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High-Performance Write Head Design and Materials

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The rapid increase in areal recording density means that a stronger writing field without side erasure is required. However, the increase in the data transfer rate makes write head optimization difficult. Moreover, it has become very important to minimize the write pole size tolerance because of the reduction in write track width. We have designed a new head throat shape with a deep gap depth that is formed with SiO_2 thin film. Our head has an advantage in gap depth tolerance as well as in write track width tolerance. We also developed soft magnetic FeCoAlO films with a saturation magnetic flux density (*Bs*) of 2.4 T for improving the overwrite (O/W) performance without worsening the side erasure characteristics. It was found that the O/W becomes less than −30 dB when the writing field is larger than the dynamic coercivity Hc0 of the medium. The side erasure was characterized by investigating the maximum tolerance field against di-bit signal degradation on the adjoining track.

1. Introduction

Because of the rapid increase in areal recording density in recent years, both a narrower write track width and a strong writing field without side erasure are required. The write head must have a stronger write field under the gap and a weak side erasure field. However, it becomes difficult to meet these requirements at higher areal densities because the write track width decreases unless the magnetic spacing between the head and medium is drastically reduced. Another source of difficulty here is the increasing coercivity of media. Moreover, the need to increase the data transfer rate (i.e., increase the writing frequency) has to be considered, particularly for enterprise model HDDs. It is very difficult but very important to optimize the design of write heads. Therefore, computer simulations are used for speedy optimization. In this paper, we describe our technique for simulating write properties.

In order to write bits on higher coercivity media, the pole tip materials of prospective writing heads must have an ultra-high magnetic induction (*B*s) of more than 2.0 T. Additionally, it is preferable that the writing head materials have soft magnetic properties in the as-deposited state and are prepared on low-temperature substrates without an applied field. This is necessary to avoid property degradation in the spin valve film of the reading head. It is well known that sputtered Fe-M-(N and/or O) (M = no-addition, Al, Ta, Zr, Rh, etc.) and electroplated CoNiFe films show soft magnetic properties; however, they only have a *B*s from 1.8 to 2.0 T.[1)-8)] We have therefore developed soft magnetic FeCoAlO films with a high *Bs* of 2.4 T. In this paper, we introduce the films' properties and the characteristics of writing heads that use them.

2. Concept for writer design

Because of the decreasing write track dimensions, it is very important to minimize the dimensional tolerances. For instance, the tolerance for the write pole width of 40 Gbit/in^2-class hard disk drives (HDDs) must be set to less than about ±0.06 µm because the effective write track is about 0.3 to 0.4 µm. The size tolerance of the write width strongly depends on how precisely we can pattern the photoresist with a stepper to form a write pole tip with electroplating. This situation led us to design the original throat shape shown in **Figure 1** and develop a new process for forming it with an accurately defined gap depth. **Figure 2 (a)** and **(b)** show scanning electron microscope (SEM) images of our write head pole tips for vertical and cross sections, respectively. Because our head throat is made of a SiO_2 sputtered thin film and is very thin and flat, the photoresist can be coated quite evenly. Also, the patterning deformation due to the reflected exposure light can be minimized because the throat edge is very steep (about a right angle), which improves the patterning precision. We designed this throat shape to minimize the write pole width tolerance.

Figure 3 (a) shows the results of simulating the overwrite (O/W) performance of our head with a thin film apex (TF apex) and those of a conventional apex shape head. The O/W estimation method is described in detail later in this paper. The overshoot of the write current (IwOVS) was assumed to be 0%. This figure shows why our head has a deeper gap depth (GD) of about 1.5 µm. The O/W for the head with GD = 1.5 µm is better than that for the head with GD = 0.5 µm when the write current is below about 40 mA. We believe that a good O/W in the lower Iw region is

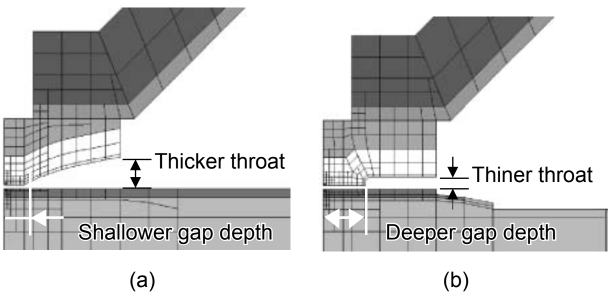

Figure 1
(a) Conventional apex shape with thick photoresist and (b) our throat design formed with a thin film (TF apex).

