Magnetization Patterns of Permalloy Networks

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Abstract—Magnetization patterns in Permalloy network junctions are obtained by use of experiments and micromagnetic simulations. In the as-deposited thin film of the honeycomb network composed of three-arm junctions, only the lowest energy configuration, which possesses ± 1 reduced net magnetic pole density in the junction center, is observed. In the as-deposited thin film of the square network composed of four-arm junctions, the configuration with the lowest energy density is the most frequently observed experimentally. The pattern of the independently existent antivortex, which has higher energy density, is for the first time observed experimentally in the square network.

Index Terms—Antidot, antivortex, micromagnetic simulation, network junctions.

I. INTRODUCTION

THE next-generation ultrahigh-density storage media is attracting much attention now. Among various future storage media, network junctions, sometimes referred to as antidot arrays, have been suggested to be a possible candidate [1]. For a submicrometer-sized network, both the magnetostatic energy and exchange energy are important in determining the magnetization patterns. Its domain structure, anisotropy, and reversal dynamics are different from those of a continuous thin film [2]. Due to the shape anisotropy, the magnetization prefers to be parallel to the boundary in order to reduce the magnetostatic energy, so it is difficult to reverse the magnetization of each junction arm. Therefore, the magnetization patterns can be very stable in the centers of the junctions. Besides, network thin films are introduced to increase thermal stability and decrease noise during information accessing [3], and they can avoid the superparamagnetic limit [1], [4]. The magnetization structures of the network junctions are crucial in determining the magnetic properties both in reversal behaviors and magnetoresistance effects; however, they are still not thoroughly studied due to their complexity.

In this paper, we investigate numerically and experimentally the possible stable states existing in the honeycomb network made of three-arm junctions and square network made of

four-arm junctions. Our result shows that different magnetization states in the junctions can be classified by counting the net magnetic charges (magnetic pole densities) accumulated over there. This provides a promising possibility to use Permalloy network junctions as bit units in ultrahigh-density storage media.

II. EXPERIMENTAL METHOD

Permalloy networks are prepared for the magnetic force microscopy (MFM) imaging. The network films are fabricated using electron beam lithography through a lift-off process. The procedures are as follows: A SiN-coated Si wafer is spun-coated with the electron resist, polymethyl methacrylate (PMMA), and then baked in the oven at 140 °C for 8 h, resulting in a resist thickness of 200 nm. An electron beam lithography process is used to write the network patterns. In the next step the sample is immersed in a 1 : 3 mixture of methyl isobutyl ketone and 2-propanol, and trenches in the shape of network are created in PMMA. Permalloy ($\text{Ni}_{81}\text{Fe}_{19}$) is deposited in a thermal evaporation system, in which the thickness is monitored by a quartz crystal. The thin film is deposited without applied field and is kept at room temperature during evaporation. Finally, patterned thin films with network shape are obtained on the substrate using a lift-off process in acetone. A Digital Instruments Nanoscope IIIa MFM is used to study the domain structures of the patterned thin films. A cobalt-coated tip is used in the tapping-lift mode. The tip magnetization is kept in the upward direction along the tip vertical axis throughout the scanning.

III. NUMERICAL SIMULATION

We carried out the numerical simulations by means of the time integration of the Landau–Lifshitz–Gilbert (LLG) equation [5], [6]. Typical material parameters of Permalloy films used in our simulations are as follows: The saturation magnetization $M_s = 800 \text{ emu/cm}^3$, and the exchange constant $C = 2 \text{ Å} = 2 \times 10^{-6} \text{ erg/cm}$. The uniaxial anisotropy constant, $K_1 = 10^3 \text{ erg/cm}^3$ [7], is too small to make any significant contribution to the total energy. To assure the accuracy of our simulation result the lateral size for each meshed cell used in the simulation is set to be 7.5 nm, which is small enough compared with the exchange length [8] of the Permalloy material. When the largest magnetization angular variation between successive iterations is below the value 10^{-8} , the system is assumed to reach the equilibrium state in our simulation.

