ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 25(4), 458-462 (2020) https://doi.org/10.4283/JMAG.2020.25.4.458

Writing and Deleting Magnetic Bubbles using Local Magnetic Fields

**Sooseok Lee, Hee-Sung Han, Dae-Han Jung, Namkyu Kim,
Myeonghwan Kang, Hye-Jin Ok, and Ki-Suk Lee***

Department of Materials Science and Engineering, Ulsan National Institute of Science and Technology, Ulsan 44919, Republic of Korea

(Received 20 November 2020, Received in final form 23 December 2020, Accepted 23 December 2020)

Magnetic bubbles are circular magnetic domains that may occur in thin magnetic films with perpendicular magnetic anisotropy (PMA). Because they can form with high topological stability and can be manipulated by external driving forces, magnetic bubbles have been considered as prominent information carriers, which are set to 1 or 0, corresponding to the presence or absence. For practical applications, such information carriers must be written and deleted in a specific area of the magnetic thin film. Herein, we report that the magnetic bubbles can be written and deleted using local magnetic fields. By applying a localized magnetic field from the magnetic tip of a magnetic force microscopy to the stripe domain structures of the PMA multilayer, bubbles can be written at room temperature via the transformation from stripe domains to magnetic bubbles. The deleting of the bubbles in the targeted area demonstrated by the local magnetic field accompanied by a uniform external field. Our findings can provide a key for manipulating information carriers in the spintronic device based on topological magnetic structures such as magnetic skyrmions and bubbles.

Keywords : magnetic bubble, magnetic domain, thin ferromagnetic film, magnetic force microscopy

1. Introduction

Recently, particle-like magnetic structures such as magnetic bubbles have attracted considerable research attentions because of their fascinating topological properties and potential applications [1-7]. They can be created in small sizes ranging from 10 to 1000 nm with high stability under various external perturbations in thin magnetic films or multilayered structures with perpendicular magnetic anisotropy (PMA) [8-13]. Another important feature is that their mobility can be manipulated efficiently by current [12, 13]. The aforementioned characteristics make them a promising candidate for novel applications in the field of spintronics [14, 15].

However, an obstacle hinders the realization of bubble-based devices; the ground state magnetic structures in the PMA films primarily favor stripe domain structures rather than magnetic bubbles [16-18]. For obtaining magnetic bubbles, an out-of-plane (OOP) magnetic field with a certain field range is required. When the OOP magnetic field is applied, the stripe domains shrink and turn them into bubbles at a certain field strength. These bubbles can exist stably only within a certain field range, below which they deform elliptically and transform back into stripe domains [18-20]. During this process, a jump-like motion of the domain walls occurs because of the randomly distributed pinning sites [19, 20]. Which reflects that the creating the bubbles by applying an external magnetic field is a stochastic process and is very difficult to control. Geometrical potential confinement is an alternative method for creating magnetic bubbles via sophisticated nano-patterning [21]. However, this method results in a decrease in a density of magnetic bubbles, which is directly linked to storage capacity.

The realization of magnetic bubble-based devices strongly depends on the ability to create and remove bubbles in a specific area of a film for fundamental investigations and practical applications. The creation and annihilation of bubbles have been addressed experimentally via various techniques, e.g., Joule heating [22], electric fields [23], and strain [24]. However, these techniques require an additional energy source, such as an external magnetic field, to keep bubbles stable. For the practical application of magnetic bubbles to information storage devices, it is

*Corresponding author: Tel: +82-52-217-2366
Fax: +82-52-217-3527, e-mail: kisuk@unist.ac.kr

necessary to maintain magnetic bubbles without additional magnetic fields.

In the present study, we demonstrate experimentally that magnetic bubbles can be generated and deleted through a local magnetic field, as well as that they can remain stably without an external magnetic field and geometric confinement. We utilized a stray field (H_{tip}) induced by magnetized tip of the magnetic force microscopy (MFM) for applying a local magnetic field to PMA thin films. As the tip–sample distance is decreases, H_{tip} becomes stronger and it reaches to the switching field of the PMA film, and the magnetization direction of the films can be switched locally and it induces creation of the magnetic bubbles [25]. We also investigated the stability of the magnetic bubbles and compared it with that of the stripe domains. Our findings can provide useful writing and deleting method for spintronic devices based on particle-like magnetic structures.

