Influences of Process Condition of Magnetron Sputtering on Magnetostrictive Susceptibility of Fe$_{2,2}$Sm Alloy Film*1

Yoshitake Nishi$^{1,2}$, Yoshito Matsumura$^1$ and Keisuke Takahashi$^{2,*2}

$^1$Unified Graduate School of Science & Engineering, Tokai University, Hiratsuka 259-1292, Japan
$^2$Department of Metallurgical Engineering, Graduate School of Engineering, Tokai University, Hiratsuka 259-1292, Japan

Since morphological interface of iron-samarium alloy thin film prepared by direct current magnetron sputtering process is controlled by substrate temperature, sputtering argon gas pressure and residual gas pressure, influences of changes of morphology and its interface on compressive (negative) magnetostrictive susceptibility of Fe$_{2,2}$Sm alloy films are investigated. Decreasing the pressures of sputtering argon gas enhances the magnetostrictive susceptibility. The high susceptibility is also found under the low pressures of residual (impurity) gas at each substrate temperatures ($T_s$) from 423 to 523 K. The clear interface cannot be observed in the densely packed amorphous phase, when the high magnetostrictive susceptibility is obtained. Since the decreasing in impurity atoms at the unclear interface easily changes the domain direction and then doesn’t prevent to move the magnetic domain wall in the amorphous phase, influences of the residual gas pressure on magnetostrictive susceptibility are explained by not only morphological interface but also its oxidation. [doi:10.2320/matertrans.47.2852]

(Received March 20, 2006; Accepted September 4, 2006; Published November 15, 2006)

Keywords: susceptibility, compressive magnetostriction, film, direct current magnetron sputtering, samarium-iron, residual gas

1. Introduction

The RFe$_2$ type cubic Laves phases of rare earth metals (R) and iron (Fe) show giant magnetostriction, as expected to apply for sensor and actuator. The giant mover strain of Terfenol-D ($\text{Tb}_2\text{Dy}_2\text{Fe}_2$), which is larger than that of commercial piezo-ceramics such as PZT, has been found with low electronic potential driving, high power generation, high responsiveness and wireless operation by magnetic field. In order to apply tiny acoustic devices, sensors and actuators driven by low intensity of magnetic field, giant magnetostrictive films have been expected. The expansive and compressive magnetostriction values have been obtained for Fe-Tb and Fe-Sm films, respectively.

Since the substrate temperature and sputtering pressure of direct current (DC-) magnetron sputtering process are important factors to control the morphology of thin film, they may affect the magnetostrictive susceptibility. In addition, the residual gas pressure, which may easily controls the interface atomic structure of morphology, should be also one of basic factors to affect the susceptibility. To apply wireless acoustic sensor and tiny actuator with high responsiveness driven by low intensity of magnetic field and low electrical potential, influences of sputtering gas pressure, substrate temperature, residual gas pressure and their combinations of morphology on magnetostrictive susceptibility of Fe$_{2,2}$Sm alloys prepared by DC-magnetron sputtering process have been investigated.

2. Experimental Procedure

A unimorph structural mover device was driven by giant compressive magnetostrictive Fe$_{2,2}$Sm alloy film deposited on a (100) plane of silicon wafer. When an applied magnetic field loaded the magnetostrictive thin film, a bending movement was obtained.

The Fe$_{2,2}$Sm alloy thin film was prepared by using DC-magnetron sputtering apparatus. The minimum vacuum pressure before sputtering and the sputtering pressure of argon gas ($P_{\text{Ar}}$) were 5.0 $\times$ 10$^{-4}$ Pa and 0.5 Pa, respectively. The mean leak rate of the chamber was about 1.64 $\times$ 10$^{-5}$ Pa$\cdot$m$^3$/s.

The residual gas pressure, sputtering pressure of argon gas and substrate temperature were varied from 2.0 $\times$ 10$^{-5}$ to 5.0 $\times$ 10$^{-2}$ Pa, from 0.2 to 1.0 Pa and from 323 to 623 K, respectively. To evaluate the sputtering conditions in the present work, quantitatively, the standard sample was prepared under 0.5 Pa of argon sputtering pressure with 5.0 $\times$ 10$^{-2}$ Pa of residual gas pressure at 323 K of substrate temperature.

