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Magneto-mechanical Effect of NiFe Thin Films Depending on the Intrinsic Magnetic Anisotropy

Seungha Yoon*

Green Energy and Nano Technology R&D Group, Korea Institute of Industrial Technology, Gwangju, Republic of Korea

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Verifying magnetic anisotropy is essential for developing flexible magnetic devices. The magneto-mechanical effect is a unique phenomenon in magnetic materials for bending geometries and produces the stress magnetic anisotropy depending on the stress direction and its magneto-striction coefficient. In addition, the fabrication process for the flexible magnetic devices, such as deposition, annealing, and patterning, significantly causes the intrinsic magnetic anisotropy to change the reversal behaviors in the devices. This study investigated the variation of the stress magnetic anisotropy in the flexible NiFe (permalloy) thin films as a function of the bending repetition and its direction when the thin films had a different easy axis caused by the sputtering process. The variation of the stress magnetic anisotropy was observed by the magnetization reversal behaviors and the typical ferromagnetic resonance field detection before and after the application of the tensile stress. The stress effect was exponentially accumulated with increasing bending repetition on the thin film in both samples. However, when the repeated stress was applied in alternating x- and y-directions, minor resonance field fluctuation was observed in the film, which had the tilted intrinsic magnetic anisotropy. This result indicated that intrinsic magnetic anisotropy during the fabrication process played an essential role in determining the amount of effective field for designing flexible magnetic devices.

Keywords : magneto-mechanical effect, inverse magneto-striction, NiFe, bending repetition

1. Introduction

Flexible devices have great potential in various applications, such as health devices, robot skin, and displays [1-4]. It has also drawn enormous attention to the magnetic thin films and spintronic devices regarding the magnetic property variation depending on bending geometry. In particular, controlling magnetic switching behavior under an external magnetic field is essential for developing magnetic sensors or memory devices [5-10]. In general, an additional magnetic anisotropy is produced due to the stress in either the tensile or compressive direction of the bending and changes the magnetic switching behavior. This effect is called the magneto-mechanical effect or inverse magneto-striction effect. The net energy in terms of the intrinsic magnetic anisotropy, magnetostriction, and applied field could be defined as

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

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, λ is the magnetostriction coefficient for permalloy, and σ is the stress resulting from either tensile or compressive bending.

This study investigated the contribution of intrinsic magnetic anisotropy in the NiFe (permalloy) thin films to the magnetic switching behavior when the film received repeated bending stress. The magneto-mechanical effect was exponentially accumulated and saturated with increasing the bending repetition. When the repeated bending direction altered on the x- and y-axis, a minor fluctuation of the resonance field was observed at the tilted intrinsic magnetic anisotropy. This result indicated that manipulating intrinsic magnetic anisotropy can provide a stable magnetic function for flexible magnetic devices.

2. Experimental

The 50 nm thick permalloy thin films (Sample A and B) were deposited on the 12 mm × 12 mm polypropylene substrate by the DC magnetron sputtering under 5 mTorr.

*Corresponding author: Tel: +82-62-600-6580
Fax: +82-62-600-6109, e-mail: yoonsh@kitech.re.kr

The seed and the capping layers comprised each 3 nm tantalum (Ta) layer for better adhesion and antioxidation, respectively. Because the samples received a different magnetic field during the sputtering at each deposition position, the intrinsic magnetic anisotropy was formed in a different direction. The intrinsic magnetization reversal behaviors of the permalloy thin films were observed by a vibrating sample magnetometer (VSM). When the bending repetition induced the magneto-mechanical effect on the thin films, a ferromagnetic resonance (FMR) [11-13] detection method was utilized to verify the amount of the stress magnetic anisotropy field.

$$\omega_{res} = \gamma_e \sqrt{(H_{eff} + 4\pi M_S)H_{eff}}$$

where, ω_{res} is the angular frequency of the ferromagnetic resonance, γ_e is the gyromagnetic ratio of the electron, and $4\pi M_S$ is the magnetization of the permalloy of 842.4 mT. H_{eff} is the effective field including the intrinsic magnetic anisotropy, the stress magnetic anisotropy, and the external magnetic field. Therefore, the shift of the external magnetic field could be considered as the stress magnetic anisotropy variation depending on the curved geometry with a bending radius of 8.5 mm and the bending direction. The self-designed bending machine uniformly generated the repeated tensile stress to a film.

