IEEE SCV Magnetics

FePt HAMR Recording Media Progress and Key Requirements

D. Weller, O. Mosendz, H.J. Richter, G. Parker, S. Pisana S. Jain, T.S. Santos, J. Reiner, V. Mehta, O. Hellwig, B. Stipe and B. Terris

HGST a Western Digital Company, San Jose Research Center, San Jose, CA

Andreas Lyberatos

Department of Materials Science & Technology, Heraklion, Greece

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HGST a Western Digital company

Topics

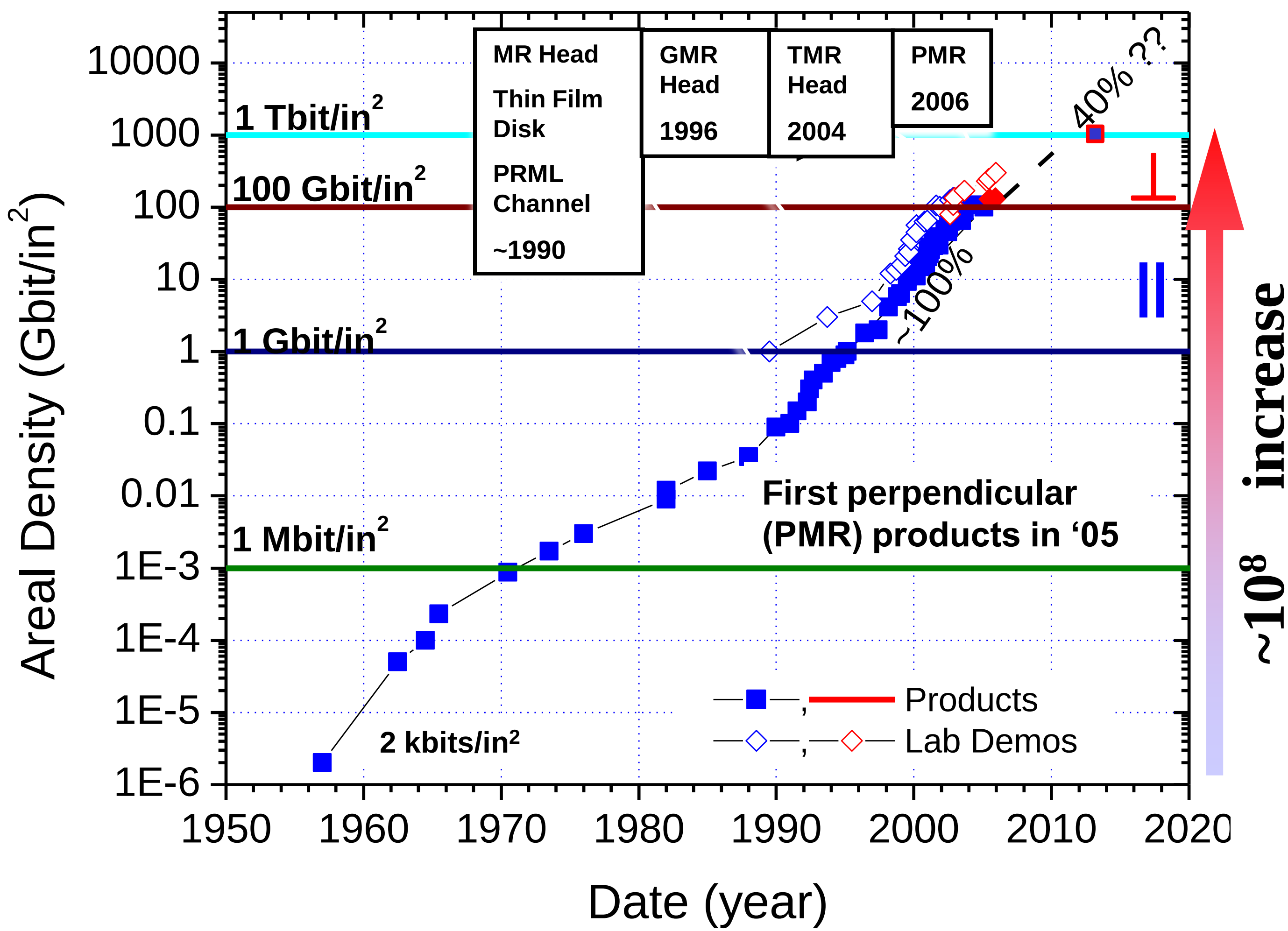
- **Introduction**
  - **Magnetic Recording Media background**
- **Chemically ordered $L1_0$ FePt media**
  - **Status and ongoing efforts**
  - **Key media parameters and requirements**
- **Thermal design**
  - **Recording time window**
  - **Modeling & Experiments**
- **Summary**
  - **Media Challenges**
  - **Key Issues**
  - **Possible Solutions**
  - **Important Research Projects**

Areal Density Progress (HDD)

Commercial products:
>750 Gbits/in², 1 TB/3.5" Platter

Demonstrations:
up to ~1 Tbit/in²

Research frontier:
≥1 Tbits/in²



Technology Options:

Longitudinal

Perpendicular

Heat Assisted

Bit Patterned

HAMR Areal Density beyond 1 Tbpsi

Seagate Reaches 1 Terabit Per Square Inch Milestone In Hard Drive Storage With New Technology Demonstration

2012-03-19

Like 0

CUPERTINO, Calif. - Seagate (NASDAQ:STX) has become the first hard drive maker to achieve the milestone storage density of 1 terabit (1 trillion bits) per square inch, producing a demonstration of the technology that promises to double the storage capacity of today's hard drives upon its introduction later this decade and give rise to 3.5-inch hard drives with an extraordinary capacity of up to 60 terabytes over the 10 years that follow. The bits within a square inch of disk space, at the new milestone, far outnumber stars in the Milky Way, which astronomers put between 200 billion and 400 billion.

Seagate reached the landmark data density with heat-assisted magnetic recording (HAMR), the next-generation recording technology. The current hard drive technology, Perpendicular Magnetic Recording (PMR), is used to record the spectrum of digitized data – from music, photos, and video stored on home desktop and laptop PCs to business information housed in sprawling data centers – on the spinning platters inside every hard drive. PMR technology was introduced in 2006 to replace longitudinal recording, a method in place since the advent of hard drives for computer storage in 1956, and is expected to reach its capacity limit near 1 terabit per square inch in the next few years.

"The growth of social media, search engines, cloud computing, rich media and other data-hungry applications continues to stoke demand for ever greater storage capacity," said Mark Re, senior vice president of Heads and Media Research and Development at Seagate. "Hard disk drive innovations like HAMR will be a key enabler of the development of even more data-intense applications in the future, extending the ways businesses and consumers worldwide use, manage and store digital content."

Hard drive manufacturers increase areal density and capacity by shrinking a platter's data bits to pack more within each square inch of disk space. They also tighten the data tracks, the concentric circles on the disk's surface that anchor the bits. The key to areal density gains is to do both without disruptions to the bits' magnetization, a phenomenon that can garble data. Using HAMR technology, Seagate has achieved a linear bit density of about 2 million bits per inch, once thought impossible, resulting in a data density of just over 1 trillion bits, or 1 terabit, per square inch – 55 percent higher than today's areal density ceiling of 620 gigabits per square inch.

The maximum capacity of today's 3.5-inch hard drives is 3 terabytes (TB), at about 620 gigabits per square inch, while 2.5-inch drives top out at 750 gigabytes (GB), or roughly 500 gigabits per square inch. The first generation of HAMR drives, at just over 1 terabit per square inch, will likely more than double these capacities – to 6TB for 3.5-inch drives and 2TB for 2.5-inch models. The technology offers a scale of capacity growth never before possible, with a theoretical areal density limit ranging from 5 to 10 terabits per square inch – 30TB to 60TB for 3.5-inch drives and 10TB to 20TB for 2.5-inch drives.

March 2012

TDK manages to cram 1.5TB per square inch, will allow for 6TB drives

By: Trace Hagan **(more)** | **Storage** News | **Posted:** Oct 3, 2012 6:09 pm

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Large data is becoming more and more prevalent, especially with the rise of the cloud. People are collecting larger collections of music, videos, and files. As Internet speeds continue to increase, the web will become even more media intensive and require larger hard drives to store all of this data.

This is where TDK's new work shines. They have managed to squish 1.5TB into a single square inch, which is really impressive. At this density, a single platter inside the drive will be able to hold 2TB. Just remember how 2TB was hard to achieve just a few years ago. Now, imagine squishing 3 platters into a drive.

That would equate to a 6TB drive, seemingly more than enough for most desktop users, and an increase for servers that are running multiple 2TB drives. The new technology also has implications on mobile 2.5-inch drives. Mobile users will be able to carry more on their internal drive and shouldn't need to rely on an external solution.

The increase in density came from improvements in the read head as well as improvements in the hard disk medium. Mass production isn't expected to begin until 2014, though, so who knows where SSD technology will be by that point.

October 2012

Tim Rausch - Seagate

…the outlook is slowing down

Tim Rausch - Seagate

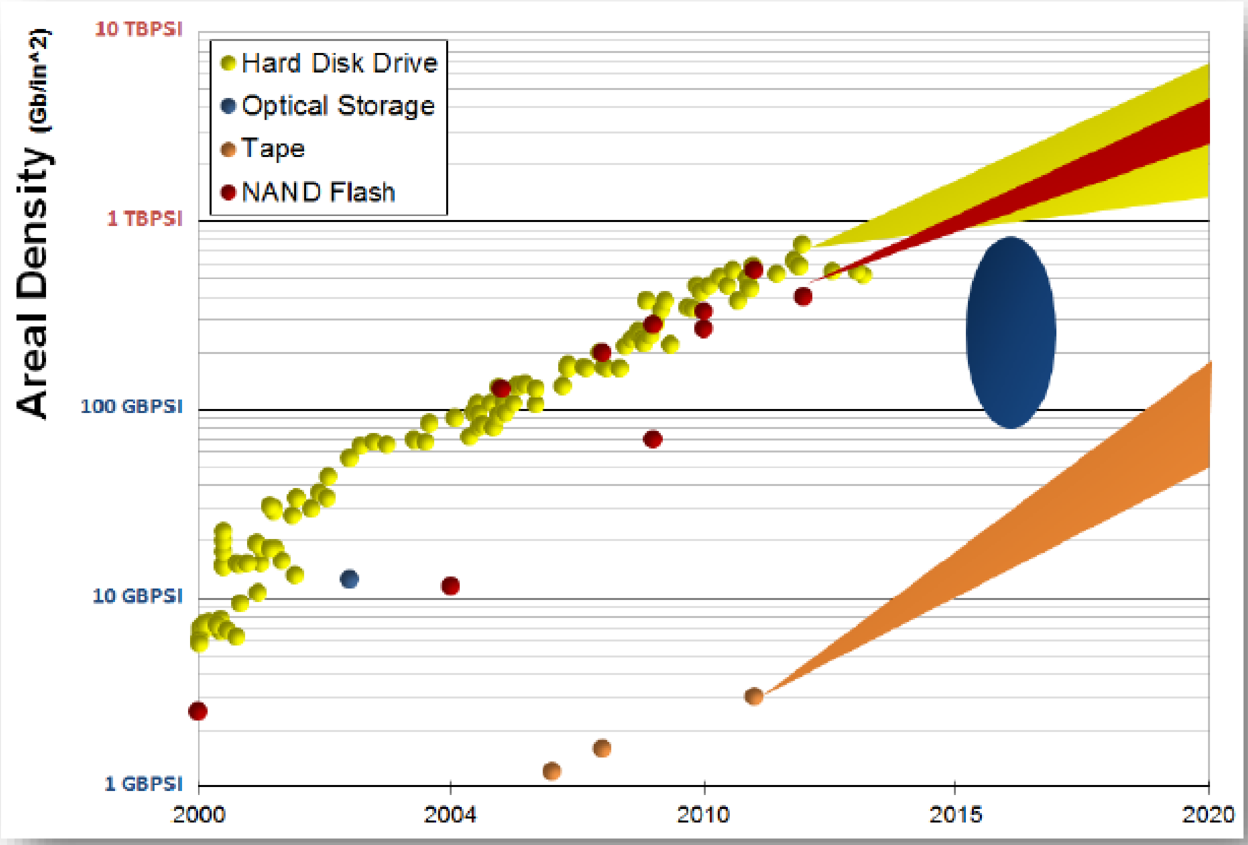
Next Technology Transitions are hard

Hard Drive
10% - 40% Growth Expected

Optical
Not clear on 4th Gen Technology

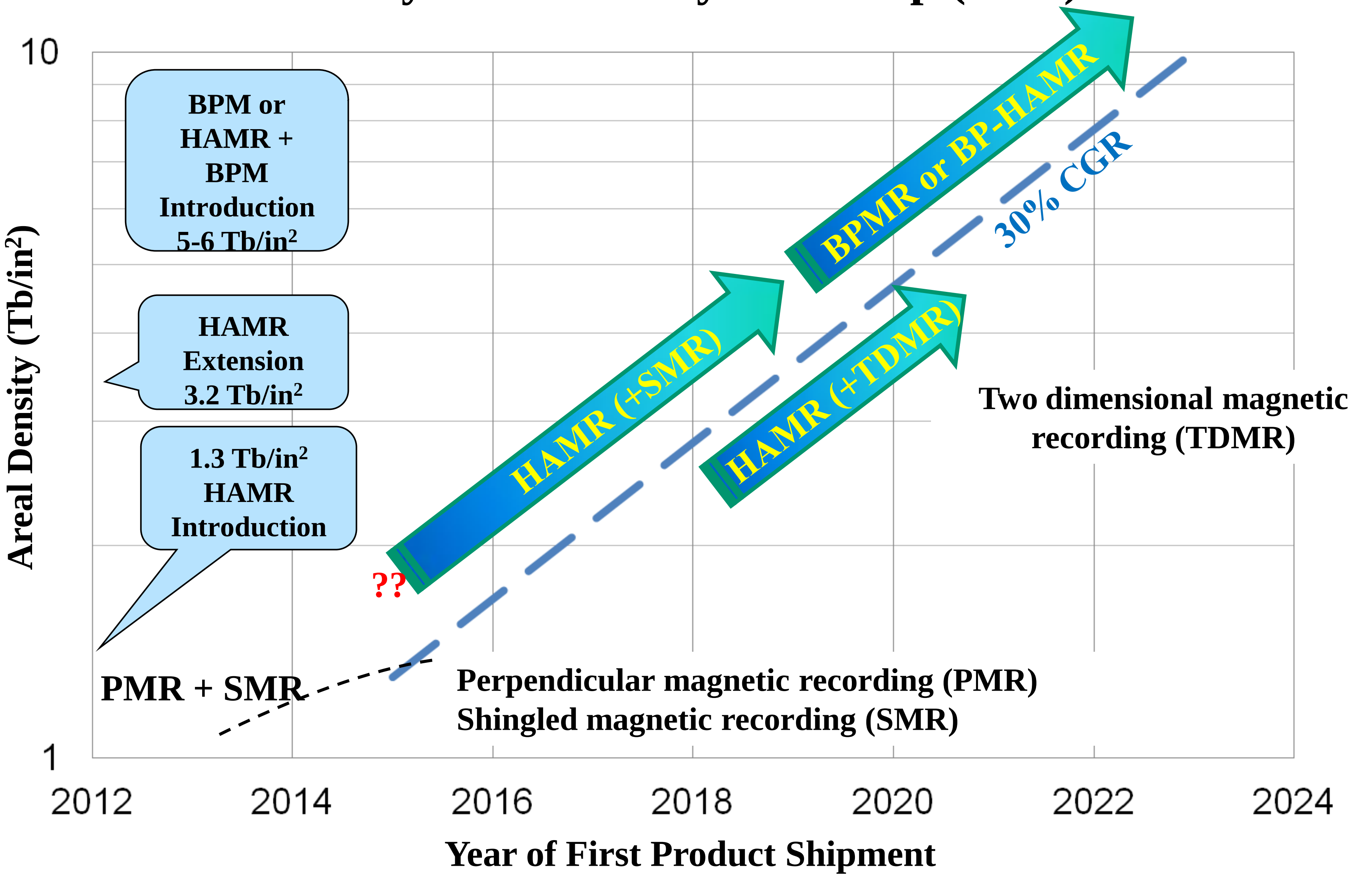
Tape
40% - 80% Growth Expected

Flash = SSD
20% - 40% Growth Expected

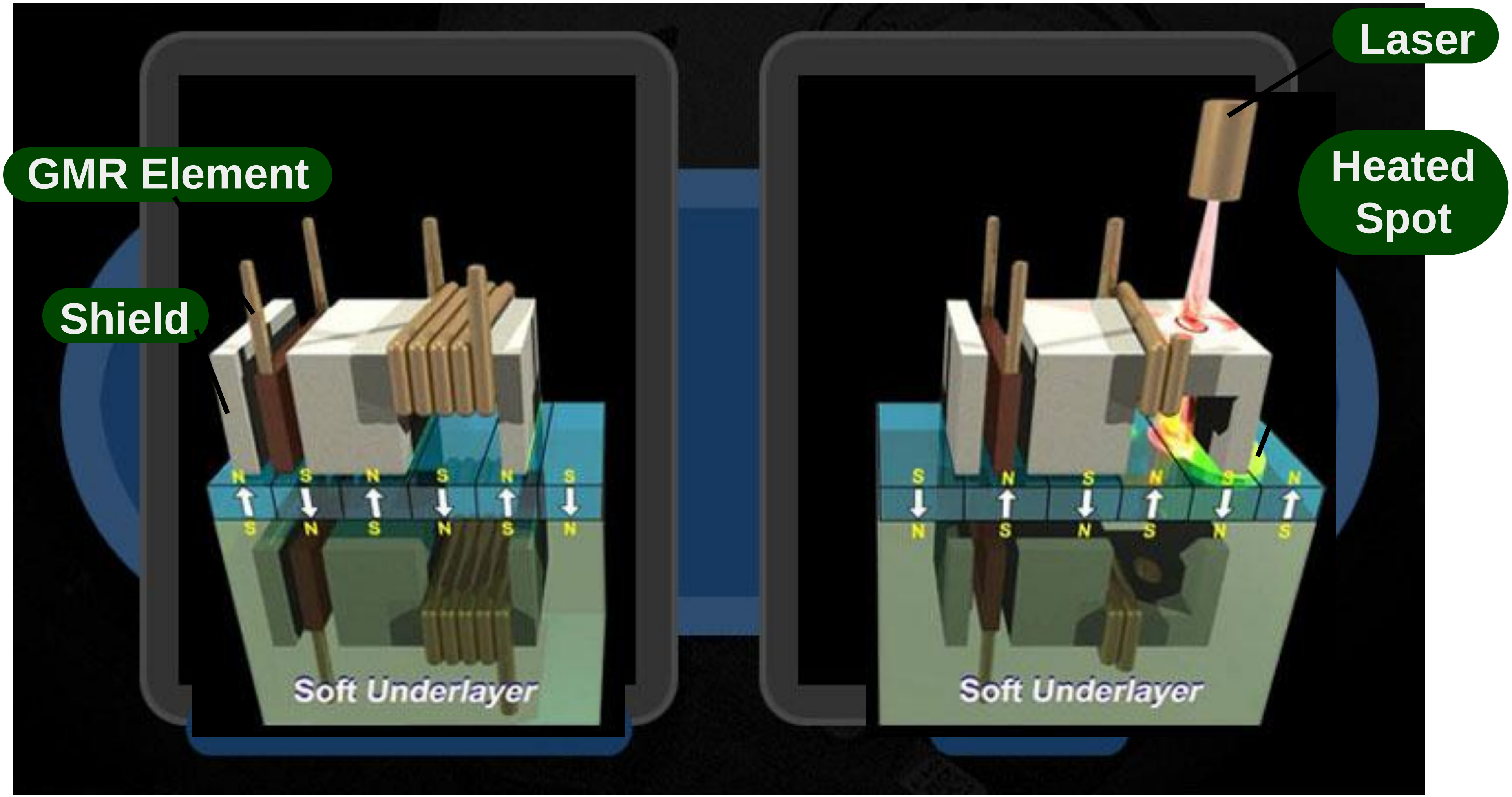


Notes:
Flash growth is flash in general and may not be representative of compute grade flash
Tape growth relies on them leveraging HDD areal density growth enablers which may not be possible

Industry Areal Density Roadmap (2013)



From PMR to Heat Assisted Magnetic Recording (HAMR)



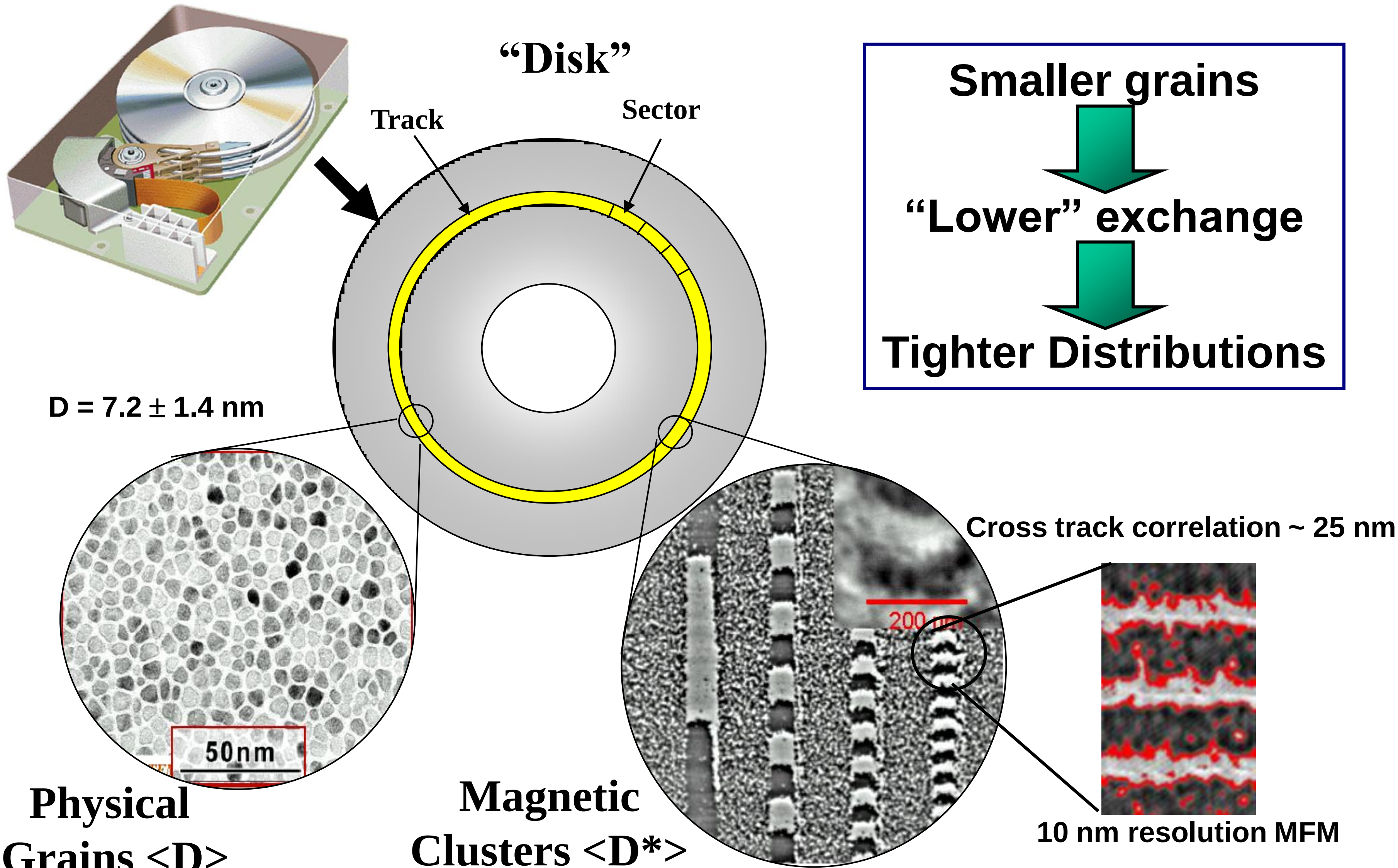
Perpendicular Recording

HAMR

Seagate 2002

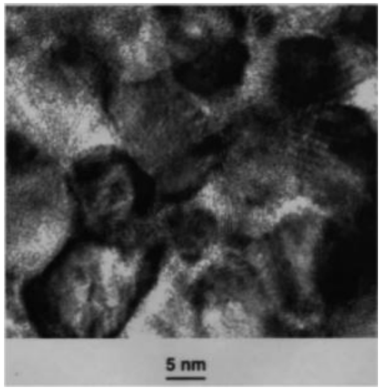
Nanostructured Disks Suppress Noise

Issue: Smaller grains require higher fields to write & maintain thermal stability



