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LETTER

Effect of SmFe and TbFe film thickness on magnetostriction for MEMS devices

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In this study, silicon based magnetostrictive structures were fabricated and finite element models using beam elements and plate elements were developed in order to access the effects of the thickness of deposited SmFe and TbFe, respectively, on magnetostriction in micro-devices. With expanded interest in micro-electro-mechanical systems (MEMS), numerous types of magnetostrictive material systems have been exhibited as micro devices. Some recent developments surrounding magnetostrictive micro-applications include physical, chemical and biological sensors, valves, micro-pumps, sound transducers, etc. [1–3]. Magnetostrictive devices show potential for high power, permanent and wireless actuators. Rare-earth magnets containing TbFe and SmFe produce large magnetostrictions under low magnetic fields, an important characteristic for MEMS. To design MEMS devices using magnetostrictive materials, magnetostrictions should be analyzed. The present study attempts to resolve the problems encountered in the finite element modeling of magnetostrictive thin film structures having large aspect ratios.

Double-layered cantilevers used to calculate the magnetostrictions consist of a thin film and substrate. When the thickness of the deposited magnetostrictive thin film is comparable with that of the substrate, the effect of the film on the bending of the cantilever should be considered. Therefore, the integration over the beam element thickness is required in the bending stiffness calculation. In this case, the element stiffness matrix is expressed as:

$$K = \int_0^{L_e} \int_{h_i}^{h_{i+1}} [B(\eta, \xi)]^T E_i [B(\eta, \xi)] w \, d\xi \, d\eta \quad (i = 0, 1) \tag{1}$$

where E_i and h_i are Young's modulus and the y coordinate of the i-th layer, respectively. $B(\eta,\xi)$is the strain-displacement matrix [4], L_e is the length of the element, and w is the width of the cantilever. However, the element described above is not capable of taking into account the effect of the cantilever width on the transverse deflection. Furthermore, because it assumes in-plane deformations only, it cannot consider the torsional deformation that arises when the magnetic field is applied perpendicularly to the magnetic easy axis. To resolve the limit, a plate element is proposed in this study.

Similar to the beam element, the element stiffness matrix of the plate element is:

$$K = \int_{A_e} \int_{h_i}^{h_{i+1}} [B_f(\eta, \xi, \varsigma)]^T D_{f,i} [B_f(\eta, \xi, \varsigma)] \, d\varsigma \, d\eta \, d\xi + \int_{A_e} \int_{h_i}^{h_{i+1}} [B_s(\eta, \xi, \varsigma)]^T D_{s,i} [B_s(\eta, \xi, \varsigma)] \, d\varsigma \, d\eta \, d\xi \tag{2}$$

The first term of the right-hand side is for the bending stiffness matrix, and the second for the shear stiffness matrix. $D_{f,i}$ is the constitutive matrices for the flexural stress and strain and $D_{s,i}$ is for the shear stress and strain. h_i and h_{i+1} are the z-coordinates of the i-th layer. A_e is the area of the plate element. $B_f(\eta, \xi, \zeta)$ and

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$B_f(\eta, \xi, \zeta)$ are the flexural strain-displacement matrix and the shear strain-displacement matrix, respectively. In order to evaluate the element nodal force due to magnetostriction of the coated magnetostrictive thin film, the anisotropic magnetostrictive stress should be considered [5, 6]. By virtue of the equivalent magnetostrictive stress, the element force vector can be expressed as

$$F = \int_A \int_{h_i}^{h_{i+1}} [B_f(\eta, \xi, \varsigma)]^T \sigma_{f,i} d\eta d\xi d\varsigma \quad (3)$$

where $\sigma_{f,i}$, is magnetostrictive stress of the i-th layer and is expressed in matrix form as

$$\sigma_{f,i} = [\sigma_{xx,i} \sigma_{yy,i} 0]^T \quad (4)$$

In this expression, $\sigma_{xx,i}$ is the equivalent magnetostrictive stress in the direction that is parallel to the applied magnetic field, and $\sigma_{yy,i}$ is the equivalent magnetostrictive stress in the direction perpendicular to the applied magnetic field.

