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Magnetostriction of fcc(110) single-crystal films of Ni-Fe, Ni, and Co under rotating magnetic fields

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Abstract. Ni-Fe, Ni, and Co(110) single-crystal films with uniaxial magnetic anisotropies are prepared on MgO(110) substrates by radio-frequency magnetron sputtering. The magnetostriction behavior under rotating magnetic fields is investigated. The Ni-Fe film shows waveforms consisting of a mixture of sinusoidal and triangular shapes under fields lower than 200 Oe. The peak of sinusoidal shape is observed when the field is applied along the easy magnetization axis, whereas that of triangular shape appears when the field is applied along the hard axis. With increasing the field from 200 to 300 Oe, the waveform changes to a usual sinusoidal shape. The waveform variation is related to the difference between the directions of uniaxial magnetic anisotropy and magnetization of magnetically unsaturated film. Waveforms consisting of sinusoidal and triangular shapes are also observed for the Ni and the Co films under low rotating fields. The threshold magnetic field where the shape changes to sinusoidal increases in the order of Ni-Fe < Ni < Co. The waveform is influenced by the symmetry and the strength of magnetic anisotropy.

1 Introduction

Soft magnetic materials have been widely used in applications such as transformers, motors, magnetic devices, etc. Magnetostriction is one of the basic material properties and the behavior gives a strong influence on the performance. In practical applications, magnetic materials are often exposed to alternating magnetic fields. It is thus important to investigate the magnetostriction behaviors under rotating magnetic fields [1, 2].

Isotropic magnetic materials show sinusoidal output waveforms of magnetostriction under magnetic fields. On the contrary, a waveform consisting of a mixture of sinusoidal and triangular shapes was observed for an oriented silicon steel plate [3]. In order to investigate the magnetostriction behaviors of anisotropic magnetic materials, it is useful to employ well-defined epitaxial magnetic films, since the structure and the magnetic anisotropy are controlled by the crystallographic orientation of single-crystal substrate. In our previous studies [4–7], (001)-oriented soft magnetic single-crystal films with in-plane magnetic anisotropies of four-fold symmetry were prepared. The films showed waveforms consisting of only triangular shape under rotating fields and the behavior was related with the wall motion of 90° magnetic domains existing in the magnetically unsaturated films. The magnetostriction behavior is considered to very depending on the symmetry in magnetic anisotropy. In the present study, soft magnetic films are deposited on MgO(110) single-crystal substrates in order to prepare magnetic films with uniaxial magnetic anisotropies. $Ni_{80}Fe_{20}$ (at. %), Ni, and Co with fcc structure are employed as film materials. The magnetostriction behaviors under magnetic fields are investigated.

2 Experimental procedure

Thin films were prepared on MgO(110) substrates with the thickness of 200 μm at 300 °C by using a radio-frequency (RF) magnetron sputtering system equipped with a reflection high-energy electron diffraction (RHEED) facility. The base pressures were lower than 4×10^{-7} Pa. Before film formation, substrates were heated at 600 °C for 1 h in the camber to obtain clean surfaces. $Ni_{80}Fe_{20}$ alloy, Ni, Co, Cu, and Pd targets of 3 in diameter were employed. The distance between target and substrate was fixed at 150 mm and the Ar gas pressure was kept constant at 0.67 Pa. The RF powers for $Ni_{80}Fe_{20}$, Ni, Co, Cu, and Pd targets were respectively adjusted to be 50, 50, 54, 29, and 30 W, where the deposition rate was 0.02 nm/s for all the materials. The film layer structures were Ni-Fe(500 nm)/MgO, Ni(500 nm)/MgO, and Co(500 nm)/Cu(10 nm)/Pd(5 nm)/MgO. Ni-Fe and Ni films of 500 nm thickness were deposited directly on MgO(110) substrates, whereas a 500-nm-thick Co film was formed on a Cu(110) single-crystal underlayer hetero-epitaxially grown on MgO substrate. The Cu underlayer was employed to stabilize the fcc structure for Co film [6]. The epitaxial orientation relationship determined by RHEED was Cu(110)[$1\bar{1}0$] || Pd(110)[$1\bar{1}0$] || MgO(110)[$1\bar{1}0$].

