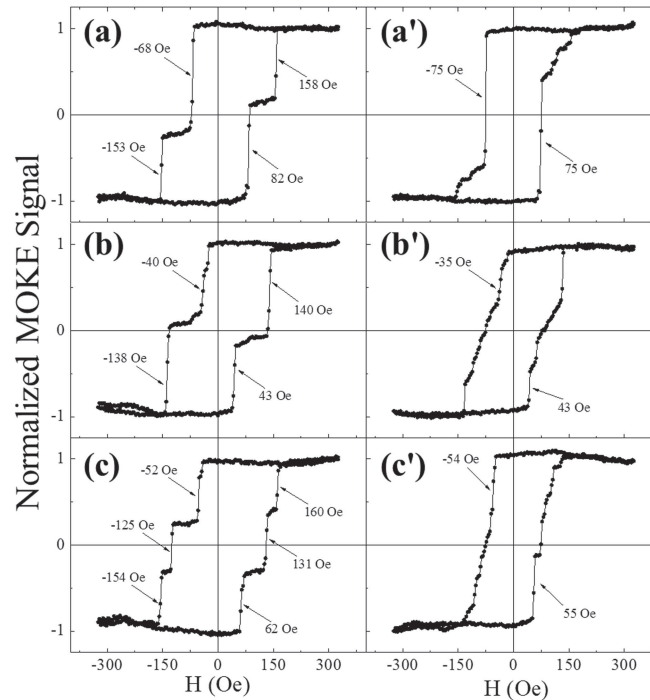


FIG. 2. The  $M$ - $H$  loops obtained by FMOKE for all the nanowires with different types of notches. The arrows indicate the pinning and/or the depinning fields.

arm decreases to be between 200 nm and 500 nm, two distinct depinning fields can be observed in a random nature, showing the stochastic depinning phenomenon.<sup>24</sup>

In contrast to the ‘type  $a$ ’ notch, the  $M$ - $H$  loop will change significantly if the notch is ‘type  $a'$ ’, as displayed in Fig. 2(a'). The descending (ascending) branch in Fig. 2(a') shows only one abrupt jump at  $H_a = -75$  Oe (75 Oe), followed by gradual changes until reaches saturation. Such a loop indicates that during the reversal process the pinning field is confined to be around 75 Oe, whereas the depinning field can be distributed in between 75 Oe and 160 Oe. This dispersed distribution of depinning field can be verified by the scattered single-shot loops observed in the FMOKE measurements (not shown here), which demonstrates that the stochastic depinning is remarkable if the notch-shape becomes symmetric in the transverse direction. Similar phenomena of stochastic DW depinning can be also found by comparing the  $M$ - $H$  loops for the nanowires with ‘types  $b$ ’ and ‘type  $b'$ ’ (or ‘types  $c$ ’ and ‘type  $c'$ ’), as shown in Figs. 2(b) and 2(b') (or Figs. 2(c) and 2(c')). In addition to the depinning process, there are two other important phenomena needed to be emphasized here. First, Fig. 2(b) shows a similar loop for the nanowire with one trapezoidal notch to that in Fig. 2(a). L. K. Bogart *et al.*<sup>4</sup> has reported that the depinning field is insensitive to the notch geometry no matter that the notch is triangular or rectangular in shape. Similar to their results, there is only slight difference ( $\sim 15$  Oe) in depinning field by comparing the loops in Fig. 2(a) and Fig. 2(b). As for the more obviously different pinning fields for these two nanowires (the difference is 28 Oe and 39 Oe for the descending and ascending branches, respectively), it may be due to structural defects, edges/surface roughness or some other artificial effects.<sup>24</sup> Secondly, as for the ‘types  $c$ ’ notch, there are three abrupt jumps at both the descending and the ascending branches, indicating the existence of one pinning field and two depinning fields. The appearance of two depinning fields for the ‘types  $c$ ’ notch may be due to the fact that the clockwise VDW and the counter-clockwise VDW can be pinned stochastically around the notch with different probabilities.<sup>24</sup> However, if this kind of notch changes from a ‘types  $c$ ’ to ‘types  $c'$ ’ by removing the transverse asymmetry, the stochastic phenomena becomes more prominent with a wider-range distribution of the depinning fields, similar to the comparative results between ‘types  $a$ ’ and ‘type  $a'$ ’ or between ‘types  $b$ ’ and ‘type  $b'$ ’.

