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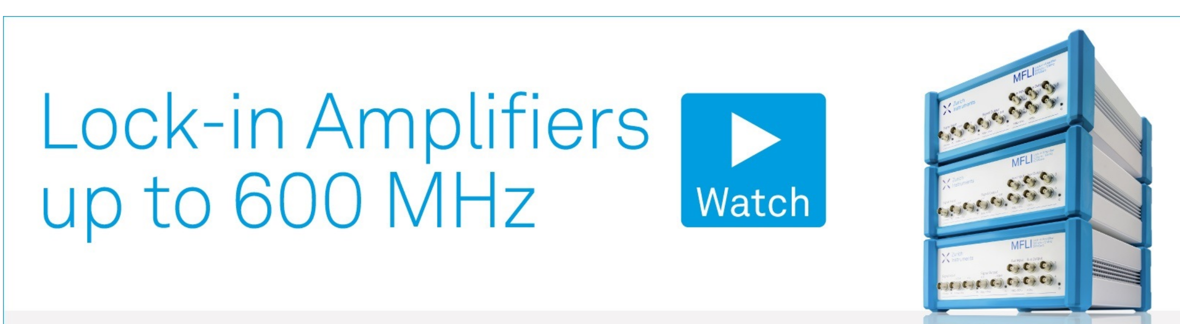

Strong in-plane anisotropy of magneto-optical Kerr effect in corrugated cobalt films deposited on highly ordered two-dimensional colloidal crystals

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The corrugated cobalt films are investigated by magneto-optical Kerr effect and vibrating sample magnetometer (VSM). The films are fabricated by depositing thin cobalt layers on a large area single-domain two-dimensional (2D) hexagonal close-packing colloidal crystal. Strong in-plane anisotropy of the Kerr rotation hysteresis loop is found in sharp contrast to isotropic hysteresis loops obtained by the VSM. The anisotropy of such magneto-optical Kerr rotation disappears when randomly distributed colloidal spheres were used as the substrate. Our observations show that the magneto-optical effect does not completely correspond with the average magnetization state in such a 2D periodic magnetic network. © *2011 American Institute of Physics*. [doi:10.1063/1.3544582]

Recently, arrays of magnetic particles have been studied intensely, owing to fundamental physics and the potential applications in high density recording media.[1,2] By controlling the size and the shape of the individual particle,[3–8] the interactions among the particles,[9,10] it is possible to manipulate the magnetic properties, for instance, tuning the magnetic anisotropy and magnetic domain configurations. While the properties of magnetic particles are studied intensely, the influence of the array ordering has not yet been explored.

Magneto-optic Kerr effect (MOKE) is one of the common methods for the investigation of magnetic as well as optical properties of these arrays. This technique shows a monolayer sensitivity and space resolution in a micrometer scale.[11–13] It is widely believed that a Kerr rotation is totally derived from magnetization-induced polarization rotation of a light beam. However, very recently, it was observed that the MOKE could be affected by surface plasmons, which are coherent electron oscillations that exist at the interface between metal and dielectric interfaces.[14–18]

In this letter, we report that the MOKE signals depend strongly on the relative orientation between the in-plane magnetic field direction and the principle axis of the highly ordered corrugated magnetic Co films. The hysteresis loop from the vibrating sample magnetometer (VSM) measurements, however, did not show any variations upon changing the relative orientation. It is further observed that such a MOKE anisotropy disappears for a randomly corrugated Co layer when randomly distributed colloidal spheres are used as the substrate.

The Co networks with an ordered spatial corrugation are prepared as follows. First, two-dimensional (2D) colloidal crystals consisting of hexagonally close-packed monodisperse polystyrene spheres (diameter $d=1.587$ μm with a size deviation of 1.3%, purchased from Duke Scientific Corp.) were prepared. A centimeter-sized single-domain 2D colloidal crystal on a glass slide can be grown using our recently developed self-assembly method. Details of the growth technique can be found in Ref. 19. A thin Co layer was then sputter-deposited on the 2D colloidal crystal. The templated Co microcaps constituted an interlinked array with the cap diameter being dictated by the colloidal spheres.

