Magneto-Optical Spectra of Ordered and Disordered FePt Films Prepared at Reduced Temperatures

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Abstract-Reflectivity and magneto-optical Kerr spectra are measured in epitaxial FePt films prepared under reduced substrate temperatures. From these spectra off-diagonal elements of conductivity tensor was calculated. By comparison with those prepared under conventional preparation conditions, the $L1_0$-ordered FePt films prepared at reduced temperatures proved to have similar electronic properties to those prepared at elevated temperatures. It is also elucidated that disordered FePt films prepared at 300°C show intermediate electronic states between ordered and disordered states.

Key words: perpendicular magnetic recording material, magneto-optical spectrum, iron platinum film, ordered structure

1. Introduction

In order to meet with the growing demands for ultra high density magnetic storage, it is strongly required to overcome the super-paramagnetic limit by using highly anisotropic magnetic materials. For this purpose, FePt film of $L1_0$ ordered structure has been intensively studied, since it possesses a large magnetic anisotropy of 7.0×10^7 erg/cc and a huge coercive field Hc.[1] Shima et al. investigated thickness-dependence of Hc in highly ordered FePt(001) epitaxial films deposited on MgO(001) substrates at 700°C and found that the Hc value as large as 40 kOe is found in the 10 nm thick film consisting of small isolated particles of approximately 50 nm in diameter. He found a drastic drop of Hc at the critical thickness of 45 nm, above which Hc become rapidly decreased.[2]

However, the temperature necessary for preparation of high chemical order was still quite high and the Hc realized was far from theoretical value. Shima et al. succeeded in preparation of $L1_0$ ordered FePt thin films by alternate deposition of Fe and Pt monatomic layers at reduced temperatures below 250°C.[3]

Recently Seki et al. investigated the order parameter S and the magnetic anisotropy Ku in off-stoichiometric $Fe_{100-x}Pt_x$ (001) films prepared on Fe seed layer grown on Pt buffer by dc sputtering at reduced temperatures (300°C) and found that the largest S and Ku is obtained in the film with $x=38$.[4]

It is also reported that for nearly stoichiometric composition of x=52 the order parameter is less than 0.2 and the easy axis is in the film plane. It is also reported that the film with the same composition becomes ordered when deposited on MgO (110) substrate.

We have been studying magneto-optical spectra in transition metal-Pt alloys or superlattices,[5-7] and reported that magneto-optical Kerr rotation spectra of the Fe-Pt alloy undergo systematic shift with composition. Cebollada et al. reported that FePt films with different degree of ordering show different feature of magneto-optical spectra.[8] Therefore, optical studies can provide a good testing tool for characterization of FePt films by observing properties closely related with electronic structures. The objective of the present work is to measure magneto-optical Kerr spectra in FePt films to elucidate the difference between the films prepared at reduced temperatures and those by conventional technique.

2. Experiments

Films of $L1_0$ ordered $Fe_{38}Pt_{62}$ and disordered $Fe_{52}Pt_{48}$ with 20 nm in thickness were prepared by dc sputtering technique on MgO (001) substrates at the substrate temperature of 300°C, using a buffer layer consisting of a seed a Fe (1 nm) layer and a Pt (40 nm) buffer layer inserted between the substrate and the FePt film.[4] $L1_0$ ordered $Fe_{52}Pt_{48}$ was also prepared on MgO(110) substrate. For comparison, 100nm-thick $L1_0$ ordered $Fe_{50}Pt_{50}$ and $L1_2$ ordered $Fe_{25}Pt_{75}$ films were prepared on MgO (001) at 780°C, and disordered $Fe_{50}Pt_{50}$ at room temperature.

