MAGNETO-OPTICAL INVESTIGATION OF LOW-DEMENSIONAL MAGNETIC STRUCTURES

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Abstract Magnetic and magneto-optical properties of Fe/Pt/Fe, Co/Pd/Co trilayers and also the sandwiches with wedge-shaped magnetic (Fe, Co) and nonmagnetic (Pt, Pd) layers were investigated. The oscillatory behavior of the saturation field H_S of the studied trilayers with changing the thickness of the nonmagnetic layer (NML) t_{NML} was revealed. That was explained by the exchange coupling between ferromagnetic layers (FML) through the nonmagnetic spacer. For the first time, oscillations of the transverse Kerr effect (TKE) with changing the Pt- and Pd-wedge thickness were discovered. Period of these oscillations was found to depend on the FML thickness and the photon energy of the incident light. TKE spectra of the examined samples were discovered to modify very strongly with increasing t_{NML}. The discovered peculiarities of magneto-optical properties of thin-film systems were explained by a concept of the spin-polarized quantum well states in the Pt and Pd layers.

Keywords: Kerr effect; Trilayers; Sandwich; Saturation field; Quantum Well State

Introduction

Compositionally modulated thin-film structures containing 3d metals have attracted growing attention for last years because of their unusual magnetic properties and potential applications to electromagnetic devices. The Fe, Co/Pt, Pd systems are especially interesting due to unique properties of Pt and Pd. In FePt and CoPd alloys, Pt and Pd become nearly ferromagnetic with an anomalously large Pauli susceptibility. The induced magnetic moment of Pt and Pd is about 0.3 – 0.4 μ_B and 0.5 μ_B, respectively. Although the Pt and Pd moments are less than those of Fe and Co, Pt and Pd affect strongly on magnetic and magneto-optical properties of the above thin-film structures [1].

Recently, the novel phenomena, such as an oscillatory exchange coupling between ferromagnetic layers (Fe, Co) through a nonmagnetic spacer (Cr, Cu, Ag, Au and so on) [2] and quantum finite effects [3] were discovered in the layered structures. In order better to understand these phenomena, the investigation of magnetic and magneto-optical properties of Fe/Pt/Fe, Co/Pd/Co trilayers and also the sandwiches with the wedge-shaped ferromagnetic (FML - Fe, Co) and nonmagnetic (NML - Pt, Pd) layers was carried out.

Experimental

The examined Fe/Pt/Fe and Co/Pd/Co trilayers were deposited on glass substrates by DC magnetron sputtering under a base pressure of less than 10^{-8} Torr and an argon gas pressure of 1×10^{-4} Torr. In the trilayers, the Pt and Pd layer was deposited between Fe and Co layers having the same thickness. Series of the trilayers with t_{FML}, equaled 2.5, 5 and 10 nm, and t_{NML}, varying from 0.4 to 4 nm, were prepared. In order to avoid oxidation, the 10-nm carbon layer covered the samples.

The Fe-wedge/Pt-wedge and Co-wedge/Pd-wedge sandwiches were prepared by molecular-beam epitaxy under ultrahigh vacuum (10^{-8} Pa). A 3-nm seed layer of Ag and a Pt (Pd)-wedge (x-wedge) layer were deposited consistently onto a MgO (001) substrate at room temperature. After completion of the deposition, the sample was annealed at 360 ^{0}C for several minutes. Then Fe (Co)-wedge (y-wedge) was deposited onto a Pt (Pd) (001)-oriented surface at room temperature. In order to avoid the oxidation, the 2-nm Au capping covered Fe (Co)-wedge. The slopes of Pt (Pd)- and Fe (Co)-wedges were equal to 0.35 and 0.3 nm/mm, respectively. Their lengths were equal to 20 mm. The existence of the periodic layered structures (well-defined interfaces) in the examined samples was confirmed by low-angle XRD data.

