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Recording physics of perpendicular media: soft underlayers

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Abstract

The results of both theoretical and experimental studies of some of the key aspects of the recording physics specific to perpendicular media with a soft underlayer are presented. Some of the discussed issues are the material requirements for the preferred soft underlayer design such as the role of magnetic anisotropy, the proper choice of the magnetic moment, and the control of the soft underlayer noise.

Keywords: Perpendicular magnetic recording; Perpendicular recording media; Soft underlayer

1. Introduction

As the storage industry ramps the areal bit densities at increasingly higher rates, thermal instabilities in recording media begin to manifest themselves [1]. Perpendicular recording technology [2] while being technically close to conventional longitudinal recording and the least difficult technology to make the transition to, if necessary [3–5], addresses the issue of thermal stability for areal bit densities exceeding 100 Gbit/in^2 [6].

One of the key aspects of perpendicular recording that makes it superior to the longitudinal recording with respect to superparamagnetic effects is the utilization of media with a soft underlayer (SUL). A single-pole head/media with a soft underlayer perpendicular recording system enables write fields in excess of 80% of $4\pi M_S$ of the pole head/soft underlayer material [7]. This doubles the fields available in longitudinal recording, thus opening the possibility to write on substantially higher anisotropy media and leading to better thermal stability. Acting as a magnetic mirror, soft underlayer effectively doubles the recording layer thickness, facilitating substantially stronger readout signals [8]. Also, the effective thickness increases due to the mirroring effects by a soft underlayer which leads to the reduction of the demagnetizing fields with a potential to further improve thermal stability [11].

While the use of perpendicular media with a soft underlayer should make it possible to postpone the superparamagnetic limit, the soft underlayer introduces a number of technical challenges. The issues related to the presence of the soft underlayer are the subject of this work.

2. Saturation moment

The importance of the relation between the moment of the soft underlayer material and the

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moment of the recording pole tip material was discussed previously [7]. It was shown that saturation of the soft underlayer can lead to a dramatic deterioration of the trailing field gradients. It follows from Maxwell's laws, div $\mathbf{B} = 0$ and $\nabla \times \mathbf{H} = 0$, that to avoid the soft underlayer saturation under the pole tip, the following inequality has to hold

$$4\pi M_{\mathrm{S\ soft\ underlayer}} \times A_{\mathrm{soft\ underlayer\ effective}} \geqslant 4\pi M_{\mathrm{S\ pole\ tip}} \times A_{\mathrm{ABS\ pole\ tip}}, \quad (1)$$

where $A_{\mathrm{soft\ underlayer\ effective}}$ is the effective area of the soft underlayer into which the magnetic flux emanating from the pole tip enters and $A_{\mathrm{ABS\ pole\ tip}}$ is the area of the air bearing surface (ABS) of the pole tip.

Fig. 1 shows a schematic of the recording pole tip/soft underlayer combination. When the separation between the ABS of the pole tip and the soft underlayer ($d \sim 10$–20 nm) is substantially smaller than the lateral dimensions of the pole tip ($l_{\mathrm{pole\ tip}} \sim 300$–$1000$ nm, $w_{\mathrm{pole\ tip}} \sim 50$–$150$ nm), the effective area of the soft underlayer, $A_{\mathrm{soft\ underlayer\ effective}}$, is approximately equal to the ABS area of the pole tip, $A_{\mathrm{ABS\ pole\ tip}}$. It follows that to avoid saturation effects in the soft underlayer the moment of the soft underlayer material has to be higher than or equal to the moment of the recording pole tip material.

Although it is possible to generate strong recording fields (with the magnitude approaching $4\pi\, M_{\mathrm{S}}$ of the pole tip) even if the soft underlayer has lower magnetic moment than the pole tip, saturation of the soft underlayer will lead to a substantial deterioration of the trailing field gradients. The results of boundary element modeling for two different head/soft underlayer combinations are presented in Fig. 2 [7]. The trailing gradients in the case of the Permalloy based soft underlayer are substantially worse than the trailing gradients in the case when an FeAlN based soft underlayer is used.

