Depinning behavior of the vortex domain wall at the asymmetric triangular notch in permalloy wires

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Abstract

The depinning field \(H_D\) of vortex domain walls in a permalloy wire with an asymmetric triangle notch was investigated through magneto-optic Kerr effect (MOKE) microscopy and micromagnetic simulations. Wires of various widths with notches fixed on the wall’s incoming side angle were studied for various outgoing side angles \(\phi\). The curves of \(H_D\) of wall versus \(\phi\) were measured by MOKE microscopy. Micromagnetic simulations were used to obtain curves of the \(H_D\) of the wall versus \(\phi\). The maximum of such a curve of tail-to-tail -clockwise wall is known as the transition angle \(\phi_T\). The shape-anisotropic energy \(E_A\) of the notch outgoing side wire and the exchange energy \(E_{Ex}\) of the wall–notch interaction competed to influence the \(\phi_T\) value. Pinning potential was increased by the \(E_{Ex}\) when \(\phi\) was smaller than the \(\phi_T\). Pinning potential was considerably reduced by the small \(E_A\) when \(\phi\) was larger than the \(\phi_T\). Furthermore, the \(\phi_T\) value changed with the decrease in the depth of the notch because \(E_A\) was influenced by notch depth.

1. Introduction

Magnetic-domain-wall-based devices, such as shift register [1], vortex domain wall trajectory [2, 3], magnetic logic devices [4–7], and the time-delay oscillator [8], have attracted considerable attention. Precise control of the wall position, stable wall structure, and adjustment of wall chiralities are critical in such applications. Creating a pinning site is a method to stabilize wall structures and control wall positions. Pinning sites are of two types, namely nongeometric and geometric. Nongeometric pinning sites are formed through a local change of magnetic properties and annealing-induced local diffusion from the nonmagnetic metal into the magnetic wire [9, 10]. Another method to generate a pinning site is through exchange bias [11, 12], which is produced from crossed ferromagnetic wires and antiferromagnetic bars [11]. In geometric pinning sites, single-notch, double-notch, antinotch, protrusion and stepped-wire methods can be used to pin the wall [6, 8, 9, 13–27]. Numerous factors, such as wall chirality, the width of magnetic wires, the thickness of magnetic wires, and the depth of notches, influence the interaction between the notch and the wall [9, 13–15, 18–20, 27] and the wall pinning potential. The competition between exchange interaction and anisotropies (e.g., crystalline anisotropy or shape-anisotropy) affect domain wall’s spatial profile [8]. Domain wall length and structure are affected by the crystalline anisotropy and the magnetic exchange interaction [24]. Studies have reported the depinning field \(H_D\) for wires with a notch [9, 13–19, 25–29]. The walls in wide wires exhibit a lower wall energy per unit cross-sectional area. Furthermore, the \(H_D\) values in wide wires are smaller than those in narrow wires [15]. The \(H_D\) values for in-plane anisotropic wires were influenced by the potential energy of side wells \(E_{W}\) and potential energy of center barriers \(E_{B}\) in the pinning potential landscape [9, 14, 15]. The \(H_D\) provides the wall energy to overcome the \(E_{W}\) or \(E_{B}\) for artificial pinning sites, such as in the notches. A shallow \(E_{W}\) or small \(E_{B}\) results in a low \(H_D\) requirement for wire depinning from the notch [15]. The wall structures of the wires of various widths differs considerably [30]. Thick and wide wires exhibit a multi-vortex wall structure [30, 31]. However, the depinning
behaviors of a wall for a wire with different symmetries of triangular notch differs considerably. As displayed in figure 1, the incoming angle ($\theta$) is the angle between the long axis of the wire and the wall injection direction side of an asymmetric triangular notch, and the outgoing angle ($\phi$) is the angle between the long axis of the wire and the wall lifting side of the asymmetric triangular notch [19]. In 2014, Brandão et al observed vortex domain wall pinning and depinning in submicron wires with an asymmetric notch with fixed $\theta$ values and various $\phi$ values; they revealed that $H_D$ increased with increasing $\phi$ values [19]. The depinning behavior is also influenced by the shape-anisotropic energy ($E_s$) of the outgoing side wire [9]. Here, $E_s$ influences $E_0$ and the pinning potential landscape. However, few studies have discussed the influence of wall depinning behavior and physics on the various $\phi$ values of a notch. To understand in-plane anisotropic wall dynamics, we focused on the wall depinning behavior in a wire with an asymmetric notch.

