Bit Patterned Media: Technical Advantages and Comparison to Granular Media

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Which comes first: Patterned Media or Energy Assist?

(a) Patterned Media

Patterned Media
Magnetic nano-islands w/ exchange coupled grains

Reader Main Pole

1 bit=1 Island

(b) Thermal Assisted

Thermal/Microwave Assisted
Energy assisted writing of thermally stable & hard-to-write media

Reader Laser Field Generating Layer

Coercive Force

Head Field

Ambient Temp $T$ (K)

Precessional Reverse

Near Field

Write Field

Microwave

$M$

$H_{ac}$

$H_{write}$

Diskcon 2010
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09 SEP 2010
The problem: thermal stability, write-ability, and density

PROBLEM:
- To increase density, need smaller grains
- Smaller grains are thermally unstable
- To avoid thermal instability, increase grain anisotropy Ku
- This increases the medium coercivity and makes the medium more difficult to write

SOLUTIONS:
- Work with higher anisotropy:
  - Capped and exchange spring media
  - Thermally assisted recording (TAR)
- Work with larger ‘grains’: patterned media

Magnetic Stability: \[ \frac{\text{energy barrier}}{\text{thermal energy}} \propto \frac{\text{anisotropy} \times \text{volume}}{k_B \times \text{temperature}} = \frac{K_u V}{k_B T} > 70 \]
The “Trilemma”

PROBLEM:
- To increase density, need smaller grains
- Smaller grains are thermally unstable
- To avoid thermal instability, increase grain anisotropy $K_u$
  - This increases the medium coercivity and makes the medium more difficult to write

SOLUTIONS:
- Work with higher anisotropy: capped and exchange spring media
- Thermally assisted recording (TAR)
- Work with larger ‘grains’: patterned media

CONVENTIONAL MEDIA

<table>
<thead>
<tr>
<th>Single Grain Magnetostatic Energy</th>
<th>Magnetization Angle</th>
</tr>
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<tbody>
<tr>
<td>$-90$</td>
<td>$0$</td>
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</table>

Magnetic Stability: $\propto$ energy barrier $/\text{thermal energy}$

$\text{Thermal Stability \\ & ATI Media Writeability}$

$\text{Media SNR}$

$\text{Thermal Stability \\ & ATI}$
What has changed?

- **Signal processing**
  - iterative decoding, etc.
  - reduced SNR requirement (65 grains ⇒ 25 grains)
- **LMR ⇒ AFC ⇒ PMR ⇒ ECC media**
  - controlled intergranular exchange
    - clusters enhance thermal stability ⇒ larger effective volume
    - manage intergranual magnetostatic interactions
  - exchange spring reversal mechanism
    - better writeability of high Ku media
- **Shingled recording (SMR)**
  - wider heads ⇒ higher write field
  - relief in tradeoffs between peak field and gradient
  - reduced ATE; relaxation of thermal stability rqmt
- **Net effect:**
  - PMR can likely extend to ~ 1 Tb/in²
  - expected gain factor from BPR reduced
PMR progress is slowing – why?

- The “Trilemma” isn’t the main problem today
  - we can make smaller grains
  - small grain media can be made thermally stable
  - we can write small grain media

- Countervailing effects are neutralizing the expected SNR and density gain
  - switching field distribution?
  - grain size distribution?
  - moment density distribution?
  - non-optimal exchange coupling and cluster size?

- Tough materials science problems to solve
  - even tougher for TAR: add thermal issues
  - but not fundamental – might be solvable

- BPM isn’t limited by grains
  - different noise and SNR mechanisms
    - grains ⇒ single domain patterned islands
    - suitable mag layers for BPM already exist
What’s the right question?