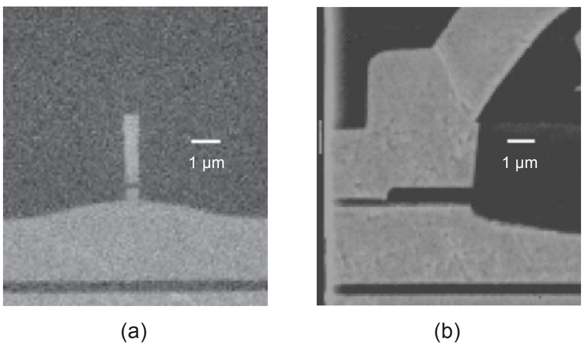

Figure 2
SEM images of write head tips for (a) air bearing surface and (b) cross section.

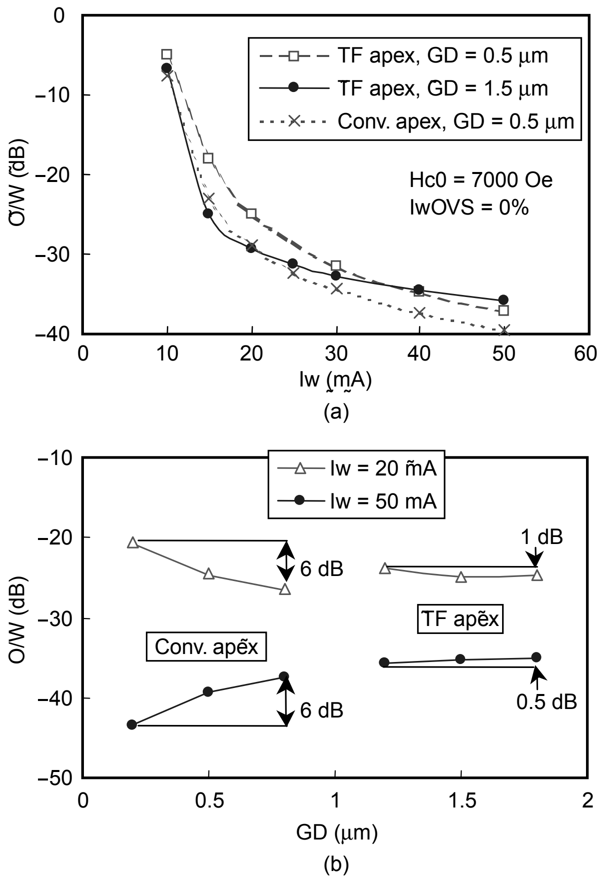

Figure 3
(a) Simulated O/W versus write current characteristics for different gap depth and (b) the gap depth dependence of O/W.

very important, but too high an O/W in the upper Iw region is not desirable because of the side erasure problem. To increase the write efficiency, a deeper GD is necessary and the magnetic resistance has to be decreased. Magnetic resistance is assumed to exist in the write gap only when Iw is small, because there is no magnetic saturation area in the head yoke and the permeability of the head yoke is much higher than that of the gap material. The magnetic resistance of the write gap can be decreased by increasing the facing area of the magnetic pole in the gap, which can be achieved by increasing the gap depth.

Moreover, our head has the advantage in gap depth tolerance shown in **Figure 3 (b)**. Based on a GD size-tolerance of ±0.3 µm, the unevenness range of O/W for a conventional apex head is about 6 dB but less than 1 dB for our TF apex head. Because of the deeper gap depth, the influence of a GD change on the write field in our head is much smaller than in the conventional head.

It is also clear, as shown in **Figure 4**, that a higher magnetic flux density (Bs) material is very effective for improving O/W performance without worsening the side erasure characteristics. Here, the side erasure is evaluated as a signal degradation of a di-bit pattern. The details of the side erasure evaluation method are described later. The larger the signal degradation, the larger the side erasure. At least a CoNiFe material having a Bs of more than 1.9 T is needed to reduce the O/W to below –30 dB. To achieve a sufficient O/W, a material with a much higher Bs is required. Therefore, we have developed an FeCoAlO material with an ultra-high Bs of 2.4 T, the details of which are also described later. By applying such a high Bs material to our deeper GD head, we have successfully obtained a good O/W performance and satisfactory side erasure characteristics.

