Perpendicular Recording

A Future Technology or a Temporary Solution?

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Outline

- Overview
- Superparamagnetic limit and the need for a new technology
- Dodging the Superparamagnetic limit … The advantages of perpendicular recording?
- A new system component: soft underlayer challenges and design considerations
- Skew Angle Sensitivity
- Playback: new signal processing schemes
- New materials challenges
- How far perpendicular recording will take us and what will come next?
From RAMAC to Microdrive

70 kbit/s
IBM RAMAC 1955
2 kbits/in²
50x24” dia disks

32 Mbit/s
IBM Microdrive 2001
15.2 Gbits/in²
1 x 1” dia disk
Progress in Magnetic Data Storage

Demos:
~100 Gbpsi long
~63 Gbpsi perp

Products:
~33 Gbpsi long
40 GB per disk

Historical 60% CGR line

Areal Density (Gbit/in²)

Year

- Longitudinal recording has been the underlying technology in the disk drive industry for the past several decades.
Scaling: Smaller heads, thinner media, lower fly heights

The Shrinking Bit Cell

<table>
<thead>
<tr>
<th>Bit length, μm</th>
<th>Trackwidth, μm</th>
<th>Density, Gb/μm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.195 μm</td>
<td>0.195</td>
<td>16:1</td>
</tr>
<tr>
<td>0.096 μm</td>
<td>1.34</td>
<td>6</td>
</tr>
<tr>
<td>0.071 μm</td>
<td>0.91</td>
<td>14.1</td>
</tr>
<tr>
<td>0.062 μm</td>
<td>0.82</td>
<td>13:1</td>
</tr>
<tr>
<td>0.045</td>
<td>0.36</td>
<td>10 Gb/μm²</td>
</tr>
<tr>
<td>0.042</td>
<td>0.19</td>
<td>20 Gb/μm²</td>
</tr>
<tr>
<td>0.041</td>
<td>0.16</td>
<td>40 Gb/μm²</td>
</tr>
</tbody>
</table>

Flying Height 5 nm

Human Hair 75,000nm

Media 10-100nm

Disk Substrate

Head

Smoke Particle

Fingerprint

S. Khizroev, D. Litvinov

Page 7
Superparamagnetic limit

- Overview of magnetic recording
- **Superparamagnetic limit** and the need for a new technology
- Dodging the Superparamagnetic limit … The advantages of perpendicular recording?
- A new system component: soft underlayer challenges and design considerations
- Skew Angle Sensitivity
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- SNR $\sim \log(N)$, $N$ - number of grains per bit
- While scaling, need to preserve number of grains per bit to preserve SNR
- Grain size is reduced for higher areal densities: 
  $$a \sim \frac{1}{\sqrt{\text{Areal Density}}}$$
Media Stability

Probability of magnetization reversal due to thermal fluctuations:

\[ f_{\pm} = f_0 \exp\left(-\frac{\Delta E_{\pm}}{k_B T}\right) \]

\[ f_0 \sim 10^9 - 10^{12}, \Delta E_{\pm} \approx K_U V \]

\[ K_U \] – anisotropy energy

\[ V \] – grain volume

Thermally stable media:

\[ \frac{K_U V}{k_B T} > 40 - 60 \]
Superparamagnetism

\[ \frac{K_U V}{k_B T} > 40 - 60 \Rightarrow V \approx a^3 \geq \frac{60 k_B T}{K_U} \]

\[ a \sim \frac{1}{\sqrt{\text{Areal Density}}} \geq a_{\text{minimum}} \approx \frac{3 \sqrt{60 k_B T}}{K_U} \]

If \( a < a_{\text{minimum}} \), medium becomes thermally unstable leading to severe deterioration of recorded data over time.

Approaches to avoid superparamagnetic instabilities:

- Decrease \( a_{\text{minimum}} \) by increasing \( K_U \)
- Increase \( a \) by decreasing the number of grains per bit
Media Writability Limit

Stable media: \( \frac{K_U V}{k_B T} \sim 40 - 60 \implies K_U \sim \frac{1}{V} \) or \( K_U \sim \frac{1}{a^3} \)

\[ H_{\text{write}} > H_0 = \alpha \frac{2K_U}{M_S} - N_{\text{eff}}M_S \sim \frac{1}{a^3} \sim \text{Areal Density}^{3/2} \]

Higher areal density media requires higher write fields !!!

\[ H_{\text{write}} \sim M_S \] of the head material

Highest \( 4\pi M_S (=B_S) \) available today is \( \sim 26 \text{ kGauss (2.6 Tesla)} \)

In longitudinal recording, the highest write field possible to generate is \( \sim 2\pi M_S \) !!!
Additional challenges: Grain Size Distribution

Grains in polycrystalline media are not uniform in size. The grain sizes are log-normally distributed.