Up to now the spin structure of the DW pinned at the notch can be characterized via MFM,<sup>1,3,15,25</sup> Lorentz microscopy<sup>4</sup> or magnetic transmission soft x-ray microscopy.<sup>19,22,23</sup> In the present work, in order to understand the above phenomena deeper, MFM was performed on all the permalloy nanowire samples at room temperature with a fine tip magnetized along its axis, which can illustrate the stray field distribution of each nanowire through the contrast difference in the MFM image. For all the measurements, the tip is perpendicular to the film plane and magnetized with a north pole at its end. Under such circumstance, the bright (dark) contrast indicates that the detection region repulses (attracts) the magnetic tip, suggesting north (south) pole-like.

Figure 3(a) shows the MFM image for the nanowire with one triangular notch ('type *a*') at the remanence state after applying a positive saturation field (320 Oe) along the nanowire and then removed shortly. The left and the right sides of the triangle notch are bright (north pole) and dark (south pole) respectively, while the contrast for the right end of the nanowire is bright. These results demonstrate that almost all the moments of the left and right arm are aligned along the positive direction and the different contrasts are resulted from stray fields produced by the notch, right end and roughness/defects of the NW. According to the FMOKE results as shown in Fig. 2(a), if  $H_a$  is in the range of the plateau, in between -68 Oe and -153 Oe, a DW will be pinned by the notch. Therefore, to verify the existence of the pinned DW, a reversal magnetic field of -100 Oe was applied along the nanowire and then removed after the total moments of the nanowire were positively saturated. Then the MFM image was recorded as shown in Fig. 3(b), in which the contrast of the right arm keeps unchanged while that of the notch left-side turns to dark. It indicates that the moments of the right arm still align along the positive direction while those in the left arm reverse to the negative direction, meaning that a DW pinned around the notch left-side. From the contrastive images shown in Figs. 3(a) and 3(b), it can be concluded that the MFM images taken under proper  $H_a$  can unambiguously demonstrate the existence of a pinned DW. Moreover, the DW's position and size can be also estimated from the contrast coverage around the notch left-side in the MFM image shown in Fig. 3(b).

With the same operation as that performed on the nanowire with 'type *a*' notch, the existence of a DW can be also verified for all of the other five nanowires by the MFM. In order to facilitate the comparison of DW distribution for all the nanowires, the corresponding MFM images are lined up in Fig. 4, which are recorded following the same protocol as that used to obtain the image in Fig. 3(b). Figs. 4(a) and 4(a') show that the dark contrast coverage around the notch left-side with 'type *a*' notch is significantly larger than that with 'type *a*' notch. Similar phenomenon is also significant for 'type *c*' and 'type *c*' notches and not too obvious for 'type *b*' and 'type *b*' notches. From the above comparison for the present nanowires, one can draw the conclusion that the size of the pinned DW with symmetric notch is generally larger than that with asymmetric notch in the transverse direction no matter that the notch shape is triangular, trapezoidal or irregularly-quadrangular.

According to the contrastive FMOKE and MFM results discussed above, one can conclude that the stochastic DW depinning becomes more prominent with a wide-range distribution of depinning fields and meantime the DW size increases with removing the transverse asymmetry of the notch. These two interesting phenomena seem to be related to each other. T. J. Hayward<sup>18</sup> reported that the thermal perturbations could have significant influences on the DW's magnetization dynamics and then affect the structure and position of DW during the propagation and pinning processes. Furthermore,

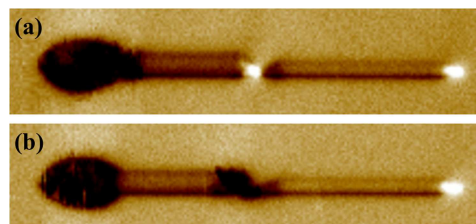


FIG. 3. The MFM images obtained at the remanent states after saturation in the positive direction (a), and after applying a reversal field of -100 Oe and removed shortly (b) by using the same magnetized tip on the nanowire with 'type *a*' notch.

