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Citation: Appl. Phys. Lett. **93**, 122502 (2008); doi: 10.1063/1.2985903
View online: http://dx.doi.org/10.1063/1.2985903
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v93/i12
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Improved media performance in optimally coupled exchange spring layer media

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(Received 14 August 2008; accepted 28 August 2008; published online 22 September 2008)

We have studied the recording performance of perpendicular exchange spring layer (ESL)-media for hard disk drive recording. In particular, we investigated the role of interlayer coupling by varying the thickness of a nonmagnetic coupling layer (CL). We demonstrate that not only the media writeability is improved upon optimizing the CL thickness, but also that substantial recording performance improvements can be achieved due to improved media noise properties. The potential of these media structures for high areal density recording is demonstrated by performing areal density measurements, which showed a substantial improvement for optimally coupled ESL-media. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2985903]

The astonishing technical progress in hard disk drive (HDD) technology during the past 20 years has brought this technology close to its physical limits.[1] In the past decade alone, the areal recording density has increased by a factor of 100, bringing today's product level bit size down to approximately $(56\ \mathrm{nm})^2$.[2] To reach this level of recording density, magnetic media grain sizes of only 8 nm diameter and below are required.[3] In addition to numerous technical challenges related to large scale fabrication of such nanocrystalline media structures, the more severe and fundamental problem is the maintenance of thermal stability. At this grain size level, thermal fluctuations can be so strong that the magnetic state becomes unstable.[4] This phenomenon is generally referred to as superparamagnetism and can result in the thermal decay of the stored information. The key parameter characterizing the stability is the product of anisotropy energy density K and grain volume V. The main media design limitation is that increasing K also raises the magnetic write field necessary to actively reverse the magnetic state of the grain.[3] Thus, simply increasing the material parameter K would make it ultimately impossible to transfer the information into a magnetic recording media in the absence of nonconventional techniques such as thermally assisted recording, for instance.[5] It is this simultaneous K dependence of writeability and stability that is the leading reason for the recent technology shift from longitudinal to perpendicular recording.[3] Perpendicular recording has a number of thermal stability advantages when compared to longitudinal recording, one of which is the fact that higher magnetic write fields can be achieved allowing for the use of higher K materials as recording media.

While it appears generally impossible to completely decouple writeability and stability for conventional recording media, it has nonetheless been demonstrated in recent years that advanced multilayered media structures can be designed in such a way that an improved writeability to stability ratio can be achieved, if one compares them to traditional single layer media designs. It is this multilayered media technology that has moved disk drive technology already far beyond an areal density of 36 Gbit/in.^{2}, which was estimated to be the superparamagnetic limit a decade ago.[6] Already in longitudinal recording technology, multilayer structures were utilized such as antiferromagnetically coupled media,[7] laminated media,[8] write assist layer technology,[9] and exchange spring layer (ESL) media,[10,11] to improve media writeability, stability or their overall recording performance.

With the transition to perpendicular recording, the search for advanced multilayered media structures has continued to push achievable recording densities even further. Hereby, there has been a substantial interest in ESL-media[12] or exchange coupled composite media,[13–16] which both utilize a combination of soft and hard magnetic materials to reduce the media grain switching field without compromising media stability. The physical origin of this improved writeability is facilitated by the layering of materials with different K in these media structures, which enables a nonuniform field reversal mode that probes an energy surface different from the one relevant for low field thermal stability. This functionality, however, requires that the interlayer coupling in such structures is tuned appropriately. Too strong a coupling will prohibit this nonuniform reversal (at least for layer thickesses appropriate for recording media), while a coupling that is too weak will decouple the reversal of the layers, causing a loss of the write assist effect from the soft layer to the hard layer altogether.[12–18] The improved writeability of these media designs can then be utilized to fabricate stable small grain media with higher anisotropy materials. Published studies on perpendicular ESL-media are mostly theoretical in nature[13,15–17] and provide only a limited set of recording results[14] that predominantly focuses on the writeability versus stability aspect. In this letter, we study writeability and recording performance of thermally stable, perpendicular ESL-media specifically as a function of the interlayer coupling strength and demonstrate that both are simultaneously improved upon optimizing the interlayer coupling.

The inset of Fig. 1 shows a schematic of the recording layer media structure prepared for this study, consisting of the following three individual layers: a 12 nm thick CoPtCr-alloy main recording layer (RL) containing an oxide segregant, a nonmagnetic CoRu-based alloy coupling layer (CL) and a 3-nm-thick low Pt CoPtCr-alloy ESL containing an oxide segregant. This recording layer stack was grown on top

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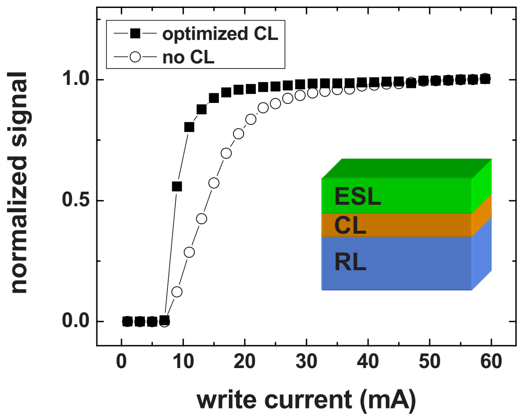

FIG. 1. (Color online) Signal vs applied write head current for an optimally coupled exchange spring media structure (■) in comparison to a reference disk without a CL (○), i.e., very strong interlayer coupling. The inset shows a schematic of the overall recording layer structure, which consists of a main RL, a CL, and the ESL.

