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Fourfold magnetic anisotropy of CoPd alloy, obtained by solid state reactions in epitaxal Pd/hcp-Co and Pd/fcc-Co bilayers

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Abstract. The solid-state reaction between epitaxial hcp-Co(110) and fcc-Co(001) thin films and Pd layers was investigated at annealing temperatures between 250 and 650 °C using X-ray diffraction and magnetic measurements. No significant intermixing of the layers occurs at annealing temperatures below 400 °C. For the atomic composition 1Co:1Pd after annealing at 450 °C the disordered solid solution fcc-Co_xPd_{1-x} is formed on the Pd/hcp-Co(110) and Pd/fcc-Co(001) interfaces. Epitaxial relationships CoPd(110)⟨-111⟩ || MgO(001)⟨100⟩ and CoPd(001)⟨100⟩ || MgO(001)⟨100⟩ between the nucleated disordered phase CoPd and the substrate MgO(001) were determined for Pd/hcp-Co(110) and Pd/fcc-Co(001) bilayers, respectively. The first magnetocrystalline anisotropy constant of the disordered CoPd phase $K_1^{CoPd} = -(1.8 \pm 0.4)\cdot 10^4$ J/m^3 for the (110) and (001) orientations was obtained.

Introduction

Multilayers with perpendicular magnetic anisotropy (PMA) continue to attract attention and are intensively investigated for practical applications as a medium for perpendicular recording media, bit-patterned media, and magnetic random access memory [1-3]. The Co/Pd multilayer samples have PMA ~ $8\cdot 10^5$ J/m^3 [4], which is slightly less than in high uniaxial magnetocrystalline anisotropy materials [5]. Experimental observations show that heating to ~ 400 °C does not change the magnetic properties of Co/Pd multilayers. However, annealing at temperatures above 400 °C causes the degradation of PMA and the in-plane direction becomes the easy axis of magnetization. It may be explained by the fact that heating causes mixing and alloying at the originally sharper Pd/Co interfaces [6,7]. Few works have been published about the formation conditions of disordered solid solutions Co_xPd_{1-x} and there is no data on their magnetic properties both in bulk samples and in thin films.

In this study, we compare the solid-phase reactions between Pd films with epitaxial hexagonal hcp-Co(110) and cubic fcc-Co(001) layers. Above 400 °C for the both samples the disordered phase CoPd with magnetic constant $K_1^{CoPd} = -(1.8 \pm 0.4)\cdot 10^4$ J/m^3 is formed.

Results and discussion

First the epitaxial hcp-Co(110) layer was created by the vacuum deposition of cobalt on an MgO (001) surface at a temperature of ~ 250 °C under a vacuum of 10^{-6} Torr. The analysis given in the work [8] showed that hcp-Co(110) crystallites grow on the MgO(001) in according with two epitaxial relations (1):

hcp-Co(110) [001] || MgO(001) [110], hcp-Co(110) [001] || MgO(001) [1-10] (1)

Assuming that the crystallites hcp-Co(110), growing along the c-axis [110] and [1-10] MgO, are exchange-coupled and their volumes are equal, the constant $K_4^{\text{hcp-Co(110)}} = K_2^{\text{hcp-Co}} = 1.2 \cdot 10^5$ J/m^3 [9]. The equality of the experimental values of $K_4^{\text{hcp-Co(110)}}$ and $K_2^{\text{hcp-Co}}$ confirms the epitaxial growth of hcp-Co(110) crystallites on MgO (001) in accordance with epitaxial relations (1). Initial Pd/α-Co(110) bilayers were formed by a deposition of the Pd layer on the surface of hcp-Co(110)/MgO(001) under the same conditions. Figure 1a shows the XRD pattern of the as-prepared Pd/hcp-Co(110) film with a 1Co:1Pd atomic composition deposited on MgO (001), which contains a strong hcp-Co(110) peak.

