Micromagnetic Simulation of the Depinning Field Domain Wall on Symmetric Double Notch Ferromagnetic Wires

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Abstract

In this paper, we investigate the depinning field domain wall on symmetric double notch ferromagnetic wires by means of micromagnetic simulation for Permalloy (Py), Cobalt (Co), and Nickel (Ni) materials. The depinning field domain wall increases as the size of the notch decreases. At a lower depinning field, the domain wall inner structure exhibited a transverse wall (TW), while at a higher depinning field, there was a transformation of the domain wall inner structure from transverse wall to antivortex wall (AVW). We also observed that the magnetization energy increased as the size of the notch decreased. This means that more energy was needed to release the domain wall from a smaller notch. Micromagnetic simulation showed that the depinning field domain wall depends on the size of the notch and on the ferromagnetic anisotropy.

Keywords: antivortex wall (AVW), ferromagnetic wire, micromagnetic, notch, transverse wall (TW)

1. Introduction

Recently, investigation of the domain wall (DW) motion in ferromagnetic nanowires has attracted a great deal of attention due to its potential in high-density and nonvolatile magnetic storage devices [1-5]. Controlling the DW motion becomes a crucial issue with regard to stable DW position in ferromagnetic nanowires. For this purpose, a constriction or notch is introduced to control the DW behavior in ferromagnetic nanowires. Numerous studies have reported on DW behavior with various geometric notch shapes in both induced magnetic [6-10] and spin current polarized [11-16] fields. In many cases, the geometry of the notch influences the DW inner structures. The DW also exhibits oscillation and transforms the inner structures around the notch. Interestingly, smaller notches act as attractive pinning potential so that the transverse wall (TW) structure can easily enter the notch and the vortex wall structure is repelled by the notch [14,17]. However, little investigation has been conducted into the DW structure and the depinning field behavior around symmetric double notches with various materials.

In this work, we investigated the depinning field domain wall around symmetric double notch ferromagnetic wires by means of micromagnetic simulation with respect to the notch size and amplitude of the magnetic field.
strength variation. Simulation was also performed on various materials: Cobalt (Co), Nickel (Ni), and Permalloy (Py) ferromagnetic wires.

2. Methods

Depinning of the field domain wall on symmetric double notch ferromagnetic wires was carried out using a publicly available micromagnetic software, OOMMF [18], based on the Landau-Lifshitz-Gilbert equation (LLG) [19]. The length of the wire \( L \) was 2000 nm, the width \( W \) was 200 nm, and the thickness \( t \) was 5 nm, as presented in Figure 1.

Triangular double notches were positioned at the center of the wire. The notch height was fixed at \( d = 50 \) nm, the lengths of bottom \( s \) varied from 10 nm to 200 nm, and the aspect ratio \( d/s \) varied from 5 to 0.25 [20]. The cell size was \( 5 \times 5 \times 5 \) nm\(^3\) and the damping factor \( \alpha = 0.1 \). Initially, a TW with a head-to-head formation was positioned at the center of the notch [21]. Then, a systematic magnetic pulse was applied to the ferromagnetic nanowire with 1-ns-long pulse in the +x direction. The material parameters for the micromagnetic simulation are given in Table 1 [22].

Figure 1. (a) Geometry and Dimension of the Ferromagnetic Wire. A TW Configuration is Positioned at the Center of the Wire. (b) A Magnetic Pulse with 1-ns-long Pulse and Rise Time of 0.1 ns is Applied in the +x Direction. The Disk Color is the Magnetization Direction

<table>
<thead>
<tr>
<th>Material</th>
<th>( M_S ) ( (\text{A/m}) \times 10^5 )</th>
<th>( A ) ( (\text{J/m}) \times 10^{12} )</th>
<th>( K ) ( (\text{J/m}^3) \times 10^3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co</td>
<td>14</td>
<td>30</td>
<td>530</td>
</tr>
<tr>
<td>Py</td>
<td>8.6</td>
<td>13</td>
<td>0</td>
</tr>
<tr>
<td>Ni</td>
<td>4.9</td>
<td>9</td>
<td>-5.7</td>
</tr>
</tbody>
</table>

Table 1. Material Parameters Used in this Simulation: Permalloy (Py), Cobalt (Co), and Nickel (Ni) [22]
3. Results and Discussion

After the magnetic pulse was applied, the DW moved from the notch. The minimum field that released the DW from the notch was known as the depinning field. With notch variation, we observed that the depinning field increased as the size of the notches decreased. The profile of the depinning field DW corresponded to the notch size variation, as shown in Figure 2 (top). We also plotted the depinning field as an aspect ratio of d/s. Interestingly, the depinning field increased until a d/s of around 2, then increased at a relatively constant rate until the aspect ratio of d/s was larger than 2 (Figure 2). The depinning field appeared to be insensitive to notch size at a high depinning field. As seen in the figure, the depinning field DW exhibited different depinning fields in the different materials. The depinning field of Co was the highest, and that of Ni was the lowest. It was mainly the anisotropy of the materials that influenced the depinning field. Defects in the wire, such as voids or rough edges, also affected the depinning field [23-24].

We also examined the inner structure of the DW when the applied field was turned on. The DW inner structure showed a TW structure for low depinning fields with a small d/s aspect ratio. Figure 3 shows the DW inner structure for Co and Ni materials at the depinning fields $H_d = 10$ mT and $H_d = 4$ mT, respectively in the case of s = 200 nm or the aspect ratio of d/s = 0.25. A similar TW structure was also observed for Py at the depinning field $H_d = 6$ mT.

We then found that DW inner structures changed from TW to AVW structures at high depinning fields when the notch size was small or the aspect ratio was large. For example, Co and Py materials showed a transformation in the DW inner structure for the notch size s = 10 nm. The depinning field of Co was $H_d = 16$ mT, and Py was $H_d = 9$ mT. Figure 4 (a) shows that the DW inner structure transformed from TW to AVW for Co at $t = 0.7$ s. In contrast, for Ni, the depinning field $H_d = 5.5$ mT at the notch size of 10 nm, and the DW inner structure maintained its TW structure, as shown in Figure 4 (b).

It can be explained that DW inner structure of Ni related to the Walker breakdown field and energy magnetization [25]. Around this field, the demagnetization energy was more than the exchange energy. Thus, DW inner structure formed TW structure.

![Figure 2. The Depinning Field with Respect to Length s (a) and the Aspect Ratio of d/s (b)](image)

![Figure 3. A Snapshot of the DW Inner Structure when the Magnetic Pulse is Turn on for the Case of s = 200 nm. The DW Maintains its TW Inner Structure (a) Co ($H_d = 10$ mT) and (b) Ni ($H_d = 4$ mT). The Disk Color Represents the Magnetization Direction](image)
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4. Conclusions

In conclusion, we investigated the depinning field DW on symmetric double notch ferromagnetic wires via micromagnetic simulation. The depinning field increases as the notch size decreases. At low depinning fields, DW inner structures maintain their TW structure, while at high depinning fields, DW inner structures change from TW to AVW. The depinning field is influenced by the geometry of the notch and the material anisotropy.

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