HARD DISK DRIVES E MEMORIE MAGNETICHE

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Preparation and Investigation of Nanostructured Magnetic Materials

- Fundamental Studies
- Magnetic Recording
- Sensors
- Biomedicine
- Energy
- Environment
- Cultural Heritage

NM²-LAB RESEARCH ACTIVITY

Fabrication
- Chemical Synthesis
- Physical Deposition
- 3D Printing

Magnetic Characterization
- Vector-VSM
- SQUID
- Hysteresisgraph

Materials
- Single-phase
- Magnetic composites
- Hybrid/multifunctional systems

Nanoarchitectures
- Thin films & heterostructures
- Patterned systems

Modeling
OUTLINE

HARD DISK DRIVES

- History of magnetic recording
- Fundamentals of hard disk technology and current issues
  - Perpendicular magnetic recording: recording medium and read/write head
  - Recording Trilemma
- Next generation recording media – Beyond 1 Tbit/in²
  - FePt-based Exchange Coupled Composite (ECC) Media
  - Energy Assisted Magnetic Recording Media (EARM)
  - Bit Patterned Recording Media (BPRM)
  - Shingled Magnetic Recording (SMR)
  - Two Dimensional Magnetic Recording

MAGNETIC RANDOM ACCESS MEMORIES (MRAM)

- Fundamental Aspects
TREND IN DIGITAL DATA STORAGE CAPACITY

Exponential
Quantity of global digital data, exabytes

1,000 (kilo)

1,000,000 (mega)

1,000,000,000 (giga)

1,000,000,000,000 (tera)

1,000,000,000,000,000 (peta)

1,000,000,000,000,000,000 (exa)

1,000,000,000,000,000,000,000 (zetta)

1,000,000,000,000,000,000,000,000 (yotta)

130
2005

1,227
2010

2,720
2012

7,910
2015

40 ZB
2020
HARD DISK DRIVES

LEADING TECHNOLOGY FOR MASSIVE DIGITAL DATA STORAGE

Current HDDs

- Recording Density: ~1 Tb/in²
- HDD sold in 2018: ~316 million
- Cost/Gb: 0.0035 US$
"All that data stored in the cloud isn't on droplets of airborne water. It's stored on hard disk drives."
HARD DISK DRIVES

...WHERE MAGNETISM PLAYS A BIG ROLE

WRITE HEAD
High \( B_s \) SOFT magnet

READ HEAD
GMR/TMR Spin Valve

RECORDING MEDIUM
High \( K_u \) HARD magnet

SMALL MOTORS
High \( (BH)_{\text{max}} \) magnet
Outline

- History of magnetic recording

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- Next generation recording media – Beyond 1 Tbit/in²
  - FePt-based Exchange Coupled Composite (ECC) Media
  - Energy Assisted Magnetic Recording Media (EARM)
  - Bit Patterned Recording Media (BPRM)
  - Shingled Magnetic Recording (SMR)
  - Two Dimensional Magnetic Recording
1898 Valdmer Poulsen invented magnetic audio recorder (*Telegraphophone*)

**Analog Recording**

**Writing Process**
- Sound $\rightarrow$ $I(t)$ $\rightarrow$ $H(t)$ $\rightarrow$ $M_r(x)$

**Reading Process**
- Sound $\leftarrow$ $I(t)$ $\leftarrow$ $B(t)$ $\leftarrow$ $M_r(x)$

**Mechanism**

Electromagnetic induction.
**History of Magnetic Recording**

*From Telegraphone to Hard Disk Drive*

1898  Valdmer Poulsen invented magnetic audio recorder *(Telegraphophone)*

1930s  AEG and BASH developed magnetic audio-tape recorder *(Magnetophone)*

- **Write/Read Head**
  - Ring inductive head

- **Recording Medium**
  - Acetate tape coated with a layer of $\gamma$-Fe$_2$O$_3$ particles
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1898</td>
<td>Valdmer Poulsen invented magnetic audio recorder (<em>Telegraphone</em>)</td>
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<tr>
<td>1956</td>
<td>AMPEX introduced magnetic video recording.</td>
</tr>
<tr>
<td>1962</td>
<td>Philips invented compact cassette.</td>
</tr>
<tr>
<td>1976</td>
<td>Panasonic invented VHS system.</td>
</tr>
</tbody>
</table>
HISTORY OF MAGNETIC RECORDING
FROM TELEGRAPHONE TO HARD DISK DRIVE

1898  Valdmer Poulsen invented magnetic audio recorder (Telegraphone)

1930s  AEG and BASH developed magnetic audio-tape recorder (Magnetophone)

1956  AMPEX introduced magnetic video recording.

1962  Philips invented compact cassette.

1976  Panasonic invented VHS system.

NO RANDOM ACCESS CAPABILITY
**History of Magnetic Recording**

**From Telegraphone to Hard Disk Drive**

1898  
Valdmer Poulsen invented magnetic audio recorder (*Telegraphone*)

1930s  
AEG and BASH developed magnetic audio-tape recorder (*Magnetophone*)