Table 1   Structures, preparation conditions and magnetic properties of FePt films investigated in this study

	Composition	Structure	Ts(°C)	Substrate and layers	Easy direction
1	$Fe_{50}Pt_{50}$	$L1_0$ ordered	780	MgO(001)/FePt100nm	perpendicular
2	$Fe_{25}Pt_{75}$	$L1_2$ ordered	780	MgO(001)/FePt100nm	isotropic
3	$Fe_{50}Pt_{50}$	Disordered	RT	MgO(001)/FePt100nm	in-plane
4	$Fe_{38}Pt_{62}$	$L1_0$ ordered	300	MgO(001)/Fe1nm/Pt40nm/FePt20nm	perpendicular
5	$Fe_{52}Pt_{48}$	Disordered	300	MgO(001)/Fe1nm/Pt40nm/FePt20nm	in-plane
6	$Fe_{52}Pt_{48}$	$L1_0$ ordered	300	MgO(110)/Fe1nm/Pt40nm/FePt20nm	in-plane[001]
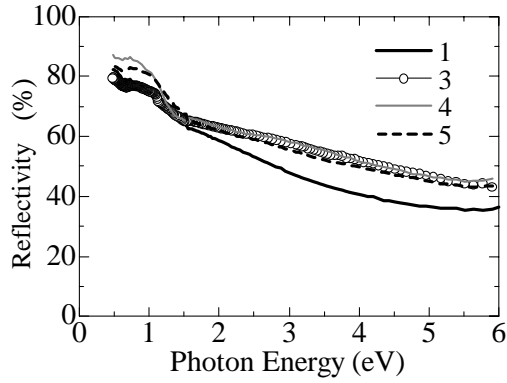
Fig. 1 Reflectivity spectra of samples 1, 3, 4, 5 listed in Table 1.

Magnetization curves have been measured using SQUID magnetometer. The composition, structure, substrate temperature and magnetic properties of samples are listed in Table 1.

The reflectivity spectra were measured using a Hitachi type U-3410 double-beam spectrophotometer with a normal reflectance attachment. As a reference aluminium mirror was used and spectra were corrected for the reflectivity of aluminium listed in the literature.[9] The absolute value of reflectivity was calibrated at 633 nm using an ellipsometry.

3. Results and discussion

3.1 Reflectivity

Reflectivity spectra of the films (Samples No. 1, 3, 4, 5 in Table 1) are shown in Fig. 1. All the samples show a spectral feature characteristic of metals; i.e., monotonous decrease in reflectivity toward higher energies. Only exceptional is the sample 1 ($Fe_{50}Pt_{50}$, prepared at 780°C, structure: ordered $L1_0$), which shows a spectral feature with downward bowing for photon energies above 2 eV. The largest difference of reflectivity from that of the other samples is seen at 4 eV. Although abbreviated for the sake of clarity the reflectivity spectra of sample 2 and 6 have the same spectral features as samples 3, 4 and 5. The low-energy part (below 1.5 eV) of reflectivity spectra in samples 4 and 5 shows unusual behaviour compared with the other samples, which may be ascribed to effect of Pt underlayer. However, we can neglect the anomaly since only a small portion of the anomalous spectrum of n and κ is used in the analysis of magneto-optical spectrum.

