Journal of Magnetics 17(4), 242-244 (2012)

ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
http://dx.doi.org/10.4283/JMAG.2012.17.4.242

Width-Dependent Transition of Magnetic Domain Configuration in Nanostructured CoFe/Pt Multilayered Nanowires

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(Received 23 August 2012, Received in final form 5 October 2012, Accepted 8 October 2012)

We report on the basis of experiments that magnetic domain structures exhibit a transition between single and dendrite domains with respect to the width of ferromagnetic nanowires. This transition is directly observed in CoFe/Pt multilayered nanowires having a width in the range of 580 nm to 4.2 μm with a magnetic force microscope. Nanowires wider than 1.5 μm show typical dendrite domain patterns, whereas the nanowires narrower than 690 nm exhibit single domain patterns. The transition occurs gradually between these widths, which are similar to the typical widths of the dendrite domains. Such a transition affects the strength of the domain wall propagation field; this finding was made by using a time-resolved magneto-optical Kerr effect microscope, and shows that the domain wall dynamics also exhibit a transition in accordance with the domain configuration.

Keywords : magnetic domain, transition, dendrite domain, nanowire-width

1. Introduction

Ferromagnetic nanowires have been extensively studied due to their potential uses in memory and logic device applications [1, 2]. Recently, nanowires with perpendicular magnetic anisotropy (PMA) have attracted considerable interest owing to their unique advantages: smaller domain structures and superior stability [3]. PMA films exhibit three distinct domain configurations: single, dendrite, and scattered-dot domains [4-8], which are formed by domain-wall motion, dendrite growth, and nucleation processes, respectively. The formation of such distinct domain configurations is determined by the counterbalance between the magnetostatic and domain wall energies [9, 10]. However, recently, it has been proposed that the geometry of magnetic nanostructures also modifies the domain configurations, resulting in a transition from the dendrite domain to the single domain with a decrease in the nanowire width [3, 11]. Magnetic nanostructures with such a single-domain configuration are advantageous for use in domain-wall-mediated applications [1, 2], because of the wall-motion-dominant domain dynamics in this configuration. In this paper, we report an experimental demonstration of the dependence of the domain-configuration transition in ferromagnetic CoFe/Pt multilayered nanowires on the width of nanowires.

2. Experiments

In this study, Si/100-nm SiO_2/5-nm Ta/2.5-nm Pt/(0.5-nm $Co_{90}Fe_{10}$/1.0-nm $Pt)_{10}$ multilayered films were prepared by dc-magnetron sputtering with a low (~0.25 Å/sec) deposition rate (CoFe). The sputtering power was kept at 10 W and the Ar sputtering pressure was 2 mTorr for all deposition processes. The base pressure was lower than 2×10^{-8} Torr. The films exhibited a strong PMA, as confirmed by the square magnetic hysteresis loop from a polar magneto-optical Kerr effect (MOKE) measurement as shown in Fig. 1(a). The coercive field of the films was measured to be approximately 130 ± 10 mT. The ferromagnetic nanowires with various widths w – ranging from 580 nm to 4.2 μm – were then patterned by electron-beam lithography and subsequent ion milling on CoFe/Pt multilayered films, as shown in Fig. 1(b). In the lithography

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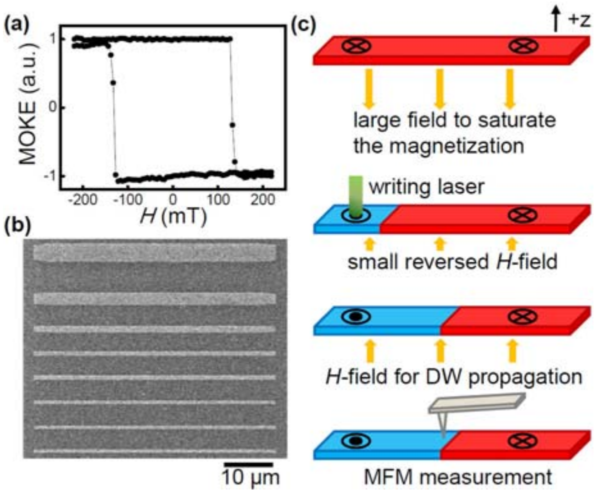

