Spin-current induced vortex displacement and annihilation in micro-scale Permalloy disk

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Abstract

The influence of the DC current injection on the magnetic vortex is investigated by measuring planar Hall resistance. We experimentally demonstrate that the vortex motion and annihilation can be induced by the DC current injection. The obtained result is quantitatively consistent with the recent theoretical study.

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Manipulation of magnetizations and domain walls by using electric currents has drawn much attention because of its potentiality for device application as well as novel spin-related physics. Electric currents passing through ferromagnets induces the torque due to the exchange interaction between the conduction electron spin and the localized magnetic moment \[1,2\]. The magnitude of the spin torque is known to be proportional to the spatial derivative of the magnetization \(\nabla M \)[3]. Therefore, a large spin torque will be exerted on a vortex core of the exchange length in the order of a few nanometers. Recent theoretical study predicts that the spin torque induces the vortex displacement normal to the applied current\[4\]. The vortex displacement is expected proportional to the spin current density. Here, we experimentally investigate the influence of the spin torque on the vortex core in the magnetic disk.

A Permalloy (Py) disk 2\(\mu\)m in diameter and 30 nm in thickness shown in the inset of Fig. 1(a) is fabricated by means of electron-beam lithography and lift-off techniques. The magnetization curve of the Py disk measured by a high-sensitive micro magneto-optical Kerr effect magnetometer is of a typical vortex. The vortex motion under the DC current injection is studied by measuring the differential planar Hall resistance (PHR) \(dV/I/dI\) with variable DC current in the range from \(-10\) mA (\(-1.6 \times 10^7\) A/cm\(^2\)) to \(10\) mA (\(1.6 \times 10^7\) A/cm\(^2\)) superimposed on the AC exciting current. The external magnetic field is applied at an angle \(\phi = 45^\circ\) with respect to the average current direction for the optimal PHR measurements. As shown in Fig. 1(b), the PHR curve without the DC current injection exhibits clearly two abrupt changes, corresponding to the vortex nucleation and annihilation. This means that the PHR measurements yield detailed information on the single vortex motion in the magnetic disk.

First, we investigate the DC current injection in the absence of the external magnetic fields. As shown in Fig. 2(a), the differential PHR varies parabolically with the DC current, but is slightly asymmetric with respect to the current. This dependence is found to be expressed by \(a_2I^2 + a_1I + a_0\). Here, \(a_2 = 2.90 \times 10^{-3}\Omega/A^2\), \(a_1 = -8.98 \times 10^{-5}\Omega/A\) and \(a_0 = 2.52 \times 10^{-2}\Omega\). The parabolic dependence of the differential PHR on the DC current is attributable to Joule heating. To clarify the effect of the spin torque, the parabolic component is subtracted from the differential PHR curve as indicated by the blue line. This linear current dependence seems consistent with the theoretical prediction if the displacement is proportional to the magnitude of PHR. We

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estimate the vortex displacement from the change of the PHR by using the magnetization curve and the PHR curve shown in Fig. 1(b). The experimentally obtained relation is \( \delta \) (nm) \( = 1.23 \times 10^{-10}J \), where \( J \) is the density of the DC current. This is quantitatively in good agreement with the relation \( \delta \) (nm) \( = 0.76 \times 10^{-10}J \), theoretically calculated in Ref. [4].

We also study the effect of the DC current injection by applying a fixed bias magnetic field. Before sweeping the current, the magnetic field has been scanned from \(-1000\) Oe to set a desired value. According to the PHR curve for \( \phi = \pi/4 \) in Fig. 1(b), increase or decrease in the PHR corresponds to the vortex displacement toward the edge or the center of the disk, respectively. We note that the direction of the vortex displacement due to the spin torque is a diagonal direction around the annihilation field of the vortex because the current near the edge flows in the azimuthal direction. By considering the relation between the direction of the vortex displacement and the current polarity in Fig. 2(a), the negative current injection should induce the vortex annihilation when the positive magnetic field is applied at \( \phi = 45^\circ \). Fig. 2(b) shows a typical differential PHR as a function of the DC current at the bias field of 181.5 Oe. The abrupt resistance change is observed at \( I = -8.4\) mA. The magnitude of the abrupt change is the same as that of the field-induced vortex annihilation in Fig. 1(b). Therefore, the observed abrupt resistance change corresponds to the current-induced 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. We also confirmed that the positive DC current injection up to \( 10\) mA does not induce the vortex annihilation. Separately measured dependence of the critical current, where the vortex annihilates, on the bias field reveals that the critical current decreases monotonically with increasing the bias as we expect that the negative DC current exerts the torque on the vortex to sweep out of the disk. A peak structure is observed in the differential PHR around \( I = -4.5\) mA. This may be related to the spin–wave excitation since the similar current-induced resistance peaks have been observed in vertical structures. However, in order to fully clarify the origin of the peak structures, the further study is indispensable.

References