

Current-induced vortex displacement and annihilation in a single permalloy disk

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(Received 6 April 2006; published 20 July 2006)

The induced motion of a magnetic vortex in a micron-sized ferromagnetic disk due to the dc current injection is studied by measuring planar Hall effect. We demonstrated that the vortex motion induced by the dc current injection has no threshold current and is proportional to the injecting current. The induced displacement deduced from the change in planar Hall resistance is quantitatively consistent with theoretical predictions. The dc current injection is also found to induce the spin torque that sweeps the vortex out of the disk at the critical current while bias magnetic fields are applied. Peak structures similar to those originated from spin wave excitations are observed in the differential planar Hall resistance curve.

DOI: [10.1103/PhysRevB.74.014424](https://doi.org/10.1103/PhysRevB.74.014424)

PACS number(s): 75.75+a, 75.70.Cn, 72.25.Ba, 72.25.Mk

Recently, controlling domain structures in the patterned magnetic structures by using electric currents has drawn much attention because of its potentiality for device application as well as novel spin-related physics.¹⁻³ Electric currents flowing in ferromagnets generate spin currents which transfer the transverse component of the spin angular momentum to the local magnetic moments while traveling through spatially varying magnetic structures such as domain walls.^{4,5} This spin torque, the magnitude of which is proportional to the spatial derivative of the magnetization ∇M ,^{6,7} drives a domain wall. For example, the magnetic force microscope observation revealed that both the transverse and vortexlike domain walls were driven by an application of high dc currents.¹ One of the important issues to be solved is to clarify experimentally how the vortexlike wall feels the spin torque. Since the magnetic vortex is a kind of a confined vortexlike wall, the vortex motion due to the spin torque can be expected. Moreover, a large spin torque will be exerted on a vortex core of the exchange length in the order of a few nanometers.⁸ Very recently, the vortex motion due to the spin torque has been investigated theoretically.⁹ They predict that the spin torque induces the force normal to the applied current expressed as $\mathbf{G} \times \mathbf{v}_s$, where \mathbf{G} and \mathbf{v}_s are, respectively, the gyrovector, defined as the product of the vortex polarity and vorticity and the drift velocity of the electron spins. The vortex displacement is expected proportional to the spin current density. The important difference from the current-induced domain wall in a magnetic wire is that there is no threshold current to induce the vortex displacement in a magnetic disk. So far, no experimental studies have been reported concerning the current-induced motion of the vortex core confined in a magnetic disk. Here we experimentally investigate the influence of the spin torque on the vortex core in the magnetic disk.

A permalloy (Py) disk 2 μm in diameter and 30 nm in thickness is fabricated by means of electron-beam lithography and lift-off techniques. The Py layer is evaporated by using an electron-beam gun at the base pressure of 10^{-10} Torr. In order to investigate the vortex displacement under dc current injection, four Cu probes 80 nm in thickness are con-

nected to the Py disk. The inset of Fig. 1 is a scanning-electron-microscope (SEM) image of a fabricated device. The resistivity of the Py layer is 14.6 $\mu\Omega\text{ cm}$ at room temperature.

We first study the magnetization process of a prepared Py disk by using high-sensitive micro-magneto-optical Kerr effect (MOKE) magnetometer laser beam of which diameter is less than 5 μm .¹⁰ Figure 1(a) shows a Kerr hysteresis loop for a single Py disk. The Kerr loop is obtained by averaging measurements 200 times. When the magnetic field is decreased from the saturated state, the Kerr signal gradually decreases, followed by an abrupt jump at the nucleation field H_n , where a single magnetic vortex is formed in the Py disk. In the remanent state, the vortex stays at the disk center. When the external magnetic field is applied, the vortex is shifted perpendicular to the magnetic field to increase the net magnetization along the field. At the annihilation field H_{an} , the vortex vanishes and the magnetization state turns out to be a single domain. Thus, the magnetization reversal of the disk takes place accompanied by nucleation and annihilation of the single vortex.¹¹ The magnetization reversal of the disk is also examined by measuring the planar Hall resistance (PHR) given by V_t/I with the probe configuration in the inset of Fig. 1(a), where V_t is the transverse voltage induced in between voltage probes. Note that the ac excitation current of 5 μA is small enough to disregard its influence on the domain structure.¹² To avoid the influence of inhomogeneous current flow in the vicinity of Cu probes, where the current distribution is disturbed, as shown in the inset of Fig. 1(b), the magnetic field is applied at an angle $\phi = \pi/4$ with respect to the average current direction for the PHR measurements. In this case, the vortex core moves along the diagonal direction $\phi = 3\pi/4$. Moreover, applying the magnetic field at $\phi = \pi/4$ produces a large PHR signal because of the angular variation given by $\sin 2\phi$, where ϕ is the angle between the magnetization and the current.¹³ As shown in Fig. 1(b), the PHR curve exhibits clear two abrupt changes, corresponding to the nucleation and annihilation. Thus, the PHR measurements yield detailed information on the single vortex motion in the magnetic disk.

