FePt (001) films with a variety of compositions were prepared on MgO (001) substrates by sputtering at reduced substrate temperature $T_s$ of $300^\circ$C, and their magnetic properties, particularly the temperature dependence of magnetization, were investigated. The film with a Pt-rich off-stoichiometric composition ($\text{Fe}_{38}\text{Pt}_{62}$) showed high chemical order and large perpendicular magnetic anisotropy, in contrast to the film with the stoichiometric composition showing poor chemical order. Besides the Curie temperature $T_c$ for $\text{Fe}_{38}\text{Pt}_{62}$ showed no large change from that of the bulk ordered alloy with the same composition, however, was lower than that of the fully ordered bulk alloy with the stoichiometric composition. This implies that the films with Pt-rich off-stoichiometric compositions have an advantage to thermally assisted magnetic recording which requires moderately low $T_c$.

**Key words:** FePt thin film, low temperature fabrication, composition, Curie temperature, recording media material

1. Introduction

The areal density of magnetic recording media has dramatically increased by means of reducing the magnetic grain size\(^1\). The ever-increasing demand for the realization of Tera bit recording is making the magnetic grain size down to nanometer scale. In such nanometer-sized grains, the instability of magnetization caused by thermal fluctuation is a crucial problem. One of the possible solutions to overcome this problem is to use ferromagnetic materials with large magnetocrystalline anisotropy.

$L_{10}$ ordered FePt alloy is one of the candidate materials for the next generation ultra-high density magnetic recording because the large uniaxial magnetocrystalline anisotropy ($K_u = 7.0\times10^5$ erg/cm\(^3\)), moderate saturation magnetization ($M_s = 1150$ emu/cm\(^3\))\(^7\), and high corrosion resistance. In addition to the excellent properties mentioned above, the large Kerr rotation of $L_{10}$ ordered phase has also attracted much attention in consideration of the application to magneto-optical recording media\(^8\)-\(^10\). However, several drawbacks for applications still remain to be solved. One is a high temperature process above $500^\circ$C usually required to form the $L_{10}$ ordered structure. Such a high temperature process accelerates the grain growth in magnetic films, leading to the reduction of signal-to-noise ratio in recording media.

Thus, a lot of studies focusing on the low temperature fabrication of FePt ordered films were reported; the use of proper under-layers\(^12\)-\(^13\), the addition of third elements\(^14\)-\(^15\), post-annealing of multilayers\(^16\)-\(^17\), ion irradiation\(^18\), alternate monatomic layer deposition\(^19\), high Ar gas pressure during sputter-deposition\(^20\), and in-situ annealing\(^21\). Another drawback is a huge coercivity due to the large $K_u$, which prevents the magnetization vectors of bits from reversing by a proper external field. Thermally assisted magnetic recording (TAMR)\(^22\) is one of the promising approaches to reverse the magnetization vectors for the materials with high coercivity. TAMR is a recording technique which reduces the coercivity by locally heating the media just beneath Curie temperature $T_c$. Recently, several studies on the reduction of the heating temperature for TAMR were also made\(^23\) since $T_c = 480^\circ$C\(^24\) of the $L_{10}$ ordered FePt alloy is considerably high, and a moderately low $T_c$ is required to avoid the large thermal stress in recording media.

Previously\(^25\), we reported that $L_{10}$ ordered structures with high perpendicular magnetic anisotropy were obtained for FePt (001) films deposited on MgO (001) substrates even at the substrate temperature $T_s = 300^\circ$C by shifting the composition of the FePt phase to a Pt-rich off-stoichiometric region. In this paper, we have investigated the magnetic properties, particularly the $T_c$ for FePt (001) films with a variety of compositions sputter-deposited on MgO (001) substrates at $T_s = 300^\circ$C, and they are compared to those of ordered and disordered states in bulk alloys.

2. Experimental procedure

Films were prepared on MgO (001) single crystal substrates using an ultrahigh vacuum magnetron sputtering system. Base pressure was below $1\times10^{-8}$ Torr, and high-purity argon ($>99.9999\%$) of 5.0 mTorr was flown during sputtering. An Fe seed layer of 1 nm and an epitaxial Pt buffer layer of 40 nm were first deposited on an MgO substrate at room temperature. Consecutively, Fe and Pt were co-deposited from the separate targets onto the Pt buffer layer at $T_s = 300^\circ$C. The typical growth rate was 0.01 nm/sec. The Fe concentration $x$ (at. %) of FePt phase was changed in the range from 19 to 68, which was determined by electron probe x-ray microanalysis (EPMA). The structural characterization was performed by x-ray diffraction (XRD) with Cu-K$\alpha$ radiation. Magnetic properties were measured by superconducting...
quantum interference device (SQUID) magnetometer and vibrating sample magnetometer (VSM).