1956  
AMPEX introduced magnetic video recording.

1962  
Philips invented compact cassette.

1976  
Panasonic invented VHS system.

1956  
IBM invented the first Hard Disk Drive

RAMAC – Random Access Memory of Accounting and Control

- Random access capability
- Multiple read/write cycles
- Capacity = 5 MB
- 50 Magnetic Disk (diameter = 24 in)
- **Recording density** = 2Kb/in²
HARD DISK DRIVES
AREAL DENSITY EVOLUTION

Current HDDs
- Perpendicular technology
- Recording Density: ~ 950 Gb/in²
- HDD sold in 2015: ~ 481 million
- Cost/Gb: 0.0035 US$

1956 IBM RAMAC (first HDD, 2 Kb/in²)
1980 Thin Film WR Head
1990 MR Read Head
1997 GMR Read Head
2001 AFC Media
2005 Perp. Media
TMR Read Head

10 Tb/in²
1 Tb/in²
100 Gb/in²
1 Gb/in²
1 Mb/in²

High-Kᵦ materials, EAMR, ECC, BPMR, SMR, TDMR

Longitudinal Recording
Perpendicular Recording

1E-6
1E-5
1E-4
1E-3
0.01
0.1
1
10
100
1000
10000
100000

Areal Density [Gb/in²]
Year
HARD DISK DRIVES
AREAL DENSITY EVOLUTION

Current HDDs
- Perpendicular technology
- Recording Density: ~950 Gb/in²
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High-Kₜ materials, EAMR, ECC, BPMR, SMR, TDMR

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<tr>
<th>Year</th>
<th>Areal Density [Gb/in²]</th>
<th>Recording Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>1956</td>
<td>1 Mb/in²</td>
<td>IBM RAMAC</td>
</tr>
<tr>
<td>1980</td>
<td>1 Gb/in²</td>
<td>Thin Film WR Head</td>
</tr>
<tr>
<td>1990</td>
<td>10 Gb/in²</td>
<td>MR Read Head</td>
</tr>
<tr>
<td>1997</td>
<td>100 Gb/in²</td>
<td>GMR Read Head</td>
</tr>
<tr>
<td>2001</td>
<td>1 Tb/in²</td>
<td>AFC Media</td>
</tr>
<tr>
<td>2005</td>
<td>10 Tb/in²</td>
<td>Perp. Media TMR Read Head</td>
</tr>
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</table>

10 Tb/in²
1 Tb/in²
100 Gb/in²
1 Gb/in²
10 Gb/in²
1 Gb/in²
10 Mb/in²
1 Mb/in²

Longitudinal Recording
Perpendicular Recording
**HARD DISK DRIVES**

**WORKING PRINCIPLE (PERPENDICULAR RECORDING MEDIA – PMR)**

![Diagram of a hard disk drive](image)

- **Writing current**: 
  - Writing field
  - Magnetic pattern
  - Clock window
  - Output voltage from head
  - Data read: 
    - 0 0 0 0 1 1 1 1 0 1 0 1 1 1..

**AREAL DENSITY (Gb/in²) = tpi x bpi**

- **tpi** = track/in; **bpi** = bit/in

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**Slide 17**
**Hard Disk Drives**
Recording Medium (PMR)

**Hard Ferromagnet**

→ It can be permanently magnetized allowing the information to be retained over time.
**HARD DISK DRIVES**
**RECORDING MEDIUM (PMR)**

**Dip-coating**
- IBD, PE-CVD, Sputtering

- Overcoat
  - Lubricant

- Recording layer

- Intermediate Layer

- Soft Underlayer (SUL)

- Adhesion layer

- Substrate

**PFPE (1 -2 nm)**
Reduces the friction and wear during the head-disk contact

**Diamond Like Carbon – DLC – & CNx (1-2 nm)**
Provides chemical and mechanical protection

**Ni-(X,Y)/Ru or Ru-(X,Y)/Ru (X, Y = Cr, Mn, W) (~ 15 nm)**
- Exchange-decouples the SUL and the magnetic layer
- Favours the epitaxial growth of the magnetic layer

**Co(Fe)TaZr-based (20 – 100 nm)**
Guides the magnetic flux from the write to the collector pole of head

**AlTi, CtTi, NiTa (5 - 10 nm)**
- Improves the adhesion of SUL
- Improves corrosion robustness of the substrate

**AlMg (Server & Desktop), Glass (Laptop)**
Performs the role of support (hard, stiff, inert, smooth)
**Miniaturized Electromagnet**

→ It supplies a write field $H_w$ high enough (i.e. $H_w > H_{sw}$) to induce the reversal of the magnetization of a bit.
Single pole Head
+ Soft Under-Layer (SUL)

Guides the magnetic flux ($\Phi$) from the write to the collector (or return) pole

It is assumed that the SUL generate a mirror image of the main pole

"The recording media is placed in the gap of the write head"
**Hard Disk Drives**

**Write Head (PMR)**

Single pole Head + Soft Under-Layer (SUL)

