Detection of Vortex Core Oscillation Using Second-Harmonic Voltage Detection Technique

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A sensitive and reliable detection method for magnetic vortex core dynamics at the remanent state has been demonstrated. Perfectly symmetric potential created in a circular-shaped disk produces twofold symmetry in the position dependence of the resistance of the ferromagnetic disk. We find that the detectable second-harmonic voltage can be induced by flowing the dc current when the circular-shaped core oscillation is excited by the microwave magnetic field. The consistent features have been observed in the current dependence and field dependence of the signals, indicating that the present method is a powerful technique to characterize the core dynamics, even at the remanent state.

Index Terms— **Anisotropic magnetoresistance (AMR) effect, RF magnetic field, second harmonic, vortex dynamics.**

I. Introduction

A MAGNETIC vortex stabilized in the micrometer-sized or submicrometer-sized ferromagnetic disk has been intensively studied, because it opens up the possibilities of advanced spintronic applications, such as high-density spintronic memory devices, vortex-based spin-torque oscillators, as well as logic operation devices [1]–[4]. The attention on magnetic vortices also arises from the numerous advantages, including negligible magnetostatic interaction, high thermal stability, and remarkably low-frequency dispersion at the resonant oscillation state [1], [5], [6]. Moreover, the static and dynamic characteristics of the magnetic vortex can be controlled by the geometrical confinement, such as the shape of the dot and the ratio between the thickness and the diameter [7]–[9]. However, further developments in the experimental characterization of the vortex characteristics, especially for the vortex dynamics, are indispensable for the further manipulation of magnetic vortices and the promotion of the practical application. So far, numerous methods for evaluating the dynamic properties of the magnetic vortex have been demonstrated [10]–[13]. In particular, electrical measurement techniques, such as homodyne detection and high-frequency impedance measurement, sensitively detect the vortex motion in small ferromagnetic disks. These electrical techniques are based on monolithic RF measurement scheme. However, this simplification strongly regulates the situation of vortex excitation and prevents the detailed study of the dynamic characteristic.

Recently, we have developed a novel detection method for vortex dynamics, in which the excitation and detection circuits are electrically separated [14]. This technique provides sensitive detection and the flexible experimental situations, leading to a detailed study of the dynamic response of the magnetic vortex. However, owing to its detection scheme, it is difficult to measure the core dynamics at the remanent state, which is the spatially symmetric domain structure. To improve this disadvantage in our evaluation method, in this paper, we develop a novel method based on the second-harmonic detection technique.

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II. Experimental Procedure

Fifty permalloy (Py) ferromagnetic circular disks were prepared on nondoped Si substrate using electron-beam lithography in combination with the conventional liftoff technique. The circular Py disks with a thickness of 40 nm and a diameter of 2 μm were deposited using electron-beam evaporation equipment under high vacuum. The center-to-center interval between the disks is 4 μm. The Py dots are connected by the Cu pads in order to make a series circuit of the chained disk. In addition, periodic Cu strip lines, which generate microwave magnetic field with high frequency, are formed on each Py disk. Here, the electrical connection between Py disks and Cu electrodes was insulated by the patterned SiO_2 film with the thickness of 100 nm.

Here, we explain the detection mechanism of vortex oscillation at the remanent state. Fig. 1(a) shows the schematic of the anisotropic magnetoresistance (AMR) measurement together with the scanning electron microscopy image of a part of the device. The resistance of the chain of the Py disks as a function of the core position is shown in Fig. 1(b). We obtained this plot by changing the magnitude and the direction of the magnetic field. Here, we assume that the vortex core linearly displaces perpendicularly to the direction of the external field when the applied magnetic field is sufficiently smaller than the annihilation field of the magnetic vortex [15], [16]. It is clearly seen that the resistance change shows the twofold symmetry. This indicates that when the vortex core has a

