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Domain-wall pinning by steplike thickness change in magnetic thin film

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A thin-film element with a steplike thickness change has been fabricated to investigate experimentally a pinning effect of domain walls by a shape control of thin-film devices. Using a Kerr microscope, domain observation has been done to measure pinning characteristics of the element. It has been shown that 40% steplike thickness change of the film thickness can realize a wall pinning, and a pinning field of 2.53 Oe is obtained. The pinning field increases with increasing steplike thickness change ratio. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2162038]

I. INTRODUCTION

Artificial wall pinning is effective in controlling a depinning field in sensor applications utilizing large Barkhausen jumps[1] and improving properties of high-frequency material applications, such as magnetic-field sensors and cores, due to suppression of wall motion.[2] Etched grooves in a garnet film having a perpendicular anisotropy were used for stabilizing stripe domains in a Bloch line memory.[3,4] 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.[5]

In the previous work, micromagnetic simulation has reported that steplike thickness change along a domain wall can produce wall pinning in an in-plane magnetization thin film.[6,7] The simulation results have indicated that a bidirectional pinning effect for magnetic fields applied along the magnetic domain was obtained at the step.

In the present work, thin-film elements with a steplike thickness change have been fabricated, and domain observation has been performed to investigate the pinning characteristics experimentally.

II. SIMULATION

Numerical simulations were performed by integrating the Landau-Lifshitz-Gilbert equation by an explicit scheme of the modified Dufort-Frankel method.[6–9] As illustrated in Fig. 1, a steplike thickness change (Δh) along the domain wall (x direction) is assumed to clarify the wall-pinning characteristics with thickness change. The cross section normal to the film plane (y-z plane) containing the thickness change 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 the x-z 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 $A = 10^{-6}$ erg/cm, gyromagnetic ratio $\gamma = 1.76 \times 10^7$ (s Oe)$^{-1}$, and damping constant $\alpha = 0.5$.[6,7] The grid element spacing is 5 nm for the film thickness $h \leqslant 300$ nm and 10 nm for $h > 300$ nm, 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.[10]

The simulation result of the dependence of the depinning field on thickness change ratio in a 150-nm-thick film is shown in Fig. 2. The result shows that the depinning field increases with increasing thickness change ratio. The pinning effect is created by the following mechanism. Although the steplike 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 the thin-film 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 steplike thickness change.

Moreover, the depinning field for the negative applied fields, wherein the wall moved in the thick-film region (left-hand side in Fig. 1), is considerably larger than that for the positive ones. This is because the wall energy per unit length in the thick-film region, that is the energy difference from the pinned wall, is larger than that in the thin-film region. The dependence of the depinning field on the thickness change ratio would also be reflected in this character.

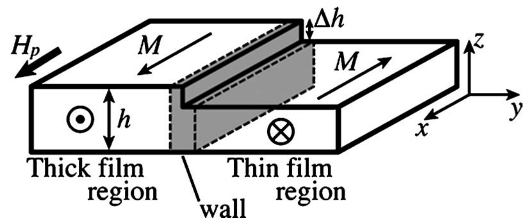

FIG. 1. A simulation model with a steplike thickness change in a thin film.

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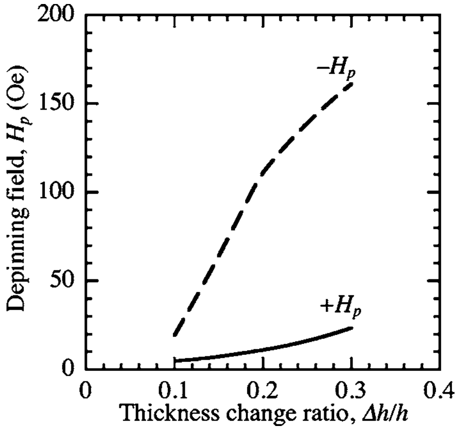

FIG. 2. Dependence of depinning fields for positive and negative magnetic fields on thickness change ratio in a 150-nm-thick film.