Fig. 1. (a) (Color online) Out-of-plane MOKE hysteresis loop of the film. (b) Secondary electron microscope (SEM) image of the nanowires with different widths. The lighter contrast indicates the wires, whereas the darker contrast corresponds to the substrate. (c) Schematics of the thermomagnetic domain writing, domain expansion, and MFM measurement procedure.

process, an electron beam resist (maN-2403) was used. The ion-milling process was done with the two incident angles (15 and 75°) to reduce the wire edge roughness. The coercive field of the nanowires was slightly increased to 130-160 mT, depending on the wire width [12, 13].

In order to examine the magnetic domain structures, we created domains by using thermomagnetic writing, as depicted in Fig. 1(c). The magnetization of the nanowires was initially saturated in the –z direction, perpendicular to the film plane, by applying a magnetic field much larger than the coercive field. A laser pulse was then focused on a local spot of the nanowire with a small magnetic field in the –z direction to selectively reverse the magnetization at the spot. The duration of the laser pulse was 500 ns and the power was about 5 mW on the wire. The typical size of the reversed domains was about 500 nm, in accordance with the size of the laser spot. Once such a reversed domain was formed, we turned off the laser and then, applied a magnetic field pulse (125 ± 5 mT and 500-1,500 ms) to further expand the reversed domain, up to several microns in size. Finally, the reversed domain images were observed through the use of a magnetic force microscope (MFM). In these MFM measurements, the scanning height was 50 nm and the scanning step was 58 nm.

3. Results and Discussion

Figure 2(a) shows the MFM images of the magnetic domains in the nanowires with various widths *w*. The darker area corresponds to the reversed domains. It is interesting to note that the observed domain patterns exhibit a smooth transition with a decrease in *w*. In wide nanowires, dendrite-domain patterns appear, whereas single-domain patterns are observed in narrower nanowires. The transition occurs gradually with the wire width between 690 nm and 1.5 μm. Note that this transition width is similar to the average width of the dendrites observed in the wide nanowires.

In order to understand the observed transition of the domain patterns, a numerical simulation is carried out on the basis of a Monte Carlo algorithm [4]. In the simulation, the nanowire is assumed to be composed of identical hexagonal single-domain cells (thickness $t_F = 15$ nm and cell-to-cell distance $d_C = 12$ nm) in a film plane with periodic boundary conditions [14]. Each cell is assumed to have a saturation magnetization M_S of 0.6 T, a uniaxial anisotropy K_U of 1.85×10^5 J/m^3, and a domain wall energy density σ_W of 1.75 mJ/m^2, which are typical values for cells in CoFe/Pt multilayered films. In Fig. 2(b), we have shown the simulated domain patterns for nanowires with various widths. Note that the simulation results basically exhibit fairly similar behavior, compared with those indicated by the MFM images.

In order to examine whether this transition has any influence on the dynamics of the domain wall, the domain wall propagation field H_P was measured with respect to *w*. Here, H_P is defined as the minimum magnetic field required for domain propagation. For this measurement, a scanning MOKE detection setup was used [15]. Initially, a reversed domain was created by thermomagnetic writ-