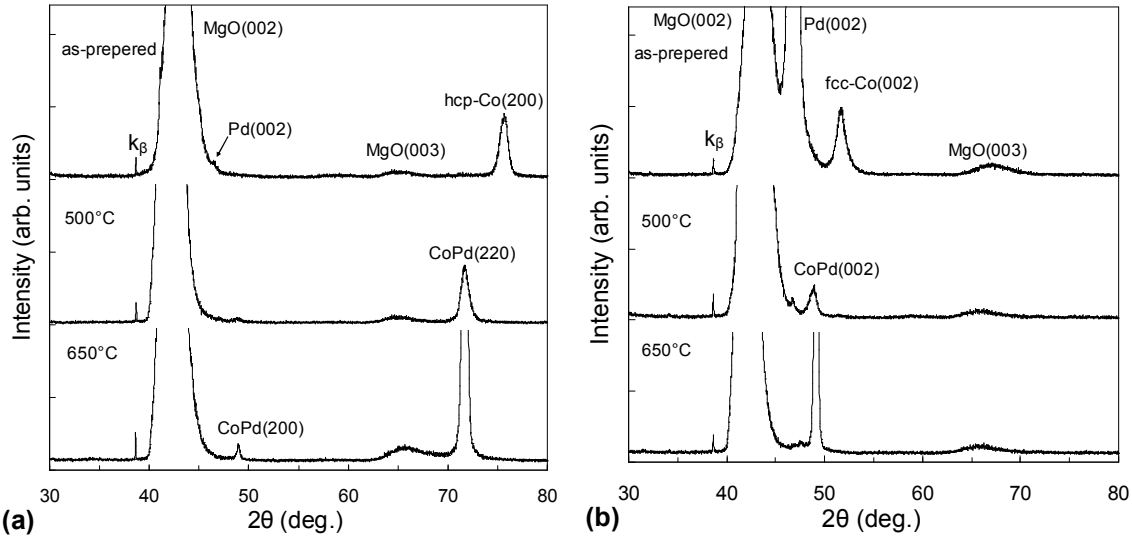

Fig. 1. XRD patterns during the solid-state synthesis at different annealing temperatures: (a) in Pd/hcp-Co(110) bilayer; (b) in Pd/fcc-Co(001) bilayers.

The epitaxial fcc-Co(001) was created by the deposition of a layer of Co on MgO(001) at a temperature of ~ 250 °C in a vacuum of 10^{-5} Torr. The easy axis of the fcc-Co(001) film coincides with the direction [110] and [1-10] of the MgO(001) substrate, which is associated with the orientation relationships (2):

[100], (001) fcc-Co || [100], (001) MgO. (2)

The starting Pd/fcc-Co(001) and Pd/hcp-Co(001) bilayers with around atomic ratios of 1Co:1Pd and a total thickness of 300 nm were obtained by sequential evaporation Pd layers at the room temperature on fcc-Co(001)/MgO(001) and hcp-Co(001)/MgO(001) samples. Figure 1b shows the XRD pattern of the as-prepared Pd/fcc-Co(001) film. Formation of the Pd(002) peak confirms cube-on-cube epitaxial growth of the Pd(001) layer on the fcc-Co(001) film (fig. 1b). The deposition of the Pd layer on the fcc-Co(001) films at a temperature of ~ 250 °C did not change the magnetic properties of the fcc-Co(001) layer.

The in-plane magnetic anisotropy was measured using the torque method with a maximum magnetic field of 18 kOe. Fourfold in-plane magnetic anisotropy constants $K_4^{\text{Pd/hcp-Co(110)}}$ and $K_4^{\text{Pd/fcc-Co(001)}}$ of the initial Pd/hcp-Co(110) and Pd/fcc-Co(001) bilayers are equal to the fourfold in-plane magnetic anisotropy constants $K_2^{\text{hcp-Co(110)}}$ and $K_1^{\text{fcc-Co(001)}}$, respectively. Figure 2 shows the relative fourfold in-plane magnetic anisotropy constants $K_{\text{eff}}^{001} = K_4^{\text{Pd/fcc-Co(001)}} / K_1^{\text{fcc-Co(001)}}$ and $K_{\text{eff}}^{110} = K_4^{\text{Pd/hcp-Co(110)}} / K_2^{\text{hcp-Co(110)}}$ as a function of the annealing temperature for Pd/hcp-Co(110) and Pd/fcc-Co(001) bilayers, respectively. Within experimental accuracy up to 400 °C, the constants K_{eff}^{001} (Fig. 2a) and K_{eff}^{110} (Fig. 2b) didn't change with respect to the annealing temperature T. This is in agreement with XRD data, which didn't show the formation of compounds on the interface between palladium and cobalt. After annealing above 400 °C the absolute values of the constants K_{eff}^{001} and K_{eff}^{110} start to decrease (Fig. 2). In both cases this foreshadows the beginning of the mixing of the Pd and Co layers and the synthesis of the CoPd phase.

