Thin Solid Films 519 (2011) 8359–8362

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Structural and magnetic properties of FePd and CoPd alloy epitaxial thin films grown on MgO single-crystal substrates with different orientations

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ARTICLE INFO

Available online 2 April 2011

Keywords:
FePd thin film
CoPd thin film
$L1_0$ ordered phase
Epitaxial growth
MgO single-crystal substrate
Perpendicular magnetic anisotropy

ABSTRACT

FePd and CoPd alloy thin films were prepared on MgO single-crystal substrates of $(001)_{B1}$, $(110)_{B1}$, and $(111)_{B1}$ orientations at 600 °C by ultra high vacuum rf magnetron sputtering. $L1_0$-FePd(001) films with the *c*-axis perpendicular to the substrate surface are obtained on MgO$(001)_{B1}$ substrates. FePd epitaxial films consisting of $L1_0$(110) and $L1_0$(011) crystals are formed on MgO$(110)_{B1}$ substrates. The *c*-axis of $L1_0$(110) crystal is parallel to the substrate surface, whereas that of $L1_0$(011) crystal is 44° canted from perpendicular direction. $L1_0$-FePd(111) films with the *c*-axis 54° canted from the perpendicular direction are formed on MgO $(111)_{B1}$ substrates. $L1_0$ ordering degree of these FePd films varies depending on the substrate orientation. On the other hand, disordered CoPd thin films of $(001)_{A1}$, $(110)_{A1}$, and $(111)_{A1}$ orientations epitaxially grow on MgO substrates of $(001)_{B1}$, $(110)_{B1}$, and $(111)_{B1}$ orientations, respectively. The magnetization properties of $L1_0$ ordered FePd and $A1$ disordered CoPd thin films are influenced by the crystal structure, the ordering degree, and the film orientation.

1. Introduction

FePd and CoPd alloy thin films with perpendicular magnetic anisotropy have been investigated recently for applications like magnetic recording media [1–5], magnetic random access memory devices [6,7], etc. The crystal structure of FePd alloy around the equiatomic composition varies between disordered $A1$ and ordered $L1_0$ structures. Here, the $A1$ and $L1_0$ are *Strukturbericht* designation symbols which specify the crystal structures. $L1_0$ ordered $Fe_{50}Pd_{50}$ (at.%) alloy has a high uniaxial magnetocrystalline anisotropy constant of 2.1×10^7 erg/cm^3 [8]. Formation of $L1_0$ ordered $Co_{50}Pd_{50}$ alloy, which is metastable and does not appear in the bulk phase diagram, is also suggested in the form of films prepared at elevated substrate temperatures [9]. In order to investigate the basic structural and magnetic properties, it is useful to employ well-defined epitaxial films, since the film crystallographic orientation and the magnetic anisotropy are well controlled. FePd$(001)_{L10}$ epitaxial thin films have been prepared on cubic single-crystal substrates of (001) orientation [1–3,6,10,11]. The influence of ordering degree on the magnetic properties [10,11] and the magnetic domain structures [1–3] were investigated. On the other hand, CoPd polycrystalline and epitaxial films have been prepared on glass [4], Si$(111)_{A4}$ [5], and MgO$(001)_{B1}$ [5] substrates. The effects of film composition and crystal structure on the magnetic properties have been reported. However, there are very few works discussing the relationship between film orientation and ordering degree for FePd and CoPd films [5,12]. In the present study, FePd and CoPd films were prepared on MgO substrates of $(001)_{B1}$, $(110)_{B1}$, and $(111)_{B1}$ orientations. The effects of substrate orientation on the structure, the ordered phase formation, and the magnetic properties were investigated.

2. Experimental procedure

FePd and CoPd alloy films of 40 nm thickness were deposited on polished MgO substrates of $(001)_{B1}$, $(110)_{B1}$, and $(111)_{B1}$ orientations at 600 °C by using an rf magnetron sputtering system equipped with a reflection high energy electron diffraction (RHEED) facility. The base pressures were lower than 4×10^{-7} Pa. Substrates were heated at 600 °C

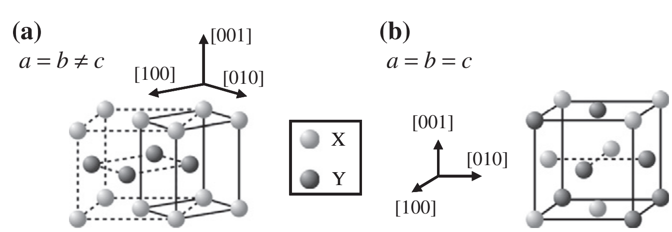

Fig. 1. (a) $L1_0$ and (b) $A1$ crystal structures showing the relationships of *a*, *b*, and *c* axes.

