Journal of Korean Magnetics Society, Volume 5, Number 5, October 1995

DEPENDENCE OF STRUCTURAL AND MAGNETIC PROPERTIES ON DEPOSITION ANGLE IN EVAPORATED Co/Pt MULTILAYER THIN FILMS

Ki-Seok Moon and Sung-Chul Shin
Department of Physics, KAIST, Taejon 305-701, KOREA

Abstract - We have investigated the effects of deposition angle on structural and magnetic properties of e-beam evaporated (4-Å Co/9.2-Å Pt)$_{23}$ multilayer thin films prepared on tilted substrates. It was found that the [111] crystallographic orientations of the multilayer thin films were not aligned with columnar growth orientations and they were remained to be normal to the substrate planes even though the deposition angle was severely oblique up to 60° . The analysis of the torque curve reveal that the intrinsic anisotropy energy was monotonically decreased with the deposition angle but the easy axis orientation parallel to the substrate normal was not much influenced by deposition angle.

I . INTRODUCTION

Co-based multilayer thin films have been the subject of considerable investigation because of their novel properties and potential technological applications [1,2]. In particular, applications of these materials to magneto-optic (MO) recording are of great interest today due to superior environmental stability and a larger Kerr effect at short wavelengths (<500 nm) compared to the current choice for MO media, rare earth transition metal (RE-TM) alloy thin films [3]. Especially, Co/Pt multilayer thin films have been reported to be the best choice owing to large spin-orbit coupling of Pt [4,5].

Magnetic properties of Co/Pt multilayer thin films seem to be very sensitive to preparation methods and condition, as well as the sublayer and total film thicknesses. Co/Pt multilayer thin films prepared by evaporation have different magnetic properties than those prepared by sputtering. For instance, the coercivity is known to be larger in evaporated multilayer films than the corresponding sputtered films [6]. It is well-known that much more energetic atoms are involved in sputtering than evaporation. These energetic atoms are expected to smear out the interfaces of constituents and to yield microstructural modification in multilayer structure.

In evaporation, magnetic properties of Co/Pt multilayer thin films were reported to be sensitively dependent on the vacuum pressure and substrate temperature [7]. This study was motivated to investigate the effects of the angle of incident vapor beam on structural and magnetic properties in evaporated Co/Pt multilayer thin films. In this paper, we report the dependence of growth morphology and magnetic properties on deposition angle of these multilayer thin films.

II. EXPERIMENTAL

Co/Pt multilayer thin films were prepared onto glass substrates by e-beam evaporation in a vacuum system maintained at about 6×10^{-6} Torr. To achieve oblique depositon, the substrates were mounted on tilted substrate holders making the angle of incident vapor beam 0° , 15° , 30° , 45° , and 60° with respect to each substrate normal. The multilayer structure was obtained by alternatively exposing the substrate to two sources via a rotating substrate holder. The substrate holder was placed 25 cm above the sources. The dwelling time spent by the substrate above each source could be controlled by a personal computer interfaced to a stepping motor which drove the substrate holder. Two sources were physically separated by stainless-steel shields to prevent cross-contamination of their fluxes. The sources were screened with a shutter driven by a stepping motor in order to prevent deposition to the the substrates during rotation of the substrate holder. Typical deposition rates of 0.28 Å/s for Co and 0.25 Å/s for Pt, monitored by two corresponding quarts crystal sensors, were kept constant within a 10-% fluctuation to achieve the same modulation wavelength in all samples. All samples were designed to have the same total thickness of 300 Å, consisted of 4-Å thick Co and 9.2-Å thick Pt sublayer. Since a series of the samples with different angles of incidence were prepared in a same run under identical conditions, possible variations of preparation conditions between different runs were eliminated.

The film structure was examined by low- and high-angle x-ray diffractometry and the growth morphology of the films was investigated by microfractography. A preferred orientation and degree of texture of the film was studied from the measurements of a rocking curve and pole figure. Magnetization was investigated using a vibrating sample magnetometer (VSM). The magnetic anisotropy was determined from analysis of a torque curve measurement at an applied field of 10 kOe.

III. RESULTS AND DISCUSSION

Most of the films in this study developed low angle x-ray diffraction peaks and a typical result is demonstrated for the sample of (4-Å Co/9.2-Å Pt)$_{23}$ prepated at the angle of incidence α = 0° in Fig. 1. Observation of low angle diffraction peaks implies the existence of a multilayer structure for the sample. The angle of the peak corresponds to the repeat distance of 13.2 Å [8]. The low angle diffractions of the samples with different α revealed that the peak position did not change, but the peak intensity became smaller and the full width at half maximum (FWHM) wider with increasing α. These results are believed to be ascribed to the shadowing effect [9]. When the vapor beam is obliquely deposited on the substrate, the shadowing effect yields each layer of the film to be composed of high and low density regions. This distribution of density could cause a variation of the superlattice period and the effect is expected to be enhanced with increasing α.