Guides the magnetic flux ($\phi$) from the write to the collector (or return) pole.

\[ H_w \approx \Omega M_s / 4\pi \]

**SOFT FERROMAGNET**

- High $M_s$ ($\sim B_s$ in small fields)
  - High $H_w > H_{sw}$
- High $\mu$
  - High efficiency (low $I$)
- Low $H_c$
  - Low Hysteresis Losses

**FeCo**

$\mu_0 M_s \sim 2.4$ T, $\mu_i \sim 900$, $\mu_0 H_C \sim 0.05$ mT
**Hard Disk Drives**

**Read Head (PMR)**

- **Giant/Tunneling Sensor**
- **Magneto-resistive (GMR/TMR)**

- **Free layer**
  - FM

- **Pinned layer**
  - FM
  - AFM

**Output voltage from head**

**Data read**: 0 1 0 1 0 1

**Recording Layer**

**Quiescent point**

Mathematical expressions:

\[ \rho = \rho_0 + \frac{1}{2} \Delta \rho \cos \theta \]

\[ \Delta \rho = \rho_{\uparrow \uparrow} - \rho_{\uparrow \downarrow} \]

**Normalized Magnetoresistance vs. Magnetization Angle (degree)**

\[ \Delta \rho_{\text{TMR}} >> \Delta \rho_{\text{GMR}} \]
**Hard Disk Drives**

**Read Head (PMR)**

Giant/Tunneling Magneto-resistive (GMR/TMR)

- **Free layer**
  - FM

- **Pinned layer**
  - FM
  - AFM

Metallic/Insulating spacer (GMR/TMR)

Output voltage from head

Data read

\[
\rho = \rho_0 + \frac{1}{2} \Delta \rho \cdot \cos \theta
\]

\[
\Delta \rho = \rho_{\uparrow\uparrow} - \rho_{\uparrow\downarrow}
\]

\[\Delta \rho_{\text{TMR}} \gg \Delta \rho_{\text{GMR}}\]
**HARD DISK DRIVES**

**READ HEAD (PMR)**

Giant/Tunneling Sensor

Magneto-resistive (GMR/TMR)

Free layer

Metallic/Insulating spacer (GMR/TMR)

Pinned layer

Data read

Output voltage from head

\[ \rho = \rho_0 + \frac{1}{2} \Delta \rho \cdot \cos \theta \]

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**Hard Disk Drives**

**Read Head (PMR)**

- **Giant/Tunneling Magneto-resistive Sensor (GMR/TMR)**
  - **Free layer**
  - **Pinned layer**
  - Metallic/Insulating spacer (GMR/TMR)

- **Recording Layer**
- **Output voltage from head**
- **Data read**

\[ \rho = \rho_0 + \frac{1}{2} \Delta \rho \cos \theta \]

\[ \Delta \rho = \rho_{\uparrow \uparrow} - \rho_{\downarrow \downarrow} \]

\[ \Delta \rho_{TMR} \gg \Delta \rho_{GMR} \]
**HARD DISK DRIVES**

**READ HEAD (PMR)**

- **Giant/Tunneling Sensor**
  - Free layer
  - Pinned layer

- **Magneto-resistive (GMR/TMR)**

- Metallic/Insulating spacer (GMR/TMR)

- Output voltage from head

- Data read: 0 1 0 1 0 1

- \[
  \rho = \rho_0 + \frac{1}{2} \Delta \rho \cdot \cos \theta
  
  \Delta \rho = \rho_{\uparrow \downarrow} - \rho_{\uparrow \uparrow}
  
  \Delta \rho_{\text{TMR}} \gg \Delta \rho_{\text{GMR}}
\]
**HARD DISK DRIVES**

**READ HEAD (PMR)**

![Diagram of a hard disk drive read head](image)

**Giant/Tunneling Sensor**

**Magneto-resistive (GMR/TMR)**

- **Free layer**: FM, AFM
- **Pinned layer**: FM

Metallic/Insulating spacer (GMR/TMR)

- **Output voltage from head**

- **Data read**: 0 1 0 1 0 1

Mathematical equation:

\[ \rho = \rho_0 + \frac{1}{2} \Delta \rho \cos \theta \]

\[ \Delta \rho = \rho_{\uparrow \uparrow} - \rho_{\downarrow \downarrow} \]

\[ \Delta \rho_{TMR} \gg \Delta \rho_{GMR} \]
**Hard Disk Drives**

**Recording Medium (PMR)**

- **Dip-coating**
- **IBD, PE-CVD, Sputtering**
- **Sputtering**

**Recording Layer**
- **PFPE (1 - 2 nm)**
  - Reduces the friction and wear during the head-disk contact

**Overcoat**
- **Diamond Like Carbon – DLC – & CNx (1 - 2 nm)**
  - Provides chemical and mechanical protection

**Intermediate Layer**
- **Ni-(X,Y)/Ru or Ru-(X,Y)/Ru (X, Y = Cr, Mn, W) (~ 15 nm)**
  - Exchange-decouples the SUL and the magnetic layer
  - Favours the epitaxial growth of the magnetic layer