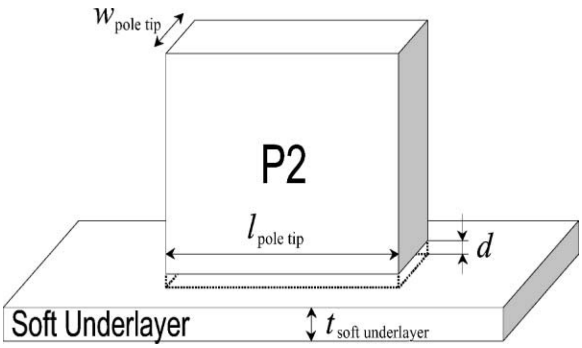

Fig. 1. A schematic of the recording head pole tip/soft underlayer combination. $l_{\mathrm{pole\ tip}}$ is the dimension along the track and $w_{\mathrm{pole\ tip}}$ is the dimension across the track, i.e. $w_{\mathrm{pole\ tip}}$ defines the track width.

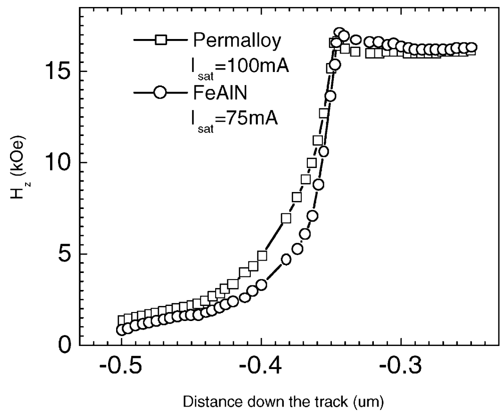

Fig. 2. Trailing fields from a single pole perpendicular write head made out of FeAlN ($4\pi\, M_{\mathrm{S}} = 20$ kG) for FeAlN and Permalloy ($4\pi\, M_{\mathrm{S}} = 10$ kG) soft underlayers.

3. Thickness

The following approximate equation gives a minimum thickness of the soft underlayer that allows to achieve maximum magnitude of the recording fields and the trailing gradients of the recording fields (it is assumed that the length, $l_{\mathrm{pole\ tip}}$, of the pole tip is substantially greater than the width, $w_{\mathrm{pole\ tip}}$, of the pole tip (see Fig. 1)

$$t_{\mathrm{soft\ underlayer\ MIN}} \sim \frac{1}{2}\frac{M_{\mathrm{S\ pole\ tip}}}{M_{\mathrm{S\ soft\ underlayer}}} w_{\mathrm{pole\ tip}}. \quad (2)$$

The validity of the above equation can be shown using arguments similar to the argument used in the previous section and is a consequence of the conservation of the magnetic flux.

Fig. 3 shows the results of the boundary element modeling of the magnitude and the trailing gradient of the field generated a pole tip

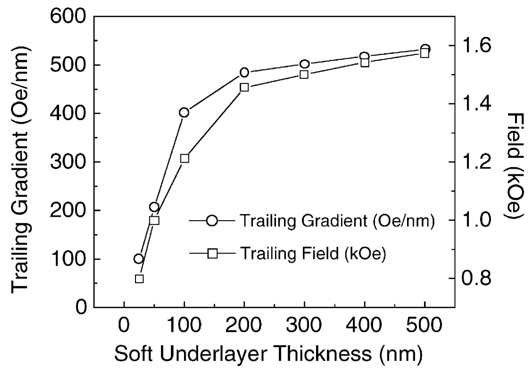

Fig. 3. The amplitude and the gradient of the trailing field generated by a single pole perpendicular write head made of FeAlN ($4\pi M_S = 20$ kG) and an FeAlN soft underlayer versus the soft underlayer thickness.

