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INTERLAYER COUPLING AND MAGNETOOPTICS IN MULTILAYERS

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Abstract - Additional magnetooptical Kerr effect (AMOKE) was observed in several multilayer structures. For Fe/Pd and Co/Cu multilayers, AMOKE enhanced the Kerr rotation in short wavelength side, while for Fe/Ag and FeSi/Cu multilayer systems the Kerr rotation enhancement appeared in long wavelength side. A number of ferromagnetic/nonmagnetic /ferromagnetic(FM/NM/FM) sandwiches showed that the AMOKE led to oscillations of Kerr rotation and Kerr ellipticity in certain wavelength range with changing NM layer thickness similar to the oscillatory interlayer coupling. The oscillation of effective optical constants related to the MOKE oscillation was observed for the first time. The mechanisms of the AMOKE were discussed.

I. INTRODUCTION

Recently interlayer exchange coupling in metallic multilayers, consisting of ferromagnetic and nonmagnetic sublayers with nanometer thickness, has been a new and interesting topic in the field of magnetism and attracted much attention of scientists and engineers. It was studied in various multilayer systems and by different experimental methods, such as magnetic curve measurement, magnetoresistance, ferromagnetic resonance and spin waves studies, magnetooptical effect and its spectra, neutron techniques, X-ray magnetic dichroism, Mossbauer spectroscopy, NMR of nuclei in nonmagnetic layers, spin resolved scanning electron microscopy and Auger spectroscopy, spin resolved photoelectron emission spectroscopy etc. Among these methods, the study of magnetooptical spectrum of multilayer structures is easy to realize and was found to provide more and more information of interlayer coupling in multilayers. In this paper a review of our studies on the interlayer coupling in several multilayer systems by magnetooptical Kerr effect (MOKE) is given.

II. PRINCIPLE OF INVESTIGATION

It is well known [1-3] that the complex polar Kerr rotation $\tilde{\theta}_k = \theta_k + i\varepsilon_k$ of a multilayer film is related to the effective complex dielectric tensor elements $\tilde{\varepsilon}_{xxe}, \tilde{\varepsilon}_{xye}$ and the effective optical constants $\tilde{n} = n_e + ik_e$ of the multilayers by

$$\tilde{\theta}_k = \frac{i\tilde{\varepsilon}_{xye}}{\tilde{\varepsilon}_{xxe}^{\frac{1}{2}}(\tilde{\varepsilon}_{xxe} - 1)} \tag{1}$$

or

$$\theta_k = \frac{A\varepsilon''_{xye} - B\varepsilon'_{xye}}{A^2 + B^2} \tag{2}$$

$$\varepsilon_k = -\frac{A\varepsilon'_{xye} + B\varepsilon''_{xye}}{A^2 + B^2} \tag{3}$$

where

$$\left.\begin{aligned} A &= -n_e^3 + n_e + 3n_e k_e^2, \\ B &= k_e^3 + k_e - 3n_e^2 k_e, \\ \tilde{\varepsilon}_{xye} &= \varepsilon'_{xye} + i\varepsilon''_{xye}, \\ \tilde{n}^2 &= (n_e + ik_e)^2 = \tilde{\varepsilon}_{xxe} \end{aligned}\right\} \tag{4}$$

All the constants with subscript e refer to the effective constants of the multilayers. They are contributed by the optical or/and magnetooptical properties of individual layers and can be calculated numerically by Fresnel equations for multilayers by using the known values of the complex optical dielectric tensor elements $\tilde{\varepsilon}_{ij}$ and the optical constants $\tilde{n}$ of the sublayers in the multilayers [1-3].