**Soft Underlayer (SUL)**
- **Co(Fe)TaZr-based (20 - 100 nm)**
  - Guides the magnetic flux from the write to the collector pole of the head

**Adhesion layer**
- **AlTi, CtTi, NiTa (5 - 10 nm)**
  - Improves the adhesion of SUL
  - Improves corrosion robustness of the substrate

**Substrate**
- **AlMg (Server & Desktop), Glass (Laptop)**
  - Performs the role of support (hard, stiff, inert, smooth)
**HARD DISK DRIVES**

**RECORDING MEDIUM (PMR) – RECORDING LAYER**

**Dip-coating**
- IBD, PE-CVD, Sputtering

**Sputtering**
- Overcoat
- Lubricant

**Recording layer**
- Intermediate Layer
- Soft Underlayer (SUL)

**Adhesion layer**
- Substrate

**PFPE (1 - 2 nm)**
- Reduces the friction and wear during the head-disk contact

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**AlMg (Server & Desktop), Glass (Laptop)**
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**Hard Disk Drives**

**Recording Medium (PMR) – Magnetic Layer (1st Generation – 2005 –)**

**CoCrPt@SiO$_2$**

- $K_U = 0.2 – 0.5$ MJ/m$^3$
- Pt: Increases $K_U \rightarrow H_{sw} \approx K_U/M_s$
- Cr, SiO$_2$: promotes grain isolation

**Granular Microstructure ($d \sim 10$ nm)**

**Stoner-Wolfarth like system**

- Single domain grains
- Weakly exchange coupled grains
- Uniaxial perpendicular anisotropy $K_U$

**Smooth surface (Ra roughness \~ 1 nm)**

**Easy axis**

**Co alloy**

- hcp (002)

**Bit Pattern**

- Core: Co-rich (magnetic)
- Boundary: SiO$_2$ (non-magnetic)

**Hard Disk Surface**

- R/W Head
- NANOSLIDER
- 20 – 40 m/s

**Ground**

- ~0.3 mm
- ~5 nm
**HARD DISK DRIVES**

**EVOLUTION OF PERPENDICULAR MAGNETIC RECORDING MEDIA**

1\textsuperscript{st} (2005)

AD $\sim$ 100 Gb/in$^2$

- Single CoCr(Pt,Ta,B) Layer

$K_1 > K_2$

7\textsuperscript{st} (2013)

AD $\sim$ 700 Gb/in$^2$

- Multilayer structures consisting of CoCrPt-Oxide magnetic layers (ML) with different anisotropy ($K_i$) separated by a non magnetic break layer (BL, e.g. Pt)

- Improved writability
- Reduction of magnetic layer thickness

**EXCHANGE COUPLED COMPOSITE MEDIA**
**Hard Disk Drives**

**Evolution of Perpendicular Magnetic Recording Media**

1st (2005)
AD ~ 100 Gb/in²

7th (2013)
AD ~ 700 Gb/in²

---

**Exchange Coupled Composite Media**

Multilayer structures consisting of CoCrPt-Oxide magnetic layers (ML) with different anisotropy (K) separated by a non-magnetic break layer (BL, e.g. Pt)

- Improved writability
- Reduction of magnetic layer thickness

---

**Nanoslider**

R/W Head

2015
AD ~ 950 Gb/in²

---

**Overcoat (<2 nm)**

**Recording layer (15 nm)**

**Intermediate Layer (15 nm)**

**SAF – SUL (50 nm)**

**Adhesion layer (5 nm)**

Substrate

Ra Rough. 3.5 Å
1.5 nm

---

**Single CoCr(Pt,Ta,B) Layer**

K₁ > K₂
ML (K₁)
ML (K₂)
ML (K₃)
ML (K₄)

K₁ > K₂ > K₃
ML (K₁)
ML (K₂)
ML (K₃)
ML (K₄)

K₁ > K₂ > K₃ > K₄
ML (K₁)
ML (K₂)
ML (K₃)
ML (K₄)
HARD DISK DRIVES
BEYOND 1 Tbit/in²

1956 IBM RAMAC (first HDD, 2 Kb/in²)
1980 Thin Film WR Head
1990 MR Read Head
1997 GMR Read Head
2001 AFC Media
2005 Perp. Media
TMR Read Head

Areal Density [Gb/in²]

Year

Longitudinal Recording
Perpendicular Recording

IBM RAMAC (first HDD, 2 Kb/in²)
1980 Thin Film WR Head
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2001 AFC Media
2005 Perp. Media
TMR Read Head

IBM RAMAC (first HDD, 2 Kb/in²)
LONGITUDINAL MAGNETIC RECORDING (LMR) MEDIA

The areal density has been increased by continuously reducing the in-plane size of the grain in order to maintain an adequate SNR.

\[ SNR \propto \log_{10}(N) \]

Higher areal density require SMALLER GRAINS \((D)\)
The in-plane size of the grain has been kept almost constant and higher areal densities have been obtained reducing the number of grains per bit (down to ~15) without compromising the SNR.
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To go in the Tbit/in² regime the grain size must be reduced to maintain an adequate SNR.