($w_{\text{pole tip}} = 0.4\,\mu$m, $l_{\text{pole tip}} = 2\mu$m) of a recording head and soft underlayers of different thicknesses. Both the soft underlayer and the pole tip are assumed to be made of FeAlN with $4\pi M_S$ values of 20 kG. It can be seen that when the soft underlayer thickness becomes smaller than 0.2 μm, the performance of the recording system deteriorates.

Media with almost identical recording layers and different soft underlayers were fabricated to test the validity of the theoretical results outlined above. The pole tip was made of $Ni_{45}Fe_{55}$ alloy with a $4\pi M_S$ of 16 kG and the soft underlayer was made of FeAlN with a $4\pi M_S$ of 20 kG. The track width ($\sim w_{\text{pole tip}}$) was 0.8 μm. According to Eq. (2), $t_{\text{soft underlayer MIN}} \sim 0.3\,\mu$m.

Fig. 4 shows the dependence of the saturation current on the thickness of the soft underlayer. For values of the soft underlayer thickness below 0.3 μm, saturation current starts to increase, which is an expected effect when the soft underlayer gets partially saturated.

Fig. 5 presents roll-off curves for three different values of the soft underlayer thickness. In agreement with the theoretical consideration and conferring with the result in Fig. 4, the resolution of the recording system starts to deteriorate when the soft underlayer thickness is less than 0.3 μm.

One of the consequences of the above discussion is the fact that to achieve an efficient write process it is not necessary to make a soft underlayer excessively thick. Soft underlayers with thickness

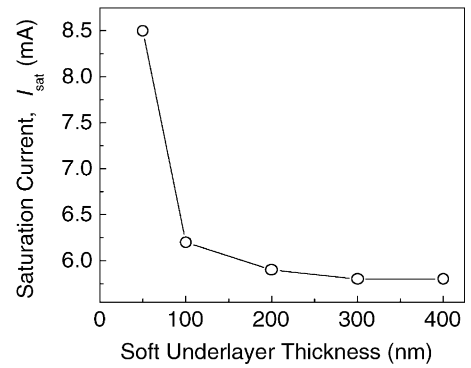

Fig. 4. Saturation current, I_{SAT}, versus different soft underlayer thicknesses. FeAlN soft underlayer and 0.8 μm wide $Ni_{45}Fe_{55}$ pole tip were used.

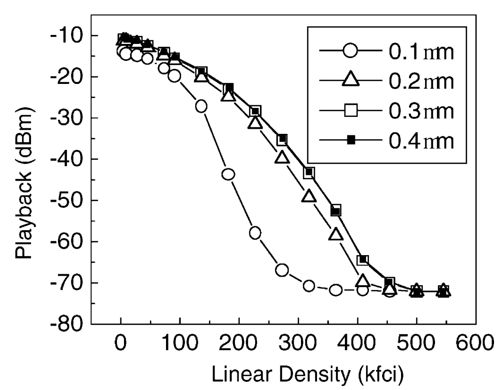

Fig. 5. Roll-off curves for FeAlN soft underlayers of different thicknesses. 0.8 μm wide $Ni_{45}Fe_{55}$ pole tip was used.

values above 1 μm have been routinely reported in literature [9]. For example, for a 100 Gbit/in^2 recording density, utilizing a 4 : 1 bit aspect ratio (track width of 160 nm), if an FeAlN pole tip is with a saturation magnetization of 20 kG and CoFe soft underlayer is with saturation magnetization of 24 kG, then a soft underlayer can be as thin as $\sim$70 nm. This makes the deposition of the soft underlayer in conventional media deposition tools a fairly straightforward process.

