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Micromagnetic study of domain-wall pinning characteristics with grooves in thin films

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The pinning characteristics of a 180° domain wall with grooves are investigated using the micromagnetic simulation. The depinning fields required to pull the wall out of the grooved region were strongly related to the pinning characteristics at each step edge. The depinning field difference between the wall movement directions was improved by the increase of the lower depinning field compared to that with the steplike thickness change. It was also found that the depinning fields for various groove widths were almost constant and the wall displacement was further suppressed by the narrower groove having the vertical edge.
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I. INTRODUCTION

Artificial wall pinning is effective in controlling the depinning field in sensor applications utilizing a large Barkhausen jump and improving the properties of high-frequency material applications, such as the magnetic-field sensor and the core, due to the suppression of wall motion. Etched grooves in a garnet film having a perpendicular anisotropy were used for stabilizing the stripe domain in a Bloch line memory.[1,2] In a narrow track single-pole head, grooves across the track can control the domain structure of a main-pole film and suppress the 90° wall motion of closure domains at the film edges when the magnetic field is applied along the longitudinal direction of the film.[3]

In the previous work, we reported the micromagnetic simulation results of the pinning characteristics of the asymmetric Bloch wall caused by a steplike thickness change in thin films having an in-plane anisotropy.[4] It has been clarified that the bidirectional pinning effect for magnetic fields applied along the magnetic domain was obtained when the spin rotation from the Bloch wall in the film center to Néel cap at the grooved side surface was across the step. The depinning field for the negative applied field which drove the wall toward the nongrooved region was considerably larger than that for the positive one which drove the wall toward the grooved region and the pinning characteristics strongly depended on the wall structure.

In this article, the pinning characteristics of a domain wall with grooves in thin films are investigated using the micromagnetic simulation. The dependences of the depinning fields on film thickness and the groove width are discussed.

II. SIMULATION MODEL

Numerical simulations were performed by integrating the Landau–Lifshitz–Gilbert equation numerically by an explicit scheme of the modified Dufort–Frankel method.[5,6] As illustrated in Fig. 1, the cross-section normal to the film plane (yz plane) containing a thickness change (Δh) is taken to be the computation region, which is discretized into a two-dimensional array. Boundary conditions on the computation region are such that the wall is in the xz plane and infinite in extent in the x direction. Material parameters used in the simulation are as follows: saturation induction $4\pi M_s = 8000$ G, uniaxial anisotropy constant $K_u = 3200$ ergs/cm^3, exchange constant $A = 10^{-6}$ ergs/cm, gyromagnetic ratio $\gamma = 1.76 \times 10^7$ (s Oe)$^{-1}$, and damping constant $\alpha = 0.5$.[4] The grid element spacings are 50 Å for the film thickness $h \leqslant 0.3$ μm, and 100 Å for $h > 0.3$ μm, respectively. The easy axis is along the x direction and magnetic fields (H_p) are applied along the magnetic domain. The time transient of the orthogonal component of an effective field was used for determining the depinning field.[7]

III. RESULTS AND DISCUSSION

The depinning fields of the asymmetric Bloch wall with the steplike thickness changes, as shown in Figs. 2(a) and

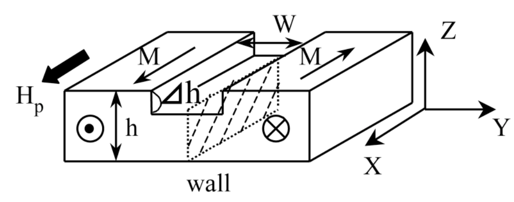

FIG. 1. Schematic drawing of a groove in a thin film.

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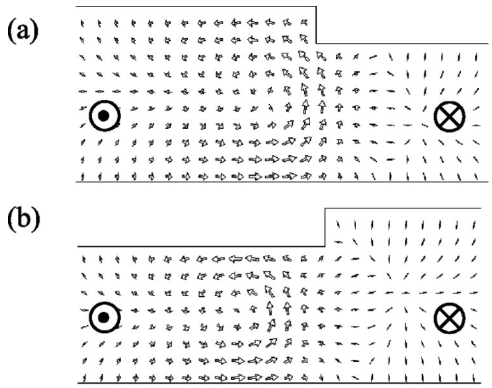

FIG. 2. Magnetization configuration of the asymmetric Bloch wall with each steplike thickness change in a 0.15-μm-thick film without the magnetic field. The step depth is 300 Å. The arrows in the figures represent the magnetization directions for every ninth (3×3) grid elements.

