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ANALYSIS OF MAGNETO-OPTICAL SPECTRA OF Pt/Co AND Pt/Fe MULTILAYERS USING OPTICAL CONSTANTS DETERMINED BY REFLECTIVITY SPECTRA BETWEEN 0.5 AND 25 eV

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Abstract-Reflectivity spectra were measured between 0.5 and 25 eV using synchrotron radiation in Pt-based multilayers and alloys, for which magnetooptical (MO) spectra had been evaluated between 1 and 6 eV. Analyses using optical constants obtained from the reflectivity revealed that the MO spectra of multilayers can well be simulated assuming the presence of an alloy layer at each interface, the layer thickness being approximately 6-10 Å. The prominent MO structures around 5-6 eV commonly observed in both Pt-based alloys were ascribed to the plasma-edge enhancement effect.
KEYWORDS: REFLECTIVITY, SYNCHROTRON RADIATION, OPTICAL CONSTANTS, Pt-BASED MULTILAYERS, PLASMA-EDGE ENHANCEMENT

INTRODUCTION

Pt-based multilayers have been intensively studied as new materials for magnetooptical (MO) disk media of next generation, due to the large MO rotation in short wavelengths as well as to the perpendicular magnetic anisotropy.[1] The large MO effect could not be explained in terms of optical interference effect in Pt/Co multilayer structures with abrupt interfaces.[2] Instead, we have suggested the existence of alloy layer at the interface between adjacent layers of Pt and transition metal.[3] In our previous paper we showed that magnetooptical spectra of Pt/Co and Pt/Fe multilayers can be simulated by means of the virtual optical constant method if we assume the existence of Pt-Co or Pt-Fe alloy layers at the interface.[4]

In the present paper we describe a method for estimating the thickness of interface alloy layers using optical simulation. For this purpose, we need spectra of σ_{xy} (the off-diagonal element of conductivity tensor), as well as ϵ_{xx} (the diagonal element of dielectric permeability tensor) for wide range of photon energies in alloys. We obtained the data of σ_{xy} between 1.2 and 5.9 eV by means of the polarization modulation technique[5,6] and that of optical constants between 0.5 and 25 eV from reflectivity measurements using synchrotron radiation.

We also have an intention to explain the prominent MO structures observed around 5-6 eV in terms of the plasma-edge enhancement effect.[7]

EXPERIMENTAL

Pt/Co and Pt/Fe multilayers as well as corresponding alloy films were prepared using the DC magnetron sputtering technique on glass substrates. Formation of multilayer structure was confirmed using the small-angle X-ray diffraction technique. Layer thicknesses and compositions of films are given in Tab. 1. In the first column are listed sample names, in which numbers in the parenthesis behind sample names refer to the designed (nominal) layer thickness of multilayers in angstrom unit. Sample names of alloys are represented by the formulae with nominal compositions in percent. The second column represents the designed thickness. The third, the fourth and the fifth column are the period determined by X-rays, the composition determined by fluorescent X-ray analysis and the realized thickness, respectively. In the last column are listed the thicknesses of Pt and transition metal layers estimated from the composition, where the presence of an alloy layer at the interface is not taken into consideration.

MO Kerr spectra were measured by means of the retardation-modulation technique[5] using a piezobirefringent modulator(PEM). The apparatus has been improved to enable the short wavelength measurements up to 5.9 eV. The details of the apparatus are described elsewhere.[6]

Reflectivity spectra were measured using a Hitachi U-3410 spectrophotometer between 0.5 and 6 eV. On the other hand, the VUV-reflectivity spectra between 2.5 and 25 eV were measured by the use of a Seya-Namioka-type spectrometer at the beam line BL-1 in the Synchrotron Radiation Laboratory of ISSP, University of Tokyo. Both spectra were combined to cover photon energies from 0.5 to 25 eV, with the connecting wavelength around 4 eV, where the continuity of the energy-derivative was observed.

Tab.1 Layer thicknesses (designed), total film thickness (designed), period (measured), composition (analyzed), total thickness (measured) and layer thicknesses (estimated from composition) of multilayers. Parameters for alloy films are also listed.