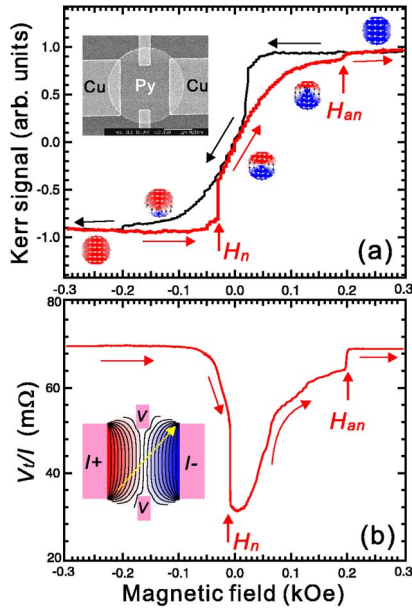


FIG. 1. (Color online) (a) Micro-MOKE hysteresis loop for a single Py disk measured at RT. The inset shows a Scanning-electron-microscope image of the fabricated Py disk. (b) Planar Hall resistance curve of the Py disk measured at RT. The inset shows the calculated spatial distribution of the electrical potential in the Py disk with the probe configuration for the PHE.

The vortex motion under the dc current injection is studied by measuring the differential PHR dV_t/dI with variable dc current in the range from -10 mA (-1.6×10^7 A/cm 2) to 10 mA (1.6×10^7 A/cm 2) superimposed on the AC exciting current. Here, the dc current is increased stepwise by 0.02 mA. Figure 2(a) shows dV_t/dI as a function of the dc current in the absence of bias magnetic fields. dV_t/dI varies parabolically with dc current, but is slightly asymmetric with respect to the current. The dc current dependence of dV_t/dI is found to be expressed by $a_2 I^2 + a_1 I + a_0$. Here, $a_2 = 2.90 \times 10^{-5}$ (Ω/A^2), $a_1 = -8.98 \times 10^{-5}$ (Ω/A) and $a_0 = 2.52 \times 10^{-2}$ (Ω). The parabolic dependence of dV_t/dI on the dc current is attributable to Joule heating.¹⁴ Maximum rise in temperature estimated from the resistance increase is 30 K, which does not affect the magnetization process.¹⁵ By considering the fact that the spin torque gives rise to the linear dependence of the vortex core displacement on the current I , the parabolic component is subtracted from the differential PHR curve to obtain a blue line in Fig. 2(a). This linear current dependence seems consistent with the theoretical prediction if the displacement is proportional to the magnitude of PHR. Now, we estimate the vortex displacement from the change in the PHR curve. In low magnetic fields, it is known that the vortex displacement is proportional to the applied external magnetic field.¹¹ The reversible linear change in the Kerr signal in the low magnetic fields in Fig. 1(a) corresponds to the vortex displacement. Therefore, the relation between the vortex displacement and the magnetic field is deduced from the slope of the Kerr magnetization curve. According to the theoretical study, the vortex moves perpendicular to the current.⁹ A similar vortex displacement is induced by applying the magnetic field along the average cur-

