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Inverse Magnetostrictive Effect in Ni_xFe_{1-x} ($1\leq x \leq 0.8$) Thin Films Deposited on a Polypropylene Substrate

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The magnetostriction effect is a unique phenomenon observed in magnetic materials due to applied stress. The permeability μ of the magnetic material increases or decreases depending on the sign of the magnetostriction coefficient λ based on the direction of the applied stress. For example, nickel has a negative λ, whereas iron has a positive λ for the same tensile (+) or compressive (-) stresses. However, the magnetostriction effect is reported to disturb the functionality of some spintronic applications, such as magnetic sensors and actuators, under the influence of an external magnetic field. Therefore, suppression of the magnetostriction effect is a challenge in developing flexible spintronic devices. In this study, the magnetostriction effect of the Ni_xFe_{1-x} thin films was investigated under different stress conditions. The composition of the thin film was manipulated by varying the deposition thickness of nickel and Ni_8Fe_2 targets using a co-sputtering system. Magnetization reversal behaviors of the Ni_xFe_{1-x} thin films were observed under the influence of an external magnetic field by using a vibrating sample magnetometer (VSM), before and after the application of bending stress. The negative magnetostriction effect of nickel was decreased by increasing the iron composition in the thin film, owing to the opposite sign of the magnetostriction coefficient. Finally, an extremely low magnetostriction was achieved at x = 0.8. The results of this study suggest that the magnetostriction effect can be controlled by varying the composition of the thin films and a sufficiently small magnetostriction effect can be observed at the permalloy composition between nickel and iron.

Keywords : inverse magnetostrictive effect, magnetomechanical effect, NiFe, permalloy

1. Introduction

Flexible devices have great potential in spintronic applications. This has drawn enormous attention on magnetic thin films and micro patterns on flexible substrates with regard to their magnetic properties that depend on bending stresses [1-6]. In particular, the magnetomechanical effect is produced due to the application of stress in either the tensile or compressive direction of the bending geometry and changes the magnetization reversal process. A stress sensor can utilize the magnetomechanical effect to verify the stress amplitude and direction as a function of bending [7-9]. Alternatively, studies have been conducted to suppress the magnetomechanical effect because negligibly small magnetostriction can provide magnetic stability without being affected by the curved geometry [10].

The physical model for understanding the magnetomechanical effect can be described in terms of the energy contributions of magnetic anisotropy, magnetostriction, and applied magnetic field. The total energy is defined as

$$E = K\sin^2(\theta_M) - \mu_0 M_S\cos(\theta_M - \theta_H) - \frac{3}{2}\lambda\sigma\cos^2(\theta_M - \theta_\sigma),$$

where, θ_H, θ_M, and θ_σ represent the angles of the applied field, magnetization, and stress, respectively. K is the intrinsic anisotropy constant during the deposition, λ is the magnetostriction coefficient for the magnetic material, and σ is the mechanical stress resulting from bending. In general structural mechanics, the sign of tensile stress is (+) and that of compressive stress is (−). The magnetostriction effect is the intrinsic property of a magnetic material, and the sign of the magnetostriction coefficient determines the easy and hard axis for the magnetization reversal. In addition, the net magnetostriction coefficient of a magnetic alloy can be modified by combining different materials exhibiting the magnetostriction effect.

In this study, the magnetomechanical effect of the

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Ni_xFe_{1-x} thin films, deposited on a conventional polypropylene (PP) substrate, was investigated depending on the parallel and perpendicular bending stresses developed in response to an external magnetic field. The composition of the thin film was manipulated by varying the deposition thickness of nickel and Ni_8Fe_2 targets using a co-sputtering system. Therefore, the negative magnetostriction effect of nickel was decreased by increasing the iron composition in the thin film, due to the opposite sign of the magnetostriction coefficient. Finally, a very low magnetostriction was achieved at x = 0.8.

2. Experimental

The 20 nm thick Ni_xFe_{1-x} thin films were fabricated on the 12 mm × 12 mm polypropylene substrate by the co-sputtering of nickel and Ni_8Fe_2 under 5 mTorr. To obtain better adhesion and antioxidation of the alloy thin films, 3 nm layers of tantalum (Ta) were utilized as the seed and capping layers. The composition of the Ni_xFe_{1-x} thin films was manipulated by varying the deposition rate of nickel and Ni_8Fe_2 targets. The deposition rates of Ni and Ni_8Fe_2 are listed in Table 1.

