Longitudinal Magneto-Optical Kerr Effect in Ce:YIG Thin Films Incorporating Gold Nanoparticles

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Abstract— We report an experimental study on optical and magneto-optical properties of Ce-substituted yttrium iron garnet thin films incorporating gold nanoparticles. Au nanoparticles were formed by heating Au thin film on cubic quartz and garnet substrate in vacuum chamber and a Ce:YIG layer was deposited on them by the aid of Pulsed laser deposition method. A large enhancement of the longitudinal Kerr effect was obtained in sample with Au nanoparticles on quartz substrate and the effect of substrate material on improving optical and magneto-optical response of samples were investigated.

KEYWORDS: Pulsed laser deposition, Au nanoparticles, longitudinal magneto-optical Kerr effect, Surface plasmon resonance.

I. INTRODUCTION

Garnet thin films have attracted much attention for various magneto-optical applications such as magnetic-field sensors, optical switchers and magneto-optical isolators [1-3]. In these magnetic thin films, many schemes have been proposed to realize the enhancement of magneto-optical Faraday rotation (FR) with enhanced transmission. A method to control the magneto-optical effect is use of them in multilayers structure such as magneto-photonic crystals (MPC) [4]. These multilayers enhanced magneto-optical effects by means of light localization in magnetic layers and enhanced light- matter interactions. But, there is an important trade-off between large FR and transmittance. Indeed there have been many experimental and theoretical studies on simultaneous enhanced optical and magneto-optical properties of 1D-MPC [4-6], use of another structure with lower thickness attracts much interest. Another prospective method to enhance the magneto-optical and optical properties is to utilize surface plasmon resonance (SPR) which is excited by coupling light and electron waves using total internal reflection, nanoparticle and diffraction grating [7]. Since localized surface Plasmon resonance (LSPR) frequencies of the metallic nanoparticles are sensitive to the permittivity of surrounding medium, these resonances and so enhanced magneto-optical (MO) response are also affected by the presence of the substrate. Thus the change in substrate may appearance as the alteration in the strength of the interaction with nanoparticles [8].

On the other hand, the high MO answer of samples and low propagation loss at higher wavelengths as well as visible region are essential in practical magneto-optical devices, which will be satisfied by new MO materials such as Ce-substituted garnet (Ce:YIG) thin films [9, 10].

As a consequence we investigated the effect of different substrates on enhanced the longitudinal magneto-optical Kerr effect LMOKE associated with LSPR in Ce:YIG thin films.

II. EXPERIMENTAL PROCEDURE

Stoichiometric garnet target with the nominal composition of $CeY_2Fe_5O_{12}$ has been fabricated by the standard solid-state reaction from Y_2O_3, Fe_2O_3 and Ce_2O_3 powders. In this method, firstly the crude materials with suitable proportions are weighed and then

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mixed completely in a mortar. For the sample a pill with the diameter of 10mm were supplied by a Hydraulic press machine and then roasted in an electronic stove to 1400°C. The phase formations of the as-milled and annealed Garnet nano-powders were investigated by X-ray diffractometer.

Au thin films with thickness of 8 nm were deposited on different substrates, cubic quartz and Silicon (Si) (100), by using thermal deposition method. In order to form Au nanoparticles, we annealed the films at 670°c in vacuum chamber for 12 min. $CeY_2Fe_5O_{12}$ films with thickness of about 100 nm were deposited using pulsed laser deposition (PLD) technique for 10 minutes. For PLD, we use a third harmonic generation of Nd:YAG laser (355 nm, 6 ns pulse duration, 10 Hz repetition rate and laser fluence of 3 J/cm^2) which was focused on a rotating target. The resultant plasma cloud of material was condensed onto the substrate which was positioned directly in front of the target at a distance of around 4 cm and its temperature kept at 670°C for various samples. All depositions were carried out in pure oxygen partial pressure of 60 mbar.

To investigate the structural properties of thin films, we use x-ray diffractometer and the field emission scanning electron microscope (FE-SEM), operated at 15 Kv, was used to observe the fabricated films. Wavelength dependent LMOKE and optical properties were measured by means of a Chromex spectrometer. The measurement setup comprised of an optical path where the light from halogen lamp passed through the collimator, polarizer, sample and analyzer before it was analyzed in the spectrometer under oblique incidence of 40°. In this method, the sample was magnetized to saturation parallel and antiparallel to incident light by the aid of applied magnetic field. The Kerr rotation angle at each wavelength corresponded to the relative shift of the intensity curve, $I_\lambda(\alpha)$, once measured in a sample magnetized to saturation and once in a sample unmagnetized [11].

III. Results and Discussion

The wide angle X-ray scans of two samples on the quartz and Si substrates are shown in Fig. 1 (a) and (b) respectively.

