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Directional dependence of vortex core resonance in a square-shaped ferromagnetic dot

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HIGHLIGHTS

- The dynamic property of a magnetic vortex confined in a square ferromagnetic dot has been investigated.
- The field dependence of the resonant property strongly depends on the direction of the magnetic field.
- The resonant frequency is strongly modified by the magnetic field along the diagonal direction of the square.

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ABSTRACT

The resonant property of the magnetic vortex confined in a square-shaped ferromagnetic dot has been investigated. We showed that the field dependence of the resonant frequency has a unique directional dependence originating from a four-fold rotational symmetry of the square. The resonant frequency is found to be strongly modulated by the magnetic field along the diagonal direction although the magnetic field applied along the side of the square hardly modified the resonant frequency. The modulation ratio of the resonant frequency defined by the ratio between minimum and maximum frequencies for the vortex resonance was found to be tuned by the lateral dimension of the square. These unique frequency tunabilities controlled by the magnitude and the direction of the magnetic field may provide additional functions in the application of the magnetic vortex systems.

1. Introduction

A magnetic vortex is a unique spin configuration in a micron or submicron-sized ferromagnetic dot and shows numerous intriguing and attractive properties both from the fundamental and technological view points. Robust thermal stability and low frequency dispersion are the representative advantages of the magnetic vortex [1–5]. Therefore, the magnetic vortex structures are considered as the promising structures of the unit cell for the spin-based electronic devices such as magnetic random access memory and spin–torque oscillators [2–5]. In addition to these attractive properties, it is another important advantage that the statical and dynamical characteristics of the magnetic vortex can be adjusted by the dot dimension and/or the configuration of the dot array. Moreover, the biological applications such as cancer detector and virus sensors have been demonstrated because of the nonresidual magnetic moment at the remanent state with high magnetic susceptibility [1,4,6]. Thus, the varieties of the application possibilities are expected by using the magnetic vortex systems.

The dynamic property of the magnetic vortex core can be described by Thiele's equation, where the trajectory of the vortex core exhibits a rotational motion around its equilibrium position about sub-gigahertz range [7–11]. The gyration motion of vortex core offers abundant fundamental behaviors because the motion equation of the core is mathematically equivalent situation for the mass point confined in the parabolic potential. However, Thiele's equation is valid only in the motion without changing the structures of the magnetic vortex such as the confined potential and the core size. Therefore, the experimental characterization of the core motion including the non-linear regime may deepen the understanding towards the basic property of vortex core and pave the way for improving the performance of the spin-based nanoelectronic devices using a magnetic vortex [10–13].

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Although most of the studies on the magnetic vortex have been carried out by employing simple circular ferromagnetic disk [14–17], several unique features have been reported in the magnetic vortex confined in other shapes. For example, in a ferromagnetic dot with a regular triangle shape, the chirality of the vortex core can be well controlled and its resonant frequency is strongly modified by adjusting the core position [18]. In a elliptical ferromagnetic disk, an anisotropic field dependence of the core resonant frequency has been reported [19,20]. Thus, the resonant properties of the magnetic vortex can be flexibly modified by tuning the geometrical shape as well as their dimension [21,22]. These facts imply that excellent novel properties are anticipated by exploring the magnetic vortex confined in a specific-shaped ferromagnetic dot. For seeking new functionalities of magnetic vortex, in the present study, we investigate the core dynamics of the magnetic vortex confined in a square-shaped ferromagnetic dot.

