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Induced Uniaxial Magnetic Anisotropy Field in Very Thin NiFe and CoZrNb Films

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***Abstract*—The induced uniaxial anisotropy field in thin permalloy and CoZrNb films was investigated. The value of the induced anisotropy field H_k of permalloy films of 77–81 at%Ni concentration was found to decrease as the film thickness decreased below 20 nm, even after annealing procedure in a magnetic field. The value of H_k at 3 nm was found to be nearly half that at 20 nm. A series of CoZrNb amorphous films showed a qualitatively similar thickness dependence of H_k. Moreover, a similar reduction of H_k was observed at 77 K. On the other hand, the easy axis of $Ni_{79}Fe_{21}$ films thinner than 20 nm was switched to the field direction by annealing with a magnetic field perpendicular to the easy axis of the as-deposited films, even at a low annealing temperature of 160°C. The absolute value of H_k in the 3 nm film after annealing at 160°C was nearly as large as in the as-deposited film. It is likely that the rearrangement of atom pairs can easily occur in the surface region, resulting in the switching of the easy axis to the annealing field direction in very thin films.**

***Index Terms*—Induced uniaxial anisotropy field, very thin permalloy film, very thin CoZrNb amorphous film, easy axis of magnetization.**

I. INTRODUCTION

FILM thickness reduction in GMR or TMR films has been one of the vital issues to realize a high resolution read head for hard disks. It is likely that the induced uniaxial anisotropy K_u of permalloy and amorphous films results from a directional atom-pair ordering mechanism like that in bulk alloys [1], and the kinetics of formation of K_u by annealing in a magnetic field have been examined [2]–[4]. The value of K_u in permalloy and amorphous thin films is likely to be influenced by a thickness reduction because of surface effects like those which affect the saturation magnetization [5]. In the present study, we examined the thickness dependence of the induced anisotropy field H_k in permalloy and CoZrNb films in the thickness range from 3 nm to 200 nm, and the induced uniaxial anisotropy in very thin soft magnetic films.

II. EXPERIMENTAL PROCEDURE

Permalloy (77, 79, and 81 at%Ni-Fe) films sandwiched by seed and protective Ta layers, were deposited by RF sputtering on glass substrates (Corning 7059, thermal expansion coefficient $\alpha = 46 \times 10^{-7}/°C$) or quartz glass substrates ($\alpha = \sim 0$). A static magnetic field of 240 Oe was applied in the film plane during the film deposition. The thickness of the seed and protective Ta layers was 5 nm. Ta/$Co_{90}Nb_6Zr_4$/Ta films were also fabricated under the same conditions. Film thicknesses were controlled by deposition times, and confirmed using glancing-incidence X-ray diffraction analysis. The films were annealed in a vacuum furnace with a magnetic field (200 Oe) applied along the easy or hard axes of the films. Magnetization loops at room temperature were measured by a magneto-optic Kerr loop tracer, and the anisotropy field of the films was measured by Torok's method [6]. Magnetization loops at temperatures lower than room temperature (down to 77 K) were measured by VSM, and the anisotropy field at these temperatures was calculated from the slope of the magnetization loops along the hard axis. Film magnetostriction was measured by an optical-cantilever method for films of 300 nm thickness.

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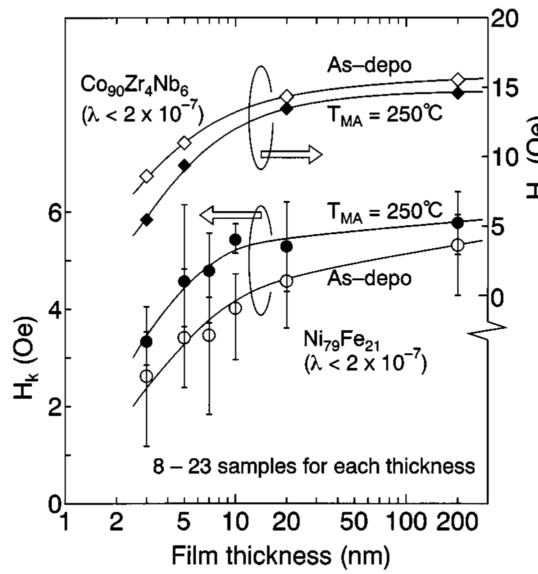

Fig. 1. Thickness dependence of H_k of the $Ni_{79}Fe_{21}$ and CoZrNb films. In the fig., the results for as-deposited films and films annealed with a magnetic field applied parallel to the original easy axis ($250°C \times 6$ h) are shown.

