HARD DISK DRIVES E MEMORIE MAGNETICHE

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nM²-Lab
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Ass. Researcher

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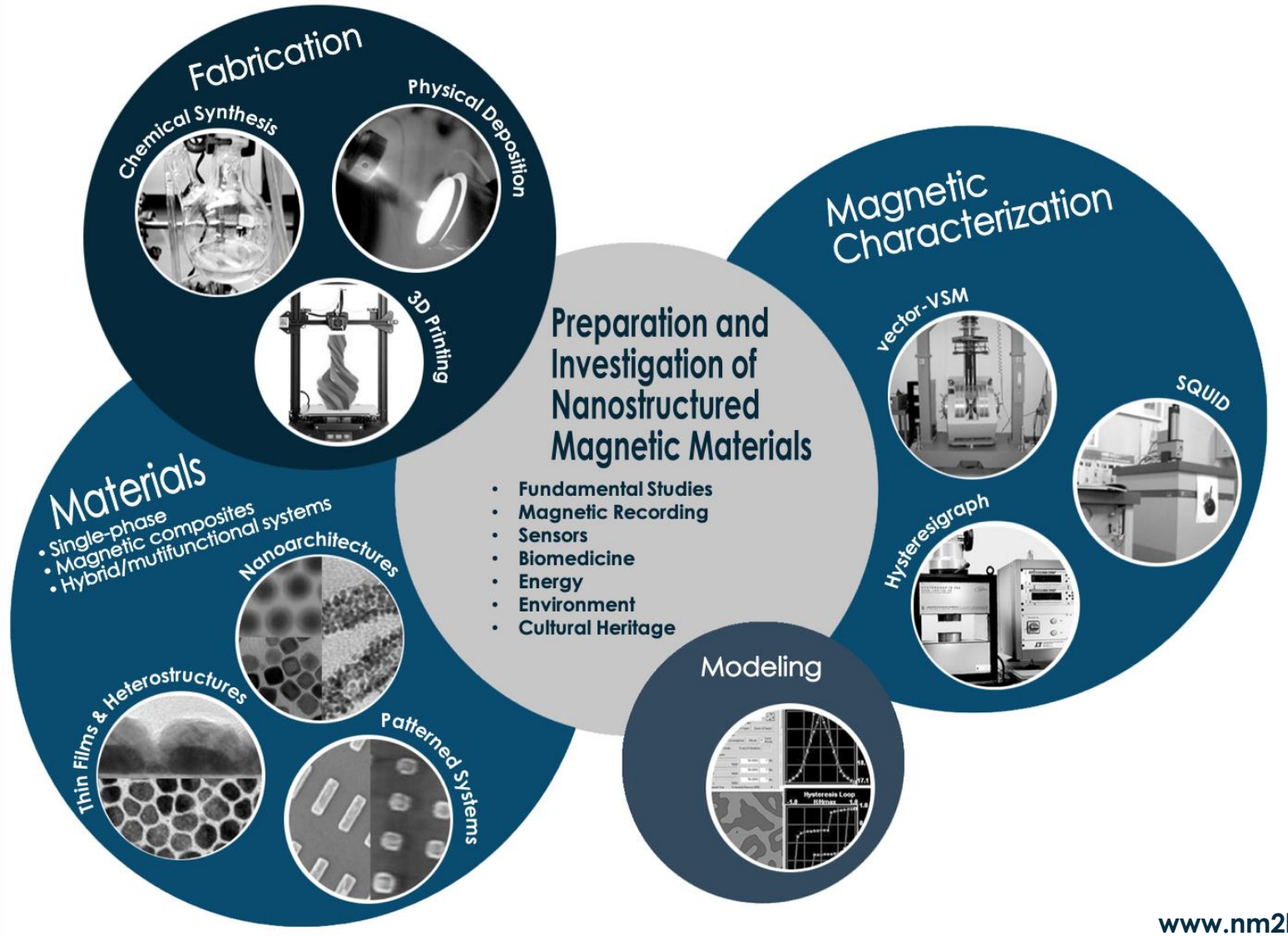
nM²-Lab
Research Activity



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OUTLINE

HARD DISK DRIVES

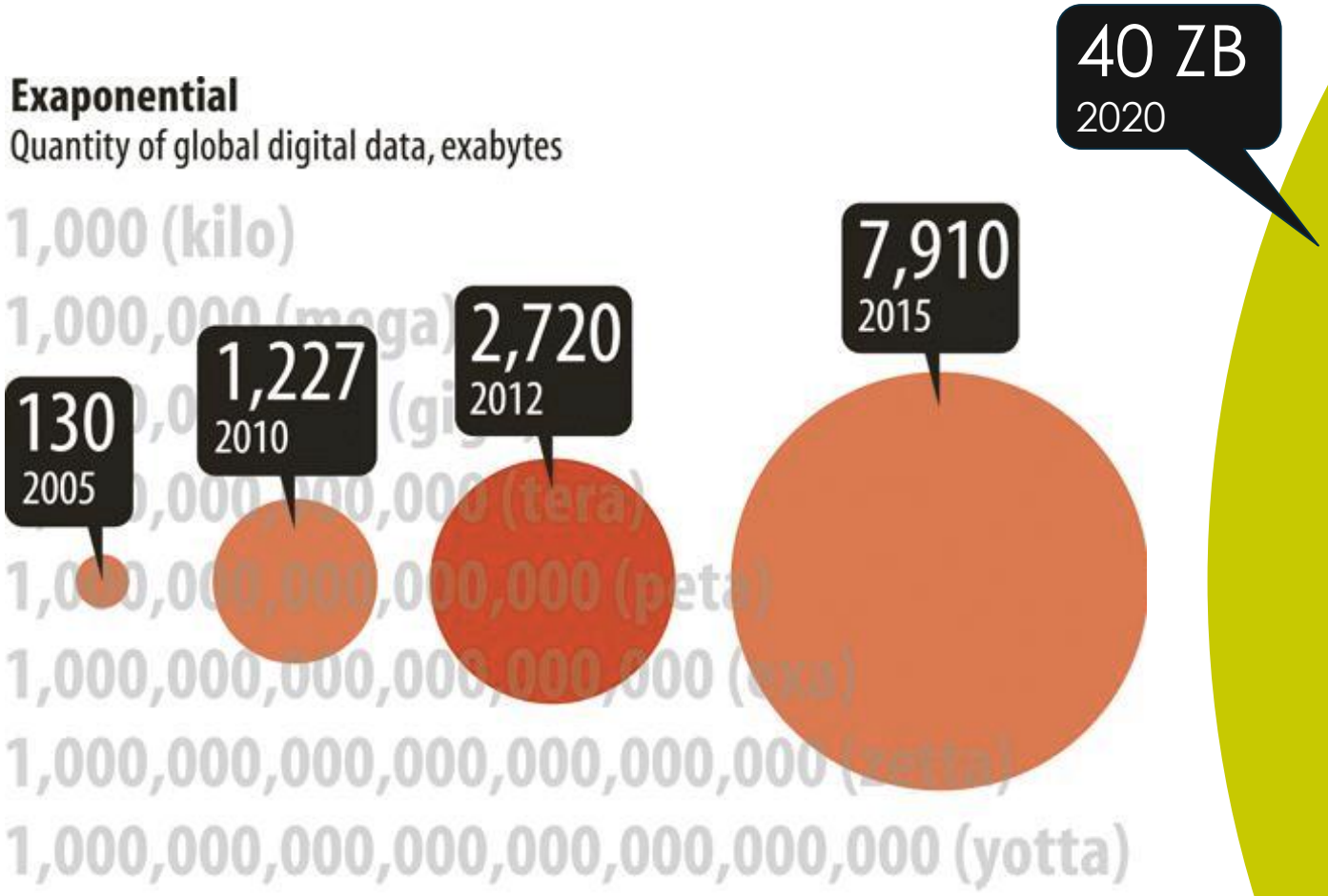
- History of magnetic recording
- Fundamentals of hard disk technology and currents issues
  - Perpendicular magnetic recording: recording medium and read/write head
  - Recording *Trilemma*
- Next generation recording media – *Beyond 1 Tbit/in*^{2}

  ☑ 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



Hard Disk Drives

Leading technology for massive digital data storage

Current HDDs

- Recording Density: ~ **1 Tb/in^2**
- HDD sold in 2018: ~ **316 million**
- Cost/Gb: **0.0035 US$**

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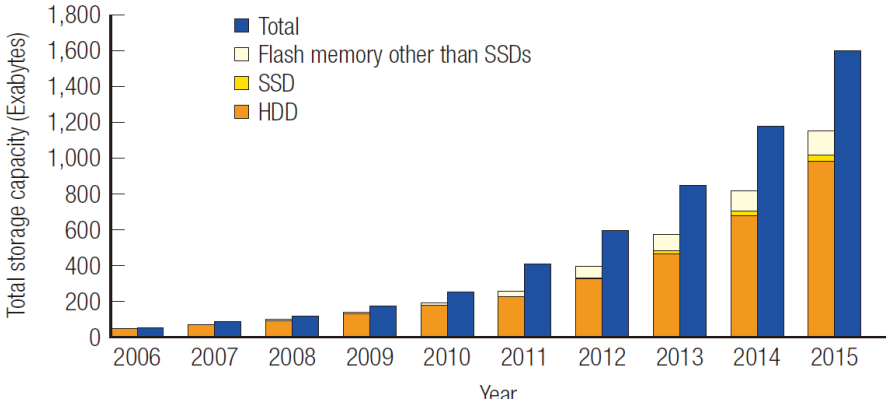
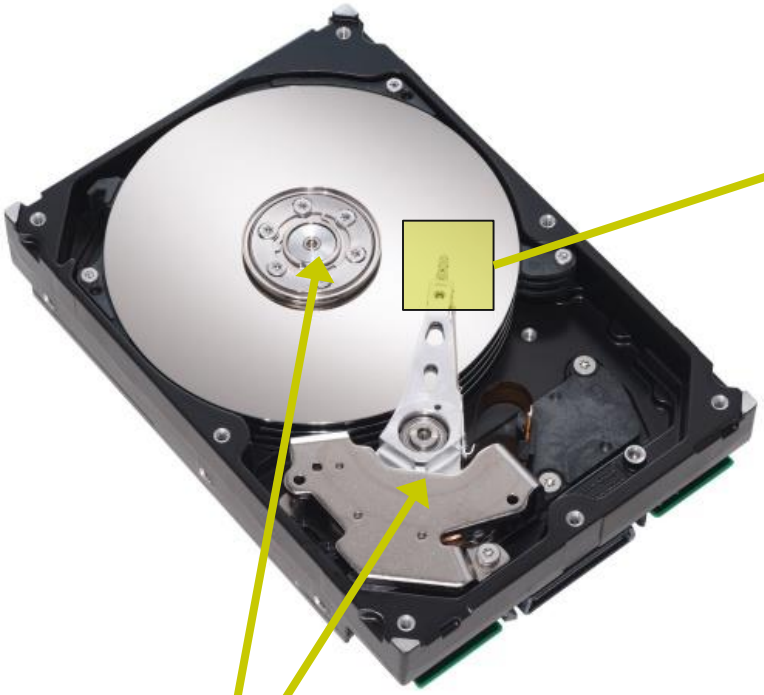


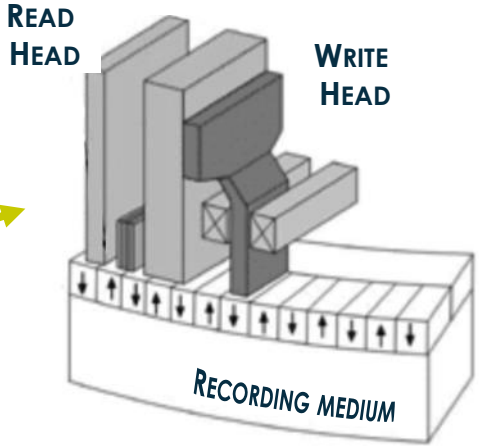
"All that data stored in the cloud isn't on droplets of airborne water. **It's stored on hard disk drives.**"

HARD DISK DRIVES

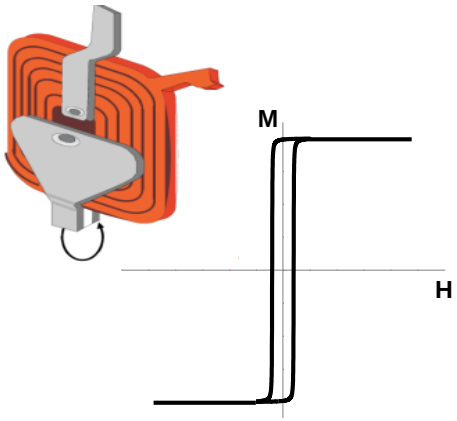
…WHERE MAGNETISM PLAYS A BIG ROLE



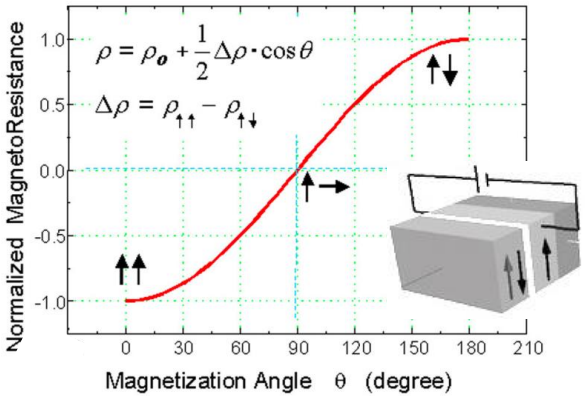
SMALL MOTORS
High $(BH)_{max}$ magnet



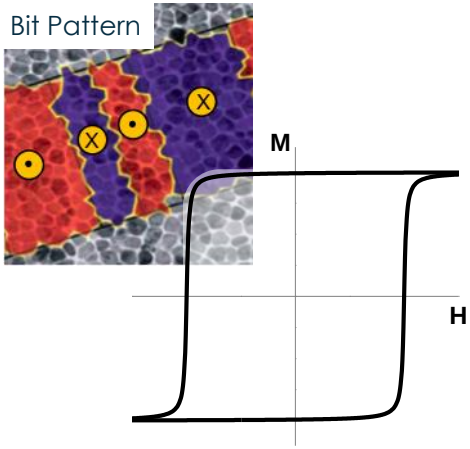
WRITE HEAD
High B_s **SOFT magnet**



READ HEAD
GMR/TMR **Spin Valve**



RECORDING MEDIUM
High K_U **HARD magnet**



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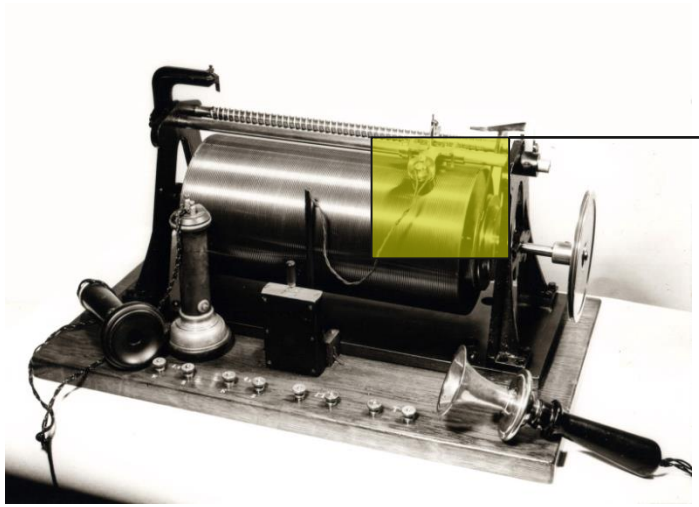
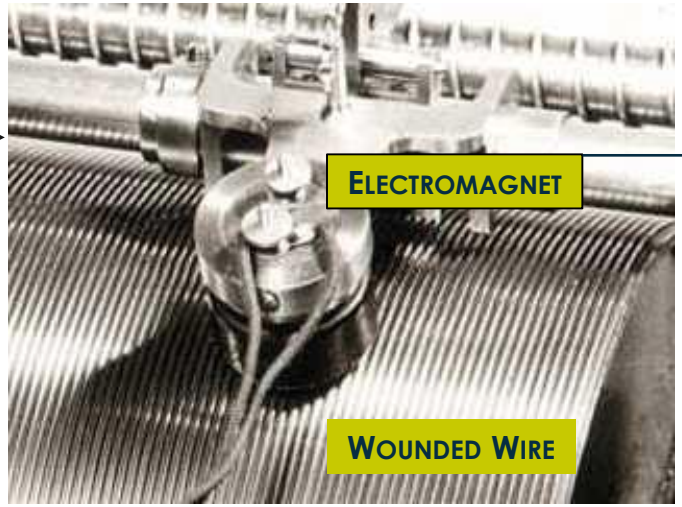
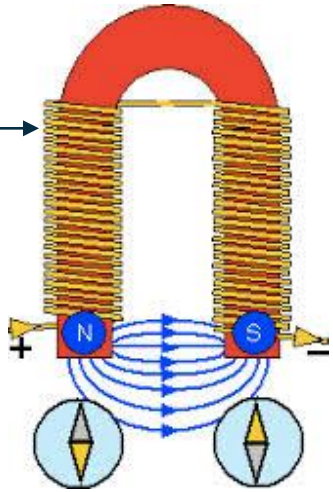
History of Magnetic Recording

From Telegraphone to Hard Disk Drive

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







Mechanism
Electromagnetic induction.

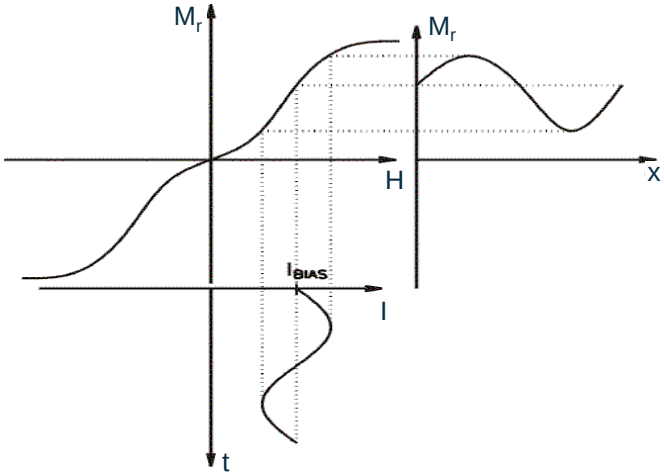
Analog Recording

Writing Process

Sound → I(t) → H(t) → $M_r(x)$

Reading Process

Sound ← I(t) ← B(t) ← $M_r(x)$



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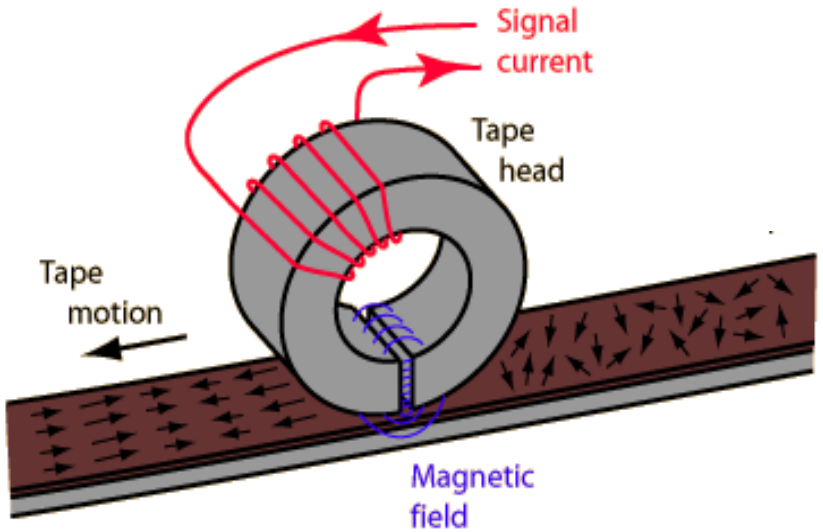

- **Write/Read Head**
  Ring inductive head
- **Recording Medium**
  Acetate tape coated with a layer of γ-Fe_2O_3 particles

History of Magnetic Recording

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1956 AMPEX introduced magnetic video recording.

1962 Philips invented compact cassette.

1976 Panasonic invented VHS system.

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NO RANDOM ACCESS CAPABILITY

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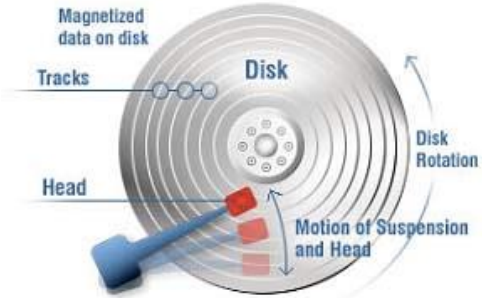
1956 IBM invented the first Hard Disk Drive

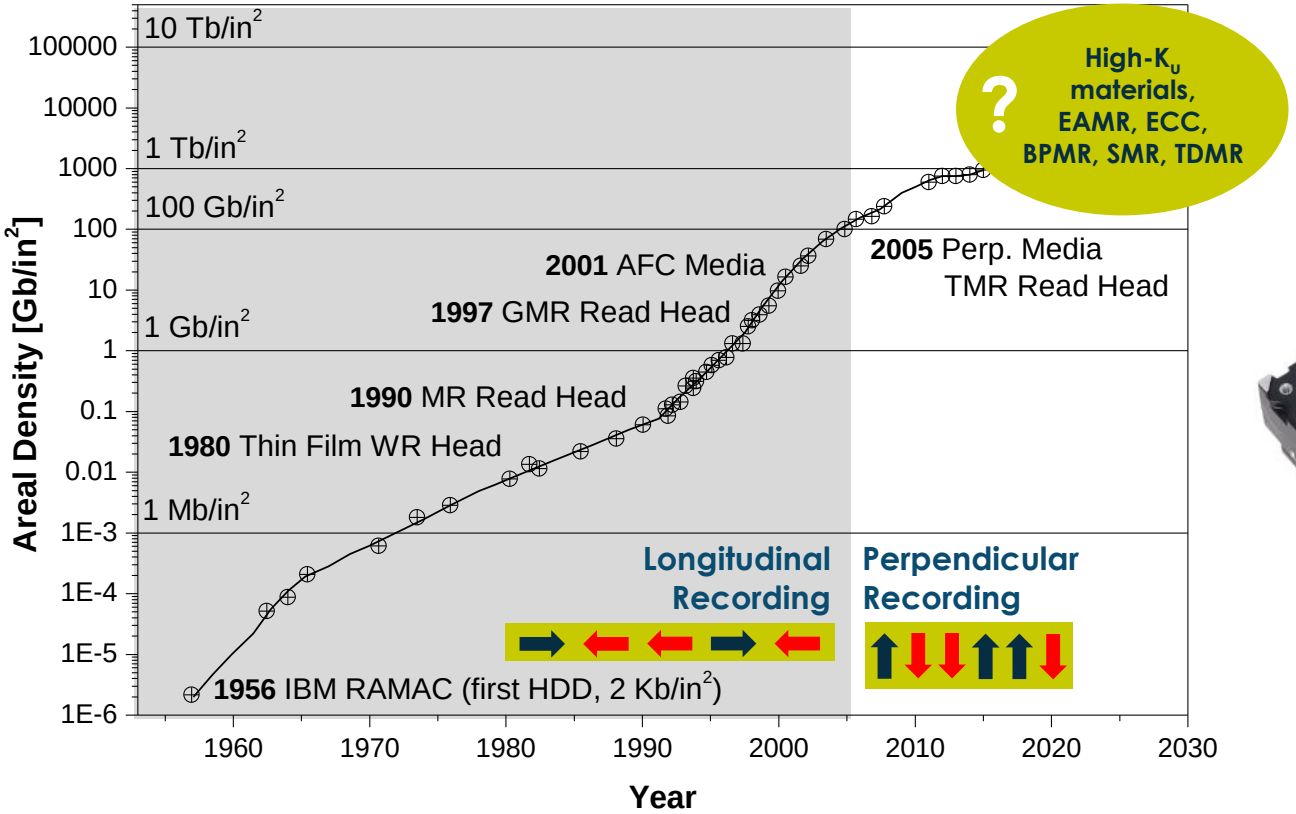
RAMAC – Random Access Memory of Accounting and Control



- Random access capability
- Multiple read/write cycles
- Capacity = 5 MB
- 50 Magnetic Disk (diameter = 24 in)
- **Recording density = 2Kb/in^2**