### 2. Experiment and simulation

We designed samples of wires with various widths and an asymmetric notch, as displayed in figure 1. A 20 $\mu$m in diameter circular pad was connected with a 20 nm-thick straight magnetic wires of widths 1 and 2 $\mu$m and length of 57 $\mu$m. To eliminate the edge domain and the formation of the wall, the wire was tapered at its ends [16, 19]. The asymmetric triangular notch had a fixed notch depth ratio (notch depth divided by wire width, $R_d$), fixed incoming angle ($\theta$), and various outgoing angles ($\phi$). In this study, $\theta = 60^\circ$ and $\phi$ was varied by $15^\circ$ from $15^\circ$ to $60^\circ$ to determine the relationship between $H_D$ and $\phi$. To transfer the designed sample patterns onto Si wafers, we used e-beam lithography and the lift-off process. Next, we deposited a 20 nm-thick permalloy ($Py$) films onto the layer of pattern transferred poly(methyl methacrylate) Si wafers through DC magneto sputtering at a background pressure of $1 \times 10^{-7}$ Torr. A magneto-optical Kerr effect (MOKE) microscope was then used to capture magnetic domain images and determine the depinning field ($H_D$) values. We used the GPU-accelerated micromagnetic simulation software Mumax3, which is based on the Landau–Lifshitz equation [32]. We eliminated magnetic charges on the left and right ends of magnetic wires to create an infinitely long wire system [30, 31] and set the wire length $L > 8$ times the wire width. Furthermore, most of our simulations were performed at a zero temperature. We used the energy minimization function to set the wall structure and then performed the field-driven wall depinning simulation in wires of various widths [30–33]. To examine to influences of thermal fluctuation and surface defects, we run the simulation with surface defects at 300 K. The surface defects were set by GrainRoughness function of Mumax3. The GrainRoughness parameters of grain size, minimal height and maximal height are 5 nm, 0 nm, and 5 nm, respectively and the random seed of the GrainRoughness are 2997, 2998 and 3000. Py was used as the simulation material of all wires; the saturation magnetization ($M_s$), exchange stiffness ($A_{ex}$), magnetic crystalline anisotropic energy constant, and damping constant were 860 emu cm$^{-3}$, 1.3 $\times$ 10$^{-6}$ erg cm$^{-1}$, 0 erg cm$^{-1}$, and 0.01, respectively. To swiftly simulate our vortex domain wall depinning behavior, we ran the simulation at cell sizes of 5 nm $\times$ 5 nm $\times$ 5 nm or 5 nm $\times$ 5 nm $\times$ 20 nm.

### 3. Results and discussion

One of the domain and depinning images of the MOKE microscope for a 2 $\mu$m-wide wire with an asymmetric triangular notch are displayed in figure 2. The $\theta$ and $\phi$ values of the notch of the wire were $60^\circ$ and $30^\circ$, respectively. Figure 2(a) displays the images of the injection field and $H_D$ of the tail-to-tail-type clockwise (TT-CW) wall, which had values of $-5.18$ and $-19.94$ Oe, respectively. The injection field and the $H_D$ of the tail-to-tail-type clockwise (TT-CW) wall, which had values of $-5.18$ and $-19.94$ Oe, respectively. The injection field and the $H_D$ of the tail-to-tail-type clockwise (TT-CW) wall, which had values of $-5.18$ and $-19.94$ Oe, respectively. The injection field and the $H_D$ of the tail-to-tail-type clockwise (TT-CW) wall, which had values of $-5.18$ and $-19.94$ Oe, respectively. The injection field and the $H_D$ of the tail-to-tail-type clockwise (TT-CW) wall, which had values of $-5.18$ and $-19.94$ Oe, respectively. The injection field and the $H_D$ of the tail-to-tail-type clockwise (TT-CW) wall, which had values of $-5.18$ and $-19.94$ Oe, respectively.
tail-type counterclockwise (TT-CCW) wall were $-5.38$ and $-11.94$ Oe, respectively, as displayed in figure 2(b). The head-to-head-type counterclockwise (HH-CCW) wall and the TT-CW wall exhibited the same symmetry of wall configuration and the same interaction between the domain wall and the notch. Therefore, their $H_D$ values were almost the same. Similarly, the $H_D$ values of the TT-CCW and HH-CW walls were identical [19]. This study focused on the TT-type domain walls. Figure 3 depicts $H_D$ as a function of $\phi$ for the TT-walls for 1- and 2 $\mu$m-wide wires. $H_D$ value of TT-walls was negative because the applied field was toward to left. Here, we defined $H_D$ value as positive value. The maximum $H_D$ values of the TT-CW wall in these wires were approximately 17.48 and 19.64 Oe, respectively, at $\phi = 30^\circ$. The $H_D$ of the TT-CCW wall was lower than that of the TT-CW wall, as displayed in figures 3(a) and (b). To understand the wall depinning behavior, we simulated the vortex wall propagation for wires with an asymmetric notch. The micromagnetic simulation revealed that the depinning behaviors of the HH-CCW and TT-CW walls in the 1 $\mu$m-wide wire were the same, as displayed in figure 3(c). This behavior was consistent with the experimental results. The maximum $H_D$ value of the TT-CW and HH-CCW walls in the simulated $H_D-\phi$ curves were approximately 74 Oe in the 1 $\mu$m-wide wire at $\phi = 35^\circ$, as displayed in figure 3(c). The simulated results were consistent with the experimental depinning behaviors and exhibited the same trend for the $H_D-\phi$ curves. The $\phi$ value of the maximum $H_D$ is defined as the transition angle ($\phi_T$). The quantitative differences in $H_D$ between the experimental and simulation results were caused by the thermal fluctuation and sample defects. To confirm the room-temperature and surface defects influences, we ran simulations of the 1000 nm-wide wire with surface defects at 300 K, as shown in figure 3(d). We chose the $\phi$ equal to 30°, 35°, and 40° to run the simulations. Blue line of figure 3(d) displayed averaged $H_D$ values that were calculated by the wires with different random seeds of GrainRoughness function. The averaged $H_D$ values with surface defects at 300 K are around 47, 56.2, and 46.7 Oe at $\phi$ equal to 30°, 35°, and 40°, respectively. Figure 3(d) revealed that room-temperature and surface defects reduced $H_D$ values, but unobviously affected $\phi_T$ value. We utilized EdgeSmooth function of Mumax3 to observe staircase effect for the notch. The simulated results with EdgeSmooth function are similar to those without EdgeSmooth function. It indicates that the staircase effect of asymmetric notches has a weak influence on our study.

