Wednesday Conference
Session 5
Perpendicular Recording: Innovation Achieved
PMR: Innovation Achieved
Implications for a New Era
of Hard Disk Drive Technology

Scott Maccabe
Vice President and General Manager
Toshiba Storage Device Division
September 21, 2005
From Evolution to Revolution: The Road to PMR

- The path to innovation in the HDD industry previously followed an *evolutionary* curve:
  - Capacity increases with improved areal density
  - Adjustments to media and head technology
  - MR to GMR to TMR
- Unfortunately, recording technology would eventually run out of room
  - End of AD road predicted within two years
  - Super-paramagnetic effect
  - Bits fluctuate due to thermal agitation
The Slowing Areal Density Curve

- MR Head, ID-less CDR
- Thin Film Head Glass Media
- MIG Head, Sputtered Media
- FDB Motor
- PRML
- MR Head, ID-less
- Thin Film Head Glass Media
- AFC Media
- GMR
- Ramp Load
- Perpendicular Recording
- 30GB/Disk (2.5” Disk)
- 100% /Year
- 60% /Year
- 30% /Year

New Technologies Discrete Media
BMR Head

Production 35% /Year
From Evolution to Revolution: The Road to PMR

The HDD industry had to be *revolutionary*

- New approach to laying data down on the disk
- Magnetic bits stand on end, reinforcing magnetic coupling
Benefits of PMR

• **Primary: Pack more data on increasingly smaller disks**
  – Stable, higher recording densities
  – Up to 10 times greater capacity than longitudinal recording

• **Bonuses: More robust product, improved quality**
  – Better recording efficiency
  – Higher BPI is possible
  – Decreased rate of thermal decay - improved stability
  – Write performance in wider temperature ranges than longitudinal recording
  – Thermal reliability

FIRST PMR HDD SHIPS 8/05
40GB, single platter
1.8-inch HDD
133 gibabits per square inch
High Barriers to Entry

PMR Challenges

• Cost
  – Tremendous R&D investment
  – New manufacturing and testing equipment

• Technology curve
  – Complicated head/media system
  – Overcome technology challenges (pole erasure, SUL domain suppression, new media process)

• Manufacturing obstacles
  – Producing viable yields
  – Greater demand for components
**Forecast for PMR Deployment: Kicking Capacity Up a Notch**

<table>
<thead>
<tr>
<th>Mobile Class</th>
<th>2007</th>
<th>2010</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5-inch GB/platter</td>
<td>120</td>
<td>250</td>
<td>760</td>
</tr>
<tr>
<td>1.8-inch GB/platter</td>
<td>80</td>
<td>150</td>
<td>500</td>
</tr>
<tr>
<td>1.0-inch GB/platter</td>
<td>20</td>
<td>35</td>
<td>60</td>
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</tbody>
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*Source: IDC*
# PMR puts SFF HDDs Ahead in the Race

**SFF HDD** (0.85-inch – 1.0-inch)

**Benefits**
- Higher capacity
- Multiple form factors
- Fast read/write
- Lower cost per GB
- Faster data transfer rates
- Better life for rewriting data

**Challenges**
- Fixed form factors
- Long development cycle for new technologies

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**Flash**

**Benefits**
- Small size for integration into portable devices
- Power management
- Shock tolerance (although 0.85-inch HDD has a similar shock spec)

**Challenges**
- Capacity limit of 8GB
- Slower read/write times
- Limited number of erase and rewrite cycles
- High cost per GB
Implications:
New Opportunities for HDDs

Higher capacity in small form factors brings new applications

- **Digital cameras (sub-one inch)**
  - Potential for built-in storage in addition to removable

- **Cell phones (sub one-inch)**
  - Converged devices: music, video, games, photos

- **Notebook (1.8-inch)**
  - Greater capacity delivers multimedia functionality
  - Able to maintain “ultra” portability with increased capacity
  - Notebooks poised to proliferate in the home

