PERPENDICULAR MAGNETIC ANISOTROPY AND MAGNETO-OPTICAL KEER PROPERTIES OF Co/(Pd-Au) METALLIC MULTILAYERS

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Abstract - We prepared Co/(Pd-Au) multilayers onto a glass substrates by rf magnetron sputtering at room temperature. Co/(Pd-Au) multilayers exhibit a magnetic easy axis perpendicular to the film plane up to a larger magnetic layer thickness than Co/Pd multilayer. Especially, Co/(Pd_{0.70}Au_{0.30}) multilayers became perpendicular at 33Å. The magnetic anisotropy can be explained by the strain effect. The role of magnetoelastic energy due to the in-plane strain in the system is pointed out and discussed. We also investigated the magneto-optical(MO) polar Kerr effect of these multilayers. The polar Kerr rotation angle θ_K increases when the Au concentration is 4.5at% compared to Co/Pd multilayers, but decreases with increasing Au content. **KEYWORDS:** PERPENDICULAR MAGNETIC ANISOTROPY, MAGNETO-OPTICAL KEER EFFECT, Co/(Pd-Au) MULTILAYERS.

INTRODUCTION

The magnetic and magneto-optical properties of metallic multilayers are of great interest both from fundamental and technological viewpoints. Metallic multilayers offer several potential advantages. Stable metal constituents with high corrosion and oxidation resistance can be selected, avoiding the necessity for protective layers. Enhancements in the polar Kerr rotation have been reported near the plasma frequency of the nonmagnetic metal in several multilayers such as Co/Au, Co/Cu multilayers[1], and near the shorter-wavelength range(about 400nm) in Co/Pt, Co/Pd multilayers[2].

As has been reported in several systems, Co/Pd, Co/Au, and Co/Pt the magnetic layer is limited a few monolayers [3][4][5][6]. Namely, Co/Pd and Co/Pt multilayers have an easy axis of magnetization perpendicular to the thin-film plane, only when the Co layers are very thin($t_{Co} < 8\text{\AA}$ in Co/Pd and $t_{Co} < 14\text{\AA}$ in Co/Pt)[4][5]. The origin of magnetic perpendicular anisotropy has been believed to be related with the change in the magnetic anisotropy of the interfacial atoms as a consequence of a reduced symmetry in their surroundings first suggested by Néel[7]. However, recent researches have indicated that perpendicular anisotropy can not be explained only by the Néel's surface anisotropy. Moreover, strain at magnetic-nonmagnetic interfaces have been suggested as possible origins, especially for the samples made by sputtering[8][9][10].

Stress and strain induced by the lattice mismatch between magnetic and non-magnetic layers can be used to change the properties of Co/Pd multilayers and play a role in getting the desired anisotropy. Comparing the lattice constant of fcc Pd, 3.889Å, and fcc Au, 4.079Å, we expected an increase of the strain with increased Au concentration. In this paper we examine the magneto-optical(MO) and magnetic properties of Co/(Pd-Au) multilayers.

EXPERIMENTAL PROCEDURES

The multilayers were prepared on a glass substrate by rf magnetron sputtering using Ar gas at the gas pressure 5mTorr. All the samples were grown on the Pd buffer layer 300Å thick at room temperature. The Pd layer thickness was kept constant at 25Å and that of Co layer was varied in the range 4 to 50Å. The addition of Au to the Pd layer was carried out by putting Au chips on the Pd target. The content of Au was determined by energy-dispersive spectrometer(EDS).

The periodic compositional modulations and crystallographic structures of these multilayer were analyzed by small and high angle x-ray diffractions(XRD) using CuK α radiation. The magnetic properties of the multilayers were investigated by means of a vibrating sample magnetometer (VSM). All measurements were carried out at room temperature. The strength of the magnetic field applied perpendicular and in-plane to the thin film ranged from -15kOe

to 15kOe. The values for the magnetic anisotropy were obtained from the area between the in-plane and perpendicular magnetization curves as measured in VSM. Magneto-optical properties of the sample side were measured in a wavelength range 350-800nm using a polar Kerr rotation measurement system at a maximum magnetic field of 15kOe.

RESULTS AND DISCUSSION

Structure and magnetic property

Typical high-angle X-ray diffraction patterns for Co/(Pd-Au) multilayers are shown in figure 1. In all compositions, the main peaks and satellite peaks can be observed and the existence of periodic structures was confirmed.

Figure 2 illustrates the hysteresis curves for a representative series ($t_{Co} \approx 16\text{\AA}$) of Co/(Pd-Au) multilayers.

It is clearly seen that with increasing the content of Au (C_{Au}), multilayered films becomes easier to magnetize in perpendicular fields and increasingly more difficult in parallel fields. But the multilayers become harder to magnetize perpendicular to the film plane, when C_{Au} is over 50at.%. These results can be explained by a strain contribution to the anisotropy.

As is well known, the magnetic anisotropy energy K_{eff} vs the Co layer thickness t_{Co} can be phenomenologically described as

$$K_{eff} \cdot t = K_v \cdot t + 2K_s \quad (1)$$

Fig. 1. X-ray diffraction patterns in the high angle region of Co/Pd_{1-x}Au_x multilayers ($t_{Co} \approx 16\text{\AA}$).