The sputtering power, deposition time, sputtering distance between target and (100) plane substrate of single silicon crystal were 200 W, 3.6 ks and 90 nm, respectively.

The enhancement of substrate temperature just after sputtering was about 30 K. The film composition was controlled by sheet area ratio of samarium (99.9%) and iron (99.9%) on the Fe-35.0 at%Sm (Fe$_{1,9}$Sm) alloy plate. Coupling samarium and iron tips on the Fe-35.0 at%Sm plate with diameter of 75 and 1 mm thick assembled a sputtering target for formation of the Fe$_{2,2}$Sm film.

The atomic ratio of Fe-Sm film was varied with increasing the Ar gas pressure from 0.2 to 1 Pa. Mean thickness of the Fe-Sm films deposited was about 2 $\mu$m.

The film composition was analyzed by Energy dispersive X-ray spectroscopy (EDS). The iron and samarium elements in the sample were homogeneously distributed. The film thickness was measured by using a cross sectional image of scanning electron microscope (SEM). Crystalline structures of the prepared film were determined by $\alpha$-20 method of thin film X-ray diffraction (Cu-Kr; X'Part-MRD, PHILIPS), where irradiation angle to sample plane was 1.5 deg.

The magnetostriction ($\Delta \lambda$) of film was measured by a

---

*1This Paper was Originally Published in J. Japan Inst. Metals 69 (2005) 671–675.
*2Graduate Student, Tokai University
bending cantilever method using a He-Ne LASER under magnetic fields from −1200 to 1200 kA/m and was estimated by a following equation,8–10

\[ A_1 = d \cdot t_s^2 \cdot E_s (1 + v_s) / 3t_l \cdot \bar{E}_f (1 - v_f). \]  

(1)

Here, \( t_s \) and \( t_l \) were the thickness values of silicon substrate and \( \text{Fe}_2\text{Sm} \) films, respectively. \( d \) and \( l \) were the bending displacement of the sample and distance of clamp and spot of LASER on film, respectively. The \( E_s \) and \( E_f \) values, the Young’s modulus of silicon substrate and \( \text{Fe}_2\text{Sm} \) film, were assumed to be 130 GPa14 and 40 GPa.14

3. Results

3.1 Influences of residual gas pressure, substrate temperature and sputtering gas pressure on sample structure

The residual gas pressure, which depends on the partial pressure of water gas,6 is one of basic factors to prepare films. Figure 1 shows X-ray diffraction patterns of \( \text{Fe}_2\text{Sm} \) film prepared at 323 K of substrate temperature under 0.5 Pa of sputtering argon gas pressure. Figure 1 shows the residual gas pressure, which depends on the partial pressure of water gas,6 is one of basic factors to prepare films, together with standard X-ray references of ICDD cards and patterns at different substrate temperatures under each sputtering pressure.

A preferred oriented remarkable crystalline peak of samarium oxide (Sm\(_2\)O\(_3\)) and/or samarium alloy at 28.5° is observed in \( \text{Fe}_2\text{Sm} \) alloy films under each residual gas pressure from \( 5 \times 10^{-2} \) to \( 2 \times 10^{-5} \) Pa at each substrate temperature \( (T_s) \) from 323 to 623 K. On the other hand, the residual (impurity) gas is mainly composed with the water gas molecules.6 Since excess \( P_r \) value enhances the formation rate of film, it prevents to grow up the preferred oriented oxide crystalline. As a result, excess \( P_r \) value forms the hydroxide, as well as oxide. Thus, the broad peak is found of the sample prepared at 1.0 Pa of \( P_r \) (see Fig. 1). Since the volume fraction of samarium oxidation mainly depends on the base (residual gas) pressure, the formations of samarium oxide (Sm\(_2\)O\(_3\)) crystalline and amorphous hydroxide are explained.

