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Recent developments in magnetic recording media

Kumar Srinivasan

Western Digital

March 19, 2019

Acknowledgments:

Ram Acharya, Gerardo Bertero, Paul Dorsey,, Mrugesh Desai, Antony Ajan, Debashish Tripathy, Shikha Jain, Hua Yuan, Tomoko Seki, Hoan Ho, Burak Ozdol, Shahid Pirzada

U.S.D.C. CENTRAL DISTRICT OF CALIFORNIA

CASE NO. 8:22-cv-01599-JVS-DFM

MR Technologies, GMBH

VS. Western Digital Technologies, Inc.

JOINT EXHIBIT JX-2057

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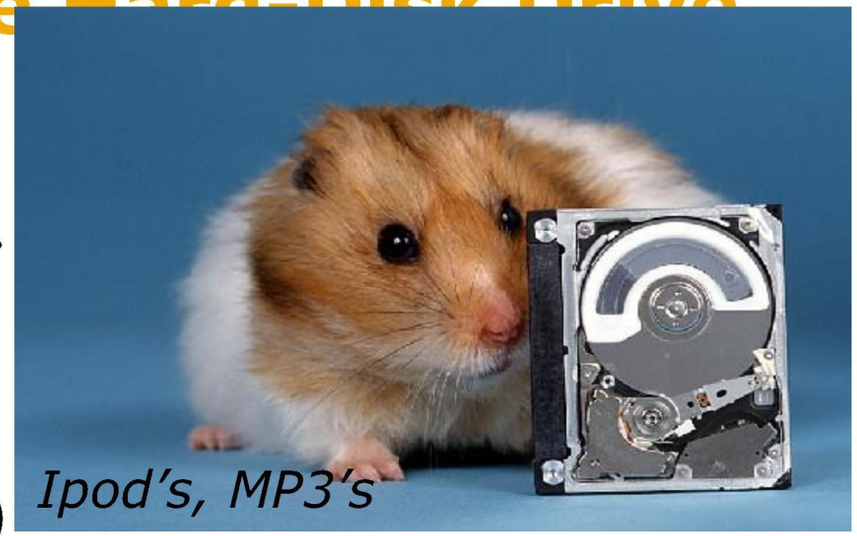
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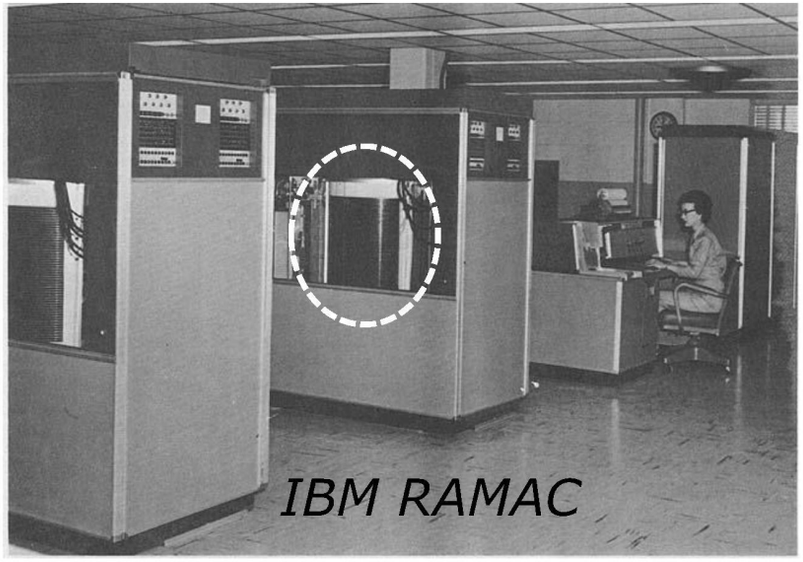
Evolution of the Hard-Disk Drive



Then…(1956)
4.4 MB

…2000's
10-20 GB

Now…
16-18 TB/drive





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Outline

Recent developments in magnetic recording media

- Introduction
  - Are HDD's still relevant?
  - The era of "Big Data"
- Current Technology - Perpendicular Magnetic Recording (PMR) media
  - Media "trilemma" and the exchange-spring principle
  - Towards graded anisotropy media
  - Grain size scaling & its limitations
  - Interfacial engineering to improve switchability
- Future Technology – Heat Assisted Magnetic Recording (HAMR)
  - The ideal HAMR medium:- FePt-X-Y
  - Single-layered vs. multi-layered segregant approach
  - Grain size progression
  - Challenges & prospects of FePt HAMR media
- Summary

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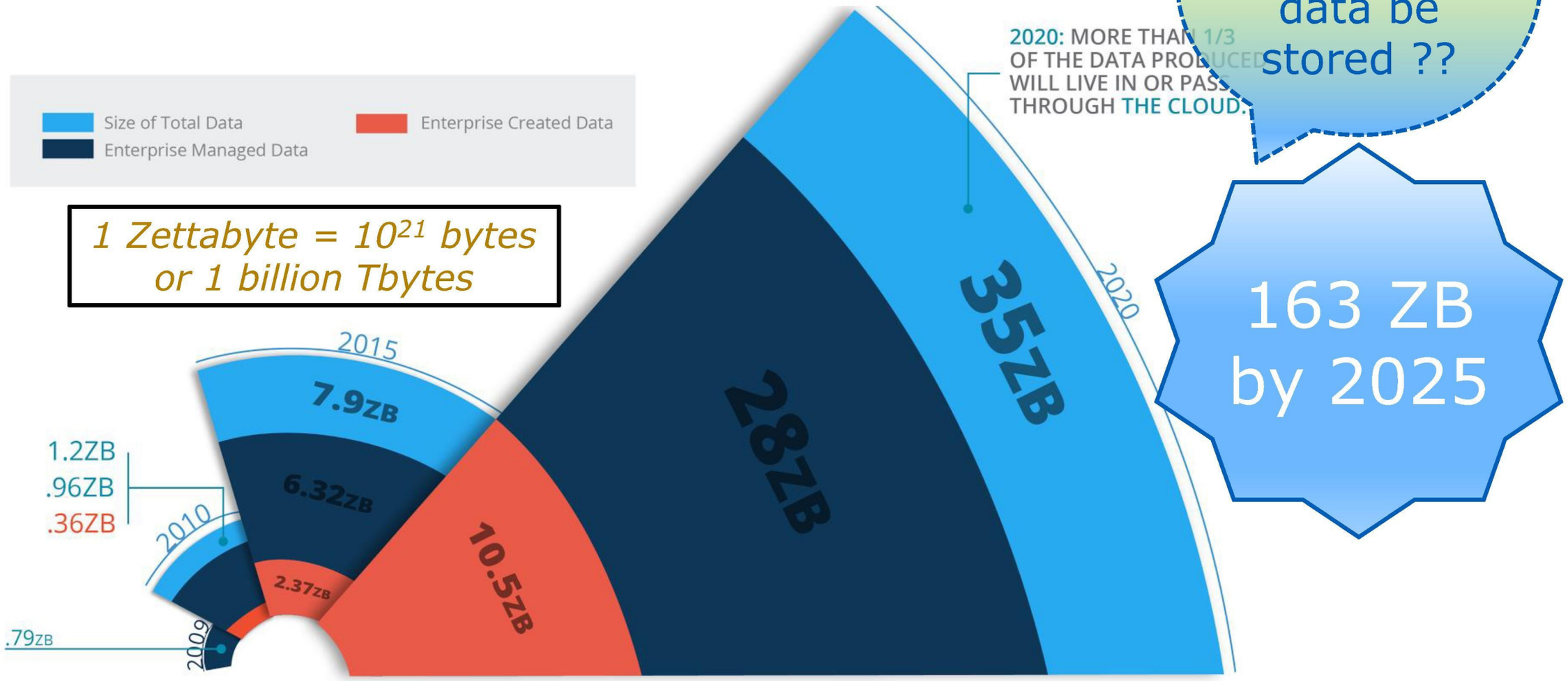
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INTRODUCTION

The era of "BIG DATA"

Where will all this data be stored ??



163 ZB by 2025

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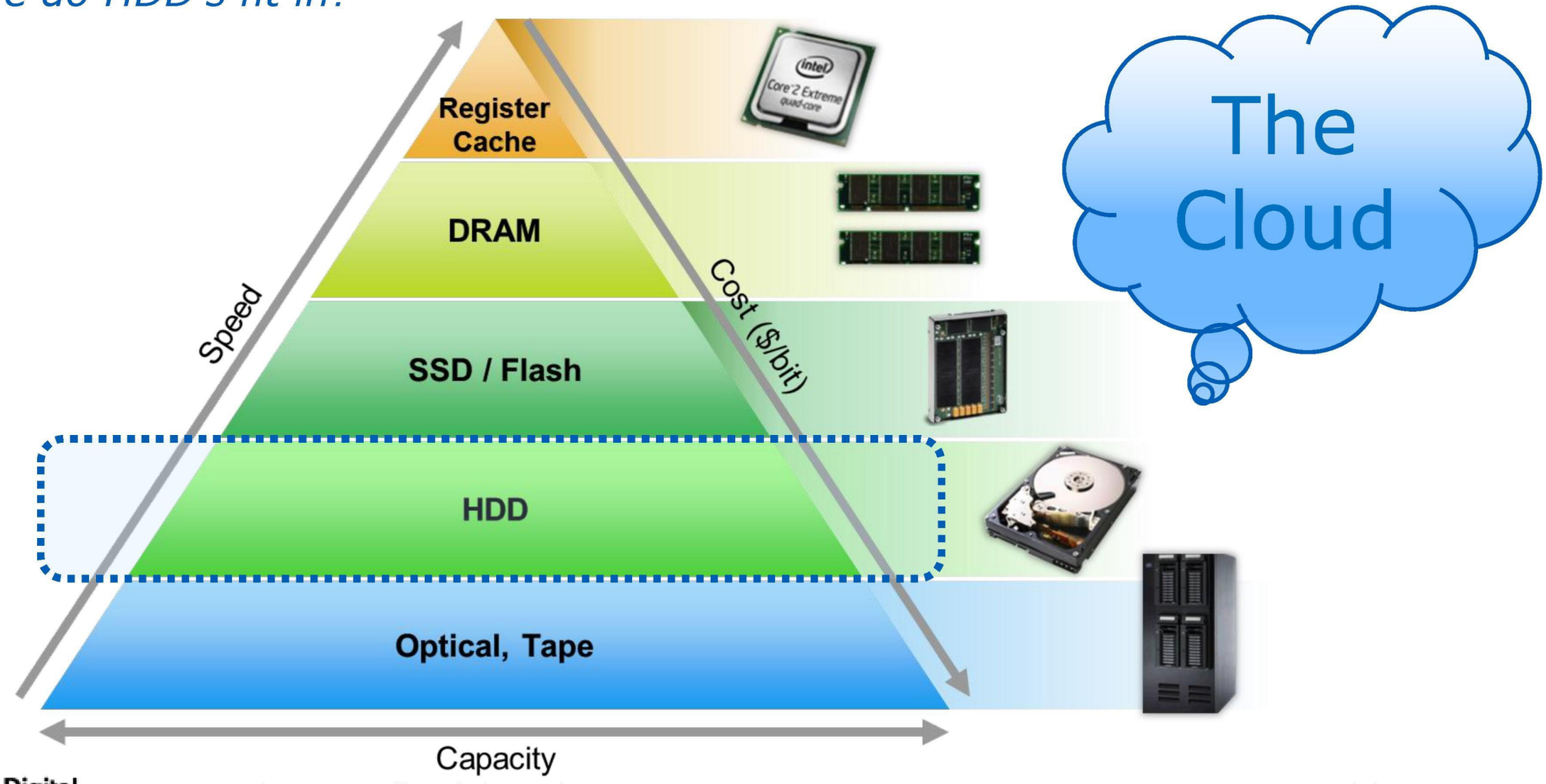
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Storage hierarchy

Where do HDD's fit in?



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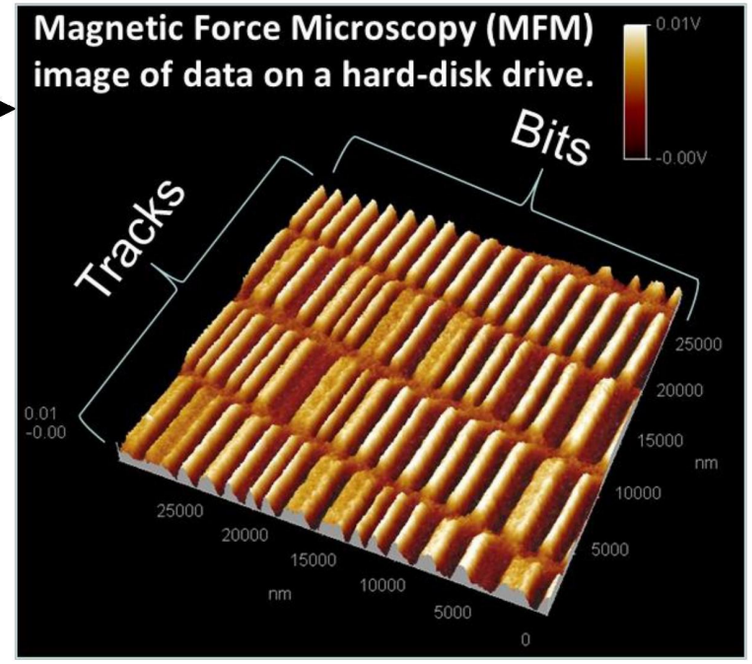
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Principles of Magnetic Recording

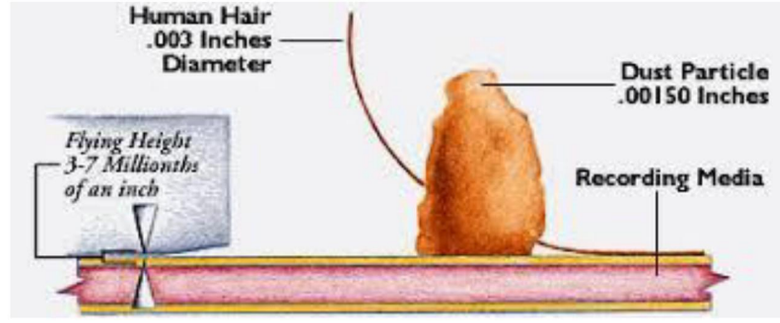
What's in a Hard-Disk Drive?





Source: http://www.cambridgenano.co.uk

- Inductive write-head to polarize the medium (N or S).
- Tunnelling Magneto-resistance (TMR) based read sensors read-back the written bits.



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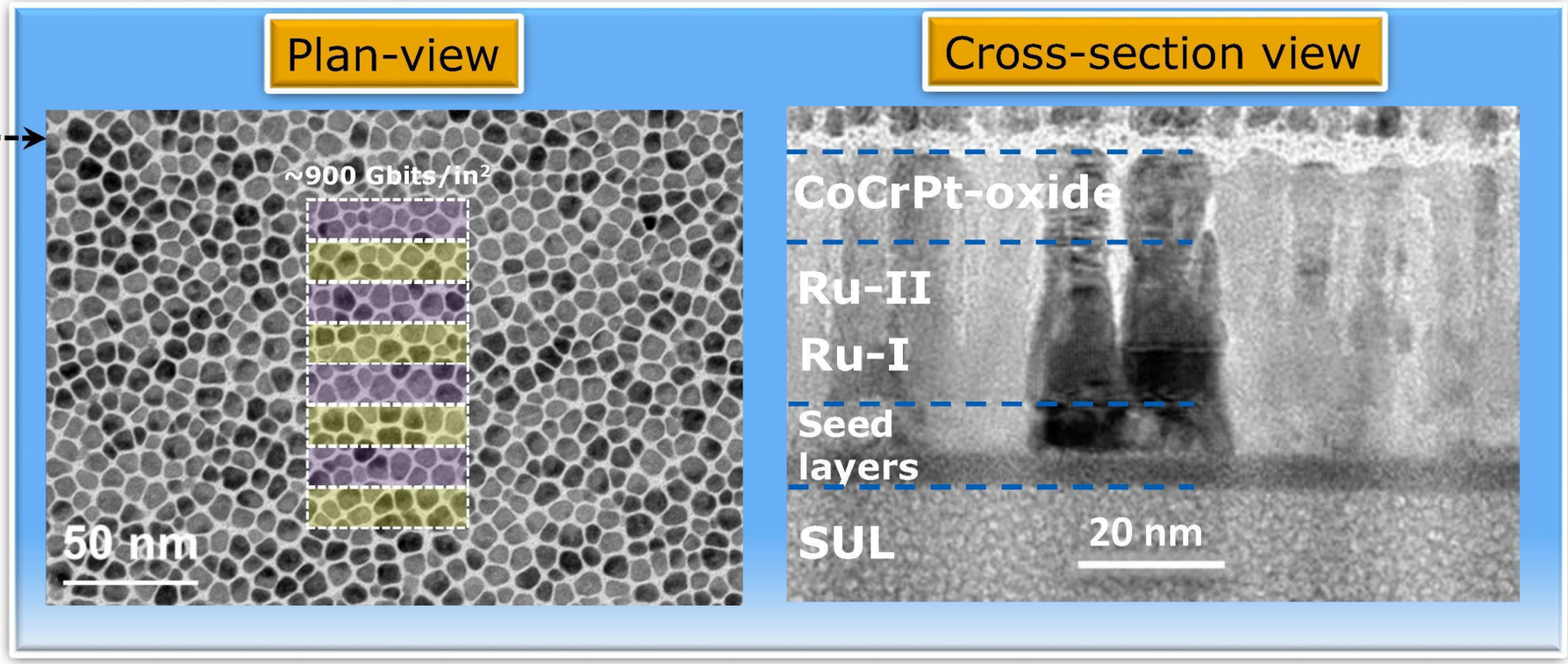
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The Magnetic Recording Medium

Modern Perpendicular Recording Media (PMR)





Core grain size (avg) ~ 7.0 nm (σ~18%)

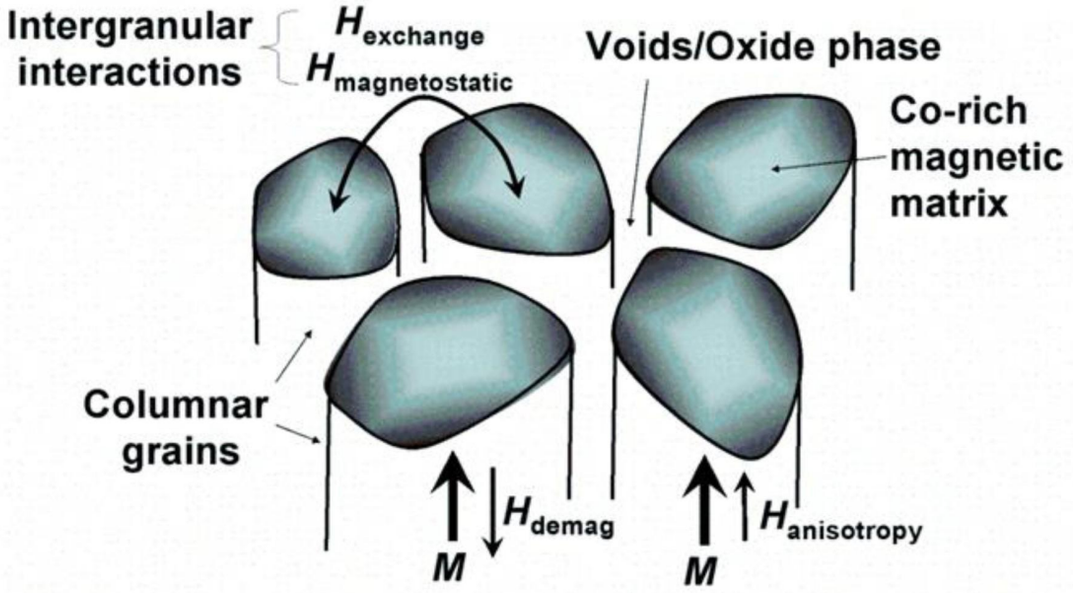
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The CoCrPt-X PMR media

Design perspectives



S. N. Piramanayagam and K. Srinivasan, J. Magn. Magn. Mater., 321, pp.485-494 (2009)

- Sputter deposition process
  - Low mobility conditions for inducing physical segregation of grains
- Hexagonal Co-Cr-Pt-Oxide
  - Cr and Oxide such as SiO_2, TiO_2 etc. for
    - i. phase separation
    - ii. magnetically isolate grains
    - iii. corrosion resistance
  - Pt for increasing anisotropy (K_u)

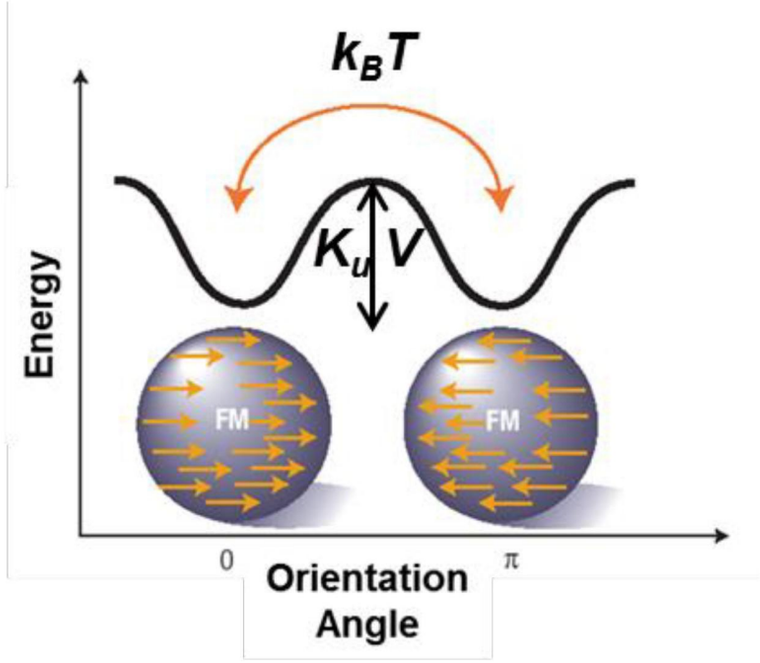
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The Media "Trilemma"

How to overcome it?



