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Approach to High-Density Recording Using CGC Structure

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Coupled granular/continuous (CGC) perpendicular media with two different continuous layers, a Co/Pd multilayer and a CoCrPtB cap layer, were compared. It was confirmed that both thickness optimized layers functioned well as exchange coupled continuous layers. A Landau–Lifshitz–Gilbert simulation was performed for various grain boundary thicknesses, and the signal-to-noise ratio improvement predicted by the simulation was in good agreement with experiments. The CGC structure was susceptible to side erasure on account of its Stoner–Wohlfarth type magnetic switching, and the recording performance was dominated by the granular layer. Controlling this behavior would enable further improvement in recording density. The benefits of discrete-track media with the CGC structure are discussed. We found that ion irradiation of the CGC media could be effective to create soft magnetic regions in between recorded tracks, which act as guard bands, improving the recording performance.

***Index Terms*—Discrete-track medium, exchange coupling, soft guard band, track edge noise.**

I. Introduction

COUPLED granular/continuous (CGC) perpendicular media were originally proposed to extend the density limit of granular perpendicular media caused by the "trilemma" of thermal instability, media noise, and writability [1]. In general, an appropriate amount of intergranular exchange coupling has been known to improve the thermal stability and reduce the saturation field. However, since excess exchange coupling tends to worsen media noise, precise control of the exchange coupling is required. The CGC structure has a significant advantage for achieving this precise control. The CGC structure consists of two layers: one is a continuous layer with strong exchange coupling and the other is a granular layer that serves to pin the magnetization in the continuous layer. The overall exchange coupling of the medium can be finely controlled by the continuous/granular layer thickness ratio. Signal-to-noise ratio (SNR) is increased due to a reduction in the medium noise arising from transition smoothing in the continuous layer [2]. The exchange coupling in CGC media also improves the thermal stability [3], [4] and reduces the switching field distribution [4]. Early CGC media used Co/Pd multilayers for the continuous layer [1], [4]. However, more recently a single CoPtCr layer tends to be used in order to satisfy productivity and process controllability issues [3]; such media are often referred to as "capped media" [5] or "stacked media" [6].

According to previous work, it was found that the magnetic written track width (Mww) was increased by excess exchange coupling. Therefore, there is another tradeoff for the continuous layer thickness between Mww and SNR [7].

In this paper, various optimizations for recent, practical CGC perpendicular recording media are investigated in terms of read/write characteristics with the aid of Landau–Lifshitz–Gilbert (LLG) micromagnetic simulations. We have previously reported on CGC media with Co/Pd multilayers as the continuous layer [4], [7]. Discussion of the CoCrPt capped layer is provided in this paper. The tendency of the CGC structure to have wide Mww and erase band widths (EBWs) is discussed, and the possibility of improvement through the use of discrete-track media (DTM) is examined.

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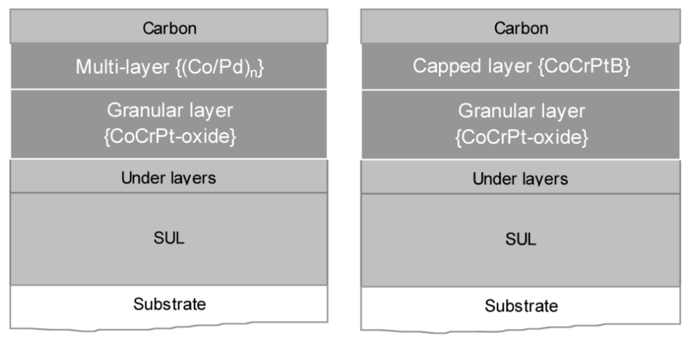

(a) (b)

Fig. 1. Structures of CGC media with (a) multilayer and (b) capped layer continuous layers.

II. Exchange Coupling in CGC Structures

A. Experimental Setup

1) CGC Media Samples: Fig. 1 shows schematic cross-sections of two types of fabricated CGC media. In one type of media, the continuous layer was formed from a $(Co/Pd)_n$ multilayer. The other type of media used a CoCrPt alloy as a continuous layer, or capped layer. The continuous layers were sputter deposited on top of the granular magnetic layer to control the intergranular exchange coupling. Detailed properties of the fabricated samples are listed in Table I. Each type had a fixed granular thickness and various continuous layer thicknesses, resulting in a range of exchange coupling strengths.

