Magneto-optical Kerr rotation and color in ultrathin lossy dielectric

JING ZHANG¹, HAI WANG¹(ª), XIN QU², YUN SONG ZHOU¹ and LINA LI³

¹ Department of Physics, Capital Normal University, Beijing Key Laboratory of Metamaterials and Devices, Key Laboratory of Terahertz Optoelectronics, Ministry of Education, and Beijing Advanced Innovation Center for Imaging Technology - Beijing, 100048, PRC
² Shenzhen High Trend Tech. Co., Ltd. - Shenzhen, 518129, PRC
³ College of Preschool Education, Capital Normal University - Beijing, 100048, PRC

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Abstract – Ultra-thin optical coating comprising nanometer-thick silicon absorbing films on iron substrates can display strong optical interference effects. A resonance peak of ∼1.6° longitudinal Kerr rotation with the silicon thickness of ∼47 nm was found at the wavelength of 660 nm. The optical properties of silicon thin films were well controlled by the sputtering power. Non-iridescence color exhibition and Kerr rotation enhancement can be manipulated and encoded individually. Non-iridescence color exhibition and Kerr rotation enhancement can be manipulated and encoded individually. The interference persists in highly absorbing films, yielding a new type of optical coating with ultrathin thickness due to the phase shifts at the boundary between lossy dielectric and air [1–10]. The non-iridescent saturated colors were evidenced in lossy germanium layers (5–20 nm thickness) deposited on gold substrate [1]. The first-order Fabry-Perot optical resonance dominated the interference in ultrathin lossy dielectric film [7,8]. Diverse absorbing materials, such as HgTe, InAs, GaAs, Ge and Si [3–10], had been reported to realize such a strong interference and its related color exhibition. However, an absorbing dielectric with the fixed optical parameters limits its optical exhibitions and applications. In our previous work [11], it is revealed by calculations that the real refractive index of dielectric plays a major role on the variations of color and Kerr signal, while the absorbing term adjusts the intensive color exhibition and Kerr enhancement at much thinner dielectric thickness.

Here, we showed that the optical properties of a silicon film are manipulated simply by the sputtering power. In a silicon/iron structure, both color exhibition and Kerr rotation were encoded and adjusted simply by the sputtering power individually. A ∼1.6° longitudinal Kerr rotation was realized at a wavelength of 660 nm with the thickness of silicon ∼47 nm, accompanying a color band transition visually. The color deviation was undetectable in a wide viewing angle with respect to the surface normal. The controllable interference in a lossy medium with a broad range optical exhibition benefits the applications of a lossy dielectric optical coating.

The silicon/iron bilayers were fabricated by DC magnetron sputtering on coverslips. The sample holders are well attached on a circulating water cooling base during deposition. The base pressure was better than 5 × 10⁻⁵ Pa. The argon flow rate was fixed as 10.0 sccm. The deposition rate of iron was 0.39 nm/s and the thickness of iron film was 100 nm. The longitudinal Kerr rotation angle (θK) of the bare iron film was 100 millidegree. Our experiment silicon target is from ZhongNuo Advanced Material (Beijing) Technology Co. Limited, with the purity 99.999%. The deposition rate of silicon with the sputtering power of 36 W, 112 W, 140 W and 250 W were 0.008 nm/s, 0.025 nm/s, 0.03 nm/s and 0.046 nm/s, respectively. Film thicknesses were examined by a surface

(ª)E-mail: wanghai_0410@qq.com (corresponding author)
The longitudinal Kerr rotation angle was measured by NanoMOKE-III (Durham Magneto Optics Ltd.) at 660 nm with 45-degree s-polarized wave incidence.

Figure 1(a) shows the schematic plot of calculation model consisting of a single dielectric layer on a ferromagnetic metal, which is an asymmetric Fabry-Perot (FP) optical cavity. An incident beam polarized perpendicular to the plane of incidence gives rise firstly to a series of reflected beams, which are also polarized perpendicular to the plane of incidence. The beams within the dielectric layer produces a Kerr component polarized parallel to the plane of incidence, which subsequently suffers multiple reflections at the boundaries of the dielectric and gives a total amplitude contribution in the beam reflected from the film. The amplitude monotonically decreases with the reflecting/refracting order. Taking s-polarized light as an example, the reflecting substrate is not ferromagnetic, p-polarized lights does not appear in the multiple reflection and refraction. However, when the reflecting substrate is ferromagnetic, reflection and refraction lights on the interfaces become new light sources for the next reflection and refraction. Both s- and p-polarized components of lights should be considered. The former represents the usual reflectance of the film for polarized light incidence, the latter represents the new p-polarized generating from the interfaces of dielectric/ferromagnetic [11,12].

