Micromagnetic Study of Domain Wall-Pinning Characteristics With Step-Like Thickness Change in Thin Film

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***Abstract*—The pinning characteristics of a domain wall with a step-like thickness change along the wall is investigated in 0.15- to 0.5–μm-thick films with an in-plane anisotropy using micromagnetic simulation based on the Landau–Lifshitz–Gilbert equation. The asymmetric Bloch wall having the structure in which the magnetostatic coupling develops between spins near the step when the wall is pinned shows the bi-directional pinning effect for magnetic fields applied along the magnetic domain. The wall energy of the pinned wall decreases with increasing step depth due to the largely decrease of the exchange energy component. The depinning field for the negative applied fields which drive the wall in the direction of the nongrooved region (thick film region) is considerably larger than that for the positive ones which drive the wall in the direction of the grooved region (thin film region). The depinning fields for both the positive and negative applied fields increase with decreasing film thickness.**

***Index Terms*—Domain wall pinning, groove, micromagnetic simulation, thickness variation.**

I. Introduction

THE control of wall depinning fields is extremely important for sensor application utilizing magnetization reversal properties with large Barkhausen discontinuities. Wall pinning is also effective in suppressing the wall motion, which improves the properties of the high-frequency material applications such as magnetic field sensor and core. Here, we present a novel pinning method of a 180° domain wall in a thin film with an in-plane anisotropy using the thickness variation along the wall. In a garnet film having a perpendicular anisotropy, the stable bubble positions can be created by the film thickness variation [1], which can be attributed to the demagnetizing field component along the film thickness direction originating from the change in the film thickness [2]. This technique has been applied to the stripe domain stabilization using etched grooves in the Bloch line memory [3]. However, the mechanism of wall stabilization in an in-plane magnetization film is different. It has also been reported that, in a narrow track single-pole head, the domain structure of a main-pole film can be controlled by forming the grooves across the track or notches at the film edges [4], [5]. The main-pole film is split up into the main-domains oriented across the track and closure domains at both sides. Using this domain control method, closure domains become smaller. The film edge parts of the 90° wall of closure domains are pinned by grooves or notches when the magnetic field is applied along the longitudinal direction of the main-pole film.

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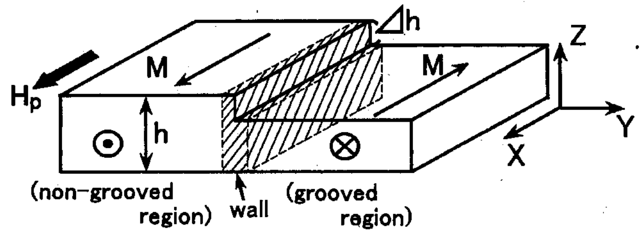

Fig. 1. Schematic drawing of step-like thickness change in a thin film.

In a thin film, the domain wall structure which takes an asymmetric Bloch wall with a vortex on one side of the wall and a Néel-like cap on each surface complicates the wall-pinning characteristics. For example, the wall energy per unit area increases with decreasing film thickness due to the increase of exchange energy. In this article, micromagnetic simulation based on the Landau–Lifshitz–Gilbert (LLG) equation has been performed to investigate the pinning characteristics of a 180° wall with a step-like change of film thickness for magnetic fields applied parallel to the magnetic domain.

II. Simulation Model

Numerical simulations were carried out by integrating the LLG equation [6]. As illustrated in Fig. 1, a step-like thickness change (Δh) along the domain wall (x direction) is assumed to clarify the wall-pinning characteristics with thickness change. The computation region (y-z plane) is the cross-section normal to the wall plane, which is discretized into a two-dimensional array. Boundary conditions are such that the wall is in the x-z plane and infinite in extent in x direction. The film is infinite in the y direction. The easy axis is along the x direction. Material parameters used in the simulation are as follows: saturation induction $4\pi M_s = 8000$ Gauss, uniaxial anisotropy constant $K_u = 3200$ erg/cm^3, exchange constant $A = 10^{-6}$ erg/cm and gyromagnetic ratio $\gamma = 1.76 \times 10^7$ (s $\cdot$ Oe)$^{-1}$. The damping constant $\alpha = 0.5$ is chosen to speed up the computation. The grid element spacings are 50 Å for the film thickness $h = 0.15$ and 0.3 μm, and 100 Å for the $h = 0.5\mu$m, respectively. Magnetic fields (H_p) are applied along the domain.