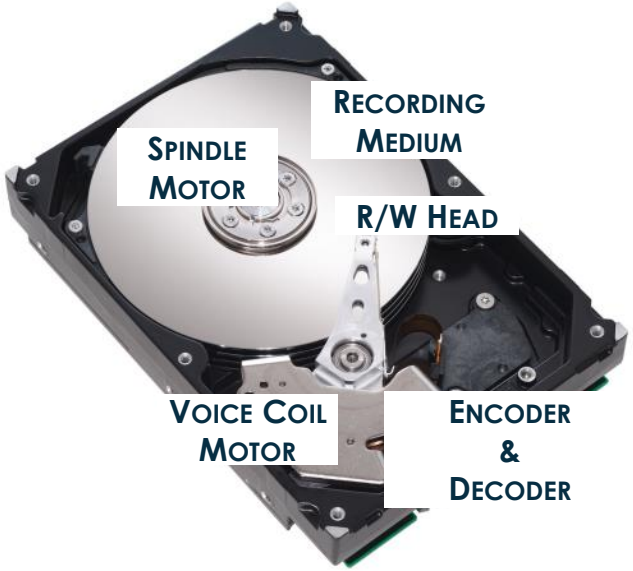
Hard Disk Drives

Areal Density Evolution



Current HDDs

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



Hard Disk Drives

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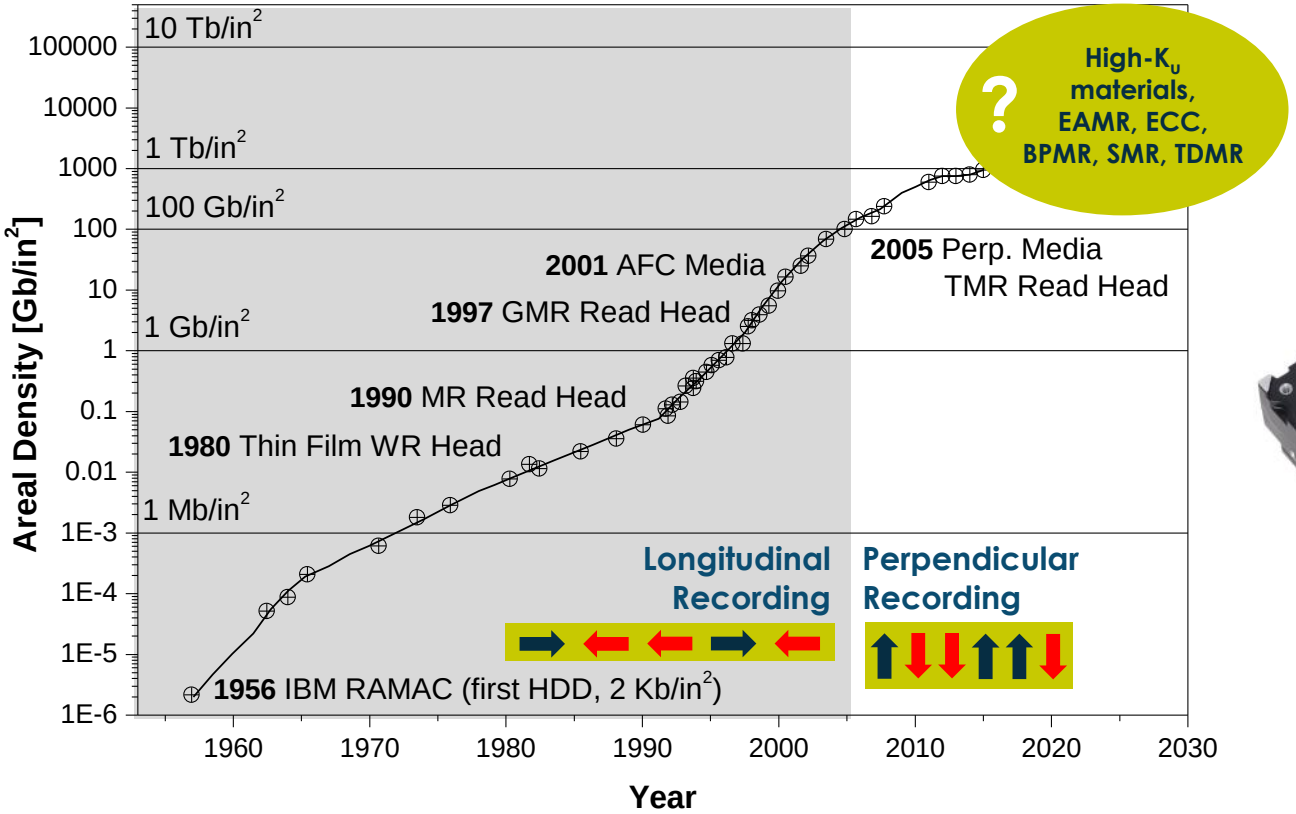

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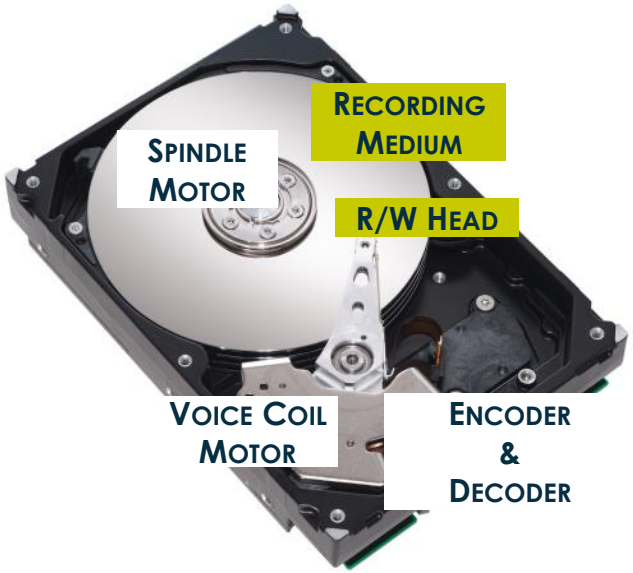
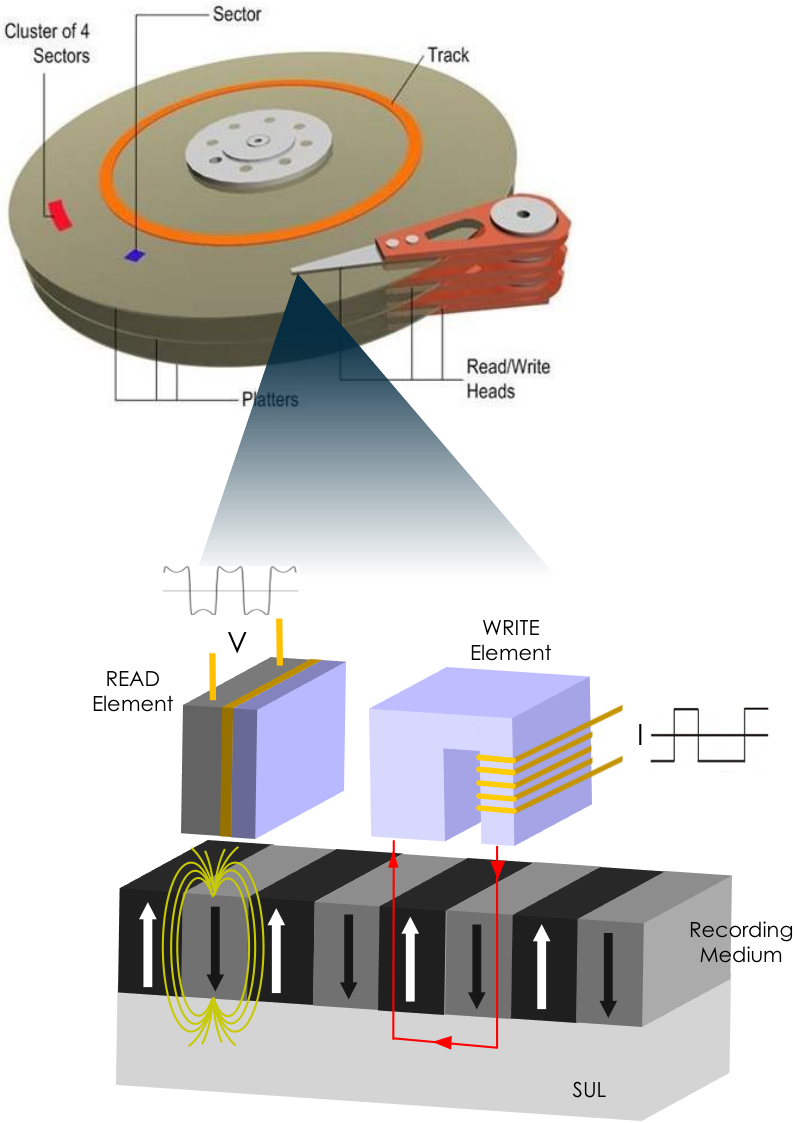
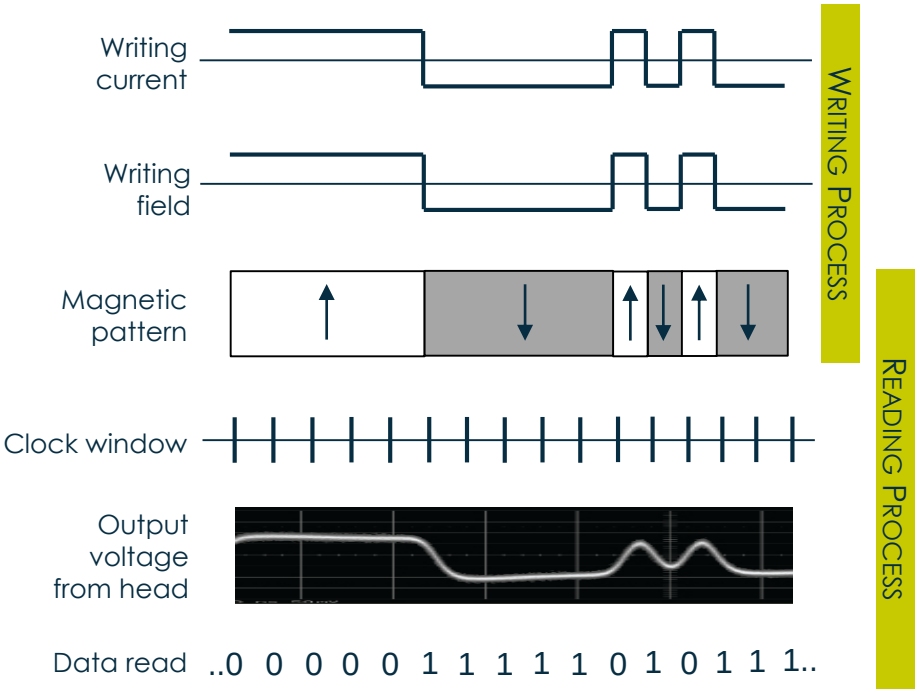


Hard Disk Drives

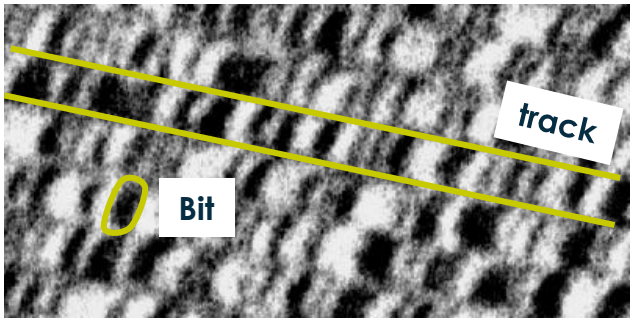
Working Principle (Perpendicular Recording Media – PMR)



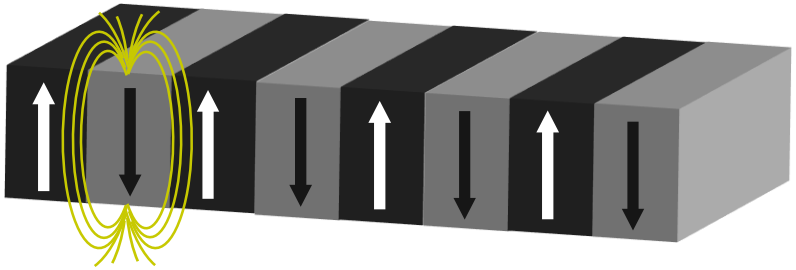


Areal Density (Gb/in^2) = *tpi* x *bpi*

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

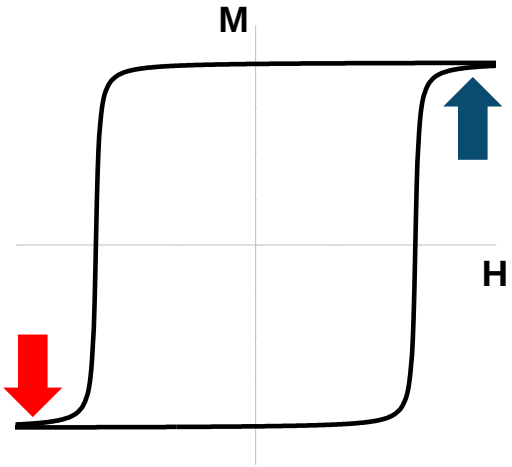


Hard Disk Drives
Recording Medium (PMR)



Hard Ferromagnet

→ It can be permanently magnetized allowing the information to be retained over time.



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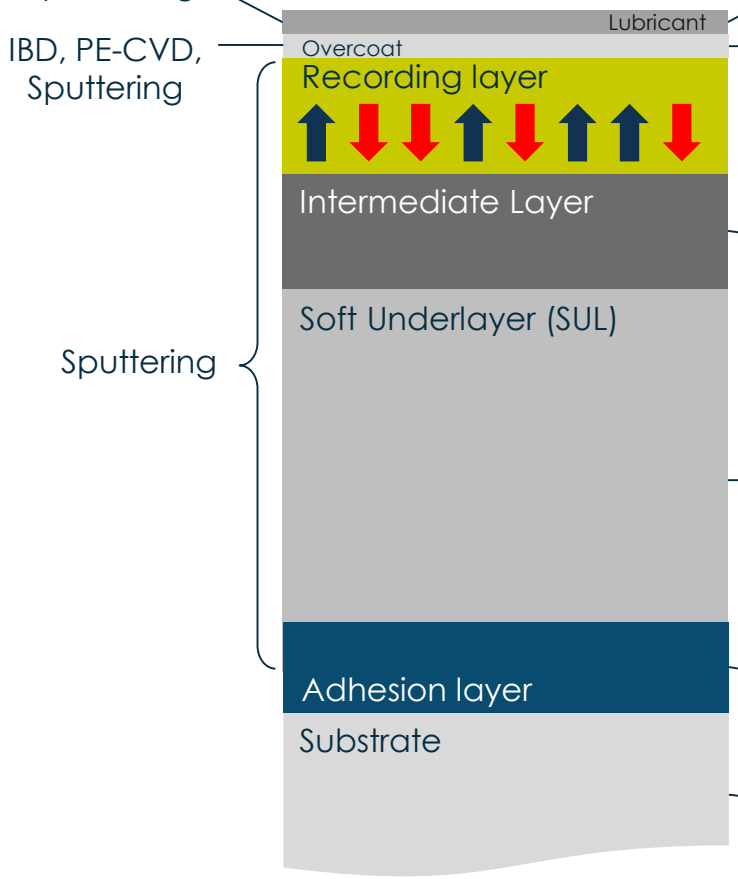


PFPE (1 -2 nm)
Reduces the friction and wear during the head-disk contact

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

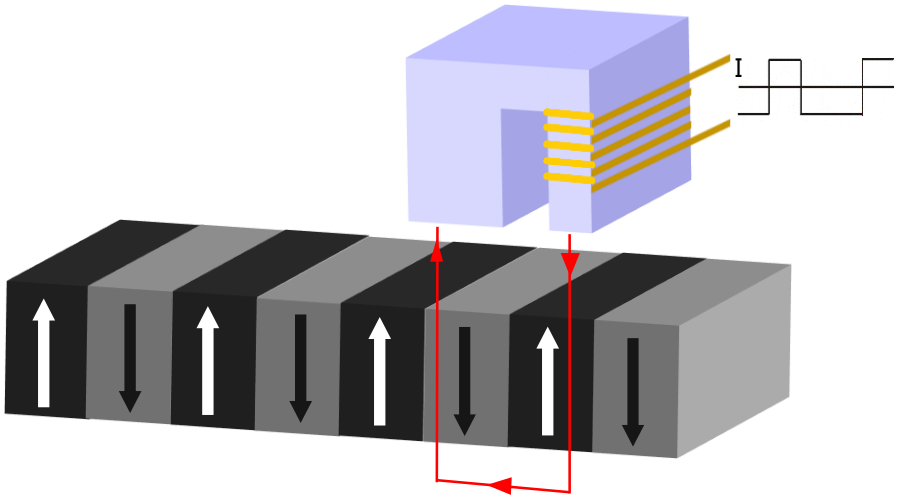
Co(Fe)TaZr-based (20 – 100 nm)
Guides the magnetic flux form the write to the collector pole of head

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)

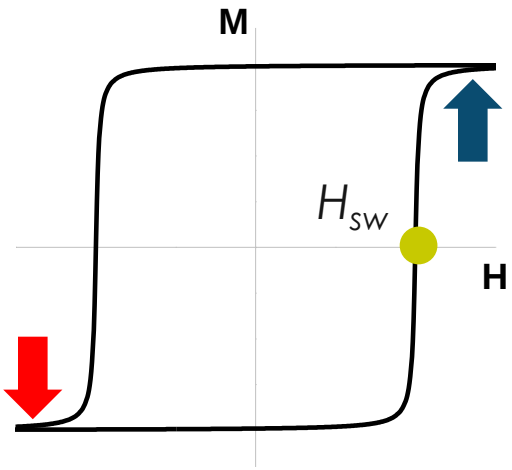
Hard Disk Drives

Write Head (PMR)



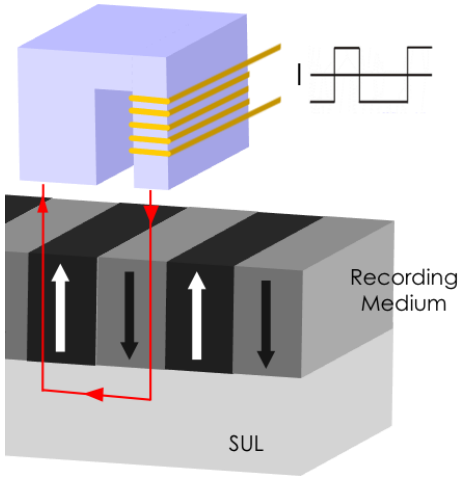
Miniaturized Electromagnet

→ It supplies a write field H_w high enough (i.e. > H_{sw}) to induce the reversal of the magnetization of a bit.



Hard Disk Drives

Write Head (PMR)

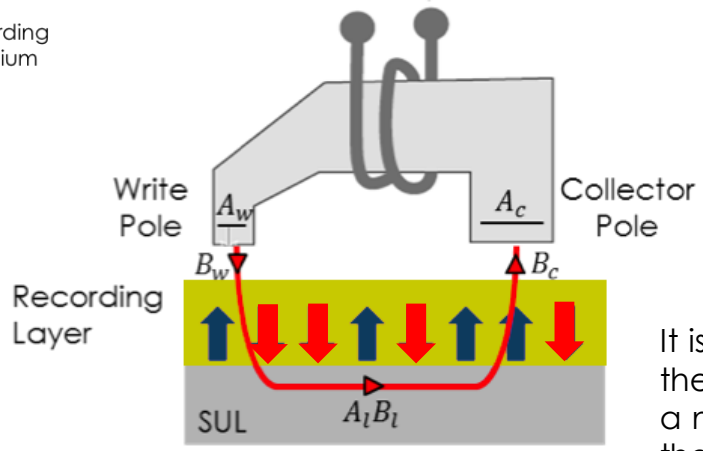


Single pole Head

+

Soft Under-Layer (SUL)

Guides the magnetic flux (Φ) from the write to the collector (or return) pole



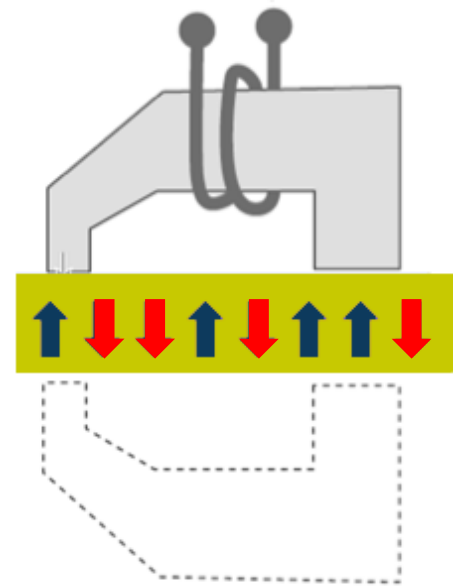
$$\Phi = A_c B_c = A_p B_p = A_l B_l$$

$$A_c > A_p \rightarrow B_c < B_p$$

B_c is not enough to record on the media

$\equiv$

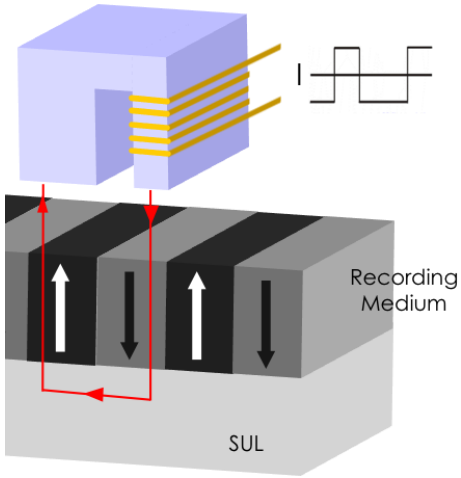
It is assumed that the SUL generate a mirror image of the main pole



"The recording media is placed in the gap of the write head"

Hard Disk Drives

Write Head (PMR)



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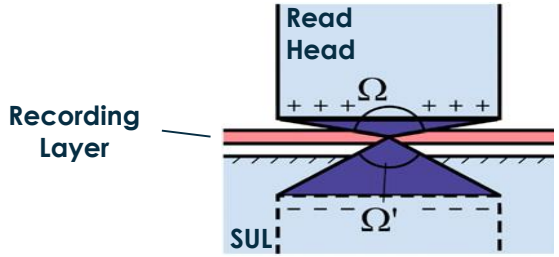
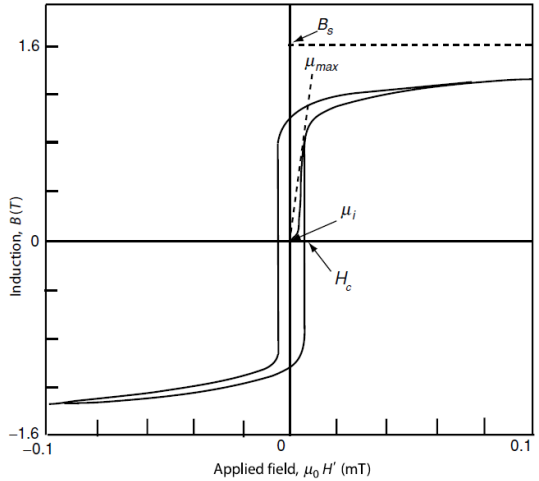


$$H_w \approx \Omega M_s / 4\pi$$



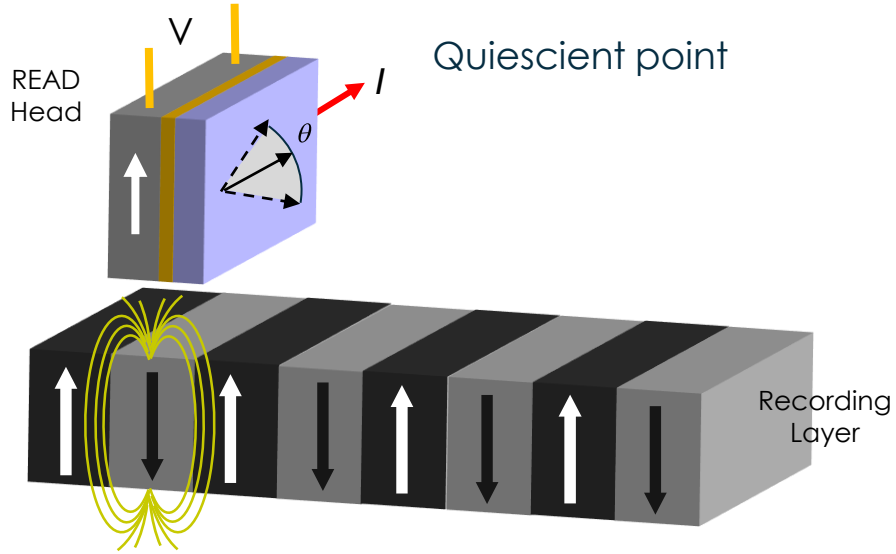
Soft Ferromagnet

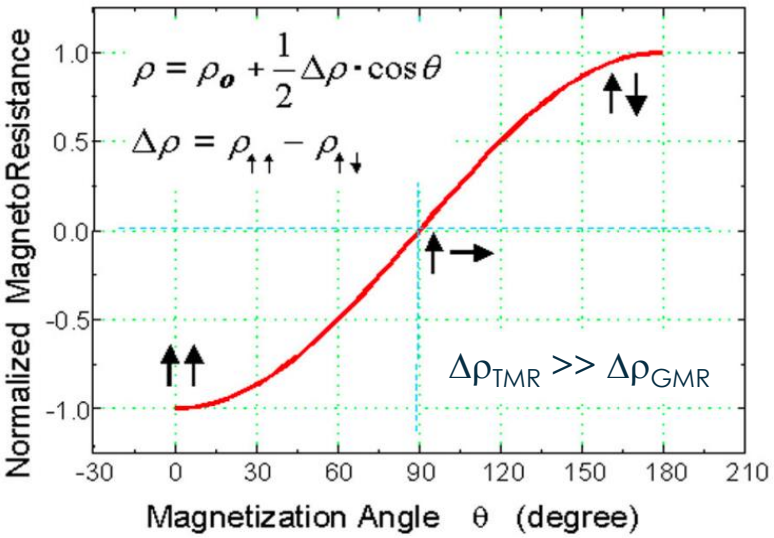
- High M_s (~ B_s in small fields)
  → High $H_w > H_{sw}$
- High μ
  → High efficiency (low I)
- Low H_c
  → Low Hysteresis Losses