\[ SNR \propto \log_{10}(N) \]
**Hard Disk Drives**

Beyond 1 Tbit/in² – Recording Trilemma

\[ SNR \propto \log_{10}(N) \]

Number of grains per bit

Higher areal density require **smaller grains** \( (D) \)

\[ \beta = \frac{\Delta E_0}{k_B T_{300}} \]

Stability Factor

\[ \frac{K_u V}{k_B T_{300}} > 60 \]

10 Years

Uniaxial Anisotropy Constant

Grain Volume

\( \Delta E_0 \)
Number of grains per bit

$SNR \propto \log_{10}(N)$

Higher areal density require SMALLER GRAINS $(D)$

$SNR$

THERMAL
STABILITY

$\beta = \frac{\Delta E_0}{k_B T_{300}}$  
Stoner-Wolfarth system

Uniaxial Anisotropy Constant

Grain Volume

$\frac{K_u V}{k_B T_{300}} > 60$

10 Years

**HARD DISK DRIVES**

BEYOND 1 Tbit/in² – RECORDING TRILEMMA

\[ SNR \propto \log_{10}(N) \]

Higher areal density require
SMALLER GRAINS (D)

\[ H_w \approx \Omega M_s / 4\pi > H_{sw} (\propto K_u) \]

**Recording Medium**

<table>
<thead>
<tr>
<th>Material</th>
<th>( K_u (10^6 \text{ J/m}^3) )</th>
<th>Write Head Material</th>
<th>( \mu_0 M_s (\text{T}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>SmCo₅</td>
<td>~ 20</td>
<td>Co₃₅Fe₆₅</td>
<td>2.4</td>
</tr>
<tr>
<td>L₁₀ FePt</td>
<td>~ 7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L₁₀ CoPt</td>
<td>~ 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co/Pt(Pd)</td>
<td>~ 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CoCrPt</td>
<td>~ 0.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Writing Field

Switching Field

SNR

WRITABILITY

THERMAL STABILITY

\[ \beta = \frac{\Delta E_0}{k_B T_300} \]

STABILITY FACTOR

Uniaxial Anisotropy Constant

Grain Volume

\[ \frac{K_u V}{k_B T_{300}} > 60 \]

10 Years

\[ \Omega \]

\[ D \]
**HARD DISK DRIVES**

**FUTURE TECHNOLOGIES OPTIONS**

**EXCHANGE COUPLED COMPOSITE MEDIA**

In soft/hard exchange coupled composites the domain wall forming in the soft phase supports the reversal of the hard phase leading to a reduction of $H_{sw}$ (improved write-ability) without affecting $\Delta E_0$ (i.e. thermal stability).

**ENERGY ASSISTED MAGNETIC RECORDING**

An external energy source (laser light or microwave field) is used to reduce $H_{sw}$ during the recording process (improved write-ability) without affecting thermal stability.

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**References**

- F. Casoli et al., Ch 6 in “Ultra-High-Density Magnetic Recording” (G. Varvaro and F. Casoli Eds.), Pan Stanford Publishing 2016
- G. Varvaro et al., JMMM 368 415 2014
- D. Suess et al., JMMM 321 545 2009
- D. Weller et al., IEEE Trans. Magn. 50 1 2014
- M. Kryder et al., Proc. IEEE 96 1810 2008
**Exchange-Coupled Composite Media**

**Exchange-Spring Systems**

**Reversal Mechanism**

- **Hp.** Soft and hard layers thick enough to fit a full domain wall
- **A – C** Nucleation of a reversed domain in the soft region
  - Reversible Reversal
    \[ H_n = 2K_s/J_s + 2A_s^2/4t_s^2M_s \]
- **D – E** Pinning/propagation of the domain wall
  - Irreversible Reversal
    \[
    H_p = \frac{2(K_h - K_s)}{\left(\sqrt{J_{s,h}} + \sqrt{J_{s,s}}\right)^2} \frac{K_sA_s}{K_hA_h}
    \]

**Gain Factor**

\[
\xi = \frac{2\Delta E_0}{M_s H_{sw} V}
\]

\[= 1 \quad \text{Single S-W Hard Phase} \]

\[1 \leq \xi \leq 2 \quad \text{Exchange-Spring System} \]
**Exchange Coupled Composite Media**

**Graded Systems**

- **Soft FM**
- **Hard FM**

**Basic principle** In a particle in a potential well, the maximum force that is required to move it from one minimum to the other depends on the gradient, which can be decreased by scaling the energy landscape in the horizontal direction, without affecting thermal stability, which is determined by the energy barrier ($\Delta E_0$).

$$K(z) = az^2$$

**Reversal Mechanism**

**Hp.** Graded layer thick enough to allow the formation of a domain wall

- **A – B** Nucleation of a reversed domain in the softest region
  $$H_n = 2K_s/J_S + 2A_s\frac{2}{4t_s^2}M_S$$