There may be two cases[3]. (1) When the interlayer interaction does not exist or can be neglected, the theoretical Kerr rotation spectra $\tilde{\theta}_k - \lambda$ of the multilayers calculated by Fresnel equations with the data of complex diagonal and off-diagonal dielectric tensor elements of ferromagnetic layer material and of the diagonal element of nonmagnetic layer material in bulk or single layer state, agree with the experimental ones semiquantitatively or qualitatively. This is true for the multilayer structures with thick nonmagnetic spacers, which implies no interlayer coupling effect and is a pure optical constant effect. One of the optical constant effect is the well known plasma enhanced MOKE as mentioned below. (2) When interlayer coupling appears in multilayers with thin nonmagnetic layers, the interlayer interaction may change the magnetic state in ferromagnetic layers and induce spin polarization of conduction elections in nonmagnetic layers. Either or both of these two effects can create AMOKE and change the total MOKE spectra. Two kinds of related phenomena have been observed in our laboratories. (a) Abnormal enhancement of MOKE in certain wavelength range which may be utilized in finding new MO materials. "Abnormal " means the enhancement does not appear with thick NM layers and cannot be explained by the optical constant effect. (b) Oscillations of MOKE of certain wavelength. Both of them are originated from certain new or modified MO or optical transitions due to the change of magnetic state in ferromagnetic layers or/and the spin polarization of nonmagnetic layers caused by interlayer coupling. In the following sections some results will be described.

III. EXPERIMENTAL METHODS

The samples were mostly prepared by rf magnetron sputtering onto water-cooled glass substrates. The vacuum system had a base pressure of 3×10^{-6}Torr. An argon gas pressure of 5×10^{-3} Torr was maintained during deposition. The layered structure was achieved by alternatively exposing the substrate to different targets via a rotating substrate holder. The thicknesses of the sublayers were controlled by the exposure time and deposition rate. To determine the deposition rate, several thick single layer films were first made and the thicknesses were measured by a talystep-type surface profilometer and by an optical interference microscope. The deposition rate is about 1.0 Å /s to 2.0Å /s. Fe/Ag/Fe sandwiches were made by ion beam sputtering technique with similar conditions.

X-ray $\theta - 2\theta$ scanning diffraction was employed to analyze the periodicity and the microstructure of the multilayers. The small angle diffraction showed that the samples were well periodically layered. The experimental intended period and the period obtained by small angle x-ray diffraction data after refraction indices connections differs by about 5%.

The magnetooptical Kerr rotation θ_k and Kerr ellipticity ε_k spectra were measured at room temperature by a MOKE spectrometer with an applied field of 10 kOe. The measurement accuracy was 0.01 degree. The electron paramagnetic resonance spectrometer of model ER-200D-SRC was used to measure the ferromagnetic resonance with a microwave frequency of 9.78 Ghz at room temperature.

IV. ABNORMAL ENHANCEMENT OF MOKE IN MULTILAYERS

According to equation (1)–(3) it is obvious that when n_e and k_e are relatively small the denominator is reduced faster than the numerator and $\tilde{\theta}_k$ may be enhanced. This is an enhancement by optical constant effect. In some nonmagnetic metals, such as Cu, Ag, Au etc. , there is a plasma resonance frequency ω_p in or near visible region. When the optical frequency is near ω_p the reflectivity of the metal drops abruptly due to plasma resonance absorption. Its optical constants change in a large range and can be very small, which reduces the effective optical constants n_e and k_e of a multilayer film containing this nonmagnetic metal layers and enhances its MOKE. The plasma enhanced peak of MOKE in bilayers and multilayers was observed in many systems experimentally and also appeared in the calculated spectra without considering the effect of interlayer coupling [1-3].

However, when the nonmagnetic layers were thin, in four systems of multilayer films we observed essential difference between experimental MOKE spectra and the calculated ones without considering the interlayer coupling . In Fig.1 and 2 the observed and calculated polar Kerr rotation spectra $\tilde{\theta}_k - \lambda$ of Co/Cu multilayers with different Cu thickness are shown[4]. For thick single Co layer film , θ_k decreases with decreasing wavelength in this wavelength range. For Co/Cu multilayers with thick Cu layers the experimental and calculated spectra took the similar shape. A θ_k peak appeared at the wavelength near the plasma frequency of Cu, λ~560 nm, when the optical constants of Cu were properly low, resulting in the reduction of effective optical constants of the multilayer system. But θ_k was smaller than that of single Co layer in the whole wavelength range, which could be understood as due to less content of Co and thus smaller effective off-diagonal elements $\tilde{\varepsilon}_{xye}$ in the numerator of equation (1)-(3). For the multilayers with thin Cu layers (10Å and 6Å) the observed θ_k spectra showed a peculiar shape, quite different from the calculated ones in Fig 2. The abnormal enhancement of θ_k in short wavelength side could not be explained by plasma enhancement and by pure optical effect. We attributed this enhancement to an AMOKE due to interlayer coupling in the multilayers with thin Cu layers. In Fe/Pd multilayers an abnormal enhancement of θ_k was also observed in short wavelength side, which could not explained by mere optical constant effect [5] . In Fe/Ag[6] and FeSi/Cu[3] multilayers an abnormal enhancement of θ_k in long wavelength side was observed when the thickness of Ag and Cu layers were small enough, down to about 10Å . Interlayer coupling was also considered as the origin of the θ_k enhancement.

