Magnetostriction of Exchange Coupled PdCo/Fe Bilayers

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The bilayers consisting of PdCo (magnetostrictive alloy) and Fe (soft magnetic alloy), PdCo (x nm) / Fe (y nm) in the layer thickness range of $10 \leq x \leq 25$ and $0 \leq y \leq 30$ have been fabricated. A drastic magnetic softening is achieved for the bilayers that the PdCo layer thickness $x \leq 15$ nm and the Fe layer thickness $y \geq 20$ nm, comparing with PdCo films. More than 70% of the saturated magnetostriction is obtained even at 50 Oe. The maximum magnetostriction of the bilayers at 50 Oe is about -70×10^{-6} . This drastic improvement of the magnetostriction response to the magnetic field occurs when both the PdCo and Fe magnetization are in-plane.

Key words: exchange coupling, magnetostriction, magnetic field response, PdCo, Fe, bilayers

1. Introduction

High magnetostrictive alloys, such as TbFe₂, need high magnetic fields to achieve the large strains due to their relatively high magnetocrystalline anisotropy¹⁾. Therefore, for the alloys, a magnetic softening is required to extend their practical applications. Many efforts have been made to reduce the magnetocrystalline anisotropy of the alloys. The pseudobinary alloy of Tb_{0.3}Dy_{0.7}Fe₂, named as Terfenol-D was found to show low magnetocrystalline anisotropy. However the saturation field (~ 15 kOe) is still high¹⁾.

Recent approach of the magnetic softening for high magnetostrictive alloys has used the exchange coupling between the magnetostrictive alloys and a soft magnetic alloy. The multilayered systems consisting of a magnetostrictive alloy and a soft magnetic alloy, TbFe / FeB sandwich films²⁾ and TbFe / FeB multilayers³⁾ have been reported. In these systems, the reduction of the coercive force was achieved. However, the magnetostriction response to the applied magnetic field was still insufficient. Moreover, the effect of the magnetic moment configuration between a magnetostrictive alloy and a soft magnetic alloy on the magnetic softening is not fully understood.

In the present study, the bilayers consisting of PdCo (magnetostrictive alloy) and Fe (soft magnetic alloy), PdCo (x nm) / Fe (y nm) have been fabricated with various layer thickness. The effect of the exchange coupling between PdCo and Fe in the bilayers on the magnetostrictive properties is investigated. The reason why we select a PdCo

alloy as a magnetostrictive alloy is that the deterioration of the magnetostrictive properties by decreasing the layer thickness is considered to be prevented by its better corrosion resistance.

2. Experimental

The PdCo (x nm) / Fe (y nm) bilayers were fabricated in the layer thickness range, $10 \leq x \leq 25$ and $0 \leq y \leq 30$. The Fe and PdCo layers were deposited on a glass substrate in this order by rf magnetron sputtering with a Fe target and by rf sputtering with a composite target (Co tips on a Pd disk), respectively.

The magnetostriction of the bilayers was determined by a cantilever method⁴⁾ in the rotating in-plane magnetic field up to 2 kOe. The bilayers for the magnetostriction measurement were deposited on glass substrates 20 mm long, 10 mm wide and 0.1 mm thick. The samples were rigidly clamped at one of the 10 mm wide edges and the deflection of another edges was determined by measuring the displacement of a He-Ne laser beam, reflected from the film surface onto a position sensitive photo diode.

The magnetization curves of the bilayers were measured by an alternating gradient magnetometer. The structure was analyzed using a X-ray diffractometer and the surface roughness of the bilayers was measured by an atomic force microscopy (AFM).

3. Results and Discussion

From the X-ray analysis, the fabricated PdCo/Fe bilayers were found to be composed of a bcc Fe layer and a fcc PdCo layer. The lattice constant of the PdCo layers is near to that of the bulk Pd₈₀Co₂₀ alloy⁵⁾. Therefore, the composition of the PdCo layer is thought to be about Pd₈₀Co₂₀. The grain size of both layers is about 7~15 nm from Scherrer's equation.

The surface roughness of the bilayers was found to decrease with increasing the Fe layer thickness from the AFM measurement. For the PdCo (x nm) / Fe (y nm) bilayers with the Fe layer thickness $y \leq 15$ nm, the surface roughness of the bilayers is larger than their Fe layer thickness, whereas the bilayers with $y \geq 20$ nm have a relatively smooth surface.

Figure 1 shows the magnetostriction changes measured

Fig.1 Magnetostriction changes measured in the film plane at 50 Oe against the angle θ between the measuring direction and the magnetic field direction for the PdCo (15 nm) / Fe (y nm) bilayers.

in the film plane at 50 Oe against the angle θ between the measuring direction and the magnetic field direction for the PdCo (15 nm) / Fe (y nm) bilayers. As seen from the figure, the θ dependence of the magnetostriction is not clear for the PdCo single layer ($y = 0$ nm) and the bilayers with a small Fe layer thickness ($y \leq 10$ nm). However, with increasing Fe layer thickness ($y \geq 25$ nm), the magnetostriction changes with $-\cos 2\theta$. These results mean that the magnetization of the bilayers with $y \geq 25$ nm is aligned to the magnetic field direction even at 50 Oe and the bilayers show a negative magnetostriction. For these bilayers, it was found that a magnetic softening is achieved by making the bilayer structure.

