Fe-Si/SiO₂ AND Fe-Si-N/SiO₂ MULTILAYER FILM
FOR SINGLE-POLE TYPE PERPENDICULAR MAGNETIC RECORDING HEAD

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Abstract --- In perpendicular magnetic recording using a single-pole head and a Co-Cr/Fe-Ni double-layer medium, it is very useful to increase the saturation induction, B_s , of the main-pole film of the head in order to realize not only a higher recording sensitivity but also a higher recording bit-density because of strong head-to-medium magnetic interaction. In this paper, the necessity of a higher B_s film for a single-pole head is shown theoretically and experimentally, and moreover the characteristics of single-pole heads made of Fe-Si/SiO₂ and Fe-Si-N/SiO₂ multilayer thin films having higher B_s of about 20 kGauss are described.

INTRODUCTION

In magnetic recording system, one of the most important features is easily rewritable. For magnetic head materials, therefore, it is required that not only the permeability but also the saturation induction is as high as possible, because of the better rewritability and a higher reproduced signal to noise ratio. In perpendicular magnetic recording, moreover, the higher saturation induction of the main-pole film of a single-pole head plays more important role to achieve an ultra-high density recording, because it results in the much sharper field distribution of a single-pole head owing to a stronger head-to-medium magnetic interaction [1].

In this paper, it will be described that a Fe-Si multilayer film which has a high saturation induction of about 20 kGauss is available for the main-pole film, and moreover a Fe-Si film containing a little nitrogen may be more useful for a head material because of not only a higher saturation induction but also a higher permeability.

THEORETICAL BACKGROUND

A computer simulation taking the head-to-medium magnetic interaction into account was recently accomplished by incorporating the magnetization model of a

medium into a finite element method [2]. Fig. 1 shows the field distributions of single-pole heads obtained by the computer simulation. For the simulation, it was assumed that a main-pole was made of a 0.2 microns thin magnetic film having a magnetic induction of 12 kGauss.

A single-pole type magnetic head has the structure of a open magnetic circuit in the absence of a recording medium. But the magnetic field distribution concentrates on the top of the main-pole of the head in the presence of the medium and then the magnetic field distribution of the head becomes much sharper and stronger as shown in Fig. 1(a), because the magnetic coupling arises between the magnetized medium and the main-pole [1]. This effect is more remarkable in the head made of a film having a higher saturation induction as shown in the Fig. 1(b). In Fig. 1(b), the maximum strength, B_{max} , and the sharpness, σ , of the perpendicular field distribution were plotted for current densities applied to the head coil. The σ is the gradient at the position where the perpendicular field strength is $B_{max}/2$. In the simulation, the saturation magnetization, the perpendicular coercivity and the thickness of a Co-Cr/Ni-Fe double-layer medium were assumed as 560 emu/cc, 800 Oe, and 0.1 microns, respectively. In the head made of a higher saturation induction film, not only the field strength becomes stronger but also the field gradient becomes sharper at a relatively lower record cur-

rent density. From this, it is expected that a single-pole head made of a high saturation induction film will result in a better recording characteristic at a higher bit density.

Fig. 1 (a) Field distribution of a single-pole head in the presence of a medium. (b) Recording current dependency of maximum strength and sharpness of field distributions of single-pole heads made of films having different saturation inductions.

FILM PREPARATIONS AND PROPERTIES

Fe-Si Film

Fig. 2 shows the coercivities, H_c , of Fe-Si single-layer films and the magnetization intensities, B_{20} , at 20 Oe for various Si contents of highly pure Fe-Si alloy targets whose oxygen content is less than 20 ppm. The films were made by a RF sputtering onto crystal glass substrates whose

thermal expansion coefficient are less than $-4 \times 10^{-7}/^{\circ}C$. The substrate temperature and the Ar gas pressure were 200 $^{\circ}C$ and 5 mTorr. Magnetic properties were measured by V.S.M.. At a 1.5 wt%Si-Fe target, we could obtain the minimum H_c of about 3.5 Oe and the high saturation induction of about 20 kGauss. This Si content is closer to 2 wt% at which the magnetostriction of Fe-Si films becomes zero [3], because the (110) plane of b.c.c. is oriented in the direction parallel to the film plane.

Fig. 3 shows the dependency of H_c on the thickness of Fe-Si single-layer films. The H_c remarkably increases over 0.3 microns in thickness and the in-plane uniaxial anisotropy is lost. This is because the columnar crystalline particles grows in

Fig. 2 Dependency of coercivities and saturation inductions of Fe-Si single-layer films on Si contents of targets.