- Too small grains are thermally unstable $\Rightarrow$ Unstable data
- Too large grains cannot be switched $\Rightarrow$ Noise

Grain Size Distribution

$y = y_0 + \frac{A}{\sqrt{2\pi}wx} \exp \left[ -\frac{\ln \frac{x}{x_c}}{2w^2} \right]$
Advantages of Perpendicular Recording

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Origins of Perpendicular Recording

1878: Magnetic Recording: Oberlin Smith

1960: G. Fan, Ampex Corporation
1977: S. Iwasaki, Magnetic Disk Perpendicular Recording Demo
Closest Alternative Technology

- Inductive "Ring" Writer
- MR Reader
- Magnetizing Coil
- Recording Media
- Longitudinal

- Inductive "SPH" Writer
- MR Reader
- Magnetizing Coil
- Recording layer
- SUL

Perpendicular
Perpendicular versus Longitudinal

Perpendicular System

Longitudinal System

Notice: Soft Underlayer (SUL) - a new system component
Soft Underlayer: Magnetic Imaging

Soft underlayer acts as a magnetic mirror:
Real head + Soft Underlayer = Real head + Image head

Recording layer is sandwitched between real and ‘image’ write poles - writing in the gap (in longitudinal recording writing is done with fringing fields)
In perpendicular recording the write process effectively occurs in the gap (Write Field $< 4\pi M_S$).

In longitudinal recording the write process is done with the fringing fields (Write Field $< 2\pi M_S$).
Write Field Comparison

- **Twice as high write field amplitude**: can write on higher anisotropy media $\Rightarrow$ better thermal stability

- **Substantially sharper field gradients**: less sensitive to grain anisotropy distribution $\Rightarrow$ sharper bit transitions $\Rightarrow$ higher areal density
Well-Aligned Recording Layers

In a typical longitudinal recording layer the magnetic anisotropy axes of individual grains are randomly oriented in the plane of the film.

In perpendicular recording layer the anisotropy axis is relatively well aligned (<2-4 degrees) perpendicular to the plane of the film.

Substantially relaxes the requirements for write field gradients. Can use thicker recording layer - better thermal stability!!! (increased $V$ in $K_U V/k_B T$ ratio)
Demag Fields at Bit Transitions

More stable magnet configuration

Demagnetizing fields destabilize recorded magnetization:
- Increased transition width
- Contribute to thermal instabilities

Perpendicular recording promotes higher areal densities !!!
Reduced Demag Field at high BAR

In contrast to longitudinal recording, in perpendicular recording higher bit aspect ratios (BAR) lead to reduce demagnetizing field - one of the major destabilizing factors leading to thermal instabilities.
Enhanced Playback due to SUL

The magnitude of the stray fields (playback) is increased due to effective media thickness increase.
Summary of Advantages

- Higher write field amplitude - can use higher anisotropy media, better thermal stability
- Higher write field gradients and well aligned recording layers - thicker media, better thermal stability
- Zero demag at transitions - sharp bit transitions, more stable recorded data
- Decrease of demag with areal density increase - improved media stability at higher areal densities
- Higher playback amplitude - improved playback performance at higher areal densities
Narrow track recording

Waveform (200nm trackwidth)

Track Profile

Bathtub curve

<table>
<thead>
<tr>
<th></th>
<th>1um track</th>
<th>.2um track</th>
</tr>
</thead>
<tbody>
<tr>
<td>D50 (kfcI)</td>
<td>200</td>
<td>190</td>
</tr>
<tr>
<td>acsn (1bit/pw50, dB)</td>
<td>21</td>
<td>19.5</td>
</tr>
<tr>
<td>Overwrite (dB)</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>
Narrow Track Recording

CoCrPtTa alloy

CoB/Pd multilayer

Current “state-of-the-art” longitudinal recording is <100 ktpi
Soft Underlayer Challenges