3. Results and Discussion

The VSM measurement shows the magnetization reversal behaviors of two permalloy thin films (Sample A and B) in Fig. 1(a) and (b), respectively. Sample A showed a larger coercive field on the y-axis than on the x-axis. In addition, the fast switching behavior was observed during the magnetization reversal when the external magnetic field was applied on the y-axis. On the other hand, Sample B showed similar coercive fields on both the x- and the y-axis. Based on the Stoner-Wohlfarth model, the shape of the hysteresis loop strongly depends on the angle between the external magnetic field and the magnetic easy-axis. The hysteresis loop shows a giant coercive field if the two are parallel. In contrast, the magnetization continuously rotates if the easy axis is transverse to the external field. Therefore, the easy axis of Sample A could be defined as the y-axis, and that of Sample B could be about 45 degrees tilted from the x-axis on the film plane.

The magnetic anisotropy field compensated for the FMR resonance field. Therefore, the external magnetic field decreased by the amount of the net magnetic anisotropy field. The FMR signals of the samples are presented in Fig. 2(a) and (b) at the resonance frequency

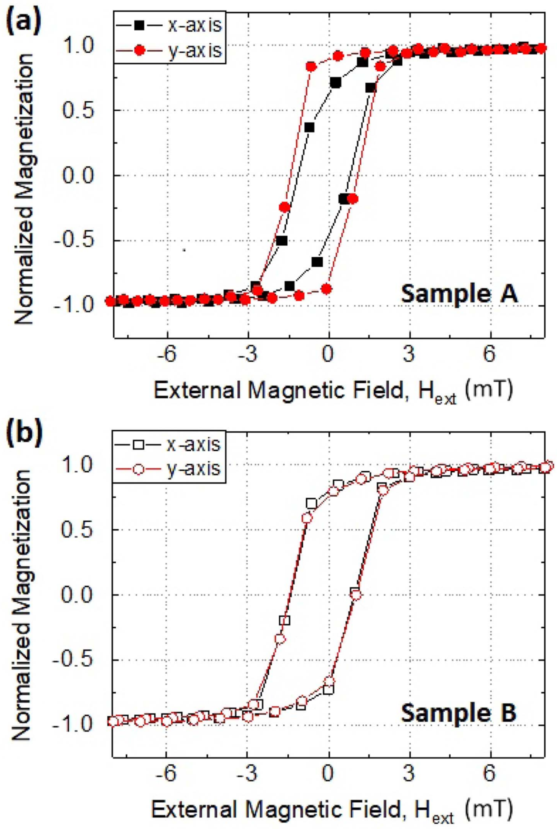

Fig. 1. (Color online) Normalized magnetization reversal behaviors of Sample A and Sample B when the position was different on the sample holder during the sputtering. (a) Because Sample A showed a larger coercive field with fast magnetic switching behaviors under magnetization reversal on the y-axis, the easy axis of Sample A could be defined as the y-axis. (b) The similar magnetization reversal behaviors indicated that Sample B had about 45 degrees rotated magnetic easy-axis from the x-axis.

of 5 GHz, respectively. Sample A showed a smaller external magnetic field for the resonance condition when the external magnetic field was applied on the y-axis rather than on the x-axis. On the other hand, the two FMR signals of Sample B had similar external magnetic fields for the resonance for applying the magnetic field on both x- and y-axis. The results were also shown in the resonance frequency variations depending on the resonance field of FMR, as shown in Fig. 2(b).

When the samples received the repeated tensile bending stress, the resonance field was observed in each released condition, as depicted in Fig. 3(a). When the film was released from the bending, the film received compressive stress. In this bending geometry, the positive magnetostriction coefficient of the permalloy thin film decided the stress magnetic anisotropy field on the y-axis at the leased