3. Designing the writer with computer simulation

3.1 Overwrite simulation on data track

When discussing the writing field, the medium's magnetic properties have to be carefully considered. We have found that in dynamic coercivity theory there is a strong correlation between the overwrite (O/W) and Hc0, which is defined as the remanent coercivity at a field duration time of ln2 ns (**Figure 5**).[9)-11)] Usually Hc0 is twice or three times as large as the normal coercivity measured with a vibrating sample magnetometer (VSM).

Figure 6 shows the overwrite values for various differences between the head field (Hh) and Hc0. In this figure, it is clear that the O/W strongly

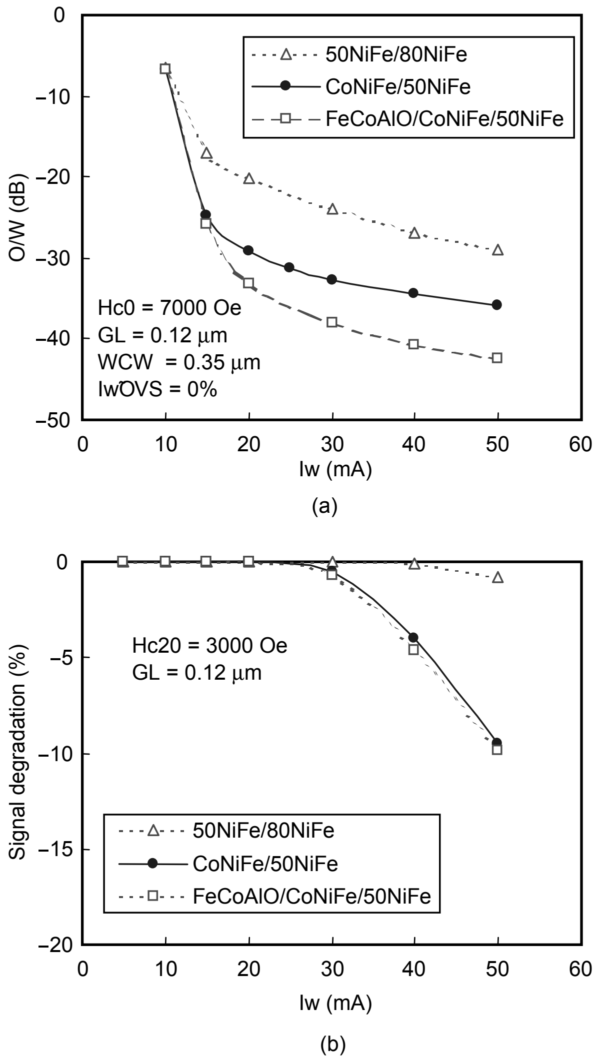

Figure 4
Simulated write current dependences of (a) O/W and (b) di-bit signal degradation on adjoining track after 100 k writes were performed for various pole material combinations.

depends on Hh-Hc0 and the correlation coefficient is about 4/500 dB/Oe. Moreover, we can conclude that the O/W becomes about –30 dB when the head writing field Hh is equal to the Hc0 of the medium when the medium's tBr is 50 Gμm (G = 10^{-4}T) and the write gap length (GL) is 0.17 μm. All of the O/W values in this figure were measured, but the head field Hh values for the solid circles were estimated using a conversion factor in the Hc0 measurement, and those for open triangles were obtained by a computer simulation that took the precise shape of the head into consideration. The conversion factor that was used was the coefficient between the DC erase field of the head and the DC current in the head coil, as obtained by dynamic coercivity measurement using a spin stand. We designed the head so that the head field becomes larger than the Hc0 of the medium in order to keep the O/W below –30 dB.

