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Magnetism of Films

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Abstract

Films of $L1_0$-structure $Fe_{50-x}Co_xPt_{50}$ films are synthesized by co-sputtering Fe, Co, and Pt on (001) MgO substrates and Si substrates with in-situ heating at 830°C. The nanostructures and magnetic properties of the films are characterized by X-ray diffraction, transmission electron microscopy, and SQUID. The compositions of the samples $Fe_{50-x}Co_xPt_{50}$ are designed to maintain an atomic (Fe+Co):Pt ratio of 50:50 while increasing the Co content in each successive sample. In all samples, the X-ray diffraction patterns from samples on MgO substrate exhibit three strong peaks, namely $L1_0 Fe_{50-x}Co_xPt_{50}$ (001), (002), and MgO (002). The X-ray and electron diffraction patterns from untextured samples deposited on Si substrates can be indexed using the $L1_0$-structure, being consistent with the result of samples on MgO substrate. Hysteresis-loop measurements show that with increase of the Co concentration from 0 to 15 at%, the saturation magnetization M_s increases from 1017 emu/cm^3 to 1165 emu/cm^3, the coercivity decreases from 30 kOe to 14 kOe, and anisotropy decreases from 67 Merg/cm^3 to 46 Merg/cm^3. The nominal maximum energy products are in the range of 39–41 MGOe.

Keywords: exchange-coupling, magnetic anisotropy, magnetic film, magnetism, permanent magnet

I. Introduction

In the history of permanent magnet development, the energy product $(BH)_{max}$ record has been mainly due to the discovery of new compounds. The achievable maximum energy product is determined by its saturation magnetization M_s and its magnetic anisotropy, $(BH)_{max} \leq 4\pi^2 M_s^2$. Another approach to increase the energy product is to exchange-couple an existing hard-magnetic compound to a soft phase with high M_s [1]–[3]. Various attempts

have been made to synthesize exchange-coupled magnets [4]–[6]. To maximize the energy product of exchange- coupled magnets, it is important to ensure high magnetization of the soft and the hard phases while maintaining the anisotropy and crystallographic alignment of the hard phase. We have recently shown [6] that $L1_0$(Fe, Co)Pt + fccFe(Co, Pt) hard and soft phase exchange-coupled magnets have excellent magnetic properties and high nominal energy products up to 64 MGOe. The easy axis of the hard phase $L1_0$ (Fe,Co)Pt is aligned using (001) single-crystal MgO substrates. Apparently, the $L1_0$ (Fe,Co)Pt has attractive properties as magnetic hard phase. In this paper, we investigate the phase stability and magnetic properties of $L1_0$ (Fe,Co)Pt as a function of Co content. Both epitaxially grown films and randomly grown films are synthesized and investigated.

II. Experimental Procedure

An AJA International sputtering system was used for film deposition. $Fe_{50-x}Co_xPt_{50}$ films were deposited on (001) oriented single-crystal MgO and on Si substrates by co-sputtering Fe, Co, and Pt targets. The sputtering rates of Fe, Co, and Pt were adjusted to deposit films with various Fe, Co, and Pt concentrations. The compositions were calculated using the sputtering rates of Fe, Co, and Pt, which were determined by X-ray reflectivity measurements of the film thicknesses. Before each deposition, a vacuum of better than 4×10^{-8} Torr was achieved in the deposition chamber, and the Ar pressure for deposition was 5 mTorr. The films of thickness 20 nm were characterized using a Rigaku x-ray diffractometer and a JEOL 2010 transmission electron microscope (TEM). The magnetic properties were measured in a Quantum Design SQUID magnetometer up to a maximum applied field of 70 kOe at room temperature.