Fig. 3 Dependency of coercivities on thicknesses of Fe-Si films.

the direction perpendicular to the surface with increasing film thicknesses as shown in Fig. 4. Fig. 4 show the structure of a 1 micron thick Fe-Si single-layer film observed by S.E.M. in the fractured cross section. In order to get a better soft-magnetic properties, therefore, it will be very useful that the growth of columnar crystalline particles are inhibited by making a multilayer film [4].

Fig. 4 Structure of an 1 micron thick Fe-Si film observed by SEM in the fractured cross section.

Fe-Si/SiO₂ Multilayered Film

A Fe-Si/SiO₂ multilayered film was made as follows: (1) The deposition of a Fe-Si film is interrupted at the relatively early stage of sputtering to stop the growth of particle size. (2) An another material is very thinly deposited as a interlayer on the thin Fe-Si layer to stop the epitaxial growth. (3) This procedure is repeated up to a desired total thickness for a main-pole.

Fig. 5 shows the change of coercive forces of Si-Fe/SiO₂ multilayer film versus the one-layer thicknesses. The total thickness is 0.2 microns, and very thin SiO₂ layers of 5 nm in thickness was chosen as the interlayer. We can see in the figure that the coercivity considerably decreases even in the two-layer film ($n=2$) as compared with the single-layer film ($n=1$). The coercivity more decreases to a constant value less than 1 Oe with decreasing the one-layer thickness or with increasing the number of layers, because the magneto-static coupling between each magnetic layer may be increased. The permeability reached about 2500 in the four-layer film laminated by a 0.05 microns thin Si-Fe layer. The magnetic properties could not be changed by any annealing.

Fig. 5 Coercive forces of Fe-Si/SiO₂ multilayer films versus thickness of each layer and comparison with those of single-layer films.

When magnetic material is used in place of a non-magnetic SiO₂ interlayer, the coercivity more decreases but closure-domain structures are observed as shown in Fig. 6, because an exchange coupling occurs between Si-Fe layers and magnetic interlayers. In Fig 6, magnetic domains of both Fe-Si/SiO₂ and Fe-Si/Co-Zr-Nb multilayer films are shown. They were observed by Bitter method on the rectangular samples of

Fig. 6 Comparison of magnetic domain structures in a Fe-Si singlelayer and Fe-Si/SiO₂ multilayer films.

100 microns in width whose hard magnetization axes are along the longitudinal direction. In a multilayer film using Co-Zr-Nb magnetic interlayers, we can clearly observe closure domains. This proves that the exchange coupling occurs between both the layers. The reproduced voltages of a narrow track single-pole head made of such a film will be unstable at every recordings [5]. Therefore non-magnetic interlayers like SiO_2 films must be used for a Fe-Si multilayer film.

Fe-Si-N/ SiO_2 Multilayer Film

In order to improve the soft-magnetic properties of Fe-Si films, it is also useful to make the crystalline particles minute by introducing N_2 gas into Ar gas in the sputtering [6]. Fig. 7 shows the change of coercive forces and saturation inductions of Fe-Si-N singlelayers with increasing the partial pressure ratio of N_2 gas to the total pressure of 5 mTorr. We can see that the magnetic induction decreases with increasing the partial pressure of N_2 gas. On the other hand, the coercivity also decreases remarkably and reaches the minimum of about 0.5 Oe even in the single layer at the N_2 gas pressure ratio of about 8%. At this gas pressure, an in-plane uni-axial anisotropy arises again, and an initial permeability increases in the hard magnetization direction and the relatively higher saturation induction is obtained at about 19 kGauss.

For a main-pole, thin Fe-Si-N layers were also laminated with SiO_2 interlayers of 5 nm in thickness to avoid the appearance of closure domains. Fig. 8 shows M-H loops of Fe-Si-N/ SiO_2 multilayer films measured for various annealing conditions. The annealing was done in rotational fields of 15 rpm and about 80 Oe or in non-rotational field of about 1250 Oe in vacuum of 1×10^{-5} Torr at 300 °C in order to change an anisotropy field strength, H_k . By annealing, the initial permeability can be increased up to about 7000 which is much higher than that of Fe-Si/ SiO_2 multilayer film. Fe-Si-N films are more stable to temperature as compared with Co-Zr-Nb amorphous film and therefore more suitable for a main-pole which is desired to have both a higher permeability and a higher saturation induction.

Fig. 7 Changes of coercive forces and saturation inductions versus partial pressure ratio of N_2 gas.

Fig. 8 M-H loops of Fe-Si-N/ SiO_2 multilayer film.