2. Experiments

For this study, an 8×8 mm^2 size [Pt (2 nm)/Co (0.9 nm)/Ta (4 nm)]$_{15}$ multilayer film was fabricated on a Si_3N_4 substrate using DC magnetron sputtering at room temperature with a base pressure of 4.8×10^{-8} Torr. A 20 nm thick Ta seed layer was deposited before growing the multilayer stack. To prevent oxidation of the sample, a 3 nm thick Pt capping layer was deposited. To observe the magnetic structures with high resolution, we employed MFM with a 15 nm thick CoCr-coated tip having low stray magnetic field (tip$_{LM}$). A two-pass scheme was used. In the first pass, the tip and sample came into close contact, and the surface information was recorded. In the second pass, only the magnetic interaction between the tip and the sample was recorded, and the distance between the tip and the sample was maintained (d_z = 80 nm). For applying a higher local magnetic field, a tip coated with 40 nm thick CoCr (tip$_{HM}$) was used. Based on numerical calculations, it is found that tip$_{LM}$ and tip$_{HM}$ can induce magnetic field of 365 Oe and 565 Oe, respectively, on the thin film.

3. Results and Discussion

3.1. Magnetic domain structures along hysteresis loop

Figure 1 shows the magnetization curve obtained using the magneto-optical Kerr effect and MFM images of the magnetic structures along the minor hysteresis curve (red solid line). At zero field, a demagnetized stripe domain was obtained as shown in the image (i). The lateral compression of stripe domains was observed by the OOP

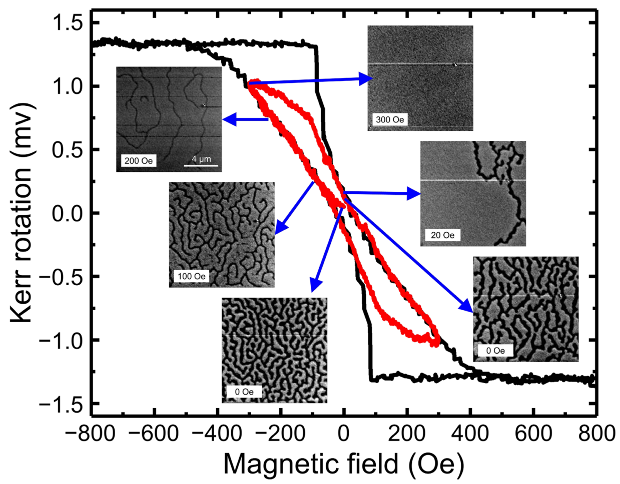

Fig. 1. (Color online) Major (black solid line) and minor (red solid line) hysteresis loops measured using the polar magneto-optical Kerr effect. MFM images were captured at increasing and decreasing external out-of-plane (OOP) magnetic fields. White and black contrasts correspond to the upward and downward magnetization, respectively.

magnetic field (see the MFM images (ii) and (iii)). On further increasing the field, the magnetic domain structures almost disappeared in this area at 300 Oe (see the MFM image (iv)). As the field strength increase, the domains tend to become thinner and eventually disappear. This suggests that strong pinning occurs at the end of each domain. Pinning can significantly contribute to stability because it prevents deformation of the magnetic structure; however, it also causes a rapid change in the magnetic structure when the strength of the external magnetic field increases to a certain value. Since the pinning sites are randomly distributed, it is difficult to predict the locations of the deformation, generation, and annihilation of magnetic structures. Although the location observed in the present experiment did not reach the saturation point, all the structures disappeared at 300 Oe. In addition, there could still be magnetic structures within the film, since the entire film is not in a saturation state.

3.2. Writing and deleting magnetic bubbles

For writing bubbles, H_{tip} should be larger than the saturation field of the sample (500 Oe) [22]. The process of writing the bubbles is illustrated in Figs. 2(a) and (b). When the magnetized tip scans through the surface, tip-induced magnetization reversal occurs at near the tip, which divides one stripe domain into two domains. Figs. 2(c)-(e) present the MFM images during the process of the bubble creation process. The initial state in Fig. 2(c) was measured via MFM scanning with tip$_{LM}$. To cut stripe domains, a contact-mode scan was performed on

