Improvement on the magneto-optical Kerr effect of cobalt film with a quadrilayer structure*

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The magneto-optical Kerr effect of the HfO_2/Co/HfO_2/Al multilayer structure is investigated in this work, and an obvious cavity enhancement of the Kerr response for the HfO_2 semiconductor is found both theoretically and experimentally. Surprisingly, a maximum value of about -3° of the polar Kerr rotation for s-polarized incident light is observed in our experiment. We propose that this improvement on the Kerr effect can be attributed to the multiple reflection and optical interference in the cavity, which can also be proved by simulation using the finite element method.

Keywords: resonant optical cavity, magneto-optical effects, magneto-optical recording

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1. Introduction

Cobalt possesses steady physical and chemical properties, and multilayer cobalt films are found to exhibit interesting enhanced magneto-optical (MO) properties.[1,2] Cobalt also has the potential to increase the Kerr rotation, especially the signal-to-noise ratio (SNR) by means of optical interference and multiple reflection.[3,4] Several methods have been proposed to optimize quadrilayer structures that result in the maximum SNR based on various figures of merit (FOMs).[5,6] For a pre-determined reflectance, a systematic design method to maximize the SNR of the quadrilayer structure by maximizing the Kerr rotation and also simultaneously producing a zero ellipticity was presented.[7,8] Since the read-out performance of an MO storage system is related not only to Kerr rotation θ_k and ellipticity ζ_k, but also the optical reflectivity R of the system, the θ_k, ζ_k, and R should be considered as being a whole in the optimizing procedure. For a system utilizing differential detection, in the case of pure shot noise, the FOM has the form $R^{1/2}(\theta_k^2+\zeta_k^2)^{1/2}$.

Usually, by using the polar Kerr effect, a carefully designed quadrilayer system containing a thin magnetic layer can realize the ultimate performance of the magnetic medium for MO readout. Typically, such quadrilayer designs should include a reflective layer as a mirror, a magnetic layer, a spacer, and a capping layer. This arrangement is particularly suited to the conventional MO recording for data writing and reading.[9] The optical cavities formed by the spacer and capping layers give rise to multiple reflections of light inside the structure. Some results on the cavity enhancement of the Kerr effect have been reported in recent years.[10,11] It was found that the cavity enhancement technique leads to a significant increase in the magneto-optical Kerr effect (MOKE) signals by modulating dielectric material of appropriate thickness for constructive reflection interference.[12] In an optimized structure, these partial reflections add up in phase, resulting in an increased polarization rotation of the reflected light. Therefore, such quadrilayer structures can maximize the SNR, which is associated with the differential readout of the polar Kerr effect.

Based on the aforementioned facts, in this work HfO_2/Co/HfO_2/Al/substrate quadrilayers are designed, and the optical cavity effects are investigated theoretically and experimentally for various optically thin quadrilayers. The hybrid structure is found to exhibit interesting MO properties, and provides a feasible way to enhance the Kerr rotation in a broad spectral region. In our theoretical calculations, all the mentioned parameters, including θ_k, ζ_k, and R, are taken into account by investigating the wavelength dependence of the MO response as well as the optical properties of the quadrilayer structure. Furthermore, we confirm the existence of the cavity effect in the quadrilayer structure experimentally. In particular, it is observed that the Kerr rotation has a maximum value about -3°. The experimental results reveal that the Kerr rotation is strongly enhanced by the resonant optical cavity in the HfO_2/Co/HfO_2/Al/substrate quadrilayer. In addition, as HfO_2 is a wide band gap semiconductor with excellent optical transmission in the visible and ultraviolet regions, which provides the potential application both for optical and semi-

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conducting properties simultaneously, we will investigate the role that a semiconductor HfO_2 plays in enhancing the Kerr signals of Co.

2. The MOKE theory and experimental method in a multilayered structure

In respect of the theoretical method, the simplified characteristic matrix technique based on solving Maxwell's equation is adopted to investigate the MO phenomenon in a quadrilayer structure.[13] When a beam of light impinges on the top of the quadrilayer from air, a fraction of the incident beam will backscatter into the air after multiple reflections. If P_i is the electric field at the bottom surface in the i layer, a relation between the electric field in air P_α and that in the semi-infinite substrate P_s can be given by

$$P_\alpha = A_\alpha^{-1} \prod_{i=1}^{4} (A_i D_i A_i^{-1}) A_s P_s \equiv \begin{pmatrix} \boldsymbol{G} & \boldsymbol{H} \\ \boldsymbol{I} & \boldsymbol{J} \end{pmatrix} P_s. \tag{1}$$

Here, matrix A_i is the 4×4 medium boundary matrix. It is related to the tangential components of the electric and magnetic fields, and to the s and p components of the electric field. D_i is also a 4×4 medium propagation matrix that is related to the s and p components of the electric field at the two surfaces of the i-th layer.

