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Annealing Effect of Co/Pd Multilayers on Magnetic Properties During Interdifusion

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An artificially modulated magnetic Co/Pd multilayer is one of the promising candidates for high density magneto-optic (MO) recording media, due to a large Kerr rotation angle in the wavelength of a blue laser beam. However, since multilayer structure, as well as amorphous structure, is a non-equilibrium state in terms of free energy and a MO recording technology is a kind of thermal recording which is conducted around Curie temperature (T_C) of the recording media, when the Co/Pd multilayer is used for the MO recording media, changes in the magnetic properties are occurred as the amorphous structure do. Therefore, the assessment of the magnetic properties in the Co/Pd multilayer during interdiffusion is crucially important both for basic research and applications. As the parameter of the magnetic properties in this research, saturation magnetization and perpendicular magnetic anisotropy energy of the Co/Pd multilayer are measured in terms of Ar sputtering pressure and heat treatment temperature. From the results of the research, we find out that the magnetic exchange energy between Co and Pd sublayers strongly affects the changes in the magnetic properties of the Co/Pd multilayers during the interdiffusion in ferromagnetic state. This discovery will provide the understanding of the magnetic exchange energy in the Co/Pd multilayer structure and suggest the operating temperature range for MO recording in the Co/Pd multilayer for the basic research and applications, respectively.

1. Introduction

In the upcoming multimedia era, magneto-optic (MO) recording technology is one of the promising candidates for high density recording information storage. Presently, popular recording materials for the MO recording in the wavelength of a red laser beam (- 600 nm) are mainly amorphous HRE-TM (heavy rare earth-transition) metal alloys. However, it is pointed out that corrosion of the rare-earth elements and the reduction of the Kerr effect in the short wavelength of a blue laser beam (- 400 nm) cannot be avoided in these amorphous alloys. To solve these problems, Co/Pd multilayers have been introduced for magneto-optic recording materials in the wavelength of the blue laser beam for the next generation [1 - 5]. Since the Co/Pd multilayer does not contain any rare-earth element, it hardly corrodes. Furthermore, the Co/Pd multilayer also possesses an enhanced Kerr effect in the wavelength of the blue laser beam relative to the currently used amorphous alloys. Ultimately, the MO recording and the Co/Pd multilayers seem to be the most promising recording technology and material for high recording density in the next generation.

The multilayer structure, as well as the amorphous structure, is a non-equilibrium state in terms of free energy[6, 7]. Furthermore, the MO recording technology is a kind of thermal recording which is conducted around Curie temperature(T_C)[8] of the recording media. In non-equilibrium state and thermal recording, when the Co/Pd multilayer is used for MO recording material, changes in the multilayer structure are induced by stress release and interdiffusion, and these affect the magnetic and magneto-optic properties[9, 10] as do structure relaxation and crystallization in the amorphous alloys. However, despite the superiority of the Co/Pd multilayer as high density MO recording material, research into magnetic properties during the interdiffusion has hardly conducted on it .

In this research, the magnetic properties of the Co/Pd

multilayers during the interdiffusion will be discussed in terms of Ar sputtering pressure and heat treatment temperature as parameters of multilayer characteristic and MO recording, respectively. Since the magnetic properties of the Co/Pd multilayer are dramatically affected by sputtering gas pressure[9,11], the properties of the multilayers deposited at different sputtering pressures have been analyzed and discussed. The multilayer deposited at lower sputtering pressure, gave a more stable multilayer structure[11-13] than the multilayer deposited at higher sputtering pressure which possessed excellent magnetic properties[11,14]. In the range of the heat-treatment temperature, when considering MO recording applications, Curie temperature (T_C) was one of the important parameters. So the heat treatment was conducted in two groups; one below T_C and the other above T_C. The interdiffusion process of the Co/Pd multilayers will be presented elsewhere in detail[15]. For the comparison of the magnetic properties with structural property in the Co/Pd multilayer during the interdiffusion, the modulation amplitude in harmonic wavelength will be evaluated as chemical order. Magnetization perpendicular (M_S) and parallel (M_P) to the multilayer plane, and perpendicular magnetic anisotropy (K_U) will be assessed as intrinsic and extrinsic magnetic properties, respectively during the interdiffusion.

2. Experimental Procedure

The Co/Pd multilayers were deposited on R-plane sapphire substrate ($2\theta = 25.60°$ and $52.50°$) in a two-target UHV (Ultra High Vacuum) dc magnetron sputtering system which was gettered with liquid nitrogen. The configuration of the sputtering system is described elsewhere[16,17]. The substrates sat on a rotating holder and passed alternately beneath the two magnetrons on which the targets of Co and Pd were attached. A fixed shield was positioned between the level of the magnetrons and that of the substrate holder, with slots cut beneath the magnetrons. The target-substrate distances were 30 mm and 40 mm for the Co and Pd, respectively. The vacuum system was pumped down to 10^{-10} Torr by a liquid nitrogen trapped diffusion pump. The sputtering gas was Ar (99.999%), processed with an Ar purifier. The sputtering pressures were at 0.7 Pa (Run No. 4457) and 2.0 Pa (Run No. 4461) in the low and the high pressure runs, respectively. The multilayers had 200 periods and total approximate effective layer thicknesses were about 4000Å for both the multilayers deposited at lower and higher pressures. The Co sublayer thickness was designed to obtain perpendicular magnetic anisotropy (less than 8 Å)[14] and maximum magnetostriction (30 at. % of Co)[5]. The estimated thickness of Co and Pd sublayers were 5.0 Å and 15. 6 Å, respectively.

The compositions of the Co/Pd multilayers were determined using an EDS (Energy Disperse Spectrometer). Curie temperature of the Co/Pd multilayers was determined by DSC (Differential Scanning Calorimeter) with a heating rate of 40°C/min and was 368 ± 5°C. The multilayer structure of the as-deposited and heat-treated Co/Pd multilayers were measured by a XRD (X-Ray Diffractometer), using small angle ($2\theta = 3° - 10°$) and medium one ($2\theta = 35°$-$50°$) X-ray diffraction with θ-2θ scanning. Cu Kα(λ=1.5406Å) radiation was used in the XRD. In order to measure the X-ray intensities precisely, scans of rocking curve and calibration of 2θ-off method were adapted. The modulation wavelengths of the Co/Pd multilayers were deduced from the positions of satellite peaks in the small angle region. The nominal sublayer thickness of each element was calculated by combining the atomic weight ratio of the composition in the multilayer, assuming that the bulk densities of pure metals could be applied. A VSM (Vibration Sample Magnetometer) is used to measure the magnetic hysteresis loops perpendicular and parallel to the multilayer planes. The maximum external magnetic field of the VSM was 10 kOe.