- Overview of magnetic recording
- Superparamagnetic limit and the need for a new technology
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**A new system component:** soft underlayer challenges and design considerations

- Skew Angle Sensitivity
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**Soft Underlayer as a Flux Conductor**

![Diagram of pole tip and magnetic flux](image)

**Magnetic Flux Conservation**

\[ \text{div} \mathbf{B} = 0 \Rightarrow \text{Magnetic flux should be conserved} \]

\[ \mathbf{B} \text{ into soft underlayer} \times A_{\text{soft underlayer effective}} = \mathbf{B} \text{ emanating from the pole tip} \times A_{\text{ABS pole tip}} \]

**Limiting Case**

In the limiting case, when the pole tip saturates (during writing):

\[ 4\pi M_S \text{ soft underlayer} \times A_{\text{soft underlayer effective}} \geq 4\pi M_S \text{ pole tip} \times A_{\text{ABS pole tip}} \]
Usage of lower moment soft underlayers can lead to the deterioration of the write field gradients.
Soft Underlayer Thickness

Both the write field amplitude and the write field gradient can deteriorate is too thin soft underlayer is used

\[ t_{\text{soft underlayer}} \geq \frac{1}{2} \frac{M_{S \text{pole tip}}}{M_{S \text{soft underlayer}}} w_{\text{pole tip}} \]
Soft underlayer introduces asymmetry into the playback system. If not designed properly, can deteriorate system’s resolution.
CoCrPtTa alloy based recording layer is capable of recording densities well in excess of 600kfc.

Further development is necessary to minimize noise and/or distortions caused by the presence of the soft underlayer.
Micromagnetics and Playback Resolution

Soft underlayer/Recording layer interface

<table>
<thead>
<tr>
<th>Material</th>
<th>Hk (Oe)</th>
<th>Ms (kGauss)</th>
<th>A x10E-6 (erg/cm)*</th>
<th>Delta (nm)</th>
<th>Linear Density (kfci)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permalloy</td>
<td>5</td>
<td>10</td>
<td>~1.0</td>
<td>112</td>
<td>226</td>
</tr>
<tr>
<td>FeAlN</td>
<td>15</td>
<td>20</td>
<td>~1.7</td>
<td>60</td>
<td>421</td>
</tr>
<tr>
<td>Ni45Fe55</td>
<td>&lt;50</td>
<td>16</td>
<td>~1.5</td>
<td>34</td>
<td>737</td>
</tr>
<tr>
<td>CoFe</td>
<td>100</td>
<td>24</td>
<td>~2.0</td>
<td>23</td>
<td>1099</td>
</tr>
</tbody>
</table>
Soft Underlayer Noise

Fields from Wall (Source of Noise)

Domain wall
(source of “magnetic charges”)

Ta/Permalloy/Pd/(Co/Pd)\textsubscript{N}
(not biased soft underlayer)

![Graph showing playback and time in seconds with values ranging from -0.15 to 0.15.](image)
Soft Underlayer Biasing

Single Transition

--- Non-biased soft underlayer
--- Biased soft underlayer

Playback (µV) (with amplification)

Time (nsec)

Soft Underlayer Biasing

-0.15
-0.1
-0.05
0
0.05
0.1
0.15

Time (s)

Hard layer

Soft underlayer

Magnets

Head

Playback

Time (s)
Skew Angle Sensitivity

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**Skew Angle Sensitivity**

- Playback: new signal processing schemes
- New materials challenges
- How far perpendicular recording will take us and what will come next?
Skew angle

Zero skew

Trailing edge

Non-zero skew

Trailing edges

Track direction

Skew angle (±15 degrees)
Skew Angle Sensitivity

Zero skew |
---
Trailing edge |

Non-zero skew |
---
Trailing edges |

Track direction

- Track width increases
- Have to decrease the track density at higher skew angles
- Loss in areal density

Skew = 0 degrees

Skew = 15 degrees

Playback Signal (mV)

Offset across the track (µin)

Track width (µ"

25kfci

250kfci

250kfci

15 -10 -5 0 5 10 15

12

14

16

18

20

22

24

26

Skew angle (degrees)
In a narrow gap single pole heads, the write field is reduced towards the leading edge, thus, minimizing the skew angle sensitivity.