SUPERPARAMAGNETIC LIMIT

$$\frac{K_u V}{k_B T} \sim 60$$

SNR ∝ log (*N*)

***N* = no. of grains/bit**

MEDIA Signal-Noise Ratio

DESIGN SPACE

THERMAL STABILITY

WRITABILITY/ SWITCHABILITY

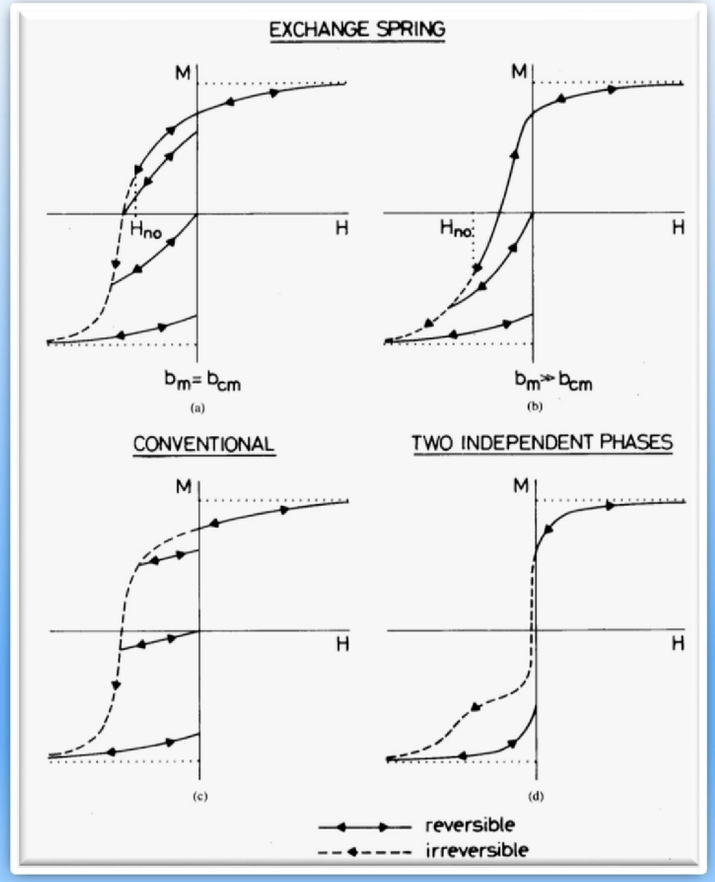
Exchange-spring "ECC" media

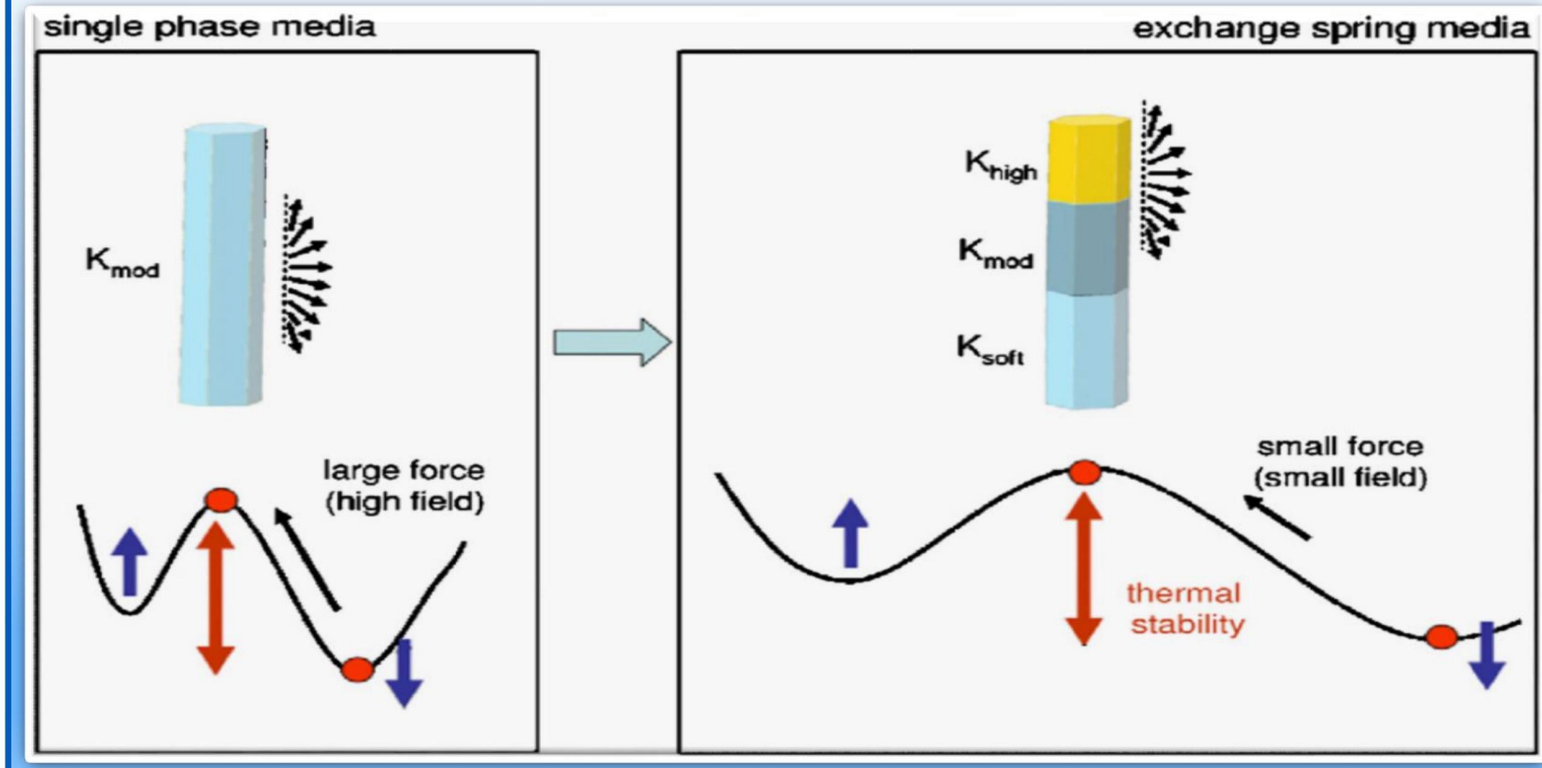
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Enter the "exchange-spring"





Suess et. al., J. Magn. Magn. Mater., 321, pp.545-554 (2009)

"The Exchange-Spring Magnet: A New Material Principle for Permanent Magnets", IEEE Trans. Magn., 27, pp.3588 (1991)

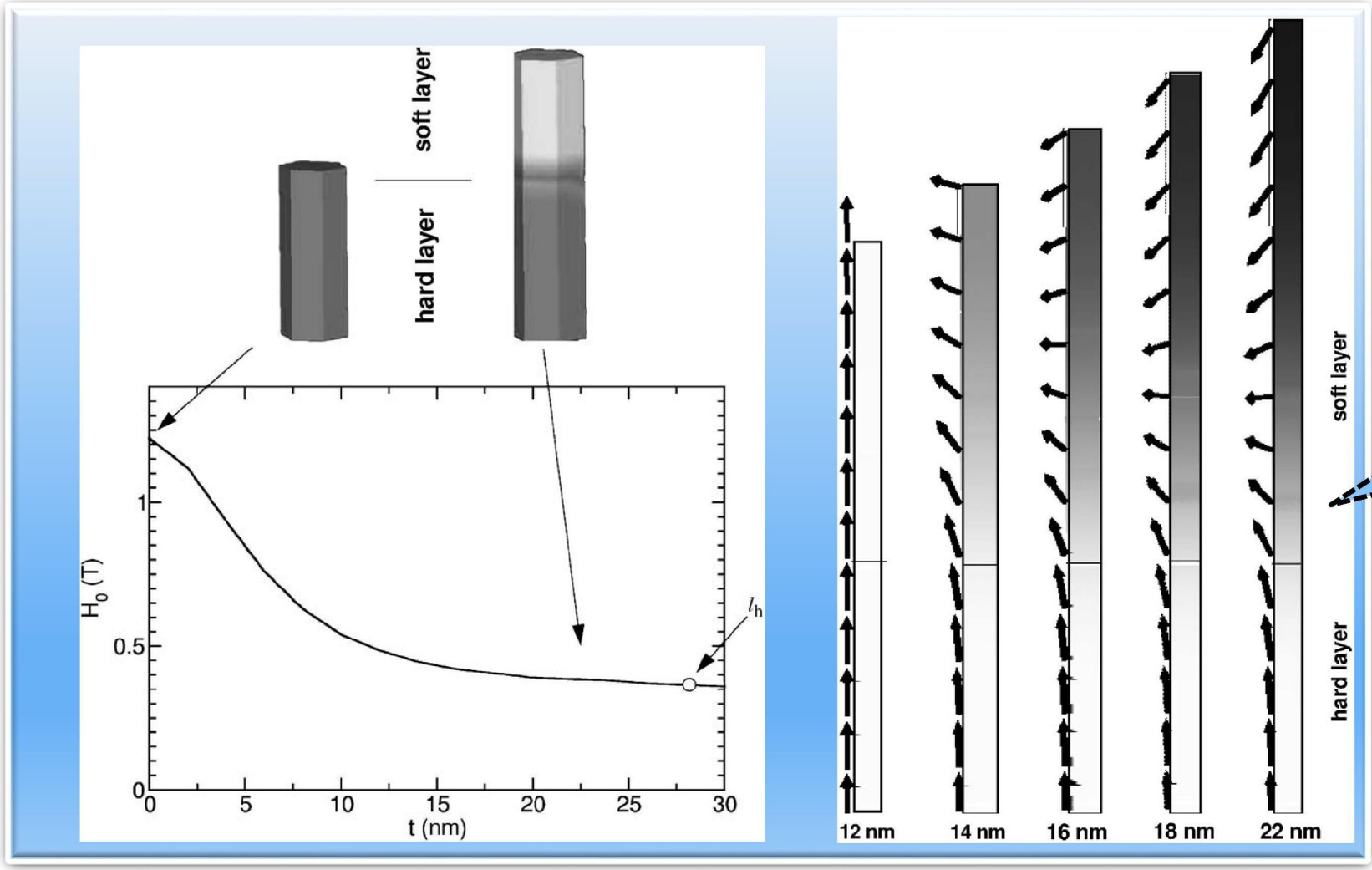
Keep the same energy barrier (thermal stability) but change the required force (field)!

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The "exchange-spring" principle



Incoherent magnetization reversal

Suess, J. Magn. Magn. Mater., 308, pp. 183-197 (2007)

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Direct evidence for "incoherent reversal"

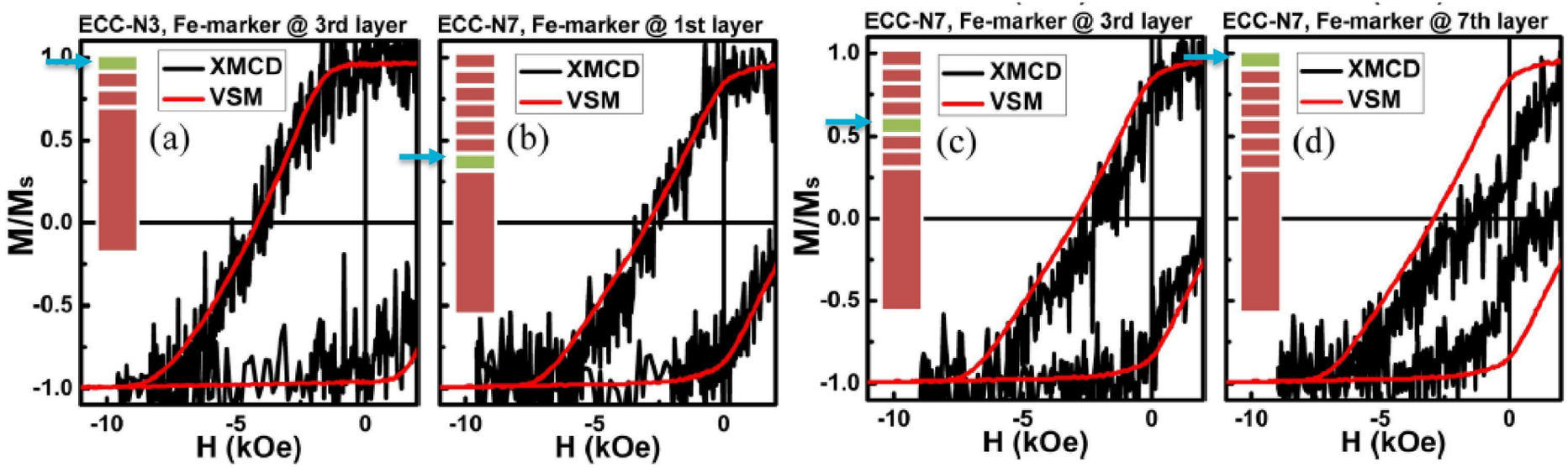
X-Ray Magnetic Circular Dichroism

APPLIED PHYSICS LETTERS **98**, 262507 (2011)

Direct probing magnetization reversal of exchange-coupled-composite media by x-ray magnetic circular dichroism

Hao-Cheng Hou,[1] Dieter Suess,[2] Jung-Wei Liao,[1] Meng-Shian Lin,[1] Hong-Ji Lin,[3] Fan-Hsiu Chang,[3] and Chih-Huang Lai[1,a)]

[1]*Department of Materials Science and Engineering, National Tsing Hua University, 30013 Hsinchu, Taiwan*
[2]*Institute of Solid State Physics, Vienna University of Technology, 1040 Vienna, Austria*
[3]*National Synchrotron Radiation Research Center, 30076 Hsinchu, Taiwan*



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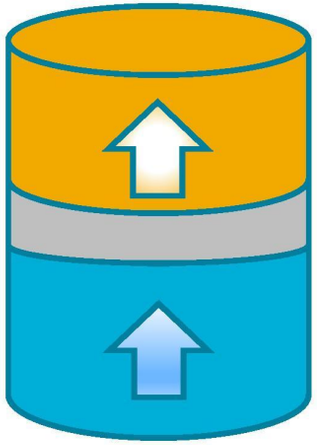
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Interfacial engineering

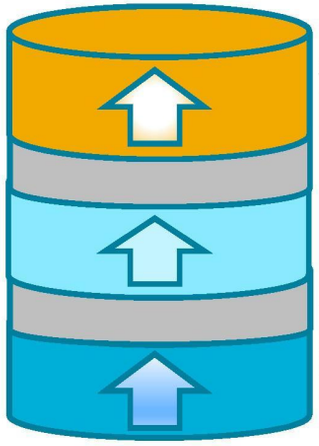
Exchange-break layers



Assist layer
high Ms/low Ku

Exchange-break layer (EBL)

Storage layer
low Ms/high Ku



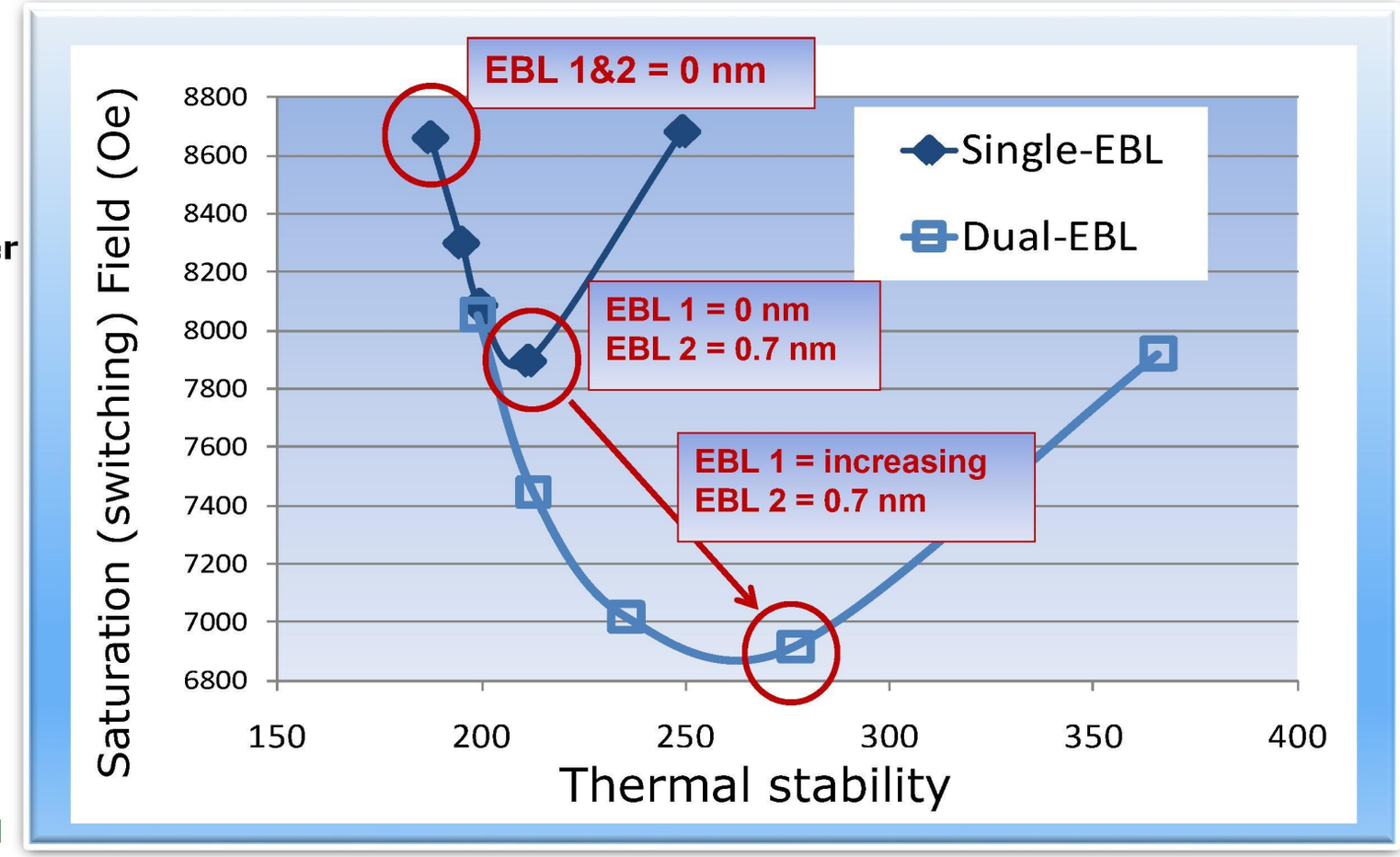
Assist layer
high Ms/low Ku

EBL2

Middle layer
med Ms/med Ku

EBL1

Storage layer
low Ms/high Ku



G. Bertero et. al., "Advanced double exchange-break PMR media structures", TMRC 2010

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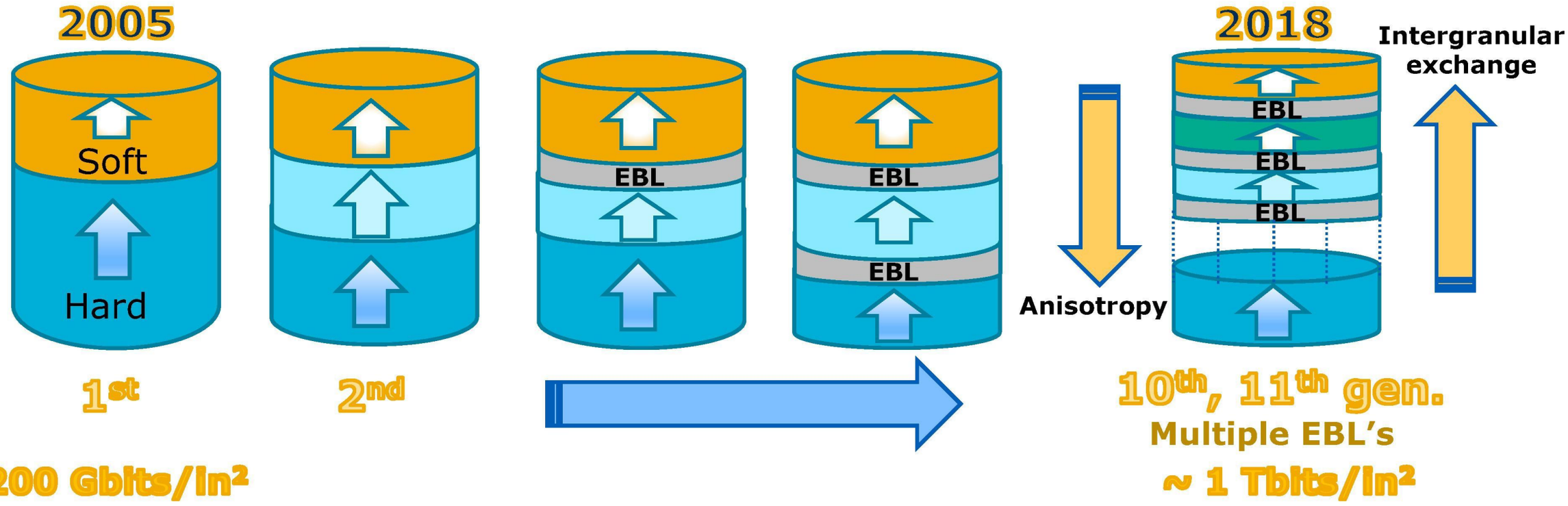
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Exchange-coupled composite media

How many EBL's?



