Magnetization process of a single magnetic ring detected by nonlocal spin valve measurement

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We investigate the magnetization process of a 200-nm-wide Permalloy ring using a nonlocal spin-valve measurement technique in a lateral geometry. The nonlocal spin signal is found to reveal the chirality of the flux closure state in the magnetic ring. The angular dependence of the magnetization process of the Permalloy ring are also studied. © 2007 American Institute of Physics. [DOI: 10.1063/1.2745311]

Domain structures in the patterned magnetic nanostructures are governed by the geometrically induced magnetostatic interactions. Recently unique artificial domain structures such as magnetic vortex \(^1\) and cross-tie wall structures \(^2\) can be stabilized in the nanoscale magnetic elements. Such patterned domain structures are useful for the application in the future spintronic devices as well as further understanding of the fundamental spin-related physics. For example, in a ferromagnetic ring with a diameter less than a few microns, the domain structures exhibit bistable states comprising the flux closure and onion states. \(^3\) The flux closure domain has a potentiality as a unit cell of high density magnetic storage because of no magnetostatic interaction. In the flux closure state, there are two degenerated domain states with different chiralities. Here the chirality means the rotational direction of magnetic moments whirling either clockwise (CW) or counterclockwise (CCW). Recently, the stabilities of onion and flux closure states and the transition between them have been investigated intensively by magneto-optic Kerr effect (MOKE), \(^3\) magnetic force microscopy, \(^4\) the magnetoresistance measurements, \(^7\) and magnetometry using two-dimensional electron gas systems. \(^8\) A chirality at the closure state in a magnetic ring is studied by a high-sensitive MOKE measurement with a focused laser beam. However, the dimension of the magnetic ring is limited by the size of the laser beam, which is at least 1 \(\mu m\) or more. Lorentz microscopy is also a powerful means for determining the chirality of the closure state. \(^9\) However, the complex experimental conditions such as membrane substrates and limited magnitude of the horizontal magnetic field restrict the experiment. Giant magnetoresistance measurements combined with an asymmetric current injection in magnetic multilayered ring reveal the chirality of the magnetic ring easily. \(^12\) However, the interlayer coupling between magnetic layers may affect the domain structure of the ring. Here, we propose a relatively simple way to detect the chirality of the closure state using lateral spin-valve geometry. \(^13\) \(^15\) The chirality is found to be easily determined from the nonlocal spin valve measurement, in which no charge current is needed in the magnetic ring.

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![FIG. 1. (Color online) (a) Scanning electron microscope image of the fabricated lateral spin valve consisting of a Py ring and a Py pad. (b) Schematic illustration of the probe configuration for the nonlocal spin valve measurement.](image-url)
However, from the MOKE result, we cannot determine the chirality of the closure state.