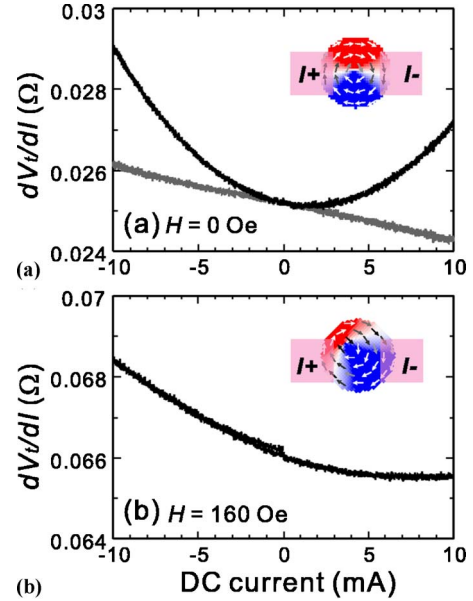


FIG. 2. (Color online) (a) Differential planar Hall resistance in the absence of the magnetic field as a function of the dc current (black line) and that except for the parabolic component (gray line). (b) Differential planar Hall resistance at the magnetic field of 160 Oe as a function of the dc current.

rent direction corresponding to $\phi = 0$. We also measure the PHR in the magnetic field at $\phi = 0$. Although the PHR does not show the simple change near the nucleation and annihilation fields because of the disturbance of the Cu probes, the PHR exhibits a linear variation in the low magnetic field corresponding to the reversible vortex displacement. Therefore, by comparing the Kerr loop and the PHR curve for $\phi = 0$ measured in low magnetic fields, we can estimate the vortex displacement as a function of the PHR. In this way, the vortex displacement due to the dc current injection is deduced from the change in PHR. The experimentally obtained relation is δ [nm] = 1.23×10^{-10} J[A/cm 2], where J is the density of the dc current. This is quantitatively good agreement with the relation δ [nm] = 0.76×10^{-10} J[A/cm 2], theoretically calculated in Ref. 9.

In the above discussion, we assumed that the linear dependence of the change in PHR is caused by the vortex displacement due to the spin torque with no direct experimental evidence of the vortex motion. To verify that the dc current moves the vortex core, we examine the current-induced vortex annihilation. As mentioned previously, the vortex displacement due to the dc current injection is expected about 10 nm nanometers even at the current of 10 mA. It thus seems difficult to annihilate the vortex only by the dc current injection without applying bias magnetic fields. Therefore, we measure the differential PHR under the dc current injection with applying a fixed bias magnetic field along $\phi = \pi/4$. Before sweeping the current, the magnetic field has been scanned from -1000 Oe to set a desired value. Figure 2(b) shows the differential PHR as a function of the dc current at a fixed magnetic field of 160 Oe. The differential PHR curve shows large asymmetry with respect to the dc current. This asymmetry is more pronounced with increasing