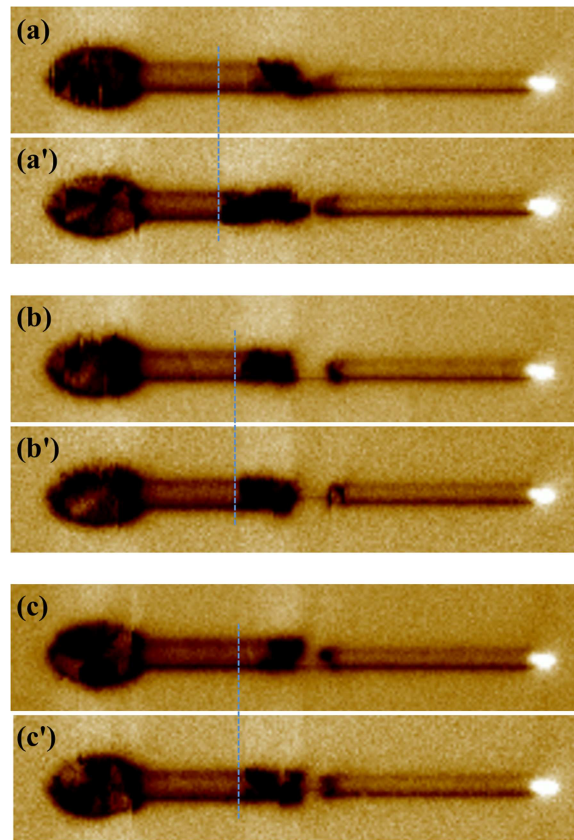


FIG. 4. The MFM images obtained under the same condition as that in Fig. 3(b) for all the nanowires with different types of notches. The blue dash lines are guides to eyes.

the edge or surface roughness will enhance the thermally-induced uncertainty. Besides, C. Wuth *et al.*<sup>20</sup> provided some experimental evidences that the configuration of a DW may become thermally activated during depinning caused by the notches. Therefore, the stochastic phenomena occurring at different stages of DW motion, especially at the DW depinning process, are affected inevitably by the thermal perturbation, edge/surface roughness or defects along the nanowires and some other extrinsic factors. According to the MFM images taken for the present nanowires, the DW size for the transversely symmetric notch is generally larger than that for the asymmetric notch with the similar notch shape. We speculate that the spin structure in the former is more complex than that in the latter, which causes the DW depinning to depend more strongly on the extrinsic factors mentioned above and results in more prominent stochasticity in the DW depinning process. Finally, it is noted that only one depinning field could be observed for the permalloy nanowire with one triangular or trapezoidal notch, which may be due to that only one type of DW (e.g. clockwise VDW) can survive during the DW depinning process in these two cases. Therefore, after comparing the nanowires with other four types of notches, it can be concluded that these two cases, i.e. the nanowire with one triangular or trapezoidal notch, are the best choices for suppressing the stochastic DW depinning phenomenon.

## CONCLUSIONS

In summary, we have performed FMOKE and MFM measurements on permalloy nanowires with six types of notches to investigate the stochastic DW depinning phenomenon. Although all the types of notches are asymmetric in the longitudinal direction, the experimental results unambiguously demonstrate that the stochastic phenomena are more prominent in the nanowires with transversely symmetric notches, accompanied with increased DW sizes. This may be resulted from more sensitive



influence by the thermal perturbation, edge or surface roughness and some other extrinsic factors. It is worth mentioning that two types of permalloy nanowires, the triangular or trapezoidal notch, close to the edge can effectively suppress the stochasticity during DW depinning, which can greatly help the designing of DW related spintronic devices with high stability and repeatability.

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