IV. RESULTS AND DISCUSSION

Fig. 1(a) shows the MFM image of the honeycomb network film in its as-deposited state. For each three-arm junction of the honeycomb network, only four possible configurations can

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Fig. 1. (a) is the MFM image of three-arm honeycomb network junctions obtained experimentally. The arms are $5\ \mu\text{m}$ in length and $1\ \mu\text{m}$ in width. The film thickness is $35\ \text{nm}$. (b) and (c) are the central part views of the spin configurations of three-arm junctions obtained numerically. The arms are $420\ \text{nm}$ in length, $75\ \text{nm}$ in width, and $30\ \text{nm}$ in thickness. The gray scale in (b) and (c) indicates the corresponding magnetic pole densities. The energy densities of (b) and (c) are $1.584 \times 10^5\ \text{erg/cm}^3$ and $2.716 \times 10^5\ \text{erg/cm}^3$, respectively.

exist, two of which are shown in Fig. 1(b) and (c). The arrows indicate the magnetization vectors of the numerical meshed cells, and the gray scale indicates the corresponding magnetic pole density distributions, which are derived from the negative divergence of the magnetization vectors in equilibrium states. The energy densities of Fig. 1(b) and (c) are $1.584 \times 10^5\ \text{erg/cm}^3$ and $2.716 \times 10^5\ \text{erg/cm}^3$, respectively. The reduced net magnetic pole density in the junction is -1 in Fig. 1(b), because the magnetization of one arm directs into the center of the junction, and the other two direct outwards. The reduced net magnetic pole density in the junction is -3 in Fig. 1(c) because the magnetizations of all arms direct outwards, so the energy density of this pattern is significantly increased. If we reverse each magnetization vector in Fig. 1(b) and (c), the same patterns can be obtained, only the polarities of the net magnetic pole densities in the junction centers being opposite. In our experimental results of as-deposited patterns, only the configuration of Fig. 1(b), which has the lowest energy density, is observed. The pattern of Fig. 1(c) is not present in the experiment because its energy density is too high.

Fig. 2(a) shows the MFM image of the square network film in its as-deposited state. For each four-arm junction of the square network, only six possible configurations can exist, four of which are shown in Fig. 2(b)–(e). The energy densities of Fig. 2(b)–(e) are $1.64 \times 10^5\ \text{erg/cm}^3$, $1.91 \times 10^5\ \text{erg/cm}^3$, $2.16 \times 10^5\ \text{erg/cm}^3$ and $3.52 \times 10^5\ \text{erg/cm}^3$, respectively. The reduced net magnetic pole density in the junction is 0 in Fig. 2(b) and (c), because the magnetizations of their two arms direct into the center of the junction, and the other two direct outwards.

The reduced net magnetic pole density in the junction is $+2$ in Fig. 2(d) because the magnetizations of its three arms direct into the center of the junction, and the other one directs outwards, so the energy density of this pattern is increased com-

Fig. 2. (a) is the MFM image of four-arm square network junctions obtained experimentally. The arms are $5\ \mu\text{m}$ in length and $1\ \mu\text{m}$ in width. The film thickness is $35\ \text{nm}$. (b) to (e) are the central part views of the spin configurations of four-arm junctions obtained numerically. The arms are $600\ \text{nm}$ in length, $75\ \text{nm}$ in width, and $30\ \text{nm}$ in thickness. The gray scale in (b) to (e) indicates the corresponding magnetic pole densities. The MFM image corresponding to (c) is indicated by dashed circle in (a). The energy densities of (b), (c), (d), and (e) are $1.64 \times 10^5\ \text{erg/cm}^3$, $1.91 \times 10^5\ \text{erg/cm}^3$, $2.16 \times 10^5\ \text{erg/cm}^3$, and $3.52 \times 10^5\ \text{erg/cm}^3$, respectively.

