Correlation between fractal dimension and reversal behavior of magnetic domain in Co/Pd nanomultilayers

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We report the experimental finding that there is a close correlation between fractal geometry and reversal mechanism of magnetic domain in Co/Pd nanomultilayers. We have measured the fractal dimension D_f of magnetic domain as well as the wall-motion speed V, the nucleation rate R, and the reversal ratio V/R in Co/Pd nanomultilayer films during magnetization reversal via time-resolved direct domain observation. Interestingly enough, D_f is inversely related to the reversal ratio V/R, which could be quantitatively explained using a micromagnetic simulation based on thermally activated relaxation model. We find that the fractal dimension is a crucial parameter to characterize magnetization reversal behavior as well as jaggedness of domain geometry. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1578185]

Magnetic domain dynamics in ferromagnetic thin films continues to be an important issue in magnetism, largely motivated by great technological interest for possible application to magnetic and magneto-optical information storage technology, magnetic random-access memory, and upcoming magnetoelectronics.[1,2] It has been reported that magnetization reversal in ferromagnetic thin films under an applied magnetic field occurs via two contrasting processes: wall-motion from existing domains and nucleation of domains at random positions, depending on film structure and composition as well as fabrication conditions.[3] These two fundamental processes often appear in a mixed way and much effort has been devoted to characterize the reversal behavior in numerous systems.[3–5] Recently, the reversal ratio V/R, which represents counterbalance between the wall-motion speed V and the nucleation rate R, has been found to be an important physical parameter to characterize different reversal processes.[5,6]

Understanding of magnetic domain geometry in ferromagnetic thin films is another important issue from both theoretical and technological point of views. It has been reported that the fractal dimension can be a characterization parameter for domain geometry, though the existence of fractal structure in magnetic domain is still controversial.[7] Many theoretical investigations within the context of random-field Ising model or the thermally activated relaxation model have been reported,[7–10] where the existence of fractal structure of domain was predicted and the effect of magnetic properties, system dimension, type of lattice, and detail of defects on the fractality are studied. Experimentally, fractal structure of domain has been observed for TbFeCo[11] and Au/Co/Au thin films,[10] where the fractal dimension was measured from observed domain images and proposed to be a characterizing parameter for noise property in magnetic and magnetooptical recording since it reflects the jaggedness of written domain.

Because domain is generated and shaped via magnetization reversal process, one can imagine a close correlation between dynamical reversal behavior and domain geometry. A few studies have been devoted to the correlation,[10,12] where the correlation between fractal dimension and the domain wall velocity is experimentally investigated. However, no study has been addressed on the quantitative correlation between the fractal dimension and the reversal parameter considering the nucleation process as well as the wall motion. In this letter, we first report our experimental discovery of correlation between fractal dimension and reversal ratio V/R of magnetic domain, together with a theoretical explanation based on a micromagnetic simulation.

We have carried out direct full-field real-time observation of magnetic domains for various Co/Pd nanomultilayers under an applied magnetic field by means of magneto-optical microscope magnetometer (MOMM). Details of MOMM are described elsewhere.[13] The magnetization was triggered by applying a magnetic field in the field range of 70%–90% of the coercivity to an initially saturated sample.

For the purpose of our study, a number of $(t_{Co}\text{-Co}/11\text{ Å Pd})_{10}$ samples with varying the Co-sublayer thickness t_{Co} were prepared on glass substrates by dc-magnetron sputtering under 2.0×10^{-7} Torr base pressure and 5 mTorr Ar sputtering pressure.[14] We focus on the samples with $2\leqslant t_{Co}\leqslant 4$ Å, all of which show square polar Kerr hysteresis loops revealing perpendicular magnetic anisotropy. It has been well known that the Co/Pd nanomultilayer system exhibits an increase of saturation magnetization and a decrease of anisotropy constant as t_{Co} increases in this thickness region.[15] Measured value of the saturation magnetization M_s by vibrating sample magnetometer increases from 250 to 420 emu/cm^3 as t_{Co} increases from 2.0 to 4.0 Å.

