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Longitudinal Magneto-Optical Kerr Effect of Nanoporous CoFeB and W/CoFeB/W Thin Films

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Abstract: Nanoporous Co₄₀Fe₄₀B₂₀ (CoFeB) and sandwich tungsten (W)/CoFeB/W thin films were fabricated via an anodic aluminum oxide (AAO) template-assisted magneto sputtering process. Their thickness-dependent magneto-optical Kerr effect (MOKE) hysteresis loops were investigated for enhanced Kerr rotation. Control of the Kerr null points of the polarized reflected light can be realized via the thicknesses of the CoFeB layers and W layers. Simulation of the thickness-dependent phase difference change by the finite element method reveals the existence of the two Kerr null points for W/CoFeB/W thin films, matching the experimental result very well. However, there are two additional Kerr null points for pure CoFeB thin films according to the simulation by comparing with the experimental result (only one). Theoretical analysis indicates that the different Kerr null points between the experimental result and the simulation are mainly due to the enhanced inner magnetization in the ferromagnetic CoFeB layer with the increased thickness, which is usually omitted in the simulation. Clearly, the introduction of non-ferromagnetic W layers can experimentally regulate the Kerr null points of ferromagnetic thin films. Moreover, construction of W/CoFeB/W sandwich thin films can greatly increase the highest magneto-optical susceptibility and the saturated Kerr rotation angle when compared with CoFeB thin films of the same thickness.

Keywords: magneto-optical Kerr effect; magnetization reversal; Kerr null point; nanoporous structure; magnetic thin films; tungsten

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1. Introduction

Apart from various heterogeneous structures, including distributed periodic systems, lumped systems, irregular and coupled waveguide systems, and controlled magnetic structures, which are available for data processing and storage in the microwave range [1], the magneto-optical Kerr effect (MOKE) describing the linearly polarized light rotation of the reflection and the relative changes in reflectivity [2–4] has been intensively used in optical and magnetic data storage, domain observation [5,6], optical isolators, and fast optical modulation [7,8]. Recently, with the acquisition of high sensing performance in small molecules at low concentrations, MOKE has been widely investigated to enhance the

sensing performance on the gas detection [9,10], liquid detection [11–13], magnetometry, magnetic phase probes [14–16], and magnetic biosensing [17–21] due to its higher figure of merit (FOM) and sensitivity (they are comprehensive parameters for evaluating sensor performance) than conventional optical-mode or magnetic-mode methods. After summarizing the sensing principle in the MOKE spectrum, it is noteworthy that the MOKE-based sensors always exhibit remarkable sensitivity, flexible light phase, polarization modulation, and a large FOM near the position where the MOKE rotation inversion appears [22,23], which is here called the Kerr null point. As the magnetization reversal, finding the Kerr null point shall be of great interest for developing the ultrasensitive technique and the laser-induced magnetization process for potential magneto-electronic and magneto-optical device applications [24–26]. In addition, Kerr null points shall imply lots of information about magnetic anisotropy, exchange bias coupling, and the polarized laser-matter interaction under field since they are related to the fundamentals of magnetization reversal, the interference of reflected light, and the light-matter interaction of magnetic and/or magneto-optical thin films under a magnetic field [26–28]. All-optical magnetization reversal in a 20 nm thick Ni film using a circularly polarized light has been demonstrated, with a reversal speed of 260 fs, which is much faster than that in other devices, such as magnetic tunneling junctions (MTJs) and giant magnetoresistance (GMR) junctions [29]. The $[\text{Co}(0.4)/\text{Pt}(0.7)]_n$ (thickness in nm, $n \leq 8$) multilayer thin films also show magneto-optical magnetization reversal [30]. While many composite iron oxide compounds have excellent magnetic properties [31,32], alloying compounds have several disadvantages. One of the disadvantages is that they are less corrosive to environmental factors, such as temperature, oxygen, and electromagnetic radiation. In this sense, oxides are more stable when used below 1000 °C. However, metal alloys and composites have excellent magneto-optical properties. This means a new method for the magneto-optical control of ferromagnetic magnetization applicable for integrated magneto-optical data [33]. Kerr null points shall promise an alternative favoring the easy manipulation of the magneto-optical control of magnetization.