- **DVR (2.5-inch)**
  - PMR brings right capacity to application
  - Better acoustics than 3.5-inch

- **Desktop (2.5-inch)**
  - Mobile drives now viable for desktop applications
  - Potential as the home server for entertainment and content distribution

- **Automotive (2.5-inch)**
  - Multimedia moves to the car
  - GPS, rear-seat entertainment, music
Conclusions: PMR Will Alter the Landscape of the HDD Industry

• Provides tremendous growth opportunities for HDD manufacturers
• A “must-have” not a value-add to do business in the HDD industry
• Fuels the continued drive to smaller form factor HDDs
• Opportunity to address pricing issues related to the value of higher capacity, especially in SFF CE devices
• A truly digital world: Innovation opens new consumer electronics and computing markets
Thank You.

Questions and Discussion
Perpendicular Recording: Is it really Necessary?

DISKCON September, 2005
Discussion Agenda

PMR and HDD Economics
PMR and Competing Storage Technologies
PMR and its Future
AD After 80

Areal Density

Gigabytes per Platter

SLOW

80
Sweet Spot Drive Size vs. # Heads (Desktop-class)

% Sweet spot is of the mix
Margins continue to increase with multi-platter drives.
Mix of Desktop-class HDDs Shipped

- 2003 Units
- 2004 Units
- 2005 Units

1-platter
2-platter
3+ platters
In 2005, 50% of WW Desktop-class revenue comes from 1-platter configurations – almost 20% from 3+ platters (up from 5% in 2003).
The Market for High Capacity is Increasing

Video Surveillance coming to a street corner near you!

PVRs

Enterprise Storage

Media Center PCs

IDC
Analyze the Future
#1 – PMR will be used to reach new, higher capacities required by various applications (video, enterprise)

#2 – PMR will be leveraged to garner an advantage from a platter perspective (not necessarily a 1-head advantage)
Competing Technologies: HDD vs Flash
$/GB – HDD pricing advantage is eroding

Flash vs 1.0” $/GB is 5:1 in 2004

Flash vs 1.0” $/GB is 2.5:1 in 2009

$/GB is not the sole criterion – capacity need and absolute cost

High capacity and multi-streaming requirements are positive for HDDs
Competition at Lower Capacities is Fierce

- Shuffle
- Nano
- Mini
- Ipod

Shipments vs. Capacity graph showing the trend of shipments for different capacities in the market.
PMR Fact Sheet

#1 – PMR will be used to reach new, higher capacities required by various applications (video, enterprise)

#2 – PMR will be leveraged to garner an advantage from a platter perspective (not necessarily a 1-head advantage)

#3 – PMR is required to stay competitive against flash – hence expect wide adoption in SFF – there is a complicated equation involving form factor, battery life, capacity, and cost… and only one person knows the answer – the consumer.
Capturing the HDD TAM in 2005

Increased competition will compel vendors to differentiate by leverage PMR
HDD economics will dictate the use of PMR in the following ways

#1 - Required to stay competitive against flash – hence expect wide adoption in SFF

#2 - Required to provide large capacities in 2.5” first (make laptop PCs more competitive with desktop PCs), then perhaps large 3.5” (the benefit is in high capacity SKU with fewest components)

#3 - Not to be leveraged in mainstream 3.5” until absolutely necessary

#4 - Will be leveraged in enterprise storage to improve data rates (PMR improves linear bit density)
Thank you

Questions:
 dreinsel@idc.com
Commercial TMR Heads for Hard Disc Drives: Characterization and Extendibility

Eric Granstrom, Ph.D.
Senior Engineering Manager
Advanced Transducer Development

Recording Heads Operation
Seagate Technology
Minneapolis, Minnesota, USA.
Acknowledgments