FeCo
$\mu_0 M_s$ ~ 2.4 T, μ_i ~ 900, $\mu_0 H_c$ ~ 0.05 mT

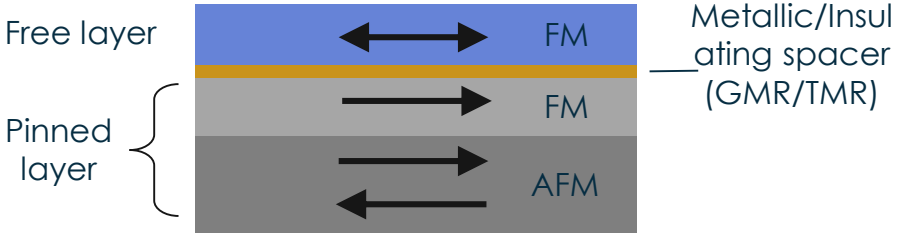
Hard Disk Drives

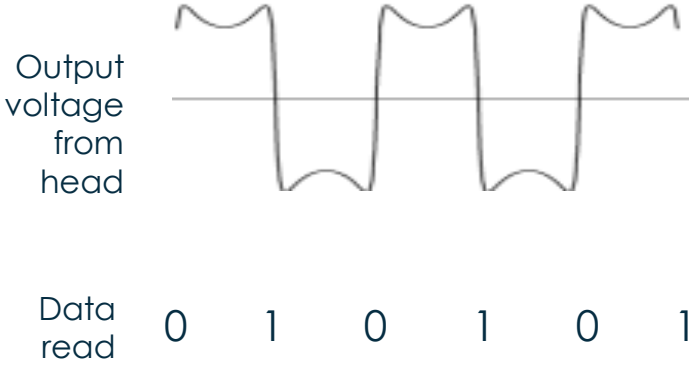
Read Head (PMR)





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





Hard Disk Drives

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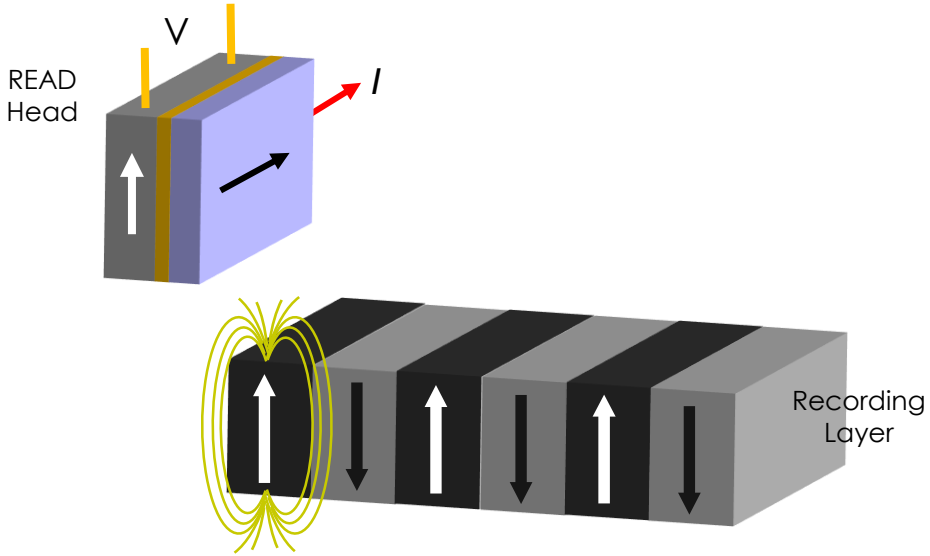

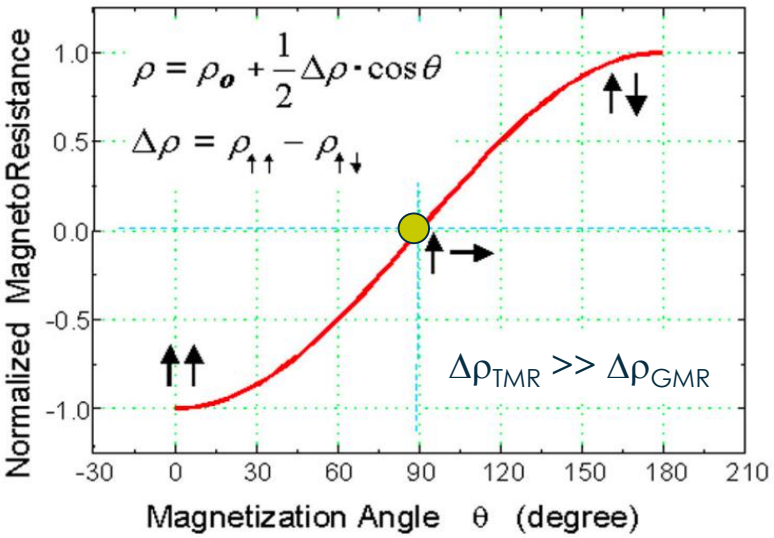

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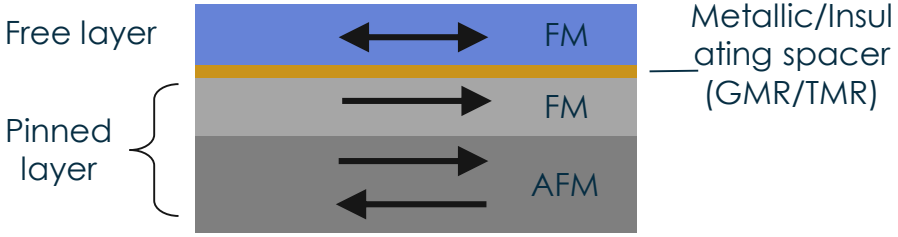

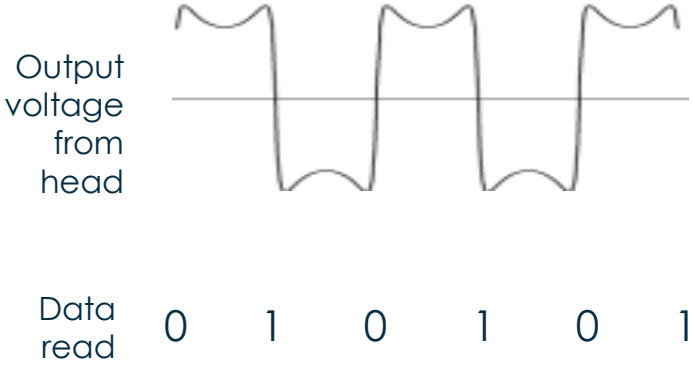

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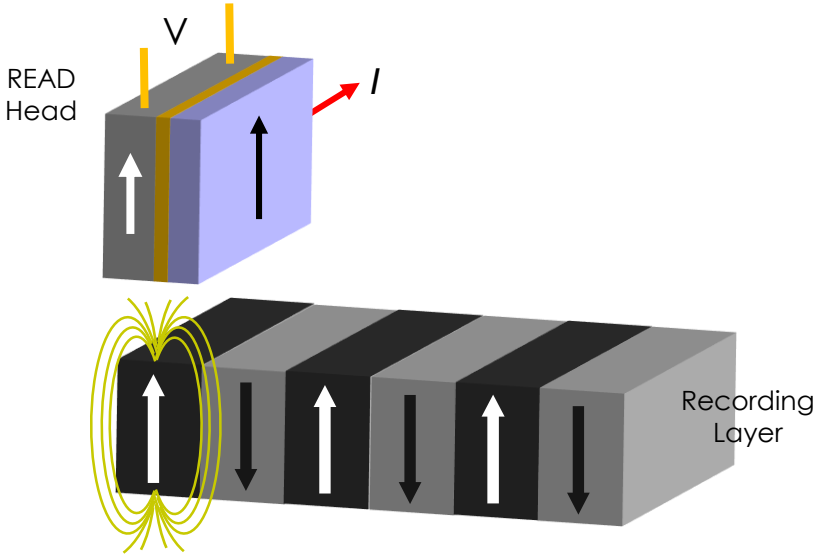

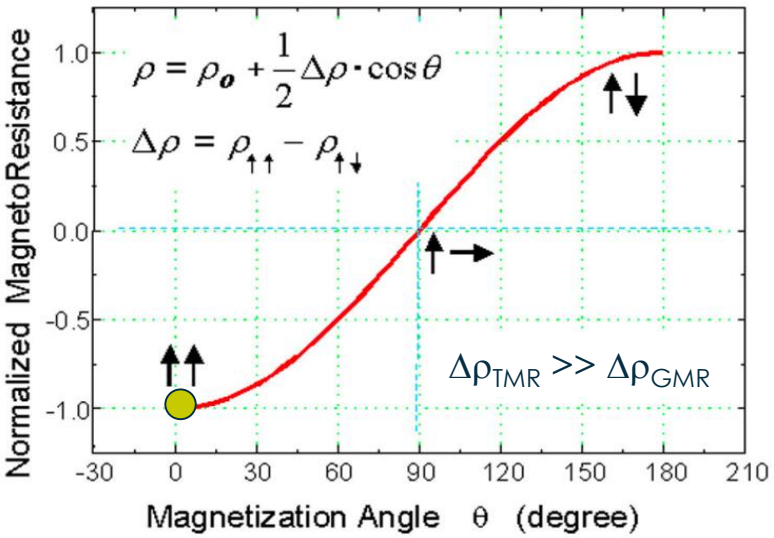

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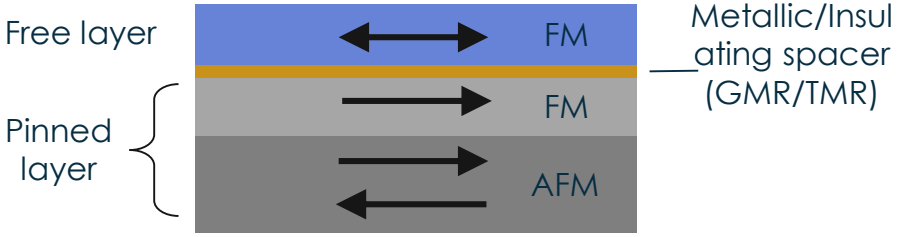

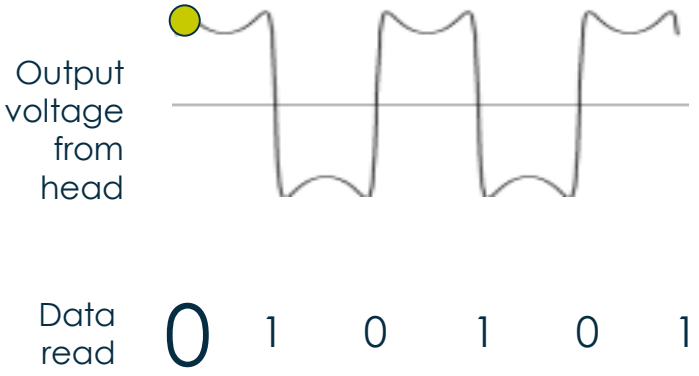

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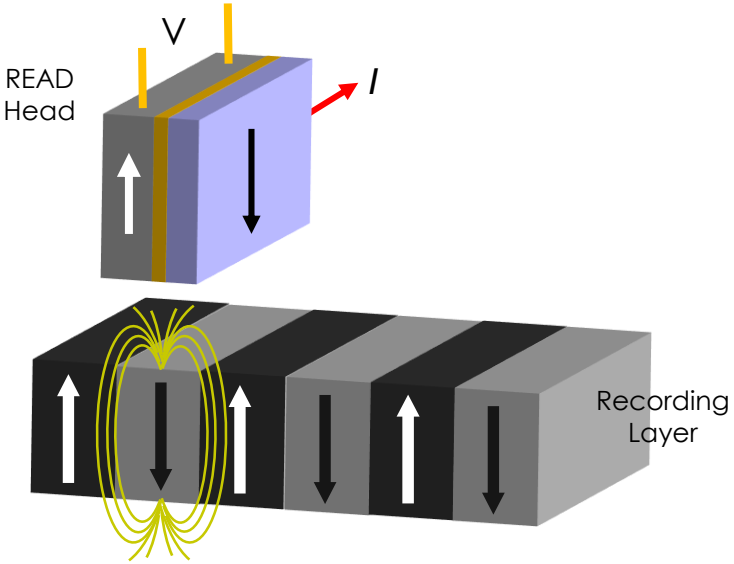
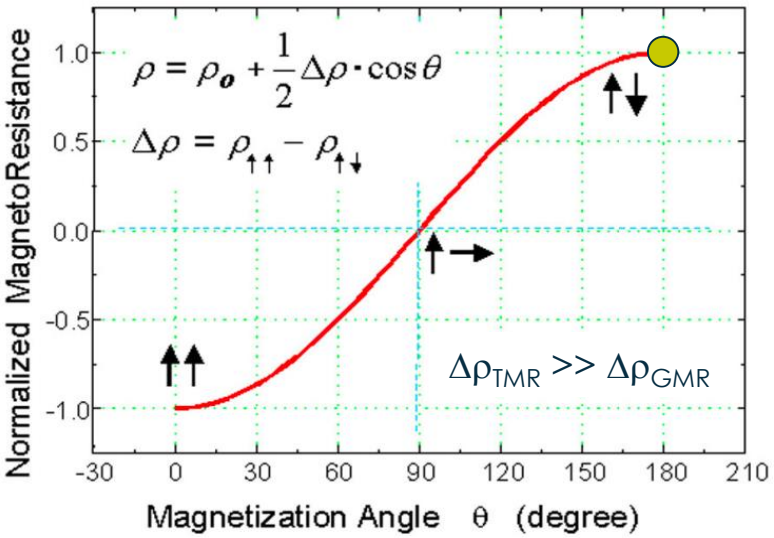
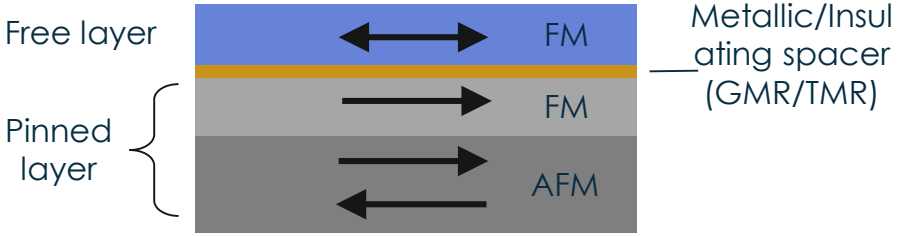
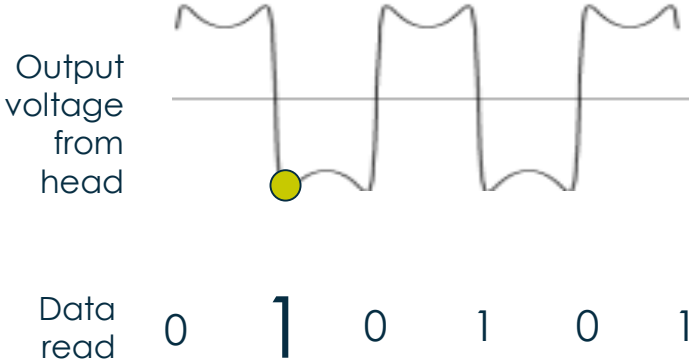
Read Head (PMR)





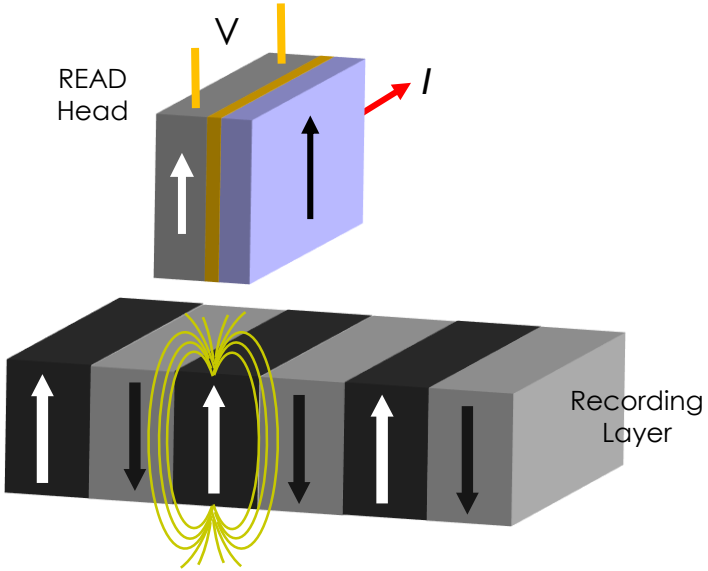
Giant/Tunneling Magneto-resistive (GMR/TMR) Sensor

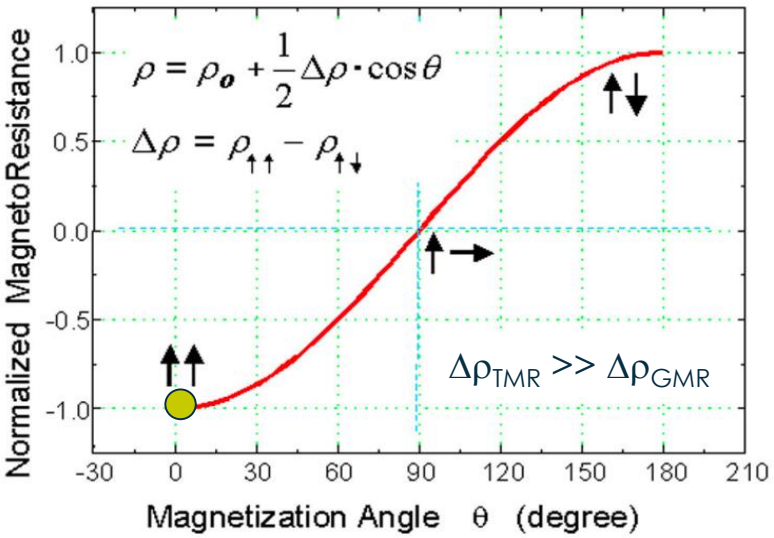




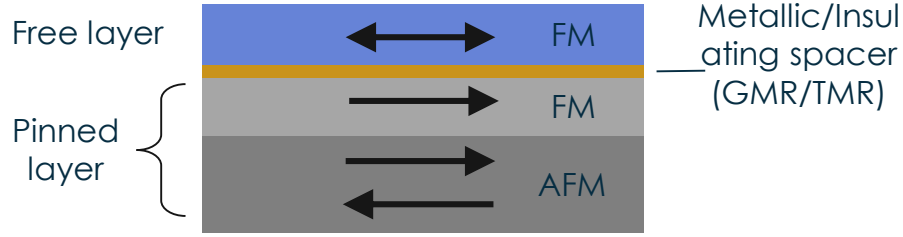
Hard Disk Drives

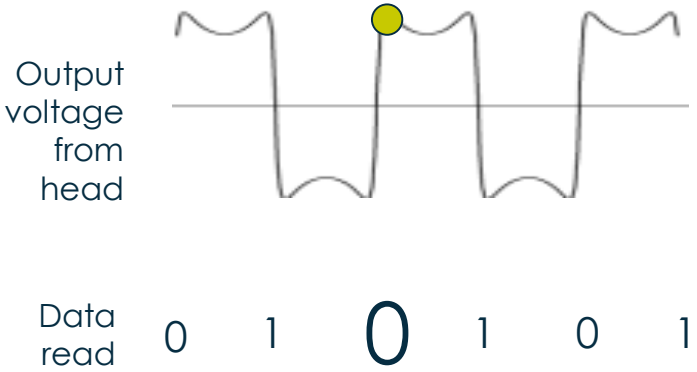
Read Head (PMR)





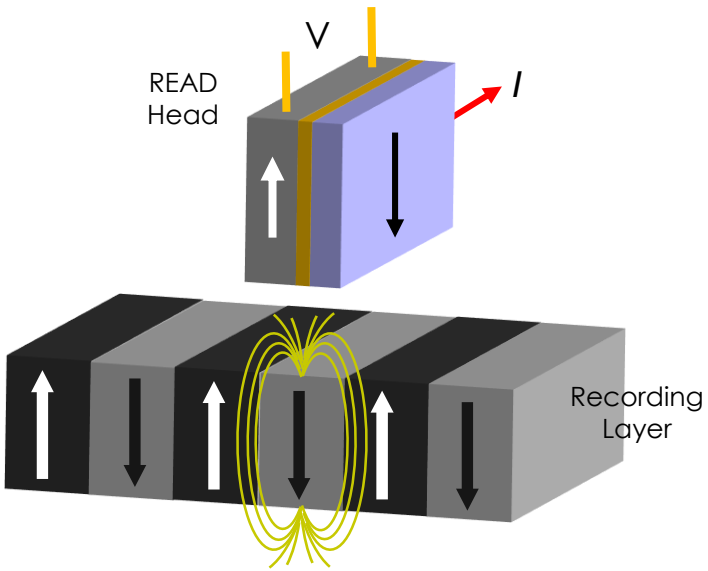
Giant/Tunneling Magneto-resistive (GMR/TMR) Sensor

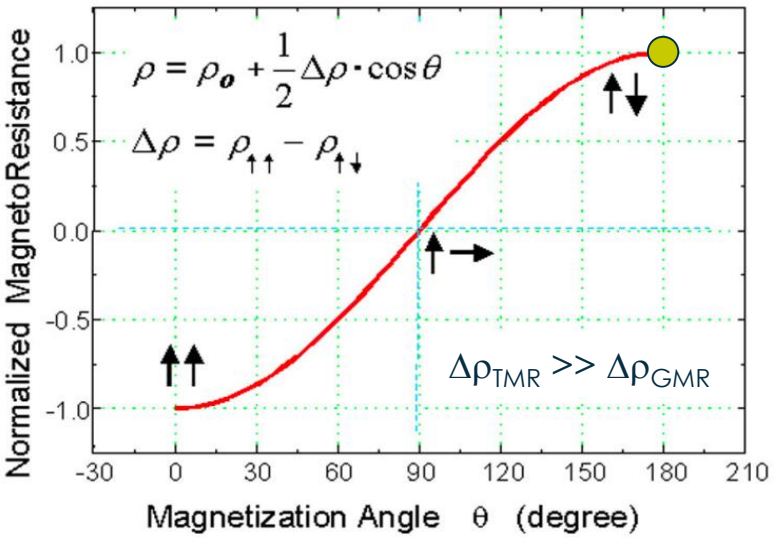




Hard Disk Drives

Read Head (PMR)





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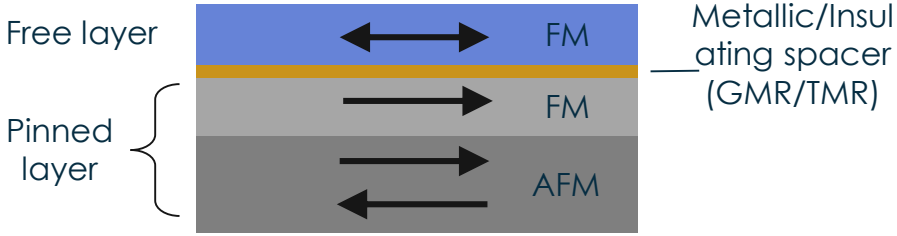
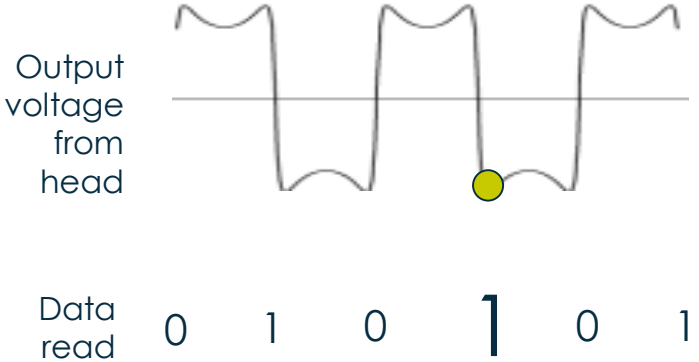
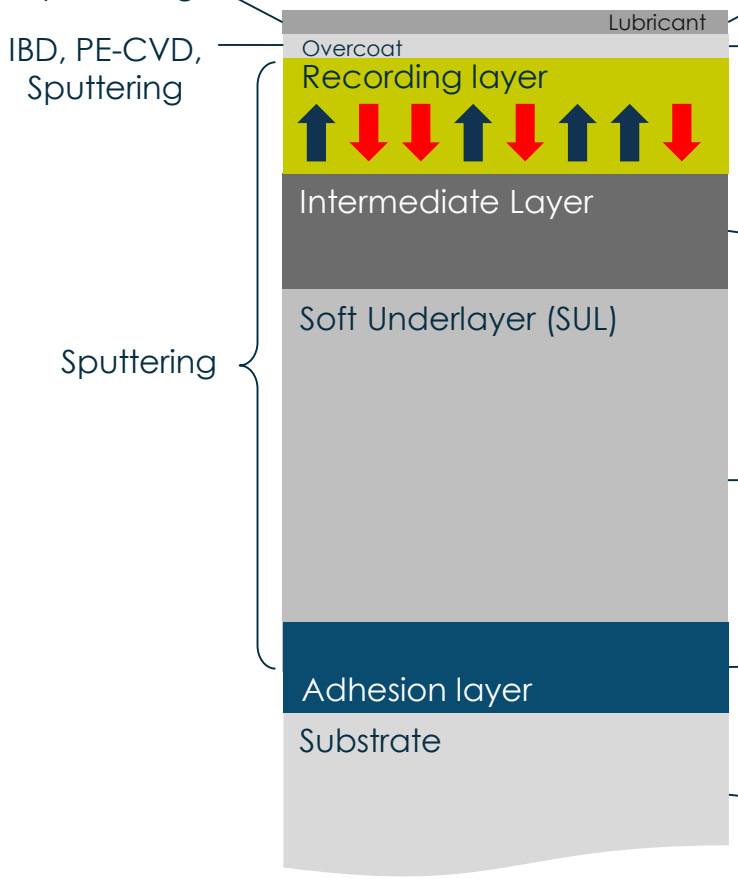