The multilayers to be heat-treated were inserted in quartz ampoules. The ampoules were sealed after being pumped up to 10^{-6} Torr and filled again with pure argon to about 200 Torr to insure good thermal contact between the sample and surroundings during heat treatment. The heat treatment temperature for the interdiffusion was divided into two groups under the consideration of application in MO recording. One was below T_C, 250°C and 350°C and the other was above T_C, 390°C and 400°C.

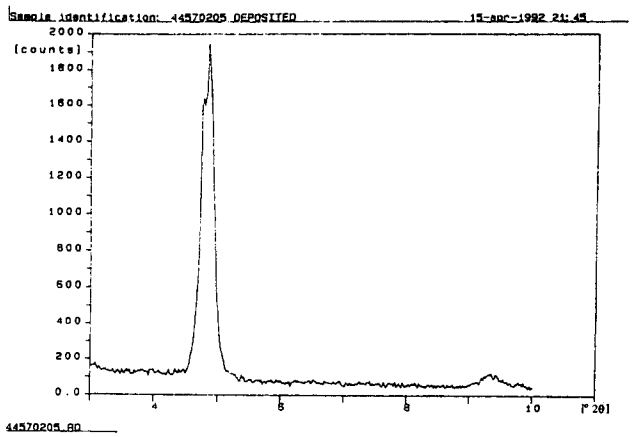
3. Results and Discussion

According to the composition analyses by EDS, the composition of the multilayers deposited at lower sputtering pressure (0.7 Pa) is 29.9 ± 0.2 at. % Co. These compositions are very close to the aimed composition for the maximum magnetostriction constant. Since the difference in composition between the multilayers is less than 3 % of each other, it will not seriously affect the main experiment which will compare the Co/Pd multilayers deposited with the same composition but different sputtering pressure.

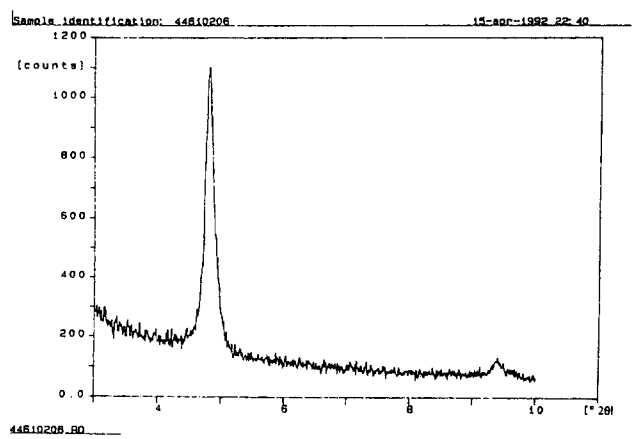
3. 1. Changes in the structural properties of Co/Pd multilayers during interdiffusion

Fig. 1 (a) and (b) display one of the X-ray diffraction satellite peaks in the small angle region ($2\theta = 3° - 10°$) for Co/Pd multilayers deposited at 0.7 and 2.0 Pa, respectively. The first and second satellite peaks are detected in these multilayer structures. The average positions of the first satellite peaks are $2\theta = 4.81° \pm 0.14°$ and $4.73° \pm 0.09°$

and which are corresponding to the modulation wavelength of λ= 18.36Å (Co = 4.44Å, Pd = 13.92Å) and 18.69Å (Co = 4.39Å, Pd = 14.30Å) for the multilayers deposited at 0.7 Pa and 2.0 Pa, respectively. The difference in the average wavelength of the multilayers may be caused by the difference in the average volume composition of the multilayers measured by EDS and the contribution of micro voids created in the higher sputtering pressure[11,14,18]. The X-ray intensity of the multilayer deposited at 0.7 Pa are larger than that at 2.0 Pa. Since the intensity is proportional to square of modulation amplitude[19], the interfaces of the multilayers deposited at 0.7 Pa appear sharper than those deposited at 2.0 Pa.



(a)



(b)

Fig. 1 (a) and (b): X-ray diffraction satellite peaks in the small angle region (2θ = 3° - 10°) for Co/Pd multilayers deposited at 0.7 Pa and 2.0 Pa, respectively.

Fig. 2 shows roughness at the interface of Co/Pd multilayer structure which is estimated from the following equation[20 - 22]

$$I \alpha \frac{1}{\sin^4\theta} \exp\{ -2 (\frac{2\pi\sigma\sin\theta}{\lambda_x})^2 \} \qquad (1)$$

I: First satellite peak intensity of multilayer

σ : Roughness at the interface of multilayer
θ : Bragg angle corresponding to composition modulation
λx : X-ray wavelength

A plot of ln ($I\sin^4\theta$) versus $\sin^2\theta$ should thus approximate a straight line whose gradient becomes steeper as s grows larger. The estimated roughness at the interface deposited at 0.7 Pa is 3.85 ± 0.04 Å and that deposited at 2.0 Pa is 4.27 ± 0.15 Å, which are coincidence with the results of X-ray diffraction curves in Fig. 1 (a) and (b).

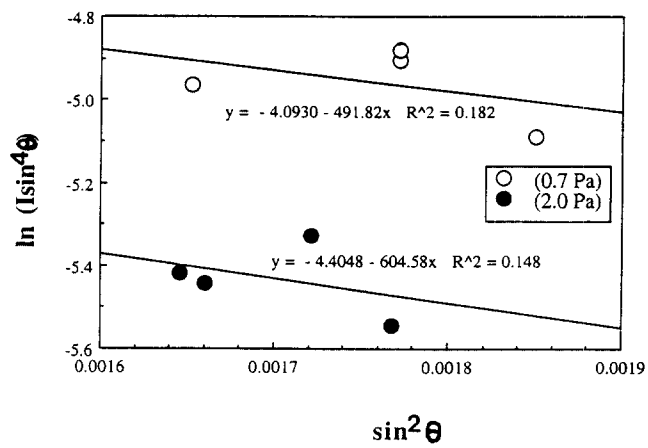


Fig. 2: Roughness at the interface of Co/Pd multilayers deposited at 0.7 Pa and 2.0 Pa

In previous research[23,24], the existence of a large coherent strain for epitaxial growth in <100> textured Co/Pd multilayers was detected at the interface, but no appreciable coherent strain arising from the <111> textured multilayer was found. Since the Co/Pd multilayers