Here, we employ the nonlocal spin valve (NLSV) measurement with the probe configuration shown in Fig. 1(b). We use the pad and the ring as the injector and the detector, respectively. Therefore, during the measurement, there is no charge current in the Py ring. We note that the NLSV signal depends on the relative angle between the injecting and detecting spins. Here, the injecting and detecting spins are the magnetization directions of the Py pad under the injecting junction and that of the Py ring under the detecting junction, respectively. As shown in Fig. 3(a), the NLSV loop exhibits a clear spin-valve signal with an asymmetric change with respect to the magnetic field where high and low resistance states correspond to antiparallel (AP) and parallel (P) states, respectively. From the two terminal magnetoresistance measurement, the switching field of the Py pad is found to be 80 Oe. In the negative sweep, the AP state stabilizes in the very narrow field range from −70 to −80 Oe, while that in the positive sweep stabilizes in the wide field range from 80 to 320 Oe. Therefore, the signal change at −70 Oe in the negative sweep corresponds to the switching from the onion to the closure state of the magnetic ring. In the negative sweep, when the ring becomes the closure state, the spin signal becomes the high resistance AP state [Fig. 3(b) 2–3]. After the switching of the Py pad, the spin signal becomes the low resistance P state [Fig. 3(b) 3–4]. The spin signal does not show the abrupt change at the high transition field from the closure to the onion state [Fig. 3(b) 4]. These results mean that the chirality of the ring in the negative sweep is CW, as shown in Fig. 3(b). On the other hand, in the positive sweep, there is no change at 70 Oe of the transition field from the onion to the closure states [Fig. 3(b) 6]. Switching of the Py pad results in the high resistance of the AP state [Fig. 3(b) 7]. Then, the magnetic configuration becomes P state after the transition from the closure to the onion states [Fig. 3(b) 8]. Thus, we can evaluate the chirality of the closure state as CW also in the positive sweep. In this way, the chirality of the closure state in the magnetic ring can be easily determined. We have repeated the measurement ten times and obtained the same asymmetric change in the signal. This means that the chirality of the closure state in the ring is always the same CW during these measurements. On the other hand, as shown in Figs. 4(a)–4(c), several types of the NLSV loops have been observed at $\phi=10$ deg during ten times measurement. As shown in Fig. 4(a), most of the NLSV loops (seven sweeps in ten sweeps) are similar to that in Fig. 3(a). Therefore, the chirality of the closure state is mainly the CW. However, in two sweeps, the field dependence is completely reversed as shown in Fig. 4(c). This loop corresponds to the CW for the positive sweep and CCW for the negative sweep. Only in one sweep, the different type of the signal loop shown in Fig. 4(b) is observed. This means that the chirality of the closure state is CCW both in the positive and negative sweeps. We also measure the NLSV loops at $\phi=20$, 30, and 45 deg. As shown in Fig. 5(a), most of the shapes of the field dependence of the spin signals are...
similar to Fig. 4(a). This means that the chirality of the closure state is mainly CW at other angle \( \phi \). The shape similar to Fig. 4(c) is often observed as seen in Fig. 5(b) and that similar to Fig. 4(b) was not observed in other angle during the ten measurements. 

One of the possible reason for the CW chirality is an exchange anisotropy due to the surface oxidation of the Py ring. Because of the two-step lift-off processes, the surface of the Py layer may be oxidized by the heating process for baking the electron-beam resist. Of course, the oxidized layer underneath the Cu electrode is removed by Ar ion etching as described in the experimental procedure. However, the removed region is smaller than the half of the Py ring surface. Therefore, the oxidized layer still remain the surface of the Py ring. When the surface of the Py ring is oxidized, the antiferromagnetic layer is formed on the Py ring below the Néel temperature. In the present experiment, the sample was cooled from room temperature (RT) to 77 K in the absence of the magnetic field. Therefore, the domain structure for antiferromagnet should be imprinted by that for ferromagnet by the cooling from RT to 77 K. When the domain structure of the Py ring is the closure state with the CW chirality at RT, the exchange anisotropy induces the CW chirality. Of course the magnitude of the exchange bias is very small. However, since the two chiralities are degenerated domain states, the exchange bias easily breaks the symmetry of the two chiralities. Therefore, the large probability of the CW chirality may be induced by the surface oxidation of the Py ring.

We also found that in the negative sweep the probability of the CCW chirality increases with increasing the angle \( \phi \). In order to explain this, the stray field from the Py pad is considered. The onion state is known to be described by paired domain walls which have a positive and negative magnetic charges as schematically shown in Fig. 6. By considering the magnetostatic interaction between the magnetic charge from the Py pad and the magnetic monopoles in the Py ring, the Py ring favors the closure state with the CCW chirality in the negative sweep and the CW chirality in the positive sweep. In this way, the stray field can explain the CCW chirality in the negative sweep. The transition field is found to decrease with increasing the angle \( \phi \). As shown in Fig. 4, the transition field at \( \phi=45 \) deg is 130 Oe which is much smaller than that at \( \phi=0 \) deg. This also can be understood by the stray field from the Py pad which assists the magnetization reversal of the Py ring.

In conclusion, we fabricated a lateral spin valve consisting of a Py ring 1 \( \mu \)m in outer diameter and 600 nm in inner diameter and a Py pad 1 \( \mu \)m in width. The field dependence of the spin signal in the NLSV measurement yields not only the transition fields between the onion and the closure states but also the chirality. This method can be applied for studying the magnetic structure of the individual magnetic ring with submicron scale and other magnetic nanostructures. However, we have to consider the influence of the stray field from the injector when the magnetic field is not applied parallel to the edge of the injector.

17. In our lateral spin valve experiments, although the loop shift of the switching of the Py wire has been never observed at room temperature, it is often observed below 77 K. Therefore, the Néel temperature for the Py oxidized layer should be in the range from 77 K to RT.