In order to examine the depinning process, we saved the Mumax3 output of the TT-CW wall parameter in the 1 $\mu$m-wide wire before the depinning state at the near $H_D$ and performed the time evolution simulations at the $H_D$. Figure 4 displays the simulated TT-CW wall depinning process for the wires with notches of $\phi = 30^\circ$, 35°, and 40°, respectively, as displayed in figure 3(c). The top of figure 4 displays the state of the wall near $H_D$ values before depinning and the state of the wall with applied fields of $-68$, $-72$, and $-64$ Oe for $\phi$ values of 30°, 35°, and 40°, respectively. When the wall approached the notch, the applied field compressed the wall at the incoming side of notch, as displayed at the top of figure 4. During the depinning process, when the wall arrived at the notch, a boundary line that was leaning to the right appeared at the right of the wall, as denoted by the black arrow in figure 4(a). Because the wall was compressed, the boundary line of the wall became an arc at the notch sharply to easily pass through the notch and go to the outgoing side of the notch with $\phi = 30^\circ$ or 35°. A new domain (green color) gradually formed from 0 to 4.6 ns in the outgoing side, as displayed in figures 4(a) and (b), and then the wall was depinned from the notch. The simulated depinning images are displayed in figure 4 at

![Image](https://via.placeholder.com/150)

Figure 2. Magnetic optic Kerr effect microscopy images for a 2 $\mu$m-wide wire with a asymmetric triangular notch. The notch has a 60° incoming angle and a 30° outgoing angle. (a) Tail-to-tail (TT)-clockwise (CW) wall pinning and depinning. (b) TT-counterclockwise (CCW) domain wall pinning and depinning. Color map shows the direction of magnetization in the magnetic images.

![Image](https://via.placeholder.com/150)

Figure 3. (a) Histogram of the $H_D$ for the wire with a 60° incoming angle and a 30° outgoing angle. (b) Histogram of the $H_D$ for the wire with a 60° incoming angle and a 30° outgoing angle. (c) Histogram of the $H_D$ for the wire with a 60° incoming angle and a 30° outgoing angle. (d) Histogram of the $H_D$ for the wire with a 60° incoming angle and a 30° outgoing angle.
19.8 ns. However, the time evolutions for the wire with \( \phi = 40^\circ \) in figure 4(c) differed from those for the wires with \( \phi = 30^\circ \) and \( 35^\circ \), as displayed in figures 4(a) and (b). The wall depinning process shown in figure 4(c) revealed that the new domain was generated on the outgoing side of the notch at an applied field caused the wall to overcome the notch pinning. The wires with higher \( E_A \) values at the incoming side of the notch and the pinning potential energy barrier \( (E_B) \) at the outgoing side of notch. For notches with the same depth and various fixed incoming angle of \( 60^\circ \), the \( E_B \) value increased with \( \phi \) increased. The simulation, as displayed in figure 4(d), were considerably reduced by the small \( E_A \) when \( \phi \) was larger.

