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Transition between onion states and vortex states in exchange-coupled Ni–Fe/Mn–Ir asymmetric ring dots

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The transition between onion states and vortex states in exchange-coupled Ni–Fe/Mn–Ir asymmetric ring dots has been investigated. A direction of domain wall motion, during the transition from the single-domain state to the vortex state via the onion state, depends on a sweep direction of an external field. This dependence fixes the directions of vortical magnetizations in the vortex states. The derivative of the amount of the domain wall motion with respect to the external field depends on the sweep direction of external field, and thus the hysteresis loop becomes asymmetric. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2164435]

I. INTRODUCTION

Studies of mesoscopic ferromagnetic elements are important because of their technological application. Especially, mesoscopic ring dots[1–4] exhibit high potential for application of cells in magnetic random access memories (MRAMs), because their shape enables one to decrease stray fields.[5] The magnetic configurations of the mesoscopic ring dots are known as follows. At the saturation field, the ring dots have single-domain states. As the field is reduced, the magnetizations follow the circumferences of the rings, and the states are called onion states.[1] At around zero field, the magnetizations predominantly follow the circumferences, and this leads to vortex states. The vortex states have either clockwise or counterclockwise magnetizations. These two vortex states correspond to digital information for memory cell applications.

The vortex states are attained through domain wall motion from the onion states. Therefore, the directions of the domain wall motion dominate the directions of the vortical magnetizations.[1] However, because of the symmetric structure, the directions of the domain wall motion, that is, the directions of the vortical magnetizations, cannot be controlled by in-plane fields. Therefore, we proposed asymmetric ring structures with partially planed outer sides, and demonstrated that the directions of vortical magnetizations in the vortex states can be controlled by the in-plane fields.[2,3] This control enables us to establish magnetic free layers for the MRAMs.

On the other hand, magnetically pinned layers with fixed magnetizations in the circular directions are also required to construct the MRAMs. In this case, exchange couplings between ferromagnetic (FM) layers and antiferromagnetic (AFM) layers are available. However, investigations concerning the exchange-coupled FM/AFM ring dots have been rarely reported.[4,6–8] Moreover, there are few investigations[4] concerning pinned layers with the circular exchange couplings in FM/AFM ring dots. Therefore, we investigate the exchange-coupled FM/AFM asymmetric ring dots, and reveal the transition between the onion states and the vortex states.

II. EXPERIMENTAL PROCEDURES

Electron beam lithography, dc sputtering, and ion milling were used to fabricate Ta (3 nm)/$Ni_{80}Fe_{20}$ (15 nm)/$Mn_{72}Ir_{28}$ (10 nm)/$Ni_{80}Fe_{20}$ (3 nm)/Ta (5 nm) asymmetric ring dots with partially planed outer sides on Si(100) substrates with 1.5 μm thick thermally oxidized layers. SEM image and sizes of the asymmetric ring dots are inserted in Fig. 1. The dots were heat treated in the process mentioned elsewhere, in order to cause a clockwise exchange-bias field as shown in Fig. 1.

The magnetization processes were observed using longitudinal magneto-optical Kerr effect (MOKE) magnetometry. The magnetic configurations were observed using magnetic force microscopy (MFM) with CoPtCr commercial MFM tips. The external field was applied in the film plane along the planed part.

Micromagnetics simulation was performed using a Landau-Lifshitz-Gilbert micromagnetics simulator.[9] The parameters for typical Permalloy™ were used.[2–4] The ring sizes used for the simulation were the same as the experi-

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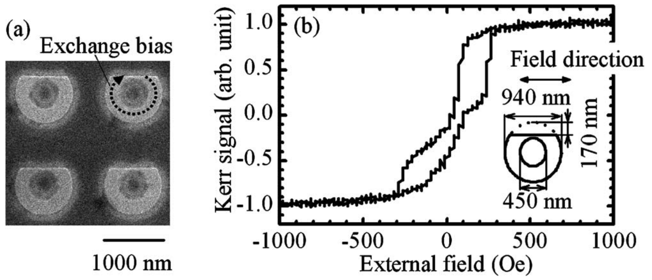

FIG. 1. (a) SEM image and (b) MOKE hysteresis loop of the Ta (3 nm)/$Ni_{80}Fe_{20}$ (15 nm)/$Mn_{72}Ir_{28}$ (10 nm)/$Ni_{80}Fe_{20}$ (3 nm)/Ta (5 nm) asymmetric ring dots. A dotted arrow on the SEM image shows the direction of the exchange bias field. The inset shows the ring sizes.

ment. The thickness of the FM layer was 15 nm. The exchange-bias field is thought to be an imaginary circular static field of 80 Oe, because the exchange-bias field of films with the same stacking structure was 80 Oe. The in-plane and perpendicular cell sizes were 10×10 nm^2 and 5 nm, respectively.