Designed values			Measured values		Estimated ratio
Sample name	Thickness (Å)	Period (Å)	Composition (Pt:Co at.%)	Thickness (Å)	Pt/TM (Å) (Å)
Pt(10)/Co(5)	2000	14.0	60.3:39.7	1840	Pt(9.5)/Co(4.5)
Pt(18)/Co(5)	500	21.4	73.98:26.02	534	Pt(17.0)/Co(4.4)
Pt(40)/Co(20)	2000	53.4	63.3:36.7	2216	Pt(37.6)/Co(15.8)
$Pt_{60}Co_{40}$	2000		60.2:39.8	1915	-
Pt(10)/Fe(5)	2000	14.6	66.98:33.02	2007	Pt(10.5)/Fe(4.1)
Pt(20)/Fe(5)	2000	24.3	81.15:18.85	2155	Pt(20.6)/Fe(3.7)
$Pt_{61}Fe_{39}$	2000		58.3:41.7	1760	-

RESULTS

Magnetooptical Spectra

Figure 1 shows spectra of polar MO Kerr rotation θ_K and ellipticity η_K in Pt-Co system, this term representing Pt(40)/Co(20), Pt(18)/Co(5), Pt(10)/Co(5) multilayers and the Pt_{60}–Co_{40} alloy, while Fig. 2 shows those in Pt-Fe system which represents Pt(10)/Fe(5) and Pt(20)/Fe(5) multilayers and $Pt_{61}Fe_{39}$ alloy. Kerr rotation and Kerr ellipticity are shown by curves with closed symbols and open symbols, respectively. It is found that Kerr rotation in the Pt-Co system except for the Pt(40)/Co(20) multilayer commonly shows a peak around 4 eV, while that in the Pt-Fe system around 4.2 eV. The energy difference of the peak positions corresponds to the difference between the zero-crossing energy of the Pt-Co alloy (~5.8 eV) and that of the Pt-Fe alloy (~6 eV). On the other hand, the largest value of Kerr ellipticity appears at the highest photon energy of measurement (5.9 eV) both in Pt-Co and Pt-Fe systems.

Reflectivity Spectra

The reflectivity spectra in films of Pt-Co system and Pt-Fe system are shown in Fig. 3 and Fig. 4, respectively. Reflectivity in Pt-Co system decreases up to 8.5 eV where it takes a minimum and increases again towards higher energies. On the other hand, the reflectivity in Pt-Fe system decreases up to 9 eV, followed by a rather flat part extending to 25 eV.

Dielectric Permeability Tensor

Optical constants n and k were deduced from the reflectivity by Kramers-Kronig analysis with appropriate extrapolation parameters determined to reproduce optical constants obtained by spectroscopic ellipsometry. Real and imaginary parts of the diagonal element ϵ_{xx} of the dielectric permeability tensor calculated from optical constants are shown in Figs. 5 and 6 for Pt-Co and