The studies of the magnetic and magneto-optical properties of the above samples were carried out employing the magneto-optical spectrometer and the magneto-optical magnetometer (described in [4, 5]) by the help of the transverse Kerr effect (TKE) δ. Here $\delta = (I - I_0)/I_0$, where I and I_0 is the intensity of the reflected light from the magnetized and nonmagnetized sample, respectively. The magnetic field was applied parallel to the sample plane and perpendicular to the plane of the light incidence. TKE spectra were measured in the $1.5 < \hbar\omega < 4.5$ eV photon energy range, at the 65°-angle of the light incidence from the sample normal. All measurements were carried out at room temperature and in open air.

Results and discussion

The examined trilayers were found to exhibit an in-plane easy axis of magnetization (EAM). Hysteresis loops along EAM were revealed to depend on the NML thickness. In particular, it was discovered that there are trilayers having a nearly square loops and trilayers exhibiting more complicated loops with high enough magnitude of the saturation field H_S. For example, Fig. 1 shows typical hysteresis loops observed in the Fe/Pt/Fe trilayers.

Fig. 2 shows the dependence of H_S on the Pt layer thickness for the trilayers with a various thickness of the Fe layer. Analogous results were obtained for Co/Pd/Co trilayers. From Fig. 2 one can see that H_S of the trilayers oscillates as a function of t_{Pt}. A period and amplitude of these oscillations Λ depends on t_{Fe}. Λ was found to be equal to 0.8, 1.2 and 1.6 nm for t_{Fe} = 2.5, 5 and 10 nm, respectively. These data can be explained by the presence of the exchange coupling J between ferromagnetic layers through the NML and its oscillatory behavior as a function of t_{Pt} (the switch from the ferromagnetic to the antiferromagnetic coupling) [2, 6, 7]. As a result, in the trilayers, there are parallel (ferromagnetic (F) coupling) and antiparallel (antiferromagnetic (AF) coupling) orientations of the magnetization in the FML. The existence of noncollinear structures is also possible for some thickness of the NML. The saturation field of the AF-coupled trilayers is more than H_S of the F-coupled that is caused by additional energy expense for overcoming the AF exchange coupling between magnetic layers. The magnitude of this additional field for AF-coupled structures is described by a relation: $H_{AF} = 4J/M_S t_{FML}$ [8]. Here J is the AF coupling constant, t_{FML} and M_S are the thickness and saturation magnetization of the magnetic layer, respectively. The magnitude of H_{AF} decreases with increasing t_{FML}. We did observe for the AF-coupled trilayers the decrease in the saturation field and in oscillation amplitude of H_S with increasing t_{FML}.

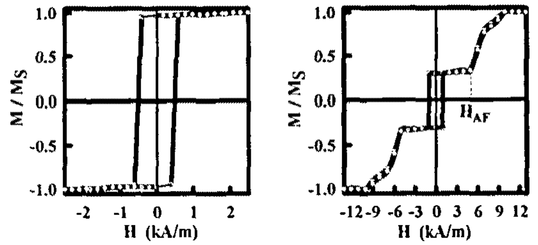

Fig. 1. Hysteresis loops along an easy axis of magnetization obtained at $\hbar\omega$ = 2 eV for the 2.5 nm Fe/Pt/ 2.5 nm Fe trilayers with t_{Pt} = 0. 4 nm (left panel) and t_{Pt} = 0.7 nm (right panel).

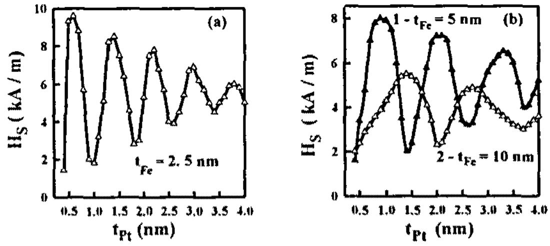

Fig. 2 Dependence of the saturation field H_S of Fe/Pt/Fe trilayers on the Pt-layer thickness: (a) t_{Fe} = 2.5 nm; (b) t_{Fe} = 5 and 10 nm (curve 1 and 2, respectively).