The remarkable peak is not observed in the sample prepared under the lowest residual gas pressure of \( 2.0 \times 10^{-5} \) Pa and sputtering gas pressure \( (P_r) \) of 0.5 Pa at 323 K of \( T_s \), under the lowest sputtering gas pressure of 0.2 Pa and residual gas pressure \( (P_r) \) of \( 5.0 \times 10^{-4} \) Pa at 323 K of \( T_s \), and at 523 K of \( T_s \) under \( 5.0 \times 10^{-4} \) Pa of \( P_r \) and 0.5 Pa of \( P_r \), as shown in Fig. 1. Although discontinuous X-ray profile with tiny peaks can be observed, crystalline phases of \( \text{Fe}_2\text{Sm} \) and \( \text{Fe}_3\text{Sm} \) are not remarkably observed in \( \text{Fe}_2\text{Sm} \) alloy films. Since an amorphous phase, a glassy structure with and without nano-crystalline, is formed under the lowest \( P_r \) value of \( 2.0 \times 10^{-5} \) Pa and the standard \( P_r \) value of 0.5 Pa at 323 K of \( T_s \), under the lowest \( P_r \) value of 0.2 Pa and the standard \( P_r \) value of \( 5.0 \times 10^{-4} \) Pa at 323 K of \( T_s \), and under \( 5.0 \times 10^{-4} \) Pa of the standard \( P_r \) value and 0.5 Pa of the standard \( P_r \) value at 523 K of \( T_s \), the broad profiles from 30 to 50° of X-ray diffraction are obtained in \( \text{Fe}_2\text{Sm} \) alloy thin film (see Fig. 1). X-ray diffraction crystalline peaks are not remarkably detected in the amorphous phase. When crystal
anisotropy and grain boundary prevent to move the domain wall, the magnetostrictive susceptibility of the amorphous phase is probably higher than that of crystalline phase. Since a single phase of amorphous structure is remarkably found in Fe$_2$Sm alloy films, no barrier prevents to move the domain wall. Therefore, the high magnetostrictive susceptibility is expected for the isotropic ferromagnetic Fe$_2$Sm alloy.

3.2 Influences of substrate temperature, sputtering gas pressure and residual gas pressure, on magnetostriction

Figure 2 shows applied magnetic field dependent magnetostriction ($\lambda$) at each magnetic field ($H$) of Fe$_2$Sm alloy film prepared at different substrate temperatures under each sputtering pressure and standard residual pressure ($P_r = 5 \times 10^{-4}$ Pa). Here, the standard residual pressure is conventionally achieved by three days evacuation in our magnetron sputtering process. The largest value of compressive magnetostriction is obtained at 573 K of substrate temperatures ($T_s$) from 0.2 to 1.0 Pa at elevated reduced substrate temperatures ($T_s/T_m$) from 0.2 to 0.4, where $T_s$ and $T_m$ are substrate temperature and liquidus, respectively.

The porous tapered grain of Zone I, generated at low substrate temperature, is observed in SEM micrograph of Fe-Sm film. Since increasing $P_s$ and $P_r$ decreases the kinetic energy of sputtering particles on collision, the short mean free pass of samarium and iron atoms on depositing surface probably explains the porous grain. In addition, active residual gas atoms often form the molecules of oxide and nitride. Both phenomena prevent to migrate the samarium and iron atoms on depositing surface, resulting in the porous grains in Zone I.

To evaluate influences of the residual pressure on magnetostriction, the limited residual pressure ($P_r = 2 \times 10^{-5}$ Pa) is often achieved by two weeks evacuation in our magnetron sputtering process. Figure 3 shows applied magnetic field dependent magnetostriction ($\lambda$) at every magnetic field ($H$) of Fe$_2$Sm alloy film prepared under each residual gas pressure from $2.0 \times 10^{-5}$ to $5.0 \times 10^{-2}$ Pa.

Applied magnetic field magnetizes the Fe$_2$Sm alloy film and also generates the compressive magnetostriction ($\lambda$). Increasing magnetic field decreases the magnetostriction. Decreasing residual gas pressure enhances the $\lambda$ value at each magnetic field. The largest value of compressive magnetostriction is 1200 ppm under the lowest residual gas pressure of $2.0 \times 10^{-5}$ Pa.