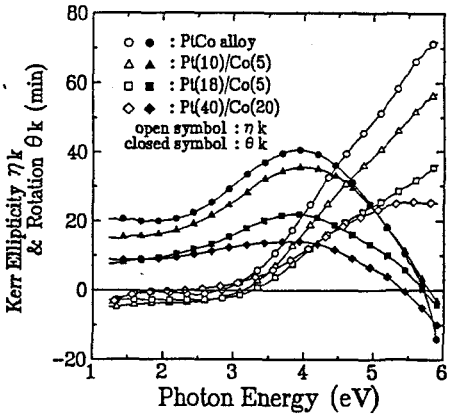

Fig.1 Magnetooptical spectra in Pt-Co system

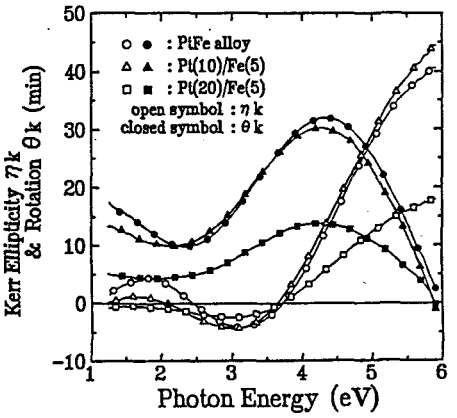

Fig.2 Magnetooptical spectra in Pt-Fe system

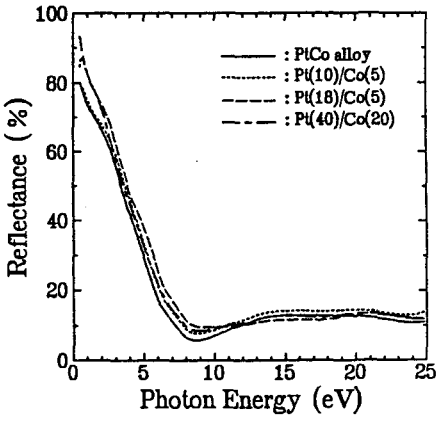

Fig.3 Reflectivity spectra in Pt-Co system

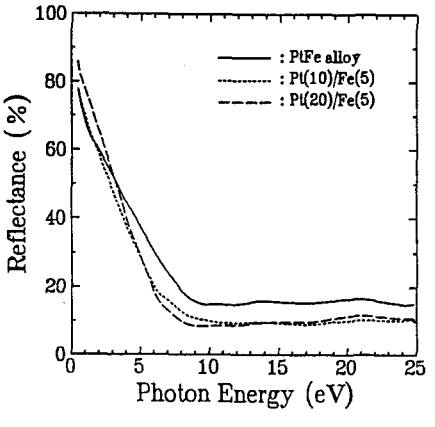

Fig.4 Reflectivity spectra in Pt-Fe system

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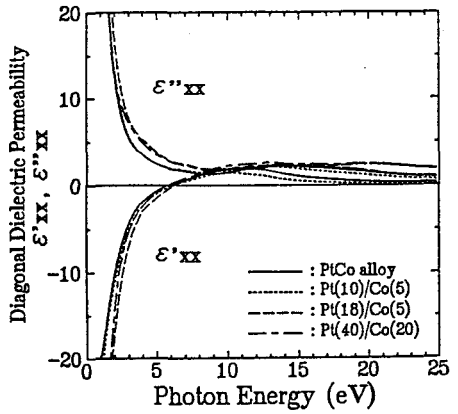

Fig.5 Diagonal permeability in Pt-Co system

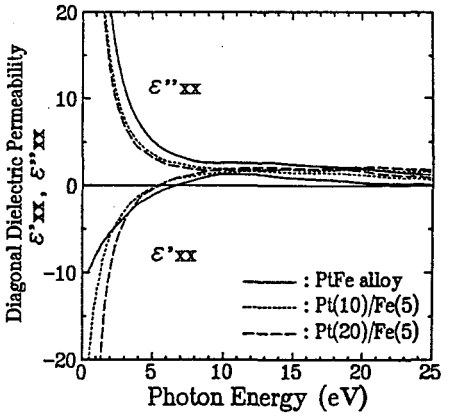

Fig.6 Diagonal permeability in Pt-Fe system

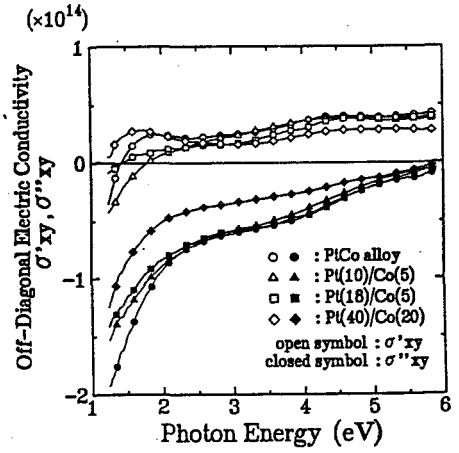

Fig.7 Off-diagonal conductivity in Pt-Co system

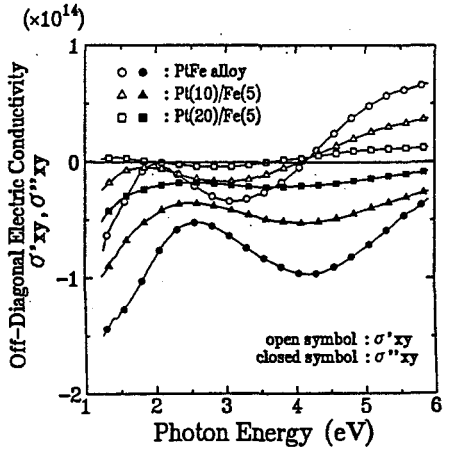

Fig.8 Off-diagonal conductivity in Pt-Fe system

Pt-Fe systems, respectively. Typical Drude-type spectral dependencies of the real part ϵ_{xx}' are observed. The plasma energies in Pt-Co and Pt-Fe alloys are found to be 6.3 and 6.8 eV, respectively.