The magneto-optical Fresnel reflection coefficients can be determined using the 2×2 matrices G and I:

$$\begin{pmatrix} r_{ss} & r_{sp} \\ r_{ps} & r_{pp} \end{pmatrix} = \boldsymbol{I}\boldsymbol{G}^{-1}. \tag{2}$$

For an s-polarized incident light, the Kerr rotation θ_{Ks} and ellipticity ψ_{Ks} can be related by

$$\theta_K^s = \theta_{Ks} + \mathrm{i}\,\psi_{Ks} = r_{ps}/r_{ss}. \tag{3}$$

For a p-polarized incident light, the Kerr rotation θ_{Kp} and ellipticity ψ_{Kp} can be written as

$$\theta_K^p = \theta_{Kp} + \mathrm{i}\,\psi_{Kp} = r_{sp}/r_{pp}. \tag{4}$$

In addition, using COMSOL Multiphysics 4.3a, a commercial electromagnetic solver based on the finite element method, we numerically demonstrate the optical cavity resonance in the quadrilayer HfO_2/Co/HfO_2/Al/silicon substrate.

For the experimental checking of the MO enhancement, the HfO_2/Co/HfO_2/Al and Co films are deposited on Si (100) substrates by multi-target magnetron sputtering in a vacuum with a base pressure of 2×10^{-5} Pa and Ar_2 pressure of 0.5 Pa. The Co and Al metals are deposited by DC magnetron sputtering, and HfO_2 films are deposited by AC magnetron sputtering. The thickness values of the Co and Al layers are 15 nm and 40 nm, respectively, the thickness of the overcoat HfO_2 dielectric layer is around 10 nm, and the thickness of the intermediate HfO_2 dielectric layer is designed to be 40 nm. The magneto-optical measurements are performed in a homemade MOKE system consisting of pulsed laser light with a 20-Hz repetition rate (Surelite OPO Plus, Continuum) working in polar geometry with a resolution of 2 mdeg in a wavelength range of 410 nm–800 nm.

3. Results and discussion

The quadrilayer structure used to study the MOKE of a practical Co disk is a HfO_2/Co/HfO_2/metallic reflector/silicon substrate, as sketched in Fig. 1. In the structure, an overcoat HfO_2 dielectric layer with a high refractive index and a low extinction coefficient, which can act as an anti-reflection and protection layer, and the intermediate HfO_2 dielectric layer, can be employed to construct an appropriate resonant optical cavity to enhance the SNR.[14] A metallic Al layer is chosen as a reflector layer. In simple terms, we use the linearly s-polarized and p-polarized light separately as incident light on the quadrilayer surface (incident angle $\theta = 2^\circ$), except for special illustration. The dielectric constant of the Co film is cited from Refs. [15] and [16], and the optical constants of Al and HfO_2 are cited from the refractive index database.[17]

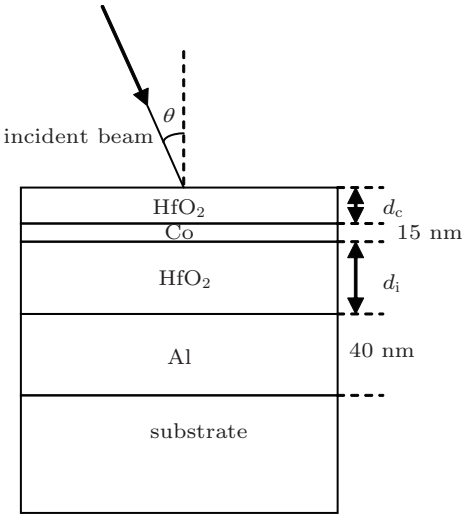


Fig. 1. Schematic diagram of the quadrilayer structure of the magneto-optic device.

Figure 2 shows a comparison of the magneto-optical (MO) polar Kerr effect property between the quadrilayer HfO_2(15 nm)/Co(15 nm)/HfO_2(20 nm)/Al(40 nm)/silicon substrate and a single Co layer film Co(15 nm)/silicon substrate, determined by numerical simulation for incident s-polarized light. In Fig. 2(a), the reflectivity of the single Co layer film is larger than that of the quadrilayer in a wavelength range of 400 nm–517 nm, and the opposite event occurs in a wavelength range of 517 nm–780 nm. Figure 2(b) shows

that the Kerr ellipticity value is within a range of 0.1°–0.38° for the quadrilayer, and −0.6°–0.1° for the single Co layer. As shown in Fig. 2(c), the absolute value of the Kerr rotation for the quadrilayer is larger than that of the single Co layer. Overall, one can see that the FOM of the quadrilayer is superior to that of the single Co layer (see Fig. 2(d)). In other words, the MO performance of the quadrilayer is better than that of the single Co layer. This result can be attributed to the complicated multiple reflection and optical interference in the quadrilayer structure, especially at short wavelengths.