Significant increase in complexity!

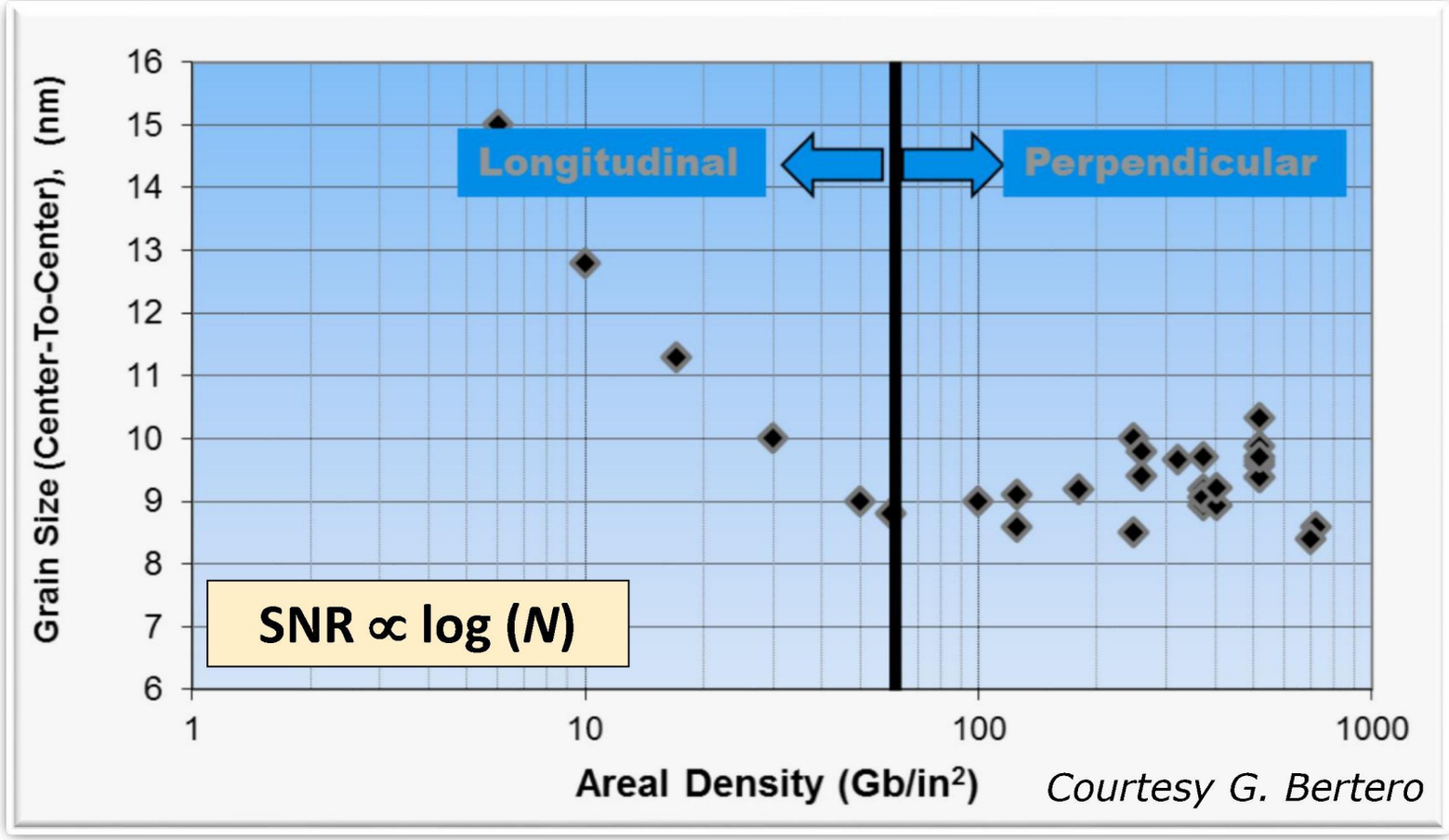
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The Grain Size Challenge

Limitations of grain size reduction



Grain size scaling appears limiting in PMR media – Why?

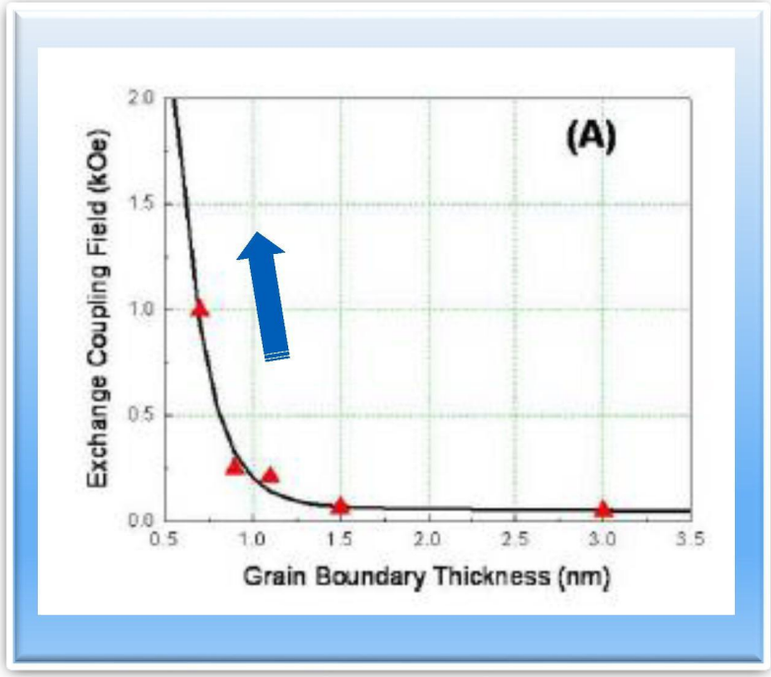
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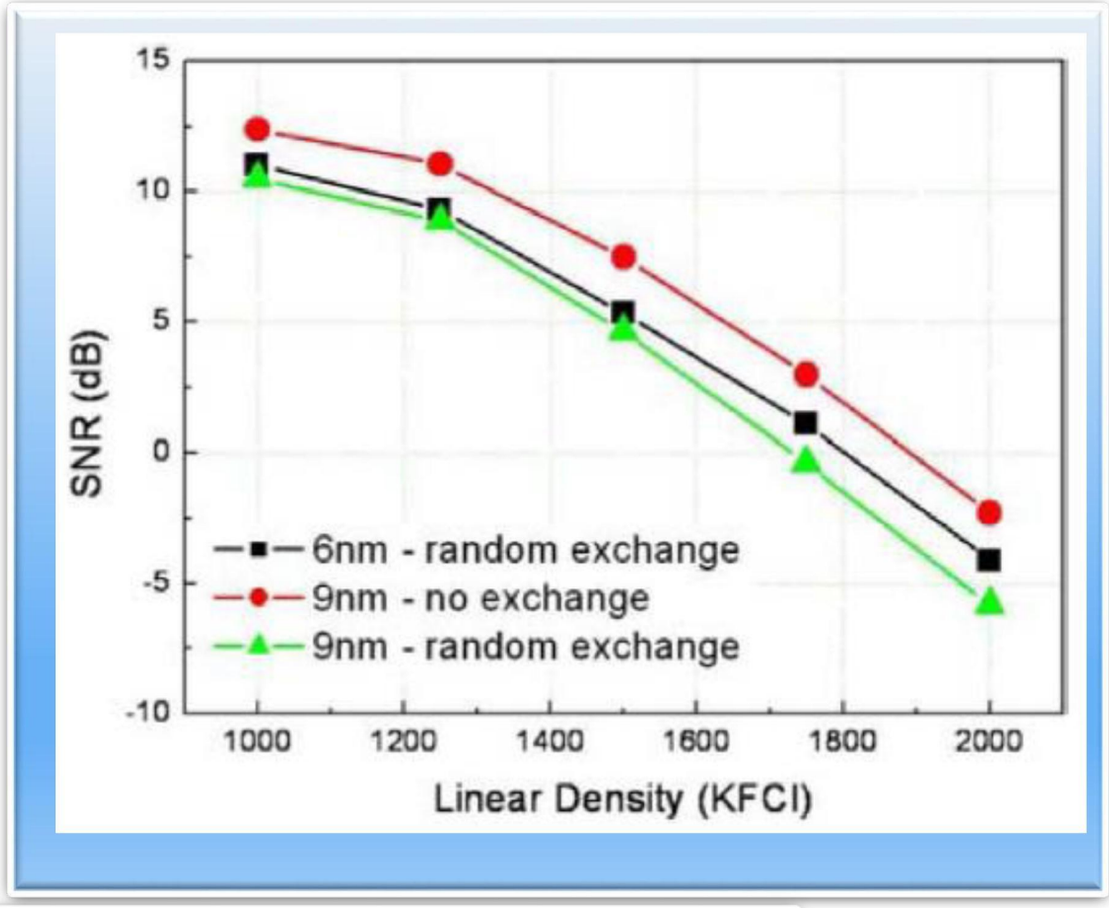
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The Grain Size Challenge

Role of intergranular exchange



J. Zhu, IEEE Trans. Magn.. "Understanding Noise Mechanism in Small Grain Size Perpendicular Thin Film Media", 46, pp.2391 (2010)



Intergranular exchange increases exponentially!

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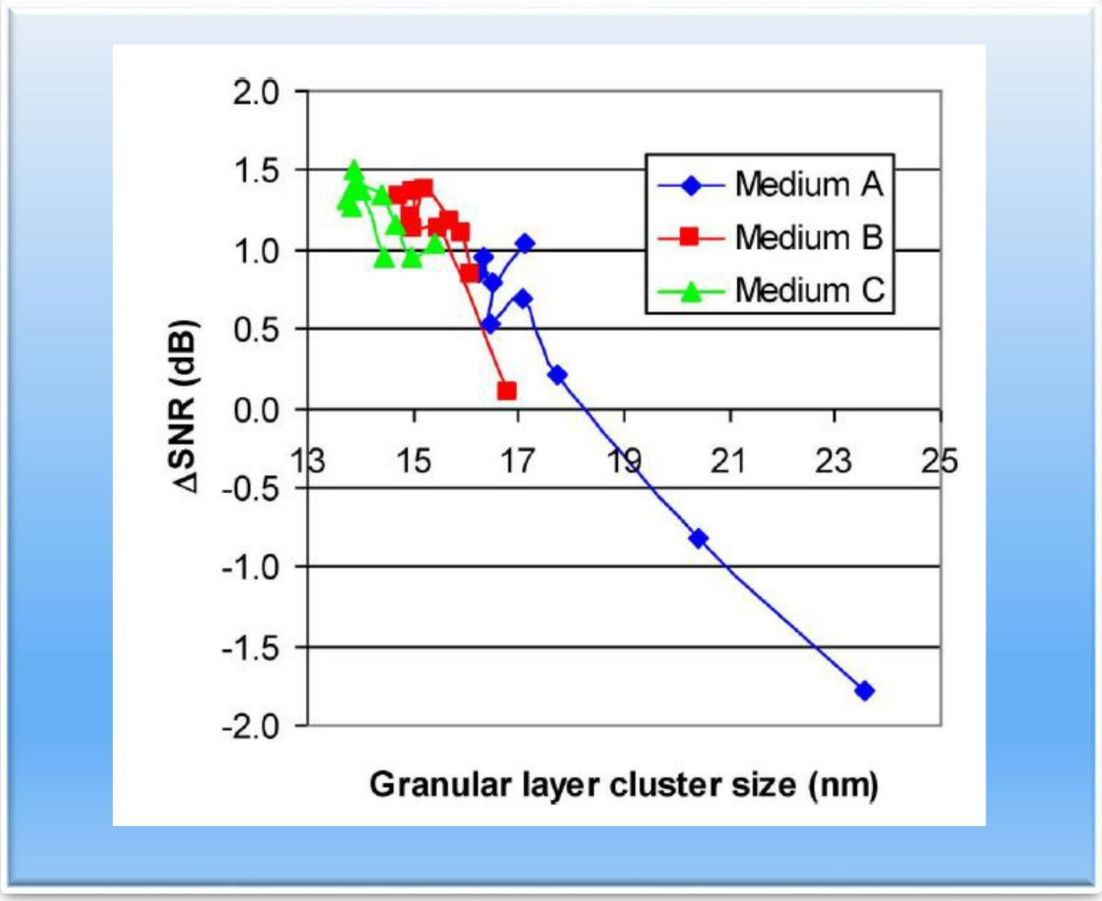
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The Grain Size Challenge

Role of intergranular exchange

	Grain pitch (nm)	Ms (emu/cc)	Ku (10^6erg/cc)	
Medium A	9.6	456	3.55	High Jex
	8.3	449	3.42	
	6.9	442	3.33	
Medium B	9.6	430	3.22	Med Jex
	8.3	427	3.25	
	6.9	429	3.05	
Medium C	9.6	429	3.09	Low Jex
	8.3	428	3.06	
	6.9	417	2.97	

Y. Ikeda, IEEE Trans. Magn.. "Magnetic Cluster Size Analysis for Small Grain Continuous Media", 48, pp.3185 (2012)



Intergranular exchange is the limiting factor!

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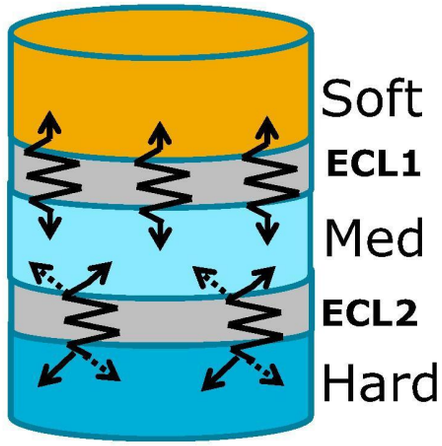
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More interfacial engineering

Can the switchability be further improved?



Type-I ECL:

Enhanced exchange-spring

Type-II ECL:

Magnetostatic/AP-coupled interface

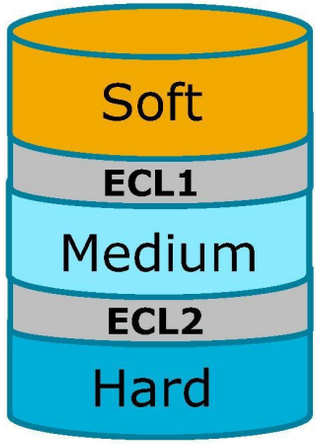
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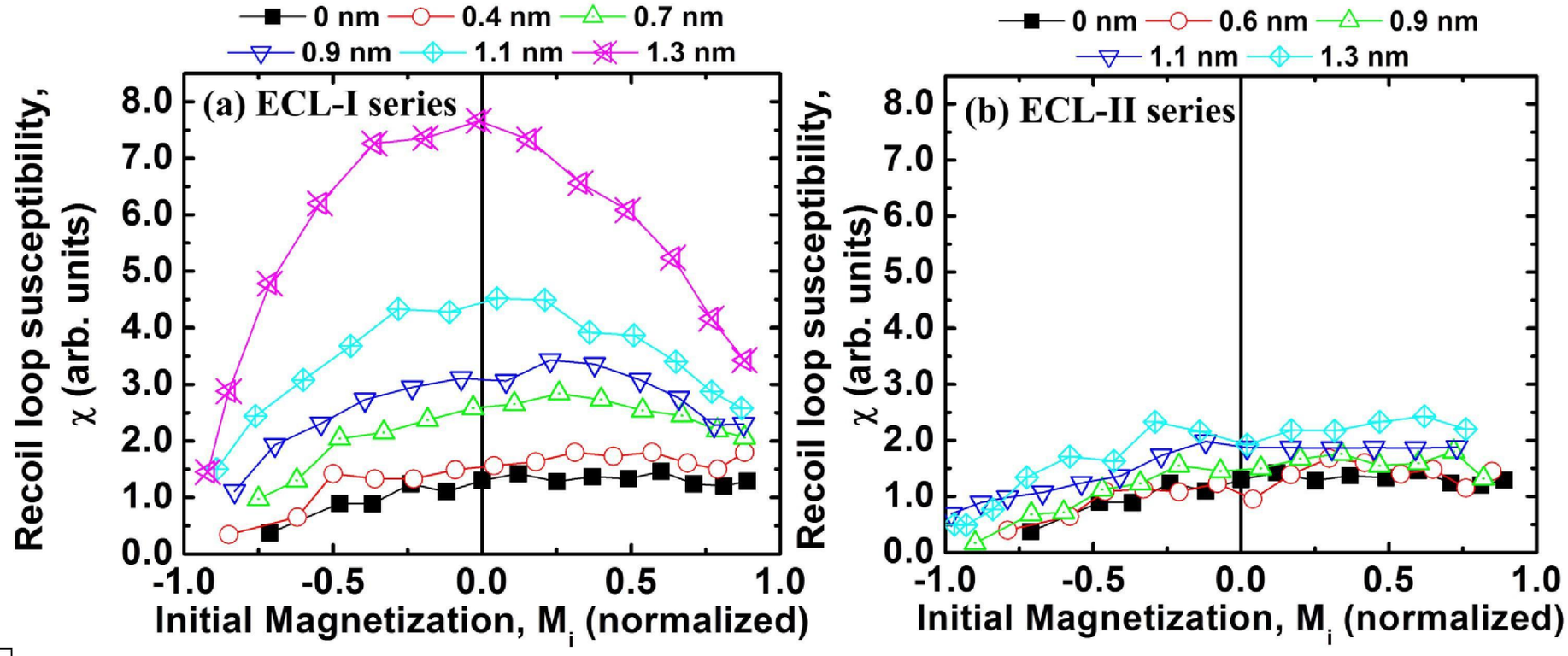
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Evidence for two different modes of reversal

Reversibility: Recoil Loop Susceptibility





K. Srinivasan et. al., 59th MMM Conf. , Paper FQ-06 (2014)

No change in susceptibility for type-II ECL series!

