Magnetic Properties and Structure of (Co\textsubscript{100-}\textsubscript{x}Fe\textsubscript{x})\textsubscript{50}Pt\textsubscript{50} Alloy Thin Films

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The magnetic properties of \((\text{Co}_{100-x}\text{Fe}_x)_{50}\text{Pt}_{50}\) \((0 \leq x \leq 100)\) alloy thin films in conjunction with the structure are studied. The intrinsic perpendicular magnetic anisotropy constant \(K_u\) measured at room temperature increases with order parameter \(S\) and decreases with tetragonality \(c/a\). This result is at variance with a calculation based on first-principle analysis at the order parameter \(S=1\). \(K_u\) increases with \(S\) for all compositions. The estimated \(K_u\) values obtained by extrapolation to \(S=1\) for \((\text{Co}_{100-x}\text{Fe}_x)_{50}\text{Pt}_{50}\) would be nearly the same for \(x\) from 0 to 56, but increases with \(x\) for \(x\) larger than 56. The present result is consistent with the theoretical one, provided that the temperature dependence of \(K_u\) is neglected.

Key words: \((\text{Co}_{100-x}\text{Fe}_x)_{50}\text{Pt}_{50}\), perpendicular magnetic anisotropy, order parameter, \(c/a\).

1. Introduction

Recently much attention has been paid to \(\text{L}_{1_0}\) alloy thin films such as \(\text{Co}_{50}\text{Pt}\) and \(\text{Fe}_{50}\text{Pt}\) systems, because they possess very high magnetic anisotropy of the order of 10\(^7\) erg/cm\(^2\). For example, ordered thin films of \(\text{Fe}_{50}\text{Pt}_{50}\) were reported to have a large magnetic anisotropy and exhibit an attractive vertical recording performance\(^{4,5}\). However, the detailed mechanism of the magnetic anisotropy in conjunction with film structure is still open to question. Also very few studies on the ternary alloy thin films of \((\text{Co}_{100-x}\text{Fe}_x)_{50}\text{Pt}_{50}\) have been carried out\(^6\). Previously, the magnetic properties in correlation to the ordering and tetragonality \(c/a\) for \(\text{Fe}_{50}\text{Pt}\), \(\text{Co}_{50}\text{Pt}\) and \((\text{Co}_{50}\text{Fe}_{50})\text{Pt}\) films were reported\(^7\). In the present paper, the influence of the chemical ordering and tetragonality on the magnetic anisotropy for a wide range of film composition for \((\text{Co}_{100-x}\text{Fe}_x)_{50}\text{Pt}_{50}\) film is discussed.

2. Experimental

Thin films of \((\text{Co}_{100-x}\text{Fe}_x)_{50}\text{Pt}_{50}\) alloys were grown onto \(\text{MgO}(100)\) substrates at substrate deposition-temperature \(T_s\) between 100 and 500°C by electron beam evaporation using \(\text{Co}\), \(\text{Fe}\) and \(\text{Pt}\) targets. The film–compositions were varied by changing the deposition rates of these targets\(^8\). The film-thickness of all the samples is about 500 Å. Measurements of the magnetic properties at room temperature were carried out using a vibrating sample magnetometer (max field : 15kOe), and a torque magnetometer (max field : 30kOe). The structural analyses were performed by X-ray diffraction using Cu-K\(_{\alpha}\) radiation.

3. Results and discussion

Figure 1 shows the X-ray diffraction spectra for the \(\theta/2\theta\) and \(\phi\) scan geometries for the \(\text{Fe}_{50}\text{Pt}_{50}\) film grown at \(T_s=500°C\). As shown in Fig.1(a), a strong sharp diffraction at around 23 degree is observed. This diffraction line is characteristic of the ordered \(\text{FePt}(\text{L}_{1_0})\) fct phase. Also, only (001), (002) and (003) lines are observed, indicating that the \(c\)-axis is along the film normal. With decreasing \(T_s\), the peak intensity of the (001) diffraction decreases. With further decreasing \(T_s\) down to about 200°C, the (200) diffraction appears, showing the mixed phase of both ordered fct structure and disordered fcc structure\(^6\).