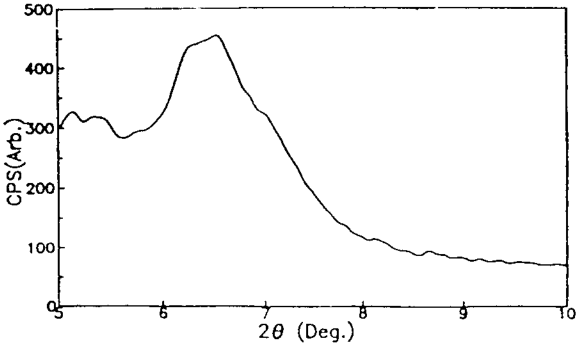

Fig. 1. Low-angle x-ray diffraction pattern of (4-Å Co / 9.2-Å Pt)$_{23}$ prepared at the incidence angle α = 0°

Fig. 2 shows high angle x-ray diffraction pattern of the sample prepared at α = 0° The result reveals that the film grows along [111] orientation having the d$_{111}$-spacing of 2.201 Å [10]. We believe that the structure of Co/Pt multilayer is hcp(002) Co/fcc(111) Pt or fcc(111) Co/fcc(111) Pt. Since the value of the d$_{111}$-spacing is one between the d-spacing of Co (2.035 Å for hcp Co, 2.047 Å for fcc Co) and that of Pt (2.263 Å), the in-plane spacing of Co expands and that of Pt contracts in Co/Pt multilayer films. But it can't be determined whether the structure of Co is hcp or fcc because

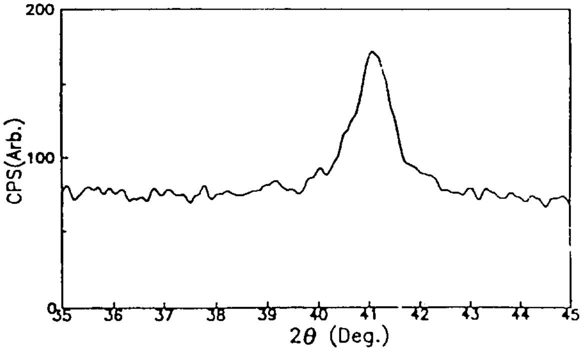

Fig. 2. High-angle x-ray diffraction pattern of (4-Å Co / 9.2-Å Pt)$_{23}$ prepared at the incidence angle α = 0°

the Co sublayer in this sample has 2 atomic layers.

One interesting result is that the [111] growth orientation is remained to be normal to the substrate plane even for the samples prepared at large α's. Fig. 3 shows x-ray rocking curves about the substrate normal for (4-Å Co/9.2-Å Pt)$_{152}$ with various α's. As seen in the figure, the peak become smaller and FWHM wider with increasing α. But the peak position does not nearly change with α. Thus, one could imagine that the [111] growth orientation of the film is mainly remained to be aligned with the substrate normal, irrespective of deposition angle. This fact was also confirmed by examining x-ray pole figures. Fig. 4 shows a typical [111] pole figure for the sample prepared at α = 45 ° . The center of the plot and the cross indicate the substrate normal and the direction of incident vapor beam, respectively. The pole density is expressed by numerical values in the given regions and has been normalized by the average value. One can clearly see that [111] direction lies along almost in the direction of the substrate normal. A similar result was observed for the sample prepared at α = 60 °

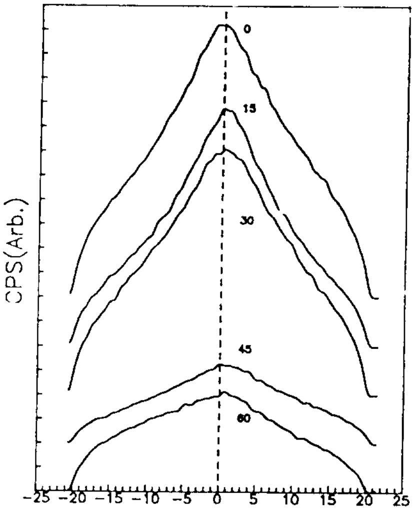

Fig. 3. X-ray rocking curves of fcc [111] texture for (4-Å Co / 9.2-Å Pt)$_{152}$ with various α 's.