We obtained high enough magnitudes of Λ. According to mechanism of the exchange coupling via RKKY-like interaction [9 – 11], Λ must be the order of π/k_F (k_F - a wave Fermi vector), equaled to 0.3 – 0.4 nm for most metals. The appearance of longer oscillation period of J correlates with computations performed with taking into of account quantum-size effects [7, 12, 13]. The enlargement of Λ with increasing t_{FML} correlates qualitatively with calculations performed in [14].

By scanning the 0.03-mm light spot along the wedge length of the studied sandwiches, the local hysteresis loop and magnetization curves were measured. The oscillations of the local values of H_S were revealed also. The period of these oscillations was found to coincide practically with the values of Λ , obtained for the trilayers.

The magneto-optical properties of the examined samples were investigated also. More important results are presented in Figs. 3, 4 and 5. Fig. 3 shows TKE spectra, obtained for the Fe/Pt/Fe trilayers and the Fe/Pt sandwich at the fixed Fe-layer thickness and various magnitudes of t_{Pt}. Fig. 4 displays the dependence of local magnitudes of TKE on the Pt thickness, obtained for the Fe/Pt sandwich at the fixed t_{Fe} and the fixed photon energy of the incident light. Fig. 5 shows the dependence of local magnitudes of TKE on Co- and Pd-layer thickness at the fixed t_{Pd} and t_{Co}, respectively, obtained for the Co/Pd sandwich at the fixed photon energy of the incident light. The magnetic field was sufficient to saturate any local part of the sample.

From Fig. 3 one can see that with increasing t_{Pt}, the characteristic peak in the TKE spectrum of bulk Fe around 1.9 eV decreases while an ultraviolet peak becomes pronounced. The possible mechanism of such change of TKE spectra is spin polarization of Pt 5d-levels [1]. Because of the high spin-orbit energy of Pt 5d-states, there are the overlaps of electronic 3d- and 5d-wave functions in the adjacent Fe and Pt layers that cause the exchange-induced spin polarization of Pt. The spin polarized Pt affects on off-diagonal component of tensor dielectric permeability of the thin-film samples and their magneto-optical spectra are modified. The quantitative comparisons of TKE in the sandwich and trilayers showed that at the same Fe and Pt layer thickness, TKE magnitudes in trilayers are larger (about 2 times) than in the sandwich. It was experimentally proved in [15] that TKE depends on a magnetic film thickness if it is smaller than the information depth of a magneto-optical signal (t_{inf}). According to [15], t_{inf} is equal to 20 - 24 nm in the $1.5 < \hbar\omega < 4.5$ eV photon energy range. In our case, the full thickness of the examined samples is smaller than t_{inf}. In consequence of it, we observed the aforesaid difference of TKE in the examined samples. Moreover, we revealed that due to the presence of two Fe-Pt interfaces in the trilayers, the Pt influence on TKE in these samples is stronger (about 2 times) than in the sandwich.

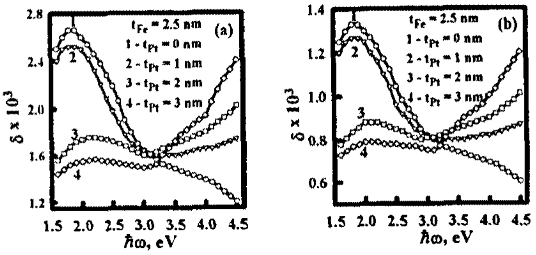

Fig. 3 TKE spectra of Fe/Pt/Fe trilayers (a) and Fe/Pt sandwich (b) at the fixed Fe-film thickness and various Pt-layer thicknesses.

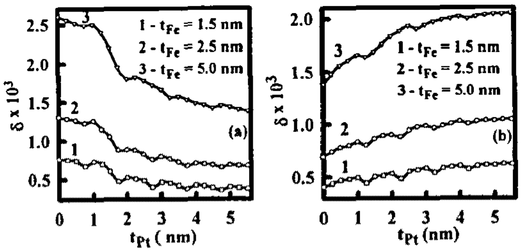

Fig. 4 Dependences of TKE on the Pt-wedge thickness, obtained the for Fe-wedge/Pt-wedge sandwich at the fixed Fe-wedge thickness and the fixed energy of incident light $\hbar\omega$ = 2 and 4 eV, (a) and (b), respectively.