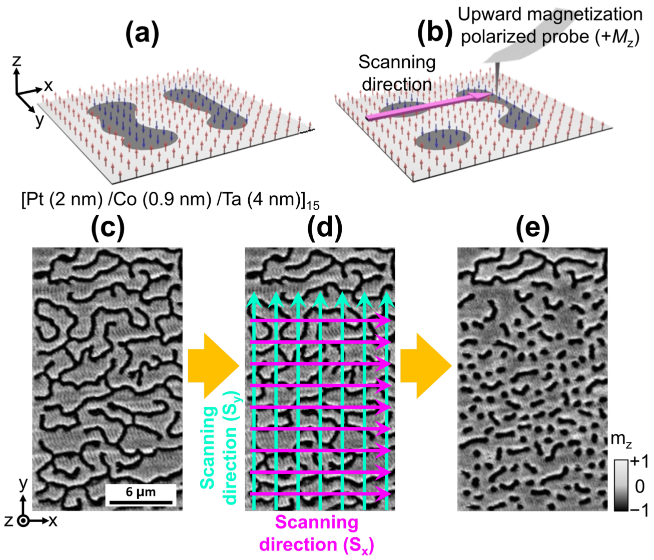

Fig. 2. (Color online) Magnetic bubbles created from dtripe domains in magnetic film at 0 Oe. (a)-(b) Schematics of splitting magnetic domains by scanning local magnetic field using magnetized tip. (c)-(f) The MFM images obtained using low stray magnetic field tip (tip_{LM}) before and after scanning the local magnetic field along the x (S_x) and y (S_y) axes.

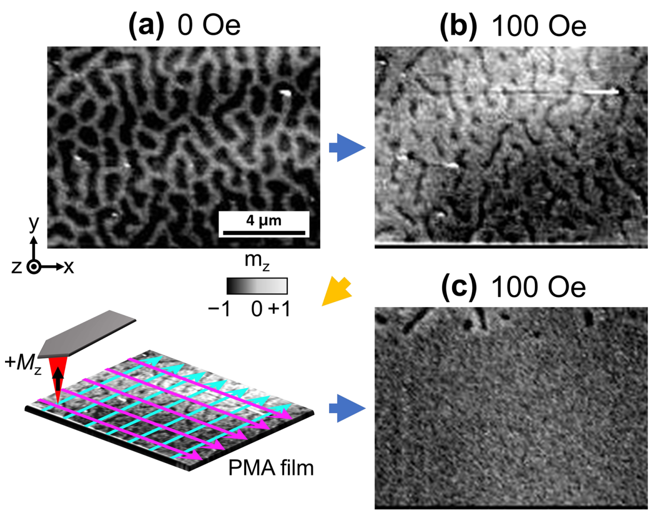

Fig. 3. (Color online) (a) The MFM image of the initial state. (b, c) Deletion of the bubbles by scanning the local magnetic field in the presence of an external OOP magnetic field.

the film along the x-axis (S_x) and y-axis (S_y) with MFM tip_{HM} to apply a stronger local magnetic field of 565 Oe as shown in Fig. 2(d). Figure 2(e) shows a magnetic domain image subsequently obtained using a tip_{LM} in the identical area. Significant changes in the magnetic domain structures are clearly observed. Most of the stripe domains transformed into a mixed state, consisting of elongated domains and bubbles, while the stripe domains remained in the upper area where tip_{HM} was not scanned. It is evident that the magnetic field from tip_{HM} was sufficiently strong to cut the domains. The bubbles formed by cutting the stripe domains were mostly circular, with a radius of 300-500 nm.

For deleting the bubbles, we used tip_{HM} combined with an external OOP magnetic field. The external magnetic field can significantly lower the energy barrier between the bubble and the saturated state [22]. An external magnetic field was applied for suppressing the structures (Fig. 3(b)), and then, scanned the surface by tip_{HM} with the magnetization aligned to the direction of the external magnetic field. Consequently, the bubbles were removed (including elongated domains) in the scanned area, while few structures remained at the upper side where the tip_{HM} was not scanned (Fig. 3(c)).

3.3. Stability of magnetic bubbles

We compared the stability of magnetic bubbles and stripe domains by investigating the recovery of their structures after applying an external OOP magnetic field of 110 Oe. By comparing Figs. 4(a) and 4(c), reveals that the location and shape of the stripe domains were significantly changed after the field was applied and back to 0 Oe, indicating that the degree of recovery of the stripe domain was very low. Figure 4(d) shows the mixed structures of magnetic bubbles and stripe domains created by scanning the upward magnetized tip_{HM} in the same area. As shown in the green circles of Figs. 4(d)-4(f), some bubbles are very robust to the OOP field. Under the OOP field of 110 Oe, the lateral size of the bubble domains in green circles decreased slightly and back to its original size when the magnetic field was turned off.