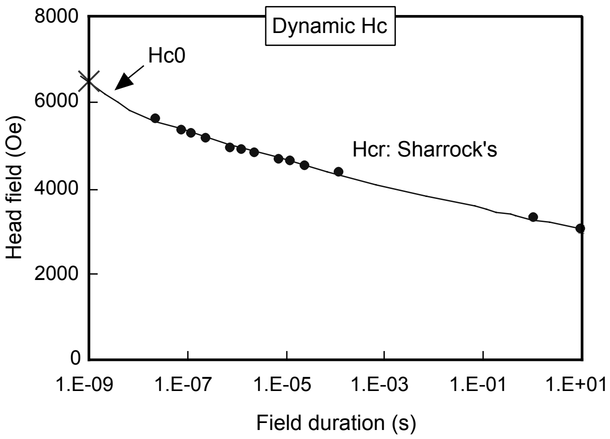

Figure 5
Dynamic coercivity measurement and the definition of Hc0.

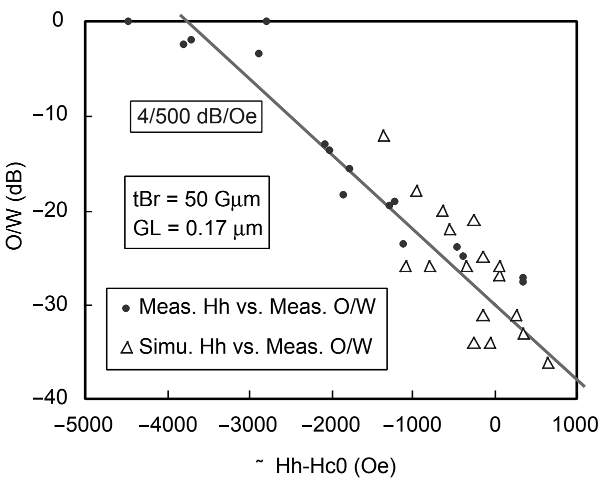

Figure 6
Relationship between overwrite and the difference between the head field and medium's Hc0.

3.2 Side-erasure simulation on adjoining track

Next, we discuss the optimization for the side erasure of adjoining data tracks. **Figure 7 (a)** shows the head field contour on the medium near the write gap. The erasing head field is widely distributed; it leaks from the edge of the lower pole and widens in the cross-track direction. The thick broken line in Figure 7 (a) indicates the maximum-intensity contour of the cross-track

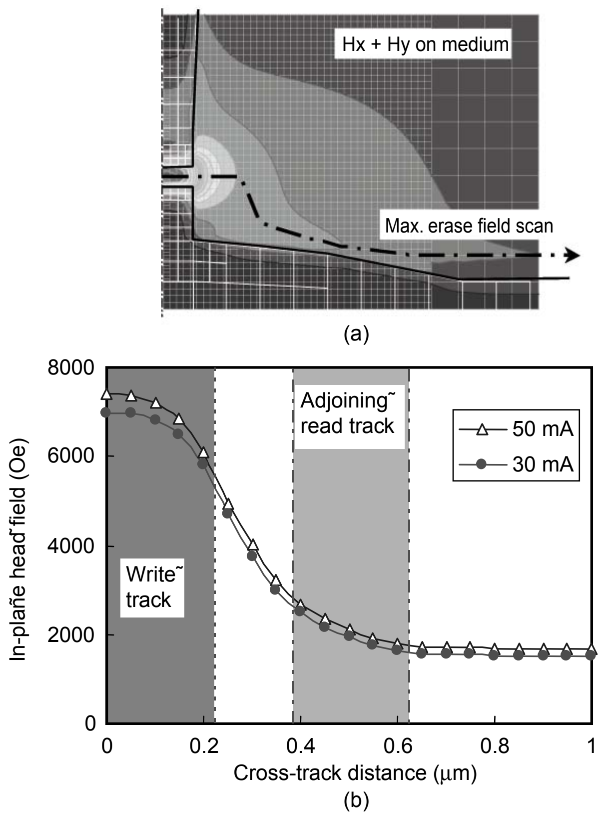

Figure 7
(a) Head field contour near write gap on medium and (b) field distribution in cross-track direction.