APPLICATION TO SINGLE-POLE HEAD

Recording Characteristics

A single-pole head [7] was fabricated after patterning Fe-Si/ SiO_2 or Fe-Si-N/ SiO_2 multilayered films to a rectangular shape for a main-pole using an ion beam etching. Recording characteristics of the heads were measured by a 5.25 inch flexible disk system using Co-Cr/Fe-Ni double-layer media composed of a 0.1 microns thick Co-Cr recording layer and a 0.5 microns thick Fe-

Ni underlayer.

To increase the reproducing resolution of a single-pole head, the main-pole must be as thin as possible, but it is difficult to make the saturation magnetization through the whole recording layer of a medium. In Fig. 9, the over-write characteristics of a single-pole head made of Fe-Si/SiO₂ multilayer film is compared with that made of an amorphous Co-Zr-Nb single-layer film whose saturation induction is about 12000. The over-write erasure values were measured as the ratio of the reproduced voltage of 40 kFRPI signals after over-writing of 90 kFRPI signals to that before the over-writing. The thicknesses of main-pole of both the heads are 0.2 microns. The perpendicular coercivity of a Co-Cr layer of medium is 770 Oe. As shown in Fig. 9, the better over-write characteristic was obtained by the head made of a Fe-Si/SiO₂ multilayer film. The difference in the over-write characteristics between both main-pole materials agrees well with that in the maximum field strengths estimated by the simulation shown in Fig. 1.

Fig. 9 Comparison of both peak-shift characteristics of single-pole head made of Fe-Si/SiO₂ multilayer film with that made of Co-Zr-Nb film.

In Fig. 10, the upper bit-densities, D_{ps20} , limited by peak-shifts were simultaneously plotted for both the heads with the over-write erasure values shown in Fig. 9. The D_{ps20} are bit-densities at which the peak-shift for NRZI 2-bits pattern reaches

20% at each record current. The hatched zones show the over-write margins of both the head made of Fe-Si and Co-Zr-Nb films. The Fe-Si head not only has a wider over-write margin to the record current but also has a higher utilizable bit-density, D_{ps20} , as compared with the head made of a Co-Zr-Nb film. Consequently, we can conclude that an Fe-Si main-pole having a higher saturation induction makes a sharper and stronger perpendicular field as shown in Fig. 1, because of the stronger head-to-medium magnetic interaction, and it results in steeper magnetization transitions in the medium or a higher recording resolution.

Fig. 10 Relationship of upper bit densities limited by 20% peak shift versus over-write erasure values at each record current.

Reproducing Characteristics

Fig. 11 shows the bit density characteristics measured by a narrow track Fe-Si/SiO₂ multilayer head of 12 microns in width. A Co-Cr layer of medium has a higher perpendicular coercivity of 970 Oe. The reproduced voltage was very stable even in such a narrow track and the higher normalized voltage was obtained as compared with the 100 microns wide track head.

In Fig. 12, the reproduced voltage of a single-pole head made of Fe-Si-N/SiO₂ multilayer films whose initial permeability is about 4600 are compared with that made of Fe-Si/SiO₂ multilayer films whose initial permeability of about 2500. The track width of head is 50 microns, and the perpendicular coercivity of a Co-Cr layer of

medium is 1260 Oe. Using the Fe-Si-N/SiO₂ multilayer film having a higher initial permeability, the reproduced voltage increases by about 1.5 times in comparison to the head made of Fe-Si/SiO₂ film. To make a narrower track main-pole, the stabilities of the domain structures and the magnetic properties must be investigated more precisely, but Fe-Si-N/SiO₂ multilayer films are more suitable on the magnetic properties for a narrow track main-pole.

Fig. 11 Bit density characteristics of a narrow track single-pole head made of a 12 microns wide Fe-Si/SiO₂ multilayer main-pole film.

Fig. 12 Comparison of bit density characteristics of single-pole heads made of a Fe-Si/SiO₂ and Fe-Si-N/SiO₂ multilayer films.

CONCLUSIONS

In perpendicular magnetic recording, the higher recording and reproducing resolutions are produced by the stronger magnetic interaction between a single-pole head and a double-layer medium. A soft-magnetic thin film having a higher saturation induction like a Fe-Si is indispensable for the main-pole of a narrow track single-pole head. A Fe-Si-N/SiO₂ multilayer film having a higher saturation induction of about 20 kGauss and a higher initial permeability up to about 7000 is very hopeful for a more highly sensitive single-pole head having a higher recording and reproducing resolutions.

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