4. Discussion

4.1 Morphological discussion

To clarify the morphological discussion, SEM micrograph is observed in Fig. 4, together with schematic diagram of Zone I, Zone T and Zone II of Thornton model.$^{15}$ Porous tapered grains separated by voids in Zone I, densely packed fibrous grain in Zone T and columnar grains in Zone II have been explained by the Thornton model.$^{15}$ SmFe$_2$ alloy thin films have been prepared by DC-magnetron sputtering process under different sputtering argon gas pressures from 0.2 to 1.0 Pa at elevated reduced substrate temperatures ($T_s/T_m$) from 0.2 to 0.4, where $T_s$ and $T_m$ are substrate temperature and liquidus, respectively.

Columnar grain with remarkable interface is found in Zone II ($P_s = 0.5$ Pa, $T_s/T_m = 0.4$) of Thornton model in Fig. 4. Since decreasing $P_s$ increases the kinetic energy of sputtering particles on collision, the long mean free pass of samarium and iron atoms on depositing surface probably corresponds to the formation of the large size columnar grains in Zone II.

On the other hand, the amorphous phase of fine densely packed fibrous grain observed in Zone T of Thornton’s Model (see Fig. 4) is found under the sputtering gas pressure from 0.2 to 1.0 Pa at different reduced substrate temperatures.
(\(T_s/T_m\)) from 0.30 to 0.37 at the standard base (residual gas) pressure of \(5.0 \times 10^{-4}\) Pa. When the residual and argon gas don’t impact to sputtering particles under their low pressures, the collision factor is not so large to decrease the kinetic energy of sputtering atoms. Namely, the low pressures of argon and residual gas don’t largely decrease the kinetic energy of sputtering particles. Thus, it enhances the mean free pass of the particles, which migrate from landing on the sample surface to meta-stable site of amorphous structure. The atom migration with long mean free pass fills into the meta-stable site of amorphous structure. In addition, amorphous phase is formed by rapidly depositing rate of DC-magnetron sputtering process, because the subsequent deposited particles rapidly deposit. Its rapid deposition prevents that the sputtering particles migrate the stable sites of the potential curve to form the crystalline. Namely, the densely amorphous formation is explained by the rapid deposition rate as well as the long mean free pass.

Based on the results of Fe-Sm film sample prepared under 0.5 Pa of sputtering argon gas pressure, the morphological boundary between Zone T and Zone II is found at about 0.4 of \(T_s/T_m\), whereas the morphological boundary between Zone I and Zone T is found at 0.3 of \(T_s/T_m\). These results correspond to the Thornton morphological model.\(^{15}\)

When the decreasing argon gas pressure decreases the kinetic energy of sputtering particles because of low probability of collisions between sputtering particles and argon gas, the fine densely packed fibrous grain can be obtained. Namely, we suggest that the \(P_s\) decreasing decreases the \(T_s/T_m\) value at the morphological boundary between Zone I and Zone T.

### 4.2 Sputtering gas pressure dependent \([d\lambda/dH]\)

To discuss the physical meaning, precisely, the magnetostrictive susceptibility \([d\lambda/dH]\) is defined as the slope of \(\lambda-H\) curve at each \(H\) value in Fig. 2. Figure 5 shows applied magnetic field dependent magnetostrictive susceptibility \([d\lambda/dH]\) of \(\text{Fe}_2\text{Sm}\) alloy film prepared under each sputtering gas pressure \((P_s)\) from 0.2 to 1.0 Pa under \(5.0 \times 10^{-4}\) Pa of \(P_r\) value at 323 K of \(T_s\). The magnetization decreases the \([d\lambda/dH]\) value. The increase in \(P_r\) value also decreases the \([d\lambda/dH]\) value at each magnetic field.