- Can minimize the loss in track density from 25% to less than 5%
Perpendicular Playback

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**Playback:** new signal processing schemes

- New materials challenges
- How far perpendicular recording will take us and what will come next?
If a conventional reader is used, the channel sees the playback signal of different shape.

Can differentiate, however, part of the information is lost.
Equivalent Perpendicular Reader

Conventional shielded reader

- Shield
- Shield
- Longitudinal media
- (G)MR element

Differential reader

- Yoke
- (G)MR elements
- Perpendicular media

Playback Signal vs. Time
Materials Challenges

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### Perpendicular Media Materials

<table>
<thead>
<tr>
<th>Overcoat</th>
<th>Composition &amp; Microstructure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>STORAGE LAYER:</strong></td>
<td>Magnetic Properties</td>
</tr>
<tr>
<td>- High squareness</td>
<td>Performance</td>
</tr>
<tr>
<td>- Exchange de-coupling</td>
<td></td>
</tr>
<tr>
<td>- Grain size control</td>
<td></td>
</tr>
<tr>
<td><strong>SOFT UNDERLAYER:</strong></td>
<td></td>
</tr>
<tr>
<td>- Efficiency of the recording system</td>
<td></td>
</tr>
<tr>
<td>- Soft underlayer noise</td>
<td></td>
</tr>
<tr>
<td><strong>Buffer layer</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Substrate</strong></td>
<td></td>
</tr>
</tbody>
</table>
# Recording layers: Higher $K_u$ Materials

<table>
<thead>
<tr>
<th>Alloy System</th>
<th>Material</th>
<th>Anisotropy $K_u$ (10^7 erg/cc)</th>
<th>Saturation Magnetization $M_s$ (emu/cc)</th>
<th>Anisotropy Field $H_k$ (kOe)</th>
<th>Minimum stable grain size $a$ (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoCrPtX</td>
<td>Co</td>
<td>0.20</td>
<td>200-300</td>
<td>15-20</td>
<td>8-10</td>
</tr>
<tr>
<td>Co-alloy</td>
<td>Co</td>
<td>0.45</td>
<td>1400</td>
<td>6.4</td>
<td>8.0</td>
</tr>
<tr>
<td>Co-alloy</td>
<td>Co3Pt</td>
<td>2.00</td>
<td>1100</td>
<td>36</td>
<td>4.8</td>
</tr>
<tr>
<td></td>
<td>FePd</td>
<td>1.8</td>
<td>1100</td>
<td>33</td>
<td>5.0</td>
</tr>
<tr>
<td>L10-phase</td>
<td>FePt</td>
<td>6.6-10</td>
<td>1140</td>
<td>116</td>
<td>2.8-3.3</td>
</tr>
<tr>
<td></td>
<td>CoPt</td>
<td>4.9</td>
<td>800</td>
<td>123</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>MnAl</td>
<td>1.7</td>
<td>560</td>
<td>69</td>
<td>5.1</td>
</tr>
<tr>
<td>Rare Earth</td>
<td>Nd2Fe14B</td>
<td>4.6</td>
<td>1270</td>
<td>73</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>SmCo5</td>
<td>11-20</td>
<td>910</td>
<td>240-400</td>
<td>2.2-2.7</td>
</tr>
</tbody>
</table>

Minimum thermally stable grain size:

$$a \approx \frac{3 \cdot \sqrt{60 \cdot kBT}}{K_u}$$
Microstructure of Recording layers

CoCrPtTa on Ti

- Average column size ~ 20nm
- Randomly oriented
- Average grain size ~ 13nm
- (00_2) fiber-like texture with texture spread of $6.3^\circ$

X-ray rocking curve

<table>
<thead>
<tr>
<th>ideal</th>
<th>non-ideal</th>
</tr>
</thead>
</table>

CoB/Pd multilayer on ITO

- Average column size ~ 20nm
- Randomly oriented
Grain Size Distribution Control

Narrowing the grain size distribution improves SNR and media stability.

\[ y = y_0 + \frac{A}{\sqrt{2\pi}wx} \exp \left( -\frac{\ln \left( \frac{x}{x_c} \right)^2}{2w^2} \right) \]
Magnetics of Recording Layers