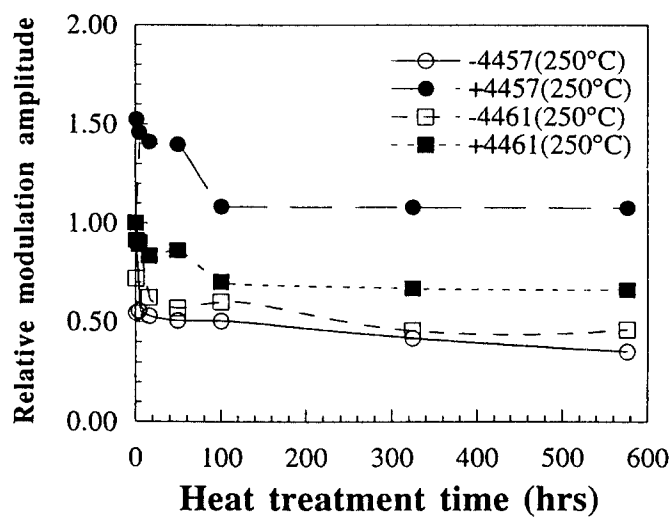


Fig. 3: Relative modulation amplitude of Co/Pd multilayers in incoherent state deposited at 0.7 Pa (4457) and 2.0 Pa (4461), and heat treated at 250°C as a function of heat treatment time

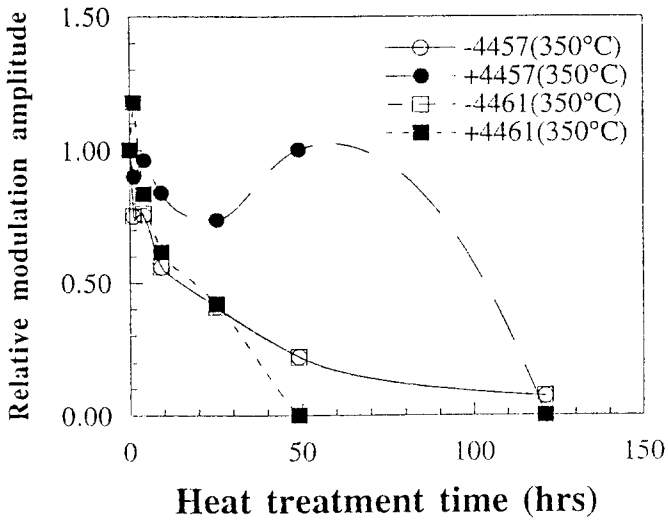


Fig. 4: Relative modulation amplitude of Co/Pd multilayers in incoherent state deposited at 0.7 Pa (4457) and 2.0 Pa (4461), and heat treated at 350°C as a function of heat treatment time

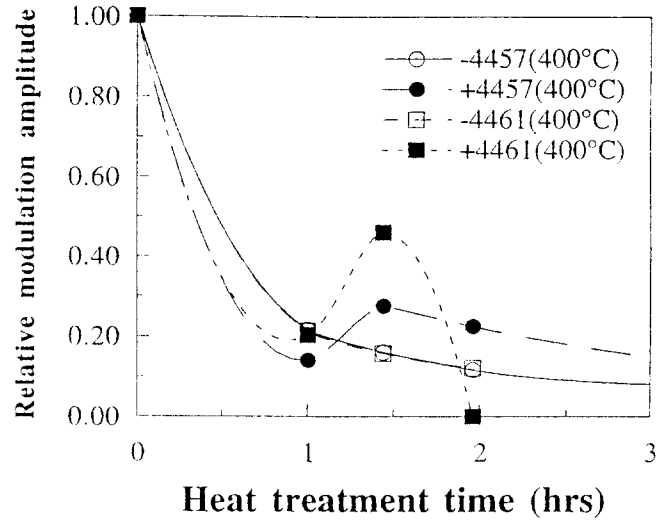


Fig. 6: Relative modulation amplitude of Co/Pd multilayers in incoherent state deposited at 0.7 Pa (4457) and 2.0 Pa (4461), and heat treated at 400°C as a function of heat treatment time

examined in this experiment are <111> textured polycrystalline multilayers, only the modulation amplitude of the Co/Pd multilayers in incoherent state is calculated [25 - 26].

Fig. 3, Fig. 4, Fig. 5 and Fig. 6 represent the changes in relative modulation amplitude of lower (–) and higher (+) satellite peaks around Co/Pd multilayer structure deposited at 0.7 Pa and 2.0 Pa during interdiffusion. The relative modulation amplitude plots on Fig. 3 and Fig. 4, and Fig. 5 and Fig. 6 are obtained from the Co/Pd multilayers heat-treated below T_C and above T_C, respectively. In the figures, the units on the Y axis are an arbitrary ratio. The arbitrary ratio of 1 represents the modulation amplitude in as-deposited and the unit of 0 stands for the absence of the compositional modulated multilayer structure. This means

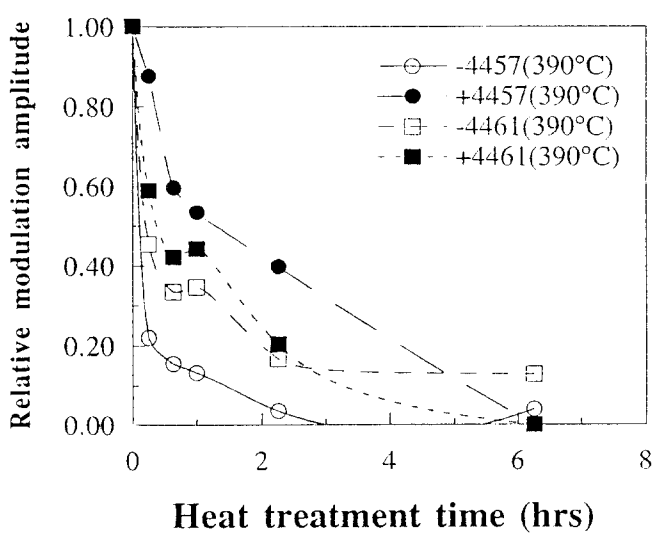


Fig. 5: Relative modulation amplitude of Co/Pd multilayers in incoherent state deposited at 0.7 Pa (4457) and 2.0 Pa (4461), and heat treated at 390°C as a function of heat treatment time