For the purpose of verification, an experimental analysis was carried out. Binary system SmFe and TbFe thin films were prepared by the DC magnetron sputtering method in a composition of Sm_xFe_{1-x} ($x = 0.47$), Tb_xFe_{1-x} ($x = 0.4$). The magnetostrictive thin films were deposited on silicon substrates (20 mm × 4 mm × 50μm) with the optimized TbFe and SmFe composition. The Ar gas pressure was below 1.2×10^{-9} Torr and a DC input power of 200 W was used for the sputtering conditions. During the sputtering process the substrate holder was heated to 300°C. The fabricated film thicknesses were measured by X-ray diffraction (XRD). Figure 1 shows the X-ray diffraction results of SmFe films in terms of the diffraction angle–intensity relation.

From Fig. 1, the film thicknesses can be calculated as follows:

$$\Lambda = \frac{I\lambda}{2\sqrt{\sin^2\theta - 2\delta}} \quad (5)$$

where I is the intensity of the upper peak point at each $2\theta\lambda$ is the wave length of SmFe and TbFe film, Λ is the film thickness and δ is the real part of the refractive index and has a value of 10^{-5}. By fitting θ–I under the condition of the positive least value of δ, Fig. 2 can be obtained. Figure 2 presents the deposited thicknesses as a function of deposition time. SmFe has a higher deposition rate relative to TbFe. With the use of linear curve fitting, the deposited thicknesses at each deposition time are calculated.

The magnetostrictions of each film were determined by measuring the differences of the curvature of the coated silicon substrates using the optical cantilever method. The curvatures of the length and width directions of the film due to external magnetic fields by the electromagnet were measured by detecting deflected the laser signals through a position sensitive detector (PSD) (Fig. 3).

The measured curvatures are converted into magnetostrictions as follows:

$$\lambda = \frac{t_s^2}{9t_f} \frac{Y_s}{Y_f} \frac{1+v_f}{1+v_s} \left(\frac{1}{R_L} - \frac{1}{R_w} \right) \quad (6)$$

where Y is Young's modulus, v is Poisson's ratio, t is thickness, R is the radius of curvature, and the subscript s, f denote the value of the substrate and

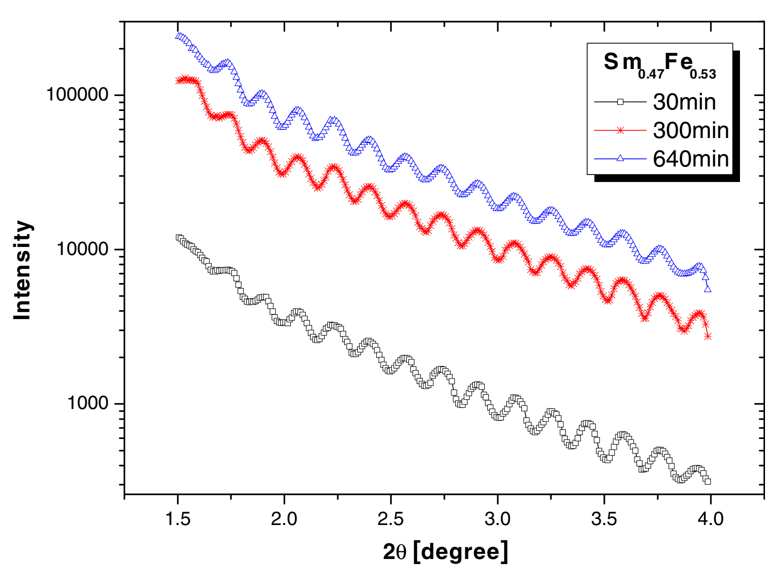

Fig. 1 X-ray diffraction of $Sm_{0.47}Fe_{0.53}$ for thickness measurement with deposited time variation