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0040-6090/$ – see front matter
doi:10.1016/j.tsf.2011.03.082

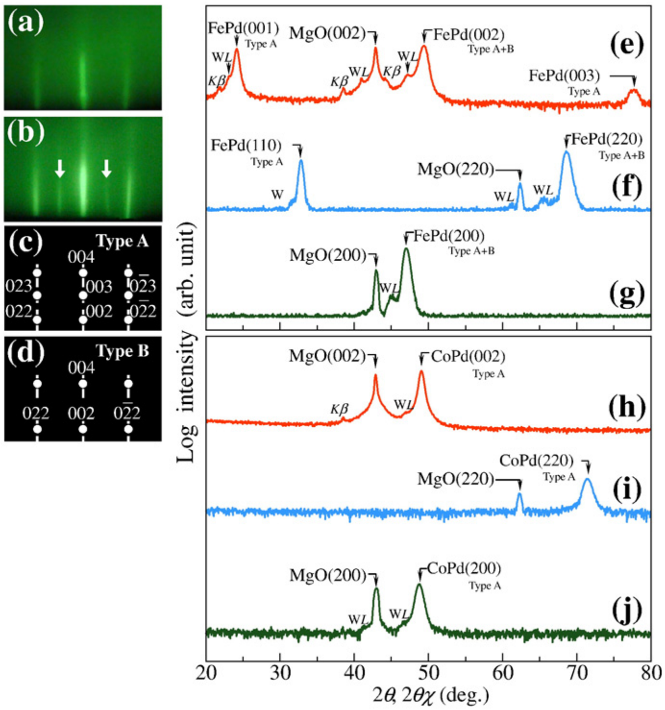

Fig. 2. RHEED patterns observed for (a) FePd and (b) CoPd films grown on MgO(001)$_{B1}$ substrates. The incident electron beam is parallel to the MgO[100]$_{B1}$ direction. The spot maps of (c) $L1_0$(001)$_{\text{Type A}}$ and (d) $A1$(001)$_{\text{Type B}}$ textures. (e, h) Out-of-plane and (f, g, i, j) in-plane XRD spectra of (e)–(g) FePd/MgO(001)$_{B1}$ and (h)–(j) CoPd/MgO(001)$_{B1}$ specimens. The scattering vector of in-plane XRD is parallel to (f, i) the MgO[220]$_{B1}$ or (g, j) the MgO[200]$_{B1}$ direction. The intensity is shown in a logarithmic scale.

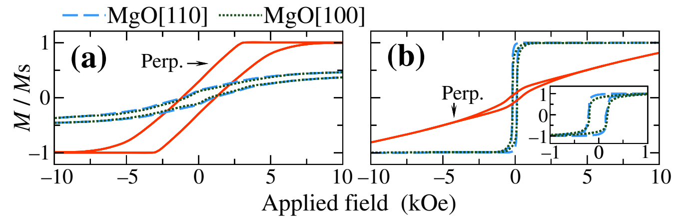

Fig. 3. Magnetization curves of (a) FePd and (b) CoPd films grown on MgO(001)$_{B1}$ substrates.

for 1 h in the chamber to obtain clean surfaces. The surface structure was checked by RHEED. The RHEED patterns observed for the substrates exhibited *Kikuchi* patterns (not shown here, [13]), indicating that the surfaces were clean and smooth. The Ar gas pressure was kept constant at 0.67 Pa and the rf powers for $Fe_{50}Pd_{50}$ and $Co_{50}Pd_{50}$ (at.%) targets were respectively fixed at 35 and 38 W, where the deposition rate was 0.02 nm/s for both materials. The FePd and the CoPd film compositions were confirmed by energy dispersive X-ray spectroscopy and the errors were less than 4 at.% from the equiatomic composition.

The surface structure was studied by RHEED. The film structure was investigated by out-of-plane and in-plane X-ray diffraction (XRD) with Cu-$K\alpha$ radiation ($\lambda = 0.15418$ nm). The long-range ordering parameter, S, of $L1_0$ ordered crystal film was calculated from the XRD data using the relationship, $S = [(I_s/I_f) \times \{(F^2 \times L \times A \times D)_f/(F^2 \times L \times A \times D)_s\}]^{1/2}$, where I is the integrated intensity, F is the structure factor, L is the Lorentz factor, A is the absorption factor, and D is the temperature factor, and subscripts f and s refer to fundamental and superlattice reflections, respectively [14]. The magnetization curves were measured by using a vibrating sample magnetometer.

