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Magnetic anisotropy and magneto-optical Kerr effect of $Co/Pd_{1-x}Au_x$ metallic multilayers

Jae-Geun Ha, Kentaro Kyuno and Ryoichi Yamamoto
Institute of Industrial Science, University of Tokyo, 7-22-1 Roppongi, Minato-ku, Tokyo 106, Japan

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Abstract. We prepared $Co/Pd_{1-x}Au_x$ multilayers on glass substrates by RF magnetron sputtering at room temperature. $Co/Pd_{1-x}Au_x$ multilayers exhibit a magnetic easy axis perpendicular to the film plane up to a larger magnetic layer thickness than do Co/Pd multilayers. In particular, $Co/Pd_{0.70}Au_{0.30}$ multilayers became perpendicular at 33 Å. The magnetic anisotropy can be explained by the strain effect. The role of the magnetoelastic energy due to the in-plane strain in the system is pointed out and discussed. We also investigated the magneto-optical polar Kerr effect of these multilayers. The polar Kerr rotation angle θ_k increases when the Au concentration is 4.5 at.% compared to Co/Pd multilayers but decreases with increasing Au content.

1. Introduction

The magnetic and magneto-optical (MO) properties of metallic multilayers are of great interest from both fundamental and technological viewpoints. Metallic multilayers offer several potential advantages. Stable metal constituents with high corrosion and oxidation resistances can be selected, avoiding the necessity for protective layers. Enhancements in the polar Kerr rotation have been reported near the plasma frequency of the non-magnetic metal in several multilayers such as Co/Au and Co/Cu multilayers [1], and near the shorter-wavelength range (about 400 nm) in Co/Pt and Co/Pd multilayers [2]. Further, perpendicular magnetic anisotropy of multilayers has been achieved in metallic multilayers without the need for high-temperature annealing.

As has been reported for several systems, Co/Pd, Co/Au and Co/Pt, the magnetic layer is limited to a few monolayers [3]–[6]. That is 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 ($t_{Co} < 8$ Å for Co/Pd and $t_{Co} < 14$ Å for Co/Pt) [4, 5]. The origin of the magnetic perpendicular anisotropy has been believed to be related to 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 research has indicated that perpendicular anisotropy cannot be explained only by the Néel surface anisotropy. Moreover, strain at the magnetic–non-magnetic interfaces has been suggested as the possible origin, especially for samples made by sputtering [8]–[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, 3.889 Å, and FCC Au, 4.079 Å, we expected an increase in the strain with increased Au concentration. In this paper we examine the MO and magnetic properties of $Co/Pd_{1-x}Au_x$ multilayers.

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2. Experimental procedures

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

The periodic compositional modulations and crystallographic structures of these multilayer were analysed by small- and large-angle x-ray diffraction (XRD) using Cu Kα 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 -16 to 16 kOe. The values for the magnetic anisotropy were obtained from the area between the in-plane and perpendicular magnetization curves as measured with the VSM. The MO properties of the sample side were measured in the wavelength range 350–800 nm using a polar Kerr rotation measurement system at a maximum magnetic field of 15 kOe.

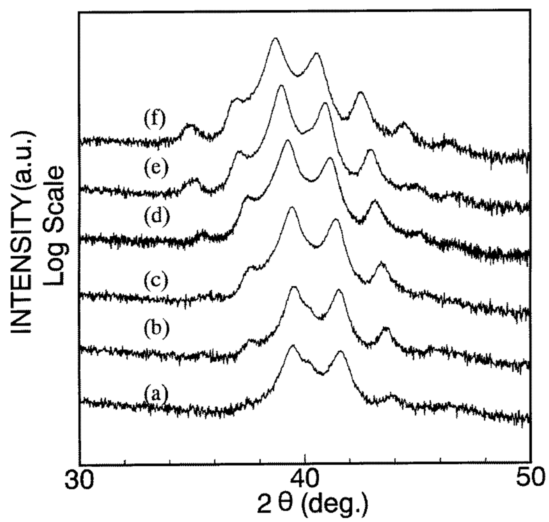

Figure 1. XRD patterns in the large-angle region of Co/Pd$_{1-x}$Au$_x$ multilayers ($t_{Co} \simeq 16$ Å) (a.u., arbitrary units): (a) Co/Pd; (b) Co/Pd$_{0.955}$Au$_{0.045}$; (c) Co/Pd$_{0.84}$Au$_{0.16}$; (d) Co/Pd$_{0.70}$Au$_{0.30}$; (e) Co/Pd$_{0.56}$Au$_{0.44}$; (f) Co/Pd$_{0.46}$Au$_{0.54}$.