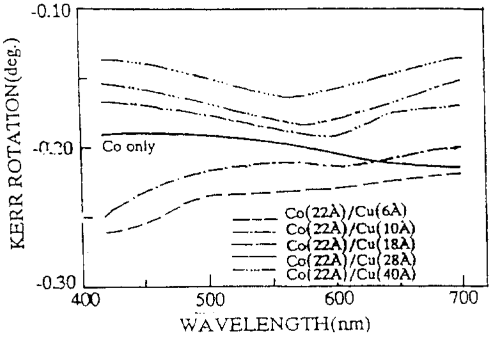

Figure.1 The experimental MOKE spectra of Co/Cu multilayers

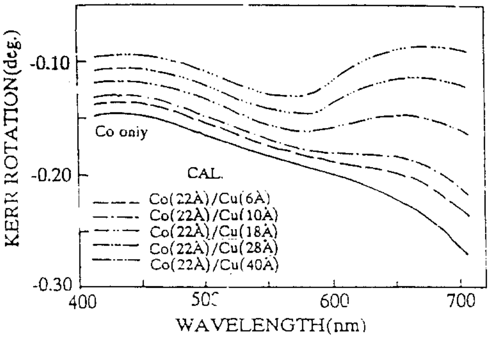

Figure.2 The calculated MOKE spectra of Co/Cu multilayers without considering the interlayer coupling.

As mentioned above, the AMOKE due to interlayer coupling may be originated from the change of the magnetic state in ferromagnetic layers or/and from the induced spin polarization of nonmagnetic layers. For the above four systems we explained the AMOKE successfully by the spin polarization in nonmagnetic layers which created an additional off-diagonal element.

In Fe/Pd multilayers it was reasonable to assume and was shown experimentally that the strong paramagnetic Pd layers were positively polarized due to the exchange interaction with adjacent Fe layers and the positive polarization of Pd layers gave rise to an AMOKE at short wavelength side as shown in the references[3-5]. In Co/Cu multilayers with thin Cu layers, by magnetometry and ferromagnetic resonance [4] and by X-ray magnetic dichroism[7] it was demonstrated that there was a net positive induced spin polarization. And it might also create an AMOKE and led to an abnormal

MOKE enhancement at short wavelength[4]. For Fe/Ag and FeSi/Cu multilayers with thin Ag and Cu layers, the abnormal θ_k enhancement could be explained by a similar theoretical model if a negative net spin polarization was assumed in Ag and Cu layers[3-6].

The creation of an AMOKE by the spin polarization of NM layers was treated with a modified Drude model of free electrons [6]. In Drude model the optical dielectric constant of free electrons is given by

$$\tilde{\varepsilon} = 1 - \frac{\omega_p^2}{\omega(\omega - i\gamma)} \qquad (5)$$

ω_p is the plasma frequency, γ is the relaxation frequency and ω the optical frequency. Scalar dielectric function does not lead to MOKE. An applied magnetic field causes a split of plasma edge for right (+) and left (-) circularly polarized light by $\omega_0 = eH/m_{eff}c$, the cyclotron frequency. The dielectric function for right and left circularly polarized light is given by :

$$\tilde{\varepsilon}_{\pm} = 1 - \frac{\omega_p^2}{\omega(\omega \pm \omega_0 - i\gamma)} \qquad (6)$$

The dielectric function becomes a tensor with the off-diagonal element $\tilde{\varepsilon}_{xy} = \frac{1}{2}(\tilde{\varepsilon}_+ - \tilde{\varepsilon}_-)$,

$$\tilde{\varepsilon}_{xy} = \frac{\omega_0 \omega_p^2}{\omega[(\omega - i\gamma)^2 - \omega_0^2]} \qquad (7)$$

