Enhancement of Magneto-Optical Effects through Polarized Pt and Pd in TbFeCo/(Pt,Pd) Multilayers

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The magnetic and magneto-optical properties of TbFeCo/(Pt, Pd) multilayer films prepared by sputter-deposition are discussed in conjunction with the multilayer structure. The effect of polarized Pt on the polar Kerr spectra is significant at ultraviolet photon energies. A drastic increase in the magnetic moment and $\omega \sigma_{xy}$ spectra for the TbFeCo/(Pt, Pd) multilayers indicate the existence of interfacial Fe-Pt and Fe-Pd alloys.

Key words: multilayer, magneto-optical Kerr effect, magnetic polarization, interfacial alloy

1. Introduction

The optimization of compositions and fabrication conditions of thin films and multilayers for short wavelength magneto-optical recording is key for future high density recording. 3d-ferromagnetic transition metals/(Pt, Pd) multilayers such as Co/Pt and Co/Pd multilayers¹⁾⁻⁵⁾ are known to exhibit a larger magneto-optical Kerr effect at short wavelengths than that of TbFeCo, since the magneto-optical effect is enhanced by polarized Pt and Pd atoms. Therefore, Co/Pt and Co/Pd multilayers have been extensively studied so far. For this reason, rare-earth transition-metal (RE-TM) films containing Pt and Pd could be potential candidates for future short wavelength recording media. However, few systematic studies have been carried out to examine the effect of Pt and Pd in RE-TM films⁶⁾⁻⁹⁾.

It is the purpose of this paper to address the origin and magnitude of observed magnetic and magneto-optical properties, both in TbFeCo/Pt and TbFeCo/Pd multilayers. A systematic study of the magneto-optical Kerr effect of both multilayers has been carried out. A model to account for the observed both magnetic and magneto-optical properties is put forward.

2. Experimental

Multilayer films of TbFeCo/Pt and TbFeCo/Pd were fabricated by sputter-deposition using TbFeCo, Pt, and Pd targets in Ar atmosphere. The multilayer structure was obtained by rotating a substrate holder over those targets and interrupting the vapor streams alternately for programmed times with shutters. The base pressure prior to deposition was better than 5×10^{-8} Torr. The Ar gas pressure was 5 mTorr during deposition. Films were deposited onto glass substrates. The substrate temperature was kept at an ambient temperature during deposition. The layer thicknesses of TbFeCo, Pt, and Pd were varied

in the ranges $t_{\text{TbFeCo}} = 30 - 100 \text{ \AA}$ and $t_{\text{Pt}}, t_{\text{Pd}} = 0.5 - 30 \text{ \AA}$, respectively. The composition of the TbFeCo layer was $\text{Tb}_{23}\text{Fe}_{69}\text{Co}_8$ determined by electron probe microanalyzer. Two different multilayer films were prepared: (i) thick multilayers of 500 - 550 $\text{\AA}$ with a 30 $\text{\AA}$ thick Pt or Pd overcoat for the measurement of magnetic properties, and (ii) thin and bare multilayers of 250 - 300 $\text{\AA}$ on a 750 $\text{\AA}$ thick Pt or Pd reflective layer for the optical measurement. Measurements of magnetic properties were carried out using a vibrating sample magnetometer. The magneto-optical polar Kerr effect and the optical constants were measured right after the deposition from the film side using a Kerr spectroscope in a photon energy from 1.4 to 6.8 eV ($\lambda = 182 - 886 \text{ nm}$)¹⁰⁾.

3. Results and Discussion

3.1 Microstructural observation

Figure 1 shows a cross-sectional TEM picture of a $5 \times \{\text{TbFeCo } 30 \text{ \AA} / \text{Pt } 24 \text{ \AA}\}$ multilayer + 30 $\text{\AA}$ SiN_x overcoat, sputtered on a glass substrate. The periodic structure can be seen, although the interfaces are not so clear.

