Proc. Schl. Eng. Tokai Univ., Ser. E
33 (2008) 25-28

Magnetostrictive characteristics of Fe-Al films formed at non equilibrium condition

by

Sho Nakamura[*1], Masahide Morita[*1], Kiyoshi Shinobe[*1] and Yoshihito Matsumura[*2]

(Received on Mar. 31, 2008 and accepted on Jul. 9, 2008)

Abstract

Magnetostrictive characteristics of Fe-Al alloy thin films formed by an ion plating process were evaluated. It was found that the Fe-40at%Al film had b.c.c structure although the Al content went over solubility limit. Note here that the solubility limit of Al into solid Fe is about 20 at%Al in equilibrium condition. This may be caused by non-equilibrium condition as shown in plasma-solid quenching peculiar to the IP. Fe-40at%Al alloy thin films prepared by ion plating showed higher magnetostriction than pure Fe.

Keywords: iron, aluminum, thin film, ion plating, magnetostriction

1. Introduction

Giant magnetostrictive materials (GMM) such as $TbFe_2$, $DyFe_2$, and $(Tb,Dy)Fe_2$ have been investigated as potential materials for actuator and sensor [1,2,3)]. Huge magnetostriction is usually found in rare-earth transition metal compounds, whereas most of magnetic transition metals and alloys show weakmagneto-elastic effects. Thin film processes have many advantages to apply as devices for micro-machin-es, opto-magnetic systems and surface acoustic wave filters. Since 1990 we have been studied systematically various preparation processes of giant magnetostrictive $(Tb, Dy)Fe_2$ thin films, and significant effect of the processes on microstructural, magnetic and magnetostrictive properties [4-8)]. Recently, Clark et al. have reported that a Fe-17at%Ga alloy single crystal shows magnetostriction of about 300 ppm at 16 kA/m [9,10)]. This is caused by enlargement of lattice parameter related to substitution of Ga into Fe(bcc) lattice. The Fe-Ga alloy will be promising as sensor and actuator in the future. However, Ga is uneasy element to use for vacuum evaporation or sputtering, because of its low melting point (~303 K) and high vapor pressure. On the other hand, Al is more suitable for vacuum evaporation or sputtering processes and inexpensive for them. Moreover, Al also placed in IIIB group and has larger atomic radius than Fe. Fe-Al thin films are corrosive-resistant materials compared with GMM. In this study, Fe-Al thin films were prepared by an ion plating process and discussed their crystal structure, magnetization and magneto strictive characteristics.

2. Experimental

2.1 Ion plating system

Figure 1 shows the schematic diagram of the ion plating (IP) system. An IP system was used for the film preparation.

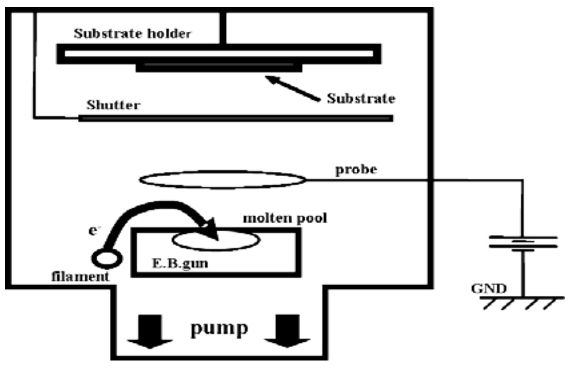

Fig. 1. Schematic diagram of IP system.

*1 Graduate Student, Course of Applied Science,
*2 Professor, Department of Energy Engineering,

This process produces variety of film character. Because dense plasma flux(~2.5A) of ionized source materials can be dosed and deposited on a substrate. In this Bunshah triode type ion plating system, the flux of the source vapor is ionized by thermal electrons accelerated from melted evaporant to a positive electrode so called "probe".

2.2 Film preparation

Bulk Fe-Al alloy samples for evaporant source materials were prepared by arc melting (the purity of each element was 99.9 %) in an Ar gas atmosphere. Composition of the film samples was dependent on the evaporant composition. Table 1 shows a deposition condition of the film formed by IP process. A substrate temperature was measured with thermocouple contacted rear side of the substrate. The substrate temperature was kept constant about definite temperature.

Table 1. Condition of the Film Formation by IP Process

Base pressure	≦ 5.0 x 10^{-4} Pa
Leak rate	≦ 1.0 x 10^{-7} Pa·m^3/sec
Substrate temperature	523 K
Electron beam power	110~120 m A x 10kV
Anode potential	50 V
Substrate	Si（100）
Source - substrate distance	20 cm
Deposition time	300 sec

The composition of the film samples was determined by using energy dispersive X-ray spectroscopy (EDX). The film structures were analyzed by X-ray diffraction (XRD) (Cu-K α). The surface observations of the film samples were used by scanning electron microscope (SEM). The in-plane magnetostriction of the films was measured by using a cantilever method described elsewhere [11]. The equation of the magneto striction is as follows

$$\Delta\lambda_{//} = D\cdot t_s^2 E_s(1+\nu_f)/3t_f l^2 E_f(1-\nu_s)$$

Here, l is a distance from clamp to free edge, D is a curvature of the film sample, subscript s and f represent substrate and film, t is thickness, E is Young's modulus and ν is Poisson's ratio (E_f and ν_f was assumed E_f = 211 GPa, ν_f= 0.29 in and E_s = 130 GPa, ν_s = 0.28 in Si(100)).

