Western Digital

Magnetic Recording and Magnetic Memory

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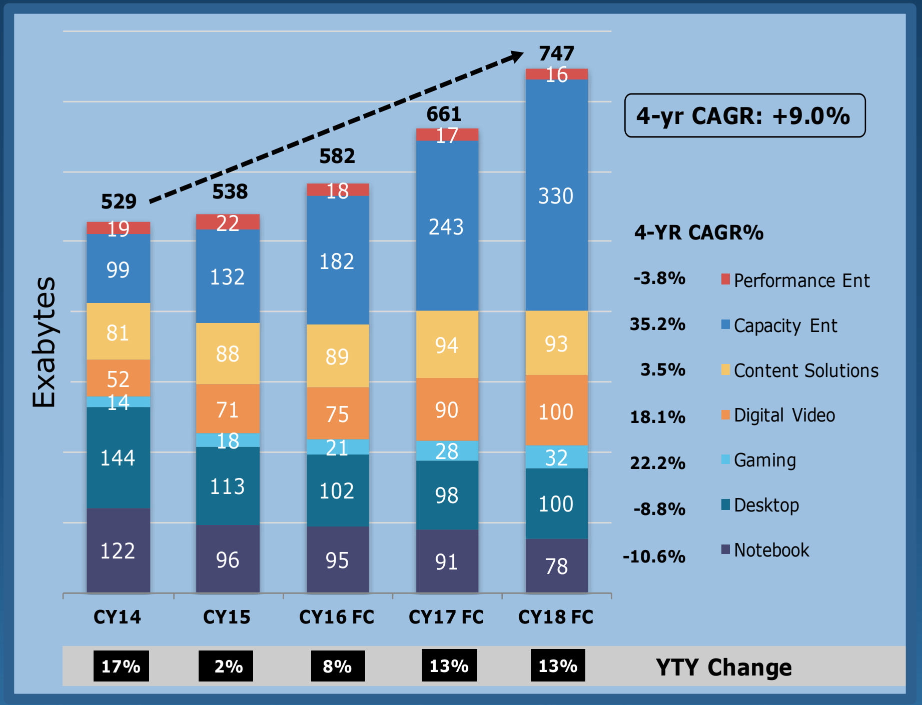
Outline

I. Hard Disk Drives
   1. Data Storage Industry --- still alive and thriving
   2. Short History of Magnetic Recording
   3. A look inside the HDD
   4. Head and Media Technology
   5. Energy-Assisted Recording Technology for the Future
      - Heat-Assisted Magnetic Recording (HAMR)
      - Microwave-Assisted Magnetic Recording (MAMR)

II. Magnetic Random Access Memory
   1. Comparison of Memory Technologies
   2. Basics of Spin-Transfer Torque MRAM and Challenges
   3. Other MRAM approaches: SOT-MRAM, VCMA

HDD Data Storage Trends

Cloud



Source: WDC

Personal CE

Client PC

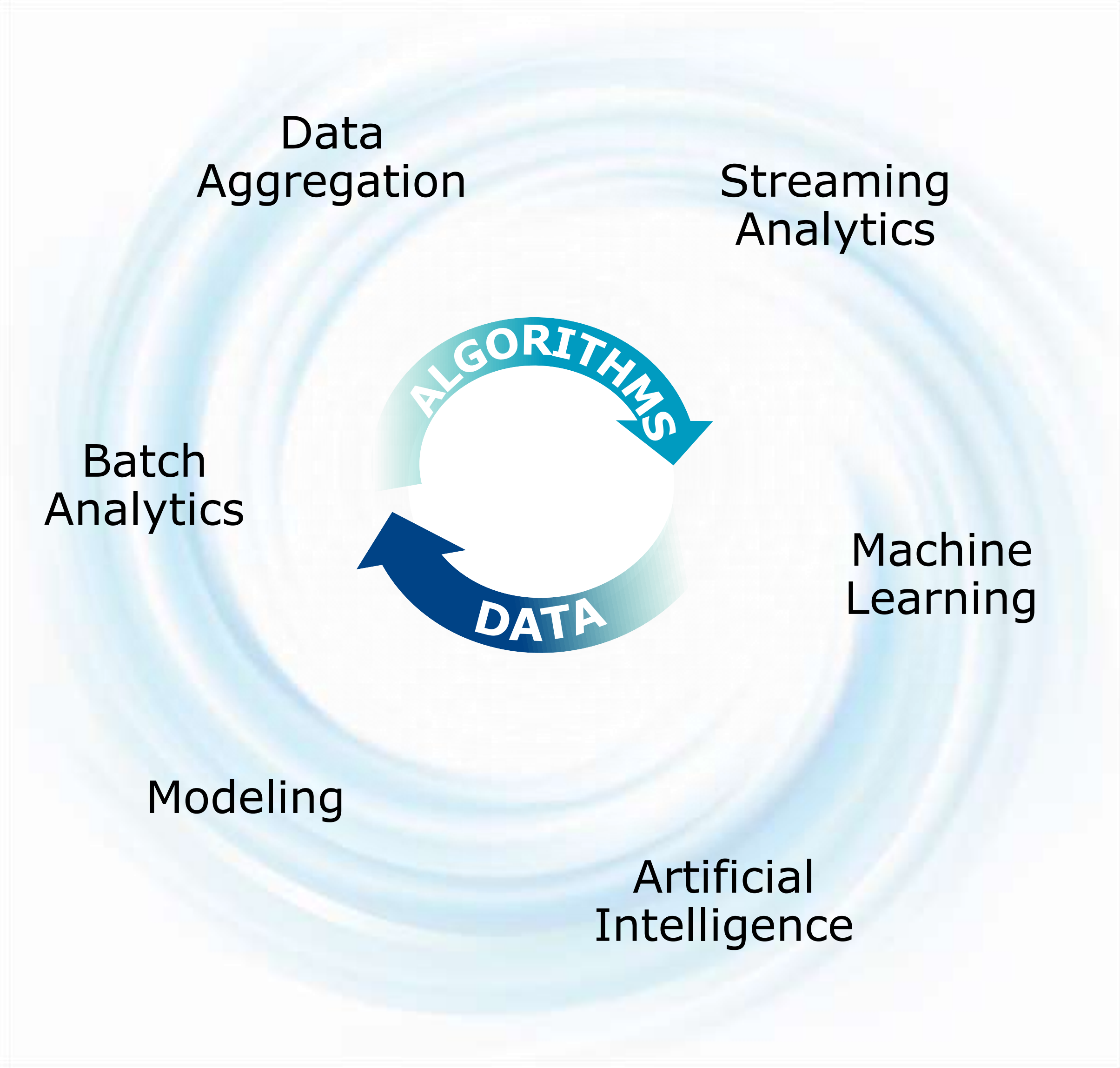
Need to continue increasing storage density of HDDs (cost/space/power)

Diverse and Connected Data Types

Tight coupling between Big Data and Fast Data

Big Data

Scale

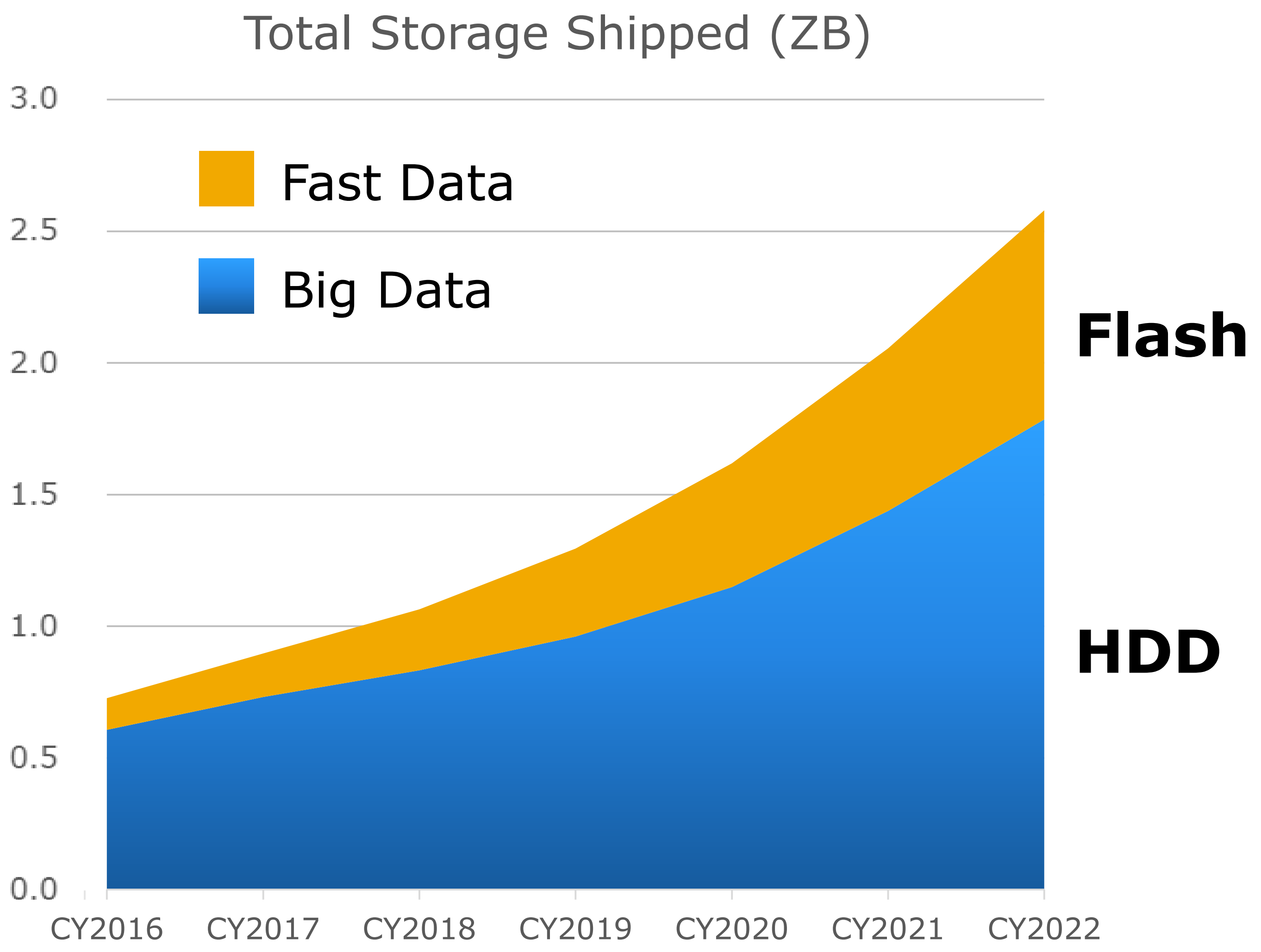


Fast Data

Performance

Insatiable Growth in Data

HDDs continue to play an important role in the future of data storage



By 2020

~70%

of the ~10 ZBs stored will **still** reside on HDDs

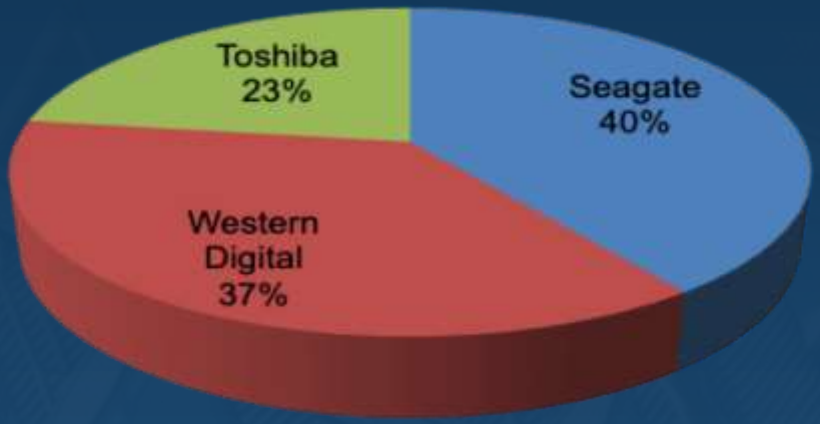
~90% in data centers

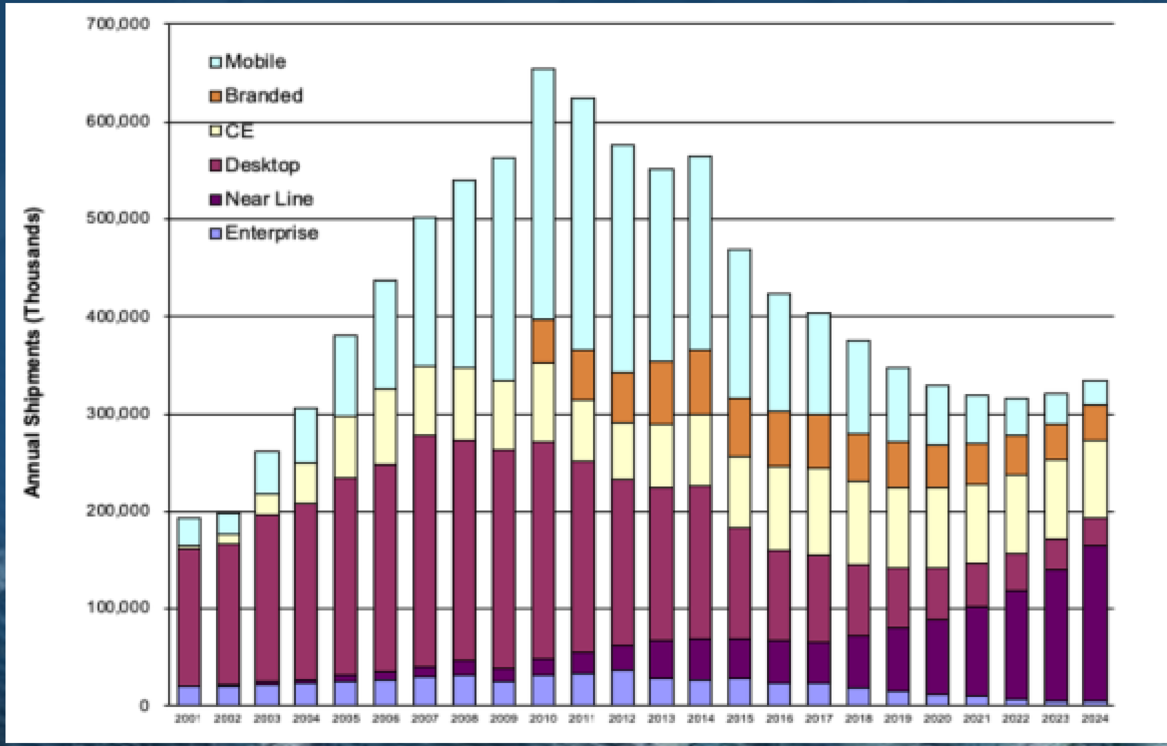
1 ZB = 10^{21} bytes
or
1 billion 1TB drives

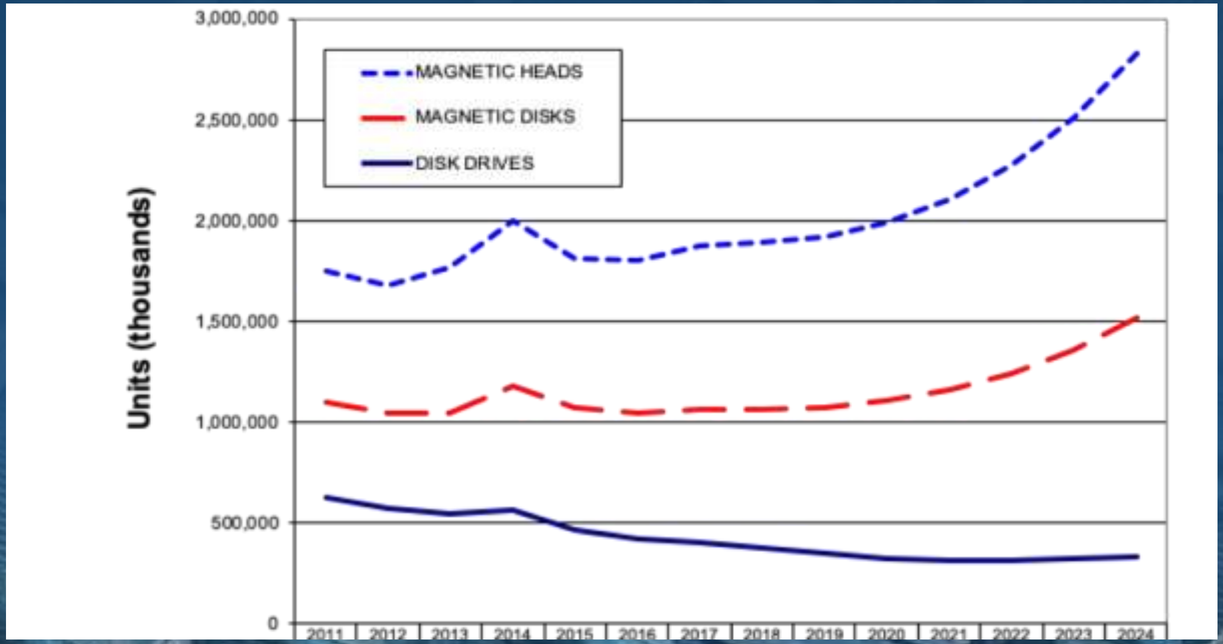
Source: WDC Analysis

Market Glance:

- 94M HDD shipped in 1st quarter 2018
- Total exabytes shipped is increasing.
- Number of drives decreasing.
- Average HDD cost ~$60







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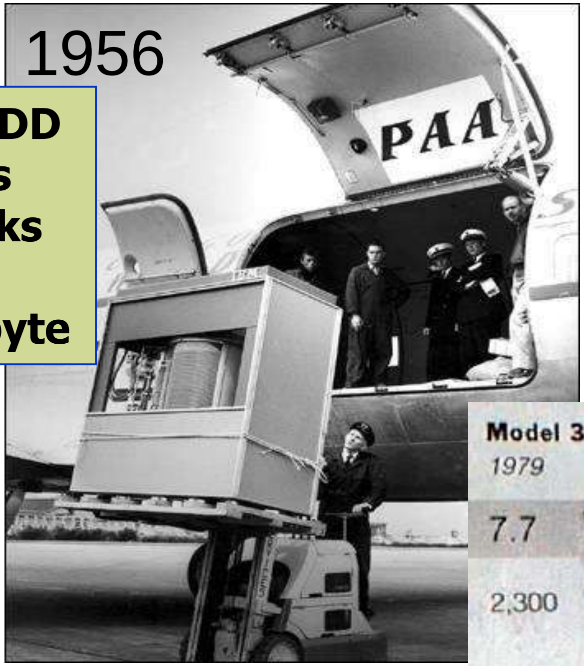
Source: Coughlin Assoc

Hard Disk Drive

History of HDDs

1956

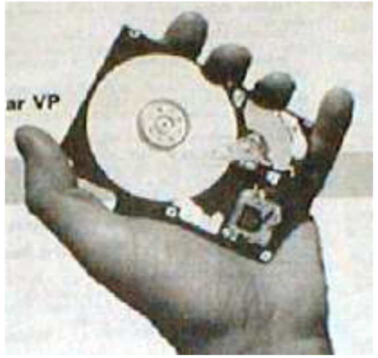


RAMAC - first HDD

- 5 MegaBytes
- Fifty 24" disks
- 2 kbits/in^2
- $10,000/Mbyte

1980's – 1990's

Towards smaller form factors



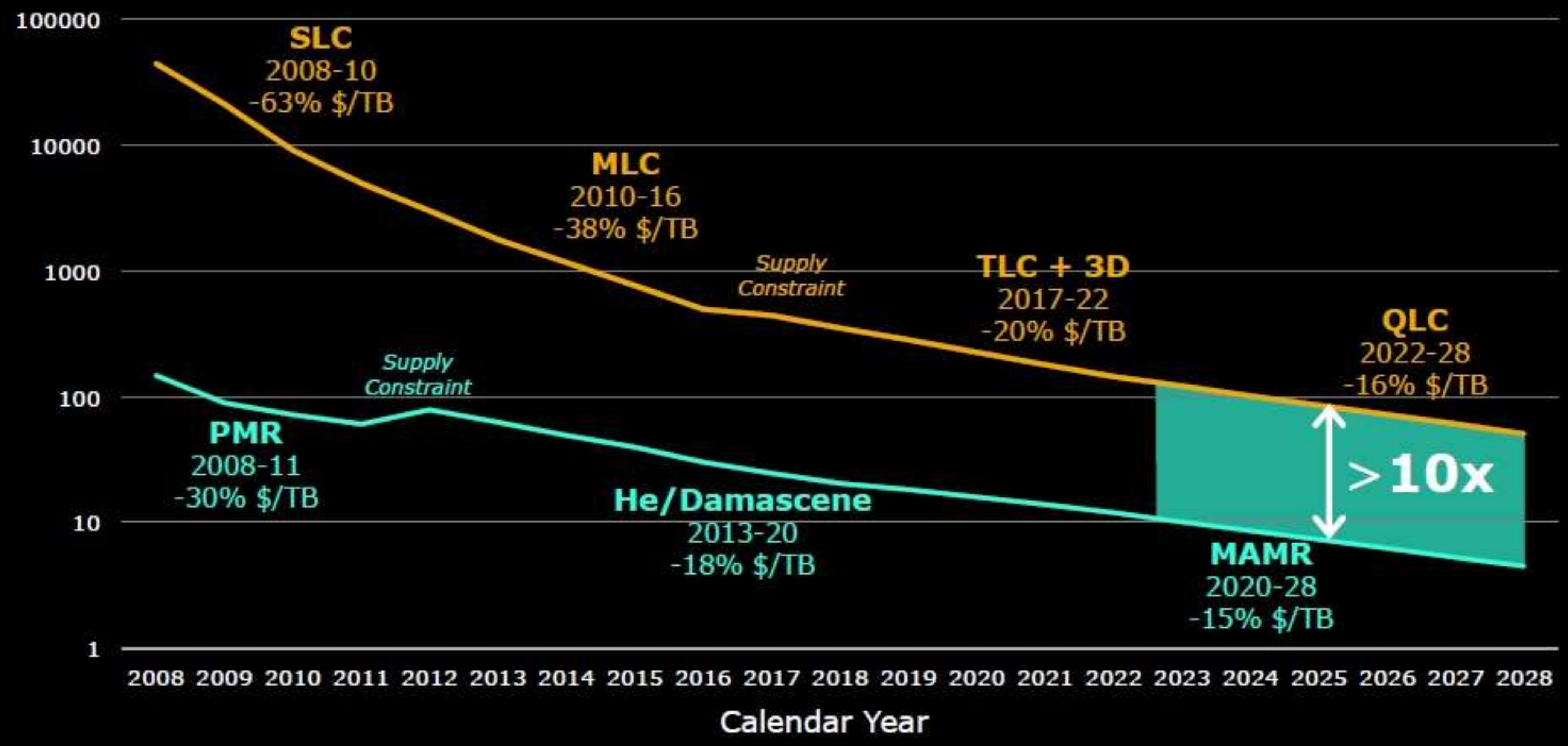
Apple iPOD

- 160 GigaBytes
- Two 1.8" disks
- 3600 RPM
- 228 Gbits/in^2
- 52 MBytes/s

The trend to ever smaller HDD's has stopped though ...

HDD vs. Flash SSD $/TB Annual Takedown Trend

MAMR will enable continued $/TB advantage over Flash SSDs



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Source: WDC Analysis

1 disk, 1 or 2 heads

TechBargains: Amazon PC Storage Sale: SanDisk 200GB only $25, WD My Book 6TB under $100 & more

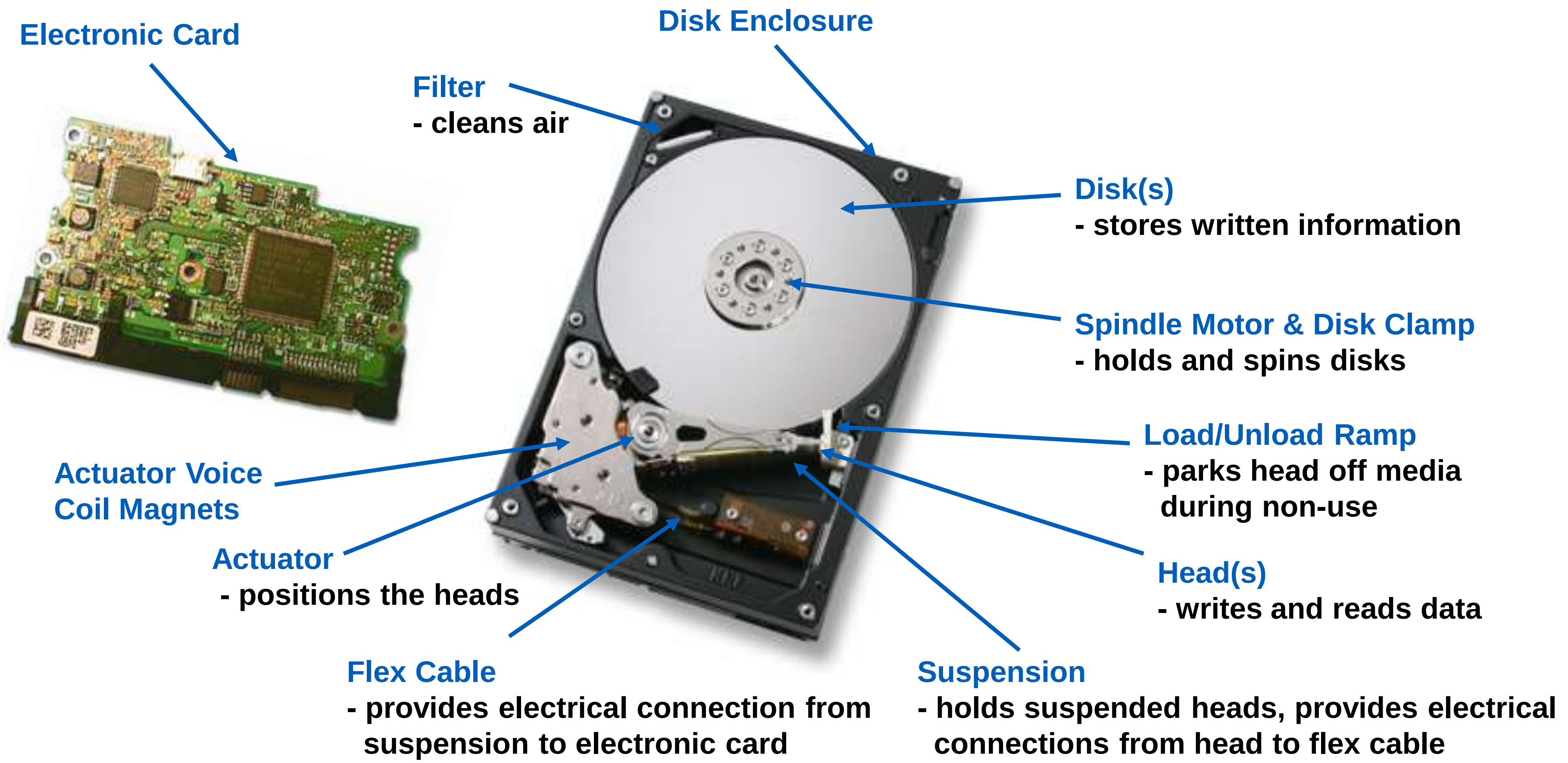
By Steven Parker · May 28, 2019 12:38 EDT 2

Amazon's Gold Box deals include Up to 65% off PC Storage Devices and Memory Cards, and up to 40% off Netgear Networking Devices. These deals are brought to you courtesy of TechBargains.

Featured Deals

- Today Only: Up to 65% off PC Storage Devices and Memory Cards at Amazon. Save on SanDisk, Western Digital, Seagate, and Toshiba storage devices like microSDXC cards, internal, external, and portable HDDs.
- Today Only: Over 20% off Netgear Routers, Modems, and WiFi Extenders at Amazon. Save more than 20% off on Netgear routers, Modems, and WiFi Range Extenders.
- SanDisk Ultra 200GB microSDXC Card with Adapter for **$25** at Amazon (list price $34.99). This is an amazing price for the 200GB capacity SanDisk Ultra microSDXC card. Great for Nintendo Switches, additional smartphone storage, or cameras.
- Toshiba Canvio Advance 1TB USB 3.0 Portable External Hard Drive for **$39.99** at Amazon (list price $53.99). Save 26% off this 1TB Toshiba Canvio Advance portable hard drive. Includes Toshiba's 2-year standard limited warranty.
- Western Digital My Book 6TB USB 3.0 Desktop External Hard Drive for **$95.96** at Amazon (list price $249.99). Looking for more storage? Get the WD My Book 6TB desktop hard drive for over

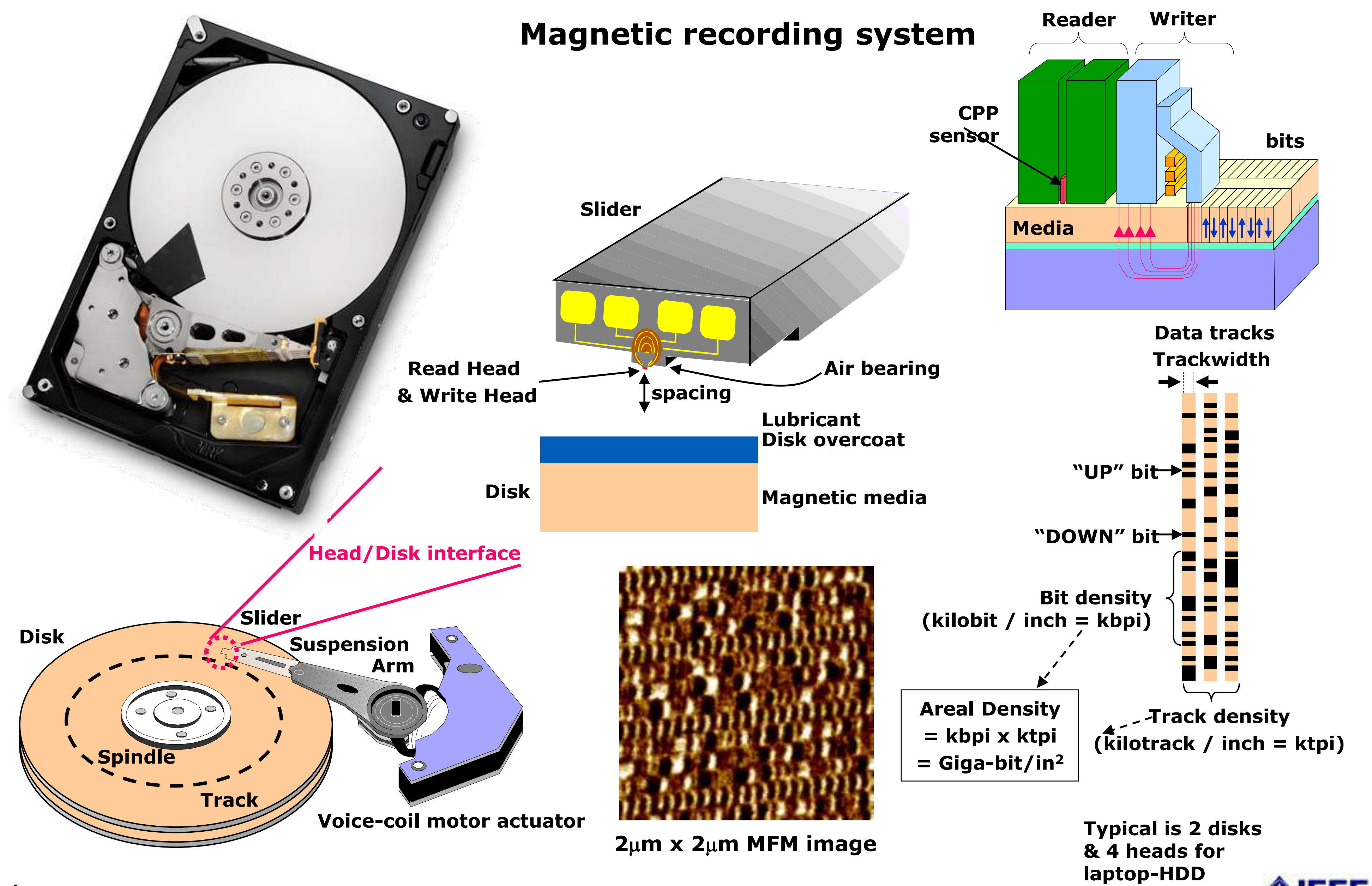
Typical Components in a Modern Disk Drive



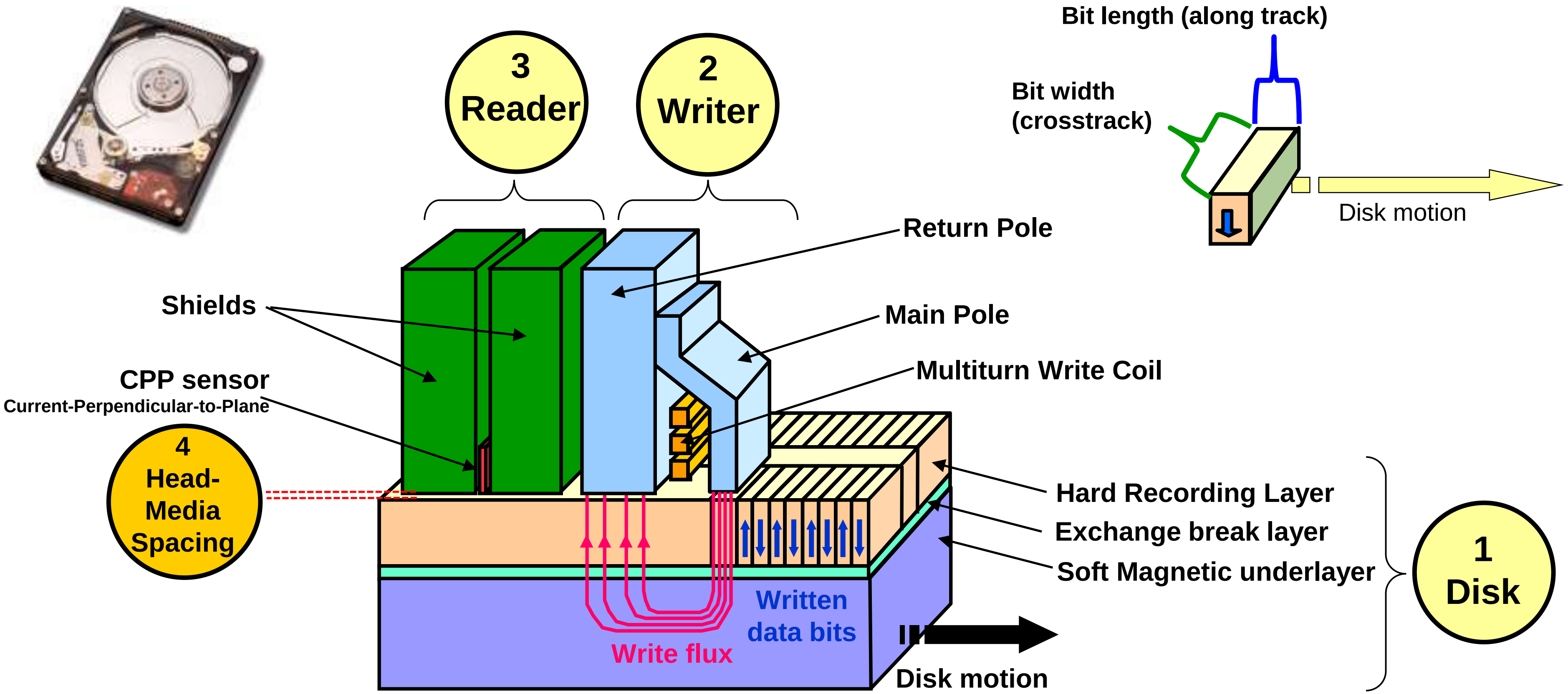
Electronic card

Provides data interface to disk controller
Control operation of disk drive (spindle, actuator, position servo)
Encodes written data and decodes read back data
Provide read/write signals to heads via flex cable

What's in the drive?