Following the procedures described in ref. 8, real and imaginary parts of the off-diagonal element σ_{xy} of the conductivity tensor were deduced using the formula

$$\sigma_{xy}' = (\omega/4\pi)(B\,\theta_K + A\,\eta_K)$$
$$\sigma_{xy}'' = (-\omega/4\pi)(A\,\theta_K - B\,\eta_K) \quad (1)$$

where A stands for $n(1-n^2+3k^2)$ and B for $k(1-3n^2+k^2)$. The results are illustrated in Figs. 7 and 8 for Pt-Co and Pt-Fe systems, respectively.

Spectra of σ_{xy} in Pt/Co multilayers except for Pt(40)/Co(20) show a surprising coincidence with that in the Pt-Co alloy especially in high energy region. On the other hand, σ_{xy} spectra in Pt/Fe multilayers do not show such a good agreement with that in Pt-Fe alloy, although the spectral features are common. It is commonly observed in both systems that spectral dependencies of σ_{xy} are rather flat and do not show any prominent structures around 5-6 eV region where prominent structures are observed in Kerr rotation and Kerr ellipticity spectra. This result suggests that the MO structures around 6 eV are not simply resulting from the electronic structures of these materials.

DISCUSSION

The presence of alloy layers at the interface is suggested from the close resemblance of σ_{xy} between the multilayer and the alloy in Pt-Co system. Analysis of the small-angle X-ray diffraction has provided an estimation of the thickness of the alloy to be 2-3 atomic layers.

A simulation of MO spectra of multilayers was performed by means of the virtual optical constant method, which proved to be a powerful tool for explaining the experimental MO spectrum in Fe/Cu multilayers.[9] In this analysis, we assumed that a Pt-Co (or Pt-Fe) alloy layer is formed with an averaged composition at the interface neglecting the gradient in the alloy composition. Then the Pt/Co or Pt/Fe multilayers can be

regarded as $[Pt/Pt\text{-}Co/Co/Pt\text{-}Co]_n$ or $[Pt/Pt\text{-}Fe/Fe/Pt\text{-}Fe]_n$.

As a composition of the Pt-Co alloy and Pt-Fe alloy at the interface, we assumed the ordered alloy of $Pt_{60}Co_{40}$ and $Pt_{61}Fe_{39}$, respectively, taking into account the similarity of the composition ratio of these alloys with that of Pt(10)/Co(5) or Pt(10)Fe(5) multilayers. In the present calculation, we employed optical constants and off-diagonal elements of $Pt_{60}Co_{40}$ alloy determined in the present study. We also used the reported values of n and k in Pt[10], Co[11] and Fe[11] and of ϵ_{xy} in Co and Fe.[12]

We performed the calculation varying the thickness x of Pt-Co or Pt-Fe alloy formed at the interface. Thicknesses of Pt and Co (or Fe) layers remaining unalloyed were readjusted so as the total composition ratio in one period remains unchanged. For this purpose, the densities of the Pt-Co and the Pt-Fe alloy were estimated using the lattice constants (a=3.8 Å with fcc structure) determined by X-ray diffraction.

As an example, simulated Kerr rotation and ellipticity spectra of the Pt(10)/Co(5) multilayer for different values of alloy thickness x are given in Figs. 9(a) and 9(b), respectively. The spectral shape as well as the peak value of Kerr effect depend strongly on the thickness of the alloy layer. When all the Co atoms in the layer are consumed, the thickness of the alloy no longer increases. In our Pt(10)/Co(5) multilayer, the maximum value of x is 6.99 Å, for which the spectrum is nearly identical to that of the alloy. The best fit to the experimental curve (dotted line) is obtained for x=6.4 Å. This means that a total thickness of Pt-Co alloy amounts as large as 12.8 Å(both Pt/Co and Co/Pt interfaces) in one period of 14 Å. Thicknesses of pure layers of Pt and Co are determined to be as small as 0.817 Å and 0.383 Å, respectively, instead of 9.5 Å and 4.5 Å listed in Tab. 1.