3. Results and discussion

3.1. Structure and magnetic anisotropy

Typical large-angle x-ray diffraction patterns for Co/Pd$_{1-x}$Au$_x$ multilayers are shown in figure 1. In all patterns, the main peaks and the sattellite peaks can be observed and the existence of periodic structures was confirmed.

Figure 2 illustates the hysteresis curves for a representative series ($t_{Co} \simeq 16$ Å) of

Co/Pd$_{1-x}$Au$_x$ multilayers. It is clearly seen that, with increasing Au content C_{Au}, the multilayered films become easier to magnetize in perpendicular fields and increasingly more difficult in parallel fields. However, the multilayers become harder to magnetize perpendicular to the film plane, when C_{Au} is over 50 at.%. These results can be explained by a strain contribution to the anisotropy.

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

$$K_{eff}t = K_v t + 2K_S \tag{1}$$

where K_S refers to the interface anisotropy per unit area and K_V is the contributions per unit volume of Co layer. K_v is generally written as

$$K_v = K_d + K_{MC} + K_{ME} \tag{2}$$

where the first term K_d is the demagnetization energy which is the shape contribution given by $K_d = -2\pi M_S^2$ (where M_S is the saturation magnetization) and K_{MC} is the magnetocrystalline energy of the bulk Co, and the last magnetoelestic energy K_{ME} is the contribution due to stress σ and the related magnetostriction λ. Using the method of Yamaguchi *et al* [11], we calculated the magnetoelastic energy of Co/Pd$_{1-x}$Au$_x$ multilayers. If we assume that the magnetic–non-magnetic interfaces are coherent, σ and K_{ME} can be expressed simply as

$$\sigma = \frac{t_B Y_A Y_B}{t_A Y_A + t_B Y_B}\eta \tag{3}$$

$$K_{ME} = -\tfrac{3}{2}\lambda_{111}\sigma \tag{4}$$

where t_i and Y_i are the thickness of layer i and the biaxial elastic modulus of (111) planes, respectively, and $\eta = (a_B - a_A)/a_A$ is the lattice mismatch; λ_{111} is the magnetostriction coefficient of (111) plane. Table 1 summarizes the strain-induced anisotropy energies K_{ME} of Co/Pd$_{1-x}$Au$_x$ multilayers. This results shows that an increase in K_{ME} is expected on increase in the lattice misfit.

Table 1. Strain-induced magnetic anisotropies of Co/Pd$_{1-x}$Au$_x$ multilayers calculated by equation (4).

Sample	K_{ME} (10^6 erg cm^{-3})
Co/Pd	1.91
Co/Pd$_{0.955}$Au$_{0.045}$	1.95
Co/Pd$_{0.86}$Au$_{0.14}$	2.06
Co/Pd$_{0.70}$Au$_{0.30}$	2.18

Figure 3 shows the effective magnetic anisotropy energy per unit volume of magnetic layer for four compositions versus magnetic layer thickness. From the intercept and slope of linear fits to the data, we can get the volume and interface anisotropies for Co/Pd and Co/Pd$_{1-x}$Au$_x$ ($x = 0.045, 0.16$ and 0.30) multilayers as listed in table 2. Co/Pd$_{1-x}$Au$_x$ multilayers exhibit a perpendicular easy axis of magnetization up to a larger magnetic layer thickness than the Co/Pd multilayer. In particular, the Co/Pd$_{0.70}$Au$_{0.30}$ multilayer became perpendicular at 33 Å. 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 the Co layer t_{Co} is below 24 Å [9]. This is believed to be due to the