III. RESULTS AND DISCUSSION

Figure 2 shows a MOKE hysteresis loop of the asymmetric ring dots. The Kerr signal is saturated at the field around 1000 Oe. As the field is swept from 1000 to −1000 Oe, the signal gradually decreases at the fields from 1000 to 100 Oe. This gradual decrease indicates that the magnetic configurations change from the single-domain states to the onion states. At the external field around 100 Oe, the signal abruptly decreases and approaches zero. The signal near zero indicates that the magnetic configurations are in the vortex states. The signal gradually changes at the external fields from 0 to −250 Oe. In this region, the vortex states are maintained. At the external field around −250 Oe, the signal abruptly decreases again. This indicates that the magnetic configurations change from the vortex states to the onion states. The signal gradually decreases and the magnetic configurations of the asymmetric ring dots change from the onion states to the single-domain states from −300 to −1000 Oe.

When the field is swept from −1000 to 1000 Oe, the changes in the signal indicate that the magnetic configurations change in a similar manner as the case of field swept from 1000 to −1000 Oe. However, the derivative of the signal in the onion states just before the transition to the vortex states are different in both cases. This leads the asymmetric hysteresis loop, and the origin of asymmetric loop will be discussed later.

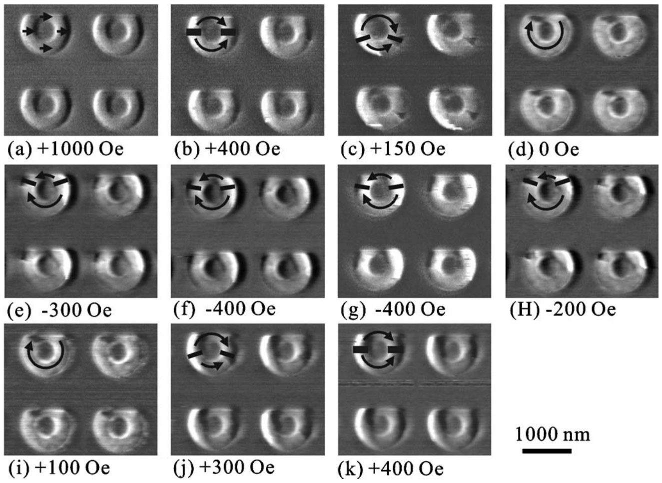

FIG. 2. MFM images of the asymmetric ring dots under the external fields. Images (a)-(f) are observed in the sweep from +1000 Oe to −400 Oe. Images (g)-(k) are observed in the sweep from −1000 to +400 Oe. Directions of the magnetizations and the domain wall positions are shown as arrows and lines, respectively.

The MFM observations were carried out to reveal the magnetization processes and the directions of the vortical magnetizations in the vortex states at around zero field. Figure 2(a)-(f) shows the MFM images for the field swept from 1000 to −400 Oe. The arrows indicate the directions of the magnetizations, and the lines indicate the positions of domain walls. At the external field of 1000 Oe, the ring dots have the single-domain states with the positive saturations [Fig. 2(a)]. At 400 Oe, the white and black spots located at the both sides of the ring dots become small [Fig. 2(b)]. This indicates that the ring dots have the onion states with two domain walls, in which the region with stray fields is localized. Further field-decrease to 150 Oe causes the domain wall motion toward to the lower parts of the ring dots [Fig. 2(c)]. The two domain walls meet and annihilate at the lower parts, and thus the magnetizations of the ring dots form the vortex states at zero field [Fig. 2(d)]. The figure also shows that the white spots are to the right of the black spots, and it indicates that the magnetization is clockwise. The field-decrease to −300 Oe causes the nucleation of reverse domains and domain walls [Fig. 2(e)]. Further field-decrease to −400 Oe causes the domain wall motion toward to the both sides, and thus the onion states are obtained [Fig. 2(f)].

On the contrary, Fig. 2(g)-(k) shows the MFM images for the field swept from −1000 to 400 Oe. At −1000 Oe, the ring dots have the negative single-domain states. At −400 Oe, the ring dots have the onion states [Fig. 2(g)]. Further field-increase to −200 Oe causes the domain wall motion toward to the upper parts [Fig. 2(h)]. The magnetizations of the ring dots form the vortex states at 100 Oe [Fig. 2(i)]. The magnetization of this vortex state is also clockwise, which is the same as that in the case of sweep from 1000 to −1000 Oe. The directions of vortical magnetizations are the same independent of the sweep direction of external field, because the directions of the domain wall motion are opposite to the case of the field swept from 1000 to −400 Oe that is shown in Fig. 2(a)-(f). The field-increase to 300 Oe causes the nucleation of reverse domains and domain walls [Fig. 2(j)], and further field-increase to 400 Oe causes the onion states [Fig. 2(k)].