It is beyond doubt that magneto-optical Kerr rotation reversal is particularly more complex in multilayered ferromagnetic and nonmagnetic systems with large magnetic anisotropy dispersion and an interfacial coupling effect than magnetization reversal, since the phenomena are related to light polarization, light-matter interaction, and interference of the reflected light under external field and inner magnetization of materials [24–28,30,33,34]. Precise regulation of this kind of MOKE rotation reversal thus becomes very important for the study of this complex phenomenon for the optimization of the microstructure and composition of magnetic thin films at nanoscale [24–30,33,34]. Of particular interest is the design and fabrication of special nano-structured thin films, including magnetic layers, for the regulation of MOKE rotation inverse and the related reversal mechanism study. To date, various nanostructures, including periodic rectangular apertures [35], optical Tamm-state structures [36,37], and prism-coupled surface-plasmon-resonance systems [38,39], have been investigated to enhance sensing performance assisted by a variety of fabrication methods, such as electrochemical deposition [40,41] and magnetron sputtering [42].

Apart from such nanostructures, the nanoporous anodic aluminum oxide template (AAO) [43] can realize the control of light propagation and modulate magneto-optical (MO) effects by tailoring the pore diameter, interpore spacing, pore length, and coating composition of multilayered MO media [44–48]. Herein, two types of nanoporous MO systems, i.e., CoFeB/AAO/Al and W/CoFeB/W/AAO/Al, were developed to investigate the possibility of controlling the null points of MO Kerr signals to achieve future high-performance sensors by regulating the phase change of the two reflection coefficients (i.e., the original s-composition and p-composition induced by the external magnetic field) and tailoring the film thickness and the interface magnetic and dielectric property. In this work, CoFeB film has excellent magneto-optical properties and in-plane uniaxial magnetic anisotropy [49], which can be induced by both stress and post-deposition annealing under a magnetic condition, leading to a significant magneto-impedance effect at a low frequency [50].

The strategy provides an alternative technique for the fabrication of smart and accurate MOKE sensors for film thickness measurement and a possible new method in the regulation of magnetization reversal via the optimization of the microstructure of multilayered thin films.

2. Experimental Section

2.1. Sample Fabrication and Characterization

To date, there are various methods for obtaining metallic alloy samples [40,41]. In this work, several single ferromagnetic CoFeB films and W (x)/CoFeB (120 nm)/W (x) trilayers were deposited on nanoporous AAO (pore diameter, 90 nm; inter-pore distance, 110 nm; pore length, 300 nm) based on an Al substrate (AAO/Al) by magnetron sputtering at room temperature and a base pressure of 4.7×10^{-4} Pa. The CoFeB target was sputtered in a 0.75 mTorr argon gas atmosphere using a radio frequency (RF) sputtering apparatus (Shenyang Pengcheng Vacuum Technology Co., Ltd., Shenyang, China) with a power density of 5.1 W/cm^2 . The W/CoFeB/W trilayers were deposited layer-by-layer from bottom to top. The W target was sputtered in a 15 mTorr Ar gas atmosphere using a direct current (DC) sputtering apparatus with a power density of 2.55 W/cm^2 . After the fabrication process, surface, and cross-sectional morphologies and compositional analyses of the CoFeB/AAO/Al and W/CoFeB/W/AAO/Al multilayer systems were performed using a field-emission (FE) scanning electron microscope (SEM) (SUPRA 55, Zeiss, Oberkochen, Baden-Württemberg, Germany). The MO effects were investigated using a Kerr measurement instrument (NanoMOKE-3, Durham Magneto Optics Ltd., Durham University Library, Stockton Road, Durham Dh1 3ly, United Kingdom) working in a longitudinal geometry (L-MOKE). As shown in Figure 1, the external magnetic field was parallel to + incident light. In our system, longitudinal MO hysteresis loops for various systems were recorded at a 660 nm wavelength at a 45° angle of incidence in s-polarization for different magnetic-field strengths.