2) Magnetic Properties: The static magnetic properties (coercivity H_c, nucleation field H_n, and saturation field H_s) were measured using a Kerr magnetometer, as shown in Fig. 2. Adding a continuous layer increased the nucleation field and reduced the saturation field and coercivity. The dependence of magnetic properties on the thickness of the continuous layer was most pronounced in the multilayer. For the capped media

TABLE I
DETAILS OF (TOP) MULTILAYER AND (BOTTOM) CAPPED LAYER SAMPLES

		Granular thickness d_g (nm)	Continuous thickness d_c (nm)	H_c (Oe)	H_n (Oe)	H_s (Oe)
Multi-layer (Co/Pd)n	Granular A	13.0	0	5920	-760	11000
	Multi #1		1.9	5290	-1070	9900
	Multi #2		4.0	4580	-2200	7000
	Multi #3		6.0	4260	-2700	5800
Cap layer CoCrPt	Granular B	15.0	0.0	3790	-620	7580
	Cap #1		4.0	5200	-1640	9270
	Cap #2		8.0	4649	-2090	7240
	Cap #3		12.0	3601	-1740	5600

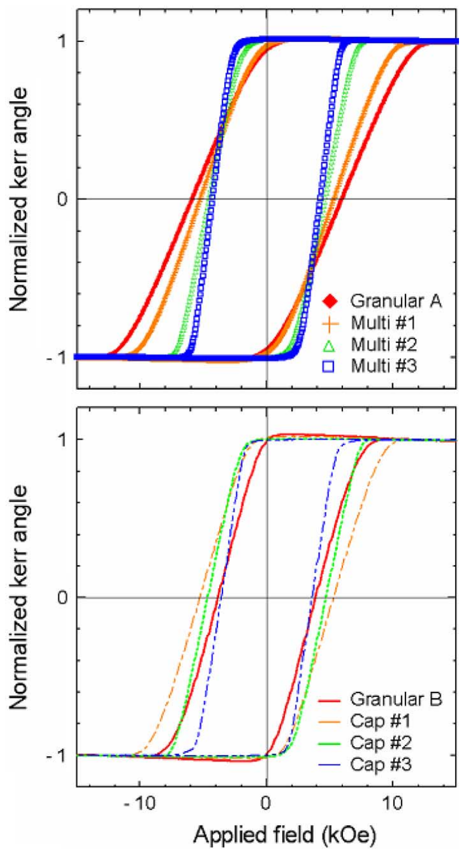

Fig. 2. Kerr loops of granular media and CGC media with (top) multilayer and (bottom) capped layer continuous layer.

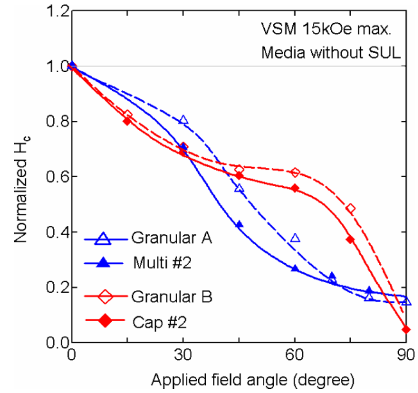

Fig. 3. Angular dependence of normalized H_c for granular, multilayer, and capped media. Media were prepared without soft underlayers for vibrating sample magnetometry measurement.

