Magnetostriction Behaviors of Single- and Poly-Crystalline Ni/Ni-Co Bi-Layer Films

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Ni(tNi nm)/Ni50Co50(100–tNi nm) bi-layer films are prepared on Cu/Pd/MgO(001) single-crystal substrates at 300 °C and on Cu/Pd/glass substrates at room temperature by varying the layer thickness, tNi, in a range of 0–100 nm. The effect of layer thickness ratio on the magnetostriction is investigated. As tNi value increases from 0 to 100 nm, the magnetostriction coefficient observed for single-crystal film along fcc[100], λfcc, monotonically decreases from a positive value of +1 × 10^-4 (tNi = 0 nm) to a negative value of –6 × 10^-5 (tNi = 100 nm), whereas that measured along fcc[111], λfct, remains almost similar, 4 × 10^-5 to 2 × 10^-5. The magnetostriction coefficient of poly-crystalline film decreases from –3 × 10^-6 to –2 × 10^-5 with increasing tNi value from 0 to 100 nm. The present study has shown that control of magnetostriction coefficient is possible by combining materials with positive and negative coefficients.

Key words: Ni, Ni-Co alloy, thin film, magnetostriction coefficient, λfcc, λfct

1. Introduction

Soft magnetic materials have been used for applications to magnetic devices, transformers, etc. In order to improve the performance, it is required to reduce the magnetostriction that causes vibration and is one of the origins for energy loss.

Ni-based alloys with fcc structure such as Ni-Fe and Ni-Co are typical soft magnetic materials. In the Ni-Co binary alloy system, fcc structure can be stabilized in the full compositional range through hetero-epitaxial thin film growth on Cu underlayer1–3. In our previous study4,5, Ni100–xCox single-crystal films of fcc(001) orientation were prepared on Cu(001) underlayers by varying Co content, x, from 0 to 100 at. %. The magnetostriction coefficient of λ0 increased from a negative value of –3 × 10^-5 to a large positive value of +1 × 10^-4 with increasing Co content, whereas that of λ111 stayed almost constant around –2 × 10^-5. The compositional dependences were similar to the case of bulk Ni-Co alloy system4,6.

Magnetostriction seems to be reduced by combining materials with negative and positive magnetostriction coefficients. In the present study, single6 and poly-crystalline Ni/Ni50Co50 bi-layer films are prepared by varying the layer thicknesses while keeping the total thickness at 100 nm. The effect of layer thickness ratio on the magnetostriction coefficient is investigated.

2. Experimental Procedure

2.1 Film preparation

A radio-frequency magnetron sputtering system equipped with a reflection high-energy electron diffraction (RHEED) facility was used for film formation. Single6 and poly-crystalline films were respectively prepared on MgO(001) single-crystal substrates of 0.3 mm thickness at 300 °C and on glass substrates of 0.14 mm thickness at room temperature. 5-nm-thick Pd buffer layers and 10-nm-thick Cu underlayers were sequentially deposited on the substrates. Then, Ni(tNi nm)/Ni50Co50(100–tNi nm) bi-layer films were formed on the underlayers. The Ni and the Ni50Co50 layer thicknesses were varied from 0 to 100 nm. The total bi-layer film thickness was fixed at 100 nm to obtain enough bending to detect by using our magnetostriction measurement system. The sputter deposition condition was similar to that of our previous work7,8.

The crystal structure and the crystallographic orientation were determined by RHEED. The resulting film structure was investigated by X-ray diffraction (XRD) with Cu-Ka radiation (wave length: 0.15418 nm). The magnetization curves were measured by vibrating sample magnetometry.

2.2 Magnetostriction measurement

Magnetostriction was measured by employing a laser displacement meter fixed on a vibration isolated table to measure the small cantilever bending with an accuracy of 1 nm. The output sensitivity was 1 V per 0.2 μm bending. A rotating magnetic field of 1.2 kOe was applied in the film plane. The rotating speed was 5 rpm.

Magnetostriction coefficient, λ, is expressed6,9 as

\[
\lambda = \frac{\Delta S}{(1 + \nu_c)} I / (2 I t t_i E_t (1 - \nu_r)),
\]

(1)
where $\Delta S$ is the measured bending, $L$ is the distance between laser beam points, $t$ is the thickness, $E$ is the Young’s modulus, $\nu$ is the Poisson’s ratio, and the subscripts of $f$ and $s$ respectively refer to film and substrate.