The surface of the sample 1 seems not perfectly specular but is slightly milky with a scattered light showing bluish in colour. It has been known that the surface morphology of FePt/MgO(100) films prepared at elevated temperatures undergoes a maze-like percolation as the thickness exceeds the critical thickness of 45 nm, the typical size of the particles being 300-400 nm.[2] Therefore the reflectivity spectrum of the sample 1 is subjected to diffraction of light by the sort of grating with average period of 300-400 nm.
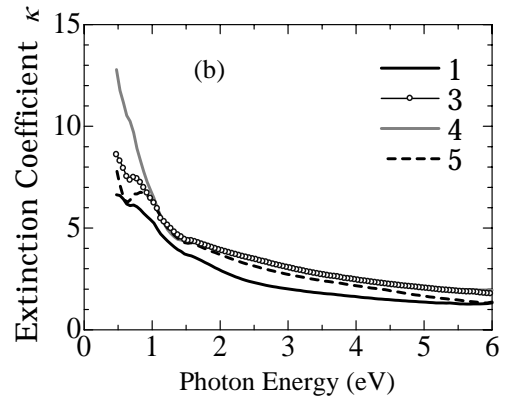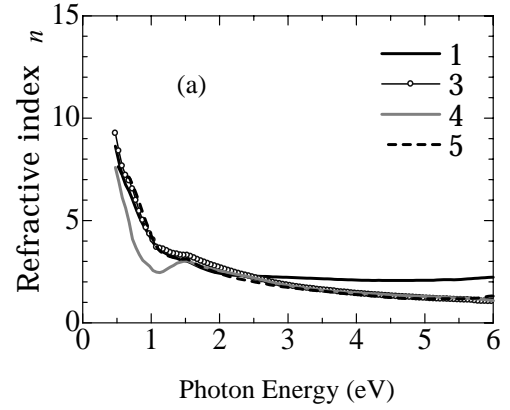

Fig. 2 Spectra of optical constants of FePt samples obtained by Kramers-Kronig analysis from reflectivity spectra

Kramers-Kronig analyses on the reflectivity spectra of FePt films were performed to deduce spectra of optical constants n and κ, which are used to obtain off-diagonal elements of conductivity tensor. The extrapolation parameters for the Kramers-Kronig analyses were optimized to reproduce the optical constants determined at 633 nm by a conventional ellipsometry. Figs. 2(a) and 2(b) illustrate the refractive index n and the extinction coefficient κ obtained by the analysis. Quite similar spectra of n and κ are obtained in samples 3, 4 and5 between 1.5 and 6 eV, while different spectrum is observed in sample 1, which may have been arising from the scattering by the surface morphology.

3.2 Magneto-optical effect

Magneto-optical spectra have been measured in all the samples listed in Table 1, among which the sample 2 shows a very small value of Kerr rotation and ellipticity; the peak Kerr rotation was no more than 0.05° and no reliable magneto-optical spectra were obtained. This result is quite reasonable taking into consideration that $L1_2$ ordered material shows antiferromagnetism in the bulk states. The small magneto-optical signal may be due to deviation from an exact $Fe_{25}Pt_{75}$ composition of $L1_2$ phase. The sample 6 has an in-plane magnetic easy axis, leading to very high saturation field (nearly 50 kOe) for perpendicular magnetization, which is far larger than the
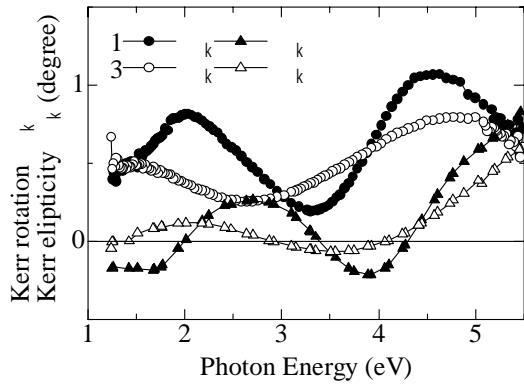
Fig. 3 Magneto-optical Kerr rotation and ellipticity spectra in samples 1 ($L1_0$ ordered) and 3 (disordered) prepared by conventional techniques on MgO(001)
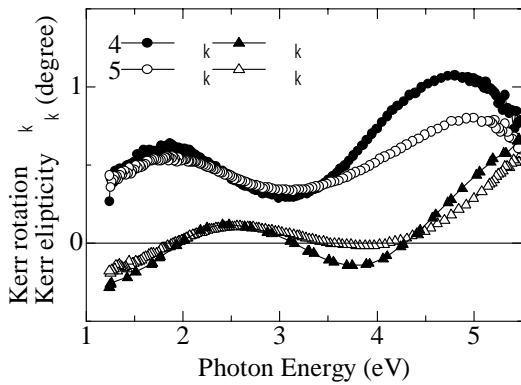
Fig. 4 Magneto-optical Kerr rotation and ellipticity spectra in samples 4($Fe_{38}Pt_{62}$ $L1_0$ ordered) and 5 ($Fe_{52}Pt_{48}$ disorder) produced at reduced temperature on Fe/Pt/MgO(001)

maximum field (14 kOe) of our apparatus. Therefore we omitted this sample from further discussion.