III. RESULTS AND DISCUSSION

A. Thickness Dependence of H_k

Fig. 1 shows the thickness dependence of the anisotropy field H_k in the $Ni_{79}Fe_{21}$ and $Co_{90}Zr_4Nb_6$ films. In the figure, two series of films are shown for each material; as-deposited films and films annealed at $250°C \times 6$ hrs with the magnetic field parallel to the easy axis of the films. It was established that an annealing time of more than 1 hour does not change the magnitude of H_k at this temperature. The value of H_k was found

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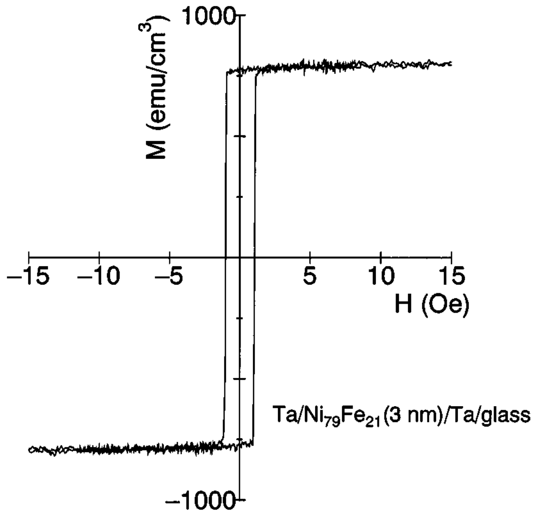

Fig. 2. A representative magnetization loop of the as-deposited 3 nm $Ni_{79}Fe_{21}$ films.

to decrease significantly as the film thickness decreased below 20 nm, and the value of H_k at 3 nm was found to be nearly half that at 20 nm. The series of CoZrNb films show a similar thickness dependence of H_k as seen in the Fig. although the values of H_k are nearly three times as large as those of the $Ni_{79}Fe_{21}$ films. The decrease of H_k with a reduction in thickness is a common behavior.

The XRD patterns of the $Ni_{79}Fe_{21}$ films indicated that these films have a fcc-(111) preferred grain orientation with the $\langle 111 \rangle$ direction perpendicular to the film plane, and no significant change of preferred grain orientation was found when the film thickness was reduced. A representative magnetization curve of the as-deposited 3 nm $Ni_{79}Fe_{21}$ films is shown in Fig. 2. The magnetization loop indicates that the thin film maintains a saturation magnetization of ~ 800 emu/cm^3, which is almost the same as that of thick films, with a large squareness of ~ 1.0 and a small coercivity along easy magnetization direction of ~ 1.0 Oe. This indicates that the films are laterally continuous structure even at a thickness of 3 nm. The values of film magnetostriction of the $Ni_{79}Fe_{21}$ and CoZrNb films were negligibly small, less than 2×10^{-7}. Moreover, a series of $Ni_{79}Fe_{21}$ films deposited on quartz substrates showed nearly the same thickness dependence of H_k. This suggests that the H_k reduction is not simply caused by a magneto-elastic effect due to a residual stress at the interface between the film and the substrate.

Fig. 3 shows the thickness dependence of H_k in $Ni_{77}Fe_{23}$ and $Ni_{81}Fe_{19}$ films, respectively. The result for the $Ni_{79}Fe_{21}$ films is shown as a dotted line for comparison. Here, the values of film magnetostriction were 2.3×10^{-6} for the $Ni_{77}Fe_{23}$ films and -3.7×10^{-6} for the $Ni_{81}Fe_{19}$ films. Almost the same thickness dependence of H_k was found to exist in both $Ni_{77}Fe_{23}$ and $Ni_{81}Fe_{19}$ films, except for slight differences in the magnitude of H_k, depending on the composition [1], although the signs of film magnetostriction of these compositions are different from one other. This result supports the conclusion that the decrease of H_k with a reduction in thickness is not due to the magneto-elastic effect.