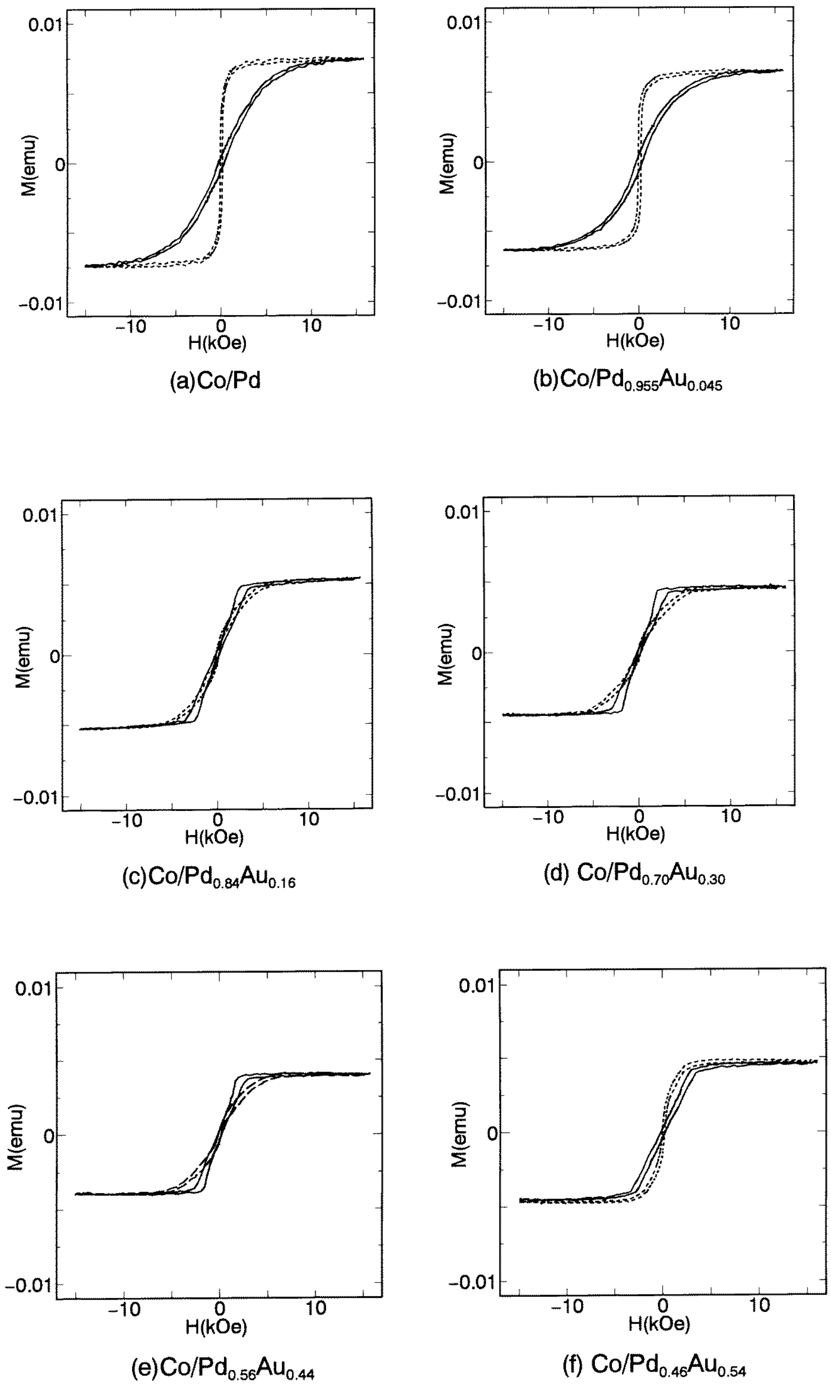

Figure 2. Magnetization hysteresis loops of a series of $Co/Pd_{1-x}Au_x$ multilayers ($t_{Co} \simeq 16$ Å), which were measured in fields parallel (– – –) and perpendicular (——) to the film plane: (a) Co/Pd; (b) $Co/Pd_{0.955}Au_{0.045}$; (c) $Co/Pd_{0.84}Au_{0.16}$; (d) $Co/Pd_{0.70}Au_{0.30}$; (e) $Co/Pd_{0.56}Au_{0.44}$; (f) $Co/Pd_{0.46}Au_{0.54}$.

Table 2. Interfacial anistropy energy K_S and volume anisotropy energy K_v of Co/Pd$_{1-x}$Au$_x$ multilayers.

Sample	K_S (erg cm^{-2})	K_v ($\times 10^6$ 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

strain effect. The estimation of in-plane strain is under investigation by the four-circle XRD method and will be published elsewhere.

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

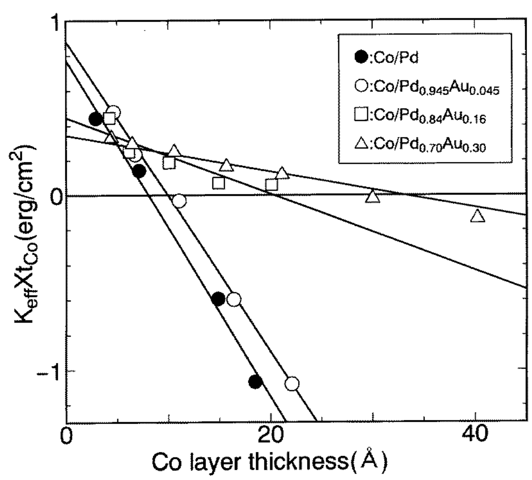

Figure 3. Plots of effective anisotropy energy K_{eff} times the Co layer thickness t_{Co} as a function of t_{Co} for Co/Pd$_{1-x}$Au$_x$ multilayers.