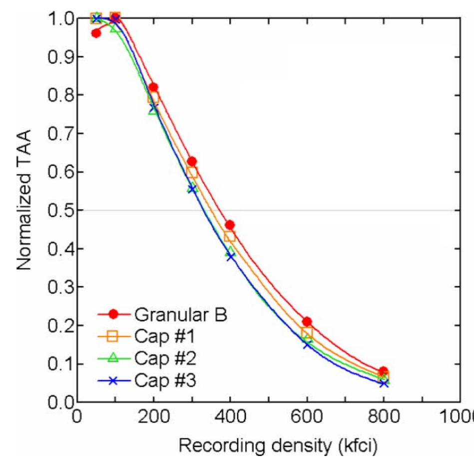

Fig. 4. TAA rolloff of media with various cap layer thicknesses as a function of linear recording density.

described here, a thin cap always tended to increase the coercivity; this tendency was also reported in [8]. Fig. 3 shows the dependence of normalized H_c on the angle of the applied field from the perpendicular axis for granular and capped media. The capped media had almost the same angular dependence as the granular media, which implies coherent Stoner–Wohlfarth reversal.

B. Read/Write Performance

To measure the read/write characteristics, a spin-stand tester was used. The single pole type write head had a trailing shield and a write width T_{ww} of 160 nm. The giant magnetoresistive reader had a read width T_{wr} of 100 nm. The write current was 50 mA, at which point the overwrite performance was saturated. An AC-erased band of width 1 μm was written at 1200 kfci with 60 mA before writing the test signals. The linear velocity was 10.16 m/s at a radius of 25.0 mm. The giant magnetoresistive reader had a read width T_{wr} of 100 nm. The write current was 50 mA, at which point the overwrite performance was saturated. An AC-erased band of width 1 μm was written at 1200 kfci with 60 mA before writing the test signals. The linear velocity was 10.16 m/s at a radius 25.0 mm.

1) Rolloff Characteristics, D_{50}, and SNR: The amplitude rolloff characteristics of capped layer media are shown in Fig. 4 and the half-amplitude densities D_{50} are shown in Table II. Increasing the cap thickness increased track average amplitude (TAA), particularly at low frequencies, but D_{50} decreased. This was because adding the cap layer increased the total magnetic layer thickness, degrading the resolution. SNR and media noise dependence as a function of linear density is shown in Fig. 5. The capped layer media showed similar trends to the multilayer media described in [7] in that a thicker continuous layer improved the SNR and reduced medium noise at low linear densities, but noise increased faster with linear density in the CGC media, leading to higher noise levels above a certain linear density.

2) Magnetic Track Width and Erase Band Width: The amplitude rolloff characteristics of capped media are shown in Fig. 4

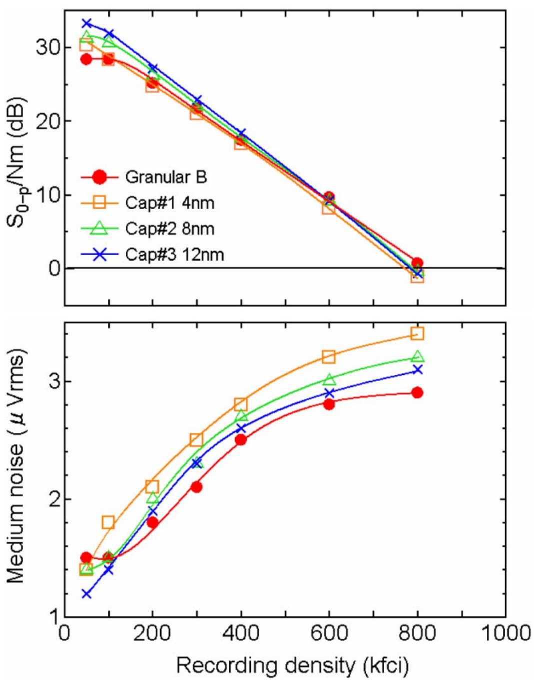

Fig. 5. SNR and media noise as a function of linear recording density for capped media.