Figure 6 shows compressive magnetostrictive susceptibility \([d\lambda/dH]_{0.1}\) at 0.1 MA/m against sputtering argon gas pressure \((P_s)\) for \(\text{Fe}_2\text{Sm}\) alloy film. The decrease in sputtering gas pressure \((P_s)\) increases the \([d\lambda/dH]_{0.1}\) value and also decreases the experimental errors of \([d\lambda/dH]_{0.1}\) values.

When the substrate temperature and residual gas pressure are constants, a linear relationship between logarithmic

\[\log_{10}(T_s/T_m) = -0.15 + 0.15 \cdot \log_{10}(P_s)\]
Fig. 5 Applied magnetic field dependent magnetostrictive susceptibility of Fe$_{2.2}$Sm alloy film prepared under each sputtering gas pressure from 0.2 to 1.0 Pa at 5.0 × 10$^{-4}$ Pa of standard residual gas pressure at 323 K of substrate temperature.

Fig. 6 Magnetostrictive susceptibility at 0.1 MA/m $|d\lambda/dH|_{0.1}$ against sputtering argon gas pressure ($P_s$) for Fe$_{2.2}$Sm alloy film.

sputtering argon gas pressure ($\log (P_s/\text{Pa})$) and logarithmic magnetostrictive susceptibility ($\log |d\lambda/dH|_{0.1}/10^{-9} \text{ m/A} \cdot \text{m}^{-1}$) is expressed by the following equation.

$$\log |d\lambda/dH|_{0.1}/10^{-9} \text{ m/A} \cdot \text{m}^{-1} = -0.44\log (P_s/\text{Pa}) + 0.35 \quad (2)$$

A magnetostrictive susceptibility at 0.1 MA/m of magnetic field of Fe$_{2.2}$Sm alloy film increases with decreasing in an argon gas pressure as sputtering gas. The mainly affected impurity is the water molecules rather than the oxygen molecules in the sputtering gas. Adsorbed water molecules at inner surface of vacuum chamber mainly convert to the water gas. In order to decrease the sputtering pressure ($P_s$) of our magnetron sputtering apparatus, opening the exhausted gas valve to evacuate enhances the conductance of argon gas flow. Since the increasing the exhausting rate of gas decreases not only the sputtering pressure ($P_s$), but also the partial pressure of water gas because of the constant generating rate of water gas from adsorbed water molecules on inner surface of vacuum system. To obtain the high magnetostrictive susceptibility in our sputtering apparatus, the sample should be prepared at the lowest value of argon gas pressure of 0.2 Pa.

When the space distance between target and substrate is about 90 nm, the decreasing $P_s$ decreases the volume fractions of crystal samarium alloy and oxide and then decreases the collision probability of sputtering particles to argon gas atom. As a result, decreasing $P_s$ doesn’t prevent to deposit. Namely, the deposition rate becomes high, because decreasing $P_s$ does not largely induce the particle scattering.

Since the residual gas pressure ($P_r$) is also strongly related to the partial pressure of water gas generated from adsorbed water molecules in vacuum system, the formation of samarium oxide crystalline is not easily formed under the low $P_r$ value. In addition, the decreasing $P_r$ is not easy to form samarium alloy crystalline from amorphous phase, although the oxides act as a catalyze to form the crystalline with low $|d\lambda/dH|$ value. Namely, when the volume fraction of amorphous phase with high $|d\lambda/dH|$ value is high, the magnetostrictive susceptibility of Fe-Sm alloy film becomes high.

In addition to the absorptions of water and oxygen molecules at morphological interface and solid solution of oxygen atom, oxidation occurs at surface and/or morphological interface. Oxygen atoms generally act as obstacles of domain wall at morphological interface, resulting in the low $|d\lambda/dH|$ value. When oxygen atoms don’t act as domain wall obstacles, the $|d\lambda/dH|$ value probably becomes high.

The experimental error probably depends on the oxidation volume and its sites at morphological interface. When they can be controlled at low $P_r$ value, the small experimental error is also found (see Fig. 6). Namely, the high magnetostrictive susceptibility with small experimental error is obtained at the low $P_r$ value (0.2 Pa).