3. Results and discussion

3.1 Structure of Fe-Al films

Figure 2 shows X-ray diffraction patterns of the film samples for Fe, Fe-17 at%Al, Fe-40 at%Al and Fe-60 at%Al prepared by IP process. It was found that the Fe-0 to 40 at%Al film had b.c.c structure although the Al content went over solubility limit. Note here that the solubility limit of Al into solid Fe is about 20 at%Al in equilibrium condition [12]. This may be caused by non-equilibrium condition as shown in plasma-solid quenching peculiar to the IP. Excess energy value accumulated inside of thin films by plasma-solid quenching was 0.3eV. Since applied voltage 50V of anode potential is bigger than excess energy, enough energy has been given to metal particles [13]. Diffraction peaks of films corresponding to lattice parameter shifted lower side of diffraction angle with increasing Al content. FeAl phase peaks were observed for Fe-Al films over 60 at%Al. Figure 3 shows lattice parameter of Fe-Al films as a function of aluminum content.
Aluminum lattice parameter increased with increasing content. This result was caused by substitution of Al into Fe (bcc) lattice. Because Al atomic radius is larger than Fe atomic radius. These samples are guessed that Al is random substitution into Fe lattice because increasing lattice parameter was lined up on Vegard's law line.

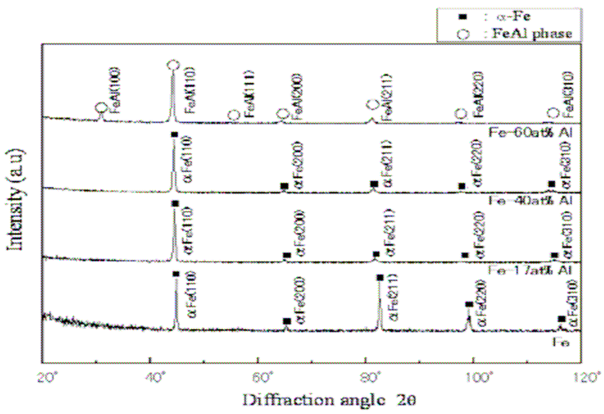

Fig.2. X-ray diffraction patterns of film samples prepared by IP process.

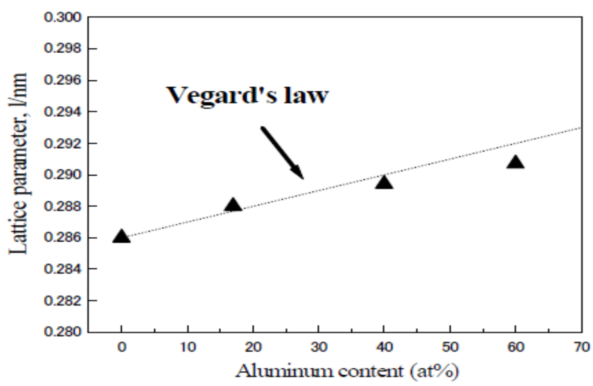

Fig.3. Lattice parameter of Fe-Al films as a function of aluminum content.

3.2 Magnetic and Magnetostrictive properties

Figure 4 shows magnetization curves of film prepared by IP process. Fe and Fe-17 at%Al showed comparable saturation magnetization with direction of in-plane and perpendicular. Compared with Fe film, the change to saturation magnetization with in-plane and perpendicular was not seen at Fe-17at% Al film. By Fe-40 at%Al film, saturation magnetization was decreased comparing with Fe film, and the direction of in-plane and perpendicular hardly showed magnetization at Fe-60 at%Al film.

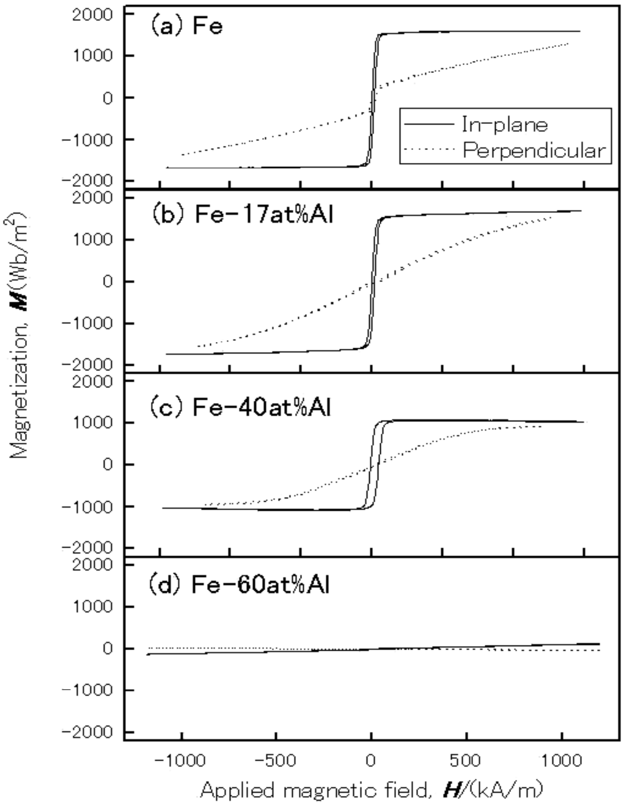

Fig.4 Magnetization curves of film prepared by IP process. (a)Fe, (b)Fe-17 at% Al, (c)Fe-40 at% Al, (d)Fe-60 at% Al