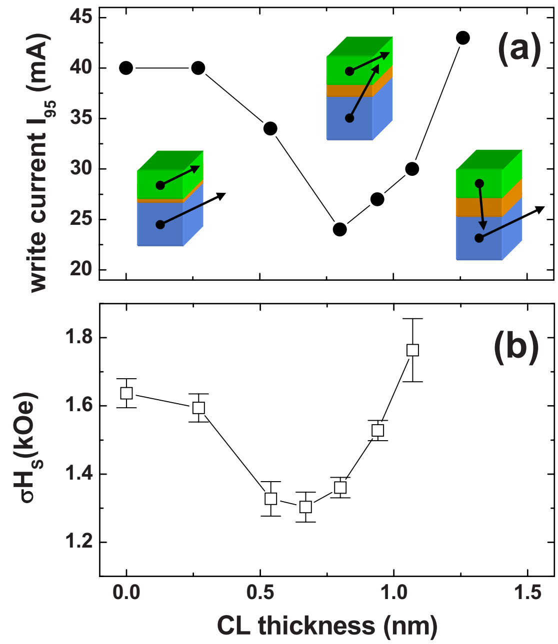

FIG. 2. (Color online) Exchange spring media properties as a function of the CL thickness: (a) writeability, given as the write head current needed to achieve 95% of the media signal saturation; (b) switching field distribution width σH_S, determined by means of the ΔH-method (Ref. 21). The schematic insets in (a) illustrate the different reversal mechanisms as a function of CL thickness.

of a suitable underlayer structure that contained a soft magnetic underlayer as well as a Ru-interlayer as a growth template. The media were covered with an overcoat layer for corrosion protection. In the experiments presented here, only the CL thickness was varied to tune the interlayer coupling strength between the RL and the ESL in order to optimize the recording media's magnetization reversal.[12] As previously demonstrated in a number of publications, an intermediate coupling strength allows for a nonuniform, but correlated magnetization reversal in each media grain, which improves writeability.[10–12,14,18] The result of this nonuniform reversal can be seen in Fig. 1, where the media saturation curves, i.e., the signal versus applied write head current dependencies, are shown for an optimally coupled exchange spring media structure (■) in comparison to a reference disk without a CL (○), i.e., very strong interlayer coupling. It is evident, that the write current necessary to saturate the optimized exchange-spring media is substantially reduced, meaning that a significant writabilty gain has been achieved in this experimental media structure.

Figure 2(a) shows the recording head write current that is necessary to achieve 95% signal saturation for disk test structures with varying CL thickness. Here, the writeability boost due to the optimized interlayer coupling is apparent as a distinct minimum that is reached for a CL thickness of 0.8 nm. As indicated by the three insets, only near this minimum is the coupling strength able to produce a clear writeability gain by means of nonuniform but correlated magnetization rotation. While the saturation current values shown in Fig. 2(a) are not a direct measure of the grain switching field, they are actually the more relevant quantities in terms of improved media switching, because they test the writeability gain directly under recording conditions. While such a writeability gain was predicted previously for the high speed field reversal that is used in magnetic recording, earlier attempts to verify these predictions were either limited to macroscopic and slow hysteresis loop measurements[14,18] or did not contain a direct comparison to the zero thickness CL disk, which is the most appropriate reference point.[19] We furthermore observe the media stability to be independent from the CL thickness with KV values of 90–100 k_BT.[20]

The demonstrated writeability gain, however, should only be considered to be an initial step toward the design of a media with improved recording performance. As we will see, other recording properties also show improvements that occur simultaneously with the ESL-media writeability gain. To understand the overall media performance behavior as a function of the interlayer coupling strength, we have measured the intrinsic switching field distributions of ESL media with varying CL thickness, using the recently developed $\Delta H(M,\Delta M)$ method.[21] This method allows one to access individual grain properties by removing intergranular coupling effects. While the structural changes in the ESL-media series under investigation here are very small, intergranular exchange interaction could nonetheless change due to alterations in the growth sequence, because the ESL is grown on top of a different CL thickness for every sample. Thus, simple hysteresis loop measurements are insufficient to extract a grain level understanding of the recording media properties. Figure 2(b) shows the standard deviation in the intrinsic switching field distribution σH_S as a function of CL thickness. As one can see from this figure, σH_S follows the same functional form as the write head saturation current, showing a clear minimum in the range of 0.5–0.8 nm, i.e., nearly simultaneous with the writeability improvement. A reduced switching field distribution width is an advantage in magnetic recording, because it allows for a more precise positioning of the magnetization transitions that make up the bit structure (reduced jitter noise) and improved resolution. These advantages then translate into higher achievable recording densities. Thus, upon tuning the CL to the point of optimized writing, one also finds an improved switching field distribution suggesting improved overall magnetic recording performance. The occurrence of this σH_S minimum as a function of CL thickness can be explained by the fact that the ESL reversal mode is most effective for hard to write media grains, while being less effective for the already easy to write media grains, similar to other write assist media schemes,