To see the growth morphology depending on the angle of incidence α in our samples, the cross-sections of the samples were examined by a scanning electron microscopy. Columnar structure was observed for all samples. This columnar microstructure has been [illegible] observed for [illegible]

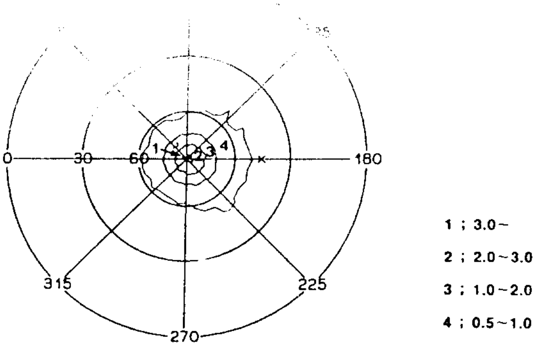

Fig. 4. The [111] pole figure for (4-Å Co / 9.2-Å Pt)$_{152}$ prepared at deposition angle α = 45°

deposited atoms having low mobility [9]. When the rate of migration of atoms in the deposited regions to the shadowed ones is smaller than the rate of void formation via shadowing, column formation occurs during deposition. It is interesting to note that the columns become more tilted with increasing the angle of incidence. The relation between the columnar growth orientation β and the angle of incident vapor beam α is plotted for Co/Pt multilayer thin films in Fig. 5. Here α and β are

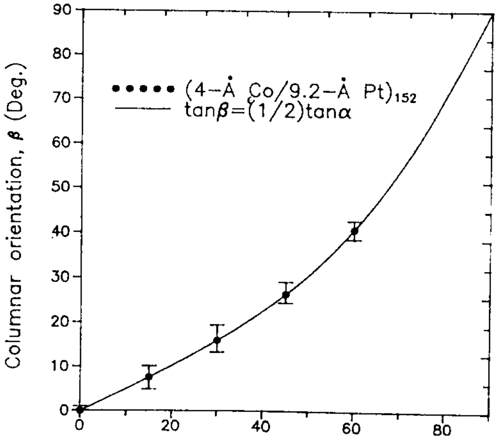

Fig. 5. Columnar growth orientation, β, vs the angle of incident vapor beam, α, in Co/Pt multilayer thin films. Here, α and β are measured from the substrate normal.

tilted angles measured from the substrate normal. Co/Pt multilayer thin films generally follow the tangential rule, tan β =(1/2) tan α [9]. According to Fig. 3 and Fig. 4, the [111] growth orientation of films is nearly aligned with the substrate normal, irrespective of angle of incidence. And we found from Fig. 5 that columnar structure developed in e-beam evaporated Co/Pt multilayer thin films generally followed the tangent rule. Thus, we may conclude that in Co/Pt multilayer thin films the [111] growth orientation is developed in the direction normal to the substrate, without following columnar growth orientation.

Fig. 6 shows the dependence of saturation magnetization M_s on α. As seen in the figure, M_s of the film at α = 0° is 1260 *emu/cc* (87.5% of a Co bulk magnetization) and it shows a monotonic decrease with increasing α. The result is believed to be mainly caused by an increase of the porous region probably due to the enhancement of the shadowing effect [9].

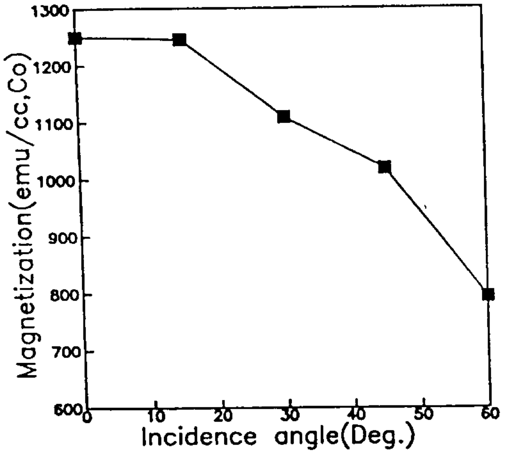

Fig. 6. Dependence of the saturation magnetization M_s on the incidence angle for (4-Å Co / 9.2-Å Pt)$_{23}$.

Fig. 7 shows the variation of the torque curve with varing α's. As noted in the figure, with increasing α the specific torque τ_p become smaller and ϕ_0 the angle where the torque is zero in the 1st quadrant of ϕ become larger. Here, the angle α is measured from the film normal.