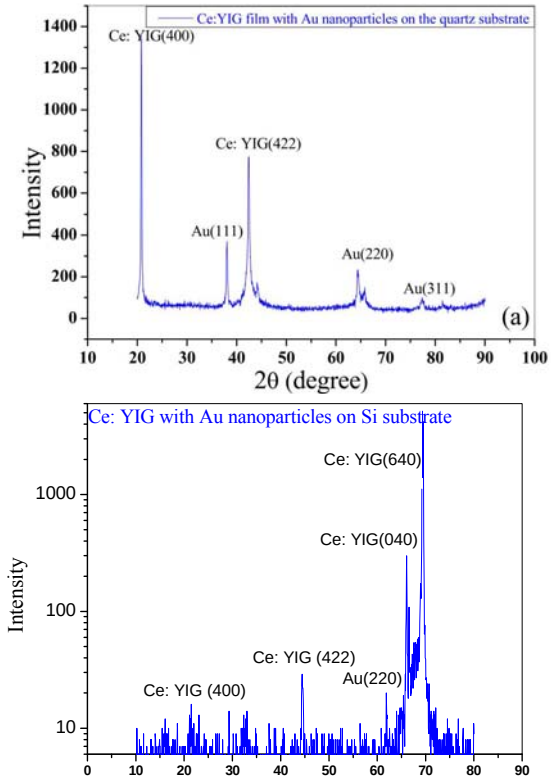

Fig. 1: XRD of Ce:YIG thin films with Au nanoparticles on the (a) Quartz substrate and (b) Si substrate.

This figure demonstrating that metallic Au is grown and crystalline garnet and Au coexist in the films.

The size and shape of the formed Au nanoparticles strongly dependent on the temperature, Au film thickness and substrates materials [7]. Fig. 2(a) and (b) shows the top view FE-SEM image of Au nanoparticles embedded in a Ce:YIG with a thickness of 100 nm on quartz and Si substrates respectively. As shown in Fig. 2, the Au nanoparticles in the sample on quartz substrate had a distorted shape and their diameter varies in the range of 70 nm and in the sample on silicon substrate, their diameter change to 100 nm and the projection of nanoparticles on the surface of film was lower than first one.

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In addition the optical and magneto-optical spectra of samples on quartz and Si substrates compared with single Ce:YIG layer without any Au nanoparticles show in Fig. 3 (a) and (b) respectively.

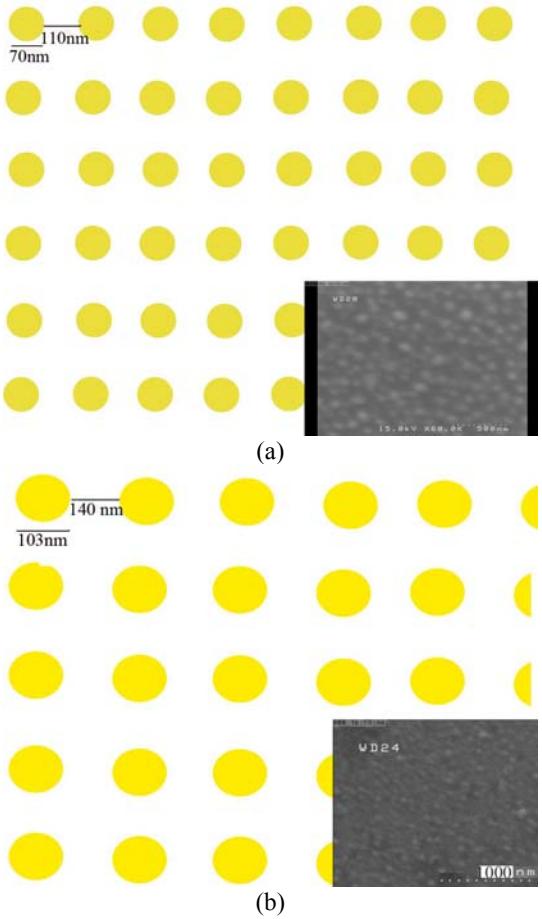

Fig. 2: FE-SEM image of Ce:YIG thin films with Au nanoparticles on the (a) Quartz substrate and (b) Si substrate.

It is clear that the attenuation occurred in two samples with Au nanoparticles that induce the excitation of SPR.

Actually, the surface plasmon polariton (SPP) is a coupled mode of electromagnetic waves and collective oscillations of free electrons in nanostructures of nobel-metal, which is accompanied by an optical near-field [12]. When the nobel-metal nanostructures are embedded in a magneto-optical (MO) medium, it is expected that the SPP of the nanostructures is coupled to the MO effects of the medium, leading to a modification and enhancement of the MO properties. Thus we see sufficiently change in optical and magneto-optical response of samples with Au nanoparticles as compared with single MO thin films.