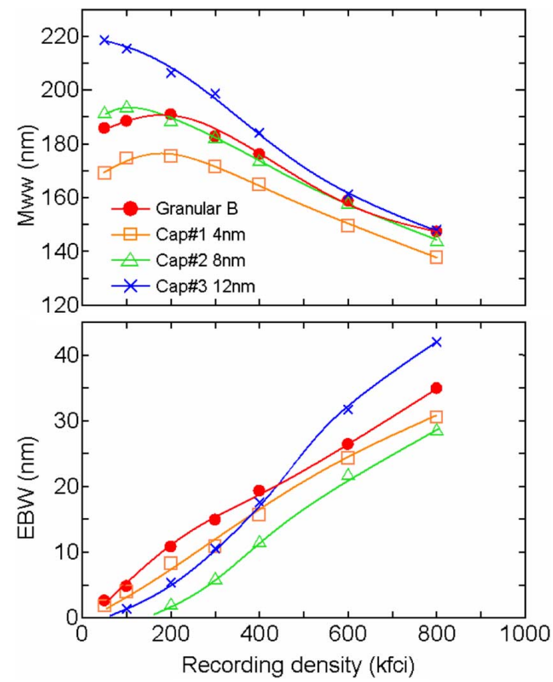

Fig. 6. Mww and EBW as a function of linear recording density for capped media.

TABLE I
D_{50} FOR CAPPED MEDIA WITH VARIOUS CAP THICKNESSES

Sample	Granular / Cap thickness	TAA_{max} (μV_{pp})	D_{50} (kfci)
Granular	15 nm / 0 nm	40.3	376
Cap#1	15 nm / 4 nm	46.1	359
Cap#2	15 nm / 8 nm	52.8	334
Cap#3	15 nm / 12 nm	56.5	331

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3) Magnetic Track Width and Erase Band Width: Fig. 6 shows the Mww and EBW as a function of linear recording density for capped media. Mww and EBW measurements were made using the IDEMA method (full width at half-maximum) and the off-track overwrite method [9]. For the medium with the thickest capped layer, Cap#3, the Mww was much wider than the granular medium and the trend was similar to that of the multilayer media. EBW became narrower in the capped media, with the reduction dependent on the cap thickness. However, the medium with the thickest cap layer had a wider EBW at high linear densities; this trend was also similar to

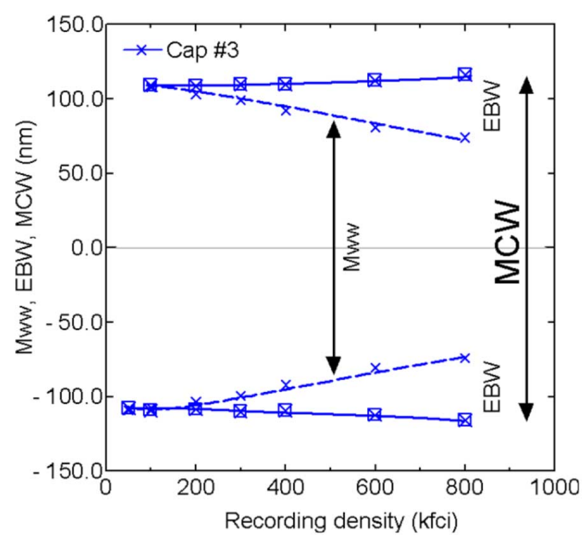


Fig. 7. Track edge position (MCW), Mww, and EBW for the medium with a 12 nm cap layer. MCW is defined as the sum of Mww and EBW.

the multilayer media. The Mww of the Cap#1 ($d_c = 4$ nm) medium was the narrowest, due to higher H_c and H_s than the granular medium.

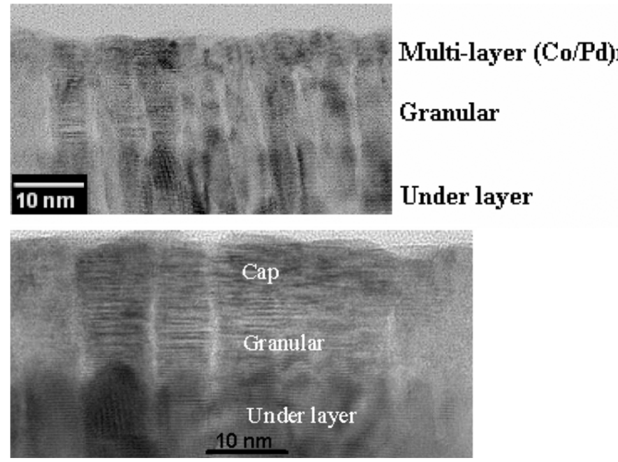
Fig. 7 indicates the relationship among Mww, EBW, and the aggregate track edge position [magnetic core width (MCW)]. Irrespective of type (cap or multilayer), media with the thickest continuous layers showed the widest Mww values. This was caused by coercivity reduction due to the exchange coupling.