Distribution Narrowing

1990 LMR



10 Gbit/in^2 product media

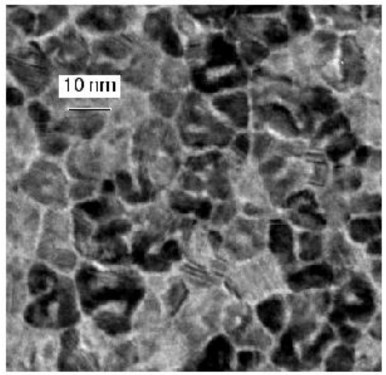
12 nm grains

$\sigma_{area} \cong 0.9$

J. Li, *et al.*, J. Appl. Phys. 85, 4286 (1999)

← CoCrPt →

2000 LMR



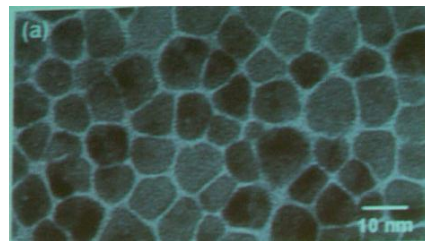
35 Gb/in^2 prototype media

8.5 nm grains

$\sigma_{area} \cong 0.6$

M. Doerner *et al.*, IEEE Trans. Mag. 37 (2001) 1052

2008 PMR



600 Gb/in^2 prototype media

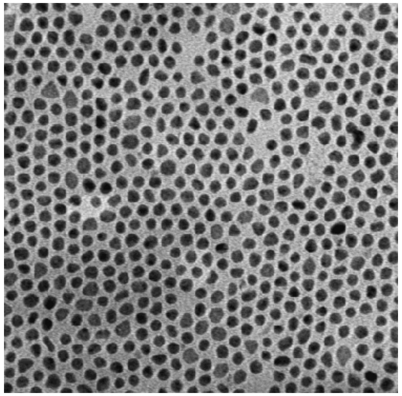
8.5 nm grains

$\sigma_{area} \cong 036$

Tanahashi *et al*. TMRC 2008

FePt SOMA

S. Sun *et al.*, Science 287,1989 (2000) 1989



Nanoparticle arrays

4 nm particles

$\sigma_{area} \cong 0.05$

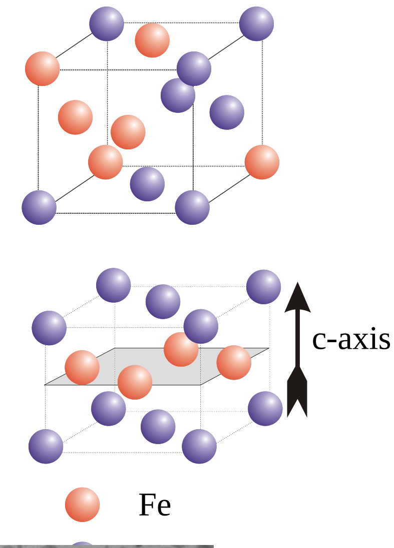
Current product densities are ~ 700-750 Gb/in^2

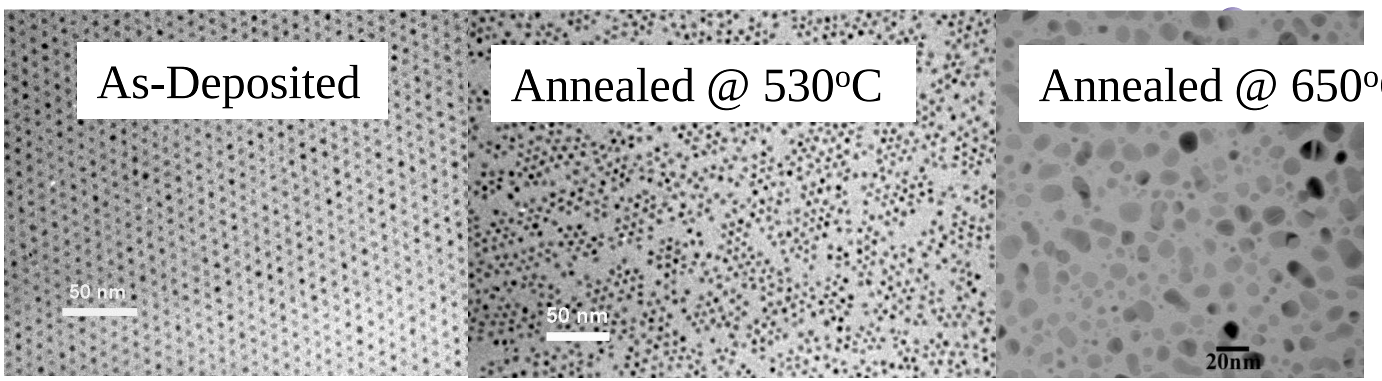
FePt Nanoparticles – *fcc-fct* phase transformation

- Annealing leads to formation of ordered, high-K_U ferromagnetic phase,
- unfortunately it also leads to particle agglomeration & disorder in the array

chemically disordered
fcc structure
superparamagnetic

chemically ordered
fct structure
ferromagnetic

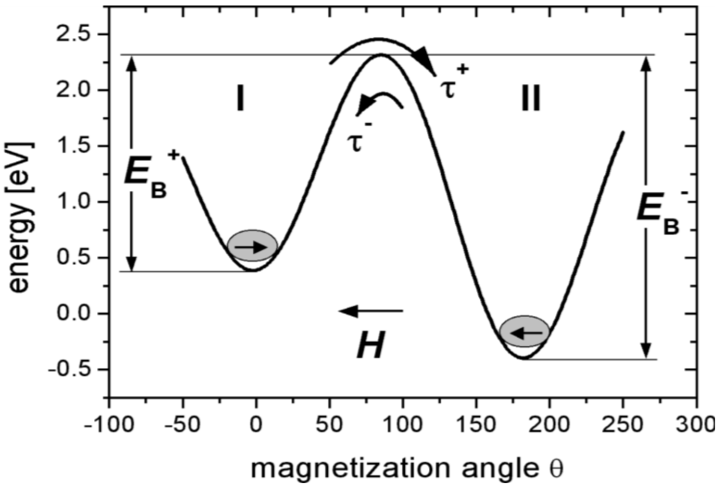




TEM from D. Weller (Seagate), presentation CC-03, Intermag '03 (Jan Thiele)

TJ Klemmer, C Liu, N Shukla, XW Wu, D Weller, "Combined reactions associated with L1(0) ordering". J Magn Magn Mater 266, 79-87 (2003)

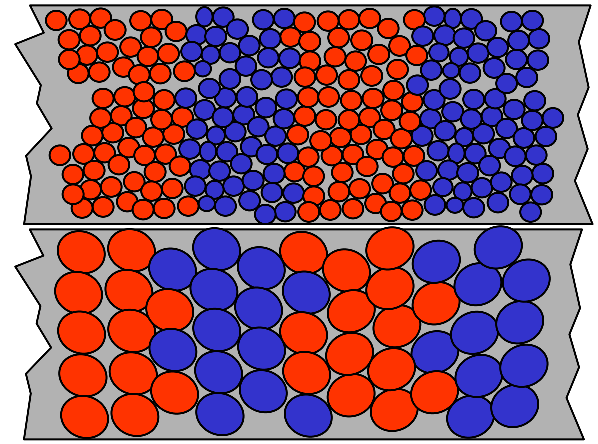
Media Design Constraints – "Trilemma"

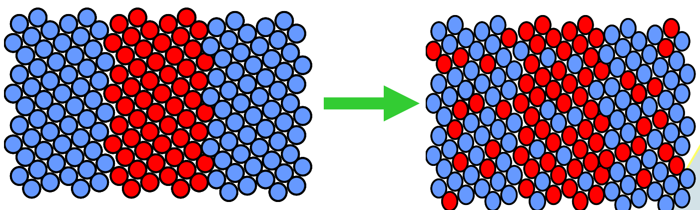


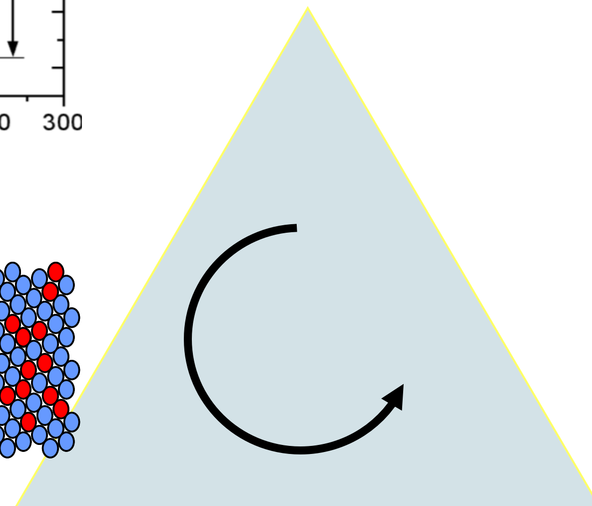
Media SNR

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

Small Grains (V)







Thermal Stability

$$E_B \cong K_u V \left[1 - \frac{|H_d|}{H_0}\right]^{\frac{3}{2}}$$

$K_u V$ = 40-60 $k_B T$

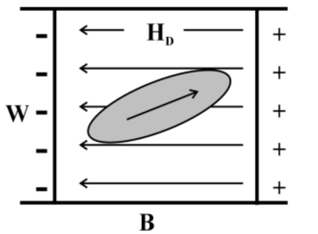
Writability

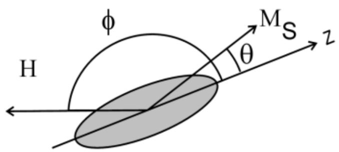
$$H_0 = \alpha \frac{2K_u}{M_s} - N_{eff} M_s$$

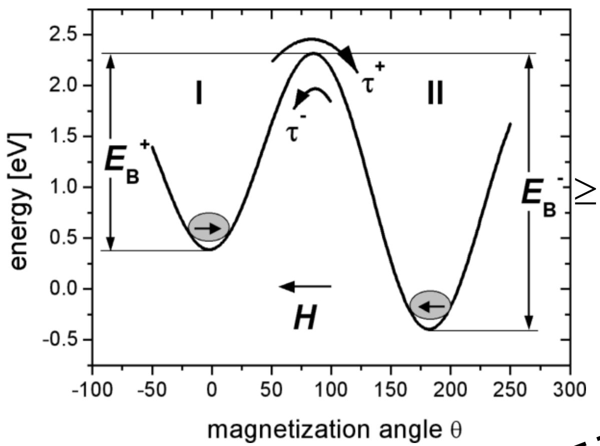
H_0 < Head Field

D. Weller and A. Moser, "Thermal Stability Limits in Magnetic Recording" IEEE Trans. Mag. 35 4423 (1999) IBM

Smallest thermally stable grain size - details







≥1.2 eV

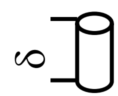
$$\tau = f_0^{-1} e^{E_B / k_B T_S}$$

$$E_B = K_u V \left(1 - \frac{4\pi M_S}{H_K}\right)^2$$

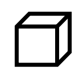
f_0: attempt frequency $\cong \alpha\gamma H_K \cong 10^9 - 10^{12}$Hz

$E_B/k_B T_S = \ln(f_0 \tau) = r_K \sim 50$ for $\tau = 10$ years

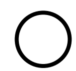
$$D_p = \left(k \frac{2 \cdot r_K \cdot k_B T_S}{H_K M_S \left(1 - \frac{4\pi M_S}{H_K}\right)^2} \right)^n$$



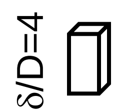
n=1/2, k=4/πδ for cylinders



n=1/3, k=1 for cubes



n=1/3, k=6/π for spheres



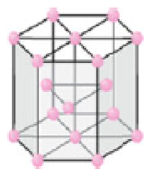
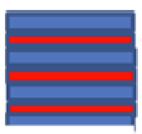
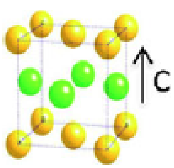
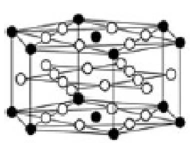
n=1/3, k=1/4 for prisms

D. Weller and A. Moser, "Thermal Effect Limits in Ultrahigh Density Magnetic Recording", *IEEE Trans. Magn.*., 35, 4423 (**1999**); D. Weller and T. McDaniel in Springer 2006 Advanced Magnetic Nanostructures, eds. D. Sellmyer and R. Skomski, chapter 11

HAMR media: high anisotropy, low Curie temp small grains

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

δ=10 nm   δ/<D>=2

	alloy system	material	K_u (10^7 erg/cm^3)	M_S (emu/cm^3)	T = 350 K H_K (kOe)	T_C (K)	D_p (a) (nm)	D_p (b) (nm)	D_p (c) (nm)	D_p (d) (nm)
	Co-alloys	$CoCr_8Pt_{22}$	0.7	500	28.0	1000[a]	7.3	7.5	8.7	6.4
		Co_3Pt	2	1100	36.4	1200	4.3	5.3	6.1	4.5
	PMR	$CoPt_3$	0.5	300	33.3	600	8.6	8.3	9.7	7.2
	CoX/Pt(Pd) multilayers	Co_3/Pt_{10}	1.2	450	53.3	~700[b]	5.5	6.2	7.2	5.4
		Co_3/Pd_{10}	0.6	360	33.3	~700[b]	7.8	7.8	9.1	6.8
	ordered	FePd	1.8	1100	32.7	760	4.5	5.4	6.3	4.7
	Ll_0/Ll_1	FePt	7	1140	122.8	750	2.3	3.5	4.0	3.0
	phases	CoPt	4.9	800	122.5	840	2.7	3.9	4.5	3.4
	HAMR	MnAl	1.7	560	60.7	650	4.7	5.5	6.4	4.8
 SmCo$_5$	rare-earth transition metals	$Fe_{14}Nd_2B$	4.6	1270	72.4	585	2.8	4.0	4.6	3.4
		$SmCo_5$	20	910	439.6	1000	1.4	2.4	2.8	2.1

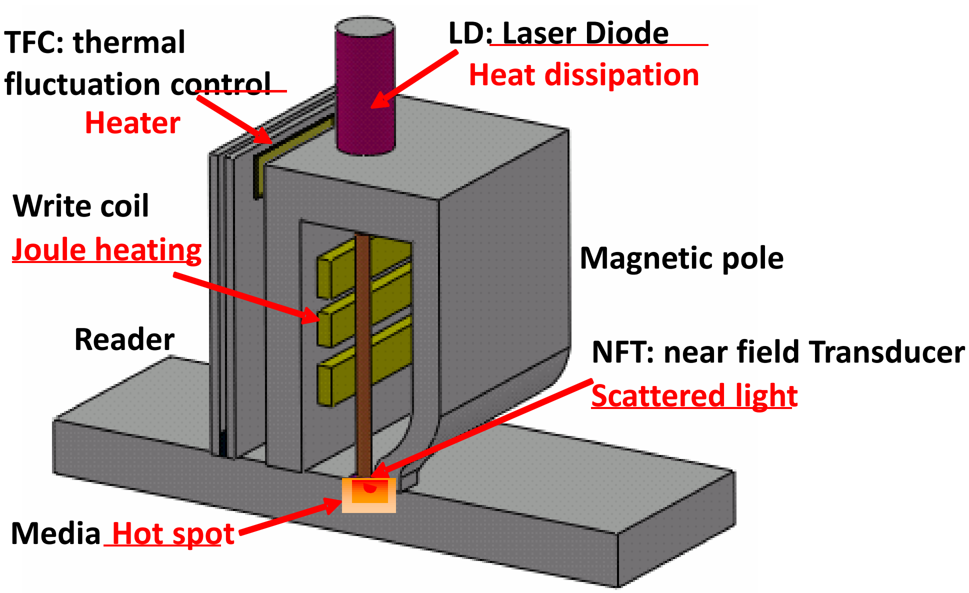
~10x higher Ku   "low" Tc   2x smaller grain dia

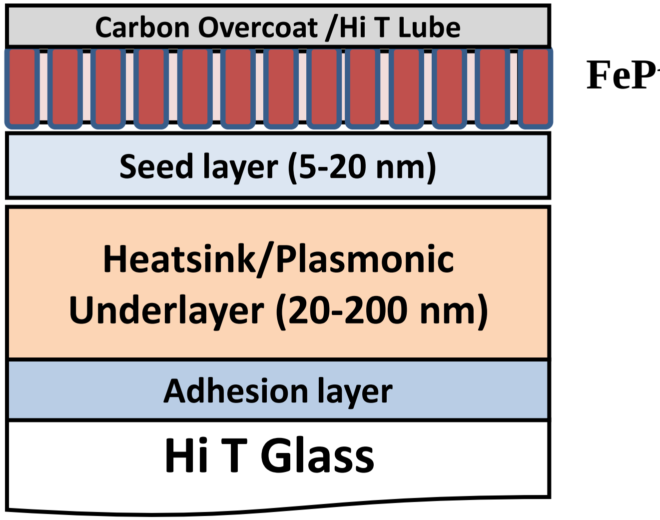
D_p is the average thermally stable grain diameter assuming $KV/k_BT = 60$ and $T = 350$ K, $k_B = 1.3807 \times 10^{-16}$ erg K^{-1} and volumes (a) $V = \pi/4 \times D^2 \times 10$ nm (cylinders), (b) $V = D^3$ (cubes), (c) $V = 4/3 \times \pi \times (D/2)^3$ (spheres) and (d) $V = \pi/4 \times D^2 \times \delta$ (cylinders with $\delta/D = 2$). The thickness δ is 10 nm or larger in today's media but will drop for smaller diameters going forward.

[a] T_C in today's alloy media depends on the Cr and Pt content and has increased.

[b] T_C in multilayers strongly depends on the Co thickness.

HAMR media: Two Key Topics



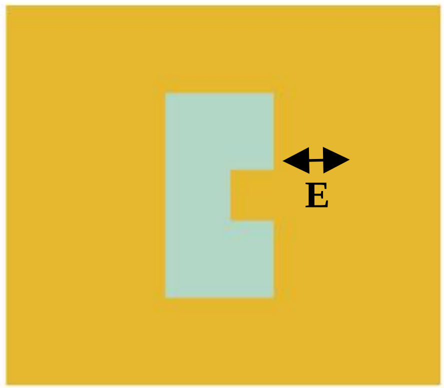


1. **Chemically ordered and textured $L1_0$ FePtX-Y (001) granular media for high areal density heat-assisted magnetic recording (HAMR)**

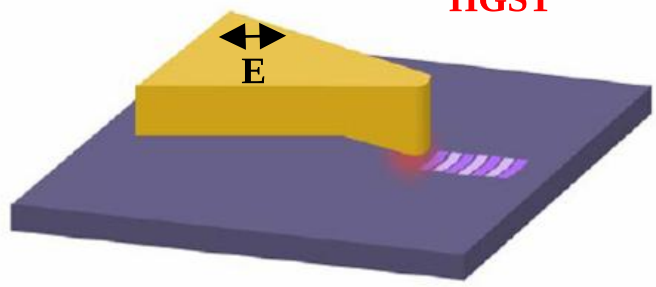
2. **Thermal design to improve the recording time window down to < 1 ns and increase the areal density beyond $1Tb/in^2$**

HAMR heads (brief): Multiple Near Field Transducer Designs

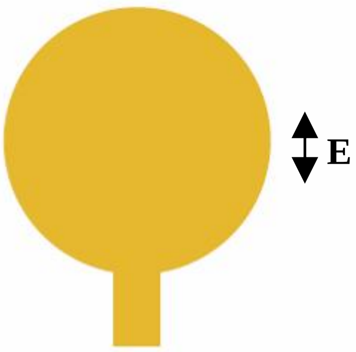
- C-aperture **HGST**



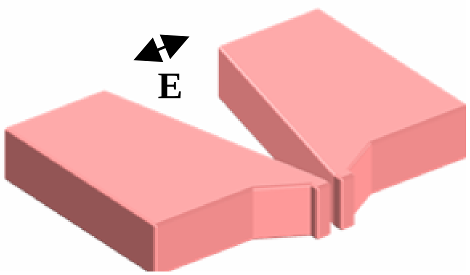
- Triangular antenna (Nanobeak) **HGST**