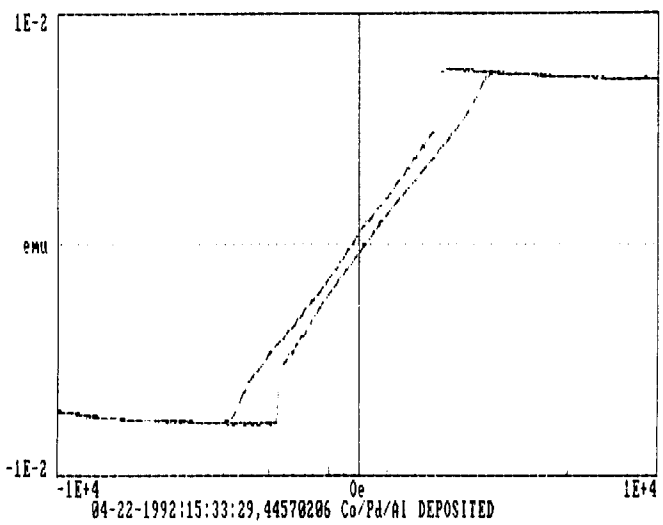
that the first satellite peak in the small angle, which is caused by composition modulation cannot be detected beyond the heat treat treatment time corresponding to 0. For example, the multilayers deposited at 0.7 Pa, and heat-treated at 250 and 350°C, or deposited at 2.0 Pa and heat-treated at 350°C demonstrate a modulation amplitude of more than 1, which heat-treated below the T_C as shown on Fig. 3 and Fig. 4. The first possibility in increase of the modulation amplitude is due to spinodal decomposition. But because Co-Pd alloy system[27] does not show spinodal decomposition, this possibility is neglected. The second possibility is as follows; as pointed out in Fig. 2, the Co/Pd multilayers display roughness at the interface, for there is not enough surface mobility at the interface during sputtering deposition. However, the initial stage of heat treatment provides the Co/Pd interface thermal energy in order to conduct surface mobility, so that this leads to an increase in the regularity at the interface in the multilayers and an enhancement of the modulation amplitude in the harmonic wave. On the other hand, the Co/Pd multilayers heat-treated above the T_C cannot detect the relative modulation amplitude above 1 as shown in Fig. 5 and Fig. 6. Interdiffusion process when heat-treated above T_C is so fast that the increase in regularity at the interface of the multilayers cannot be measurable. In the heat treatment above T_C, the modulation amplitudes are simply reduced by the alloying at the interface due to interdiffusion in the multilayer and finally arrive at 0 of the modulation amplitude. Generally on the figures, the multilayers deposited at 0.7 Pa and heat-treated below T_C collapse more slowly than those deposited at 2.0 Pa and heat-treated above T_C. When both all of the multilayers deposited at 0.7 Pa and 2.0 Pa are heat-treated above T_C, in spite of the small temperature gap, their modulation amplitudes

collapse very rapidly compared to those heat-treated below T_C. For example, the multilayers heat-treated below T_C (350°C) and above T_C (390°C) have their modulation amplitude collapsed around 120 and 3 hours, respectively. This drastic collapse in the modulation amplitude is presumably related to the fast interdiffusion process above T_C of the Co/Pd multilayer structure which is paramagnetic state. This will be discussed in elsewhere[15] in terms of the absence of magnetic exchange energy in the Co/Pd multilayer.

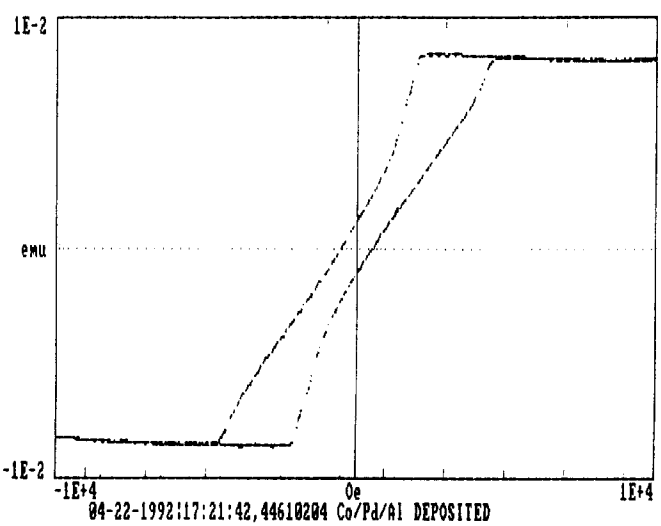
3. 2. Changes in the magnetic properties of Co/Pd multilayer during interdiffusion

3. 2. 1. Intrinsic magnetic properties of Co/Pd multilayer during interdiffusion

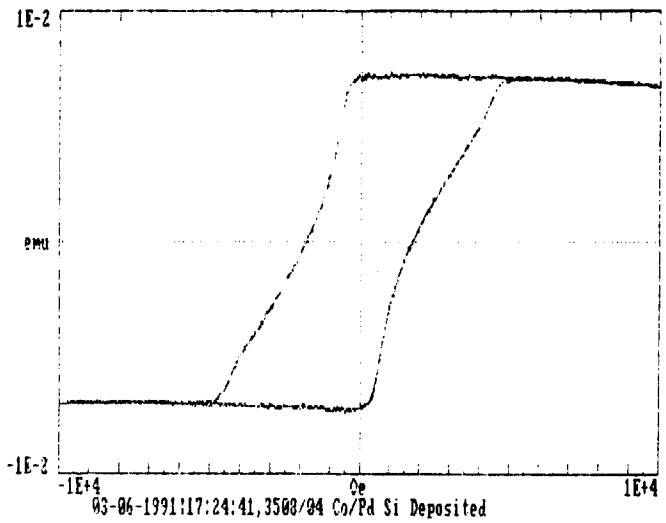
Figs. 7 (a), (b) and (c) show one of the magnetic



(a)



(b)



(c)

Fig. 7 (a), (b) and (c): Magnetic hysteresis loops of Co/Pd multilayers deposited at 0.7 Pa, 2.0 Pa and 2.4 Pa, respectively measured perpendicular to the multilayer planes

hysteresis loops in the Co/Pd multilayers deposited at 0.7, 2.0 and 2.4 Pa, respectively perpendicular to the multilayer planes. The Co/Pd multilayers deposited at 2.4 Pa were fabricated on the same conditions those of 0.7 Pa and 2.0 Pa for as-deposited magnetic properties only. As the sputtering pressure is increased, the properties desirable for magnetic recording increase, for example the coercive force (H_C), remanent magnetization ratio (M_R/M_S) and squareness of hysteresis loop. Thus, the as-deposited Co/Pd multilayers at higher pressures display superior magnetic properties for magneto-optic recording media. In this experiment, it is found that the as-deposited saturation magnetization (M_S) of the Co/Pd multilayers is 477.5 ± 0.5 emu/cm^3 at 0.7 PA, 435.5 ±8.5 EMU/CM^3 AT 2.0 Pa and 380 ± 16.0 emu/cm^3 at 2.4 Pa. These show similar values of previous works[1,3,4,11,14,28]. M_S for all of the multilayers exceeds that of the Co/Pd multilayers when Pd is regarded as a non-magnetization element (about 330 emu/cm^3). It was indicated in previous research [1 - 5] that the exceeded M_S was caused by induced magnetization of polarized Pd atoms at the interface. The difference in M_S with respect to the sputtering pressure was mainly caused by the degree of polarized Pd atoms at the interface and the creation of micro voids in taper structure[29] due to the shadowing effect during the deposition. As the Co/Pd multilayers deposited at a lower pressure have a smoother interface and denser structure than those deposited at a higher pressure, larger polarization of Pd sublayer and higher density of ferromagnetic elements is expected in the Co/Pd multilayers deposited at the lower pressure.