III. Results

To perform phase identification, we used Si substrates for deposition of (Fe,Co)Pt films. Such films have the crystal grains oriented randomly and are suitable for identification of all phases present. Figure 1 shows the XRD patterns for samples with different atomic concentrations of Co: x = 0, 5, 10, 15, 17.5 at%. The Si (111) peak is the strongest due to the large volume of the Si substrate. Ten peaks from $Fe_{50-x}Co_xPt_{50}$ samples, (111), (110), (200), (001), (222), (220), (202), (112), (112), and (311), are identified in good agreement with the lines deduced from the $L1_0$ structure.
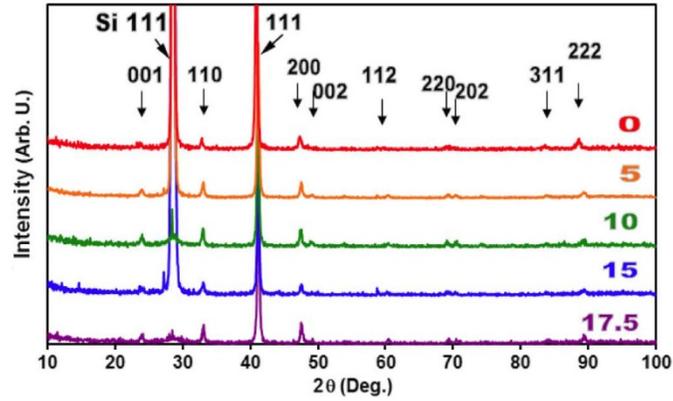
Figure 1. X-ray diffraction patterns of $L1_0$ $Fe_{50-x}Co_xPt_{50}$ films on Si substrate. The content of Co (at%) is shown in each spectrum. All lines are from $L1_0$ $Fe_{50-x}Co_xPt_{50}$ films except Si (111).

Figure 2(a) is a TEM image showing the particles in a sample with 17.5 at% Co grown on Si substrate. These particles are isolated from each other and randomly oriented. The corresponding electron diffraction pattern is shown in figure 2(b). This pattern is indexed using the $L1_0$ structure, being consistent with the X-ray diffraction.
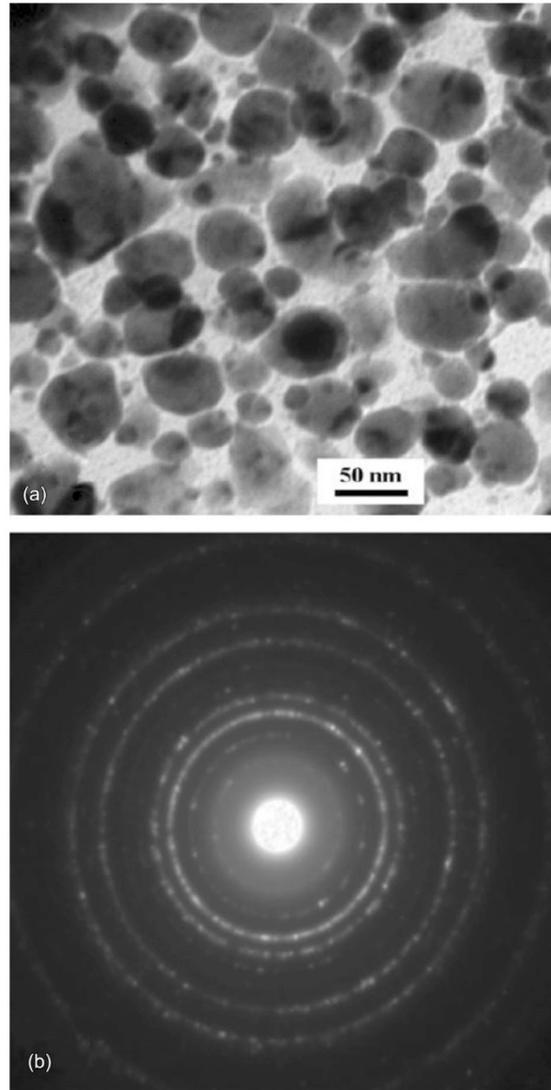
Figure 2. (a) TEM bright field image of film on Si substrate. (b) Corresponding electron diffraction pattern.