3.2 Magnetic properties

Figure 2 shows the saturation magnetization M_s of (a) TbFeCo/Pt and (b) TbFeCo/Pd multilayers at 298 K as a function of Pt and Pd volume fraction $v_{\text{Pt}}, v_{\text{Pd}}$, defined as $v_{\text{Pt}}(v_{\text{Pd}}) = t_{\text{Pt}}(t_{\text{Pd}}) / \lambda$ ($\lambda = t_{\text{TbFeCo}} + t_{\text{Pt}}(t_{\text{Pd}})$). M_s is normalized to the total volume. The dependence of M_s on $v_{\text{Pt}}(v_{\text{Pd}})$ is shown as solid curves for $t_{\text{TbFeCo}} = 30 \text{ \AA}$ and 50 $\text{\AA}$

Fig. 1 Cross-sectional TEM picture of a $5 \times \{\text{TbFeCo } 30 \text{ \AA} / \text{Pt } 24 \text{ \AA}\}$ multilayer + 30 $\text{\AA}$ SiN_x overcoat.

in the figures. The cross marks are M_s values for multilayers with $t_{\text{Pt}}(t_{\text{Pd}}) = 12 \text{ \AA}$ and various t_{TbFeCo} thicknesses. In Fig. 2(a), the solid curves represent that M_s increases up to $t_{\text{Pt}} = 12 \text{ \AA}$ for both the thicknesses of t_{TbFeCo} . This result may imply that the drastic increase in M_s is attributed to an alloying taking place over the interfacial regions, leading to an induced magnetization. In order to explain the behavior of M_s with v_{Pt} , a model is proposed. The model assumes the interfacial regions, as shown in Fig. 2(c). The total magnetization in multilayers is then expressed by

$$M_{\text{total}} = M_{\text{TbFeCo}}[(t_{\text{TbFeCo}} - \delta)/\lambda] + M_a(2\delta/\lambda) + M_i, \quad (1)$$

where M_{TbFeCo} , M_a , and M_i are, respectively, the magnetization of TbFeCo, the interfacial alloy, and the induced magnetization in Pt layers, and δ is the thickness of the alloyed region. As seen in Fig. 2(a), M_s decreases gradually for thicker t_{Pt} than $12 \text{ \AA}$, indicating an increase of non-magnetic Pt atoms. Consequently, the Pt thickness, in which Pt atoms are entirely alloyed, is determined to be up to $t_{\text{Pt}} = 12 \text{ \AA}$. Therefore, the magnetization of the interfacial alloy M_a was estimated through the samples of $t_{\text{Pt}} = 12 \text{ \AA}$. Thus, 2δ is equal to t_{Pt} for the sample of $t_{\text{Pt}} = 12 \text{ \AA}$. In Eq. (1), the first and third terms are negligible compared with the second term. Equation (1) is thus simplified as $M_{\text{total}} = M_{\text{TbFeCo}} + M_a v_{\text{Pt}}$. M_a is determined from a slope of the straight line in the figure and found to be $1,090 \pm 20 \text{ emu/cm}^3$.

TbFeCo/Pd multilayers exhibit a very similar correlation in Fig. 2(b) to the case of TbFeCo/Pt multilayers. M_s increases up to $t_{\text{Pd}} = 12 \text{ \AA}$. In addition, the magnetization of the interfacial alloy M_a is also estimated to be $1,100 \text{ emu/cm}^3$ from the dashed line. The increase of M_s can roughly be correlated with the increase of a volume fraction of the interfacial alloy for both Pt and Pd cases. It is rather surprising to find that the interfacial alloy region has such a high magnetization. These high M_a values suggest that the magnetic moment from Fe atoms is dominant in the alloys (it is plausible that Co atoms are negligible in amount) while Tb atoms have a minor magnetic contribution to the total. An existence of Fe-Pt and Fe-Pd alloys at the interfaces may be responsible for such high moments. This hypothesis is discussed in conjunction with magneto-optical properties. Note that the estimated M_a values of $1,100 \text{ emu/cm}^3$ are comparable to the equiatomic composition both in Fe-Pt and Fe-Pd alloy systems^{11), 12)}.

