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Angular control of multi-mode resonance frequencies in obliquely deposited CoZr thin films with rotatable stripe domains*

Chao-Zhong Li(李超众), Chang-Jun Jiang(蒋长军), and Guo-Zhi Chai(柴国志)†

Key Laboratory for Magnetism and Magnetic Materials of the Ministry of Education, Lanzhou University, Lanzhou 730000, *China*

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We investigate the angular-dependent multi-mode resonance frequencies in CoZr magnetic thin films with a rotatable stripe domain structure. A variable range of multi-mode resonance frequencies from 1.86 GHz to 4.80 GHz is achieved by pre-magnetizing the CoZr films along different azimuth directions, which can be ascribed to the competition between the uniaxial anisotropy caused by the oblique deposition and the rotatable anisotropy induced by the rotatable stripe domain. Furthermore, the regulating range of resonance frequency for the CoZr film can be adjusted by changing the oblique deposition angle. Our results might be beneficial for the applications of magnetic thin films in microwave devices.

Keywords: angular control, multi-mode resonance, rotatable stripe domain, non-uniform precession

PACS: 75.70.Ak, 75.30.Gw, 76.50.+g, 75.78.Fg **DOI:** 10.1088/1674-1056/abccb4

1. Introduction

The cut-off frequency of magnetic material is one of the most critical properties for its application in microwave devices, such as tunable inductors, tunable resonators, phase shifters, and tunable filters.[1–3] To meet the requirements of magnetic microwave devices used in different frequency ranges, it is necessary to adjust the cut-off frequency of magnetic material. The cut-off frequency of magnetic film is determined by the frequency of ferromagnetic resonance (FMR)[4] caused by the uniform precession of magnetic moment.[5] The FMR mode frequency $f_{\rm uni}$ of magnetic film can be given by the Kittel's equation with $f_{\rm uni} = (\gamma/2\pi)\sqrt{H(H+4\pi M_{\rm S})}$,[6] where H represents an effective magnetic field including the external field and the anisotropy field, γ and $M_{\rm S}$ are the gyromagnetic ratio and the saturation magnetization, respectively. Obviously, the FMR frequency can only be tuned by regulating the H for a given material with a fixed $M_{\rm S}$. Different methods, including oblique deposition,[7–9] exchange bias,[10] exchange-coupled multilayer structures,[11–18] and depositing on pre-stressed substrates,[19,20] are often employed to adjust the $f_{\rm uni}$ by changing the anisotropy of the magnetic films. But they are no longer effective once the sample works in devices, because these methods are applied during the sample preparation. The magnetoelectric-coupling is an effective way to adjust the FMR frequency by electric field instead of the change of anisotropy field.[21] However, the external electric field also restricts the using of the magnetoelectric-coupling in many applications. In our previous work,[22] we proposed a rotatable anisotropy system with combined uniaxial anisotropy and rotatable stripe domain, whose easy magnetization direction can be controlled by applying a sufficiently large magnetic field along an arbitrary direction,[23–25] to realize the angular control of the $f_{\rm uni}$. Thus, the system with rotatable magnetic anisotropy would be a good candidate for realizing the angular control of the $f_{\rm uni}$ in a single film.

Nevertheless, in some special structures of magnetic materials, there are not only the FMR mode but also other resonance modes resulting from the non-uniform precession. The spin wave resonance is one of the non-uniform modes dominated by exchange interaction, which has been fully studied in theory and experiment.[26,27] However, the resonance frequency of the spin wave mode can seldom be controlled because of its stability in a certain magnetic film.[28] The optical mode resonance, as another non-uniform resonance mode, has also been extensively studied in bilayer or trilayer film with two ferromagnetic layers coupled by the ferromagnetic or antiferromagnetic interlayer exchange interaction.[13,15,29] The optical mode resonance frequency can be tuned by using the variable strength of the interlayer exchange coupling through changing the thickness values of the different layers.[30] Due to the interlayer exchange coupling, the precessions of magnetic moments in different layers can be fully out-of-phase. Many researches including our recent research revealed that the similar out-of-phase resonance mode also exists in the film with stripe domain structure.[31–34] In the films with stripe domains, the magnetic moments in neighboring domains or domain walls are not completely parallel or antiparallel.[35,36] Therefore, the high-frequency resonance mode related to the out-of-phase precession in the film with stripe domain structure is called the non-uniform precession mode instead of the

