Detection of vortex-core dynamics using current-induced self-bistable rectifying effect

M Goto¹, H Hata¹, A Yamaguchi¹-², H Miyajima¹, Y Nakatani³, T Yamaoka⁴ and Y Nozaki¹, ⁵
¹Department of Physics, Keio University, 3-14-1 Hiyoshi, Yokohama, Kanagawa 223-8522, Japan
²PRESTO, JST, Honcho, 4-1-8, Kawaguchi, Saitama 332-0012, Japan
³University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan
⁴SII Nanotechnology Inc., RBM Tsukiji Bldg., Shintomi, Chuo, Tokyo 104-0041, Japan
⁵CRESTO, JST, 5, Sanbancho, Chiyoda-ku, Tokyo, 102-0075, Japan
E-mail to M.G.: mgoto@phys.keio.ac.jp
to A.Y.: yamaguch@phys.keio.ac.jp

Abstract. A magnetic vortex core confined in a micron-scale magnetic disk is resonantly excited by spin-polarized radio-frequency (rf) current and rf field. We show that rectifying voltage spectra caused by the vortex core resonance is dependent on the core polarity. Rectifying voltage spectra are given by the superposition of the polarity-dependent term and the polarity-independent term. The sign of the polarity-dependent rectifying voltage reverses when the sign of polarity P or external field H is reversed. This experimental result can be explained by the anisotropic magnetoresistance effect caused by the vortex core motion.

I. Introduction
The magnetic vortex state in micron-scale soft magnetic disk often exhibits a characteristic equilibrium configuration in which the magnetization curls within the plane of the disk around a singular point with out-of-plane magnetization [1, 2]. The vortex core is a small object, with a

\[ P = \pm 1, C = \pm 1 \]

Figure 1. Schematic diagram of magnetic vortices. Black arrows indicate the direction of magnetization. Four magnetic vortex states, polarity (up or down) and chirality (clockwise or counterclockwise), are shown. P and C denote polarity and chirality, respectively.
diameter of only ~10 nm in Fe\textsubscript{19}Ni\textsubscript{81} disk. In particular, when a vortex confined in the disk is driven out of equilibrium by either a magnetic field or a spin-polarized current, the vortex core gyrates around its equilibrium position.

A magnetic vortex is characterized by two Boolean parameters, the polarity and the chirality as shown in figure 1. The polarity is defined by the core magnetization direction pointing out of the plane of the vortex, either up or down \((P = \pm 1)\). The chirality is defined by the direction of rotation of the magnetization around the vortex core, either clockwise or counterclockwise \((C = \pm 1)\). These four states are degenerated; it is difficult to identify the vortex state \([3]\). Here, we present a detection of vortex core dynamics using current-induced rectifying effect.

**II. Experimental Setup**

Fe\textsubscript{19}Ni\textsubscript{81} disk with diameter of 3 \(\mu\)m and thickness of 30 nm were patterned directly onto a polished MgO substrate by means of electron-beam lithography and lift-off techniques. We had designed the circular disk with two tags on both sides; this shape enabled us to control the vortex polarity and chirality as shown in figures 2a and b. The polarity was controlled by the magnetic field of 5 kOe normal to the plane \([4]\), and the chirality was controlled by the in-plane saturation magnetic field along magnetization reversal process \([5]\). We controlled the polarity and chirality simultaneously to apply the oblique magnetic field from sample plane. We applied the magnetic field of 5 kOe to the

![Figure 2](image-url)

**Figure 2.** Schematic and MFM images of polarity- and chirality-controlled magnetic disks. a, polarity-control method for applying magnetic field of 5 kOe normal to the plane. b, chirality-control method for applying in-plane saturation magnetic field. Two tags of circular disk nucleate a chirality-controlled vortex core. c, The method for applying in-plane and out-of-plane magnetic field simultaneously. We apply the magnetic field of 5 kOe to the sample on the brazen oblique foundation, and the tilt angle \(\theta\) is 10°. d, MFM image of the designed disk with \((P, C) = (+1, +1)\).

![Figure 3](image-url)

**Figure 3.** Measurement circuit and optical microscope image of the Fe\textsubscript{19}Ni\textsubscript{81} disk in the absence of external magnetic field. The + direction of external magnetic field \(H\) is defined as shown in this figure.
sample on the brazen oblique foundation, with a tilt angle $\theta = 10^\circ$ as shown in figure 2c. In order to reveal the relation between the vortex state and rectifying spectra, the vortex state is confirmed by the direct magnetic force microscope (MFM) observation before measurement of the rectifying spectra. Figure 2d shows the MFM image of the circular disk with two tags. This direct observation enabled us to confirm the up polarity and clockwise circulation.