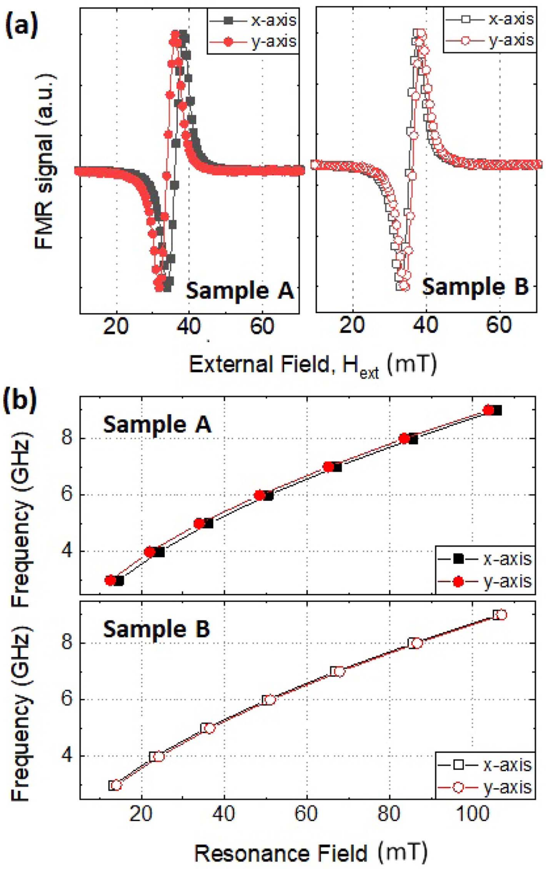

Fig. 2. (Color online) Ferromagnetic resonance signals of Sample A and Sample B depend on the switching axis. (a) Sample A showed a lower resonance field on the y-axis than on the x-axis. On the other hand, Sample B indicates similar resonance fields under 5 GHz resonance frequency. (b) The resonance frequency depends on the external magnetic field for the samples.

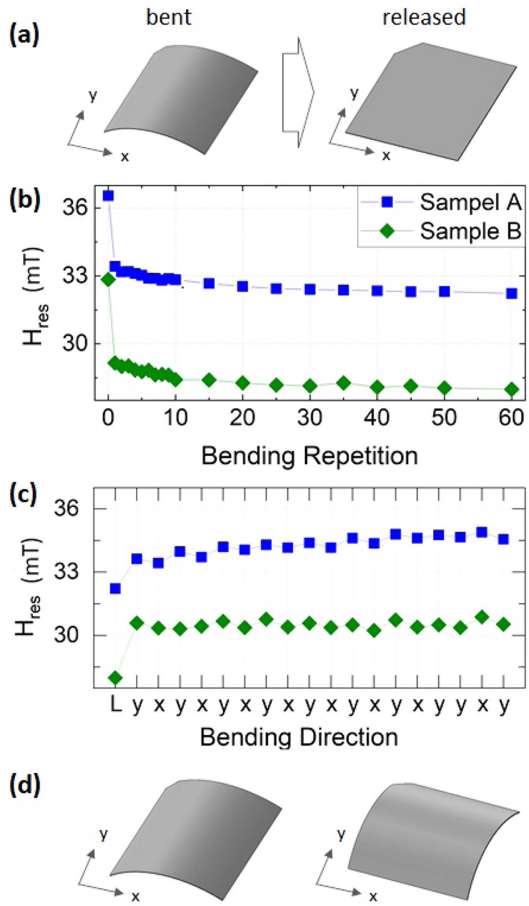

Fig. 3. (Color online) (a) The bending geometry of Sample A and B for tensile stress. The permalloy receives the reversed (compressive) stress when the film is released. (b) The resonance field of Sample A and B depend on the bending repetition. The stress magnetic anisotropy is assisted exponentially as a function of the repetition number and saturated after 60 bending cycles. (c) Sample B shows stable resonance field variation when the opposite stress is applied. (d) The geometry for the alternate bendings in opposite directions.

condition. In addition, the stress magnetic anisotropy accumulated and saturated on the y-axis by increasing the bending repetition. The stress magnetic anisotropy-assisted resonance field variations in both samples were shown in Fig. 3(b) when bending repetition increased to 60 cycles. The external magnetic field was applied to the y-axis and the radio-frequency field from the microwaves induced transverse to the external field.

Next, the thin films received the opposite bending stress from the saturation of stress effect on the y-axis, as “L” in Fig. 3(c). Therefore the magneto-mechanical effect produced the stress magnetic anisotropy field on the x-axis. Because the stress effect decreased exponentially with increasing the bending repetition, the first opposite bending significantly shifted the resonance field. However, the resonance field did not dramatically change when the additional bending was repeated in the alternating x- and y-axis directions. In particular, the resonance field of Sample B was stable with increasing the alternating bending repetition when the intrinsic magnetic anisotropy was tilted from the bending direction. The repeated alternating bending geometry is represented in Fig. 3(d).

4. Conclusion

The stress magnetic anisotropy is significant in controlling the magnetic functions in spintronic devices for flexible applications. In particular, the bending repetition could drive the magneto-mechanical effect's accumulation and saturation. This study applied the bending repetition to the permalloy thin films on polypropylene substrates with different intrinsic magnetic anisotropy during the deposition. When the tensile bending stress was repeated for 60 cycles, the two samples showed similar saturation behaviors of the stress magnetic anisotropy. When the repeated tensile stress was applied on alternating x- and y-direction, Sample B showed minor variation in the resonance field. Therefore, this result indicated that intrinsic magnetic anisotropy during the deposition played an essential role in determining the amount of effective field for designing flexible magnetic devices.

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