The hysteresis loops were measured using a SQUID at room temperature in magnetic fields applied in-plane ($\parallel$) and perpendicular ($\perp$) to the film plane . The loops of thin films are affected by the internal demagnetizing field, which was determined by setting dM/dH = infinity at H = H_c [7]. This correction does not change M_s or H_c, but it does change the energy product. Figure 3 shows the hysteresis loops of $Fe_{50-x}Co_xPt_{50}$ films deposited on MgO substrate. As expected for aligned magnets, there is a significant difference between the out-of-plane loops and in-plane loops. The magnetic anisotropy K_1 is deduced from the in-plane loop ($\parallel$) and perpendicular loop ($\perp$) as performed in [8]. The coercivity H_c, saturation magnetization M_s, magnetic anisotropy K_1, and energy product $(BH)_{/max}$ for ($\perp$) loops

are plotted as a function of Co content in figure 4. The coercivity H_c and anisotropy K_1 decrease while M_s increases with increasing Co content. The nominal energy product $(BH)_{max}$ varies in the range of 39~41 MGOe.
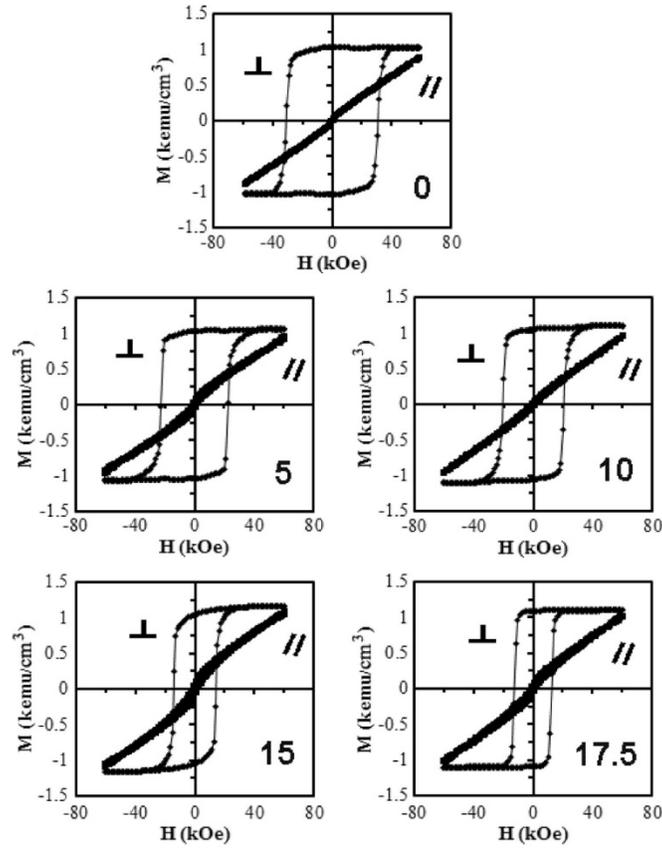

Figure 3. Hysteresis loops of $L1_0$ $Fe_{50-x}Co_xPt_{50}$ films deposited on MgO substrates. x is shown in each loop.
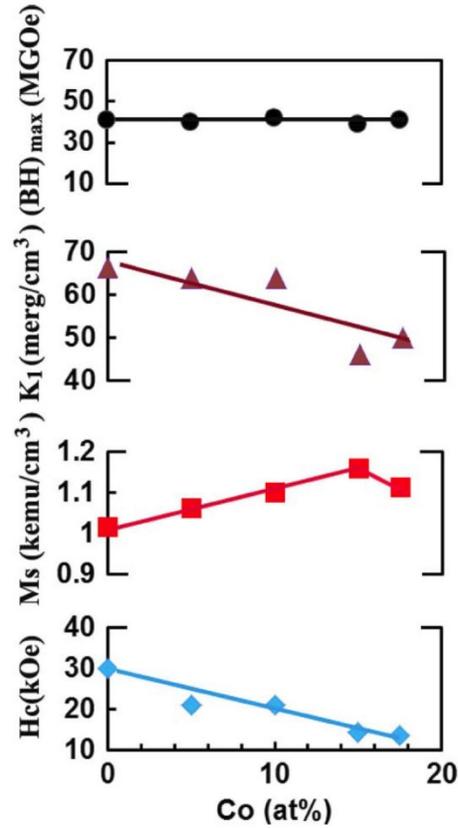
Figure 4. Variation of magnetic properties of $L1_0$ $Fe_{50-x}Co_xPt_{50}$ films with Co content. The films were deposited on MgO substrates.