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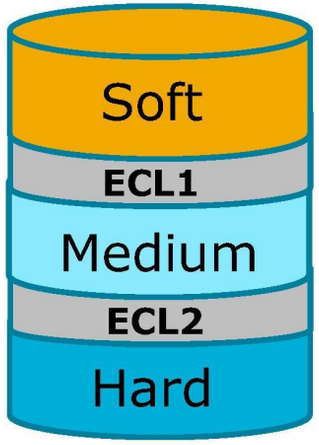
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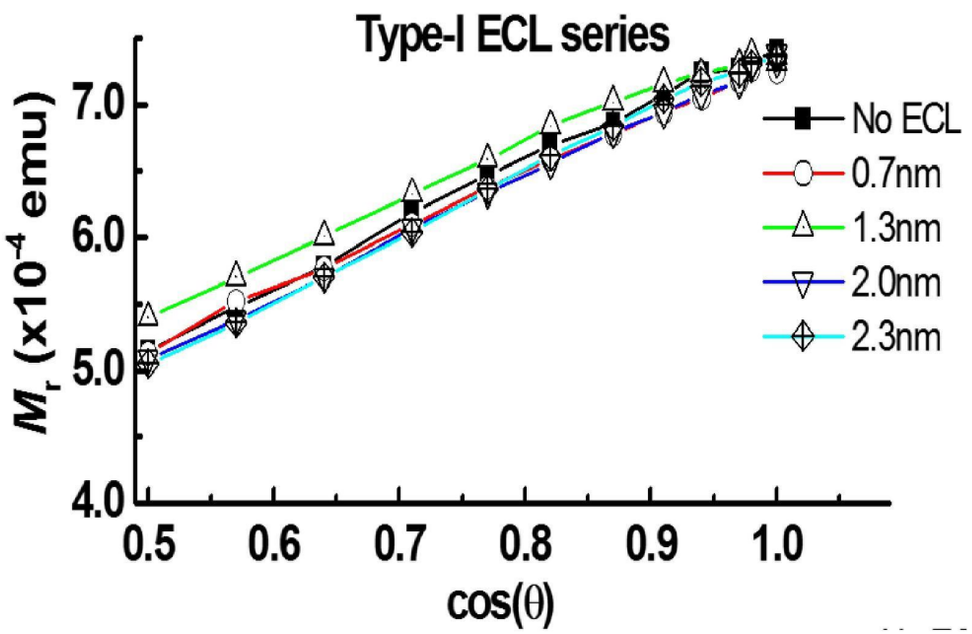
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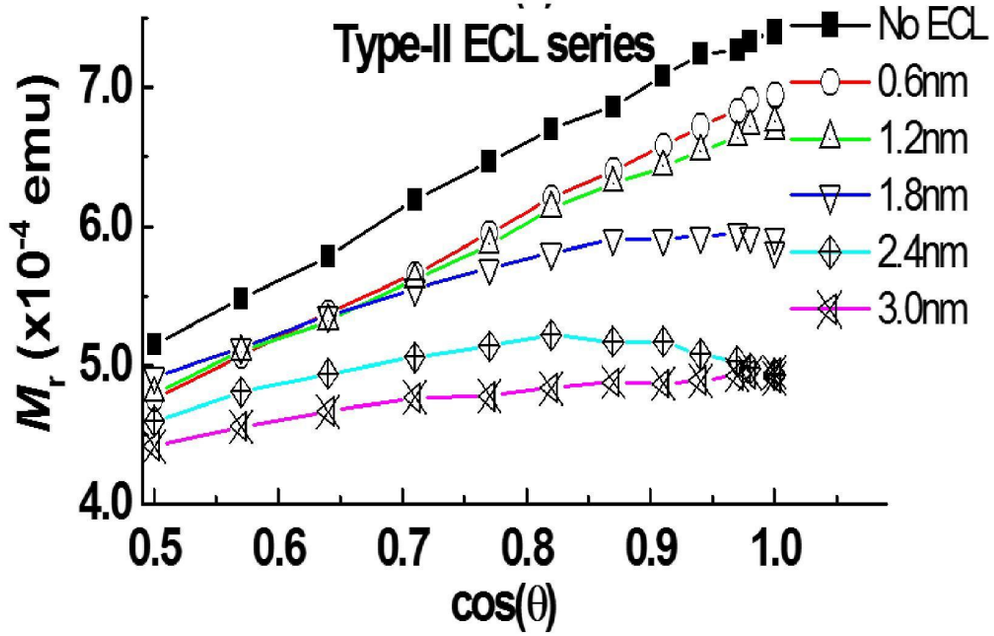
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More evidence for two reversal modes

Angular dependence of remanent magnetization







K. Srinivasan et. al., 59th MMM Conf. , Paper FQ-06 (2014)

Linear cos(Θ) dependence for type-I

Complex dependence for type-II

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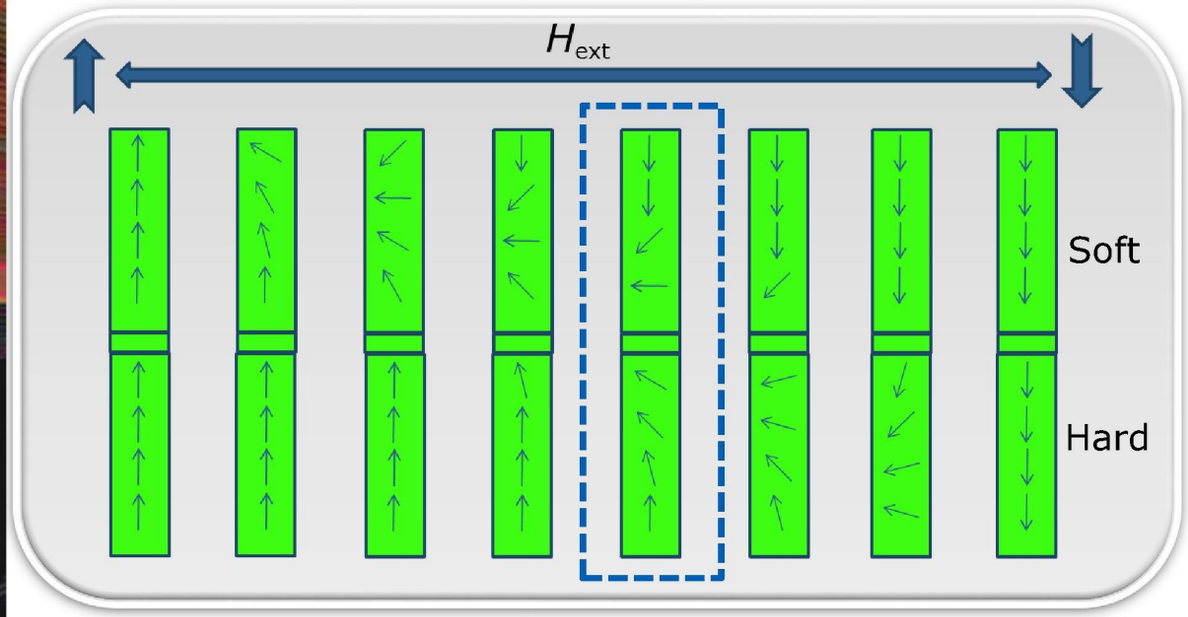
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Two types of switching mechanisms

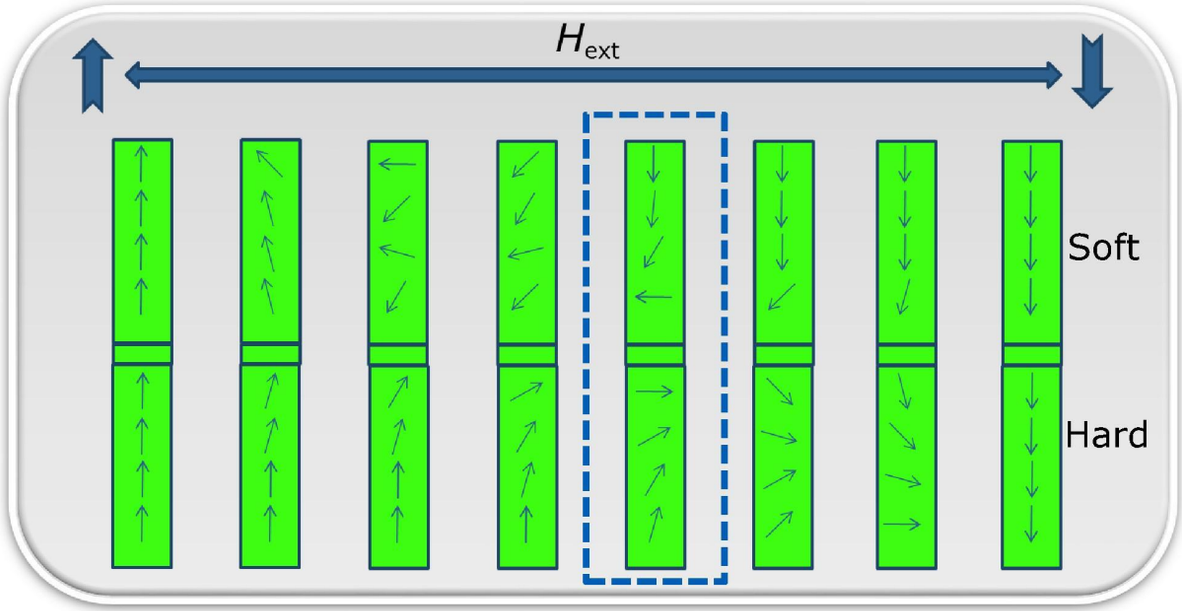
What interfacial "tuning" can do

Type-I ECL



Exchange-spring

Type-II ECL



Magnetostatic /AP-coupled

K. Srinivasan et. al., 59th MMM Conf. , Paper FQ-06 (2014)

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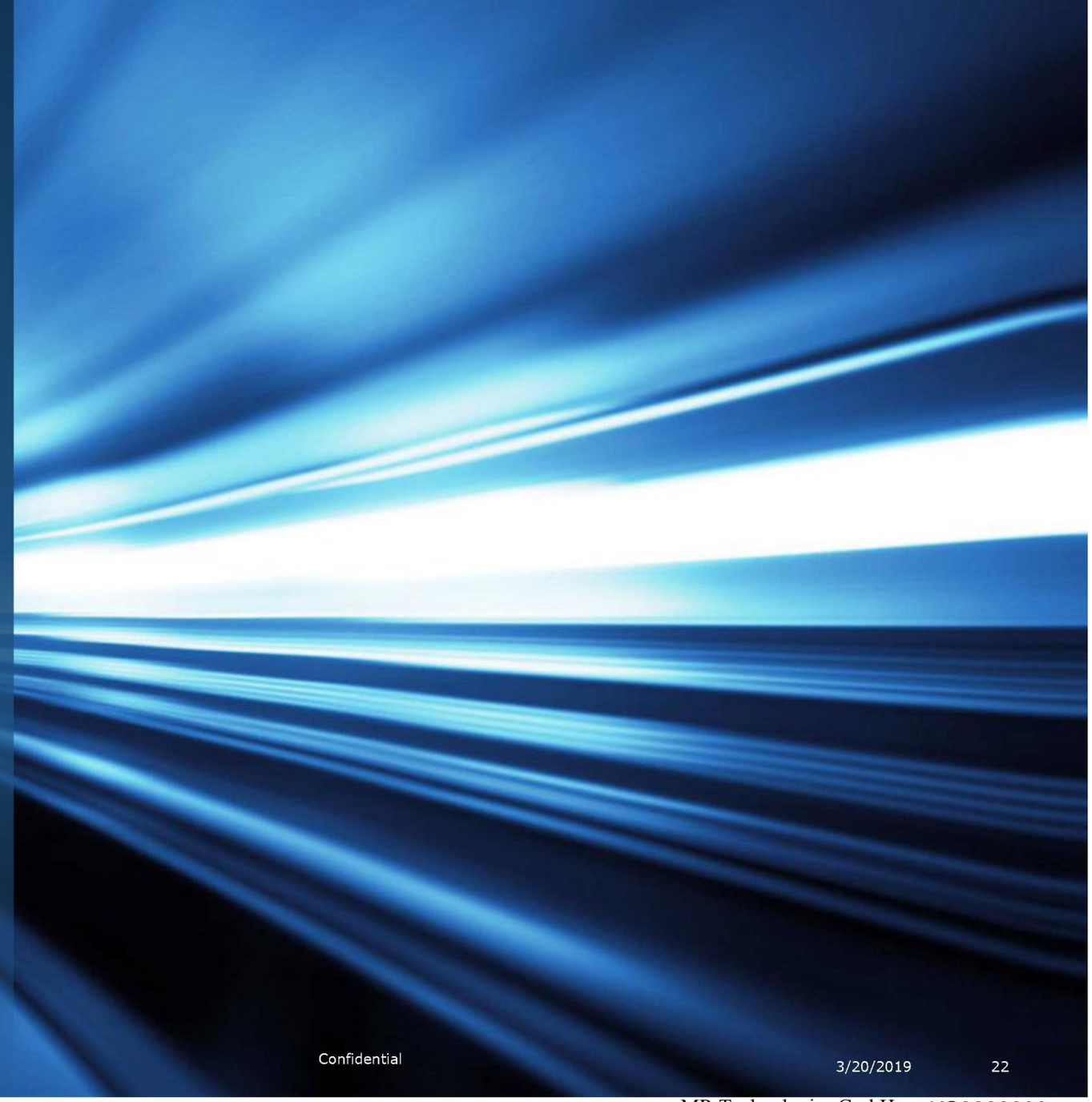
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So much for the present…

…what about the future??



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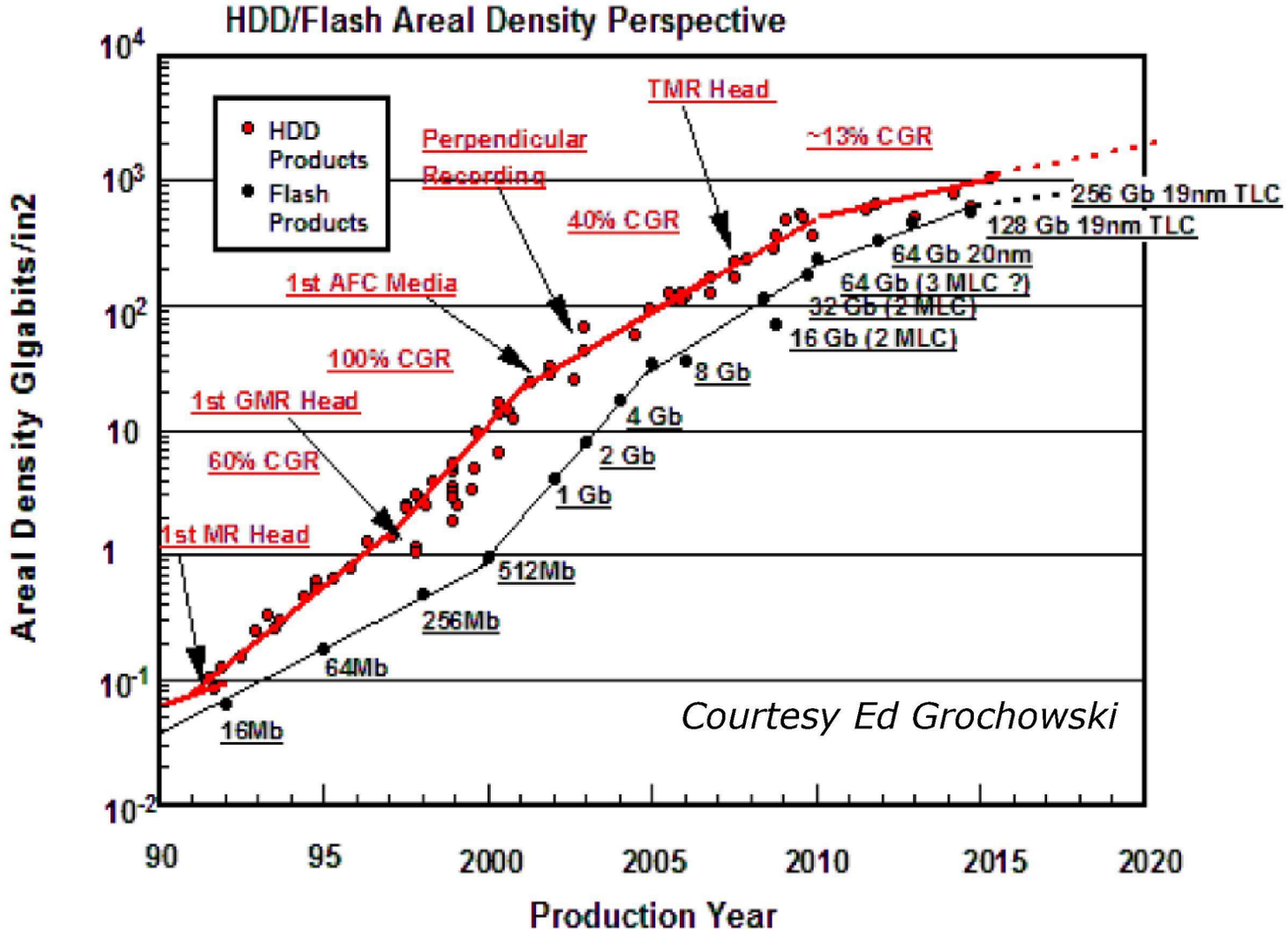
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Where is magnetic recording headed?



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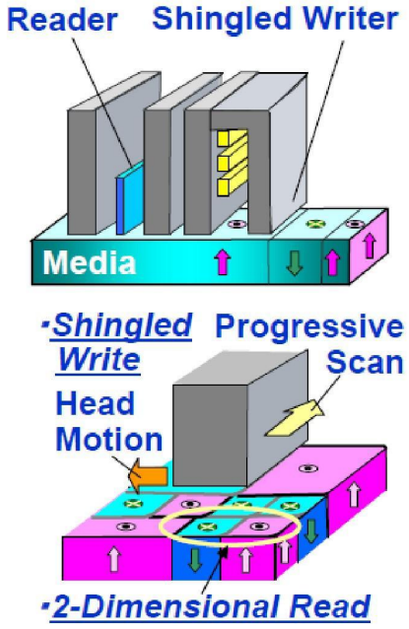
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Future technology options

Current

Shingled / Two Dimensional Magnetic Recording

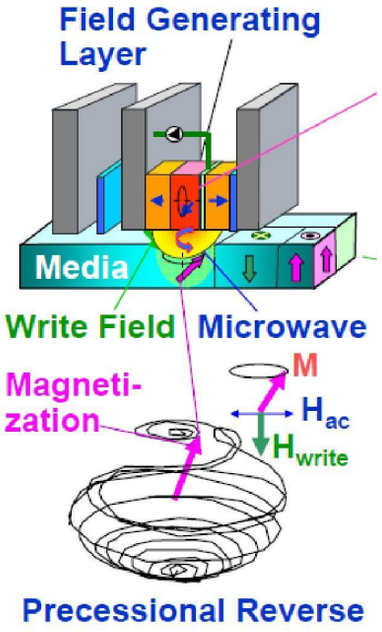


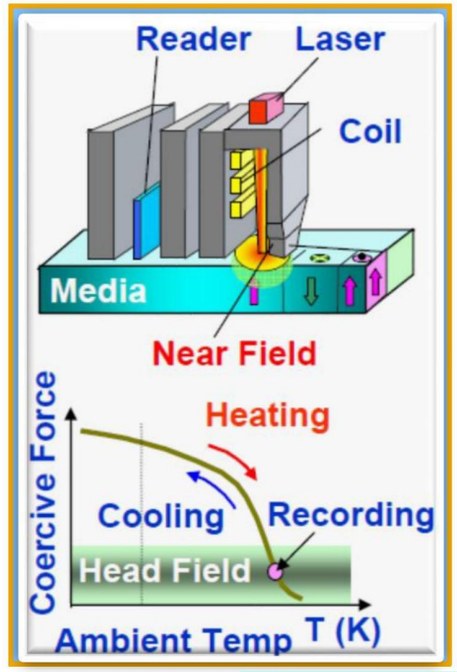
Source:

Y. Shiroishi, FA-01, Intermag (2009)

Near-term

Microwave-Assisted / Heat-Assisted Magnetic Recording

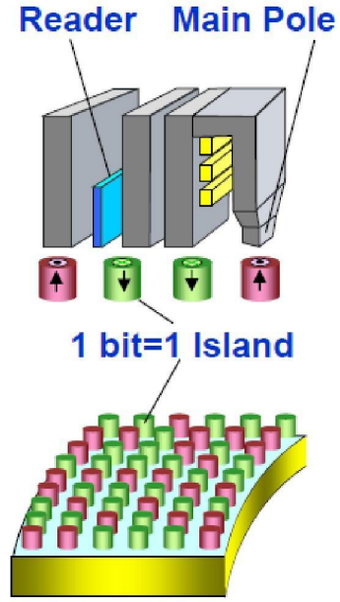




$$\frac{dH_{eff}}{dx} = \frac{dH_k}{dT} \cdot \frac{dT}{dx}$$

Far-out

Bit Patterned Media



- ***Very high Ku*** magnetic materials enable media with smaller thermally stable grains.
- Higher temperature gradients allow for ***high effective field gradients***.