Figure 3 shows magneto-optical Kerr rotation and ellipticity spectra in samples 1 ($L1_0$ ordered) and 3 (disordered) prepared by conventional techniques on MgO(001). The ordered sample 1 shows a Kerr rotation peak at 4.5 eV with the value exceeding 1° and another peak at 2 eV with slightly small rotation, whereas disordered sample 3 shows smaller broad peaks around 1.5 and 5 eV. This result is consistent with the reported spectra of Cebollada et al., in which the Kerr rotation spectrum of the ordered $Fe_{50}Pt_{50}$ film shows two distinct peaks at 2 eV and 4.8 eV while that of disordered film show broad and small peak around 1.5 eV and higher energy peak above 5.5 eV.[8]

Figure 4 shows magneto-optical Kerr rotation and ellipticity spectra in samples 4 ($Fe_{38}Pt_{62}$ $L1_0$ ordered) and 5 ($Fe_{52}Pt_{48}$ disorder) produced at reduced temperature on Pt / Fe /MgO(001). It may be desirable if we can compare samples with the same $Fe_{52}Pt_{48}$ composition in both ordered and disordered states. Unfortunately $Fe_{52}Pt_{48}$ prepared at low-temperature is disordered and deviation from stoichiometry is necessary to get ordered state. This is the reason why we used $Fe_{38}Pt_{62}$ composition as an

ordered state sample. The spectral features of sample 4 is more or less smoothed, which may be associated with relatively low order parameter of sample 4, since sharpness of optical spectral shape generally reflects good crystallinity of the sample.

Since samples 4 and 5 are prepared on the Pt buffer layer, the optical effect of Pt may be taken into account. We believe this effect is negligible considering the similarity of reflectivity (above 1.5 eV) spectra of samples 4 and 5 to those of samples 1 and 3.

In order to associate the measured magneto-optical spectra with the electronic structures inherent to the samples it is desirable to use spectra of off-diagonal elements of the conductivity tensor σ_{xy},. In addition, off-diagonal conductivity multiplied by angular frequency, i.e., $\omega\sigma_{xy}$, is useful since it can be directly related to the joint density of states. The off-diagonal element of conductivity tensor σ_{xy} can be evaluated from Kerr rotation θ_K and Kerr ellipticity η_K with an aid of optical constants n and κ using the following equations;

$$\sigma'_{xy}=\omega\{\kappa(n_0^2-3n^2+\kappa^2)\theta_K+n(n_0^2-n^2+3\kappa^2)\eta_K\}/4\pi$$
$$\sigma''_{xy}=-\omega\{n(n_0^2-n^2+3\kappa^2)\theta_K-\kappa(n_0^2-3n^2+\kappa^2)\eta_K\}/4\pi.$$

(in cgs units)

Figure 5 illustrates spectra of the imaginary part of off-diagonal conductivity multiplied by the angular frequency calculated from experimental data of magneto-optical Kerr spectra and optical constants in samples 1, 3, 4 and 5.