Recording Basics → Scaling



Most straightforward method to increase storage bit density is to shrink everything

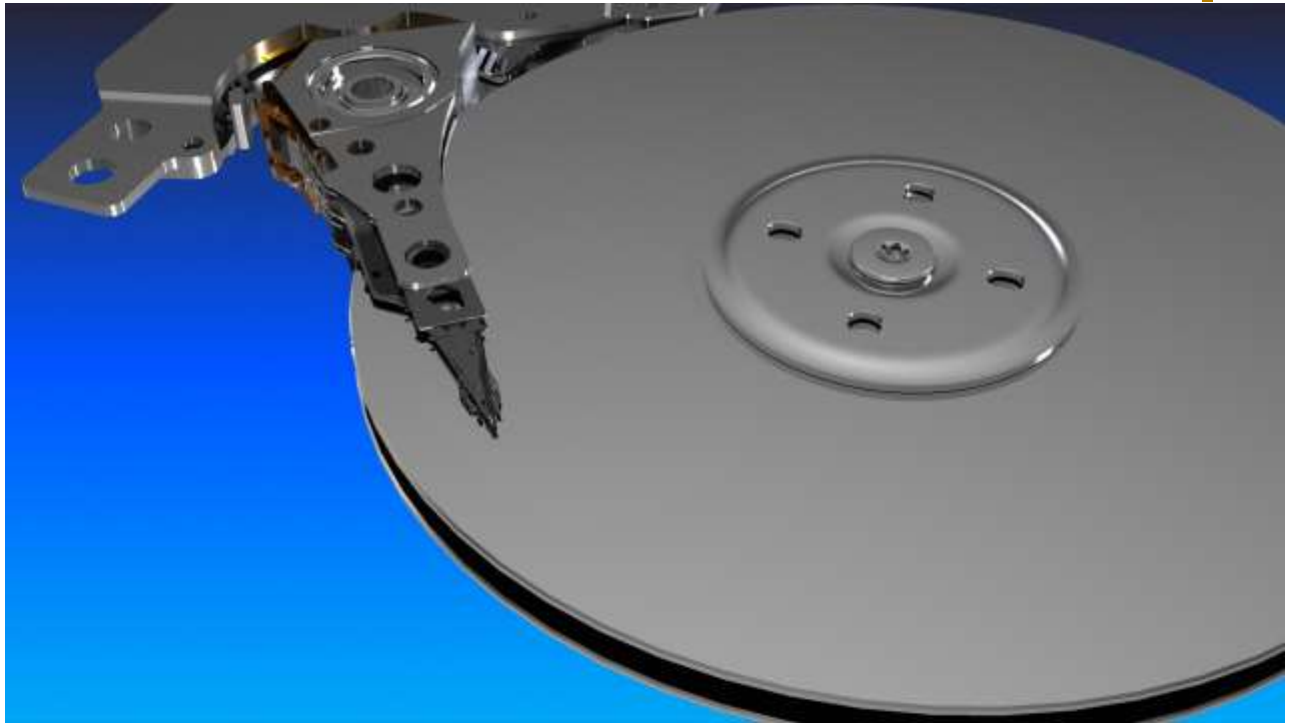
→ scale down (head dimensions, media thickness, media grain size, head-media spacing, etc…)

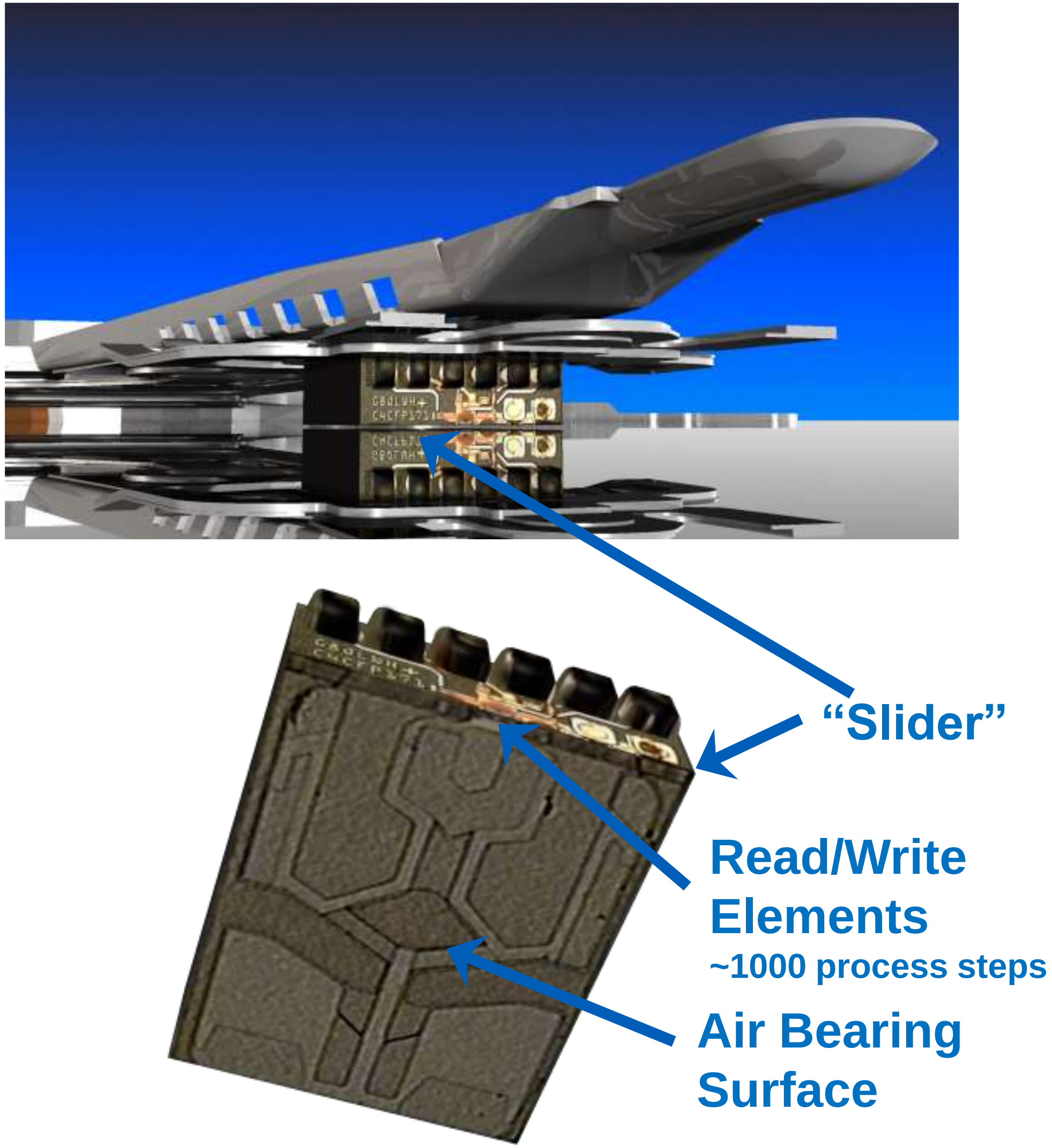
Must maintain signal-to-noise ratio while scaling

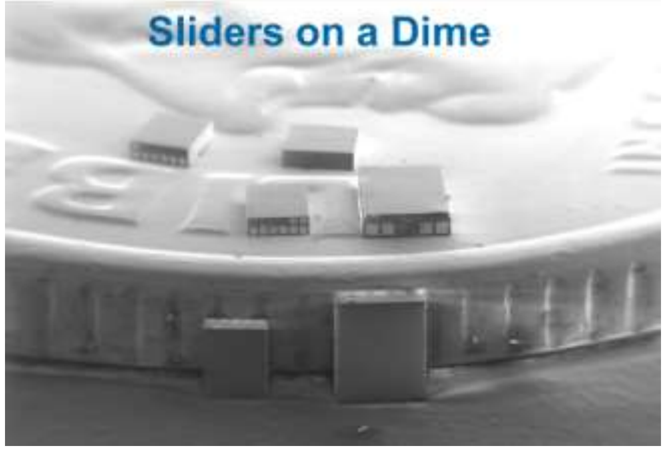
→ New technologies to boost signal and/or reduce noise

(Ex: Longituginal recording → perpendicular; Anisotopic magnetorestive sensor → giant magnetoresistive sensor)

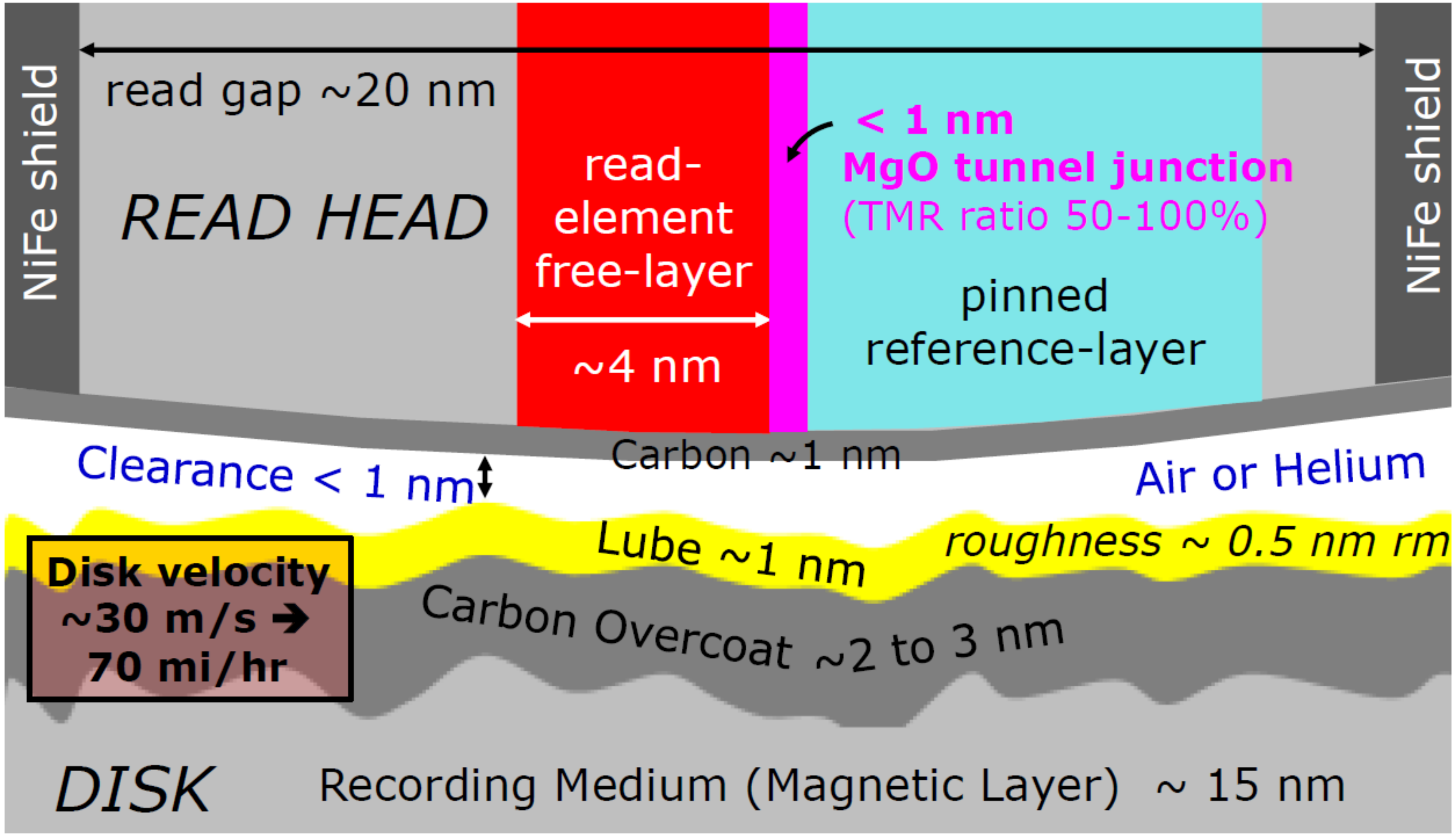
The HDD Head: Extreme Close-up





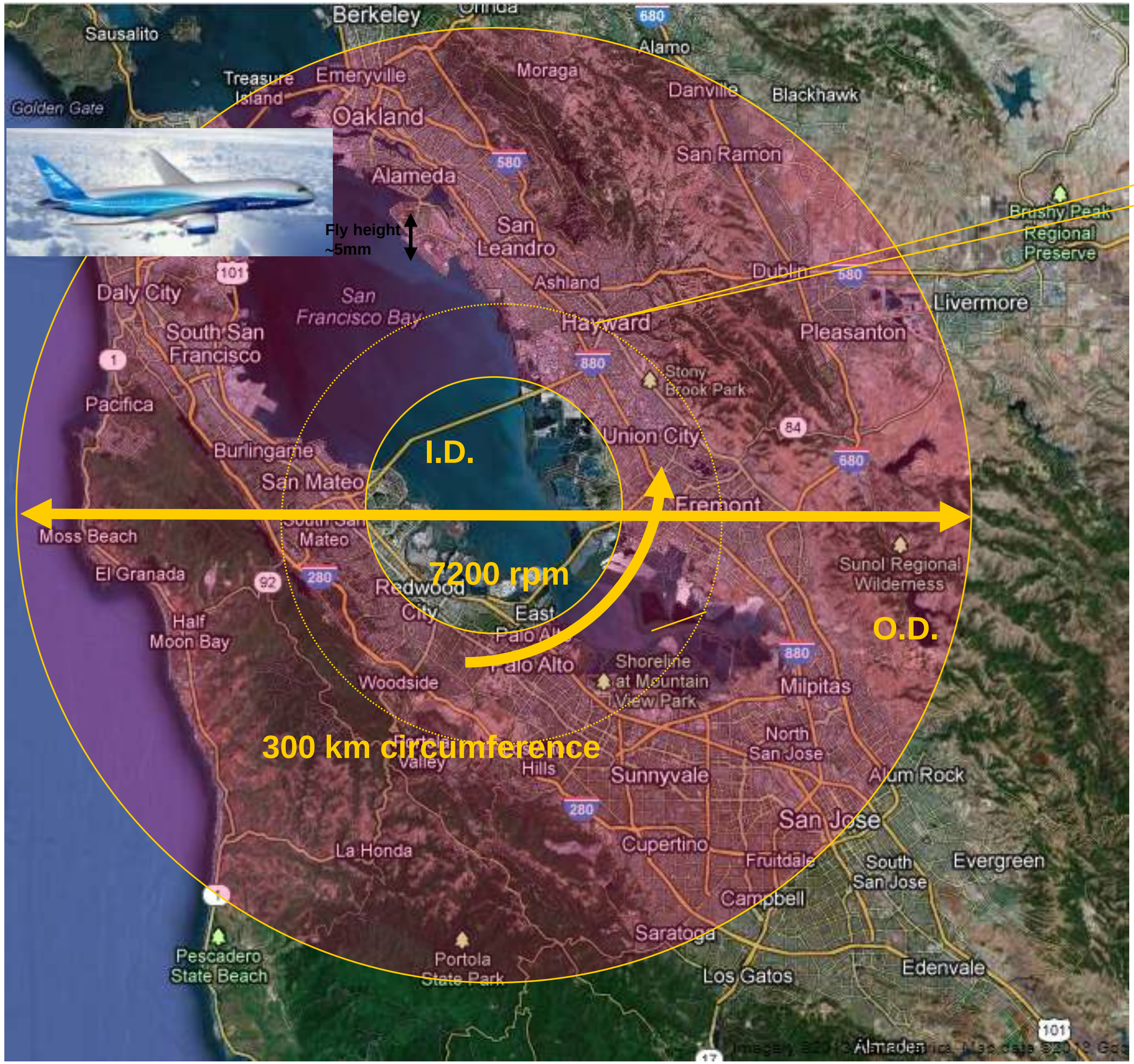


Head-Disk Interface



R. Wood, ISPS 2016

Today~700Gb/in^2 (now 1Tb/in^2), HMS~8-10nm, BL~15nm, SCALED×10^6



Disk = SF Bay Area (95 km dia)

1bit = 1 finger (1.5 × 8cm)

Head = Boeing 787

Fly speed @ O.D.
= 7200 rpm × 300 km
= 0.12 c (c=3x10^{8}m/s)

Fly height = 5mm

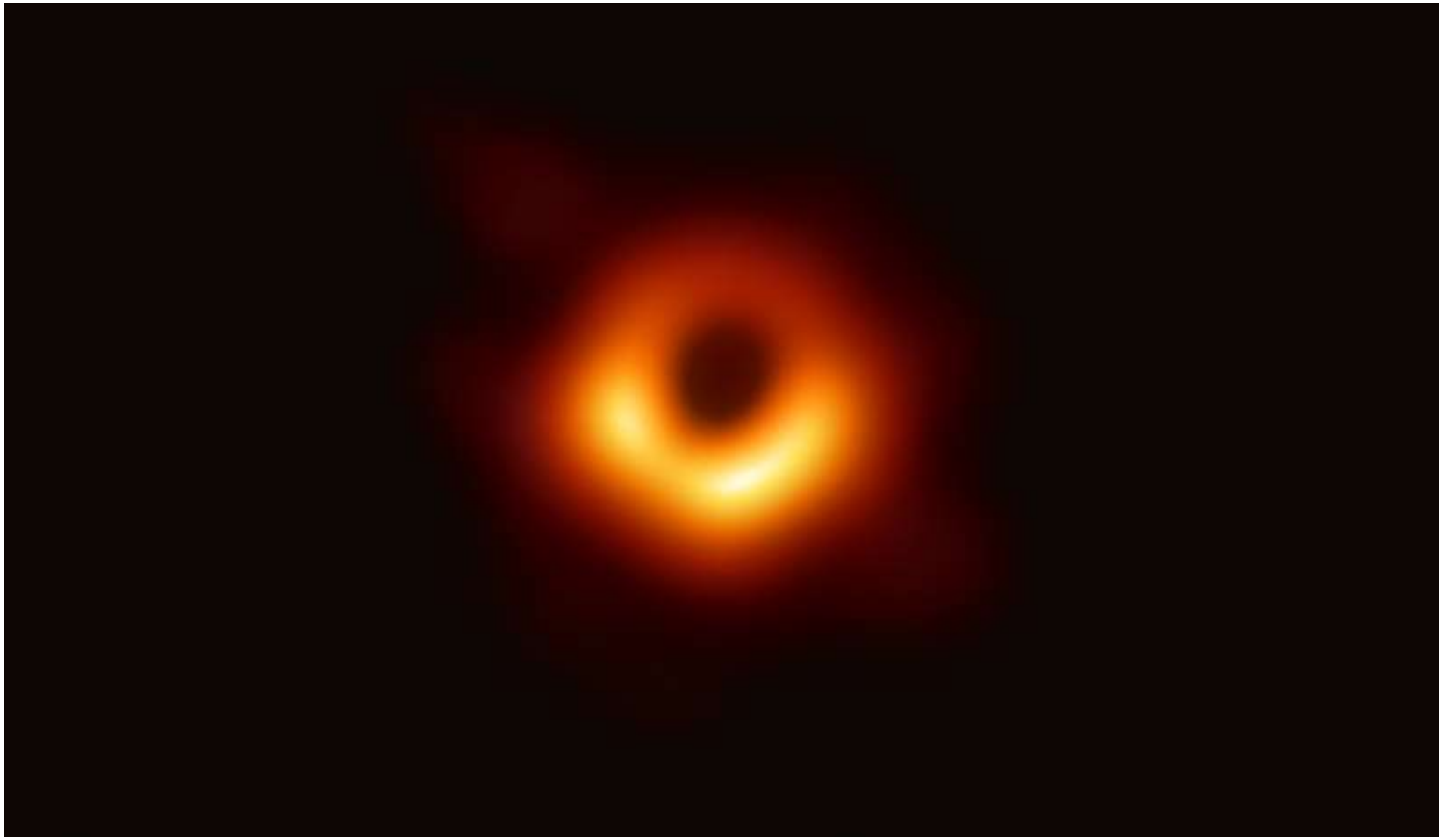
HDD × 1 million =
"a Boeing 787 flying at 12% of the speed of light (at disk's O.D.) 5mm above a 95 km wide disk and seeking, reading and writing bits of information the size of a human's finger"

Helium-Sealed HDDs

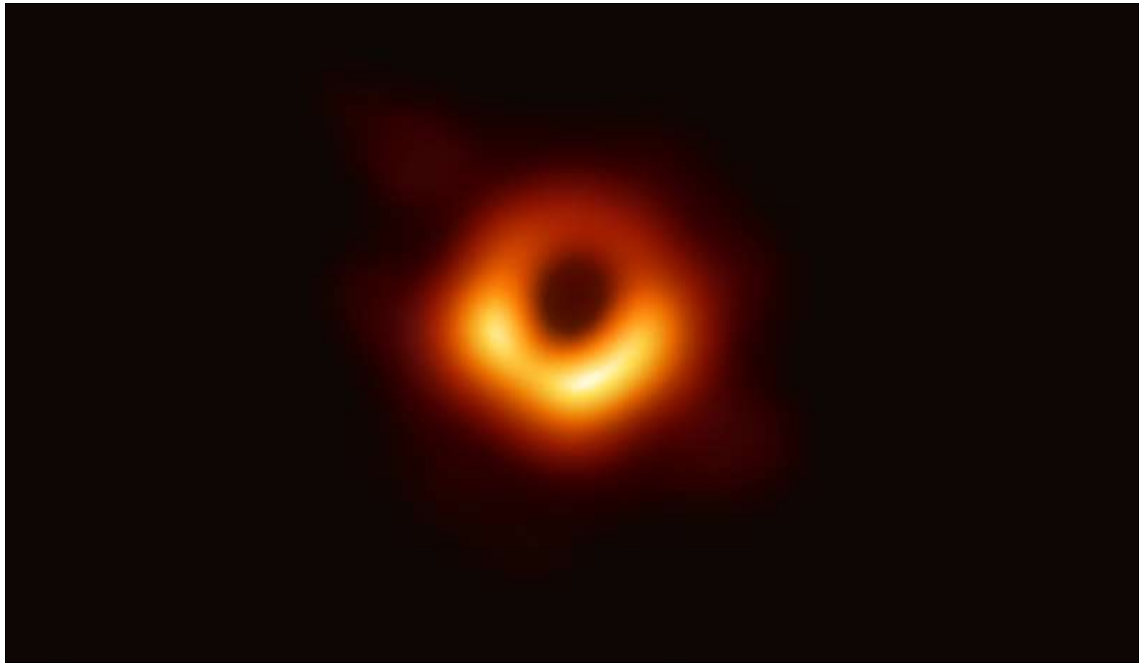
- 2013: First helium-sealed drive from HGST, 6TB Ultrastar He6 had 5 disks
- Breakthrough in sealing the helium in the drive
- Current generation: 14TB, Ultrastar He14 has 8 disks
- Advantage of He: less drag → less power & less noise. Thinner disks, pack in more disks → higher capacity drives

Source: blog.westerndigital.com

What is it ? And why is it here?



Black hole



Western Digital's HGST 8TB helium-filled drives were used, whereas capacity and cost limitations ruled out SSDs.

They wrote time-slice data using a round-robin algorithm across the 32 hard drives. These drives are mounted in groups of eight in four removable modules.

The low ambient air density at the telescope sites necessitated sealed, helium-filled hard drives, both for the system disk for recorders and also in all the data recording modules. Ordinary air-filled drives crashed when tried out in 2015; the air was too thin to provide the cushion needed to support the heads.

Microactuator

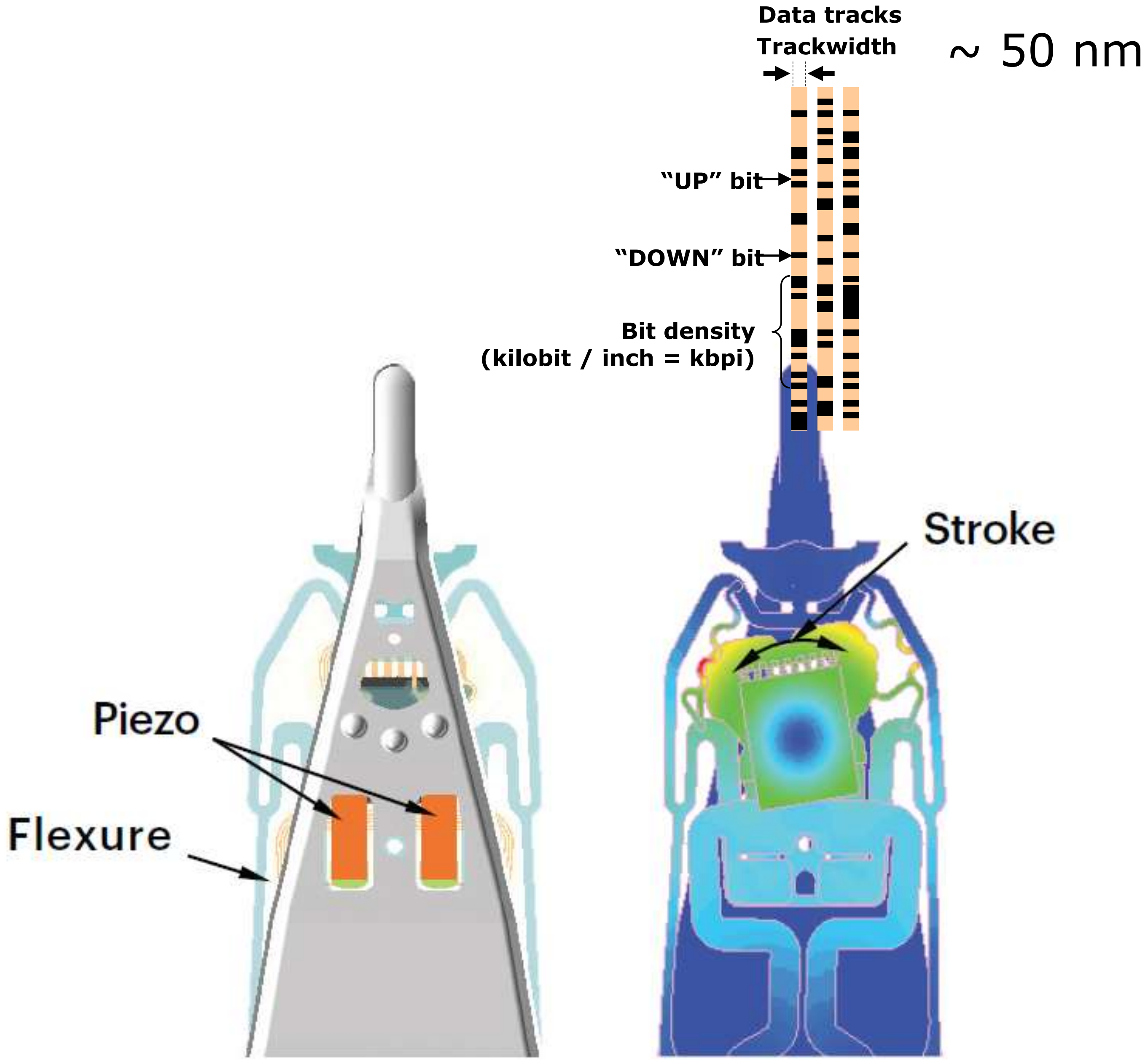
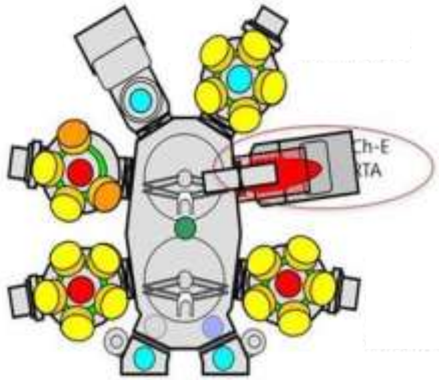
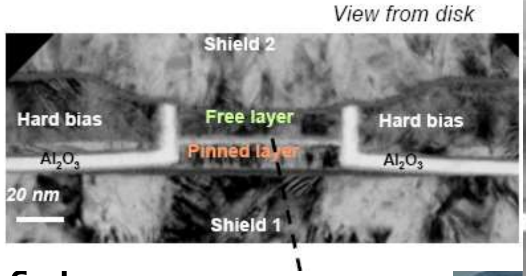


Figure 1. WDMA structure and actuation

Snapshot of manufacturing heads & media

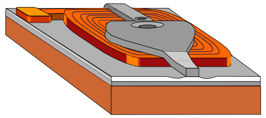
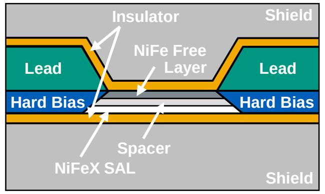
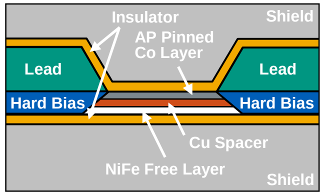
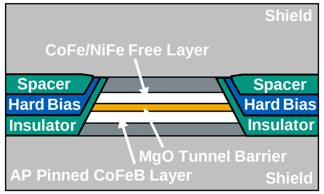




<u>Read/write heads:</u>
1 wafer (150 or 200 mm)
has ~100,000 heads
Wafer spends 4 months in the fab

<u>Media:</u>
20-24 sputter chambers
Sputter output ~ 800-1500 disks/hour
→ new disk every 3.5 sec

Read Head Sensor Technologies

Year	1st Density (Gb/in²)	Sensor Technology	Structure	MR Effect	Sense Current Geometry
1979	0.01 Gb/in²	Thin-film Inductive		N/A	N/A
1991	0.1 Gb/in²	MR Sensor		Anisotropic MR	CIP
1997	2 Gb/in²	Spin Valve		Giant MR	CIP
2006	100 Gb/in²	Tunnel Valve		Tunneling MR	CPP
?	>1Tb/in²	?	?	?	?