Figure 1. Longitudinal magneto-optical measurement configuration.

2.2. Simulation

The MO properties of the CoFeB/AAO/Al and W/CoFeB/W/AAO/Al multilayer systems were simulated by the finite element method using COMSOL Multiphysics (version: 5.6) [51]. An equation deduced using the transfer matrix method from a semi-infinite layer was employed to approximately calculate the Kerr signal [52]. For the incident beam

in the s-polarization, the Kerr rotation θ and the ellipticity φ were simulated as functions of the reflection coefficients r_{ij} ($i, j = s, p$) as follows:

$$\theta = \frac{1}{2} \left(\tan^{-1} \left(\frac{2 \operatorname{Re} \left(\frac{r_{ps}}{r_{ss}} \right)}{\left(1 - \left| \frac{r_{ps}}{r_{ss}} \right|^2 \right)} \right) \right) \quad (1)$$

$$\varphi = \frac{1}{2} \left(\sin^{-1} \left(\frac{2 \operatorname{Im} \left(\frac{r_{ps}}{r_{ss}} \right)}{\left(1 + \left| \frac{r_{ps}}{r_{ss}} \right|^2 \right)} \right) \right) \quad (2)$$

where the modulus $\left| \frac{r_{ps}}{r_{ss}} \right|$, the real part $\operatorname{Re} \left(\frac{r_{ps}}{r_{ss}} \right)$, and the imaginary part $\operatorname{Im} \left(\frac{r_{ps}}{r_{ss}} \right)$ are considered close to zero. Then, the Kerr signal Ψ can be expressed as follows:

$$\Psi = \frac{r_{ps}}{r_{ss}} = \theta + \varphi i = \rho e^{i\delta} = \rho \cos(\delta) + \rho \sin(\delta) i \quad (3)$$

where, ρ is the modulus of the reflection coefficient ratio; δ is the phase difference of the two components of the reflection light, caused by the interaction of the light with the thin films in which the horizontal component travels at a speed different from the vertical component. From Equation (3), the sign of the Kerr rotation can be controlled by the phase difference δ that is a function of the film thickness (t), effective refractive index (n_{eff}), and MO constant (Q) of CoFeB film. A simplified computational model is shown in Figure 2. For s-polarized incident light with a wavelength of 660 nm, the simulation needs to account for the interplay of several parameters: (a) the permittivity tensor or complex index of the refraction of every layer, (b) the MO constant of the CoFeB layer, and (c) film thicknesses.

Figure 2. (a) Hexagonal honeycomb structure covered with a CoFeB film. (b) The periodic cell used to calculate the magneto-optical Kerr signal. (c) A schematic illustration of the electric field $\vec{E}$, external magnetic field $\vec{M}$, and the sample surface.

For the isotropic CoFeB, the purely optical components can be expressed using $\epsilon_{xx} \approx \epsilon_{yy} \approx \epsilon_{zz} \approx \epsilon = N^2$, where N is the complex refractive index of the magnetic material. All the remaining components equal zero when considering L-MOKE in s-configuration for

the CoFeB nanoporous thin film. Thus, the permittivity tensor of CoFeB can be expressed using Equation (4) with an anti-symmetric tensor as follows:

$$\varepsilon^L = \begin{pmatrix} \varepsilon & 0 & 0 \\ 0 & \varepsilon & -i\varepsilon Q \\ 0 & i\varepsilon Q & \varepsilon \end{pmatrix} \quad (4)$$

Here, Q is activated by magnetization along the x -axis, and the appearance of the Kerr rotation originates from off-diagonal terms. The MO coupling constant $Q = 1.3 \times 10^{-2} + 9.9 \times 10^{-5}i$ of the CoFeB film can be obtained from a magnetic home-made ellipsometric measurement.