In Pd(001)/fcc-Co(001) bilayers, after annealing at 500 °C, the Pd(002) and fcc-Co(002) peaks were strongly reduced and a new reflection of the disordered (002) fcc-CoPd phase was formed (Fig. 1b). As the annealing temperature increased to 650 °C, the (002) CoPd reflection grew strongly, while the peaks of Pd(002) and fcc-Co(002) disappeared completely (Fig. 1b). This implies that the epitaxial growth of the CoPd(001) crystallites occurs and inherits the (001) orientation of the fcc-Co(001) initial films. The lack of (001) superstructure reflex suggests that the formed CoPd is a disordered phase. The epitaxial relationship CoPd(001) ⟨100⟩ || MgO(001) ⟨100⟩ of the CoPd(001) phase and the MgO substrate were determined by the asymmetric φ-scan of {113} reflections of the CoPd(001) phase and MgO(001) substrate. Figure 2a shows that the value K_{eff}^{001} decreases at 400°C and above 550 °C is practically unchanged. This is in agreement with the completion of the CoPd synthesis. This makes it possible to estimate the first constant $K_1^{CoPd} = -(1.8 \pm 0.4)\cdot 10^4$ J/m^3, which has a negative value, since the easy axis coincides with the [110] and [1-10] directions of CoPd(001) films.

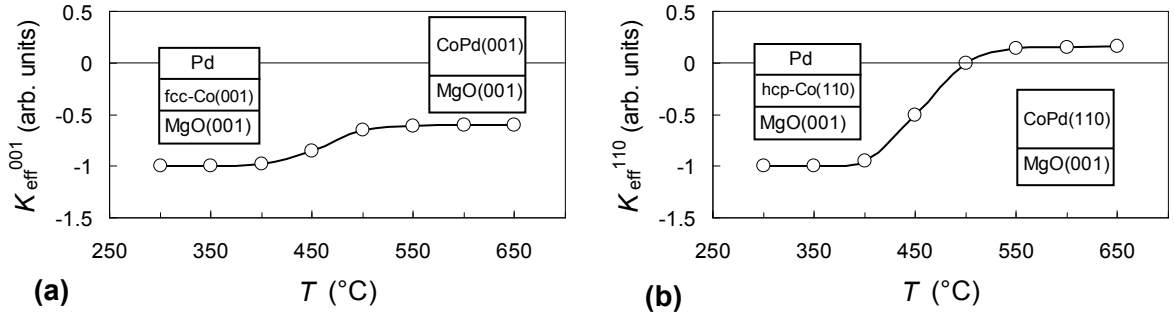

Fig. 2. Changes in fourfold in-plane magnetic anisotropy K_{eff}^{001}, K_{eff}^{110} and schematic representation the solid-state reaction as function annealing temperatures: (a) in Pd/fcc-Co(001) bilayers; (b) in Pd/hcp-Co(110) bilayers.

The X-ray pattern of Pd/hcp-Co(110) bilayers, after annealing at 500 °C, shows a reduction of the hcp-Co(110) peak and a formation of a new, strong (110) CoPd peak (Fig. 1a). With an increase of the annealing temperature to 650 °C, the reflection (110) CoPd strongly grows, which is associated both with a volume increase and the growth of crystal perfection on the CoPd(110) phase (Fig. 1a). Magnetic anisotropy of the Pd/hcp-Co(110) bilayer changes according to the phase composition evolution. After annealing at 450 °C the absolute value of the constant K_{eff}^{110} starts decreasing, which is associated with the start of the CoPd (110) and above 500 °C the constant K_{eff}^{110} changes ~~a~~ sign (Fig. 2b). This is due to the fact that above 550 °C the set of synthesized CoPd(110) crystallites have easy axes coinciding with the [100] and [0-10] directions of MgO(001) substrates. The in-plane epitaxial relations between the CoPd(110) and the MgO(001) substrate were determined by the asymmetric scans of CoPd(110){222} and MgO(001){311} reflections:

$$\text{CoPd}(110)\ \langle -111\rangle \parallel \text{MgO}(001)\ \langle 100\rangle \tag{3}$$

Figure 3 shows four possible variants for the orientation of the CoPd(110) crystallites on the MgO(001) surface, which satisfy the epitaxial relations (3). The magnetic anisotropy energy density $E(\varphi)$ of exchange-coupled CoPd(110) crystallites which satisfy the epitaxial relations (3) are described by the expression (4).

$$E(\varphi) = K_4^{CoPd(110)} \sin^2\varphi \cos^2\varphi = 3/4\ K_1^{CoPd} \cos 4\theta\ \mathrm{Sin}^2\varphi \cos^2\varphi, \tag{4}$$

where φ is the angle between the saturation magnetization M_S and the [100] MgO direction, and θ is the angle of disorientation of CoPd(110) crystallites relative to the [100] and [010] directions of MgO(001) (Fig. 3). For CoPd(110) crystallites satisfying the epitaxial relation (3), the angle θ is about 35.26°. Substituting in the $K_4^{CoPd(110)} = 3/4\ K_1^{CoPd} \cos 4\theta$ experimental value $K_4 = +(1.0 \pm 0.4)\cdot 10^4$ J/m^3 and $\theta \cong 35.26°$, we obtain the value $K_1^{CoPd} = -(1.8 \pm 0.4)\cdot 10^4$ J/m^3. An important point is that following expression (4) the constant $K_4^{CoPd(110)}$ has a different sign than the K_1^{CoPd} constant.