Fig. 8 and Fig. 9 show saturation magnetization (M_S) of

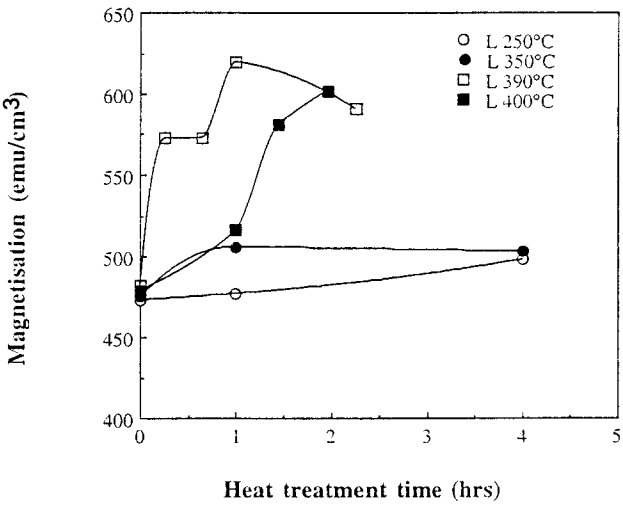


Fig. 8: Saturation magnetization (M_S) of Co/Pd multilayers deposited at 0.7 Pa and heat treated in the initial range of heat treatment

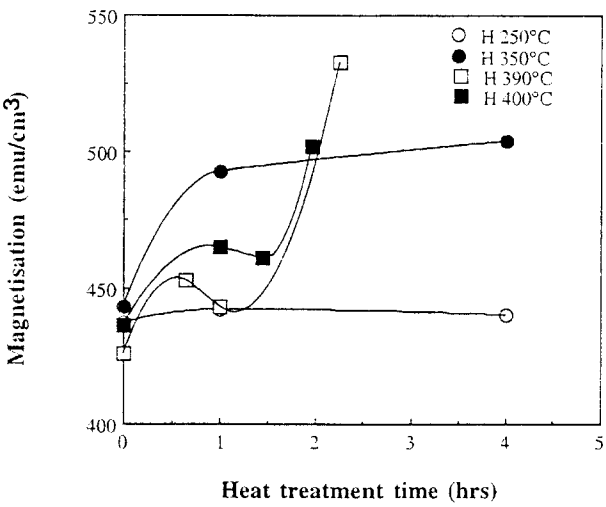


Fig. 9: Saturation magnetization (M_S) of Co/Pd multilayers deposited at 2.0 Pa and heat treated in the initial range of heat treatment

Co/Pd multilayers deposited at 0.7 Pa and 2.0 Pa, respectively and measured perpendicular to multilayer planes in the initial range of heat treatment time for the stress release. Generally, after the heat treatment conducted for the stress release, M_S values should be the same as those for the as-deposited state, though the magnetic process shows change. However, M_S of the Co/Pd multilayers is increased due to the change in the modulation amplitude at the interface of the multilayers as shown in Fig. 3, Fig. 4, Fig. 5 and Fig. 6. The increments of M_S in the Co/Pd multilayers heat-treated above the T_c are rapid and those heat-treated below the T_c are slow. Especially, the former where the multilayers were deposited at 2.0 Pa and heat treated at 390 and 400°C, and the latter where the multilayers were deposited at 0.7 Pa and heat treated at 250 and 350°C. Since the M_S of Co sublayer is 330 emu/cm^3, the increase of M_S in the Co/Pd multilayers is strongly dependent on the polarized degree of Pd sublayer, which is affected by degree of stress state in the multilayer structure.

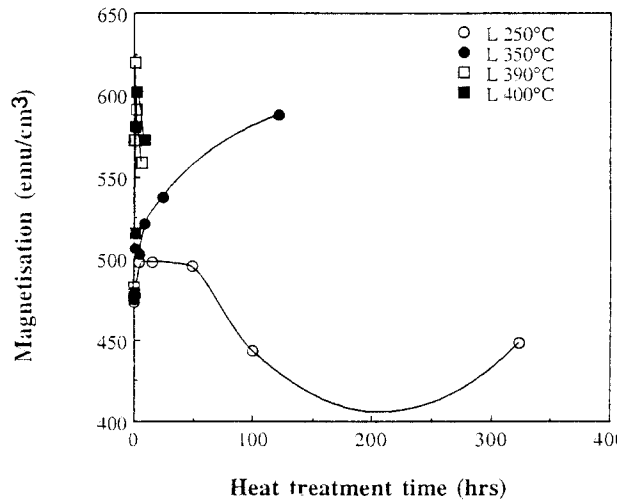


Fig. 10: Saturation magnetization (M_S) of Co/Pd multilayers deposited at 0.7 Pa and measured perpendicular to the multilayer planes during interdiffusion

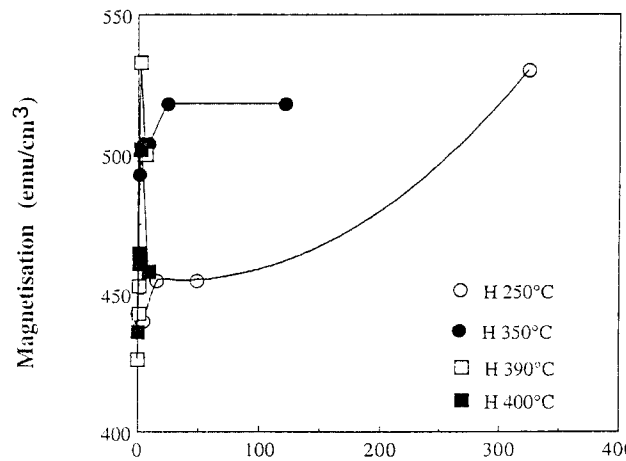


Fig. 11: Saturation magnetization (MS) of Co/Pd multilayers deposited at 2.0 Pa and measured perpendicular to the multilayer planes during interdiffusion

Fig. 10 and Fig. 11 show the changes of saturation magnetization (M_S) of the Co/Pd multilayers deposited at 0.7 Pa and 2.0 Pa, respectively measured perpendicular to the multilayer planes during the interdiffusion. M_S of all the multilayers deposited at 0.7 Pa and 2.0 Pa is increased by the interdiffusion process, compared with those in as-deposited state. The changes in M_S are classified into two kinds in both the multilayers. The multilayers heat-treated

below the T_C perform interdiffusion process and maintain the multilayer structure within the heat-treatment time ranges, which were verified by the change of the modulation amplitudes in Fig. 3 and Fig. 4. The multilayers heat-treated above the T_C show a decrease in M_S after interdiffusion which was extrapolated from the modulation amplitude in Fig. 5 and Fig. 6. This means that when the multilayer structure had disappeared, the contribution of the induced magnetization arising from the polarized Pd to M_S in Co/Pd multilayer began to be removed. Ultimately, the saturation magnetization will reach those of corresponding CoPd alloys in composition.

