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Magnetoresistance of Magnetostatically Coupled Multilayered Rings

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1. Introduction

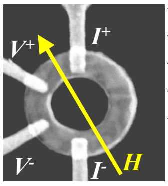
Thin film nanorings have attracted much attention because of their characteristic magnetic configurations, which are the flux-closure "vortex state" and the bi-domain "onion state" [1]. Since the magnetic moments are oriented circularly along the ring in the vortex state, it yields a minimal stray field and an internal degree of freedom of the chirality, which will provide potential applications in technologies such as the magnetic random access memory.

For such physical and technological interests, ring-shaped pseudo-spin valves (PSV) have been investigated using methods such as magneto-optical Kerr effect [2], giant magnetoresistance [3] and tunneling magnetoresistance [4]. In the PSV rings, magnetostatic coupling among ferromagnetic layers becomes a crucial problem.

In this study, we have fabricated a PSV ring and have investigated the magnetostatic interaction by using the current in-plane giant magnetoresistance (CIP-GMR) measurement. The CIP-GMR measurement is one of the candidate methods for investigating the magnetic properties in PSV rings, because relative angles of the magnetization direction between two ferromagnetic layers are detected. Furthermore, the chirality of the vortex state is detected when the alignment of the voltage probes are optimized [5]. We have confirmed the formation of vortex states and could distinguish vortex states between top and bottom rings from the detailed analysis of the magnetoresistance (MR) values. The magnetostatic interaction between top and bottom rings gives rise to the instability of the vortex states.

2. Experimental

The PSV ring structure was fabricated by electron beam lithography and lift-off process. The layer structure of the PSV ring consists of Co (20 nm)/Cu (10 nm)/Co (50 nm) from the top to the bottom. The different thickness of Co rings provides different coercive fields between top and bottom Co layers. The inner and outer radii of the PSV ring are 0.6 μm and 1.2 μm, respectively. We put four Au probes on top of the PSV ring to measure the GMR. An SEM image of the fabricated sample is shown in Fig. 1. The four probe voltage measurement was performed by a lock-in technique at room temperature. The direction of external magnetic field is applied in the plane and 30 degree tilted from the current probe direction as shown in Fig. 1. By using the above measurement configuration, we can assign different magnetic configurations.



Layer	Thickness
Co (Top)	20 nm
Cu	10 nm
Co (Bottom)	50 nm
Outer diameter : 1.2 μm	
Inner diameter : 0.6 μm	

Fig.1 An SEM image of a fabricated PSV ring. Four probes are put on the PSV ring to apply the current and to measure the voltage drop. An in-plane external magnetic field is applied along the direction of the arrow.

The MR data is shown in Fig. 2. Four distinctive voltage plateaus were observed. The lowest voltage value at high positive magnetic fields correspond to the onion states both in the top and the bottom layers, which are parallel to the external magnetic fields. By decreasing magnetic field down to H = 0 kOe, the voltage increased to a first small step of 7.517 mV, corresponding to the magnetization switch in the top layer from the onion state to the vortex state. Further decrease of magnetic field leads to the highest voltage value of 7.527 mV. This is due to the magnetization reversal in the top layer from the vortex state to the reversed-onion state, resulting in the anti-parallel onion states between the top and the bottom layers. After the antiparal-

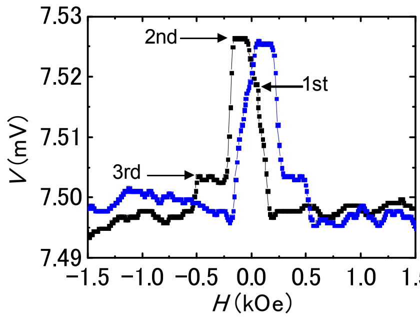


Fig. 2 Magneto-resistance of PSV ring structure. Four different voltage plateaus correspond to different magnetic configurations. The applied current is 1.0 mA.

lel onion state, a rapid decrease in the voltage appeared and we had the third voltage plateau at 7.503 mV. We can assign that this stable magnetic configuration results from the magnetization change in the bottom layer to the vortex state. Finally, we have the reversed-onion states both in the top and the bottom layers at higher negative magnetic fields, in which the voltage value is the same as the ones in the positive magnetic fields.