- **C – E** Pinning/propagation of the domain wall
  $$H_p = \left[\frac{1}{2J_s} \frac{\partial E(z)}{\partial z}\right]_{\text{max}} = \left[\frac{1}{2J_s} \sqrt{AK(z)} / \partial z\right]_{\text{max}}$$
  $$K(z) = az^2 = z^2K_h / t_G^2$$
  $$H_p = (2/J_s)\sqrt{AK_h / t_G}$$

$$H_{sw} = \max(H_n, H_p)$$

If $H_p > H_n$

$$\Delta E_0 = 2FJ_sH_{sw}t_G$$

$$1 \leq \xi = \frac{2\Delta E_0}{M_SH_{sw}V} \leq 4$$

**Graphs**

- **Small Force (Small Field)**
- **Large Force (High Field)**
**ENERGY ASSISTED MAGNETIC RECORDING (EAMR)**

**HEAT-AMR**

**WRITING PROCESS**

A tightly focused laser beam is used to increase the medium temperature up to a value close to $T_c$ where the anisotropy of the medium is low and thus only a very small field is required to switch the media. High-$K_u$ materials can be used.

**READ-OUT PROCESS**

Is performed with a magneto-resistive head at room temperature

---

ENERGY ASSISTED MAGNETIC RECORDING (EAMR)

**High-T Lubricant**
To withstand repeated temperature changes ranging from an ambient temperature to near $T_c$, which may cause the desorption and decomposition of lubricant molecules.

**L1₀-FePt**
$T_c$ (~ 750 K) is too high for practical applications and need to be reduced down to 500 K by adding a third element (e.g., Ni, Cu) without compromising $K_u$.

**Ag, Au, Al, Cu, Cr (20 – 200 nm)**
Establishes proper thermal gradients and optimizes write power requirements.

**Energy Assisted Magnetic Recording (EAMR)**

**Writing Process**
A transverse AC magnetic field with a frequency matching the ferromagnetic resonance frequency of the media induces a precession mode of the magnetization around the easy-axis that allows lowering the coercivity when a DC external field is applied along the easy direction.

High-$K_u$ materials can be used.

**Read-out Process**
Is performed with a magneto-resistive head.

---

E. Gage et al., Ch 4 in “Ultra-High-Density Magnetic Recording” (G. Varvaro and F. Casoli Eds.), Pan Stanford Publishing 2016

ENERGY ASSISTED MAGNETIC RECORDING (EAMR)

MICROWAVE-AMR

3D Magnetic Recording

HARD DISK DRIVES
TOWARDS 1 Tbit/in² AND BEYOND – RECORDING TRILEMMA

\[ SNR \propto \log_{10}(N) \]

Higher areal density require SMALLER GRAINS (D)

\[ \beta = \frac{\Delta E_0}{k_B T_{300}} = \frac{K_u V}{k_B T_{300}} > 60 \text{ 10 Years} \]

SNR
THERMAL STABILITY

Number of grains per bit

\( N \)

Stability Factor

Uniaxial Anisotropy Constant

Grain Volume
HARD DISK DRIVES
Towards 1 Tbit/in² and Beyond – Recording Trilemma

\[ SNR \propto \log_{10}(N) \]

Higher areal density require SMALLER GRAINS \((D)\)

\[ \beta = \frac{\Delta E_0}{k_B T_{300}} = \frac{K_u V}{k_B T_{300}} > 60 \] (10 Years)

STABILITY FACTOR
**Bit Patterned Magnetic Recording (BPMR)**

\[ \beta = \frac{K_u V}{k_B T_{300}} > 60 \]

**Conventional Media**
- Continuous granular recording media
- Multiple grains per bit
- Boundaries between bits determined by grains
- Thermal stability unit is one grain

**Bit Patterned Media**
- Highly exchange coupled granular media
- Multiple grains per island, but each island is a single domain particle
- Bit locations determined by lithography
- Thermal stability unit is one dot

2 - 5 Tbit/in^2 with CoCrPt

40 - 50 Tbit/in^2

Hard Materials (e.g. L1_0-FePt)
ECC
EARM

D. Makarov et al., Ch 7 in “Ultra-High-Density Magnetic Recording” (G. Varvaro and F. Casoli Eds.), Pan Stanford Publishing 2016
## Bit Patterned Magnetic Recording (BPMR)

### Nano-Lithography
- Accuracy
- Resolution
- Large Area Order
- Cost
- Time-consuming

### Main Challenges
Extreme fabrication requirements:
- Low cost
- Fast process
- High resolution
- Large area order

<table>
<thead>
<tr>
<th>Density (Tb/in²)</th>
<th>Bit period (nm) BAR=1</th>
<th>Bit period (nm) BAR=4</th>
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<tbody>
<tr>
<td>1</td>
<td>25.4</td>
<td>12.7</td>
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<tr>
<td>5</td>
<td>11</td>
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<tr>
<td>10</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>40</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

![Diagram showing bit patterns and density calculation](image)