Special thanks to all the dedicated Seagate folks spanning various divisions

Specifically

Seagate Recording Heads Operation, Minneapolis, MN, USA
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Seagate Personal Storage Operation, CO, USA
Bill Cross, John Sarcaadi

Seagate Asia Operations, Singapore, Malaysia, Thailand, China

And Many More
Industry First TMR Head Product

Seagate 2.5" Laptop Drive Momentus II
Sept, 2004

Other product families starting at 80-100Gb/in²
TMR Head Technology Development

Scientific discovery to Product Introduction:


- High end products
- Personal storage
- Mobile-laptop
- Consumer electronics
HDD Growth and CE Market: SFF

- Digital
- Mobile
- Virtual
- Personal

Source: Hewlett Packard

High Areal Density

Consumer Electronics

SFF + Capacity
For > 100 Gb/in²: Reader Technologies

Areal Density vs. Magnetic Bit Sizes

<table>
<thead>
<tr>
<th>Density</th>
<th>Magnetic Bit Sizes</th>
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<tbody>
<tr>
<td>10 Gb/in²</td>
<td>32 ktpi x 345 kbpi</td>
</tr>
<tr>
<td>20 Gb/in²</td>
<td>45 ktpi x 445 kbpi</td>
</tr>
<tr>
<td>40 Gb/in²</td>
<td>75 ktpi x 530 kbpi</td>
</tr>
<tr>
<td>100 Gb/in²</td>
<td>167 ktpi x 600 kbpi</td>
</tr>
<tr>
<td>200 Gb/in²</td>
<td>200 ktpi x 1,000 kbpi</td>
</tr>
<tr>
<td>1 Terabit/in²</td>
<td>1,000 ktpi x 1,000 kbpi</td>
</tr>
</tbody>
</table>

Experimental MR Effect

- AMR (~2%)
- GMR (~20%)
- TMR (20-230%)
- CPP-GMR (up to 50%)

High MR ratio translates to High Signal-to-Noise ratio
How Do GMR and TMR Work?

- Resistance of device depends on electrons undergoing spin-dependent scattering at interfaces/bulk films
  - Many of the electrons don’t scatter at all which limits $\Delta R/R(\%)$

- Resistance of device depends on electrons undergoing spin-dependent tunneling through the barrier layer
  - More electrons must do this which produces higher $\Delta R/R(\%)$
TMR Reader Design Structure

Seagate Unique Upper Shield
Seed and PM cap layer
- Needed to magnetically isolate magnets and shield

Permanent Magnet
hard bias layer

Electrical Isolator
- Needed to force current to flow through reader stack

TMR runs cooler (vs. GMR) since heat conducts directly into top and bottom metal shields

FEM model: ~60 C

TUNNEL BARRIER

TOP SHIELD / ELECTRODE

FREE LAYER

SAF PINNED LAYER

BOTTOM SHIELD / ELECTRODE

Heat flow

CPP - Current perpendicular to Plane
TMR Product ABS TEM Image

- Free sensing layer
- Thin insulating barrier < 1 nm thickness
- Antiferromagnet for pinning the fixed layer

- Abutted junction layout with hard bias
- Reader width ~ 90-100nm and Shield spacing ~ 80nm
Commercial TMR Head SEM Images

- Manufactured using standard production processes
- Dry ion mill for junction formation
- Inductive writer electrically isolated from TMR reader
- TMR junction height defined by slider polishing process
Understanding TMR Barrier Physics

**Barrier Height** \( \bar{\varphi} = 93.13 \text{ meV} \)

**Barrier Width** \( d = 8.59 \text{ A} \)

**Barrier Asymmetry** \( \Delta \varphi = -5.122 \text{ meV} \)

(J. Nowak, Intermag 2004, invited paper CD-01)
Why TMR Head: Improved Output Signal

- Current in plane SV is reaching limit
  - Free layers are rotating as much as is stable
  - Temperatures are at maximum allowable values
  - No practical and reliable paths for further improvement

- Migration to TMR gives higher signal
  - Provides margin for performance-reliability trade-offs
  - Numerous options for future improvements
Higher $\Delta R/R$ and much smaller parasitic resistance leads to higher amplitude and higher SNR (>3dB).