4. Soft underlayer to the air-bearing surface of the recording head distance

Apart from the clear advantages of having the soft underlayer as close as possible to the

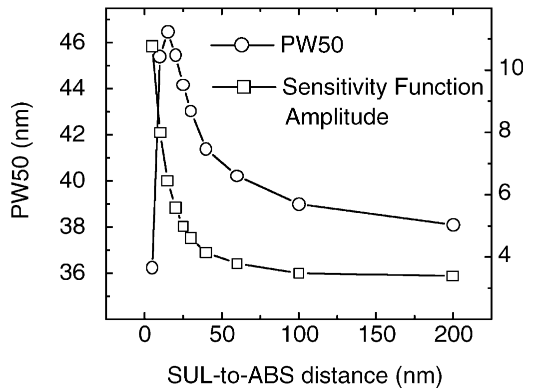

Fig. 6. The dependence of the amplitude of the read sensitivity function and of the PW50 on the SUL-to-ABS distance.

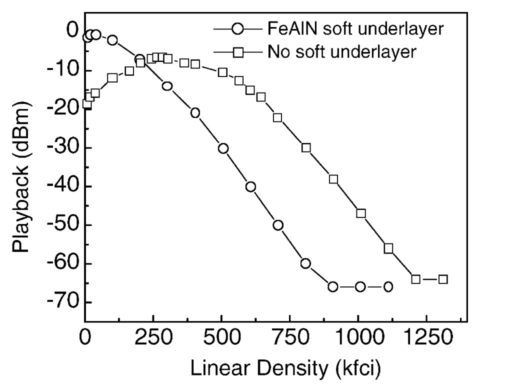

Fig. 7. Roll-off curves for media with and without soft underlayers.

recording head for better write field gradients [7], certain consideration related to the playback performance of the perpendicular recording system should be taken into account while designing perpendicular media with a soft underlayer. Fig. 6 shows the dependence of the PW50 and the amplitude of the read sensitivity function of a 30 nm thick reader as a function of the soft underlayer to the air-bearing surface of the recording head (SUL-to-ABS) distance.

Two effects can be seen in Fig. 6. As expected, the amplitude of the read sensitivity function decreases with the increase of the separation between the soft underlayer and the ABS, i.e. the closer the soft underlayer to the ABS, the higher playback signal can be expected. This trend suggests to minimize the SUL-to-ABS spacing.

The other observation, which is critical to optimizing the perpendicular system's resolution, is that there exists a maximum in the value of the PW50 as the SUL-to-ABS distance is varied. From Fig. 6, it is obvious that a special care should be undertaken to correctly choose SUL-to-ABS distance. It will be seen below from the experimental data, that this effect can substantially deteriorate the playback performance of a perpendicular recording system, in which media with a soft underlayer is used, thus making it, potentially, even worse than the playback performance of a perpendicular recording system in which media without a soft underlayer is used.

Fig. 7 compares roll-off curves for the media with and without a soft underlayer (close to identical CoCr alloy based recording layers were used). The dramatic effect of using perpendicular media with a soft underlayer in which the SUL-to-ABS distance is not optimized is clearly observed.

5. Anisotropy: micromagnetics of a soft underlayer

This section addresses the micromagnetics of a soft underlayer in the presence of stray fields generated by a recording layer. It is confirmed that relatively high anisotropy soft underlayer materials need to be utilized to optimize the performance of the recording system [10]. As was elaborated in Ref. [10] when the characteristic bit size in the recording layer becomes comparable to the characteristic *in-plane* length, δ, in the soft underlayer film (often referred to as the domain wall thickness), the imaging ability of the soft underlayer deteriorates affecting the playback performance. This characteristic length δ is defined by the following relation:

$$\delta \sim \sqrt{A/K_U} = \sqrt{A/2\pi H_K M_S}, \qquad (3)$$

and its value along with other selected material properties are summarized in Table 1 for several soft underlayer candidates.