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†Corresponding author. E-mail: chaigzh@lzu.edu.cn

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optical resonance mode.[31,36,37] By employing the Landau Lifshitz's equation,[38] the Kittel's formula of the non-uniform precession mode under zero field can be replaced by[30,34,39,40]

$$f_{\mathrm{non-uni}} = \frac{\gamma}{2\pi}\sqrt{(H+H_{\mathrm{ex}})(H+4\pi M_{\mathrm{S}}+H_{\mathrm{ex}})}, \quad (1)$$

where $f_{\mathrm{non-uni}}$ is the resonance frequency of non-uniform precession mode, and H_{ex} is the effective field caused by the inter-domain exchange coupling. This behavior has been verified in our paper,[34] in which the $f_{\mathrm{non-uni}}$ can be adjusted by tuning the strength of inter-domain exchange coupling dependent on the domain width.

In this paper, CoZr thin films, each with a large saturation magnetization and a small magneto-crystalline anisotropy, are chosen to form stripe domain structures and construct rotatable anisotropic systems.[34] Combining the non-uniform precession mode with the rotatable anisotropy, the multi-mode resonance is achieved in the obliquely deposited CoZr thin film with rotatable stripe domains. Furthermore, the angular control range of multi-mode resonance frequency can be adjusted more flexibly by changing the oblique deposition angle.

2. Experimental details

The 250-nm-thick CoZr thin films were obliquely deposited on 1 cm×2 cm Si (100) substrates from a pure Co target decorated with six doping Zr cylinders by radio frequency magnetron sputtering. The diameter of Co target was 3 inches (1 inch = 2.54 cm). The diameter and the height for each of small Zr cylinders were 1.8 mm and 3 mm, respectively. Six Zr cylinders were uniformly arranged on the sputtering area of the Co target. The background pressure of the vacuum chamber was 8.5×10^{-5} Pa. The sputtering power was chosen to be 100 W and the Ar pressure was 0.25 Pa during the deposition. A series of samples was obtained at different oblique deposition angles of 0°, 10°, 30°, 40°, 45°, and 50°.

The Co component in each CoZr film can be detected to be 81.25% from the result of energy dispersive x-ray spectroscope (EDX, JEOL JSM-5600LV, Japan). The static hysteresis loops were measured in plane by using a vibration sample magnetometer (VSM, Lakeshore 7304, USA) and the magnetic domain images were taken by a magnetic force microscope (MFM, Asylum Research MFP3D, UK). The frequency-dependent permeability spectra of the samples were obtained by a vector network analyzer (VNA, Agilent E8363B, USA) equipped with a short-circuited microstrip line[41,42] in a frequency range of 100 MHz–9 GHz at room temperature. With this facility, the angle-dependent permeability spectra were investigated by using a home-made angular scaler.