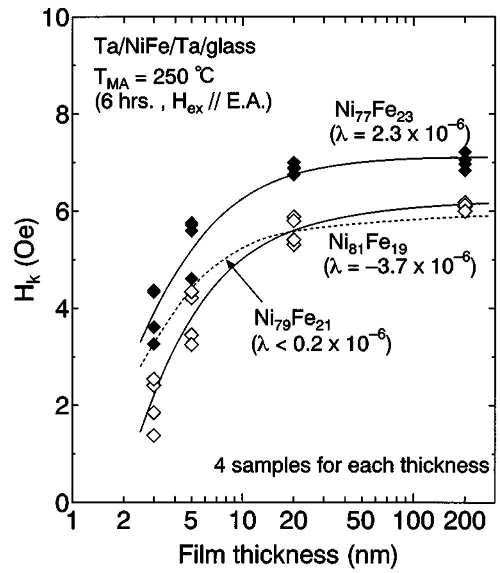

Fig. 3. Thickness dependence of H_k of the $Ni_{77}Fe_{23}$ and $Ni_{81}Fe_{19}$ films.

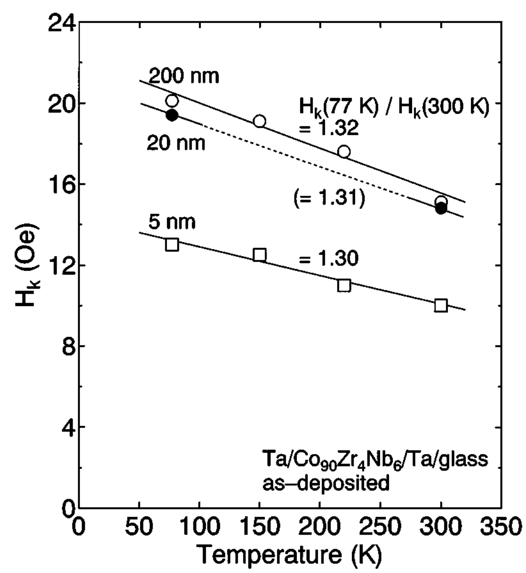

Fig. 4. Temperature dependence of H_k for the CoZrNb films with various film thicknesses.

Fig. 4 shows the temperature dependence of H_k in the as-deposited CoZrNb films with thicknesses of 200, 20 and 5 nm. The values of H_k of these films increase almost linearly as the temperature decreases. The value of H_k at 77 K, $H_k(77\ \mathrm{K})$, of the 20 nm film is ~ 20 Oe, which is almost the same as that of the 200 nm film. However, the value of $H_k(77\ \mathrm{K})$ of the 5 nm film is ~ 13 Oe, which is smaller than the others. These temperature dependencies of H_k result in a similar thickness dependence of H_k at 77 K as that at 300 K as shown in Fig. 5. The important point is that the ratio of $H_k(77\ \mathrm{K})$ to $H_k(300\ \mathrm{K})$ is not thickness dependent, having an almost constant value of 1.3–1.32. This result implies that there is no significant difference in the origin of the induced anisotropy between the very thin and thick films, and the reduction of H_k in very thin films is caused by additional factors.

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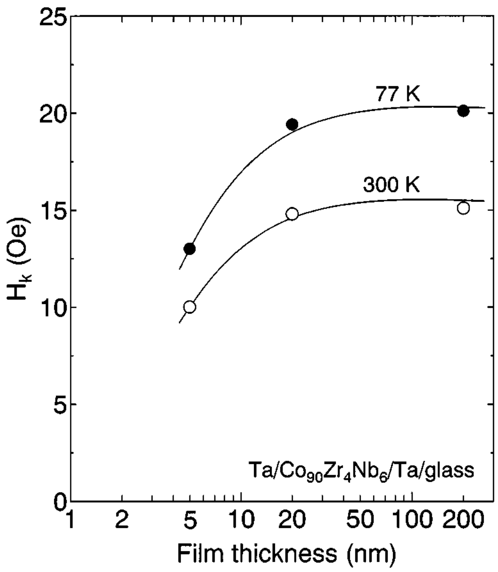

Fig. 5. Thickness dependence of H_k for the CoZrNb films at 77 K and 300 K.