(a) Co/Pd (b) Co/Pd_{0.955}Au_{0.045} (c) Co/Pd_{0.84}Au_{0.16}
(d) Co/Pd_{0.70}Au_{0.30} (e) Co/Pd_{0.56}Au_{0.44} (f) Co/Pd_{0.46}Au_{0.54}

where K_s refers to the interface anisotropy per unit area and K_v is the bulk contributions per unit volume of Co layer.

Figure 3 shows the effective magnetic anisotropy energy per unit volume of magnetic layer for four compositions with magnetic layer thickness. From the intercept and the slope of linear fits to the data, we can get the interface and volume anisotropies for Co/Pd and Co/(Pd-Au), i.e. Co/Pd_{1-x}Au_x ($x = 0.045, 0.16, 0.30$) multilayers as listed in Table I. Co/(Pd-Au) multilayers exhibit a perpendicular easy axis of magnetization up to a larger magnetic layer thickness than the Co/Pd multilayer. In figure 3, by a linear fit, we find that the

Fig. 2. Magnetization hysteresis loops of a series of Co/(Pd-Au) multilayers ($t_{Co} \approx 16\text{\AA}$). They were measured in fields parallel(—) and perpendicular(---) to the film plane.

(a) Co/Pd (b) Co/Pd_{0.955}Au_{0.045} (c) Co/Pd_{0.84}Au_{0.16}
(d) Co/Pd_{0.70}Au_{0.30} (e) Co/Pd_{0.56}Au_{0.44} (f) Co/Pd_{0.46}Au_{0.54}

Fig. 3. Plots of effective anisotropy energy K_{eff} times the Co layer thickness t_{Co} as a function of t_{Co} for Co/(Pd-Au) multilayers.

Sample	K_s (erg/cm^2)	K_v ($10^6 erg/cm^3$)
Co/Pd	0.39	-9.63
Co/Pd _{0.955} Au _{0.045}	0.44	-8.88
Co/Pd _{0.86} Au _{0.14}	0.22	-2.19
Co/Pd _{0.70} Au _{0.30}	0.17	-1.05

Tab. I. Interfacial anisotropy energy K_s and volume anisotropy energy K_v of Co/(Pd-Au) multilayers.

transition ($K_{eff} = 0$) to a perpendicular easy axis occurs at $t_{Co} \approx 33\text{\AA}$ for Co/(Pd_{0.70}Au_{0.30}) multilayer. This is a surprising result. The high quality (111) epitaxial multilayer manufactured by MBE exhibits a perpendicular easy axis of magnetization when the thickness of Co layer is below $24\text{\AA}$ [9]. This is believed to be due to the strain effect.

Volume anisotropy energy K_v is generally written as

$$K_v = K_d + K_{MC} + K_{ME} \quad (2)$$

where the first term K_d is the demagnetization energy which is the shape contribution, $K_d = -2\pi M_s^2$ where M_s is the saturation magnetization, and K_{MC} is the magnetocrystalline energy of the bulk Co, and the last magnetoelastic energy (K_{ME}) is the contribution due to stress (σ) and the related magnetostriction (λ). Using the method by Yamaguchi et al.[11], we calculated the magnetoelastic energy of Co/(Pd-Au) multilayers. If we assume that the magnetic/nonmagnetic interfaces are coherent, σ and K_{ME} can be expressed simply by as

Sample	σ ($10^{10} \text{ dyne/cm}^2$)	K_{ME} (10^6 erg/cm^3)	K_v (10^6 erg/cm^3)
Co/Pd	3.26	5.38	-1.83
Co/Pd _{0.955} Au _{0.045}	3.33	5.50	-1.72
Co/Pd _{0.86} Au _{0.14}	3.51	5.79	-1.42
Co/Pd _{0.70} Au _{0.30}	3.72	6.14	-1.08

Tab. II. Strain-induced magnetic anisotropies K_{ME} of Co/(Pd-Au) multilayers calculated by equation(4).

$$\sigma = \frac{t_B Y_A Y_B}{t_A Y_A + t_B Y_B} \eta \quad (3)$$

$$K_{ME} = -\frac{3}{2} \lambda_{111} \sigma \quad (4)$$

where t_i and Y_i and are thickness of layer i , the biaxial elastic modulus of (111) planes, respectively and $\eta = (a_B - a_A) / a_A$ is the lattice mismatch, $\lambda_{111} = -1.1 \times 10^{-4}$ is the magnetostriction coefficient of (111) plane which is the calculated value by the first-principle method[12]. Table II summarizes the strain-induced anisotropy energies of Co/(Pd-Au) multilayers. This result shows that the increase of K_v can be expected by the increase of the strain induced lattice mismatch.

It is common practice to write equation (1) as $K_{eff} = K_v + K_s/t$, assume K_s to be constant and consider K_v to be inversely proportional to t . However, it has been reported that the magnetoelastic energy due to the in-plane strain play a role to create and stabilize the easy axis perpendicular to the film plane[8][11]. Therefore, magnetoelastic anisotropy can become important.