- Frequently asked question: Thermal assist or patterned media?
  - perhaps not the right question
  - mixes head and media issues

- Media question: Conventional segregated grain media or patterned media?
  - decouple grain engineering from areal density
  - different media noise mechanism
  - even with a TAR head, patterned media can be the better choice

- Head question: Conv. write head or thermal assist head?
  - thermal assist head offers
    - thermal assist for high Ku media
    - increased effective field gradient
  - can use a TAR head for either reason or both

\[ \frac{dH_{eff}}{dx} = \frac{dH_w}{dx} + \left( \frac{dH_{sw}}{dT} \right) \times \left( \frac{dT}{dx} \right) \]
Conventional recording vs. bit patterned recording

- Bit shape: defined by head field profile (curved) vs. patterned island shape
- Noise: grain statistics vs. patterning roughness and tolerances
- Thermal stability and bit errors: grain reversal vs. island reversal
Switching field distribution (SFD) and write field gradient

RULE: No head switch with center of any island within uncertainty zone

CONSEQUENCE: Wide switching field distribution and finite head field gradient limit density
BAR and write field gradient requirements

BAR = 2:1

- low side gradient
- typical WAS shingle head

OK!

- strong enough to write every island
- weak enough not to write any island

BAR = 0.87:1 (hcp)

- high downtrack gradient
- typical WAS shingle head

- isotropic corner head
- unphysical corner head
BAR and write field gradient requirements

- **BAR = 2:1**
  - strong enough to write every island
  - weak enough not to write any island
- **BAR = 0.87:1 (hcp)**
  - low side gradient
  - high downtrack gradient

- Even a head with isotropic high gradient is not optimal for BAR ≤ 1:1
- Corner curvature may require BAR > 1:1
- Finite TMR (track misregistration) pushes BAR even higher
- Optimal BAR ~ 2:1 or a little less
Hypertracks: best of both worlds?

- Write and read a pair of adjacent tracks simultaneously
- Island Aspect Ratio = 1
  - Best case for lithography and media fabrication
- Bit Aspect Ratio = 3.46 (for hexagonal close packed array)
  - Very attractive for servo, heads, and drive integration
  - Can use wide R/W elements

However...
- Still need side gradient appropriate for BAR = 0.87 to avoid writing adjacent hypertrack
- “Modified hcp” array can help, but no longer easy to make by self-assembly
Fabricating BPM: different than semiconductors

INTRODUCTION

- Smaller features sooner
- Higher volume (1 billion disks/year)
- Lower cost target (< $5/disk)
- Periodic features
- One lithography level; no overlay
- Can tolerate 1E-4 defect rate
- Can map out large defects
Patterned media: fabrication overview

**Template Fabrication**

- Rotary stage e-beam Patterning
- Directed self-assembly
- Master template fabrication
- Template replication

**Media Fabrication Process**

1. ML or alloy mag film deposition
2. Nanoimprint
3. Pattern transfer (etch / implant)
4. Planarization
5. Lube and burnish
6. Inspection

**Template Fabrication**

- 1 master (e-beam + self-assembly)

**Media Fabrication Process**

1. Patterned imprint resist
2. Etching
3. Ion implantation
4. Planarization
5. Mask removal
6. 10,000 replicated nanoimprint templates
7. 100,000,000 patterned disks

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Block copolymer self-assembly (with and without guiding)

- **Substrate surface**
- **Self-assembly (anneal @170°C)**
- **PMMA phase (cylindrical)**
- **PS phase**
- **Etch PMMA phase**
- **Cylindrical pore**

(PS-b-PMMA) thin film

**UNGUIDED**
(no long-range order)

H. Yoshida, Hitachi Ltd.

**Directed Self-Assembly**
(with chemical contrast guiding patterns)

- Pre-patterned substrate
- Apply PS-b-PMMA
- Self-assembly

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Directed self-assembly with 1:1 and 4:1 guiding

(500 Gb/In²)

Pattern Rectification
L_s = 39nm; L_p = 39nm

Density Multiplication
L_s = 78nm; L_p = 39nm

(1000 Gb/In²)