C. Simulation

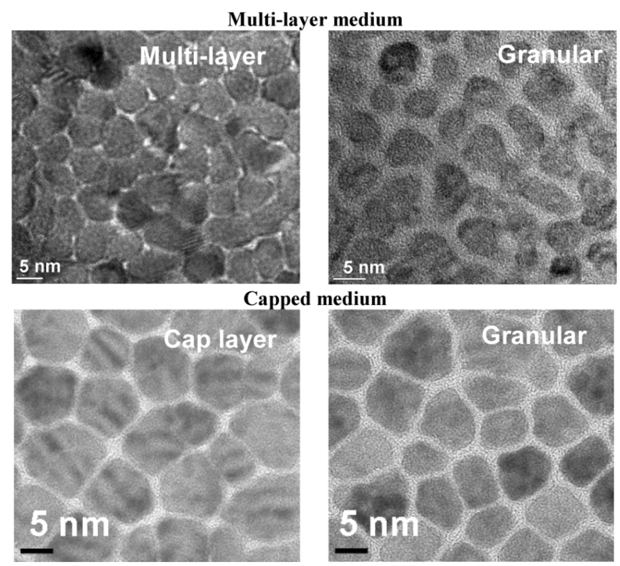
1) Simulation Model: Cross-sectional transmission electron microscopy images of the multilayer and cap layer media are shown in Fig. 8(a) and plan view images in Fig. 8(b). The cross-sectional images show that both granular layers have clear grain boundaries, and the continuous layers have thinner grain boundaries than the granular layers. The plan view shows that the grain boundary thickness in media with a cap layer is larger than that of media with a multilayer, leading to reduced intergranular exchange coupling in the capped media. According to the transmission electron microscopy images, a simulation model was established in which the granular and continuous layers had different intergranular boundary thicknesses, as illustrated in Fig. 9. We assumed that the increase in the boundary thickness reduced the exchange coupling between neighboring grains. For a boundary thickness d_{ij}, the exchange coupling strength was assumed to decrease exponentially as Ae^{1-d_{ij}/d_0} [10], where d_0 is the atomic spacing (0.2 nm) and A is the exchange coupling constant (10 erg/cm^2). This form of variation of exchange coupling strength with boundary thickness gave a good fit to experimental data for granular media, in which the oxide content was varied to alter the boundary thickness. The medium model was divided into several layers. The magnetic spacing, including the flying height of the head and the overcoats of the head and medium, was 6 nm. The recording layer, consisting of the continuous and granular layers, had a maximum thickness of 14 nm. The intermediate layer, between the recording layer and the soft magnetic underlayer, had a thickness of 4.5 nm. The average grain boundary thickness, and hence the exchange coupling, was varied by changing the grain boundary thickness parameter B. Thus, the area of the medium occupied by grains was $100 \times (1–0.18)^2 = 67\%$ of the total area, leaving 33% occupied by the grain boundaries. The average grain pitch was 7.5 nm and the grain size (diameter) dispersion was 9.5%. The easy axis dispersion was 3°. The anisotropy energy K_u varied from 3.2×10^6 to 4.5×10^6 erg/cm^3 with a 10% dispersion among the grains. The saturation magnetization M_s was 500 emu/cm^3 and the temperature was 300 K. The write head had both side shields and trailing shields, and the main pole width was 38 nm. The head field rise time (zero -90%) was 0.12 ns. Readback waveforms were calculated using the sensitivity function of a 30-nm-wide magnetoresistive (MR) reader with a 25 nm gap length and output waveforms were normalized to the MR head response obtained from an isolated transition.