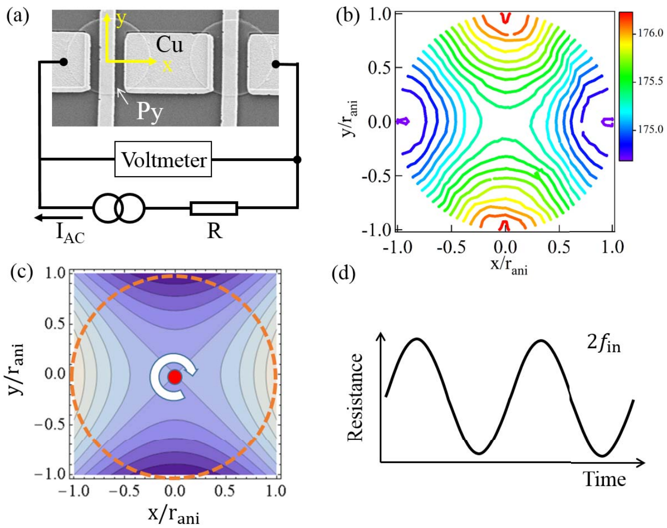

Fig. 1. (a) Scanning electron microscopy image of a part of the fabricated device together with the probe configuration for AMR measurement. (b) Resistance of the circular disks as a function of the vortex core position. (c) and (d) Schematic of the second-harmonic signal generation due to the circular core oscillation.

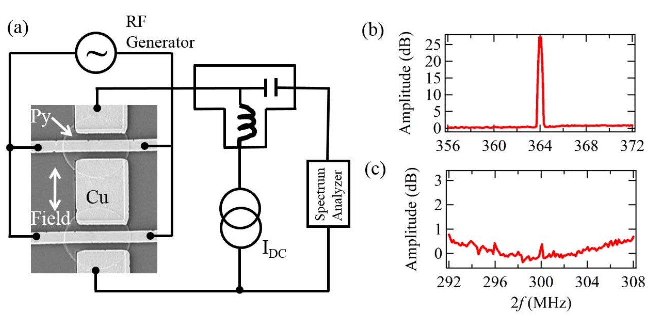

Fig. 2. (a) Circuit diagram used for the second-harmonic signal measurement together with the scanning electron microscopy image of a part of the fabricated device. (b) Representative voltage spectrum under the microwave magnetic field with the frequency of 182 MHz (ON-resonant state) and (c) that with the frequency of 150 MHz (OFF-resonant state).

circular trajectory with the frequency f, the second-harmonic resistance change is expected. Therefore, when the dc current flows in the disk, the second-harmonic voltage will be induced, as shown in Fig. 1(c) and (d). Using spectrum analyzer, we can detect the signal related to the vortex oscillation.

Fig. 2(a) shows the diagram of the measurement circuit. We flow the microwave current with the specific frequency f_{in} in the periodical Cu electrodes. This induces the voltage change with the frequency $2f_{in}$ under the dc current flow. In particular, when the vortex core is resonantly excited, the induced voltage with the frequency $2f_{in}$ becomes large. However, when f_{in} is far from the resonant frequency of the vortex core, the core oscillation becomes very small. Therefore, by changing the input microwave frequency f_{in} with monitoring the spectrum of the voltage, we can characterize the resonant motion of the magnetic vortex core.

III. Result and Discussion

First, to confirm the validity of the aforementioned detection scheme, we measured the spectrum of the voltage induced by the dc current under the microwave magnetic field. Fig. 2(b) and (c) show the voltage spectra for $f_{in} = 182$ MHz and $f_{in} = 150$ MHz, respectively. We confirmed that a clear voltage peak exists at $f = 364$ MHz corresponding to $2f_{in}$ in the spectra for $f_{in} = 182$ MHz. However, for $f_{in} = 150$ MHz, only a small peak at a level similar to the noise level is observed. This indicates that the resonant frequency of the vortex core is close to 182 MHz.

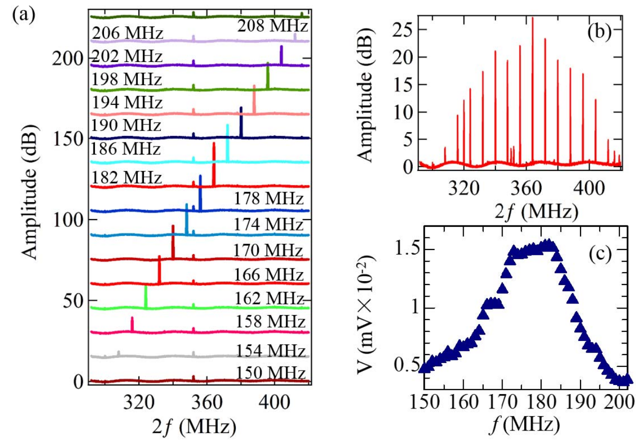

Fig. 3. (a) Voltage spectra for various input RF frequencies in the range of 150–208 MHz. Here, the spectrum was measured every 4 MHz, and each spectrum was vertically shifted to clarify. (b) Voltage spectra for various input RF frequencies signals without offset. (c) Frequency dependence of the dc voltage measured by the previously developed lock-in technique under a small in-plane magnetic field.