For the theoretical simulations, the diagonal terms of the permittivity tensors for CoFeB and W were determined using the equation $N^2 = (n + ik)^2$ (where n is the refractive index and k is the extinction coefficient) by employing the spectral dependence of the complex refractive index of the films obtained from the ellipsometry measurement (Horiba UVISSEL, Horiba Scientific, Paris, France). Additionally, when elliptically polarized light is reflected through the film, its polarization state is changed to another elliptically polarized light. The thickness value is finally obtained by obtaining the azimuth angle of the starter and the azimuth angle of the detector, using the fact that the film thickness exists as a function of these two parameters. The wavelength dependent n and k of CoFeB layers and W layers are plotted in Figure 3. At 660 nm, the values of n and k for CoFeB films are 3.66 and 1.16, respectively, and those for W films are 3.58 and 1.30, respectively. The relative permittivity of Al_2O_3 is 3.11 and Al used in the simulation is obtained from Ref [53].

Figure 3. Wavelength-dependent refractive index n and extinction coefficient k of (a) CoFeB layers and (b) W layers.

3. Results and Discussion

CoFeB Thickness Dependent MOKE of Nanoporous CoFeB/AAO/Al Thin Films

Nanoporous CoFeB/AAO/Al thin films with CoFeB layers with thicknesses from 12 to 372 nm were fabricated by a magneto-sputtering process. Figure 4a shows one top-viewed image of the pure AAO substrate by SEM (SUPRA 55, Zeiss, Oberkochen, Baden-Württemberg, Germany), revealing the nearly hexagonal arranged nanoporous surface morphology with a pore diameter of 90 nm and an interpore spacing of 110 nm. The cross-section of the pure AAO substrate reveals uniform long straight holes in the AAO substrate (Figure 4b). Figure 4c,d show the top surface image and the cross-section image of one representative CoFeB/AAO thin film with a CoFeB thickness of 51 nm. These images revealed slightly reduced surface nanopore diameters of about 80 nm and petal-like arrayed nanopore structures that were connected by equilateral triangles with the side length equal to the inter-pore spacing of 110 nm.

Figure 4. (a) Wide surface and (b) cross section SEM images of a porous AAO film (pore diameter, 90 nm; inter-pore spacing, 110 nm) without any coating. (c) Surface SEM image of a 51 nm thick CoFeB film fabricated on the AAO substrate of 90 nm pore diameter. (d) Cross section SEM image of thin films coated with 51 nm CoFeB layer on the AAO substrate of 90 nm pore diameter.

The ferromagnetic layer thickness-dependent MOKE of nanoporous CoFeB/AAO/Al thin films was investigated via the s-polarized longitudinal-MOKE (L-MOKE) hysteresis loops, which are summarized in Figure 5, with the CoFeB layer thickness increasing from 12 to 372 nm. Determining the thickness of thin films on AAO templates is often a challenge. Traditionally, however, researchers have typically deposited thin films on AAO and smooth substrates (e.g., glass and wafer) using the same deposition time. The film thickness on the smooth substrate was then characterized using an optical ellipsometer or atomic force microscope. In our experiments, we used this method to characterize the film thickness on AAO templates. It was surprisingly found that there was one inversion of the Kerr hysteresis loops appearing from 51 to 66 nm, and then no further inversion was observed as the CoFeB thickness was continuously increased up to 372 nm. For the precise critical thickness confirmation of the inversed Kerr hysteresis loop, three more Kerr hysteresis loops with thicknesses of 55, 58, and 61 nm were further measured. As shown in Figure 6, CoFeB/AAO thin films showed a critical thickness between 51 and 55 nm, during which a relative inversion of the Kerr hysteresis loops occurred, suggesting that the MOKE rotation angle can be reduced to zero, so called the Kerr null point. This null point indicates an abrupt MOKE polarization change and/or a magnetization change of thin films as CoFeB thickness is increased from 51 to 55 nm, which may be used for ultrasensitive ellipsometers for the thickness or the related magnetic/optical signal measurement. The estimated CoFeB thickness for the Kerr null point of CoFeB thin films is about 51.8 nm according to the thickness-dependent Kerr rotation angle.

Figure 5. s-polarization L-MOKE hysteresis loops for CoFeB/AAO thin films with CoFeB thicknesses from 12 to 372 nm (the CoFeB thickness of each film sample is labeled in the upper right of each subfigure), excited at a laser wavelength of 660 nm and an inducing angle of 45° .