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The surface structure was studied by RHEED. The resulting film structure was investigated by $2\theta/\omega$-scan out-of-plane and $2\theta\chi/\phi$-scan in-plane X-ray diffractions (XRDs) with Cu-Kα radiation (wave length: 0.15418 nm). The magnetization curves were measured by using a vibrating sample magnetometer. The magnetization structure was observed by Kerr microscopy.

The magnetostriction was measured by cantilever method using a laser displacement meter under in-plane rotating magnetic fields (H_{rot}) up to 1000 Oe. The magnetostriction coefficient of λ [8] is expressed as

$$\lambda = \{\Delta S t_s^2 E_s(1+\upsilon_f)\}/\{3L^2 t_f E_f(1-\upsilon_s)\}, \quad (1)$$

where ΔS is the measured bending (2nd harmonic output value of magnetostriction), L is the distance between laser beam points, t is the thickness, E is Young's modulus, v is Poisson's ratio, and the subscripts of f and s respectively refer to film and substrate. When the magnetostriction is measured under a rotating field, the relationship among λ, λ_{100}, and λ_{111} [9] is given as the following formula,

$$\lambda = (3/2)\lambda_{100}(\alpha_1^2\beta_1^2+\alpha_2^2\beta_2^2+\alpha_3^2\beta_3^2) + 3\lambda_{111}(\alpha_1\alpha_2\beta_1\beta_2+\alpha_2\alpha_3\beta_2\beta_3+\alpha_3\alpha_1\beta_3\beta_1), \quad (2)$$

where the α is the cosine of angle between the magnetization and the three crystal axes (a, b, c) and the β is the cosine of angle between the direction of relative change in length and the crystal axes. In the case of fcc(110) single-crystal film, the (α_1, α_2, α_3) and the (β_1, β_2, β_3) are respectively expressed as ($(1/2^{1/2})\sin\psi$, $(1/2^{1/2})\sin\psi$, $\cos\psi$) and (0, 0, 1), where the direction of magnetostriction measurement is along fcc[001] and ψ is the angle of magnetization direction with respect to fcc[001]. By substituting the α and the β values into the equation (2), the following relation is given,

$$\lambda = (3/2)\lambda_{100}\cos^2\psi. \quad (3)$$

3 Results and discussion

Figures 1(a-1)–(c-1) show the RHEED patterns of Ni-Fe, Ni, and Co films deposited on MgO(110) substrates observed by making the incident electron beam parallel to MgO[1$\bar{1}$0]. Clear diffraction patterns corresponding to fcc(110) texture are recognized for all the films, as shown by the indices in the pattern of figure 1(a-1). The epitaxial orientation relationship is determined by RHEED as fcc(110)[1$\bar{1}$0] || MgO(110)[1$\bar{1}$0]. fcc(110) single-crystal films are obtained. Figures 1(a-2)–(c-2) and (a-3)–(c-3) show the out-of-plane and in-plane XRD patterns, respectively. Here, the in-plane patterns are measured by making the scattering vector parallel to MgO[1$\bar{1}$0]. fcc(220) reflections are observed in the out-of-plane patterns, whereas fcc(2$\bar{2}$0) reflections are recognized in the in-plane patterns. The XRD confirms the epitaxial orientation relationship determined by RHEED.

Figure 2 shows the in-plane magnetization curves measured for the Ni-Fe(110) single-crystal film. The film shows a uniaxial magnetic anisotropy. The easy magnetization direction is recognized along fcc[001], whereas the hard direction is observed along fcc[1$\bar{1}$0]. The result is in agreement with a theoretical study showing the in-plane easy magnetization direction of fcc(110) single-crystal films with the negative 1st