When the magnetostriction of fcc(001) single-crystal film is measured under a rotating magnetic field, a relationship among $\lambda$, $\lambda_{100}$, and $\lambda_{111}$ is given \(^7\) as the following formula,

$$
\lambda = (3/2) \lambda_{100} \left[ a^2 \beta_1^2 + a^2 \beta_2^2 + a^2 \beta_3^2 - (1/3) \right] + 3 \lambda_{111} (a_1 a_2 b_1 + a_2 a_3 b_2 + a_3 a_1 b_3), \quad (3)
$$

where $a$ is the cosine of angle between the magnetization and the three crystallographic axes ($a$, $b$, $c$) and $\beta$ is the cosine of angle between the direction of relative change in length and the axes. When the observation directions are fcc[100] and fcc[110], ($\lambda_{100}$, $\lambda_{110}$) values are respectively (1, 0, 0) and (1/2, 1/2, 0), whereas ($a_1$, $a_2$, $a_3$) values are (cos$\psi$, sin$\psi$, 0) for both cases. Here, $\psi$ is the angle of magnetization direction with respective to fcc[100]. By substituting $a$ and $\beta$ values to Eq. 2, the following relations are given,

$$
\lambda = (1/4) \lambda_{100} (1 + 3 \cos 2\psi), \quad (3)
$$

$$
\lambda = (1/4) \lambda_{100} + (3/4) \lambda_{111} \sin 2\psi. \quad (4)
$$

### 3. Results and Discussion

Figures 1(a)–(e) show the RHEED patterns observed for Ni($t_{Ni}$ nm)/Ni$_{50}$Co$_{50}$(100–$t_{Ni}$ nm) films with different $t_{Ni}$ values formed on Cu/Pd/MgO(001) substrates. Here, the incident electron beam is parallel to Cu[100] and MgO(100). Figure 1(f) shows the schematic diagram of diffraction pattern calculated for fcc(001) single-crystal surface with reconstructed structure of (2×2). The observed diffraction patterns are in agreement with the simulated pattern. Therefore, Ni($t_{Ni}$ nm)/Ni$_{50}$Co$_{50}$(100–$t_{Ni}$ nm) single-crystal films grow epitaxially on the underlayers. The crystallographic orientation relationship is determined as Ni(001)[100] || Ni$_{50}$Co$_{50}$(001)[100] || Cu(001)[100]. Figure 2 shows the 2$\theta$ scan out-of-plane XRD patterns, fcc(002) and fcc(004) reflections from the Ni($t_{Ni}$ nm)/Ni$_{50}$Co$_{50}$(100–$t_{Ni}$ nm) films are recognized around the diffraction angles, 2$\theta$, of 51° and 122°, respectively. It is noted that fcc(004) reflections from the Ni and the Ni$_{50}$Co$_{50}$ layers are separately observed for the bi-layer films [Figs. 2(b)–(d)]. The result indicates that atomic mixing at the Ni/Ni$_{50}$Co$_{50}$ interface is not so high. The lattice constants of Ni layers in films with $t_{Ni}$ = 25, 50, 75, and 100 nm are estimated to be 0.3514, 0.3516, 0.3518, and 0.3519 nm, whereas those of Ni$_{50}$Co$_{50}$ layers in films with $t_{Ni}$ = 0, 25, 50, and 75 nm are calculated to be 0.3528, 0.3529, 0.3529, and 0.3528 nm, respectively.

These values are similar to the bulk values ($a_{Ni}$ = 0.3524 nm, $a_{Ni_{50}Co_{50}}$ = ($a_{Ni}$) + ($a_{Ni-Co}$)/2 = 0.3534 nm), suggesting that the strains in Ni and Ni$_{50}$Co$_{50}$ layers are small.
Properties. The single- and poly-crystalline films are poly-crystalline films show isotropic in-plane magnetic in-plane directions (not shown here). The there were no differences in the curves measured along fcc\[110\] and fcc\[100\] and measured no clear differences in the magnetization curves when the magnetic field is applied along fcc\[110\], in-plane magnetic anisotropy, which is reflecting the magnetocrystalline anisotropy of fcc crystal with the nearly saturated at a magnetic field of 1.2 kOe, which is observed. The results show that poly-crystalline films with fcc structure are formed on glass substrates. Figures 3(a-1)–(e-1) and (a-2)–(e-2), respectively, show the RHEED and the XRD patterns of Ni(\(t_{Ni}\) nm)/Ni\textsubscript{50}Co\textsubscript{50}(100–\(t_{Ni}\) nm) films formed on Cu/Pd/glass substrates. Ring-like RHEED patterns and XRD patterns showing fcc(111) and fcc(200) reflections are observed. The vertical dotted lines show the strength of magnetic field (±1.2 kOe) used for magnetostriction measurements. Figure 4 shows the in-plane magnetization curves of single-crystal films. The films are easily magnetized when the magnetic field is applied along fcc[110], whereas the magnetization curves measured along fcc[100] saturate at higher magnetic fields. There were no clear differences in the magnetization curves measured along fcc[100] and fcc[010] and measured along fcc[110] and fcc[1\(\bar{1}\)0] (not shown here). Therefore, the single-crystal films show four-fold symmetries in in-plane magnetic anisotropy, which is reflecting the magnetocrystalline anisotropy of fcc crystal with the easy magnetization axes parallel to fcc<111>. Figure 5 shows the magnetization curves of polycrystalline films. There were no differences in the curves measured along in-plane directions (not shown here). The polycrystalline films show isotropic in-plane magnetic properties. The single- and polycrystalline films are nearly saturated at a magnetic field of 1.2 kOe, which is used for magnetostriction measurements.