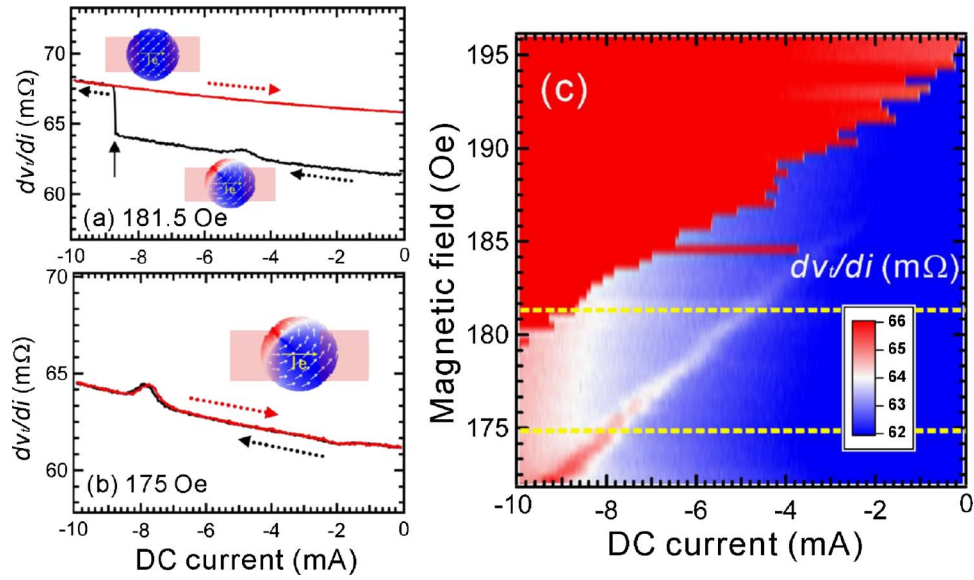


FIG. 3. (Color online) (a) Differential planar Hall resistance as a function of the dc current at the magnetic field of 181.5 Oe. (b) Differential planar Hall resistance as a function of the dc current at the magnetic field of 170 Oe. (c) Differential planar Hall resistance as a function of the dc current and the bias magnetic field in the range from 170 to 195 Oe. The dc current is swept from 0 to -10 mA.

the bias field. This can be understood as follows. The vortex core moves perpendicular to the magnetic field, toward the edge of the disk with the applied magnetic field. When the magnetic field is applied at $\phi = \pi/4$, the vortex core shifts along the diagonal direction corresponding to $\phi = 3\pi/4$. The numerical calculation of the current distribution inside the disk in Fig. 1(b) shows that the current near the edge flows in the azimuthal direction. Therefore, the direction of the vortex displacement due to the spin torque is the same as that due to the magnetic field near the annihilation field. According to the PHR curve for $\phi = \pi/4$ shown in Fig. 1(b), increasing or decreasing the PHR corresponds to the vortex displacement toward the edge or the center of the disk, respectively. Therefore, the negative current injection should induce the vortex annihilation when the positive magnetic field at $\phi = 45^\circ$ is

applied. The current induced vortex annihilation is observed in the magnetic field range from 180 Oe to 195 Oe. Figure 3(a) shows a typical differential PHR as a function of the dc current exhibiting the vortex annihilation. Once the vortex is swept out of the disk by the dc current injection, the vortex does not nucleate in the disk even if the dc current decreases. Figure 3(c) shows the differential PHR dependence on the dc current for various bias fields. The critical current I_{an} , where the vortex annihilates, decreases monotonically with increasing the bias field. This tendency is consistent with our expectation that the negative dc current exerts the torque which sweeps the vortex out of the disk.

As in Ref. 9, the direction of the vortex displacement due to the spin torque depends on the vortex polarity and chirality. We performed a similar current-induced vortex annihila-

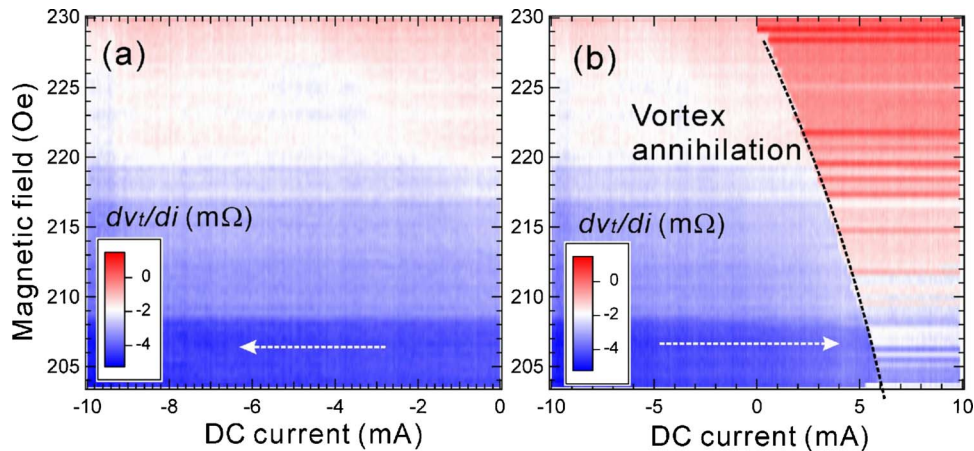


FIG. 4. (Color online) (a) Differential planar Hall resistance of a different magnetic disk with the same dimension as a function of the dc current for various bias magnetic fields in the range from 203 to 230 Oe. The differential PHR is measured with sweeping the dc current from 0 to -10 mA in a fixed applied magnetic field. (b) Differential planar Hall resistance as a function of the dc current for various the bias magnetic fields in the range from 203 to 230 Oe. The differential PHR is measured with sweeping the dc current from -10 to 10 mA in a fixed applied magnetic field.

