Domain Reversal Simulation for Anisotropy-Energy Fluctuation

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Abstract—Influence of a nonuniform anisotropy distribution on domain reversal dynamics in ferromagnetic thin films has been investigated. A micromagnetic model has been developed adopting a Monte Carlo algorithm to examine the thermally activated reversal process. In this study, the uniaxial magnetic anisotropy magnitude is spatially nonuniform. Interestingly, the simulation results demonstrate the crucial importance of the nonuniform anisotropy variation on the domain reversal dynamics. The reversal behavior is altered from wall-motion dominant to nucleation dominant with a small change in the spatial anisotropy distribution.

Index Terms—Anisotropy variation, domain reversal, micromagnetic simulation, structural irregularity, thin films.

I. INTRODUCTION

Domain reversal dynamics in ferromagnetic thin films has been an area of extensive study in magnetism during the last few decades, largely motivated by the possibility of magnetic applications such as high-density data storage and sensing technology, as well as by fundamental interest in novel magnetic properties such as perpendicular magnetic anisotropy and giant magneto-resistance [1]–[3]. Recently, interest in this phenomenon has rapidly grown because of experimental observation of the contrasting magnetization reversal dynamics between wall-motion dominant and nucleation dominant processes exhibited in similar samples of many systems [4]–[8]. Numerous studies have been carried out to clarify the origin of the contrasting reversal behaviors. Magnetic properties have been suggested as a possible origin of the phenomena [4], [5]. On the other hand, structural irregularities, such as lattice mismatch, interfacial roughness, and local structural variations, have been suggested as another origin of the phenomena [7], [8]. The evident effect of the structural properties still remains controversial.

In this paper, we report the micromagnetic prediction of contrasting reversal behaviors dependent on the structural nonuniformity of thin films. A micromagnetic model has been developed to simulate the domain reversal process. In this model, the structural nonuniformity was simulated by a spatial fluctuation in the uniaxial perpendicular anisotropy, since the anisotropy is a very structural-sensitive magnetic property [9]. Using this model, the change in domain reversal process has been investigated with varying degrees of fluctuation in anisotropy.

II. MICROMAGNETIC MODEL

A micromagnetic model of uniaxial anisotropy has been developed adopting a Monte Carlo algorithm to determine the thermally activated reversal process [4], [10]. In this model, the film is considered to be composed of nano-size single domain cells on hexagonal lattices lying in the XY plane with periodic boundary conditions as shown in Fig. 1 [11]. The volume $V_c$ of the hexagonal unit cell is given by $\sqrt{3} t_f d_c/2$, where $t_f$ is the film thickness and $d_c$ is the distance between the centers of the nearest cells. Each cell has the saturation magnetization $M_s$ and uniaxial perpendicular magnetic anisotropy $K_{u}$, and each cell boundary has wall energy density $\sigma_w$. The magnetic energy $E$ of a cell having the angle of magnetization direction $\theta$ from the $+z$ axis is given by

$$E = K_u V_c \sin^2 \theta - M_s V_c (H_c + H_d) \cos \theta + \left(3 - \frac{1}{2} \cos \theta \sum_k \cos \theta_k \right) \frac{d_c t_f \sigma_w}{3}, \quad (1)$$

where the first term is the uniaxial anisotropy energy, the second term is the magnetostatic energy due to both the external field $H_c$ and the demagnetizing field $H_d$ normal to the film, and the last term is the domain-wall energy summed over the six neighbors having the magnetization direction $\theta_k$. The demagnetizing field $H_d$ in the cell is calculated by summing the magnetostatic field from the magnetization of other cells within the $N$th nearest cells by considering the magnetostatic interaction energy between the surface magnetization distribution of the cells. We took $N = 40$, where $H_d$ was almost saturated to its asymptotic value [12].

The magnetic energy $E$ has two minima at $\theta = 0$ and $\pi$ with a maximum in between. The energy barrier $E_b$ to reverse is the
difference in energy between the initial value and the maximum, and is given by
\[ E_b = K_u V_c \left( 1 + \cos \theta - \cos \theta_k \right)^2, \]
where \( \theta \) and \( \theta_k \) are the initial magnetization direction of the cell and the nearest neighbors, respectively. The probability \( P \) of a cell to reverse through the energy barrier \( E_b \) by thermally activated fluctuation in time \( \Delta t \) is
\[ P = P_0 \exp \left( -\frac{E_b}{k_B T} \right) \Delta t \]
where \( P_0 \) is the probability constant. The value \( P_0/\Delta t \) is determined in order to make \( \sum_{x,y} P(x,y) = 1 \) by preliminary calculation of \( P/P_0 \Delta t \) over the whole sample. A cell is determined to reverse when a random value ranging \([0, 1]\) is greater than the probability \( P \) of the cell. The total domain pattern is constructed from each state of individual cells.

