The Feasibility of Magnetic Recording at 10 Terabits Per Square Inch on Conventional Media

Roger Wood[1], *Fellow, IEEE*, Mason Williams[2], *Fellow, IEEE*, Aleksandar Kavcic[3], and Jim Miles[4]

[1]Hitachi Global Storage Technologies, San Jose, CA 95193 USA
[2] San Jose, CA USA
[3]University of Hawaii, Manoa, HI USA
[4]University of Manchester, Manchester, U.K.

This paper proposes a new approach to magnetic recording based on shingled writing and two-dimensional readback and signal-processing. This approach continues the use of conventional granular media but proposes techniques such that a substantial fraction of one bit of information is stored on each grain. Theoretically, areal-densities of the order of 10 Terabits per square inch may be achievable. In this paper we examine the feasibility of this two-dimensional magnetic recording (TDMR) and identify the significant challenges that must be overcome to achieve this vision.

***Index Terms*—Areal-density, capacity, granular media, magnetic recording, shingled writing, two-dimensional.**

I. Introduction

EIGHT years ago, a paper was published predicting that conventional recording would reach a limit at around 1 Terabit/in^2 [1]. That view is still widely held even though current products are already approaching 400 Gb/in^2, with recent growth at a remarkable 30%–50% per year! The fundamental limiting factor is thermal stability of the magnetic grains comprising the recording medium. To assure continued capacity growth in Hard Disk Drives there are intense efforts on two alternative technologies: heat-assisted magnetic recording (HAMR) and bit patterned media (BPM). Both approaches require the medium to be radically redesigned.

For HAMR, a near-field laser embedded in the write head heats a tiny spot on a very high coercivity medium. This reduces the coercivity sufficiently for the head fields to switch the medium. Such high coercivity media can be kept stable at smaller grain-sizes thus supporting smaller data-bits and allowing continued areal-density growth. The development of an ultrafine grained medium with very high anisotropy and with suitable thermal and magnetic properties is critical to the success of HAMR [2].

For BPM, the medium is engineered with well-defined magnetic islands occurring in known positions (in contrast to conventional medium where grains fall in random positions). The write-process is carefully synchronized with the island positions such that each island now stores exactly one bit of data. Creating a very regular array of tiny well-formed islands with consistent magnetic properties over an entire disk surface is a considerable challenge [3].

Given the difficulties of creating such novel media for either HAMR or BPM, this paper introduces an alternative scheme that extends the use of conventional media but takes more radical approaches for writing, reading, and signal-processing. Fig. 1 shows an example outlining the proposed new scheme which we refer to as TDMR (two-dimensional magnetic recording). Here a conventional recording medium with 20 Teragrains/in^2 is expected to record 10 Tb/in^2 (on average, each user bit is stored on 2 grains).

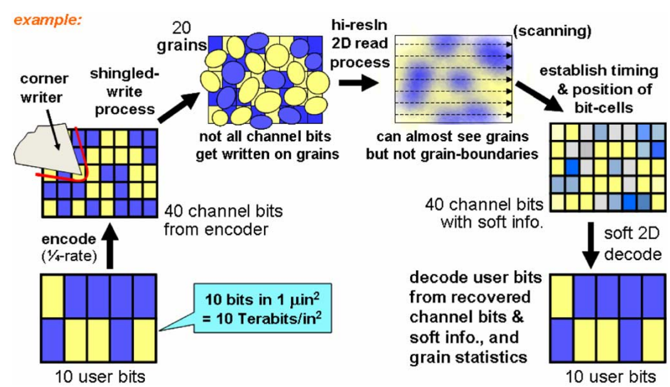

Fig. 1. Toy example illustrating two dimensional magnetic recording (TDMR). Here we arbitrarily show exact ratios of 1 user bit to 2 grains to 4 channel bits. At 10 Tb/in^2, each square microinch records 10 user bits on 20 random grains each of approximately 6 nm diameter. The code rate is one-quarter (300% overhead). Shingled writing with a corner-writer is necessary to maintain high fields but does preclude conventional "update-in-place." Readback is accomplished using information gathered from several immediately adjacent tracks, either from successive scans or from an array head. A powerful two-dimensional soft decoder recovers the user data.