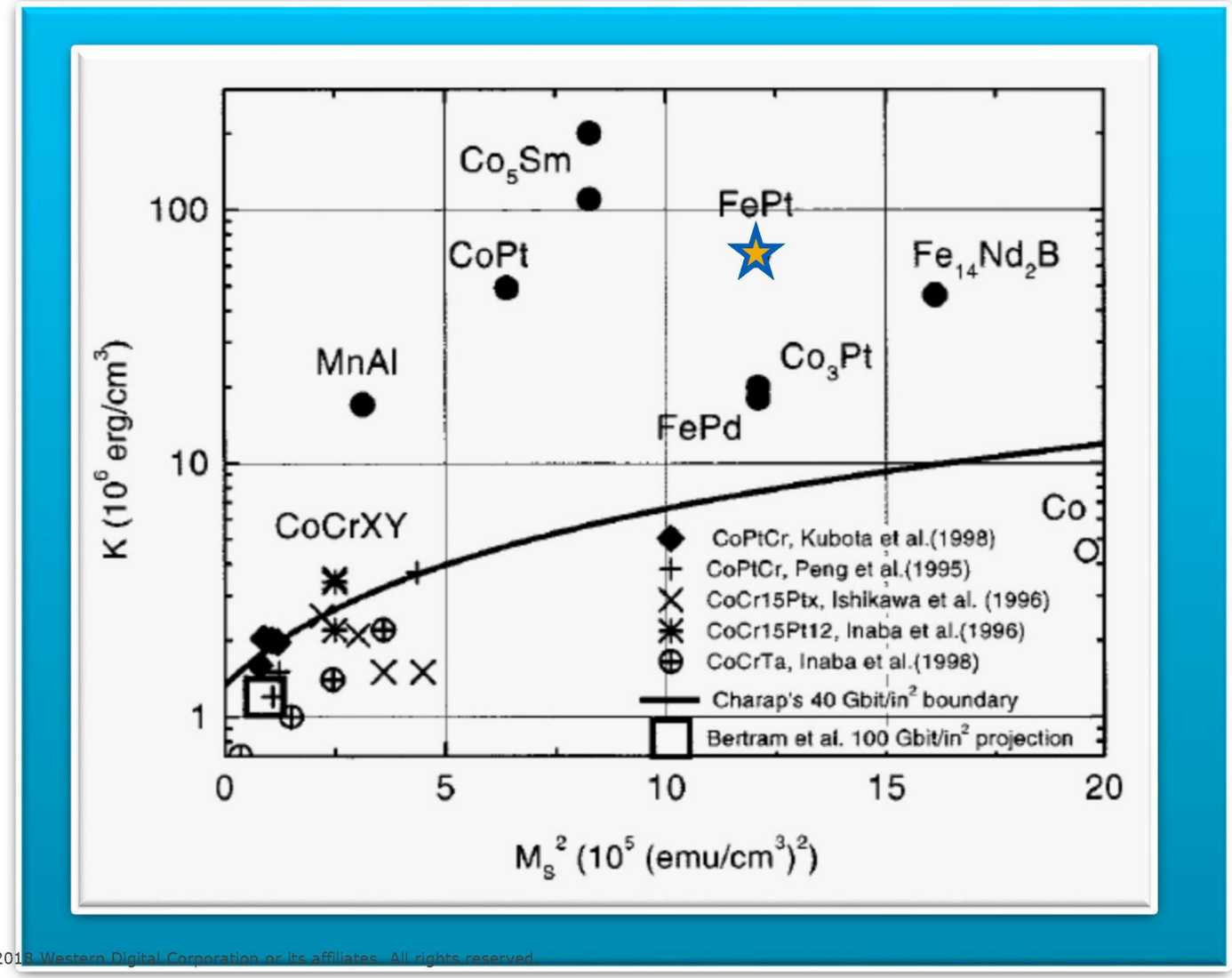
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Media material choices

What are the high Ku magnetic materials?



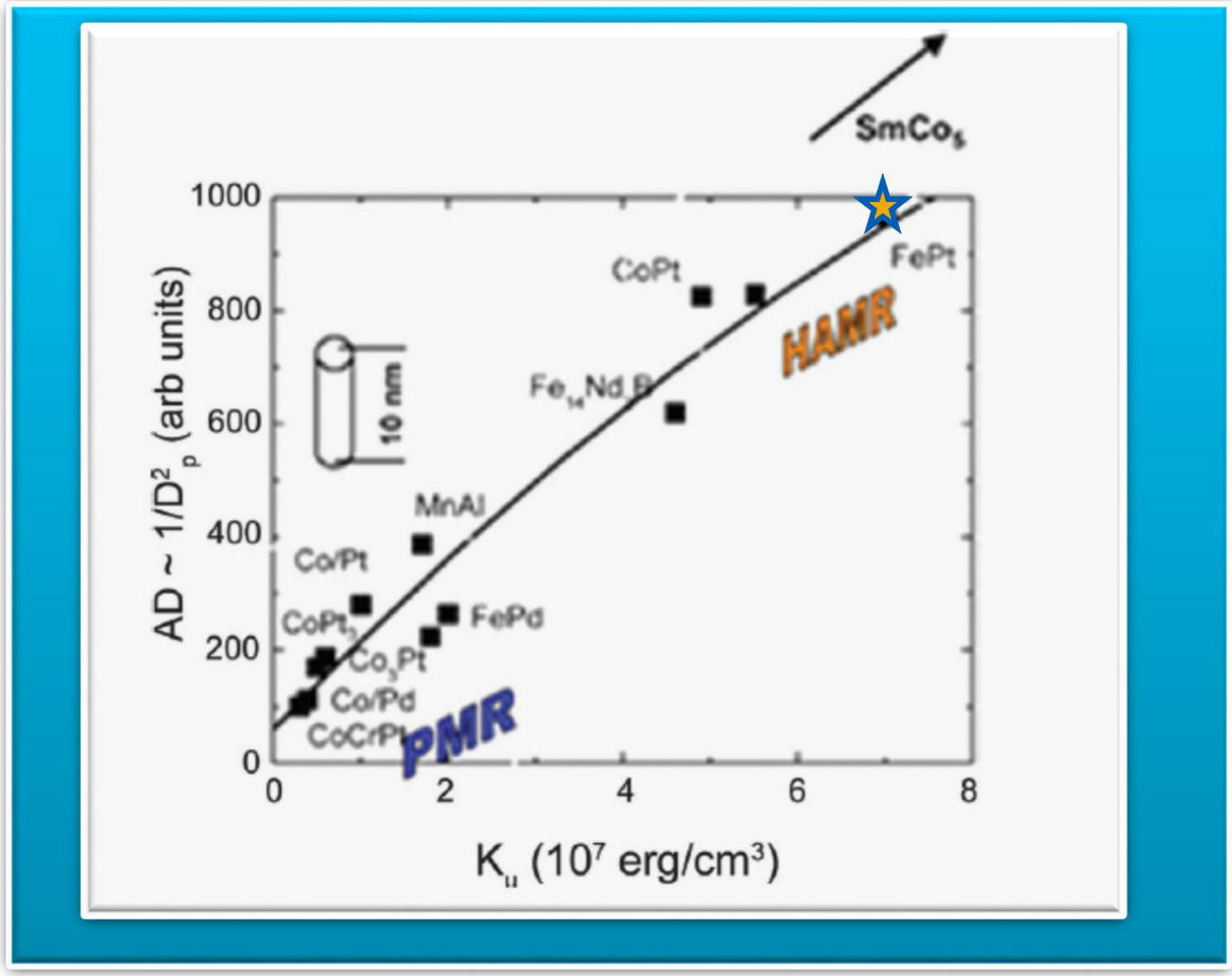
Weller et al., IEEE Trans Magn., 36, pp. 10 (2000)

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Media material choices

Grain size scaling & areal density



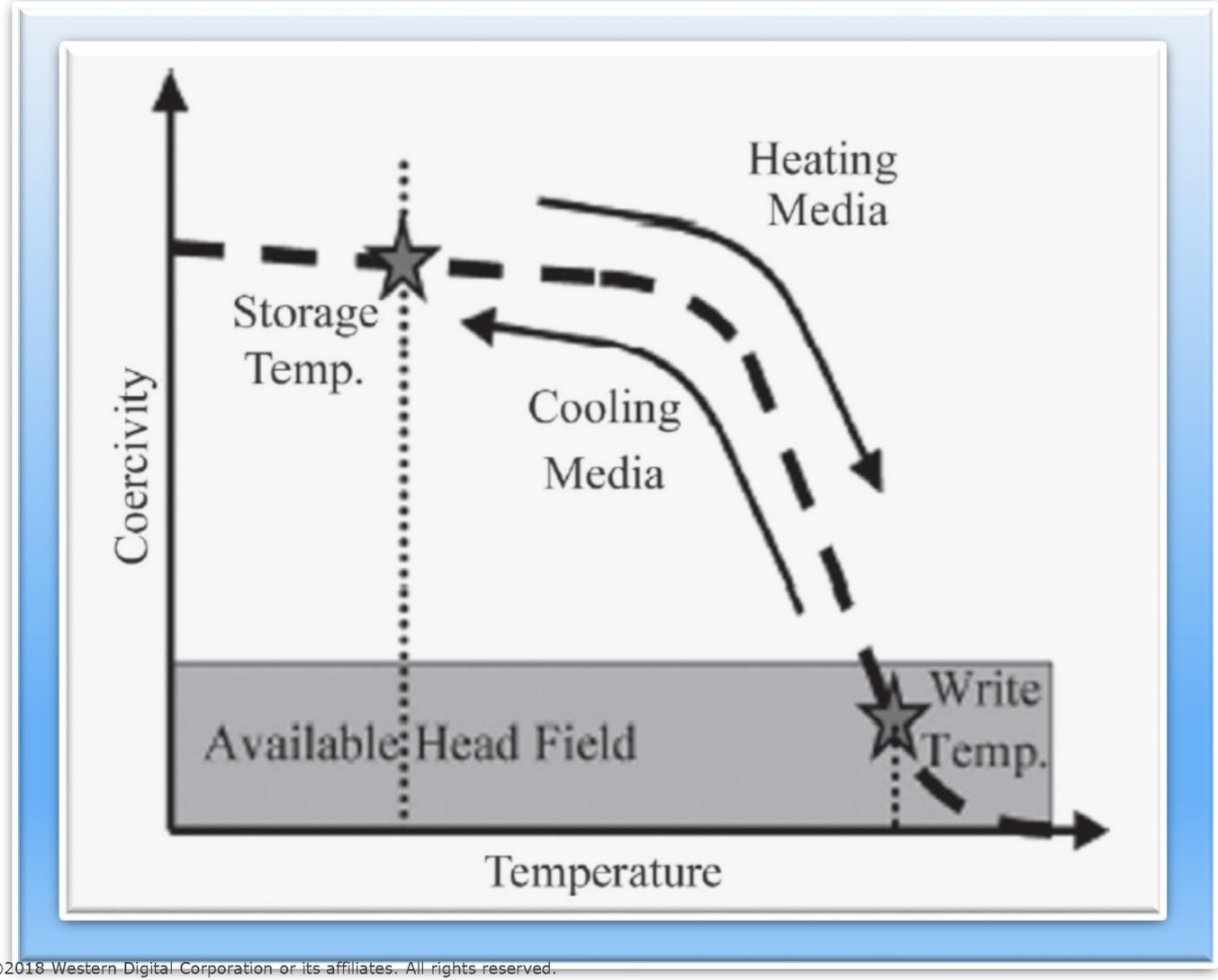
***E. Gage et. al., ch.4** "Energy Assisted Magnetic Recording", **in** "Ultrahigh Density Magnetic Recording",*
eds. Gaspare & Varvaro (2016)

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Heat-assisted magnetic recording

HAMR scheme



***E. Gage et. al., ch.4** "Energy Assisted Magnetic Recording", **in** "Ultrahigh Density Magnetic Recording",*
eds. Gaspare & Varvaro (2016)

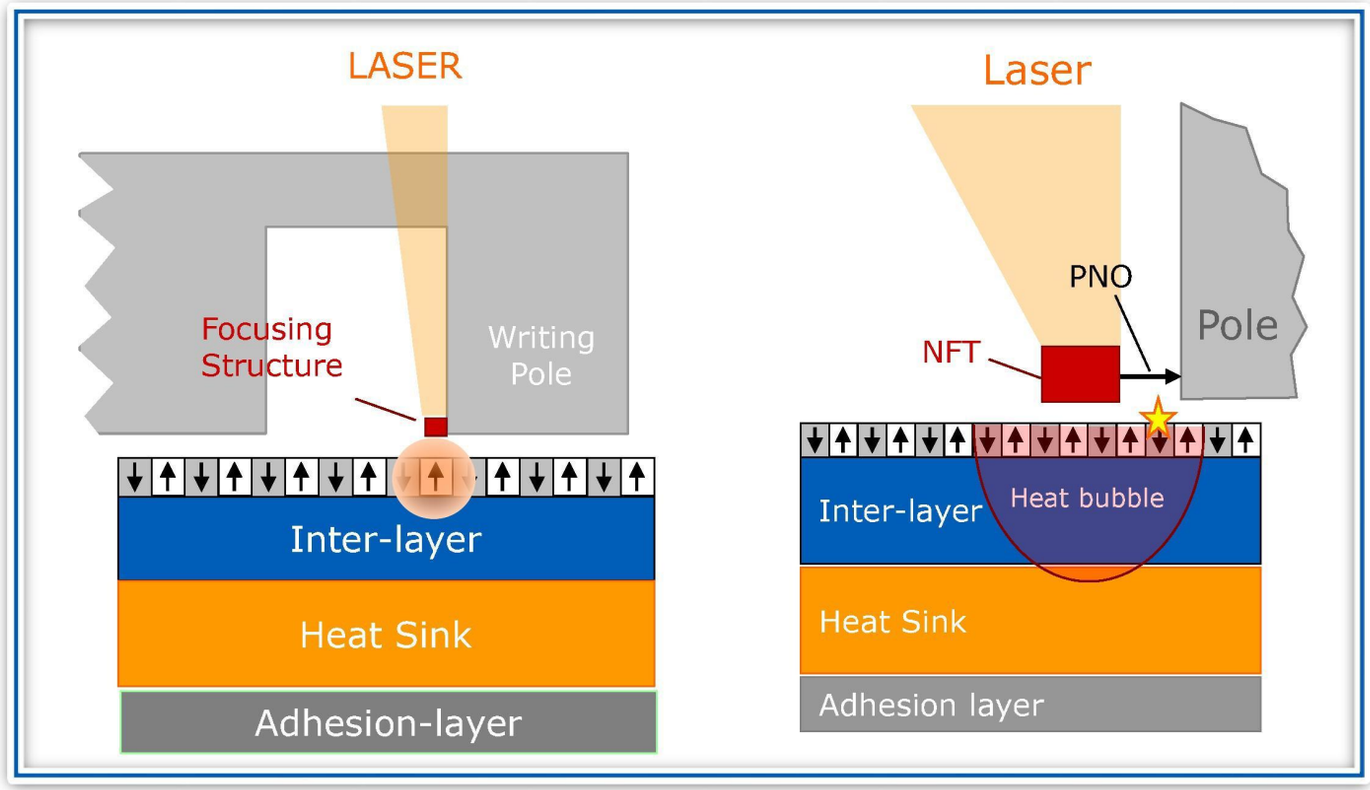
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Heat-assisted magnetic recording

Principles of HAMR recording



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

Thermal gradient is a key enabler

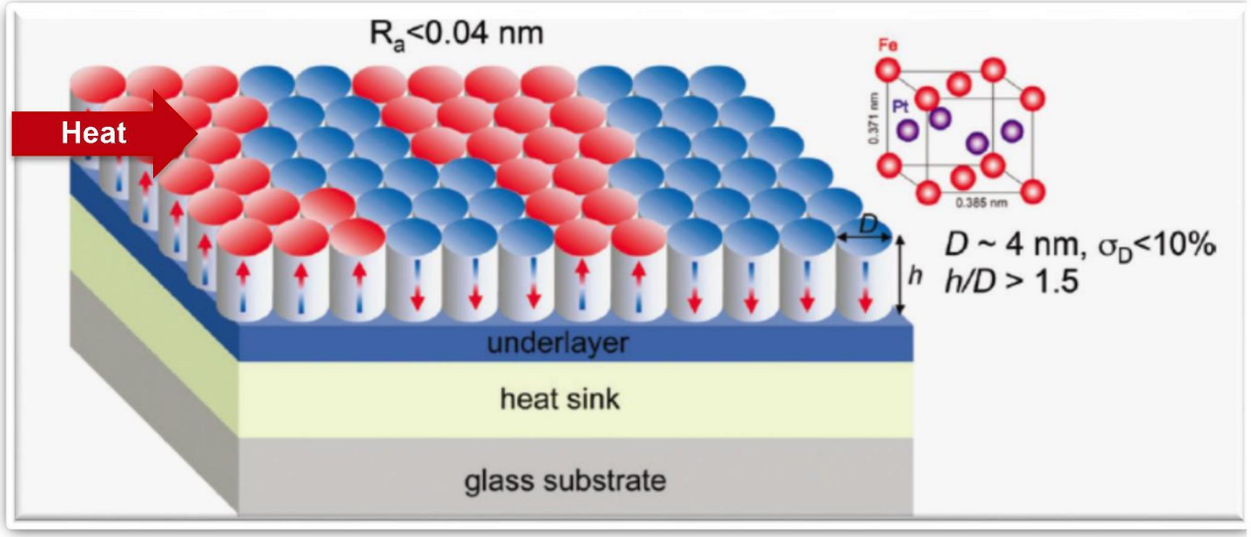
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The Fe-Pt HAMR recording medium

Media requirements: Ideal



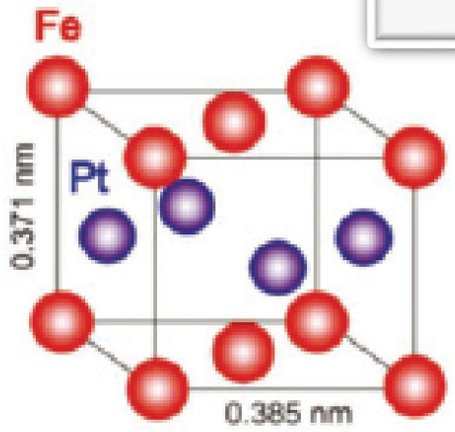


Table 5.1 HAMR media requirements for 2 and 4 Tbit/in^2 released from the Advanced Storage Technology Consortium (ASTC)

Areal density (Tbit/in^2)	2	4
Grain size, D (nm)	6	4.3
Center-to-center distance, D_p (nm)	7	5.1
Size distribution, σ (%)	10–15	10–15
$\mu_0 M_s$ of ferromagnetic layer (T)	0.88	1
$\mu_0 M_s$ of ferromagnetic grain (T)	1.1	1.26
K_u (MJ/m^3)	3.5	5
$\mu_0 H_k$ (T)	8	10
$\sigma H_k / H_k$	5–10	5–10
T_c (°C)	480	430
$\sigma T_c / T_c$ (%)	2	2
Angular distribution, σ_θ (°)	2	0.8
Media thickness, t (nm)	9	8.2
Grain aspect ratio (h/D)	1.29	1.6
Grains/bit	6.7	6.2

K. Hono et. al., ch.5** "L10 FePt granular films for HAMR media", **in** "Ultrahigh Density Magnetic Recording", **eds. Gaspare & Varvaro (2016)