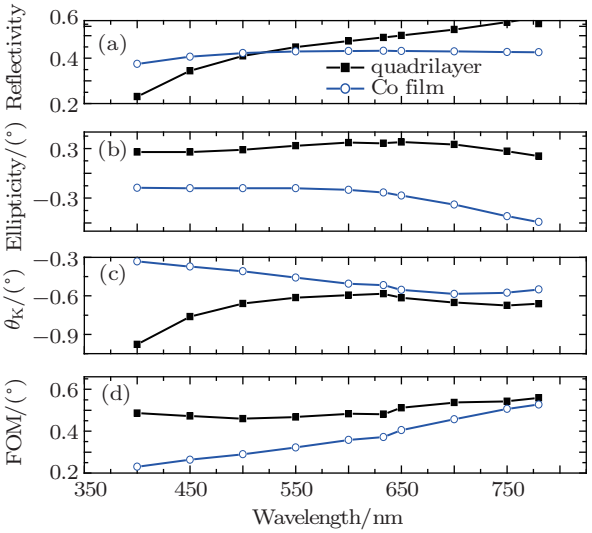


Fig. 2. (color online) Comparisons of (a) reflectivity, (b) ellipticity, (c) Kerr rotation, and (d) the FOM between the two kinds of samples.

By sweeping the thickness values of the cap and spacer in the HfO_2/Co/HfO_2/Al/silicon substrate structure with the Co film layer kept at 15-nm thickness for incident *s*-polarized light, optimal optical resonant cavities are achieved in the wavelength within a range of 400 nm–780 nm. In the optimization procedure, elementary conditions for MO readout, i.e. small Kerr ellipticity and reasonable reflectivity, are used. Figure 3 shows the optimum FOM and the corresponding reflectivity, polar Kerr rotation, Kerr ellipticity, and also the relevant thickness values of the cap and spacer layer. Generally, the thickness values of the cap and intermediate cannot be the same for an optimal design due to the difference between the dielectric environments surrounding the two HfO_2layers.

As indicated in Fig. 3, for a thin magnetic layer, the intermediate and cap layers make a considerable contribution to the interference structure and the enhancement of the Kerr effect. The thickness values of the spacer and cap layers, corresponding to the optimum FOMs, are depicted in Fig. 3(b). As can be seen, the cap thickness is continuously smooth, while the optimum intermediate thickness has an abrupt rise from the wavelength range 500 nm to 550 nm. In Fig. 3(c), the magnitude of the Kerr rotation in a wavelength range of 400 nm–500 nm is greater than 1°, which is large enough to be detected by simple instruments. Simultaneously, an almost vanishing ellipticity in this wavelength range avoids any additional compensating optical element, thereby reducing the size of the readout system. The results show that this structure exhibits outstanding MO performance for a comparatively short visible wavelength.

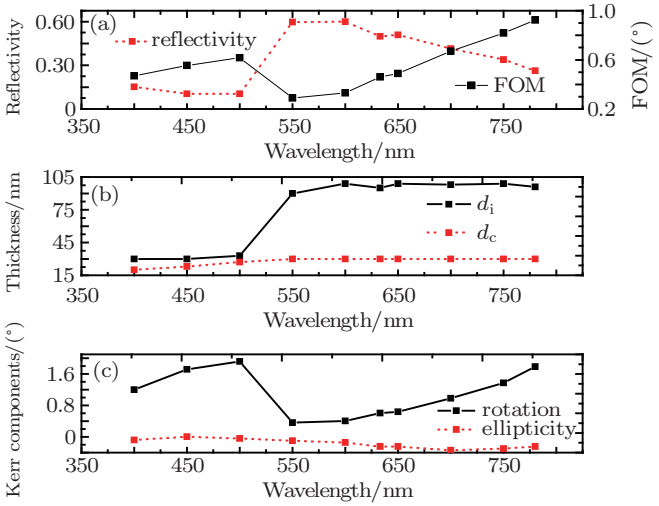


Fig. 3. (color online) The wavelength dependences of (a) the optimized FOM and corresponding reflectivity, (b) the thickness values of the cap and intermediate layers, and (c) the Kerr rotation, Kerr ellipticity.