Figure 1(a) shows the schematic setup of the MOKE measurement. A laser beam of 670 nm wavelength is *S*-polarized by a Glan–Thompson polarizer and impinged on the sample surface. The angle of the incidence is 40° and the size of the laser beam is about 1 mm in diameter. After passing through a second polarizer, the specular beam is collected by the photodiode. The field dependent Kerr rotation is calculated through the change of the intensity. The magnetic field is aligned along the plane of incidence and parallel to the sample surface. This geometry is sensitive to the magnetization component along the field direction if the magnetic easy axis of the film is within the film plane.[20] Figure 1(b) shows a field emission scanning electron microscopy (SEM) image of the prepared sample. From the SEM image as well as the laser diffraction pattern given in the inset of Fig. 1(b), the long-range ordering of the Co-caped colloidal

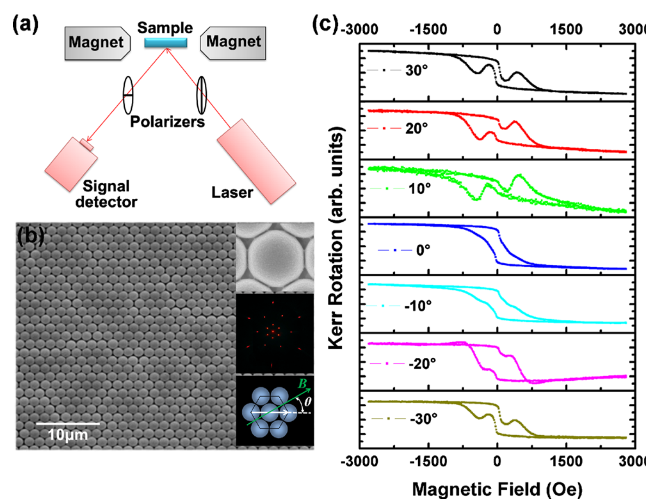

FIG. 1. (Color online) (a) Schematic of the longitudinal magneto-optic measurement setup. (b) Field emission SEM image of a corrugated Co layer deposited on a 2D colloidal crystal consisting of PS spheres with a diameter of 1.587 μm. Insets: top, a magnified portion of the sample; middle, laser diffraction pattern obtained by normally impinging a laser beam (wavelength $\lambda=633$ nm and spot size of 1 mm) on the sample; bottom, the angle (θ) between the principle axis of the 2D triangle lattice and the direction of the magnetic field. (c) Kerr hysteresis loops measured at different angles (θ) in steps of 10°. The nominal Co thickness on the spheres is 40 nm.

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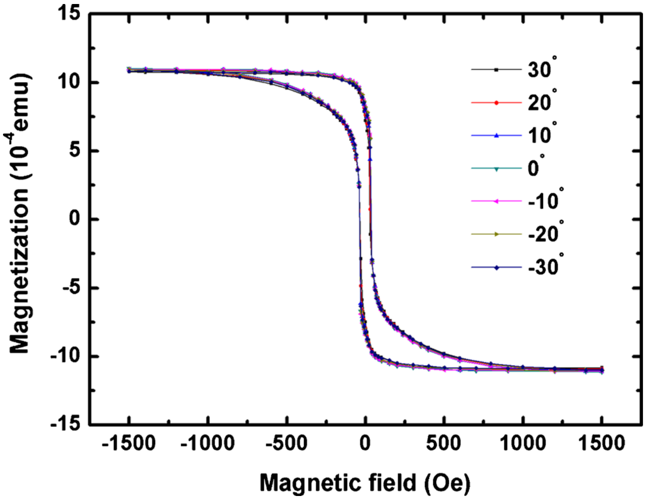

FIG. 2. (Color online) Magnetic hysteresis loops measured by VSM with the sample orientation set at different angles (θ) relative to the external magnetic field within the sample plane. The same sample as in Fig. 1 is used.