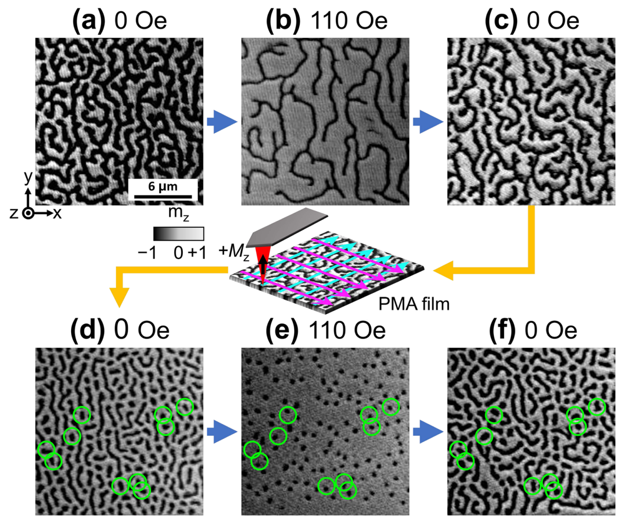

Fig. 4. (Color online) Comparison of the stability of (a-c) stripe domains and (d-f) bubbles.

While some bubbles and stripe domains were changed significantly. Their robustness might be coming from the topological protection of magnetic bubbles. According to the domain wall structure, magnetic bubbles can have different topological numbers such as 0 or integer numbers. As shown by Je *et al.* [7], the stability of magnetic bubbles to an external field can be significantly different according to its topological number. In our experiments, the bubbles in the green circles might have an integer topological number, and thus, they show robustness to an external magnetic field in Fig. 4. On the contrary, most of the domains and other bubbles show significant transformation since they might have 0 topological numbers, and thus, they do not have topological protection. However, there is no direct evidence to figure out the topological protection of magnetic structures in our experiments. For obtaining topological differences among structures, it is necessary to measure the annihilation field strength of each structure as shown in Ref. [7]. Furthermore, additional numerical and theoretical studies are required to understand the detailed mechanism of the local-field induced magnetic-bubble generation with a different topological number.

4. Conclusion

We demonstrated the writing and deleting of the magnetic bubbles by scanning local magnetic fields using a magnetized MFM tip in a specific area of a PMA film. A highly localized magnetic field induced by the magnetized tip can cut stripe domains and form bubbles without an external field. Accompanied by an external OOP magnetic field, the scanning of magnetized tip removes the magnetic structures. The proposed method can create robust bubble structures and be used for manipulating information carriers in magnetic bubble-based spintronic devices.

Acknowledgment

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (NRF-2016M3D1A1027831, NRF-2019R1 A2C2002996 and NRF-2020M3F3A2A03082987). It is also funded by the 2019 Research Fund (1.190038.01) of UNIST (Ulsan National Institute of Science and Technology).