Furthermore, magnetoelastic energy can contribute to both K_s and K_v terms in equation (1) because of the stress gradient or periodic stress variation coupled with compositional variation along the film normal. At the interfaces the lattice strain exceeds the measured average value and this will contribute to the interface anisotropy K_s . The increase of K_v with addition of Au can be explained to be due to strain contribution to K_v . Although other factors such as the atomic mixing or compound formation[13], or the polarization of the Pd layers at the interface[5] may contribute to the perpendicular anisotropy, magnetoelastic effects due to the in-plane strain are quite important in understanding the perpendicular anisotropy of magnetic multilayers.

Fig. 4. The polar Kerr rotation spectra of Co/(Pd-Au) multilayers ($t_{\text{Co}} \approx 16\text{\AA}$).

(a) Co/Pd (●●●●) (b) Co/Pd_{0.955}Au_{0.045} (■ ■ ■ ■)
(c) Co/Pd_{0.70}Au_{0.30} (▼ ▼ ▼ ▼) (d) Co/Pd_{0.56}Au_{0.46} (▲ ▲ ▲ ▲)

Magneto-optical(MO) Kerr effect

Magneto-optical hysteresis loops at $\lambda=400\text{nm}$ for these multilayers are measured. As the content of Au(C_{Au}) increases, the hysteresis loops become easier to magnetize perpendicular to the film plane until $C_{\text{Au}}=44\text{at.}\%$. But the multilayers become harder to magnetize perpendicular to the film plane, when C_{Au} is over $50\text{at.}\%$. These results are consistent with the results in Figure 2.

The spectra of the polar Kerr rotation angle θ_k , measured in a magnetic field of 15kOe , i.e., in the saturation state, are shown in Figure 4. The Kerr effect increases at $C_{\text{Au}}=4.5\text{at.}\%$ compared to Co/Pd multilayers, but decreases with increasing Au content. The shape of the spectra is similar to Co/Pd multilayers. But the enhancement in the polar Kerr rotation near the shorter-wavelength range (about 400nm) in Co/Pd multilayers decreases with increasing Au content. The decrease of θ_k with increasing Au content can be explained to be due to reduction of polarized Pd.

CONCLUSIONS

We have used magnetron sputtering to deposit Co/(Pd-Au) multilayers onto a glass substrate. Co/(Pd-Au) multilayers exhibit a magnetic easy axis perpendicular to the film plane up to a larger magnetic layer thickness than Co/Pd multilayer. Especially, Co/(Pd_{0.70}Au_{0.30}) multilayers became perpendicular at $33\text{\AA}$. The relation between magnetic anisotropy and lattice strain can be explained as magnetoelastic energy due to

lattice mismatch between the adjacent layers. The role of magnetoelastic energy due to the in-plane strain in the system is pointed out and discussed. We also investigated the magneto-optical(MO) polar Kerr effect of these multilayers. The polar Kerr rotation angle θ_k increases at $C_{\text{Au}}=4.5\text{at.}\%$ compared to Co/Pd multilayers, but decreases with increasing Au content.

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REFERENCES

- [1] T. Katayama, H. Awano, Y. Nishihara, and N. Koshizuka : IEEE Trans. Magn., **23**, 2949 (1987).
- [2] S. Hashimoto and Y. Ochiai : J. Magn. Magn. Mater., **88**, 211 (1990).
- [3] P. F. Carcia, A. D. Meinhaldt, and A. Suna : Appl. Phys. Lett., **47**, 178(1985).
- [4] P. F. Carcia : J. Appl. Phys., **63**, 5066(1988).
- [5] F. J. A. den Broeder, H. C. Donkersloot, H. J. G. Draasima, and W. J. M. de Jonge : J. Appl. Phys., **61**, 4317(1987).
- [6] F. J. A. den Broeder, D. Kupier, A. P. van de Mosselaer, and W. Hoving : Phys. Rev. Lett., **60**, 2769(1988).
- [7] L. Néel : J. Phys. Radium, **15**, 225(1954).
- [8] B. Zhang, Kannan M. Krishnan, C. H. Lee, and R. F. C. Farrow : J. Appl. Phys., **73**, 6198(1993).
- [9] Brad N. Engel, Craig D. England, Robert A. Van Leeuwen, Michael H. Wiedmann, and Charles M. Falco : J. Appl. Phys., **70**, 5873(1991).
- [10] Brad N. Engel, Craig D. England, Robert A. Van Leeuwen, Michael H. Wiedmann, and Charles M. Falco : Phys. Rev. Lett., **67**, 1910(1991).
- [11] A. Yamaguchi, S. Ogu, W.-H. Soe, and R. Yamamoto : Appl. Phys. Lett., **62**, 1020 (1993).
- [12] K. Kyuno : "Theoretical study on the magnetic anisotropy of metallic multilayer", Ph. D. Thesis, Univ. Tokyo, Japan(1994).
- [13] N.-H. Cho, Kannan M. Krishnan, C. A. Lucas, and R. F. C. Farrow : J. Appl. Phys., **72**, 5799(1992).