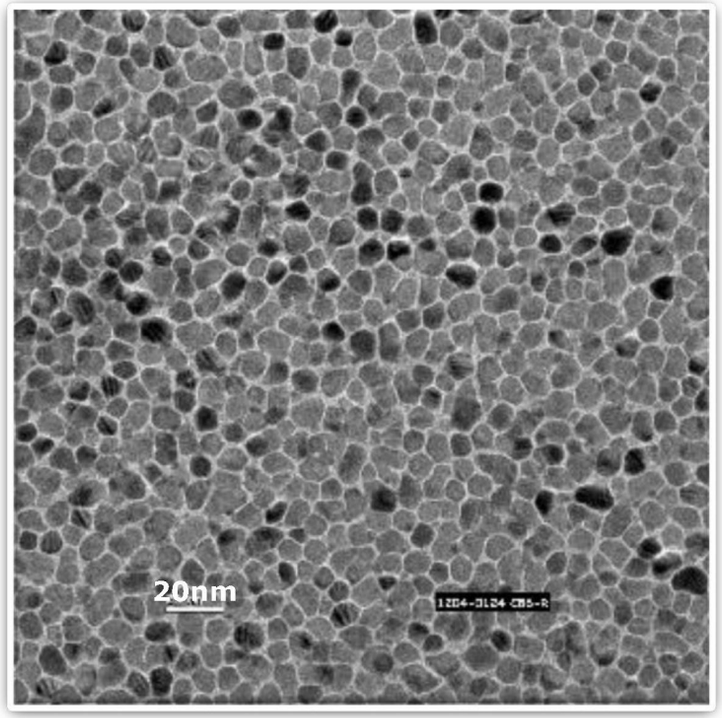
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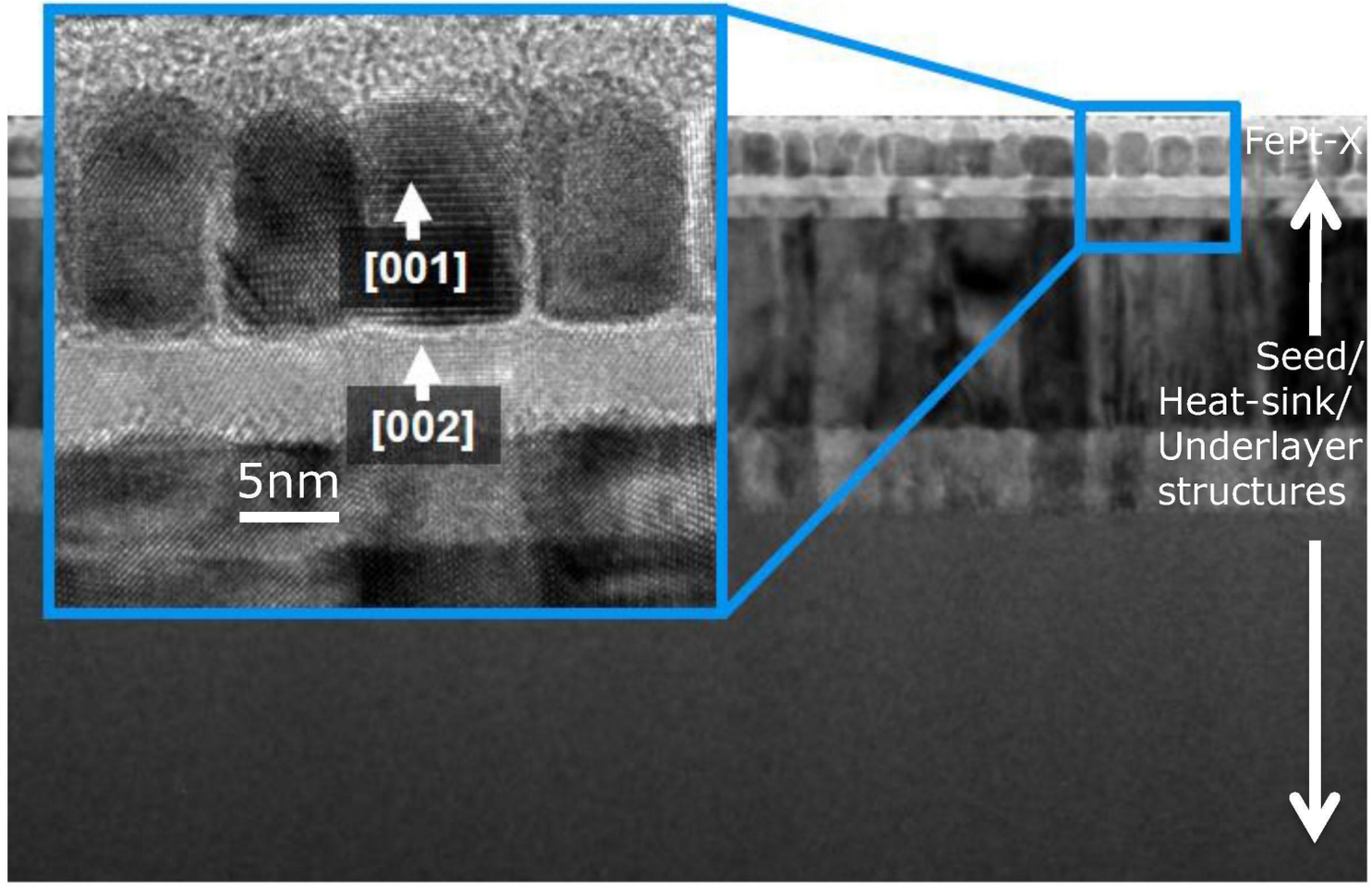
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The Fe-Pt HAMR recording medium

Actual Media





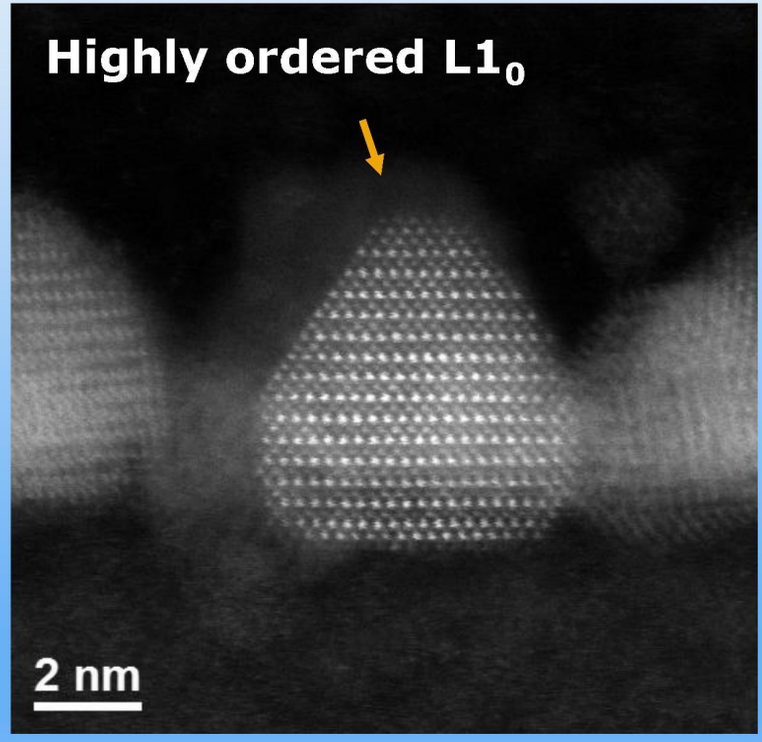
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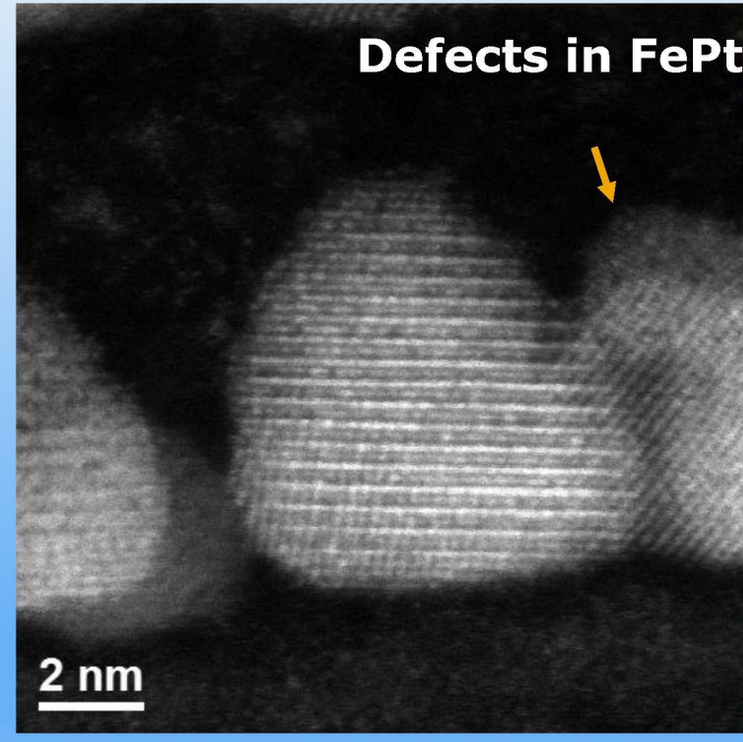
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Challenges of HAMR recording medium

Defective grains



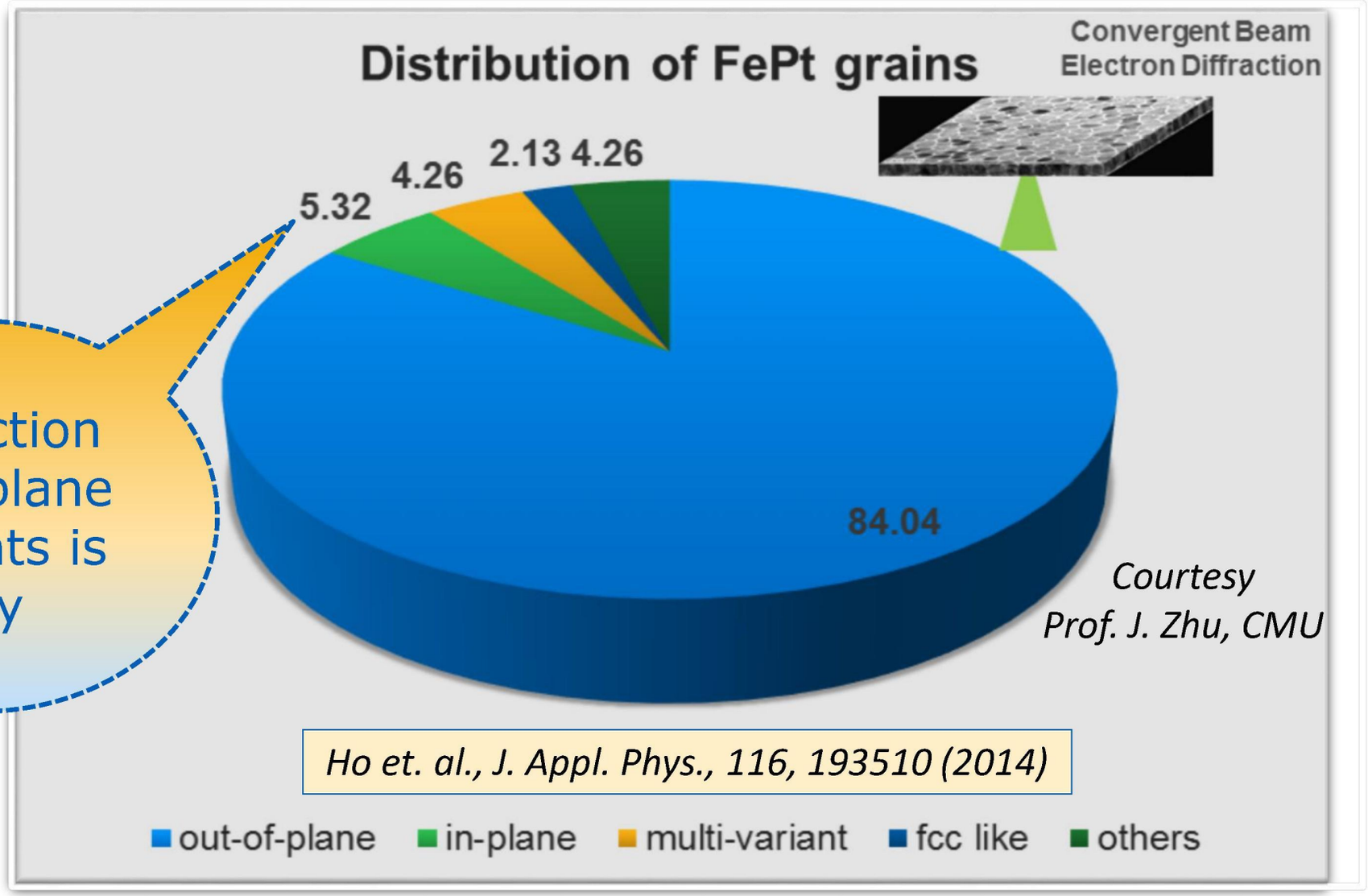


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Challenges of HAMR recording medium



Reduction of in-plane variants is key

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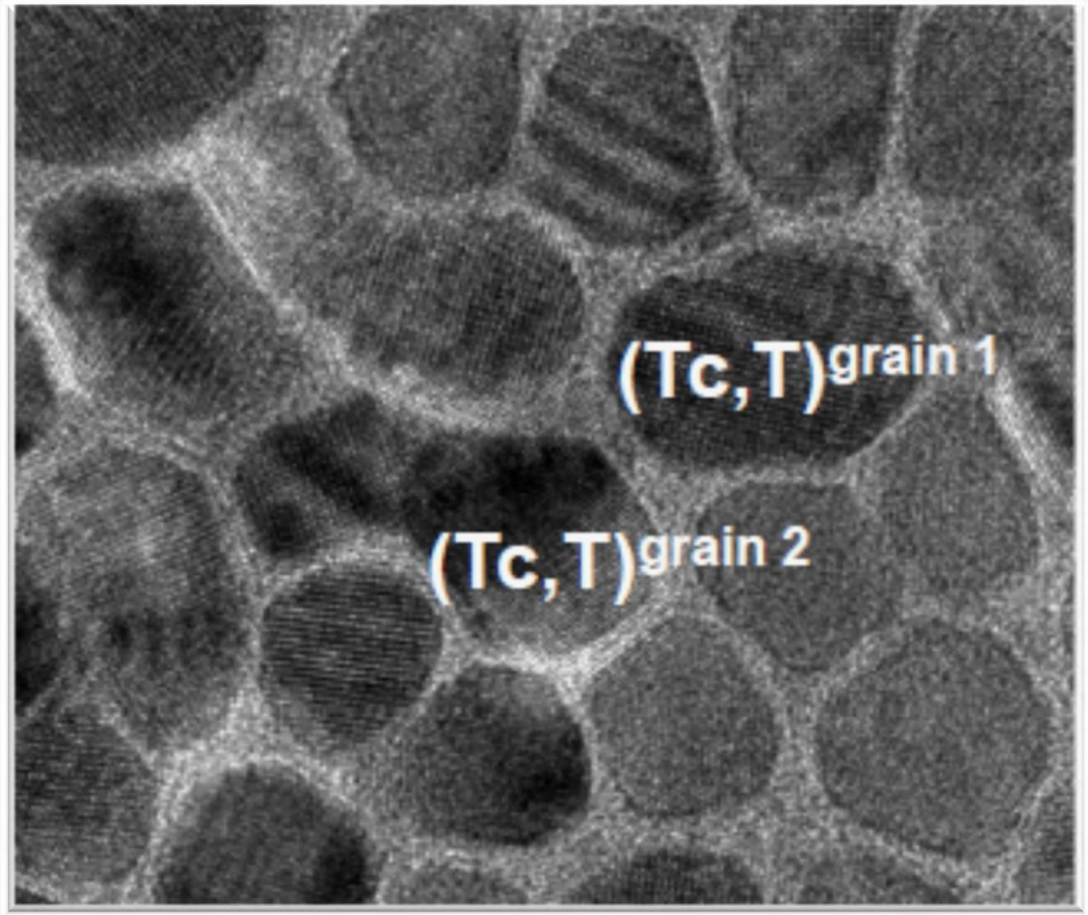
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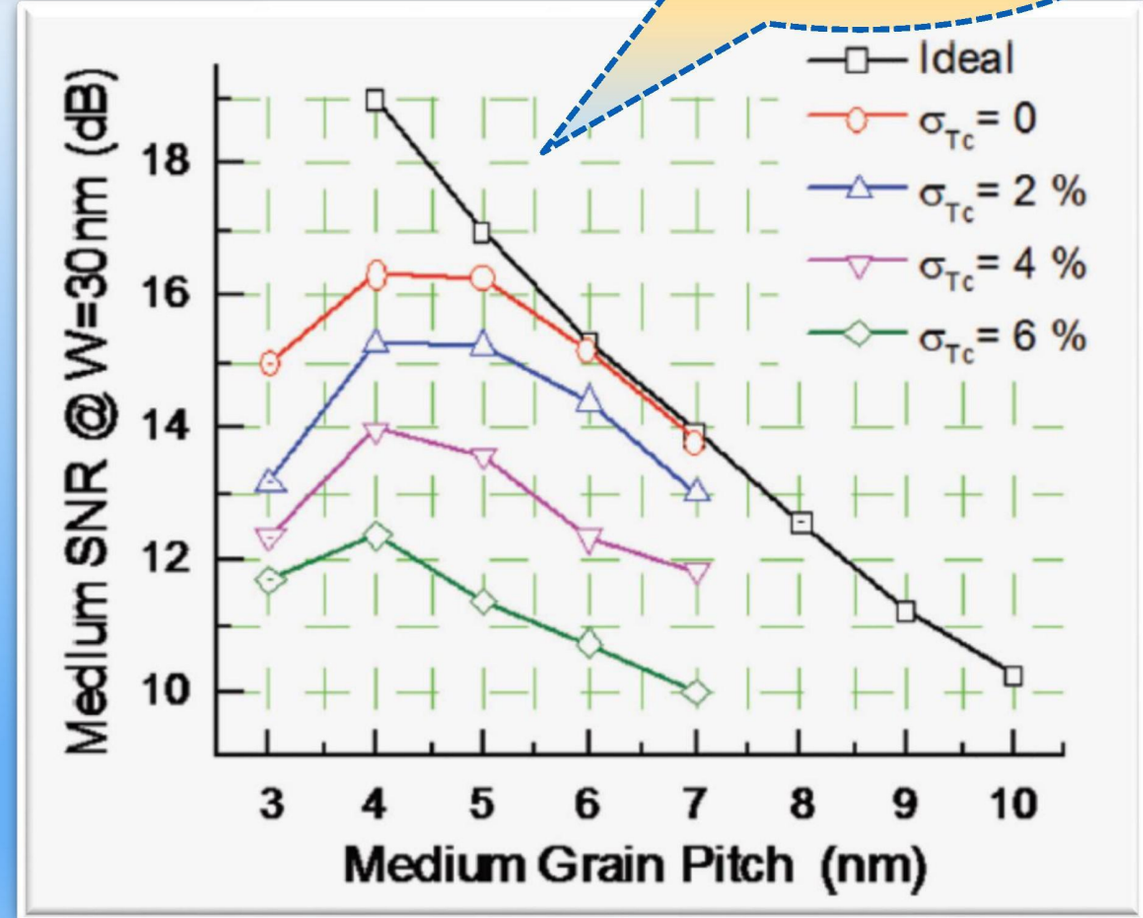
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Challenges of HAMR recording medium

Tc distribution

Tc variation needs to be minimized





Zhu et al., J. Appl. Phys., 115, p. 17B744 (2014)

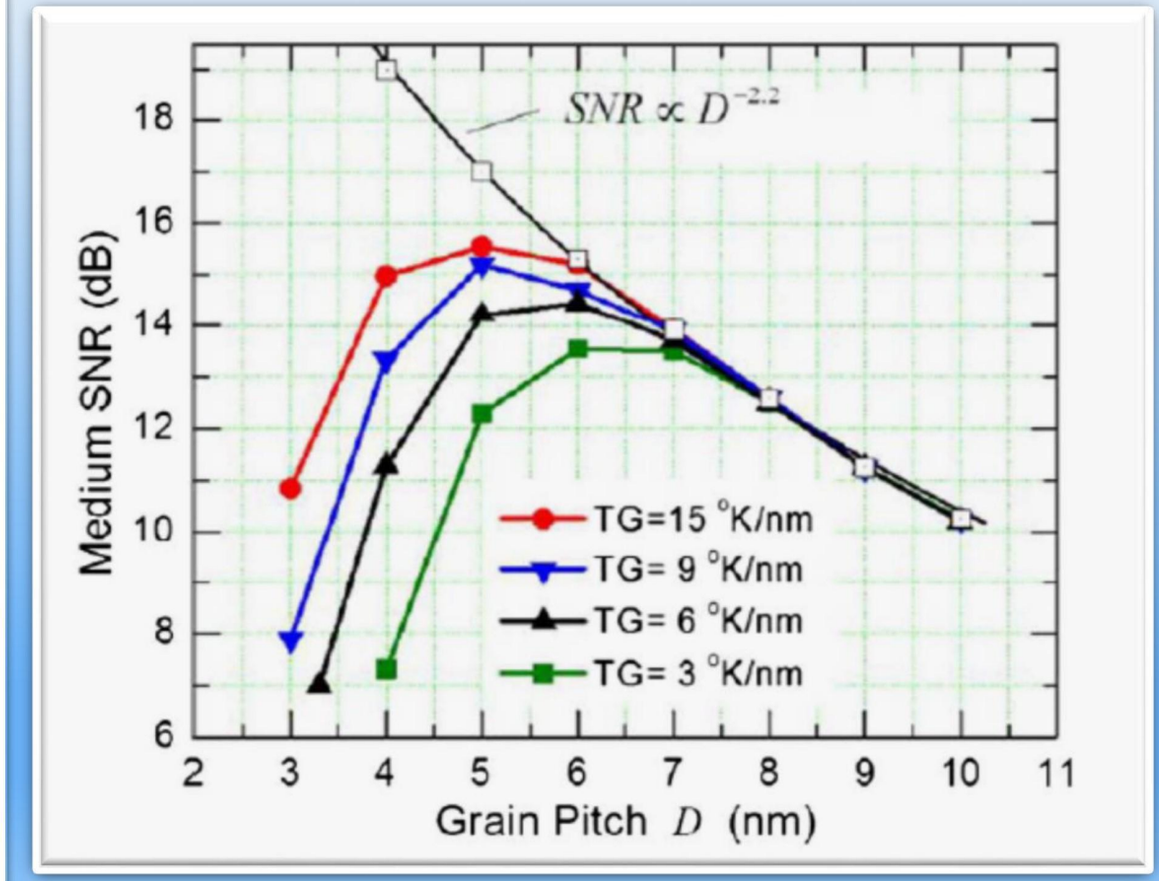
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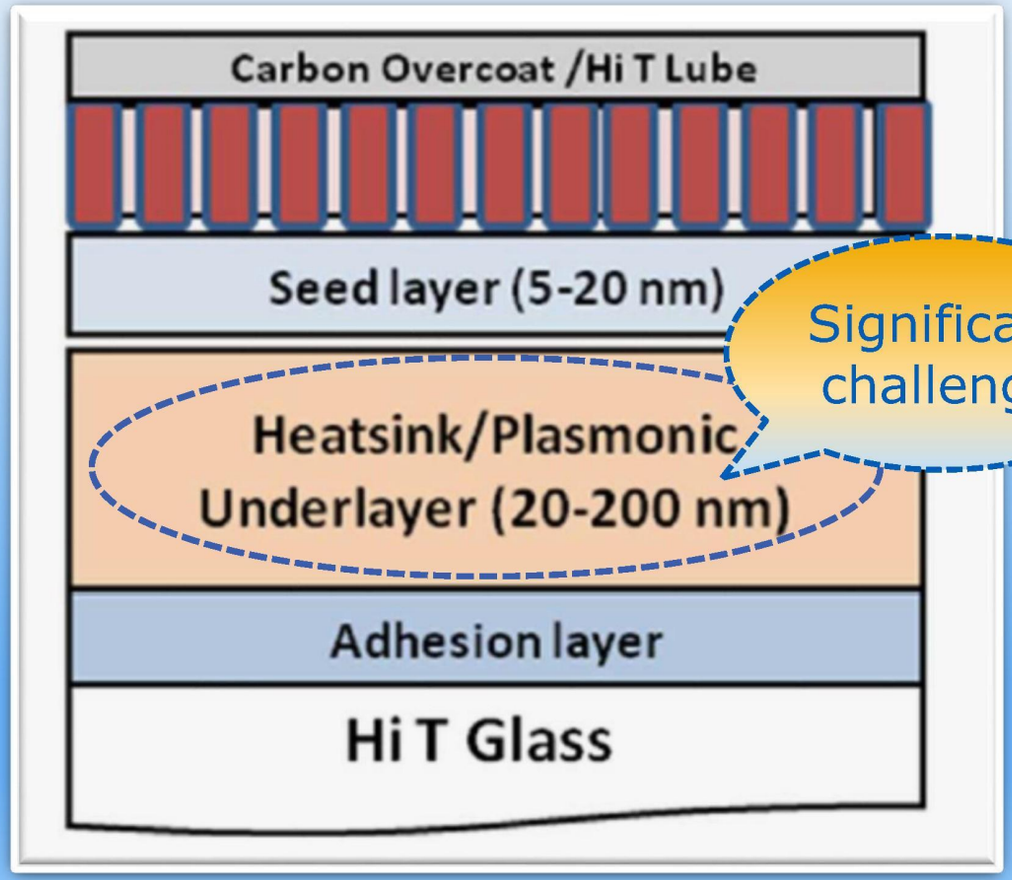
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Challenges of HAMR recording medium