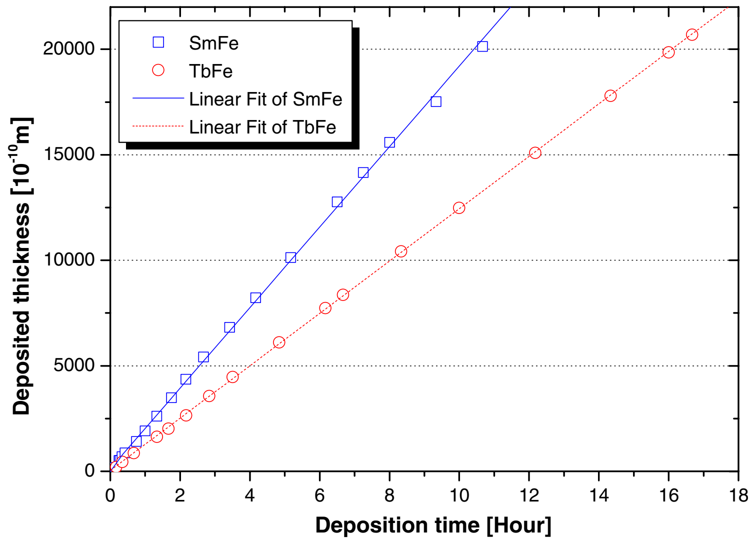

Fig. 2 Deposited thicknesses of SmFe and TbFe versus deposition time from measured XRD

film, respectively. The calculated magnetostrictions can be expressed as deflections.

The numerical results obtained using the beam and plate elements respectively are compared with the experimental results in Fig. 4. Because the Si substrate has almost zero torsional deformation under the applied magnetic fields, deflections obtained using the plate elements coincide well with those using beam elements. To confirm the torsional deformation effect of the plate element, deflections of a polyimide substrate which has greater flexibility along the width direction, due to application of an external magnetic field are presented in Fig. 5. Numerical results of the plate and beam elements are compared with experimental results from Honda et al. (1994) [7].

In Fig. 5, when the substrate has larger flexibility than polyimide, or Poisson's ratio of the deposited film has a non-zero value (less than 1), the analysis results using the plate element show better agreement with the experimental results than those for the beam element. Differences between the numerical results and experimental results are attributed to insufficient information about elastic properties, the interpolation scheme used for magneto-elastic coefficients, and the ΔE effects, i.e., that Young's modulus of the material depends on the state of the magnetization. Thus, the elastic tensor of the magnetic material changes according to the magnetic field [8]. The results for the numerical and experimental analyses are in close agreement.

Figure 6a shows the effects of the SmFe (Sm 47at.%) thickness in a rage of 0.05–2 μm with a Si substrate on the deflection of the cantilever. Dramatic changes in the magnetostriction are observed in the low-field region (up to 0.2 Torr), which is of special interest for applications in micro-systems. From an application point of view, it is necessary for magnetostrictive films to exhibit large magnetostriction in low magnetic fields. There is no measured substrate deflection with film thickness below 500 Å. However, with an increased thickness of the deposited layer, the gradient of the magnetostriction is increased rapidly.