2(b), for positive $(+H_p)$ and negative $(-H_p)$ applied magnetic fields are investigated. The arrows in Fig. 2 represent the magnetization directions for every ninth (3×3) grid elements. For the positive applied fields ($+x$ direction), the wall moves in the direction of the right-hand side in Figs. 2(a) and 2(b). The depinning fields for the positive and negative applied fields in Fig. 2(a) and for the positive applied field in Fig. 2(b) as a function of the film thickness are plotted in Fig. 3. The step depth ratio to the film thickness $(\Delta h/h)$ is 0.2. The depinning field for $-H_p$ in Fig. 2(b) is not obtained (less than 0.2 Oe). Similar to the film thickness dependence of the depinning fields in Fig. 2(a), the depinning field for $+H_p$ in Fig. 2(b) also decreases with increasing film thickness due to the decrease of the exchange energy per unit area.[4] The larger depinning fields are obtained when the wall moves toward the nongrooved region in both Figs. 2(a) and 2(b).

Next, the pinning characteristics of a domain wall with grooves were examined. Figure 4 shows the simulation results of the pinned wall configurations with the groove having the depth $\Delta h = 300$ Å and the width $W = 600$ Å in a 0.15-μm-thick film for (a) $H_p = 0$ Oe (initial state), (b) -30 Oe, and (c) $+30$ Oe, respectively. The arrows in the figures represent the magnetization directions for every ninth (3×3) grid elements. When the magnetic field H_p is applied

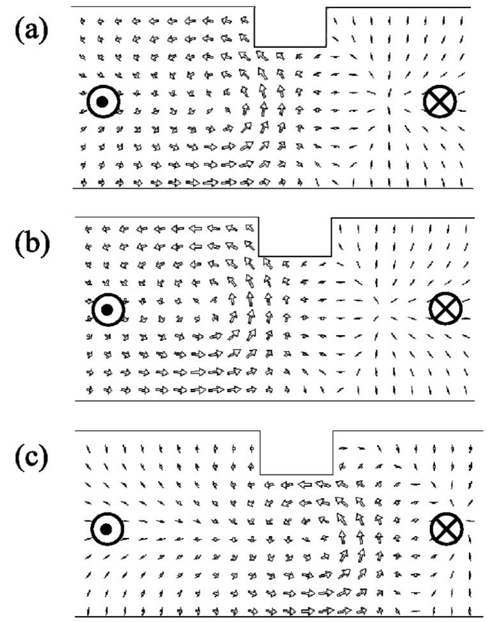

FIG. 4. Magnetization configuration of the pinned wall with the groove for the magnetic fields of (a) 0 Oe (initial), (b) -30 Oe, and (c) 30 Oe in a 0.15-μm-thick film. The groove width and depth are 600 and 300 Å, respectively.

for the wall of Fig. 4(a), the wall moves in the direction of the left-hand side for $-H_p$ and the right-hand side for $+H_p$, and is pinned at each grooved edge, as shown in Figs. 4(b) and 4(c), respectively. In both cases of Figs. 4(b) and 4(c), the wall returns to the initial position [Fig. 4(a)] after the magnetic field is off. Figure 5 shows the film thickness dependence of the depinning field caused by the groove. The groove width and the depth ratio to the film thickness are 600 Å and 0.2. The depinning fields for $+H_p$ and $-H_p$ are approximately equal to those for $+H_p$ in Fig. 2(a) and for $-H_p$ in Fig. 2(b), respectively. Therefore, the difference between the depinning fields for $+H_p$ and $-H_p$ due to the asymmetric wall structure is improved by the increase of the lower depinning field compared to that with the steplike thickness change, as shown in Fig. 3. The depinning fields for various groove widths in a 0.15-μm-thick film are indicated in Fig.

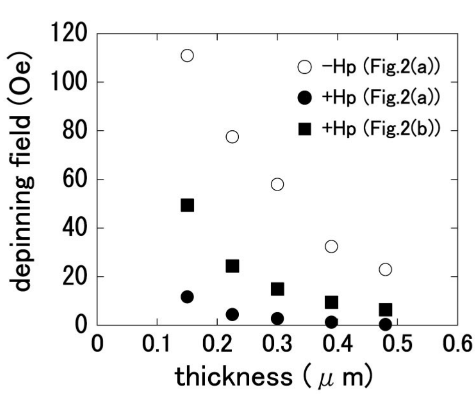

FIG. 3. Film thickness dependence of the depinning fields for the positive (●) and negative (○) magnetic fields in Fig. 2(a) and for the positive magnetic field (■) in Fig. 2(b). The step depth ratio to the film thickness is 0.2.