Thermal gradient (TG)





Weller et al., IEEE Trans. Magn., 50, p. 3100108 (2014)

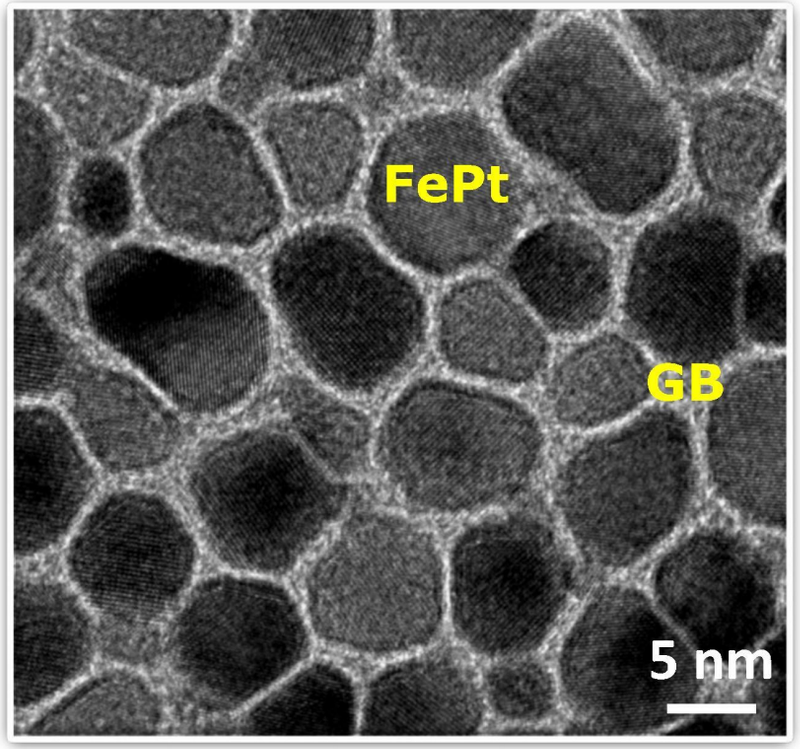
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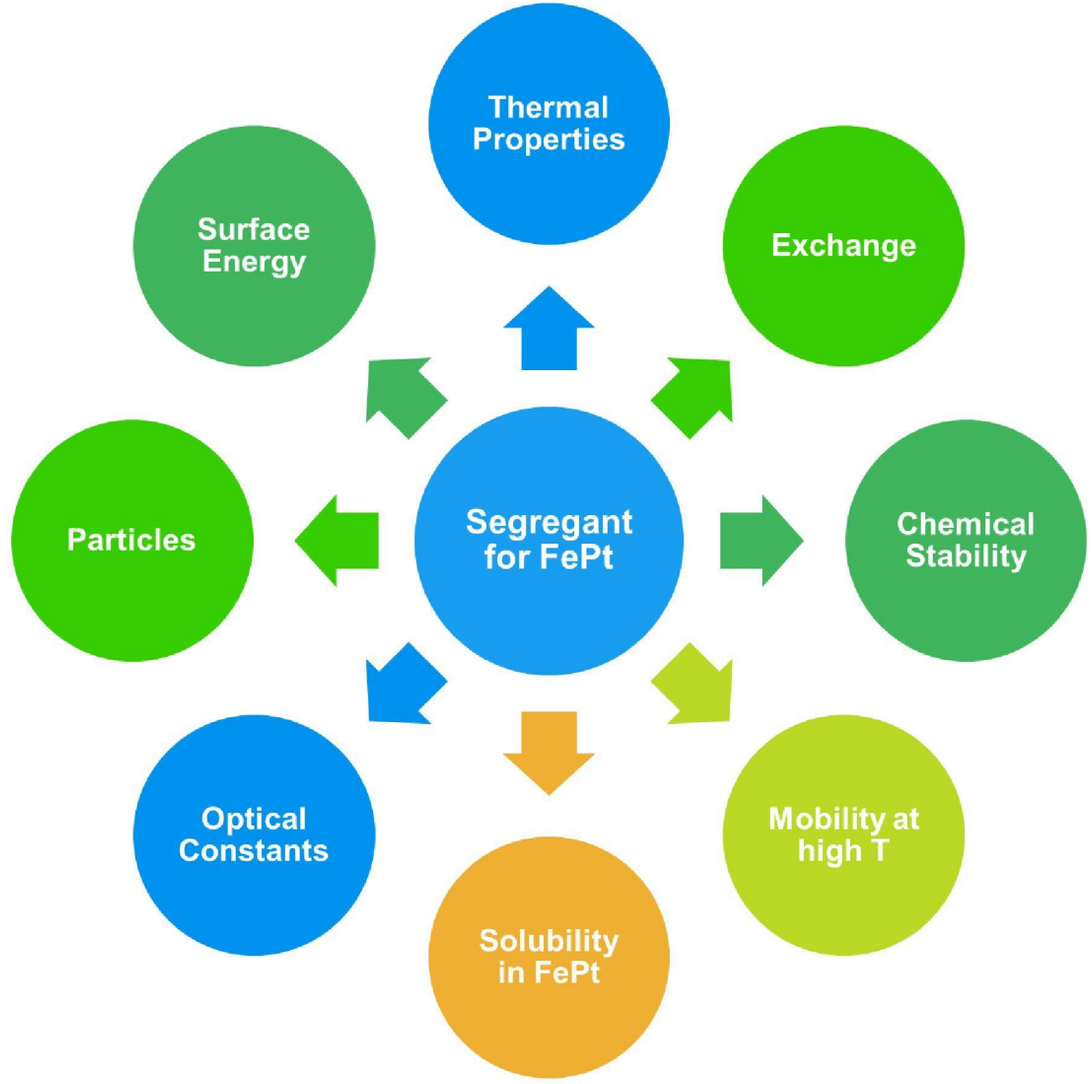
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The FePt-X media system

Design perspectives



Grain boundary – C, SiO2, B, other oxides, nitrides & carbides



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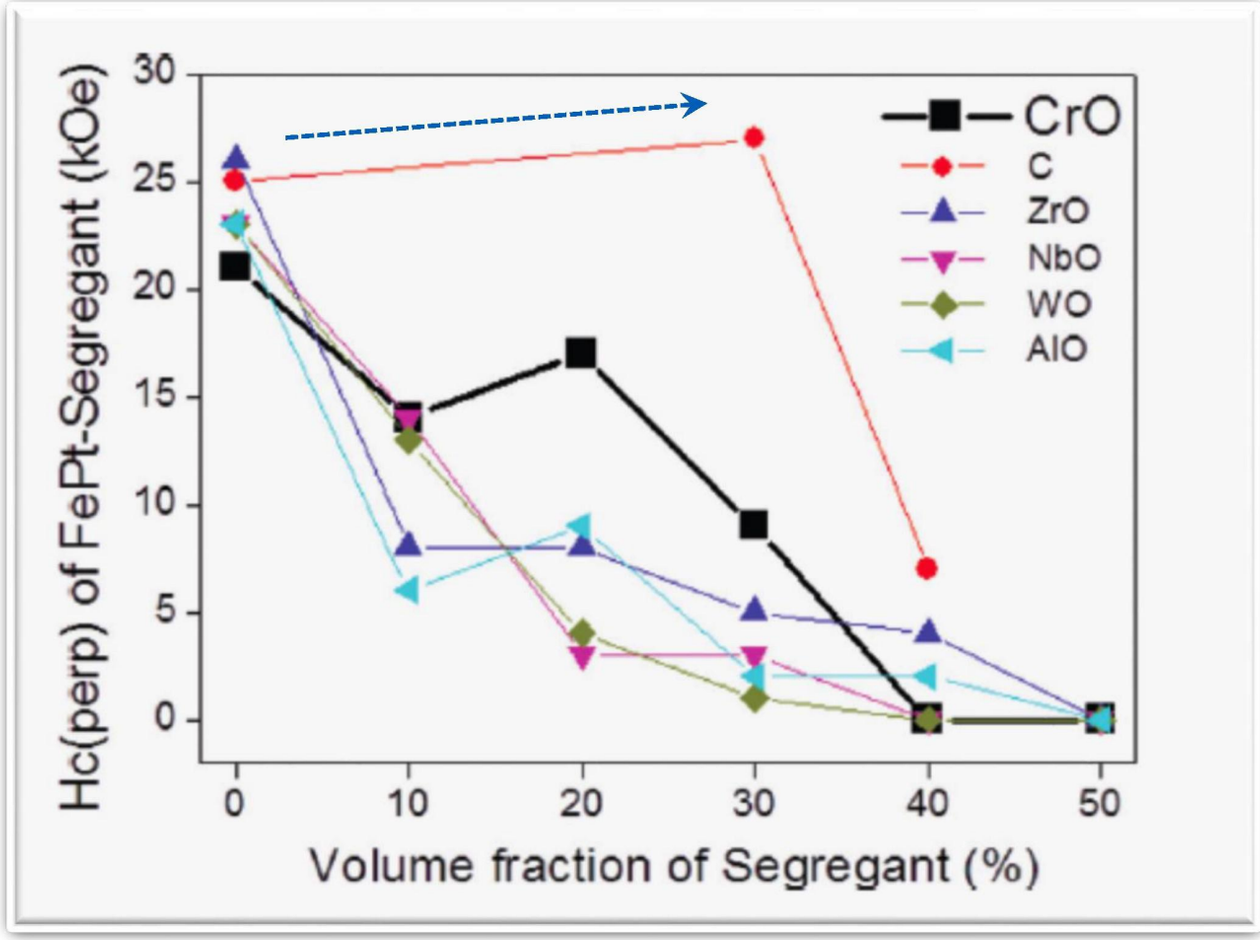
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The "ideal" segregant

Effect on magnetic properties

Carbon is a unique sergegant!



Shiroyama et. al., IEEE Trans. Magn., 49, p. 3616 (2013)

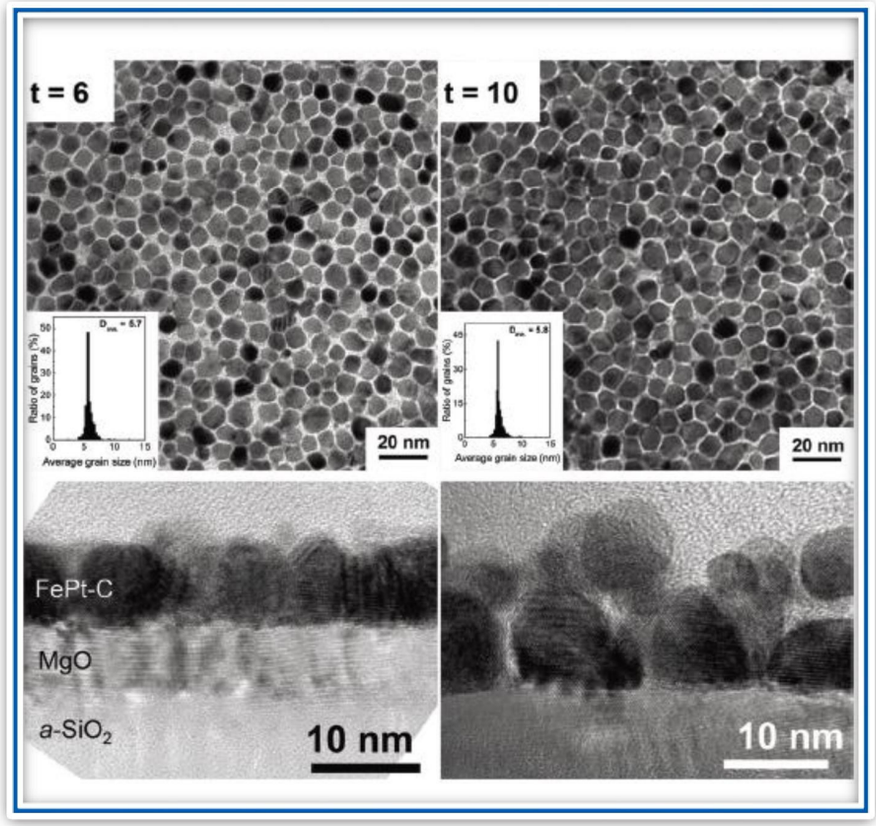
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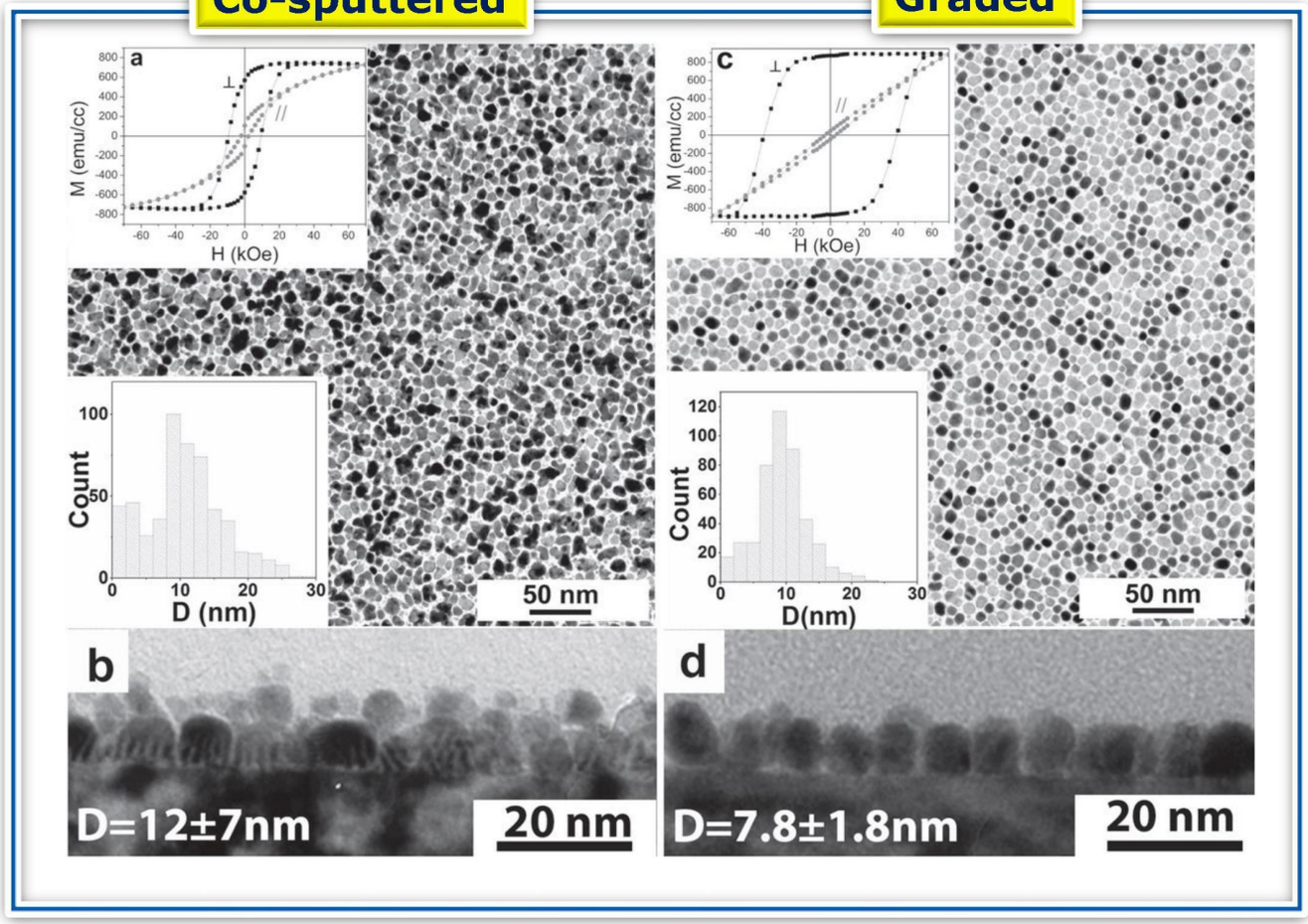
Single-layered FePt-X systems

FePt-C



A. Perumal et. al., Appl. Phys. Expr., 1, p. 101301 (2008)

Co-sputtered **Graded**



Varaprasad et. al., IEEE Trans. Magn., 51, p. 3200904 (2015)

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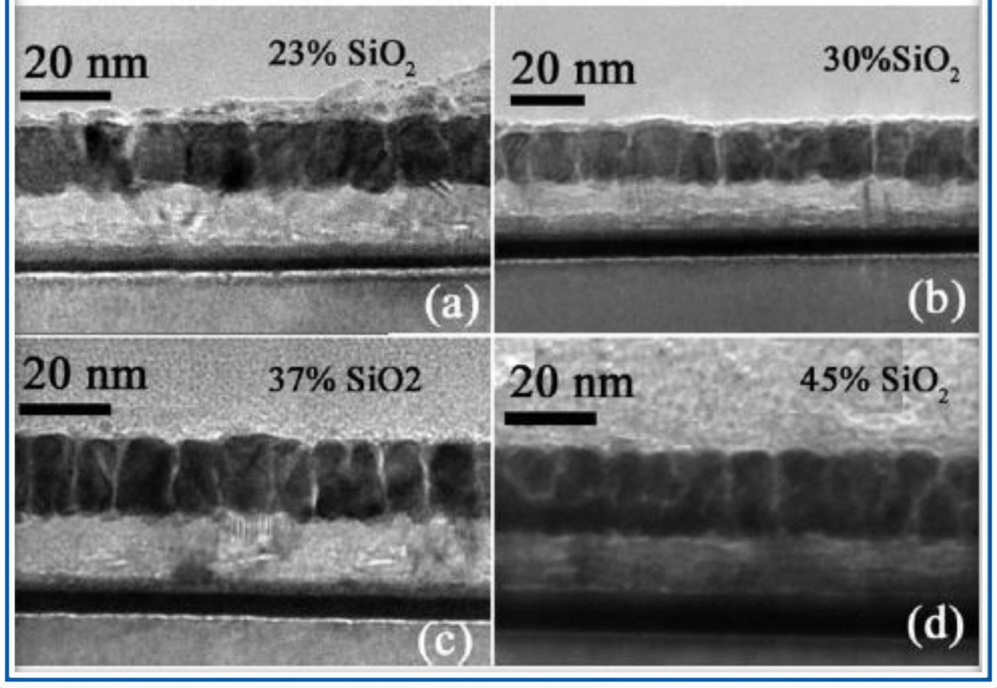
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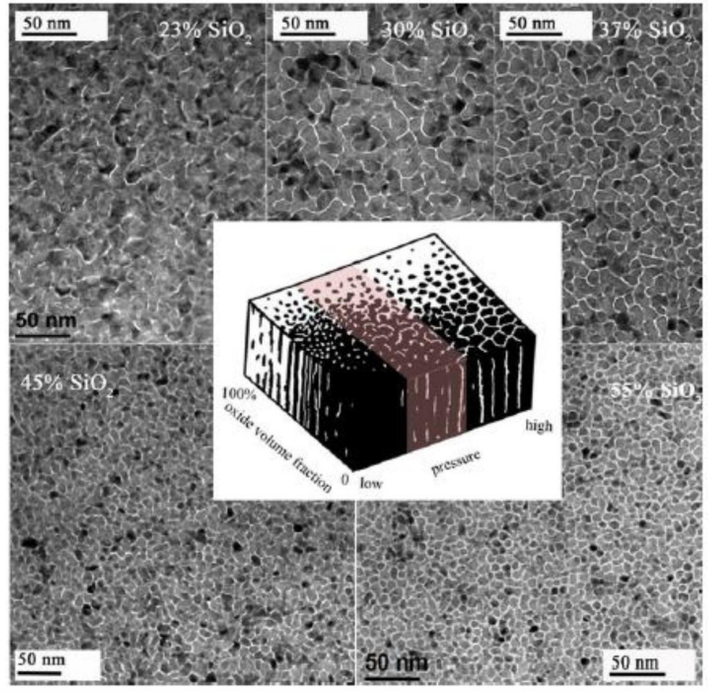
Single-layered FePt-X systems