2. Method

We fabricated a chain of the square ferromagnetic dots on a non-doped Si substrate by the conventional lift-off technique. Here, the 40-nm-thick ferromagnetic Permalloy (Py) film was evaporated by electron-beam evaporation under the pressure of 2×10^{-7} Pa. About the lateral dimensions of the square dots, we prepared three kinds of samples with different lateral dimensions. Here, the diagonal distance of the square l varied from 1 μm to 3 μm while the thickness of Py dots in all samples is 40 nm. We note that the diagonal distance corresponds to the diameter of the circumscribed circle for the square dot. We confirm that the domain structures at the remanent state for the square dots perfectly form magnetic vortex structure even for the square dot with $l=3$ μm by using magnetic force microscopy (MFM) (model NanoNavi/E-sweep, SII NanoTechnology) with low moment magnetic probes. The chirality distribution was random because the nucleation energy for both chiralities is degenerate [23]. The dynamic properties of the vortex core confined in the square dot have been evaluated by the reflection impedance (S_{11}) measurement using a standard vector network analyzer [12,18]. As shown in Fig. 1(c), a single Cu strip line with 500 nm in width and 200 nm in thickness was deposited on the top of the ferromagnetic dots. We note that the narrow strip line enables us to detect the resonant oscillation of the magnetization sensitively [18]. The in-plane static magnetic field at an angle ϕ with respect to the strip line was applied to adjust the equilibrium position of the vortex core. Here, we study the field dependence of the resonant property at $\phi=0$, $\pi/4$ and $\pi/2$.

3. Results and discussion

Fig. 2(a) shows S_{11} signals as a function of the input RF frequency at the remanent state for the three different samples. In all of the samples, the resonant signature was clearly observed as a peak of the signal. The resonant frequencies for the samples with $l=1$ μm, 2 μm and 3 μm are 405 MHz, 210 MHz and 145 MHz, respectively. These monotonic changes with the lateral dimension come from the change of the magneto-static energy and are consistent with the conventional understandings [21]. In Fig. 2(b), we compare the resonant frequency at the remanent state for the various shapes of the ferromagnetic dots [18,24]. Here, the horizontal axis corresponds to the diameter of the circumscribed circle. The square dot was found to have intermediate values between the circle and the triangle. This indicates that the confined potential for the vortex core is related to the size of the ferromagnetic dot. So, the magnetic vortex confined in the triangular dot feels the largest restoring force because the average distance from the edges is shortest.

We then study the field dependence of the resonant property of the magnetic vortex in the square dot as well as its anisotropy. In the triangular ferromagnetic dot, when the vortex core approaches to the vertex of the triangle, the resonant frequency increases because of the enhancement of the confined potential [18]. A similar modulation is also expected in the square-shaped ferromagnetic dot by moving the core around the corner of the square because the vortex structures confined in the corners for the square and triangle are resemble each other, as shown in Fig. 3(a). Moreover, as shown in Fig. 3 (b), when the core moves toward the side of square, the vortex behaves similar to the triangular dot. Therefore, we expect an insensitive change of the resonant frequency by the application of the magnetic field along the side. First we apply the magnetic field perpendicular to the Cu strip ($\phi=\pi/2$), which is a diagonal direction for the square. In this case, the equilibrium core position shifts along the Cu strip. As can be seen in Figs. 4(a) and 4(b), the resonant frequency increases with increasing the magnitude of the magnetic field for both polarities. This feature is consistent with our expectation that the confined potential is enhanced when the core moves toward the corner. On the other hand, as shown in Figs. 4(c) and 4(d), when the magnetic field is applied along the side of the square ($\phi=\pi/4$), the change of the resonant property is negligibly small. This in-sensitive behavior is also consistent with the above scenario that the effective confined potential for the vortex core is not modified when the core moves toward the side of the ferromagnetic dot [18]. Thus, in the square-shaped ferromagnetic dot, the field dependence of the resonant frequency strongly depends on the direction of the