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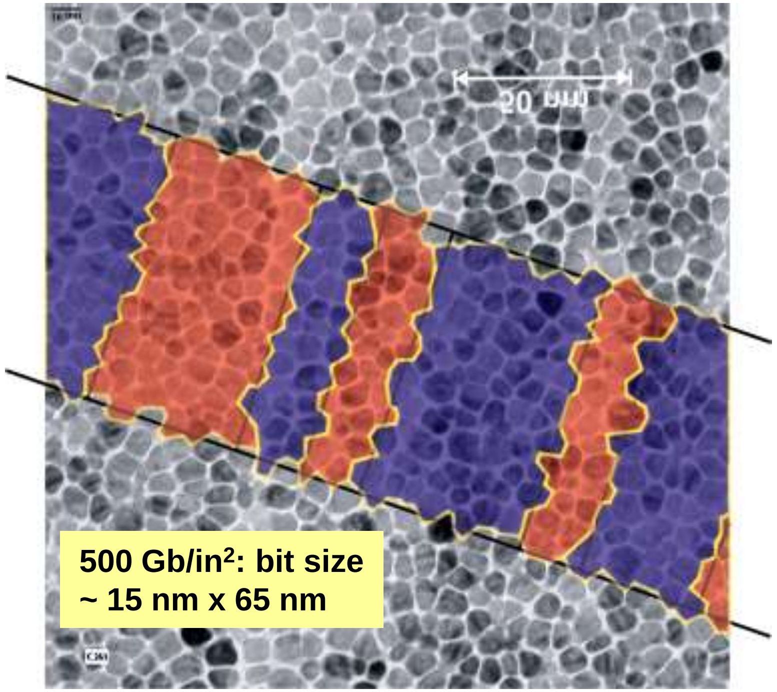
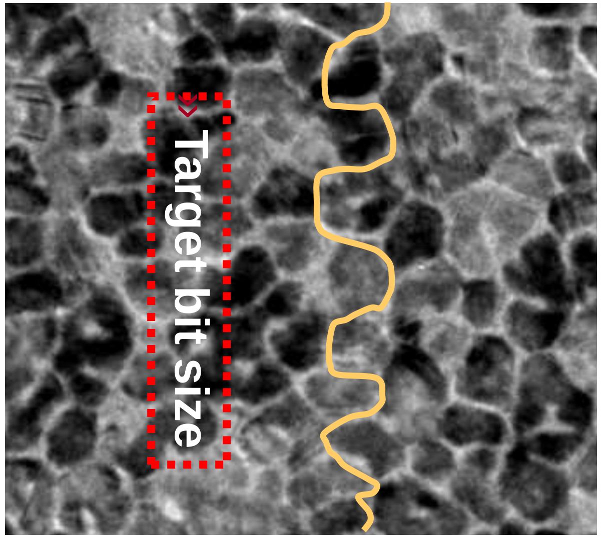
Bit Density vs Grain Size → Media noise

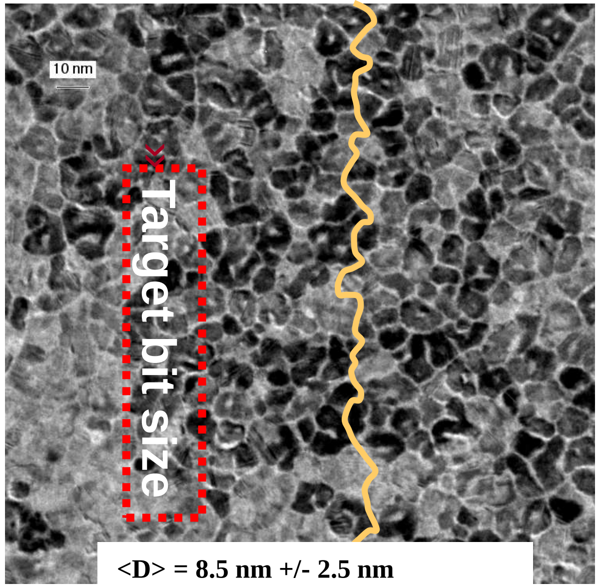
The edges of each recorded bit follow the grain boundaries
→ edge noise



→For smaller bits (higher density), need **smaller grain sizes** to avoid increasing noise

→**Scale media microstructure** together with rest of recording system





More noise

Less noise

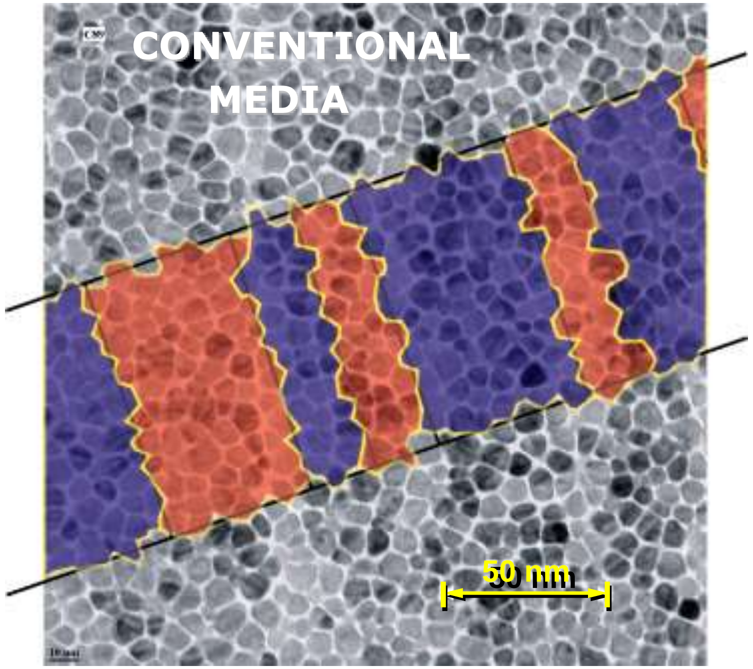
$$SNR \propto \frac{B}{D}\sqrt{\frac{R_W}{D}}$$

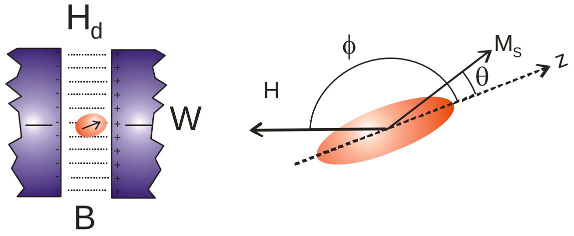
B=bit length
D=grain diameter
R_w= reader width

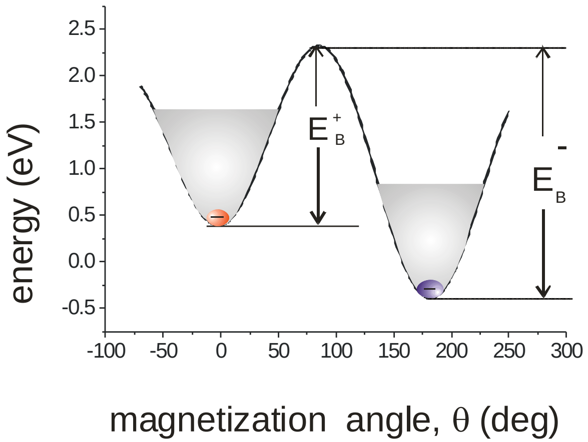
Data Density, Grain Size, and Thermal Stability

stored magnetic energy ∝ anisotropy x volume
thermal energy ∝ temperature and time

$$\frac{K_u V^*}{k_B T}$$







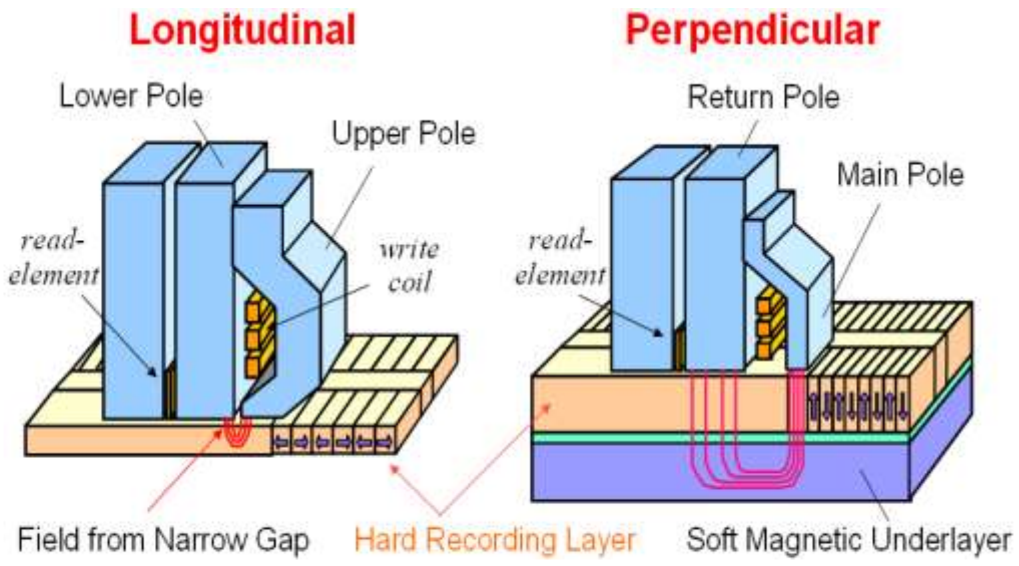
- to increase density, need to scale grains smaller
- smaller grains are thermally unstable (data erases itself!)

SOLUTIONS:

- improved writability (perpendicular media)
- work with larger grains: patterned media
- work with higher anisotropy: energy assisted recording

Perpendicular Magnetic Recording (PMR)

- **Essential to continued areal density growth**
  - Higher head fields, higher coercivity, thicker media, greater thermal stability
  - First product introductions in 2005 and 2006

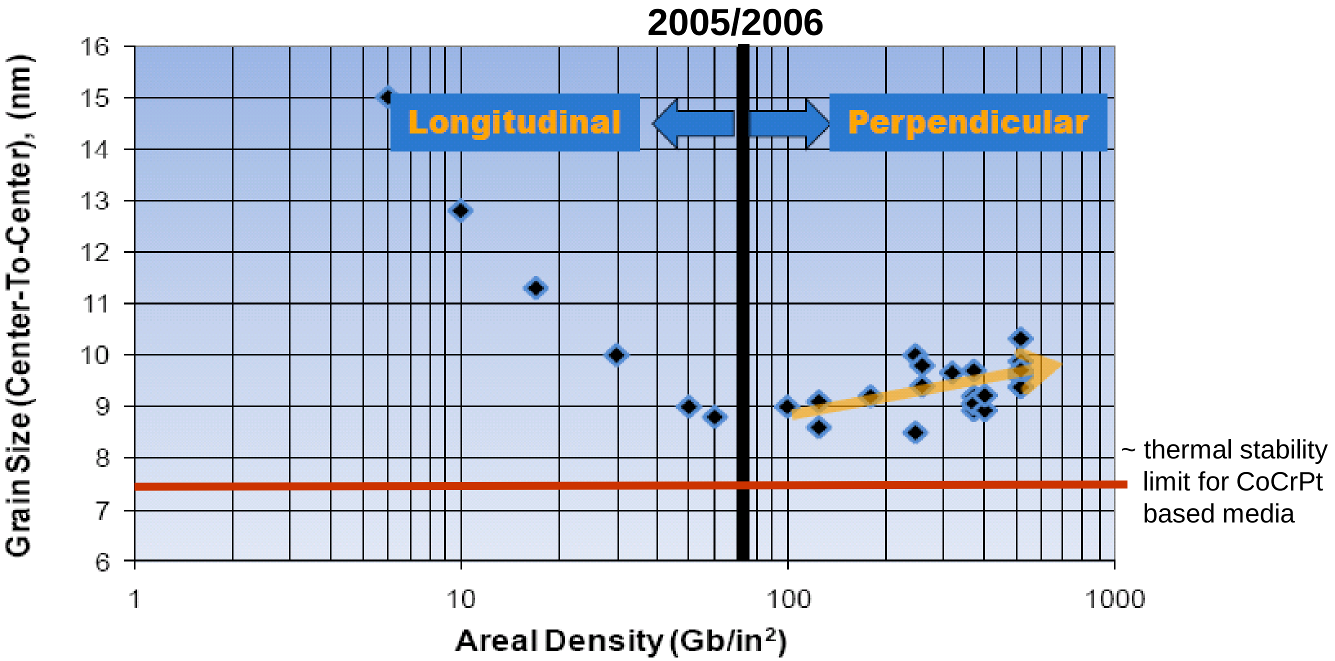


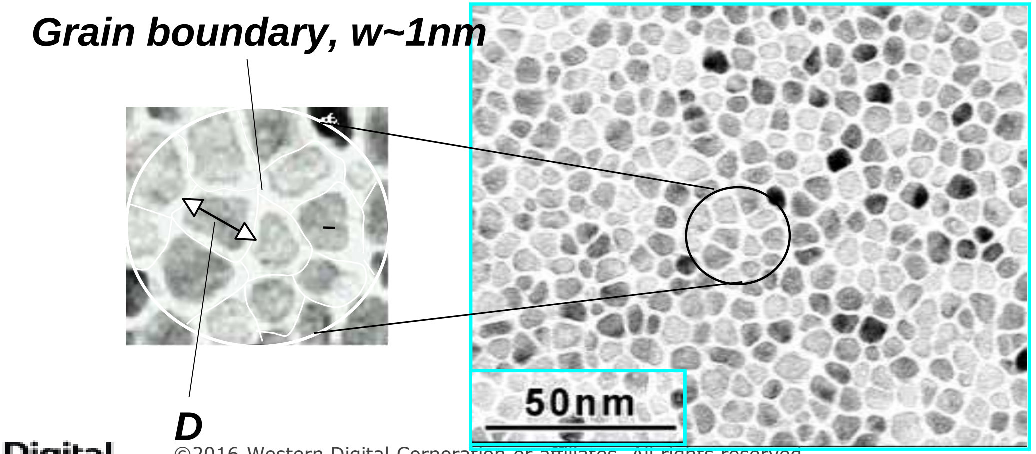
- **All HDD are perpendicular.**
- **Media is part of write head.**
- **Enabled new media technology, such as exchange spring**

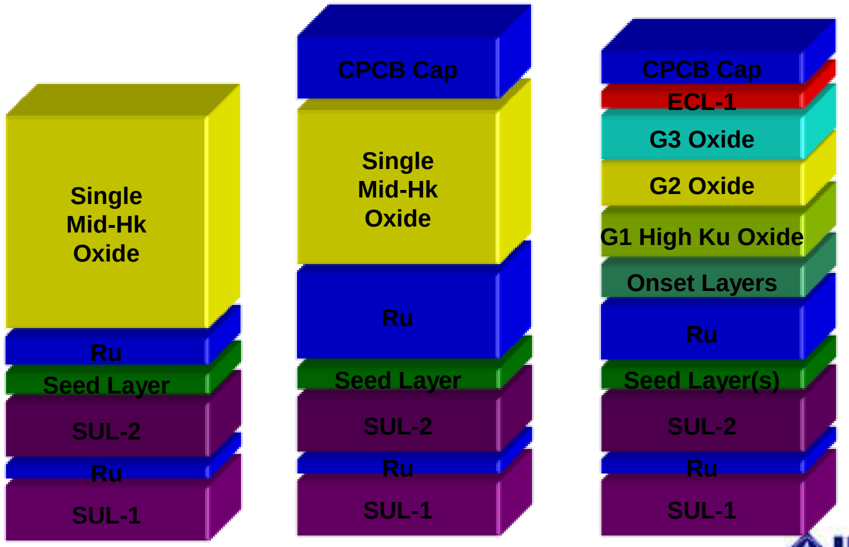
Grain Size vs Areal Density

Grain size has been constant since PMR was introduced, but density still increased 5-fold from 150-750 Gb/in^2

Progress via reduction in magnetic cluster size and distribution (lateral exchange) by using a multi-layered media structure







Why Grain Size has not decreased

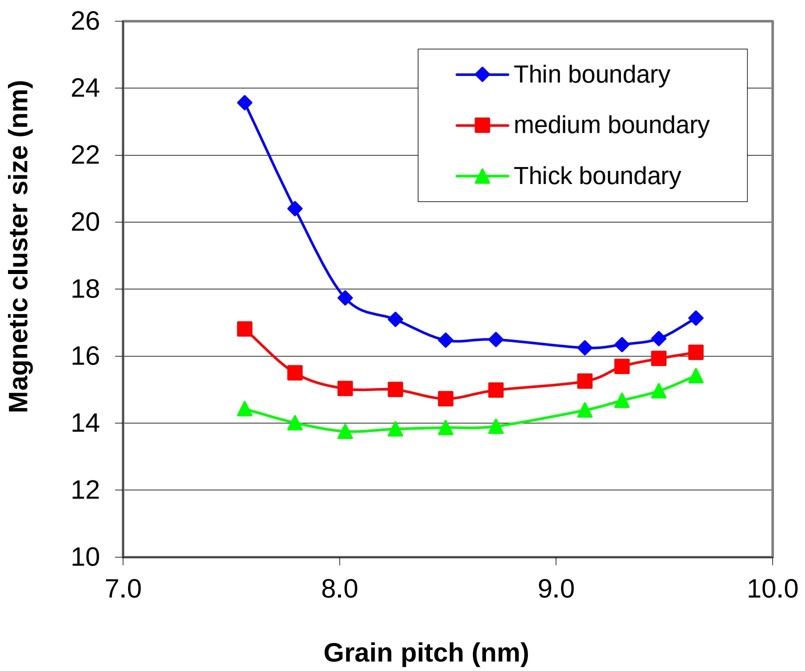
When using smaller grain Ru to reduce CoCrPt grain pitch,

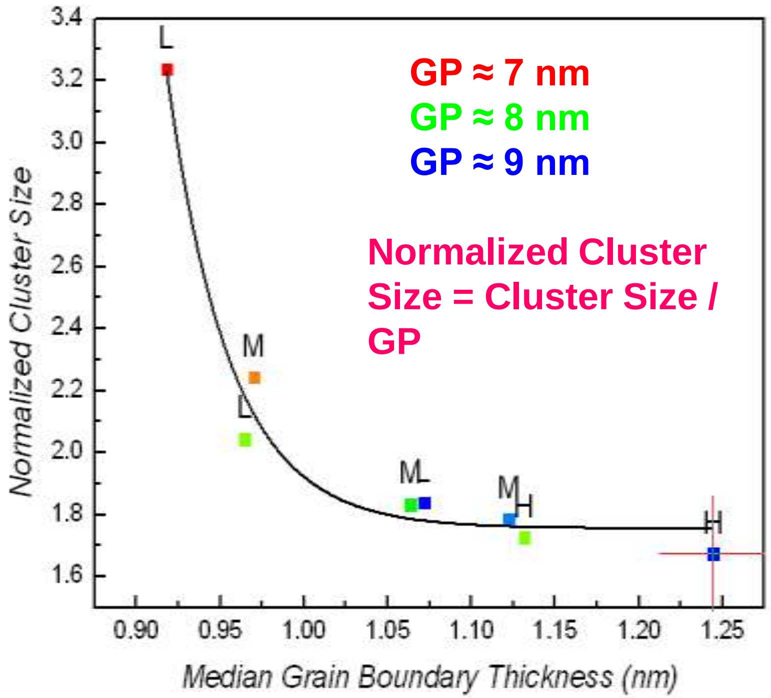
➔ thinner grains boundaries

➔ more lateral exchange between grains

➔ larger magnetic cluster size (measured by MFM, scattering, loops,…)

➔ negates benefit of smaller grains, and also leads to larger exchange distribution

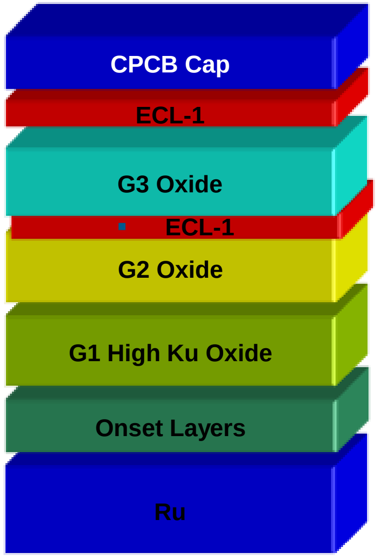


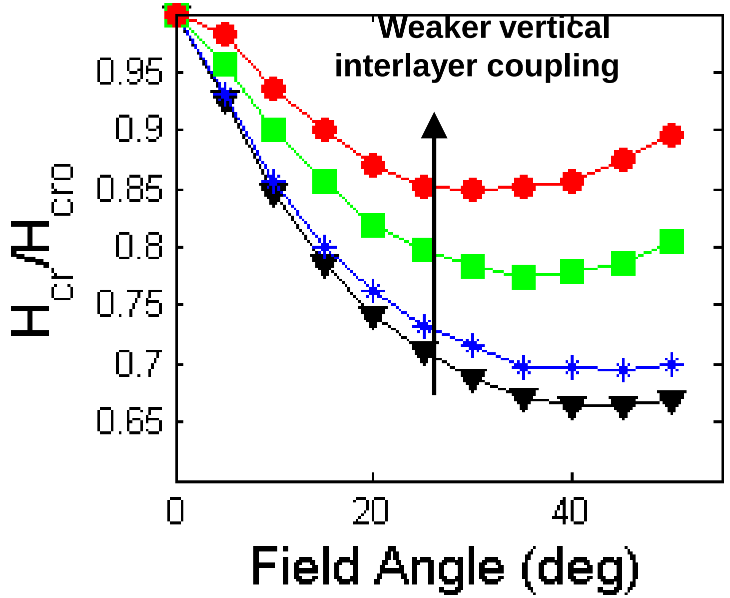


Exchange Control Layers

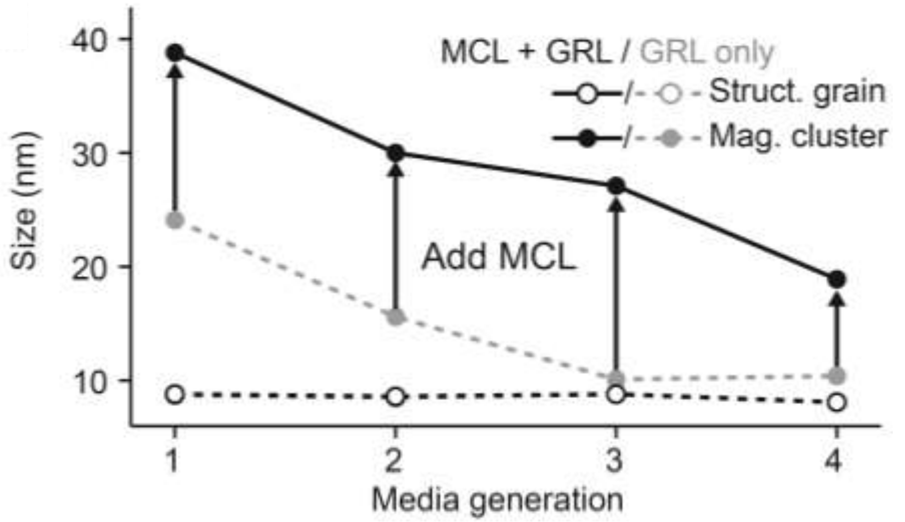
Solution to actually reducing grain size from here on:

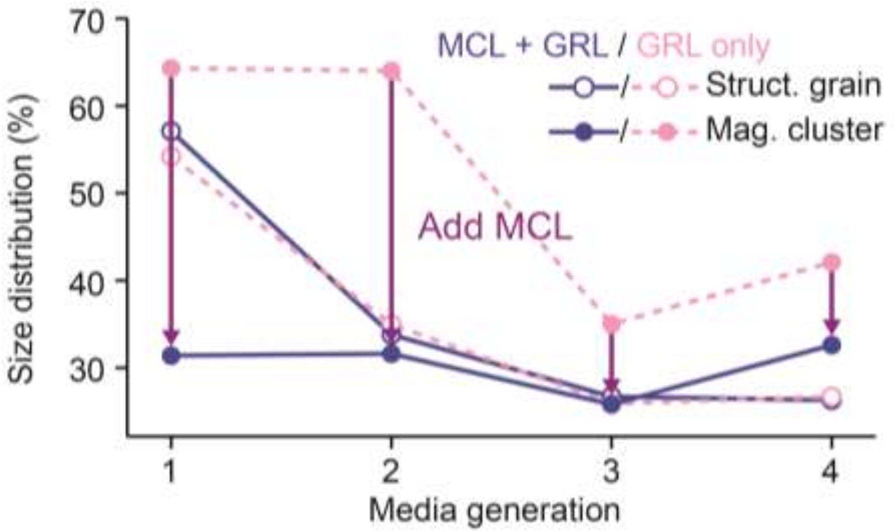
➔reduce grain core, fixed boundary thickness
➔ maintains cluster size, but reduces thermal stability
➔ need to increase Ku
➔ too hard to write
➔ reduce vertical exchange to allow more incoherent rotation, also reduced lateral exchange in cap
➔ **But,** reduced lateral exchange also increases distributions !

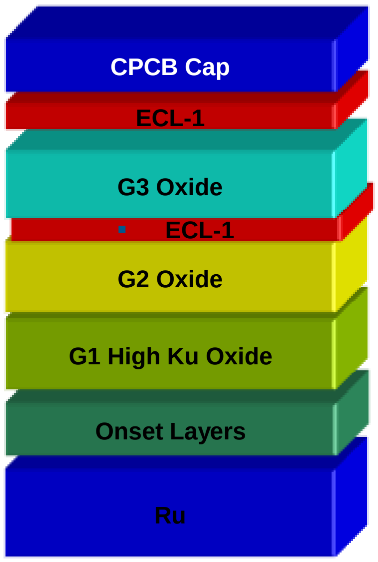


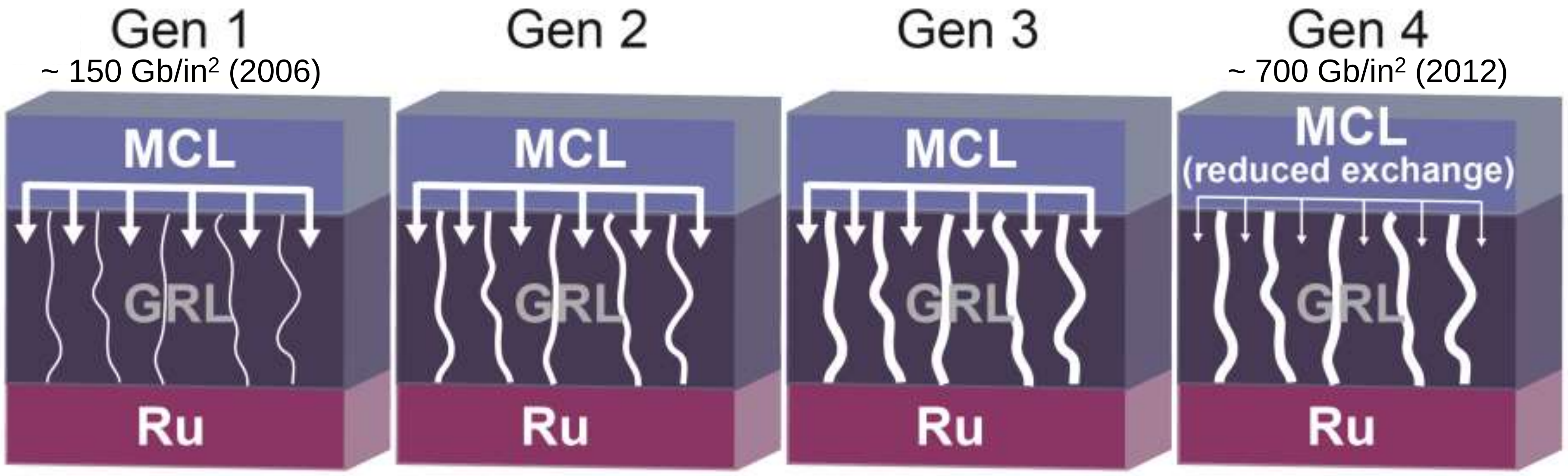


SAXS Study of PMR Media (distributions)









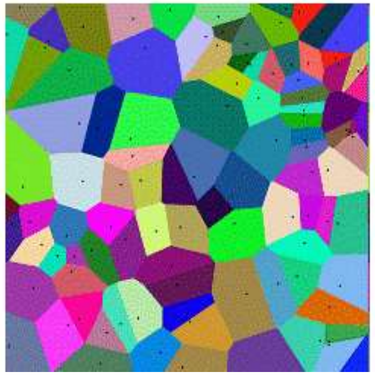
MCL = Magnetic Cap Layer, GRL = Granular Recording Layer

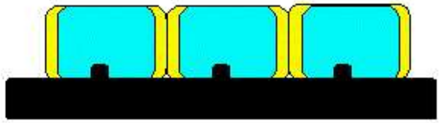
T. Wang, B. Terris, O. Hellwig et al, APL 2013

Grain Size & Boundary Width Distributions

Veronoi

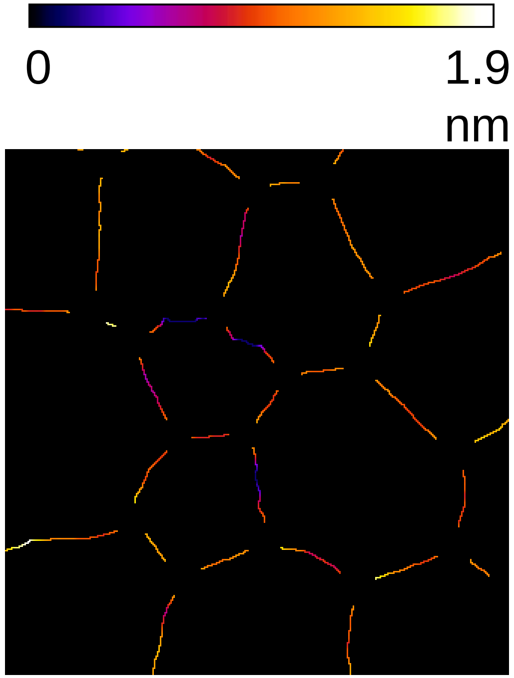
Tesselation





50A TaN/[60A CuN/10A Ta]10/50A TaN

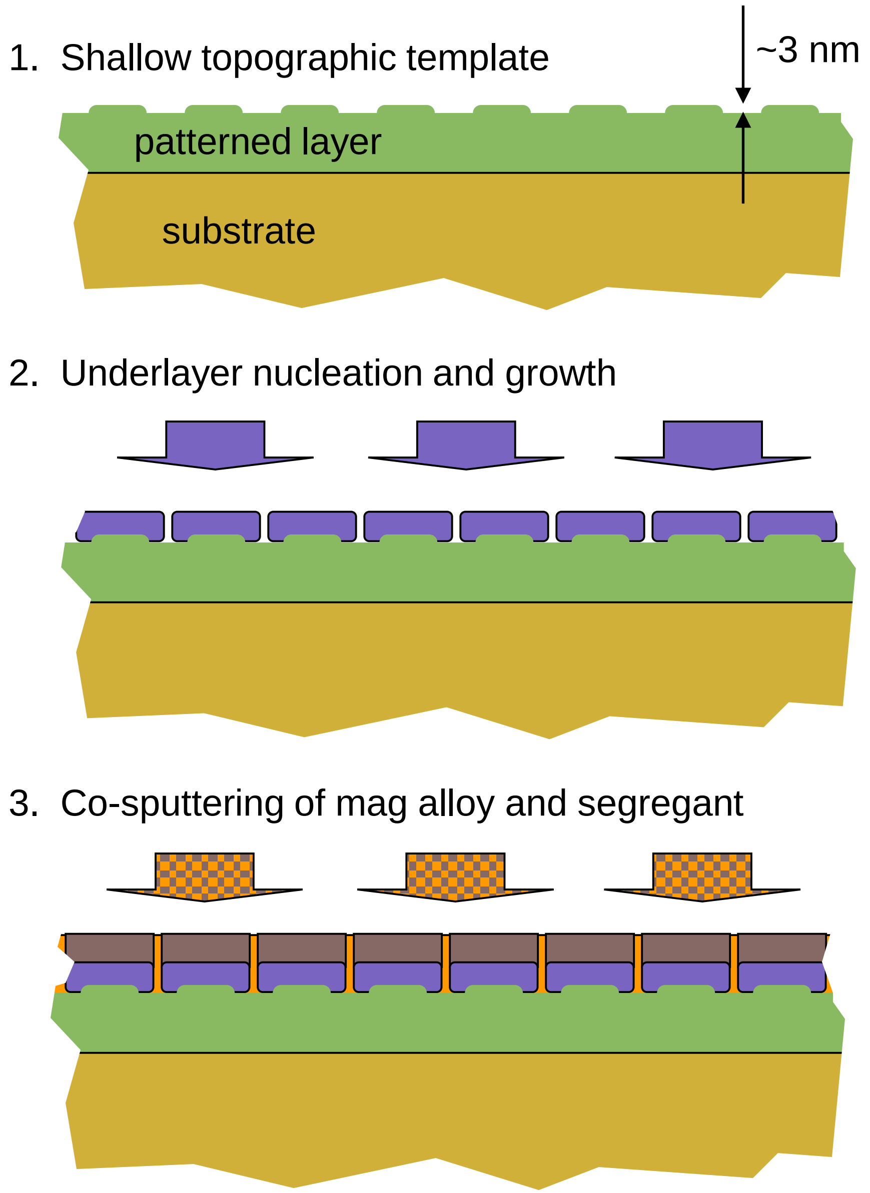
Measured grain boundary width



Variation in grain boundary width

- **Voronoi growth will have ~22% size distribution**
  - Random grain seeds, isotropic 2D growth
  - Exchange exponential in boundary thickness
- ***How can we better define grain nucleation sites?***

Templated growth of BPM

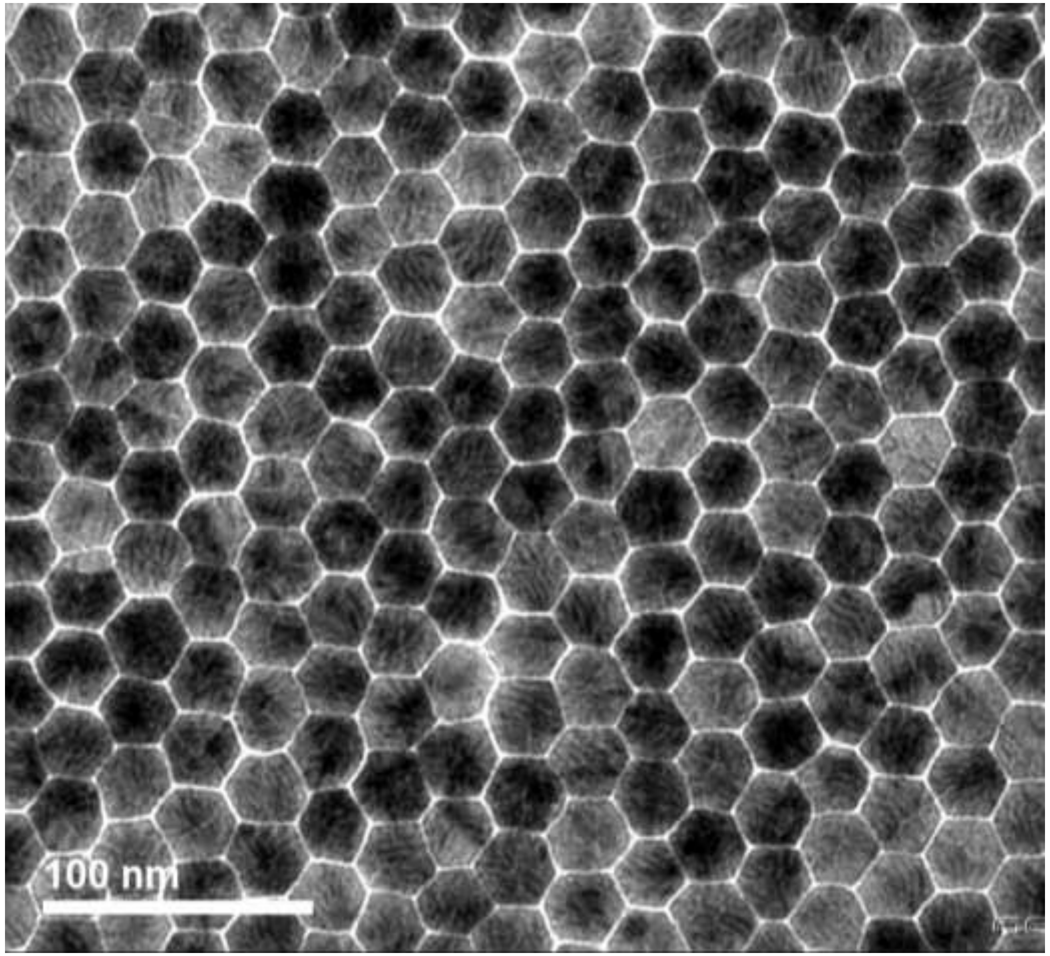


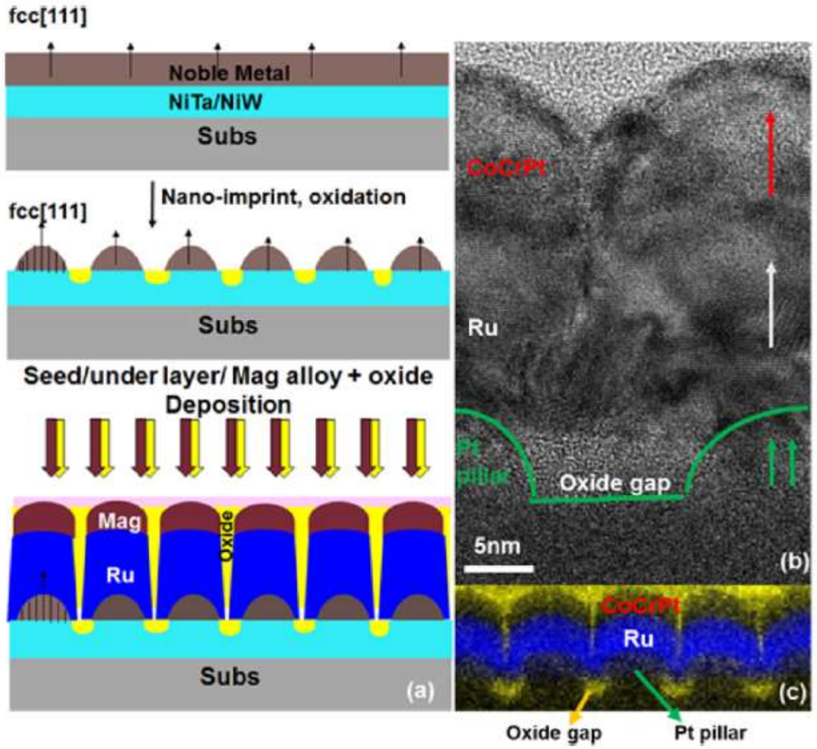
US7776388B2 (2007)
US8048546B2 (2009)
- Other in following years