Low deposition rates of the sputtering targets were maintained to precisely control the thickness of the films. The nickel and iron composition was calculated by the weight percent based on the deposition thickness of the Ni_xFe_{1-x} thin films, where x = 1, 0.93, 0.9, 0.86, and 0.8.

Magnetization reversal behaviors of the Ni_xFe_{1-x} thin films were observed under the influence of an external magnetic field by using a vibrating sample magnetometer (VSM), before and after the application of bending stress. Both tensile (+) and compressive (-) stresses were induced on the films with a bending radius of 8.5 mm. The bending geometries are presented in Fig. 1. The magnetic domains can be deformed in a magnetic material by the application of stress; this is called the magnetomechanical effect or the inverse magnetostrictive effect. When the magnetic thin films were released from the bending condition, an opposite stress was induced in them; magnetization reversal behaviors were observed under this condition.

Table 1. Sputtering deposition rates of Ni and Ni_8Fe_2 at different bias currents.

Ni target		Ni_8Fe_2 target	
Current (mA)	Deposition rate (nm/s)	Current (mA)	Deposition rate (nm/s)
35	0.028	30	0.028
50	0.043	50	0.042
70	0.053	70	0.057

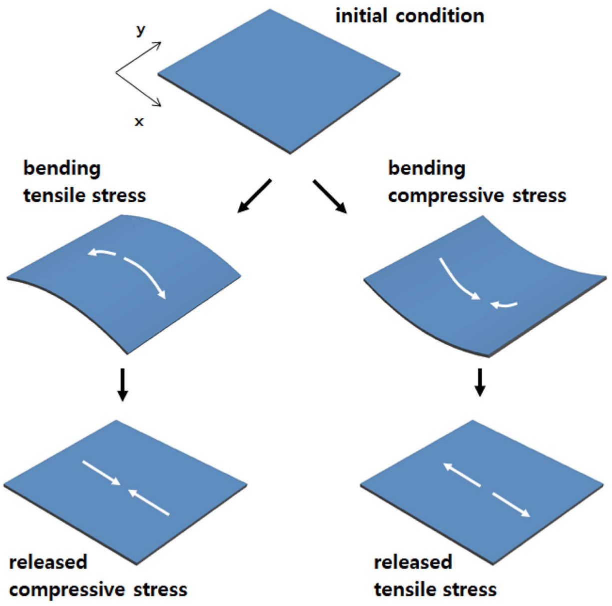

Fig. 1. Stress direction on the center of the thin film depending on the bending geometry.

3. Results and Discussion

The magnetization reversal behaviors of the Ni_xFe_{1-x} thin films after being subjected 30 rounds of tensile (+) and compressive (-) bending stresses are depicted in Fig. 2. When the film received the stress during the bending and the releasing process, the strain was focused on the central region along the bending axis. Therefore, two different switching behaviors were observed during the magnetization reversal. However, the total magnetic switching behavior could be simply understood by the stress effect based on the Stoner-Wohlfarth model. As shown in Fig. 2(a), when the magnetic field was parallel to the bending direction (x-axis), nickel showed rapid magnetization reversal on being subjected to tensile (+) bending stress, marked in red, whereas the reversal was slow on being subjected to compressive (-) bending stress, marked in blue. As previously discussed, on being released from the bending condition, the thin films experience a reversed stress. Therefore, a compressive (-) stress was induced in the thin films after being released from the tensile (+) bending stress, and a tensile (+) stress was induced in them after being released from the compressive (-) bending stress. Because of the negative magnetostriction of nickel, the compressive (-) and tensile (+) stresses acting under the released condition made the magnetic domains point parallel and perpendicular to the magnetic field, respectively. Therefore, the hysteresis