The inability of the soft underlayer to image high frequency spacial variations of the magnetization in the recording layer causes an effective formation of a magnetically *dead* layer at the top of the soft underlayer [10] leading to an effective

Table 1
Selected material properties for Permalloy, FeAlN, $Ni_{45}Fe_{55}$ with high stress induced anisotropy, and FeCo where H_K—anisotropy field, $4\pi M_S$—saturation moment, A—exchange constant, LD—linear density corresponding to dimension δ

Material	H_K (Oe)	$4\pi M_s$ (kG)	$A \times 10^{-6}$ (erg/cm)	δ (nm)	LD (kfci)
$Ni_{81}Fe_{19}$	5	10	1.0	112	226
FeAlN	15	20	1.7	60	420
$Ni_{45}Fe_{55}$	50	16	1.5	34	737
$Fe_{65}Co_{35}$	100	24	2.0	23	1100

increase of the SUL-to-ABS (air-bearing surface) distance. As shown in Fig. 6, the increase of the SUL-to-ABS distance will lead to accelerated roll-offs.

The experimental data presented below demonstrates the micromagnetic behavior of the soft underlayer leading to accelerated roll-offs, indeed, takes place and strongly depends on anisotropy of the soft underlayer material.

Media with close to identical recording layers (Co/Pd multilayer based) and different soft underlayers were spin-stand tested. The similarity of recording layer was confirmed via measuring M–H loops and microstructure of the films. All the measured parameters for the recording layers such as coercivity, saturation moment, nucleation field, grain size, grain size distribution, etc. were within 1–2% error bar for all recording layers.

Fig. 8 shows the roll-off curves for three media with different soft underlayers. It is clear that the roll-off of the playback signal is significantly more dramatic if soft underlayer materials with lower H_K's are used.

It should be emphasized that the decrease in soft underlayer relative permeability from 2000 for Permalloy to 320 for high anisotropy $Ni_{45}Fe_{55}$ cannot explain the observed behavior. Boundary element based macromagnetic calculations show that lowering relative permeability of the soft underlayer from infinity to ~ 50 has virtually no effect on the playback characteristic of the recording system [8].

In summary, as outlined above and in Ref. [10], the inability of a soft underlayer with low magnitude of H_K to perfectly image the magnetic bits in a recording layer at high linear density, may lead to distortions in the playback signal. The deteriorated imaging results in the loss of resolution (increased PW50 and decreased amplitude of the read sensitivity function) and, subsequently, in the deterioration of recording system performance.

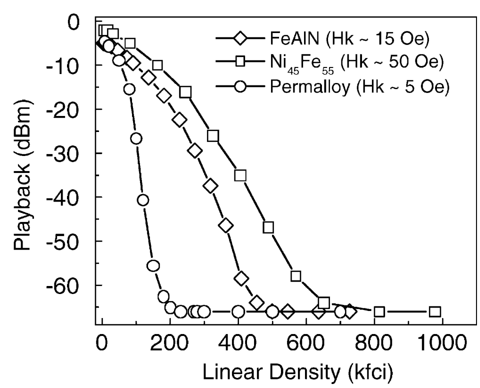

Fig. 8. Roll-off curves for media with identical recording layers and different soft underlayers.

6. Magnetic biasing

Among the technical challenges introduced by the presence of a soft underlayer is the fact that it contributes an additional source of noise [9]. A not properly optimized soft underlayer material can introduce a significant amount of noise into the playback signal. The noise results from effective charges resulting from domain walls in the soft underlayer. A solution to this problem is magnetic biasing of the soft underlayer [10].

Fig. 9 shows a schematic of the experimental setup to study the effect of magnetic biasing of the soft underlayer on the noise. The magnetic biasing was achieved using two NdFeB permanent magnets placed in the vicinity of the media. The placement of the magnets was such that it allowed to achieve complete saturation of the soft underlayer underneath the reader. Special care was necessary to arrange the magnets sufficiently far from the recording head ($\sim$ 2cm away) in order not to affect the properties of the read element.

Fig. 10 shows the playback signals from the two media with the as-deposited non-biased (a) and magnetically biased (b) soft underlayers. A substantial level of noise attributed to the presence of a large number of domain walls (confirmed by magnetic force microscopy) in the soft underlayer can be seen in Fig. 10a. A drastic reduction of the noise (by at least 10 dB) is clearly observed in Fig. 10b where the soft underlayer is magnetically biased.