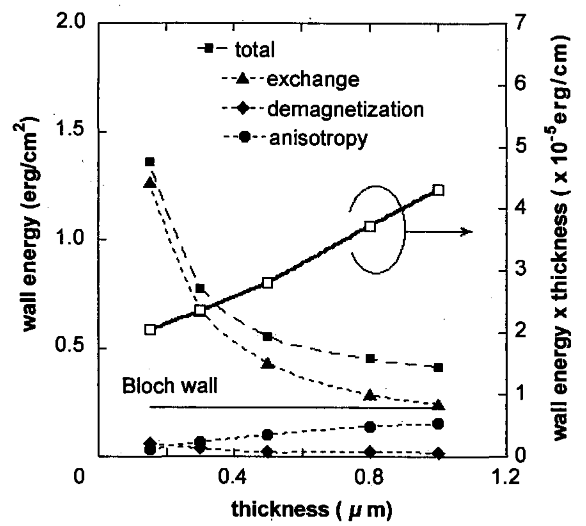

Fig. 2. Total, exchange, demagnetization, and anisotropy energies of wall without the step as a function of film thickness. The energy of ideal Bloch wall and the results of wall energy per unit area multiplied by film thickness, that is, the total energy of domain wall per unit length along the wall, are also indicated.

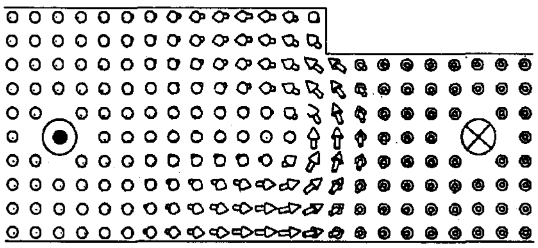

Fig. 3. Magnetization configuration stabilized by step-like thickness change in a 0.15-μm-thick film. Thickness change ratio is 0.2.

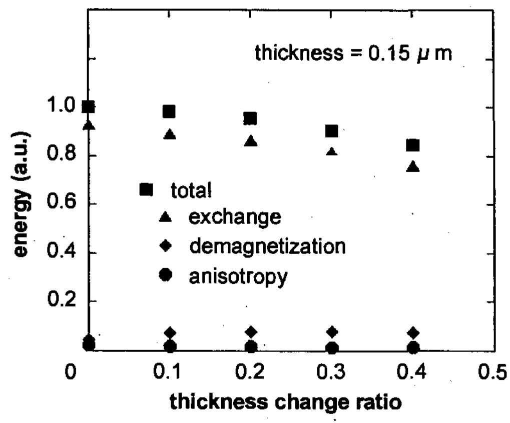

Fig. 4. Normalized total, exchange, demagnetization, and anisotropy energies of wall as a function of thickness change ratio. Film thickness is 0.15 μm.

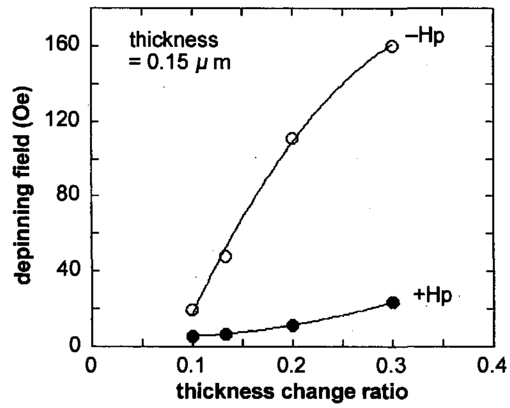

Fig. 5. Dependence of depinning fields for positive and negative magnetic fields on thickness change ratio in a 0.15-μm–thick film.

III. Results and Discussions

First, magnetic configurations of the asymmetric Bloch wall in various thick films without the thickness change were computed. Fig. 2 shows the wall energy per unit area, and each component of exchange, demagnetization and anisotropy as a function of film thickness. For comparison, the thin solid line represents the energy of the ideal Bloch wall $4(A \cdot K_u)^{-1/2}$. The results of the wall energy per unit area multiplied by the film thickness, that is the wall energy per unit length along the wall, are also indicated. The wall energy drastically increases with the decrease of film thickness less than 0.5 μm, where the exchange energy becomes dominant [7]. However, the wall energy per unit length still increases monotonically with increasing film thickness within this range.

The simulation result of the wall configuration with the step-like thickness change $\Delta h = 300$ Å in a 0.15-μm-thick film is shown in Fig. 3. The arrows in the figure represent the magnetization directions for every ninth (3×3) grid elements. As shown in the figure, the asymmetric Bloch wall is stabilized at the step. The important point to note is that the pinning effect of domain wall is obtained for both directions of wall displacement (+y and −y directions) in this case as mentioned after. In order to investigate the wall-pinning mechanism, the total, exchange, demagnetization, and anisotropy energies of domain wall as a function of step-like thickness change ratio (Δh/h) are plotted in Fig. 4. The film thickness is 0.15 μm. All energies are normalized by the total energy without the step. The wall energy decreases with increasing step depth due to the largely decrease of the exchange energy component. On the other hand, the demagnetization energy of the pinned wall with the step is larger compared to that without the step. This suggests that the pinning effect is created by the following mechanism. Although the step-like thickness change is in the pinned wall area, the rotation of magnetization in the pinned wall is more gradual compared to the wall existing in grooved region due to the magnetostatic coupling between the spins near the step. As a result, the exchange energy of the pinned wall largely decreases due to the decrease of the wall area by the groove.