In the present paper, the relationship between $L1_0$ and $A1$ structures is discussed. The unit cell of $L1_0$ structure in relation to that of $A1$ structure is shown in Fig. 1, and thus the indexing is different between these structures. However, another method has also been conveniently used to index the $L1_0$ structure based on the $A1$ structure with the atom positions in the (002) occupied with the Y atoms. Here, the latter method is employed to make the comparison in crystal structure simple.

3. Results and discussion

3.1. Film deposition on MgO(001)$_{B1}$ substrates

FePd and CoPd alloy epitaxial films were obtained on MgO(001)$_{B1}$ substrates. Fig. 2(a) shows the RHEED pattern observed for an FePd film deposited on MgO(001)$_{B1}$ substrate. A clear diffraction pattern consisting of only the streaks is observed for the FePd film. The pattern corresponds to $L1_0$(001) [Fig. 2(c)] and/or $A1$(001) [Fig. 2(d)] textures. The epitaxial orientation relationships of FePd(001)[100]$_{L10}$ (Type A) and FePd(001)[100]$_{A1}$ (Type B) || MgO(001)[100]$_{B1}$ are determined by comparing the RHEED patterns observed for the film and the substrate. The c-axis of $L1_0$-FePd(001) film is perpendicular to the substrate surface. Fig. 2(e)–(g) shows the out-of-plane and the in-plane XRD spectra of the FePd film. In the out-of-plane spectrum [Fig. 2(e)], the FePd(001)$_{L10}$ and the FePd(003)$_{L10}$ superlattice reflections are clearly observed in addition to the FePd(002)$_{L10}$ + (002)$_{A1}$ fundamental reflection. The S value is calculated from the FePd(001)$_{L10}$ superlattice and the FePd(002)$_{L10}$ + (002)$_{A1}$ fundamental reflections to be $S = 0.6$. In the in-plane spectrum shown in Fig. 2(g), only the FePd(200)$_{L10}$ fundamental reflection is observed, which indicates that the film does not include FePd(100)$_{L10}$ crystal whose c-axis is parallel to the substrate surface.

A clear RHEED pattern similar to the case of FePd film deposited on MgO(001)$_{B1}$ substrate is observed for a CoPd film deposited on MgO(001)$_{B1}$ substrate, as shown in Fig. 2(b). The pattern also corresponds to $L1_0$(001) [Fig. 2(c)] and/or $A1$(001) [Fig. 2(d)] textures. However, the existence of $L1_0$(001) crystal is not recognized by XRD which is described later. Thus, the CoPd film consists of only the $A1$(001) crystal. The epitaxial orientation relationship is determined by RHEED as CoPd(001)[100]$_{A1}$ (Type B) || MgO(001)[100]$_{B1}$. The streaks noted by the arrows in Fig. 2(b) show that the CoPd film has a reconstructed surface of $c(2\times2)$ structure. Fig. 2(h)–(j) shows the out-of-plane and the in-plane XRD spectra. In these spectra, no superlattice reflections are observed, whereas the CoPd(002)$_{A1}$, the CoPd(220)$_{A1}$, and the CoPd(200)$_{A1}$ fundamental reflections are clearly observed.

Fig. 3(a) and (b) shows the magnetization curves of the FePd and the CoPd films, respectively. Magnetocrystalline easy axis of bulk $L1_0$ ordered FePd alloy is parallel to the c-axis [8]. The FePd film with the c-axis perpendicular to the film surface shows perpendicular magnetic anisotropy. The magnetization curves are almost isotropic in the in-plane measurements. The magnetization property of FePd film is reflecting the magnetocrystalline anisotropy of $L1_0$ ordered FePd alloy crystal. The CoPd film shows in-plane anisotropy. The film is easily magnetized when the magnetic field is applied along the MgO[110]$_{B1}$ (|| CoPd[110]$_{A1}$) direction, similar to the case of epitaxial Co(001)$_{A1}$ single-crystal films [15]. Although, the bulk $A1$ Co crystal has the easy magnetization axes along $A1$<111> directions [16], Co(001)$_{A1}$ films are easily magnetized along the Co[110]$_{A1}$ direction due to an overlap of magnetocrystalline anisotropy and demagnetization field. Therefore, the in-plane magnetic anisotropy of CoPd films is considered to be reflecting the magnetocrystalline anisotropy of $A1$ disordered CoPd alloy crystal.

3.2. Film deposition on MgO(110)$_{B1}$ substrates

FePd and CoPd epitaxial films were also obtained on MgO(110)$_{B1}$ substrates. Fig. 4(a) shows the RHEED pattern observed for an FePd film deposited on MgO(110)$_{B1}$ substrate. Four kinds of reflections shown in