As mentioned earlier, the domain walls in the onion states move to opposite direction in two cases. The derivative of the amount of domain wall motion with respect to the external field also differs at the region between the single-domain states and the onion states just before the transition to the vortex states. These differences are thought to be caused by the exchange coupling between the FM layers and the AFM layers. The asymmetry of the MOKE hysteresis loop, which is shown in Fig. 1, can be explained by these two differences.

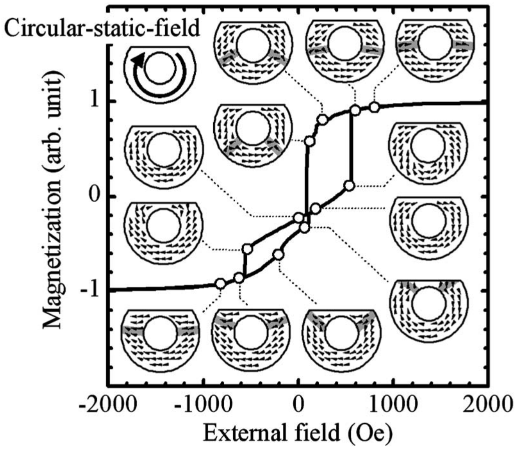

FIG. 3. Calculated hysteresis loop and magnetic configurations of the asymmetric ring dot with the same geometrical parameters as those of the experimental specimen. The circular static field of 80 Oe is applied in the circular clockwise direction, that is shown as an arrow.

The micromagnetics simulation is carried out to understand these two differences. The simulation is performed by the calculation of the Zeeman energy, the magnetostatic energy, the exchange energy in the FM layers, and the anisotropy energy due to the exchange coupling between the FM layers and AFM layers. The anisotropy energy is considered as the interaction between the magnetizations of the FM layers and the circular static field. Figure 3 shows a calculated hysteresis loop and magnetic configurations of the FM/AFM asymmetric ring dot. The hysteresis loop is asymmetric, and shows about the same feature as the Kerr hysteresis loop. As shown in Fig. 3, the direction of domain wall motion is also the same as the experimental results. Therefore, these two features can be understood considering the four energy terms. According to the calculation, the exchange energy in the FM layers is about 100 times as low as the Zeeman energy and the magnetostatic energy in the onion states and the vortex states. Thus, we neglect the exchange energy in this discussion.

Let us consider the origin which dominates the direction and the amount of the domain wall motion in the FM/AFM dots. Generally, the Zeeman energy and the magnetostatic energy dominate the magnetic states of symmetric ring dots without the AFM layers. In the symmetric ring dots, the magnetic states change from the single-domain states to the vortex states via the onion states in order to decrease the magnetostatic energy, as the field decreases from the saturation field.[1] In the asymmetric ring dots without the AFM layers, the domain walls move toward to the upper parts independent of the field sweep direction because of the asymmetric shape.[2] The planed parts cause the stray field, and thus the magnetostatic energy of the upper domains is higher than that of the lower domains. Hence, the domain walls move in order to decrease an volume of the upper domains.[2,3]

On the other hand, the magnetic states of the FM/AFM asymmetric ring dots are also affected by the anisotropy energy due to the exchange coupling. First, we consider the case of the sweep from the negative field to the positive field. To decrease the volume of the upper domains with high magnetostatic energy, the domain walls move toward to the upper parts. Moreover, the growth of domains with the clockwise magnetizations decreases the anisotropy energy due to the FM/AFM coupling. In other words, the domain walls move to decrease both the magnetostatic energy and the anisotropy energy. Therefore, the derivative of the amount of domain wall motion with respect to the external field becomes large, although the Zeeman energy slightly increases.

For the case of the sweep from the positive field to the negative field. The domain wall motion toward to the upper parts decreases the magnetostatic energy. However, as shown in Fig. 3, the domain walls move toward to the lower parts. This means that the contribution of the anisotropy energy is larger than that of the magnetostatic energy. In this case, because the domain wall motion decreases the anisotropy energy, but increases the magnetostatic energy and the Zeeman energy, the decrease in the total energy becomes small compared with the case of the sweep from the negative field to the positive field, and thus the derivative of the amount of domain wall motion with respect to the external field becomes small.

IV. CONCLUSIONS

We have investigated the transition between the onion states and the vortex states in the exchange-coupled Ni-Fe/Mn-Ir asymmetric ring dots. The direction of the domain wall motion, at the transition from the single-domain states to the vortex states via the onion states, depends on the sweep direction of external field. Thus, the directions of the vortical magnetizations in the vortex states are constant. The derivative of the amount of the domain wall motion with respect to the external field depends on the sweep direction of external field, and thus the hysteresis loop becomes asymmetric.

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