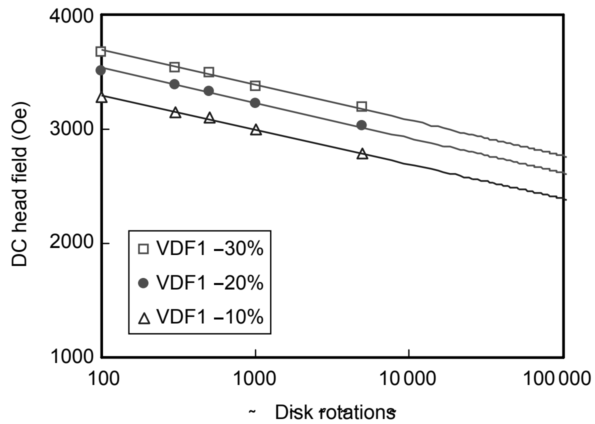

Figure 8
Relationship between di-bit signal degradation and the number of disk rotations with various DC head fields.

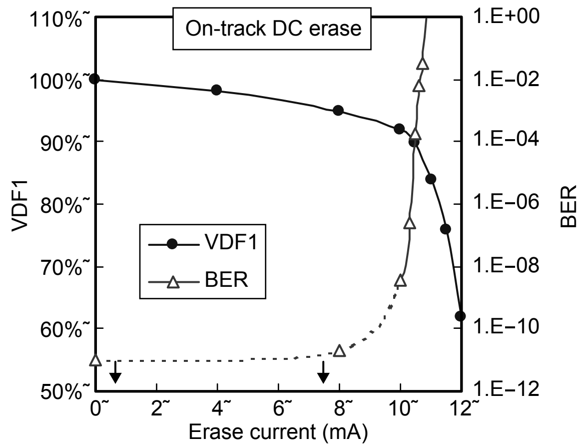

Figure 9
Relationship between di-bit signal degradation (VDF1) and bit error rate (BER).

leakage field. **Figure 7 (b)** shows how this field drops off away from the write pole center. We define the side erasure field as the average value of the leakage field in the adjoining read track area. The erasure field is about 1900 Oe [Oe = (1000/4π)A/m] and 2100 Oe for currents of 30 mA and 50 mA, respectively.

In order to find the maximum tolerance of the side erasure field, we investigated the di-bit signal degradation against the number of times the disk was rotated while various DC head fields were applied solely to the track in which di-bit data was written.[12] The results are shown in **Figure 8**. Here, the head field was estimated using the conversion factor obtained in the dynamic coercivity measurement described in the previous section. In the figure, the lines for VDF1−10%, VDF1−20%, and VDF1−30% indicate the erasure field strengths in which the di-bit signal is degraded by 10%, 20%, and 30%, respectively. The results show that when the erasure field was less than 2350 Oe, the di-bit signal was degraded less than 10%, even when the same track was erased 100 000 times. Because the di-bit signal was degraded in proportion to the logarithm of the number of disk rotations, we can conclude that the erasure mechanism is just the thermal degradation due to the DC field.

Figure 9 shows the relationship between the di-bit signal degradation (VDF1) and the bit error rate (BER). Here, VDF1 and BER were measured after DC erasure with various erase currents on tracks written with a di-bit pattern and random patterns. Because the bit error rate becomes suddenly worse when the di-bit signal falls below about 90%, the maximum tolerance of VDF1 degradation is determined to be 10%. We designed the head so that the side erasure field is less than 2350 Oe in order to keep VDF1 below 10% and obtain a sufficient BER.

4. Development of ultra-high *B*s material

As described above, we needed a material with a much higher *B*s to obtain a large enough O/W without worsening the side erasure characteristics. To meet this need, we developed an FeCoAlO material with a *B*s of 2.4 T.

4.1 Experimental procedures

FeCoAlO films were sputtered using compacted targets of $Fe_{70}Co_{30}$ alloy and Al_2O_3 powders at 2 kW on water-cooled Al_2O_3-TiC substrates in an Ar atmosphere. During deposition, an aligning magnetic field to induce atomic pair order was not applied to the substrates and the substrate

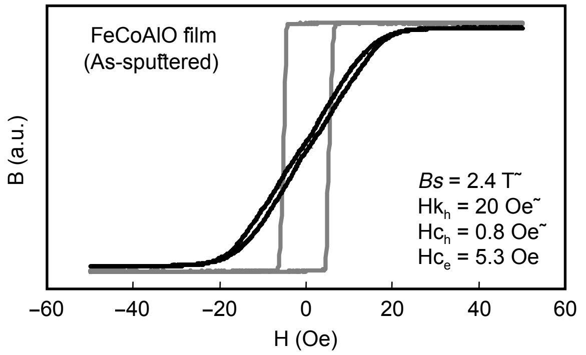

Figure 10
B-H curves measured along easy axis and hard axis for as-sputtered FeCoAlO film.