Templated Bit Patterned Media

After several cycles of learning

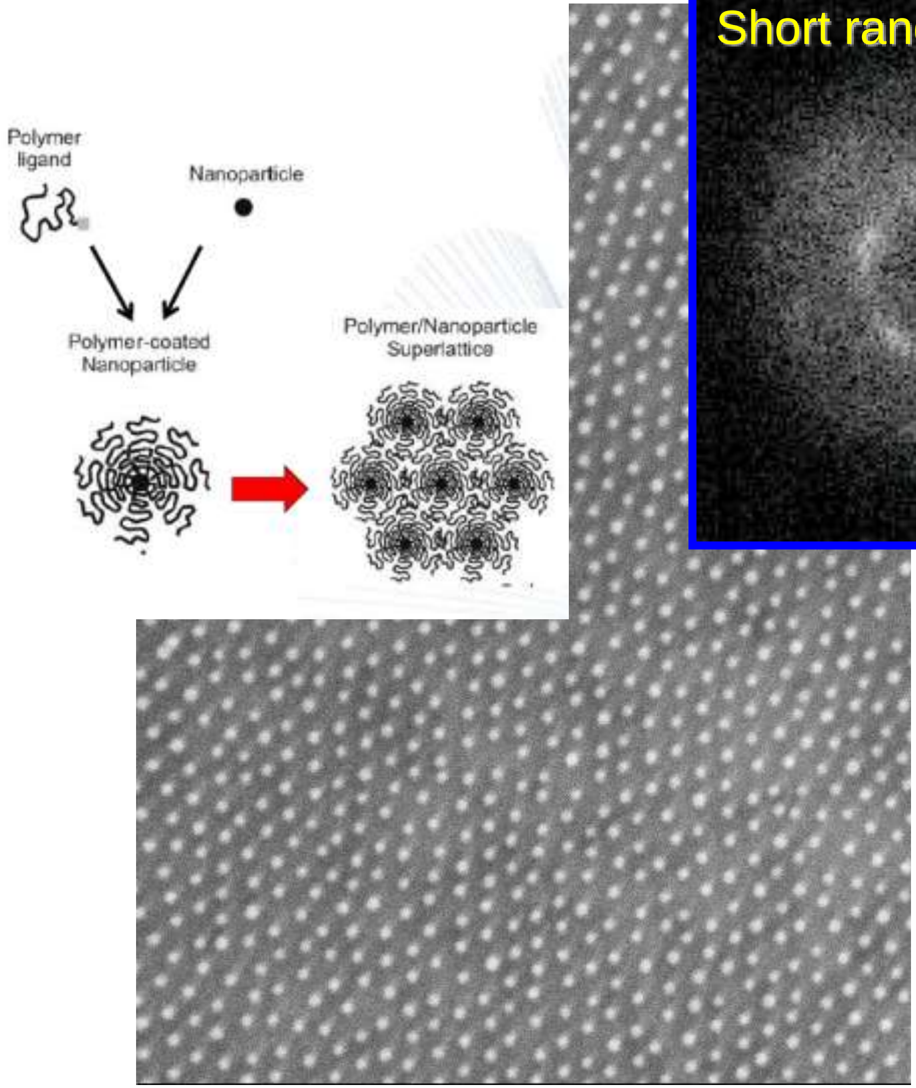
En Yang et al., *Nano Lett. 15, 4726* ***(2016)***

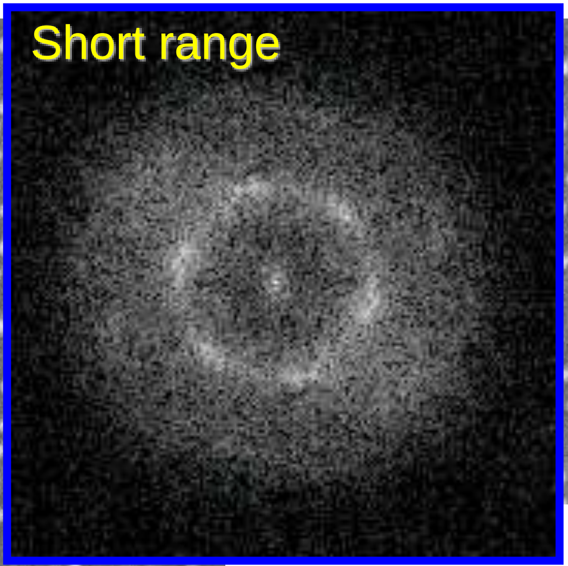


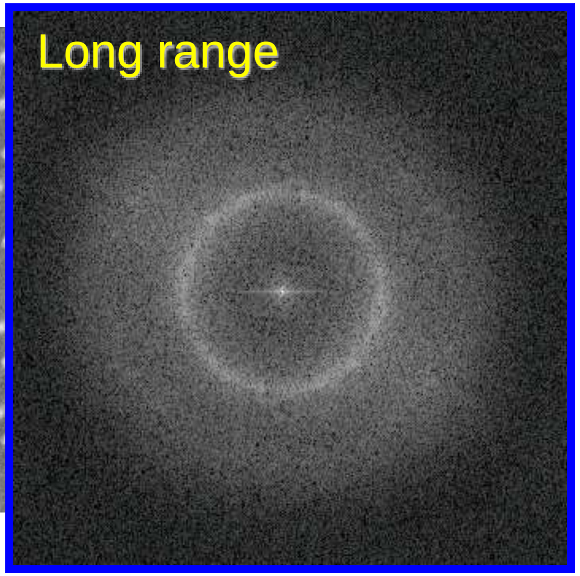


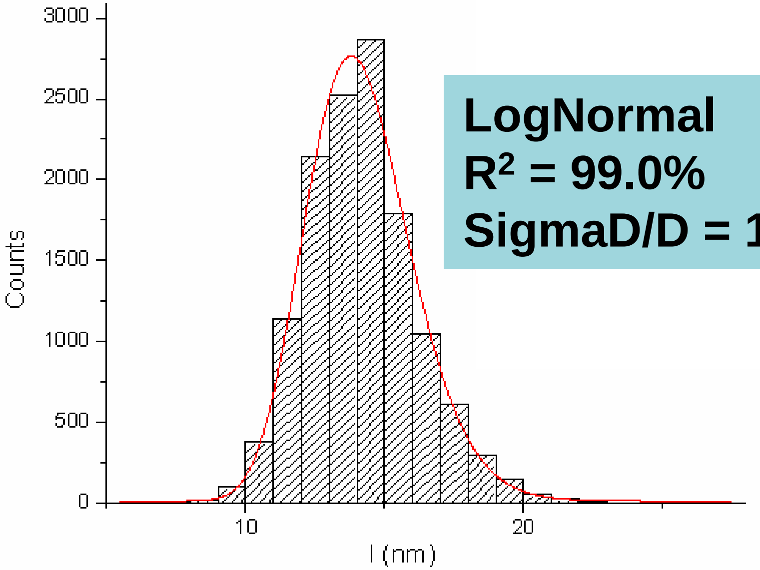
Innovation: Pattern crystalline Pt pillar. Grow Ru on top of it

Search for Naturally Ordered Nucleation Sites





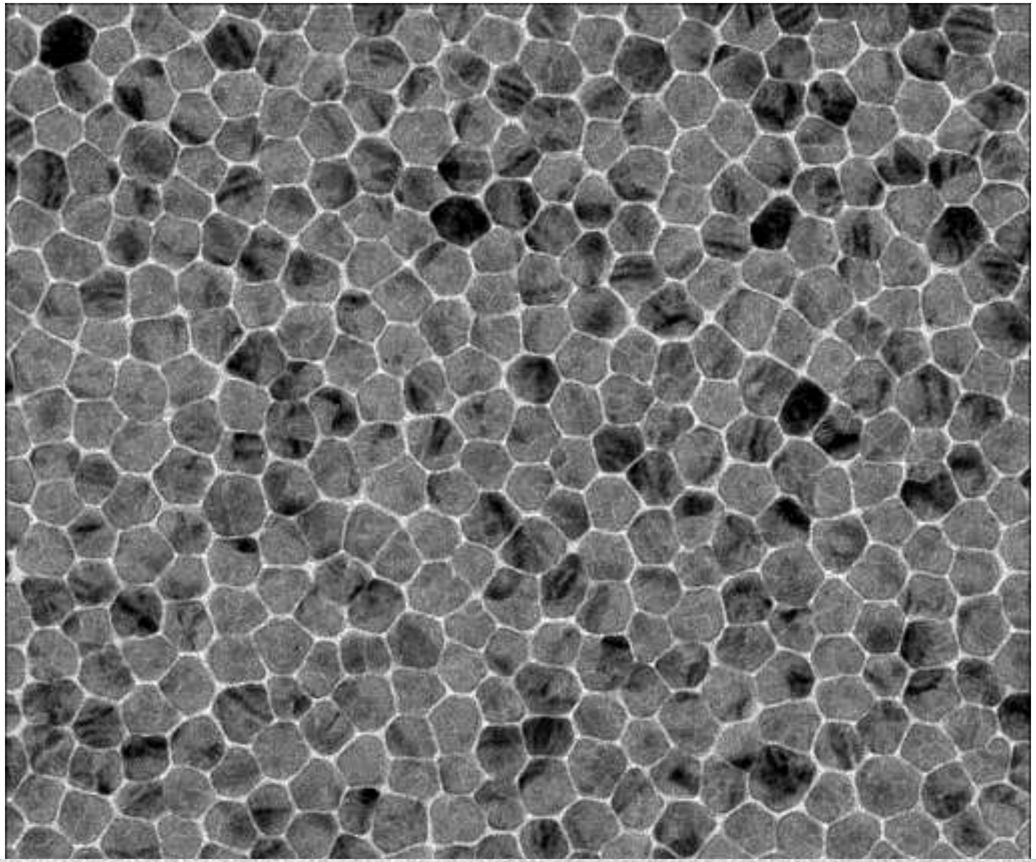


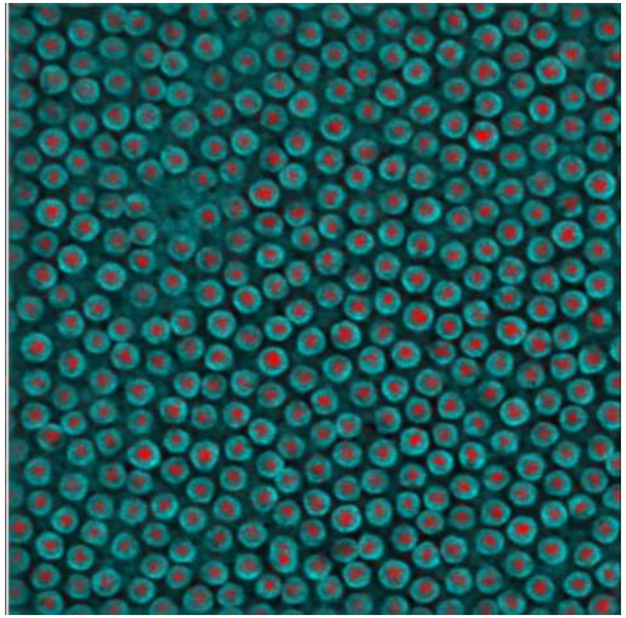


LogNormal
$R^2 = 99.0\%$
SigmaD/D = 13.4%

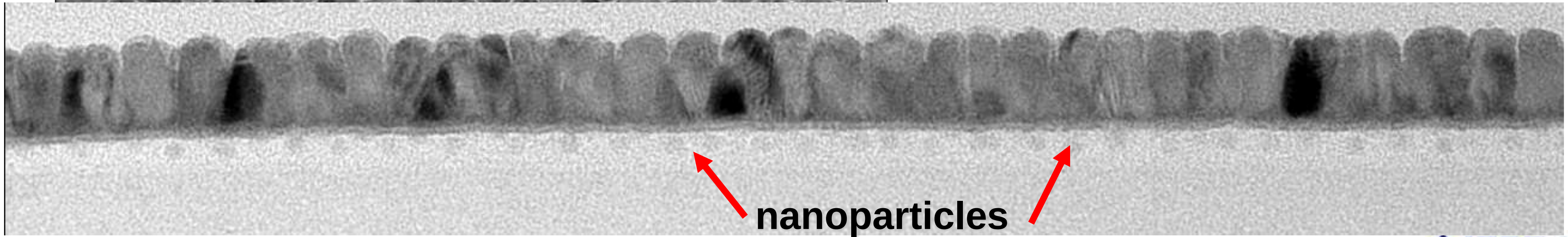
TEM Evidence of Templating Effect

$\sigma_D/D = 8.03\%$



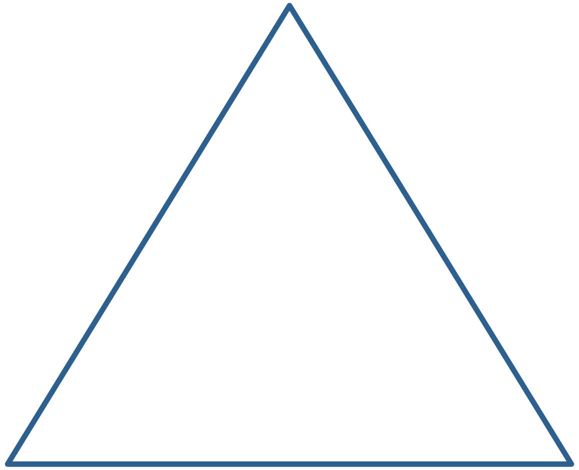


EFTEM, red=Fe



Storage Trilemma: SNR, thermal stability, writability

$$\frac{\text{energy barrier}}{\text{thermal energy}} \propto \frac{\text{anisotropy x volume}}{k_B \text{ x temperature}} = \frac{K_u V}{k_B T}$$



$$SNR \propto \frac{B}{D}\sqrt{\frac{R_W}{D}}$$

B=bit length

D=grain diameter

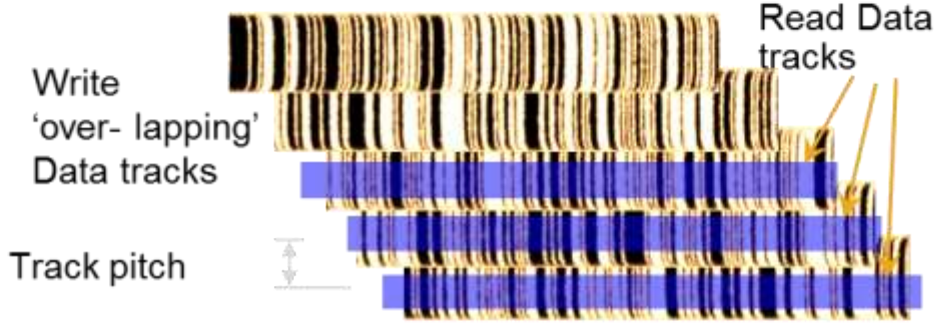
R_w= reader width

$H_{head} \sim H_{k,}\text{media} \sim K_u$

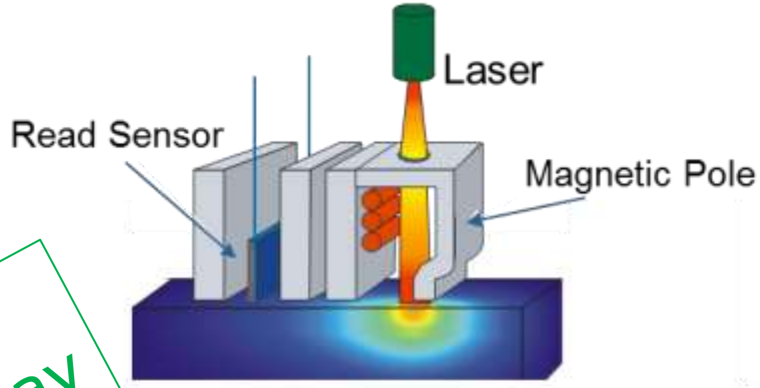
The problem:
To increase SNR, need small grains.
Small grains are thermally unstable.
To avoid thermal instability, increase grain anisotropy Ku.
Increasing Ku increasing media Hc and makes the medium more difficult to write.

Overcoming the Trilemma

Shingled Magnetic Recording (SMR)

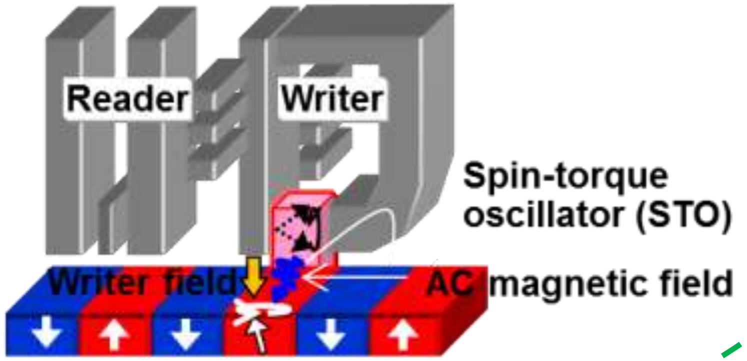


Heat Assisted Magnetic Recording (HAMR)

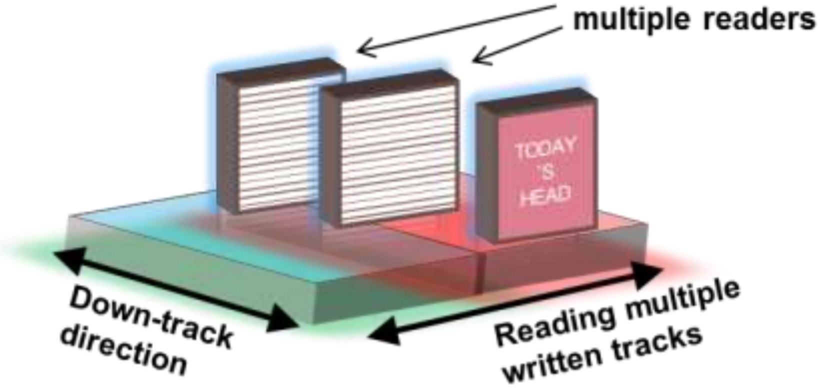


More on these today

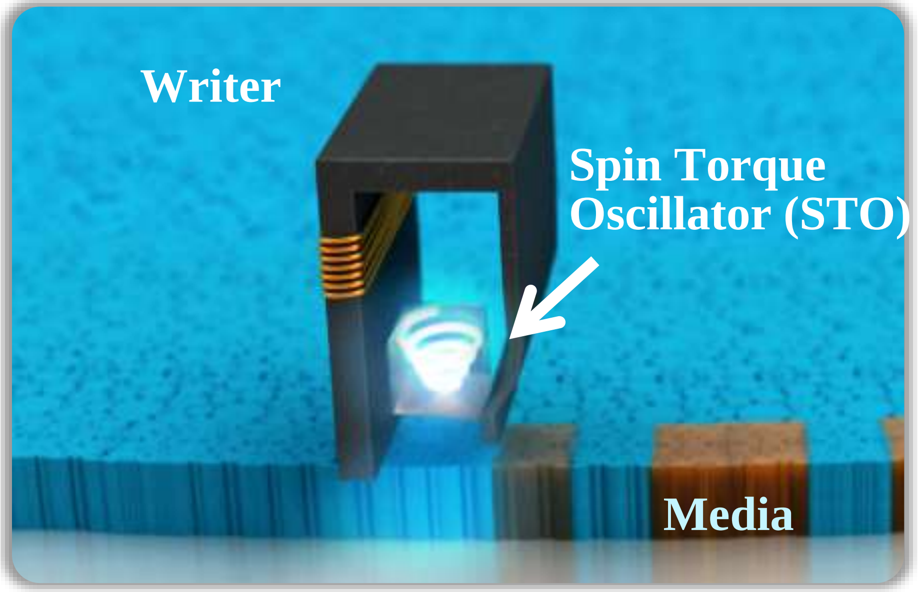
Microwave Assisted Magnetic Recording (MAMR)

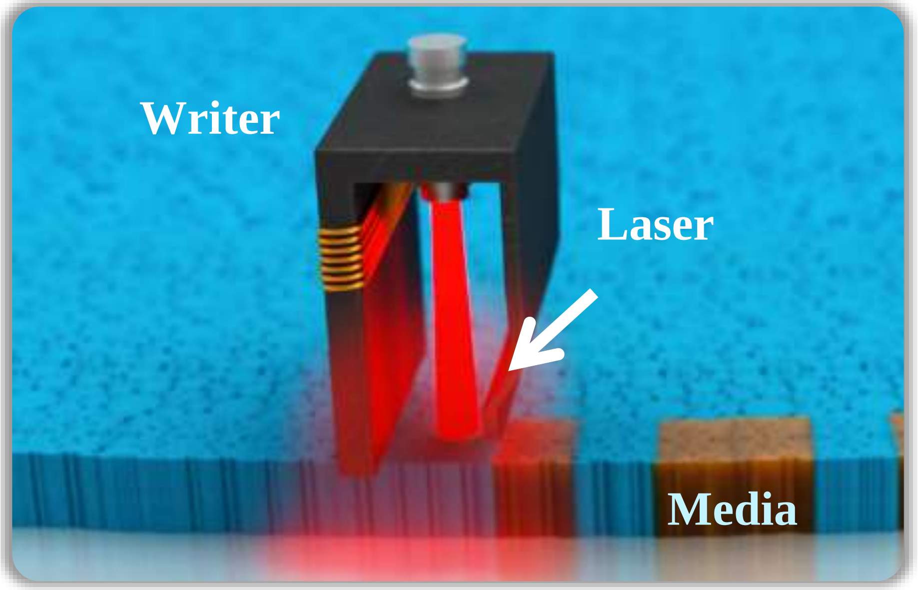


Two Dimensional Magnetic Recording (TDMR)



Energy Assisted Magnetic Recording: MAMR and HAMR





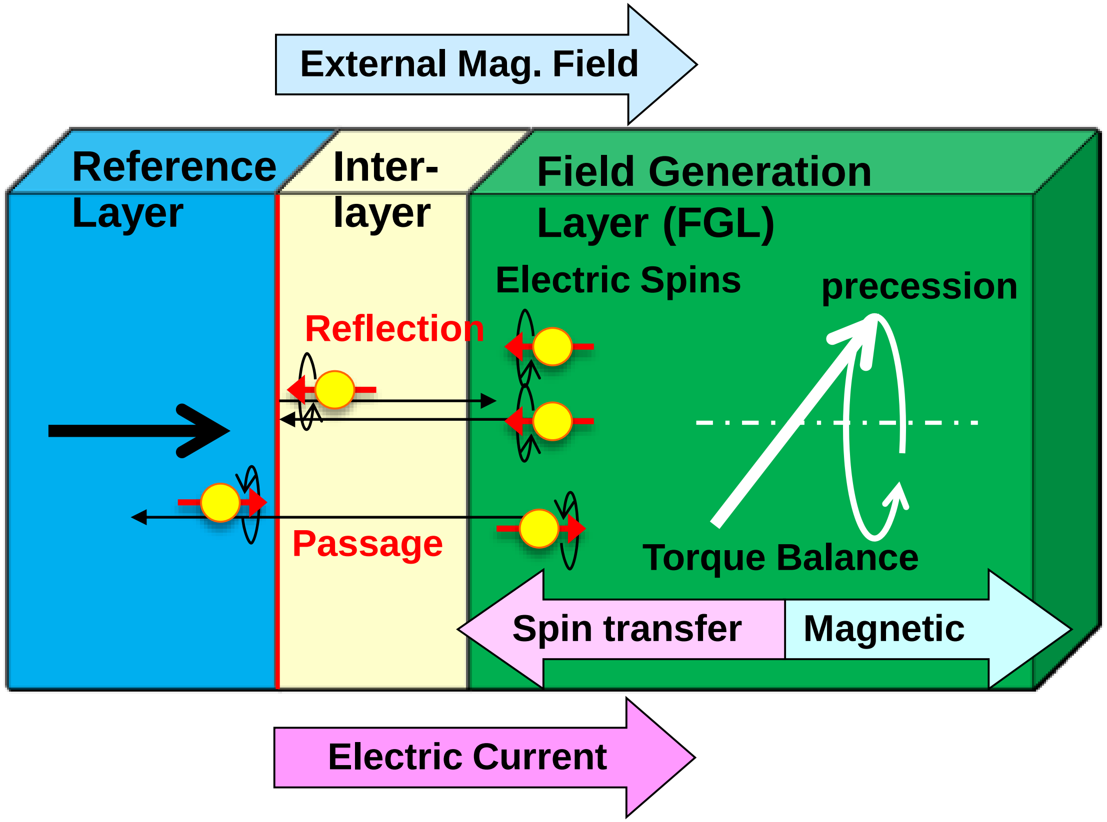
- Microwave fields emitted by a Spin Torque Oscillator (STO) allows writing higher coercivity media
- Heat from laser allows writing higher coercivity media

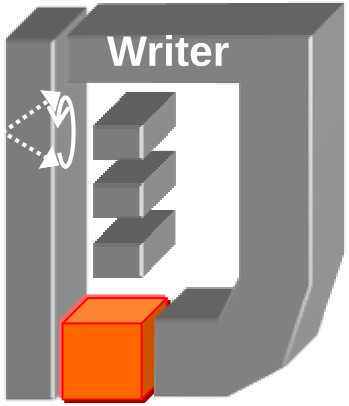
	MAMR	HAMR
AD	Zhu[1]: 4 Tb/in^2	Victora[2]: 4.7 Tb/in^2
Media	Grain=4.5nm, Hk=40kOe, KuV/kT=60	Grain=5.5nm, Hk=75kOe, KuV/kT>100
Head	STO=45nmx12nm, 35GHz ideal in-plane rot.	NFT=36nm lollipop, narrow reader

1: J.-G. Zhu, "SNR and Areal Density Gain in MAMR With Segmented Media," IEEE Trans. Magn., vol. 50, no. 3, 3200809-1 – 3200809-9.
DOI: 10.1109/TMAG.2013.2285215
2: Z. Liu,Y. Jiao, and R. H. Victora. "Composite media for high density heat assisted magnetic recording," Appl. Phys. Lett. 108, 232402 (2016);
https://doi.org/10.1063/1.4953231

Spin Torque Oscillator (STO)

- Leveraging the progress of spintronic technology, STO is the most critical development area in MAMR application

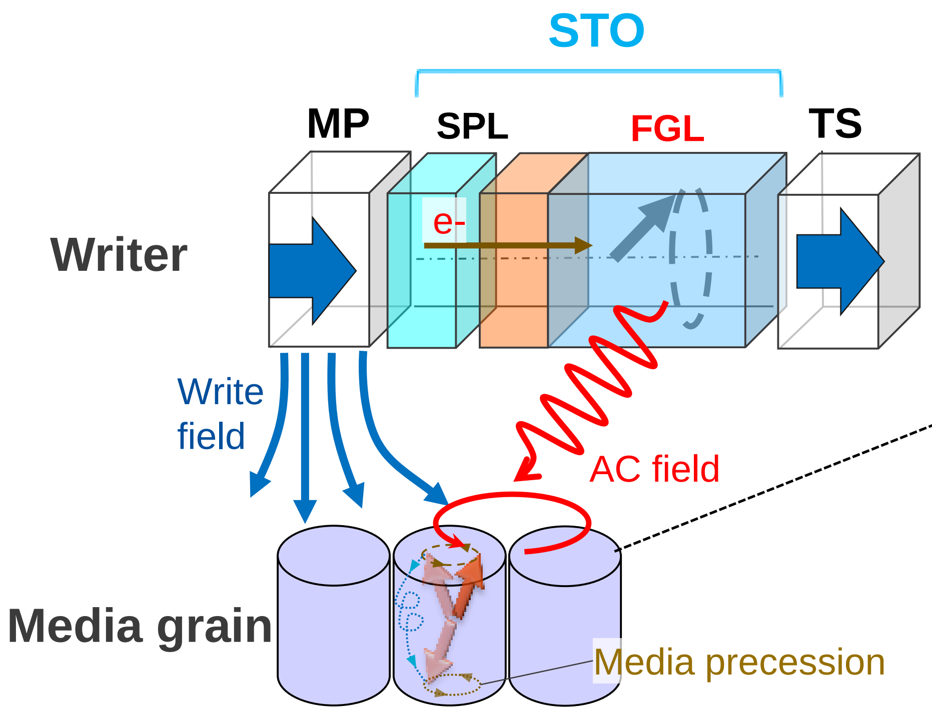


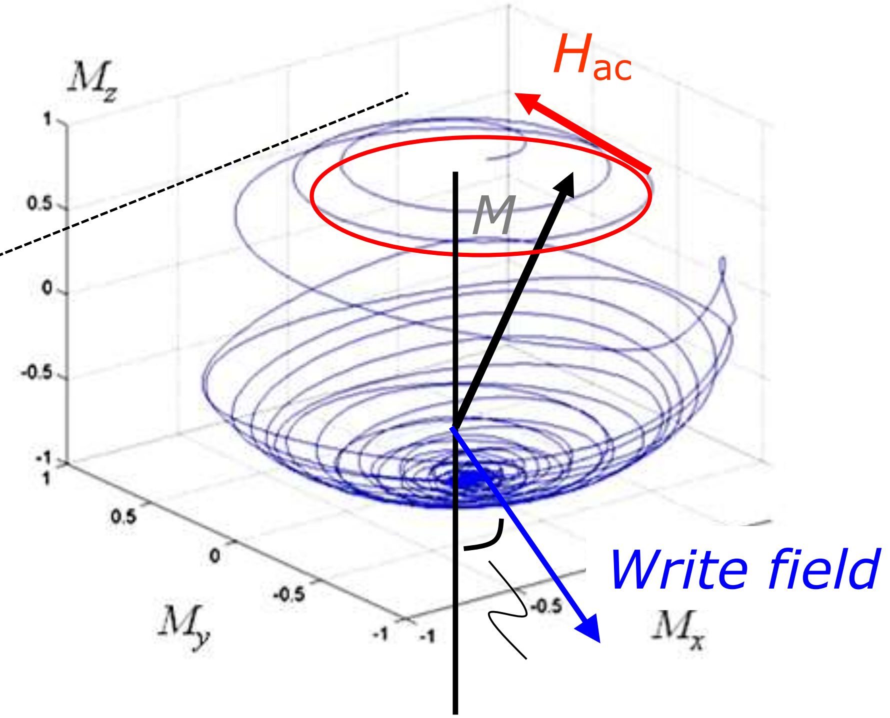


Spin-torque oscillator (STO)

MAMR Working Principles

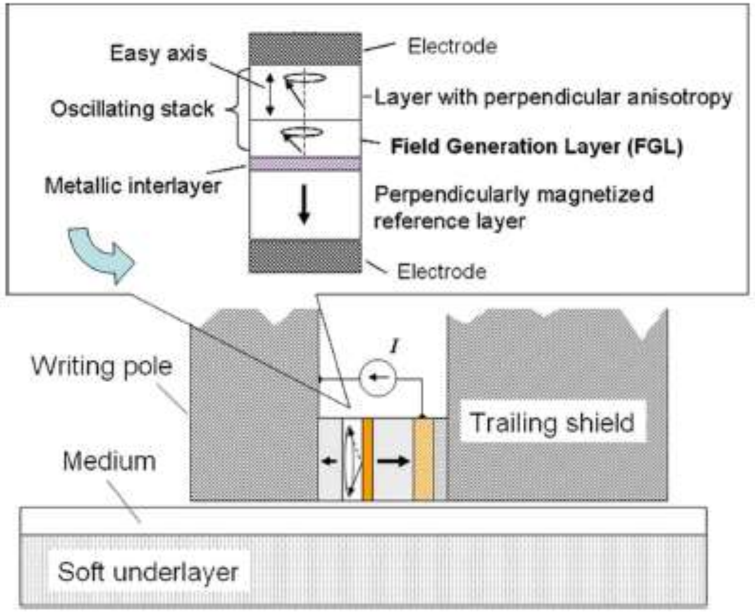
- STO generates an AC magnetic field.
- AC field assists media switching via media FMR (Ferromagnetic resonance)
- Media structure tuned for optimum frequency response
- MAMR technology enables writing of high Hk media.