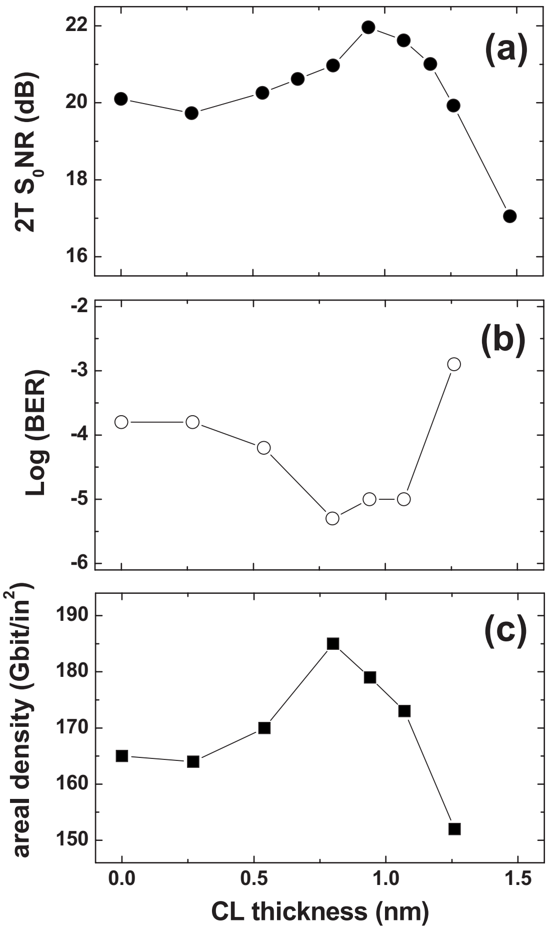

FIG. 3. ESL media properties as a function of the CL thickness: (a) signal-to-noise ratio S_0NR measured at $2T$ i.e., twice the target bit length T for the linear recording density of 950 kfci. (b) BER for a linear recording density of 950 kfci. (c) Areal recording density.

such as the write assist layer[9] or the magnetic torque layer media.[22] Thus, as one tunes the CL thickness to optimize the nonuniform reversal mode, one not only shifts the switching fields to lower values, but also reduces their size distribution. This physical picture is corroborated by model calculations.[12]

The recording performance as a function of CL thickness was tested experimentally and the results are shown in Fig. 3 for the same series of disk structures used to generate the data in Fig. 2. Figure 3(a) displays the signal-to-noise ratio as a function of CL thickness. Specifically, we plot here the quantity $2T$ S_0NR, which is the ratio of the isolated signal pulse to the media noise at 2 times the target bit size length T, i.e., half the target bit density. This quantity, which should be improved for properly optimized CLs due to the reduced switching field distribution width, indeed shows an improvement of up to 2 dB if compared to the fully coupled structure without a CL. Furthermore, the curve exhibits the expected optimum for intermediate CL thickness. Figure 3(b) shows the corresponding bit error rate (BER) data, measured at a constant linear density of 950 kilo flux changes/in. (kfci). A lower BER indicates better recording performance because the written signal can be recovered with fewer errors. Thus, the observed BER minimum for intermediate CL thickness represents the expected improvement in the RL quality, consistent with the better media signal-to-noise ratio found in Fig. 3(a). Furthermore, it should be mentioned that the size of the BER improvement, almost 1.5 orders of magnitude, is very considerable.

While improved SNR and BER are important, the most relevant quality test of a recording performance is the achievable areal recording density. This is particularly important for comparing media with different writeability. Often times, on-track improvements in SNR and BER can be observed for easy to write disks because wider tracks are written, which reduces track edge noise and improves the linear recording performance. These improvements often do not translate to improved storage densities because of reduced track densities. Shown in Fig. 3(c) are measured recording densities for using a product level recording head (135 Gbit/in^2 nominal density). The BER was required to be better than 10^{-5} on track and to posses a 15% off-track capability with BER $<10^{-3}$. Consistent with all other measurements, we find the optimized ESL-structure to show a substantial improvement in areal density over the rigidly coupled media structure without CL. These data clearly demonstrate the potential of ESL-media as a viable perpendicular recording technology.

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