The color, \( \theta_K \) and reflectivity variation with different silicon thickness (5–55 nm) at the sputtering power of 80 W in a silicon/iron structure are shown in fig. 1(b). Color of the sample starts as yellowish brown at thinner Si thickness, follows by drab, then purple gray, and ends up as dark blue. As the reflectivity approaches to its minimum, \( \theta_K \) finds its maximum (~1.6\(^\circ\)) around the thickness of silicon layer ~47 nm. A big jump of \( \theta_K \), from a positive 1.6\(^\circ\) to a negative 0.35\(^\circ\), is observed in the curve of \( \theta_K \) vs. \( d \). The peak and valley difference of \( \theta_K \) is ~1.95\(^\circ\), and the corresponding thickness difference of silicon is ~4.3 nm. Compared to the maximum longitudinal Kerr rotation (0.1\(^\circ\)) obtained in the bare thin iron film, the enhancement factor of \( \theta_K \) is ~16. The yellow and red solid lines in fig. 1(b) are the simulation results for \( \theta_K \) and reflectivity by an asymmetric Fabry-Perot model, which match well with the experiments. The simulation parameters are illustrated in figure caption and the details can be referred to [11]. Qureshi et al. reported that a quite huge optical Kerr effect had been realized by 320 nm SiO\(_2\) in infrared regime, which can explore the use of optical coatings for near-field and far-field measurements of the polar Kerr effect in small magnetic structures. For a single layer of SiN (70 nm) on nickel, a Kerr rotation increase of a factor of 5 at 785 nm wavelength, and a reduction in the size of the smallest nanomagnet that they could measure [13,14]. An enhancement \( \theta_K \) at 660 nm with the ultrathin single lossy dielectric coating benefits the lateral spatial resolution improvement of ferromagnetic domain observation, due to the small modification of surface morphology as well as the high signal-to-noise ratio.

The optical properties of silicon can be adjusted by the fabrication parameters, such as the sputtering power, the chamber pressure, the substrate temperature, the flow rate of argon gas, and the target-to-substrate distance, etc. Here, we demonstrate the optical properties manipulation by the sputtering power, varying from 36 to 250 W. Two typical experimental and calculation results of \( \theta_K \) with different sputtering powers are shown in fig. 2(a). As the sputtering power is 36 W, a positive peak value of \( \theta_K \) (0.5\(^\circ\)) is obtained at \( d \approx 54 \text{ nm} \), and then the positive \( \theta_K \) reaches its maximum (1.6\(^\circ\)) at the sputtering power of 80 W. The amplitude of \( \theta_K \) falls into a negative peak valley (0.35\(^\circ\)) at \( d \approx 27 \text{ nm} \) with the sputtering power of 250 W. It is noted that increasing the sputtering power, the maximum \( \theta_K \) with a significant sign jump appears at thinner silicon thickness.

The optical properties of silicon film rely on its complex refractive index: the real refractive index (\( n_2 \)) and the absorption coefficient (\( k_2 \)). Figure 2(b) shows the
Fig. 2: (Color online) (a) Experimental and theoretical $\theta_K$ vs. the thickness of coating. Two different colored lines represent the $\theta_K$ spectra with the sputtering power of 36 W and 250 W, respectively. The solid lines are the theoretical results and the dot lines are the measured results. (b) The optical properties of the Si film as a function of the sputtering power. Blue and red solid lines represent the simulation of the real part of refractive index of Si and the absorption coefficient of Si, respectively. Single dots demonstrate the experiment results. (c) Six typical theoretical $\theta_K$-d curves with different sputtering power. The insert plots in (c) are peak and valley difference of $\theta_K$ and the thickness difference of Si under different sputtering power.

optical properties of Si films as a function of the sputtering power. $n_2$ and $k_2$, acquired from the best simulation for $\theta_K$-d curves at the wavelength of 660 nm, increase linearly with the increase of sputtering power ranging from 36 to 250 W. $n_2$ varies from 2.4 to 4.1 and $k_2$ changes from 0.01 to 0.15. The increase of the refractive index and the extinction coefficient are attributed to the dense uniform film. With the increase of sputtering power, the energy loss of the sputtering particles in collision with argon gas molecules reduces [15]. A set of $n_2$ and $k_2$ corresponds to a certain sputtering power. It is noted that by tuning the oxygen/argon flow rate ratio, the refractive index of dielectric film can be adjusted also. Recently, Mao et al. presented that in the structure of two metallic films spaced by a SiO$_x$ dielectric layer, the absorption coefficient of SiO$_x$ is controlled systematically to realize a new type of color filter with a broad angle insensitivity [16].