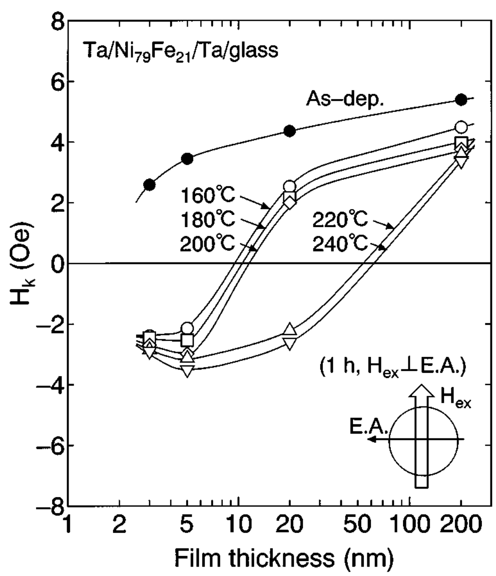

Fig. 6. Thickness dependence of H_k for the Ta/$Ni_{79}Fe_{21}$/Ta films. Here, the results for films annealed with a magnetic field applied perpendicular to the original easy axis are shown.

B. Easy Axis Direction

Fig. 6 shows the thickness dependence of H_k in $Ni_{79}Fe_{21}$ films annealed at various temperatures with the magnetic field applied parallel to the hard axis of the as-deposited film. In this study one sample at each thickness was subjected to the annealing at temperature increments of 20°C, and for one hour at each temperature, and the H_k value after annealing at each temperature is plotted in the figure. A negative value of H_k means that the easy axis is oriented in the direction of the field during annealing. The H_k values of these films before annealing (as-deposited) are also shown for comparison.

Annealing at 220°C reduces the H_k value at 200 nm thickness, but the easy axis still remains in its original direction. At this same annealing temperature, the easy axis of the 20 nm film is switched to the annealing field direction. It should be noted that the direction of H_k in films thinner than 5 nm is switched to the annealing field direction even at a low annealing temperature of 160°C. The absolute value of H_k in the 3 nm films after annealing at 160°C is nearly as large as that in the as-deposited film.

It is likely that the rearrangement of atom-pairs [1] can easily occur in the surface region, resulting in the switching of the easy axis to the annealing field direction in the very thin films. Very high diffusion speed of atoms at film interfaces or grain boundaries, compared to the solid diffusion speed, probably accounts for this easier rearrangement of atom-pairs in very thin films. The higher mobility of surface atoms disrupts the alignment of atom-pairs parallel to the field direction during the film deposition and annealing process, resulting in the smaller induced anisotropy of very thin films. Another possible cause of the H_k reduction of the very thin films is the surface anisotropy [7] through a change of film magnetostriction [8]. However, the present thin films maintain good soft magnetic properties even at a thickness of 3 nm as shown in Fig. 2, whereas a significant change of film magnetostriction is likely to degrade these soft magnetic properties. From the technical point of view, the decrease of H_k with the thickness reduction will be a problem for read heads in the future. The low H_k will result in unstable magnetization rotation at high frequency. Moreover, the easy change of easy axis at relatively low temperature will be a problem to realize long term reliability at the operating temperature of hard disk drives. A further investigation of the induced uniaxial anisotropy in very thin films, from the physical and technical points of view, is probably vital to realize read heads in the future.

IV. Conclusion

The induced anisotropy field H_k in thin permalloy films of 77–81 at%Ni concentration was found to decrease as the film thickness decreased below 20 nm, even after an adequate annealing procedure with a magnetic field. The value of H_k at 3 nm was found to be nearly half that at 20 nm. A series of CoZrNb amorphous films showed a qualitatively similar thickness dependence of H_k. Moreover, this reduction of H_k was similarly observed at 77 K. On the other hand, the easy axis of permalloy films thinner than 5 nm was switched to the field direction by annealing with a magnetic field perpendicular to the easy axis of the as-deposited films, even at a low annealing temperature of 160°C. It is likely that the rearrangement of atom pairs can easily occur in the surface region, resulting in the switching of the easy axis to the annealing field direction in very thin films.

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