Hard Disk Drives

Recording Medium (PMR)



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

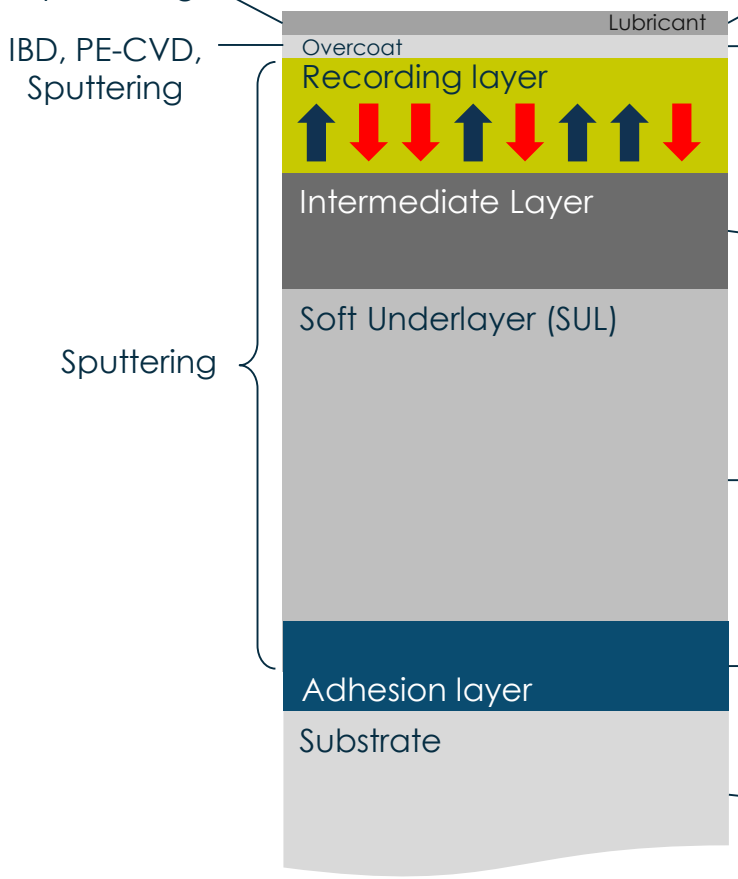
Co(Fe)TaZr-based (20 - 100 nm)
Guides the magnetic flux form the write to the collector pole of the head

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)

Hard Disk Drives

Recording Medium (PMR) – Recording Layer



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Ni-(X,Y)/Ru or Ru-(X,Y)/Ru (X, Y = Cr, Mn, W) (~ 15 nm)
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Co(Fe)TaZr-based (20 - 100 nm)
Guides the magnetic flux form the write to the collector pole of the head

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- Improves corrosion robustness of the substrate

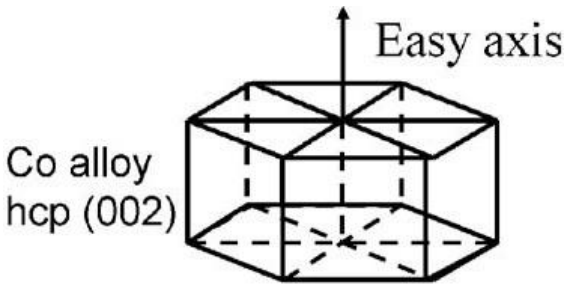
AlMg (Server & Desktop), Glass (Laptop)
Performs the role of support (hard, stiff, inert, smooth)

Hard Disk Drives

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

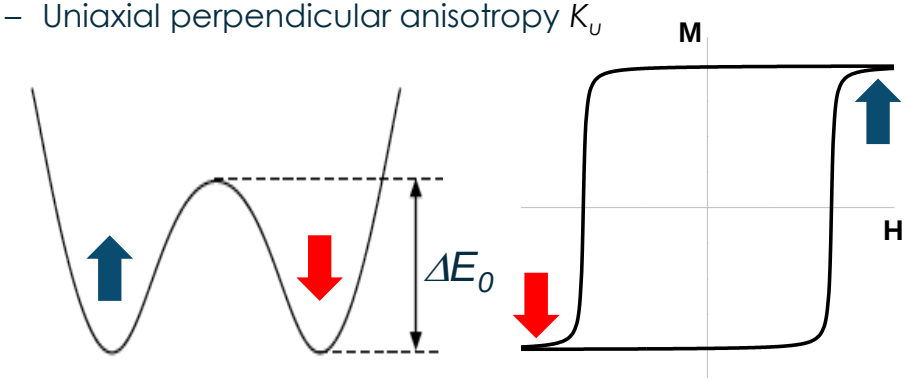
$CoCrPt@SiO_2$

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

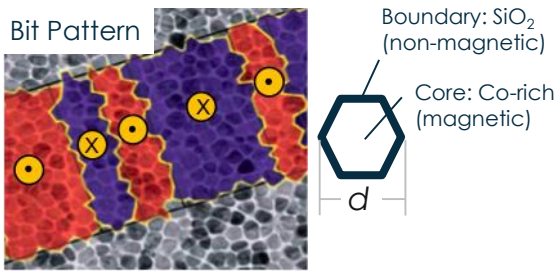


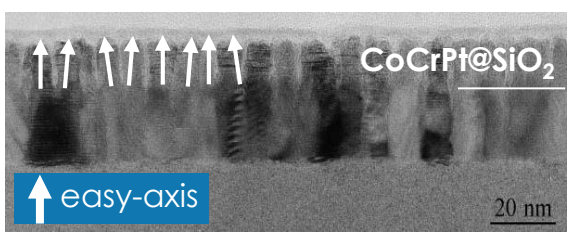
Stoner-Wolfarth like system

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

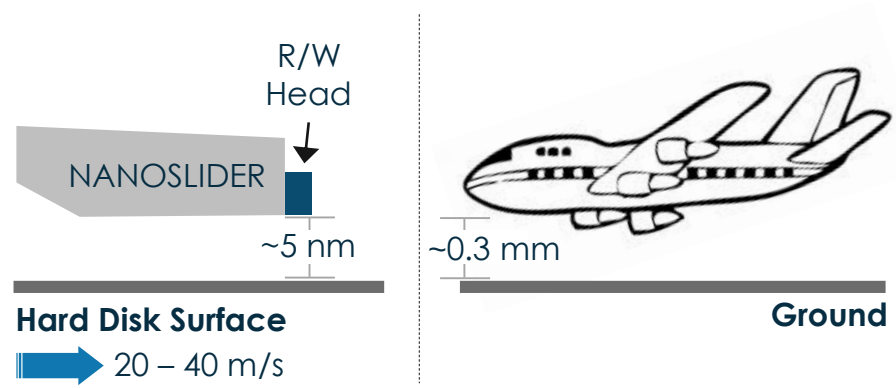


Granular Microstructure (*d* ~ 10 nm)





Smooth surface (Ra roughness ~1 nm)



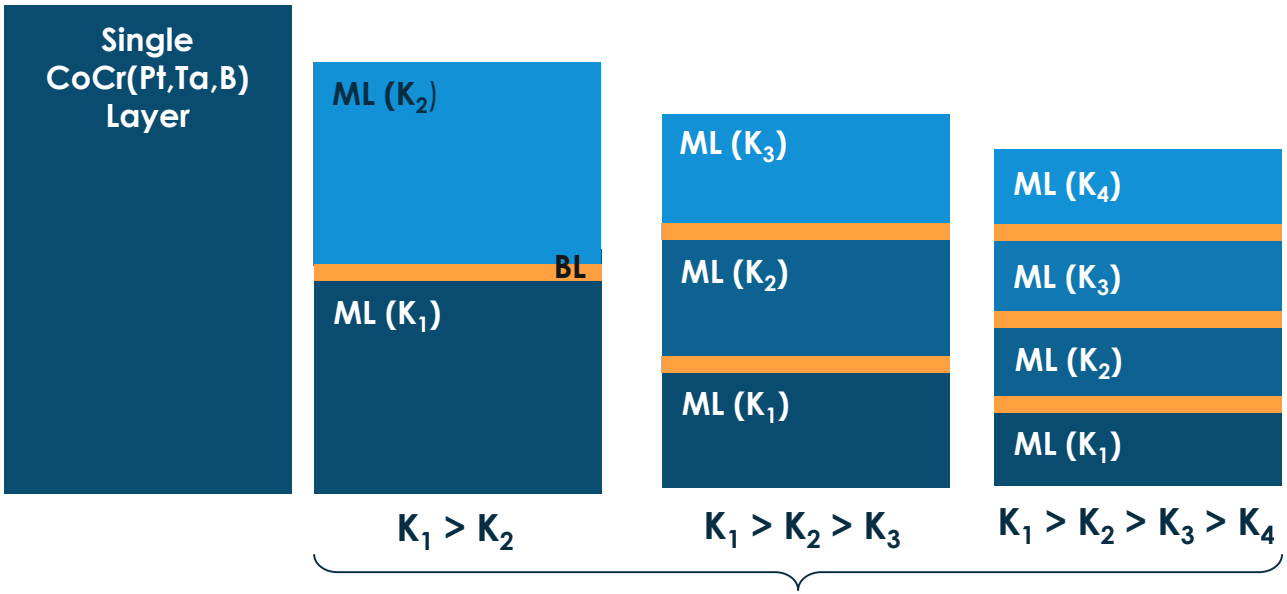
Hard Disk Drives

Evolution of Perpendicular Magnetic Recording Media

1st (2005)
AD ~ **100 Gb/in²**

Generation

7st (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

Hard Disk Drives

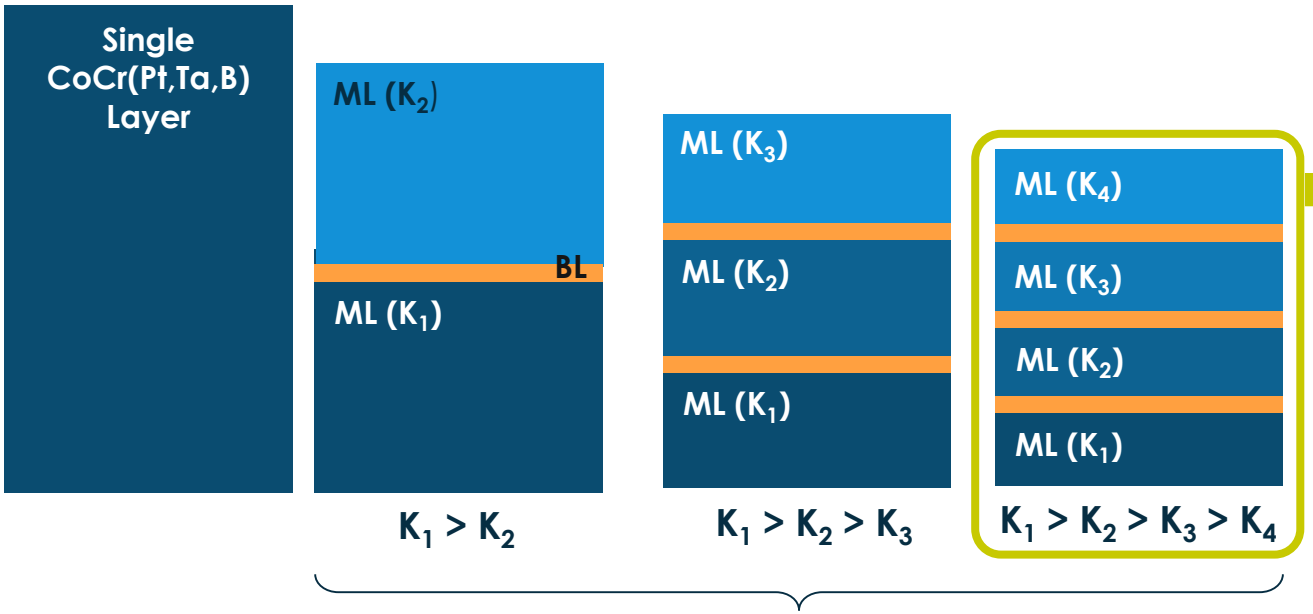
Evolution of Perpendicular Magnetic Recording Media

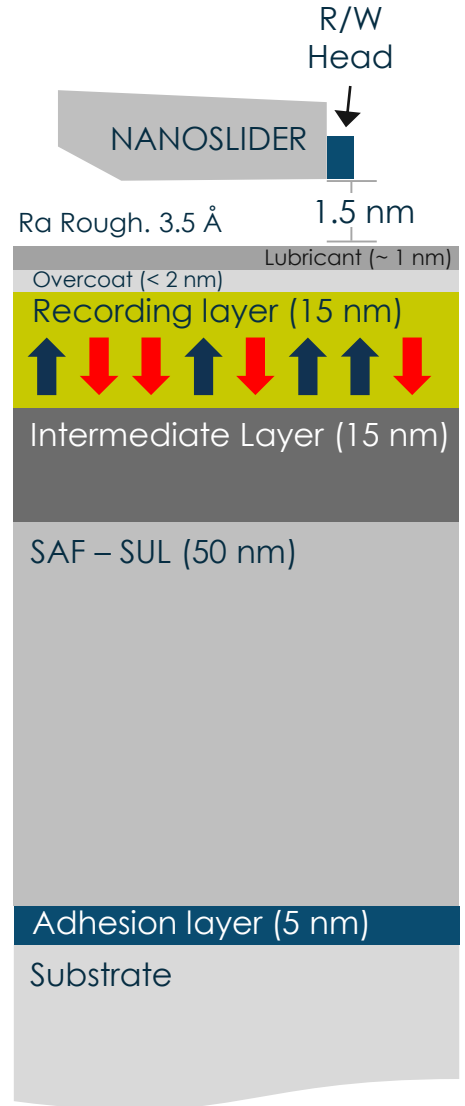
1st (2005)
AD ~ **100 Gb/in²**

Generation

7st (2013)
AD ~ **700 Gb/in²**

2015
AD ~ **950 Gb/in²**





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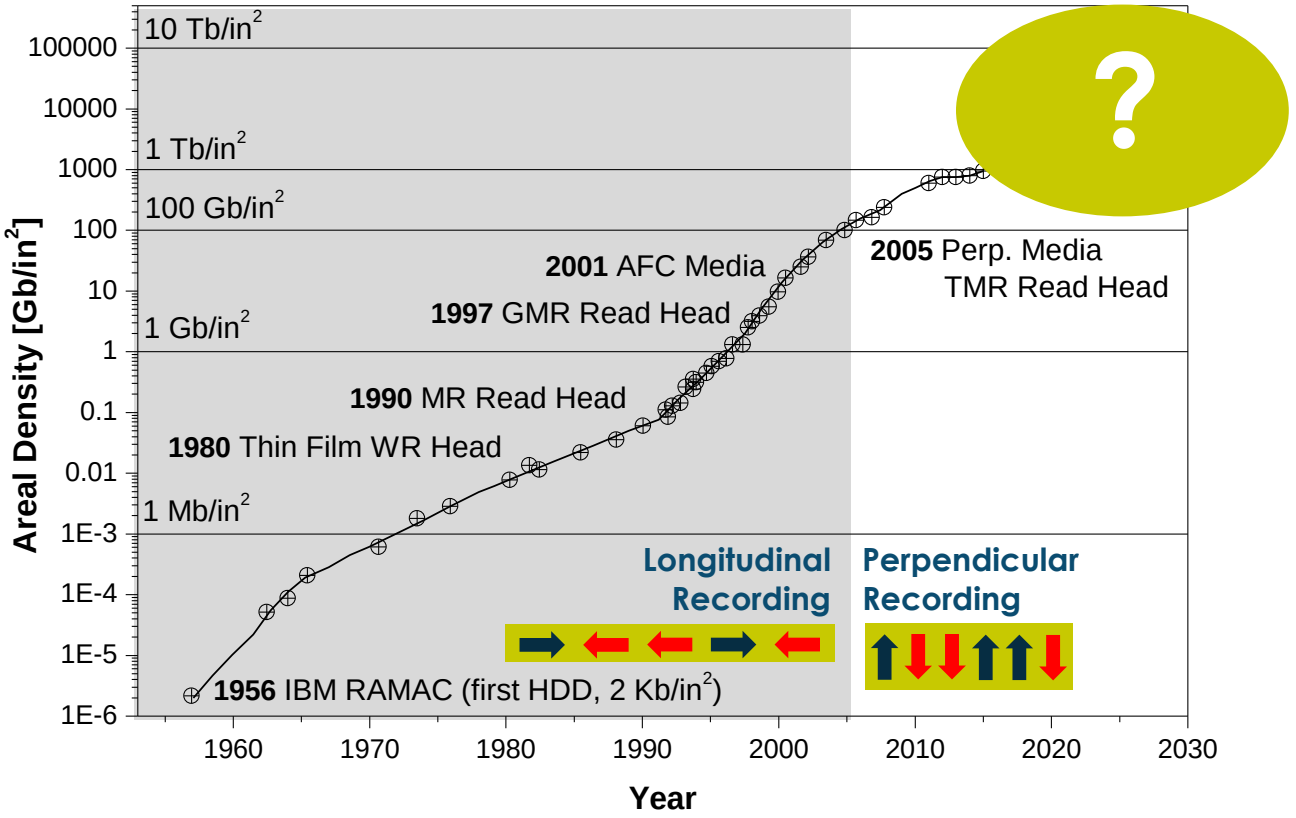
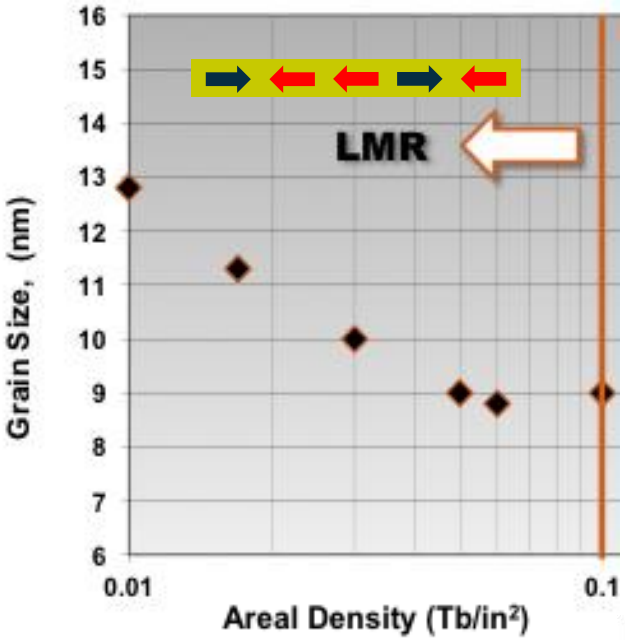
Hard Disk Drives

Beyond 1 Tbit/in^2



Hard Disk Drives

Beyond 1 Tbit/in^2 – Recording Trilemma



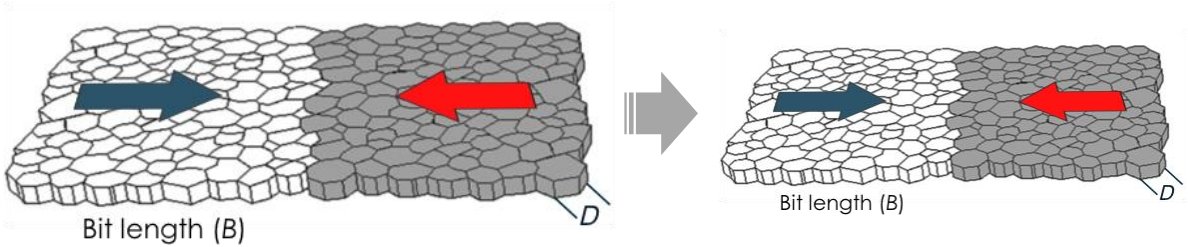
Longitudinal Magnetic Recording (LMR) Media

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

Number of grains per bit

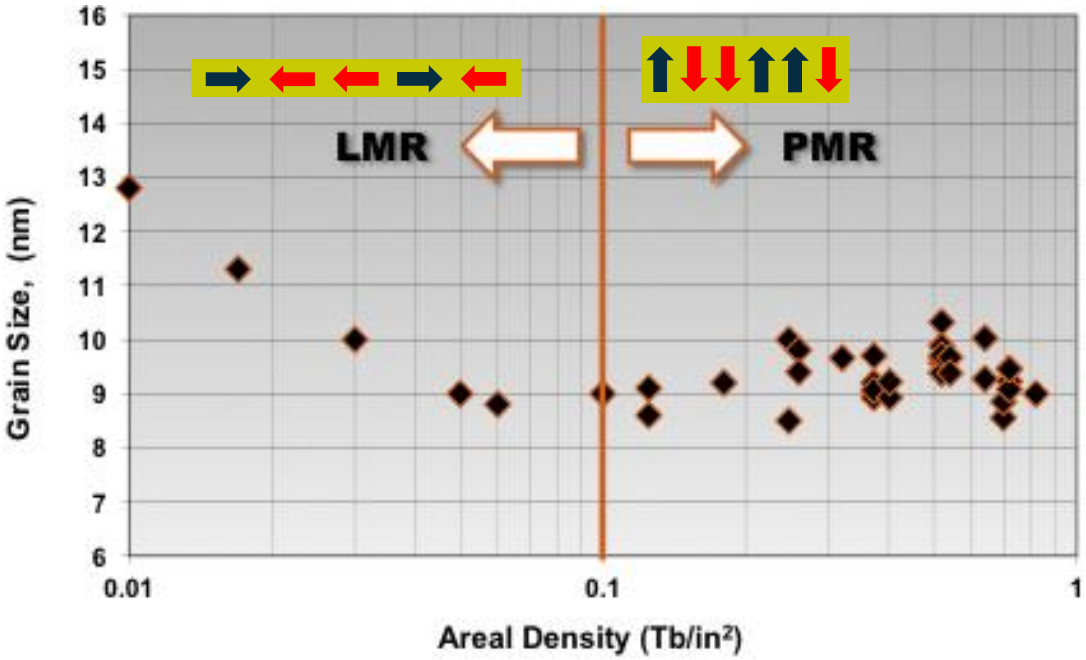
$$SNR \propto Log_{10}(N)$$

Higher areal density require SMALLER GRAINS (D)



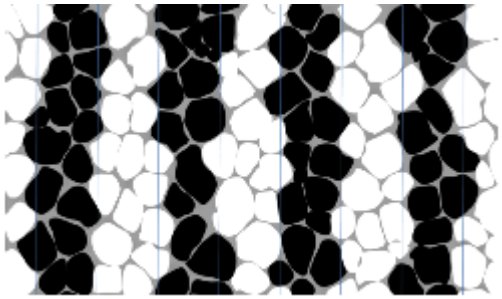
Hard Disk Drives

Beyond 1 Tbit/in^2 – Recording Trilemma



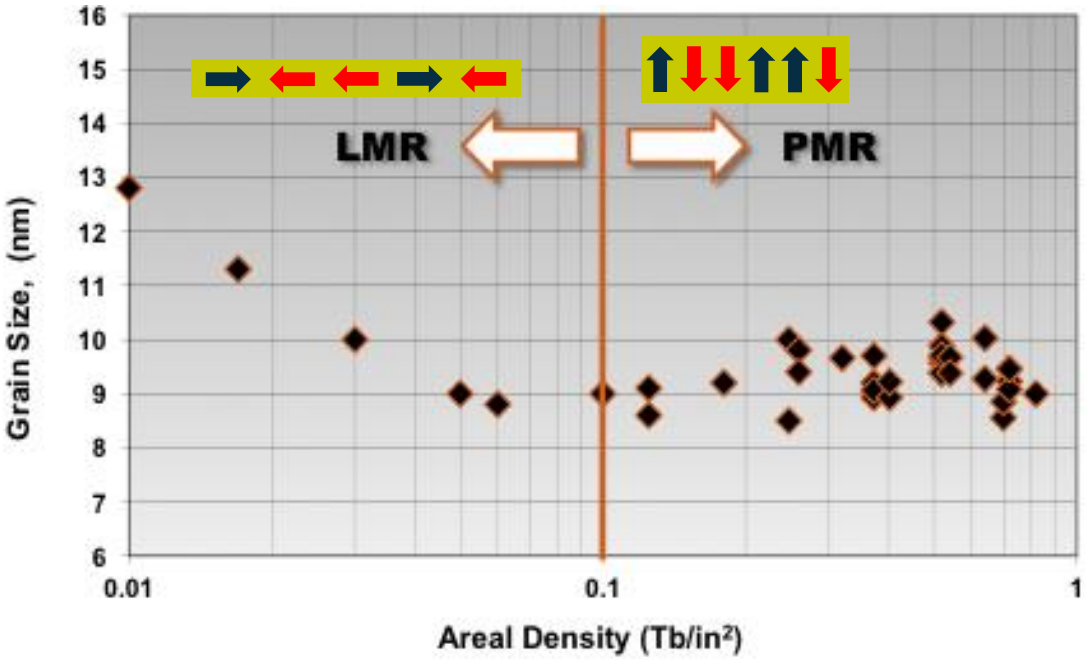
Perpendicular Magnetic Recording (PMR) Media

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.