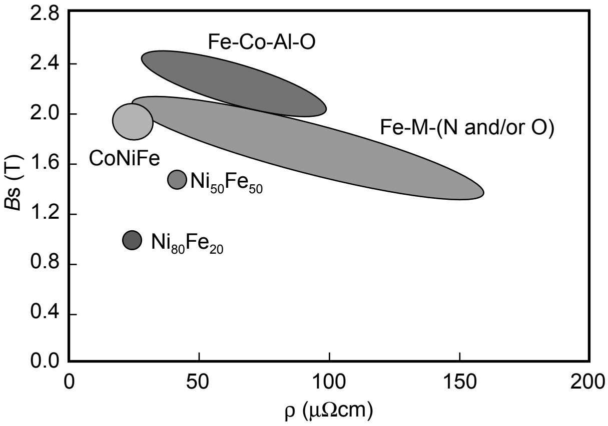

Figure 11
Relationship between magnetic induction *B*s and electrical resistivity *ρ* for various materials.

temperature was kept below 70°C. The alloy concentrations in films were varied by adjusting the FeCo/Al_2O_3 mixing ratios of the targets. The film thickness was 0.15 to 0.3 µm. The magnetic properties were evaluated using VSM, a *B-H* loop tracer, and a permeameter. The resistivity *ρ* was measured using a DC four-point probe method. The film structure was characterized by selected area diffraction (SAD) and transmission electron microscopy (TEM). The corrosion resistance of the FeCoAlO films was evaluated from the anodic polarization curves. Film specimens with a square area of 0.64 cm^2 were exposed to a 0.01N KCl electrolyte at room temperature. A saturated calomel electrode (SCE) was used as the reference electrode.

4.2 Film properties

We have developed soft magnetic FeCoAlO materials having a *B*s of 2.4 T, which is close to the limit of *B*s in thermal equilibrium ferromagnetic alloys. **Figure 10** shows the easy-axis and the hard-axis B-H curves of an as-sputtered film of one of these materials. These measurements were carried out using a 5-inch diameter Al_2O_3-TiC wafer. The FeCoAlO film is magnetically soft and has uniaxial magnetic anisotropy. The hard-axis anisotropy field is estimated to be Hk_h = ~20 Oe from the minor *B-H* loop measured in a driven field of ±1 Oe. The hard-axis coercivity Hc_h shows a low value of less than 1 Oe. The skew angle is within ±3 degrees. From these results, it is suggested that the FeCoAlO film has magnetic uniformity in the wafer area; that is, the dispersion of magnetic anisotropy is very low. Moreover, no degradation of the film's soft magnetic properties is observed after annealing at 300°C, so it has sufficient thermal stability to withstand magnetic head fabrication processes.

Figure 11 shows the relationship between the magnetic induction *B*s and resistivity *ρ* for our FeCoAlO films. The figure also shows the relationships for $Ni_{80}Fe_{20}$, $Ni_{50}Fe_{50}$, CoNiFe, and Fe-M-(N and/or O) alloy films for comparison. The *B*s (2.2 to 2.4 T) and *ρ* (40 to 80 µΩcm) values of the FeCoAlO films are higher than those of the other soft magnetic films. Therefore, the FeCoAlO films are attractive for use as writing head materials, because of their potential for providing a high overwrite field and a high frequency response. As the additional nonmagnetic elements in the ferromagnetic films increases, the moment decreases according to the simple dilution law, and the impurity scattering increases according to the Nordheim law. Consequently, the *B*s of the Fe-C-Al-O films decreases linearly with increasing *ρ*. A similar tendency in the *B*s vs. *ρ* is also observed for the Fe-M-(N,O) films.