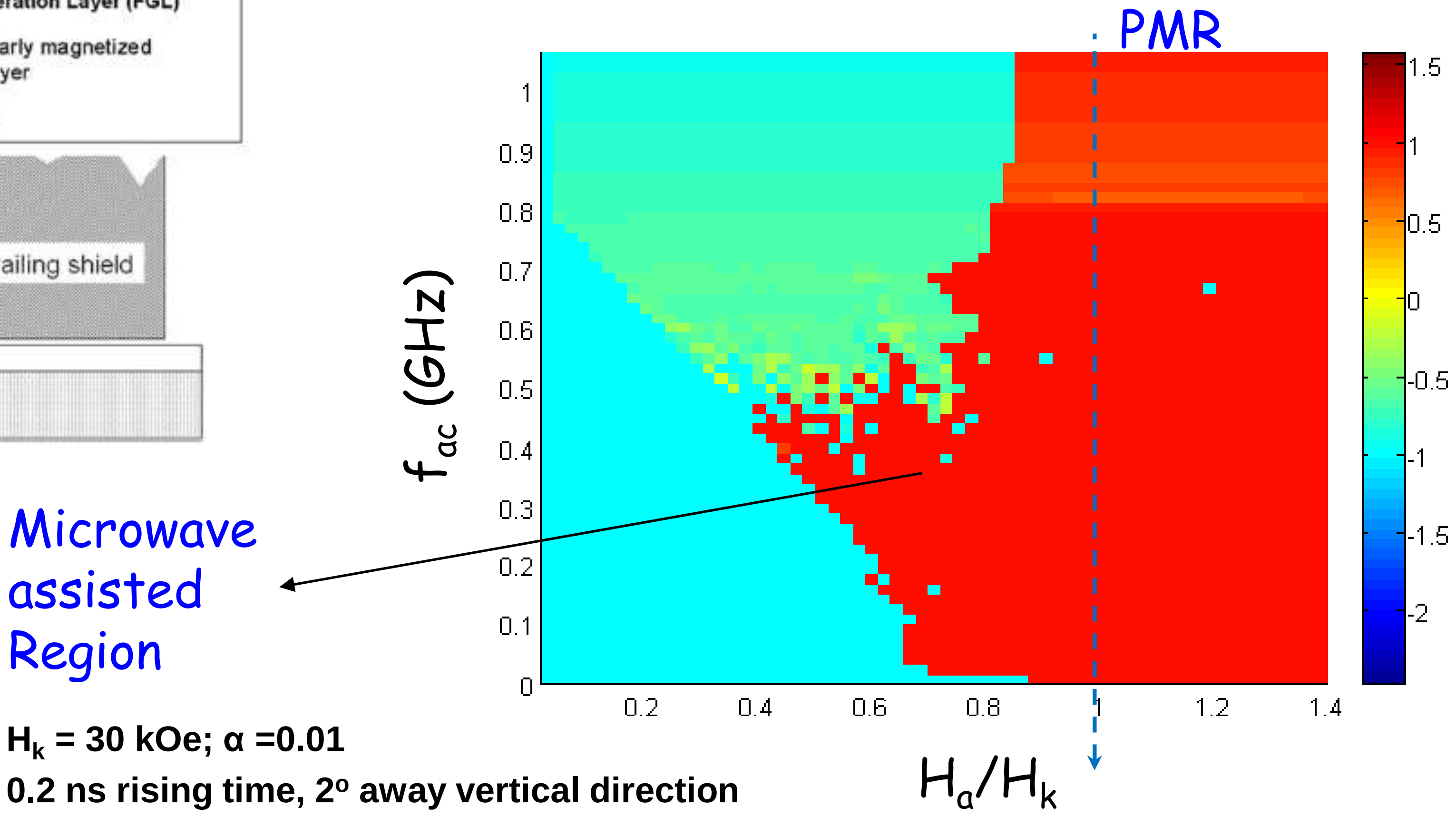
Microwave Assisted Recording (MAMR)

J. Zhu, Carnegie Mellon Univ.



STO: LLG + spin transfer

$$\frac{\partial \mathbf{m}}{\partial t} = -\gamma(\mathbf{m} \times \mathbf{H}_{\text{eff}}) + \alpha\left(\mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t}\right) - \beta(\mathbf{m} \times (\mathbf{m} \times \mathbf{p}))$$



Media: H_k = 30 kOe; α =0.01

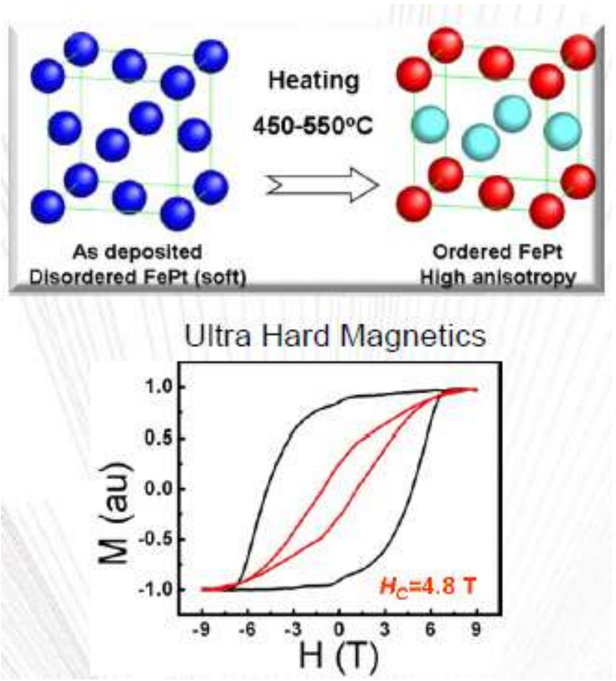
Applied field H_a: 0.2 ns rising time, 2° away vertical direction

AC field H_{ac}: H_{ac}/H_k = 0.1

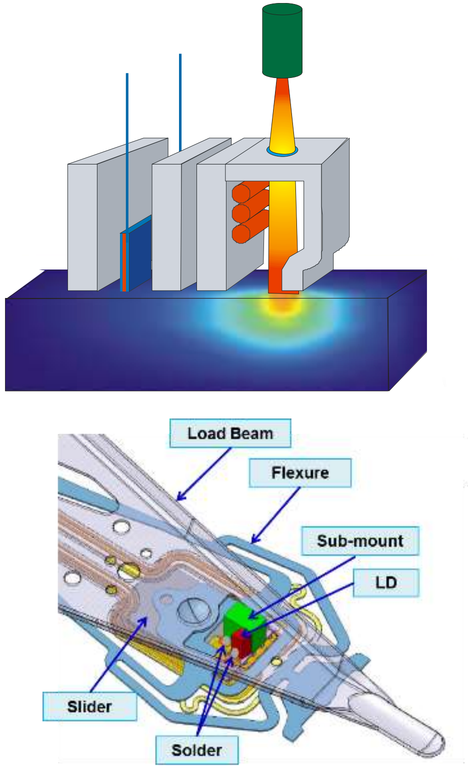
HAMR : Heat Assisted Magnetic Recording

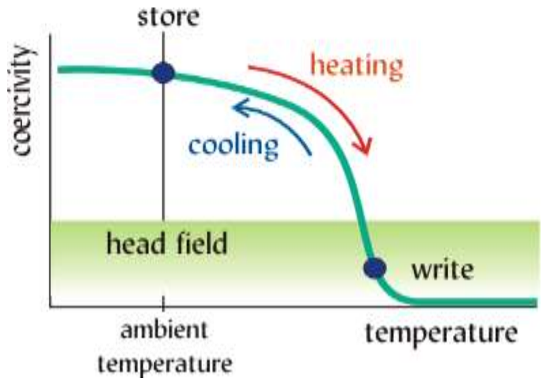
- HAMR is a scalable technology. Opportunity for 1.0 to 4.0 Tbpsi
- FePt media allows grain size scaling to support much higher density than PMR
  - ✓ Effective field gradient several times higher than PMR ➔ Small grains and high SNR
- Near Field Heating by Laser spot with Write head and making data track < 50nm

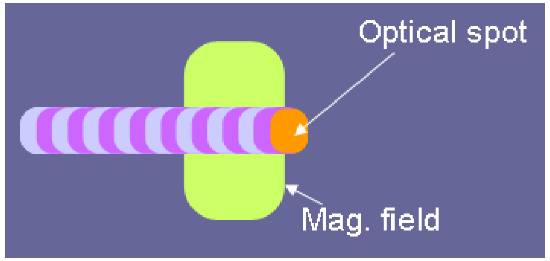
Ultra Hard FePt Media



Laser + Magnetic Head





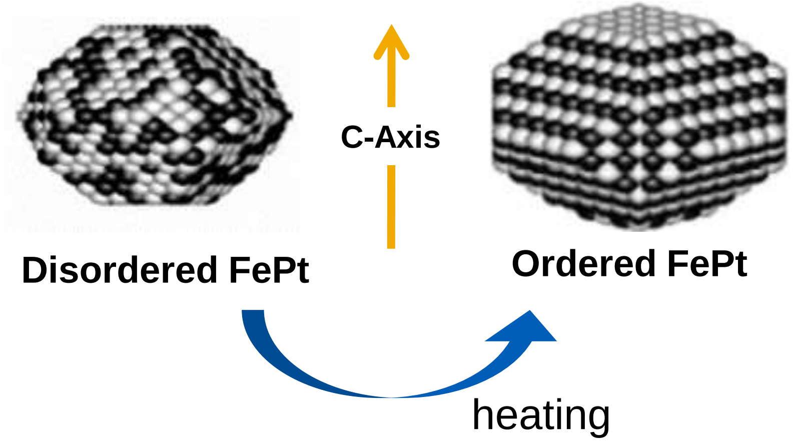


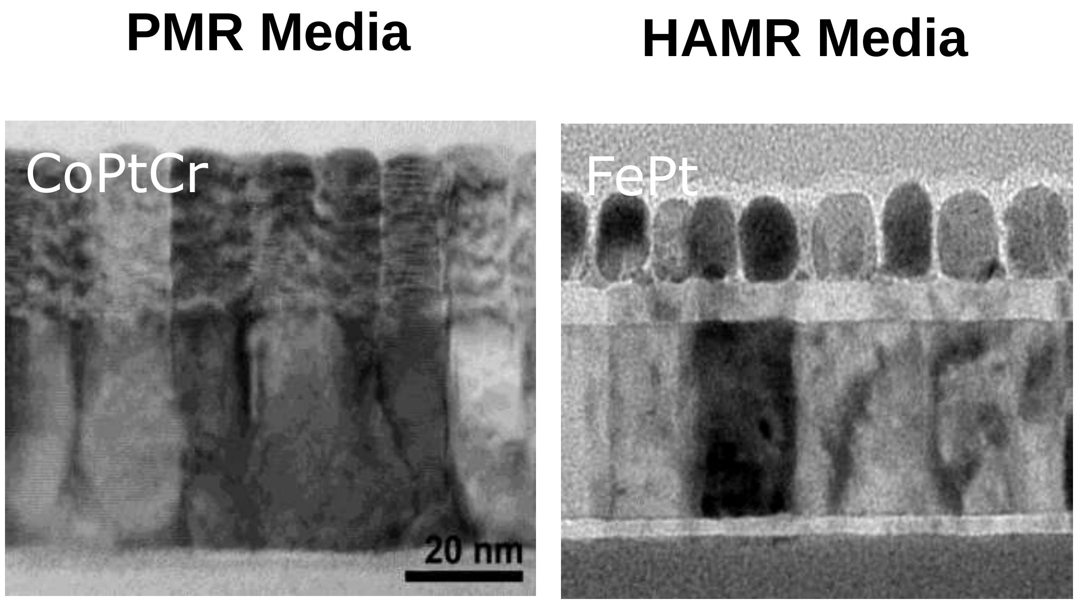
$$\frac{dH_{eff}}{dx} = \frac{dH_k}{dT} \cdot \frac{dT}{dx}$$

HAMR Media Design

- New magnetic material alloy : FePt.
- High temperature growth needed to form proper crystallographic phase – requires new high-temperature substrate.
- Multiple FePt layers and segregants required for microstructure optimization. Difficult to make as thick as for PMR.
- Minimize the variation of Curie Temperature of each grain.
- Thermal design of heat sink➔ maximize thermal gradient and minimize power.

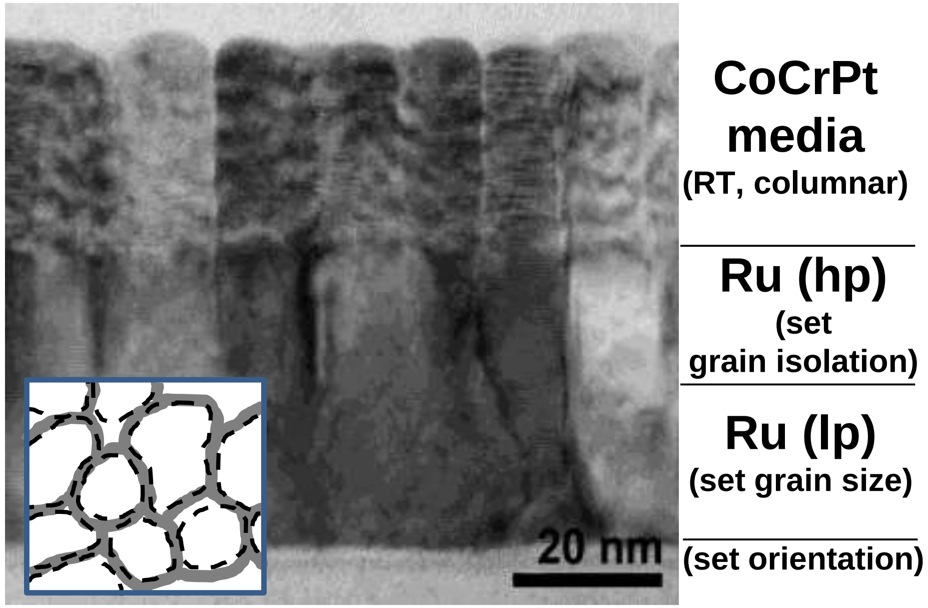
$$\frac{dH_{eff}}{dx} = \frac{dH_k}{dT} \cdot \frac{dT}{dx}$$





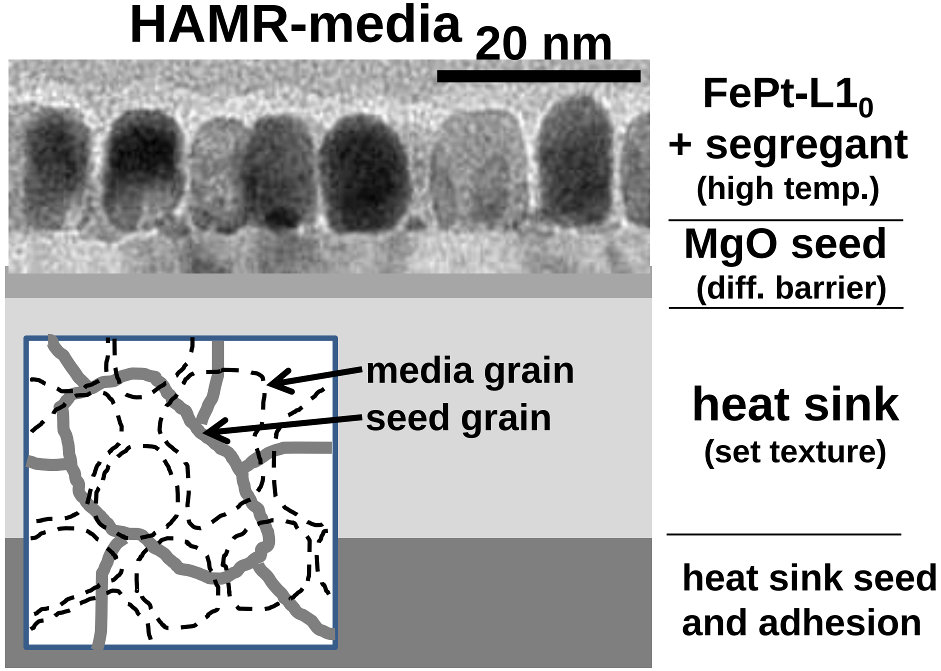
Comparison: PMR media versus HAMR media

PMR-media



- all RT deposition process (no inter-diffusion)
- high pressure Ru grain isolating layer
- 1:1 grain relation between seed and media
- step by step structure built up of grain orientation, grain size and grain isolation

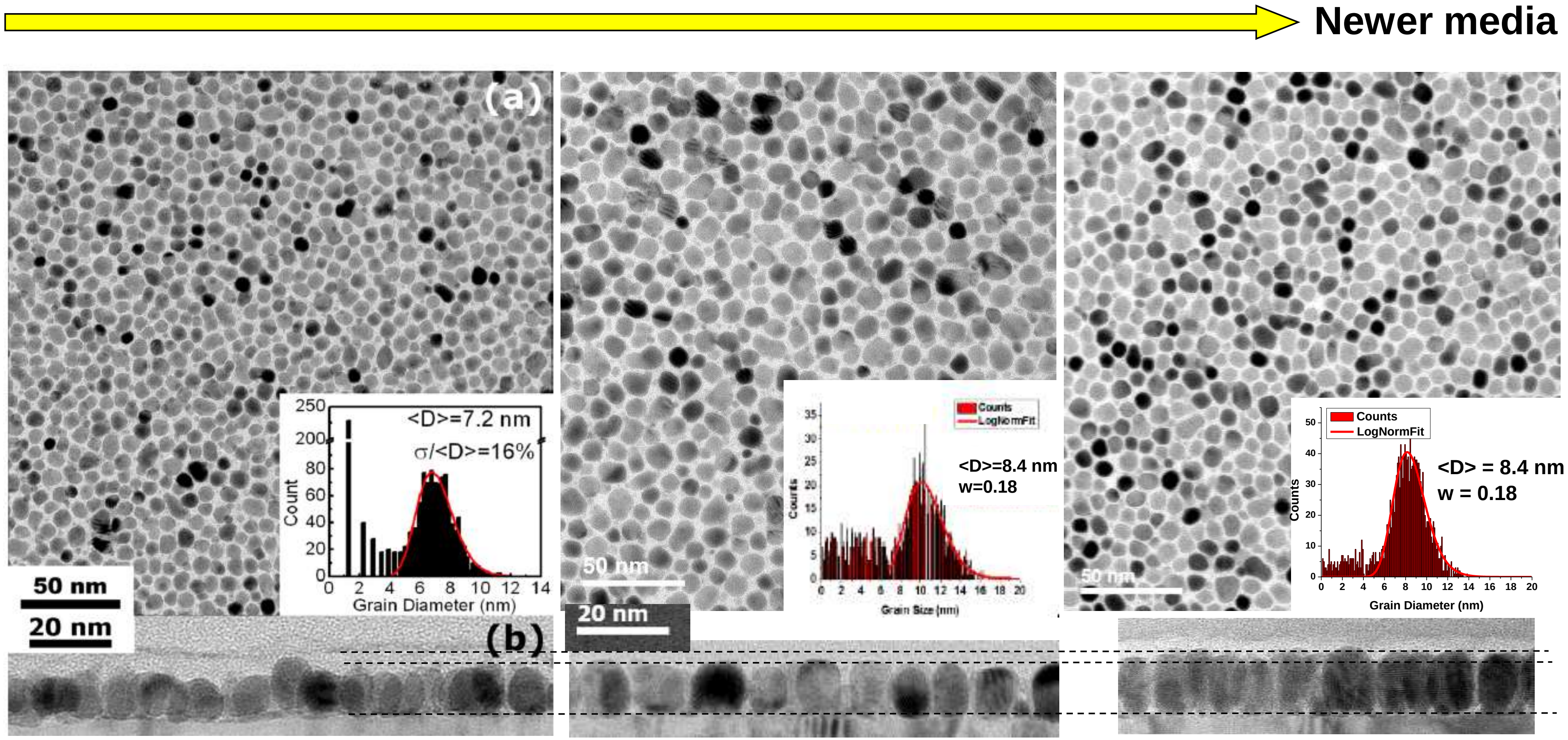
HAMR-media



- high temperature media deposition (L1$_0$-order)
- MgO seed also acts as diffusion barrier
- continuous grains in MgO seed
- no 1:1 grain relation between seed and media
- epitaxy sets grain orientation, easy axis

In addition to traditional PMR media parameters, new media parameters become important for HAMR, such as optical and thermal layer design, thermal gradients, Tc, sigma Tc, …

HAMR media microstructure evolution



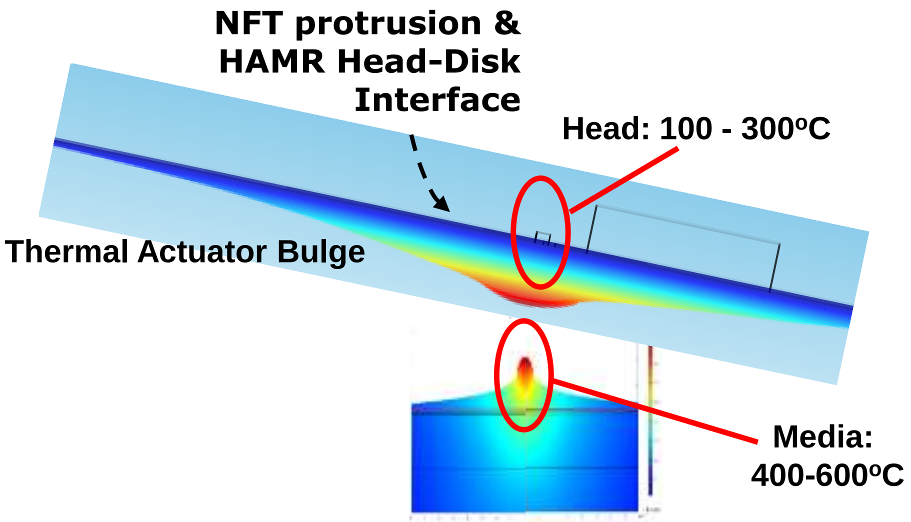
- small grains
- tight size distribution
- spherical grains
- low signal
- rough media

- larger grains
- tight size distribution
- more columnar grains
- increased signal
- smoother media

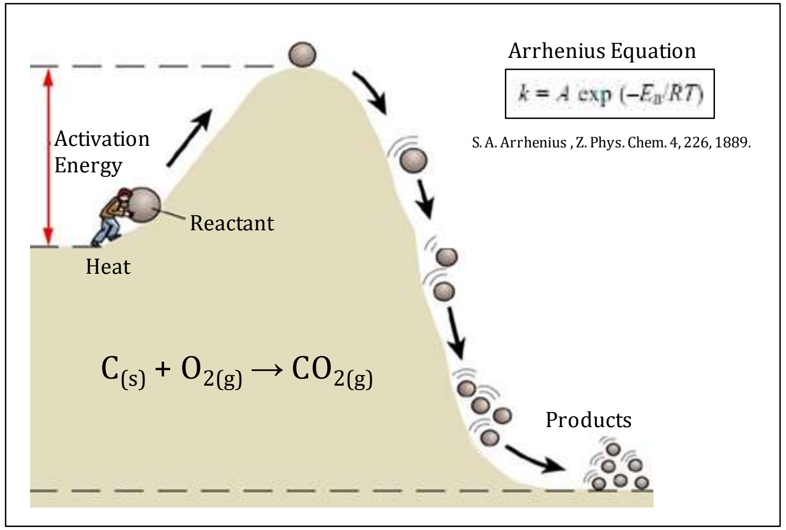
- smaller grains
- tight size distribution
- even more columnar grains
- further increased signal
- smoother media

Head-Disk Interface Challenges

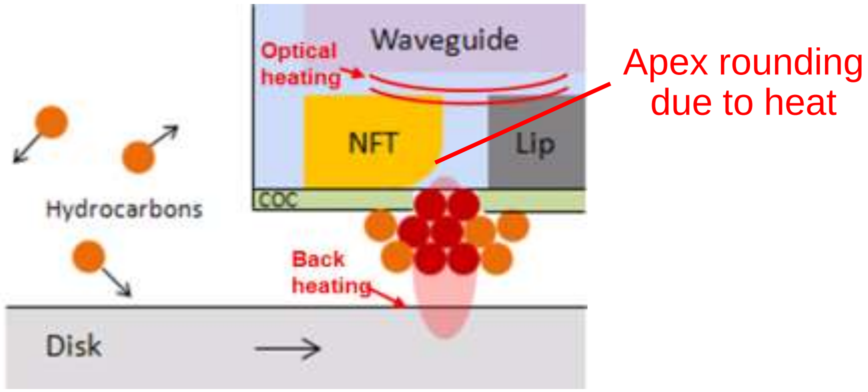
Laser Induced Protrusion



Oxidation of Carbon Overcoats

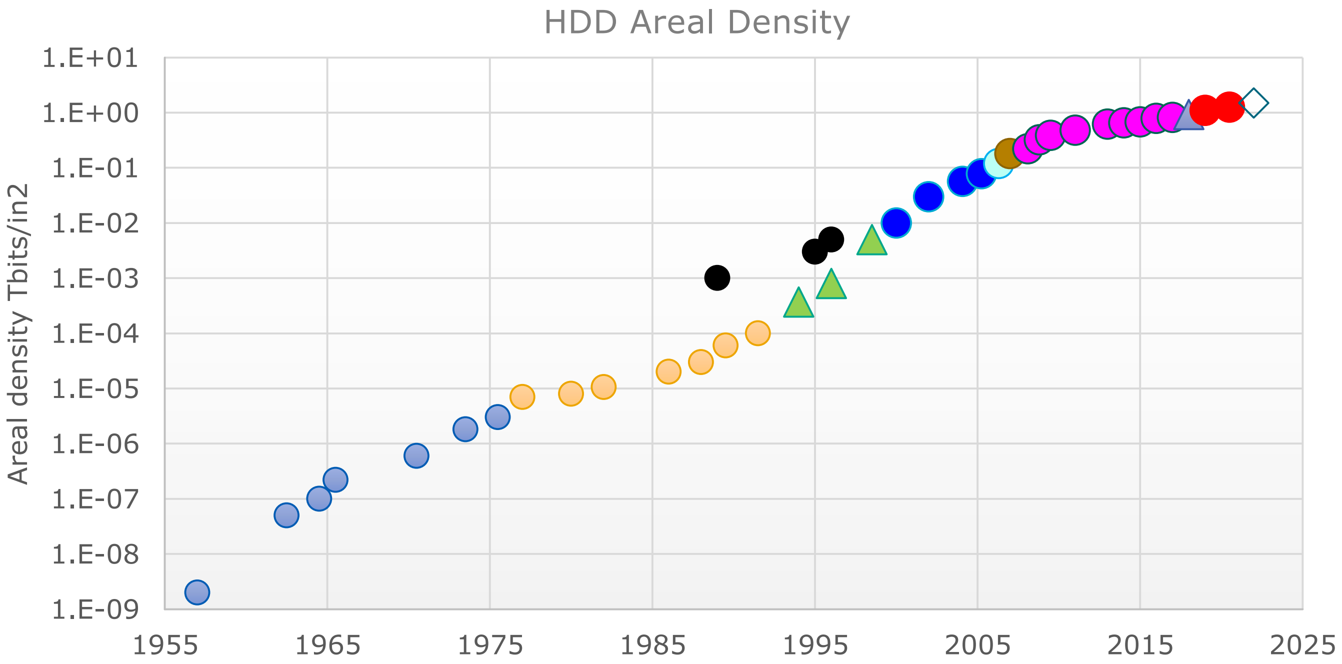


- New heat sources (laser diode, scattered light, NFT heating) cause protrusion over various time-scales and length-scales and new challenges for maintaining low head disk spacing and high recording performance.
- High temperatures can cause oxidation (combustion) of thin carbon overcoats on head and disk over the lifetime of a product.
- Intense optical/thermal fields can lead to carbonaceous build up on NFT. Contact can also lead to back heating.



Conclusions on HDD

- HDDs will be around for a long time to come
- The modern HDD is packed with high-tech engineering of many disciplines
- Major discoveries at the basic research level enabled the rapid growth of storage capacity
- Energy-assisted recording – MAMR or HAMR – is a promising future technology for recording densities beyond 1Tb/in^2. Engineering breakthroughs are needed to make it a reality.



Magnetic Memory

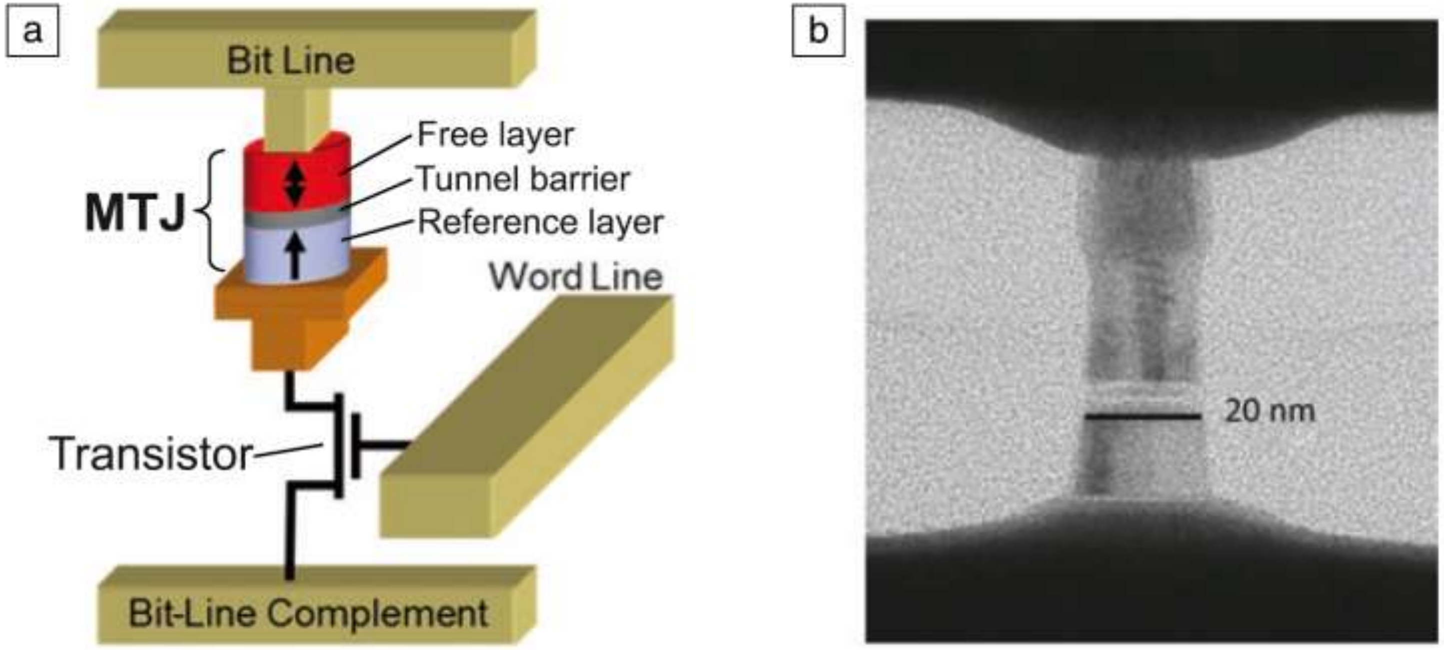
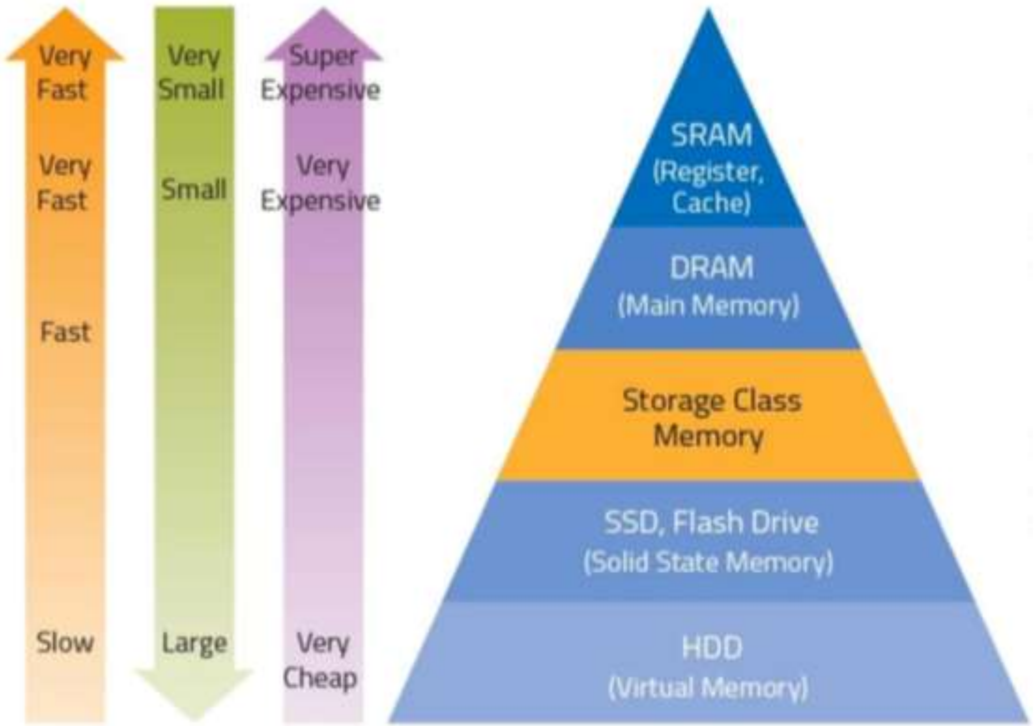
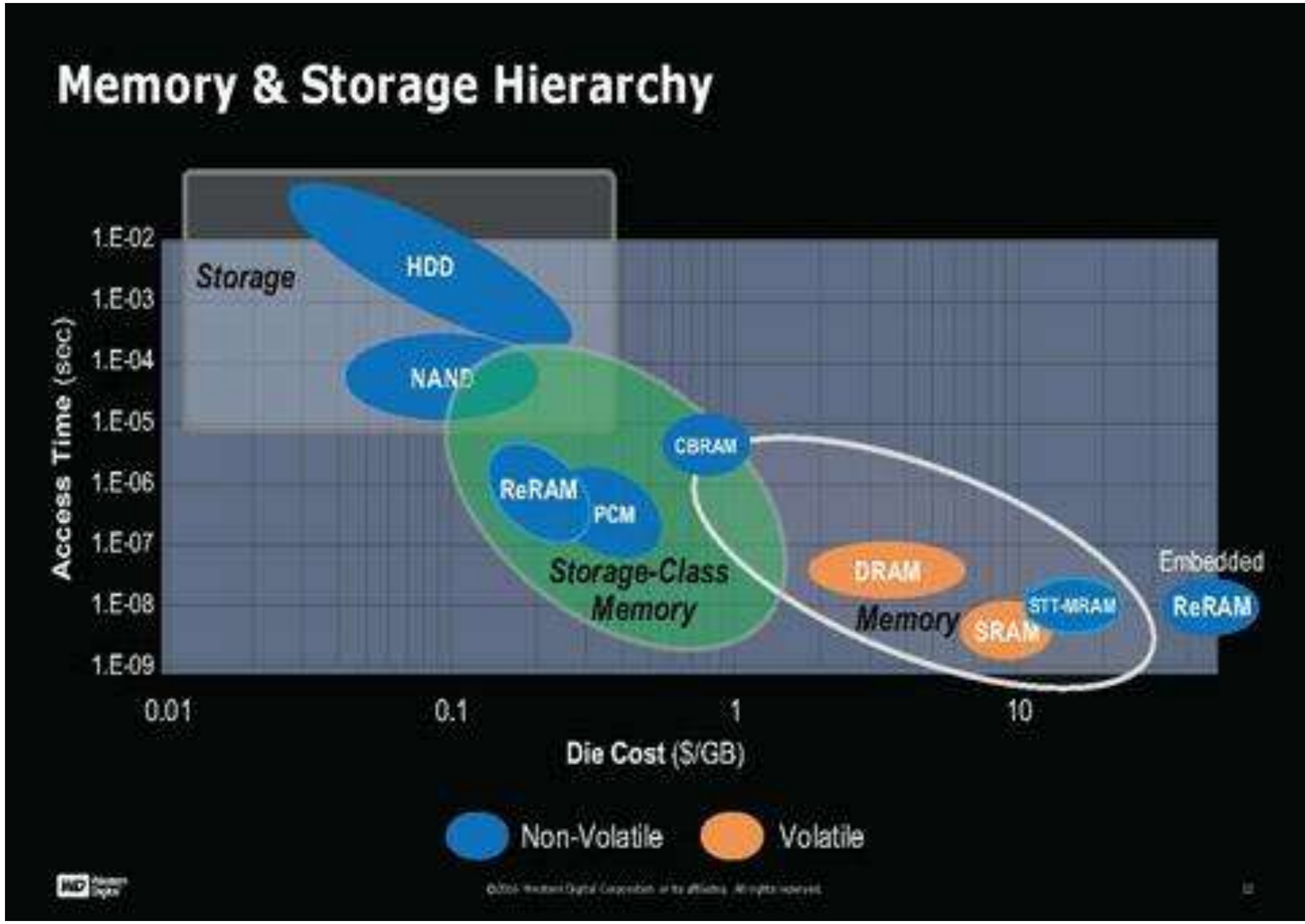


Figure 4. (a) Schematic of a spin-transfer-torque magnetoresistive random-access memory bit cell. (b) Cross-sectional transmission electron microscope image of a 20-nm dia. perpendicular magnetic tunnel junction (p-MTJ). Photo courtesy of IBM.