In Fig. 1 we demonstrate typical domain evolution patterns of $(t_{Co}\text{-Co}/11\text{ Å Pd})_{10}$ with $t_{Co}=2.0$, 2.5, 3.0, 3.5, and 4.0 Å, observed by means of the MOMM under a constant applied field, where the gray code corresponds to the reversed switching time. It can be vividly seen that irregularity and jaggedness of domain wall patterns appear to increase as

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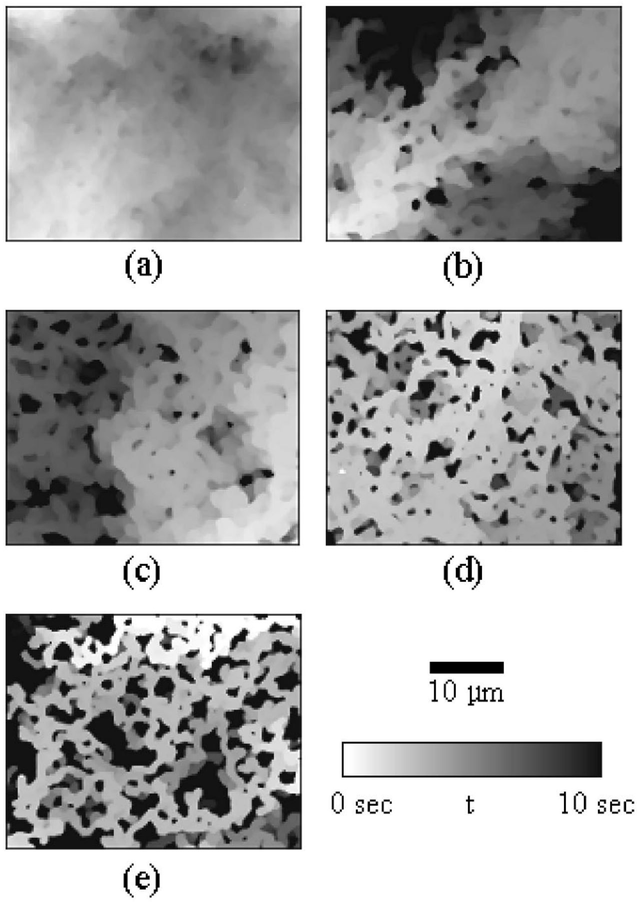

FIG. 1. Domain evolution patterns of (t_{Co} Å Co/11 Å Pd)$_{10}$ samples prepared with varying t_{Co} of (a) 2.0, (b) 2.5, (c) 3.0, (d) 3.5, and (e) 4.0 Å, respectively. The observed area is 40×32 μm^2 and the gray-level represents the elapsed time from 0 to 10 s in the process of domain evolution.

t_{Co} increases, which is expected from the measured M_s values. Domain patterns become irregular and jagged in case of high demagnetization energy to close the magnetic flux at the surface and thus, to minimize the magnetic energy.[16] It is also understandable from the fact that as t_{Co} increases, anisotropy constant K_u decreases[15] and thus, domain wall energy is reduced, which makes the formation of irregular domain pattern possible. Interestingly enough, direct domain observation reveals that not only the geometry of domain patterns but also the reversal process in this system is found to be sensitively changed with the increase of t_{Co}, as clearly seen from Fig. 1. With increasing t_{Co}, we witness that domain reversal process changes from a wall-motion dominant process to a nucleation dominant one.

To quantitatively understand the geometry of domain, we have investigated the fractality of magnetic domain of our samples. It is well known that the fractal dimension D_f is obtainable from the scaling relation among geometrical parameters such as perimeter, area, and ruler length.[17] In this work, the fractal dimension is determined from the perimeter-area scaling relation.[17] For this, we have measured perimeter and area of magnetic domain from time-dependent reversal patterns from 10% to 30% reversal of the samples. The perimenter-area scaling relations for all samples are plotted on a log–log scale in Fig. 2, where one can find a nice linear relationship in each sample, which enables us to determine D_f. We find that D_f increases from 1.04 ± 0.06 to