It is reported that the uniaxial magnetic anisotropy of FeCoAlO films which have a *B*s = ~2 T and a ρ = ~100 μΩcm results from the directional order induced by the applied field during sputtering, and further, the direction of the easy axis can be controlled by a field applied during annealing.[13] However, the uniaxial magnetic anisotropy for our FeCoAlO films with *B*s = ~2.4 T is obtained without an applied field during sputtering and is almost unchanged after annealing at 300°C in 3 kOe. That is, the magnetic annealing effect is not observed in our films. Accordingly, we conclude that the origin of anisotropy in our films is different from the origin in the films described above.

It is known that the appearance of magnetic anisotropy for sputtered films is closely related to the film structure, for example, the grain shape and texture. We investigated the film structure for an FeCoAlO film with a *B*s = ~2.4 T using SAD and TEM. **Figure 12** shows the SAD pattern and the TEM image in the as-sputtered state. In the SAD pattern, only the diffraction rings of the body-centered cubic structure (bcc) phase are observed, and unusual crystal orientations such as (110) texture cannot be found. On the other hand, the TEM image indicates that the grains have an anisotropic shape. The major axis and minor axis of the grains are about 15 to 30 nm and 5 to 15 nm, respectively. It has been suggested that the magnetic anisotropy in granular Fe-Al-O alloy films results from anisotropic coupling between the magnetic grains.[14] We performed a concentration analysis of our FeCoAlO films using an energy dispersive x-ray spectroscope (EDS) with a 3 nm diameter electron beam. The analysis showed hardly any detectable difference in alloy concentrations between the grains and the grain boundaries. The reason for this is that the total content of Al and O elements in the films is less than 5 at.%, so the FeCoAlO films have no intergrain oxide. The Al and O atoms are dissolved in the bcc phase, so it is not possible to explain the magnetic anisotropy as resulting from the magnetic interactions between grains caused by the net anisotropic structure of intergrain oxide. Thus, it seems that, from the above-mentioned facts, the origin of uniaxial magnetic anisotropy in our FeCoAlO films is closely related to the following factors:

1) A shape magnetic anisotropy which originates in the anisotropic grain.
2) A magnetoelastic effect caused by anisotropic residual stress $\Delta\sigma_{aniso.}$ which is induced into the anisotropic grains ($E_{ela.} = 3\lambda\Delta\sigma_{aniso}/2$; $\sigma = \sigma_{iso.} + \Delta\sigma_{aniso.}$, where σ is the residual stress in the films).

Therefore, the film microstructures are the critical factor for controlling the uniaxial magnetic anisotropy of the soft magnetic FeCoAlO films. If the anisotropy of the FeCoAlO films is dominated by 2), it would be feared that the soft magnetic properties would deteriorate due to thermal relaxation after annealing. However, no change in the magnetic properties was observed when the FeCoAlO films were annealed at 300°C.

Figure 13 shows the frequency response of

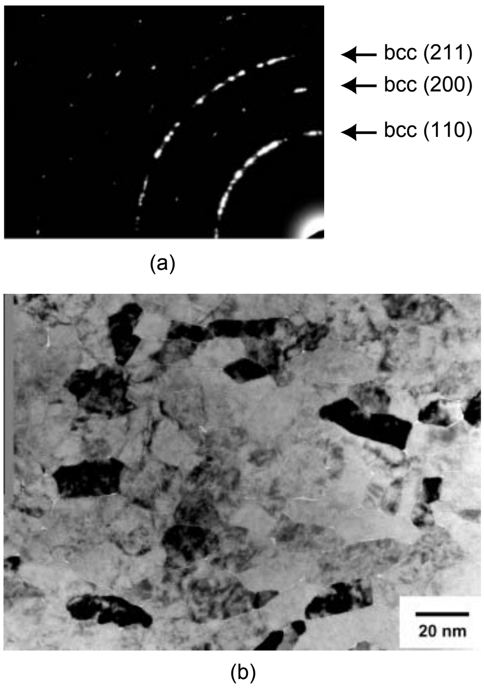

Figure 12
(a) SAD pattern and (b) TEM image of as-sputtered FeCoAlO film.

the permeability, as measured along the hard axis, for the as-sputtered FeCoAlO film with *B*s = 2.4 T. The real part of the permeability μ' for the 150 nm-thick FeCoAlO film has a high value of more than 1000 and remains constant up to around 1 GHz. The solid line in this figure is a calculated result for μ' based on the Landau-Lifshitz model and shows a good agreement with the measured μ'. These results show that our FeCoAlO films are suitable for high-speed writing on ultra high density media.