- Lollipop **Seagate**



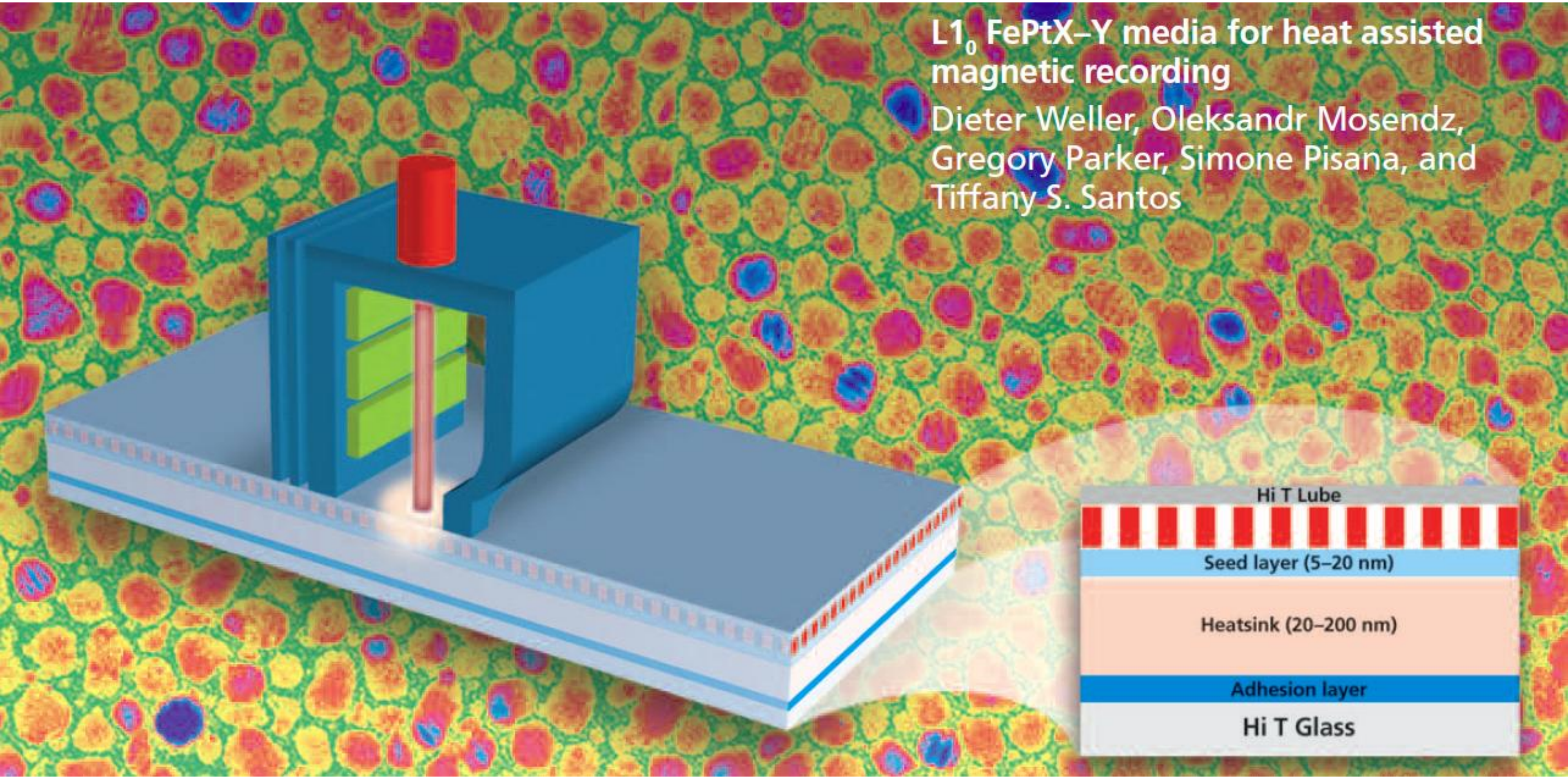
- Waveguide/Needle **Berkeley, CMU**



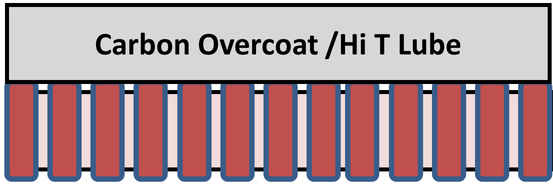
All transducers can produce very small heat spots
Common challenge is reliability

Barry Stipe

pss – physica status solidi A **210**, 1245-1260 (2013) paper



HAMR Media Stack

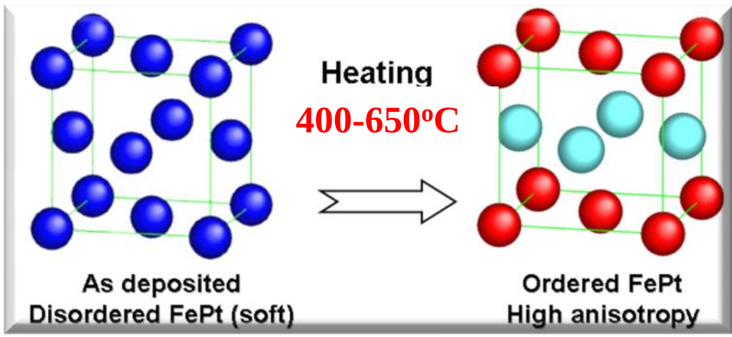


FePt + segregant

Proper segregants promote grain isolation and define grain shape:

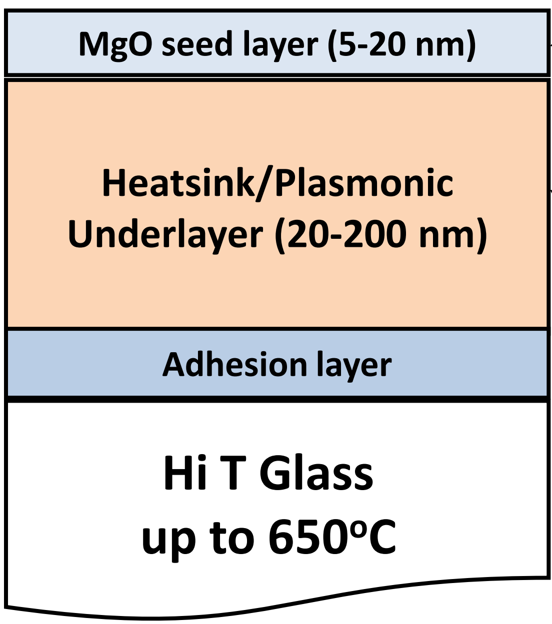
Carbon, SiO_2, SiN_x, B_2O_3

other nitrides, oxides, carbides



Heating

A1 – $L1_0$ chemical ordering transition



Seed layer for $L1_0$ order for FePt

MgO: FCC rocksalt, a = 0.421nm

<001> orientation, 9% mismatch

Others: **CrRu, CrMo, TiN, TiC, Cr, Ag, Pt**

Heat Sink / Plasmonic Underlayer: smooth

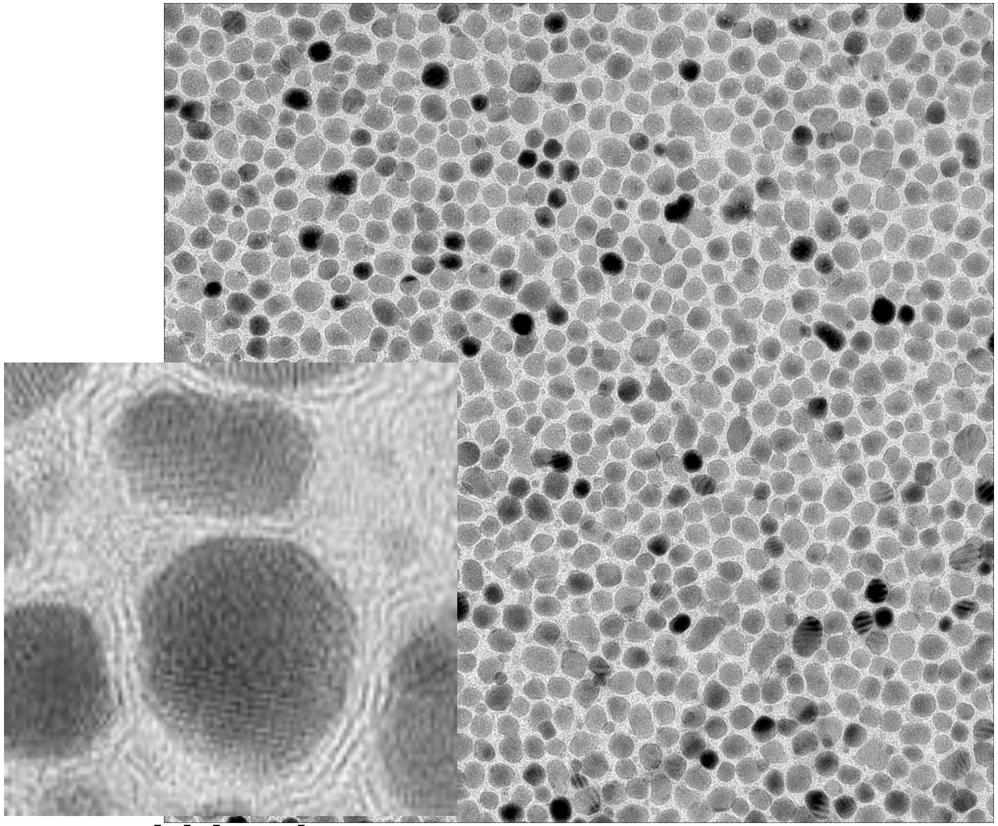
Examples: **AgX, AlX, CuX, CrX, AuX, etc.**

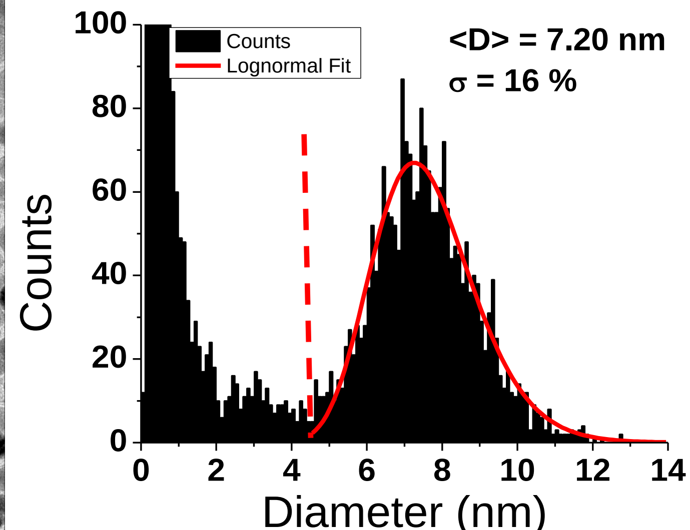
Adhesion layer

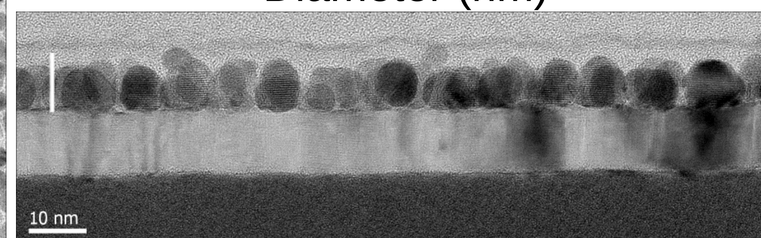
Example: **NiTa**

“Early” FePt HAMR media microstructure – spherical grains

Granular FePtAg-C media grown at ~550°C 2011





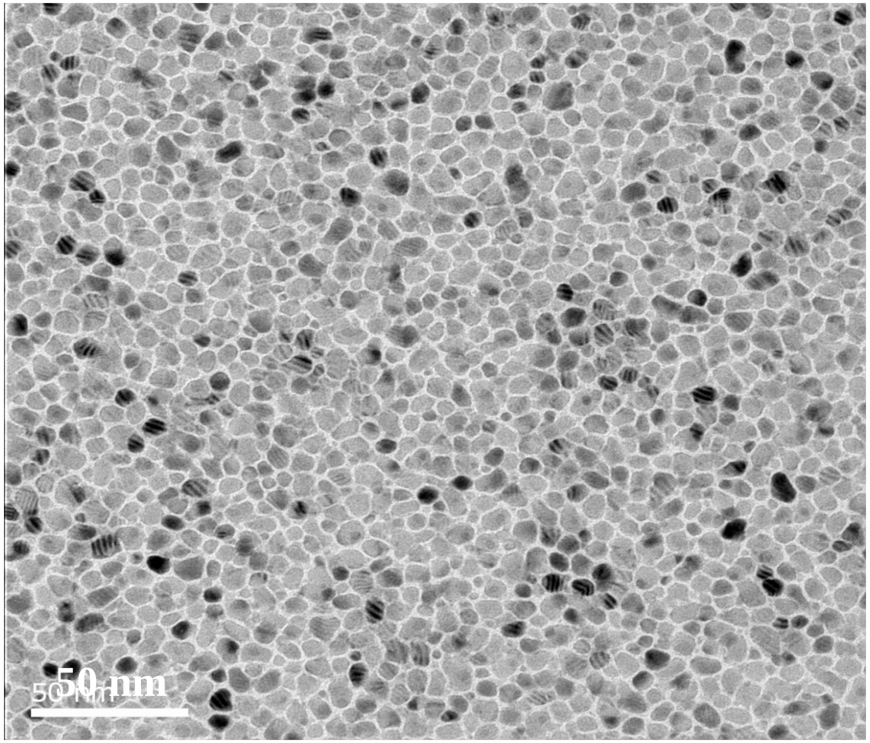


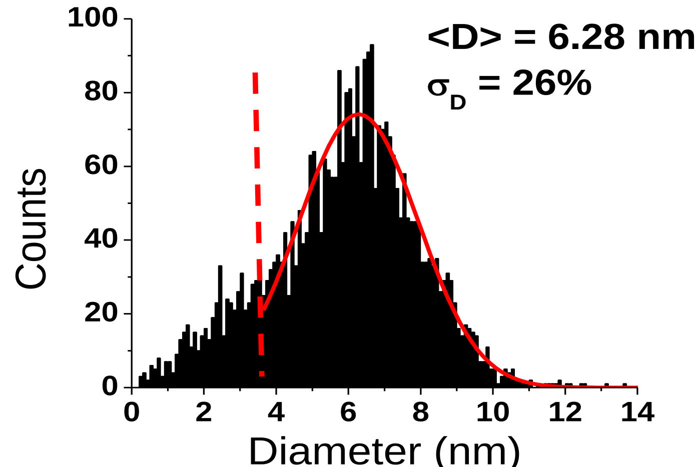
Graphitic Sheets

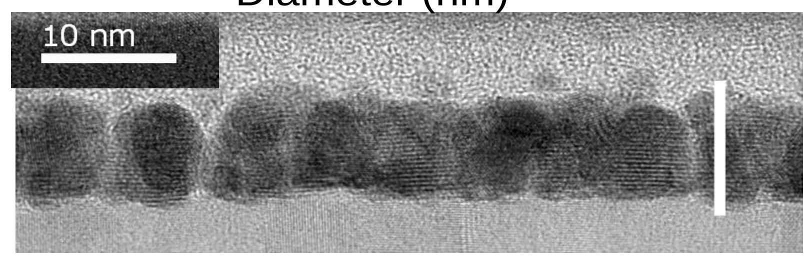
- **Used a new Lean 200 sputter tool w/ 20 chambers**
- **Low thickness δ ~ 7 nm and relatively high roughness**
- **Average grain size <D>~7.2 nm, grain pitch <P>~9 nm**
- **grain aspect ratio δ/D~1**
- **many small grains D<3 nm (thermally unstable)**

“More recent” FePt media – dual layers w/ more cylindrical grains

Granular FePtX-Y media grown at ~620ºC 2012





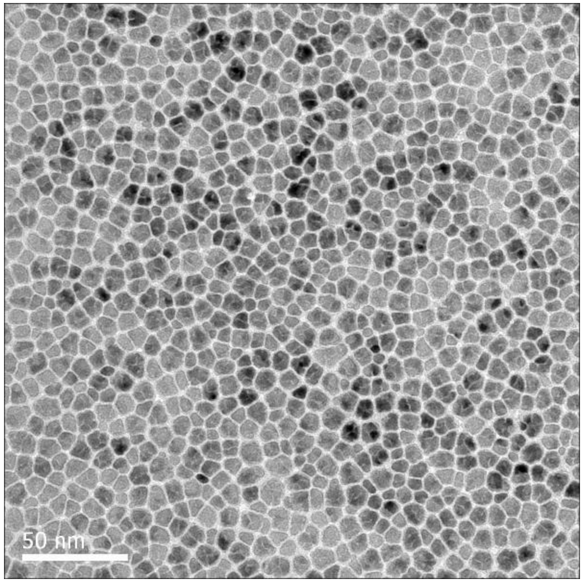


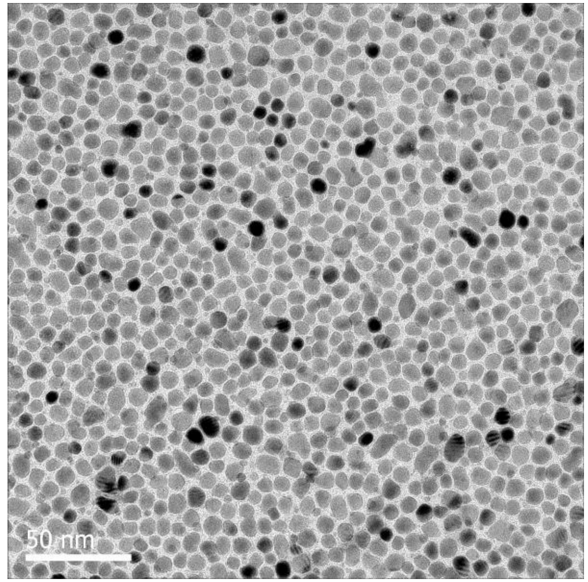
- **higher thickness δ ~ 10 nm → improved read back signal**
- **average grain size <D>~6.3 nm, grain pitch~ <P>~7.3 nm**
- **grain aspect ratio δ/D~1.6**
- **less grains with D < 3.5 nm**
- **smoother surface**
- **BUT: worse grain size distribution**

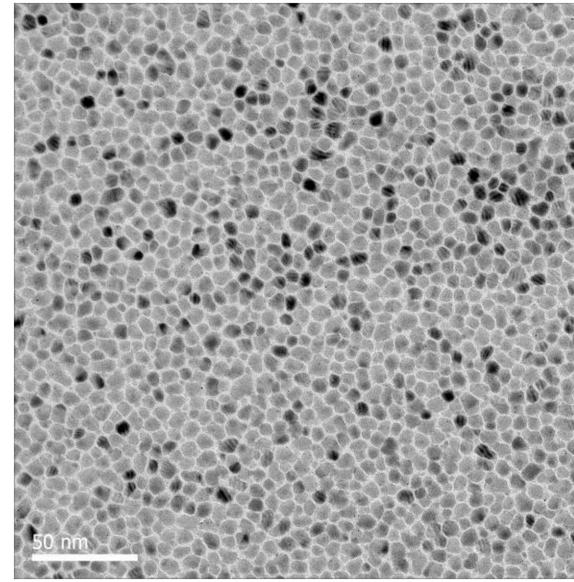
D. Weller et al., Phys. Status Solidi **A 210**, 1245 (2013)

Grain Size and Microstructure from CoCrPt PMR to FePt HAMR 2013

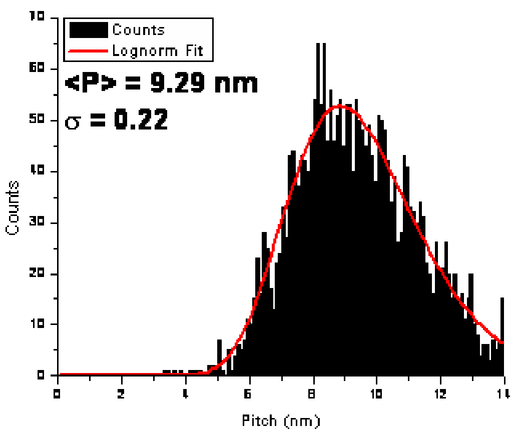
Typical PMR | HAMR Media | HAMR: more Voronoi and columnar

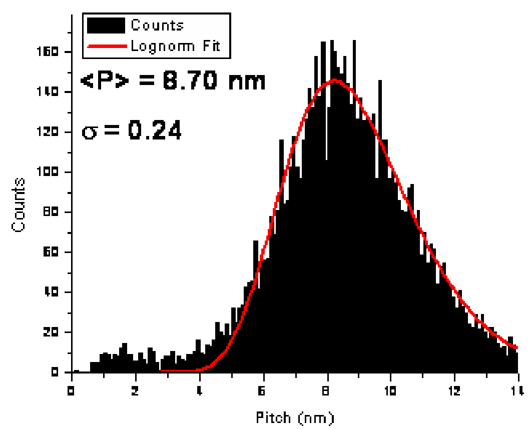


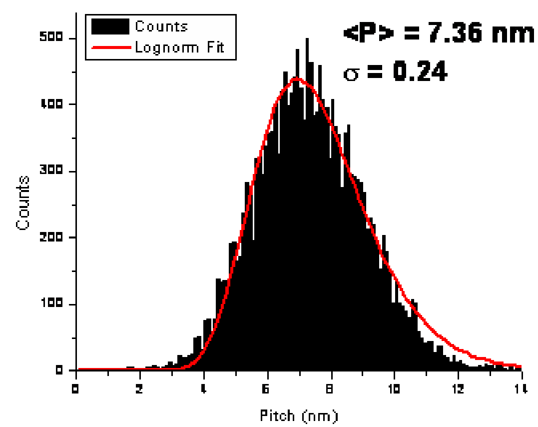




Improved Grain Size (Pitch) & Distributions

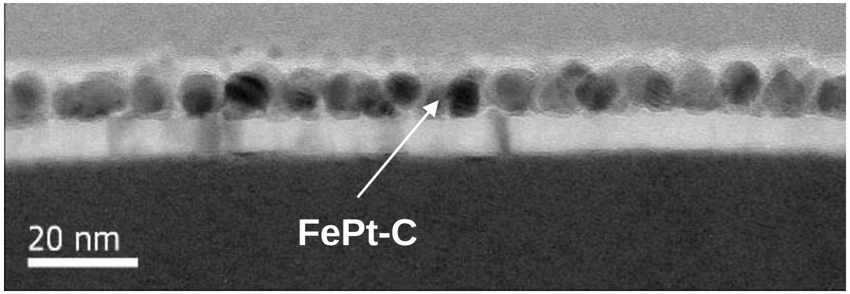


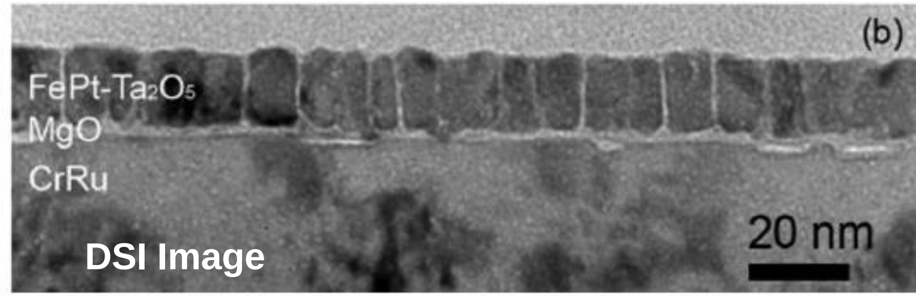




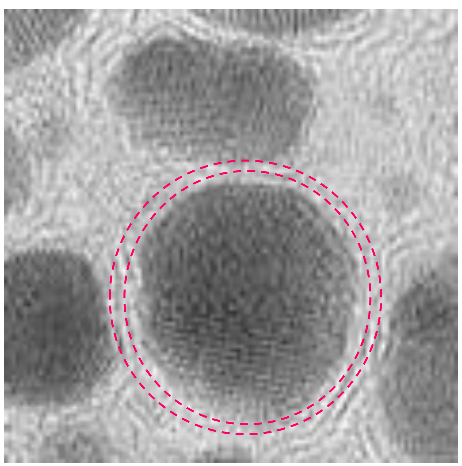
Importance of Columnar Grains

Spheres *VS.* **Columns**





Graphitic Sheets

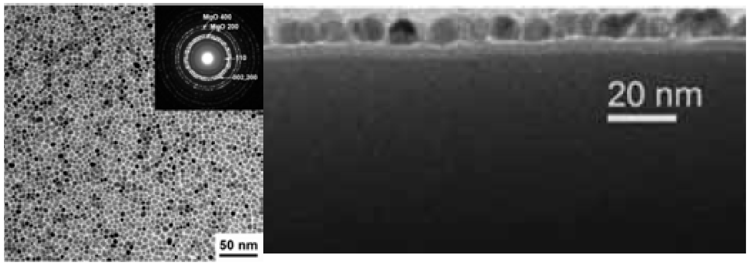


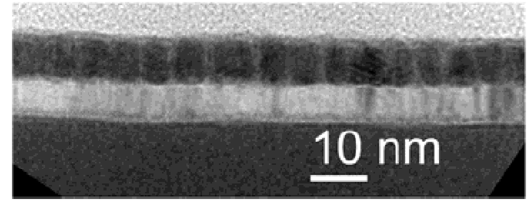
Advantages of columnar grain growth:

- **Decouple grain diameter from grain thickness.**
- **Thicker media will increase readback signal.**
- **Smoother surfaces and better flyability.**
- **Get laterally smaller, thermally-stable grains.**
- **Narrow distribution in optical absorption and consistent vertical heat flow from grain to grain.**
- **Enable functional layered structures.**

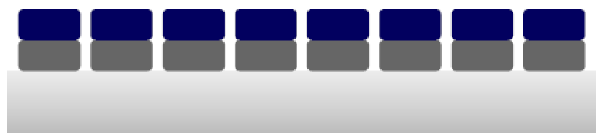
K. Hono - Nat'l Institute of Materials Science Japan (NIMS)

FePt-C as template + FePt-TiO_2 for columnar growth



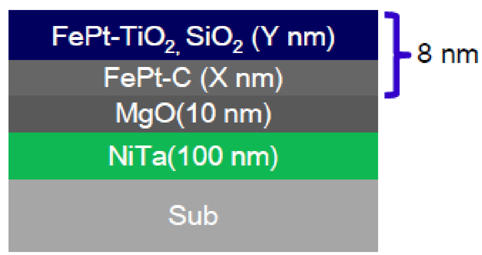


K. Hono
2013 ASTC
presentation



FePt-TiO_2, SiO_2 **dual mag layers**

FePt-C



@ 600 oC

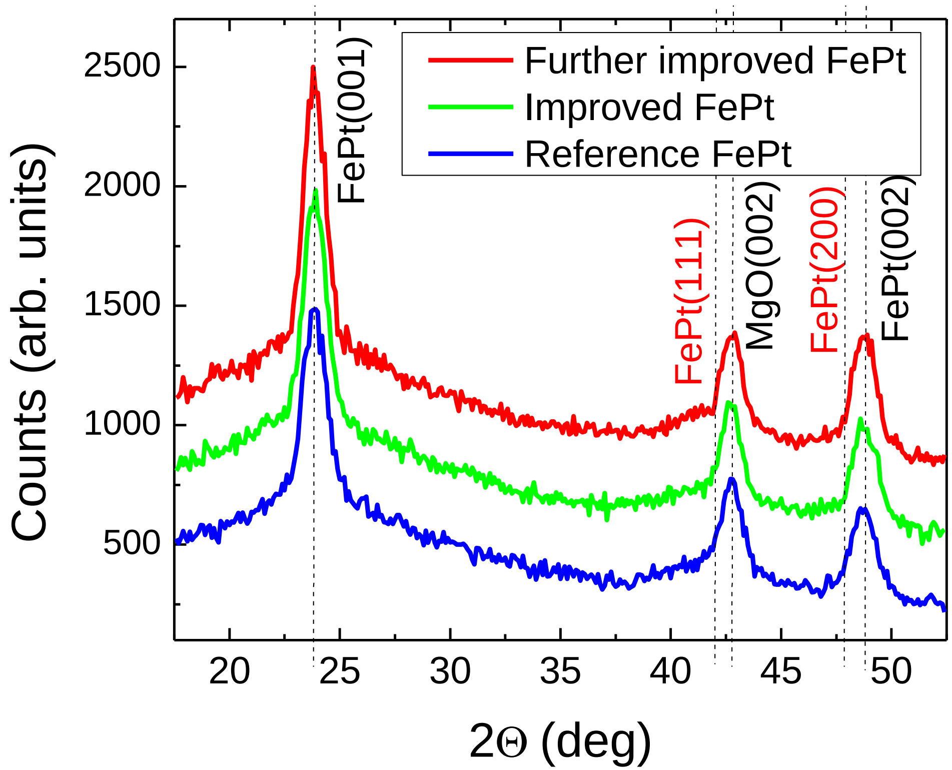
@RT

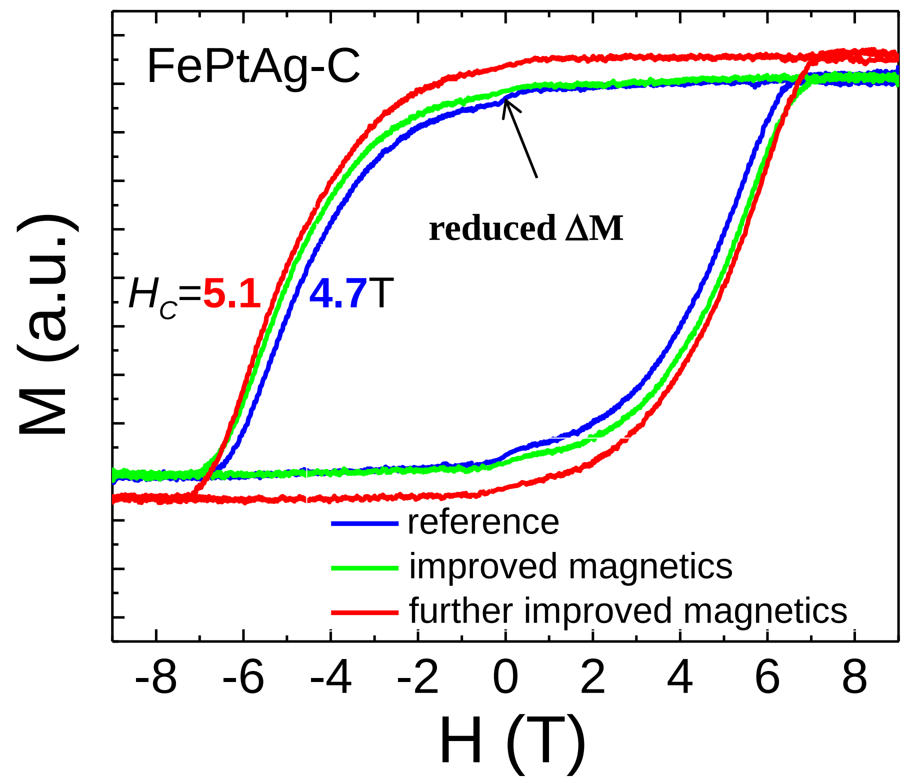
C segregant (40 vol%)	SiO_2 or TiO_2 segregants (50 vol%)
1. Good particle separation	1. Poor particle separation
2. High degree of $L1_0$ ordering	2. Poor degree of $L1_0$ ordering
3. Spherical type grains	3. Cylindrical type grains
4. Rough surface	4. Excellent surface smoothness

Currently working on C and Y_2O_3 or Cr_2O_3 segregants to combine these 2 effects

XRD and MOKE hysteresis of improved media 2013

(001)/(002) XRD ratio 1.9 – 2 → chemical ordering S~0.90

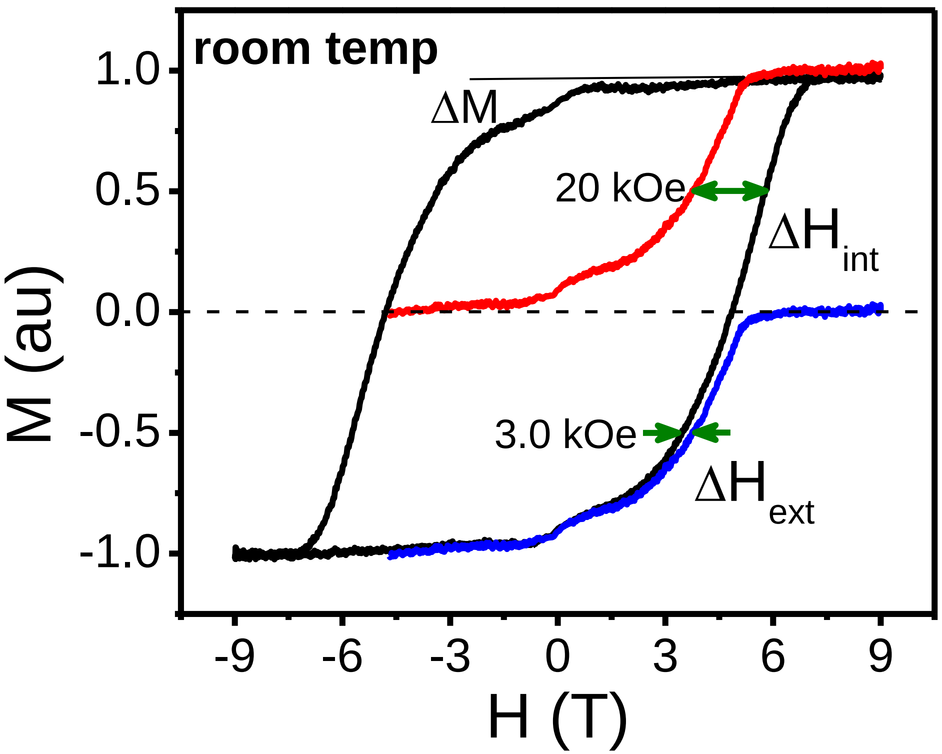




Modified deposition parameters result in suppression of very small grains and reduced noise in recorded media

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

Minor Loop Analysis: Switching Field Distribution 2011



At room temperature

Small *eSFD* → small cluster size (14nm) → low exchange and magnetostatic interactions

Large *iSFD*: $\sigma_{\text{int}}^2 = \sigma_{vol}^2 + \sigma_{\text{axis}}^2 + \sigma_{Hk}^2$

σ_{int} = 15 kOe (VSM)

Grain volume distribution: **σ_{vol} = 3.7 kOe**

- from TEM grain size analysis

Grain texture distribution: **σ_{axis} = 6.6 kOe**

- from rocking curve width, XRD

Anisotropy distribution: **σ_{Hk}=12.9 kOe**

- from VSM, may arise from variations in $L1_0$ order, lattice strain & defects

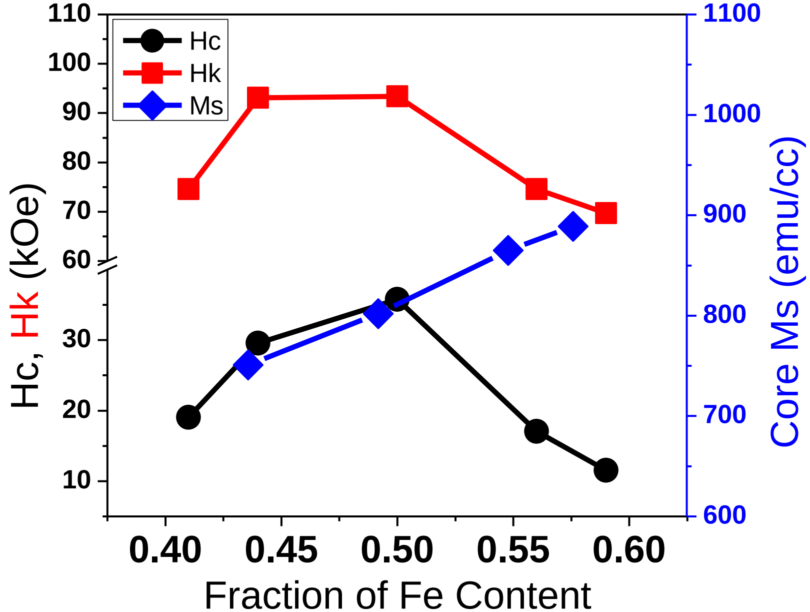
What is iSFD at the recording temperature, near Tc ?

Micromagnetic model needed to go beyond these estimates

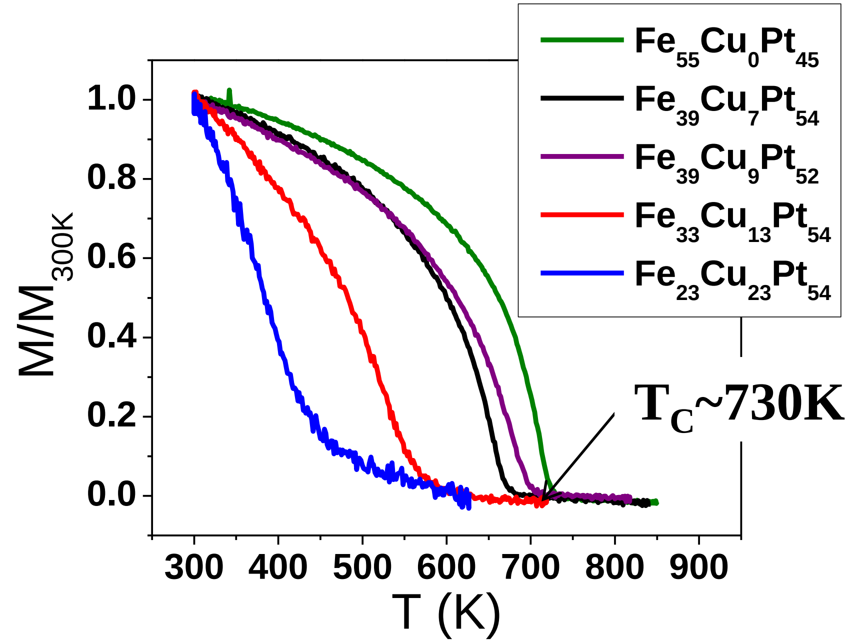
S. Pisana, et al., J. Appl. Phys. 113, 043910 (2013)

Composition dependence in Fe_xPt_{1-x}–C and $Fe_XCu_YPt_Z$

granular



continuous

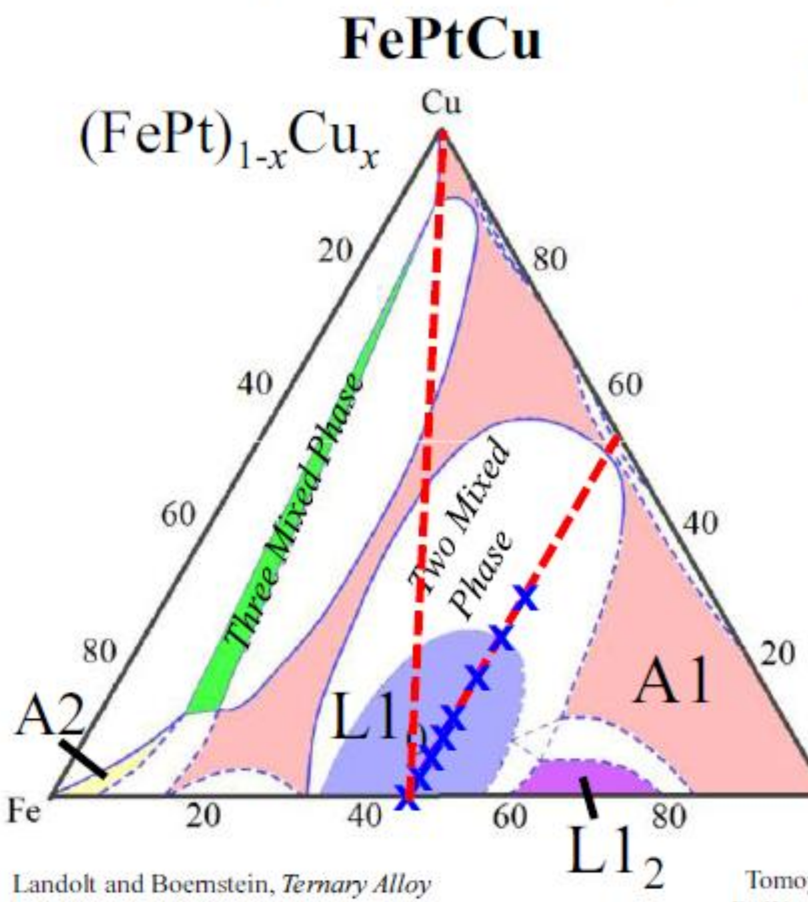


Optimal values of coercivity and anisotropy at x=50%

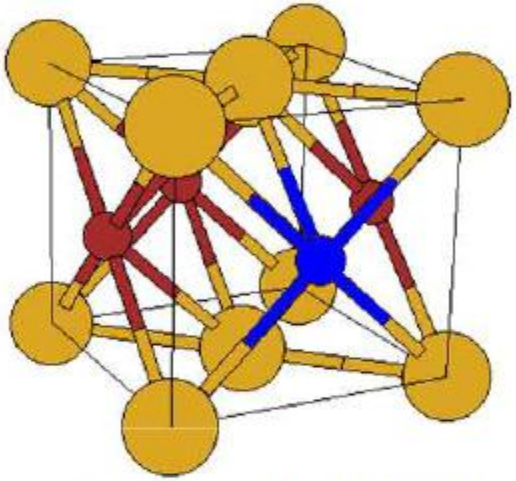
Curie temperature reduction to 600-650K by adding 9-13at% Cu

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

Forming ternary alloys to improve ordering



Landolt and Boernstein, *Ternary Alloy Systems*. (Springer-Verlag Berlin, 2008)

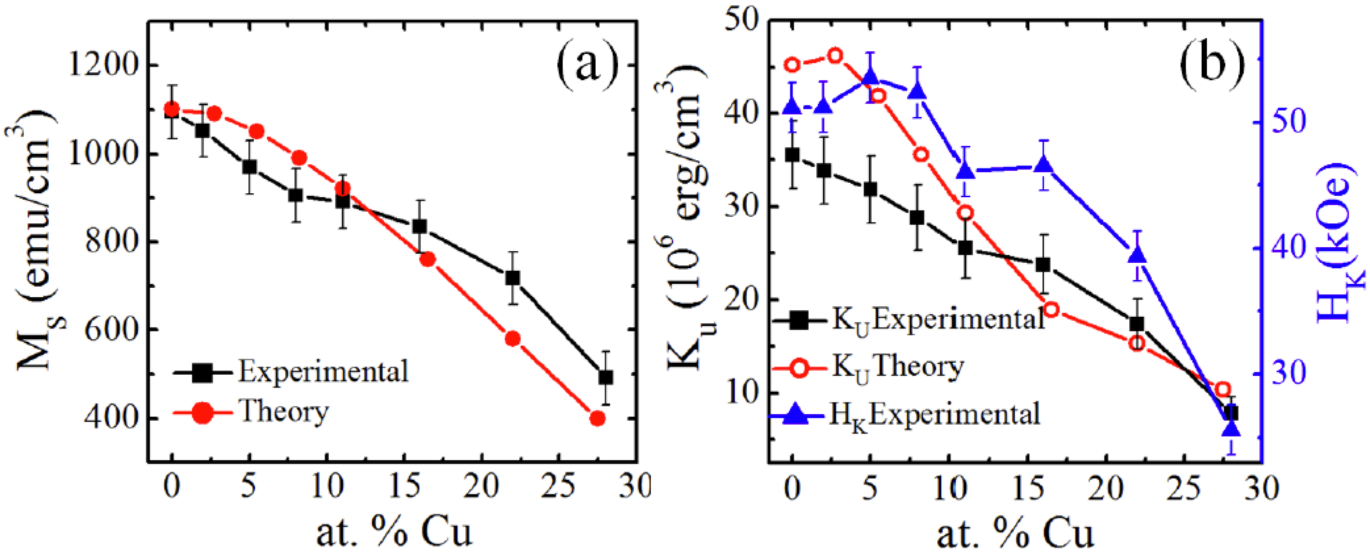


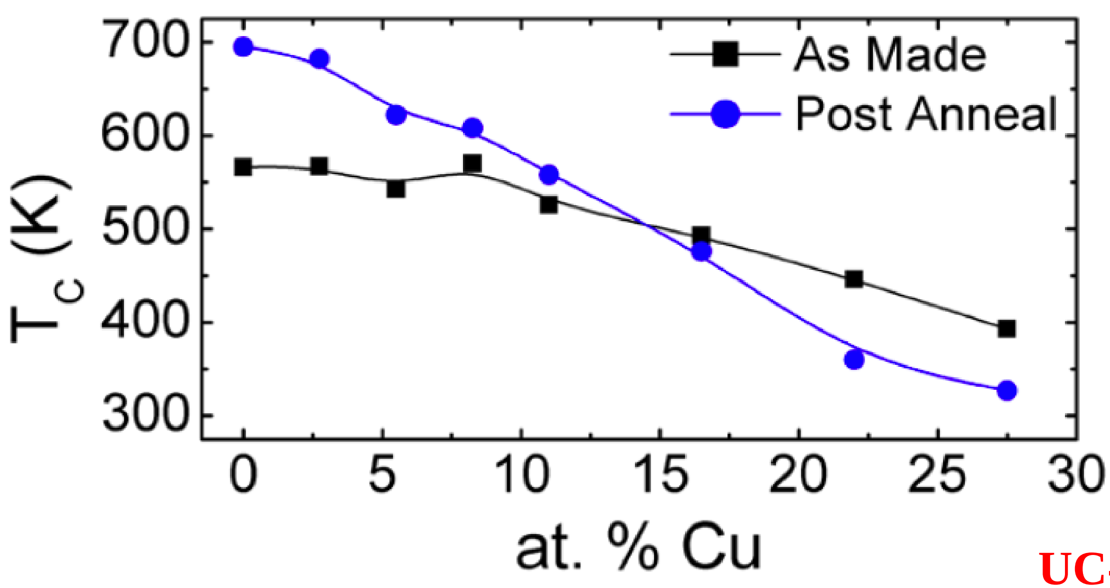
http://cst-www.nrl.navy.mil/lattice/index.html

Tomoyuki Maeda *et al.*, Appl. Phys. Lett. **80**, 2147 (2002)
B. Wang and K. Barmak, J. Appl. Phys. **109**, 123916 (2011)