The magnetic biasing saturates soft underlayer film forcing it into a pseudo-single domain state. Thus magnetic biasing effectively sweeps the domain walls out of the soft underlayer material. This results in the elimination of the soft underlayer noise.

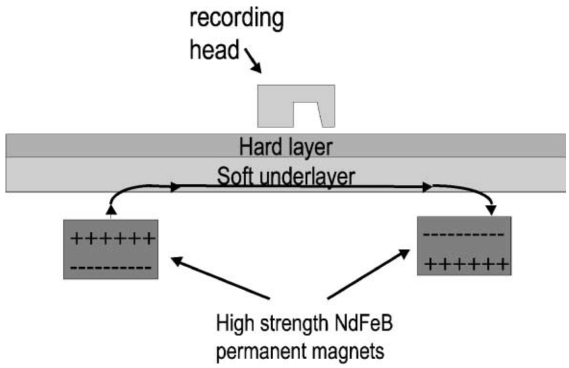

Fig. 9. A schematic of experimental setup to magnetically bias soft underlayer film.

7. Summary

Various aspects of perpendicular media recording physics related to the use of a soft underlayer have been discussed. It is shown that to fully optimize the performance of a recording system, the saturation moment of the soft underlayer material has to be equal to or higher than the saturation moment of the recording pole tip.

The importance of a proper choice of SUL-to-ABS distance for the optimized performance of a perpendicular recording system, in which media with a soft underlayer is used is stressed. It is shown, that if that distance is not chosen properly, the resolution of the recording system becomes substantially worse than the resolution of an equivalent perpendicular recording system optimized for the same areal densities, in which media without a soft underlayer is used.

Furthermore, it is demonstrated that to improve the playback efficiency, it is desirable to use high anisotropy soft underlayer materials. Also, the reduction of the soft underlayer noise via soft underlayer magnetic biasing has been demonstrated. Finally, it is shown, both experimentally and theoretically, that for high density recording systems it is not necessary to make the soft underlayer excessively thick as it was proposed by various authors in earlier publications.

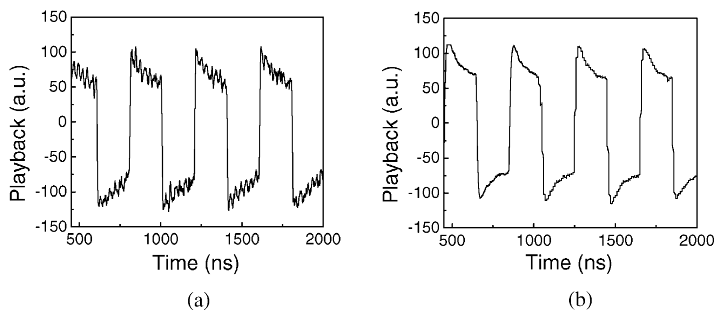

Fig. 10. Playback signal from two media with different soft underlayers. (a) Soft underlayer with a large number of stripe domains. (The presence of stripe domains was confirmed using magnetic force microscopy.) (b) Biased soft underlayer with domain walls swept out from the soft underlayer material.

A proper choice of the hard and the easy axes of the soft underlayer material should be emphasized. This is applicable to both write and read processes. To avoid hysteretic behavior and associated non-linearities, such as the Barkhausen noise, it is strongly desirable to have the easy axis of a soft underlayer material to be radially aligned. When the easy axis is radially aligned, the magnetization switching during the write process will be accomplished via magnetization rotation, while during the read process, the application of the radial biasing field will efficiently wipe the domain walls out of the soft underlayer.

In summary, although there are many similarities between perpendicular and conventional longitudinal recording, the specifics native to perpendicular media should be clearly understood and taken into account to design an efficient perpendicular recording system.

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