The anodic polarization curve for the sputtered (SP) FeCoAlO film is shown in **Figure 14** together with the curve for an electroplated (PL) CoNiFe film. It is known that CoNiFe films electroplated using a plating bath with no saccharin have a good corrosion resistance.[8] The rest potential (RP) and the pitting potential (PP) of the FeCoAlO film are –60 mV vs. SCE and +410 mV vs. SCE, respectively. These values in a 0.01N KCl environment are very high compared with those of the plated CoNiFe films (RP = ~ –360 mV vs. SCE and PP = ~ +200 mV vs. SCE). Therefore, the FeCoAlO films have sufficient corrosion resistance to withstand magnetic head fabrication processes.

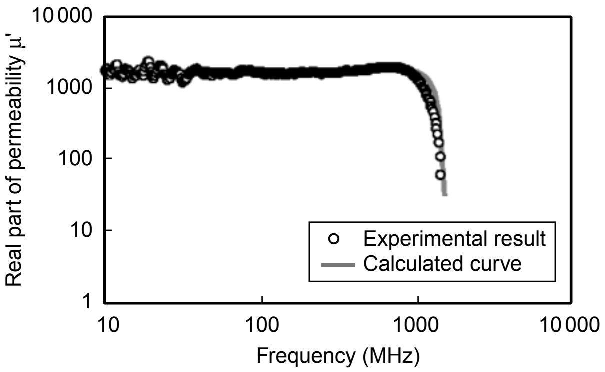

Figure 13
Frequency response of the real part of permeability μ' for as-sputtered FeCoAlO film with *B*s = 2.4 T.

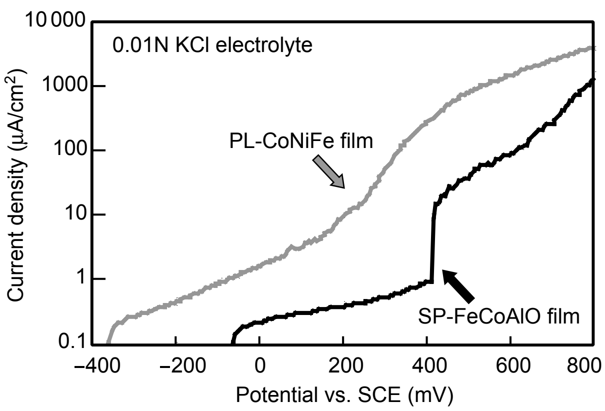

Figure 14
Anodic polarization curve of as-sputtered FeCoAlO film.

5. Conclusion

We have designed a new head throat formed by SiO_2 sputtered thin film which has a deep gap depth. This throat shape enables us to reduce the write track width tolerance. The deep gap depth leads to better O/W in the lower write current region and can widen the gap depth margin. The unevenness range of O/W for a conventional head is about 6 dB but less than 1 dB for our new head. When designing the write head, we investigated and clarified the relationship between the medium's magnetic properties and the head field distribution. We found that the O/W becomes less than –30 dB if the writing field is larger than the Hc0 of the medium when the medium's tBr is 50 Gμm and the write gap is 0.17 μm. We also found by investigating di-bit degradation that the erasure field on the adjoining track had to be weaker than 2350 Oe for our medium.

We have developed soft magnetic FeCoAlO materials with a *B*s = 2.4 T, which is close to the limit of *B*s in thermal equilibrium ferromagnetic alloys. Films of these materials show a μ' of more than 1000 which remains constant up to around 1 GHz. The electrical resistivity is about 45 μΩcm. The films' microstructures, for example, their anisotropic grains, are the critical factor for controlling the films' uniaxial magnetic anisotropy. The good magnetic thermal stability and high corrosion resistance of these films means they can withstand the fabrication processes for magnetic heads. Therefore, these FeCoAlO films can be advantageously applied in writing heads.

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