Shingled-write with a specially designed "corner writer" will be necessary in order to maintain high write fields and to maximize both down-track and cross-track field gradients [4]. Shingled-writing is viewed as essential even though it precludes "update-in-place" and may require a new interface protocol and an intelligent on-board data management system. The reader must also have very good down-track and cross-track resolution, especially since a low bit-aspect ratio of perhaps 2:1 is envisioned to minimize short-wavelength spacing losses. Signal processing is done in two dimensions using information available across several adjacent tracks. This requires either an array head that reads many tracks simultaneously, or a single head that is progressively scanned to build up equivalent information

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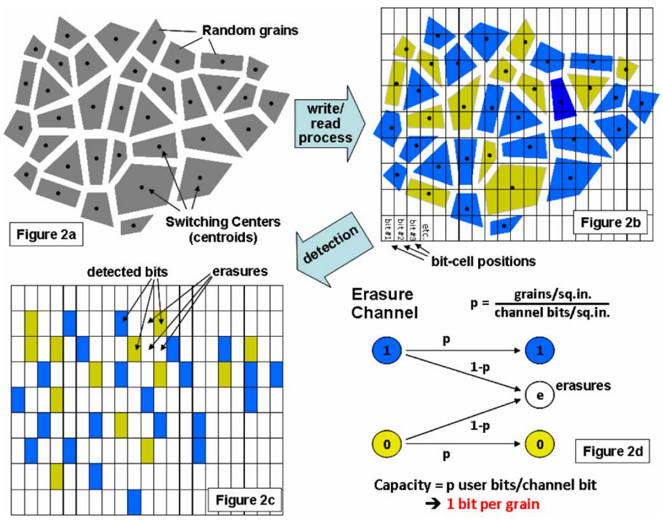

Fig. 2. Illustrates the one-bit-per-grain capacity bound. The medium comprises grains that are random in size and shape (Fig. 2(a)). The write process knows nothing of the location of the grains but switches each grain according to which bit-cell the grain centroid lies in (Fig. 2(b)). The readback process has very high resolution and very low noise and can identify the polarity of each grain and the position of its centroid (also Fig. 2(a)). If no grain centroid falls in a bit-cell then the cell is declared an erasure otherwise the polarity of the grain is reported for that bit-cell (Fig. 2(c)). This corresponds to an erasure channel (Fig. 2(d)). The information capacity of such a channel is simply given by the probability, p, that a bit-cell does not correspond to an erasure. In the limit of high channel bit-cell density, the probability, p, becomes equal to the number of grains per unit area divided by the number of bit-cells per unit area. That is a limiting capacity of one user bit per grain.

in memory. The application of powerful detection techniques cross-track as well as down-track is a central feature of this new scheme.

The ability to achieve data densities such that each user bit is stored on very few grains is not a forgone conclusion. Conventional granular media has no long range order and it is totally impractical to synchronize written data with individual grains. However, there are considerable grounds for optimism and certainly this presents an open and fertile research area.

II. Capacity Bounds

The ability to store each bit of information on very few random grains is a central argument for the TDMR approach. We start by examining this largely unexplored territory.

A. One-Bit-Per-Grain

It was shown in the earlier paper [1] that for tiny, sparse grains and readback with very high resolution and low noise, that the information capacity of such a system approaches one user bit per grain. This is true despite the random positioning of the grains. The system requires no knowledge of the grain positions during writing. However, on readback, the detection process must identify not just the polarity but *also the position of each grain* with respect to the written data. The capacity argument is as follows. If a grain does fall in a bit-cell then the polarity of that grain is reported. If no grain falls within a bit cell, an erasure is declared. The capacity of such an "erasure channel" is given by the probability that a bit is not an erasure. In the limit of very high channel-density and very sparse grains, the capacity reduces to one user-bit per grain.

The one-bit-per-grain argument can be extended to a system with finite size grains only if the grain positions and shapes can be identified during readback to a level such that the system can determine which written bit cell was responsible for setting the magnetization of a given grain. Fig. 2 depicts a system with extremely high resolution such that the grain boundaries and the details of each grain are resolved and where, for each grain, an effective center of switching can be deduced at which the write process is assumed to act. The limiting capacity is again one-bit-per grain.

B. Capacity Loss Due to Inability to Distinguish Grain Boundaries—Example With 1-D Channel

For real granular structures where the grain boundaries cannot be reliably observed and the grain positions and sizes cannot be identified with certainty, the capacity is less than one bit per grain. The calculation of capacity bounds for such a 2-D array of grains has not yet been addressed and presents a formidable challenge. However, by examining a very simple 1-D channel, we get a glimpse of what the capacity loss might be for such a 2-D system.

Fig. 3(a) shows a 1-D channel where the grains have random lengths but where the information about the grain boundaries cannot be distinguished on readback (unless the grains on either side have opposite polarity). The grains have randomly selected lengths of 1, 2, or 3 channel bits. For ease of calculation we assume grain boundaries coincide with the channel bit boundaries. Relaxing this constraint may further reduce the capacity. However we believe this simple model captures the essence of the problem in that the boundaries between similarly magnetized grains *cannot* be discerned on readback (in contrast to the one-bit-per grain arguments in Section II-A). For the write-process, we assume the grain takes the polarity of the last bit seen (this proved more convenient and is in some ways more intuitive than using the centroid). Again a high resolution noiseless readback process is assumed (but one that cannot distinguish grain boundaries).