III. EXPERIMENT

$Ni_{80}Fe_{20}$ films with a thickness of 150 nm and with an in-plane uniaxial anisotropy are deposited by rf sputtering. To obtain a uniaxial anisotropy, a dc field of 30 Oe is applied to the thin film during rf sputtering. A magnetization curve of the film without step is measured with a vibrating sample magnetometer (VSM). The thin-film elements with steplike thickness changes of 15 and 60 nm are fabricated by a lift-off process, as shown in Fig. 3. The thickness change ratios are 0.1 and 0.4, respectively. Magnetic domains of the elements are observed by using a Kerr microscope. After applying a dc field of −30 Oe, enough to configure a saturation state, the dc field to the domain-wall direction is reduced to zero and increases to positive direction in order to observe pinning and depinning near the step of the film.

IV. RESULTS AND DISCUSSION

The coercivity and the anisotropy field of the film without a step are about 0.5 and 5 Oe, respectively. Figure 4 shows the domain patterns of the 15-nm-step element. The dark and bright domains have magnetizations pointing in upward and downward directions, respectively. In the saturation state, magnetization direction is fully upward at a dc field of −30 Oe. In decreasing the field to −0.63 Oe, reversal domains having downward magnetization component nucleate at the edge of the film, as shown in Fig. 4(b). These reversal domains grow and move toward the step position as

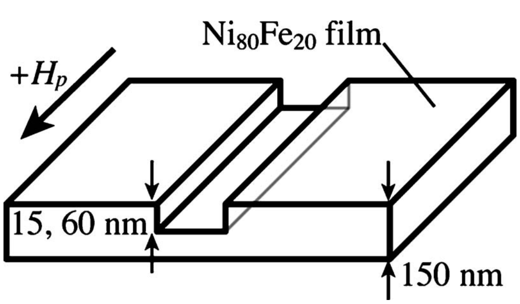

FIG. 3. A schematic view of a fabricated element with a steplike thickness change.

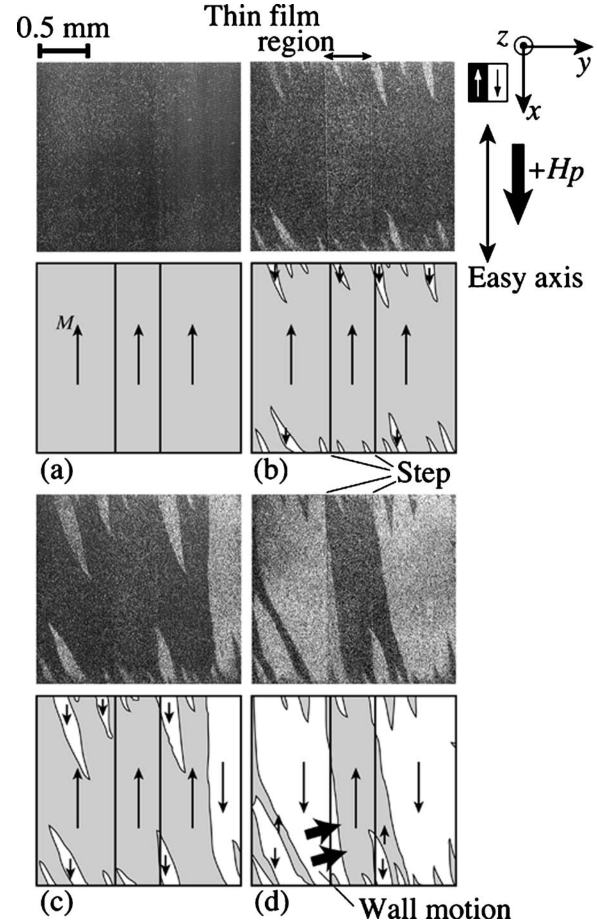

FIG. 4. Domain patterns of the element with 15 nm step: (a) a dc field of −30 Oe, (b) −0.63 Oe, (c) −0.35 Oe, and (d) −0.30 Oe.

the negative field decreases, as seen in Fig. 4(c). When the field reaches −0.30 Oe in Fig. 4(d), a domain wall moves easily over the step from the thick-film region to the thin-film region. It was found that wall pinning is not observed at the step in the 15-nm-step (0.1 thickness change ratio) element.