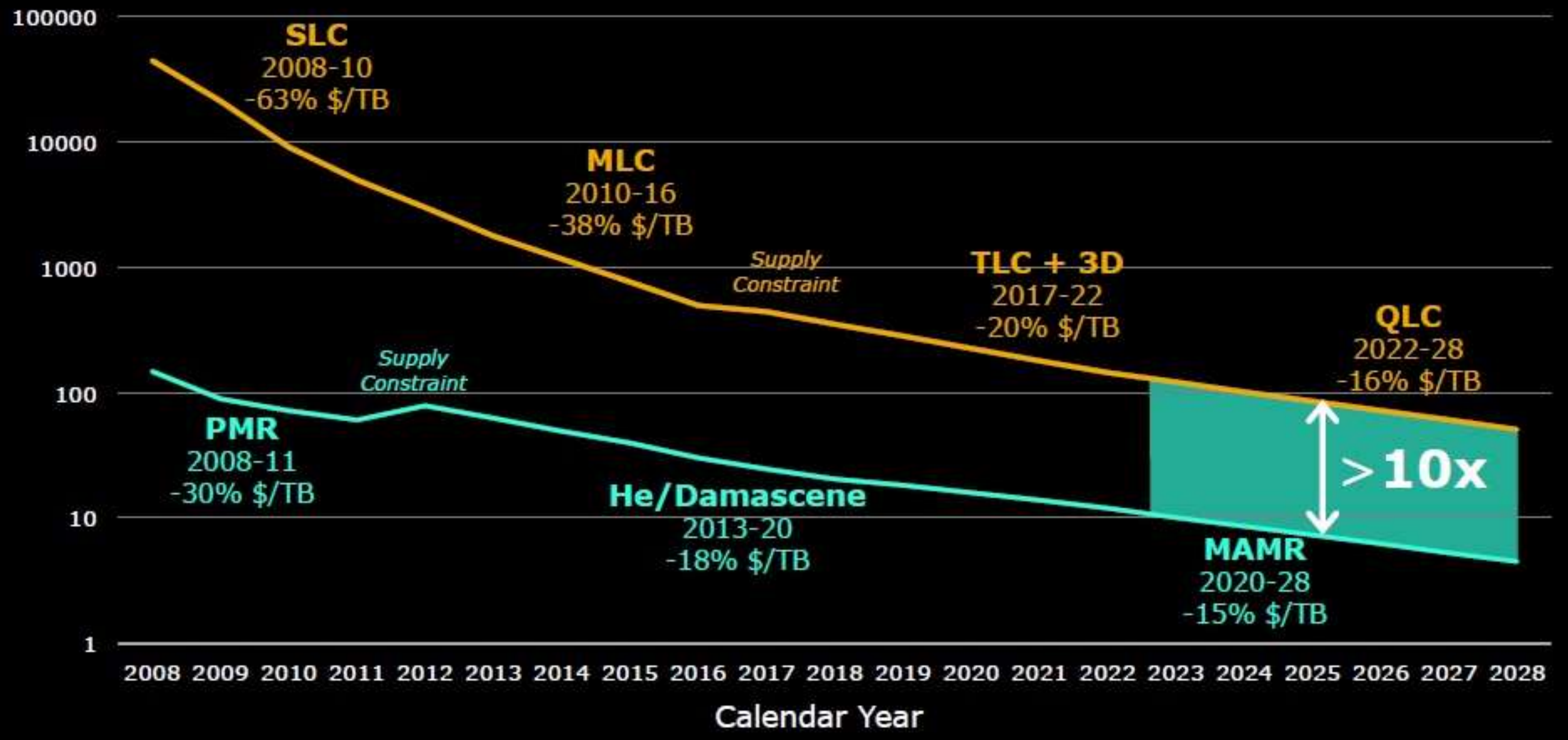
Memory and Storage Hierarchy





HDD vs. Flash SSD $/TB Annual Takedown Trend

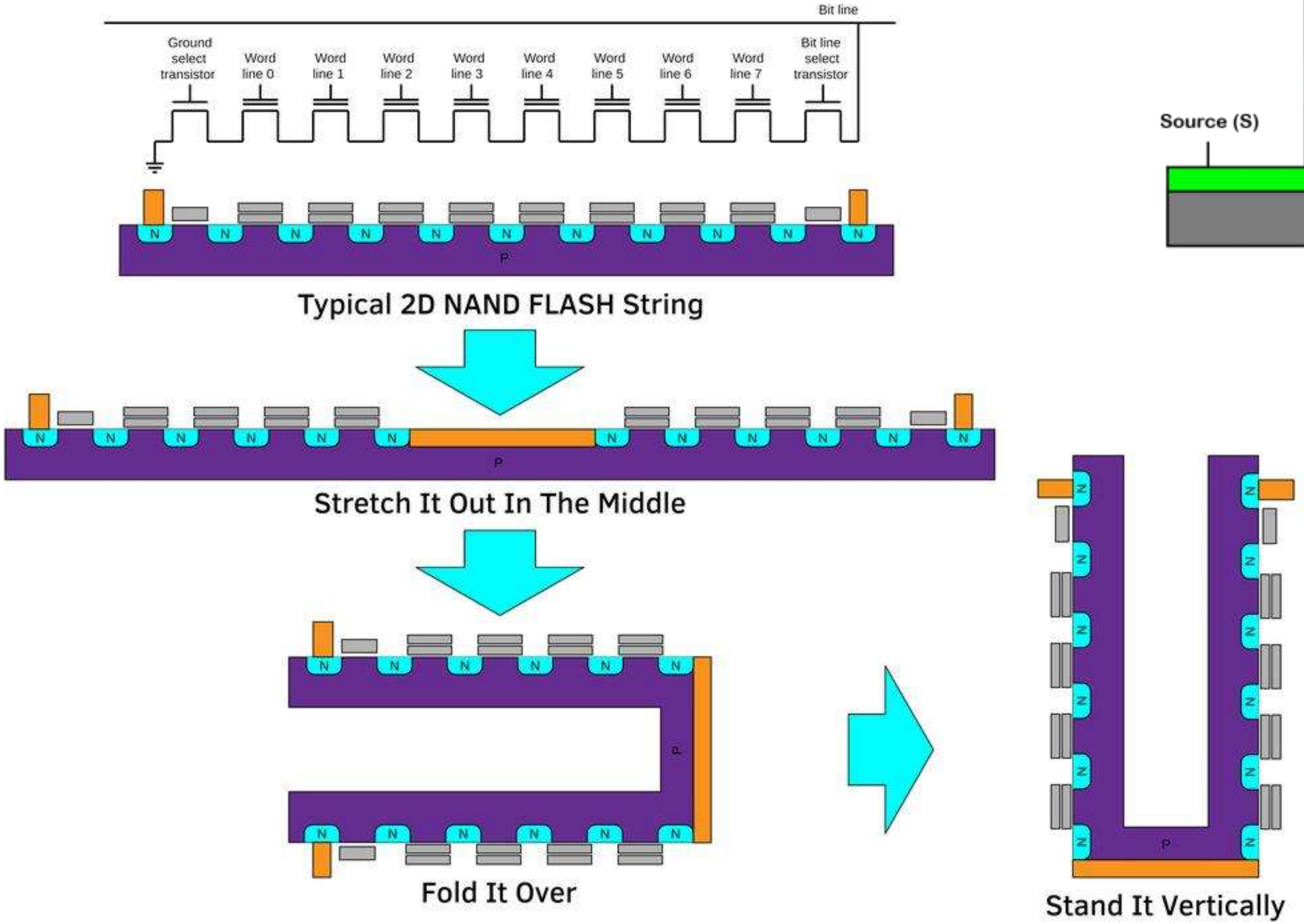
MAMR will enable continued $/TB advantage over Flash SSDs

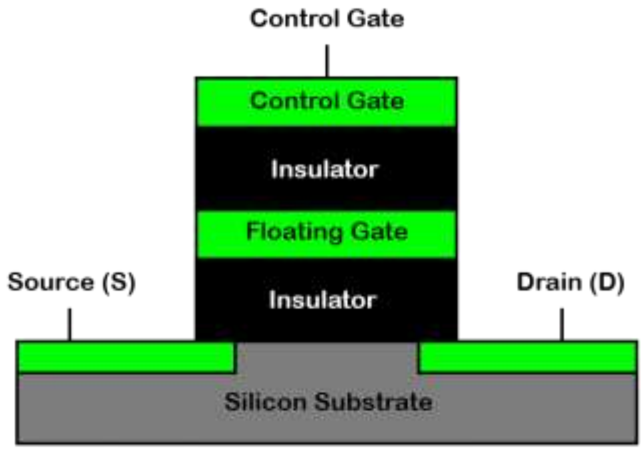


Western Digital

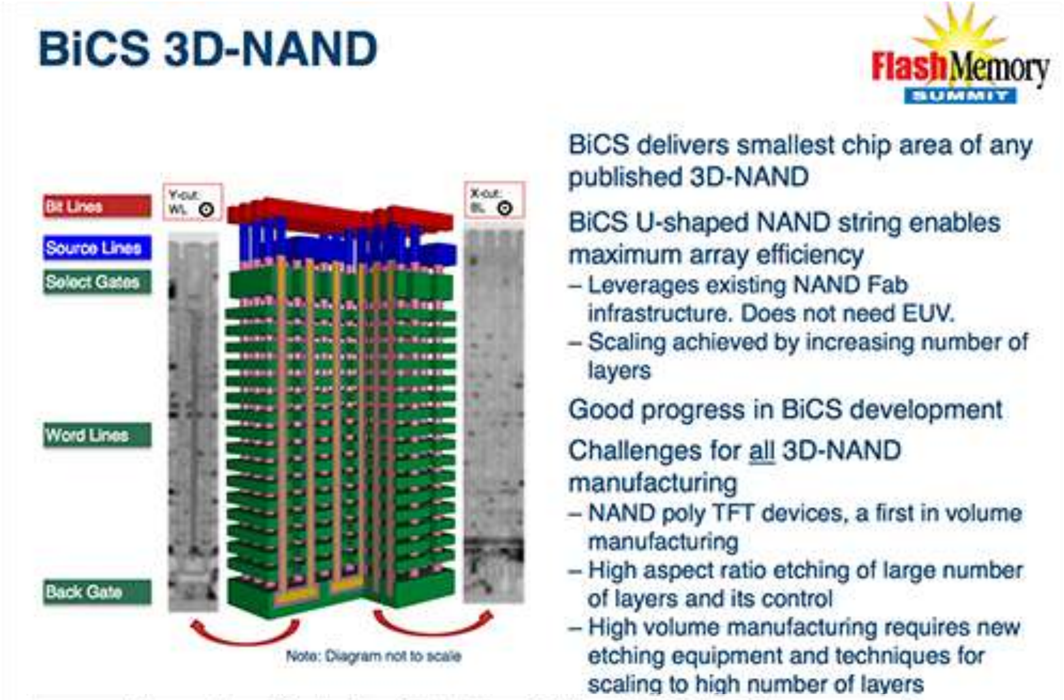
Source: WDC Analysis

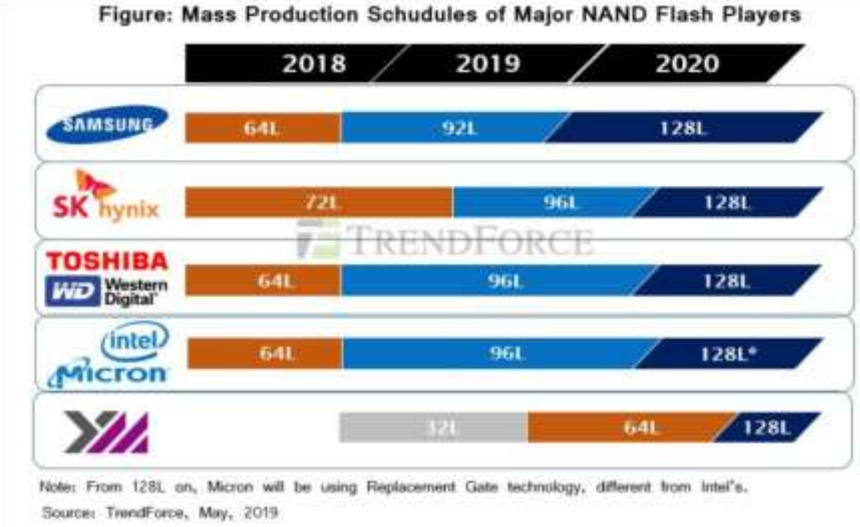
2D to 3D NAND

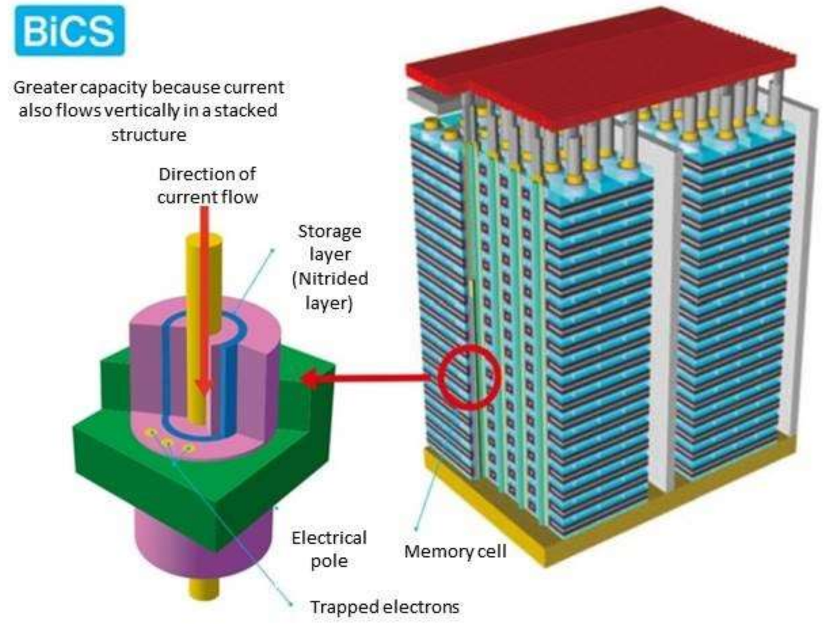

Bit line
Ground select transistor
Word line 0
Word line 1
Word line 2
Word line 3
Word line 4
Word line 5
Word line 6
Word line 7
Bit line select transistor
N
P
Typical 2D NAND FLASH String
Stretch It Out In The Middle
Fold It Over
Stand It Vertically


Control Gate
Control Gate
Insulator
Floating Gate
Source (S)
Insulator
Drain (D)
Silicon Substrate

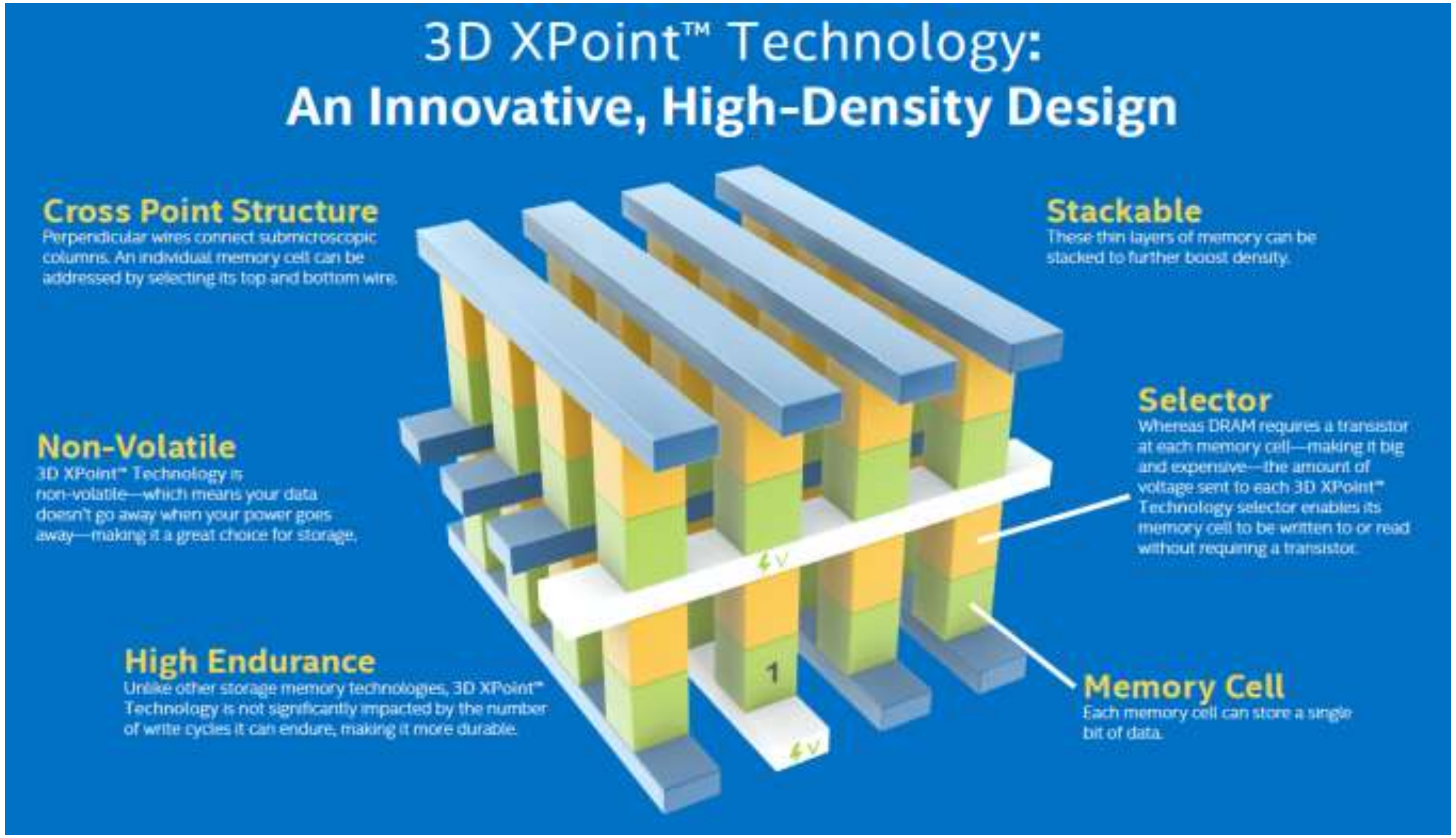
Flash Technology -- BiCS

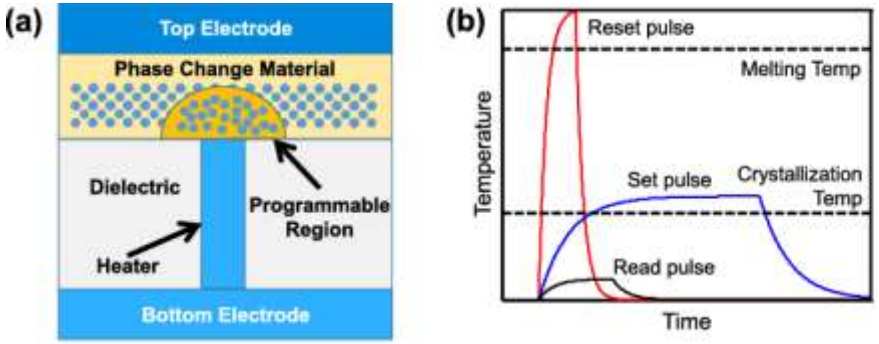


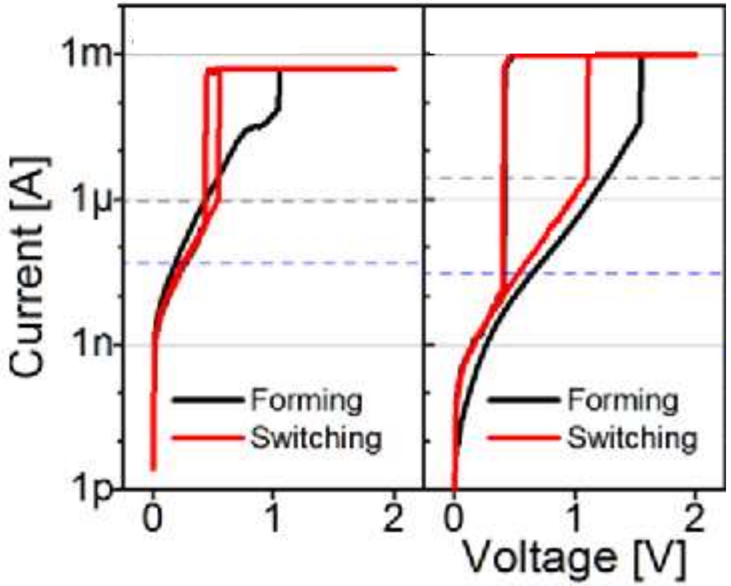




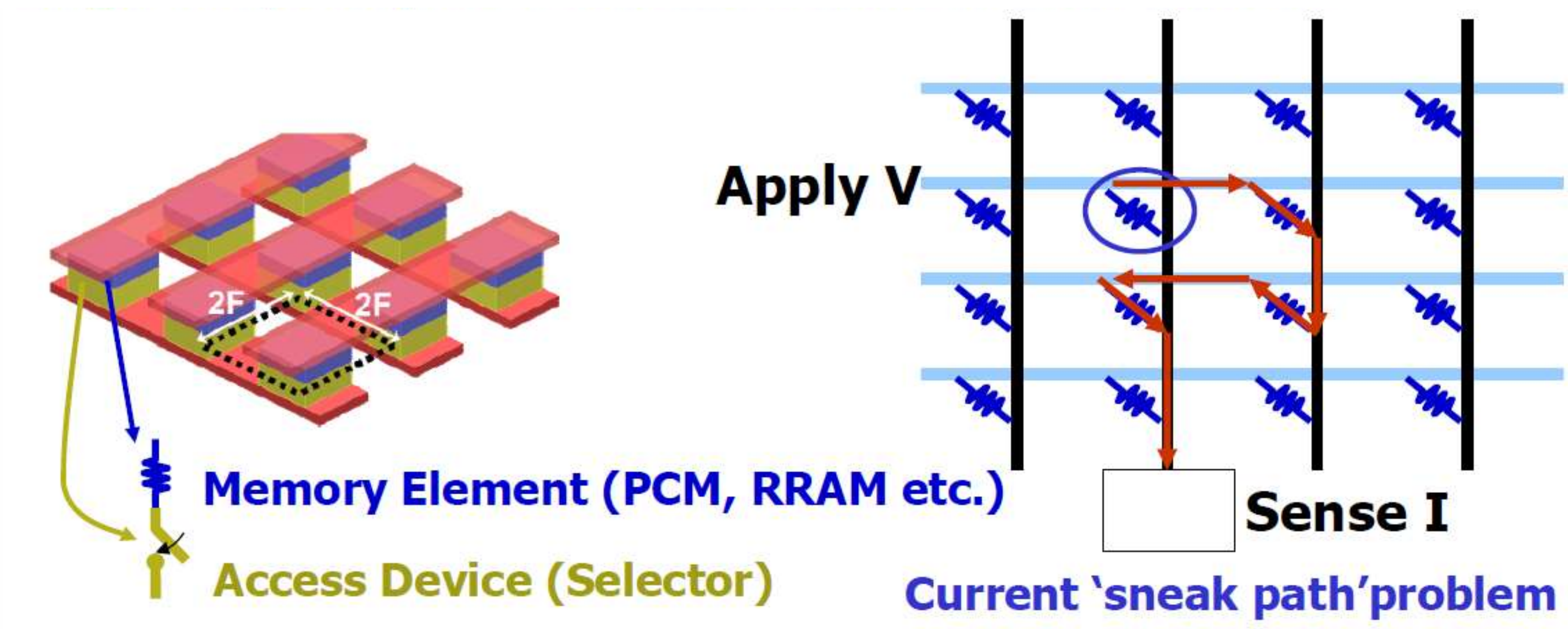
Intel Optane
3D Phase Change with Selector



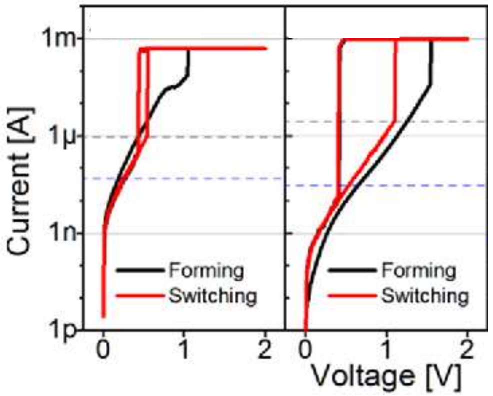




3D Crosspoint



- Access device required for each memory element
  - Eliminate sneak paths
    - Reduce power and unintended selection
    - Apply V/2 on word and bit lines – only V on selected cell
  - Diodes or non-linear I-V devices
  - Unipolar or dipolar depending on memory cell type



Present and emerging memory landscape

Table 1 | Comparison of key features of existing and emerging memories.

	SRAM	eDRAM	DRAM	eFlash (NOR)	Flash (NAND)	FeRAM	PCM	STT-MRAM	RRAM
Endurance (cycles)	Unlimited	Unlimited	Unlimited	**10^5**	**10^5**	10^{14}	**10^9**	Unlimited	**10^9**
Read/write access time (ns)	<1	1–2	30	10/**10^3**	100/**10^6**	30	10/100	2–30	1–100
Density	**Low (six transistors)**	Medium	Medium	Medium	High (multiple bits per cell)	**Low (limited scalability)**	High (multiple bits per cell)	Medium	High (multiple bits per cell)
Write power	Medium	Medium	Medium	**High**	**High**	Medium	Medium	Medium	Medium
Standby power	**High**	Medium	Medium	Low	Low	Low	Low	Low	Low
Other	**Volatile**	**Volatile. Refresh power and time needed**	**Volatile. Refresh power and time needed**	**High voltage required**	**High voltage required**	**Destructive readout**	**Operating T<125°C**	**Low read signal**	**Complex mechanism**

Significant disadvantages are marked in bold. Estimates for emerging memories are based on expectations for functioning chips, not demonstrations of individual bits. See text for abbreviations.

STT-MRAM is the only emerging memory technology that combines endurance, speed and energy efficiency of SRAM and DRAM with non-volatility of Flash.

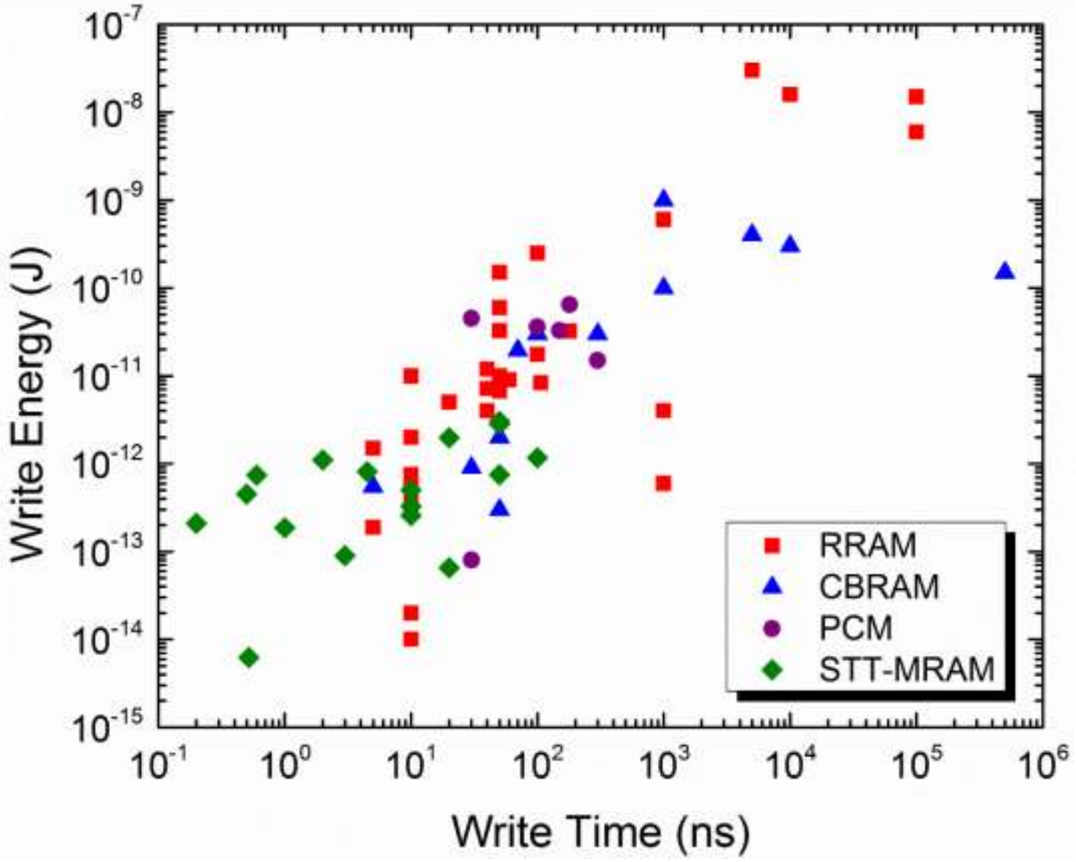
Figure from:
A. D. Kent and D. C. Worledge, Nature Nanotech. **10**, 187 (2015).

- STT-MRAM is the only candidate to replace SRAM in cache memory and DRAM in both embedded and stand alone applications.
- STT-MRAM also provides high performance alternative for embedded flash (NOR) in applications where non-volatility is required.
- PCM and RRAM are better suited for storage applications where higher density is required and lower endurance and slower speed can be tolerated.

Energy-speed performance of emerging memories

Based on reported experimental results

STT-MRAM speed has advantage in terms of speed and energy efficiency over other emerging memory technologies.



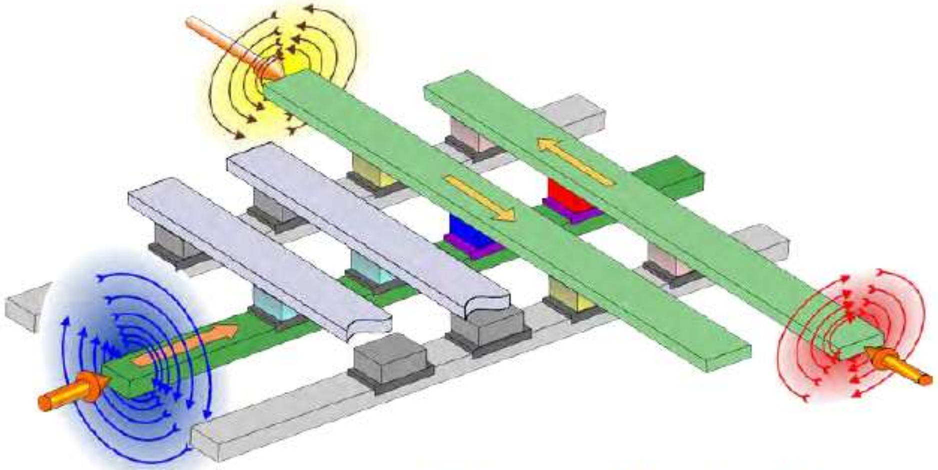
H.-S. P. Wong, C. Ahn, J. Cao, H.-Y. Chen, S. B. Eryilmaz, S. W. Fong, J. A. Incorvia, Z. Jiang, H. Li, C. Neumann, K. Okabe, S. Qin, J. Sohn, Y. Wu, S. Yu, X. Zheng, "Stanford Memory Trends," https://nano.stanford.edu/stanford-memory-trends, accessed May 16, 2018.