In Fig. 3(b) we plot a lower capacity bound for this 1D channel configuration. Markov process optimization was used to compute the bound [6]. In this case a third-order Markov source is adjusted to maximize the information rate (the result for a second-order source is only slightly different). We see that for, say, 25% "grain-length" sigma, the capacity is a surprising 0.87 bits per grain. This corresponds to a 13% loss in information capacity due to the inability to identify the exact lengths of adjacent grains having the same polarity.

In the real world there will be myriad other major sources of degradation. These include, perhaps most fundamentally, the interaction field between grains during writing as well as the intrinsic switching field distributions. In addition, there will be significant readback noise coupled with very limited readback resolution. Much work remains to be done.

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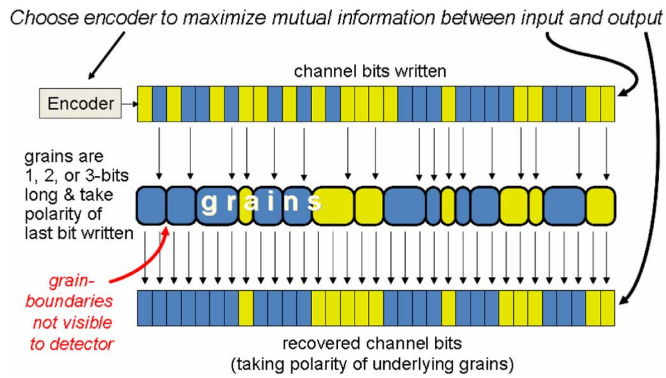

Fig. 3(a). Model for simple 1-D channel that allows a simple capacity bound to be calculated. Grains occur randomly with lengths of 1, 2, or 3 channel bits. The writing process is represented by each grain assuming the magnetization of the last channel bit it sees. On readback each channel bit simply takes the polarity of the underlying grain (perfect resolution, no additive noise). The boundary between grains of the same polarity cannot be distinguished. The information rate is computed assuming a Markov data source.

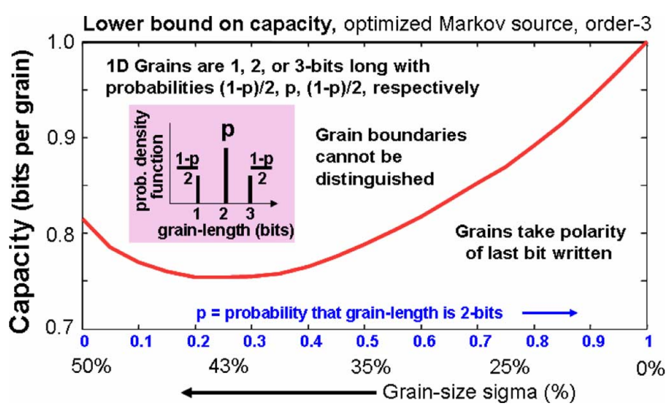

Fig. 3(b). Lower bound on capacity for the 1-D channel as a function of the probability distribution of the grains. Grains of length 2 have probability p. Grains of lengths 1 and 3 are equiprobable. The capacity bound is computed as the information rate maximized over a third-order Markov source [6]. Expressed in "bits per grain" the capacity of the system exceeds 80% for reasonable grain-size distributions.

III. Shingled Writing

To achieve the highest areal densities we are forced to use relatively small diameter grains, yet these grains must have sufficient volume to be thermally stable. The net result is grains that are much taller than they are wide. Although, with sufficiently small spacing, intense fields can be generated over areas localized to a grain diameter, the penetration of such fields is limited to less than a grain diameter and certainly to much less than the grain height. For example, a pole-tip 5 nm square may be able to generate a reasonable field at the top of a 5 nm diameter grain, but the field (and gradients) say 15 nm further away at the bottom of the grain will be much smaller.

Shingled-write with a specially designed "corner writer" overcomes this problem since there is no longer a narrow pole-tip that has to match the track-pitch [4]. Here the fields are constrained only on one edge down-track and one edge cross-track. The vertical fields will be more uniform through the thickness of the medium. Also, with a head of this design, there are no constrictions limiting the amount of flux approaching the corner. Because of these two factors, much higher fields