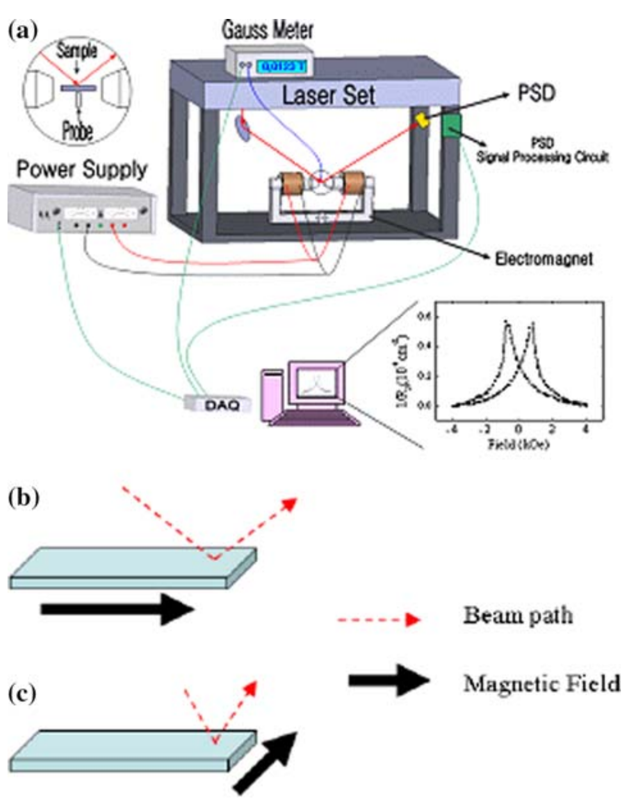

Fig. 3 Schematic view of measurement setup for magnetostriction (**a**) and Applied magnetic field directions on the substrates; (**b**) Length direction and (**c**) Width direction

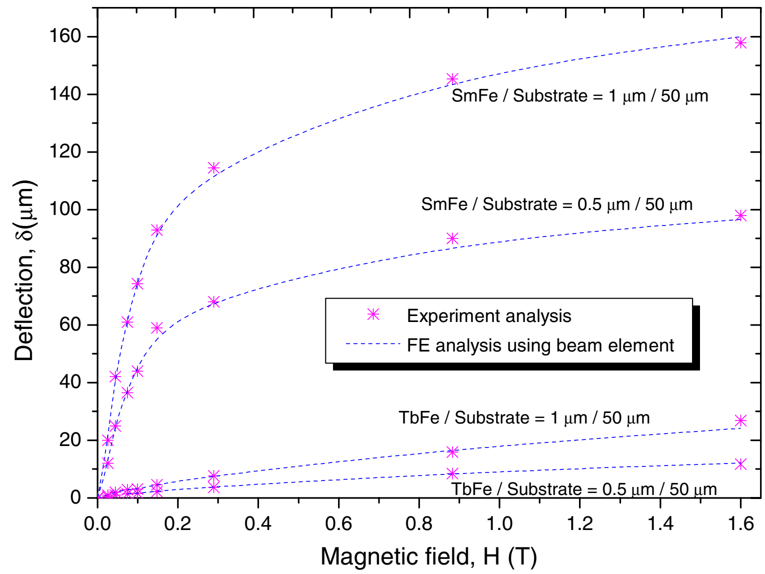

Fig. 4 Comparison of numerical results with the experimental results

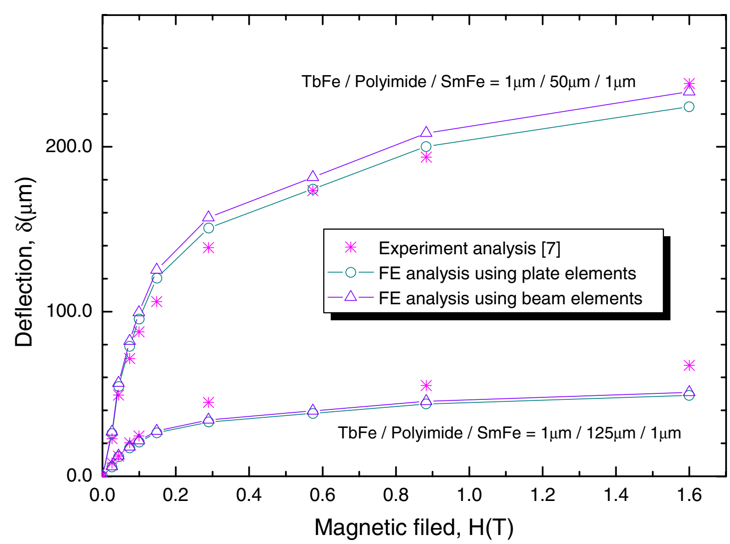

Fig. 5 Comparison of numerical results with experimental results of polyimide substrates

More than 100 μm deflections can be observed at 0.1 Torr in the case of 2 μm film thickness.