Higher SNR leads to better Bit Error Rate and better Off-Track Performance capability.

Identical conditions except TMR vs. GMR over ~1000 product parts.
Comparison of TMR and GMR Head Performance in Production

- Better Bit Error Rate translates to higher product yields
Comparison of TMR and GMR: Noises

- TMR head has higher electronic noise due primarily to higher resistance
- Characteristic low frequency $1/f$-like noise can be reduced significantly with optimum design and process (Design A)
Recording Subsystem SNR with TMR Head

- Media SNR limited System SNR
- TMR head low frequency noise contribution is practically negligible.
Evaluation of TMR Head: No Electromigration

- Degradation dependence on bias frequency known to be signature of electromigration
- \( f = 0.1 \text{ Hz to 1 MHz}, 15 \text{ min. continuous application 3 mA signal}, \ J_{\text{peak}} \approx 3 \times 10^7 \text{ A/cm}^2 \)
- 4 groups of 32 parts evenly distributed across a resistance range
- DC current stress sampled data is consistent with AC test.

Key results:
- No significant effect of bias frequency over 7 orders of magnitude in frequency (with DC).
- No signature of electromigration up to 1 MHz in the TMR heads.
TMR Op. Temp. and Init. Bias Dependence

- TMR degradation (R loss) is directly proportional to ambient temperature (T) and initial bias voltage (V) for all devices stressed under the same current density (J).
- Thermally activated behaviors: oxygen redistribution in barrier $\sim$ $E_a \sim 2.7$eV

TMR Heads:
- T1=$25^\circ$C
- T2=$50^\circ$C
- T3=$100^\circ$C
- T4=$125^\circ$C

50$^\circ$C ambient
J=167mA/um$^2$
Degradation snapshot after 10hr constant J bias stress
ESD/EOS Sensitivity Measurements

- ESD voltage damage threshold for our TMR head is higher than its counterpart from GMR samples of the same dimensions
- This is due to the fast thermal dissipation in TMR heads

F1 – Amplitude
MR – Resistance
~ 1000 parts Mean
Seagate Tester
## Reader temperature (TGMR vs SV)

<table>
<thead>
<tr>
<th></th>
<th>Drive Max bias</th>
<th>Temp rise</th>
</tr>
</thead>
<tbody>
<tr>
<td>SV</td>
<td>150 mV</td>
<td>67°C</td>
</tr>
<tr>
<td>TGMR</td>
<td>100 uW</td>
<td>26°C</td>
</tr>
</tbody>
</table>

- The reader peak temperature rise is much lower on TGMR than SV.
- This temp reduction can be demonstrated as an important contributor to TGMR having greater life performance than SV for a comparable design point.
## Perceived vs True Challenges of TMR

<table>
<thead>
<tr>
<th>Perceptions</th>
<th>Facts</th>
</tr>
</thead>
</table>
| **Manufacturing**  
  • Barrier formation  
  • Junction formation  
  • RA and TMR ratio control |  
  • Enabled by advanced deposition technology & BIC metrology |
| **Reliability & Performance**  
  • TMR will be less stable |  
  • Not correct based on drive and component stress testing  
  • Long term thermal stability demonstrated |
| **Resistance mean and sigma will be too high to be practical** |  
  • Resistance mean enabled with proper design and well controlled by robust SPC  
  • Ranges are easily accommodated by pre-amps |
| • Noise will be too high to realize any gains |  
  • Actual Error Rates improved by 0.6 decade over similar GMR |
TMR Heads Going Perpendicular

Seagate Introduces World’s First 2.5-Inch Perpendicular Record Drive; First Major HDD Maker to Deliver Notebook PC Drive with Hardware-Based Full Disc Encryption Security