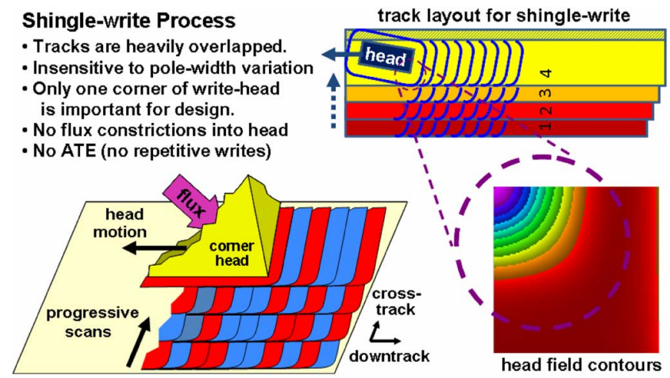

Fig. 4. Illustration of shingled-writing. Tracks are written sequentially and heavily overlapped as they are written. Since only one corner of the head is involved in determining the written magnetization pattern, the design of a "corner head" is thus much relaxed compared to a conventional head. There are no longer any constrictions limiting the flux entering the corner, so high field levels can be maintained. Field gradients however are still very dependent on what can be achieved in terms of magnetic spacing and the distance to the soft-underlayer (perpendicular recording). High field gradients must be simultaneously achieved in both down-track and cross-track directions implying very closely-spaced field contours with a very tight radius of curvature. However adjacent track erasure (ATE) becomes a non-issue because there are no repetitive writes to a single track.

can be obtained that can penetrate the medium to much greater depths. The implication is that field magnitudes and thus grain sizes and thermal stability can be maintained much better as we push to these ultimate storage densities.

A. *Advantages and Disadvantages of Shingled-Writing*

There are a number of overwhelmingly positive aspects of shingled writing and of the corner writer (Fig. 4). These advantages include the higher fields (and thus higher field gradients) that can be obtained as well as the freedom from the effects of most process tolerances (pole-tip width, flare-point, shield throat-height, etc.). In addition, because tracks must be written sequentially, adjacent track erasure (ATE), which occurs when a single track is written repetitively and damages an immediately adjacent track, is a nonissue. This allows a relaxation in the design constraint on the maximum head field that is allowed to fringe onto the adjacent tracks.

A significant disadvantage is that "update-in-place" is no longer possible. Tracks are written sequentially in one direction cross-track. Therefore a single track or portion of a track cannot be altered without first recovering many tracks of subsequently written data. After the target track is updated, the recovered tracks must be rewritten back onto the disk.

One approach to organizing data on a drive was described by Kasiraj and Williams [4]. In this case the head is assumed to be symmetric, to be of moderate overall width, and to be roughly rectangular with two "corners" either of which can be used to write shingled tracks. In an outer region of the disk, the outer corner (further from the disk spindle) is pertinent and tracks are written successively shingled with the head moving towards the inner radius. In an inner region of the disk, the other corner of the head is relevant and tracks are written successively shingled with the head moving towards the outer radius. In both cases, the skew is such that it helps avoid the long footprint of the rectangular pole-tip from damaging prior tracks. In these two

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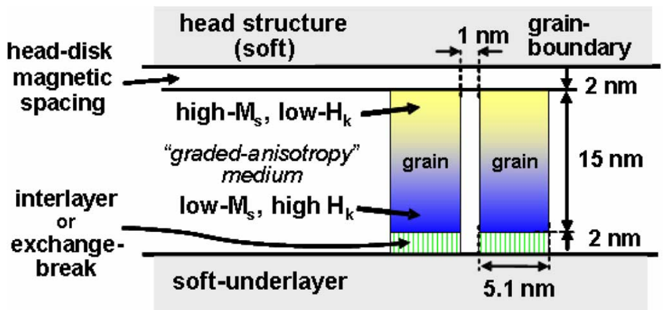

Fig. 5. Illustrating possible grain dimensions for a 20 Teragrain/in^2 medium. Ms, Hk, and vertical and in-plane exchange are all graded through the thickness. Switching is nucleated at the top of the grain where the head fields and gradients are highest (accordingly, in calculating the "effective head field," we take the field averaged only over the top half of the grain). The grains are illustrated here as if they were hexagonal. A hexagonal grain 5.1 nm across-flats has the same area as a 5.4 nm circle (see Section IV-A).

broad regions, tracks are organized into bands of perhaps 100 tracks. Between bands a gap depending on the head erase-width will be necessary.

For many applications, e.g., digital video recording, most of the data can be written sequentially in such bands with little loss of performance. However, some meta-data with information such as volume table-of-contents and last-access-time requires frequent updating. In concept, this data can be kept in a small number of dedicated tracks written using the natural full write-width at mid-radius where the skew is small. The operating system or device driver would have to be capable of communicating to the drive microcode whether particular data is metadata or not, perhaps by selection of a range of logical sector numbers. This would clearly require agreement and effort by system and drive designers [5].

Despite these major issues at the system-level and with respect to the interface protocols, shingled-writing is viewed as an essential enabler of the TDMR approach.

B. Scaling and Recording Medium Design

For 10 Tbit/in^2, we would like to see all dimensions approximately three times smaller than at 1 Tb/in^2. This would include all the write-head dimensions and, of course, the head-medium spacing which would drop to about 2 nm from 6 or 7 nm [1]. Unfortunately, because of the thermal stability limit, the medium thickness is not expected to scale in this way and the soft underlayer will remain disproportionately far away. Here we propose a simple "recipe" for the medium that allows us to proceed with a plausible head-field calculation.