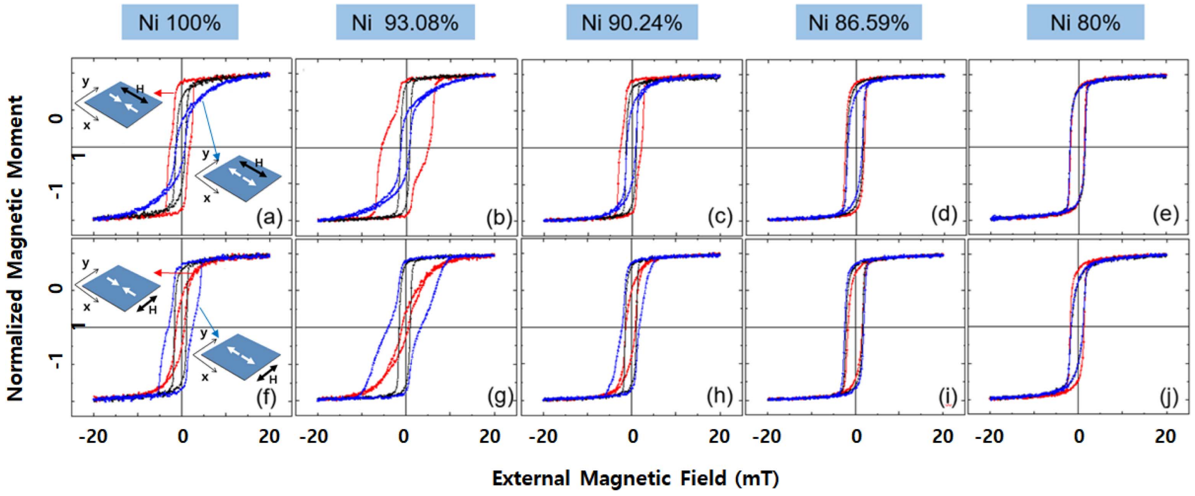

Fig. 2. Hysteresis loops of Ni_xFe_{1-x} thin films after tensile and compressive bending stress, when the Ni composition varied from 1 to 0.8. The opposite stress was induced under the released condition.

curves appeared similar to the magnetization curves under both the easy and hard axes. When the magnetic field was induced in the perpendicular direction (y-axis), opposite magnetization reversal behaviors were observed, as shown in Fig. 2(f). The magnetization reversed rapidly after the application of compressive (-) bending stress (blue curve), while slow magnetic switching was observed after the application of tensile (+) bending stress (red curve).

By increasing the iron composition of the Ni_xFe_{1-x} film from 0 to 20 %, the magnetization curves varied more bluntly for both the parallel and perpendicular magnetic fields, as shown in Figs. 2(a)-(e) and Figs. 2(f)-(j), respectively. Finally, isotropic magnetization reversal behavior of the thin films in the magnetic field direction was measured at $x = 0.8$. The results suggest that the negative magnetostriction of nickel was suppressed by increasing the iron composition of the Ni_xFe_{1-x} films, and a very low magnetostriction was observed at $x = 0.8$ in the Ni_xFe_{1-x} film.

Remanent magnetization is used for verifying the magnetization behavior of a material under the applied magnetic field. Fig. 3 shows the normalized residual magnetic moment of the films depending on the bending repetitions after positive magnetic saturations. The weak and intrinsic magnetic anisotropy resulting from the morphology of the polypropylene surface can be defined at the switching curves, colored black in Fig. 2. When the film received the stress from bending, the stress anisotropy became dominant with an increase in the bending repetitions. The normalized remanence of the released condition increased in the two measurements after the application of tensile (+) bending stress in the x-axis under a parallel magnetic field and compressive (-) bending stress in the y-axis under a perpendicular magnetic field, as shown in Figs. 3(a) and (d), respectively. However, the normalized remanent magnetic moment of the released condition decreased after increasing the tensile (+) bending stress under a perpendicular magnetic field (Fig. 3(b)) and compressive (-) bending stress under a parallel magnetic field (Fig. 3(c)). These behaviors demonstrate that