Figure 2 shows the applied magnetic field dependence of the planer magnetostriction for these PdCo (15 nm) / Fe (y nm) bilayers. The value of the planer magnetostriction was calculated by using Klokholm's formula⁶⁾ based on the bending-beam theory. Here, the total bilayer thickness (a) and the PdCo layer thickness (b) were used as the film thickness in Klokholm's formula. The latter planer magnetostriction shown in Fig.2(b) corresponds to the magnetostriction normalized by the PdCo layer thickness. In the same figure, the magnetostriction of a PdCo single layer is also shown.

As seen in Fig.2(a), the saturated magnetostriction of bilayers is smaller than that of the single layer. However, in weak magnetic fields, the magnetostriction of most bilayers rapidly increases and the magnetostriction of the bilayers is larger than that of the single layer. For the bilayers with

Fig.2 Planer magnetostriction, $\frac{2}{3} \left(\left(\frac{\delta \ell}{\ell} \right)_{//} - \left(\frac{\delta \ell}{\ell} \right)_{\perp} \right)$ of

the PdCo (15 nm) / Fe (y nm) bilayers vs applied magnetic field. The planer magnetostriction was calculated by the total bilayer thickness (a) and normalized by the PdCo layer thickness (b).

$y \geq 25$ nm, more than 70% of the saturated magnetostriction is obtained even at 50 Oe. The maximum magnetostriction of the bilayers at 50 Oe is about -70×10^{-6} . As the results, it was found that the magnetostriction response to magnetic field is improved by combining the magnetostrictive alloy with the magnetic soft layer.

As seen in Fig.2(b), the normalized magnetostriction of the bilayers with the Fe layer thickness $y \geq 25$ nm is about -200×10^{-6} . This value is nearly the same as the saturated magnetostriction constant λ_s of the bulk $\text{Pd}_{80}\text{Co}_{20}$ alloy⁷⁾. Therefore, the value of these bilayers could be explained by the magnetostriction of the PdCo layer.

However, for the bilayers with a small Fe thickness, the normalized magnetostriction is smaller than the magnetostriction of the bulk PdCo alloy. From the AFM results mentioned above, these low magnetostrictive bilayers with a small Fe thickness have a rough surface. Therefore, for these low magnetostrictive bilayers, it is considered that the homogeneous and continuous distortion do not occur on the film plane due to the rough interface between these layers.

Figure 3 shows the in-plane ($//$) and perpendicular ($\perp$) hysteresis loops for the PdCo (15 nm) / Fe (y nm) bilayers. Here no demagnetizing field correction is done in these

Fig. 3 Magnetization vs the magnetic field parallel (//) and perpendicular ($\perp$) to the film plane for the PdCo (15 nm) / Fe (y nm) bilayers.

loops. As seen from these figures, it was found that all bilayers have an in-plane anisotropy on the whole. For the in-plane hysteresis loops, the saturation field of the magnetization decreases with increasing Fe layer thickness. On the other hand, the perpendicular hysteresis loops have two magnetization components. One is saturated at high magnetic field above 20 kOe. The other is saturated at lower magnetic field about 3 kOe. The former magnetization component is considered to be mainly caused by the Fe layer magnetization because the saturated field is near the anisotropy field of a Fe film. Therefore the Fe layer magnetization is thought to be in-plane. On the other hand, the latter magnetization component is considered to be associated with the PdCo layer magnetization and the shape of low field PdCo magnetization changes with the Fe layer thickness. The bilayer with $y = 20$ nm shows a rectangular hysteresis, whereas the other bilayers show a reversible hysteresis. Here, it is considered that the former and the latter PdCo bilayers have perpendicular and in-plane magnetization, respectively.

Comparing these results with above mentioned magnetostrictive properties, it was found that the effect of the magnetic softening by combining with the soft magnetic layer is dominant when both the PdCo and Fe magnetization are in-plane. In this case, the magnetization process of the PdCo layer is considered to be caused by the domain wall motion started from the Fe layer. On the other hand, when

the PdCo layer shows the perpendicular magnetization, the magnetization process of the PdCo layer is thought to be caused by the magnetization rotation overcoming the perpendicular magnetic anisotropy. Therefore, the former process is considered to need lower magnetic fields than the latter one.

The change of the PdCo magnetic easy axis is thought to be caused by the change of the internal stress in the films, because the magnetic anisotropy of PdCo films is sensitive to the internal stress in the films⁸⁾.

For our fabricated bilayers, the PdCo (x nm) / Fe (y nm) bilayers with $x \leq 15$ nm and $y \geq 20$ nm show drastic improvement of the magnetostriction response to the magnetic field. All the bilayers with $x \geq 20$ nm have the perpendicular magnetization of PdCo, therefore no drastic magnetic softening occurs.

Now we try to fabricate the bilayers with a smooth interface and a controllable magnetic easy axis of the PdCo layer. The effect of the magnetic softening for these bilayers will be reported in elsewhere.

4. Conclusions

PdCo (x nm) / Fe (y nm) bilayers in the layer thickness range, $x \leq 15$ and $y \geq 20$ nm show the drastic improvement of the magnetostriction response to the magnetic field. More than 70% of the saturated magnetostriction is obtained even at 50 Oe. The maximum magnetostriction of the bilayers at 50 Oe is about -70×10^{-6} . This drastic magnetic softening occurs when both the PdCo and Fe magnetization are in-plane.

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