3. Results and discussion

Figure 1 shows the magnetization curves for the FePt films with (a) x = 52 and (b) 38, which are representative results reported in Ref. 25. Solid and broken lines denote the magnetization curves with applied field perpendicular and parallel to the film plane, respectively. The easy magnetization axis for x=38 is perpendicular to the film plane, in contrast to the result for x = 52, where the easy magnetization axis is in the film plane. It has been found that the large perpendicular anisotropy is obtained at a Pt-rich off-stoichiometric composition in the case of T_s=300°C. The detail structural analysis has also revealed that all the films have epitaxially grown on an epitaxial Pt (001) buffer layer.

The lattice constants of a- and c-planes, c/a, the degree of long-range order S, saturation magnetization M_s, and uniaxial magnetic anisotropy K_u as a function of x are summarized in Figs. 2 (a), (b), (c), (d), and (e), respectively. Figure 2 (a) indicates that a remains almost constant for 30≤x≤38, and then, it decreases with increasing x. On the other hand, c decreases monotonically for 19≤x≤38, and is constant for 38<x≤62. Consequently, c/a holds a minimum at x=38 as shown in Fig.2 (b). Figure 2 (c) shows S evaluated from the integrated XRD intensities of fundamental and superlattice peaks by numerical fitting. The detail procedure for the evaluation of S was described in Refs. 9 and 19. High S is obtained in a Pt-rich off-stoichiometric region. For x=38, S holds a maximum value of 0.6±0.1. On the other hand, the result around the stoichiometric composition shows poor S. In Fig. 2 (d), M_s tends to decrease slightly with decreasing x from 62 to 30, which is caused by the reduction of Fe concentration. And M_s decreases drastically for x=19, indicating the formation of the FePt_3 phase. The L1_2 ordered FePt_3 phase is antiferromagnetic below 170K and paramagnetic at room temperature, whereas the disordered FePt_3 phase is ferromagnetic at room temperature. It is considered that the film with x=19 includes both ordered and disordered phases, leading to the drastic decrease of magnetization. K_u shown in Fig. 2 (e) was determined from the area

Fig. 2 (a) The lattice constants of a- and c-planes, (b) c/a, (c) the degree of long-range order S, (d) saturation magnetization M_s, and (e) uniaxial magnetic anisotropy K_u for the FePt (001) films as a function of the Fe concentration x.
enclosed between the magnetization curves in magnetic fields parallel and perpendicular to the film plane, with the correction of shape anisotropy energy (-2pM$^2$). The easy magnetization axis is in the film plane for x=52 and $K_u$ shows a quite small value ($6 \times 10^6$ erg/cm$^3$). On the other hand, for x=38, the easy magnetization axis is perpendicular to the film plane, and $K_u$ holds a maximum value of $1.8 \times 10^7$ erg/cm$^3$. It should be noted that S and $K_u$ hold maxima at a Pt-rich off-stoichiometric composition (x=38) for the films deposited on MgO (001) substrates at $T_s = 300°C$.

Figure 3 shows the temperature dependence of magnetization for the FePt films with a variety of compositions ((a) x=62, (b) 52, (c) 45, (d) 38, (e) 34, and (f) 30 at. %). In order to evaluate $T_c$, $M^2$-T plots were performed. The external field applied perpendicular to the film plane was 2 kOe. For $62 \leq x \leq 45$, $T_c$ increases with decreasing x, and a maximum value of $T_c = 375°C$ is obtained for x=45. With further decreasing x, $T_c$ decreases. For x=38, $T_c$ is 320°C.

$T_c$ as a function of x is shown in Fig. 4. For comparison, $T_c$ of bulk ordered and disordered alloys are also denoted by dotted and broken lines, respectively. $T_c$ for x=52 shows the value between bulk ordered and disordered alloys. This is consistent with the XRD result showing poor chemical order. With decreasing x, $T_c$ approaches the value of bulk ordered alloy. $T_c$ for x=38 is almost equal to that of bulk ordered alloy, indicating high chemical order, which is also consistent with the XRD result. Moderately low $T_c$ with keeping large perpendicular magnetic anisotropy in a Pt-rich off-stoichiometric region is promising for TAMR.

4. Summary

We have investigated the structural and magnetic properties in the FePt (001) films with a variety of compositions sputter-deposited on MgO (001) substrates at $T_s = 300°C$. S and $K_u$ hold maxima at the Pt-rich off-stoichiometric composition (x=38). $T_c$ for x=52 is lower than that of bulk ordered alloy. On the other hand, for x=38, $T_c$ is almost equal to that of the fully ordered bulk alloy with the same composition (320°C), and, it is lower than that of the fully ordered bulk alloy with the stoichiometric composition (480°C). The $L_{10}$ ordering with Pt-rich off-stoichiometric compositions may therefore facilitate not only the low temperature fabrication of FePt ordered films but also thermally assisted magnetic recording, leading to the realization of ultra-high density magnetic recording.

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