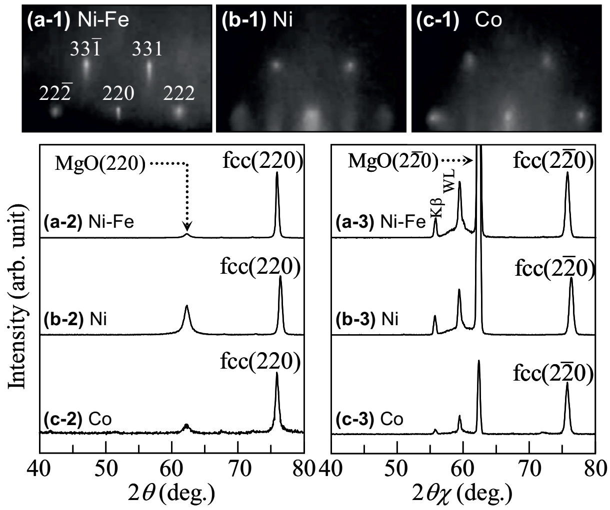

Fig. 1. (a-1)–(c-1) RHEED and (a-2)–(c-2) out-of-plane and (a-3)–(c-3) in-plane XRD patterns of (a) Ni-Fe, (b) Ni, and (c) Co films deposited on MgO(110) substrates. The incident electron beam is parallel to MgO[1$\bar{1}$0]. The scattering vector of XRD is parallel to (a-2)–(c-2) MgO[110] or (a-3)–(c-3) MgO[1$\bar{1}$0]. The XRD intensity is shown in a linear scale.

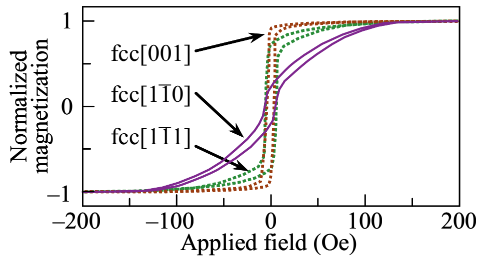

Fig. 2. Magnetization curves measured for an Ni-Fe(110) single-crystal film.

magnetocrystalline anisotropy constants [10]. The saturation field (H_s) measured along fcc[1$\bar{1}$0] is 180 Oe. Higher saturation field is considered to be observed in the order of Ni-Fe < Ni < Co.

Figure 3(a) shows the output waveforms of magnetostriction of the Ni-Fe film measured under different H_{rot} values, where the rotation angle of φ shows the applied field direction with respect to fcc[001]. A waveform consisting of a mixture of sinusoidal and triangular shapes is observed under the H_{rot} values lower than 200 Oe. The waveform is very similar to that observed for an oriented silicon steel plate [3]. The peak value of sinusoidal shape appears when the H_{rot} is applied along fcc[001] or fcc[00$\bar{1}$], that is, the easy magnetization axis. On the other hand, the peak value of triangular shape is observed when the H_{rot} is applied along fcc[1$\bar{1}$0] or fcc[$\bar{1}$10], that is, the hard axis. A waveform consisting of only sinusoidal shape starts to be observed at the H_{rot} value of 300 Oe and it remains unchanged up to H_{rot} = 1000 Oe. Figure 4(a) shows the 2nd harmonic output of magnetostriction as a function of H_{rot}. The output increases with increasing the H_{rot} value up to 300 Oe and the output is kept constant at around 0.054 V above the H_{rot} value. The result indicates that the magnetization fully saturates at H_{rot} = 300 Oe. The H_{rot} value is slightly larger than the H_s value (180 Oe) estimated from the magnetization curve data shown in figure 2. Although the film seems to magnetically saturate at the field of 180 Oe in the magnetization curve, the magnetization may not