Optimistically we assume that a granular recording medium can be created at about 20 Teragrains/in^2 (for a regular hexagonal array of grains, the center to center separation is 6.1 nm). We assume a 1 nm grain boundary, as in Fig. 5.

Assuming a core Ms of 8 kGauss (445 emu/cc mean including grain-boundaries) and an $\mathrm{H_k}$ of 25 kOe, we find that a thickness (grain height) of 15 nm is required to achieve a minimal stability factor, KuV/kT, of 60. Such a low stability factor would be adequate only for a medium where the demagnetizing fields are largely canceled by intergranular exchange and where the distributions of size and anisotropy and exchange are exceptionally tight.

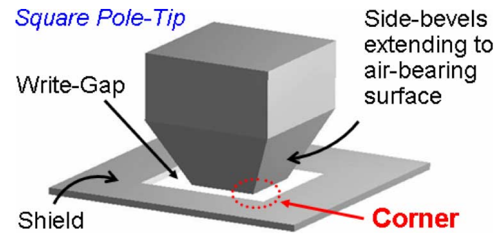

Fig. 6. Conceptual head design. A square pole-tip is illustrated although only one corner is needed for shingled writing. Strong fields can be generated because the main-pole can be tapered all the way to the air-bearing surface. Lapping variations can cause variations in pole-width but this is unimportant with shingled writing. A wrap-around shield is separated from the main pole by a gap about equal to the head to soft-underlayer spacing. For clarity, the shield is drawn here as being very thin.

We also need to take additional steps to ensure that the medium is adequately "writable" by the limited head field. This can be helped considerably by engineering the medium to have low anisotropy and high moment at the top of the grains in the film, where the switching process can be readily nucleated by the strong head-fields and gradient. The bottom portion of the grains then needs to have much higher anisotropy to ensure stability against thermal decay [7]. For the following section, we assume that the axial switching field can be reduced to 12.5 kOe from the 25 kOe required for a "Stoner–Wohlfarth" medium of similar moment and stability.

Such a medium must be exquisitely engineered with its anisotropy, saturation-magnetization, and exchange all carefully graded through the thickness and with extremely consistent properties from grain to grain. In addition, it is still advantageous to minimize interlayer thickness. We assume a 2-nm interlayer for the field calculations in the next section.

Although designing media for thermal stability is challenging, the demands are less than for BPM, where large gaps between islands inevitably mean that grain-volume is lower and thermal stability is harder to ensure. Conventional granular media has naturally very thin grain-boundaries.

C. Example of Corner-Head Design for Ultra-High Density

Fig. 6 shows an example of a head design for shingled writing which preserves large write fields and gradients through the use of wrap-around shields and zero-flare distance, i.e., the flare of the main pole extends all the way to the air-bearing surface. The critical geometry here resembles that described by Ise *et al.* [8], though not necessarily fabricated with a planar process. We similarly assume high drive currents and a high 2.4 Tesla moment in the pole-tip to create the high field values shown in [8]. The shield thickness in Fig. 6(a) is shown as less than the optimum value in the interest of clarity, and return poles, pedestals and coils are omitted from the illustration. The shield may be magnetically connected to the return pole or float near the soft-underlayer potential. The write gap-length of 19 nm is set equal to the distance from the head to the soft underlayer.

Fig. 7 plots the effective field from the head and shows a "write bubble" contour at 12.5 kOe. The effective field is based

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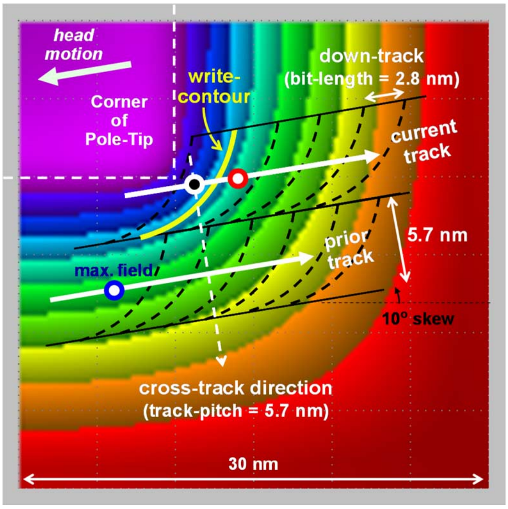

Fig. 7(a). Shingled write process superimposed on contours of effective field The field contours are drawn at increments of 10% of the maximum effective head field of 19 kOe. The effective field is calculated using the angular dependence in [7], The medium is assumed to be designed such that the axial switching field is 1/2 of that of a Stoner–Wohlfarth particle with similar thermal stability. The outlines of the bits are shown as written by a write contour of 12.5 kOe. A channel bit density of 40 Terabits/in^2 is assumed and a bit aspect ratio of 2:1. The head skew is 10°.