Hard Disk Drives

Beyond 1 Tbit/in^2 – Recording Trilemma



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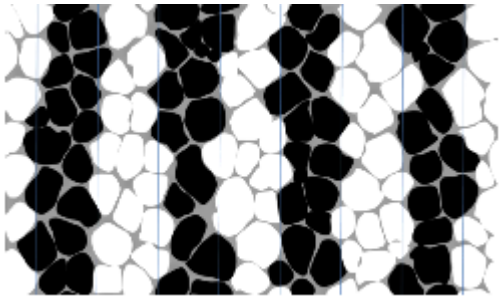
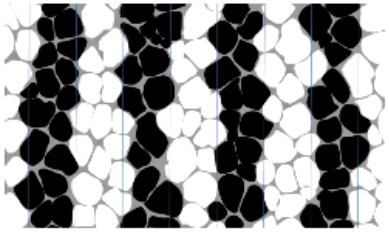


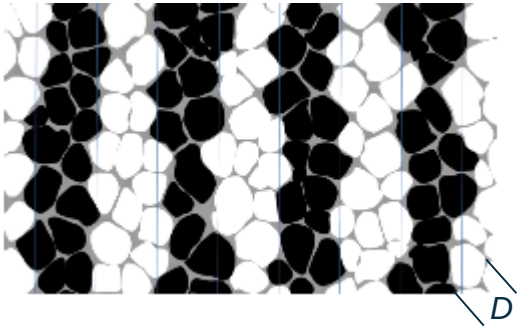
To go in the Tbit/in^2 regime the grain size must be reduced to maintain an adequate SNR.

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



Hard Disk Drives

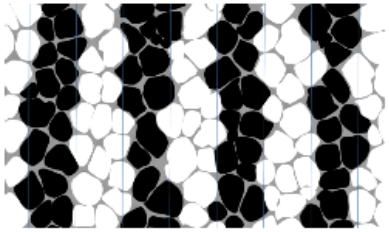
Beyond 1 Tbit/in^2 – Recording Trilemma

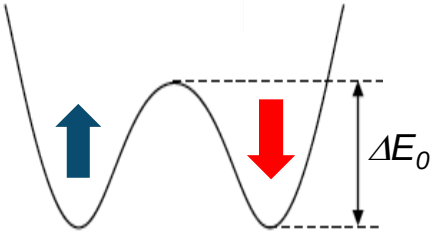


Number of grains per bit

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

Higher areal density require SMALLER GRAINS (D)





Uniaxial Anisotropy Constant

Grain Volume

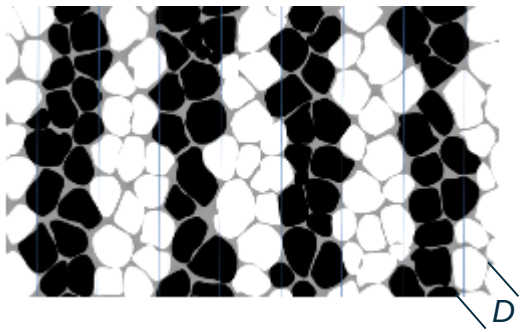
$$\beta = \frac{\Delta E_0}{k_B T_{300}} \overset{\text{Stoner-Wolfarth system}}{=} \frac{K_u V}{k_B T_{300}} > 60$$

10 Years

STABILITY FACTOR

Hard Disk Drives

Beyond 1 Tbit/in^2 – Recording Trilemma



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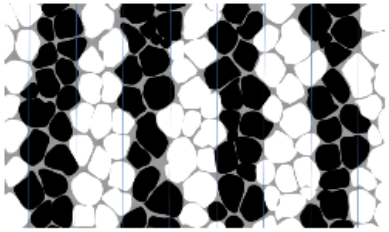

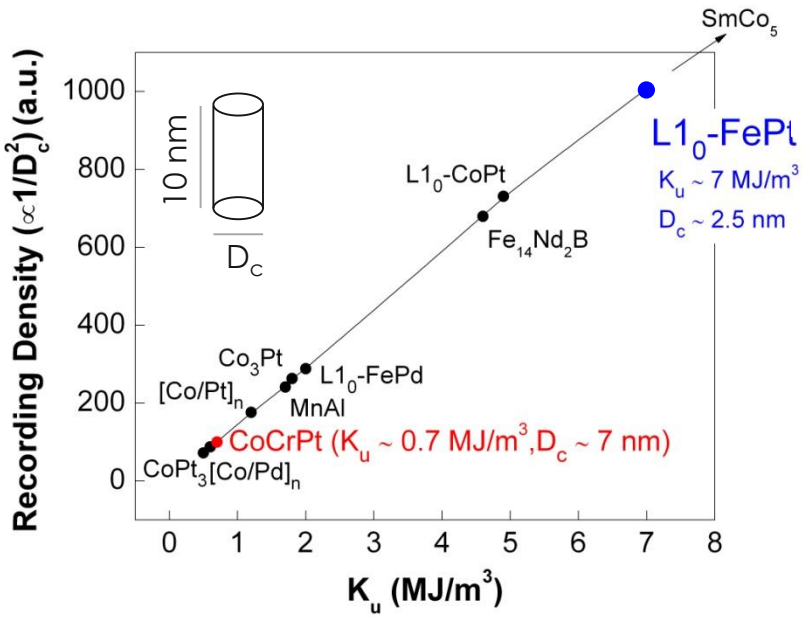

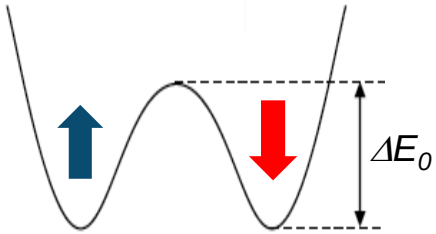

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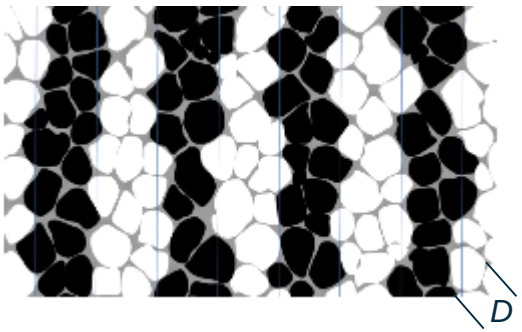
10 Years

STABILITY FACTOR

D. Weller et al., *Phys. Status Solidi A* 210 1245 **2013**

Hard Disk Drives

Beyond 1 Tbit/in^2 – Recording Trilemma



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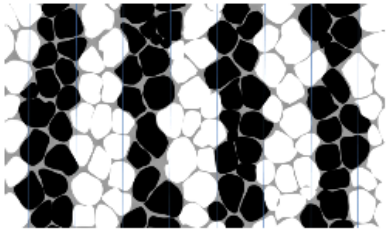
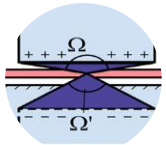
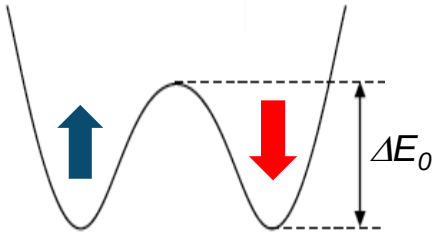




Switching Field

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

Writing Field



Recording Medium Material	K_u (10^6 J/m^3)	Write Head Material	$\mu_0 M_s$ (T)
$SmCo_5$	~ 20	$Co_{35}Fe_{65}$	2.4
$L1_0$ FePt	**~ 7 → $\mu_0 H_{sw}$ ~ 5-6 T**		
$L1_0$ CoPt	~ 5		
Co/Pt(Pd)	~1		
CoCrPt	~0.7		

Uniaxial Anisotropy Constant

Grain Volume

Stoner-Wolfarth system

$$\beta = \frac{\Delta E_0}{k_B T_{300}} = \frac{K_u V}{k_B T_{300}} > 60$$

10 Years

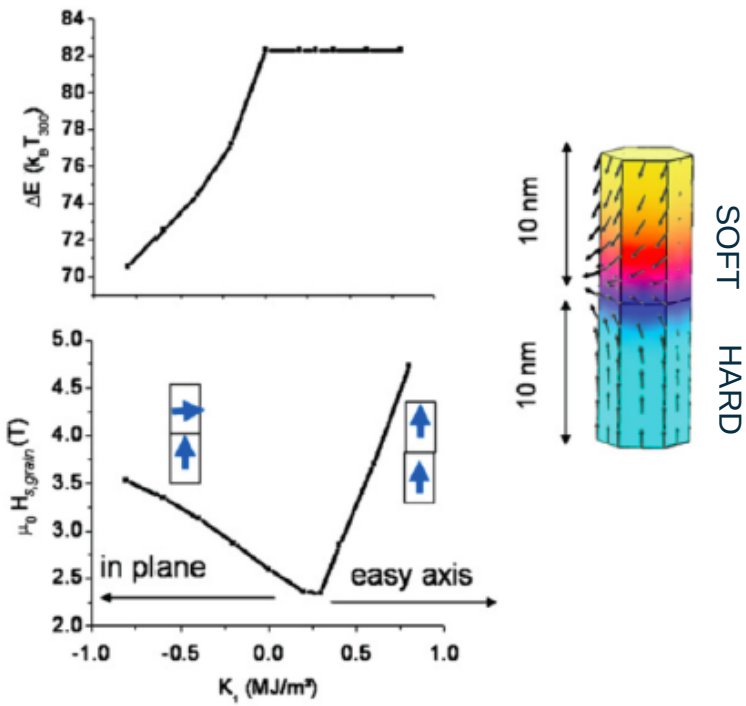
STABILITY FACTOR

HARD DISK DRIVES

FUTURE TECHNOLOGIES OPTIONS

EXCHANGE COUPLED COMPOSITE MEDIA

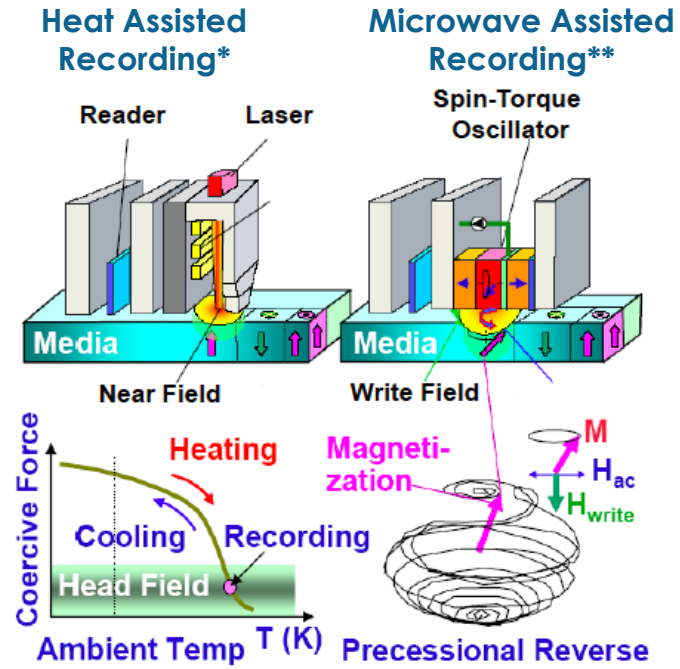
In soft/hard exchange coupled composites the domain wall forming in the soft phase supports the reversal of the hard phase leading to a reduction of H_{sw} (improved write-ability) without affecting ΔE_0 (i.e. thermal stability).



- 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**

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.

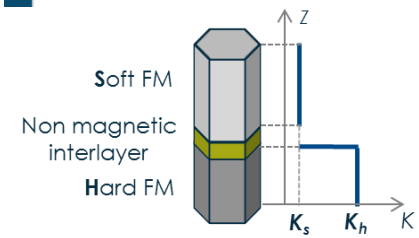


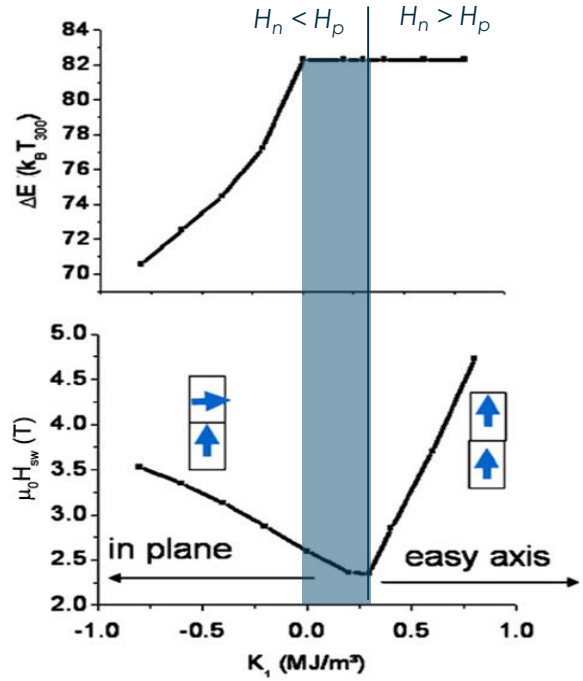
*D. Weller et al., *IEEE Trans. Magn.* 50 1 **2014**
J.G. Zhu *et al.*, *IEEE Trans. Magn.* 44 125 **2008**

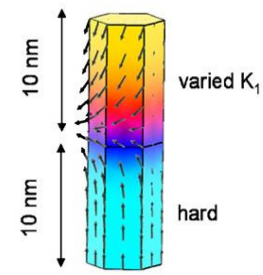
S. Okamoto et al., J. Phys. D: Appl. Phys. 48 353001 **2015
M. Kryder *et al.*, Proc. *IEEE* 96 1810 **2008**
E. Gage *et al.*, Ch 4 in "Ultra-High-Density Magnetic Recording", (G. Varvaro and F. Casoli Eds.,) Pan Stanford Publishing **2016**

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 regior
Reversible Reversal

$$H_n = 2K_s / J_S + 2A_s p^2 / 4t_s^2 M_S$$

D – E Pinning/propagation of the domain wall
Irreversible Reversal

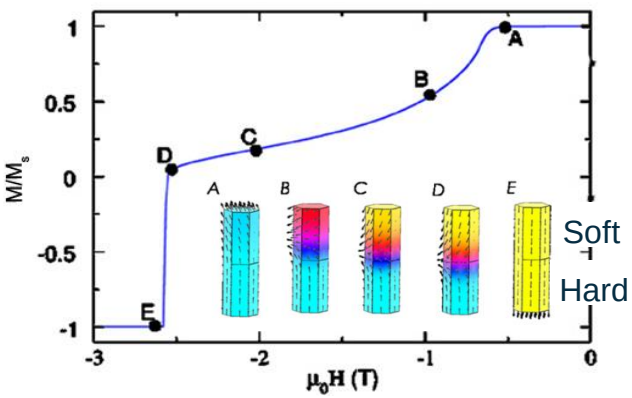
$$H_p = \frac{2(K_h - K_s)}{\left(\sqrt{J_{s,h}} + \sqrt{J_{s,s}}\right)^2} \left(1 - \frac{K_s A_s}{K_h A_h}\right)$$

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

If $H_p > H_n$

$$H_{sw} = H_p \sim (K_h - K_s)/2J_s$$

$$\Delta E_0 \propto \sqrt{A_h K_h}$$



GAIN FACTOR

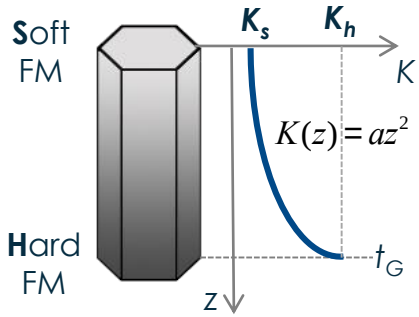
$$\xi = \frac{2\Delta E_0}{M_S H_{sw} V}$$

$x = 1$ Single S-W Hard Phase

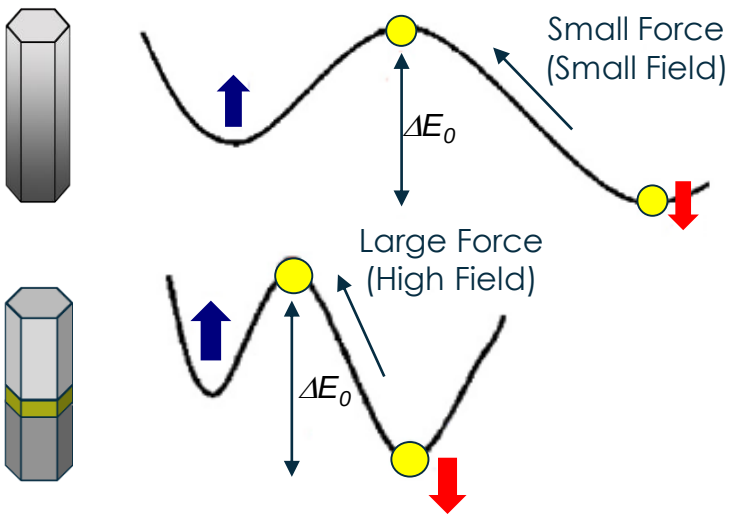
$1 \le \xi \le 2$ Exchange-Spring System

Exchange Coupled Composite Media

GRADED Systems



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 (ΔE_0).*



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

$$H_n = 2K_s / J_S + 2A_s p^2 / 4t_s^2 M_S$$

C – E Pinning/propagation of the domain wall

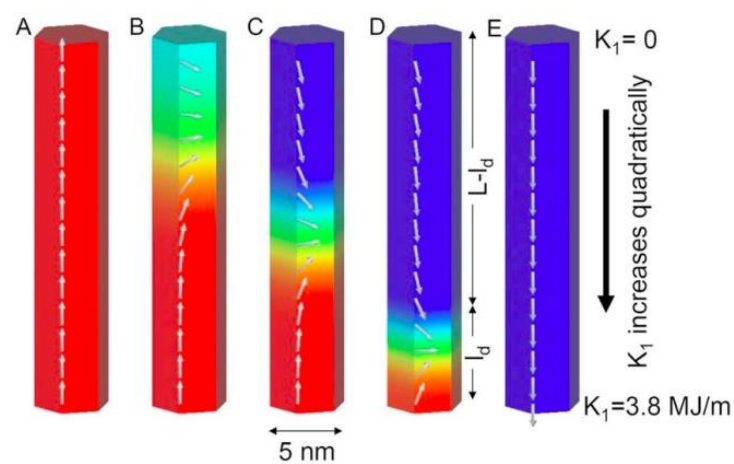
$$H_p = \left[(1/2J_s)\partial E(z)/\partial z\right]_{\max} = \left[(1/2J_s)\partial\sqrt{AK(z)}/\partial z\right]_{\max}$$

$$K(z) = az^2 = z^2 K_h / t_G^2 \Rightarrow H_p = (2/J_s)\sqrt{AK_h/t_G}$$

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

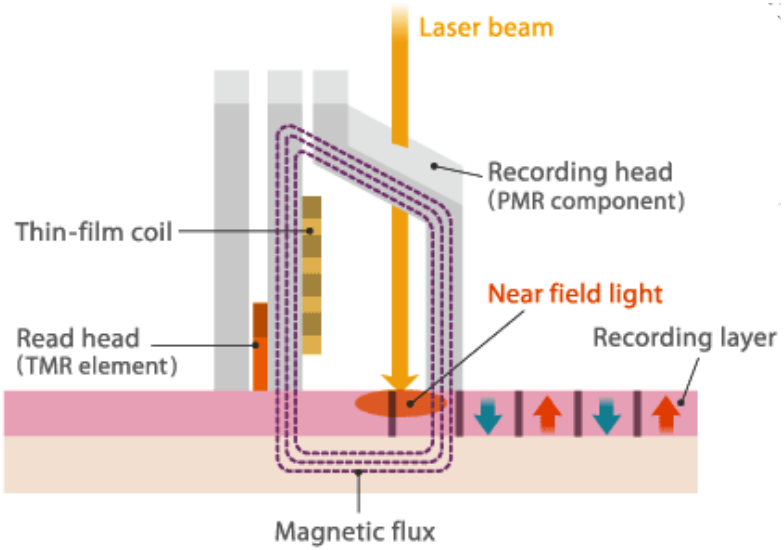
If $H_p > H_n$ $\begin{cases} H_{sw} = (2/J_s)\sqrt{AK_h/t_G} \\ \Delta E_0 = 2FJ_s H_{sw} t_G \end{cases}$

$$1 \le \xi = \frac{2\Delta E_0}{M_S H_{sw} V} \le 4$$



Energy Assisted Magnetic Recording (EAMR)

HEAT-AMR



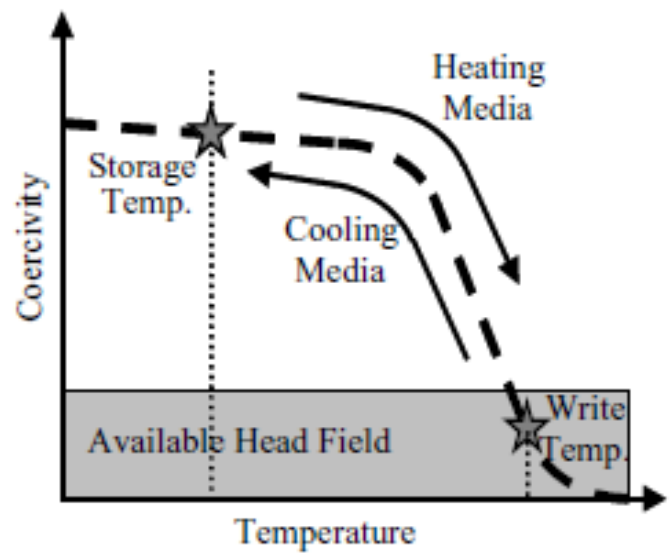
Writing process

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

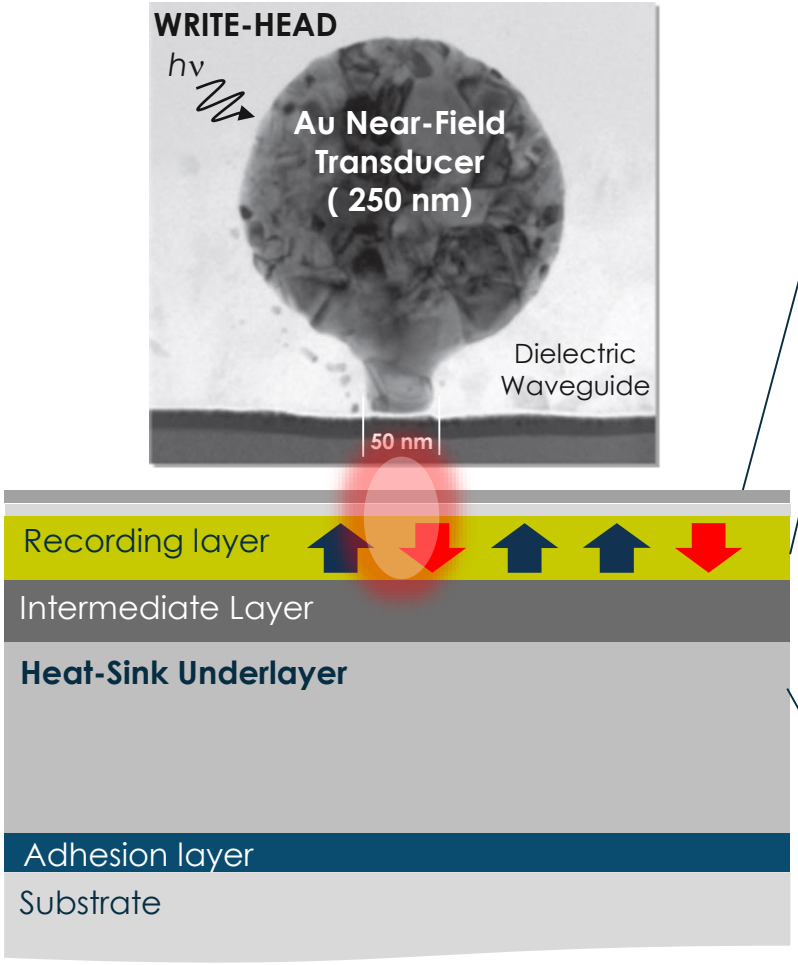
Is performed with a magneto-resistive head at room temperature



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)

HEAT-AMR

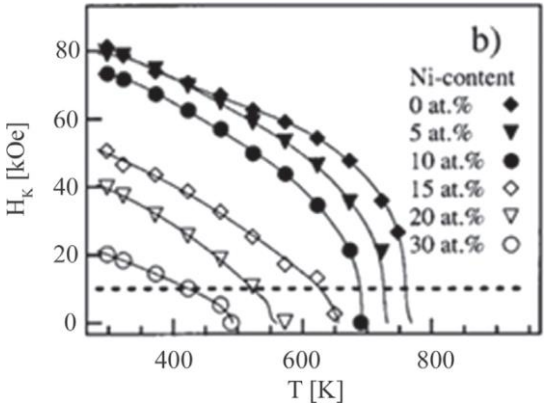


High-T Lubricant

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

$L1_0$-FePt

T_c (~ 750 K) is to 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.