3.3 Magneto-optical properties

Figure 3 shows a photon energy E_p dependence of (a) the polar Kerr rotation angle θ_K and (b) ellipticity η_K of TbFeCo/Pt and TbFeCo/Pd multilayers with $t_{\text{TbFeCo}} = 30 \text{ \AA}$ and $t_{\text{Pt}}, t_{\text{Pd}} = 12 \text{ \AA}$. A spectrum of TbFeCo single film is also given in this figure for comparison. As seen in the figure, the absolute magnitude for θ_K of the TbFeCo/Pt multilayer increases for E_p above 3 eV . The peak position of the θ_K enhancement is around 5 eV . The

Fig. 2 Saturation magnetization of (a) TbFeCo/Pt and (b) TbFeCo/Pd multilayers as a function of Pt and Pd volume fraction and (c) a model of interfacial regions.

η_K spectrum of the multilayer also exhibits a negative peak above 5 eV . The enhancement in both θ_K and η_K becomes saturated at $t_{\text{Pt}} = 12 \text{ \AA}$ ^{8), 9), 13)}, which is in agreement with the thickness at which the maximum magnetic moment is observed in the TbFeCo/Pt multilayer. On the other hand, little enhancement due to Pd is found in the spectra of the TbFeCo/Pd multilayer. The difference is clearly found in the ultraviolet spectral range. This result may shed light on the origin of the magneto-optical effect in the TbFeCo/Pt multilayer.

In order to understand the origin of the magneto-optical enhancement for the TbFeCo/Pt multilayer, Kerr spectra for the {TbFeCo30Å/Pt12Å} multilayer were simulated using the MULTILAYER computer program¹⁴⁾. The result of Kerr rotation and ellipticity is shown in Fig. 4. The following two cases were considered in the simulation. The one is a multilayer structure without any polarized Pt, indicated as “Un-polarized Pt” (dashed curve). The other is a “FePt alloy” spectrum (solid curve),

Fig. 3 (a) polar Kerr rotation angle and (b) ellipticity of TbFeCo/(Pt, Pd) multilayers as a function of photon energy.

Fig. 4 Simulation of (a) the polar Kerr rotation angle and (b) ellipticity for a {TbFeCo 30 Å / Pt 12 Å} multilayer as a function of photon energy.

where a 6 Å thick FePt alloy layer was assumed to be present at each interface between TbFeCo and Pt layer. This second hypothesis is based on the analysis of the magnetic moment with Pt layer thickness, as mentioned above. The dielectric elements (ϵ_{xx} and ϵ_{xy}) for TbFeCo and disordered Fe₅₀Pt₅₀ alloy¹⁵⁾ films were calculated from measured data to use for the simulation. Also, optical constants (n and k) for Pt and Pd in literature¹⁶⁾ were used. As shown in Fig. 4, the “FePt alloy” spectra and experimental ones (open circle) are qualitatively similar to each other, including the two negative peaks located at around 5 eV in θ_K and above 5 eV in η_K .

In principle, an investigation of the magneto-optical transitions should be carried out using the imaginary part of the off-diagonal conductivity elements σ_{xy} , which is more directly related to the spin-polarized magneto-optical transitions. Figure 5(a) compares the $\omega\sigma_{xy}$ spectra of the TbFeCo/Pt multilayer, together with measured data for TbFeCo, Fe, and disordered Fe₅₀Pt₅₀ alloy films and literature data for polarized Pt¹⁷⁾. It seems that the peak of $\omega\sigma_{xy}$ at about 5 eV in the TbFeCo/Pt multilayer reflects the behavior of the FePt alloy, implying that the high energy ultraviolet peak is resulted in the electronic structure similar to that of Fe-Pt alloys. The previous experimental investigation on disordered Fe-Pt alloys has clearly shown that the high energy ultraviolet peak can be attributed to transitions on Pt atomic sites¹¹⁾. The spectrum of the disordered FePt alloy is in reasonable agreement with a spectrum of L1₀-type ordered FePt alloy calculated based on first principles¹⁸⁾. However, the discrepancy is present, i.e., the calculated ordered FePt exhibits positive peaks at 2.5 and 4.5 eV, which are,