3. Results and discussion

Figures 1(a) and 1(b) show the hysteresis loops of CoZr thin films, which present the static magnetic properties of CoZr thin films grown by vertical deposition and oblique deposition. The loops measured along the easy axis marked as EA have the largest remanence magnetization (M_{r}). When the direction is perpendicular to the easy axis but still in plane, it is defined as the hard axis marked as HA. The hysteresis loops of the vertical sputtered CoZr thin film are shown in Fig. 1(a). The magnetization first decreases linearly with the change of field value from saturation to negative due to the rotation of the magnetization in the domain, and then suddenly reverses to opposite direction because of the motion of domain walls. This is a typical characterization of hysteresis loops of thin films with stripe domains when the magnetic field decreases from the saturated field.[37] The hysteresis loops of its EA and HA are nearly coincided, indicating that the vertically sputtered film is isotropic. Figure 1(b) shows the hysteresis loops of the film grown by an oblique deposition angle at 40°. The M_{r} in the EA loop is significantly larger than that in the HA loop due to the weak perpendicular anisotropy possessed by the stripe domain structure.[35,43–45] That is, part of magnetic moments in the film are warped out of the film plane along the z-axis direction. While the hysteresis loop is measured along the EA, the magnetic moments are more likely to lie in the plane. Thus, the z-component of magnetization in the EA is less than that in the HA. This can be verified by the differences between the light and dark area of the MFM images. The hysteresis loop along the HA in Fig. 1(b) is induced by the competition between the uniaxial anisotropy and the rotatable stripe domain structure of CoZr film. Figures 1(c)–1(e) display the magnetic domain images of CoZr films in the remanence state. The different colors in the magnetic domain images represent the value of Δf measured by MFM, which are related to the out-of-plane component of magnetization. Figure 1(c) is the magnetic domain image of the vertically sputtered CoZr thin film. The MFM images in Figs. 1(d) and 1(e) illustrate the rotatable stripe domains existing in the obliquely deposited CoZr thin film at 40°, of which the magnetic domain direction can be rotated after applying an external saturation field.

Figure 2 shows the real parts (Figs. 2(a) and 2(b)) and imaginary parts (Figs. 2(c) and 2(d)) of permeability spectra of the pre-magnetized CoZr films measured along the EA and HA, respectively. Most of the real parts and imaginary parts of the permeability spectra have two resonance peaks except those samples with oblique deposition angles larger than 40°. The stripe domains are placed along the direction of the microstrip line when we measure the permeability spectra, which means that the precessions of magnetic moments along the magnetic domains are driven by the microwave magnetic field perpendicular to the direction of the microstrip line. Therefore, the uniform precession mode resonance peaks can be detected. The f_{uni} measured along the EA increases with the increase of oblique deposition angle (Figs. 2(a) and 2(c)).

However, while being measured along the HA (Figs. 2(b) and 2(d)), the $f_{\rm uni}$ decreases with the increase of oblique deposition angle. As shown in Fig. 2, the higher resonance peaks related to the non-uniform precession resonance modes are also clearly detected when oblique deposition angles of the films are less than 40°. The non-uniform precession mode is generated by the exchange interaction induced by the precessions of unparallel magnetic moments.[31,33,34,36] For the films deposited at higher oblique deposition angles, the resonance peaks are too weak to be clearly detected. According to the Acher's limit, $(\mu_s - 1)f_{\rm r}^2 = [(\gamma/2\pi)4\pi M_{\rm S}]^2$,[46,47] it can be understood that the permeability becomes smaller when the resonance frequency turns larger. Thus, the possible reason of the undetected non-uniform mode resonance might be the gradually reducing resonance intensities that are lower than the measurement accuracy of our instrument at the high resonance frequency. As shown in Fig. 2, the obtained resonance frequency of non-uniform precession mode along the EA increases with the oblique deposition angle increasing. The measurement accuracy of our equipment should be improved to study more details of the non-uniform mode in future researches.