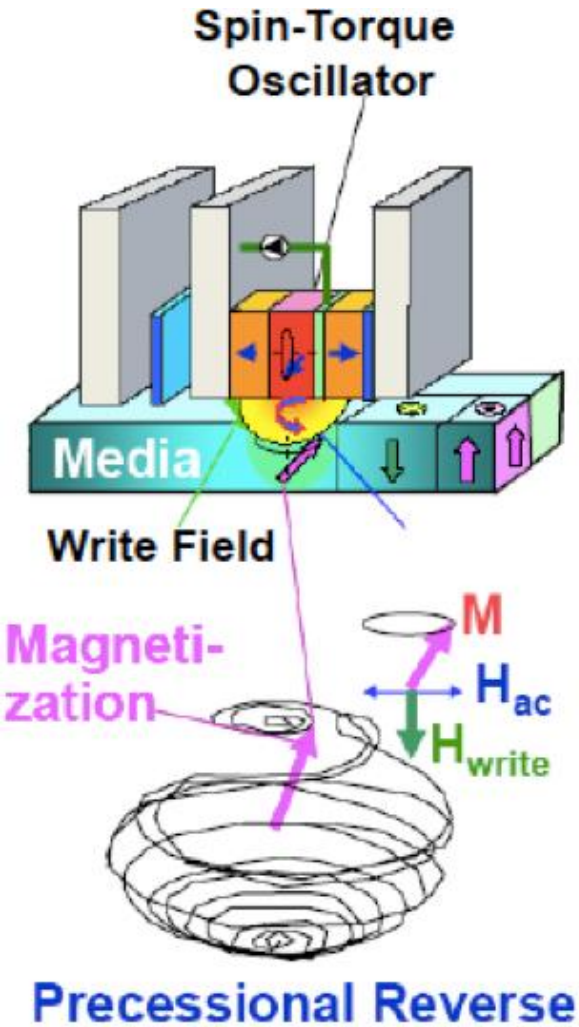
J.U. Thiele *et al.*, *J. Appl. Phys. 91 6595* **2002**

Ag, AU, Al, Cu, Cr (20 – 200 nm)

Establishes proper thermal gradients and optimizes write power requirements

Energy Assisted Magnetic Recording (EAMR)

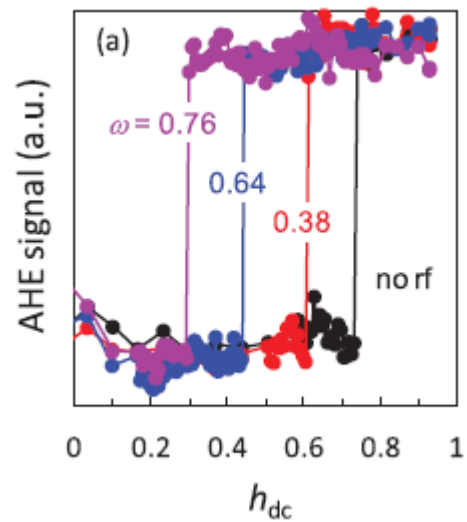
MICROWAVE-AMR



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.



Okamoto *et al.*, *J. Phys. D: Appl. Phys.* 48 353001 **2015**

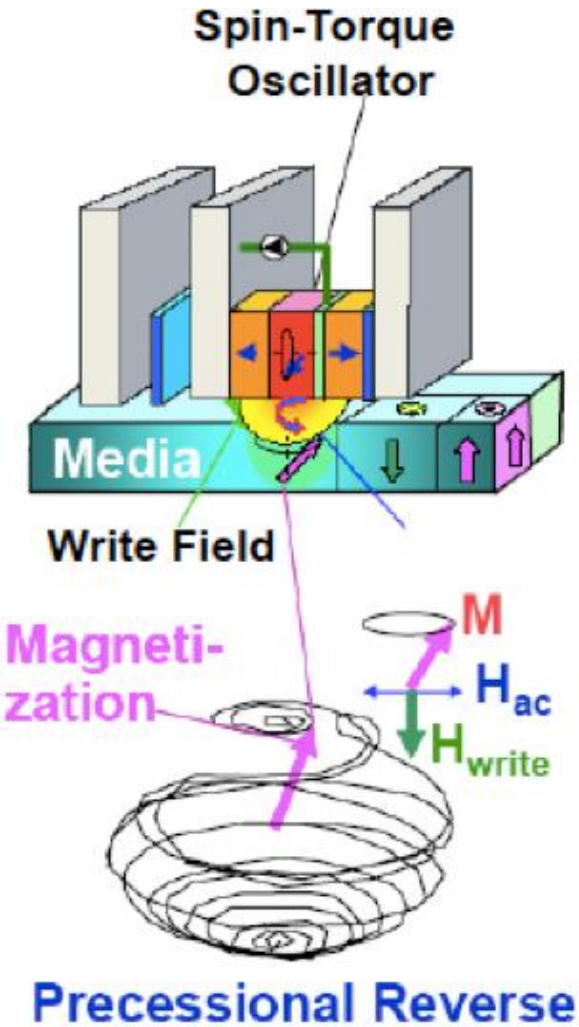
Read-out process

Is performed with a magneto-resistive head.

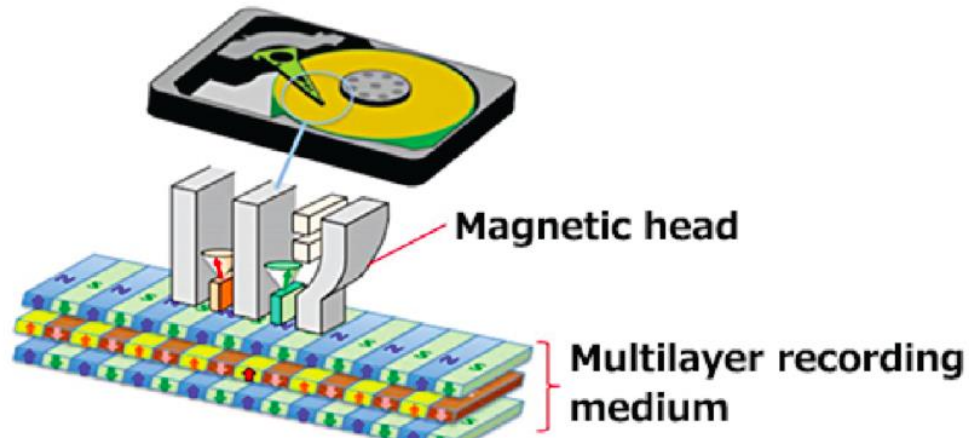
E. Gage *et al.*, Ch 4 in "Ultra-High-Density Magnetic Recording" (G. Varvaro and F. Casoli Eds.), Pan Stanford Publishing **2016**

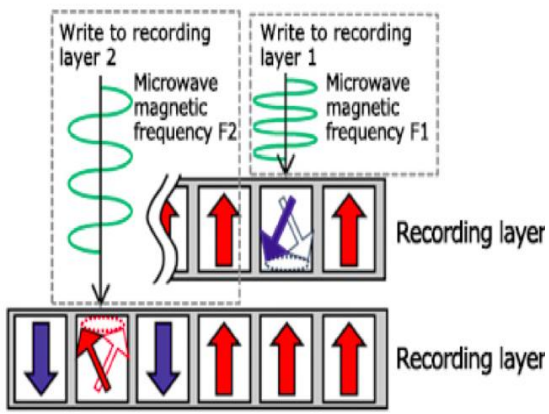
Energy Assisted Magnetic Recording (EAMR)

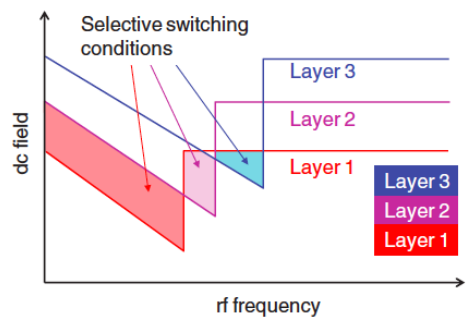
MICROWAVE-AMR



3D Magnetic Recording



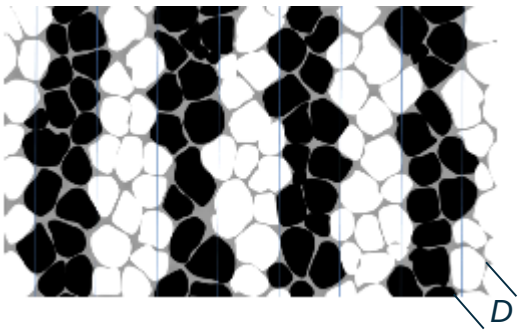




Okamoto et al., J. Phys. D: Appl. Phys. 48 353001 **2015**

Hard Disk Drives

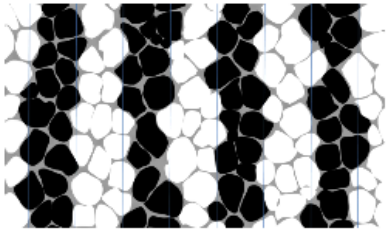
Towards 1 Tbit/in^2 and Beyond – Recording Trilemma

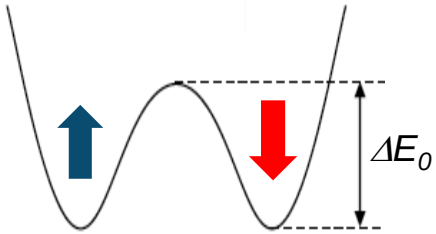


Number of grains per bit

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

Higher areal density require SMALLER GRAINS (D)





Uniaxial Anisotropy Constant

Grain Volume

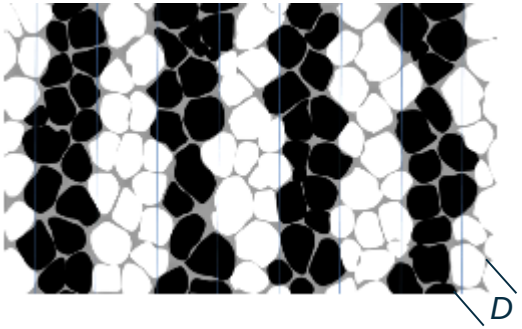
$$\beta = \frac{\Delta E_0}{k_B T_{300}} \overset{\text{Stoner-Wolfarth system}}{=} \frac{K_u V}{k_B T_{300}} > 60$$

10 Years

STABILITY FACTOR

Hard Disk Drives

Towards 1 Tbit/in^2 and Beyond – Recording Trilemma



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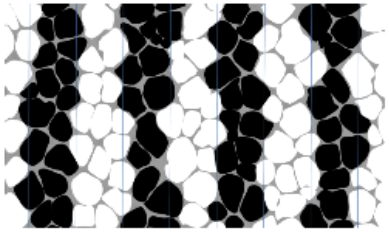

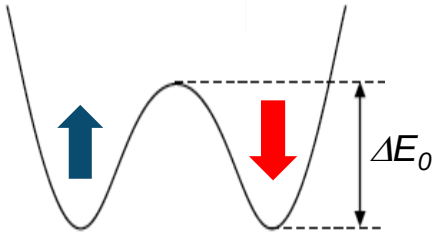

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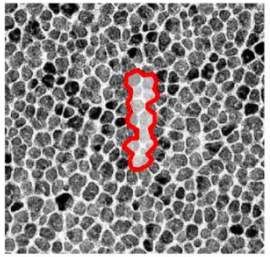
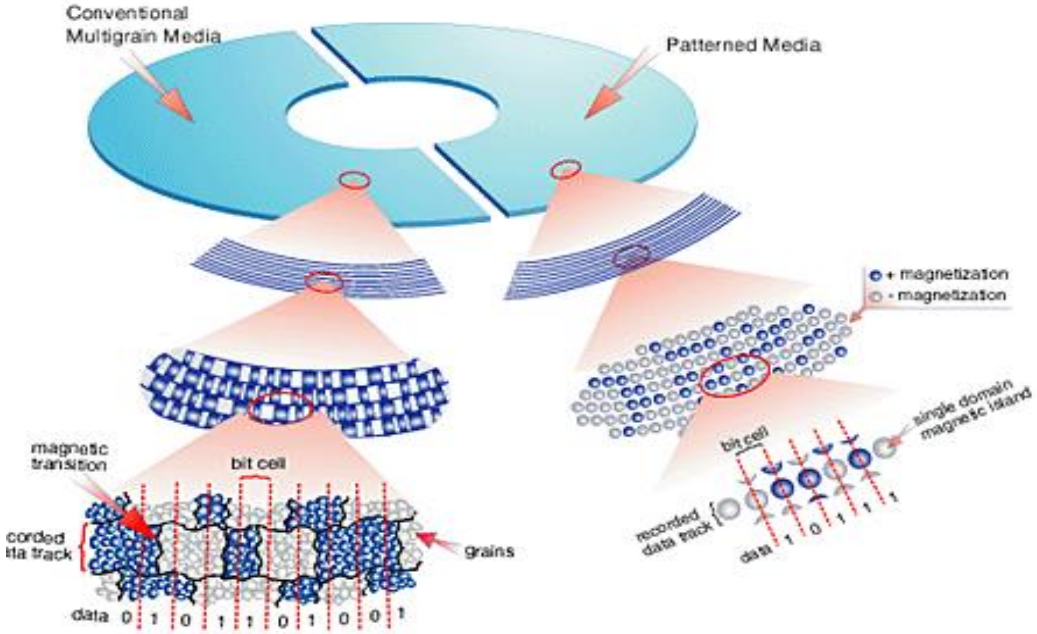
10 Years

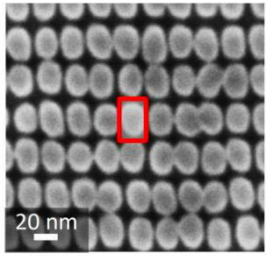
STABILITY FACTOR

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/in² with CoCrPt

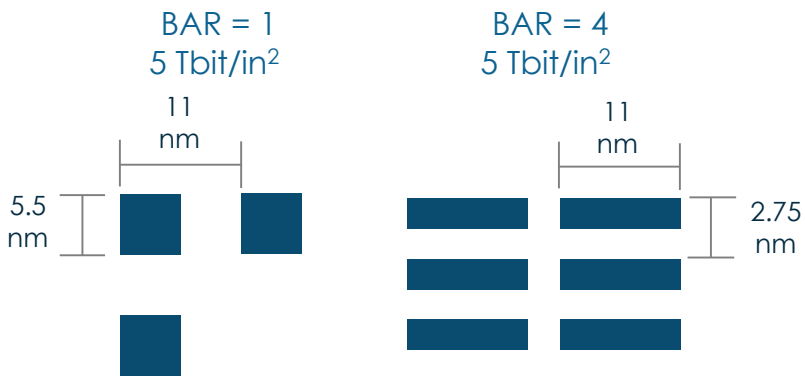
40 - 50 Tbit/in² { Hard Materials (e.g. $L1_0$-FePt), ECC, EARM

D. Makarov *et al.*, Ch 7 in "Ultra-High-Density Magnetic Recording" (G. Varvaro and F. Casoli Eds.), Pan Stanford Publishing **2016**

T.R. Albrecht et al., *IEEE Trans. Magn.* 51 1 **2015**

Bit Patterned Magnetic Recording (BPMR)

Density (Tb/in^2)	Bit period (nm) BAR=1	Bit period (nm) BAR=4
1	25.4	12.7
5	11	5.5
10	8	4
40	4	2



Main challenges

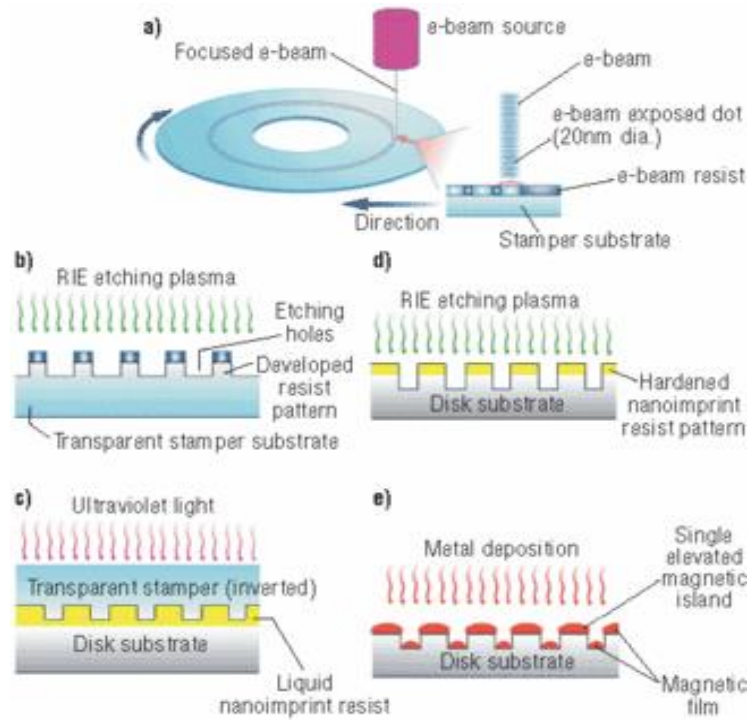
Extreme fabrication requirements:

- Low cost
- Fast process
- High resolution
- Large area order

Nano-Lithography

- Accuracy
- Resolution
- Large Area Order

- Cost
- Time-consuming



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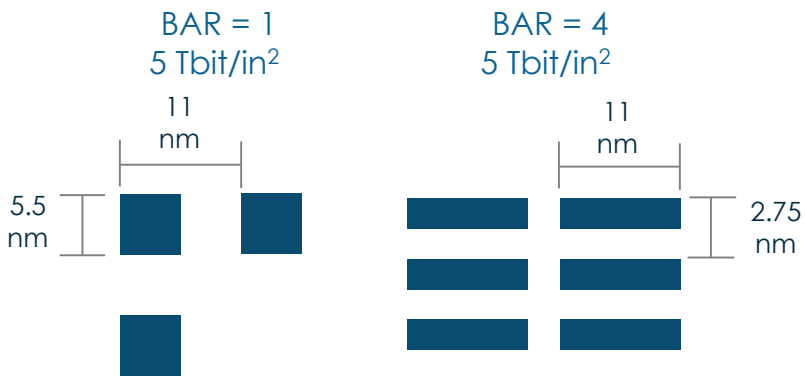


Main challenges

Extreme fabrication requirements:

- Low cost
- Fast process
- High resolution
- Large area order

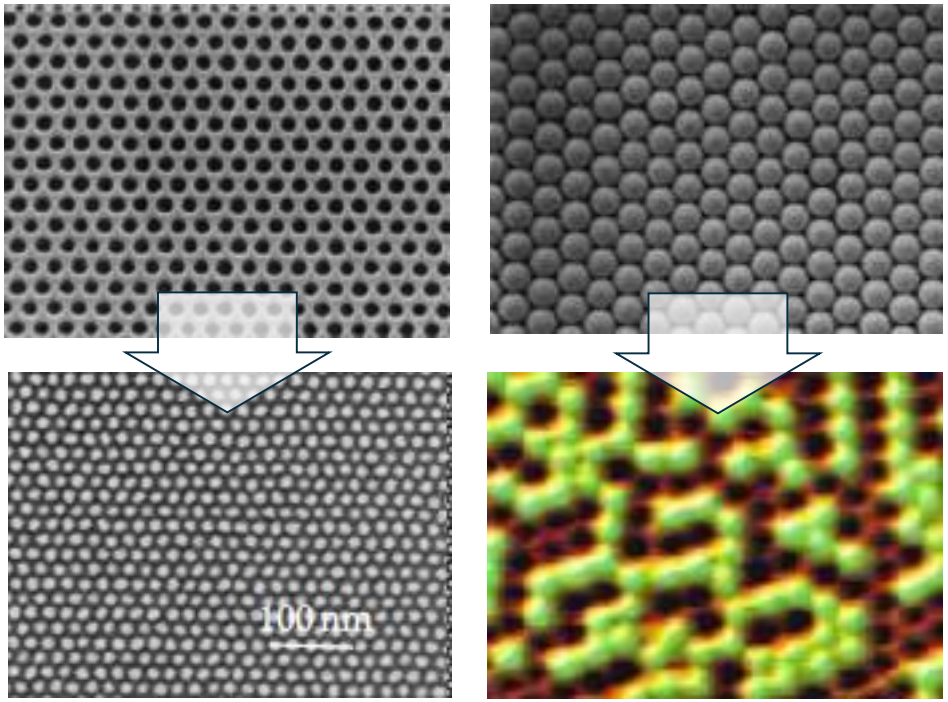
Template-Assisted Self-assembly

- Accuracy
- Resolution
- Large Area Order

- Cost
- Time-consuming

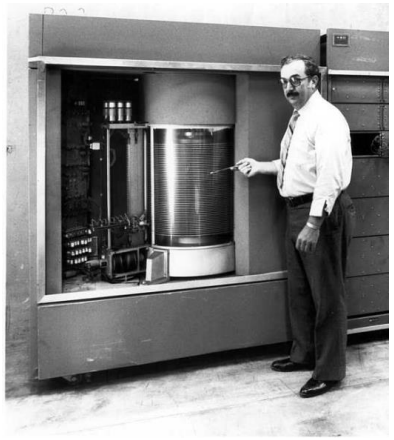
Block-Copolymers

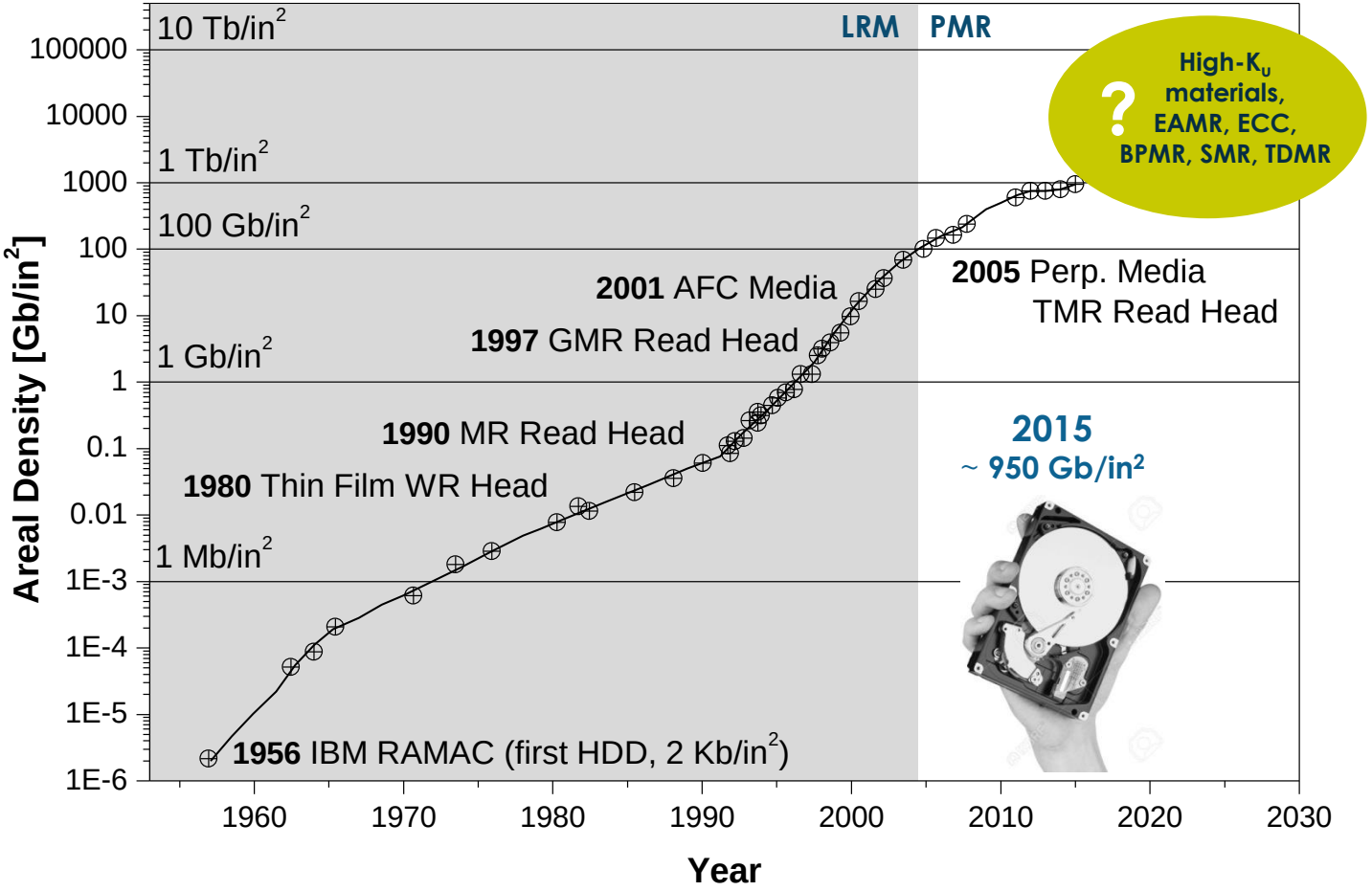
Nano-spheres



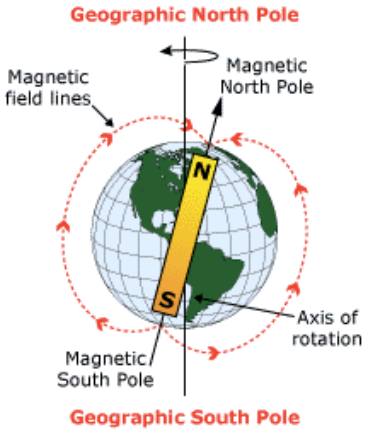
Final Remarks

1956
RAMAC (IBM)
2 Kb/in²

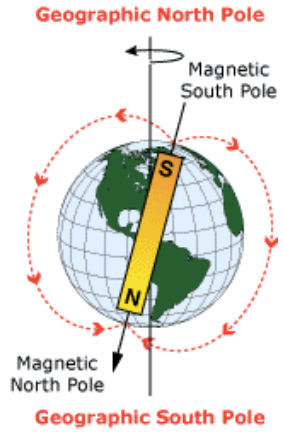




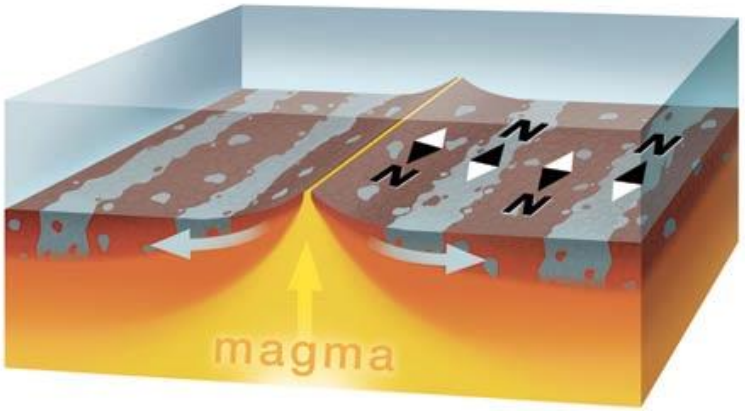
GEOMAGNETISM

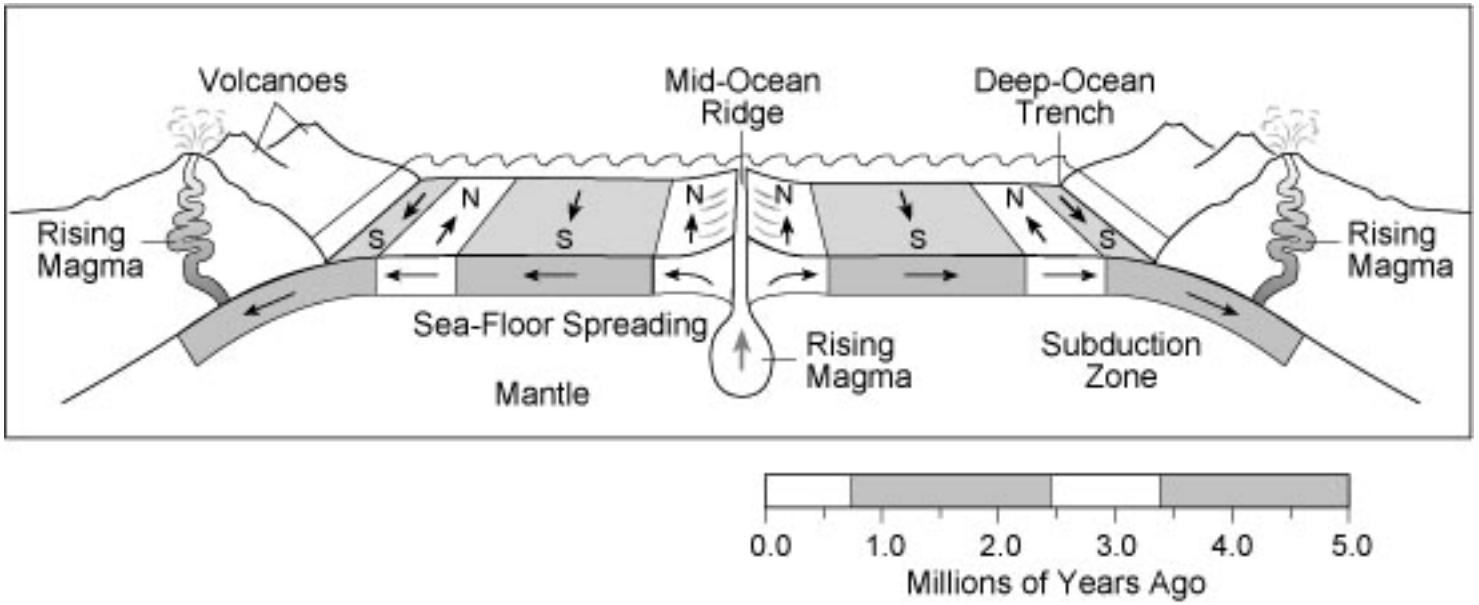


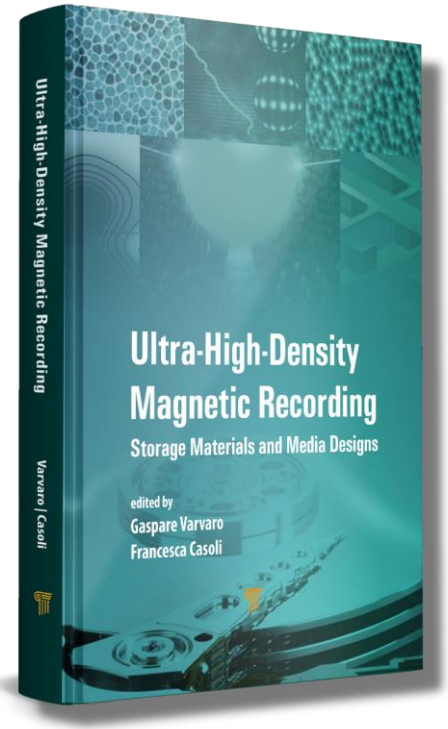
Normal polarity



Reverse polarity







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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.

Table of Contents

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*

OUTLINE

HARD DISK DRIVES

- History of magnetic recording
- Fundamentals of hard disk technology and currents issues
  - Perpendicular magnetic recording: recording medium and read/write head
  - Recording *Trilemma*
- Next generation recording media – *Beyond 1 Tbit/in*^{2}

  ☑ 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

Memory	Main field of application	Advantages	Drawbacks
HDD	Secondary data storage device in computers	• High density (~1 Tbit/in^2) • 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/in^2) • 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/in^2)
DRAM/SDRAM	Primary memory in computers	• High density (>500 Gbit/in^2) • Low cost (~1 $/Gbit) • Superfast read and write speeds (~200 Gbit/s)	• Volatile • Constant refreshing of data • Drains power

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NON-VOLATILE	**FLASH**	• Long-term external storage • Firmware • SSD drives	• Nonvolatile • Very high density (> 1 Tbit/in^2) • Low cost (<1 $/Gbit)	• Moderate read and write speeds (~6 Gbit/s) • Limited endurance
VOLATILE	**SRAM**	Cache memory in computers	• Fast read and write speeds (~35 Gbit/s) • Low power consuming	• Volatile • Low density (~4.5 Gbit/in^2)
VOLATILE	**DRAM/SDRAM**	Primary memory in computers	• High density (>500 Gbit/in^2) • Low cost (~1 $/Gbit) • Superfast read and write speeds (~200 Gbit/s)	• Volatile • Constant refreshing of data • Drains power

Memories Categories

	Memory	Main field of application	Advantages	Drawbacks
NON-VOLATILE	**HDD**	Secondary data storage device in computers	• High density (~1 Tbit/in^2) • Very low cost per byte stored (~0.004 $/Gbit)	• Moderate read and write speeds (~1 Gbit/s) • Bulky moving parts • Power consuming
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	MRAM ***M**agnetic* ***R**andom* ***A**ccess* ***M**emory*	• Military and space applications • Universal Memory in computer	• Nonvolatile • Fast read and write speeds (~1 Tbit/s) • High density (~128 Gbit/in^2) • Low power consumption • Unlimited write endurance • Radiation hardness	High writing currents

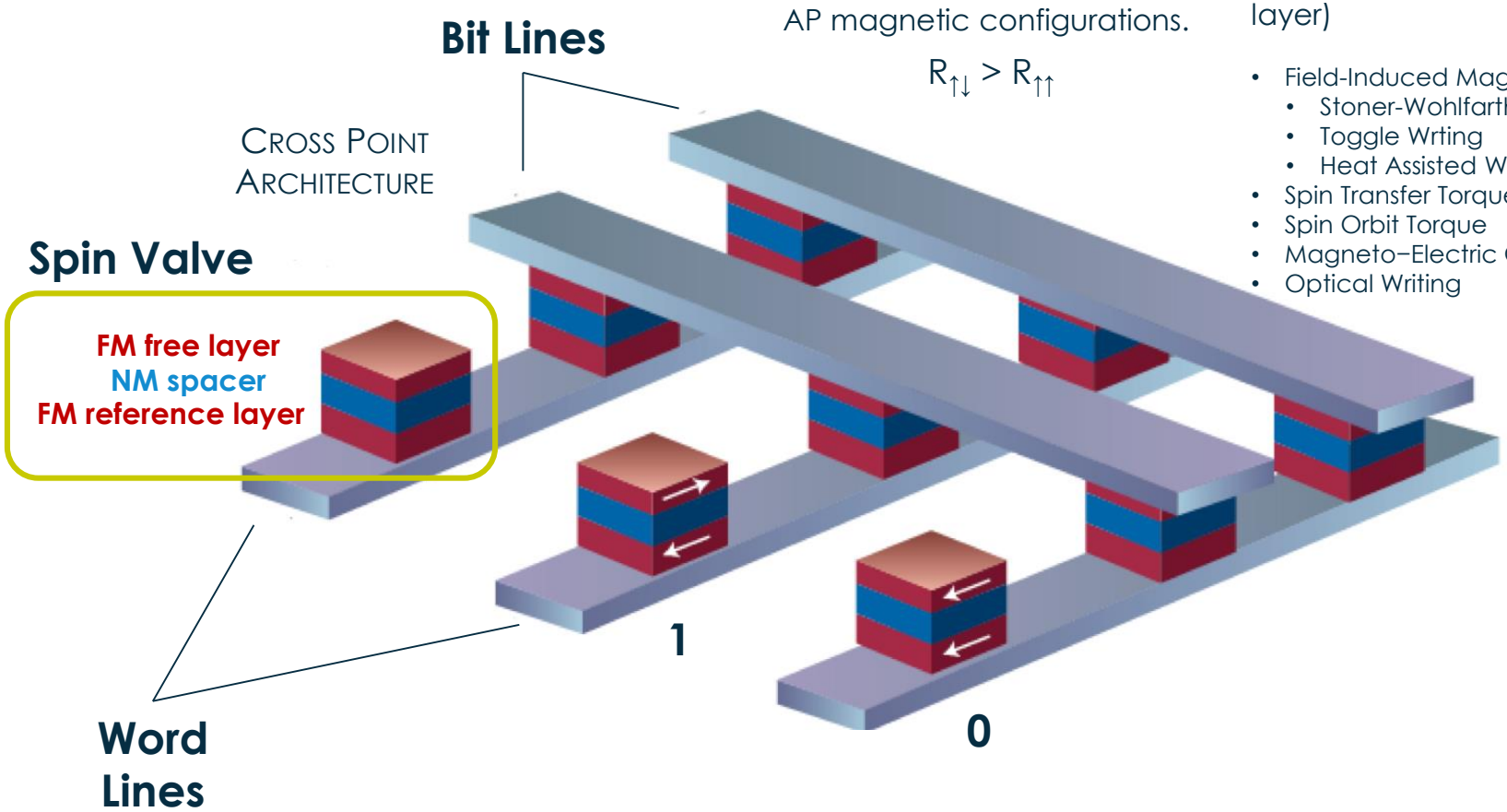
Basics of MRAM Working Principle

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

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

Writing Process
Setting the magnetization of the free layer (P or AP to the reference layer)

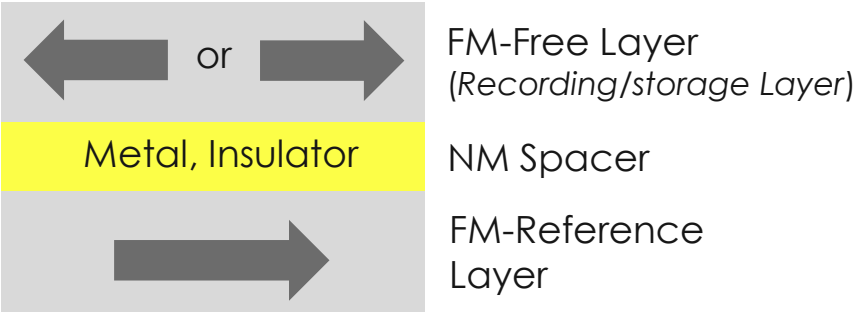
- Field-Induced Magnetic Switching
  - Stoner-Wohlfarth Writing
  - Toggle Wrting
  - Heat Assisted Writing
- Spin Transfer Torque
- Spin Orbit Torque
- Magneto–Electric Coupling
- Optical Writing



C. Chappert et al., Nat. Mat. 6, 813 **2007**

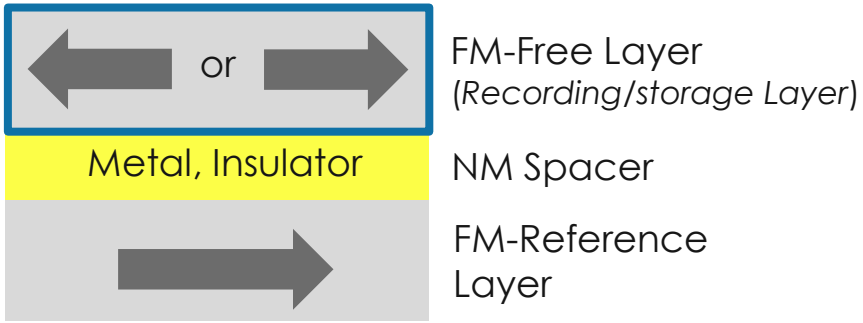
MRAM Structure

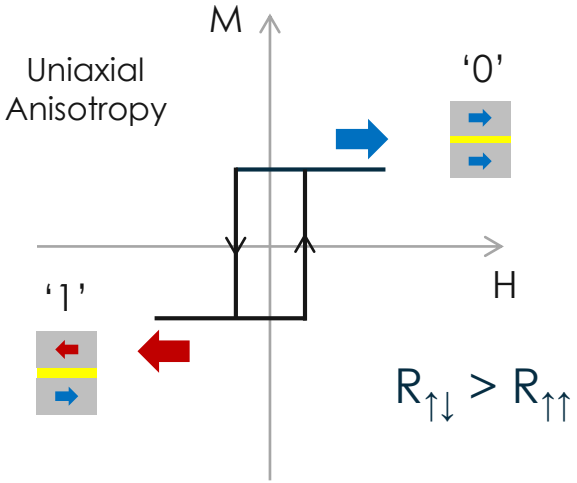
Spin Valve



MRAM Structure

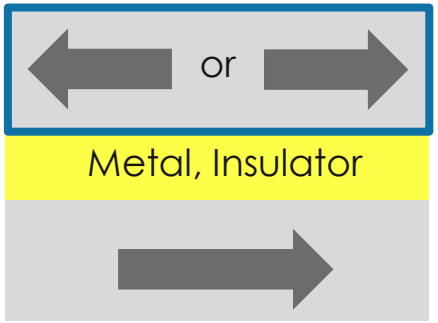
Spin Valve





MRAM Structure

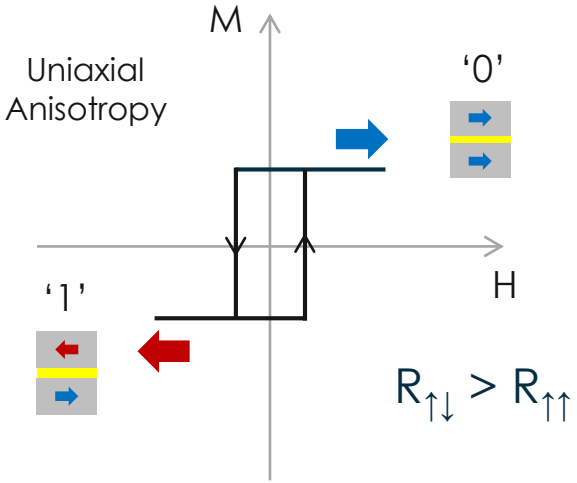
Spin Valve

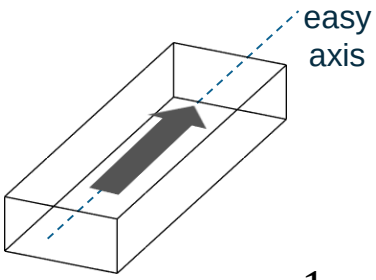


FM-Free Layer
(Recording/storage Layer)

NM Spacer

FM-Reference Layer

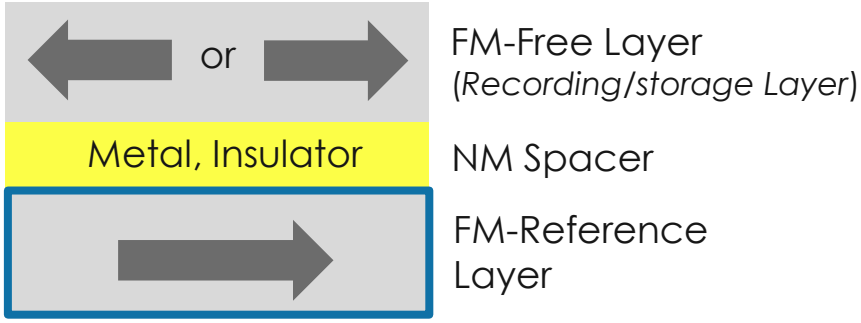




$$K_{sh} = -\frac{1}{2}\mu_0 M_s^2$$

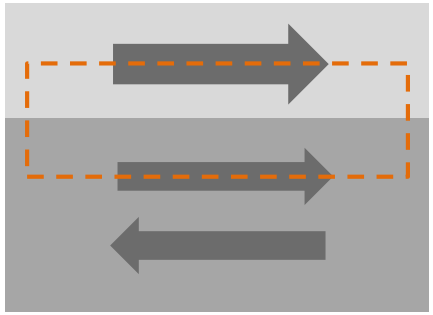
MRAM Structure

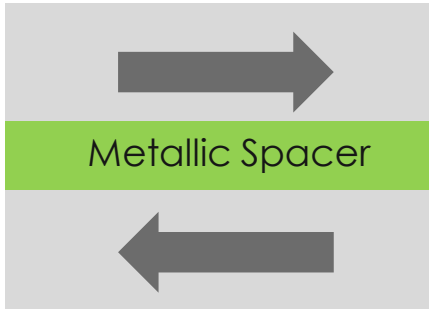
Spin Valve



Exchange Bias coupling with an AFM

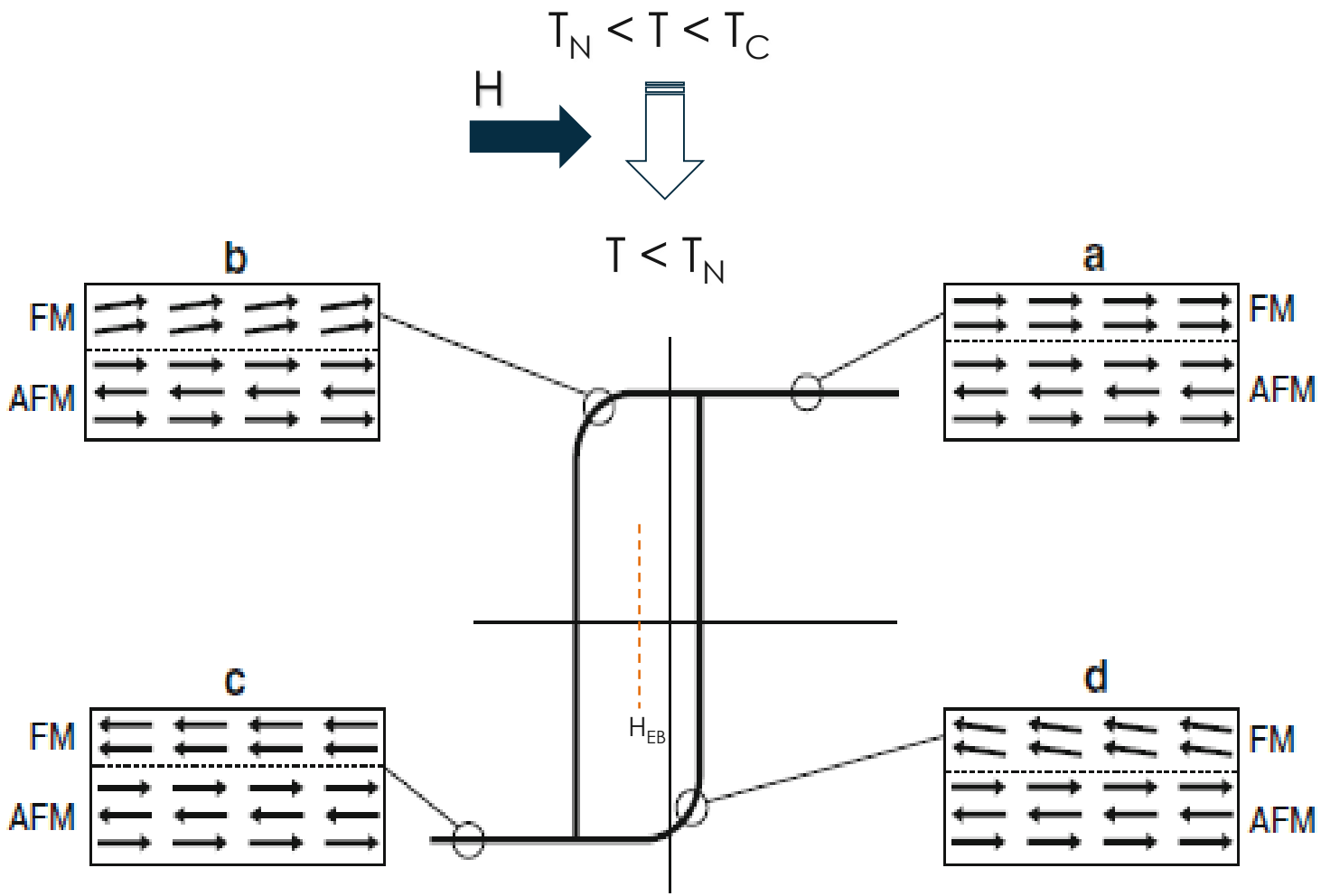
Synthetic Antiferromagnets (SAF)