Figure 6. s-polarization L-MOKE hysteresis loops of CoFeB/AAO thin films with CoFeB layer thicknesses of (a) 51, (b) 55, (c) 58, and (d) 61 nm, excited at a laser with wavelength of 660 nm and an inducing angle of 45° .

Although there is no further MOKE hysteresis inverse with the further increase of CoFeB thickness of these nanoporous thin films, their Kerr rotation angle and magnetic susceptibility can be further regulated by the CoFeB thickness. Table 1 gives the highest Kerr susceptibility (χ , mdeg/Oe, the maximum value of slope along the hysteresis cycle,

from the peaks of the differential curves of the Kerr rotation hysteresis loops), the saturated Kerr rotation angles (θ_S , mdegree, or mdeg) at the positive saturation magnetic field corresponding to the positive hysteresis loop (e.g., the case with the CoFeB thickness of 51 nm)), and the mean coercivities (H_c , the mean value of the left field ($H_{c,L}$) and the right field ($H_{c,R}$) as the Kerr rotation angles become zero), with the CoFeB thickness increase. The highest saturated Kerr rotation of 179.9 mdeg can be obtained as the CoFeB thickness is increased to 61 nm. The highest magnetic susceptibility of 6.61 mdeg/Oe can be obtained as the CoFeB thickness is increased up to 372 nm and the corresponding coercivity (H_c) of this thin film can be as small as 48.5 Oe, but the saturated Kerr rotation angle is only 131.1 mdeg.

Table 1. CoFeB thickness (t , nm) depending on the highest MOKE susceptibility (χ , mdeg/Oe), coercivity (H_c , Oe), and MOKE saturation rotation angle (θ_S , mdeg) of the CoFeB thin films on AAO substrates.

t	12	22	51	55	58	61	66	73	88
χ	0.04	0.05	0.09	−1.96	−1.61	−3.61	−2.36	−4.56	−4.34
H_c	460.0	168.2	242.9	175.0	83.2	157.3	95.1	107.6	123.2
θ_S	14.5	3.3	22.6	−85.0	−48.6	−179.9	−144.9	−155.0	−124.7
t	95	103	110	120	129	140	246	266	372
χ	−4.26	−4.68	−1.69	−1.21	−2.69	−0.11	−1.58	−0.81	−6.61
H_c	134.1	143.2	98.3	130.5	127.8	27.9	76.6	53.2	48.5
θ_S	−145.0	−138.2	−106.8	−70.0	−130.9	−32.4	−125.2	−70.4	−131.1

To further seek the Kerr null points for expanded sensing range, metallic W layers were introduced to construct the W/CoFeB/W/AAO nanoporous thin films by consideration of the high spin-orbit coupling and magnetic pinning effect of W to the ferromagnetic layer. A series of W/CoFeB/W/AAO multilayered nanoporous thin films with the W thickness ranging from 4 to 126 nm and a fixed 120 nm thick CoFeB middle layer were fabricated by a magnetron-sputtering process. Figure 7a shows a representative surface SEM image of the W/CoFeB (120 nm)/W/AAO thin film with each W layer 129 nm thick. Clearly, the surface morphology (Figure 7a) showed the reduced pore size of about 10 ± 2 nm and a petal-like structure formed by nearly discrete equilateral triangles with side lengths equal to the inter-pore spacing after deposition with two W layers (totally 258 nm) and one middle CoFeB layer of 120 nm thick. Compared with the pure 90 nm AAO porous film (Figure 4b) and the CoFeB/AAO thin films with 51 nm thick CoFeB (Figure 4d), the cross-section SEM image of the W/CoFeB/W/AAO thin film also indicated the shrunk pore size and the formation of three distinct layers (Figure 7b). A combination of element analysis of the thin films by the energy-dispersive X-ray spectrum (EDS: Figure 7c) and the above SEM images reveals the successful fabrication of W/CoFeB/W/AAO sandwich nanoporous thin films on AAO substrates. The sandwich thin film has a Fe/Co/W atomic ratio of 3.46/3.52/5 and the Co/Fe ratio matches the target composition ($\text{Co}_{40}\text{Fe}_{40}\text{B}_{20}$) very well.