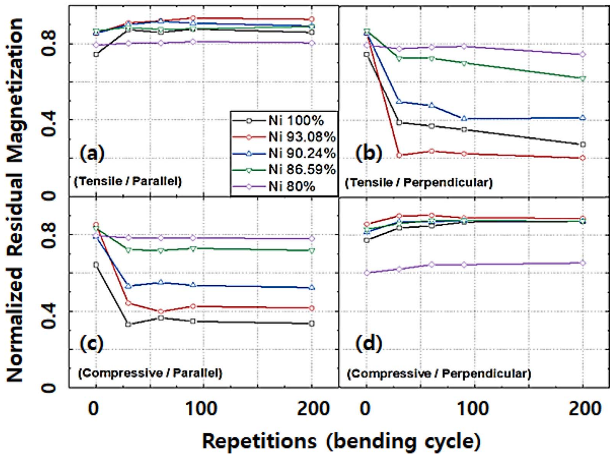

Fig. 3. Variations of the normalized residual magnetic moments, when the Ni composition varied from 1 to 0.8. The remanence of the thin films increased with the bending repetitions after the tensile bending stress (+) with the parallel magnetic field and after the compressive bending stress (-) with the perpendicular magnetic field, as shown in (a) and (d), respectively. The decrease of the remanence depending on the bending repetition is shown in (b), and (c), where the induced magnetic field was perpendicular to the film after the tensile bending stress (+) and parallel to the film after the compressive bending stress (-), respectively.

the negative magnetostriction of nickel is still dominant and can deform the magnetic domains perpendicular to the stress effect under the released condition. However, the residual magnetizations of the Ni_8Fe_2 film did not change significantly on increasing the bending repetitions than those of other films with different iron and nickel compositions. Evidently, the positive magnetostriction of iron suppressed the negative magnetostriction of nickel. Therefore, the ultra-low magnetostriction of the Ni_8Fe_2 film can be utilized in various spintronic devices, such as flexible sensors and memory and wearable devices, to support the magnetically isotropic functions independent of the bending stress.

4. Conclusion

The magnetomechanical effect is the most important parameter in the designing of flexible devices. Additionally, suppression of the magnetostriction effect is very important to obtain a stable performance under the application of bending stresses. In this study, the magnetomechanical effect was investigated by measuring the magnetization reversal behaviors of the Ni_xFe_{1-x} thin films deposited on a polypropylene substrate on being subjected to tensile (+) and compressive (-) bending stresses. The negative magnetostriction of nickel produced the easy- and hard-axis domain formation under the application of tensile (+) and compressive (-) bending stresses, respectively. On increasing the iron composition, the variation of the magnetic hysteresis could be manipulated due to the reverse magnetostriction of iron, and a very low magnetomechanical effect was obtained at x = 0.8. Therefore, the results of this study suggest that the magnetostriction effect can be controlled by varying the composition of the thin films and a sufficiently small magnetostriction effect can be observed at the permalloy composition between nickel and iron.

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References

[1] S. Zhao, Y. Zhao, B. Tian, J. Liu, S. Jin, Z. Jiang, Z. Zhou, and M. Liu, ACS Appl. Mater. Interfaces **12**, 41999 (2020).
[2] M. S. Ansari, M. H. D. Othman, M. O. Ansari, S. Ansari, and H. Abdullah, Ceram. Int. **46**, 19302 (2020).
[3] X. Chen and W. Mi, J. Mater. Chem. C **9**, 9400 (2021).
[4] T. Vemulkar, R. Mansell, A. Fernández-Pacheco, and R. P. Cowburn, Adv. Funct. Mater. **26**, 4704 (2016).
[5] A. Bedoya-Pinto, M. Donolato, M. Gobbi, L. E. Hueso, and P. Vavassori, Appl. Phys. Lett. **104**, 062412 (2014).
[6] I. G. Serrano, J. Panda, F. Denoel, Ö. Vallin, D. Phuyal, O. Karis, and M. V. Kamalakar, Nano Lett. **19**, 666 (2019).
[7] K. Eun, K. J. Lee, K. K. Lee, S. S. Yang, and S.-H. Choa, Int. J. Precis. Eng. Manuf. **17**, 699 (2016).
[8] E. S. Bastos, C. Bormio-Nunes, T. G. R. Clarke, and F. P. Missell, Sensors **20**, 3557 (2020).
[9] Y. Chen, C. Hu, Z. Wang, Y. Li, S. Zhu, W. Su, Z. Hu, Z. Zhou, and M. Liu, AIP Adv. **10**, 105310 (2020).
[10] G. Muscas, P. E. Jönsson, I. G. Serrano, Ö. Vallin, and M. V. Kamalakar, Nanoscale **13**, 6043 (2021).