This corresponds to a change of sign for K_{eff}^{110} at the synthesis of CoPd(110) crystallites in the Pd/α-Co(110) bilayers (fig. 2a). The obtained absolute value of K_1^{CoPd} for the films is more than two times less than the value for bulk samples [10]. The causes for this significant difference remain unclear.

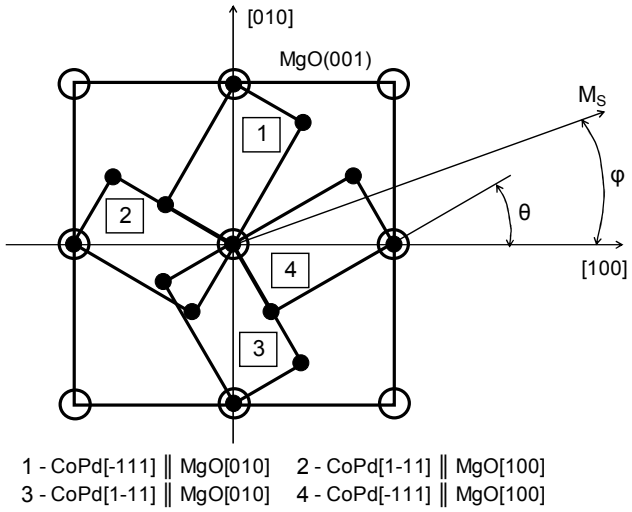

Fig. 3. Schematic representation of four equivalent variants of CoPd(110)⟨-111⟩ ‖ MgO(001)⟨100⟩ orientation relationships between CoPd (110) crystallites and MgO(001) substrate.

Conclusions

We have compared the structural and magnetic evolutions of the Pd/hcp-Co(110) and Pd/fcc-Co(001) bilayers with 1Co:1Pd composition as functions of the annealing temperature. Above 450°C the synthesis of the disordered fcc CoPd phase starts and finishes completely at 650 °C. The estimation of the first magnetocrystalline anisotropy constant $K_1^{CoPd} = -(1.8 \pm 0.4)\cdot 10^4$ J/m^3 of the CoPd disordered phase was obtained.

References

[1] B.M. Lairson, W. Liu, A. P. Payne, C. Baldwin, and H. Hamilton, J. Appl. Phys. 77 (1995) 6675.

[2] B.D. Terris, J. Magn. Magn. Mater. 321 (2009) 512.

[3] S. Mangin, D. Ravelosona, J. A. Katine, M. J. Carey, B. D. Terris, E. E. Fullerton, Nature Mater. 5 (2006) 210.

[4] Z. Liu, R. Brandt, O. Hellwig, S. Florez, T. Thomson, B. Terris, H. Schmidt, J. Magn. Magn. Mater. 323 (2011) 1623.

[5] D. Weller, A. Moser, L. Folks, M.E. Best, W. Lee, M.F. Toney, M. Schwickert, J.-U. Thiele, and M.F. Doerner, IEEE Trans. Magn. 36 (2000) 10.

[6] M. Gottwald, K. Lee, J.J. Kan, B. Ocker, J. Wrona, S. Tibus, J. Langer, S.H. Kang, and E.E. Fullerton, Appl. Phys. Lett. 102 (2013) 052405.

[7] A. Murdoch, A.G. Trant, J. Gustafson, T.E. Jones, T.C.Q. Noakes, P. Bailey, C.J. Baddeley, Surf. Sci. 608 (2013) 212.

[8] Yu.V. Goryunov, M.G. Khusainov, I.A. Garifullin et al., J. Magn. Magn. Mater. 138 (1994) 216.

[9] E. Gu, M. Gester, R.J. Hicken, C. Daboo, M. Tselepi, S.J. Gray, J.A.C. Bland, L.M. Brown, T. Thomson and P.C. Riedi, Phys. Rev. B 52 (1995) 14704.

[10] N. Miyata, M. Hagiwara, Y. Ichiyanagi, K. Kuwahara, H. Matsufuji, J. Phys. Soc. Jpn. 55 (1986) 961.