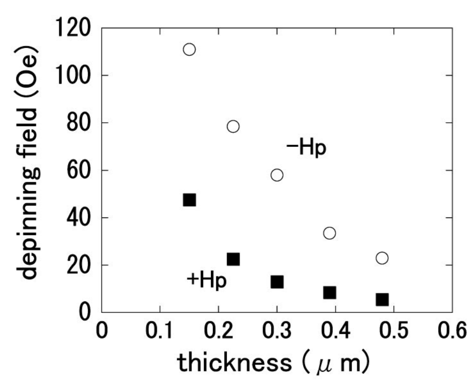

FIG. 5. Dependence of the depinning field of the wall with grooves for the positive (■) and negative (○) magnetic fields on the film thickness. The groove width and the depth ratio to the film thickness are 600 Å and 0.2, respectively.

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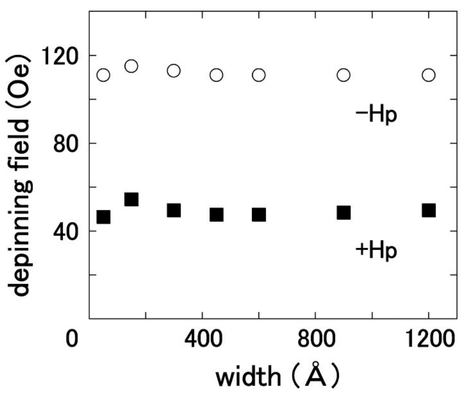

FIG. 6. Depinning fields for the positive (■) and negative (○) magnetic fields as a function of the groove width in a 0.15-μm-thick film. The groove depth is 300 Å.

6. The groove depth is 300 Å. Both the depinning fields for the positive and negative magnetic fields are almost constant. These results suggest that the pinning effect is dominated by the magnetization state in the vicinity of the step edge. Simulations showed, however, that the shape of step affected the pinning characteristics, for example, the depinning field for $-H_p$ in Fig. 2(a) drastically decreased, as the slop became gentler. The influence of groove shape is under investigation.

Figure 7 shows the groove width dependence of wall displacement for the applied magnetic fields of 10, 20, and

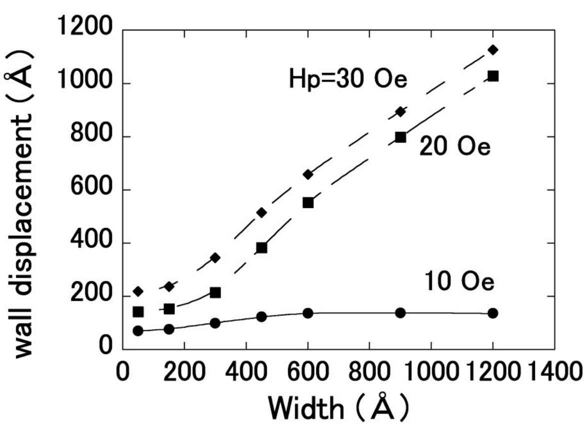

FIG. 7. Groove width dependence of the wall displacement for each applied magnetic field.

30 Oe. The wall displacement is defined as the distance between the pinned wall positions for $-H_p$ and for $+H_p$. The initial wall position is at the left-hand edge of the groove, as shown in Fig. 4(a). As mentioned before, after the magnetic field was off, the wall which pinned at the right-hand edge for the positive applied magnetic field returned to the initial position for the grooves having the width up to 600 Å. On the other hand, for the grooves having the width more than 900 Å, the wall still existed near the right-hand edge. The wall displacement linearly increases with increasing groove width more than 300 Å for $H_p=20$ and 30 Oe. For $H_p=10$ Oe, the wall displacement is quite small. This is because that the amplitude of the applied field is lower than the depinning field for $+H_p$ in Fig. 2(a) (see Fig. 3) and the wall is pinned for $+H_p$ at the left-hand edge of the groove. The wall displacement is further suppressed with the narrower groove having the vertical edge.

IV. CONCLUSIONS

We have simulated the pinning characteristics of a domain wall with grooves in thin films. The amplitudes of the depinning fields of the wall with grooves are approximately equal to those with each steplike thickness change for the applied field which drives the wall to the nongrooved region, respectively. The depinning field difference between the wall movement directions is improved by the increase of the lower depinning field compared to that with the steplike thickness change. Simulation results suggested that the pinning effect is dominated by the magnetization state in the vicinity of the step edge. This character is reflected in the depinning fields and the wall displacement for various groove widths. As a result, the wall displacement is further suppressed by the narrower groove having the vertical edge.

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