2) Simulation Results: To maximize thermal stability, it is necessary to increase the medium K_u as much as the magnetic field of the write head permits. However, high K_u granular media have very high saturation fields, leading to writability problems, particularly at low linear densities. For this reason, it is necessary to introduce exchange coupling into the granular media. Fig. 10 shows simulation results comparing media with several continuous layer boundary thicknesses (B_c) and $K_u = 4.0 \times 10^6$ erg/cm^3. The media with the narrowest grain boundaries and strongest exchange coupling $(B_c = 0.06)$ showed a rapid variation of SNR as a function of exchange coupled layer thickness. As the average grain boundary thickness increased, the variation of SNR with continuous layer thickness was reduced and the optimum continuous layer thickness (for maximum SNR) increased.

Fig. 11 is a simulation result of MCW and Mww as a function of continuous layer ratio at $B_c = 0.10$ and $K_u = 4.0 \times 10^6$ erg/cm^3. Increasing the continuous layer ratio slightly increased



(a)



(b)

Fig. 8. (a) Cross-section transmission electron microscopy images of (top) multilayer medium Multi#2 and (bottom) capped medium Cap#2. (b) Plan view transmission electron microscopy images of (top) multilayer medium Multi#2 and (bottom) capped medium Cap#2.

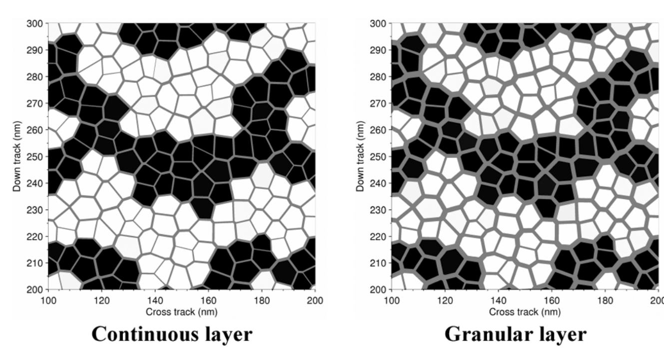


Fig. 9. Images of part of the continuous and granular layers in the simulation. The grain boundary width was increased in the granular layer.

Mww; however, MCW expanded in proportion to the continuous layer ratio, leading to an increase in EBW. Although the

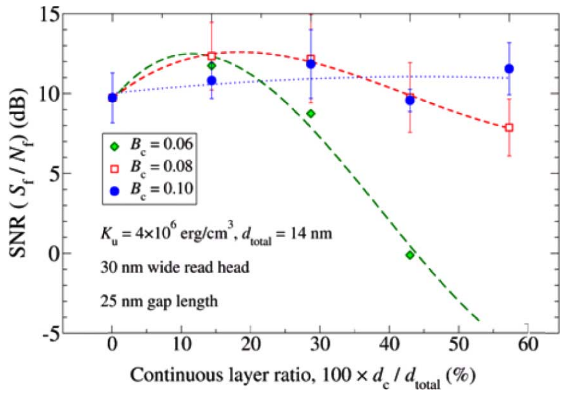


Fig. 10. SNR versus continuous layer thickness ratio at a linear density of 907 kfci for simulated CGC media with various grain boundary thicknesses B_c in the continuous layer.

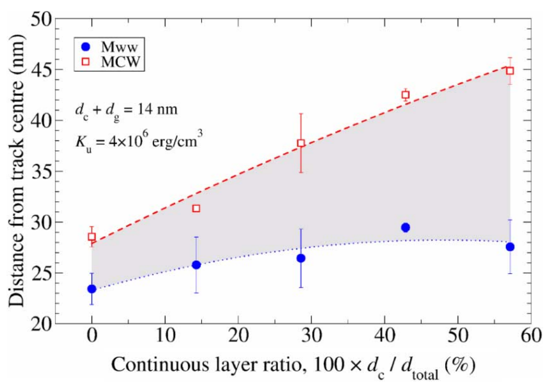


Fig. 11. MCW and Mww positions from simulations of written tracks at 907 kfci in media with $K_u = 4.0 \times 10^6$ erg/cm^3 as a function of continuous layer ratio (continuous layer thickness d_c/total magnetic thickness d_{total}). $B_c = 0.10$. The shaded area indicates the EBW.