MRAM with a magnetic field

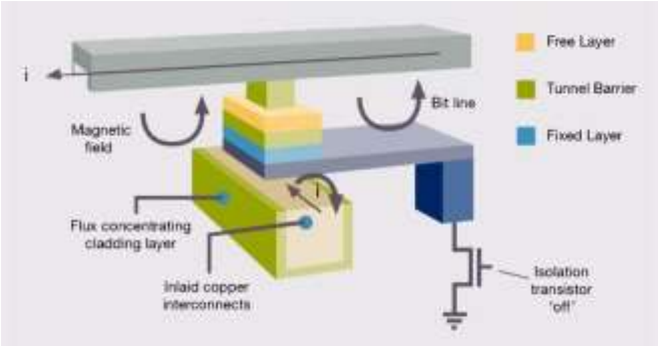
More than 20 years ago: Field-MRAM

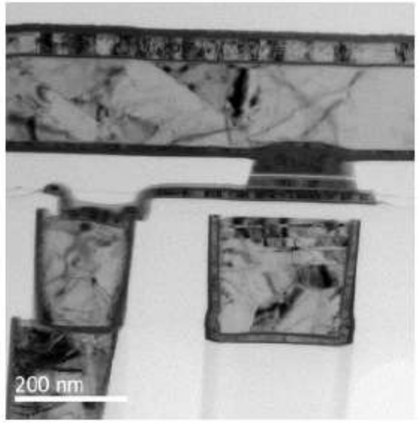
1st research program: IBM/Motorola (1995)
1st product: Freescale/Everspin (2006)

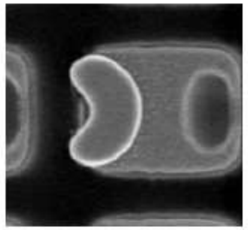
Issue in scaling – field disturb of half-select bits
No selector !



From S. Parkin and K. Roche IBM







What is a STT-MRAM cell

CMOS transistor + magnetic tunnel junction (MTJ)

Physical sketch:

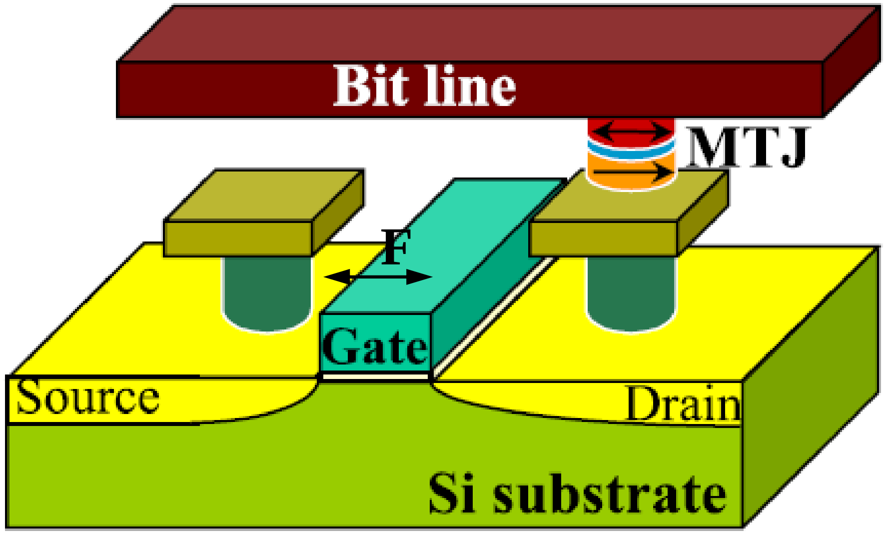
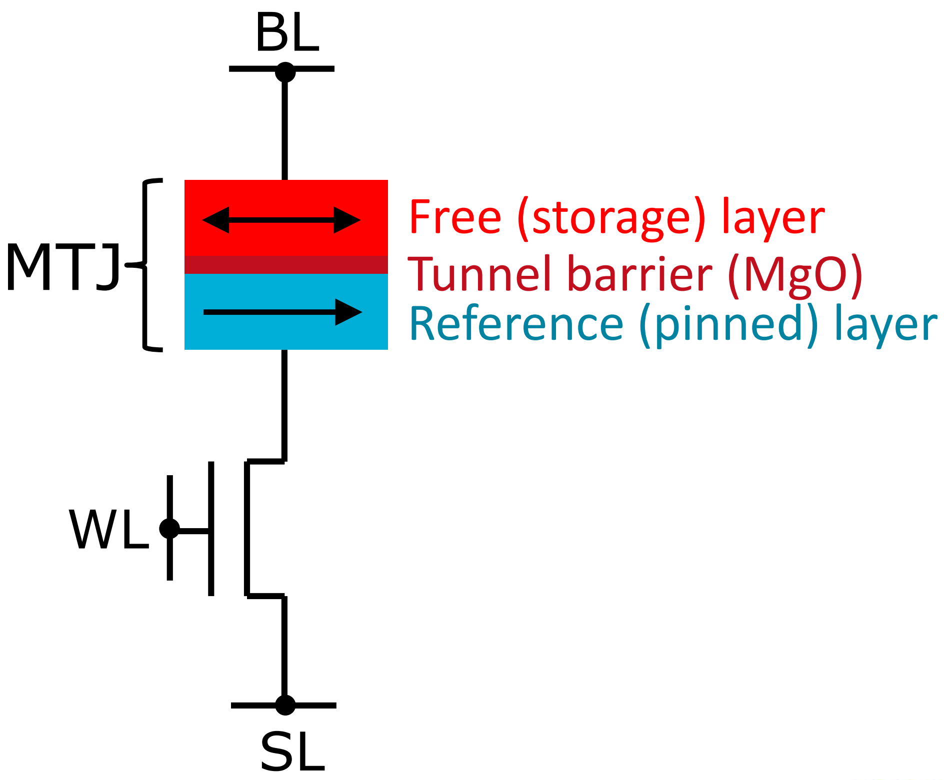


Figure from:
D. Apalkov et al.,
Proceedings of IEEE **104**,
1796 (2016)

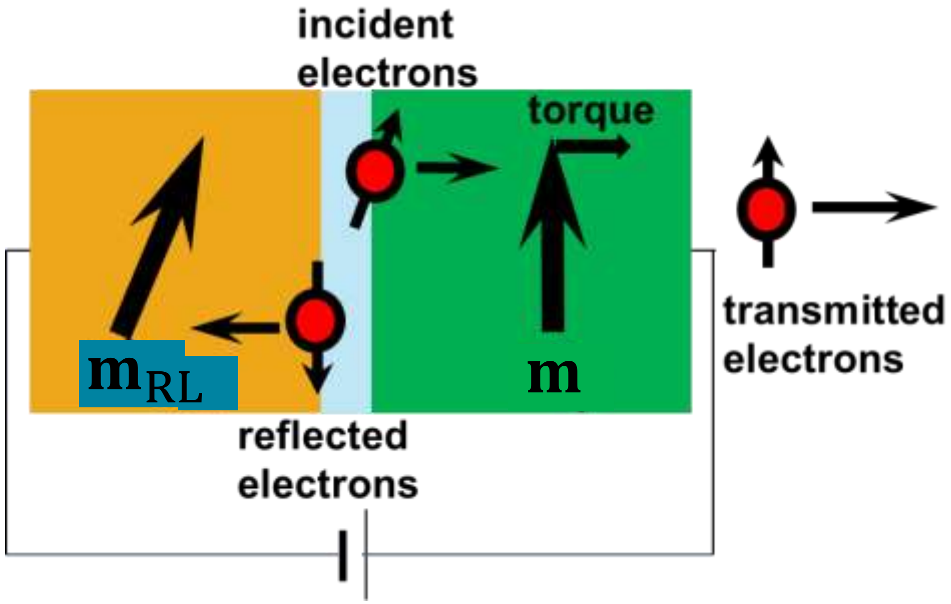
Symbolic description



Physics of the writing operation

Writing operation of STT-MRAM is based on spin transfer torque switching of the magnetization

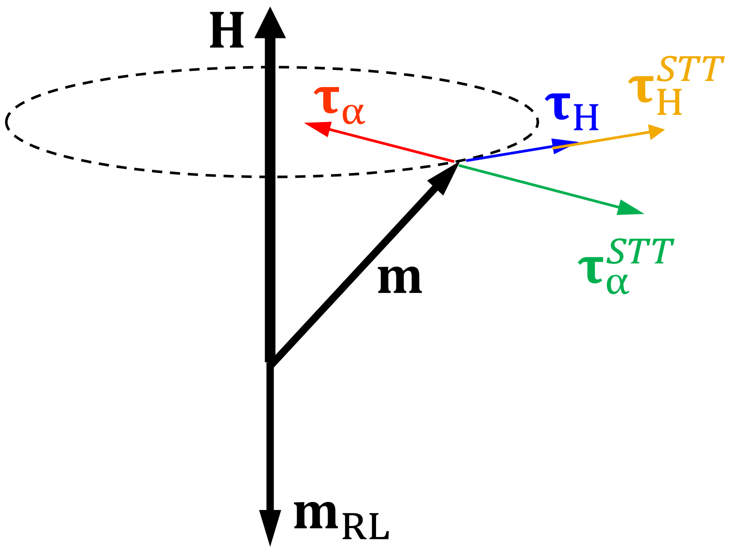
toy model



Tunneling electrons from one electrode interact with second electrode and are either reflected back or transmitted with new spin orientation. By conservation of angular momentum, the second electrode feels a torque acting upon it. If incoming electric current is high enough, torque can be large enough to switch **m**.

Landau-Lifshitz-Gilbert-Slonczsewski

$$\frac{d\mathbf{m}}{dt} = \underbrace{-\gamma\mu_0\mathbf{m}\times\mathbf{H}}_{\boldsymbol{\tau}_{H}} \underbrace{-\alpha\gamma\mu_0\mathbf{m}\times(\mathbf{m}\times\mathbf{H})}_{\boldsymbol{\tau}_{\alpha}} \underbrace{+\gamma\mu_0\eta\frac{\hbar}{2e}\frac{J}{M_s t}\mathbf{m}\times(\mathbf{m}\times\mathbf{m}_{RL})}_{\boldsymbol{\tau}_{\alpha}^{STT}} \underbrace{+\gamma\mu_0\eta'\frac{\hbar}{2e}\frac{J}{M_s t}\mathbf{m}\times\mathbf{m}_{RL}}_{\boldsymbol{\tau}_{H}^{STT}}$$

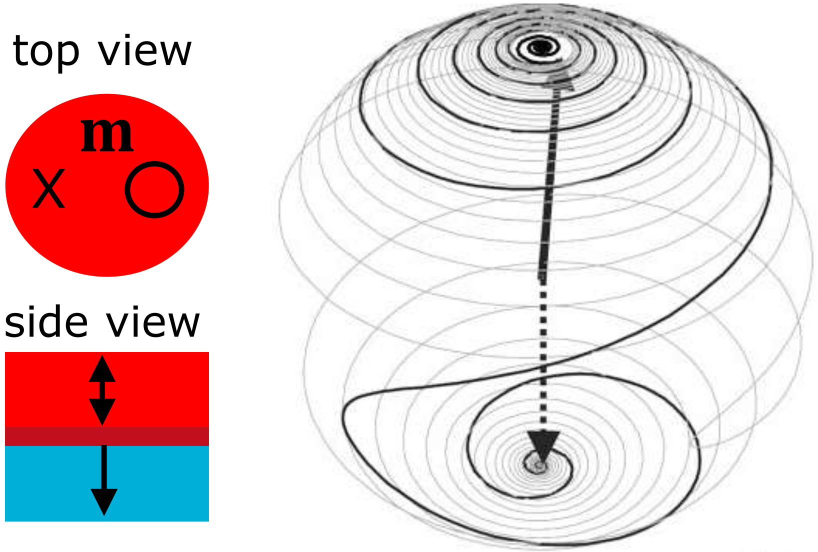


- $\boldsymbol{\tau}_{\alpha}^{STT}$ oposses $\boldsymbol{\tau}_{\alpha}$ and if large enough it causes switching of the direction of **m**.
- $\boldsymbol{\tau}_{H}^{STT}$ affects precessional frequency, but does not cause switching of **m**.

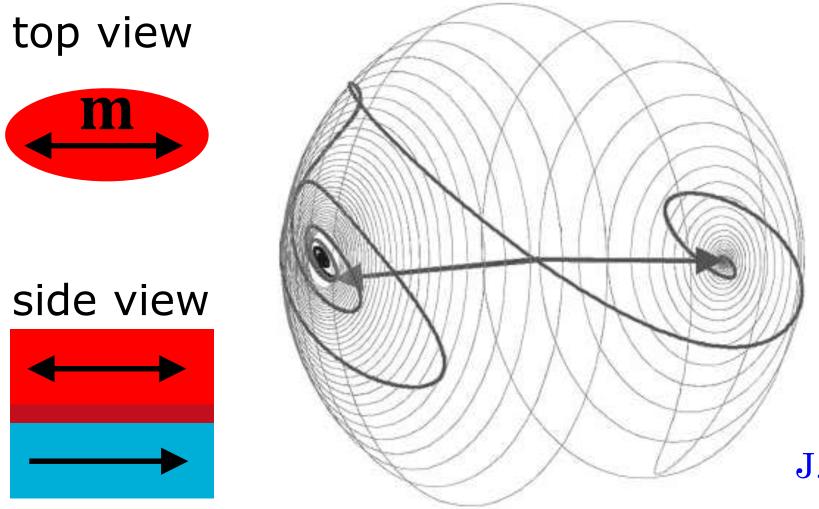
Spin transfer torque switching

Perpendicular vs in-plane magnetic free layer

Perpendicular bits
single uniaxial anisotropy



in-plane bits
shape + easy plane anisotropy



STT needs to overcome demagnetization field $H_{\perp}$

J. Z. Sun, Phys. Rev. B **62**, 570 (2000)

$$J_{c0} = \frac{2e\alpha}{\hbar\eta}\mu_0 M_s t H_K$$

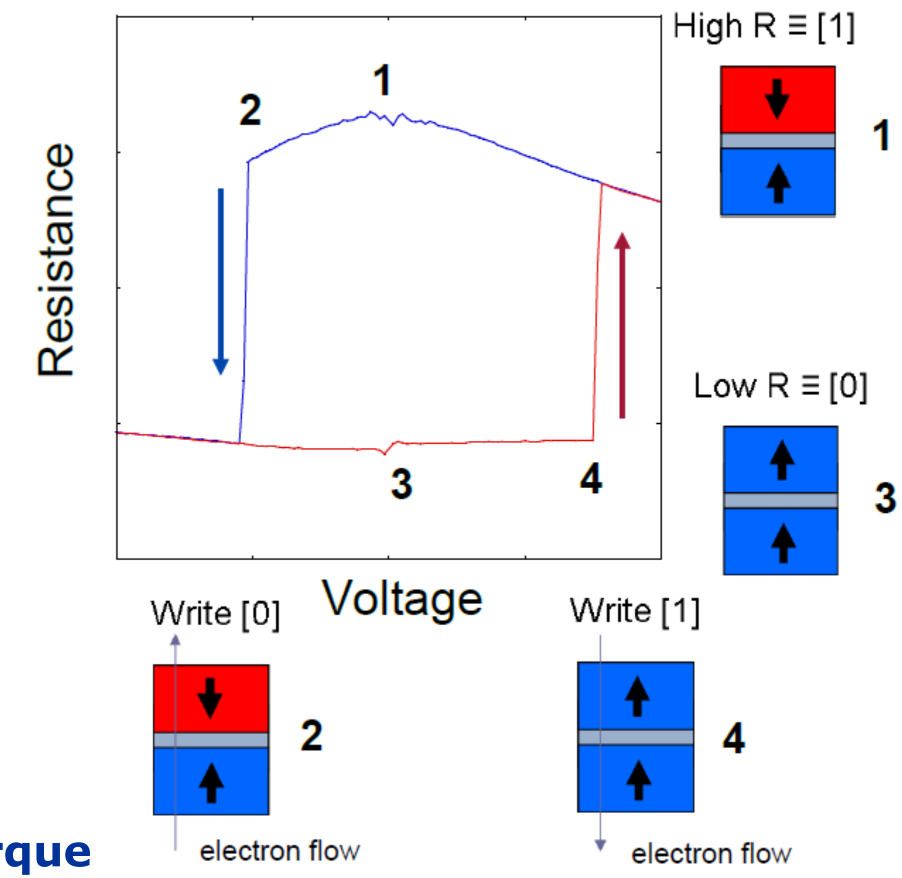
$$J_{c0} = \frac{2e\alpha}{\hbar\eta}\mu_0 M_s t\left(H_K + \frac{H_{\perp}}{2}\right)$$

Lower J_{c0} for perpendicular STT-MRAM
=> faster, more power efficient, denser, better endurance than in-plane MRAM

Writing and Reading the magnetization in a MTJ

Write with high current
Read with low current

Read:
Tunnel Magnetoresistance

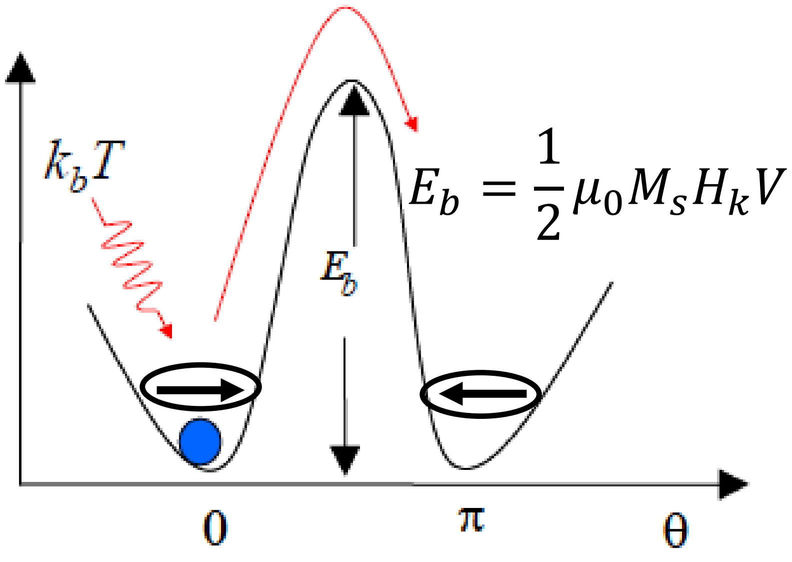


Write:
Spin Transfer Torque

Courtesy: L. Thomas, MSST 2017

Physics of the non-volatile storage

Non-volatility of STT-MRAM is due to uniaxial magnetic anisotropy of the free (storage) layer H_k



- For thermally activated magnetization reversal of a single domain particle with uniaxial and easy plane anisotropy only, switching probability P_{SW} over time t is described by the Neel-Brown relaxation time formula with relaxation time ⍰ and energy barrier E_b:

$$P_{SW}(t) = 1 - \exp\left(-\frac{t}{\tau}\right) \qquad \tau = \tau_0 \exp\left(\frac{E_b}{k_B T}\right)$$

τ_0 - inverse attempt frequency ~ 1 ns   W. F. Brown, Phys. Rev. 130, 1677 (1963).

$$\Delta = \frac{E_b}{k_B T}$$ - thermal stability factor

Most applications require $P_{SW} < 10^{-7}$ at elevated temperatures (> 40 ^{o}C or more) -> $\Delta > 60$

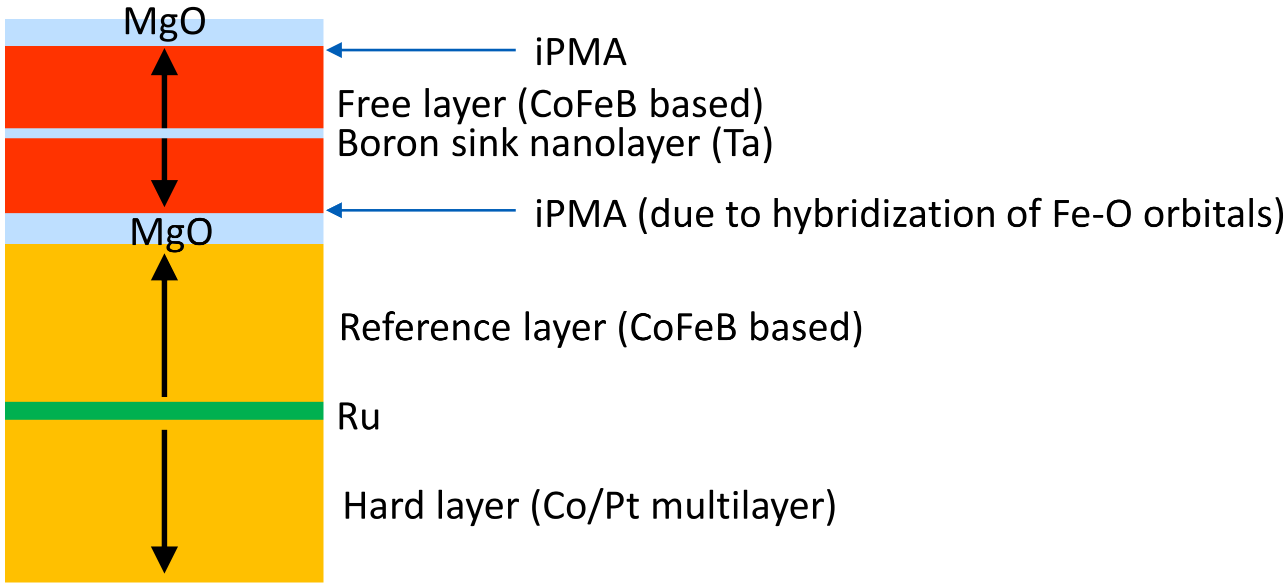
Smaller bits need higher magnetic anisotropy in order to maintain the required thermal stability

Impossible to maintain high enough thermal stability with just shape anisotropy below ~60 nm size

High density applications -> perpendicular STT-MRAM

Perpendicular STT-MRAM

Due to interfacial perpendicular magnetic anisotropy (iPMA)



$$\Delta = \frac{\mu_0 M_s H_k^{eff} V}{2 k_B T}$$

$$H_K^{eff} = \frac{2K_U^S}{\mu_0 M_s t_{FL}} - N_{zz} M_s$$

K_U^S - interfacial magnetic anisotropy energy density

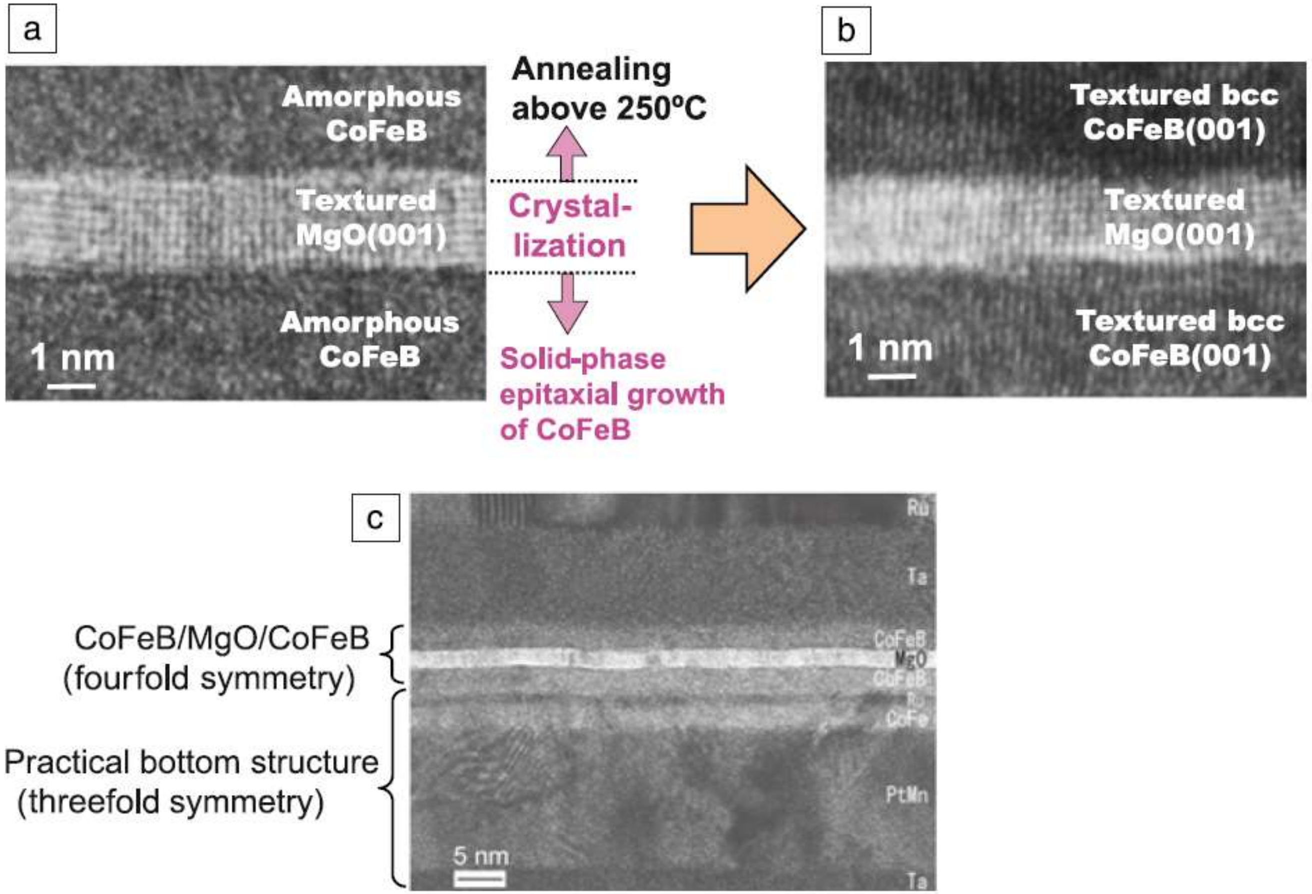
N_{zz}- demagnetization factor

Interfacial PMA competes with demagnetization energy

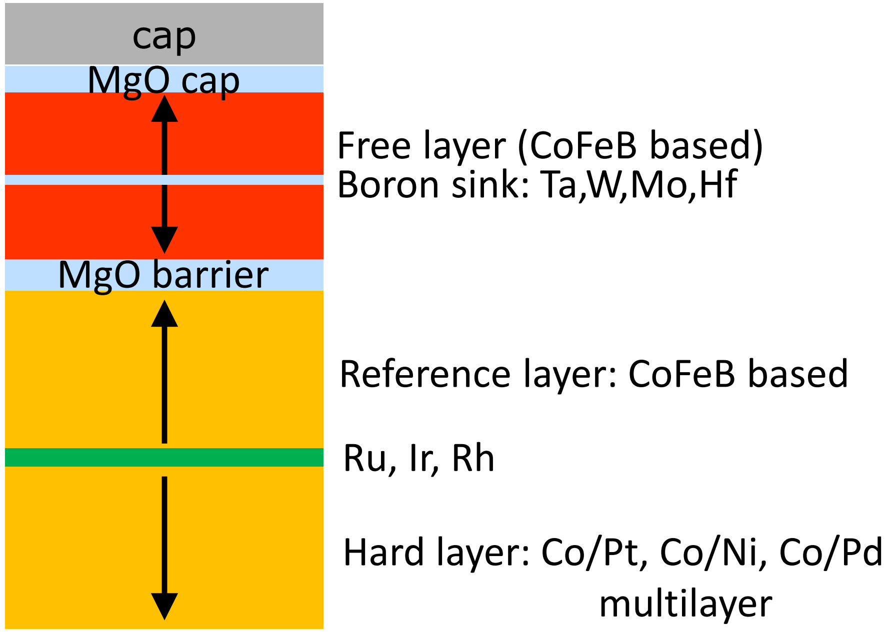
Effective perpendicular magnetic anisotropy is difference between interfacial anisotropy field and demagnetization field

Possible to obtain high enough H_K^{eff} to have $\Delta > 70$ for small device size

Materials for Perpendicular STT-MRAM



Yuasa et al, MRS Bulletin May 2018



Recent development of STT-MRAM memories

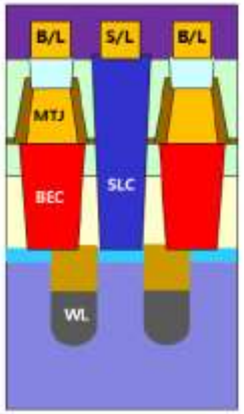


Fig. 1. Schematic diagram of bit cell structure.

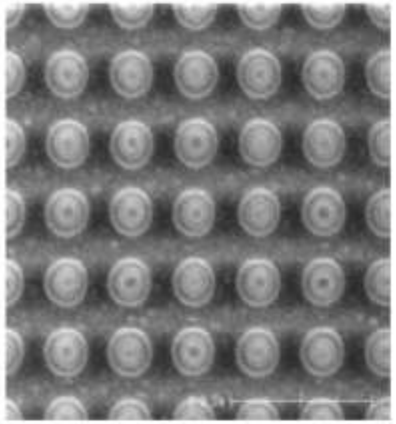


Fig. 2. Top view SEM image of MTJ array. Extremely tight pitched MTJ array was formed by patterning process.

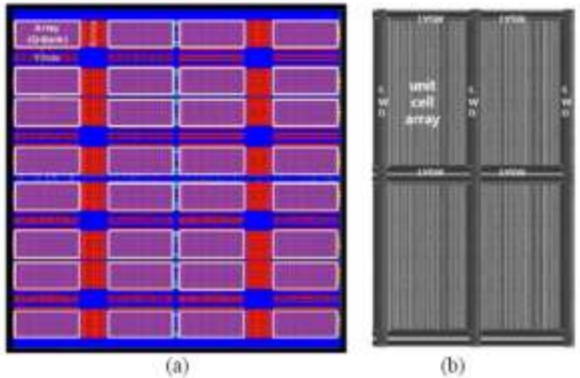


Fig. 3. (a) 4Gb STT-MRAM chip floor plan, and (b) symmetric unit cell array blocks.

- Demonstration of stand-alone 4 Gb STT-MRAM main memory (to replace DRAM) by SK Hynix/Toshiba.

S.-W. Chung et al., IEDM16 -659 (2016)

- Demonstration of 8Mb 1T-1MTJ STT-MRAM embedded in 28nm CMOS logic (to replace SRAM) by Samsung.

Y. J. Song et al., IEDM16 - 663 (2016)

Fig. 1. Block diagram of 8Mb 1T-1MTJ STT-MRAM macro which consists of 4x2Mb cell

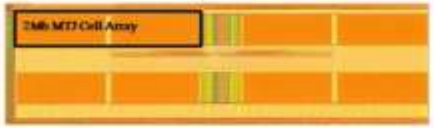


Fig. 2. Micrograph of 8Mb macro chip

Items	Description
CMOS D/R	28nm LPP logic
Density	8Mb
Cell architecture	1T-1MTJ
Unit cell size	0.0364 μm^2
MTJ	perpendicular MTJ based on MgO/CFB
MTJ size	38~45nm
Clock Frequency	40MHz
IO Width	x32/x64
Redundancy	Rows & Columns
Power Supply (Core/IO)	1.0V/1.8V

Table 1. Key characteristics of 8Mb embedded STT-MRAM

Significant development of STT-MRAM for both stand alone and embedded memory platforms.

Embedded MRAM has arrived

June 2017 According to reports, Taiwan Semiconductor Manufacturing Company (TSMC) is aiming to start producing embedded MRAM chips in 2018 using a 22 nm process. This will be initial "risk production" to gauge market reception

Sept 2017 --- GLOBALFOUNDRIES Announces Availability of Embedded MRAM on Leading 22FDX® FD-SOI Platform

March 2019
SAN FRANCISCO — Samsung announced commercial production of its first embedded MRAM (eMRAM) product based on its 28-nm FD-SOI process.