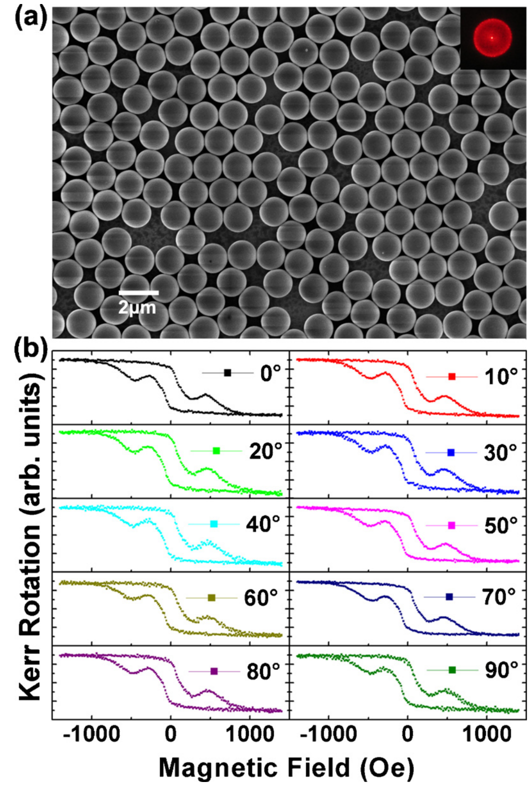

FIG. 3. (Color online) (a) Field emission SEM image of 40 nm Co layer deposited disordered colloidal spheres. The diameter of the polystyrene spheres is 1.587 μm. The inset shows the laser diffraction pattern. (b) Kerr loops measured under different magnetic field directions within the sample plane.

crystal is confirmed. Because of the periodicity in the generated Co network, there are different orders of diffracted light spots. In our measurements, only the specular beam is collected. In order to characterize the anisotropy, we rotate the sample within the film plane and measure the Kerr hysteresis loops for different θ, the angle between the magnetic field and the principle axis of the 2D triangle lattice. In our measurements, θ is systematically varied from $-30°$ to $+30°$ with the negative sign indicating an anticlockwise rotation. All measurements are carried out at room temperature.

Figure 1(c) shows the measured in-plane angle dependent Kerr hysteresis loops of a 40 nm Co film deposited on two-dimensional colloidal crystals. One can notice that the Kerr hysteresis loops are significantly different for different values of θ. For $\theta=-30°$, there are two conspicuous steps in the Kerr hysteresis curve. With slightly increasing θ, the two-step feature becomes less pronounced. And at $\theta=0°$, such steps are almost vanished and change to a smoother hysteresis loop. With further increasing θ, the two-step feature appears again. After 60° of rotation, the Kerr loop repeats its original feature that we observed at $\theta=-30°$, as a result of the sixfold symmetry of the periodic network. Such a feature has not been reported before in the capped magnetic lattice systems.[21–23] Our results clearly demonstrate a strong anisotropy of MOKE in a periodically corrugated Co film deposited on the surface of a single-domain 2D colloidal crystal. The observed sixfold anisotropy of the Kerr hysteresis loop suggests its strong correlation with the highly ordered 2D colloidal crystal substrate. To further confirm this, a controlled experiment with a smooth Co film of the same thickness was prepared and the same measurement condition was used. We, however, did not find any strong angle dependence of the Kerr hysteresis loops. Instead, only a weak uniaxial anisotropy with variation range of about 20 Oe for the coercive field was observed.

In order to search the origin of the observed sixfold anisotropy of the Kerr loops, we measured the magnetic hysteresis loops for the same sample in Fig. 1 by VSM. Figure 2 shows the corresponding in-plane angle dependent VSM results. Interestingly, we find that the total magnetic moment of the sample obtained by the VSM does not change regardless of the variation of the in-plane angle between the periodic Co network principle axis and the external magnetic field direction. The dramatic difference between the Kerr loops and the VSM loops obviously shows that the MOKE does not coincide with the magnetization state in our patterned Co films.