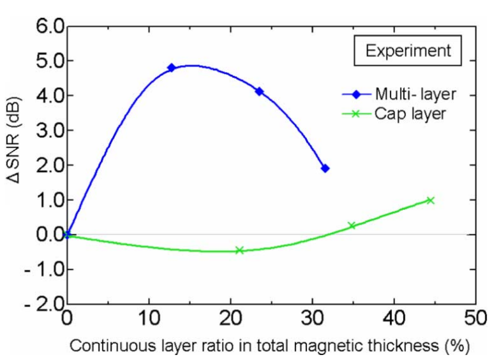


Fig. 12. SNR improvement over a granular medium as a function of continuous layer thickness ratio for multilayer and capped media at 400 kfci.

SNR was improved, MCW expansion may restrict increases in the track density.

D. Measurements

Fig. 12 shows experimental measurements of the SNR improvement over a granular medium as a function of continuous layer thickness ratio.

The optimum continuous layer thickness depended on the continuous layer material. The two layers should have different exchange coupling strengths to the granular layer; the multilayer's exchange coupling stiffness was greater than that of the capped layer. For the capped media, the cap layer grains grow epitaxially on top of the granular layer, which consists of segregated grains with thick boundaries, reducing the exchange coupling strength. In contrast, the multilayer had stronger exchange coupling. Therefore, a thin layer is sufficient to provide the necessary exchange coupling to the granular layer. This gives an advantage by allowing a reduction of the gap between the head and soft underlayer, increasing the head field gradient. The current CGC structure can be optimized by stronger exchange coupling, which may give greater hysteresis loop squareness, or a smaller switching field distribution.

III. Discussion

A. Concept of DTM With CGC

Fig. 13 shows experimental measurements of MCW and EBW for granular A, granular B, capped medium (Cap#3 d_c = 12 nm), and multilayer medium (CGC#1 d_c = 1.9 nm). Although the Cap#3 medium had the thickest cap layer, its Mww at 800 kfci was almost the same as the granular B medium. The EBW of the Cap#3 medium was wider than the granular B medium because H_c was reduced by excessive exchange coupling. The CGC media have improved SNR, even after accounting for the expansion of the written tracks. We believe that the ideal conditions, under which the maximum benefit of the CGC structure would be realized, would be if the erase bands were to be removed, as shown in the right-hand side of Fig. 13. Fig. 14 shows the concept of DTM with CGC structure, similar to that reported by Tang *et al.* [11]. In the granular medium some isolated, reversed grains appear within the written track, as indicated by the circles [Fig. 14 (upper left)]. On the other hand, the CGC medium (lower left) had no isolated, reversed grains. The magnetic write width, indicated by the square boxes in Fig. 14, was expanded in the CGC medium. Thus, implementation of DTM should suppress this track expansion, as shown in the lower right image of Fig. 14. DTM fabrication has been reported using several patterning techniques, e.g., lithographical etching with a planarized surface [12] or ion implantation patterning [13]. Ion irradiation modifies the magnetic properties of the media [14]; therefore, we propose the use of soft guard-band media.

B. Soft Guard Band

As described above, increasing exchange coupling to improve the switching field distribution expands the written tracks, while implementation of DTM addresses the problem of the angular sensitivity. On the other hand, the structure of the write head is not easy to change. A media structure to produce higher magnetic field gradients was examined, although it was also effective to increase the magnetic field inclination.