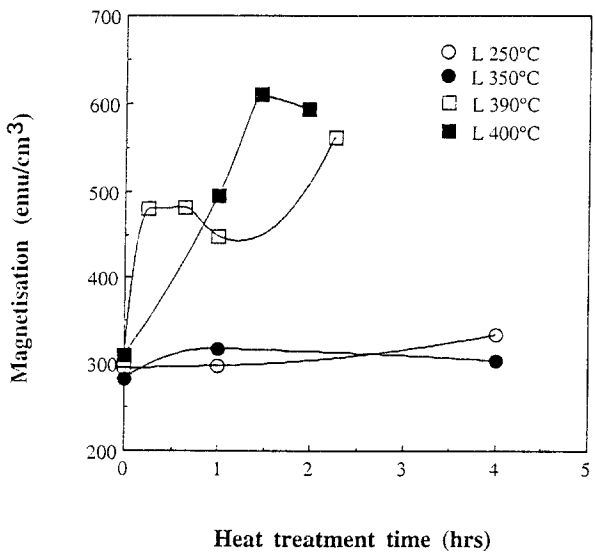


Fig. 12: Magnetization (M_P) of Co/Pd multilayers deposited at 0.7 Pa and measured at 10 kOe parallel to the multilayer plane in the initial range of heat treatment

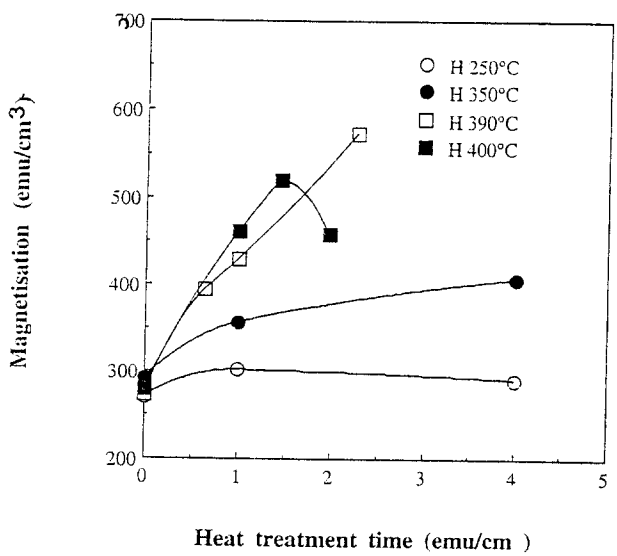


Fig. 13: Magnetization (M_P) of Co/Pd multilayers deposited at 2.0 Pa and measured at 10 kOe parallel to the multilayer plane in the initial range of heat treatment

Fig. 12 and Fig. 13 show the magnetization (M_P) deposited at 0.7 Pa and 2.0 Pa, respectively and measured parallel to multilayer planes in the initial range of heat treatment time for the stress ralease. Parallel magnetization (M_P) values defined the magnetization parallel to the multilayer planes, measured by V_{SM} at 10 kOe. M_P of as-deposited multilayers deposited at 0.7 Pa and 2.0 Pa is 300 and 280 emu/cm^3, respectively, at 10 kOe. These are smaller than as-deposited M_S values in the Co/Pd multilayers (477.5 0.5 emu/cm^3 for 0.7 Pa and 435.5 8.5 emu/cm^3 for 2.0 Pa). On both of the figures, M_P in the multilayers heat-treated both below and above T_C increases compared with as-deposited ones. However, the increase of M_P heat-treated below T_C is slower than those heat-treated above T_C. This fact is related to the existence of magnetic exchange energy term in the interdiffusion below T_C as discussed in elsewhere[15].

Comparing Fig. 12 and Fig. 13 with Fig. 8 and Fig. 9, the parallel magnetization (M_P) is simultaneously increased with the perpendicular (saturation) magnetization (M_S) by the stress release. To interpret this fact qualitatively, the magneto elastic anisotropy energy (K_{ME}) due to the coupling of stress and magnetostriction must be considered. It is well known that the CoPd alloy[30] and Co/Pd multilayer[14] possess a large negative magnetostriction constant (= -130 x 10^{-6}), and the Co/Pd multilayers deposited at lower and higher pressure maintain the compressive and the tensile stresses in the matrix of the multilayers, respectively[14][31]. When K_{ME} exists in any direction, the direction is the easy or hard axis depending on the sign of the coupling[32]. Since the magnetostriction of Co/Pd multilayer is negative as the tensile stress is involved in Co/Pd multilayer, the contribution of K_{ME} is added to total perpendicular magnetic anisotropy (K_U). On the contrary, the contribution of K_{ME} is subtracted from K_U for the compressive stress in the multilayers. Purely considering the stress release process during the heat treatment, the role of K_{ME} on K_U in the multilayers is disregarded due to the release of stress, and M_P finally reach M_S in as-deposited state. However, M_P deposited at 0.7 Pa and 2.0 Pa were 615 ± 5 emu/ cm^3, respectively. These values exceed M_S of as-deposited states by 30% and 25% for the multilayers deposited at 0.7 Pa and 2.0 Pa, respectively. The increase in M_P during the heat treatment is not due to the increase of technical magnetization process in minor hysteresis loop which is introduced by removing the stress in the Co/Pd matrix, but is due to the increase of M_S itself in saturated hysteresis loop which is due to the removal of compressive stress in the Pd lattice in the Co/Pd multilayers. This phenomena strongly supports the fact that the increment of M_S and M_P during the heat treatment simultaneously shows up the effect of removing compressive stress in Pd lattice and the effect of arising from more polarized Pd sublayer.