III. RESULTS AND DISCUSSION

To investigate the influence of the structural nonuniformity, a random fluctuation was assigned to the uniaxial perpendicular anisotropy of each cell, since the perpendicular magnetic anisotropy, rather than the saturation magnetization, is sensitive to the structural irregularity in ferromagnetic thin films [8], [9]. The anisotropy distribution \( K_u(x,y) \) was chosen to be spatially noncorrelated as well as to have a Gaussian distribution in magnitude with the standard deviation \( \delta \):
\[ K_u(x,y) = \bar{K}_u (1 + \delta \cdot f(x,y)), \]
where \( \bar{K}_u \) is the mean value of the anisotropy and \( f(x,y) \) is the spatially noncorrelated fluctuating function having a unit standard deviation. In the simulation, the same function \( f(x,y) \) and the same magnetic properties were used, except the magnitude of fluctuation \( \delta \) was varied. The magnetic parameters in the simulation were chosen as the typical values of the magnetic properties in Co/Pd nanomultilayered system [4], [5] as listed in Table I.

Interestingly, magnetization reversal behavior was very sensitive to the degree of the fluctuation in anisotropy. Fig. 2 shows the simulated domain patterns of magnetic thin films having the uniaxial anisotropy fluctuation \( \delta \) of (a) 0, (b) 2, and (c) 4%, respectively. The figures were grabbed at 10, 30, and 50% reversal as denoted at the top of each column, respectively, and the black regions in figures illustrate the reversed domain patterns from the saturated state.

From the figures, one can vividly observe the contrasting domain reversal behaviors among the samples. Wall-motion dominant reversal is clearly seen from Fig. 2(a). In this sample, the domain is hardly nucleated. But once nucleated, domains expand gradually in size at all domain boundaries by wall-motion. Finally, a large regular domain is clearly observed. On the other hand, nucleation dominant reversal is vividly observed as shown in Fig. 2(c). In this system, the nucleation occurs at a number of places, but the nucleated domain grow only marginally in size. The domain expands anisotropically by means of the nucleation adjacent to the existing domain boundaries. Then, the dendrite-like domains are formed throughout the whole area of the sample. An intermediate reversal behavior mixed with domain-wall expansion and random nucleation is seen in Fig. 2(b). The domain reverses not only by growth of random jutting-out nucleation but also the areal expansion of the domain wall in every domain boundary. Thus, the ragged domains rather than a single regular domain are formed, and the domains are larger in size than those in Fig. 2(c).

It is interesting to point out that these contrasting domain patterns result from only a few percentage anisotropy fluctuation. This degree of anisotropy fluctuation is often observed in real films due to structural irregularities generated during the vacuum deposition since the anisotropy is a structure-sensitive magnetic property [8]. Note that the contrasting domain patterns shown in Fig. 2 are truly matched to the experimentally observed domain reversal behaviors between the wall-motion dominant reversal and the nucleation dominant one [4], [5]. These results demonstrate the crucial influence of the nonuniformity in the magnetic properties on the reversal process. Thus, by considering the structural nonuniformity one can explain the contrasting reversal behaviors among the same compositional samples prepared by different preparation conditions including film thickness, underlayers, substrates, deposition techniques, and so on.
It is worthwhile to note that the present results are quite contrastive compared with the previous one: the contrasting reversal behavior could be explained by the change in the magnetic properties in uniform films [4]. The reversal behavior is determined by both the spatial irregularity and the magnetic properties, but it is not easy to distinguish the difference between these two origins in real films.

IV. CONCLUSION

We have investigated the influence of the nonuniformity in magnetic anisotropy on the domain reversal dynamics using a micromagnetic model which considers the nonuniform magnetic properties. The domain reversal dynamics is very sensitive to the anisotropy fluctuation: the reversal behavior was changed from wall-motion dominant to nucleation dominant with a few percent change in the anisotropy fluctuation. We conclude that the spatial fluctuation in anisotropy is a possible origin governing the contrasting magnetization reversal dynamics.

REFERENCES