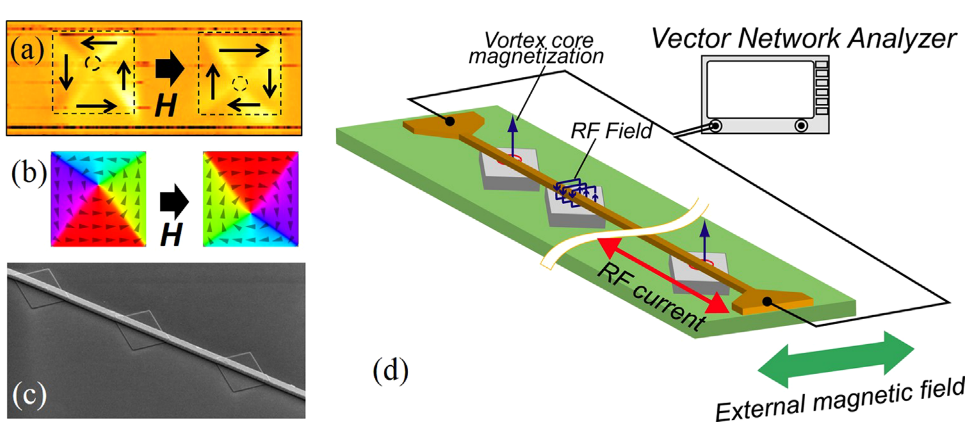

Fig. 1. (a) Spatial distribution of the spin structure in the squared Permalloy dot observed by magnetic-force microscope; (b) numerically simulated vortex structures stabilized in squared dot under the external field parallel to the edge; (c) SEM image of part of the fabricated device; (d) schematic illustration of the sample structure together with the SEM image of the fabricated sample.

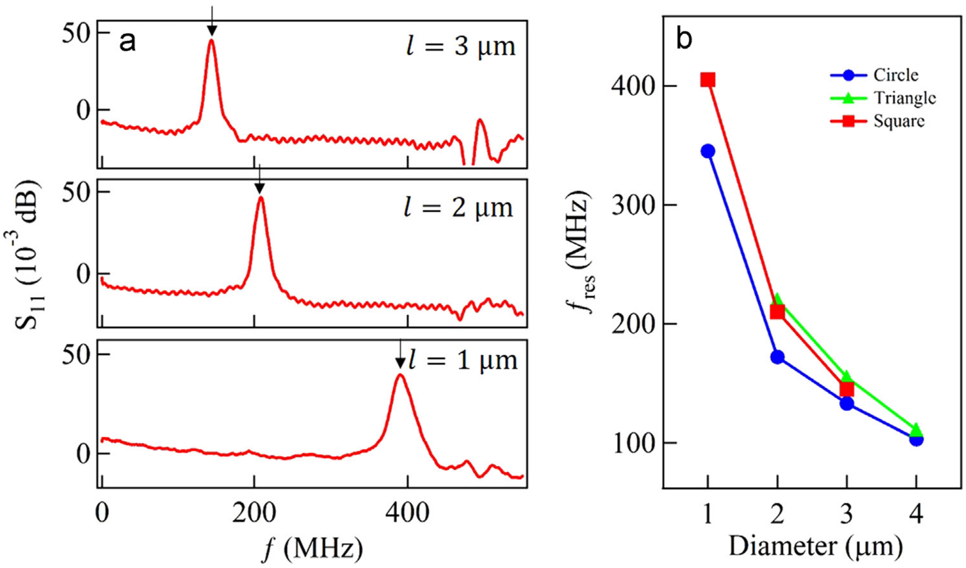

Fig. 2. (a) S_{11} spectra as a function of the input RF frequency for the square-shaped ferromagnetic dot with the diagonal distance $l=1$ μm, 2 μm and 3 μm, at the remanent state; (b) comparison of the resonant frequency of the magnetic vortex confined in circular, square and triangular ferromagnetic dot as a function the diameter of the circumscribed circle.

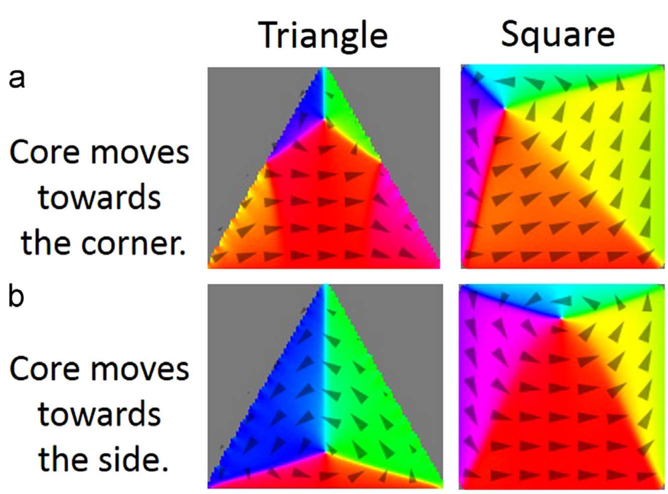

Fig. 3. Magnetic vortex structures (a) trapped in the corner of the triangle and square and (b) trapped around the side edges.