tion experiment using a different sample with the same dimensions. For the current injection measurement, the dc current is swept from 0 to -10 mA, and then is swept back from -10 mA to 10 mA. The PHR for this sample is 280 m Ω larger than the previous one. This is due to small misalignment of the transverse voltage probes between which the longitudinal voltage drop is produced. Figure 4(a) and 4(b) show the differential PHR dependence on the dc current for various bias fields with the dc current swept from 0 to -10 mA and from -10 mA to 10 mA, respectively. To clarify the spin torque contribution, the parabolic component originated from Joule heating by the dc current and the background resistance due to the misalignment are subtracted from the raw data. As shown in Fig. 4(a), the negative current injection around the annihilation field does not induce the vortex annihilation. However, the positive current injection clearly annihilates the vortex as in Fig. 4(b). This result implies that, for this sample, the positive current is effective for the vortex annihilation, and supports that the vortex is annihilated by the spin torque. The difference in the polarity of the current from the previous sample can be understood by considering the chirality and polarity of the magnetic vortex. The chirality determines the vortex response to the in-plane magnetic field,¹⁶ whereas the polarity does the response to the current injection.⁹ The vortex chirality and polarity are determined by several uncontrollable experimental conditions. A misalignment of the external magnetic field generates the perpendicular component of the magnetic field which may align the vortex core at a certain direction.¹⁷ A slight asymmetry in the shape of magnetic disk affects the vortex chirality.¹⁶ There are two conceivable combinations to explain the present result. One is that the vortex has the same chirality as that in the previous sample with the opposite polarity. In this case, the direction of the vortex displacement induced by the spin torque is opposite to the previous experiment shown in Fig. 3 because of the opposite polarity, *i.e.*, *opposite gyrovector*. Therefore, the positive current sweeps the vortex out of the disk. The other is that the chirality of the vortex is opposite to the previous one but the vortex

polarity is the same. In this case also, the vortex shift due to the bias field is opposite direction to the previous case. The spin torque induced by the positive current thus effectively induces the vortex annihilation.

Finally, we discuss the peak structures observed in the PHR before the vortex annihilation in Fig. 3(a). The current I_p , where the peak structure appears, monotonically decreases with increasing the bias field as in Fig. 3(c). This tendency is similar to that of I_{an} , implying that the peak in the PHR is related to the magnetic domain structure. Similar current-induced resistance peaks have been observed in vertical structures consisting of a point contact between a single ferromagnetic layer and nonmagnetic probe¹⁸ and a nanopillar consisting of the magnetic multilayer¹⁹ which are explained as the spin-dependent scattering due to the spin-wave excitation. The peak structures in the PHR observed in the present experiment could be related to the spin-wave excitation. Two-types of translational and radial, of spin wave modes are known in a magnetic vortex system.^{20,21} The observed peak structures may correspond to such spin wave modes. However, in order to fully clarify the origin of the peak structures, the further study of microwave measurement is indispensable.

In conclusion, we study the response of the magnetic vortex under the dc current injection by measuring PHE. The dc current injection is found to induce the vortex displacement without any threshold current. The observed change in the PHE due to the dc current injection is consistent with the theoretical prediction that the vortex displacement is proportional to the current. The current-induced vortex annihilation is observed when a fixed bias magnetic field close to the annihilation field is applied. The peak structures similar to those observed in the vertical magnetic structures are observed in the differential PHR curve right before the current-induced vortex annihilation.

The authors would like to thank Y. Iye and S. Katsumoto for the use of microfabrication facilities and J. Shibata and Y. Nakatani for valuable discussions.

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