References

[1] S.-G. Je, D.-H. Kim, S.-C. Yoo, B.-C. Min, K.-J. Lee, and S.-B. Choe, Phys. Rev. B **88**, 214401 (2013).
[2] A. Fert, V. Cros, and J. Sampaio, Nat. Nanotechnol. **8**, 152 (2013).
[3] N. Nagaosa and Y. Tokura, Nat. Nanotechnol. **8**, 899 (2013).
[4] T. Suzuki, J. Magn. Magn. Mater. **31-34**, 1009 (1983).
[5] R. D. Lock and J. M. Lucas, Radio Electron. Eng. **42**, 435 (1972).
[6] P. I. Bonyhard, J. E. Geusic, A. H. Bobeck, Y. S. Chen, P. C. Michaelis, and J. L. Smith, IEEE Trans. Magn. **9**, 433 (1973).
[7] S.-G. Je, H.-S. Han, S. K. Kim, S. A. Montoya, W. Chao, I.-S. Hong, E. E. Fullerton, K.-S. Lee, K.-J. Lee, M.-Y. Im, and J.-I. Hong, ACS Nano **14**, 3251 (2020).
[8] G. Chen, A. Mascaraque, A. T. N'Diaye, and A. K. Schmid, Appl. Phys. Lett. **106**, 24 (2015).
[9] C. Bran, A. B. Butenko, N. S. Kiselev, U. Wolff, L. Schultz, O. Hellwig, U. K. Roessler, A. N. Bogdanov, and V. Neu, Phys. Rev. B **79**, 024430 (2009).
[10] L. Fallarino, A. Oelschlägel, J. A. Arregi, A. Bashkatov, F. Samad, B. Böhm, K. Chesnel, and O. Hellwig, Phys. Rev. B **99**, 024431 (2019).
[11] Z. Wang, M. Guo, H.-A. Zhou, L. Zhao, T. Xu, R. Tomasello, H. Bai, Y. Dong, S.-G. Je, W. Chao, H.-S. Han, S. Lee, K.-S. Lee, Y. Yao, W. Han, C. Song, H. Wu, M. Carpentieri, G. Finocchio, M.-Y. Im, S.-Z. Lin, and W. Jiang, Nat. Electron **3**, 672 (2020).
[12] W. J. Jiang, P. Upadhyaya, W. Zhang, G. Yu, M. B. Jungfleisch, F. Y. Fradin, J. E. Pearson, Y. Tserkovnyak, K. L. Wang, and O. Heinonen, Science **349**, 283 (2015).
[13] G. Yu, P. Upadhyaya, Q. Shao, H. Wu, G. Yin, X. Li, C. He, W. Jiang, X. Han, P. K. Amiri, and K. L. Wang, Nano Lett. **17**, 261 (2017).
[14] R. Tomasello, E. Martinez, R. Zivieri, L. Torres, M. Carpentieri, and G. Finocchio, Sci. Rep. **4**, 6784 (2014).
[15] K. M. Song, J.-S. Jeong, B. Pan, X. Zhang, J. Xia, S. K. Cha, T.-E. Park, K. S. Kim, S. Finizio, J. Raabe, J. Y. Chang, Y. Zhou, W. Zhao, W. Kang, H. Ju, and S. Woo, Nat. Electron. **3**, 148 (2020).
[16] C. Kittel, Phys. Rev. **70**, 965 (1946).
[17] O. Hellwiga, A. Bergera, J. B. Kortrightb, and E. E. Fullerton, J. Magn. Magn. **319**, 13 (2007).
[18] K. Chesnel, A. S. Westover, C. Richards, B. Newbold, M. Healey, L. Hindman, B. Dodson, K. Cardon, D. Montealegre, J. Metzner, T. Schneider, B. Böhm, F. Samad, L. Fallarino, and O. Hellwig, Phys. Rev. B **98**, 224404 (2018).
[19] T. W. Noh and D. W. Kim, Phys. Rev. Lett. **92**, 7 (2004).
[20] A. Singh, J. C.T Lee, K. E. Avila, Y. Chen, S. A. Montoya, E. E. Fullerton, P. Fischer, K. A. Dahmen, S. D. Kevan, M. K. Sanyal, and S. Roy, Nat. Commun. **10**, 1988 (2019).
[21] P. Ho, A. K. C. Tan, S. Goolaup, A. L. G. Oyarce, M. Raju, L. S. Huang, A. Soumyanarayanan, and C. Panagopoulos, Phys. Rev. Appl. **11**, 024064 (2019).

[22] S.-G. Je, M.-S. Jung, M.-Y. Im, and J.-I. Hong, Curr. Appl. Phys. **8**, 1201 (2018).

[23] M. Schott, A. Bernand-Mantel, L. Ranno, S. Pizzini, J. Vogel, H. B'ea, C. Baraduc, S. Auffret, G. Gaudin, and D. Givord, Nano Lett. **17**, 3006 (2017).

[24] Y. Nii, T. Nakajima, A. Kikkawa, Y. Yamasaki, K. Ohishi, J. Suzuki, Y. Taguchi, T. Arima, Y. Tokura, and Y. Iwasa, Nat. Commun. **6**, 8539 (2015).

[25] V. L. Mironov, B. A. Gribkov, S. N. Vdovichev, S. A. Gusev, A. A. Fraerman, O. L. Ermolaeva, A. B. Shubin, A. M. Alexeev, P. A. Zhdan, and C. Binns, J. Appl. Phys. **106**, 053911 (2009).

[26] S. Zhang, J. Zhang, Q. Zhang, C. Barton, V. Neu, Y. Zhao, Z. Hou, Y. Wen, C. Gong, O. Kazakova, W. Wang, Y. Peng, D. A. Garanin, E. M. Chudnovsky, and X. Zhang, Appl. Phys. Lett. **112**, 132405 (2018).