Furthermore, the magnetoelastic energy can contribute to both K_v and K_S terms in equation (1) because of the stress gradient or periodic stress variation coupled with chemical variation along the film normal. At the interfaces the lattice strain exceeds the measured average value and this will contribute to the interface anisotropy. In table 2, K_S for Co/Pd$_{0.955}$Au$_{0.045}$ multilayers is increased compared with the Co/Pd multilayer. Towards the centre of the Co layers the lattice strain will be less than the average value. The average strain–stress field within the Co layer will contribute to K_v. The increase in K_v on addition of Au can be explained to be due to the strain contribution to K_v. Although other factors such as the atomic mixing or compound formation [12] 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

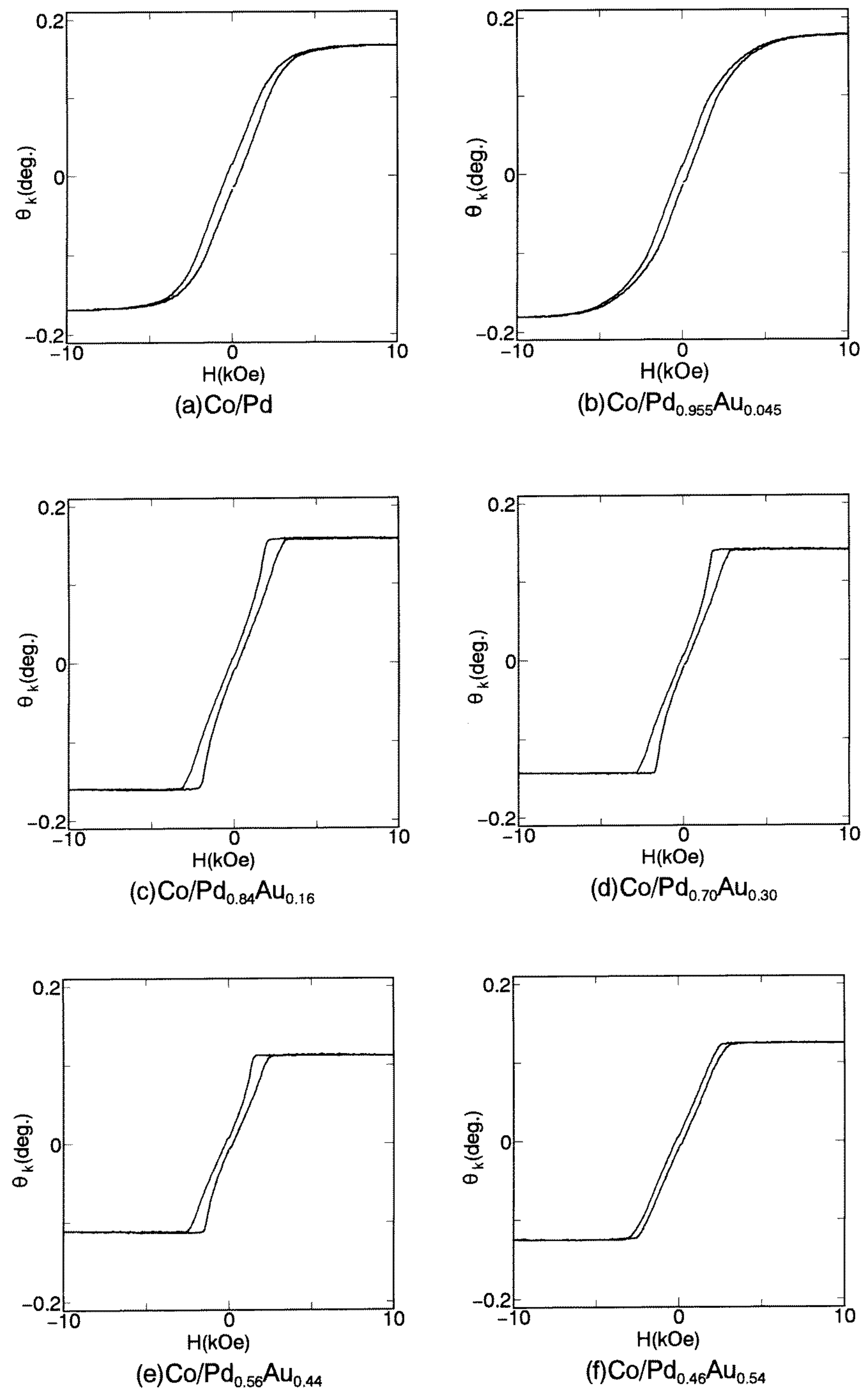

Figure 4. Kerr hysteresis loops of a series for $Co/Pd_{1-x}Au_x$ multilayers ($t_{Co} \simeq 16$ Å) measured at $\lambda = 400$ nm: (a) Co/Pd; (b) $Co/Pd_{0.955}Au_{0.045}$; (c) $Co/Pd_{0.84}Au_{0.16}$; (d) $Co/Pd_{0.70}Au_{0.30}$; (e) $Co/Pd_{0.56}Au_{0.44}$; (f) $Co/Pd_{0.46}Au_{0.54}$.

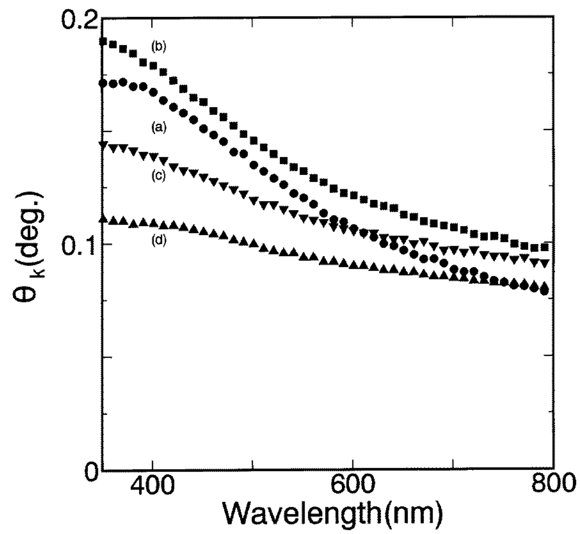

Figure 5. The polar Kerr rotation spectra of Co/Pd$_{1-x}$Au$_x$ multilayers ($t_{Co} \simeq 16$ Å): (a) Co/Pd (●); (b) Co/Pd$_{0.955}$Au$_{0.045}$ (■); (c) Co/Pd$_{0.70}$Au$_{0.30}$ (▼); (d) Co/Pd$_{0.56}$Au$_{0.44}$ (▲).

of magnetic multilayers.

3.2. Magneto-optical Kerr effect