Since the films possess the \(c\)-axis along the film normal, in order to estimate the lattice constant \(a\) of the fct, a so-called \(\phi\) scan diffraction analysis. For this measurement, X-rays are irradiated at a glancing angle (about 0.5 degree) and the 2\(\theta\) angle is fixed at 47 degree, corresponding to the \(\text{FePt}(200)\) diffraction. Then, the sample is rotated about an

![Fig. 1 XRD profiles of (a) \(\theta/2\theta\) and (b) \(\phi\) scans for \(\text{Fe}_{50}\text{Pt}_{50}\) sample at \(T_s=500°C\).]
axis normal to the film plane, and the diffraction pattern is observed. As seen in Fig 1(b), very sharp peaks are found at every 90°. This result indicates that this film shows the four-fold symmetry around the axis of the film normal. Because the irradiated area of this method is almost same as the sample size, this film can be considered as a single crystal. Then, the lattice constant \(a\) is determined by changing the 2\(\theta\) angle so as to obtain the maximum intensity of the (200) diffraction. The lattice constant \(a\) for this sample is found to be about 3.87 Å. The misfit parameter between the film and MgO(100) substrate is about 9% for this case.

Fig 2 shows the \(T_s\) dependences of the lattice constants (\(a\) and \(c\)) and the ratio of \(c/a\) for Fe\(_{80}\)Pt\(_{20}\) films. Also shown are the bulk data for \(a\) and \(c\) denoted by the dotted lines\(^5\).

The in-plane and out of plane lattice constants of FePt for \(T_s=100^\circ\mathrm{C}\) is found to be \(a=3.81\,\mathrm{Å}\) and \(c=3.80\,\mathrm{Å}\). With increasing \(T_s\), \(a\) increases and \(c\) decreases, and then both become nearly constant above about \(T_s=300^\circ\mathrm{C}\) (\(a=3.87\,\mathrm{Å}\) and \(c=3.71\,\mathrm{Å}\)). The ratio of \(c/a\) decreases with increasing \(T_s\). It is mentioned that the data of \(c/a\) given in previous paper\(^6\) was based on the bulk value of \(a\) (--- in Fig 2), which is different from those of the present thin films.

The total torque amplitude \(L\) is given as

\[
L = (2\pi M_s^2 - |K_1 + K_2|) \sin 2\alpha + \frac{1}{2} K_2 \sin 4\alpha.
\]  

(1)

Here, \(M_s\) is the saturation magnetization, \(\alpha\) the angle between the easy axis and the direction of magnetic moment, and \(K_1\) and \(K_2\) are the magnetic anisotropy constant of the \(\sin^2\alpha\) and \(\sin^4\alpha\) components, respectively. When \(M_s\), \(K_1\) and \(K_2\) are given, \(L\) as a function of \(\alpha\) can be obtained, then the torque amplitude for \(\sin 2\alpha\) and \(\sin 4\alpha\) components \((L_{2\alpha}, L_{4\alpha})\) can be calculated. For a sample with a magnetic anisotropy field \(H_a\), which is much higher than the applied field, \(L_{2\alpha}\) cannot accurately be estimated on the basis of the conventional extrapolation method using the \(1/H\) dependence of the torque amplitude of the 2-fold symmetry\(^6\). In such a case, a more appropriate method to estimate the magnetic anisotropy must be used. In this study, the \(L_{2\alpha}\) and \(L_{4\alpha}\) components as a function of external fields \((H_a)\) are simulated for given \(K_1\), \(K_2\) and \(M_s\) values. Then, the experimental data are fitted with the simulated results, by choosing \(K_1\) and \(K_2\) values as fitting parameters. One example is given in Fig 3 where the comparison of \(L_{2\alpha}\) and \(L_{4\alpha}\) as a function of \(H_a\) between the measurement (dots) and calculation (lines) for Co\(_{80}\)Pt\(_{20}\) film grown at 500°C is made, where the \(K_1\) and \(K_2\) are taken to be about \(7 \times 10^6\) and \(6 \times 10^6\) erg/cc, respectively.
Fig. 5 (a) $K_x$ vs. $c/a$ and (b) $K_x$ vs. $S$ for $x = 0, 56, 76, \text{and} 100$.