The wall depinning behavior is related to the wall pinning potential energy landscape [9, 15, 28]. As indicated in [9], the wall pinning potential well or barrier is generated by the asymmetric notch. Both the shape of the notch and the wire width influence the wall depinning behavior. Therefore, the depinning behaviors in figure 4 are influenced by the potential energy of the side well \( (E_W) \) at the incoming side of the notch and the pinning potential energy barrier \( (E_B) \) at the outgoing side of notch. For notches with the same depth and \( \theta \), the \( E_W \) values are almost the same [9]. Therefore, the influence of \( E_W \) on the depinning behavior can be ignored, and the \( E_B \) dominates the \( H_B \). The \( E_B \) value is composed of the local exchange energy \( (E_{EX}) \) and \( E_A \). \( E_{EX} \) denotes the exchange energy between the right side of the wall and the magnetic moments located at the outgoing side region of the notch, and \( E_A \) indicates the shape-anisotropic energy of the outgoing side wire. \( E_{EX} \) is affected by the dot product between right side the wall and magnetic moments located at the outgoing side region. Direction of moments located at outgoing side region is aligned along outgoing side. Therefore, \( E_{EX} \) increased with \( \phi \) increased. The various \( \phi \) changed both \( E_A \) and \( E_{EX} \). Thus, \( E_B \) can affect the depinning behavior. During the depinning process of the wall, the applied field caused the wall to overcome the notch pinning. The wires with higher \( \phi \) values exhibited larger \( E_{EX} \) values because of the greater interaction between the right side of the wall and the magnetic moments located at the outgoing side region of the notch. However, \( E_A \) became smaller as the \( \phi \) value increased because the local demagnetic energy density increased and a new wall was created from the outgoing side region of the notch, which facilitated depinning. \( E_A \) and \( E_{EX} \) competed for the influence on depinning. When the \( \phi \) was smaller than \( \phi_T \), \( E_{EX} \) increased with increases in \( \phi \), but \( E_A \) slowly decreased at the same time. These results increased \( E_B \), which resulted in a higher \( H_B \). \( E_A \) was strongly dependent on \( \phi \). \( E_A \) decreased slowly for small angles but decreased rapidly for large angles, with \( \phi_T \) as the crossover point. As the \( \phi \) was further increased, the influence of \( E_A \) exceeded that of \( E_{EX} \). \( E_B \) and \( H_B \) were considerably reduced by the small \( E_A \) when \( \phi \) was larger.
than the $\phi_T$. To reduce the local demagnetization energy density, a vortex wall core and a new wall were created at the outgoing side of the notch, and the $H_D$ was then reduced, as displayed in figures 3 and 4(c). We ran the simulation of 400- and 500 nm-wide wires with $\theta = 45^\circ$ and $60^\circ$ to examine the influences of $\theta$. Figure 5 revealed that the incoming side of the notch affected $E_W$ and $H_D$ values, but both $\phi_T$ values appeared at $\phi = 35^\circ$. It indicates that the incoming side of the notch has less influence on $E_A$ and $E_{EX}$.

To confirm the effect of $E_A$, we simulated half wires with a single arm of outgoing side wire. The single-arm wires exhibited a left half wire with a half notch with depth $R_d$ fixed at 50%. Figure 6(a) displays simulations of a single-arm wire. We simulated the single-arm wires without a wall initially, as displayed in figure 6. The
simulations revealed a single-arm wire with a reversal field \(H_R\), which caused the single arm to shift from a negative saturation state to a positive saturation state. The \(H_R-\phi\) curves were plotted for single-arm wires to compare the simulated \(H_R\) for whole wires with a notch. Figure 6(b) displays the results of 300-, 400-, and 500 nm-wide single-arm and whole wires. For single-arm wires, the \(H_R\) value decreased with \(\phi\). Furthermore, the \(H_R\) values of single-arm wires differed considerably from those of the whole wires. However, the decreasing trends of \(H_R\) and \(H_B\) were quite similar between \(\phi\) values of \(35^\circ\) and \(90^\circ\) for all simulated wires. The shape of the single-arm wire was the same as the right side of the whole wires but differed on the left side. The reversal of the magnetic saturation state depended on \(E_A\) for the single-arm wires. For the single-arm wire, magnetic switching behavior was only affected by outgoing side of notch. The \(H_B\) for the single-arm wires only depended on \(E_A\) and decreased as \(\phi\) increased. These results displayed a same trend when \(\phi\) larger than the \(\phi_T\) for both single-arm wire and whole wire. It displayed the \(E_A\) that was dominant in the depinning behavior for \(\phi\) larger than the \(\phi_T\). For the whole wire simulation, the wall \(H_D\) values increased with \(\phi\) increased when the \(\phi\) smaller than \(\phi_T\). It indicated that the \(E_{Ex}\) increased with \(\phi\) increased because \(E_{Ex}\) value was composed of \(E_{Ex}\) and \(E_A\). The \(H_{DZ}\) values were affected by \(E_{Ex}\) for the range of \(\phi\) to \(\phi_T\). As displayed in figure 6(b), the competition between \(E_A\) and \(E_{Ex}\) is independent on the wire width.