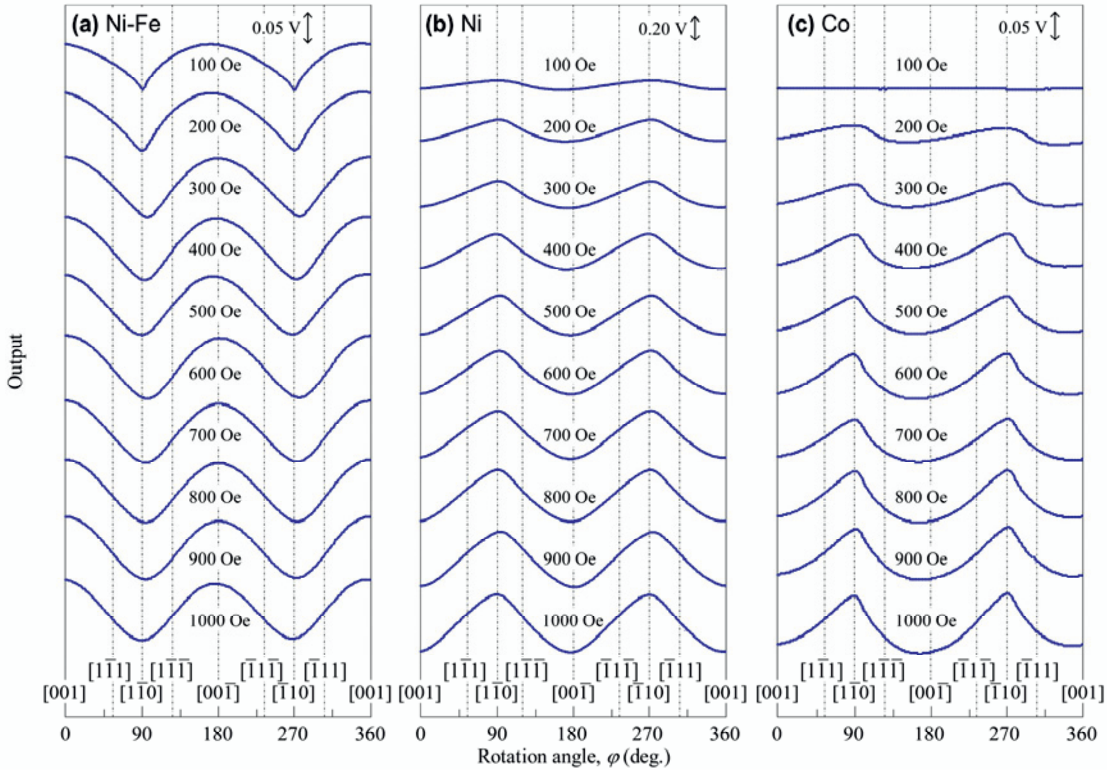

Fig. 3. Output waveforms of magnetostriction measured for (110)-oriented (a) Ni-Fe, (b) Ni, and (c) Co single-crystal films.

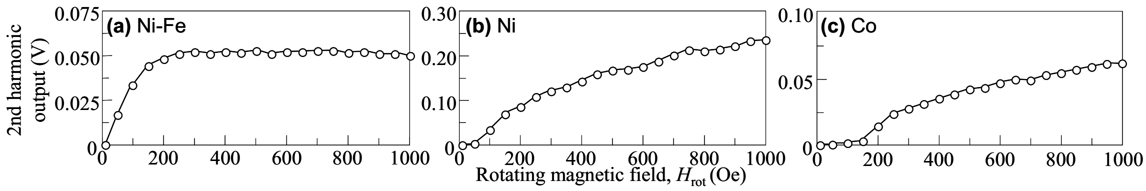

Fig. 4. 2nd harmonic outputs of magnetostriction measured for (110)-oriented (a) Ni-Fe, (b) Ni, and (c) Co single-crystal films as a function of applied magnetic field.

fully saturate up to 300 Oe. When the output reaches the constant value, the waveform becomes a usual sinusoidal shape due to that the magnetization reversal occurs under a rotating field.

In order to study the mechanism of triangular waveform, the magnetization structure was observed. Figure 5(a) shows the Kerr microscope images of the Ni-Fe film observed under different magnetic fields, where the field is applied along fcc[001], that is, the easy magnetization axis. With increasing the field from –5 to +3 Oe, the contrast changes from bright to dark tone. The result indicates that the magnetization reverses, as shown in the schematic diagrams of figure 5(b). Figure 5(c) shows the Kerr microscope images observed by applying the field along fcc[1$\bar{1}$1], that is, the direction 55° rotated from the easy axis. A single magnetic domain is observed under a field of –5 Oe [figure 5(c-1)]. With increasing the field up to +3 Oe, domain walls are apparently formed along fcc[001], which is reflecting the uniaxial magnetic anisotropy. It is also noted that the magnetization direction is not parallel to the applied field direction. With further increasing the field up to +20 Oe, the domain walls disappear and a single domain is formed. By taking into account the magnetization curve data shown in figure 2, the magnetization direction is not still parallel to the applied field direction, however the magnetization direction is not parallel to the applied field, while the film seems to be magnetically saturated along fcc[001].