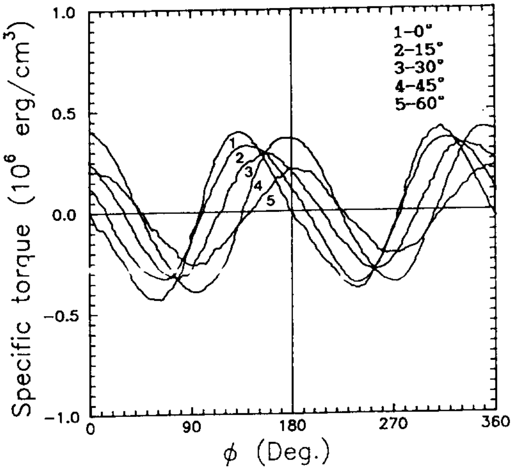

Fig. 7. Variation of the torque curve with the incidence angle for (4-Å Co / 9.2-Å Pt)$_{23}$

To estimate the intrinsic anisotropy energy and the easy axis orientation, the torque curves were analyzed by a simple model described as follows [11]. We assume that a film has an uniaxial anisotropy with single easy axis making an angle δ from the subatrate normal. We consider only the 1st order anisotropy energy constant K_u and ignore any higher order terms. Then

$$K_u^2 = K_s^2 + \tau_p^2 + 2K_s\tau_p\cos(2\phi_o) \qquad (1)$$

$$\delta = \phi_o - (1/2)\tan^{-1}\left(\frac{K_s\sin(2\phi_o)}{K_s\cos(2\phi_o)+\tau_p}\right) \qquad (2)$$

, where K_s is the shape anisotropy energy of $2\pi M_s^2$, K_u is the 1st order anisotropy energy constant, and δ is the orientation of the magnetic easy axis measured from the film normal.

In Table I, we summarize the calculated result according to Eqs. (1) and (2). A monotonic decrease of K_u with increasing α is believed to be closely- correlated with the structural change of the sample. K_u associated with an interface is phenomenologically decreased as $K_u = 2K_{int}/t_{Co} + K_v$, where K_{int} is the surface anisotropy originating from the interface per unit area, t_{Co} is the Co thickness, and K_v is the volume anisotropy consisting of the shape anisotropy, magnetocrystalline

Table I. Magnetic parameters of (4-Å Co / 9.2-Å Pt)$_{23}$ prepared at oblique incidence.

α (°)	τ_p (10^6dyn · cm/cm^3)	ϕ_o (°)	K_s (10^6 erg/cm^3)	K_u (10^6 erg/cm^3)	δ (°)
0	1.7	0.0	9.8	11.5	0.0 ± 0.1
15	1.5	8.2	9.7	11.2	1.1 ± 0.1
30	1.2	20.0	7.7	8.8	2.6 ± 0.3
45	1.2	41.5	6.5	6.8	5.1 ± 0.5
60	0.7	45.0	4.0	4.0	4.9 ± 0.6

anisotropy, and magnetoelastic anisotropy. As discussed earier, the texture and interface of a film become poor with increasing α. Thus the magnetocrystalline and the surface anisotropies. are expected to be decreased with α. The shape anisotropy is also decreased with α due to a smaller M_s for a higher α. In Table I, it is very interesting to note that the easy axis orientation is remained to be nearly normal even for the sample prepared at α = 60° . This result reflects the fact that the major origin of the perpendicular magnetic anisotropy in this system is associated with the surface anisotropy together with the magnetocrystalline anisotropy.

IV. CONCLUSIONS

We have studied the growth morphology and magnetic properties in obliquely-deposited e-beam evaporated Co/Pt multilayer thin films. With increasing angle of incidence, [111] crystallographic orientation of multilayer thin films were not aligned with the columnar growth orientation and they were remained to be normal to the substrate plane. Also, it was found from the analysis of the torque curve that the intrinsic anisotropy energy was monotonically decreased with the angle of incidence but the magnetic easy axis orientation was nearly aligned with the substrate normal.

REFERENCES

[1] S. Hashimoto, Y. Ochiai, and K. Aso, J. Appl. Phys. **67**, 4429 (1990).

[2] S.-C. Shin and A. C. Palumbo, J. Appl. Phys. **67**, 317 (1990).

[3] S. Hashimoto and Y. Ochiai, J. Magn. and Magn. Mater. **88**, 211 (1990).

[4] K. H. J. Buschow, P. G. V. Engen, and R. Jongebreur, J. Magn. and Magn. Mater. **38**, 1 (1983).

[5] J. S. Griffith, *The Theory of Transition-Metal Ions* (Cambridge at the university press, Cambridge, 1971), chap. 5.

[6] P. F. Carcia, S. I. Shah, and W. B. Zeper, Appl. Phys. Lett. **56**, 2345 (1990).

[7] S. M. Paik, S. Kim, and I. K. Schuller, Phys. Rev B, **43**, 1843 (1991).

[8] T. Shinjo and T Takada, *Metallic superlattices* (Elsevior, Amsterdam, 1987), p. 9.

[9] H. J. Leamy and A. G. Dirks, J. Appl. Phys. **49**, 3430 (1978).

[10] N. Sato, J. Appl. Phys. **64**, 6424 (1988).

[11] S. -C. Shin and C. -S. Kim, IEEE Trans. Magn. **27**, 4852 (1991).