**BAR = 1**
- 11 nm
- 5 Tbit/in²

**BAR = 4**
- 2.75 nm
- 11 nm
- 5 Tbit/in²

**Density (Tb/in²)**
- 1: 25.4 nm
- 5: 11 nm
- 10: 8 nm
- 40: 4 nm
**Bit Patterned Magnetic Recording (BPMR)**

### Main Challenges

Extreme fabrication requirements:
- Low cost
- Fast process
- High resolution
- Large area order

### Template-Assisted Self-assembly

- Accuracy
- Resolution
- Large Area Order
- Cost
- Time-consuming

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</table>

BAR = 1
5 Tbit/in²

BAR = 4
5 Tbit/in²

5.5 nm

2.75 nm

50 nm

Block-Copolymers

Nano-spheres
**Final Remarks**

- **1956** RAMAC (IBM) 2 Kb/in$^2$
- **1980** Thin Film WR Head
- **1990** MR Read Head
- **1997** GMR Read Head
- **2001** AFC Media
- **2005** Perp. Media TMR Read Head
- 2015 ~ 950 Gb/in$^2$

### Areal Density [Gb/in$^2$]
- 10 Tb/in$^2$
- 1 Tb/in$^2$
- 100 Gb/in$^2$
- 1 Gb/in$^2$
- 1 Mb/in$^2$

### Year

- **High-K$_u$ materials, EAMR, ECC, BPMR, SMR, TDMR**

- **IBM RAMAC (first HDD, 2 Kb/in$^2$)**
GEOMAGNETISM

Normal polarity

Reverse polarity

Volcanoes

Mid-Ocean Ridge

Deep-Ocean Trench

Rising Magma

Sea-Floor Spreading

Mantle

Subduction Zone

0.0 1.0 2.0 3.0 4.0 5.0

Millions of Years Ago

Gaspare.varvaro@ism.cnr.it | www.nm2lab.com
Ultra-High-Density Magnetic Recording
Storage Materials and Media Designs

G. Varvaro & F. Casoli (CNR. Italy) Eds.

- Covers the most recent progress and developments in magnetic recording from the media perspective, including theoretical, experimental, as well as technological aspects.
- Provides an overview of the emerging classes of magnetic memories regarded as potential candidates for future information storage devices.
- Contains contributions from worldwide experts from university, public research institutions and industry.
- Includes comprehensive references together with clear and thorough figures complement each section.

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*
OUTLINE

HARD DISK DRIVES

- History of magnetic recording
- Fundamentals of hard disk technology and current issues
  - Perpendicular magnetic recording: recording medium and read/write head
  - Recording Trilemma
- Next generation recording media – Beyond 1 Tbit/in²
  - ✔ FePt-based Exchange Coupled Composite (ECC) Media
  - ✔ Energy Assisted Magnetic Recording Media (EARM)
  - ✔ Bit Patterned Recording Media (BPRM)
  - ❌ Shingled Magnetic Recording (SMR)
  - ❌ Two Dimensional Magnetic Recording

MAGNETIC RANDOM ACCESS MEMORIES (MRAM)

- Fundamental Aspects
# Memories Categories

<table>
<thead>
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<th>Memory</th>
<th>Main Field of Application</th>
<th>Advantages</th>
<th>Drawbacks</th>
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| HDD     | Secondary data storage device in computers | • High density (~1 Tbit/in²)  
• Very low cost per byte stored (~0.004 $/Gbit) | • Moderate read and write speeds (~1 Gbit/s)  
• Bulky moving parts  
• Power consuming |
| FLASH   | • Long-term external storage  
• Firmware  
• SSD drives | • Nonvolatile  
• Very high density (> 1 Tbit/in²)  
• Low cost (<1 $/Gbit) | • Moderate read and write speeds (~6 Gbit/s)  
• Limited endurance |
| SRAM    | Cache memory in computers | • Fast read and write speeds (~35 Gbit/s)  
• Low power consuming | • Volatile  
• Low density (~4.5 Gbit/in²) |
| DRAM/S DRAM | Primary memory in computers | • High density (>500 Gbit/in²)  
• Low cost (~1 $/Gbit)  
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• Constant refreshing of data  
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<td>• Unlimited write endurance</td>
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<td>• Radiation hardness</td>
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<tr>
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**Non-Volatile**

**Volatile**

- DRAM
- SRAM
- HHDD
- FLASH
- MRAM
- Magnetic Random Access Memory

- Military and space applications
- Universal Memory in computer
- High writing currents

**Languages:**
- English
- Italian (gaspare.varvaro@ism.cnr.it | www.nm2lab.com)
**Basics of MRAM Working Principle**

### Cross Point Architecture

- **Spin Valve**
  - FM free layer
  - NM spacer
  - FM reference layer

- **Bit Lines**
- **Word Lines**

### Writing Process
Setting the magnetization of the free layer (P or AP to the reference layer)
- Field-Induced Magnetic Switching
- Stoner-Wohlfarth Writing
- Toggle Writing
- Heat Assisted Writing
- Spin Transfer Torque
- Spin Orbit Torque
- Magneto-Electric Coupling
- Optical Writing