Moreover, the \(R_d\) of the notch was simulated to confirm the influence of \(E_A\) and the \(\phi\). We varied the \(R_d\) to adjust the competition between \(E_A\) and \(E_{Ex}\) for the 400- and 500 nm-wide wires with asymmetric notches and various \(R_d\) values, as displayed in figure 7. In these simulations, the \(\theta\) of the notch was the same and the \(\phi\) of notch was varied. The \(\phi_T\) value in the \(H_{DZ}-\phi\) curves was dependent on the \(R_d\) for the wires, as illustrated in figures 7(a) and (b). With the same wire asymmetry, the notch with the larger \(R_d\) resulted in a smaller \(\phi_T\) value. For both 400- and 500 nm-wide wires simulations, the \(\phi_T\) values for the wires with \(R_d\) between 30% to 85% were approximately \(50^\circ\) to \(10^\circ\), respectively, which revealed that the \(\phi_T\) value was almost independent on the width of the wires, as illustrated in figure 7(c). Because of anisotropy, the moments on both sides of the notch tend to align the edge of the notch. Deeper notches exhibit higher magnetic moments aligning the sides of the notch.

Large \(R_d\) values enhanced the energy depth of \(E_{Ex}\) and increased the \(H_D\) value. The Large \(R_d\) changed \(\phi_T\) value because depth of notch affected the competition between \(E_A\) and \(E_{Ex}\). The notch with a high \(R_d\) extended the length of the outgoing side of the notch, which produced a strong influence on \(E_A\) for the HH-CCW wall depinning. A small \(E_A\) due to the large \(R_d\) leads to the reduced \(H_D\) value. The anisotropy of notch with high \(R_d\) lead the \(E_A\) was easily to dominate the depinning behavior. Moreover, a high \(R_d\) resulted in a large local demagnetic energy density at the outgoing side of the notch. Therefore, a new domain was easily generated at the outgoing side of the notch for reducing the total energy.

Figure 6. (a) Example of an outgoing side–single–arm simulation. (b) Applied field (H)–outgoing angle (\(\phi\)) curves of the outgoing side–single–arm simulation reversal field \(H_{DZ}\) and whole wire simulation depinning field \(H_D\). Open symbols and solid symbols displayed the single-arm simulations and whole wire simulations, respectively. X-axis label of 60 degrees \(\phi\) (degrees) means the notch has a fixed incoming angle of 60 degrees and various \(\phi\).
4. Conclusion

We performed MOKE microscopy and micromagnetic simulations on Py wires with asymmetric triangular notches to investigate the factor influencing the wall depinning behavior. The maximum of the $H_D$–$f$ curves, which is known as the $f_T$, is well observed for all wires. The experiments revealed that the $f_T$ was independent on wire widths. Micromagnetic simulations revealed that the $f_T$ values in the $H_D$–$f$ curves of the TT-CW and HH-CCW walls for wires with an asymmetric triangular notch were influenced by $E_A$ and $E_x$. Simulations of wires with asymmetric triangular notches revealed the competition between $E_A$ and $E_x$ for influencing the curves. The single-arm and various $R_d$ values simulations also revealed the affection of $E_A$ for depinning behavior. $E_x$ dominated $H_D$ in the HH-CCW and TT-CW walls for $\phi < \phi_T$, and $E_A$ dominated $H_D$ for $\phi > \phi_T$. The simulation of the wall depinning for the notch with various $R_d$ values revealed that the $f_T$ value decreased as $R_d$ increased and was almost independent of the wire width.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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