This formula was used by Krinchik in calculating the MOKE of Fe, Co and Ni with spontaneous magnetization[8], in which the external magnetic field was replaced by an effective field H_e. We used this formula to calculate the additional MOKE produced by the spin polarized conduction electrons in NM layers due to interlayer coupling and found good agreement between calculated MOKE spectra with a reasonable value for the adjustable parameter ω_0 and the experimental ones. Fig.3. shows the MOKE spectra of Fe (10Å)/Ag (10Å) and Fe (60Å)/Ag (60Å) multilayers. Obviously, for the former specimen the calculated spectrum without considering the AMOKE deviates from the data points in long wavelength side in an essential way, while by considering the AMOKE of the spin polarized conduction elections, the calculation agrees well with the experiment. Here the direction of the spin polarization had to be assumed opposite with respect to the magnetization of Fe layers. Otherwise the θ_k enhancement would be in short wavelength side, as the case of Co/Cu and Fe/Pd multilayers. For Fe (60Å)/Ag (60Å) multilayers, no need to consider the interlayer coupling effect.

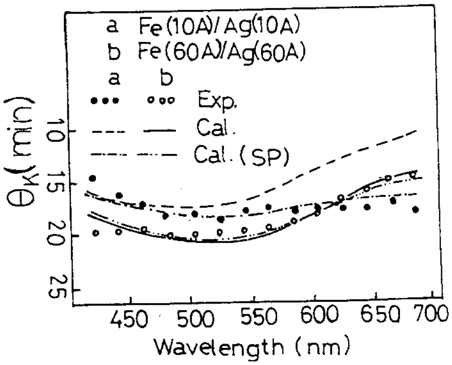

Figure.3 θ_k spectra of Fe/Ag multilayers. Dots are experimental data. Lines are calculated spectra with and without considering the AMOKE of the spin polarization of Ag

For FeSi/Cu multilayers, the situation was similar to that of Fe/Ag multilayers.

In summary, from our previous studies on Fe/Pd, Co/Cu, Fe/Ag and FeSi/Cu multilayers it was found that when the nonmagnetic layers were thin an abnormal θ_k enhancement appeared experimentally, which could be explained by an additional MOKE caused by the spin polarization of conduction electrons in nonmagnetic layers due to interlayer coupling. For Fe/Pd and Co/Cu multilayers, the θ_k enhancement was in short wavelength side, which could be explained as due to an AMOKE created by a positive net spin polarization of Pd and Cu. For Fe/Ag and FeSi/Cu multilayers, the θ_k enhancement was at long wavelengths and a negative net spin polarization of Ag and Cu layers was required. It seems there is a rule of thumb as follows. When the abnormal θ_k enhancement is in short wavelength side the spin polarization of conduction electrons in nonmagnetic layers producing the additional MOKE is positive. When the abnormal θ_k enhancement is in long wavelength side the spin polarization is negative. Whether this rule is true or not needs more investigations. In addition, before the effect of the change of the magnetic state in ferromagnetic layers on the AMOKE is clearly studied the above conclusion can not be taken as unambiguous.

V. OSCILLATION OF MAGNETOOPTICAL KERR EFFECT WITH NONMAGNETIC LAYER THICKNESS

More detailed study of the dependence of additional MOKE of various multilayers and sandwiches on nonmagnetic layer thickness showed a fairly general behavior of MOKE oscillation as a function of nonmagnetic layer thickness in a certain wavelength region and concurrent enhancement of Kerr rotation and antiferromagnetic [9] or ferromagnetic coupling [10] was reported . We have observed similar oscillation of MOKE in various systems , such as FeCo/Cu/FeCo[11] , CoCr/Cu, Ag, Al/CoCr, Co/Al/Co, Fe/Au/Fe and Fe/Ag/Fe sandwiches and CoCr/Cu multilayers. In fig.4 the dependence of MOKE of Fe(40Å)/Ag/Fe(40Å) sandwiches on Ag spacer thickness is shown. The Kerr rotation and ellipticity of the sandwiches oscillate concurrently as function of Ag spacer thickness with a period of about 14 Å. By ferromagnetic resonance we found the resonance field H_{res} also oscillated with respect to Ag spacer thickness with the same period and the maxima of H_{res} coincided precisely with the peaks of θ_k and ε_k. According to the reference [12] the peaks of θ_k and ε_k correspond to the antiferromagnetic states indicated by H_{res} maxima of the sandwiches.