Pattern Rectification
L_s = 27nm; L_p = 27nm

Density Multiplication
L_s = 54nm; L_p = 27nm

1-D stretching / compressing for circular tracks

<table>
<thead>
<tr>
<th>Radius = 14.8mm</th>
<th>15.0mm</th>
<th>15.3mm</th>
<th>15.5mm</th>
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<tbody>
<tr>
<td>Lx = 37.6nm</td>
<td>38.1nm</td>
<td>38.9nm</td>
<td>39.3nm</td>
</tr>
</tbody>
</table>

- With chemical contrast guiding, block copolymer can stretch or compress with guiding pattern over about 4% range.
- Such compliance allows self-assembly of curved pattern for circular tracks.
- Track patterns grouped in “zones” with OD not more than 4% larger than ID of each zone.
- Zone recording is already standard in hard disk drives.

Δr < 4%

U.S. patent application
US20090196488A1 (published 8/6/09)
High BAR: density multiplication of lamellae

BAR=2
Down-track Pitch=27nm
Track pitch = 54nm
Density: 442 Gdot/in²

Skewed patterns also possible by this method

Lamellar phase block copolymers for high bit aspect ratio

U.S. patent application US20090308837A1, published 12/17/09
Three contributors to switching field distribution

- Physical patterning uniformity
  - island size and shape
  - regularity of spacing

- Material nonuniformity

- Inter-island dipole interactions (data dependent)
Improving SFD with exchange bridge ("capped" BPM)

Balancing of opposite influences:
- Dipole interaction is negative
- Exchange interaction via bridge is positive

Li et al., J. Appl. Phys. 105, 07C121 (2009)

Homogeneous BPM

\[ H_r/H_K \sim 0 \%
\]
\[ SFD \sim 0\%
\]

Capped BPM

\[ H_r/H_K \sim 2\%
\]
\[ SFD \sim 2\%
\]

\[ M_{S,sh} = 900 \text{ emu/cm}^3
\]
\[ H_K = 35 \text{ kOe}
\]
\[ w \times w = 36 \text{ nm}^2
\]
\[ t_h = 8 \text{ nm}
\]

\[ M_{S,\text{cap}} = 1000 \text{ emu/cm}^3
\]
\[ J = 1.25 \text{ erg/cm}^3
\]
\[ K_{\text{cap}} = 0 \text{ erg/cm}^3
\]
\[ t_{\text{cap}} = 6 \text{ nm}
\]
BPM areal density progress

100 Gb/in²

200 Gb/in²

300 Gb/in²

500 Gb/in²

1E-3 BER

~ 10 Gb/in² (multiple islands/bit)
Combination of TAR and BPM (BP-TAR) is capable of extremely small track pitch
- 24nm track pitch with similar notch width
- Near-field focusing on islands
- Restricted lateral heat flow

Five times lower threshold laser power compared to continuous media using same head

Solves TAR media problem and BPM write head problem

BPM + thermal assist head: 1 Tb/in²  B. Stipe et al., Nature Photonics 2010
Summary

- **PMR areal density progress is slowing down**
  - even though we haven’t really reached the “Trilemma”
  - deriving expected SNR and density gains from smaller grains is difficult
- **Patterned media is a unique solution to the problem**
  - breaks the dependence between grain optimization and density
  - completely different noise mechanisms
    - grain statistics vs. patterning tolerances
  - PMR, TAR, MAMR all depend on solving the problems of granular media
- **Likely patterned media design point**
  - BAR ~ 2:1; shingle head
- **Patterned media areal density progress**
  - 500 Gb/in² with conventional write head (limited by head)
  - 1 Tb/in² with thermal assist head (exploiting enhanced effective field gradient only)
- **Economically viable**
  - $1 cost adder for patterning looks feasible at high volume
    - single lith. layer, no overlay, high defect tolerance (way cheaper than semiconductor)
  - Can maintain HDD competitive advantage over solid state