High performance energy conversion of Fe-Pd thin film

Hiromasa YABE, Kazuya OGURI, Haru-Hisa UCHIDA, Yoshihito MATSUMURA, Hirohisa UCHIDA and Yoshitake NISHI

TOKAI University, 1117 Kitakaname, Hiratsuka, Kanagawa, 259-1292 Japan

TEL: +81-463-58-1211 (ex.4206) FAX: +81-463-58-1812

e-mail: am026429@keyaki.cc.u-tokai.ac.jp

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Fe-Pd alloy thin film prepared by DC magnetron sputtering process shows high performance energy conversion on giant magnetostriction. Fe-Pd thin film has strain changes induced by thermal shape memory effect (TSME) and giant magnetostriction at room temperature. Magnetostriction of 200 ppm at 1 kOe was equal to the strain induced by TSME for 4 K from 303 K to 307 K.

Keywords : Fe-Pd, energy conversion, giant magnetostriction

I. INTRODUCTION

Fe-Pd alloy thin films prepared by DC magnetron sputtering process show large magnetostriction and high magnetostrictive susceptibility at low magnetic field from earth magnetic field to 0.2 kOe at room temperature. The maximum magnetostriction (λ_H) was about 200 ppm and the maximum magnetostrictive susceptibility ($\partial \lambda_H / \partial H$) was 0.9 ppm/Oe at 0.08 kOe. It was the highest value for thin films developed up to 2001. Fe-Pd thin film shows giant magnetostriction at room temperature and strain change of thermal shape memory effect (TSME) against temperature.¹ Therefore, we have started the study of high performance energy conversion of Fe-Pd thin films.

II. EXPERIMENTAL

To get the high magnetostrictive susceptibility, a DC magnetron sputtering was performed to form the film of the fine columnar texture of Fe-45at%Pd eutectoid alloy.²⁻³ Controlling the amount of Pd on the Fe target changed the chemical composition. The samples were deposited about 2 μm in thickness on silicon single crystal wafer of (100) plane. Leak rate was $5.0 \times 10^{-7} \text{ Pa} \cdot \text{m}^3/\text{s}$ under $3.9 \times 10^{-5} \text{ Pa}$ total gas pressure. The sputtering was performed under $6.0 \times 10^{-2} \text{ Pa}$ of Ar gas partial pressure with 200 W of sputtering power and 3600 s of sputtering time. The film composition was analyzed by energy disperse X-ray spectroscopy (EDS; JSM-6301F, JEOL) and electron probe microanalysis (EPMA; EPMA-8705, SHIMAZU). The contaminant concentrations were measured by auger electron spectroscopy (AES;

PHI-155-15, ALVAC PHI inc.). The film crystal structure was analyzed by X-ray diffraction (XRD; X'Pert-MRD, PHILIPS) and by transmission electron microscope (TEM; H-9000 NAR, HITACHI). The magnetic property was measured by a vibration sample magnetometer (VSM; Model BHV-55, RIKEN). The film texture was observed by means of field emission scanning electron microscopy (FE-SEM; JEM-6000 series WDS/EDS system, JEOL). The magnetostriction (λ_H) of film was measured by a bending method generally used for bi-metal and was estimated by a following equation.^{4,5}

$$\lambda_H = d \cdot t_s^2 \cdot E_s (1 + \nu_s) / [3 t_f \cdot \ell^2 \cdot E_f (1 + \nu_f)] \quad (1).$$

Here t_s and t_f were the thickness of silicon substrate and Fe-45at%Pd film, respectively. ν_s and ν_f were the Poisson's ratio of silicon substrate and film. d was bending distance of the sample (Fig. 1). ℓ is the distance of clamp and spot of laser on film. E_s and E_f were Young's modulus of silicon substrate and Fe-45at%Pd film, respectively. The Young's modulus was measured by a nano-indenter method (nano-indenter; ENT-1100a, ERIONIX). The tensile loading stress dependence of magnetostriction on Fe-45at%Pd was measured by following method (Fig. 1).

The tensile stress of sample was calculated by following equation.

Fig. 1. Schematic diagram of the measurement system.

$$\sigma_{s+f} = (P_w + P_s) / A_{s+f} \quad (2),$$

$$\sigma_f = (P_w + P_s) / A_f \quad (3).$$

Here σ_{s+f} was the tensile stress of sample overall, P_w was the load by weight, P_s was the load by sample and A_{s+f} was the cross sectional area of sample (film area + substrate area), respectively. σ_f was the tensile stress of sample nominal and A_f was the cross sectional area of film.

III. RESULTS AND DISCUSSIONS

Stress dependence of magnetostriction

Figure 2 shows relationship between the applied magnetic field and the magnetostriction $\lambda_{//}$ of Fe-45at%Pd film. Solid and broken lines denote for unloaded and loaded samples magnetostriction, respectively. With the loading stress getting large, the magnetostriction decreased.

Figure 3 shows relationship between tensile stress and maximum magnetostriction $\lambda_{//max}$ of Fe-45at%Pd thin film. The larger the overall loading stress (σ_{s+f}), the smaller the $\lambda_{//max}$ becomes rapidly above loading stress 23 kPa. The larger the nominal loading stress (σ_f), the smaller the $\lambda_{//max}$ becomes rapidly, above loading stress 3.5 MPa. We concluded that the large magnetostriction could be obtained above the critical point of loaded stress.

Fig. 2. Change in magnetostriction $\lambda_{//}$ against applied magnetic field $H_{//}$ of unloaded and loaded Fe-45at%Pd film. Tensile stress (σ_{s+f}) was 659 kPa.

Fig. 3. Change in maximum magnetostriction $\lambda_{//max}$ against loading stress σ of Fe-45at%Pd thin film.

Thermal shape memory effect of Fe-45at%Pd film

Figure 4 shows relationship between temperature and strain of Fe-45at%Pd thin film. The broken line denotes the thermal shape memory effect (TSME) and solid line denotes the giant magnetostriction (GM). The higher the temperature, the larger the strain induced by thermal shape memory effect of Fe-45at%Pd thin film.

Magnetostriction of 200 ppm at 1 kOe was equal

to the strain induced by TSME for 4 K from 303 K to 307 K.

Fig. 4. Change in strain of thermal shape memory effect (TSME) against temperature, and giant magnetostriction (GM) at room temperature of Fe-45at%Pd film.

IV. CONCLUSION

Fe-Pd alloy thin film prepared by DC magnetron sputtering process shows the high performance energy conversion on giant magnetostriction. The high responsiveness magnetostriction induced from earth magnetic field to 1 kOe. Magnetostriction of 200 ppm at 1 kOe was equal to the strain induced by TSME for 4 K from 303 K to 307 K.

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