### Reading Process
Measuring the change of resistance between P and AP magnetic configurations.

\[ R_{\uparrow\downarrow} > R_{\uparrow\uparrow} \]
MRAM Structure

Spin Valve

Metal, Insulator

FM-Free Layer (Recording/storage Layer)

NM Spacer

FM-Reference Layer
MRAM Structure
Spin Valve

FM-Free Layer (Recording/storage Layer)
Metal, Insulator
NM Spacer
FM-Reference Layer

Uniaxial Anisotropy

M

H

R_{\uparrow\downarrow} > R_{\uparrow\uparrow}
MRAM Structure

Spin Valve

- FM-Free Layer (Recording/storage Layer)
- Metal, Insulator
- NM Spacer
- FM-Reference Layer

Uniaxial Anisotropy

'0'

'1'

$K_{sh} = -\frac{1}{2} \mu_0 M_s^2$

$R_{\downarrow\downarrow} > R_{\uparrow\uparrow}$
MRAM Structure

Spin Valve

- Metal, Insulator
- FM-Free Layer (Recording/storage Layer)
- NM Spacer
- FM-Reference Layer
- Exchange Bias coupling with an AFM
- Synthetic Antiferromagnets (SAF)
- Metallic Spacer
MRAM Structure
Spin Valve | Reference Layer – AFM Pinning Layer (Exchange Bias)

$T_N < T < T_C$

$H < T < T_N$

$T < T_N$

$H_{EB}$
MRAM Structure
Spin Valve | Reference Layer – AFM Pinning Layer (Exchange Bias)

- Metal, Insulator
- NM Spacer
- FM-Free Layer
- FM-Reference Layer
- AFM Layer

Magnetization reversal of the free layer
Magnetization reversal of the reference layer
Offset $H_{EB}$
MRAM Structure

Spin Valve | Reference Layer – AFM Pinning Layer (Exchange Bias)

- Metal, Insulator
- NM Spacer
- FM-Free Layer
- FM-Reference Layer
- AFM Layer

Magnetization reversal of the free layer
Magnetization reversal of the reference layer
Offset
H<sub>EB</sub>
MRAM Structure

Spin Valve | Reference Layer – SAF Layer (Interlayer Exchange Coupling)

Metal, Insulator

- - + +

FM-Free Layer

or

NM Spacer

Metallic Spacer

- - + +

FM-Reference Layer

Synthetic Antiferromagnet (SAF)
$J_{ex}$ oscillates with the thickness of the spacer layer with a dependence that is well described by a RKKY–like exchange coupling model.

- $J_{ex} < 0 \rightarrow$ AFM coupling
- $J_{ex} > 0 \rightarrow$ FM coupling

$A_1(\AA)$: Spacer-layer thickness corresponding to the first peak of AFM exchange-coupling.

$\Delta A_1(\AA)$: Range of spacer-layer thickness of the first AFM region.

$J_1$ (erg/cm$^2$): Magnitude of the AFM exchange-coupling at the first peak.

$P(\AA)$: Oscillation period
**MRAM Structure**

**Spin Valve | Reference Layer – SAF Layer (Interlayer Exchange Coupling)**

- **FM-Free Layer**
- **Metal, Insulator**
- **NM Spacer**
- **Metallic Spacer**
- **FM-Reference Layer (SAF)**

Diagram illustrating the magnetization reversal of the free layer and the zero offset.
**MRAM Structure**

**Spin Valve | Reference Layer – AFM + SAF**

- Metal, Insulator
- **FM-Free Layer**
- NM Spacer
- **FM-Reference Layer**
  - Synthetic Antiferromagnet (SAF)
- Metallic Spacer
- **AFM Layer**
MRAM Structure
Spin Valve | In-plane vs. Out-of-Plane Magnetization

- Higher stability of time and temperature.
- Two magnetic stable states are intrinsically defined → elongated bit are not needed.

Smaller bit size → Higher recording densities
**Reading Process**

![Diagram of reading process]

- **P state**
  - $R_{\uparrow\uparrow} < R_{\uparrow\downarrow}$
  - $0 < 1$

- **AP state**
**Reading Process**

- **P state**
  - \( R_{\uparrow\downarrow} < R_{\uparrow\uparrow} \)
  - \( \Delta R/R = (R_{\uparrow\downarrow} - R_{\uparrow\uparrow})/R_{\uparrow\uparrow} \)

- **AP state**
  - \( 0 < 1 \)

**Metallic Spacers**
- GMR Spin Valve
- Insulating Spacer
- TMR Spin Valve

*Up to 55%*
- JMMM 200, 274 (1999)
*Up to 604%*
- APL 93, 082508 2008
Setting the magnetization of the free layer parallel or antiparallel to that of their reference layer.

- Field-Induced Magnetic Switching
  - Stoner-Wohlfarth Writing
  - Toggle Writing
  - Heat Assisted Writing
- Spin Transfer Torque
- Spin Orbit Torque
- Magneto-Electric Coupling
- Optical Writing
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THANK YOU FOR THE ATTENTION