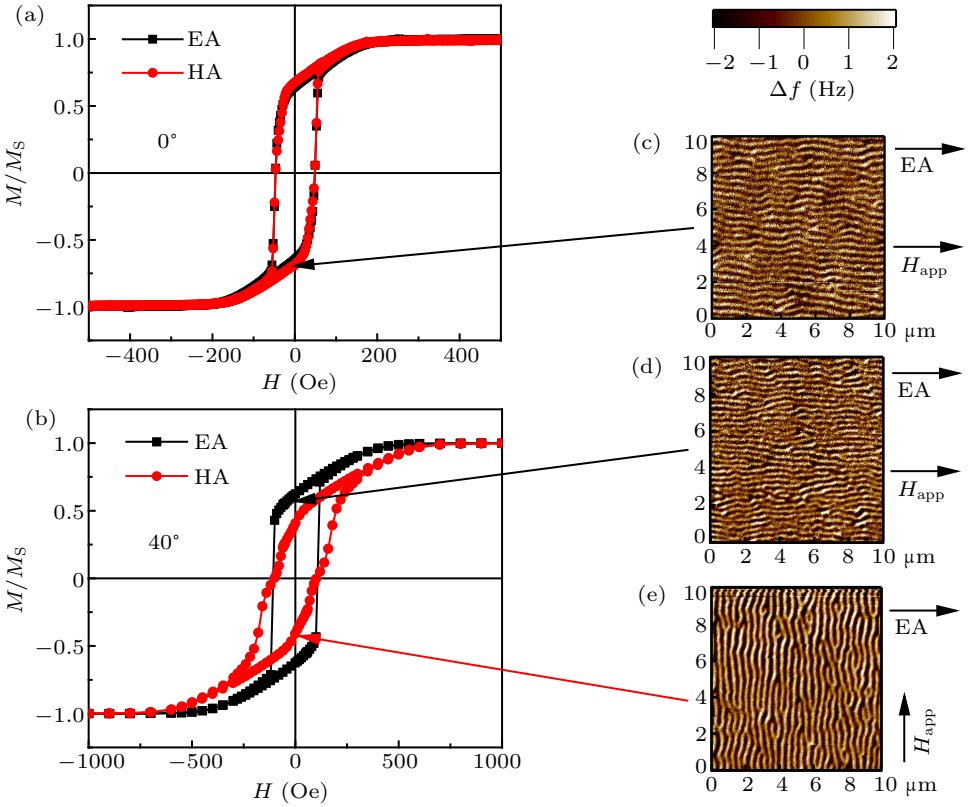


Fig. 1. Hysteresis loops of (a) vertically deposited and (b) obliquely deposited CoZr thin films at oblique deposition angle 40°. Dark lines are measured along easy axis direction of uniaxial anisotropy, which have maximum remnant magnetization, marked as EA, and red lines are taken along perpendicular direction of easy axis direction, marked as HA. MFM images of (c) vertically and ((d) and (e)) obliquely deposited CoZr thin films, with arrows indicating directions of easy axis and applied external fields. The unit 1 Oe = 79.5775 A·m^{-1}.

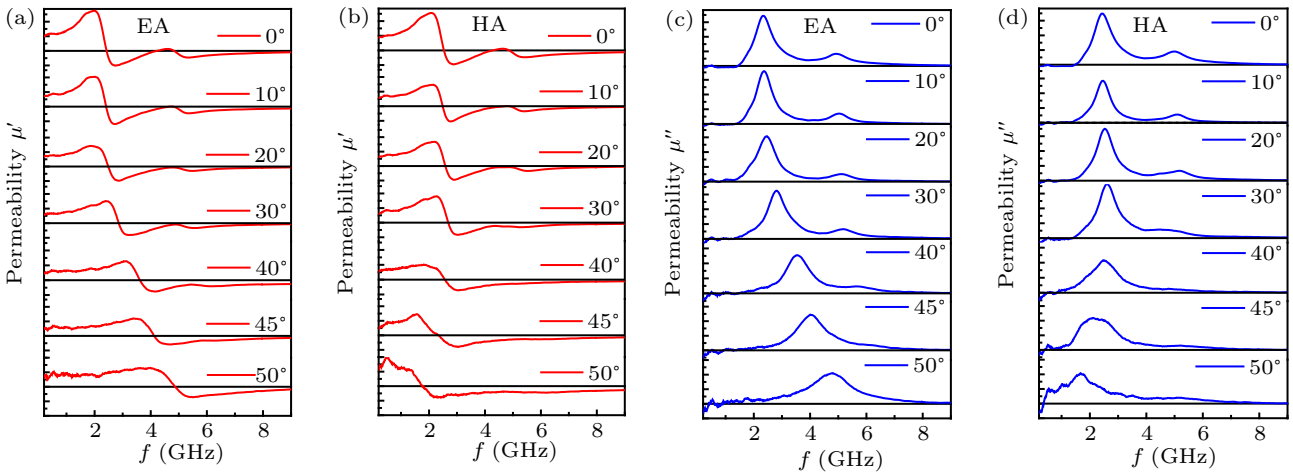


Fig. 2. Permeability spectra of CoZr thin films measured at zero external field. Real parts of permeability spectra measured along (a) easy axis and (b) hard axis, and imaginary parts of permeability spectra measured along (c) easy axis and (d) hard axis.