magnetic field. We want to emphasize that the directional modulation of the resonant property in the square dot is larger than the triangular dot. If we focus on the resonant frequency at $H=200$ Oe in Fig. 4, the resonant frequency at $\phi=\pi/2$ is approximately 300 MHz, which is almost twice of that at $\phi=\pi/4$. Thus, a large modulation of the resonant frequency has been obtained by $\pi/4$ rotation of the magnetic field. These unique properties of the vortex confined in the square dot are useful for detecting not only the magnitude of the vortex but also the direction of the magnetic field.

We then study the field dependence of the resonant property of the magnetic vortex in the square dot as well as its anisotropy. First we apply the magnetic field perpendicular to the Cu strip ($\phi=\pi/2$), which is a diagonal direction for the square. In this case, the equilibrium core position shifts along the Cu strip. As can be seen in Fig. 4(a), the resonant frequency increases with increasing the magnitude of the magnetic field for both polarities. We note that a similar modulation feature has been observed in a magnetic vortex confined in the regular triangle. In the triangular ferromagnetic dot, when the vortex core approaches to the vertex of the triangle, the resonant frequency increases because of the enhancement of the confined potential [18]. Since the similar situation is also expected in the square-shaped ferromagnetic dot by moving the core around the corner of the square, the modulation of the resonant frequency observed in Fig. 4(a) is caused by the enhancement of the confined potential. On the other hand, as shown in Fig. 4(b), when the magnetic field is applied along the side of the square ($\phi=\pi/4$), the change of the resonant property is negligibly small. We also want to emphasize that the similar in-sensitive behavior was obtained in the triangular dot when the core moves toward the side of the triangle [18]. This is exactly the same situation in the case of Fig. 3(b). Therefore, the effective confined potential for the vortex core is not modified when the core moves towards the side of the ferromagnetic dot. Thus, in the square-shaped ferromagnetic dot, the field dependence of the resonant frequency strongly depends on the direction of the magnetic field.

As mentioned above, in the square dot, the resonant frequency is significantly modulated by the application of the magnetic field along the diagonal direction. Here, we discuss about the size dependence of the modulation ratio of the resonant frequency. Fig. 5 (a) shows the image plot of S_{11} spectra as a function of the magnetic field along the diagonal direction ($\phi=\pi/2$) for the samples with $l=1$ μm, 2 μm and 3 μm. In all of the samples, the resonant frequency increases with increasing the magnitude of the magnetic field. We now focus on the modulation ratio η defined by the maximum resonant frequency divided by the resonant frequency at $H=0$. Fig. 5(b) shows the modulation ratio η as a function of the diagonal distance l. It can be clearly seen that η monotonically increases with increasing the size of the square. We want to emphasize that the difference in the maximum resonant frequency is smaller than the difference in the minimum resonant frequency, which corresponds to the resonance at the remanent state. This means that the confined potential for the magnetic vortex does not depend on the lateral dimension so much when the core is located in the vicinity of the corner. This can be understood by the fact that one square is perfectly fit at the corner of the other square.