The concept of soft guard band media has been suggested [15]. We found that ion irradiation of CGC media can be used to create regions of soft magnetic material [14]. Thus, we propose magnetically discrete media with high-permeability guard bands. The guard bands were fabricated by ion irradiation to reduce the local coercivity and obtain higher permeability. Fig. 15 shows the results of a simulation of the effect of varying the guard band permeability on the cross-track head field distribution in the center of the recording layer. Compared with a permeability of one, higher permeability in the guard bands reduced

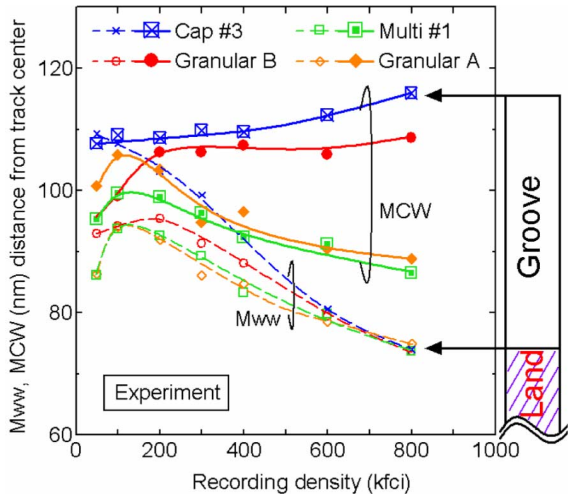
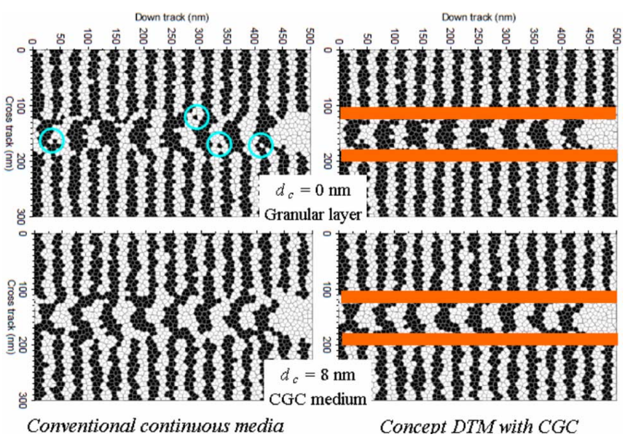


Fig. 13. Measurements of track edge (MCW), Mww, and EBW for granular A, Cap#3, granular B, and Multi#1 media at various linear densities. A schematic example of groove and land in DTM media is shown on the right.



(a) (b)

Fig. 14. Simulations of tracks written at 907 kfci in media with $\mathrm{Ku} = 3.2 \times 106$ erg/cm^3. (Top) Granular medium and (bottom) CGC medium have different continuous layer thicknesses dc. (a) Conventional continuous media; (b) the concept of DTM with CGC media.

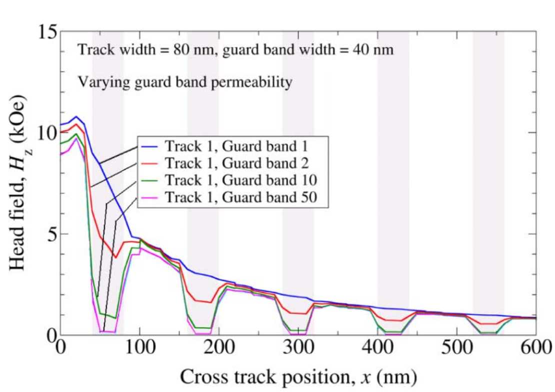


Fig. 15. Head fields in the middle of the recording layer for various guard band permeabilities. Track permeability $= 1$. The shaded areas indicate the location of the guard bands.

the field in the guard bands and increased the head field gradient at the track edges.

IV. Conclusion

CGC media consisting of two different continuous layers, a Co/Pd multilayer and a CoCrPtB capped layer, were investigated. Both continuous layers function as exchange coupling layers. Based on transmission electron microscopy images, an LLG simulation introduced media models in which the continuous layer had a different grain boundary thickness and, thus, different exchange stiffness. The simulation results agreed with experimental results in terms of the variation of SNR with continuous layer thickness, and SNR was enhanced at the optimum thickness. The written track width of CGC media still tended to expand due to the exchange coupling. We propose to implement the concept of DTM with CGC structure to remove the track edge issues. Soft magnetic groove formation with ion irradiation technique was investigated. High-permeability guard bands should improve the write performance.

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