According to the aforementioned simulations, the MO properties of the optimized quadrilayer structures are exhibited in detail. However, the condition of the cavity resonance in our MO system has not been examined yet. In the following, we will experimentally investigate the existence of the cavity effect in the quadrilayer structure. Figure 4 shows the experimental and theoretical spectra of the polar Kerr rotation for the HfO_2(11 nm)/Co(15 nm)/HfO_2(40 nm)/Al(40 nm)/silicon quadrilayer substrate. An out-of-plane field of up to 1.7 T is applied. Figure 4(a) shows that the high enhancement of the MO Kerr rotation is obtained in the spectral region. As for *s*-polarized incident light, the Kerr rotation has a maximum value of −3° at a wavelength of 540 nm. In addition, the giant Kerr rotation is achieved to be 2.25° at a wavelength of 535 nm for *p*-polarized incident light (incident angle $\theta = 2°$). The Kerr rotation value is almost six times as large as that of the same thick cobalt layer film at a wavelength of 540 nm (see Fig. 2). On the other hand, one can see that the signs of the Kerr rotation are opposite to each other for the two kinds of polarized incident light beams in a wavelength range of 430 nm–610 nm, but they are the same in a wavelength range of 610 nm–710 nm. This result may be ascribed to the fact that *s*-polarized and *p*-polarized incident light own different boundary relations for the multilayer interface. In addition, using the aforementioned matrix technique, the theoretical calculation results are obtained and shown in Fig. 4(b), and consequently, a quantitative agreement between the theory and experiment is attained.

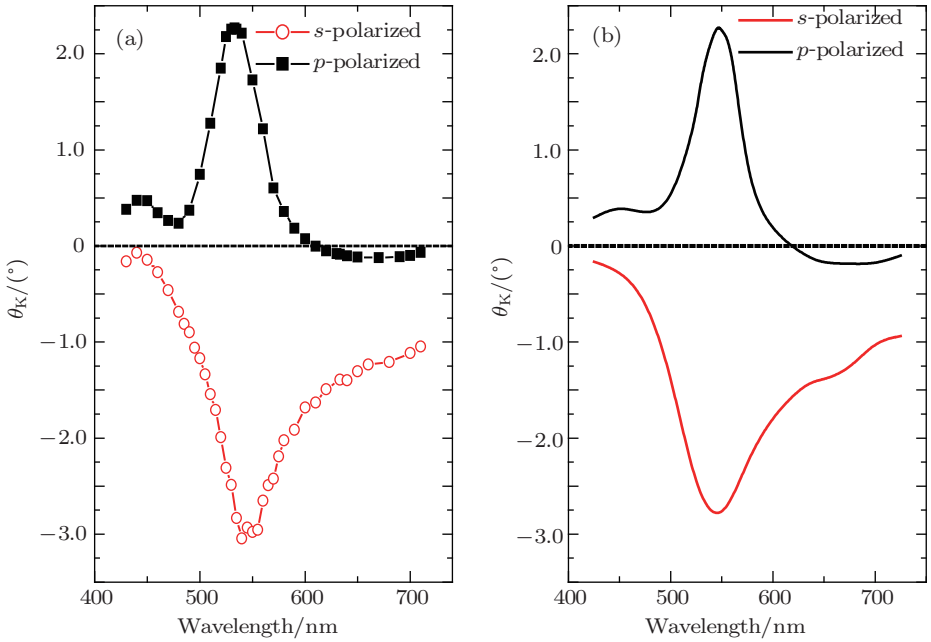


Fig. 4. (color online) The experimental and theoretical Kerr spectra for the HfO_2(11 nm)/Co(15 nm)/HfO_2(40 nm)/Al(40 nm)/silicon quadrilayer substrate. (a) The experimental measurements for *s*-polarized and *p*-polarized incident light beams, respectively. (b) Theoretical simulations for *s*-polarized and *p*-polarized incident light beams, respectively.

Figure 5 presents the reflectivity spectra for the two kinds of polarized incident light beams. The reflectivity spectra are measured by an ellipsometer. As can be observed from Fig. 5, there are dips on both the incident *s*-polarized and *p*-polarized light reflectivity spectra. For comparison, the position of the Kerr spectra peak/dip in Fig. 4(a) corresponds to the low value of reflectance in Fig. 5. Therefore, the enhanced Kerr effect is related to the occurrence of weak reflection. These results imply that the enhanced Kerr rotation is attributed to the cavity resonance in the quadrilayer.