Figure 3(a) shows the relation between the resonance frequency and the oblique deposition angle. The $f_{\rm uni}$ increases from 2.47 GHz to 4.80 GHz along the EA, but decreases from 2.32 GHz to 1.86 GHz along the HA, which is consistent with our previous result.[25] The $f_{\rm non-uni}$ increases from 4.89 GHz to 5.79 GHz along the EA. In other words, the resonance frequency can be tuned in a wide frequency range from 1.86 GHz to 5.79 GHz by combining with the rotatable anisotropy and the inter-domain exchange coupling. The damping α of the film is another key property of the high frequency magnetic material. As shown in Fig. 3(b), the α for each of the films is less than 0.2 when oblique deposition angle is less than 30°, then the value of α increases to 0.5 when oblique deposition angle increases to 50°.

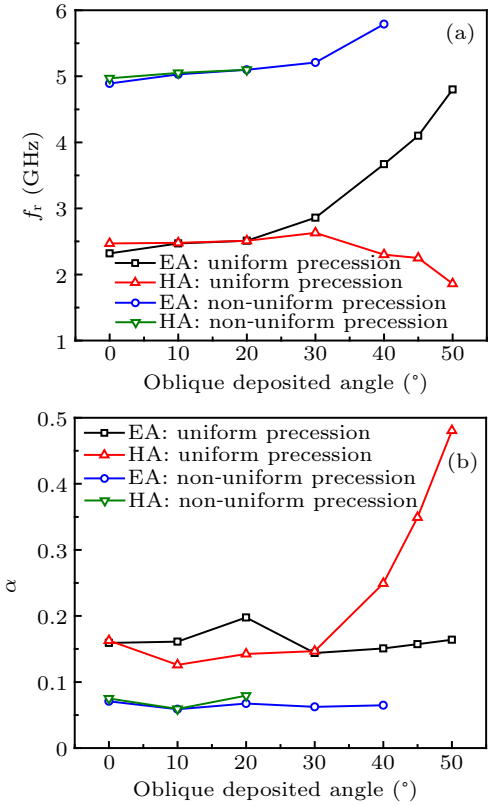


Fig. 3. Obliquely deposited angle dependence of (a) resonance frequency and (b) damping α.

To further understand the angular dependence of high-frequency permeability of CoZr films and compare the experimental results with the results from the theoretical model, the relationship between $f_{\rm uni}$ and inplane angle θ of the CoZr film is shown in Figs. 4(a) and 4(b). Figure 4(a) shows the results of the vertically deposited film, and figure 4(b) displays the $f_{\rm uni}$ *versus* θ curve of the obliquely deposited CoZr film. The results can be explained by

$$f_{\rm uni} = \frac{\gamma}{2\pi}\sqrt{\left(H_k\cos 2\theta + H_k^{\rm rot}\right)\times 4\pi M_{\rm S}}, \qquad (2)$$

where H_k is the uniaxial anisotropy field, $H_k^{\rm rot}$ is the rotatable anisotropy field, and θ is the angle between the measuring direction and the EA of uniaxial anisotropy.

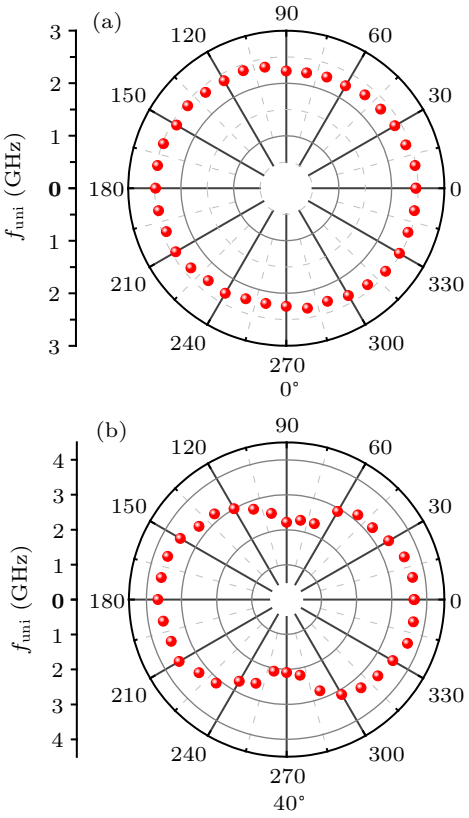


Fig. 4. Angular dependence of resonance frequency of uniform precession mode in obliquely deposited CoZr thin films at oblique deposition angle of (a) 0° and (b) 40°.