The W thickness-dependent s-polarization L-MOKE of these W/CoFeB (120 nm)/W/AAO nanoporous thin films were studied. As shown in Figure 8a, the Kerr rotation angle first decreased as the W thickness increased from 4 to 32 nm. This is evident for sample W (32 nm)/CoFeB/W (32 nm), where the line shape of MOKE hysteresis suggests the presence of two different contributions of opposite signs. In some cases, when two magneto-optical contributions are present, they can be isolated, which has been performed in iron oxide nanoparticles using magnetic circular dichroism, allowing discrimination between magnetite and maghemite [16]. Subsequently, the Kerr rotation angle is increased (Figure 8b) as the W thickness is increased from 42 to 74 nm. Thus, the Kerr rotation hysteresis loops change their direction as the W thickness increases from 32 to 42 nm, resulting in the first Kerr null point at the W thickness between 32 and 42 nm. When the W thickness was continuously increased

to more than 74 nm, the rotation angle was reduced again, leading to a second Kerr rotation hysteresis loop inverse as the W thickness was increased from 95 to 116 nm (Figure 8b,c). The second Kerr rotation hysteresis loop inverse leads to a second Kerr null point with the W thickness between 95 and 116 nm. To unambiguously demonstrate these results, the W thickness-dependent saturated Kerr rotation angles for a positive saturation magnetic field are plotted in Figure 8d, demonstrating two Kerr null points with the estimated critical W thicknesses of 37 nm and 113 nm, respectively.

Figure 7. (a) Surface SEM image, (b) cross section SEM image, and (c) surface EDS spectrum of one of W/CoFeB (120 nm)/W multilayer thin films with a W thickness of 129 nm on the AAO substrate of 90 nm pore diameter and inter-spacing of 110 nm.

Figure 8. Magneto-optical hysteresis loops versus magnetic-field strength of AAO patterned with multilayered W/CoFeB/W structures. The W thickness is (a) 4~32 nm, (b) 42~95 nm, and (c) 116~126 nm. (d) The W thickness-dependent saturated Kerr rotation angle at the positive saturation magnetic field corresponding to the positive hysteresis loop (e.g., the case with the W thickness of 74 nm).

Table 2 gives the highest Kerr susceptibility (χ), the saturated Kerr rotation angles (θ_S) and the mean coercivity (H_c) at different W thicknesses. The highest χ for W/CoFeB (120 nm)/W nanoporous thin films can be increased from 1.21 mdeg/Oe to 3.04 mdeg/Oe as 4 nm thick W layers are introduced on the top and bottom of the pure CoFeB nanoporous film. Its coercivity (H_c) can be reduced from 130.5 Oe of the pure CoFeB films to 116.5 Oe, correspondingly. W/CoFeB/W nanoporous thin films exhibit the highest Kerr rotation angle of 198.6 mdeg as the W thickness is increased to 74 nm, higher than that of the pure CoFeB thin films with the same CoFeB thickness (70 mdeg), which is still higher than the highest Kerr rotation angle of the pure CoFeB thin films with the CoFeB thickness of 61 nm (179.9 mdeg).

Table 2. The highest susceptibility (χ , mdeg/Oe), the coercivity (H_c , Oe) and the saturated rotation angle (θ_S , mdeg) of the W/CoFeB (120 nm)/W thin films at different W thicknesses (t , nm).

t	4	11	21	32	42	63	74	84	95	116	126
χ	−3.04	−1.26	−1.02	0.142	0.311	0.813	2.98	1.40	0.33	−0.03	−0.06
H_c	116.5	142.5	145.5	354.9	101.1	153.0	111.8	131.9	151.8	194.3	59.1
θ_S	−85.4	−75.2	−42.6	9.6	16.9	16.1	198.6	109.0	15.5	−2.0	−2.9