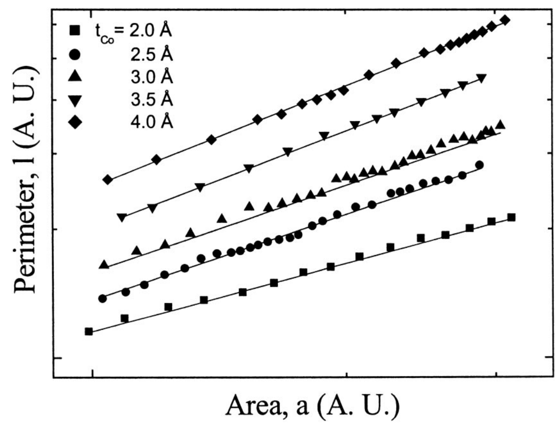

FIG. 2. Perimeter vs area of domain evolution pattern during 10%–30% reversal of observed area for the samples with various t_{Co}. The solid line is the best fit for the perimeter-area scaling relation.

1.58 ± 0.05 with increasing t_{Co}. For each sample, it seems that D_f does not show a clear dependence on the strength of an applied field in the field range of this work (70%–90% of H_C) within the measurement error. Note that D_f of each sample is truly coincident with the degree of jaggedness of the corresponding domain evolution pattern in Fig. 1, which directly demonstrates that the fractal dimension indeed can be used as a parameter to characterize jaggedness of domain as suggested in Ref. 11.

To investigate the correlation between fractal geometry and reversal behavior, we have measured the wall-motion speed V, the nucleation rate R, and the reversal ratio V/R. They could be quantitatively determined from time-dependent domain reversal patterns by the method described in Ref. 18. The V and R are found to be exponentially dependent on the strength of an applied field in the field range of this work. This exponential dependency can be well explained by a thermally activated relaxation model.[3] On the contrary to V and R, V/R does not depend on the strength of an applied field, but it mainly depends on the type of the overall reversal behavior.[5,6] The V/R of each sample decreases from 5.66 ± 1.80 to 0.34 ± 0.08 with the increase of t_{Co}, as plotted in Fig. 3. Note that as V/R decreases, the reversal behavior of corresponding sample changes from the

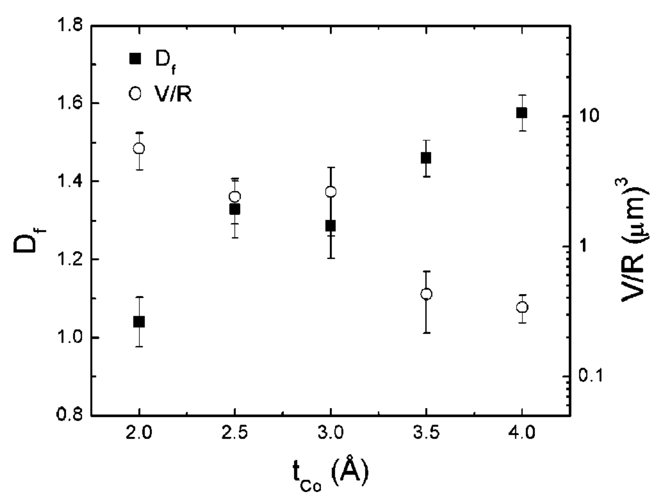

FIG. 3. Fractal dimension D_f of (t_{Co} Å Co/11 Å Pd)$_{10}$ with respect to t_{Co}. Reversal ratio V/R with respect to t_{Co}.

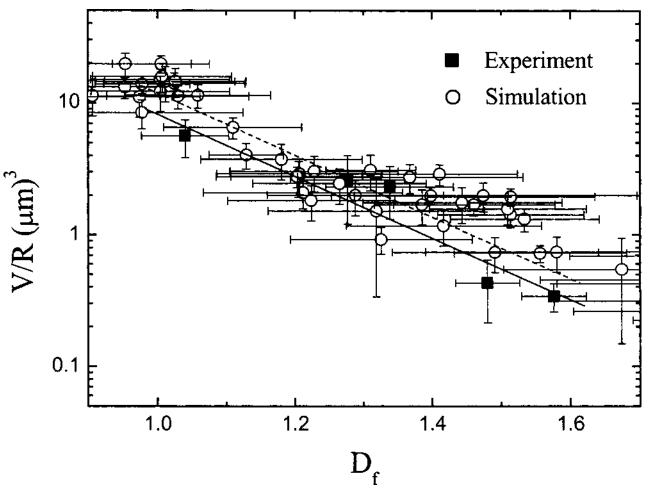

FIG. 4. Correlation between the fractal dimension D_f vs the reversal ratio V/R determined from experiment (solid square) and simulation (open circle). The error is determined in the same way as in Fig. 3.