FePt-SiO2

Cross-section



Plan-view



Yang et. al., J. Appl. Phys., 111, p. 07B720 (2012)

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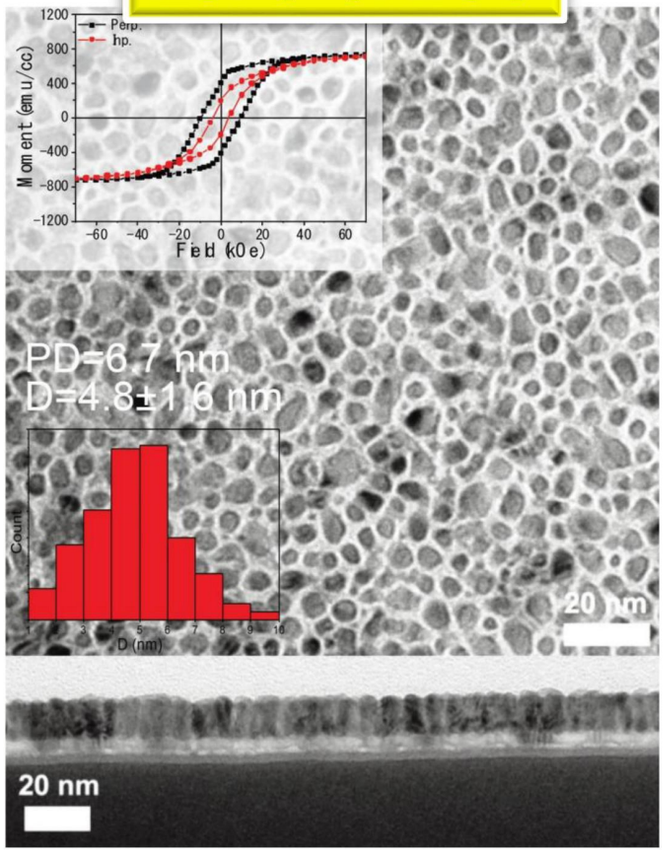
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Single-layered FePt-X systems

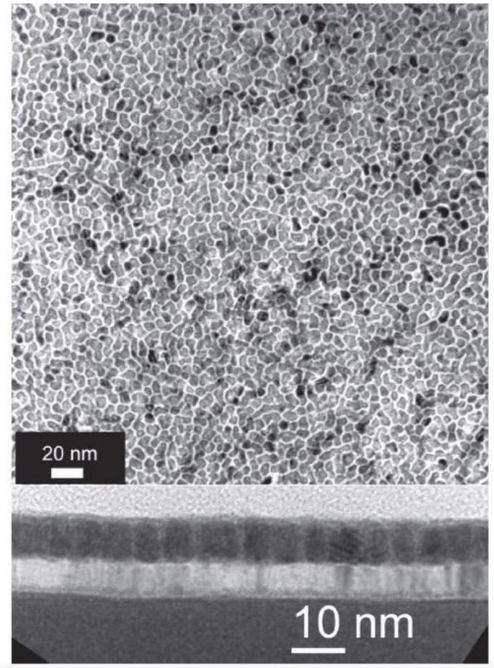
Types of segregants: FePt-Cr2O3 & FePt-TiO2

FePt-Cr2O3



Shiroyama et. al., IEEE Trans. Magn., 50, p. 3202404.1 (2015)

FePt-TiO2



Varaprasad et. al., IEEE Trans. Magn., 49, p. 718 (2013)

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Multi-layered approach: FePt-X/FePt-Y systems

Segregant type pro's & con's

C segregant (40 vol%)	SiO_2 or TiO_2 segregants (50 vol%)
1. Good particle separation	1. Poor particle separation
2. High degree of $L1_0$ ordering	2. Poor degree of $L1_0$ ordering
3. Spherical type grains	3. Cylindrical type grains
4. Rough surface	4. Excellent surface smoothness

Weller et. al., *"A HAMR Media Technology Roadmap to an Areal Density of 4 Tbits/in²"*, ***IEEE Trans. Magn., 50, p. 3100108 (2014)***

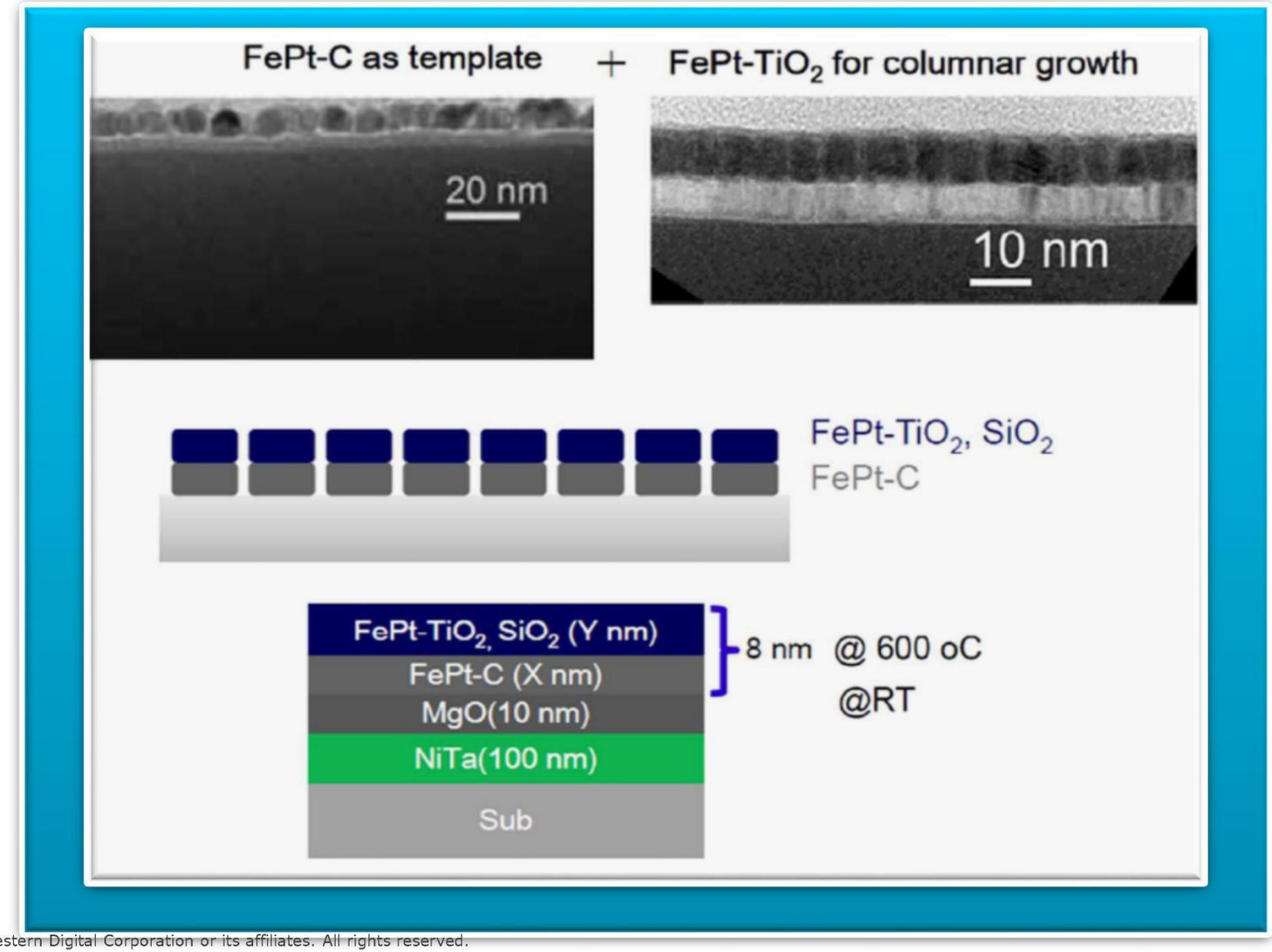
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Multi-layered approach: FePt-X/FePt-Y systems

Combining segregant types



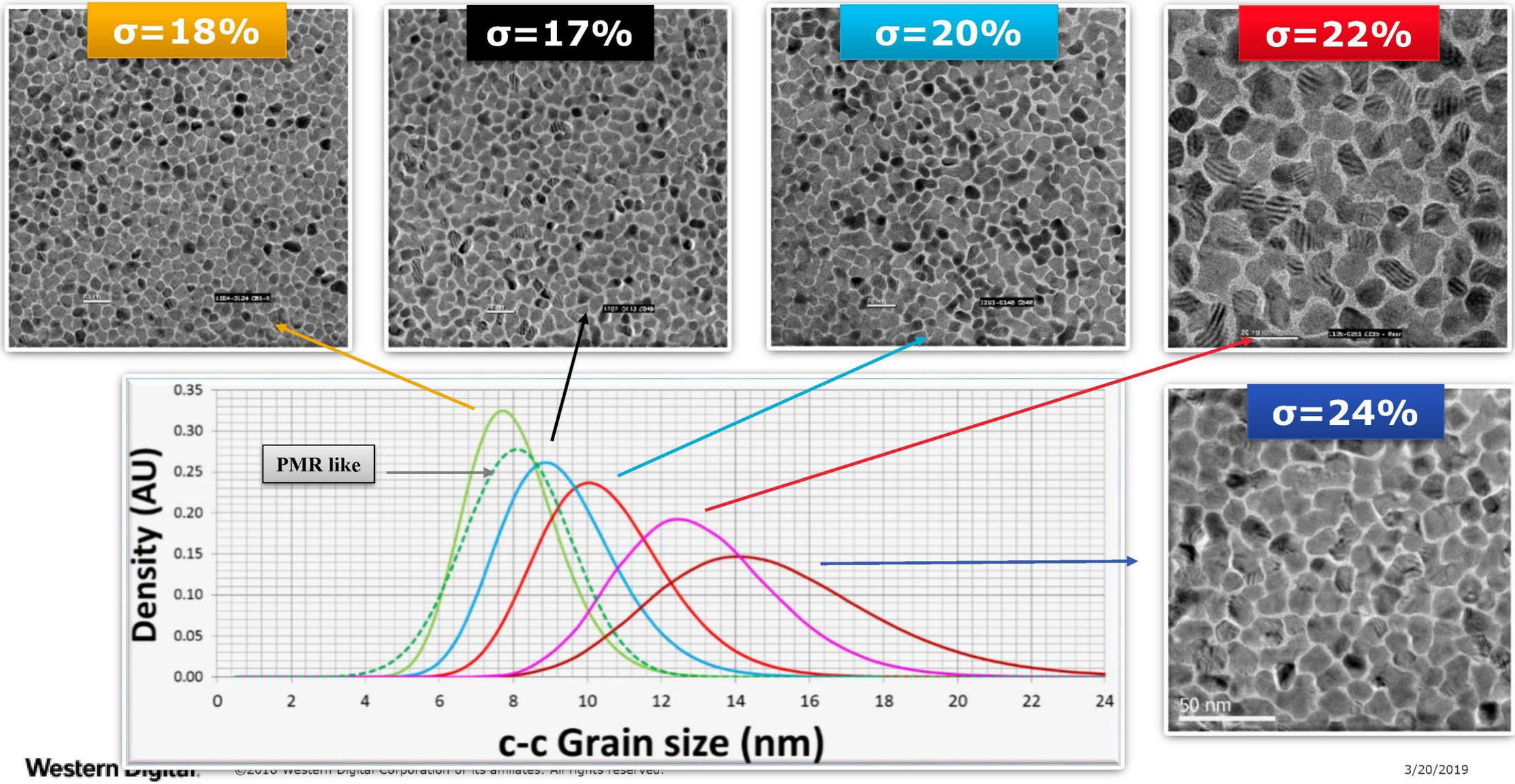
Weller et. al., *"A HAMR Media Technology Roadmap to an Areal Density of 4 Tbits/in²"*, ***IEEE Trans. Magn., 50, p. 3100108 (2014)***

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HAMR media grain size progression



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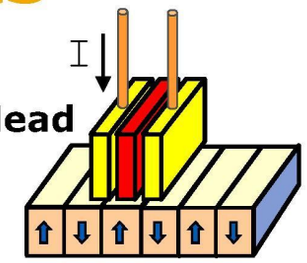
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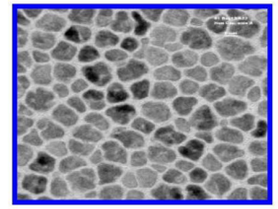
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HAMR prospects

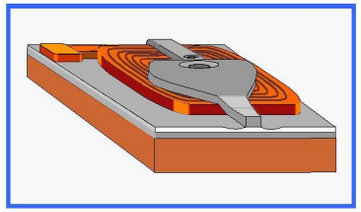
Read Head

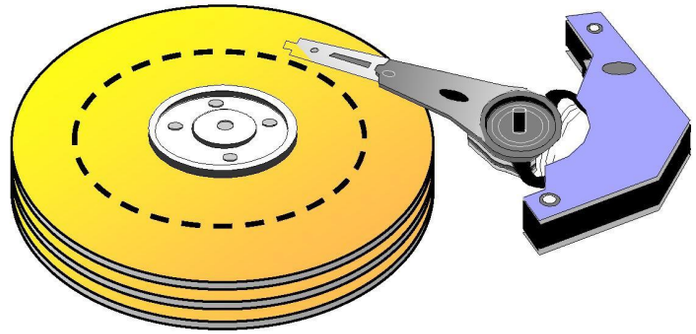


Media

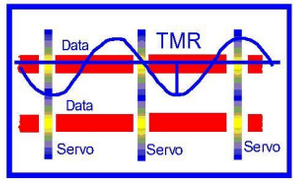


Write Head w/ Laser

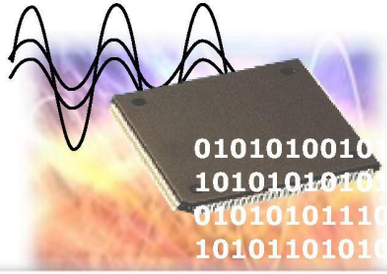




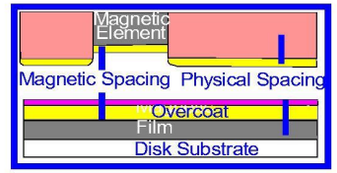
Servo Mechanics



Signal Processing



HDI Reliability



Significant challenges all-around…

…but a lot of progress made

HAMR drives could be commercialized by the industry within the next few years!

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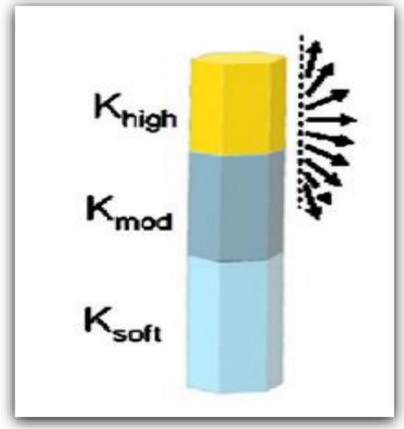
Summary

Recent developments in magnetic recording media

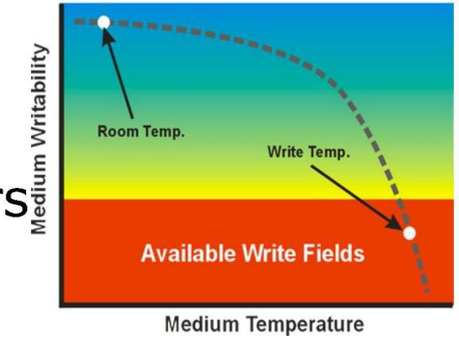


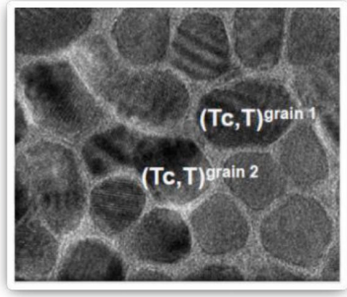
- The Future of HDD technology is still bright
  - Cloud/archival storage will be key

- PMR is the prevailing magnetic storage technology
  - Grain size scaling does not benefit PMR (exchange-dominated)
  - The "exchange-spring" principle in ECC media has guided most of the advances in PMR media since inception



- HAMR is in the near-term outlook for HDD
  - Significant challenges overcome, but many still remain
  - HAMR HDD could be commercialized in the next few years





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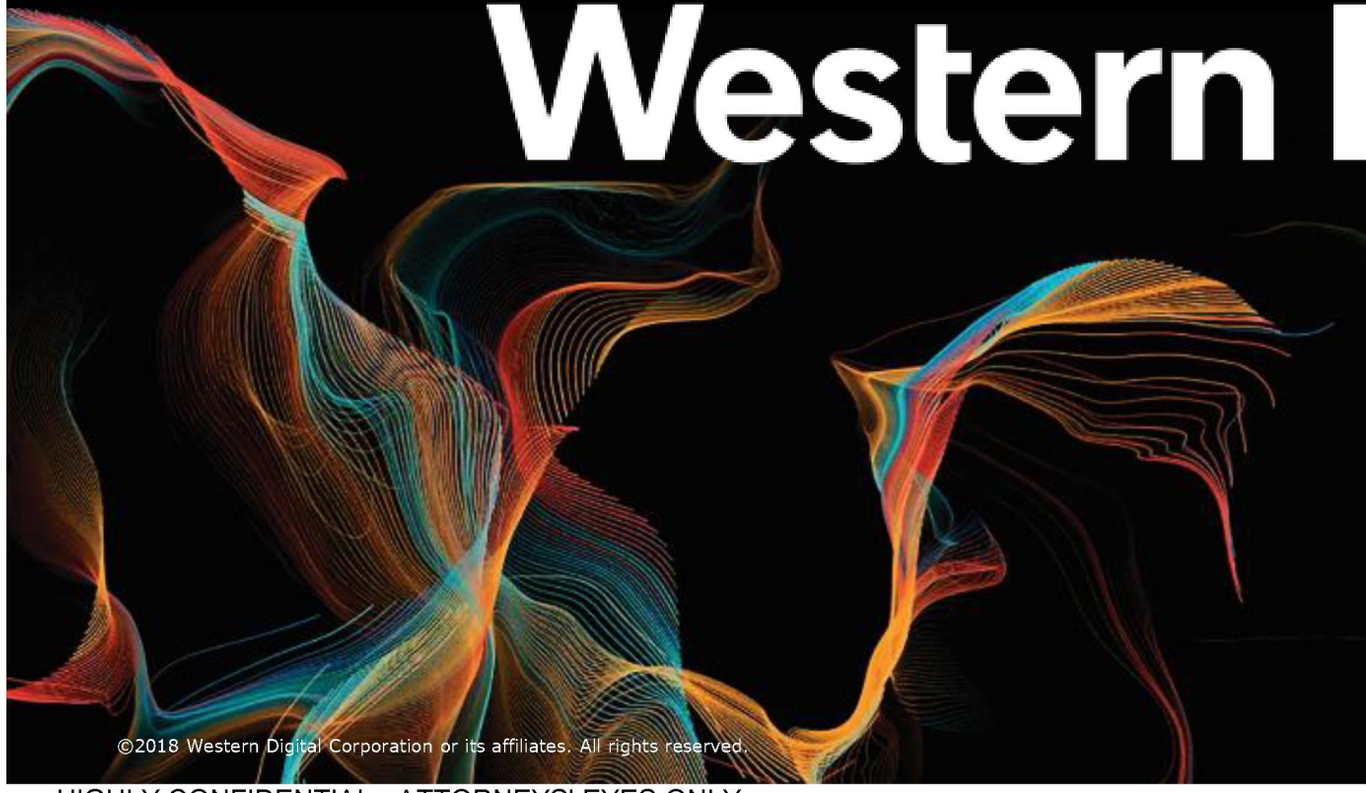
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