Micromagnetic simulation of wall transition structures with self-induced helical anisotropy and their pinning effects

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Abstract. A three-dimensional micromagnetic simulation has been performed to clarify the effect of self-induced anisotropy on domain wall behaviours, such as wall broadening and wall pinning, with wall transitions. Simulation results of the broadening of the domain wall with the transitions agree qualitatively with the Kerr microscope observation: for the wall transition which has a Bloch line between two C-shaped walls without a cap switch at each surface, the broadening of each Neel cap mainly occurs toward the opposite directions and the jog along the wall also becomes larger; for the wall transition which has a cap switch with a Bloch line, Neel caps still keep the same position after broadening. Details of pinning characteristics of the domain walls with the wall transitions by the self-induced helical anisotropy will also be presented.

1. Introduction

Amorphous ribbons annealed in a demagnetized state exhibit magnetization reversal with large Barkhausen discontinuities due to the domain wall pinning. The mechanism for the wall pinning is self-induced uniaxial anisotropy during annealing by the domain wall itself [1]. Schafer et al. revealed the pinned wall broadening and magnetization reversal process in a ribbon with a Perminvar-type hysteresis loop using Kerr microscope observation [2]. They also observed the wall transitions in the free and pinned wall and proposed three basic transitions based on wall chirality change and vortex position of C-shaped walls. These structures were also observed by high-resolution MFM images [3,4] and detailed three dimensional magnetic structures of wall transitions were displayed by micromagnetic simulations assuming the iron or permalloy films [5-8].

So far we have reported the self-induced anisotropy effects on the domain wall behaviours, such as wall broadening and wall pinning, using a two-dimensional micromagnetic simulation assuming the cross-section normal to the film plane [9, 10]. It has been clarified that pinning characteristics is strongly related to the wall structure and the different depinning fields are obtained for the movement direction of the C-shaped wall due to the asymmetric configuration. It is well known that the wall transition, i.e. Bloch lines, affects the wall motion. Argyle et al. investigated responses of the domain walls for various pulse shapes and the experimental results indicated that complicated wall structure can influence the motion of domain walls in permalloy in thin-film heads [11].
In this study, a three-dimensional micromagnetic simulation is performed in order to clarify the effects of self-induced helical anisotropy on the broadening of the domain walls with the transitions. The influence of wall transitions on the wall pinning characteristics is also investigated.

2. Simulation mode
Numerical simulations are carried out using energy minimization based on the conjugate gradient method. The simulation region is discretized into $N_x \times N_y \times N_z$ cubic cells. The wall is set in the $yz$-plane. In order to investigate the influence of the wall transitions on the pinning characteristics, a periodic boundary condition is used in the $y$-direction. Self-induced anisotropy is modeled as follows [12]: first, with the uniform easy axis set normal to the wall ($x$-direction), the domain wall profile is calculated. After relaxation, the easy axis profile is set to the wall profile and the domain wall profile is then calculated. This procedure is iterated, setting the easy axis profile at each iteration to the domain wall profile from the preceding iteration when wall broadening phenomena are investigated. The material parameters used in the simulation are as follows: saturation induction $4\pi M_s=8000$ Gauss, uniaxial anisotropy constant $K_u=6400$ erg/cm$^3$ and exchange constant $A=10^{-6}$ erg/cm.