Fig. 5 $\omega\sigma_{xy}$ spectra of (a) TbFeCo/Pt multilayer, TbFeCo, Fe, disordered Fe₅₀Pt₅₀ alloy, and polarized Pt¹⁷⁾ and (b) TbFeCo/Pd multilayer, TbFeCo, Fe, and FePd alloys¹⁹⁾.

respectively, higher and lower, compared with the disordered FePt spectrum. Figure 5(b) shows the case of the TbFeCo/Pd multilayer with literature data for Fe-Pd

alloy films¹⁹⁾. The peak of $\omega \sigma_{xy}$ at about 5 eV in the TbFeCo/Pd multilayer is not matching with that of the Fe-Pd alloys. Rather than Fe-Pd alloys, the observed result corresponds to that of pure Fe. A comparison of $\omega \sigma_{xy}$ spectra in the ultraviolet region indicates that the peak value of $\omega \sigma_{xy}$ of the TbFeCo/Pt multilayer is significantly higher than that of the TbFeCo/Pd multilayer.

It is quite surprising that such a small amount of Fe-Pt and Fe-Pd alloys existing at the multilayer interfaces gives rise to an ultraviolet magneto-optical Kerr effect, together with a drastic increase in the magnetic moment. Qualitatively speaking, $\omega \sigma_{xy}$ spectra can be explained by the fact that the magneto-optical strength of interband transitions is proportional to the product of spin-polarization (i.e., magnetic moment) and spin-orbit coupling energy. The former quantities for both multilayers are very similar to each other, as can be seen in Fig. 2(a), (b). The latter quantity, i.e., an actual value of the spin-orbit coupling parameter for Pt 5d states is roughly three times that of Pd 4d states²⁰⁾. Therefore, the difference of $\omega \sigma_{xy}$ spectra between the TbFeCo/Pt and TbFeCo/Pd multilayers in Fig. 5(a), (b) reflect the difference in transitions between 5d and 4d states.

As discussed in the above analyses of the magnetic moment and $\omega \sigma_{xy}$ spectra, the composition of the interfacial Fe-Pt and Fe-Pd alloys seems to be near the equiatomic. Equiatomic FePt and FePd form very similar intermetallic alloys and compounds, where Pt and Pd atoms exhibit a similar polarization in the presence of iron. Armelles *et al.*¹²⁾ has reported that the strength of magneto-optical transitions is larger in FePt than in FePd, being roughly scaled with the spin-orbit coupling of Pt and Pd d-bands in the ultraviolet spectral range. In the case of multilayers, the band structure near interfaces is modified. Therefore, a more detailed analysis needs to be considered based on a state of the interfacial region which modifies a degree of the spin-polarization and the spin-orbit coupling.

4. Conclusions

The magnetic and magneto-optical properties of TbFeCo/(Pt, Pd) multilayer films prepared by sputter-deposition have been studied. The saturation magnetization of both multilayers drastically increases with a thickness of Pt and Pd layers up to 12 Å. The absolute magnitude for the polar Kerr rotation angle of TbFeCo/Pt multilayers increases at ultraviolet photon energies. The peak position of the enhancement is around 5 eV. On the other hand, little contribution from Pd is found in the spectra of TbFeCo/Pd multilayers. The peak of $\omega \sigma_{xy}$ at about 5 eV in TbFeCo/Pt multilayers reflects the behavior of Fe-Pt alloys and shows a much higher value than that of TbFeCo/Pd multilayers. This result implies that the difference of $\omega \sigma_{xy}$ spectra between both multilayers reflects the difference in transitions between Pt 5d and Pd 4d states. A drastic increase in the magnetic moment and $\omega \sigma_{xy}$ spectra suggest the existence of interfacial Fe-Pt (-Co + Tb) and Fe-Pd (-Co + Tb) alloys,

and this possibility is supported by a simulation of the Kerr spectra for a proposed model of interfacial regions.

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