The waveform consisting of triangular and sinusoidal shapes will be explained by considering the directions of uniaxial magnetic anisotropy and magnetization. Figure 6(a) shows the simplified model of an fcc(110) single-crystal film with a uniaxial magnetic anisotropy. The free energy of whole system (E) is consisting of a magnetic anisotropy energy and an energy supplied from H_{rot}. The E is thus expressed as

$$E = K_{\mathrm{u}}\sin^2\psi - H_{\mathrm{rot}}M_{\mathrm{s}}\cos(\psi-\varphi), \quad (5)$$

where K_{u} is the uniaxial anisotropy energy and M_{s} is the saturation magnetization. In this case, the magnetization direction is determined so that the E becomes minimum, that is, $\partial E/\partial\psi = 0$. Therefore,

$$\begin{aligned}(\partial E/\partial\psi)/(2K_{\mathrm{u}}) &= \sin\psi\cos\psi - H_{\mathrm{rot}}(M_{\mathrm{s}}/2K_{\mathrm{u}})\sin(\varphi-\psi)\\ &= \sin\psi\cos\psi - (H_{\mathrm{rot}}/H_{\mathrm{k}})\sin(\varphi-\psi)\\ &= \sin\psi\cos\psi - h\sin(\varphi-\psi)\\ &= 0, \end{aligned} \quad (6)$$

where H_{k} is the anisotropy field and h is defined as $H_{\mathrm{rot}}/H_{\mathrm{k}}$. By solving the equation (6) and substituting ψ into the equation (3), the λ of fcc(110) single-crystal film under a rotating field is given. Assuming the h values of 1 and 20, the waveforms are calculated as shown in figure

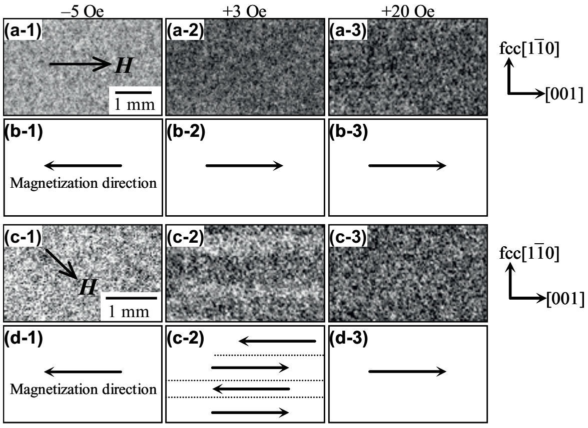

Fig. 5. (a, c) Kerr microscope images of an Ni-Fe(110) single-crystal film observed under magnetic fields of (a-1, c-1) –5, (a-2, c-2) +3, and (a-3, c-3) +20 Oe. The field is applied along (a) fcc[001] or (c) fcc[1$\bar{1}$1]. (b, d) Schematic diagrams of magnetic domain structures of (a, c), respectively.

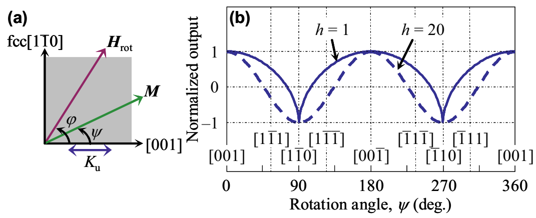

Fig. 6. (a) Schematic model showing the angles of ψ and φ with respect to the crystallographic direction of fcc(110) single-crystal film. (b) Magnetostriction analysis model of a waveform consisting of a mixture of sinusoidal and triangular shapes.

6(b), where the output is normalized. The waveform with $h = 1$ where H_{rot} equal to H_k is very similar to that of Ni-Fe film observed under low magnetic fields in the present study.