Figure 5 shows a dependence of the Al content to magnetostriction. Maximum value of magnetostriction at 15kA/m was 150 ppm in the Fe-40 at%Al. The film samples showed higher magnetostrictive susceptibility and larger magnetostriction at low magnetic fields in comparison with pure Fe film. The magnetostriction increased with increasing aluminum content. Fe-60 at%Al film showed almost non magnetostriction.

Increasing Aluminum content tended to increase magnetostriction. This result was caused by lattice instability due to increasing lattice parameter [9)10)14)]. Fe-60at%Alfilm showed almost non magnetostriction.This result is considered the probable caused by changing α-Fe phase to paramagnetic Fe-Al phase.

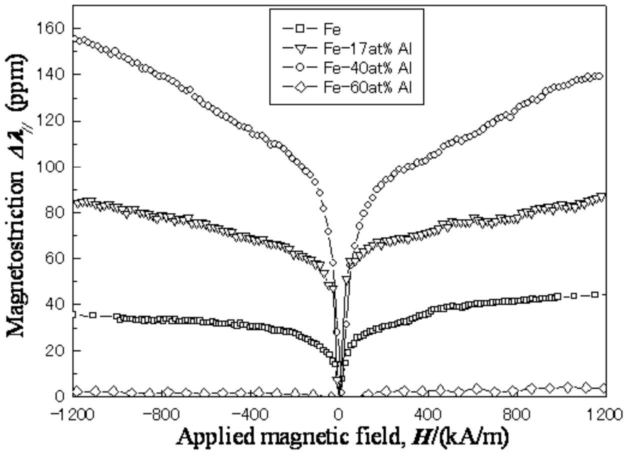

Fig.5 Magnetostriction of film samples prepared by IP process.

4. Conclusion

In this study, Fe-Al thin films were prepared by an ion plating process and discussed with their crystal structure and magnetostrictive characteristics. It was found that Fe-40at% Al film had b.c.c structure although the Al content went over solubility limit. Increasing Aluminum content tended to increase magnetostriction. This result was caused by lattice instability due to increasing lattice parameter. These samples formed in this study indicated its toughness and anti-corrosion to be superior to rare-earth transition metal compounds.

5. Acknowledgements

This study was financially supported by the Japan Society for the Promotion of Science (JSPS) for Grant in Aid for Scientific Research (C) as for "Design of Magnetostrictive Susceptibility on Thin Film" with No.19560709. And this study was made in the frame of Development of Advanced Production processes for Energy Conversion Materials, Future Science & Technology Joint Research Center, Tokai University.

References

1) *A. E. Clark*: Ferromagnetic Materials, 1,(1980), 7.

2) *H. Wakiwaka and Y. Yamada*: J. Magn. Soc. Jpn. 25, 8, (2001), 1425.

3) *V. Koeninger, Y. Matsumura, T. Noguchi, H.H. Uchida, H. Uchida, H.Funakura, H. Kaneko and T. Kuroki*: International symposium on giant magnetostrictive materials and their applications.,(1992), 151.

4) *A. Kadowaki, M. Takeuchi, Y. Matsumura and Y.Nisi:* Journal of the Japan Institute of Metals, 68,(2004), 2.

5) *V. Koeninger, Y. Matsumura, H. Uchida, H.HUchida, H. Funakura, H. Kaneko and T. Kurino* J Adv Sci., 5, (1993), 1.

6) *M. Wada, H. Uchida, Y. Matsumura, H.kaneko and H.H.Uchida*: Symposium on Electromagnetic and Dynamics., (1996), 8.
7) *H. Uchida et al.* J. Alloy & comp, 211/212. 576-580(1994)
8) *M. Wada et al.* J. Alloy & comp, 258.143-148(1997)
9) *Clark.A.E*: IEEE Trans Magn., 36, 5, (2000), 3238.
10) *T A Lograsso, A R Ross, D L Schlagel, A E Clark and M Wun-Fogle*: J Alloy Compd., 350, (2003), 95.
11) *A C Tam and H Schroeder*: IEEE Trans.Magn., 25, (1989), 2629.
12) *J.R.Davis*: ASM Specialty Handbook Aluminum and Aluminum Alloys., ASM International The Materials Information Society, (1993), 547.
13) A. A. Novakova, O. V. Agladze, S. V. Sveshnikov and B. P. Tarasov, NanoStractured Mat. 10, 3, (1998), 365-374.
14) *D. A. Eelman, J. R. Dahn, G. R. Mackay and R. A. Dunlap*: J Alloy Compd., 266, (1998), 234.