MO hysteresis loops measured at $\lambda = 400$ nm for these multilayers are shown in figure 4. The orientation is consistent with the positive sign of the Kerr rotation. As the Au content C_{Au} increases, the hysteresis loops become easier to magnetize perpendicular to the film plane until $C_{Au} = 44$ at.%. However, the multilayers become harder to magnetize perpendicular to the film plane, when C_{Au} is over 50 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 15 kOe, i.e. in the saturation state, are shown in figure 5. The Kerr effect increases at $C_{Au} = 4.5$ at.% compared to Co/Pd multilayers but decreases with increasing Au content. The shape of the spectra is similar to that for Co/Pd multilayers, but the enhancement in the polar Kerr rotation near the shorter-wavelength range (about 400 nm) for Co/Pd multilayers decreases with increasing Au content. The decrease in θ_k with increasing Au content can be explained as due to reduction in polarized Pd. The increase in θ_k at $C_{Au} = 4.5$ at.% may be due to the strain contribution to θ_k, but it is not clear whether this phenomenon originates from the strain effect of the multilayer. Further theoretical and experimental studies are necessary.

4. Conclusions

We have used magnetron sputtering to deposit Co/Pd$_{1-x}$Au$_x$ multilayers onto glass substrates. Co/Pd$_{1-x}$Su$_x$ multilayer exhibits a magnetic easy axis perpendicular to the film plane up to a larger magnetic layer thickness than the Co/Pd multilayer. In particular, Co/Pd$_{0.70}$Au$_{0.30}$ multilayers became perpendicular at 33 Å. The relation between magnetic anisotropy and lattice strain can be explained as due to magnetoelastic energy from 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 MO polar Kerr effect of these multilayers. The polar Kerr rotation angle θ_K increases at $C_{Au} = 4.5$ at.% compared to Co/Pd multilayers but decreases with increasing Au content.

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