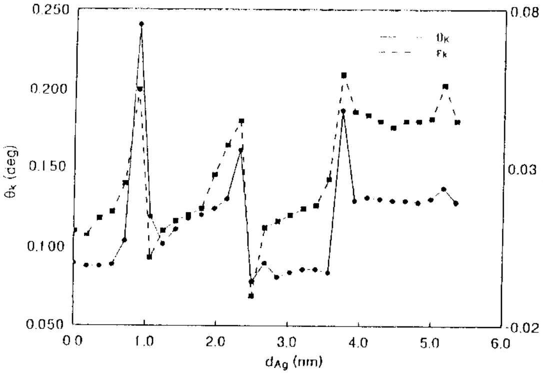

Figure.4 The dependence of θ_k and ε_k of Fe(40Å)/Ag/Fe(40Å) structures on Ag layer thickness at the wavelength of 450 nm

In order to look at the mechanism of the MOKE oscillation, we measured the effective optical constants of Fe/Ag/Fe sandwiches. For the first time an oscillation of the n_e and k_e was observed as a function of Ag layer thickness with the same period as shown in fig.5. The minima of n_e and k_e coincided with the maxima of the MOKE. Our preliminary studies showed that the oscillation of the MOKE of Fe/Ag/Fe sandwiches is mainly due to the oscillation of effective optical constants n_e and k_e instead of the oscillation of effective off-diagonal dielectric tensor element $\tilde{\varepsilon}_{xye}$. The microscopic mechanism of the oscillation of n_e and k_e needs further study.

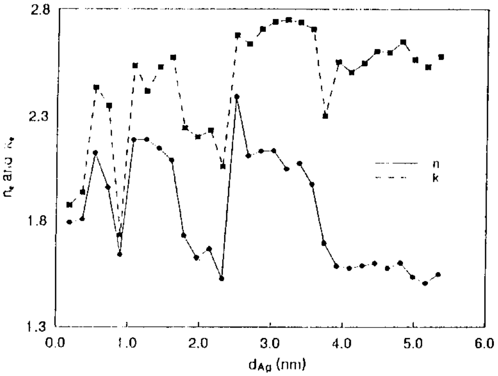

Figure.5 The dependence of effective optical constants on Ag spacer thickness for Fe(40Å)/Ag/Fe(40Å) structures at the wavelength of 450nm

VI. SUMMARY AND DISCUSSION

Additional MOKE was observed in various multilayers and sandwiches. It could enhance θ_k at a certain wavelength range and resulted in MOKE oscillations as a function of nonmagnetic spacer thickness. The effective optical constants of Fe/Ag/Fe sandwiches were found to oscillate with respect to Ag spacer thickness , which was the major reason of the MOKE oscillation of Fe/Ag/Fe sandwiches. The study of the AMOKE is still in its preliminary stage. The new finding that the oscillation of the effective optical constants of Fe/Ag/Fe sandwiches was the major reason of the oscillation of the θ_k and ε_k calls our attention to carry out comprehensive studies of the AMOKE in various systems to clarify whether the effective optical constant oscillation due to interlayer coupling is a general phenomena in multilayer structures, what its microscopic mechanism is and how the changes of $\tilde{\varepsilon}_{xye}$ and $\tilde{n}_e$ contribute to AMOKE in different systems. It is also interesting to identify the two origins of the AMOKE, i.e. the effect due to the change of magnetic state in ferromagnetic layers and due to the induced spin polarization in nonmagnetic layers on the AMOKE. The recent results of the correlation between the AMOKE and quantum well states in multilayer structures[14] together with our results in this paper showed that the easily accessible measurement of magnetooptical effect related to spin dependent electron transitions, and also the optical constants measurement are methods providing more and more microscopic information of interlayer interaction in ultrathin films.

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