4.3 Residual gas pressure dependent $|d\lambda/dH|$ The residual gas pressure, which mainly depends on the partial pressure of water gas and easily controls the interface atomic structure, is one of basic factors to determine the magnetostrictive susceptibility ($|d\lambda/dH|$). Figure 7 shows the magnetic field dependent $|d\lambda/dH|$ value under each residual gas pressure for Fe$_{2.2}$Sm alloy film. The magnetization from 0.1 to 1.2 MA/m decreases the $|d\lambda/dH|$ value under each residual gas pressure. Although increase in residual gas pressure also decreases the $|d\lambda/dH|$ value at each magnetic field, decreasing residual gas pressure from 5 × 10$^{-4}$ to 2 × 10$^{-5}$ Pa enhances the compressive magnetostrictive susceptibility at each magnetic field from 0.02 to 0.15 MA/m.

Figure 8 shows the magnetostrictive susceptibility ($|d\lambda/dH|_{0.1}$) at 0.1 MA/m against residual gas pressure for Fe$_{2.2}$Sm alloy film. Decreasing residual gas pressure enhances the compressive magnetostrictive susceptibility at each magnetic field. When the substrate temperature and sputtering gas pressure are constants, a linear relationship between
Influences of Process Condition of Magnetron Sputtering on Magnetostrictive Susceptibility of Fe$_2$Sm Alloy Film

The high magnetostrictive susceptibility values are obtained for Fe$_2$Sm thin films heated from 474 to 523 K of substrate temperature.

Figure 10 shows magnetostrictive susceptibility (|dλ/dH|) at 0.1 MA/m against reduced substrate temperature (T$_r$/T$_m$). Here, T$_m$ is melting point (1553 K) under the standard sputtering (0.5 Pa) and standard residual (5.0 × 10$^{-2}$ Pa) gas pressures. The high |dλ/dH| values are obtained for Fe$_2$Sm thin films heated from 0.30 to 0.37 of (T$_r$/T$_m$), although low susceptibility values are obtained for films heated below 0.27 or above 0.4 of T$_r$/T$_m$. When the T$_r$ is 323 K (T$_r$/T$_m$ = 0.20) and 523 K (T$_r$/T$_m$ = 0.34), the volume fractions of crystalline samarium and oxides become low, resulting in high volume fraction of amorphous phase with high magnetostrictive susceptibility.\(^{18}\)

On the other hand, the high volume fraction of the crystalline phases with low magnetostriction and the low volume fraction of amorphous phase with high magnetostriction are observed in Zone II of Thornton model in Fig. 4, when the substrate temperature is 623 K (T$_r$/T$_m$ = 0.4).\(^{18}\)

4.5 Effects of morphological interface on |dλ/dH| in Zone T

The high magnetostrictive susceptibility (|dλ/dH|) is obtained at the optimum substrate temperature from 0.30 to 0.37 of T$_r$/T$_m$ (see Fig. 10) under the lowest sputtering pressure of 0.2 Pa (see Fig. 6) in Zone T. In order to explain the high magnetostrictive susceptibility, Thornton morphological model\(^{15}\) and SEM micrograph are convenient tools. The influences of substrate temperature and sputtering argon gas pressure related to kinetic energy of sputtering (depositing) particles on morphological texture can be explained for DC-magnetron sputtering process. Namely, the model exhibits influences of both thermal energy of Fe$_2$Sm alloy film prepared at different substrate temperatures.

The Fe-Sm alloy thin films are prepared by DC-magnetron sputtering process at elevated substrate temperatures (T$_s$) from room temperature to 673 K under the constant P$_s$ and P$_r$ values. Figure 9 shows applied magnetic field dependent magnetostrictive susceptibility of Fe$_2$Sm alloy film prepared at different substrate temperatures.

4.4 Substrate temperature dependent |dλ/dH|

The Fe-Sm alloy thin films are prepared by DC-magnetron sputtering process at elevated substrate temperatures (T$_r$; substrate temperature) from room temperature to 673 K under the constant P$_s$ and P$_r$ values. Figure 9 shows applied magnetic field dependent magnetostrictive susceptibility of Fe$_2$Sm alloy film prepared at different substrate temperatures.