UC Davis – Seagate

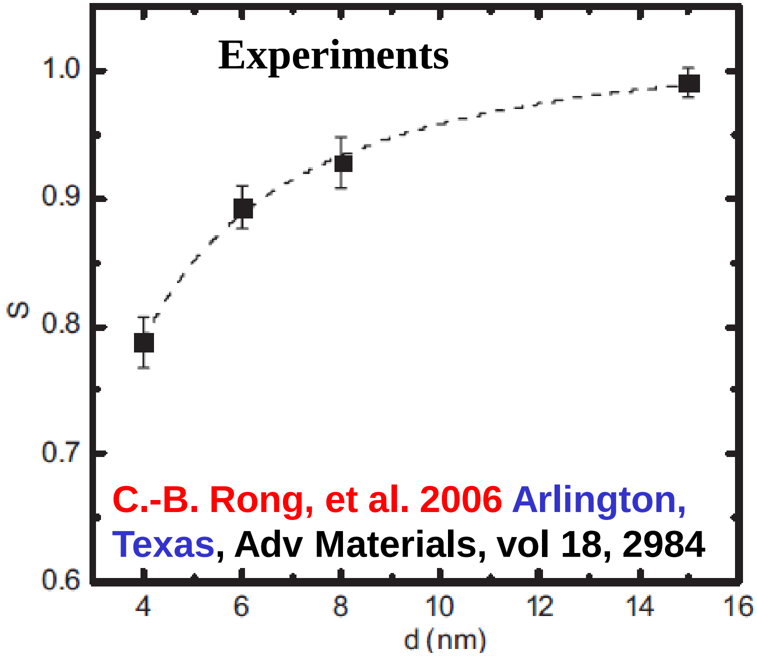
FeCuPt IEEE SCV 11/19/13

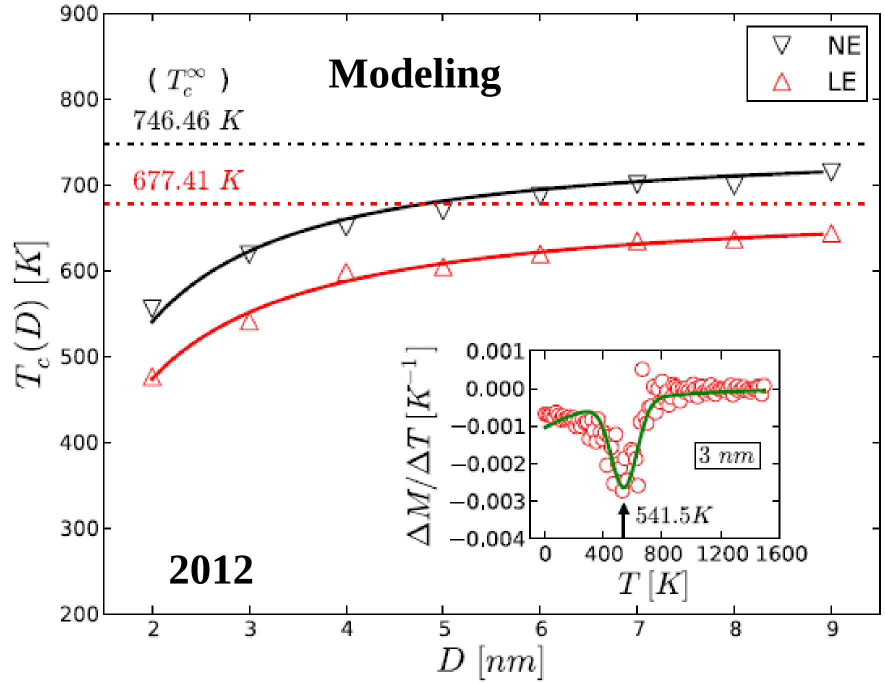




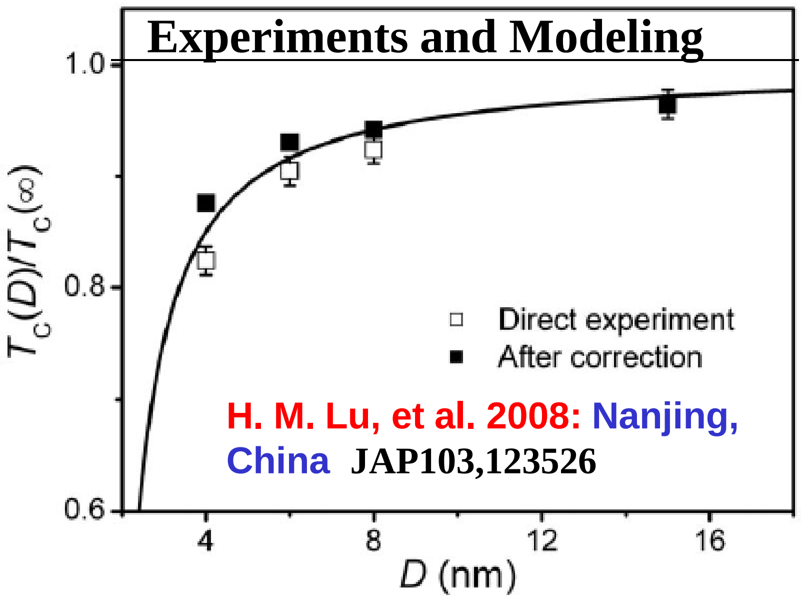
UC-Davis - Seagate

Chemical ordering S and Curie temperature T_C vs grain size



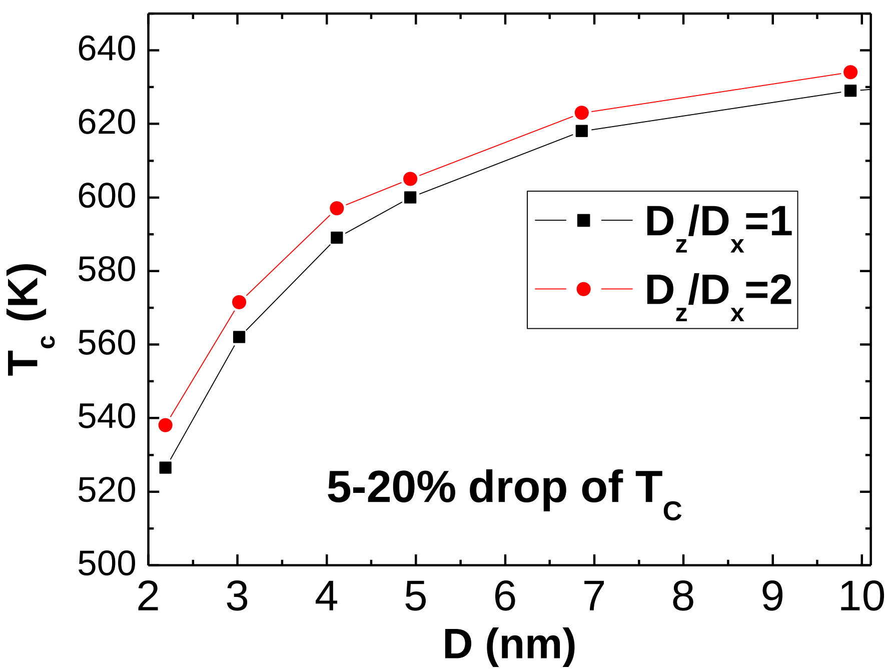


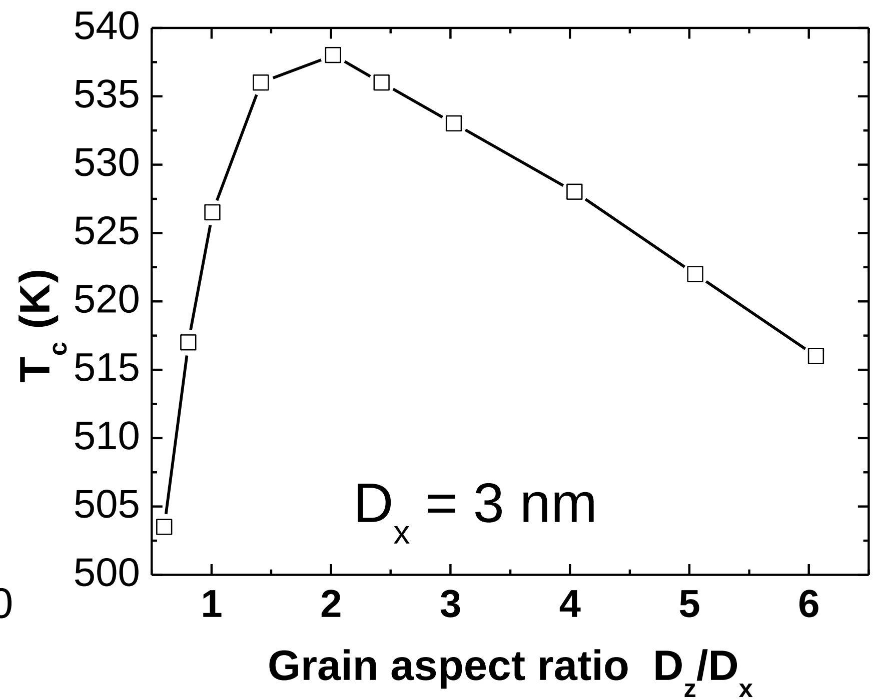
O. Hovorka, ….., G. Ju, R. W. Chantrell, 2012: "The Curie temperature distribution of FePt granular magnetic recording media", APL 101, 052406 York U. - Seagate



A. Lyberatos, D. Weller, G. Parker, 2012: "Size dependence of the T_C of $L1_0$-FePt nanoparticles" JAP 112,113915 Crete U. – HGST (→ next slide)

Effect of grain size and aspect ratio on T_C





Finite size scaling theory $$T_c(D) = T_c(\infty)\left(1 - x_o D^{-1/\nu}\right)$$ **ν~0.7+/–.09**

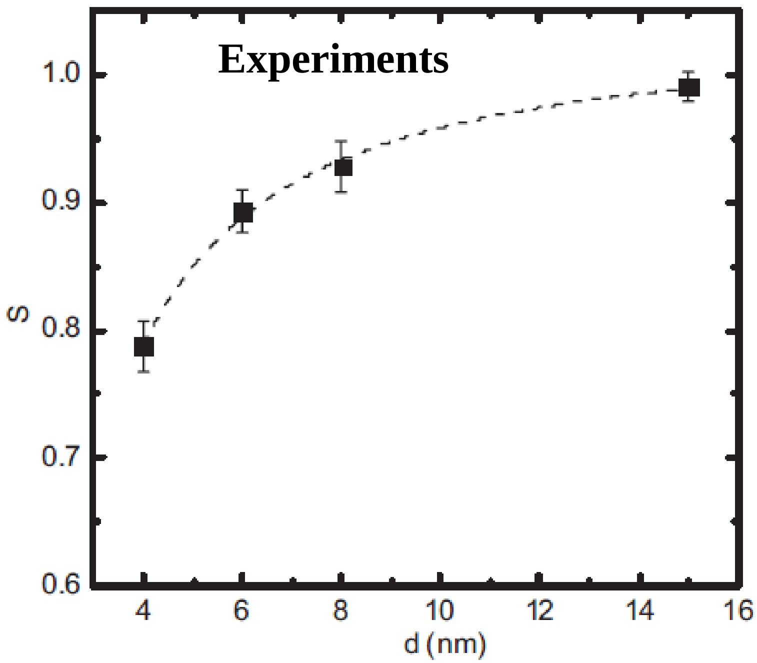
- **T_C smaller than 750 K due to exchange truncation/abandonment in single particle modeling**
- **Cylindrical grains with an aspect ratio of ~2 reduce x_0 by ~20%, i.e. "minimize" the grain size induced reduction of T_C**
- **ν=0.7+/–0.09 is compatible with 3D Ising/Heisenberg models**
- **T_c determined from peak susceptibility χ(T) using Monte Carlo method**

A. Lyberatos, D. Weller, G. Parker, "Finite size effects in *$L1_0$*-FePt nanoparticles" J. Appl. Phys. **114**, 233904 **(2013)**

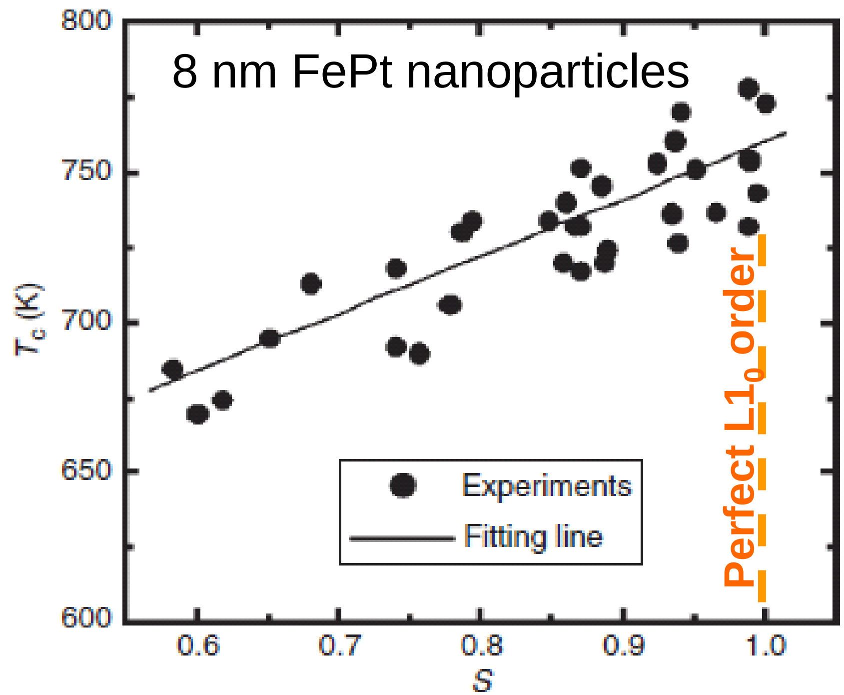
HGST a Western Digital company

$L1_0$ Chemical Order Parameter & Curie temperature

$L1_0$ Order Parameter vs grain size



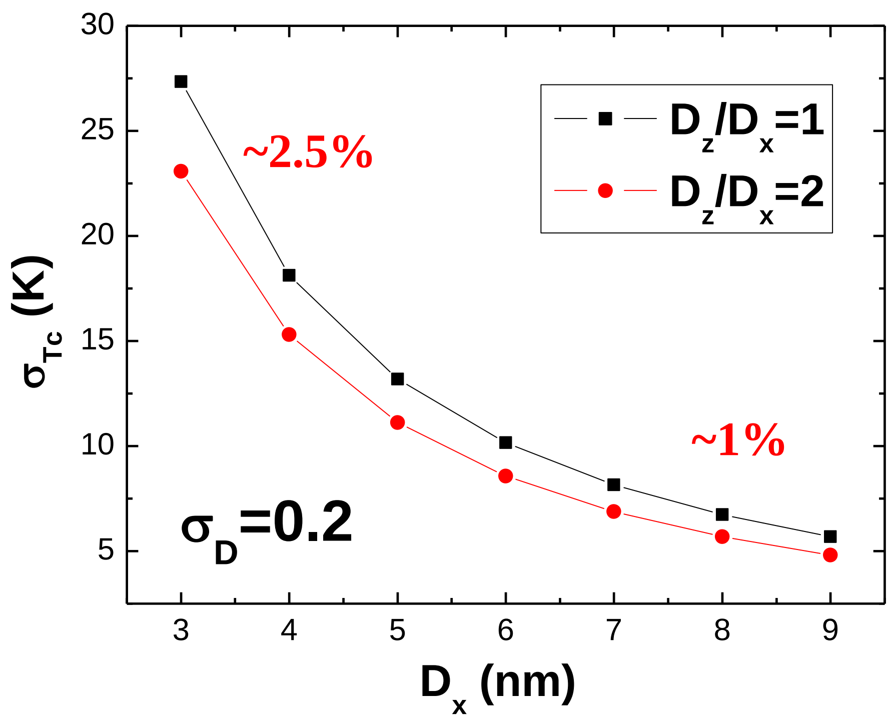
Curie temperature vs $L1_0$ Order Parameter



Chuan-bing Rong, Daren Li, Vikas Nandwana, Narayan Poudyal, Yong Ding, Lin Wang, Hao Zeng, and J. Ping Liu, Size-Dependent Chemial and Magnetic Ordering in $L1_0$-FePt Nanoparticles", Adv Materials, vol 18, 2984 (2006) - **Arlington, Texas**

σ_{TC} vs grain diameter D_x

Atomistic Calculations



- Variations in T_c arise from the dispersion in grain size and chemical order.
- Recording performance is highly sensitive to T_c and H_K distributions.
- **Reducing D increases σ_{Tc} /T_C from ~1% (D=8nm) to ~2.5% (D=4nm).**

A. Lyberatos, et al, "Size dependence of T_C of $L1_0$-FePt nanoparticles" J. Appl. Phys.. **112**, 113915 **(2012)**

"Structure and Magnetic Properties of $L1_0$-Ordered Fe-Pt Alloys and Nanoparticles"

Table 5.2 The room temperature magnetic behaviour (para - paramagnetic; ferro - ferromagnetic; af - antiferromagnetic) and magnetic properties of the main phases in the Fe–Pt system: the Curie temperature T_c, the anisotropy constant K_1, the anisotropy field $H_A = 2K_1/\mu_0 M_s$, the saturation magnetisation M_s, the upper limit of energy density $(BH)_{max} = \mu_0 M_s^2/4$, the domain wall-width δ_w, the exchange length l_{ex} and the critical single-domain particle size D_c.

	Compound	Structure (space group)	Magnetic behaviour	T_c (K)	K_1 (MJ/m^3)	$\mu_0 H_A$ (T)	$\mu_0 M_s$ (T)	$\mu_0 M_s^2$ / 4 (kJ/m^3)	δ_w (nm)	l_{ex} (nm)	D_c (nm)	References
	α-Fe	$A2$ ($Im\bar{3}m$)	ferro	1043	0.046		2.16	928	30	1.5	7	Kneller and Hawig (1991), Skomski and Coey (1999)
Disordered	Fe_3Pt	bcc martensite[a]	para									Kussmann and von Rittberg (1950), Sumiyama et al. (1983)
	FePt	$A1$ ($Fm\bar{3}m$)	ferro	585			1.5	448	≈15			Kussmann and von Rittberg (1950), Menshikov et al. (1974)
	$FePt_3$	$A1$ ($Fm\bar{3}m$)	ferro	425			0.8	127				Bacon and Crangle (1963)
Ordered	Fe_3Pt	$L1_2$ ($Pm\bar{3}m$)	ferro	410			1.8	645	≈15			Kussmann and von Rittberg (1950), Menshikov et al. (1975), Sumiyama et al. (1978), Hai et al. (2003b)
	FePt	$L1_0$ ($P4/mmm$)	ferro	750	6.6	11.5	1.43	510	6.3	2.0	560	Kussmann and von Rittberg (1950), Ivanov et al. (1973), Vlasova et al. (2000)
	$FePt_3$	$L1_2$ ($Pm\bar{3}m$)	para (af below 160 K)									Bacon and Crangle (1963), Maat et al. (2001)

T_C =585 K

Full chemically ordered T_C =750 K

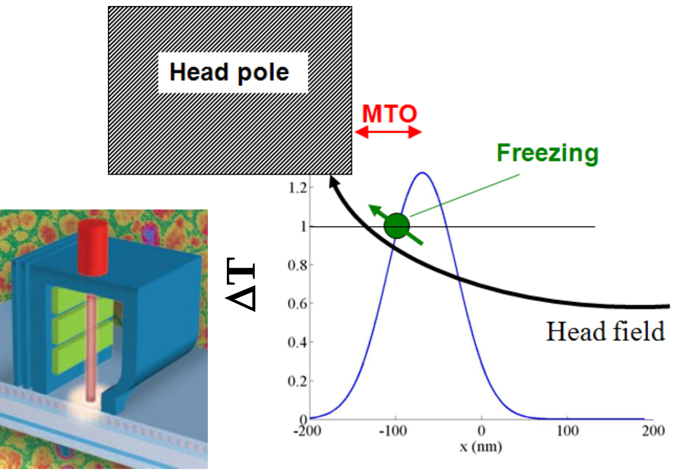
[a] fcc ($A1$) Fe_3Pt starts to transform to a bcc martensite already at room temperature (Sumiyama et al., 1983).

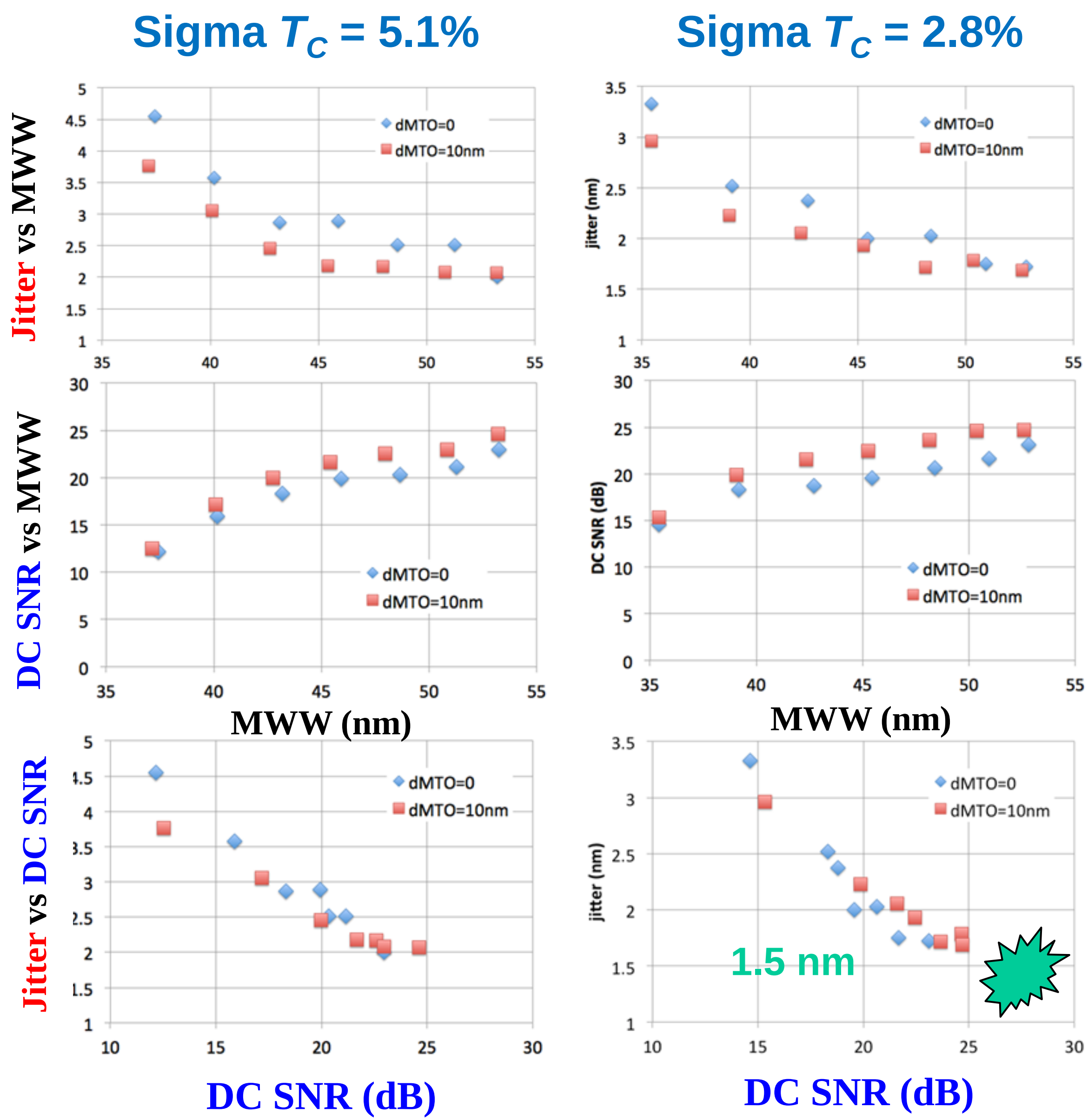
Strong dependence of T_C on chemical ordering A1 → $L1_0$ (ΔT_C =165K)

Kussmann, A, von Rittberg, G.Grfn., "Study of conversions in the Platinum –Iron System ", Z. Metallkd. 11, 470 (1950);
A. Z. Menshikov, Yu. A. Dorofeev, V. A. Kazanzev,. S. K. Sidorov, Fiz. metal. metalloved. 38, 505 (1974).