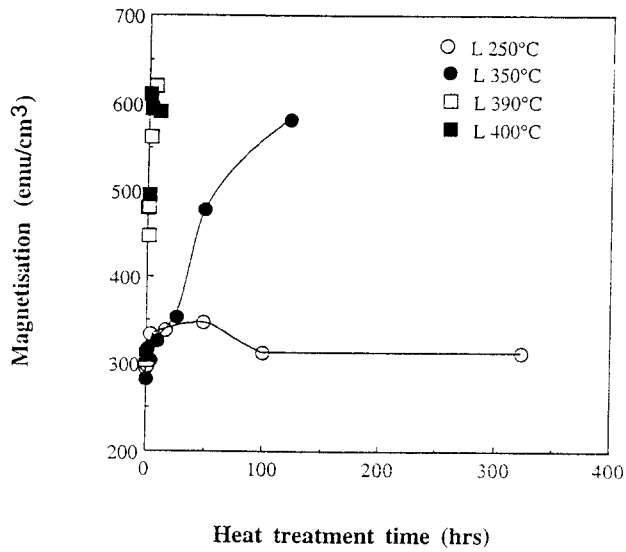


Fig. 14: Magnetization (M_P) of Co/Pd multilayers deposited at 0.7 Pa and measured at 10 kOe parallel to the multilayer plane during interdiffusion

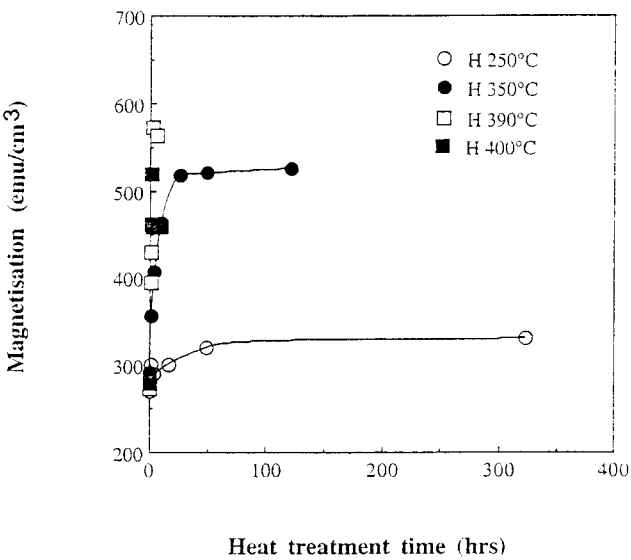


Fig. 15: Magnetization (M_P) of Co/Pd multilayers deposited at 2.0 Pa and measured at 10 kOe parallel to the multilayer plane during interdiffusion

Fig. 14 and Fig. 15 display the parallel magnetization (M_P) of Co/Pd multilayers deposited at 0.7 Pa and 2.0 Pa, respectively and measured in parallel direction to the multilayer planes . On both figures, M_P increases during stress release and interdiffusion. These increases in M_P are the same origin as the increase in M_S by means of the stress release of Pd sublayers which was mentioned in Fig. 10 and Fig. 11. This means thermal energy provided by the heat treatment expands Pd sublayers and disperses Co atoms in the Pd sublayers. As a result, the Pd sublayers maintain more tensile stress state and induce a larger polarized magnetization than that of as-deposited Pd sublayers in the Co/Pd multilayers[33][34]. After the interdiffusion process, M_P is constant due to the increase of in-plane anisotropy energy or slightly decreased due to the loss of polarized Pd, despite a large decrease of M_S.

3. 2. 2. Extrinsic magnetic properties of Co/Pd multilayer during heat treatment

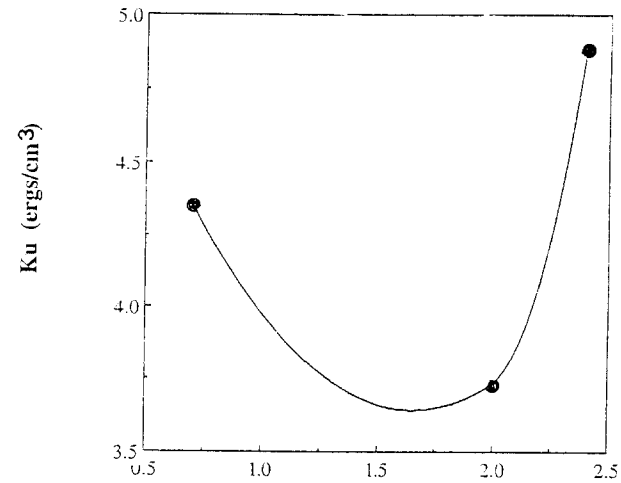


Fig. 16: Changes in uniaxial perpendicular magnetic anisotropy (K_U) of Co/Pd multilayers in as-deposited state with respect to Ar sputtering pressure

Fig. 16 displays the uniaxial perpendicular magnetic anisotropy (K_U) of as-deposited Co/Pd multilayers with respect to Ar sputtering pressures. K_U was measured by VSM perpendicular and parallel to the multilayer plane upto 10 kOe. The K_U is obtained by calculation as follows[35],

$$H/M_P = \frac{4K_2}{M_S^4} M_P^2 + \frac{2K_1}{M_S^2} \quad (2)$$

H : External magnetic field
M_P : Magnetization parallel to multilayer plane
M_S : Saturation magnetization
K_1 and K_2 : Magnetic anisotropy constant

from which it can be seen that the anisotropy constants can be evaluated by plotting a graph of M_P^2 and H/M_P, the slope and the intercept being $4K_2/M_S^4$ and $2K_1/M_S^2$, respectively. K_U is the sum of these anisotropy constants,

$$K_U = K_1 + K_2 \quad (3)$$

On Fig. 16, K_U of the multilayers deposited at 0.7, 2.0, 2.4 Pa display 4.2 ± 0.3, 3.6 ± 0.2 and 4.6 ± 0.5 ergs/cm^3, and these compare well with the values fround by other researchers[14]. All K_U values are positive in terms of the sputtering pressure. This means that the as-deposited

Co/Pd multilayers have preferred perpendicular magnetic anisotropy. As compared to K_U in the Co/Pd multilayers, K_U of $Co_{27}Pd_{73}$ alloys deposited at 0.5, 2.0 and 2.4 Pa displayed 0.5, 1.2 and 1.8 x 106 ergs/cm^3, respectively[36].