Figure 5 shows the domain patterns of the 60-nm-step element. Nucleation of reversal domains and growth of the domains also occur when a dc field decreases after a saturation state. The wall pinning at the step is observed at the field of +0.64 Oe, as shown in Fig. 5(c). After that, the rapid wall motion due to the depinning of the pinning wall occurs when the applied field is increased to +2.53 Oe, as shown in Fig. 5(d). The result shows that the 60-nm-step element having 0.4 thickness change ratio can realize the wall pinning by the steplike thickness change as predicted in the computer simulation. It is clear that the depinning field increases with increasing step height and the positive depinning field $+H_p$ is +2.53 Oe in this case. The intensity of the depinning field is approximately 2.5% for the simulation result, however. It seems that a shape of broad step edge causes the small depinning field compared with the value of the simulation. The simulation results performed by varying the shape of thickness change have suggested that the depinning field decreased as a slope becomes gentler.[6]

Although observation of a negative wall depinning from

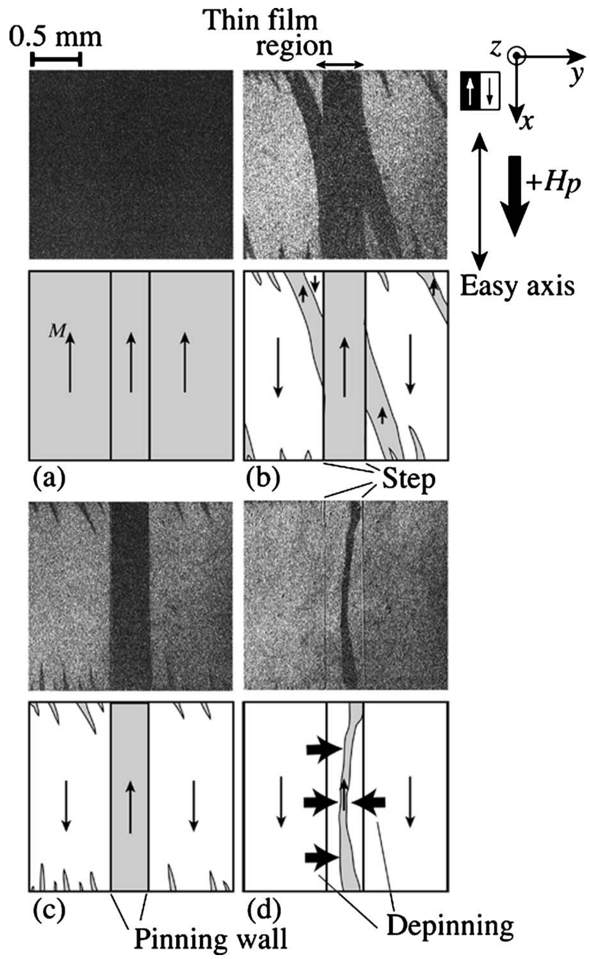

FIG. 5. Domain patterns of the element with 60 nm step: (a) a dc field of −30 Oe, (b) +0.10 Oe, (c) +0.64 Oe, and (d) +2.53 Oe.

thin-film region to thick-film region was tried, nucleation and growth of another reversal domain occurred and the wall reached the step before depinning the pinned wall at the step. The negative depinning field $-H_p$ cannot be measured in this study. However, the negative depinning field is at least larger than the positive one as predicted in the simulation, because the negative field as another wall reaches the step is larger than the positive depinning field.

V. CONCLUSION

In the present work, a thin-film element with a steplike thickness change has been fabricated to investigate experimentally a pinning effect of domain walls by a shape control of thin-film devices. It has been shown that 40% steplike thickness change of the film thickness can realize a wall pinning and a positive pinning field of +2.53 Oe is obtained. The intensity of the depinning field is very small and approximately 2.5% for the simulation result, however. This will necessitate future investigations about the relation between a step shape and the depinning field. Nonetheless, the simply fabricated thin film with the steplike thickness change will allow us to control high-frequency magnetic properties due to domain-wall pinning, and it is notable that the computer simulation can at least predict qualitatively the pinning field.

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