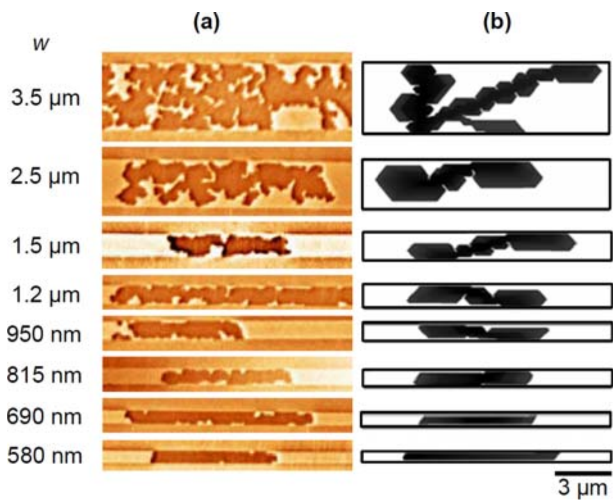

Fig. 2. (a) (Color online) MFM images of magnetic domains in CoFe/Pt multilayered nanowires for different values of the wire width *w*. The wire widths are denoted in each image. (b) Domain patterns predicted by the Monte Carlo simulations.

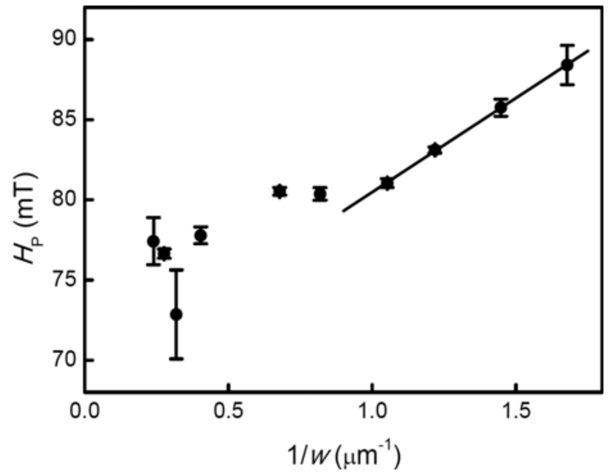

Fig. 3. The relationship between the domain wall propagation field H_P and the wire width w. The solid line is the best linear fit for narrow nanowires.

ing as described above and the MOKE detection spot was located at a position, 2 μm away from the reversed domain. A magnetic field was then applied in the +z direction. The magnitude of the applied magnetic field was increased from zero, until an abrupt change of the MOKE signal was detected. Such an abrupt change of the MOKE signal indicates the passage of the domain wall through the detection spot. This measurement procedure enabled us to determine H_P as the smallest magnetic field for the domain propagation. This measurement procedure was repeated for the nanowires with various w. The results are summarized in Fig. 3. The figure clearly shows that in narrow nanowires, H_P exhibits a linear relation with the inverse of w; it is well known that such dependence on $1/w$ can be ascribed to the domain wall pinning due to edge roughness [12, 13, 16, 17]. In such cases, H_P is known to be the sum of the intrinsic depinning field H_D and the extrinsic depinning field H_E [12]. For the single-domain configuration, it has been analytically predicted [12, 17] that H_E shows a $1/w$ dependence, which is given by $H_E = (\sigma_W \sin\theta/2M_S w)$, with the angle of edge roughness θ. On the other hand, in case of wide nanowires, such a linear relation is not valid for widths above 950 nm. The observation that nanowires wider than 950 nm exhibit dendrite domain patterns shows that the domain configuration influences the domain wall propagation process. This observation may be explained by two features of the dendrite domain patterns: a domain wall having a large length has more intrinsic domain wall pinning sites [12] and the expanding region of dendrite growth takes a longer time (in comparison to the time taken for the unidirectional growth of the single-domain patterns) to approach the probing point.

4. Conclusion

We demonstrate a transition from the dendrite to the single domain with respect to the width of ferromagnetic nanowires. The domain patterns are found to change gradually by reducing the width and finally, the single domain pattern was realized in nanowires narrower than 690 nm, which is much wider than the typical size of modern magnetic nanodevices. This result implies that the films – originally exhibiting dendrite domain patterns – can be used in domain-wall-mediated nanowire applications.

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (2012-003418). JCL, BCM and KHS were supported by the KIST Institutional Program and pioneer research center program (2011-0027905) through NRF funded by MEST. We would like to thank C.-W. Lee, Y. J. Cho, and S. Seo at Samsung Advanced Institute of Technology for sample preparation.

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