In previous research[18], K_U for the polycrystalline Co/Pd multilayers was the competition between positive interface anisotropy (K_S) and negative volume anisotropy (K_V). With respect to the sputtering pressure, K_S and K_{ME} in K_V were variable factors to govern K_U in Co/Pd multilayers. As the sputtering pressure was increased, the quality of the interface deteriorated. Since K_S in the multilayers depends strongly on the quality of the interface, K_S was reduced[14] in the higher sputtering pressure. On the other hand, K_{ME} was favoured perpendicular anisotropy at the higher pressure. The reasoning was that the higher pressure introduces tensile stress in the direction normal to the multilayer plane, and the CoPd alloy system exhibits a large negative magnetostriction constant of the order of 10^{-4} in a Pd-rich region[30], and Co/Pd multilayer also possesses a large negative magnetostriction constant[14]. The magneto elastic anisotropy (K_{ME}) induced by magnetostriction and stress is evaluated by the formula $K_{ME} = -3/2\ (\lambda\sigma)$ (λ: magnetostriction, σ: stress). It is assumed that at the higher pressure, K_{ME} adds to K_U in the Co/Pd multilayer since the sign of tensile stress is positive.

In the multilayers deposited at 0.7 Pa, the interface magnetic anisotropy energy (K_S) is a predominant factor in the uniaxial magnetic anisotropy energy (K_U). The multilayers deposited at 2.0 Pa display the lowest values of magnetic anisotropy energy. This is the result of the decrease in K_S due to the deterioration at the interface, and no contribution from K_{ME} due to the compressive stress state in the Co/Pd multilayers. However, as the sputtering pressure is further increased, K_U abruptly increases. This

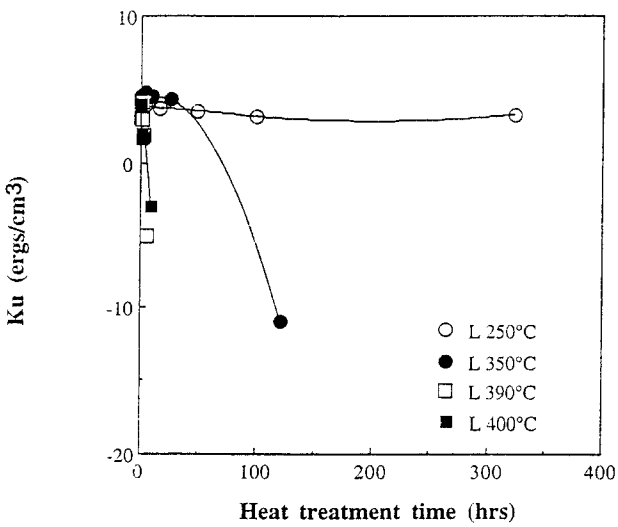


Fig. 17: Changes of uniaxial perpendicular magnetic anisotropy (K_U) of Co/Pd multilayers deposited at 0.7 Pa during interdiffusion

tensile stress also develops K_{ME} perpendicular to the Co/Pd multilayer planes[14,37]. This results in that K_{ME} adds to K_U in the Co/Pd multilayers deposited at higher sputtering pressure. In spite of the deterioration of the interface, the multilayers deposited at 2.4 Pa display the highest magnetic anisotropy, due to the role of the addition of K_{ME}. In conclusion, the change in the K_U of the multilayers in terms of the sputtering pressure can be explained by the compromise between the K_S and K_{ME}.

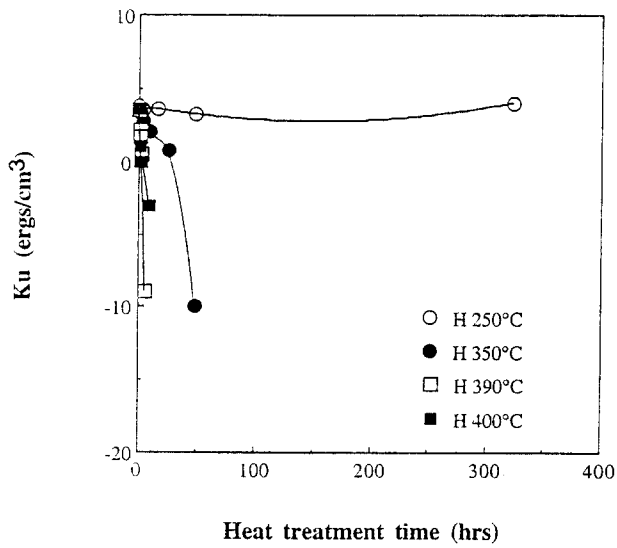


Fig. 18: Changes of uniaxial perpendicular magnetic anisotropy (K_U) of Co/Pd multilayers deposited at 2.0 Pa during interdiffusion

Fig. 17 and Fig 18 illustrate the changes in the uniaxial perpendicular magnetic anisotropy energy (K_U) of the Co/Pd multilayers deposited at 0.7 Pa and 2.0 Pa, respectively during heat treatment. In the as-deposited state, K_U for the multilayers deposited at 0.7 Pa and 2.0 Pa is 4.2 0.3 erg/cm^3 and 3.6 0.2 erg/cm^3, respectively. On both figures, K_U after heat treatment at 250°C is positive and is stable during the heat treatment as long as the multilayer structure is maintained. On the other hand, K_U values heat-treated at the other temperatures are lower than the as-deposited values and even converted to negative, which mean that the easy magnetization axis is rotated in-plane. The turning points from positive sign to negative one coincide well with zero modulation amplitude, presented in Fig. 3, Fig. 4, Fig. 5 and Fig. 6. Thus when the interdiffusion between the Co layer and Pd layer is completed, the easy axis is converted from perpendicular to parallel in the multilayer planes. This means that the main origin of K_U in the Co/Pd multilayers can be attributed to K_S caused by the interfaces of the artificially modulated multilayers. The curvatures heat-treated above T_C are more rapid than those heat-treated below T_C. Furthermore, the multilayers deposited at 2.0 Pa are more rapidly converted to a negative sign than those deposited at

0.7 Pa. This shows that the perpendicular magnetic anisotropy is more stable in the multilayers if deposited at lower sputtering pressure and heat-treated below T_C.

4. Conclusions

The Co/Pd multilayers were deposited at 0.7 Pa and 2.0 Pa, and investigated the changes in the magnetic properties as a function of heat treatment temperature and time. The heat-treated temperature for the Co/Pd multilayers was divided into below and above Curie temperature (T_C). Intrinsic (magnetization) and extrinsic (perpendicular magnetic anisotropy energy) magnetic properties, compared with structural property (modulation amplitude) were discussed in Co/Pd multilayer during the stress release and interdiffusion. Both of the structural and the magnetic properties of the Co/Pd multilayers heat-treated above (T_C), which were in paramagnetic state, were rapidly changed compared with those below T_C, which were in ferromagnetic state. We attribute the rapid changes in the properties to the absence of magnetic exchange energy between Co and Pd sublayers in the paramagnetic state. In application of Co/Pd multilayers as a MO recording media, the operating temperature range just below T_C is strongly recommended for the thermal stability of the multilayer structure.

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