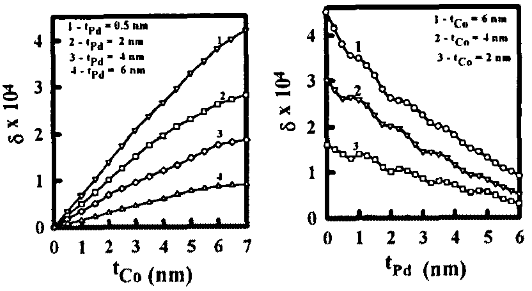

Fig. 5 Dependences of TKE on the Co- and Pd-wedge thickness, obtained the for the Co-wedge/Pd-wedge sandwich at the fixed Pd- and Co-wedge thickness (left and right panels, respectively) ($\hbar\omega$ = 2 eV).

Analogous results were obtained for Co/Pd/Co trilayers and Co/Pd sandwich, which were explained also by the exchange-induced spin polarization of Pd due to the overlaps of electronic 3d- and 4d-wave functions in the adjacent Co and Pd layers.

Analysis of the observed dependences of TKE as function of the wedge-thickness showed the following. At the fixed NML thickness, TKE increases with enlarging of the FML thickness and has non-linear dependence on t_{FML}. At the fixed FML thickness, with increasing the NML thickness, TKE decreases at $\hbar\omega = 2$ eV and increases at $\hbar\omega = 4$ eV. That correlates very well with the foregoing data. TKE has oscillatory behavior as a function of t_{NML}. Period of these oscillations Λ_1 enlarges with increasing t_{FML} and the photon energy of incident light. The oscillation amplitude of TKE decreases with increasing t_{FML}. The Pt and Pd influence on TKE was found to retain up to $t_{NML} \approx 4$ nm.

The observed oscillations of TKE can be interpreted as arising from spin-polarized Quantum Well States in the NML. According to [16], in a nonmagnetic film, deposited on a ferromagnetic substrate, the electronic states exhibit some quantum-size effect due to a distinction of electron reflections on the nonmagnetic and ferromagnetic boundaries. Actually, on the nonmagnetic and ferromagnetic boundaries, there are spin-independent and spin-dependent reflections of the electrons, respectively. As a result, in the nonmagnetic layer there is some nonzero spin polarization having an oscillatory dependence on the thickness of this layer. These changes of electronic structure of the NML on the magnetic substrate cause the oscillatory behavior of magneto-optical properties of thin-film systems.

The enlargement of the oscillation period of TKE Λ_1 with increasing the photon energy of incident light correlates very well with computations performed in [16, 17]. The decrease of the oscillation amplitude of TKE with increasing t_{FML} can be explained by the dropping influence of the above-described interface effects on the magneto-optical properties of the sample.

It should be pointed out that the oscillatory behavior of TKE as a function of t_{FML} did not be discovered. According to the calculation of the finite-size Au/Fe systems within local-spin density approximation [18], with increasing number of Au-layers, the relative changes in the induced magnetic moment of Au-layer at the surface are wide (showing the change of a sign) while those of Fe monolayer are very small. One can propose that in our case, the strong spin polarization of Pt and Pd causes mainly the magneto-optical properties of the studied sandwich.

Conclusion

The magnetic and magneto-optical properties of Fe/Pt/Fe, Co/Pd/Co trilayers and also the sandwiches with wedge-shaped magnetic (Fe, Co) and nonmagnetic (Pt, Pd) layers were investigated. The oscillatory behavior of the saturation field H_S with changing the NML thickness was revealed. That was explained by the exchange coupling between ferromagnetic layers through the nonmagnetic spacer. For the first time, TKE oscillations with changing the Pt- and Pd-wedge thickness were discovered. These data were explained by a concept of the spin-polarized quantum well states in the Pt-and Pd-layers. The strong influence of Pt and Pd on TKE spectra of the examined samples was observed. That was explained by a concept of the exchange-induced spin polarization of the Pt and Pd layers.

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