For Immediate Release

SEAGATE INTRODUCES WORLD’S FIRST 2.5-INCH PERPENDICULAR RECORDABLE HARD DRIVE: FIRST MAJOR HDD MAKER TO DELIVER NOTEBOOK PC DRIVE WITH HARDWARE-BASED FULL DISC ENCRYPTION SECURITY

SCOTTS VALLEY, Calif. – 08 June 2005 –

• Seagate 160GB 2.5-Inch Notebook Drive Sets New Capacity Benchmark
• Seagate Full Disc Encryption Delivers Strong, Easy-to-Use Data Security

Momentus 5400.3
2.5-Inch Storage for Mainstream Notebooks

PRODUCT DESCRIPTION
Momentus 5400.3 is the first Seagate® product utilizing perpendicular recording technology. This innovative technology allows Seagate to deliver the industry’s highest capacity of 160 GB in a single 2.5-inch disc drive. Perpendicular recording also enables a more reliable, faster performing drive. Using a thicker recording layer and standing the bits on end frees room on the disc, which lessens the chance of thermal decay. This higher thermal stability delivers increased performance in demanding high temperature and rugged operating environments.

THE SEAGATE ADVANTAGE
Seagate designed Momentus drives with the end customer in mind. With the best combination of performance and mobility, Momentus 5400.3 is ideal for mainstream notebook PCs. Additional features, such as Seagate QuietStep™ ramp load technology and a 5-year warranty for distribution, make Momentus 5400.3 the most obvious choice. These drives are also a good fit in certain non-PC applications, including external storage, printers/copiers, non-mission critical blade servers, and other storage applications that require robustness.

SPECIFICATIONS
- Capacity (GB): 40, 60, 80, 120, 160
- Interface: UltraATA/100 or SATA/150 Mbit
- Cache (MB): 8
- Average Seek (ms): 12.5
- Spin-up time (rpm): 5400
- Rotational speed (rpm): 5400
- Latency (ms): 15
- Shock (Operating/Non-Operating): 900
- Acoustics, Idle (dB): >2.5

APPLICATIONS
- Mainstream notebooks
- Tablet PCs
- External 2.5-inch drives
- Printers and copiers

Seagate is a registered trademark of Seagate Technology LLC. Seagate Technology LLC products are protected under numerous U.S. and foreign patents and pending applications. ©2005 Seagate Technology LLC. All rights reserved. No reproduction of materials without permission.
The same TMR head achieved 240Gb/in² AD demonstration in perpendicular recording on Seagate media.

- Diamondback Channel for Longitudinal used. True perpendicular channel can improve the performance further.

Seagate Standard
Z. Zhang et. al.,
IEEE Tran. Magn, 2002
Bathtub Curves at 240 Gb/in²

OTC values strongly depend on the test method and reference level

(Diamondback Channel)

- 95% TP
- 100% TP
- PE

20% TP

Cross Track Position (nm)

log(BER)

( S. Mao, et. al., MMM 2002, Miami)
The same TMR head achieved 274Gb/in² AD using a 1 bit error OTC out of a 100 BYTE (800 bits) (ref to HGST 230G news release).

Advanced TMR could extend the technology beyond 300Gb
Summary

- **TMR head technology has been commercialized for HDD by Seagate in 2004**
  - TMR has demonstrated equivalent or better process and wafer yields compared to GMR/SV.
  - TMR has over 3X amplitude relative to GMR, resulting in better BER, off-track capability for narrow heads, and areal density advantage.
  - TMR head technology has extended the application of longitudinal recording to higher areal densities. It has also been used in Seagate's products of perpendicular recording: 274Gb/in2 (ref: one bit/100 BYTE) has been demonstrated with the same TMR reader design as is used in current production of Seagate drives.

- **TMR is a mature and capable Reader Technology for Seagate that is being integrated into all Product Platforms**