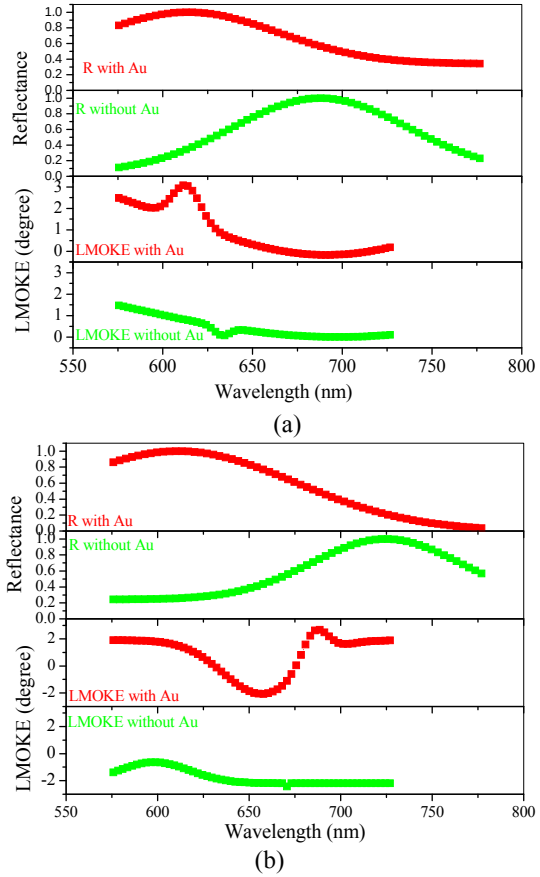

Fig. 3: Optical and magneto-optical response of Ce:YIG thin films with Au nanoparticles as compared with single Ce:YIG thin film on the (a) Quartz substrate and (b) Si substrate.

The attenuation by the SPP yields to a large blue shift in reflectance spectrum for samples which this shifts is 75 nm for sample on quartz substrate and 116 nm for second sample on silicon substrate. This rises from this fact that a frequency of the SPR depend on the size, shape and arrangement of the nanoparticles, as well as the kinds of metal [13]. This difference confirmed by FE-SEM image of two samples as shown in Fig. 2. One can see from this figure that the near-field feature of the nanoparticles (diameter of nanoparticles/

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distance between their centres) differs from each other in two samples (0.38 in sample 1 and 0.42 in sample 2). The slightly difference in the near-field feature of nanoparticles is the main reason of low difference in the full width at half maximum (FWHM) of the reflection spectra. But larger nanoparticles in the sample on silicon substrate yield to larger blue shift in reflection spectra.

Additionally, LMOKE spectra associated with the SPR compared with single Ce:YIG thin films are shown for two samples without eliminating the substrates contribution. Our results show that in the sample on quartz substrate, the LMOKE angle was 3.7 times larger than that the intrinsic LMOKE of Ce:YIG thin film at 611 nm. Another sample on silicon substrate shows 1.1 times larger Mo response at 657 nm.

Since the SPR wavelength varies by size of Au nano-structures [14, 19], it can be understood that the first sample with various nanoparticles, have sufficient enhancement and lower bandwidth in comparison with second one. The Au nanoparticles in second sample were not completely projected on the surface, and the surface to surface spacing between the nearest neighbors Au nanoparticles is much larger than earlier one. Subsequently, the near field contributions don't influences effectively on the MO effect of Ce:YIG thin films. Also decrease in number of surface nanoparticles leads to a blue shift of the SPR absorption peak in sample on silicon substrate [15].

Also the angle of FR is phenomenologically determined by both the diagonal and off-diagonal part of electric permittivity. Increasing in diagonal and off-diagonal part of the dielectric tensor by means of Au nanoparticles is another aspect to enhanced LMOKE. The incorporation of Au nanoparticles and excitation of the SPP is thus thought to modify the off-diagonal part the refractive index of films [16-18].

As mentioned above, when the noble metal nanostructures are embedded in a MO medium, the SPR and then MO responses depend on the size of the nanoparticles, the distance between them, the angle of incidence of the electromagnetic wave and, importantly, on the Mo transition wavelengths.

An increase in particle size is associated with increasing SPR wavelength. This fact confirmed our investigation that larger nanoparticles in the sample on silicon substrate yield a higher SPR wavelength.

IV. CONCLUSION

In this paper, we present the study of the optical and magneto-optical properties of crystalline Ce:YIG thin films with Au nanoparticles deposited with PLD technique at cubic quartz and silicon substrate. Our results show that large enhancement of the LMOKE was obtained in samples with Au nanoparticles on quartz substrates due to the SPR and increase in refractive index of sample. Also the SPR wavelength shifted to higher wavelength in sample on silicon substrate, as compared with the first one, because the surface to surface spacing between the nearest neighbors Au nanoparticles. The factor of enhancement in second sample on silicon substrate is much lower than the first sample on quartz substrate.

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