Understanding these MOKE features (e.g., layer thickness and composition dependent Kerr inversion and angle rotation) of multilayered ferromagnetic nanoporous films shall pave a new approach for fabricating magnetic nanostructure devices for ultrasensitive MOKE sensing devices. Theoretically, this MOKE hysteresis loop inversion (or experimentally, the susceptibility of Kerr rotation angle changes its direction) can be attributed to an abrupt shift in the phase difference caused by the reflection coefficient change of r_{ps} and r_{ss} (see Equation (3)) and/or by the in plane magnetization direction change of the thin films since ϵQ in Equation (4) is equal to the gyration vector (g , as shown in Equation (5)) [54].

$$\epsilon Q = g = \epsilon_0 \chi^{(m)} H \quad (5)$$

The off-diagonal element (g) represents the magnetically-induced part and is directly proportional to an internal magnetization (M) and the incident wavelength (λ), as shown in Equation (6) [54].

$$g = g(M, \lambda) \quad (6)$$

Introduction of the non-magnetic double tungsten layers helps to modifies MOKE hysteresis loops of the thin films by solely studying the interference among the light reflected from air-W/CoFeB/W interfaces and AAO/Al interfaces regardless of the effect from the internal magnetization of the thin films. This is confirmed by simulations of the cosine values as a function of the W thickness-dependent $\cos(\delta)$ in the W/CoFeB(120 nm)/W/AAO thin films and the CoFeB thickness-dependent $\cos(\delta)$ in the CoFeB/AAO thin films. Figure 9a shows that the $\cos(\delta)$ spectra exhibited two null points as the W thickness was increased from 4 to 140 nm, which occurred at the W thickness of 41 nm and 86 nm, respectively. The deviation from the experiment values (37 and 113 nm) is mainly due to neglect of the in-plane magnetization of the CoFeB layer and the pinning effect of the W layer on the surface magnetization of the CoFeB layer, and partially due to some variation in the W thickness measurement. The simulation result on the $\cos(\delta)$ spectra for CoFeB/AAO nanoporous thin films (Figure 9b) reveals three null points as CoFeB thickness is increased from 12 to 372 nm, which are 24, 128, and 201 nm, which is different from the experimental result. It will not be surprising as you consider the fact that the simulation only considers the light reflected from the air-CoFeB/AAO/Al interfaces but neglects the much enhanced in-plane magnetization of the CoFeB films due to increased thickness. Since the values of n and k at 660 nm for CoFeB are almost the same as those for W (Figure 3), the thickness-dependent $\cos(\delta)$ spectrum of the CoFeB/AAO thin films is very similar to that of the W/CoFeB/W/AAO

thin films. If the total thickness of the W/CoFeB/W layer (the addition of the CoFeB thickness and the total W layer thickness (the top layer and the bottom layer)) is used, the thickness-dependent $\cos(\delta)$ spectra match very well. As the ferromagnetic CoFeB layer is thin enough (e.g., 120 nm or less), the Kerr rotation may be dominated by the interference of the reflected light partially polarized by the surface magnetization of the CoFeB films, nearly following Equations (1)–(3), which may cause a complete destructive interference at a certain thickness and result in one null point for pure CoFeB thin films. With the further thickness increase of the CoFeB layer, the in-plane magnetization becomes increasingly strong. The in-plane magnetization will be the dominant factor to polarize the inducing light and increase the Kerr rotation angle. Even though the increased thickness still causes the interference of the reflected light, it will not be possible to reduce the L-MOKE rotation angle to zero due to the significantly enhanced polarization by the strong in-plane magnetization of the thick ferromagnetic CoFeB layer. As for W/CoFeB/W/AAO thin films, there will be no further increased in-plane magnetization besides the surface pinning effect or possible spin-orbit coupling since W is a kind of non-ferromagnetic material, leading to an additional Kerr null point with the thickness increase of the W layer.

Figure 9. (a) The calculated $\cos(\delta)$ for the W/CoFeB (120 nm)/W thin films with the W layer thickness changing from 4 to 140 nm; (b) the calculated $\cos(\delta)$ for the CoFeB/AAO thin films with a CoFeB layer thickness from 12 to 372 nm.