Figure 3(b) shows the output waveforms of magnetostriction of the Ni(110) film. A waveform consisting of a mixture of sinusoidal and triangular shape is observed and it approaches to a usual sinusoidal shape with increasing the H_{rot} value. Figure 3(c) shows the waveforms of the Co(110) film. A waveform consisting of a mixture of sinusoidal and triangular shape is also observed up to H_{rot} = 1000 Oe. Figures 4(b) and (c) show the 2nd harmonic output values. With increasing the H_{rot} value, the output increases for both films. The result suggests that the Ni and the Co films are not magnetically saturated at H_{rot} = 1000 Oe.

The phase of output waveform reverses between the Ni-Fe and the Ni or the Co films, indicating that the sign of λ is different. By using the equations (1) and (3), the λ_{100} values of Ni-Fe, Ni, and Co single-crystal films with fcc(110) orientation were estimated from the respective outputs measured under H_{rot} = 1000 Oe, where the magnetization of Ni-Fe film fully saturates, whereas those of Ni and Co films are not magnetically saturated. The output values of Ni-Fe, Ni, and Co films are 0.054, 0.23, and 0.061 V and the λ_{100} values are calculated to be 5.8×10^{-6}, -2.5×10^{-5}, and -5.9×10^{-6}, respectively. The λ_{100} values of Ni-Fe and Ni films are almost in agreement with those of bulk $Ni_{80}Fe_{20}$ ($\lambda_{100} = 2\times10^{-6}$ [11]) and Ni ($\lambda_{100} = -4.6\times10^{-5}$ [12]) crystals. A comparison is not possible for the Co(110) film, since there are no reports on the λ_{100} measurement of bulk fcc-Co crystal. In the case of Ni-Fe, the small difference seems to be attributable to the form of thin film involving crystallographic defects, since the Ni-Fe film is fully magnetically saturated at H_{rot} = 1000 Oe. In the case of Ni, the difference can be mainly due to that the Ni film is not fully saturated at H_{rot} = 1000 Oe.

4 Conclusion

fcc(110) NiFe, Ni, and Co single-crystal films with uniaxial magnetic anisotropies are prepared on MgO(110) singe-crystal substrates. The magnetostriction behavior under rotating magnetic fields is investigated. The Ni-Fe film shows a waveform consisting of a mixture of sinusoidal and triangular shapes under H_{rot} values lower than 200 Oe. With increasing the H_{rot} value up to 300 Oe, the waveform changes to a usual sinusoidal shape. The deformed waveform is related to the difference between the directions of uniaxial magnetic anisotropy and magnetization of magnetically unsaturated film. The Ni and the Co films also show such similar deformed waveforms under low H_{rot}. The H_{rot} value where the distorted waveform approaches to a sinusoidal shape is observed to be higher in the order of Ni-Fe < Ni < Co, which is reflecting the increasing order of magnetic anisotropy.

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References

1. M. Enokizono, S. Kanao, G. Shirakawa, IEEE Trans. Magn. **31**, 3409 (1995)
2. L. Varga, H. Jiang, T. J. Klemmer, IEEE Trans. Magn. **34**, 1441 (1998)
3. M. Enokizono, T. Suzuki, J. D. Sievert, IEEE Trans. Magn. **26**, 2067 (1990)
4. T. Ohtani, T. Kawai, M. Ohtake, M. Futamoto, EPJ Web of Conf. **40**, 11004 (2013)
5. Y. Asai, T. Kawai, M. Ohtake, M. Futamoto, EPJ Web of Conf. **40**, 17001 (2013)
6. T. Ohtani, T. Kawai, M. Ohtake, M. Futamoto, J. Korean Phys. Soc. (to be published)
7. T. Ohtani, T. Kawai, M. Ohtake, M. Futamoto, J. Magn. Soc. Jpn **37**, 210 (2013)
8. T. Kawai, S. Ouchi, M. Ohtake, M. Futamoto, Thin Solid Films **519**, 8429 (2011)
9. B. D. Cullity, C. D. Graham, *Introduction to Magnetic Materials* (Addision Wesley, Massachusetts, 1992)
10. E. W. Lee, Rept. Prog. Phys. **18**, 1848 (1955)
11. J. W. Shilling, G. L. Houze, IEEE Trans. Magn. **10**, 195 (1974)
12. J. E. Fisher, J. Goddaed, J. Phys. Soc. Jpn. **25**, 413 (1968)