- Typically $S = \frac{M_r}{M_s} < 1 \Rightarrow$ Thermal stability? DC noise
- $S=1 \Rightarrow$ No DC noise; Thermally stable
- Extremely thin ITO buffer is sufficient to promote high $H_c$
- By adjusting thicknesses of Co and Pd in a bi-layer structure can make films with $H_c > 10,000$ Oe

$\text{Al/NiP/Ti(5nm)/CoCr}_{18}\text{Pt}_{10}\text{Ta}_{3}(50nm); \ H_c = 2.77 \text{ kOe}$

$\text{ITO}(5\text{nm})/(\text{Co3/Pd10}) \times 20; \ H_c = 6.9\text{kOe}$
Roll-off Curves / Media Noise

CoCr-alloy recording layer / FeAlN/Ta/NiFe soft underlayer / Single pole head

Overwrite $> 39\text{dB}$

$D_{50} \sim 200 \text{ kfc}$

$A_{CSN\,1\text{bit/PW50}} \sim 21\text{dB}$

$D_{50} \sim 140 \text{ kfc}$

$A_{CSN\,1\text{bit/PW50}} \sim 15\text{dB}$

(CoB/Pd)$_n$ on ITO recording layer / FeAlN/Ta/NiFe soft underlayer / Single pole head

Playback Signal (dBm)

Linear Density (kfc)

Seagate

S. Khizroev, D. Litvinov

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Adelphi, Maryland, April 15, 2002
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Perpendicular System at 1 Tbit/in\(^2\) (NSIC)

- Superparamagnetic behavior is not avoided but delayed
- It is believed that \(\sim 1\) Tbit/in\(^2\) is possible to achieve with perpendicular magnetic recording (\(\sim 10\times\) gain from longitudinal recording)

A 1Tbit/in\(^2\) design:

**Medium:**
Perpendicular polycrystalline with SUL: \(H_c=12,000\) Oe; \(M_s=6360\) Gauss; Thickness = 9nm; Grain-diameter: 8nm with \(\sigma=1\)nm

**Read Head:**
Read-width: 30 nm, Sensitivity: 1 mV peak-peak; Resistance: 50 ohms

**Write Head:**
Write-width: \(=37\)nm; Saturation: \(4\pi M_s = 20,000\) Gauss

**Head/Disk Interface:**
Magnetic Spacing: 6.5nm to top of medium; 1nm overcoat
What comes next?

Main driving force: to further delay the superparamagnetic limit

Thermally assisted writing

Patterned media

\[
\frac{KuV}{k_B T}
\]

Change \( k_B \)?...

Cryo-drive
HAMR - Heat Assisted Magnetic Recording

- Magnetic Head
- MR Sensor
- Magnetic Recording
- Laser
- Bits
- Magnetic Field

Magneto-Optical Recording

~ 10Tbit/in² is conceivable with HAMR + polycrystalline medium (10x gain)
Different Approaches to HAMR

Far Field Light Delivery System:

Near field light delivery system defines track-width; magnetic head defines bit length:

Near Field Light Delivery System with Global Magnetic Field:

Near field light delivery system and magnetic head co-located to define bit and track:
Patterned Media/Self-Ordered Magnetic Arrays

- Major challenge is finding low cost means of making media
- Above 50Tbit/in\(^2\) is conceivable with HAMR + Patterned Medium (5x gain)

Nanoparticle arrays – 9 “Tbit/in\(^2\)”

6.3 ± 0.3 nm FePt particles

Future of Perpendicular Recording

It is believed that future generations of magnetic recording technologies are likely to be based on perpendicular recording due to advantageous nature of perpendicular recording with respect to high areal densities:

- higher write fields
- high trailing and side write field gradients
- well aligned medium
- absence of demagnetizing fields at bit transitions
- higher amplitude playback signal
Summary: Technology Options

Superparamagnetism - fundamental problem!

1. Shift to smaller grains without increasing \( H_o \) (~2x gain)
   - AFC media
2. Enhance Write Efficiency (5-10x gain)
   - Perpendicular Magnetic Recording
3. Use smaller Grains & Deal with Write Field Problem (~10x gain)
   - Heat Assisted Magnetic Recording (HAMR)
4. Single Grain per Bit Recording combined with HAMR (~5x gain)
   - Self Ordered magnetic Array media (SOMA)

Ultimate Recording Density > 50 Tbit/in\(^2\) conceivable