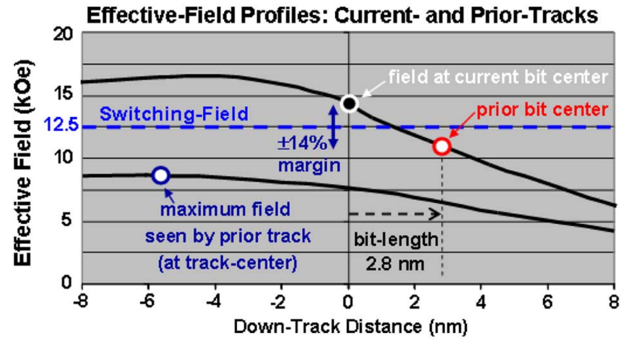

Fig. 7(b). Effective fields are plotted along the centerlines of the current and previously written tracks. The field values circled on the chart above correspond to the center of the current bit-cell (blue), the center of the previous bit-cell (red), and the maximum field seen on the centerline of the adjacent track (green). The margins between writing or not writing vs. switching field are about ±14% of the switching field, 12.5 kOe. (In this analysis the field was not integrated over the finite grain-width. This would further reduce this margin).

on the average field integrated through only *the top half* of the thickness of the medium (reflecting the idea that switching is nucleated at the top of the grain). We use the angular dependence of the graded medium from [7] to calculate an "effective field." The medium thus switches at 12.5 kOe effective field independent of field angle.

Superimposed on Fig. 7(a) are lines illustrating the shingled-write process. As in the example in Fig. 1, we assume a "channel" bit density of 40 Terabits/in^2 (corresponding to 10 Tb/in^2 user bits). The bit aspect ratio is 2:1. The write-contour is drawn at 12.5 kOe reflecting the medium's switching field as if it were a continuous medium. The write contour forms a tangent to the track-edge. Here we show a skew of 10 degrees during the single-write process.

In order to gauge the adequacy of the write-field gradients, we plot effective field as a function of down-track and cross-track position starting at the "center" of the bit-cell currently being written (Fig. 7(b)). The three field values picked out in Fig. 7 correspond to the center of the current bit-cell, the center of the previous bit-cell, and the centerline of the previously written shingled track.

The margin against inadvertently writing or not writing is only about 14% of the switching field. The switching field distribution on the grains in the medium must therefore be significantly better than 14%. The interaction-fields between the grains must be similarly small. We note that one advantage of having a high filling factor medium (f = 15 nm/19 nm) and a heavily shielded write head is that the demagnetizing fields, including fields from neighboring grains, are all reduced by a factor of 1-f, here down to 21% of the original fields levels. A calculation of the magnetostatic interaction-field from an array of randomly magnetized grains in this configuration with ideal imaging reveals a satisfactorily small sigma of 147 Oe which is only 1.2% of the switching field. Of course, it remains an open question whether heads can be designed and fabricated with sufficiently high gradients and whether media can be created with sufficiently tight distributions of magnetic parameters and grain size.

IV. Two-Dimensional Readback

Aside from the use of shingled-writing to ensure adequate fields, the essence of this new technique is the use of two-dimensional signal-processing. In this way, all the signal-processing power that enables us to work with very high levels of intersymbol interference (ISI) can be equally applied to combat inter-track interference. Two-dimensional signal-processing implies that we have available reasonably high-resolution information in the cross-track dimension as well as the down-track dimension. Such information might be obtained using either an array of closely spaced sensors or by building up similar information in memory using several passes of a single head. Here we use a simple idealized model of the write process to examine which grains get switched by which bits and also what the readback signals would look like under reasonable assumptions for reader resolution.

A. Simulation of Writing and Reading

A sample simulated medium of randomly shaped grains was created in a 57 nm square. One hundred initial nucleation points were spaced 5.7 nm apart on a square lattice, making a density of 20 Teragrains/in^2. A random structure was then created using the process described in [9]. During the process, the distance between the surfaces of grains was constrained to be no less than 0.7 nm at any point. The resulting grains have an average area of 22.6 nm^2, corresponding to a 5.37 nm circle. The standard deviation of the grain diameters is 8.4% of the mean, and the standard deviation of the grain area is 16.8%.