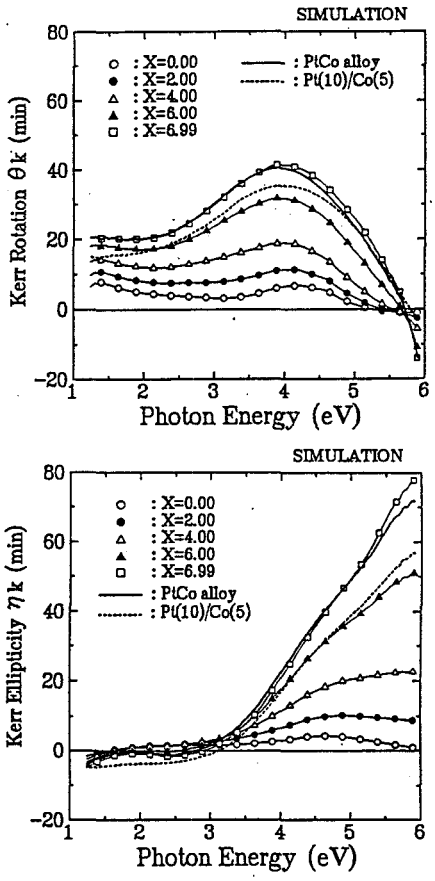

Fig.9 Dependence of spectra of (a) θ_K and (b) η_K on x (interfacial alloy thickness)

Similar calculations have been carried out in the other multilayers of Pt-Co and Pt-Fe systems. Thicknesses of Pt, Pt-Co or Pt-Fe and Co or Fe which provide the best fit to the experiment are listed in Tab. 2. Kerr rotation and Kerr ellipticity spectra calculated using these thickness values are given in Figs. 10 and 11 in Pt-Co and Pt-Fe systems, respectively. Most of the characteristic features observed in experimental spectra of Figs. 1 and 2 are reproduced in the simulated spectra.

Tab.2 Estimated thicknesses of Pt, Co or Fe and Pt-Co or Pt-Fe layers which provides the best fit to experimental spectrum.

Sample name	Pt (Å)	Co or Fe (Å)	Pt-Co or Pt-Fe sum of 2 layers (Å)	Period (Å)
Pt(10)/Co(5)	0.817	0.383	12.8	14.0
Pt(18)/Co(5)	5.535	0.265	15.6	21.4
Pt(40)/Co(20)	22.38	9.02	22.0	53.4
Pt(10)/Fe(5)	1.82	0.00	12.78	14.6
Pt(20)/Fe(5)	13.86	1.44	9.00	24.3

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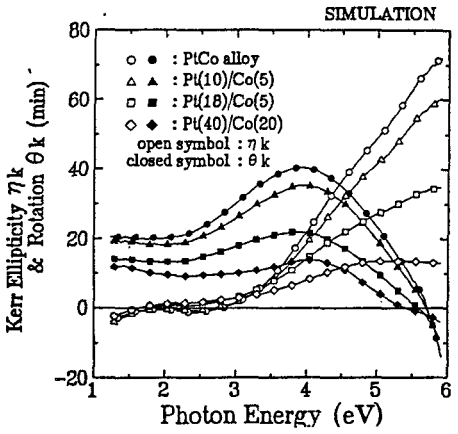

Fig.10 Simulated magnetooptical spectra in Pt-Co system with alloy layer with thicknesses listed in Tab.2

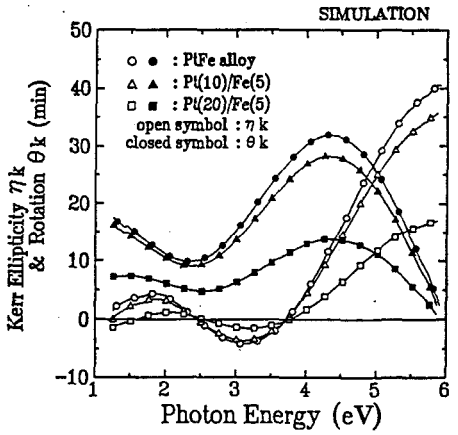

Fig.11 Simulated magnetooptical spectra in Pt-Fe system with alloy layer with thicknesses listed in Tab.2