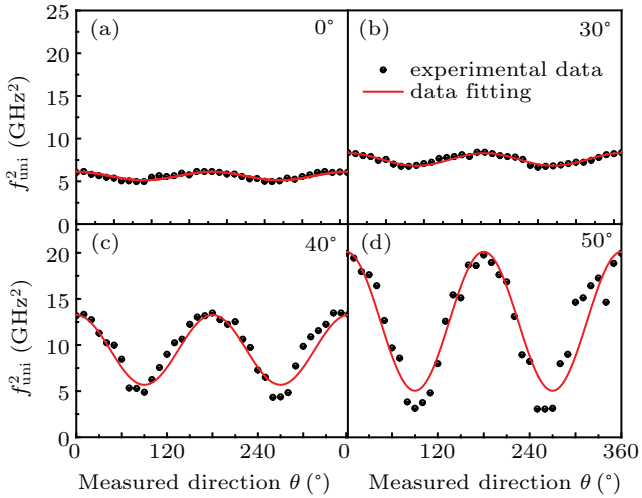


Fig. 5. Experimental results and fitting curves of angular dependence of square of resonance frequency of uniform precession mode in obliquely deposited films at oblique deposition angle of (a) 0°, (b) 30°, (c) 40°, and (d) 50°, respectively.

The angular dependence of $f_{\rm uni}^2$ in Fig. 5 can be fitted by Eq. (2). As shown in Figs. 5(c) and 5(d), the variation of $f_{\rm uni}$ correspondingly increases with the oblique deposition angle gradually increasing to 50°. That is due to the stronger uniaxial anisotropies induced by the larger oblique deposition angles in those films. The increase of uniaxial anisotropy is usually explained by the so-called self-shadow effect, resulting from a tilted or elongated columnar structure of the grain.[48] By fitting Eq. (2), the uniaxial anisotropy field H_k and the rotatable anisotropy field $H_k^{\rm rot}$ can be separated as shown in

Fig. 6. Both H_k and $H_k^{\rm rot}$ increase as the oblique deposition angle increases. The increasing of rotatable anisotropy can be explained by gradually reducing the width of the domain from the MFM image in Fig. 1.

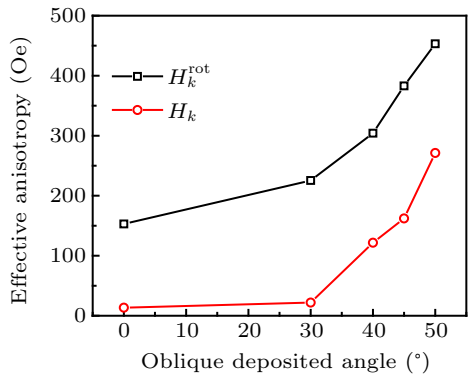


Fig. 6. Oblique deposition angle dependence of rotatable anisotropy (dark squares and black line) and uniaxial anisotropy (red circles and red line) in obliquely deposited CoZr thin films.

4. Conclusions

We report the controllable resonance frequency in obliquely deposited CoZr thin films with rotatable stripe domains. The angular control of resonance frequency originates from the angular tunable effective anisotropy in plane, arising from the competition between the uniaxial anisotropy induced by oblique deposition technique and the rotatable anisotropy produced by rotatable stripe domains. Furthermore, the non-uniform precession resonance mode which is induced by the exchange coupling of magnetic moments in adjacent domains can broaden the adjustable resonance frequency range. Finally, a wide range of resonance frequency from 1.86 GHz to 5.79 GHz is realized in a single film, which might be useful for high-frequency microwave devices.

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