3. Results and discussions
It is well known that the $180^\circ$ domain wall takes the asymmetric Bloch type in the film thickness range assumed in the simulation [13]. Wall transitions T1, T2 and T3 assumed in the simulation are illustrated in Fig.1 [2]. The transition T1 is indicted along an up chirality wall where the vortex position changes from $-x$ side to $+x$ side of the wall along the $y$-direction. Transition T2 is obtained by combining two C-shaped walls having opposite chirality whose vortices are on the same side. Finally, transition T3 is obtained by combining two C-shaped walls having opposite chirality whose vortices are on opposite sides. As a result, T1 does not have a Bloch line between two C-shaped walls but has a cap switch at each surface; T2 has a Bloch line with a cap switch; T3 has a Bloch line without a cap switch. A pinned wall broadening with the wall transitions is simulated with $128 \times 512 \times 32$ cubic cells of side $a=15$ nm (film thickness $=500$ nm). Figure 2 shows the magnetization configurations at the top layer ($xy$-plane), near transitions T2 and T3, respectively, (a) with the uniform easy axis set normal to the wall and (b) with the easy axis set to the wall profile (iteration number $n=5$). The arrows in the figures represent the magnetization directions for every fourth ($4 \times 4$) cells. Comparing the magnetization configuration, one can observe that there is a transverse shift ($x$-direction) between Neel cap regions for the transition T3 while there is no transverse shift for T2. In Fig. 1(b), both the walls become wider after 5 iterations due to the decrease of the anisotropy energy [9, 12]. The Bloch line of transitions T2 and T3 along the wall also rotates gradually after iteration. As shown in the figure, the Neel cap regions of two C-shaped walls for T2 keep the same position in the $x$-direction after broadening. For T3, the Neel cap broadening mainly occurs toward the opposite directions in each C-shaped wall and the transverse shift also becomes larger at both the top and bottom surfaces. This can be attributed to the vortex position as shown in the next figure. These simulation results agree qualitatively with the Kerr microscope observation [2]. For T1 which also has a jog of Neel cap region along the wall like T3, the transverse shift also became larger after broadening. Figure 3 shows the magnetization angle ($xy$-plane component), measured counter-clockwise from the $-x$-axis, at the

![Figure 1. Schematic drawing of wall transitions T1, T2 and T3 assumed in the simulation [2].](image-url)
top layer along a line normal to the left-side wall of the T3 transition in Fig. 2, before and after iteration (n=5). The Neel cap profile, especially in the vortex side, becomes more gradual after iteration. When the wall region is defined as the points where the magnetization angle first comes within 10% of ±90°, the extended distances for the upper side (vortex side) and lower side in Fig. 2 are 45 and 105 nm, respectively. It has been revealed in both the experiment and micromagnetic simulation that the amount of the wall broadening increases with increasing film thickness [9]. We computed the wall broadening of the C-shaped wall in a 1µm-thick film using the two-dimensional micromagnetic simulation. In this case, extended distances of the wall region for the vortex side and opposite side were 195 and 300 nm for iteration number n=3, and, 270 and 450 nm for n=10, respectively.

Wall pinning characteristics with the self-induced helical anisotropy are simulated with 128×1024×15 cubic cells of side a=10 nm (film thickness =150 nm). Magnetic fields along the y-direction are applied to estimate the pinning field of walls with and without the wall transitions. When the positive magnetic field is applied, the wall moves toward the lower side (−x-direction) in Fig. 2. The simulated depinning fields are summarized in Fig. 4. Symbol T0 in the figure means the simple C-shaped wall having no wall transition. For T0 and T2 whose vortices are on the same side of the wall, depinning fields are different in the wall movement directions due to the asymmetric wall structure [10]. Depinning fields for the negative applied field which pushes the wall toward the vortex side are larger than those for the positive applied field. For T1 and T2 whose vortices are on opposite sides,
Figure 3. Magnetization angle $\Phi$ at the top layer along a line normal to the left-side wall of the T3 transition in Fig. 1 before and after iteration (iteration number n=5).

Figure 4. Depinning fields of walls with and without wall transitions normalized by the anisotropy field $H_k$ for positive and negative applied fields.

depinning fields for the positive and negative applied fields are the same. In this case, the depinning field is limited to the smaller depinning field of the C-shaped wall. As shown in the figure, depinning fields of the domain wall with the transitions slightly decrease due to the inhomogeneity of pinning site along the wall. The smallest depinning field is obtained for the transition T2 which has a Bloch line with a cap switch. However, the influence of wall transitions, i.e. a Bloch line and a Neel cap switch, with the period of 5.1 $\mu$m on the depinning field is smaller compared with that of the asymmetric configuration of the C-shaped wall.

4. Conclusions
The effect of the self-induced anisotropy on domain wall behaviors, such as wall broadening and pinning, with the wall transitions was simulated. For transitions T1 and T3, the transverse shift between Neel cap regions becomes larger after broadening due to the two C-shaped walls whose vortices were on opposite sides. Combinations of C-shaped walls also affected the wall pinning characteristics. Depinning fields of the walls having the transitions with the period of 5.1 $\mu$m slightly decreased. The influence of wall transitions on the depinning field is smaller compared with that of the asymmetric configuration of the C-shaped wall.

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