pared to the patterns of Fig. 2(b) and (c). The reduced net magnetic pole density in the junction is -4 in Fig. 2(e) because the magnetizations of all arms direct outwards, so the energy density of this pattern is increased even more. If we reverse each magnetization vector in Fig. 2(d) and (e), the same patterns can be obtained, only the polarities of the magnetic pole densities in the junction centers being opposite. Therefore, including the two configurations with zero reduced net magnetic pole densities, a total of six possible configurations can exist in the junction. In our experimental results of as-deposited patterns, the configuration of Fig. 2(b), which has the lowest energy density, is the most frequently observed experimentally as shown in Fig. 2(a). It is worth noting that the pattern with the configuration of Fig. 2(c) is for the first time observed experimentally in the square network, which is indicated by the dashed circle in Fig. 2(a). The configuration in the center of the junction in Fig. 2(c) is the so-called antivortex core, which was previously believed to exist, together with vortices, only in the cross-tie domain wall. It was thought not being able to exist independently. In the patterned thin film with very special shape, such antivortex core is also independently existent observed by Shigeto *et al.* [9]. The patterns of Fig. 2(d) and (e) are not present in the experiment because their energy densities are too high.

V. CONCLUSION

In this paper, magnetization patterns existing near the junctions of Permalloy network are obtained by means of experi-

ments and numerical simulations. In the as-deposited thin film of honeycomb network, only the configuration with the lowest energy density is observed; while in the square network thin film we observe two lower-energy configurations with zero net magnetic pole densities in the junction center. The configuration of the independently existent antivortex in a square network is for the first time observed experimentally. It requires further investigation for obtaining and controlling in the experiment all configurations with higher energy densities to apply them to the ultrahigh-density storage media.

REFERENCES

- [1] R. P. Cowburn, A. O. Adeyeye, and J. A. C. Bland, "Magnetic domain formation in lithographically defined antidot permalloy arrays," *Appl. Phys. Lett.*, vol. 70, pp. 2309–2311, 1997.
- [2] P. Vavassori, G. Gubbiotti, G. Zangari, C. T. Yu, H. Yin, H. Jiang, and G. J. Mankey, "Lattice symmetry and magnetization reversal in micron-size antidot arrays in permalloy film," *J. Appl. Phys.*, vol. 91, pp. 7992–7994, 2002.
- [3] J.-G. Zhu and H. Fang, "Micromagnetic study of network media," *IEEE Trans. Magn.*, vol. 34, no. 4, pp. 1609–1611, Jul. 1998.
- [4] L. Torres, L. Lopez-Diaz, and J. Iniguez, "Micromagnetic tailoring of periodic antidot permalloy arrays for high density storage," *Appl. Phys. Lett.*, vol. 73, pp. 3766–3768, 1998.
- [5] M. E. Schabes, "Micromagnetic theory of nonuniform magnetization processes in magnetic recording particles," *J. Magn. Magn. Mater.*, vol. 95, pp. 249–288, 1991.
- [6] N. A. Usov and S. E. Peschany, "Flower state micromagnetic structure in fine cylindrical particles," *J. Magn. Magn. Mater.*, vol. 130, pp. 275–287, 1994.
- [7] I. A. Campbell and A. Fert, *Ferromagnetic Materials*, E. P. Wohlfarth, Ed. Amsterdam, The Netherlands: North-Holland, 1980, vol. 2.
- [8] E. D. Boerner, H. N. Bertram, and H. Suhl, "Dynamic relaxation in thin films," *J. Appl. Phys.*, vol. 87, no. 9, pp. 5389–5391, 2000.
- [9] K. Shigeto, T. Okuno, K. Mibu, T. Shinjo, and T. Ono, "Magnetic force microscopy observation of antivortex core with perpendicular magnetization in patterned thin film of permalloy," *Appl. Phys. Lett.*, vol. 80, pp. 4190–4192, 2002.