The coplanar waveguide structure made from Au (80 nm) / Cr (5 nm) was connected to the disk, and the center conductive strip line was placed on the disk as shown in figure 3 [6]. A sinusoidal continuous wave rf current with a power of -13 dBm was subsequently injected into the disk by a signal generator in the frequency range between 10 MHz and 200 MHz. A dc voltage along the rf current direction was measured via the bias-tee, which separates the dc and rf components of the current. The measurement circuit and an optical microscope image of the disk are shown in figure 3.

Figure 4 a, b. External field dependence of rectifying voltage spectra at $P=+1$ (red lines) and $P=-1$ (blue lines) c, polarity and external field dependence of rectifying voltage spectra. d, The polarity-dependent rectifying voltage $V_{P,dep}(P, C, H, \omega)$.
The external field parallel to the rf current was applied in the range of -50 Oe to 40 Oe. Here, the Hall electrode was not used. All measurements were performed at room temperature. The + direction of the external field is defined as shown in figure 3.

### III. Experimental Result

Figures 4a and b show the external field dependences of the rectifying voltage spectra at $P = +1$ and $P = -1$, respectively. The chirality was kept counterclockwise ($C = -1$) in this study. Above $H = +10$ Oe, the spectra for $P = +1$ are convex upwards, while the spectra for $P = -1$ are convex downwards. In contrast, below $H = -10$ Oe, the spectra for $P = +1$ are convex downwards, while the spectra for $P = -1$ are convex upwards. This result demonstrates that the sign of the rectifying voltage reverses when the sign of polarity $P$ or external field $H$ is reversed. These spectra at variable external field are in the same graph as shown in figure 4c to compare the dependence of rectifying voltage spectra on polarity. This figure in the vicinity of $H = 0$ Oe demonstrate that the polarity dependence of rectifying voltage is vanished, while the rectifying voltage is not vanished. These experimental results demonstrate that rectifying voltage is given by the superposition of polarity-dependent term and polarity-independent term. The experimental rectifying voltage spectra can be explained by the following equations,

1. $V(P, C, H, \omega) = V_{P\text{ dep}}(P, C, H, \omega) + V_{P\text{ indep}}(C, H, \omega)$
2. $V_{P\text{ dep}}(-P, C, H, \omega) = -V_{P\text{ dep}}(P, C, H, \omega)$
3. $V_{P\text{ dep}}(P, C, -H, \omega) = -V_{P\text{ dep}}(P, C, H, \omega)$

Here $V(P, C, H, \omega)$, $V_{P\text{ dep}}(P, C, H, \omega)$ and $V_{P\text{ indep}}(C, H, \omega)$ are total rectifying voltage, polarity-dependent and polarity-independent rectifying voltage, respectively. The rectifying voltage $V(P, C, H, \omega)$ is given by the superposition of polarity-dependent term $V_{P\text{ dep}}(P, C, H, \omega)$ and polarity-independent term $V_{P\text{ indep}}(C, H, \omega)$. $P$, $C$, $H$ and $\omega$ are polarity, chirality, external magnetic field and frequency of rf current, respectively. $V_{P\text{ dep}}(P, C, H, \omega)$ is derived from equation (1) and equation (2),

$$V_{P\text{ dep}}(P, C, H, \omega) = \frac{1}{2}\{V(P, C, H, \omega) - V(-P, C, H, \omega)\}$$  

The spectrum represented by equation (4) is shown in figure 4d.

### IV. Analysis

Our model is twofold; first we derive the trajectory of the vortex core position $r$ under the rf current density $J$, and second, we calculate the time dependence of the anisotropy magneto-resistance (AMR) based on the trajectory. The $(x, y, z)$ coordinate system is defined as schematically shown in figure 3. In general, the motion of a vortex core can be described by spin torque included Thiele equation [3, 7],

$$G(P) \times (\mathbf{u} - \mathbf{r}) = -\frac{\partial U}{\partial r} - \alpha \mathbf{D} \mathbf{r} + \beta \mathbf{D} \mathbf{u}$$