IV. Discussion

The $L1_0$-structure FePt has the composition range from 35 at% Fe to 55 at% Fe while $L1_0$-structure CoPt from 42 at% Co to 73 at% Co, which indicate that both compounds are stable in a relatively wide composition range. The lattice parameters of FePt a = 3.838 A c = 3.715 A and CoPt a = 3.803 A c = 3.701 A have 1% mismatch in a and 0.4% in c. Such small mismatches lead to very low strain energy in mixture, meeting the conditions for two compounds to form a ternary compound with continuous composition variation between the two. Based on first-principles calculations of the electronic structure of $L1_0$ (FeCo)Pt performed by Maclaren et al. [9], the system shows phase separation below 650°C above which a continuous $L1_0$ structure of $Fe_{50-x}Co_xPt_{50}$ is formed, in agreement with our experimental result.

We observed a consistent increase of M_s with increasing Co content in ($Fe_{50-x}Co_xPt_{50}$) films for x < 15. However, the absolute value of M_s in FePt in our data is lower than 1140 emu/cm³. Brown et al.'s first-principles electronic structure calculations show that the energy difference between ferro-magnetic ordering and antiferromagnetic ordering in FePt

is small [10]. Perfectly ordered FePt has a tendency to become antiferromagnetic. If a portion of FePt becomes antiferromagnetic, the magnetization of FePt will decrease. The addition of Co to FePt reduces the degree of order and therefore reduces the tendency to become antiferromagnetic, which would increase magnetization. The M_s value of 1165 emu/cm^3 obtained in the sample $Fe_{35}Co_{15}Pt_{50}$ is higher than 1140 emu/cm^3 of FePt which suggests magnetization enhancement in FePt by addition of Co. The same trend was also observed by Chen et al. [11].

The magnetic properties M_s = 1160 emu/cm^3, K_1 = 4.6 MJ/m^3 for $Fe_{35}Co_{15}Pt_{50}$ are comparable with those of $Nd_2Fe_{17}B$ with M_s = 1281 emu/cm^3, K_1 = 5 MJ/m^3. Both FePt (T_c= 750 K) and CoPt (T_c = 840 K) have higher T_c than $Nd_2Fe_{17}B$ (T_c = 585 K). The $Fe_{50-x}Co_xPt_{50}$ compounds are expected to have T_c between 750 K and 840 K. The mechanical properties and oxidation resistance of $Fe_{50-x}Co_xPt_{50}$ are expected to be better than $Nd_2Fe_{17}B$. The only disadvantage of $Fe_{50-x}Co_xPt_{50}$ is its cost. If a suitable element E can be found to replace Pt partially, the cost can be reduced. $Fe_{50-x}Co_xPt_{50-y}E_y$ would be an excellent candidate for high performance permanent magnet with higher T_c, better mechanical and oxidation properties.

V. Conclusions

X-ray and TEM investigations indicate that a stable $L1_0$-structure phase exists in the composition range of x = 0 to 17.5 at% in $Fe_{50-x}Co_xPt_{50}$ films. The magnetic properties of $L1_0$-structure FePt are modified by addition of Co. A consistent increase in saturated magnetization M_s, and a decrease in anisotropy K_1 and coercivity H_c with increasing Co content from x = 0 to x = 15 at% are observed. The measured nominal maximum energy product varies in the range of 39~41 MGOe. Our results indicate that the $L1_0$-structure $Fe_{50-x}Co_xPt_{50}$ has good magnetic properties, possibly higher , better mechanical properties, and better oxidation resistance than $Nd_2Fe_{17}B$.

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