To help visualize the writing process and to get some indication of the losses that might be incurred during writing, a highly simplified write process was simulated. A square array of 14×14 channel bits was created to cover the 57×57 nm area of the medium (channel density $= 40$ Tb/in^2). This channel data array was then applied to the recording medium as a raster-scan from left to right, with successive scans moving

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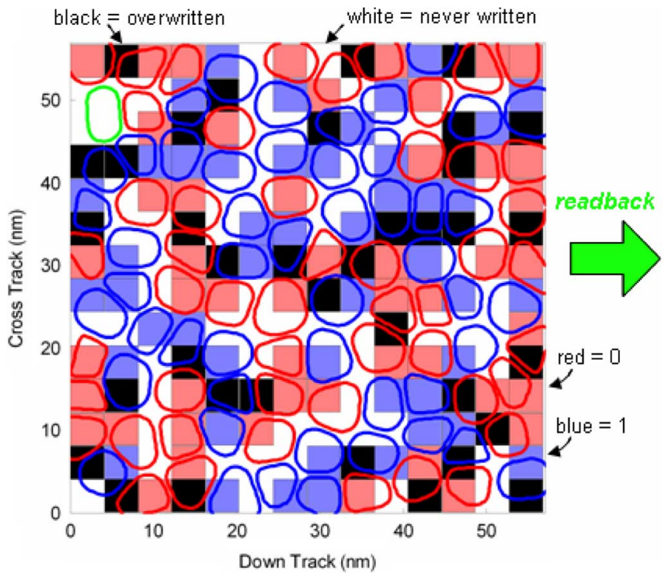

Fig. 8. Illustration of the write process on a random granular medium. The channel bits to be written are shown as filled-in squares while the medium grains are shown by outline. Red and blue denote "0" and "1". The medium grains are colored according to their final state and the channel bits that were successfully written are colored according to their value. White channel bits did not succeed in reversing a grain. Black channel bits were subsequently overwritten. One grain not written by any channel bit is colored green.

from bottom to top (Fig. 8). At each step, if the area of the bit-cell overlapped more than 30% of the grain area, then the grain was written with the value of that channel bit. Many grains get written more than once before assuming their final value. Occasionally a grain is not written by any bit and retains its initial (random) magnetization.

Fig. 8 shows the results of such a write simulation. Of the 196 channel bits, 63 bits failed to reverse a grain (shown white), while 36 channel bits were written to grains that were subsequently rewritten by another channel bit (shown black). As anticipated, since there are twice as many channel bits as there are grains, close to 50% of the channel bits were "recorded" on a grain, while 50% were lost.

The readback signal was calculated by cross-correlating the pattern of magnetized grains with a 2-D read head sensitivity function obtained following Wilton and McKirdy [10]. The down-track resolution in current perpendicular systems corresponds to $\mathrm{T50/T} \sim= 1$ where T50/T is the 50% transition response time divided by the bit-length. By analogy, here we design the reader (Fig. 9) to have a "T50" resolution (both down-track and cross-track) slightly better than the grain size.

The resulting 2D read-back image can be seen in Fig. 10. The narrow grain-boundaries that separate grains cannot be seen at all. Nor can individual grains be clearly distinguished. However, there is hope in that we can roughly delineate the boundaries between groups of grains of opposing polarity. The challenge is to recover all the original user data using just this image plus any *a priori* information about grain statistics.

B. Signal Processing and Data Recovery

The ability to apply sophisticated signal processing to recover user information is central to the TDMR concept. All possible advantage must be taken of information collected in

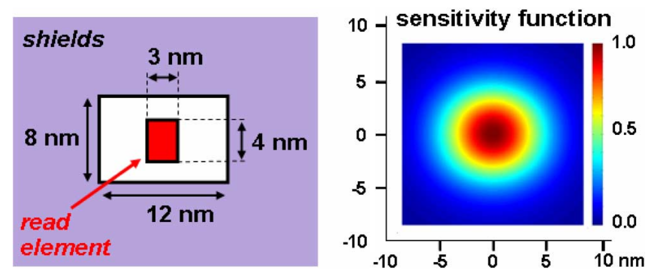

Fig. 9. A very tiny, fully-shielded read-sensor is necessary to get the desired down-track and cross-track resolution (approximately equal to the grain-size). For this configuration, the modeled step-responses down-track and cross-track have 50% widths (T50) of 5.2 nm and 4.8 nm, respectively.

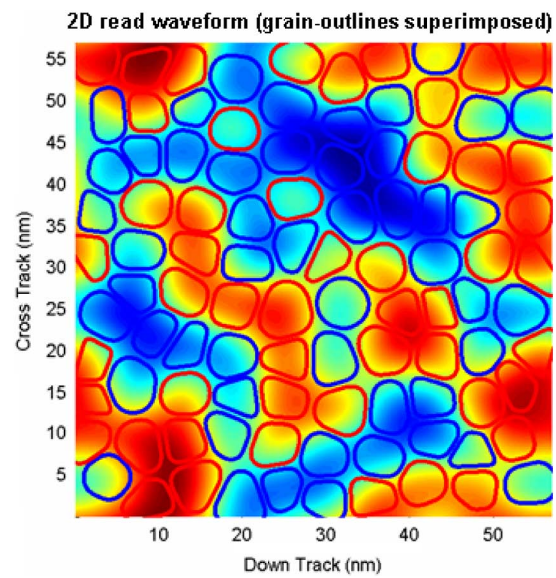

Fig. 10. Illustration of the 2-D readback signal obtained by cross-correlating the magnetized grains in Fig. 8 with the readback sensitivity function corresponding to Fig. 9. The replay head signal is shown as a 2-D colormap. In practice, the vertical axis would by sampled by consecutive passes of a single read head or by the individual elements of an array head. To avoid losing information, the sampling pitch would need to be somewhat smaller than the grain-size and perhaps comparable to the track-pitch of the channel-bits. The underlying grains, colored according to their written polarity, are reproduced here for reference.