Figure 2(c) shows calculated $\theta_K$-d spectra with six different sputtering powers. The $\theta_K$-d curves exhibit a peak-valley characteristic, which moves to the thinner dielectric thickness with the increase of the sputtering power. As the sputtering power is lower than 54 W, the peak value dominates the feature of peak-valley structure. $\theta_K$-d experiences a significant transition while the sputtering power is larger than 100 W, where the valley plays a major role for the $\theta_K$-d. Between 54 and 100 W, a huge $\theta_K$ single can be achieved in a narrow dielectric thickness range due to the best impedance matching condition [11,17]. However, in view of application, a stable $\theta_K$ single of a real sample needs a certain dielectric thickness tolerance. In our experiments, the best experimental condition is achieved as: $\theta_K > 1.5^\circ$ under $\sim$80 W for silicon deposition with $\sim$1 nm silicon thickness tolerance. The peak and valley difference of $\theta_K$ and d, derived from experiment data, are presented in the inserted plot of fig. 2(c), in which the best experimental condition regime is indicated by two black dashed lines. Recently, Daria et al. realized ultrahigh sensitivity detection on the environment refractive index variation by the transversal magneto-optical Kerr effect [18]. An intense magneto-optical Kerr effect (MOKE) resonance in an ultrathin lossy dielectric thin film allows for more precise thickness measurements of the MOKE resonance position and shift.

The front views of the resulting samples taken under ambient sunlight are given in fig. 3(a). The four sections correspond to different sputtering powers of silicon thin films. Each sample comprises an optically thick iron deposited on a coverslip with a film of silicon gradually varying thickness. The color bands with the sputtering power of 36 W, 112 W, 140 W and 250 W, respectively. (b) The fabricated sample taken at different incident angles 10°, 20°, 50°, 70° with the sputtering power of 250 W.

Fig. 3: (Color online) Photos of the samples comprising optically thick iron deposited on a coverslip, with a film of silicon of gradually varying thickness. (a) The color bands with the sputtering power of 36 W, 112 W, 140 W and 250 W, respectively. (b) The fabricated sample taken at different incident angles 10°, 20°, 50°, 70° with the sputtering power of 250 W.
dielectric coating is significantly less sensitive to the angle of incidence. As shown in fig. 3(b), there are no observable color variations in a broad range observation angle, ranging from 0 to 70 degree. The intense interference is realized in an ultra-thin lossy dielectric film on reflecting metal substrate structure, due to the non-trivial optical phases aroused by the absorption terms accumulating at the interfaces [19–22]. Such a non-trivial phase accumulation in ultrathin film is small, yielding a wide viewing angle [2].

Table 1 demonstrates a spectrum of non-iridescent colors including blue, yellow, and purple with different $\theta_K$ by controlling the sputtering power of silicon. The sputtering powers are set as 112 W, 140 W and 250 W. As seen from table 1, yellow with the $\theta_K$ of +0.133°, +0.12° and +0.118°; blue with the $\theta_K$ of −0.46°, −0.21° and +0.13°; purple with the $\theta_K$ of −0.36°, +0.17° and +0.16°. The advantage of our approach is that same color but different $\theta_K$ can be achieved in ultrathin lossy dielectric films (first color period) by only using the varying sputtering power method.

In summary, a $\sim$1.6° longitudinal Kerr rotation is reported in silicon/iron structure at the wavelength of 660 nm, which can be applied to enhance the lateral spatial resolution or improve observation sensitivity. The optical properties of silicon film are manipulated simply by the sputtering power, resulting in the Kerr rotation enhancement and non-iridescent color exhibition. The color is insensitive to the incidence angle in a broad range. The color and $\theta_K$ can be individually encoded in ultrathin lossy films by controlling the sputtering power. Some promising applications are expected, such as ultrathin domain detectors, anti-counterfeiting, information coding, solar cells, and even biochemical sensors.

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Magneto-optical Kerr rotation and color in ultrathin lossy dielectric

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