To evaluate the resonant property more clearly, we measure the spectra for various input RF frequencies around 180 MHz. Here, the spectra under the input RF frequency in the range of 150–208 MHz were measured every 4 MHz. As can be seen in Fig. 3(a), the spectra for various input frequencies show the resonant feature. From the results, the resonant frequency can be recognized as 182 MHz, where the signal becomes the maximum value. To verify the reliability of the present results, we confirmed the resonant properties of the magnetic vortex using our previously developed technique [14]. Here, to introduce the spatial asymmetry, we introduce a small in-plane magnetic field with the magnitude of 30 Oe, much smaller than the annihilation field of the magnetic vortex. Since the resonant frequency of the magnetic vortex confined in the circular disk is almost independent of the core position, the resonant property similar to the remanent state is expected. As can be seen in Fig. 3(c), we confirmed that the resonant frequency of the vortex is ~180 MHz, which is consistent with the results in Fig. 3(a) and (b).

We then investigate the dc current dependence of the induced voltage. Since the voltage is linearly proportional to the current, we expect a logarithmic dependence on the dc current in the signal. Fig. 4(a) shows the spectrum induced by the RF magnetic field with the frequency of 182 MHz for various dc current. The peak magnitude monotonically increases with increasing the dc current. Moreover, as can be seen in Fig. 4(b), its dependence clearly shows the logarithmic dependence.

Finally, we investigate the field dependence of the spectrum under the RF magnetic field with 182 MHz. As can be seen

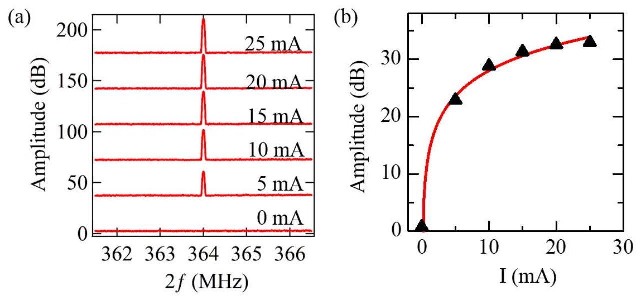

Fig. 4. (a) Voltage spectra under the microwave magnetic field with the frequency of 182 MHz for various dc current in the absence of the magnetic field. (b) Current dependence of the amplitude of the resonant peak of the second-harmonic signal. Solid line: logarithmic curve fitted to the experimental data.

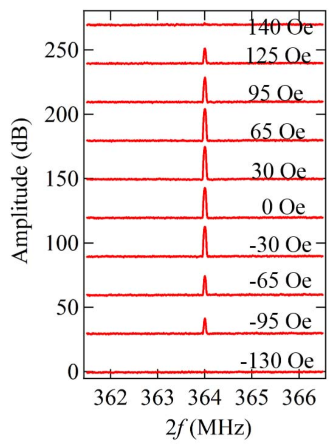

Fig. 5. Voltage spectra under the microwave magnetic field with the frequency of 182 MHz for various static in-plane magnetic fields.

in Fig. 5, the signal does not show a significant change less than 65 Oe both for the positive and the negative magnetic fields. However, above 90 Oe, the peak amplitude starts to decrease and finally disappears. This is because the core potential deviated from the ideal parabolic shape when the magnetic field is close to the annihilation [7], [17]. When the magnetic field exceeds 120 Oe, the vortex core annihilates, resulting in the perfect elimination of the twofold symmetry in the resistance.

IV. CONCLUSION

To investigate the magnetic vortex core dynamics at the remanent state, we have developed a novel method based on the electrically separated excitation and detection circuits with the spectrum analyzer. The signature of the vortex core resonance is well detected as the second-harmonic signal induced by the twofold symmetric resistance change. The current and field dependence of the second-harmonic signal show the features consistent with the previously reported results. This technique may be extended to the higher order frequency generator voltage, faster than the intrinsic precession frequency.

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