the cross-track dimension and every effort must be made to operate as close to capacity as possible at extremely low SNR. Conventional 1D detectors are able to operate with high levels of inter-symbol interference (ISI). The corresponding 2D detector must be designed to operate with similarly high levels of inter-track interference (ITI). Prototypes for conventional 1-D channels are now being built with iterative detectors. Such detectors with suitable codes and on long blocks are able to closely approach information capacity limits. Similar techniques must be developed for 2-D detection. This must be done despite the fact that there is no practical 2D version of a Viterbi detector or its soft-detection derivatives.

To bound the problem, let us consider two extremes (though both assuming negligible readback noise). If, from the 2-D readback waveform in Fig. 10, it were possible to identify the exact shapes, positions and polarities of all the individual grains, and if we had exact knowledge of the write-process, then the capacity (Section II-A) for a large recorded area would be 1 bit-

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per-grain or 20 Tb/in^2. At the other extreme, if the detection process is simply to check the polarity of this 2-D readback waveform as sampled at the center of each channel bit-cell, then we find that 61 of the original 196 channel bits are reported with the wrong polarity—an error-rate of 31%. A binary channel with this error-rate has a theoretical capacity of 0.105 user bits per channel bit or 4.2 Terabits/in^2. Somewhere between the former impossibly "perfect" detection process and the latter hopelessly crude detection scheme there perhaps exists an approach that yields the 10 Tbits/in^2 goal while maintaining reasonable overall complexity.

C. Timing and Position Recovery

It is critical during detection that the recovered 2-D readback waveform be accurately aligned and referenced against the original channel bit-cell positions. However, conventional SNR measures are likely to be so poor as to be even below zero dB! The readback waveforms in TDMR will be totally dominated by the huge noise produced by the random granularity of the medium. A simple rule of thumb states that the area devoted to timing and position recovery increases inversely with signal-to-noise ratio (power). For example, if TDMR exhibits an SNR 15 dB lower than a conventional system, it will require 30 times more area devoted to timing and position recovery. Current systems already dedicate about 10% overhead to these functions, so this is quite a challenge.

Since the SNR is so poor and thus the density of extractable timing and position information so low, the supporting servo-mechanical system will require extraordinary stability such that the head-disk velocity vector stays very constant over distances of perhaps hundreds of thousands of bits.

V. Conclusions and Discussion

This paper has reviewed the prospects for recording at 10 Tb/in^2 with particular focus on the new TDMR scheme. The challenges for any scheme at such densities are enormous. Linear and track densities exceeding 4500 kBPI and 2200 kTPI are implied at 2:1 bit aspect ratio. At the low code-rates suggested here, actual encoded (channel) densities will be higher still. Extremely high resolution writers and readers will be needed with total magnetic spacing probably not exceeding 2 nm and a tracking accuracy around $1/2$ nm (1-sigma). However, for media we only assume 'substantial' evolutionary advances. The media should be fine-grained ($\sim$6 nm dia) and have adequate thermal stability and reasonable switching field. Much tighter switching-field and grain size/shape distributions than today's media will be needed.

This paper scarcely begins to enumerate the challenges ahead. In signal processing, the highest priority perhaps is to establish a theoretical information capacity: firstly for some 2-D equivalent of the 1-D channel in Fig. 3, then secondly for more complete channels where distributions and noise sources are more realistically included. Next should follow the development of practical 2-D detection schemes including the accurate estimation of 2-D position (timing and track-position) of each bit-cell. The shingled-write process with a specially designed corner-writer is equally central to this proposal. The corner-writer is defined by the three facets forming the corner point plus the geometry of the surrounding shield and the media soft-underlayer. The choice of and optimization of the corner-writer geometry so as to create the largest fields and the highest 2-D gradients is largely unexplored. The creation of a suitable readback sensor is a huge challenge but is common to any proposal for 10 Tb/in^2 (for TDMR there is the additional option of creating an array head). Perhaps the ultimate challenge is the requirement (again for any 10 Terabit/in^2 scheme) for a magnetic spacing of roughly 2 nm.

Two-dimensional magnetic recording (TDMR) is an exciting new option for ultrahigh densities. However, considerable, carefully coordinated research will be needed to fully assess the viability of this new approach.

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