We have examined the pinning characteristics of the asymmetric Bloch wall as shown in Fig. 3 for positive ($+H_p$) and negative ($-H_p$) magnetic fields applied along the magnetic domain. For the positive applied fields ($+x$ direction), the wall moved in the direction of the grooved region (right-hand side in Fig. 3). The time transient of the orthogonal component of an effective field was used for determining the depinning field [8]. It was confirmed that, in a 0.15-μm-thick film with the step of 300 Å in depth, the depinning fields for the damping constant α ranging from 0.1 to 1.0 were equal. Dependence of the depinning field on thickness change ratio in a 0.15-μm-thick film is shown in Fig. 5. The depinning field for the negative

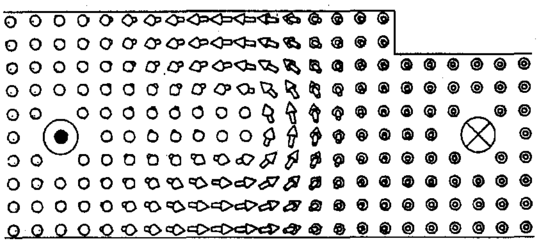

Fig. 6. Magnetization configuration of wall in the nongrooved region. Film thickness is 0.15 μm and thickness change ratio is 0.2.

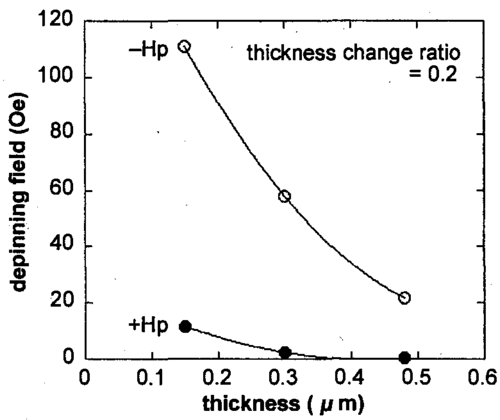

Fig. 7. Dependence of depinning fields for positive and negative magnetic fields on film thickness. Thickness change ratio is 0.2.

applied fields is considerably larger than that for the positive ones. This is because the wall energy per-unit length in the nongrooved region, that is the energy difference from the pinned wall, is larger than that in the grooved region. The dependence of the depinning field on the thickness change ratio would also reflected this character. The depinning field for the negative applied fields sharply decreases compared to that for the positive ones, as the thickness change ratio decreases. It was also found that the domain wall received the repulsive force when the wall existing in the nongrooved region as shown in Fig. 6 moved toward the step edge by the positive applied fields. It is ascribed to the increase of demagnetization energy at the step edge caused by the y component of magnetization near the film surface. The amplitude of magnetic field required to overcome the repulsive force was 21 Oe for the thickness change of 300 Å. The simulation results performed by varying the shape of thickness change suggested that this repulsive force rapidly decreased, as the slop became gentler.

Fig. 7 shows the depinning field as a function of film thickness. The step-like thickness change ratio is 0.2. The depinning field decreases with increasing film thickness. In a 0.5-μm-thick film, the pinning effect for the positive applied field becomes quite small: the depinning field is less than 0.4 Oe. The film thickness dependence of the depinning filed is similar to that of the exchange energy of wall as indicated in Fig. 2.

Finally, we briefly mention the pinning characteristics of the domain wall having the different structure: the chirality of the Bloch wall is the same as Fig. 3 but the direction of the vortex (the chirality of each Néel-like cap) is opposite. In a 0.15-μm -thick film with the step of 300 Å in depth, bi-directional wall pinning like Fig. 3 was not observed. But the unidirectional pinning effects were obtained when the wall in nongrooved region moved to the grooved region by positive applied fields and when the wall in the grooved region moved to the nongrooved region by negative applied fields.

IV. Conclusion

Numerical simulation shows the pinning effect of the domain wall in thin films with the step-like thickness change. Bi-directional pinning effect for magnetic fields applied along the magnetic domain is obtained in the case of the wall as shown in Fig. 3. The depinning field for the negative applied fields which drive the wall in the direction of the nongrooved region is considerably larger than that for the positive ones which drive the wall in the direction of the grooved region. The depinning fields for both the positive and negative applied field increase with decreasing film thickness.

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