Figures 6(a) and (b) show the output waveforms of magnetostriction of Ni\textsubscript{50}Co\textsubscript{50} (\(t_{Ni}=0\) nm) and Ni (\(t_{Ni}=100\) nm) single-crystal films measured along fcc[100] under the in-plane rotating magnetic field of 1.2 kOe, respectively. Phase of waveform is different between the two cases, suggesting that the Ni\textsubscript{50}Co\textsubscript{50} and the Ni films have positive and negative \(\lambda_{100}\) values, respectively. Figures 6(a)–(d) show the output waveforms of...
films with $t_{Ni} = 60, 62, \text{ and } 75$ nm. These films show

$$\lambda$$

values of Ni($t_{Ni}$ nm)/Ni$_{50}$Co$_{50}$(100–$t_{Ni}$ nm) films with

$\zeta_{Ni} = (a) 0, (b) 25, (c) 50, (d) 60, (e) 62, (f) 75, (g) 85, \text{ and } (h) 100$ nm formed on Cu/Pd/MgO(001) substrates. The observation direction is along fcc[110].

Figures 6(d)–(f) show the waveforms of single-crystal films with $t_{Ni} = 0, 25, 50, \text{ and } 60$ nm. As $\lambda$ value increases from 0 to 60 nm, the amplitude of output gradually decreases, which indicates that the $\lambda_{100}$ value decreases. The magnetostriction is apparently reduced by combing the Ni$_{50}$Co$_{50}$ crystal with positive $\lambda_{100}$ value and the Ni crystal with negative $\lambda_{100}$ value. Figures 6(d)–(f) show the waveforms of single-crystal films with $\zeta_{Ni} = 60, 62, \text{ and } 75$ nm. These films show small amplitudes. The phase of waveform reverses with increasing $t_{Ni}$ value from 60 to 75 nm. The sign of magnetostriction changes from positive to negative around $t_{Ni} = 62$ nm. Figures 6(f)–(h) show the waveforms of single-crystal films with $t_{Ni} = 75, 85, \text{ and } 100$ nm. The amplitude increases with increasing $t_{Ni}$ value. Figure 7(a) summaries the $\lambda_{100}$ values of single-crystal films as a function of $t_{Ni}$. Here, the $\lambda_{100}$ values are calculated by using Eq. 3. The $\lambda_{100}$ value monotonically decreases from a positive value of $+1 \times 10^{-4}$ ($t_{Ni} = 0$ nm) to a negative value of $-6 \times 10^{-5}$ ($t_{Ni} = 100$ nm) with increasing $t_{Ni}$ value. Figure 8 shows the waveforms of single-crystal films with different $t_{Ni}$ values measured along [110]. The amplitude and the phase of waveform do not vary depending on $t_{Ni}$ value. Figure 7(b) shows the variation of $\lambda_{111}$ value as a function of $t_{Ni}$, where the $\lambda_{111}$ values are calculated by using Eq. 4. The $\lambda_{111}$ value slightly increases from $-4 \times 10^{-5}$ to $-2 \times 10^{-5}$, as $t_{Ni}$ value increases from 0 to 100 nm.

Figure 9 shows the waveforms of poly-crystalline films. As $t_{Ni}$ value increases, the amplitude increases, though the phase dose not change. Figure 7(c) shows the $\lambda$ values, which are estimated by using Eq. 1. The $\lambda$ value decreases from $-3 \times 10^{-6}$ to $-2 \times 10^{-5}$ with increasing $t_{Ni}$ value from 0 to 100 nm.

The present study demonstrates that reduction of
magnetostriction is possible by combining materials with negative and positive magnetostriction coefficients.

4. Conclusion

Single- and poly-crystalline Ni/Ni_{50}Co_{50} bi-layer films are prepared by varying the layer thicknesses while keeping the total thickness at 100 nm. The effect of layer thickness ratio on the magnetostriction is investigated. The $\lambda_{100}$ values of Ni_{50}Co_{50} ($t_{Ni} = 0$ nm) and Ni ($t_{Ni} = 100$ nm) single-crystal films are positive ($+1 \times 10^{-4}$) and negative ($-6 \times 10^{-5}$), respectively. As $t_{Ni}$ value increases from 0 to 62 nm, the $\lambda_{100}$ value decreases from positive to nearly 0. With further increasing $t_{Ni}$ value, the $\lambda_{100}$ value decreases to negative. On the other hand, the $\lambda_{111}$ value remains almost similar ($-4 \times 10^{-5}$ to $-2 \times 10^{-5}$). The $\lambda$ value of poly-crystalline film decreases from $-3 \times 10^{-6}$ to $-2 \times 10^{-5}$ with increasing $t_{Ni}$ value from 0 to 100 nm. The present study demonstrates that reduction of magnetostriction is possible by combining materials with negative and positive magnetostriction coefficients.

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