With the help of OOMMF numerical simulation [6], we have checked the validity of our assignment. Saturation magnetization M_S = 1.4x10^6 A/m, exchange stiffness constant A = 3.0x10^{-11} J/m, crystalline anisotropy constant K_1 = 5.2x10^5 J/m^3, damping constant α = 0.5, and cell size = 10 nm were used in the simulation. The calculated magnetization curves for single Co rings are relatively simple as shown by a curve with upward triangles for Co ring of 20 nm thickness and by a curve with downward triangles for Co ring of 50 nm thickness in Fig. 3, and they show clear transition between the onion and the vortex states.

The magnetization for Co /Cu /Co PSV ring is shown by a curve with solid squares. By decreasing magnetic field from high positive value, two steps of the magnetization curves are observed before crossing the zero magnetic field. The first (second) step at 0.14 kOe (0.06 kOe), indicated by A (B) in Fig.3, is transition from the onion(vortex) to the vortex(reversed onion) state in the top layer, whereas the corresponding transitions in the single-layer ring happen after crossing the zero magnetic field. The promotion of the magnetization transition of the top layer in the PSV ring suggests that the magnetostatic interaction leads to an anti-parallel magnetic state between the top and the bottom rings so that it becomes a flux closed state to decrease the magnetostatic energy. The magnetization processes described above show a good agreement with the magnetoresistance measurement, in which the two-step voltage increases toward the highest voltage observed around zero magnetic field. Further decrease of the magnetic field, transition from the onion to the vortex state is observed in the bottom ring, which is indicated by C. This magnetic configuration, which the bottom (top) layer is the vortex (reversed-onion) state, also agrees with the intermediate voltage level between -0.26 kOe and -0.49 kOe in Fig.2.

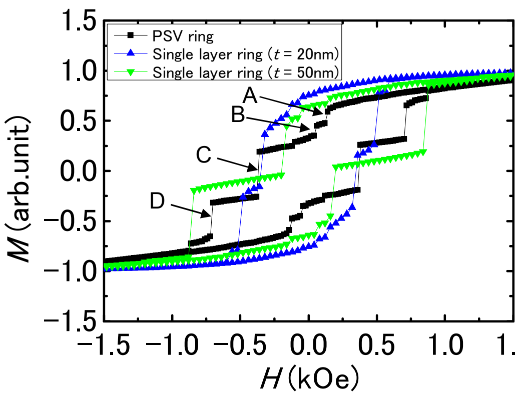


Fig. 3 Calculated magnetization curves for two single Co ring and Co/Cu/Co PSV ring structures.

Finally in a large negative magnetic field, the magnetization in the bottom layer changes, indicated by D in Fig.3, to the reversed onion state, which corresponds to the lowest voltage value in Fig.2.

In Fig.2, two intermediate plateaus of the voltage are observed. The one appears around zero magnetic field, in which the top (bottom) layer remains the vortex (onion) state. The other intermediate state is between -0.26 kOe and -0.49 kOe in which the top (bottom) layer is in the reversed-onion (vortex) state. These two plateaus show different voltage, which indicates that we can determine the chirality of the vortex state [5]. From Fig.2, the vortex chirality of the top and the bottom layers are both counter-clockwise. MR measurements were iteratively carried out. Although we have found from the experiments that the vortex state tends to become the identical chirality in the two layers, obvious relationship has not been seen between the magnetostatic interaction and the chirality of the vortex state from the numerical simulation. Thus, the deviation of the chirality likely results from defects of the ring edge, which act as pinning sites of domain walls.

3. Conclusions

We have studied the magnetization reversal process affected by magnetostatic interaction in the PSV ring structure by using the four-probe GMR measurement. We have observed four distinctive MR values, from which we have assigned magnetization configurations in each steps. Magnetostatic interaction has found to stabilize the anti-parallel onion states between the top and the bottom rings, which is the flux closure configuration to decrease the magnetostatic energy.

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