The spectrum of the sample 1 ($Fe_{50}Pt_{50}$, $L1_0$ ordered) shows two distinct peaks at 2.1 eV and 5 eV. According to ab-initio calculation by Yamaguchi et al. the low-energy peak of the imaginary part of the off-diagonal conductivity σ''_{xy} is associated with p →d transition on Pt while the high-energy peak with d→f transition on Pt, the f band being strongly hybridized with 3d state of Fe.[10] On the other hand, σ''_{xy} of the sample 3 ($Fe_{50}Pt_{50}$, disordered) shows a reduced peak around 4.6 eV and a weak peak around 1.7 eV. Effect of disorder may cause smaller Fe-Pt hybridization leading to the smaller magneto-optical response at high-energy peak. The spectral features of $\omega\sigma_{xy}$ of the sample 4 (off-stoichiometric $Fe_{38}Pt_{62}$, prepared at 300°C, $L1_0$ ordered) with two distinct peaks at 2 eV and 4.8 eV is quite similar to those of the sample 1, except for a slight shift of the minimum position toward lower energy side. This may be explained by the difference in the composition between sample 1 ($Fe_{50}Pt_{50}$) and sample 4 ($Fe_{38}Pt_{62}$), taking into account our previous result that the minimum position of Kerr rotation in $Fe_{40}Pt_{60}$ film is shifted by 0.5 eV toward lower energy side from that in $Fe_{50}Pt_{50}$ film.[6]

On the other hand, concerning the sample 5 ($Fe_{52}Pt_{48}$ prepared at 300°C), which has been identified as a disordered film from the XRD measurement, the high-energy feature of Kerr rotation spectrum is similar to that of disordered sample 3 prepared at room temperature, whereas the low energy position does not agree with the position of sample 3 but rather agrees with that of ordered
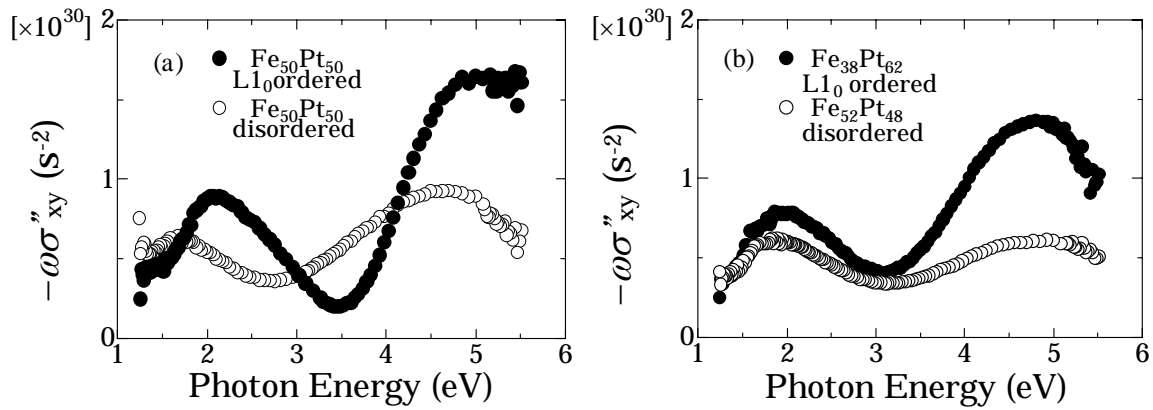
Fig. 5 Spectra of the imaginary part of the off-diagonal conductivity in FePt alloy films multiplied by the angular frequency $\omega\sigma''_{xy}$. (a) Samples 1 and 3, and (b) Samples 4 and 5.

sample 4. This result can be explained by the fact that order parameter S of the sample with $Fe_{52}Pt_{48}$ composition takes a value of 0.2. Therefore we conclude that the $Fe_{50}Pt_{50}$ sample 5 is not completely disordered like the sample 3 but partially ordered.

4. Conclusion

Magneto-optical spectrum of the $L1_0$ ordered off-stoichiometric FePt alloy film prepared at low-temperatures is found to be quite similar to those of stoichiometric FePt alloy prepared at elevated temperatures. On the contrary, magneto-optical spectrum of the low-temperature fabricated disordered stoichiometric FePt films show intermediate spectrum between those of ordered and disordered films.

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