Currently, an exact calculation of the MOKE of the interconnected Co half-shell arrays is not yet available. However, a qualitative explanation for the observed MOKE anisotropy can be made by considering the unique quasi-three-dimensional topography feature and the long-range order of the Co film network as follows. First, the templated Co microcaps with a nominal thickness of 40 nm should be interlinked[24] to each other, as shown in the inset of Fig. 1, and it is plausible that the magnetic domains, especially within the area at the connections among the equator of the spheres, may change when the sample is rotated under the magnetic field within the sample plane. The MOKE could be sensitive to these tiny magnetic configuration changes, while these tiny changes have negligible effect on the total magnetic moment of the film detected by VSM. Second, the optical interference[25] between the magnetic-optical response and the periodic topographical pattern may also contribute to the anisotropy of the MOKE.[21]

The MOKE anisotropy was found only in a highly ordered Co network patterned on a single-domain colloidal crystal. When disordered colloidal spheres were used as the substrate, the MOKE was found to be nearly independent on the magnetic field direction within the sample plane. Figure 3(b) shows the Kerr loops of a typical disordered sample [see the SEM image in Fig. 3(a)]. The Kerr loops were found to

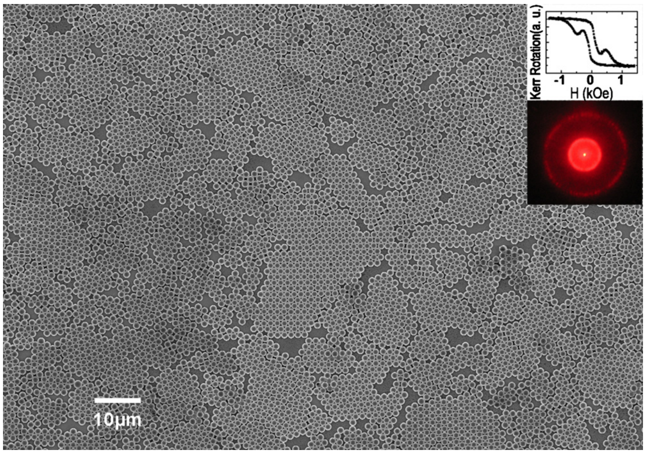

FIG. 4. (Color online) Field emission SEM image of 40 nm Co deposited on sample of short-range order. The diameter of the polystyrene spheres is 1.587 μm. MOKE loop and laser diffraction patterns of the sample are shown in the inset.

show two conspicuous steps in each Kerr hysteresis curve. Although the Kerr hysteresis curve shape was quite similar to that of a highly ordered Co network at $\theta = \pm 30°$, it shows almost no difference upon varying the magnetic field direction within the sample plane. Our observations clearly demonstrate that the MOKE anisotropy in Fig. 1(c) is originated from the high ordering of the array.

Furthermore, even in the sample with short-range order, as shown in Fig. 4, no MOKE anisotropy is found in our measurements. A recent study of hexagonal antidot Fe films[18] shows that no anisotropy in MOKE was detected in a microstructured planar Fe layer by changing the in-plane magnetic field direction. The authors explain that the absence of the anisotropy was due to more than one structural domain that was covered in the illumination spot (~ 1 mm^2). Our results of the sample with short-range order confirm this point. So, it is probably due to lager-area single structural domain [Fig. 1(b)] within light illumination spot as well as the three-dimensional topography of the microstructures that permit the anisotropy in Fig. 1(c) detectable.

Here, we will not attend to analyze the configuration of the magnetic domain in detail, because most caps on the microsphere are interconnected to the surrounding six other ones, as well as the three-dimensional topography of the templated film, which makes it difficult to give out the specific magnetic configuration. Very recently, some related works have been reported to reveal the properties of magnetic caps deposited on microspheres.[22,23] These works can provide some insights for the magnetic configuration of the caps. However, further effort may be needed to clearly interpret these Kerr loops reported here.

In summary, a strong in-plane magneto-optical anisotropy is observed in a Co thin film formed on a single-domain 2D colloidal crystal substrate. Such an effect is found to disappear when the Co film is formed on randomly distributed colloidal spheres or a monolayer with only a short-range ordering. In recent studies, magnetic-optic effect has been explored in magnetophotonic crystals[26] and magnetic plasmonic crystals[27–29] containing magnetic materials, where the optical properties of these microstructured media are found to be controllable under an external dc magnetic field. From our studies, it is anticipated that the optical response could be further tailored when the static field is applied along different symmetry axes of the crystals.

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