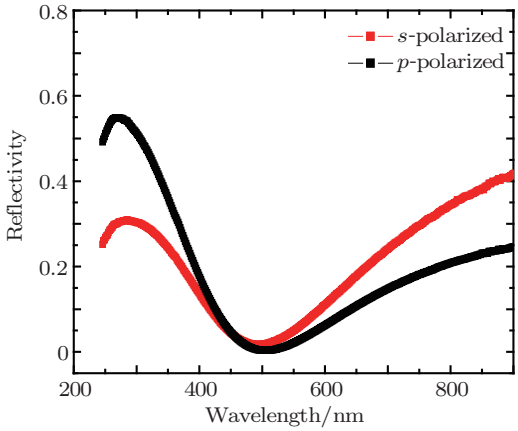


Fig. 5. (color online) The reflectivity spectra of the two kinds of polarized light beams for the HfO_2(11 nm)/Co(15 nm)/HfO_2(40 nm)/Al(40 nm)/substrate quadrilayer.

In order to further clarify the cavity resonance effect on the MO response with the aforementioned experiment, we calculate the distribution of the electric field intensity in the incoming light field by employing COMSOL Multiphysics 4.3a software. This commercial software has been widely adopted in photonics theoretical analysis in recent years. The development of some novel photonics is related to the use of this software.[18–20] Figure 6 shows the electric field distribution along the incidence plane of the same multilayer structure for the two kinds of incoming *s*-polarized plane wave sources with wavelengths of 540 nm and 700 nm. The amplitude of the incoming electric field wave is set to be unit, and the theoretical calculation corresponds to the aforementioned experimental results in Fig. 4. The electric field intensity between the cobalt layer and intermediate HfO_2 layer in Fig. 6(a) is larger than that between the two corresponding layers in Fig. 6(b). For comparison, it is possible to consider that the optical cavity resonance occurs around an incident wavelength of 540 nm (see Fig. 6(a)), and therefore the cavity effect causes a giant Kerr rotation. Apparently, this phenomenon is due to a substantial contribution from the interference effect arising as a result of the summation of the waves reflected from the interfaces of the optical cavity. Consequently, it is clarified that the optical cavity resonance can enhance the Kerr rotation of the multilayer structure by modulating the incident light wavelength and keeping the intermediate and capping HfO_2 layers unchanged.

In view of our measurements and the simulations mentioned above, it is noted that the Kerr rotation can be greatly increased when the cavity resonance is achieved, but simultaneously the reflectivity is so low that the Kerr signal is difficult to test using the Kerr spectrometer and leads to a low FOM. Therefore, in order to improve the Kerr signal performance,

the sharp peak of the cavity resonance should be avoided in application. In this respect, it is significant to investigate the condition of the cavity resonance in our MO system.

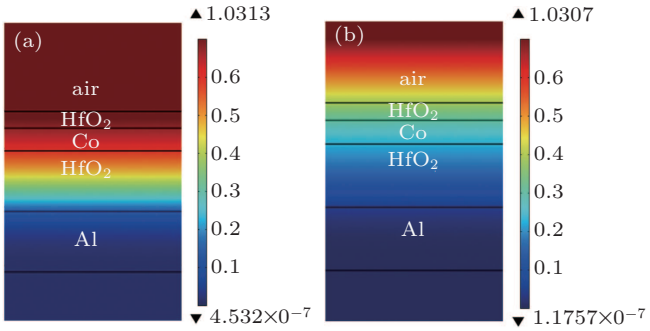


Fig. 6. (color online) The distributions of electric field intensity in the HfO_2(11 nm)/Co(15 nm)/HfO_2(40 nm)/Al(40 nm)/silicon quadrilayer substrate illuminated by incident *s*-polarized light. (a) The simulation of wavelength 540 nm, and (b) the simulation of wavelength 700 nm. The left and right boundaries are set to be periodic.

4. Conclusions

Based on theoretical and experimental methods, the MOKE of the quadrilayer HfO_2/Co/HfO_2/Al/substrate structure is investigated in this study. Using the matrix technique, the polar Kerr rotation and optimal FOM are calculated in detail. The cavity enhancement of the magneto-optical Kerr response of the multilayer for the semiconductor HfO_2 is foreseen by theoretical calculation. Furthermore, the large Kerr effect is observed experimentally for the quadrilayer film. In particular, the polar Kerr rotation value about -3° for *s*-polarized incident light is observed in our experiment. The simulation and the experimental results are found to be in good agreement. It is strongly confirmed that the enhanced magneto-optical Kerr response originates from the optical cavity effect of the quadrilayer structure. The tuning of the MO behavior renders the system important for technological applications in MO data storage media, magnetic field sensors, and the new field of optoelectronics.

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