The dependence of $K_x$ on $T_x$ for (Co$_{100-x}$Fe$_x$)$_{50}$Pt$_{50}$ alloy films is shown in Fig. 4. The $K_x$ increases with $T_x$ for all the alloy films in a temperature range between 200 and 300°C, and then becomes nearly constant. The maximum values obtained are about $5 \times 10^3$, $3.6 \times 10^3$, $2 \times 10^3$ and $1.5 \times 10^3$ erg/cc for $x = 100, 76, 56$ and $0$, respectively.

As discussed before, the Fe$_{50}$Pt$_{50}$ samples deposited at $T_x=500°C$ consist of the partially ordered phase. The order parameter $S$ can be estimated using

$$S = \sqrt{\frac{I_{(001)} F_x^2 L_x^2 A_x D_x}{I_{(002)} F_x^2 L_x^2 A_x D_x}}. \quad (2)$$

Here $I_{(001)}$ and $I_{(002)}$ are the integrated intensities for (001) and (002), respectively, $F$ the structure factor, $L$ the Lorentz-polarization factor, $A$ the absorption correction factor, $D$ the temperature factor, and the subscripts $x$ and $y$ correspond to those for the superlattice and the fundamental diffractions, respectively. The values of $F$, $L$ and $A$ are calculated for the present case. The temperature factor has been experimentally determined from $I_{(001)}$ and

Fig. 6 Estimated and calculated $K_x$ values at $S = 1$ of (Co$_{100-x}$Fe$_x$)$_{50}$Pt$_{50}$ films.

$I_{(003)}$ using the equation given by Debye$^9$. Using the experimental result for the temperature factor, eq.(2) becomes

$$S = 0.85 \sqrt{\frac{I_{(001)}}{I_{(002)}}} \quad (3)$$

On the other hand, the $S$ can also be evaluated using the (003) diffraction. In this case, $S$ can be given as

$$S = 3.6 \sqrt{\frac{I_{(003)}}{I_{(002)}}} \quad (4)$$

It is found that both eq.(3) and (4) provides the $S$ values in agreement within 5% accuracy. For example, the values of $S$ for $x=50$ grown at $500°C$ are 0.87 and 0.89 for eq.(3) and (4), respectively. In the case of CoPt the coefficient using $I_{(001)}$ and $I_{(002)}$ is about 0.85. Therefore, eq.(3) was used for all compositions.

Fig. 5 shows the dependence of $K_x$ on the order parameter $c/a$ and the ratio $S$ for Fe$_{50}$Pt$_{50}$, (Co$_{100-x}$Fe$_x$)$_{50}$Pt$_{50}$ and Co$_{50}$Pt$_{50}$ films. As shown in Fig.5(a), it is seen that $K_x$ is dependent on $c/a$, increasing with decreasing $c/a$. It is of interest to note that the dependence of $K_x$ on $c/a$ seems to be on a single curve, being independent of alloy composition. First-principle calculations predict that $K_x$ increases with increasing $c/a$\(^9\). This result is at variance with the present results. However in this calculation the perfect ordering is assumed ($S = 1$) for all values of $c/a$, while in reality $c/a$ and order parameter $S$ are dependent on each other as also here observed. In the same composition, with increasing $S$, $c/a$ decreases. As shown in Fig.5(b), the $K_x$ decreases with $S$.

Fig. 6 shows the estimated $K_x$ values at $T = 300K$ of (Co$_{100-x}$Fe$_x$)$_{50}$Pt$_{50}$ as a function of $x$ obtained by extrapolation to $S=1$ using Fig.5(b) and also the result of $K_x$ values at $T=0$ K by first-principle calculation\(^10\). The
estimated $K_a$ would be nearly the same for $x$ from 0 to 56 and increases with $x$ for $x$ larger than 56. The present observation is consistent with the theoretical result, provided that no temperature dependent effect is taken into account.

4. Summary

The evolution of the perpendicular magnetic anisotropy $K_a$ with the order parameter $S$ of the fct($L_1_2$) ordered phase and also with $c/a$ is investigated for different film compositions in (Co$_{100-x}$Fe)$_x$Pt$_{50}$. The $K_a$ is found to increase with $S$ and to increase with decreasing tetragonality $c/a$. The evolution of $K_a$ on $c/a$ is at variance with theoretical predictions. It is of interest to note that the dependence of $K_a$ on $c/a$ is on a single curve, being independent of alloy composition. The compositional dependence of $K_a$ estimated at $S=1$ is qualitatively in agreement with the theoretical prediction.

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References

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