Realistic Recording Model - Effects of Sigma T_C and MTO

Thermal and Field Contours





MTO=magnetic field temperature offset

- Realistic head fields used here.
- dMTO=10nm means 10nm closer to pole.
  - Reducing MTO improves both jitter and DC SNR.
  - Better field angle.
- Reducing media sigma T_c improves jitter and, to a lesser extent, DC SNR.

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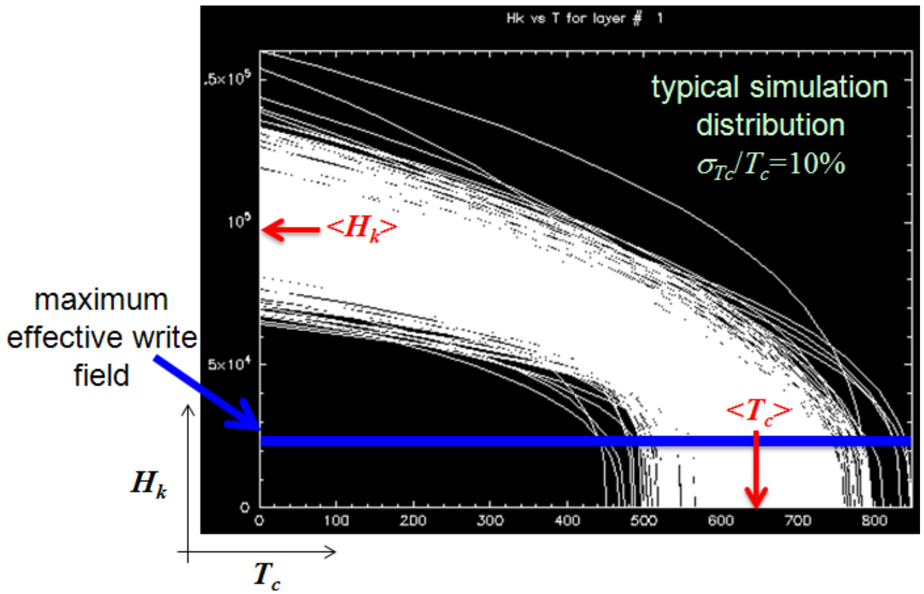
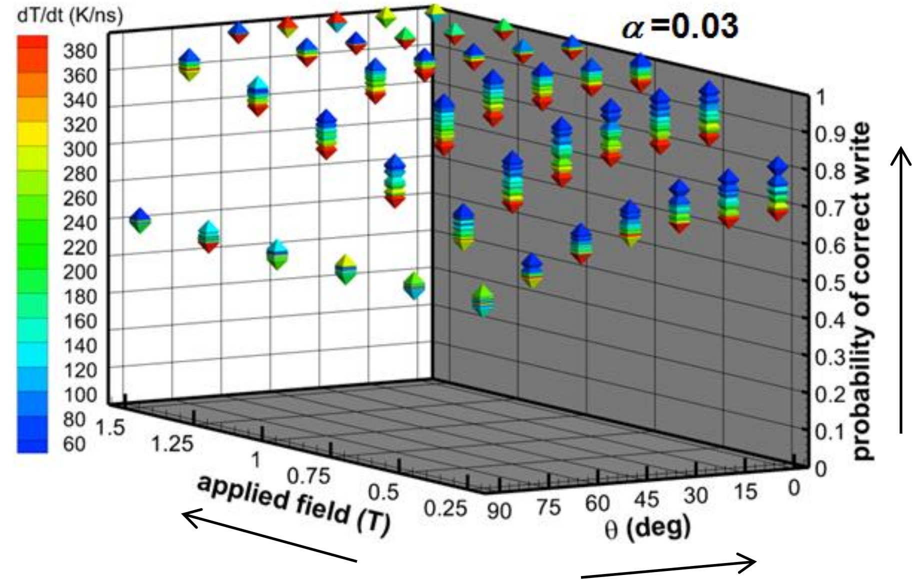
Grain Model and Field Cooling



dT/dt (K/ns)



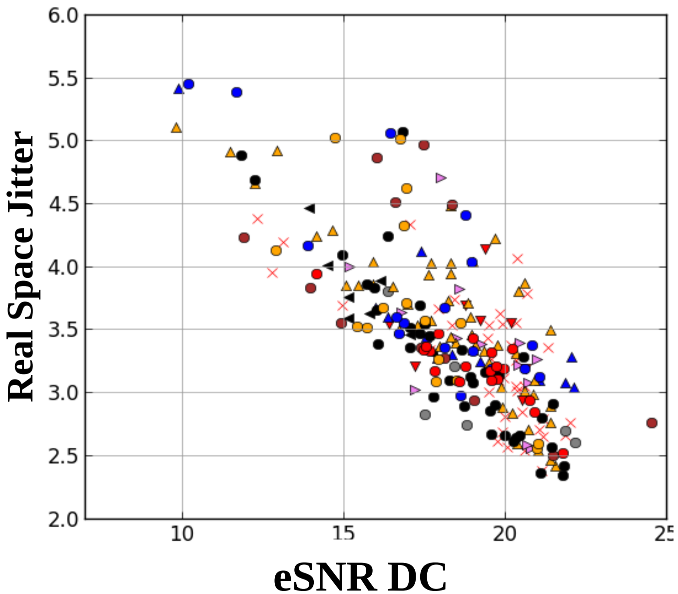
$$\frac{M_s(T)}{M_s(0)} = \left(1 - \frac{T}{T_c}\right)^{\beta} \qquad \frac{H_k(T)}{H_k(0)} = \left(\frac{M_s(T)}{M_s(0)}\right)^{1.1}$$

- β=0.324 for bulk material.
- For atomistic model see:
  - Lyberatos *et al*, JAP 2012.
- Include variation in H_k and T_c.
- **High *dT/dx* at T_c will mask T_c variation.**

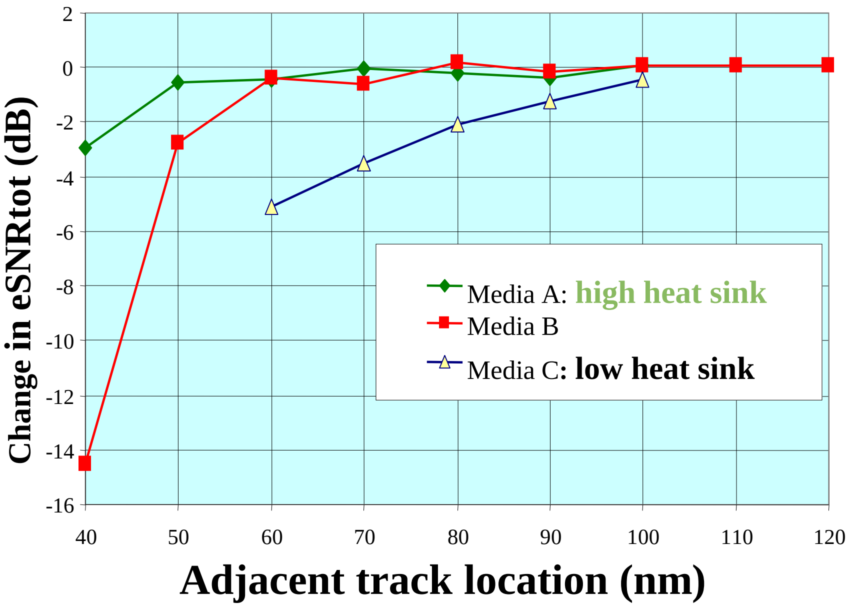
- "LLB-like" model.
- Field cooling:
  - Take all grains above T_c.
  - Apply uniform field.
  - Cool grains at constant *dT/dt*.
- **Field angle, field amplitude, and cooling rate have major impacts on DC noise.**

Jitter, DC SNR, and Squeeze experiments

Data for Various Integrated Heads and Recording Conditions



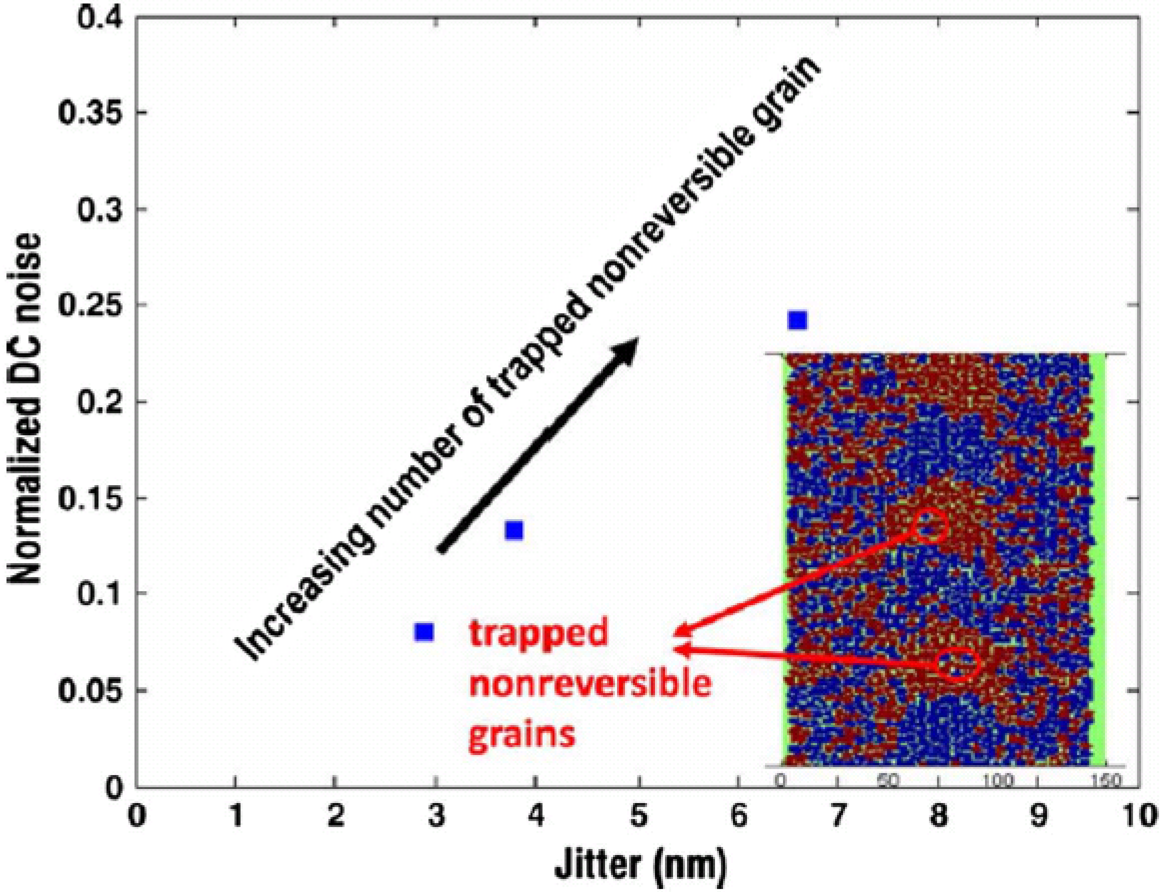
Squeeze vs. Heatsink using an Integrated Head



- Jitter and DC noise tend to be correlated but gradient and sigma T_c mostly affect jitter.
  - **Best jitter still significantly behind PMR**. Easy to match or beat PMR on track pitch.
- **Head:** need high gradient, small **MTO**, high field angle.
- **Media:** need high gradient, columnar grains, low distributions (T_c, H_k, texture …).
- High cross-track gradient for track pitch and low ATI (adj track interference)

MTO=magnetic field temperature offset

DC noise vs jitter (model)



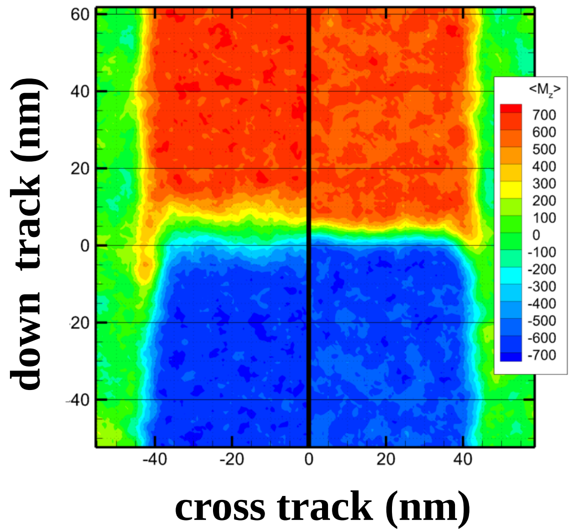
Xiaobin Wang, Kaizhong Gao, Hua Zhou, Amit Itagi, Mike Seigler, Edward Gage, "HAMR Recording Limitations and Extendibility" IEEE Trans Mag. 49, (2013) 686

D. Weller, G. Parker, O. Mosendz, E. Champion, B. Stipe, X. Wang, T. Klemmer, G. Ju, A. Ajan, "A HAMR Media Technology Roadmap to an Areal Density of 4 Tbpsi" IEEE Trans Mag 50 (2014) 3100108

dT/dx gradient and σ_{TC} effect on writing – model + experiments

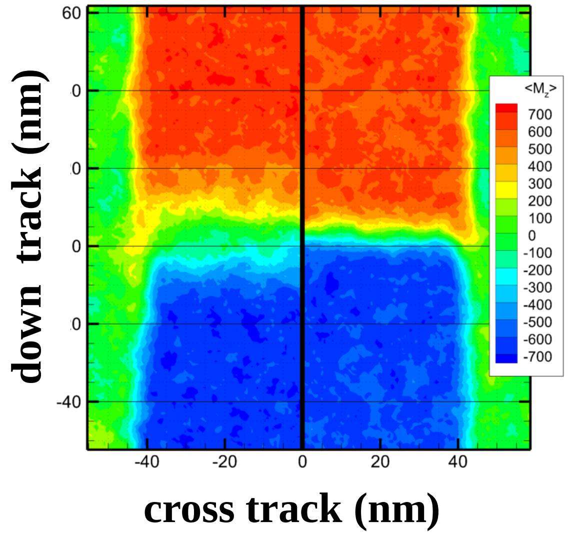
Lower Sigma Tc (2.8%)

3 K/nm 9 K/nm



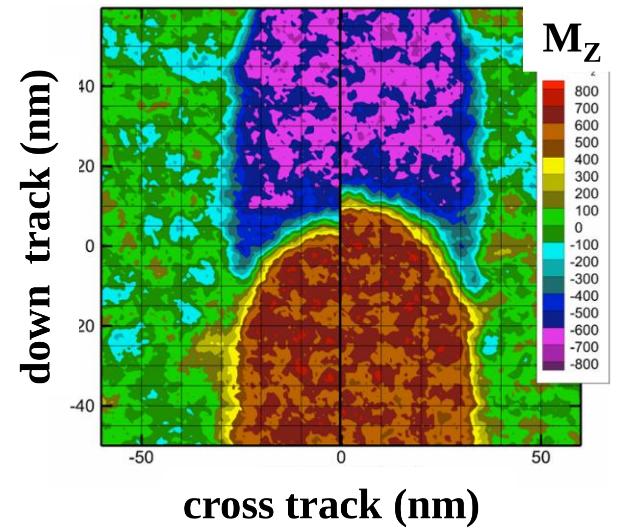
Higher Sigma *Tc* (5.1%)

3 K/nm 9 K/nm

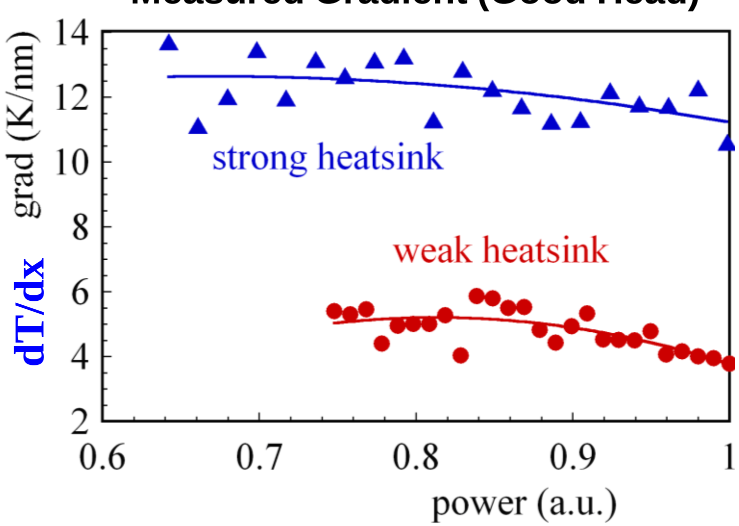


Effect of Power Modulation

P 1.1 x P

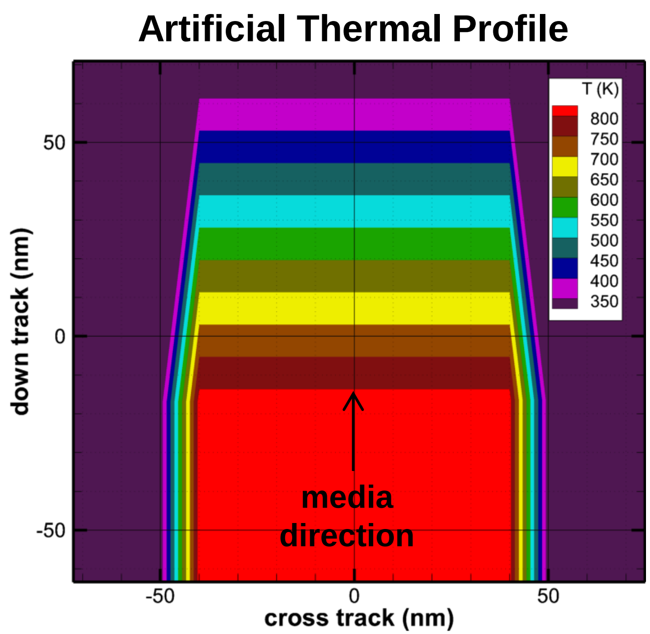


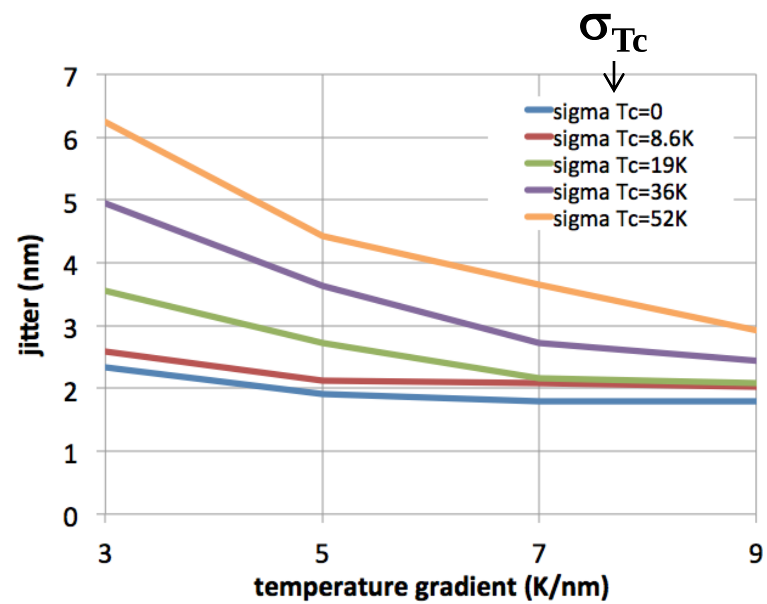
Measured Gradient (Good Head)

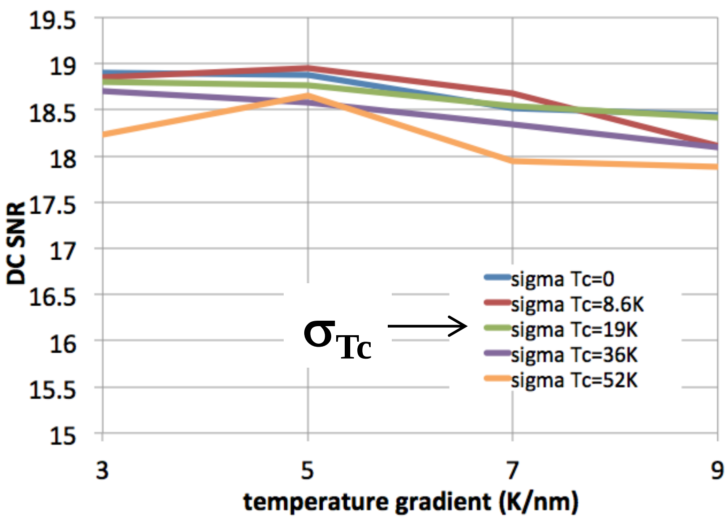


- **Down-track thermal gradient can be determined by transition shift or jitter method.**
  - Cross-track gradient from MWW with assumptions.
- **Gradient is given by: ΔT(write) x power modulation/transition shift.**
- **Media heat-sinking strongly modulates thermal gradients and improves track-squeeze capability without SNR loss.**
- Head degradation reduces gradient significantly.
- **Need both high gradient and low sigma T_c for optimal recording ➔ need to measure sigma T_c.**