STT-MRAM challenges

Scaling cell size < 20 nm for high density memories

$$\Delta = \frac{\mu_0 M_s H_k V}{2k_B T}$$

As volume of the free layer decreases H_k has to increase in order to maintain the required thermal stability -> increase in iPMA

$$J_{c0} = \frac{2e\alpha}{\hbar\eta}\mu_0 M_s t H_k$$

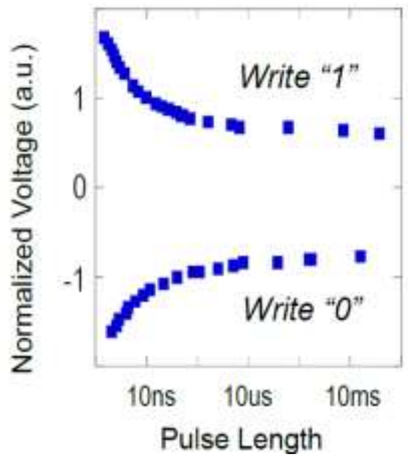
Need switching current reduction for lowering power, endurance, higher speed, and shrinking the transistor footprint -> reduced damping α is crucial and/or Mst

Fabrication of high density memory arrays
-> research into milling and etching methods for MTJs in tight pitch arrays

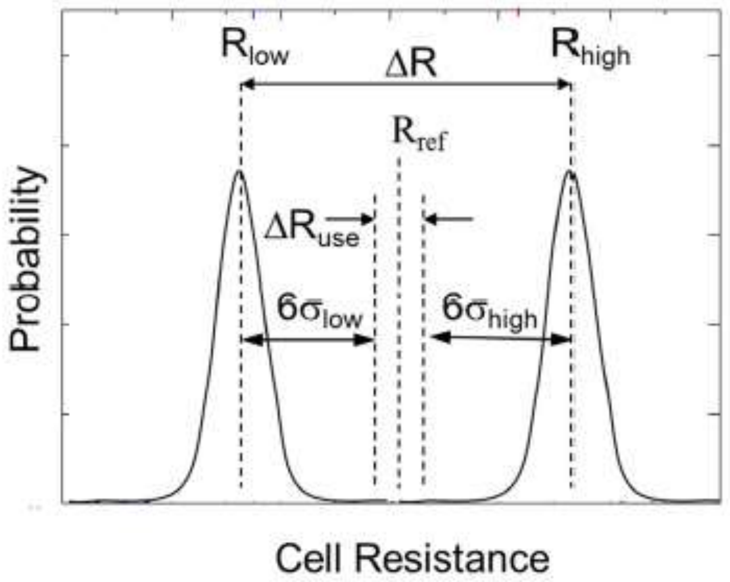
Maintaining tight distribution of relevant resistances, voltages and Δs at small dimensions
-> materials and process uniformity

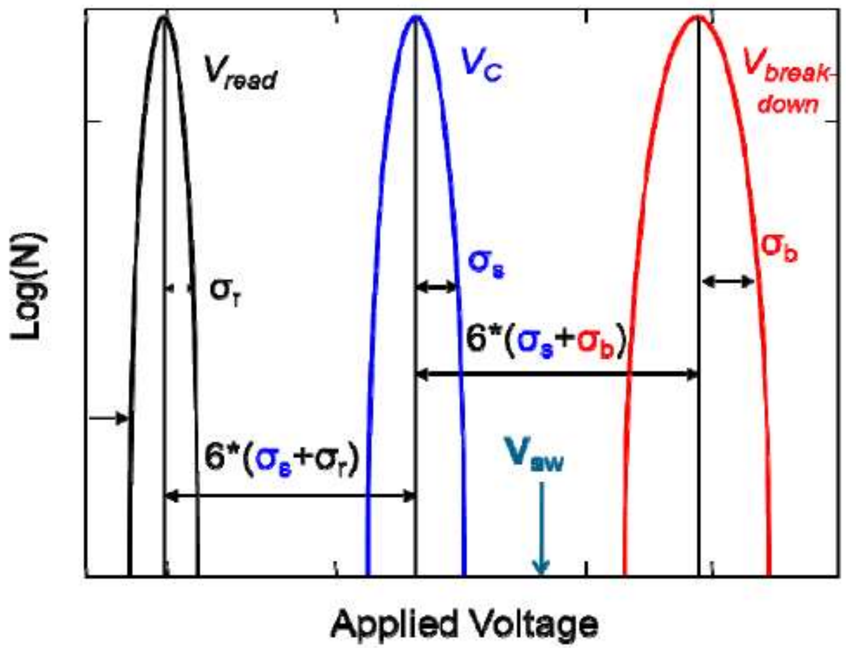
Increasing TMR may be required to compensate for wider R distributions

Alternative memory cell designs may be required for sub-10 nm scaling, as well as ultrafast applications that require high endurance and power efficiency, such as cache memories



Distributions





Dmytro Apalkov, J. Slaughter

Examples of MRAM Research areas

- Improve STT efficiency
  - Reduce damping and Mst
  - Double MTJ – increase torque
  - Add spin polarization layers
- High Density Patterning
  - Ion beam etching at pitch
- Small devices
  - Shape anisotropy
- Crosspoint MRAM
- SOT and VCMA

Spin orbit torque (SOT)-MRAM

Alternative MRAM cell design for high speed/endurance and power efficiency

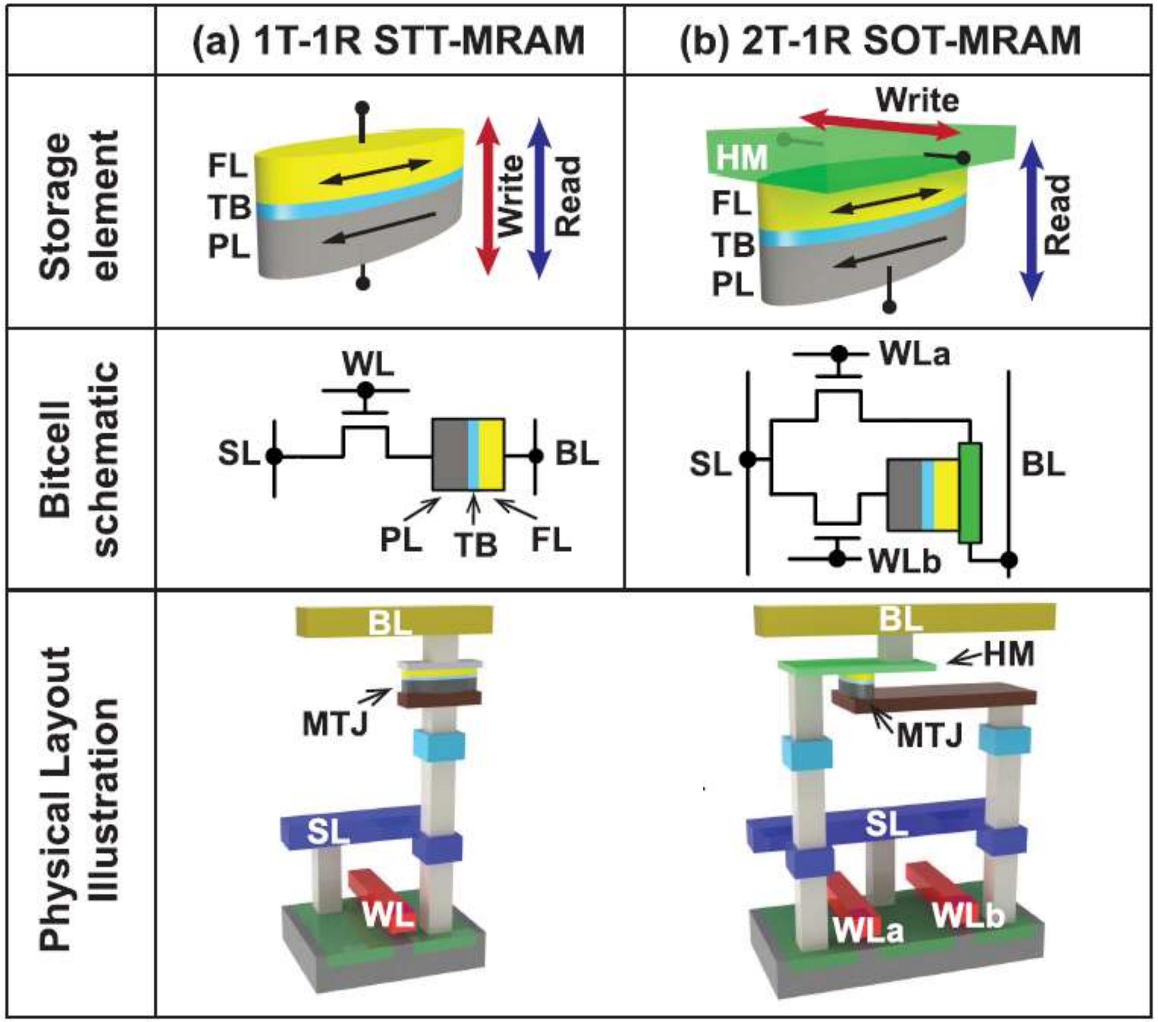
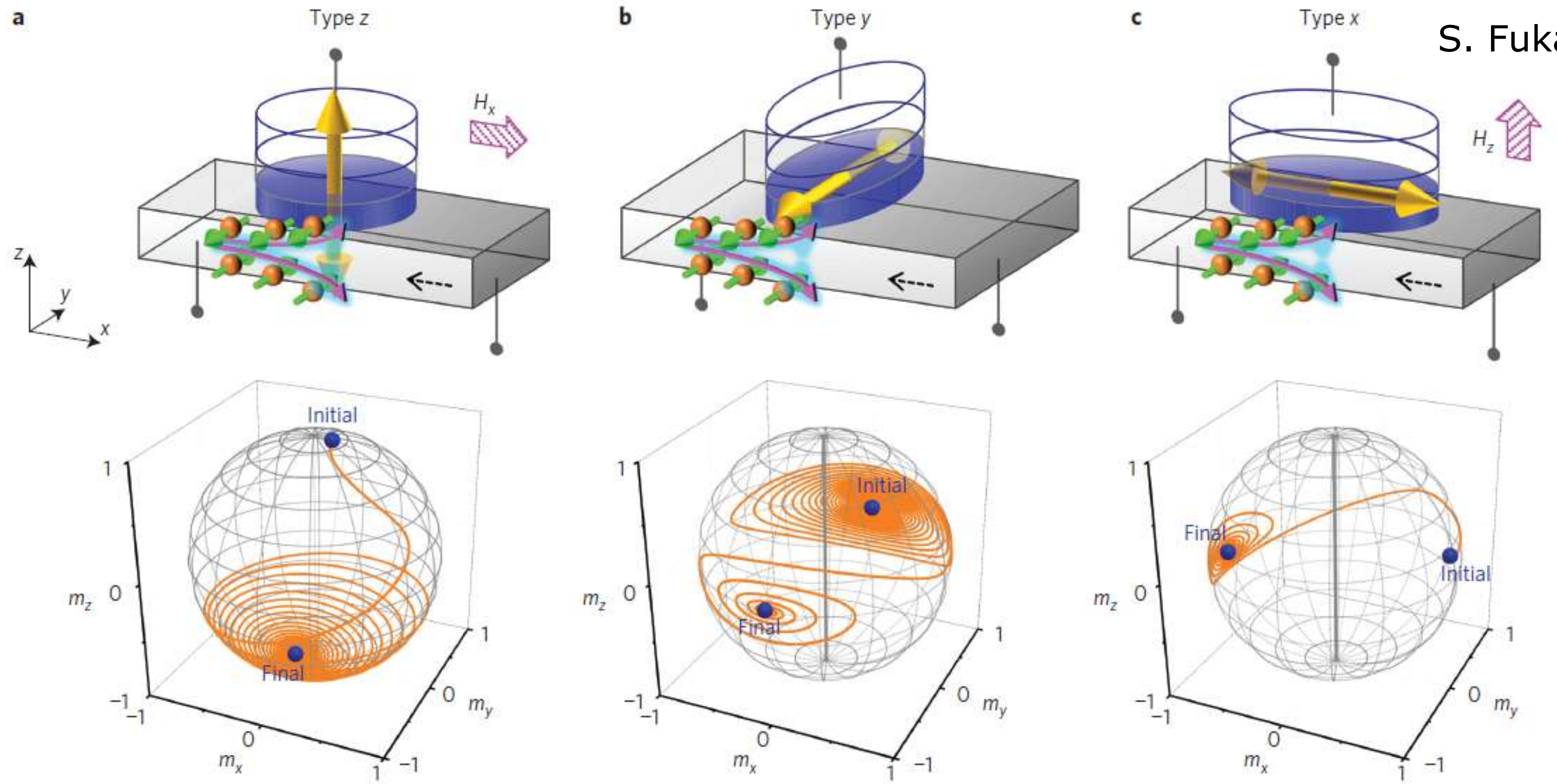


Figure from: Y. Kim et al., IEEE Trans. Electron Devices 62, 561 (2015)

- Basic SOT-MRAM cell:
  - consists of spin-orbit torque layer (typically a heavy metal like Pt, Ta) in contact with MTJ
  - to write current is passed through SOT layer, while to read it is passed through MTJ
  - cell is 3-terminal and requires2 transistors per cell to controllably write and read

- SOT-MRAM potential advantages:
  - higher endurance (as write voltage is never applied across tunnel barrier)
  - lower write-energy (as write current is applied through low resistance metal instead of high-resistance MTJ)
  - higher writing speed (as higher overdrive current can be applied due to the above)
  - lower write error rate (for the same reason as the above)

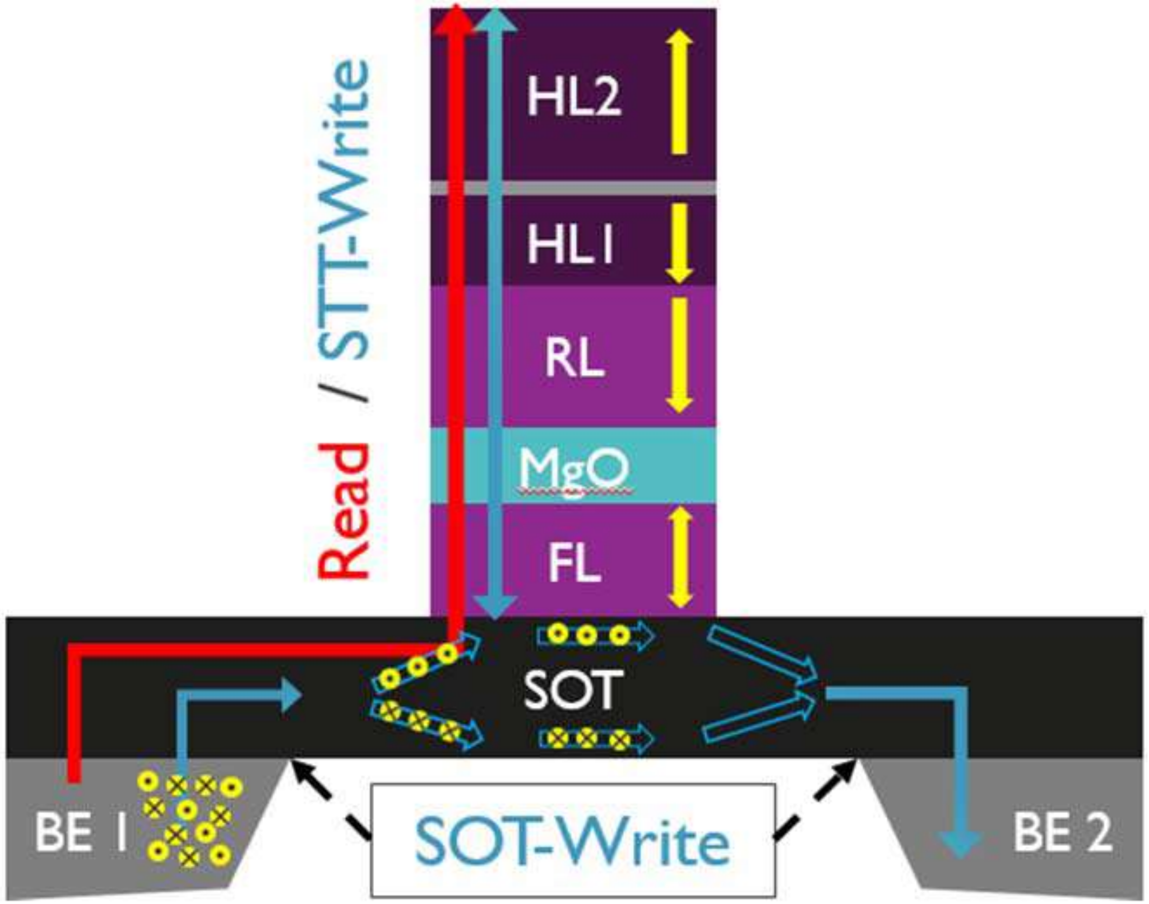
Type-x, type-y, type-z SOT devices

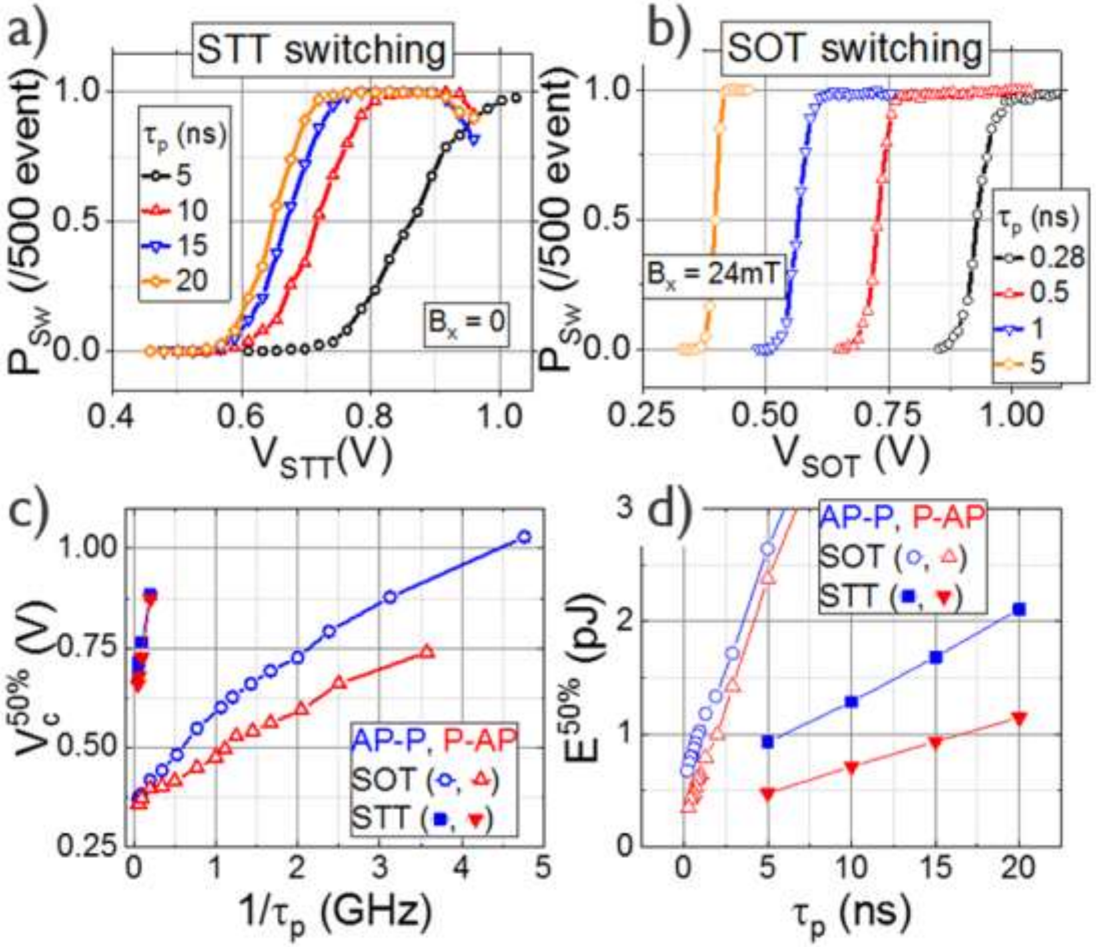


S. Fukami et al, Nature Nanotech 11, 621 (2016)

Type Z	Type Y	Type X
PMA	In-plane	In-plane
Highest density	Lower density	Lower density
fastest	Precessional, slower	fastest
Highest current	Lowest current	Middle current
Bias field (x-y)	No field	Bias field (z)

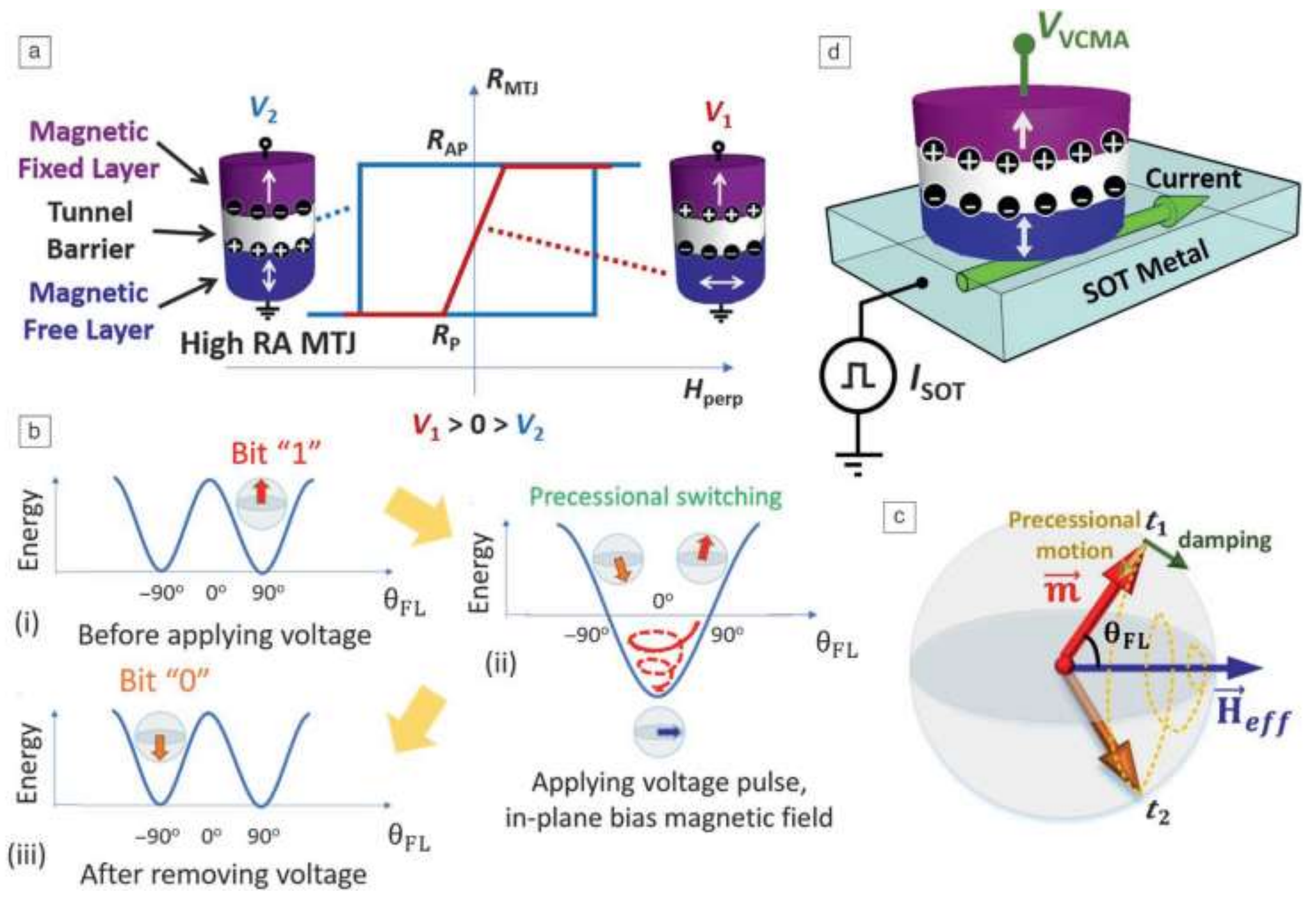
SOT Switching (IMEC)



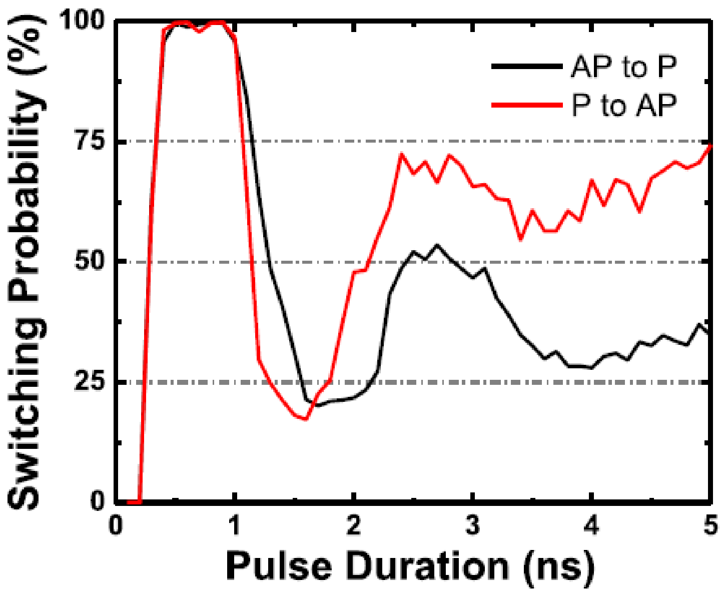


Garello et al, VLSI 2018

VCMA (Wang et al, UCLA)



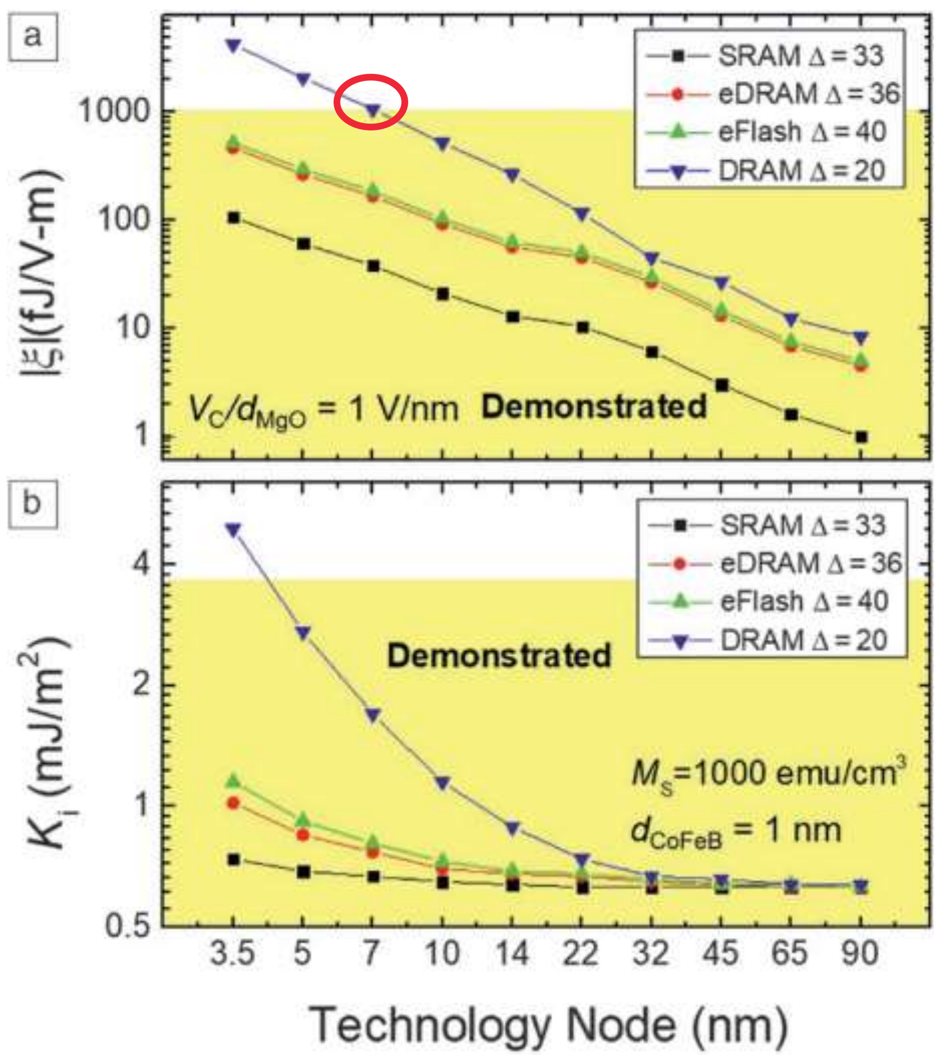
Li et al, MRS Bulletin 2018



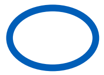
Amiri, IEEE Trans Magn 51, 2015

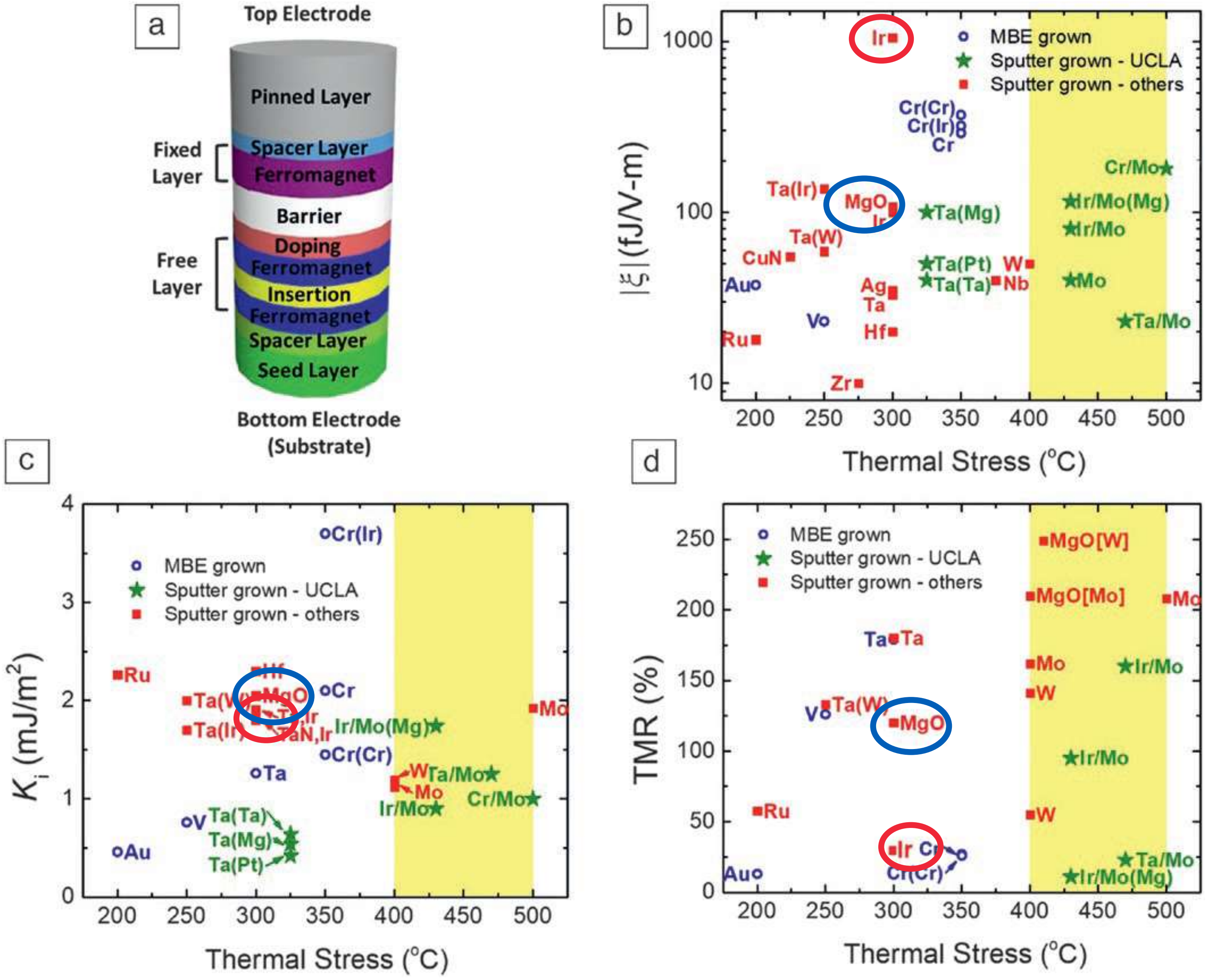
VCMA (Wang et al, UCLA)

Requirements



Materials





Li et al, MRS Bulletin 2018

VoCSM (Toshiba)

SOT + VCMA

- The VCMA is used to select the bit to write
- This can work in a chain; in a cross-point configuration, however, sneak paths would make it impossible to read the bit.
- In theory, this idea gets bit density close to that of a 1T-1R memory, since the large "write" transistor is shared by many bits, and each bit has a small "read" transistor that requires very little current.
- Read can be done in a polarity that helps increase the energy barrier, reducing read disturb

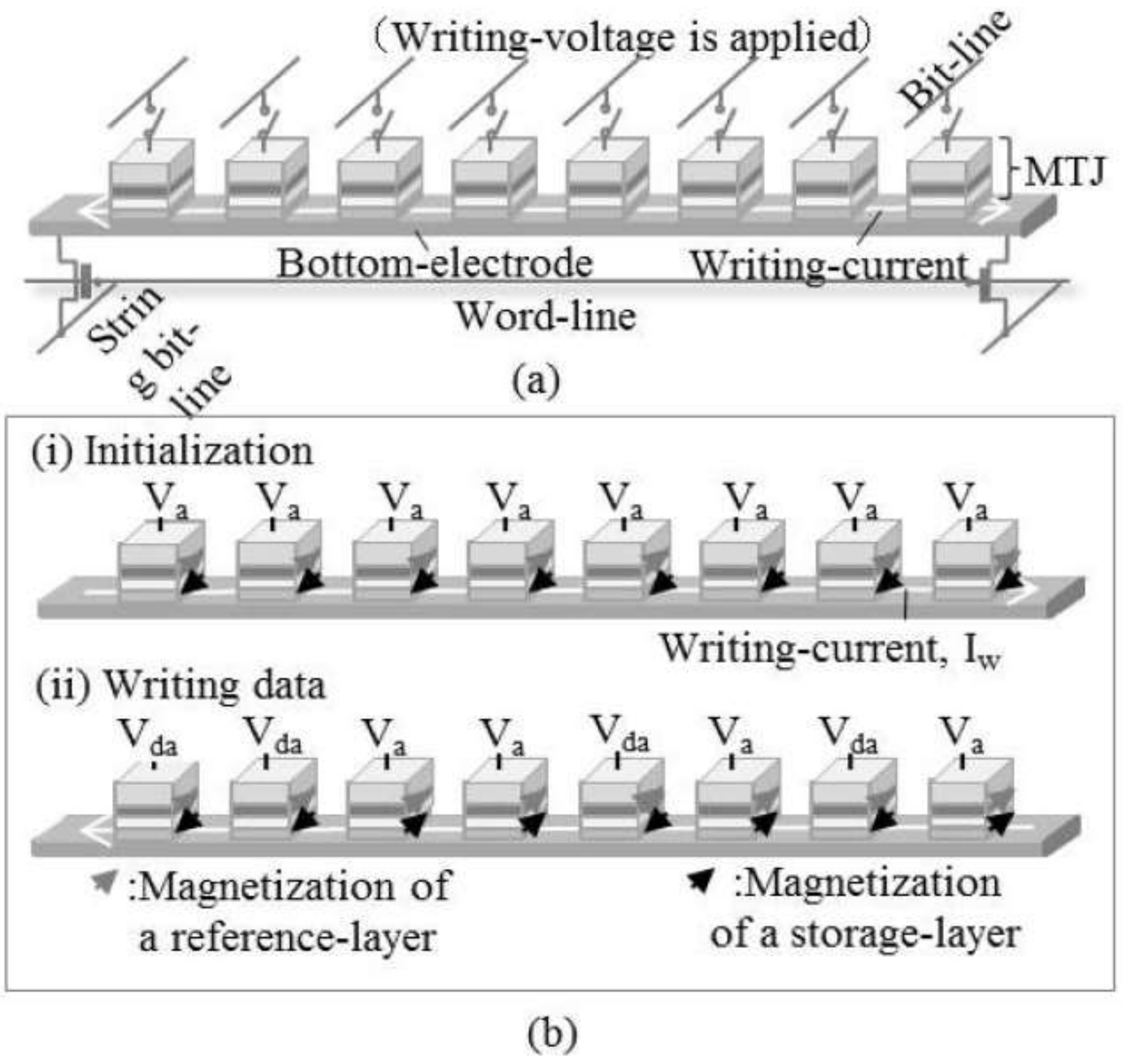


Fig. 1 A schematic drawing of the VoCSM and the VoCF-writing Scheme (a) A schematic drawing of one string of the VoCSM (b) Schematic drawing of the VoCF-writing sequence of (i) and (ii) to write data set of (1,1,0,0,1,0,1,0)

Yoda et al, IEDM 2016

Conclusions on MRAM

- **STT-MRAM is the only emerging memory technology that combines endurance, speed and energy efficiency of SRAM and DRAM with non-volatility of Flash**
- **Working chips have been demonstrated**
- **Several companies are offering/developing MRAM for embedded and stand alone memory applications**
- **Further materials, process and device physics developments are needed for pushing the memory cell size below 20 nm, to enable > 10 Gb memory capacities.**
- **New technology applications are becoming feasible with new physics**

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