Finally, we point out the importance of the relationship between the device configuration and the direction of the core displacement. Fig. 6(a) and (b) shows the image plots for the field dependence of S_{11} spectra for the square with the diameter of

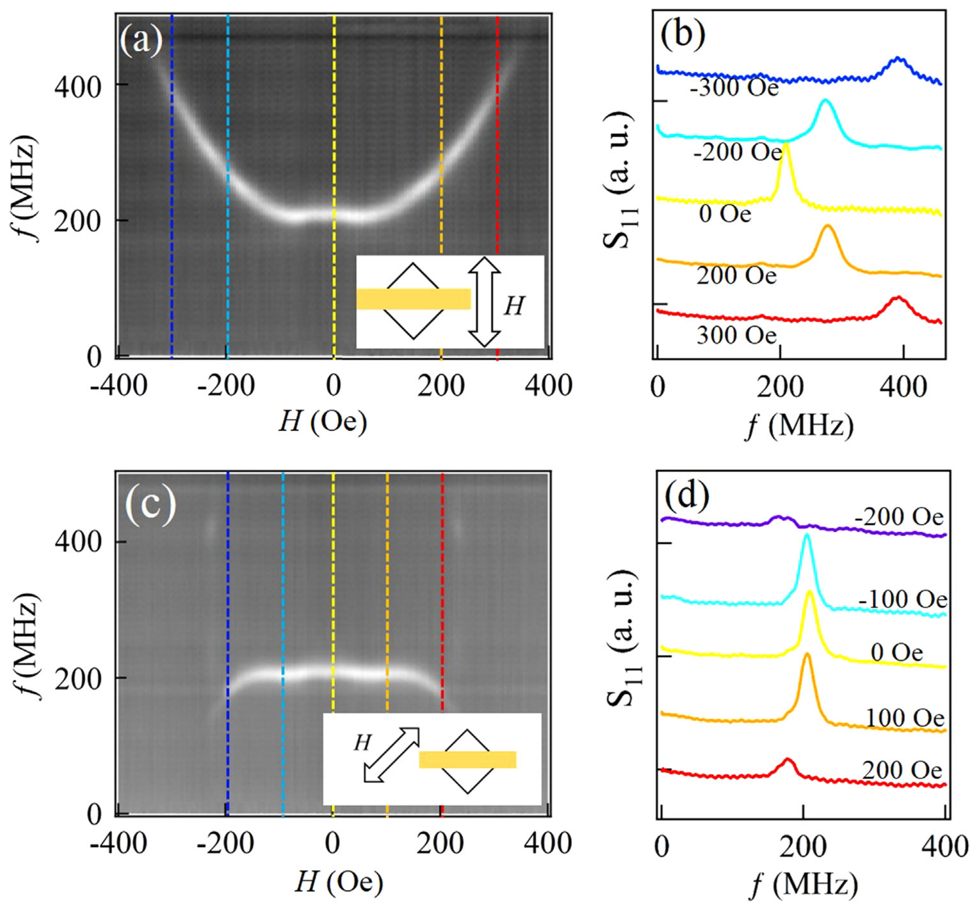

Fig. 4. (a) Image plot of S_{11} signal spectra as a function of external magnetic field perpendicular to the strip line ($\phi = \pi/2$) and (b) the representative spectra observed at several magnetic fields; (c) image plot of S_{11} signal spectra as a function of external magnetic field along the side of the square ($\phi = \pi/4$) and (d) the representative spectra observed at several magnetic fields.