The deflections of the cantilevers with TbFe (Tb 40at.%) film thickness in a range of 0.05–2 μm with a Si substrate are shown in Fig. 6b. Rapid gradient changes with thickness variation are also observed here, but the magnitudes are smaller than those for the SmFe and higher nonlinear behavior between 0.07 and 0.12 Torr is observed. SmFe and TbFe films both develop a transitional knee in the data between 0.05 and 0.1 Torr, as shown in Fig. 6. This is due to the correlation between the shifting of domains and the changes of the state of magnetization in the magnetostrictive film. Magnetostriction is the change in shape and size of a body when its state of magnetization is changed by a magnetic field. Magnetization induces strains. At low magnetic field levels, the strain is linear with a rapid gradient. In this process, the magnitude of the magnetization within a domain has not changed appreciably; only its orientation with respect to local crystal axes has been altered. Above the low magnetic field levels, where the domains have completely shifted, the intrinsic magnetization is changed, which contributes to the transitional knee. However, in TbFe, the effect of developed intrinsic magnetization under a low magnetic field makes kink shape in Fig. 6b.

To summarize the present study, finite element models were developed to predict magnetostrictions of respective SmFe and TbFe deposited film structures of thicknesses. The model deformations were verified by

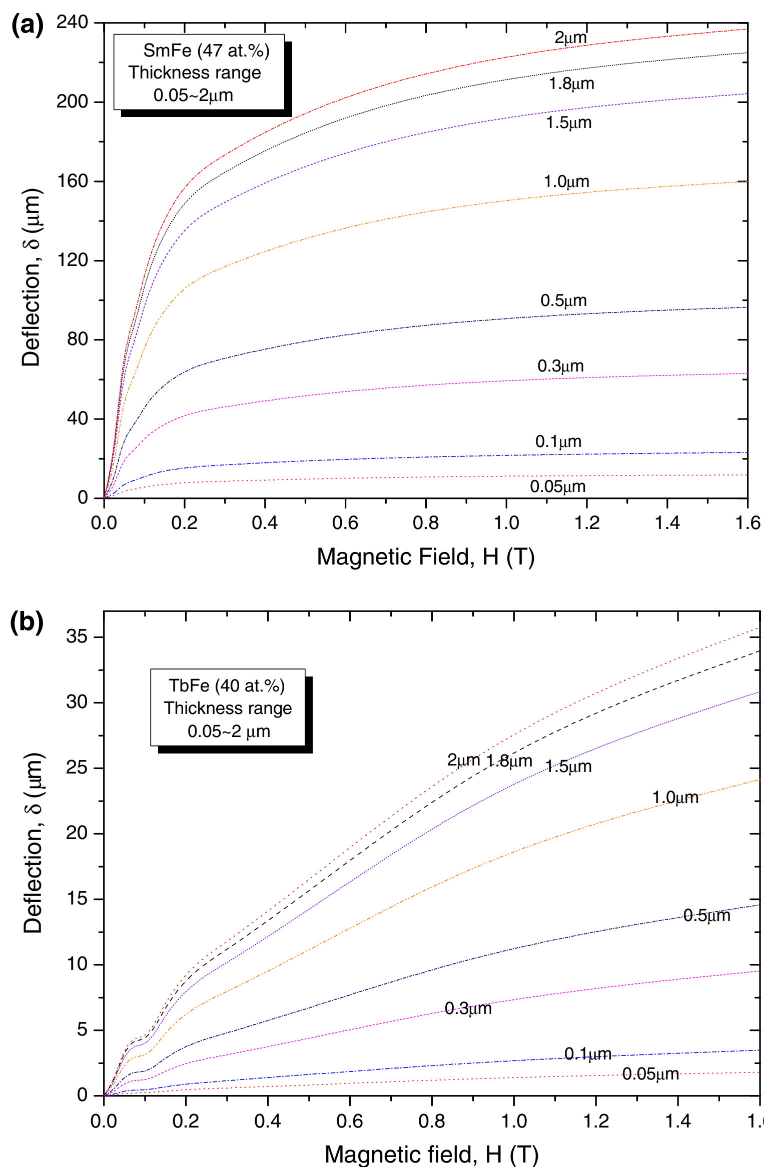

Fig. 6 Effects of the film thicknesses of (**a**) SmFe (47at.%) and (**b**) TbFe (40at.%) to the deflections

experimental results. Our next objective in this ongoing study is to design micro-wireless actuators using the developed numerical models.

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