Recording Model (simplified) - dT/dx gradient



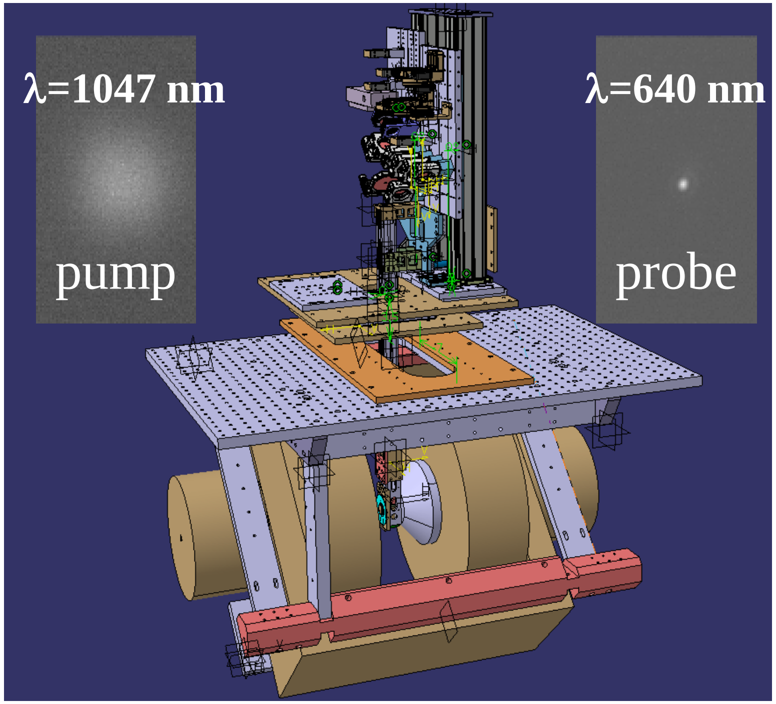




- Simplified writing:
  - **Apply constant themal gradient *dT/dx*.**
  - **Apply uniform write field.**
  - **Switch write field polarity.**
- Perpendicular write field magnitude (7kOe), write field **linear ramp in 0.4 ns** and non-Gaussian T_c - distribution used.
- **Jitter strongly depends on sigma T_c and *dT/dx*.**
- **Smaller effects on DC noise.**

Pulsed Kerr Tool measuring Thermal Remanence

Pulsed Kerr Tool (TRM)



Sigma T_c

Pump: ~65 μm dia (1/e²)
200 Hz pulsed Nd:YLF laser λ=1047 nm

Probe: ~5.5 μm dia (12x smaller)
CW laser λ=640 nm

"**CW**" refers to a **laser** that produces a continuous output beam

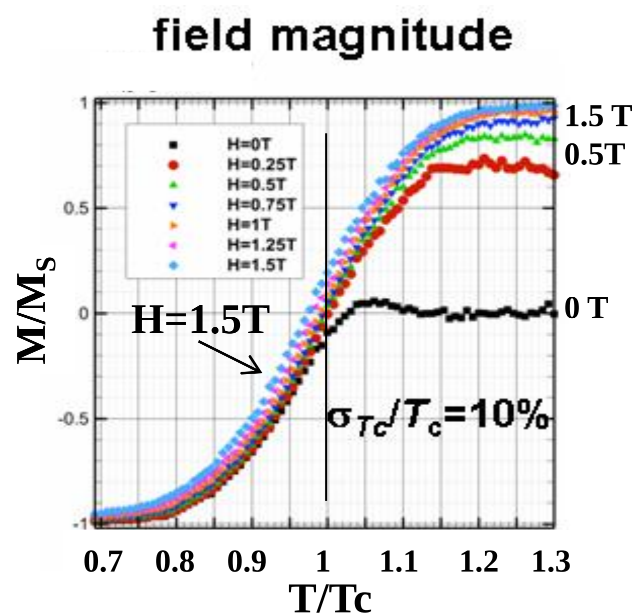
- Tool measures thermal remanence after nanosecond laser pulse in known applied field
  - Short pulse ensures fast cooling and 1D heat flow
- Remanence vs. field and angle can be used to characterize grain freezing effects
- **Remanence vs. pulse power can be used to measure sigma-T_c**

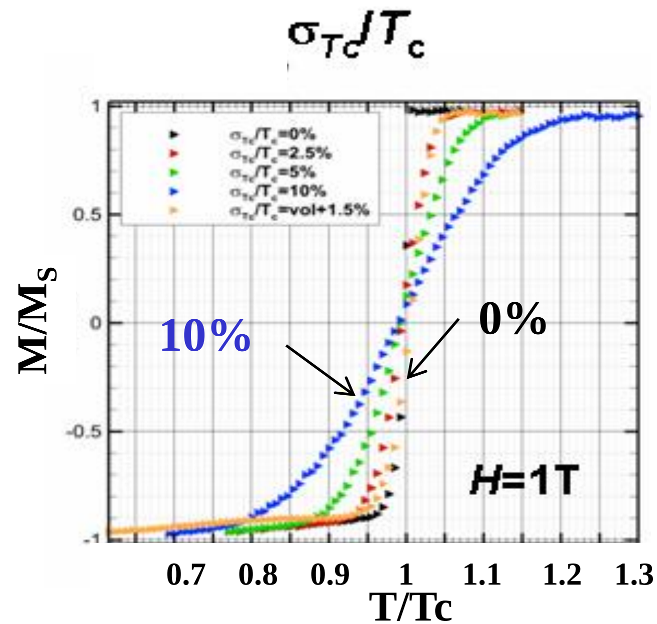
S. Pisana, S. Jain, J.W. Reiner, G.J. Parker, C.C. Poon, O. Hellwig and B.C. Stipe "Measurement of the Curie temperature distribution in FePt granular magnetic media" to be published

Remanence vs. pulse power to measure sigma T_C

modeling

1 ns pump pulse

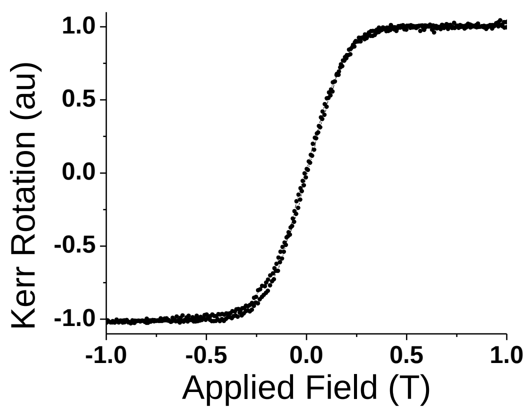


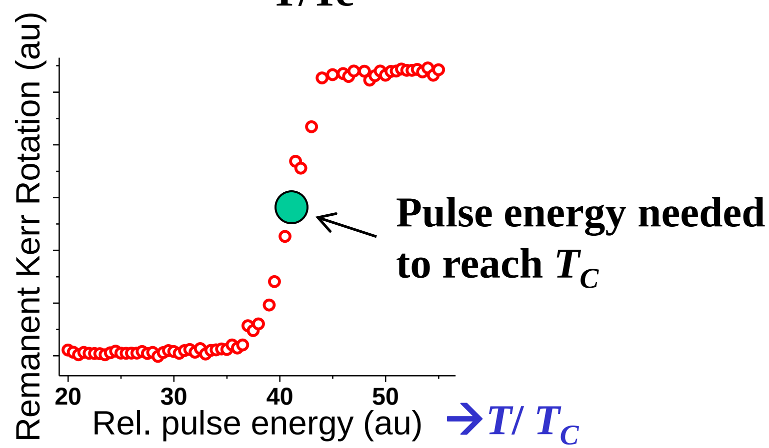


experiments

5 ns pump pulse

measure several ms after pump @ each point

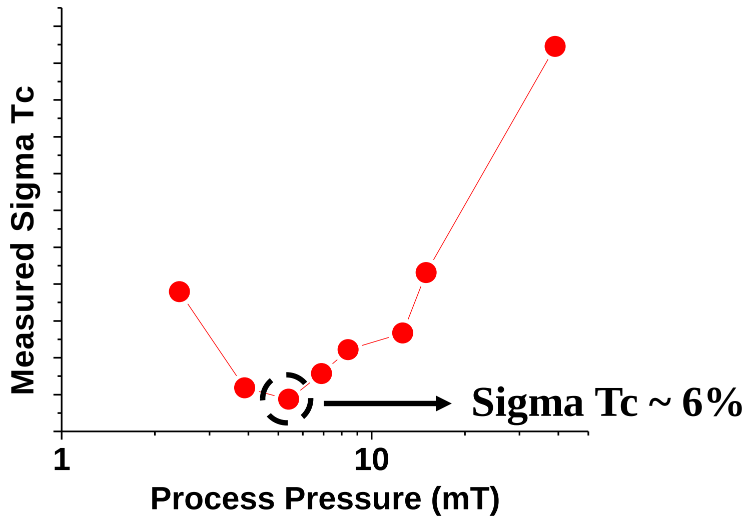




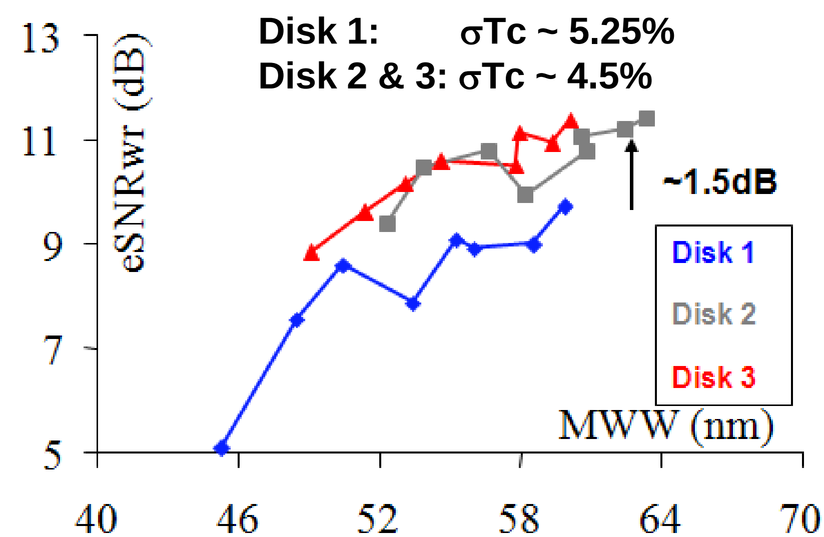
S. Pisana, S. Jain, J.W. Reiner, G.J. Parker, C.C. Poon, O. Hellwig and B.C. Stipe “Measurement of the Curie temperature distribution in FePt granular magnetic media” to be published 2014

Curie Temperature Distribution σ_{TC} and Performance

Sputter Optimization



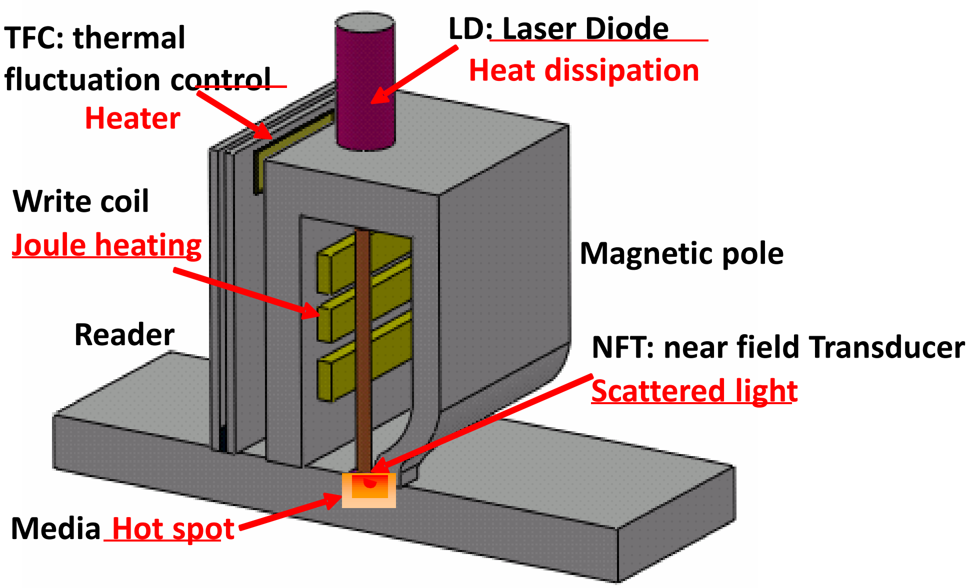
Segregant Optimization

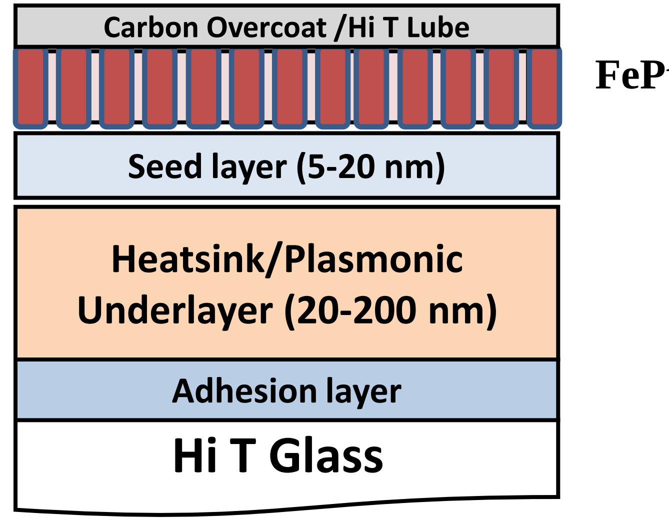


MWW=Magnetic Write Width

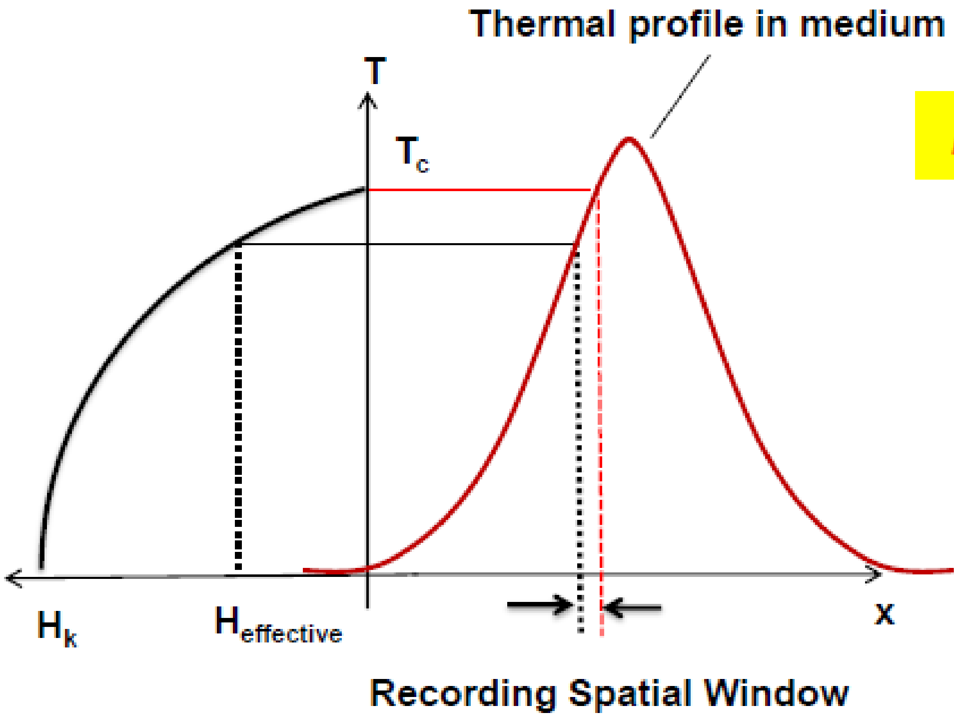
- **Sigma T_c from the Thermal Remanence (TRM) tool can be used to optimize various sputter condition.**
- Measurement of distributions has good correlation with recording performance
- **In the example above only the segregant Y in FePtX-Y was changed**

Recording Time window





1. Chemically ordered and textured $L1_0$ FePtX-Y (001) granular media for high areal density heat-assisted magnetic recording (HAMR)
2. **Thermal design to improve the recording time window down to < 1 ns and the areal density beyond 1Tb/in^2**



Recording Time Window

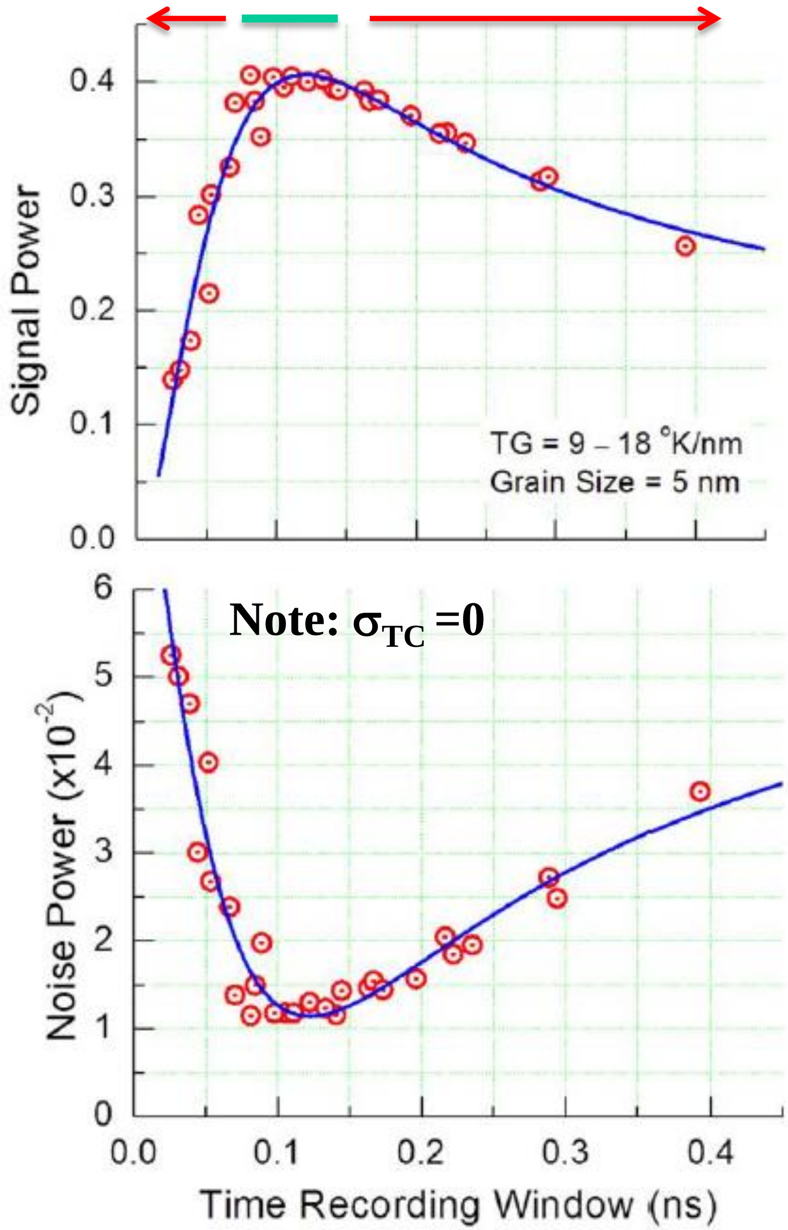
$$\Delta t = \frac{T_c - T_{rec}}{\frac{dT}{dx} \cdot v}$$

A. Lyberatos modeling recently showed that the freezing temperature increases with recording field, therefore the recording time window decreases [1].

Andreas Lyberatos (to be published 2014)

Jian-Gang (Jimmy) Zhu, Hai Li, "Understanding Signal and Noise Dependences in HAMR", IEEE Trans Mag. 49, 765 (2013)

Recording time window needs to be optimized into proper range



•Modeled signal and noise power dependence on recording field amplitude at recording thermal gradients TG: 18 K/nm, 15 K/nm, 12 K/nm, and 9 K/nm.

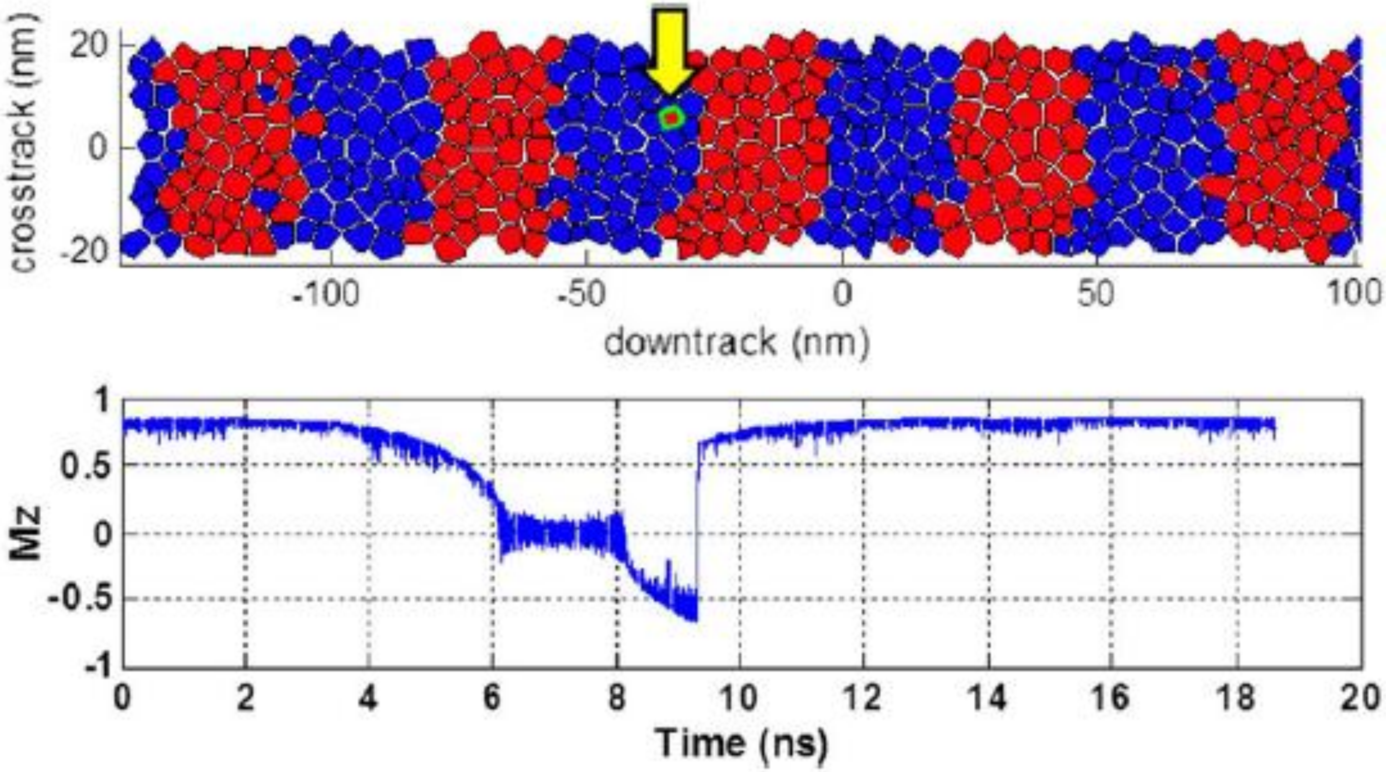
•Tight correlation between signal and noise in the recording time window

•A recording time window narrower or broader than the optimum of 0.1-0.2 ns yields incomplete recording or thermal decay and degrades SNR

• Generally, mechanisms that cause recording time window variation will likely cause media noise

Jian-Gang (Jimmy) Zhu, Hai Li, "Understanding Signal and Noise Dependences in HAMR", IEEE Trans Mag. 49, 765 (2013)

Time evolution of a grain – recorded but reversed later



15 K/nm Thermal gradient; 5 nm avg grain size

Jian-Gang (Jimmy) Zhu, Hai Li, "Understanding Signal and Noise Dependences in HAMR", IEEE Trans Mag. 49, 765 (2013)