The highest magnetostrictive susceptibility measured is 8.5 × 10$^9$ m/A under the lowest value of residual gas pressure of 2 × 10$^{-9}$ Pa.

\[ \log (P_r/P_a) = -0.19 \log (P_r/P_a) - 0.15 \] (3)

The logarithmic residual gas pressure (log (P$_r$/Pa)) and logarithmic magnetostrictive susceptibility (log |dλ/dH|) obtained at 0.1 MA/m is expressed by the following equation.
The drop of $|d\lambda/dH|_{|T_s|}$ from 0.20 to 0.27 of $T_s/T_m$ is large, as shown in Fig. 8. Since the reaction rate between impurity and samarium atoms at clear interface of porous tapered grains in Zone I increases at elevated temperatures, the formed barrier (obstacles) prevents to move the domain wall. Thus, the $|d\lambda/dH|_{|T_s|}$ tremendously decreases at elevated temperatures from 0.20 to 0.27 of $(T_s/T_m)$ in ZONE I (see Fig. 10).

On the contrary, the low substrate temperature generally decreases the rate of oxidation at clear interface of porous tapered grains in Zone I. Since the clear interface, which doesn’t largely trap the impurity atoms, is not effective barrier to prevent to move the domain wall, decreasing the substrate temperature from 0.27 to 0.20 in ZONE I in Fig. 2 enhances the $|d\lambda/dH|_{|T_s|}$ value (see Fig. 10).

On the other hand, columnar phase with remarkable interface is also found in Zone II ($P_s = 0.5$ Pa, $T_s/T_m = 0.4$) in Fig. 4. Since the remarkable interface among columnar grains probably act as the obstacles (barrier) to prevent to move the domain wall, the low magnetostrictive susceptibility (see Fig. 10) is explained in Zone II of SmFe$_2$ alloy thin films.

5. Conclusion

Influences of residual gas pressure, substrate temperature and argon gas pressure on negative (compressive) magnetostrictive susceptibility of SmFe$_2$ alloy thin films prepared by direct current magnetron sputtering process are investigated.

(1) The magnetostrictive susceptibility ($|d\lambda/dH|_{|T_s|}$), sensitive to morphological structure change in the densely packed amorphous phase, increases with decreasing the pressure of argon gas ($P_s$/Pa) and is expressed by a following equation.

$$\log |d\lambda/dH|_{|T_s|}/10^{-9} \text{ m/A} = -0.44\log(P_s/\text{Pa}) + 0.35$$

(2) The magnetostrictive susceptibility ($d\lambda/dH|_{|T_s|}/10^{-9} \text{ m/A}$) obtained at 0.1 MA/m of the densely packed amorphous phase decreases with increasing the pressure of residual gas ($P_r$/Pa) and is expressed by a following equation.

$$\log |d\lambda/dH|_{|T_s|}/10^{-9} \text{ m/A} = -0.19\log(P_r/\text{Pa}) - 0.15$$

(3) High magnetostrictive susceptibility of fine densely packed amorphous phase is found at each substrate temperatures ($T_s$) from 423 to 523 K.

(4) When the residual gas pressure affects the density of impurity atoms at the unclear morphological interface in densely packed fibrous amorphous phase, the high magnetostrictive susceptibility can be explained that the decreasing in impurity atoms at the unclear interface doesn’t probably prevent to move the magnetic domain wall in the amorphous phase.

(5) The low substrate temperature generally decreases the rate of oxidation at clear interface of porous tapered grains in Zone I. When the clear interface is not effective barrier to prevent to move the domain wall, decreasing the substrate temperature from 0.27 to 0.20 in ZONE I enhances the magnetostrictive susceptibility.
Acknowledgement

Authors would like to thank to Dr. M. Takeuchi, Mr. Y. Masuda, Mr. A. Kadowaki, Mr. Y. Tsukayama of Tokai University for their useful helps.

REFERENCES