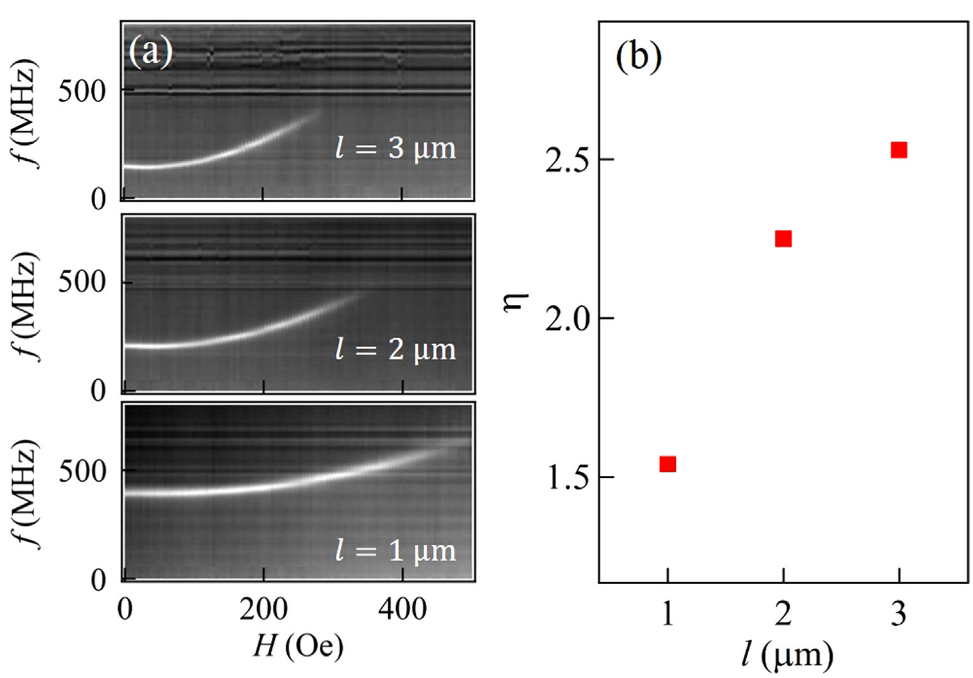

Fig. 5. (a) Image plot of S_{11} spectra for the square dot with $l = 3$ μm as a function of the external magnetic field along the diagonal direction ($\phi = \pi/2$); (b) the modulation ratio η as a function of the diameter distance, where the modulation ratio is defined as the ratio of maximum resonant frequency to the resonant frequency at remanent state.

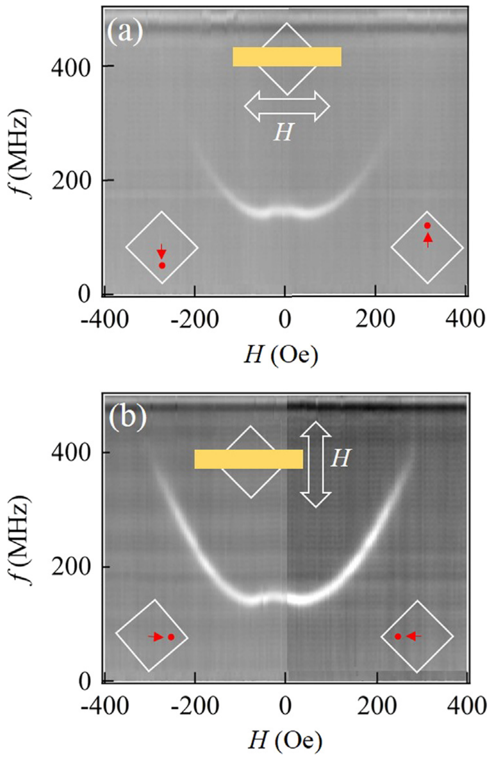

Fig. 6. Image plots of S_{11} spectra for the square dot with $l=3$ μm as a function of external magnetic field at (a) $\phi=0$ and (b) $\phi=\pi/2$.

3 μm, where the magnetic field is applied along two different diagonal directions. We clearly confirm that the resonant signature in Fig. 6(a) disappears at much lower magnetic field than that in Fig. 6(b). Since the vortex core moves perpendicular to the magnetic field [25], the core should shift out of the strip line by the application of the magnetic field along the strip line ($\phi=0$). Therefore, the results indicate that the narrow strip line can detect the core oscillation only in the vicinity the Cu strip line.

4. Conclusion

We have investigated the resonant property of the magnetic vortex stabilized in a square-shaped ferromagnetic dot. The resonant frequency takes an intermediate value between the circular and triangular disks with the same diameter of the circumscribed circle and thickness. This is because the magnitude of the confined potential decreases with increasing the area size of the dot. The field dependence of the resonant frequency shows a unique directional dependence reflecting the four-fold rotational symmetry. The significant modulation of the resonant frequency can be realized in the square with the diagonal distance of 3 μm under the in-plane magnetic field perpendicular to the strip line. These modulation properties are useful for detecting the vector information of the magnetic field and may provide additional functionalities in microwave spin devices based on the magnetic vortex.

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