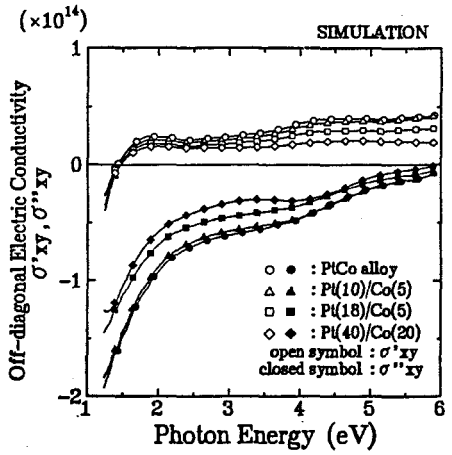

Fig.12 Simulated off-diagonal conductivity in Pt-Co system

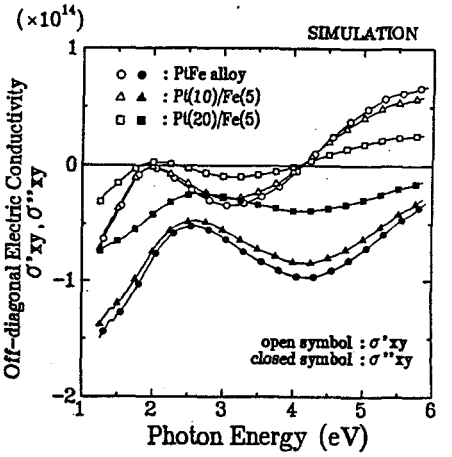

Fig.13 Simulated off-diagonal conductivity in Pt-Fe system

Simulated spectra of off-diagonal conductivity σ_{xy} were also calculated and are shown in Figs. 12 and 13, for Pt-Co and Pt-Fe systems, respectively. Most of the spectral features are reproduced, with several differences found in detailed structures, suggesting formation of alloys with different compositions.

In the last place, we give discussion on the strong magnetooptical structures observed around 5-6 eV in both Pt-Co and Pt-Fe alloys. As mentioned previously, spectral dependencies of σ_{xy} around 5-6 eV are considerably flat and do not show any prominent structures as seen in the raw magnetooptical spectra.

Kerr rotation θ_K and Kerr ellipticity η_K can be expressed in terms of ϵ_{xy} and ϵ_{xx} by formula

$$\theta_K + i\eta_K = \epsilon_{xy}/(1-\epsilon_{xx})\sqrt{\epsilon_{xx}} \quad (2)$$

where ϵ_{xy} is given by $(4\pi i/\omega)\sigma_{xy}$.
We suspected that the MO-structure in Pt-based alloys in the short wavelengths are due to vanishing ϵ_{xx} in the denominator of above formula. This may be the case in the Pt-based alloys, in which ϵ_{xx}' crosses zero (i.e., plasma resonance occurs) around 6 eV as shown in Figs. 5 and 6. To confirm this we simulated spectra of θ_K and η_K by eq.(2), using the measured spectra of ϵ_{xx} and the constant value of σ_{xy} determined experimentally at 5.9 eV. The results are shown in Fig. 12, which clearly shows an enhancement effect of the magnetooptical structure around 6 eV where the plasma resonance occurs in both Pt-Co and Pt-Fe alloys. Such effect was first pointed out by Feil and Haas [7] and is known as "plasma-enhancement effect".

Taking into consideration that the energy positions of the plasma edge are quite identical in Pt-Co and Pt-Fe alloys, we tentatively estimate that the Fermi surfaces of Pt-Co and Pt-Fe alloys exist in the Pt-origined band and not much influenced by charge transfer by alloying.

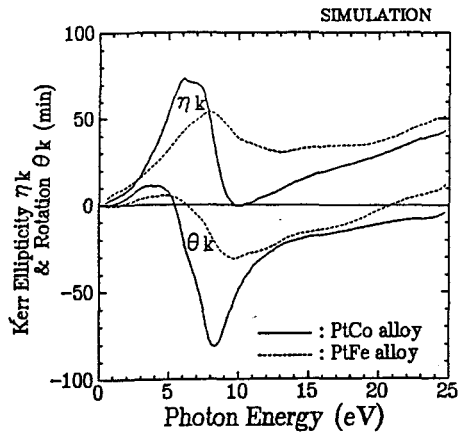

Fig.14 Simulated Kerr rotation and Kerr ellipticity in Pt-Co (solid) and Pt-Fe alloys (dotted) assuming σ_{xy} does not depend on energy

CONCLUSION

Magnetooptical spectra in Pt-based multilayers were simulated assuming the presence of alloy layer at the interface. In this analysis optical constants determined from the reflectivity spectra measured with synchrotron radiation were employed. The alloy layer thickness was estimated to be 6-10 Å. It became clear that short-wavelength MO structure of the Pt-based alloys are determined by the enhancement effect at the plasma edge.

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