As a result, introducing heavy metal layers of high spin-orbit interaction (e.g., W) on the top and/or bottom of the ferromagnetic layer provides a new type of system for obtaining Kerr rotation reversal, and the physical mechanism is different from that of manipulating the sign of Kerr rotation in magnetoplasmonic systems, in which the concerted action of nanoplasmonics and magnetization can control the sign of rotation of the reflected light's polarization in ferromagnetic nanostructures [8,55–57]. With respect to the interference pattern formed by light reflected from the air-CoFeB and AAO/Al interfaces in the pure CoFeB (120 nm)/AAO/Al nanoporous thin film, this interference may be significantly affected by the enhanced in-plane magnetization of the film as the CoFeB thickness is increased more than a certain value. As the tungsten layers are introduced, no further enhanced magnetization can be introduced into the sandwich structural W/CoFeB/W thin film since the ferromagnetic CoFeB layer thickness is fixed but the pinning effect (note: it will not be affected by the W thickness increase too much) on the magnetization of CoFeB layer by the two W layers. The phase difference by the reflection coefficients r_{ps} and r_{ss} change due to the interference of the reflected light might lead to additional null points. In addition, a very thin layer of heavy metal can increase the L-MOKE rotation angle and the related magneto-optical susceptibility and reduce the coercivity. However, this study also confirms that improved inner magnetization and/or surface magnetization is still the main consideration for further enhanced Kerr rotation angle and magneto-optical susceptibility.

4. Conclusions and Perspectives

Kerr rotation loop inversion (i.e., the Kerr null points) of nanoporous ferromagnetic CoFeB/AAO/Al multilayer systems with CoFeB layer thicknesses of 12~372 nm was revealed experimentally and theoretically. The CoFeB film showed a critical thickness of 51~55 nm, at which a relative inversion of the Kerr hysteresis loops was observed. Furthermore, the introduction of W layers induced a second inversion of the Kerr signal in the system. The simulation of the phase difference between the reflection coefficient change caused by the interference of the reflected light and the theoretical analysis of the different inner magnetization dependent Kerr rotations for the pure CoFeB/AAO thin films and W/CoFeB (120 nm)/W/AAO thin films indicate that these Kerr null points are possibly determined by the combination effects of the in-plane magnetization and the interference of the reflected light. As for the CoFeB/AAO systems, the interference of the reflected light will be dominated as the CoFeB layer is thin enough, but the in-plane magnetization will be increased greatly with the ferromagnetic CoFeB layer thickness increase, leading to only one Kerr null point. As for W/CoFeB (120 nm)/W nanoporous thin films, the phase difference between the reflection coefficients change caused by the interference of the reflected light is always dominated due to the non-ferromagnetic W layer. In addition, the introduction of W layers can greatly increase the near zero field magneto-optical susceptibility (the highest χ : -3.04 mdeg/Oe @ $W = 4$ nm) and the saturated Kerr rotation angle (θ_S : 198.6 mdeg @ $W = 74$ nm) by construction of W/CoFeB (120)/W sandwich nanoporous thin films by comparing with the pure CoFeB thin films ($\chi = -1.21$ mdeg/Oe; $\theta_S = 70$ mdeg). The coercivity of the W/CoFeB/W nanoporous thin film at a W thickness of 4 nm is 116.5 Oe, smaller than the pure CoFeB thin films with the same CoFeB thickness of 120 nm (130.5 Oe). Understanding these MO features of the multilayered ferromagnetic nanoporous thin film systems with non-magnetic metallic layers of various thicknesses for tunable MO effects and flexible phase modulation will pave a new approach for fabricating magnetic nanostructure devices for ultrasensitive magneto-optical sensing applications. Particularly, tunable MOKE effects and flexible phase modulation significantly rely on MOKE susceptibility, ellipticity, and reflectance (related to dielectric change or refractive index change), which are suitable for future ultrasensitive magnetometry, thickness sensors, and biosensors of high resolution.

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