wall-motion dominant process to the nucleation dominant one, which can be directly witnessed from domain evolution patterns in Fig. 1. The trend of V/R with varying t_{Co} is understandable by considering demagnetization energy, since the saturation magnetization of each sample increases as t_{Co} increases. A thinner film has weak demagnetization energy due to its weak magnetization and thus, it prefers large domain configuration achieved by the wall motion process, whereas a thicker film has strong demagnetization energy and thus, domain splits into the narrow stripe patterns to minimize demagnetization energy.[3] In addition to demagnetization energy, the decrease of K_u is also responsible for the stripe-patterned domain, since reduced K_u means reduced energy cost in generation of domain wall. From this point of view, the rapid decrease of V/R with t_{Co} seems to be quite explainable.

Here, we like to stress that the static geometry parameter D_f and the dynamic reversal parameter V/R seem to be clearly correlated. It should be reminded that both the fractal dimension D_f and the reversal ratio V/R are not dependent on the strength of an applied field within the measurement error in the range of 70%–90% of H_C, whereas V and R exhibit exponential dependency. Therefore, relating D_f to V/R rather than V and R should be more general. Interestingly, V/R and D_f show an inverse relation to each other as clearly demonstrated in Fig. 4, where a large V/R corresponds to a low D_f, and vice versa. We like to mention that D_f certainly tends to increase as the reversal behavior becomes nucleation dominant, since nucleations produce much long range roughness, as compared to the case of only one nucleation site. It is interesting to note that V/R can be approximated as $\sim\exp(E_N - E_W)$ based on thermally activated relaxation model,[5,6,10] where E_N and E_W represent the nucleation and the wall-motion activation energy. The relation between D_f and $\log(V/R)$ can be expressed as $D_f \sim (E_W - E_N) + \mathrm{C}$, where C is a constant related with Barkhausen volume or minimum size of activated domain.[5,19] We find that D_f is directly proportional to the difference between two activation energies for the nucleation and the wall-motion processes.

To understand the observed relation, theoretical study has been carried out by Monte-Carlo simulation adopting a simple uniaxial anisotropy model.[7,20] In this model, the film is considered to be composed of nanosized identical single domain cells on hexagonal lattices lying in the XY plane with the periodic boundary condition, as described in Ref. 18. In Fig. 4, we plot V/R vs D_f, which are obtained via Monte-Carlo simulation by varying the anisotropy constant K_u from 1×10^4 to 1×10^7 erg/cm^3 and the saturation magnetization M_s from 150 to 450 emu/cm^3 when increasing t_{Co} from 2 to 4 Å and the exchange stiffness of 5.0×10^{-7} erg/cm^3 at 300 °K. Note that a clear trend of the inverse correlation between D_f and V/R exists over whole region of the simulation. According to the simulation, we witness that there exists a transition in reversal behavior from wall-motion dominant to nucleation-dominant one, when the ratio of the magnetostatic energy over the anisotropy energy, $2\pi M_s^2/K_u$, is increased, as reported in Ref. 18. This transition of reversal behavior is accompanied by corresponding changes of D_f and V/R D_f increases and V/R decreases as $2\pi M_s^2/K_u$ increases. Here, we want to stress that our direct observation and theoretical simulation reveal that the nucleation rate, as well as the domain-wall velocity, is generally correlated to the domain-wall fractality D_f is proportional to R, but inversely proportional to V. It should be noted that the reversal ratio V/R including the information of both the nucleation and the wall motion is found to be a more legitimate parameter in correlation with D_f. We like to mention that consideration of microstructural irregularities is desirable for better simulation,[21,22] which is beyond the scope of the present work.

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