Here $G(P) = -P\frac{2\pi M_S}{\gamma} \mathbf{e}_z$ is the polarity dependent gyrovector. $L$ and $M_S$ are the thickness and saturation magnetization of the disk, respectively, and $\gamma$ is the gyromagnetic ratio. $\mathbf{u}$ is the spin torque interaction term of the current and the magnetization, which is given by $\mathbf{u} = \frac{\mu_B p J}{e M_S} \mathbf{e}_x$ and is proportional to the current density $J$, with Bohr magneton $\mu_B$, electron charge $e$ and spin polarization ratio $p$. $\alpha$ is the Gilbert damping, $\beta$ is the non-adiabatic contribution to the spin-transfer torque and $D$ is the diagonal element of damping tensor. $U$ denotes the sum of exchange energy, magnetostatic energy and Zeeman energy in magnetic disk. We approximate the parabolic potential...
well; \( U(r) = \frac{1}{2} \kappa (r - r_0)^2 \), where \( r_0 \) is the equilibrium position of the vortex core, and \( \kappa \) is the effective stiffness coefficients.

The resistance in magnetic disk depends on the position of vortex core arising from the AMR effect in Fe\(_{19}\)Ni\(_{81}\) [8]. The resistance decreases with moving the vortex core in the direction of the current (±x direction), and increases with moving the vortex core in the direction perpendicular to the current (±y direction), respectively. Then, we approximate the disk resistance near the center of the disk by the following equation,

\[
R = R_0 - a_x x^2 + a_y y^2
\]  
(6)

Here \( x \) and \( y \) are the vortex core position. Proportionality constant are defined \( a_x \) and \( a_y \). \( R_0 \) is the resistance for \( x=y=0 \) (the vortex core position is the center of the disk).

The solution of equation (5) can be written in the form,

\[
\begin{align*}
X(\omega) &= x_0 + \text{Re}\{X(\omega)\exp(i\omega t)\}, \\
y(\omega) &= y_0 + \text{Re}\{Y(\omega)\exp(i\omega t)\},
\end{align*}
\]  
(7)

where \( x_0 \) and \( y_0 \) are the equilibrium position of the vortex core. \( X(\omega) = X'(\omega) + iX''(\omega) \) and \( Y(\omega) = Y'(\omega) + iY''(\omega) \) are the complex oscillation amplitudes [3]. As can be seen from equation (7), the polarity \( P \) only exists in \( y \). This is because the direction of gyroforce \( G(P) \times \mathbf{u} \) in equation (5) depends on the polarity. Then, we substitute \( x \) and \( y \) into equation (6). As a result, the rectifying voltage \( V_{dc} \) is derived from resistance \( R \) in equation (6) and rf current \( I = I_0 \exp(i\omega t) \), where \( I_0 \) is the amplitude of current. Then, we obtain the rectifying voltage,

\[
V_{dc} = -a_x I_0 x_0 X'(\omega) + a_y I_0 y_0 Y'(\omega)
\]  
(8)

By considering the fact that \( y_0 \) is proportional to the external field when the vortex core position is near the center of the disk, the sign of the second term spectrum \( a_y I_0 y_0 Y'(\omega) \) in equation (8) reverses when the sign of polarity \( P \) or external field \( H \) is reversed. Therefore, the experimental rectifying voltage spectrum can be explained by the following equation,

\[
V_{P-0}(\omega) = a_y I_0 y_0 Y'(\omega)
\]  
(9)

The experimental result as shown in figure 4 can be explained on the basis of the equation (9). The details of the calculation have been given by supplementary information in reference [3].

V. Conclusion

We have demonstrated the dependence of rectifying voltage spectra excited by the rf current on vortex polarity in the micron-scale magnetic disk. These experimental spectra are good agreement with our analytical model. Our experimental result provides a way to detect the vortex core state by using current-induced rectifying effect.

[1] Wachowiak A, et al. 2002 Science vol 298, p 577
[2] Shinjo T, Okuno T, Hassdorf R, Shigeto K and Ono T 2000 Science vol 298, p 930
[3] Moriya R, Thomas L, Hayashi M, Bazaliy B Y, Pettner C and Parkin P S, 2008 Nature. vol 4, p 368
[4] Okuno T, Shigeto K, Ono T, Mibu K and Shinjo T, 2002 J. Magn. Magn. Mater vol 1, p 240
[5] Taniuchi T, Oshima M, Akinaga H and Ono K, 2005 J. Appl. Phys. vol 97, p 10J904
[6] Yamaguchi A, Motsi K, Miyajima H, Hirohata A, Yamaoka T, Uchiyama T and Utsumi Y, 2009 Appl. Phys. Lett. vol 95, p 122506
[7] Thiele A A, 1973 Phys. Rev. Lett. vol 30, p 230
[8] Kasai S, Nakatani Y, Kobayashi K, Kohno H and Ono T, 2006 Phys. Rev. Lett. vol 97, p 107204