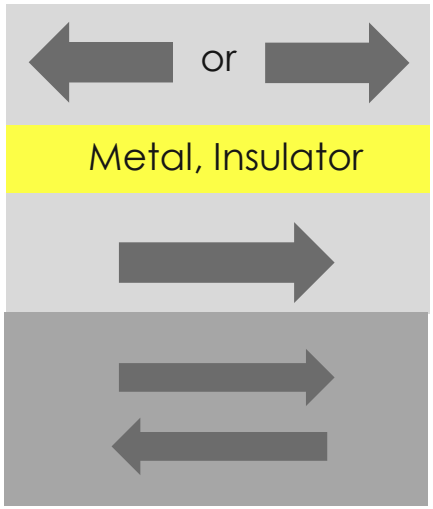
MRAM Structure

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



MRAM Structure

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

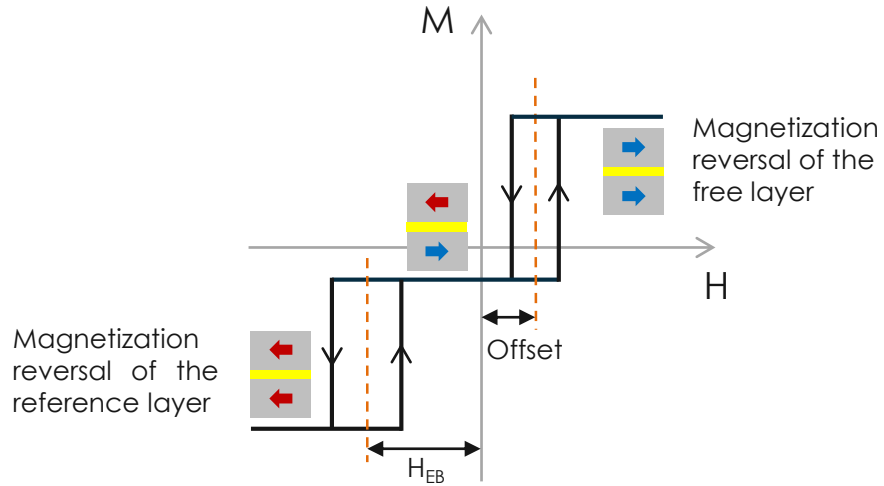


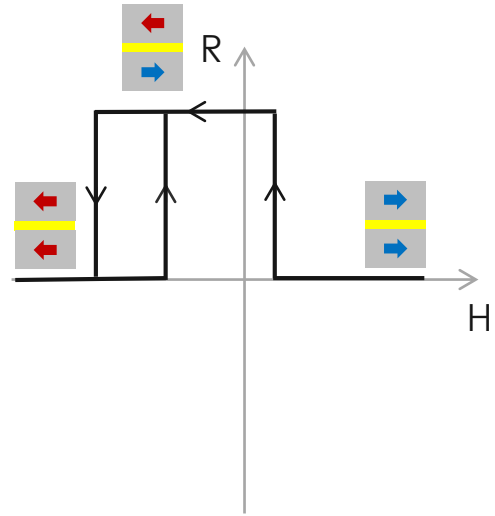
FM-Free Layer

NM Spacer

FM-Reference Layer

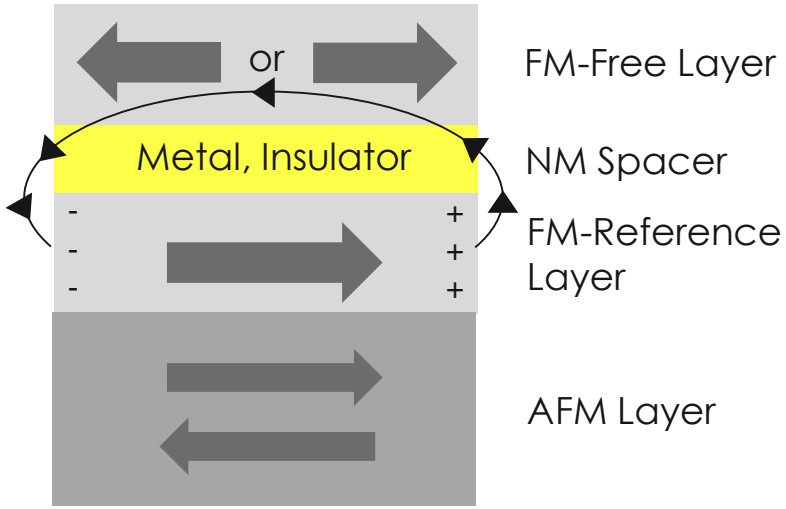
AFM Layer

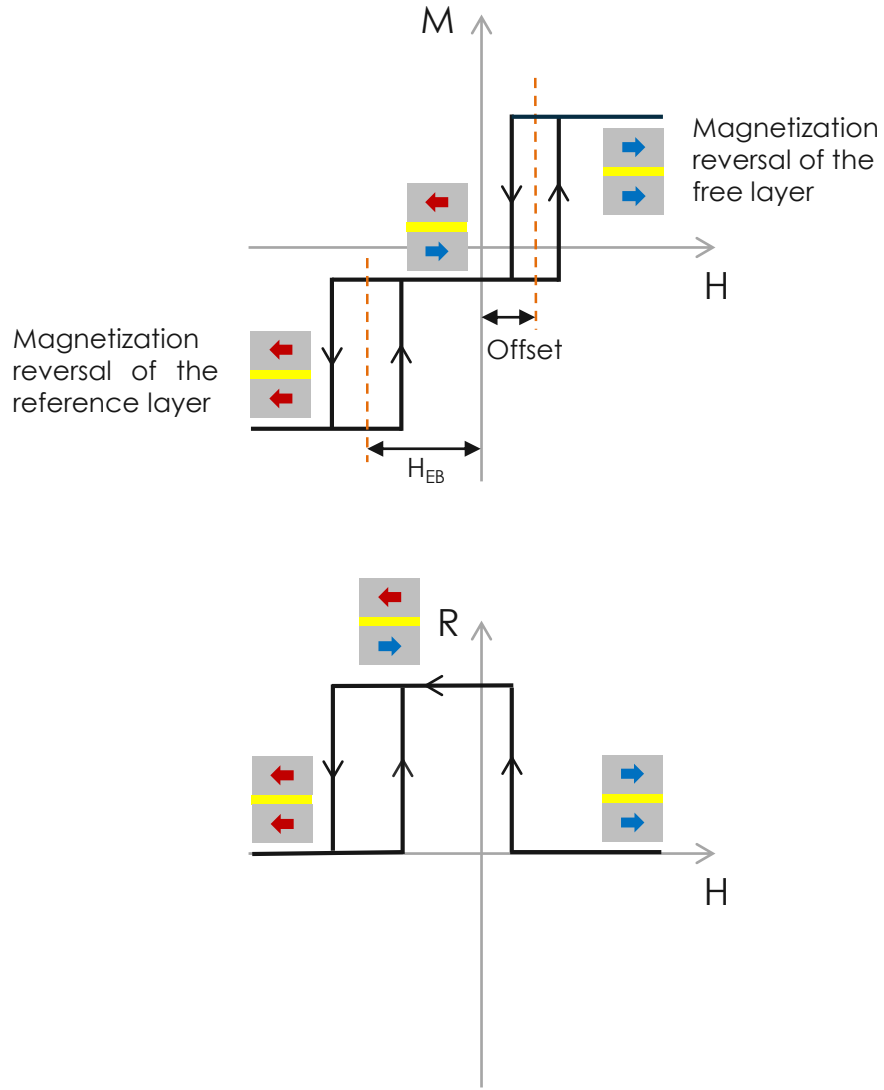




MRAM Structure

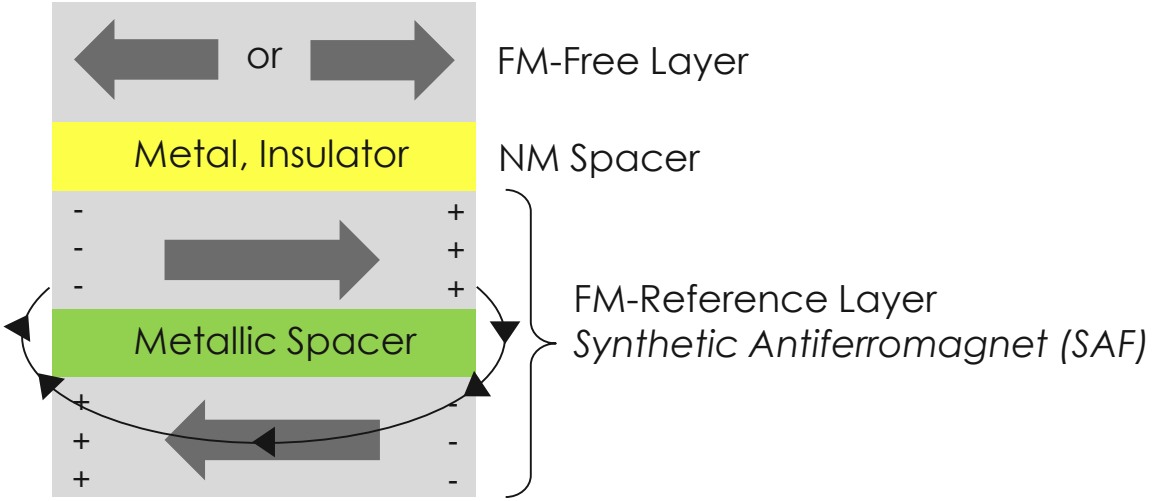
Spin Valve | Reference Layer – AFM Pinning Layer (Exchange Bias)





MRAM Structure

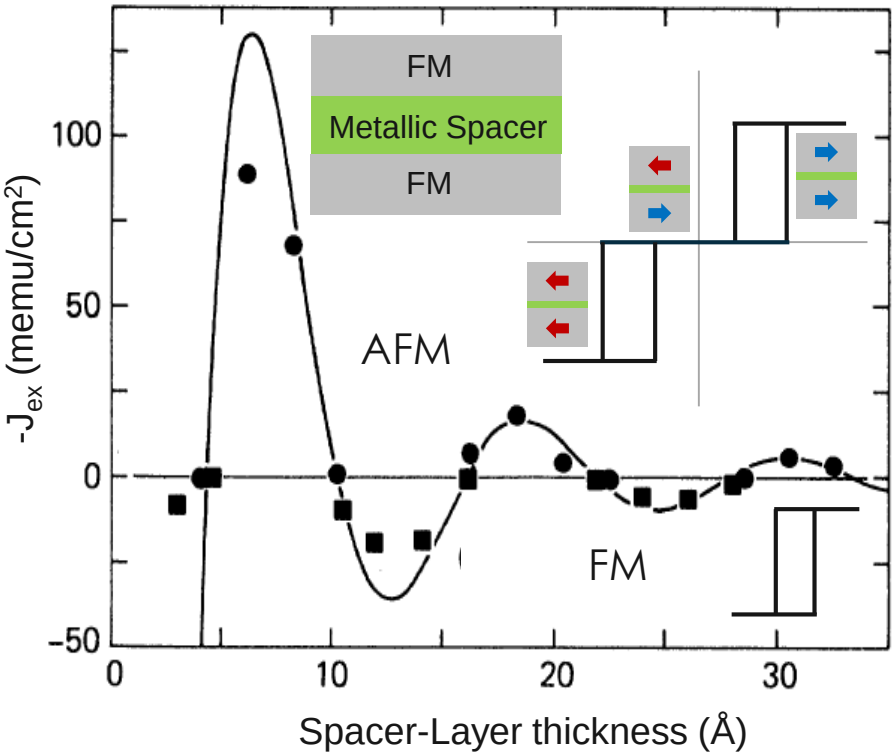
Spin Valve | Reference Layer – SAF Layer (Interlayer Exchange Coupling)



MRAM STRUCTUREE

SPIN VALVE | REFERENCE LAYER – SAF LAYER (INTERLAYER EXCHANGE COUPLING)

S.S.P. Parkin, *Phys. Rev. Lett. 67, 3598 (1991)*



Ti	V		Cr		Mn	Fe		Co		Ni	Cu	
No Coupling	9	3	7	7		Ferro-Magnet		Ferro-Magnet		Ferro-Magnet	8	3
	0.1	9	.24	18							0.3	10
2.89	2.62		2.50		2.24	2.48		2.50		2.49	2.56	
Zr	Nb		Mo		Tc	Ru		Rh		Pd	Ag	
No Coupling	9.5	2.5	5.2	3		3	3	7.9	3	No Coupling	No Coupling	
	.02	*	.12	11		5	11	1.6	9			
3.17	2.86		2.72		2.71	2.65		2.69		2.75	2.89	
Hf	Ta		W		Re		Os	Ir		Pt	Au	
No Coupling	7	2	5.5	3	4.2	3.5		4	3	No Coupling	No Coupling	
	.01	*	.03	*	.41	10		1.85	9			
3.13	2.86		2.74		2.74	2.68		2.71		2.77	2.88	

fcc, bcc, hcp, complex cubic

A_1 | ΔA_1 | J_1 | P

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

$J_{ex} < 0$ → AFM coupling

$J_{ex} > 0$ → FM coupling

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

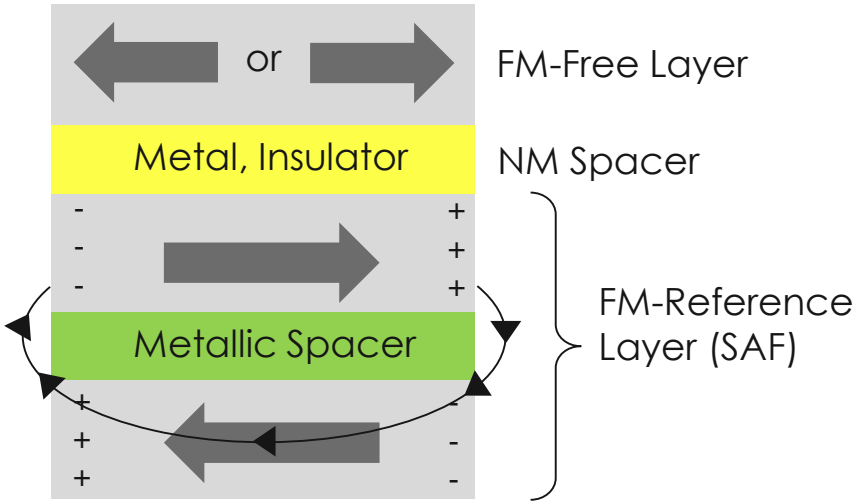
ΔA_1(Å): Range of spacer-layer thickness of the first AFM region.

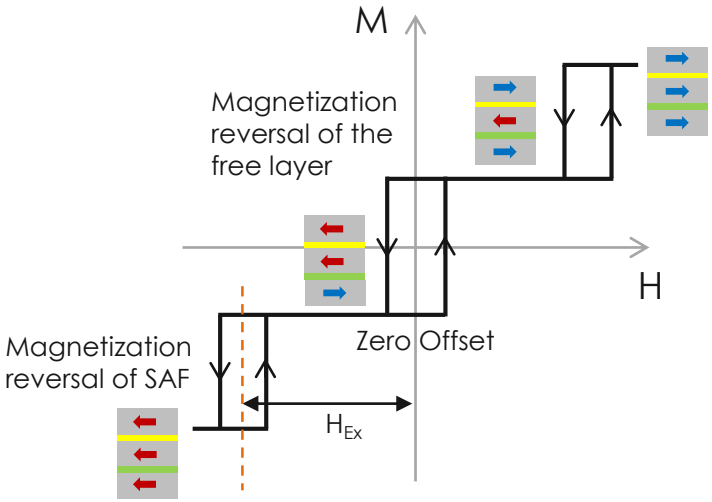
J_1 (erg/cm^2): Magnitude of the AFM exchange-coupling at the first peak.

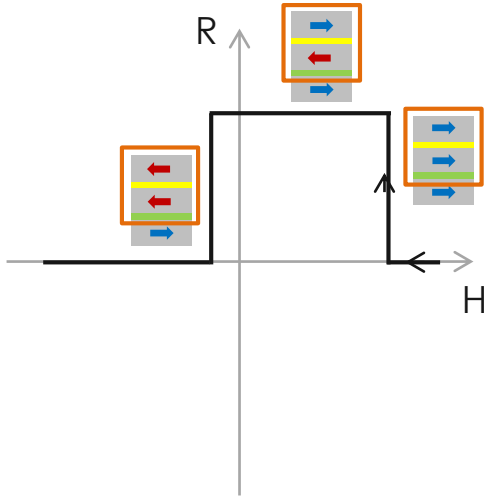
P(Å): Oscillation period

MRAM Structure

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

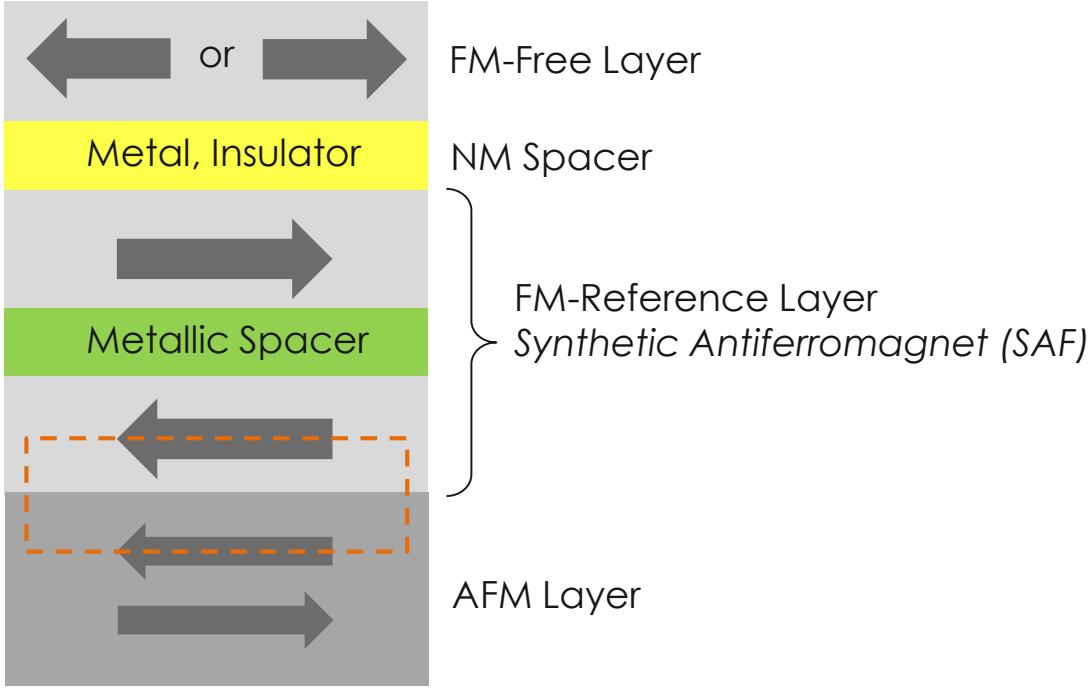






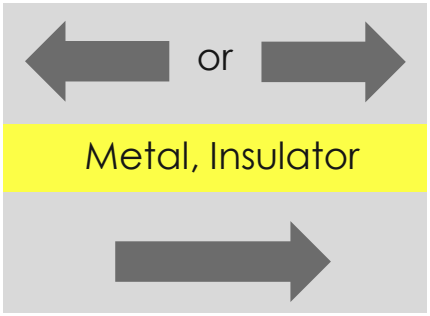
MRAM Structure

Spin Valve | Reference Layer – AFM + SAF



MRAM Structure

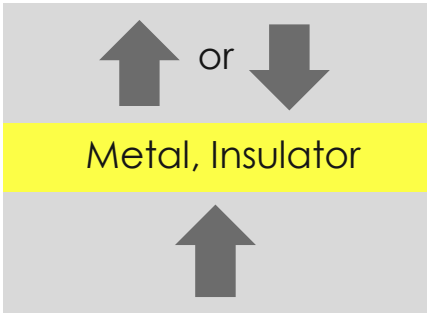
Spin Valve | In-plane vs. Out-of-Plane Magnetization



FM-Free Layer

NM Spacer

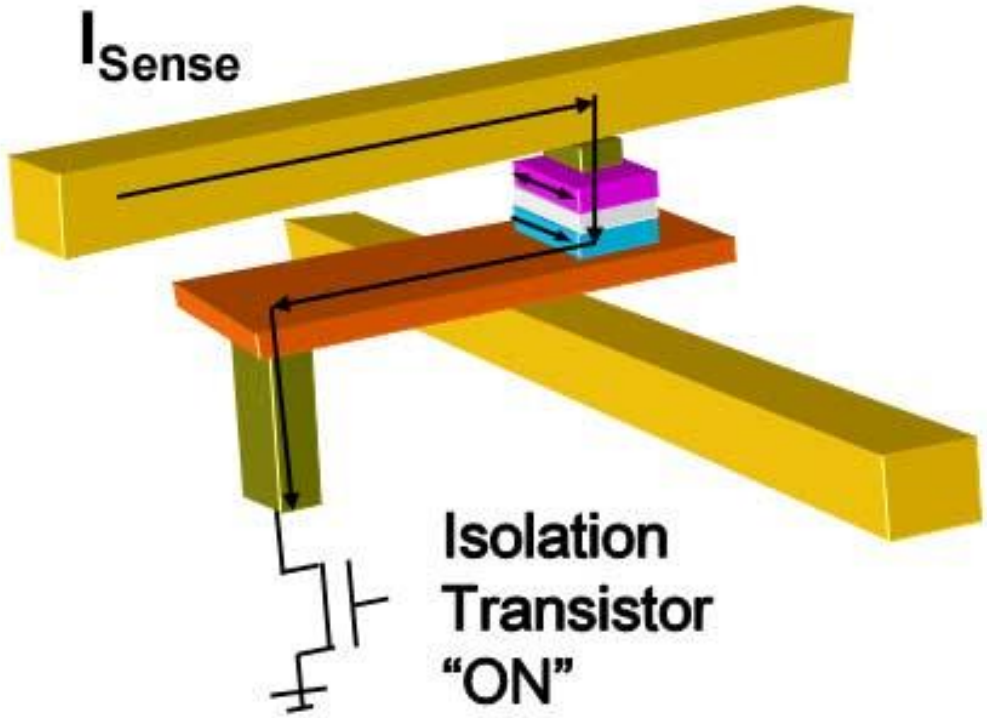
FM-Reference Layer

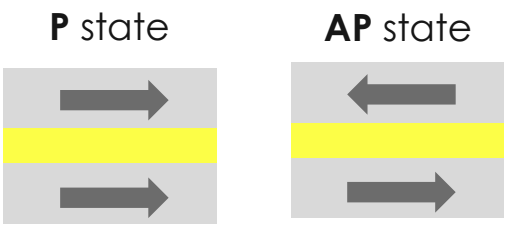


- Higher stability of time and temperature.
- Two magnetic stable states are intrinsically defined → elongated bit are not needed.

Smaller bit size → Higher recording densities

Reading Process

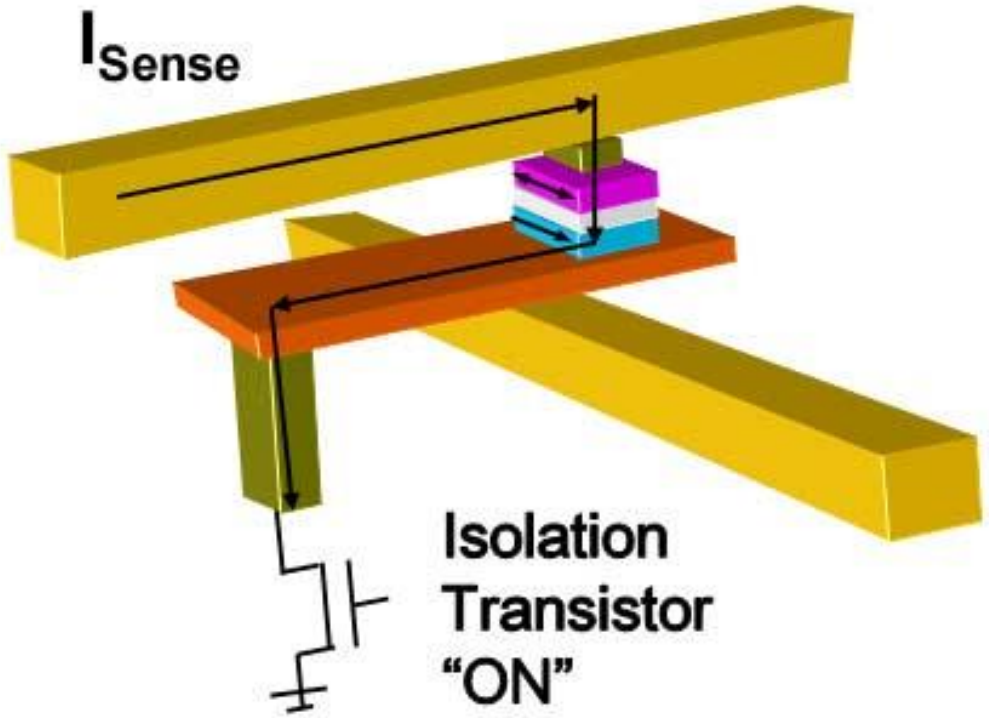


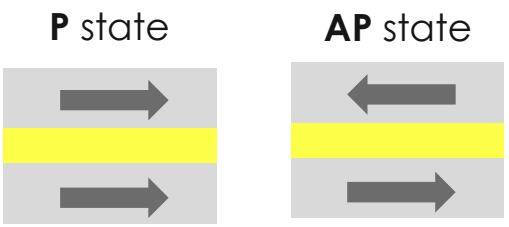


$R_{\uparrow\uparrow} < R_{\uparrow\downarrow}$

0 **1**

Reading Process





$R_{\uparrow\uparrow} < R_{\uparrow\downarrow}$

0 **1**

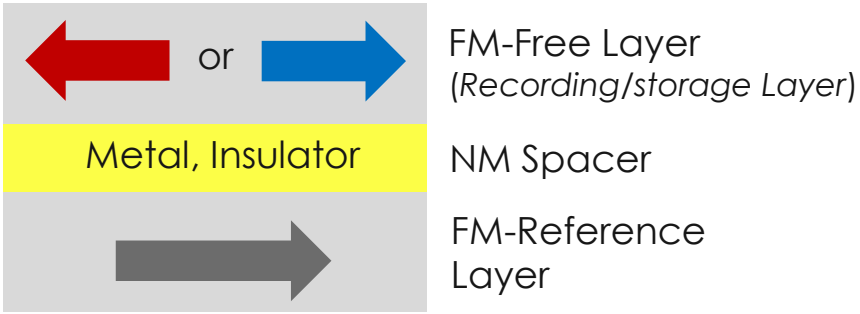
$\Delta R/R = (R_{\uparrow\downarrow} - R_{\uparrow\uparrow})/R_{\uparrow\uparrow}$

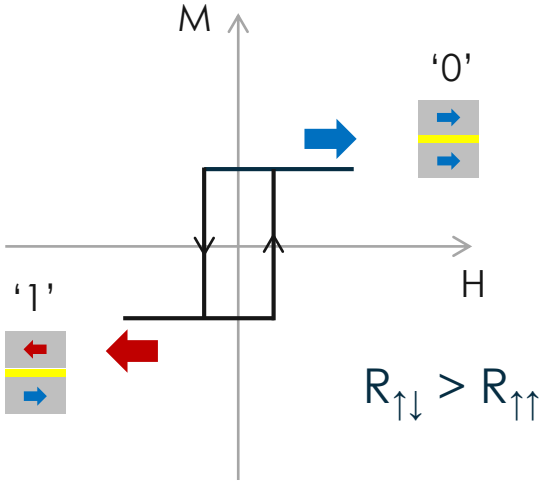
Metallic Spacer GMR Spin Valve	up to 55 % JMMM 200, 274 (1999)
Insulating Spacer TMR Spin Valve	up to 604 % APL. 93, 082508 2008

Writing Process

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