Heating-cooling (recording) time window

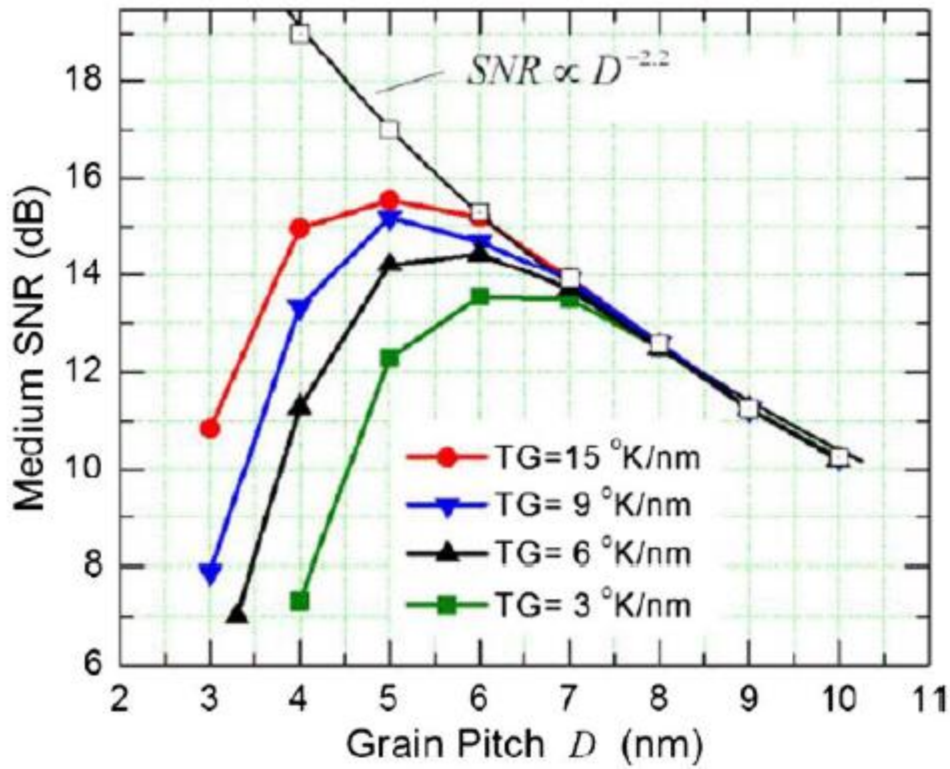
$$\Delta t = \frac{T_C - T_{rec}}{\frac{dT}{dx} \cdot v}$$

	Greg Parker **HGST**	Jimmy Zhu **CMU**
Tc-Trec (K)	40	50
dT/dx	7	15
v (10^9nm/s)	15	20
Δt (ns)	**0.381**	**0.167**
Δt(ps)	381.0	166.7

CMU (Jimmy Zhu) talks about an optimum time window of **Δt ~ 100-200 ps** assuming **dT/dx = 15 K/nm**, $\Delta T = T_c - T_{rec}$ = 50 K and ν = 20 m/s

HGST (Greg Parker) comes up with **Δt ~ 300-400ps** (twice as high) using **dT/dx = 7 K/nm**, $\Delta T = T_c - T_{rec}$ = 40K and ν = 15 m/s

SNR vs grain pitch and thermal gradient



Calculated SNR vs grain pitch D. For each data point, the recording field amplitude is optimized for maximum SNR. The open squares reflect SNR without thermal agitation for recording with thermal gradient TG = 15 K/nm. The read track width is fixed at W = 30 nm. Model assumptions include H_K = 60 kOe, M_S = 750 emu/cc, t = 10 nm, σ_{HK} = 10%, σ_{Tc} = 0% and $dH_K/dT \sim 600$ Oe/K.

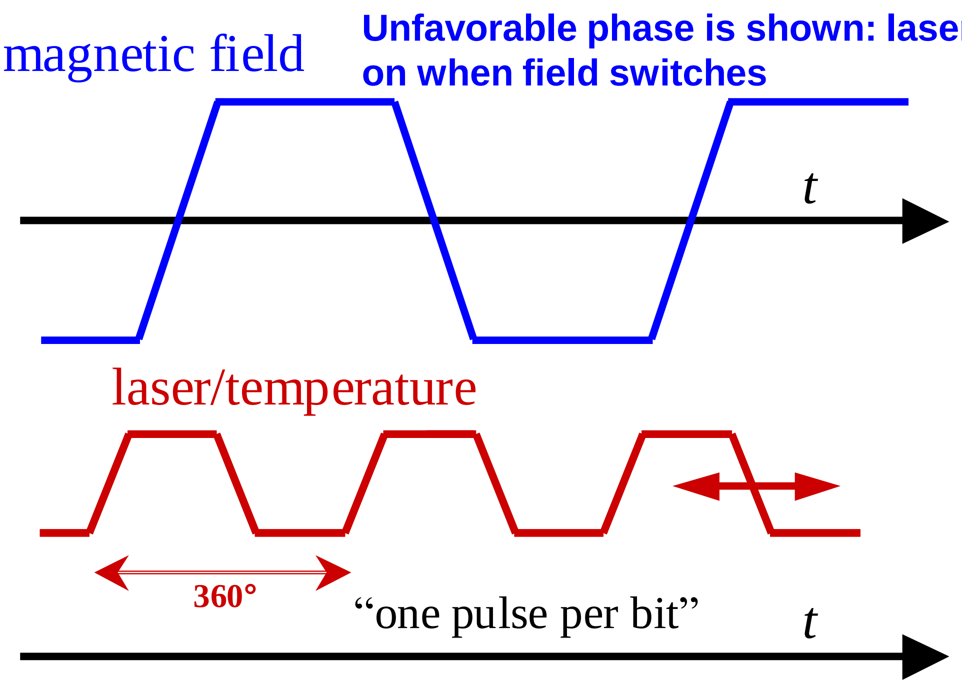
Jian-Gang Zhu and Hai Li, "Understanding Signal and Noise in HAMR" IEEE Trans Mag 49, 765 (2013)
D. Weller, G. Parker, O. Mosendz, E. Champion, B. Stipe, X. Wang, T. Klemmer, G. Ju, A. Ajan, "A HAMR Media Technology Roadmap to an Areal Density of 4 Tbpsi" IEEE Trans Mag 50, 3100108 (2014)

Pulsing the Laser in HAMR Recording

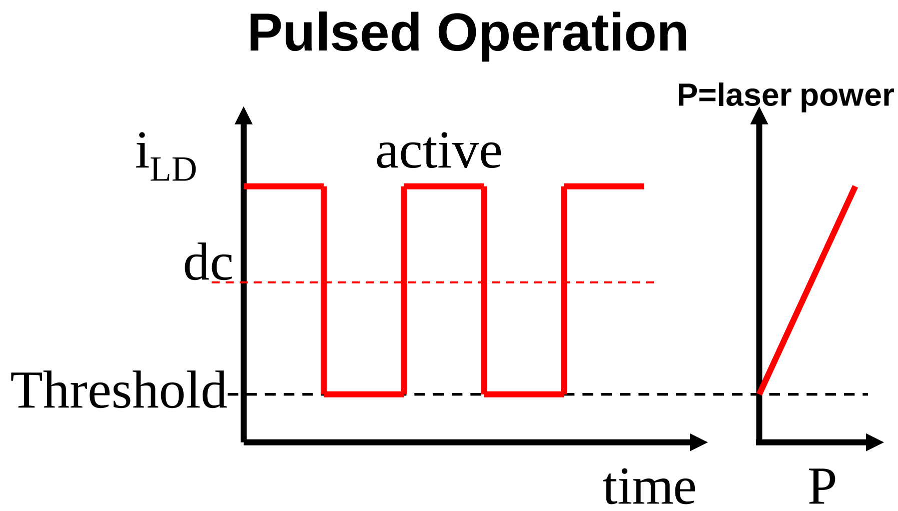
- **Why Pulsing?**
- **Reason #1**
  - **Laser only switched on when needed**
  - **Can lead to lower mean temperatures of the NFT => longer head life**
    - **Head life is a known problem for HAMR**
- **Reason #2:**
  - **Increased temperature gradient can lead to improved recording performance**
- **Pulsed operation means that the laser power modulation is deep – the laser is switched off**

Yiming Wang et al, "Pulsed Thermally Assisted Magnetic Recording" *IEEE Trans. Magn*. 49, 739 **(2013)** **(Headway)**

HAMR Recording with Pulsed Laser Operation



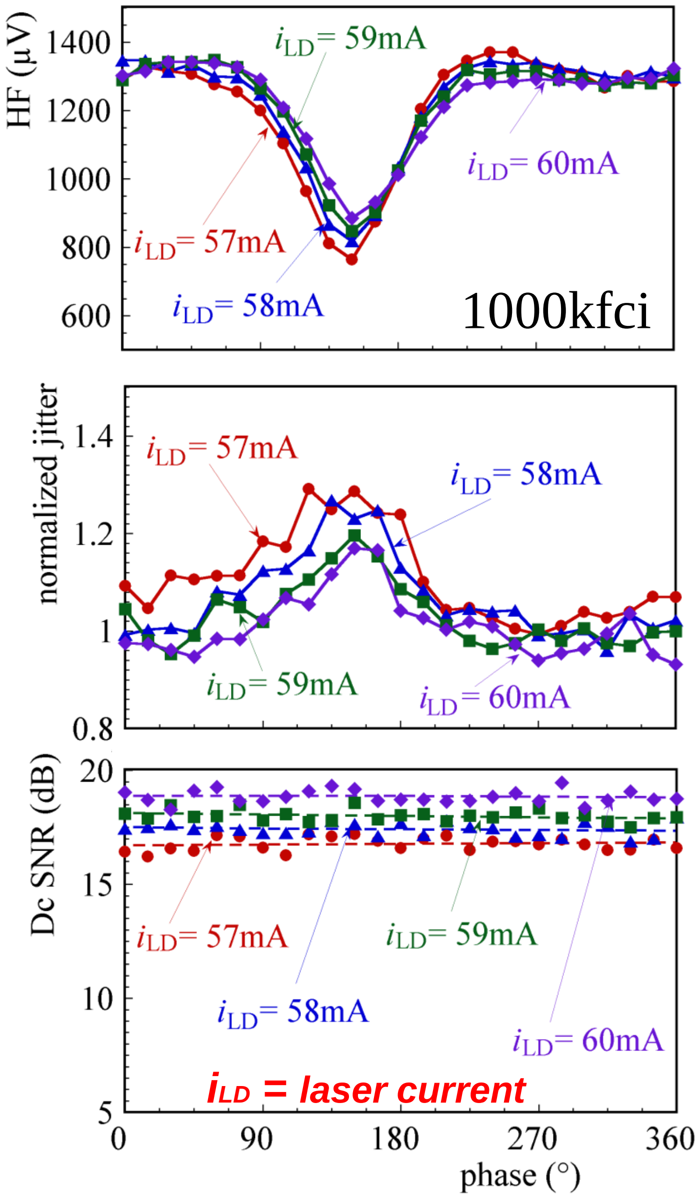
i_{LD}=threshold current the laser needs to turn on



- **Pulsed laser operation is an alternative scheme for HAMR recording**
- **In this case the laser is pulsed synchronously with the writing clock such that there is one laser pulse per bit**
  - **The phase between write clock and laser clock has to be controlled**
- **Pulsing decreases the time window available for recording**

H.J. Richter, G. Parker, M. Staffaroni, B.C. Stipe, "Heat Assisted Magnetic Recording with Laser Pulsing" IEEE Trans Mag **(2014)**

Effect of Laser Pulsing on Recording Performance Experiments

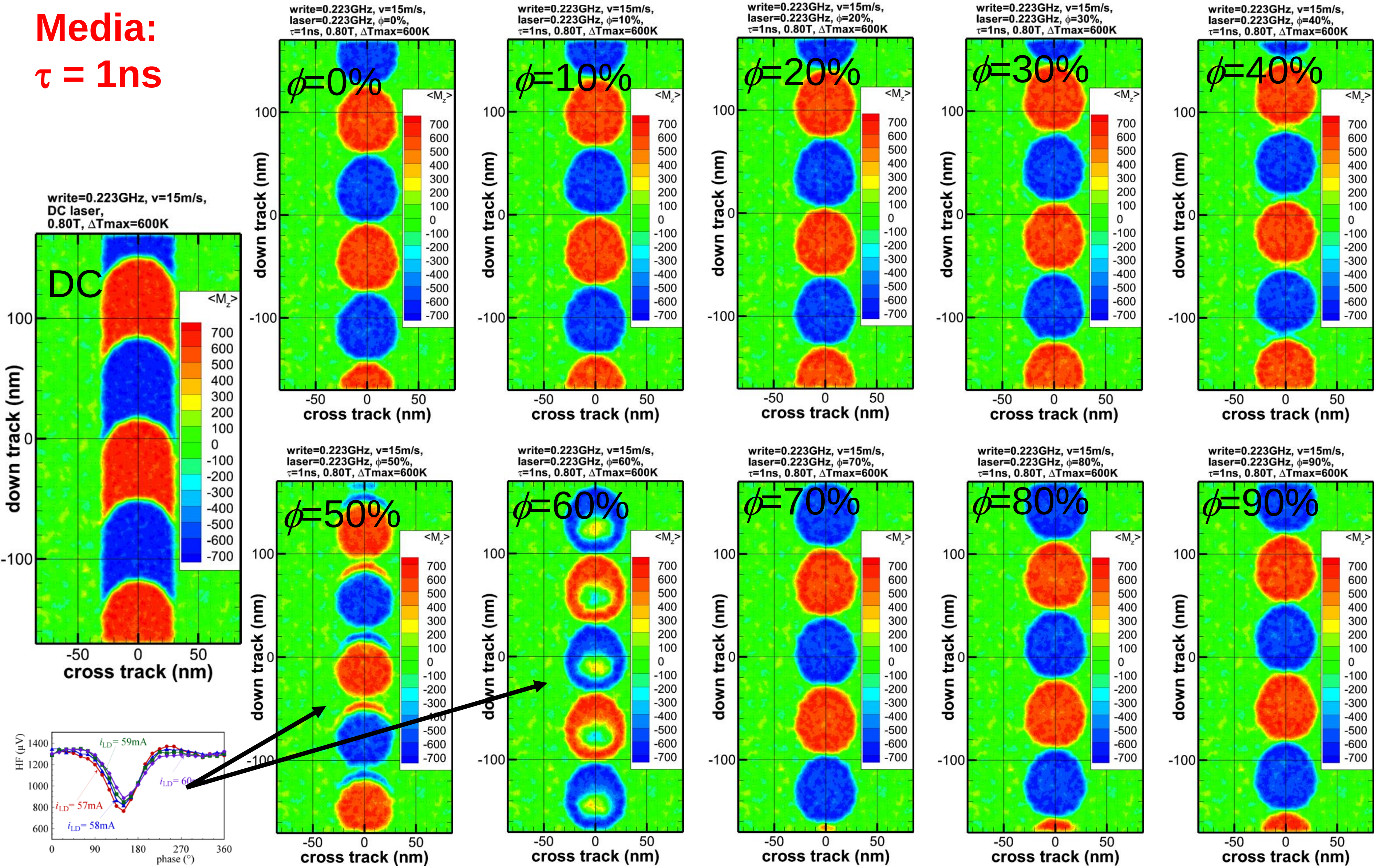


- **High frequency amplitude (HF) shows a dip**
- **The jitter deteriorates when the phase between the write field and the laser pulse is not optimized**
- **DC SNR is not affected by phase**
  - **(Note: multiple pulses per "long bit")**
  - **Confirms that phase of laser pulses affect only transitions**

H.J. Richter, G. Parker, M. Staffaroni, B.C. Stipe, "Heat Assisted Magnetic Recording with Laser Pulsing" IEEE Trans Mag **(2014)**

Micromagnetic Modeling of Phase Effect of HAMR w/ Pulsing

Media:
τ = 1ns



Key HAMR Media Requirements for AD > 1.5 Tbpsi

Areal Density (Tb/in^2)	2	4
KTPI	700	1155
KBPI	2800	3464
BAR	4	3
thermal gradient @ writing (K/nm)	14	18
D_p center to center (nm)	7.0	5.1
D core (nm)	6.0	4.3
σ / mean grain diameter	0.1-0.15	0.1-0.15
M_S film (emu/cm^3) (300 K)	700	800
M_S core (emu/cm^3)	875	1000
K_u (erg/cm^3) (300 K)	3.50E+07	5.00E+07
H_K (kOe) (300 K)	80	100
σ_{HK}/H_K (%)	5.0-10.0	5.0-10.0
T_C (K)	<=750	700 - 750
σ_{Tc}/T_C (%)	2.0	2.0
σ_θ (deg)	2.0	0.8
media thickness (nm)	9	8.2
thickness / grain size ratio	1.29	1.60
SUL requirement	yes	yes
jitter (nm)	1.55	1.43
jitter / bit length (%)	17.1	19.5
grains / bit	6.7	6.2
grains / read width	4.0	3.7

1+ Tbpsi has been achieved by Seagate

Industry focuses on solving key issues going forward

ASTC 2012

D. Weller, G. Parker, O. Mosendz, E. Champion, B. Stipe, X. Wang, T. Klemmer, G. Ju, A. Ajan
"A HAMR Media Technology Roadmap to an Areal Density of 4 Tbpsi"
HGST, Western Digital & Seagate
IEEE Trans Mag 50, 3100108 (2014)

MEDIA CHALLENGES	KEY ISSUES	POSSIBLE SOLUTIONS	IMPORTANT RESEARCH PROJECTS
Curie temperature distribution	low σ_{Tc}/Tc ~ 2% requirement	improved sputter conditions, seed layers, growth temperature and optimized exchange coupling	new characterization techniques, correlation of σ_{Tc}/Tc with grain size distribution
grain size and shape control	grain size fluctuations causing Curie temperature distributions, effective writeability and bit definition	improved seedlayers, optimized deposition conditions, propergrain segregants	alternative FePt texture layers
3-5 nm grains at high areal density	increased switching field and grain size distributions	controlled and improved strain and surface anisotropy	density functional and atomistic calculations of the effect of increasing surface/volume ratio on Tc and Ku
thermal design and control for AD>3Tb/in^2	effective thermal gradient and delivery of energy to FePt, achieving sufficient SNR	using high thermal conductivity heat sinks (HS) and/or plasmonic underlayers (PUL)	thermal-electomagnetic multiphysics modeling of near field transducers (NFT) and plasmonic underlayers (PUL)
grain morphology	control of the mean and distribution of grain size and thickness/diameter aspect ratio, columnarity, grain boundary width and roughness	improved segregants, alloys, alloy stacks, well textured underlayers, optimized growth rate etc.	FePtX-Y with new alloy components X and segregants Y, multiple layer structures and new seed layers with proper (200) orientation
dc noise reduction	rapid thermal cooling leading to incomplete magnetization reversal, dc noise affecting high data rate	optimize high data rate (short cooling time), single and multiple layers and thicker media with proper texture and orientation	DC noise model based on Tc and grain size distributions

Summary and Future Statements

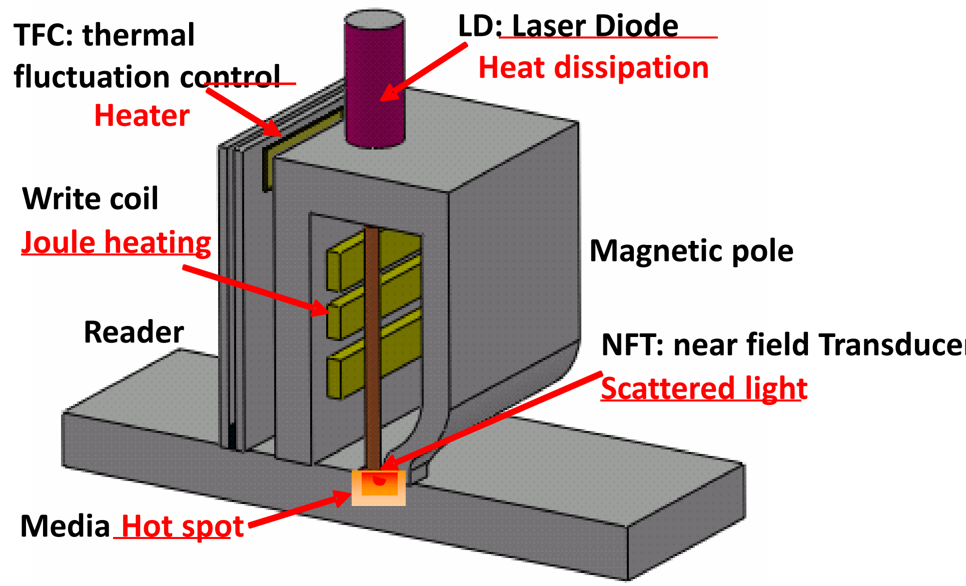
A better understanding of HAMR recording has been achieved
- much improved granular $L1_O$ FePtX-Y media
- better heads and optimized recording time ~1ns aiming toward ~0.2-0.4 ns
- many challenges are focused on

The main goal remains to extend the Areal Density beyond 1 Tb/in^2

Seagate expects to start selling HAMR drives in 2016, Chief Technology Officer Mark Re said (Oct 1, 2013)

The technology is very, very difficult, and there has been a lot of skepticism if it will ever make it into commercial products, said IDC's John Rydning, adding that the consensus in the HDD industry seems to be that HAMR won't ship before 2017 (IDC = International Data Corporation)

THANK YOU



"HAMR is a refreshing change from predictability. Quite a roller-coaster ride." – Chris Rea (Seagate)

Other slides

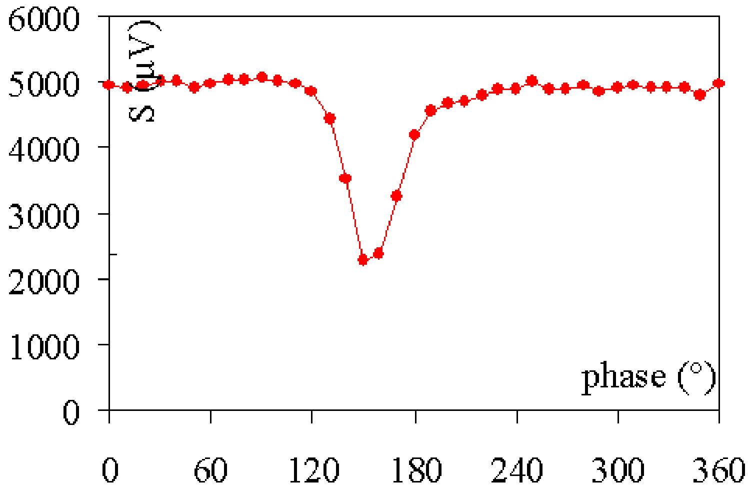
Abbreviations

LMR: Longitudinal Magnetic Recording
PMR: Perpendicular Magnetic Recording
HAMR: Heat Assisted Magnetic Recording
TEM: Transmission Electron Spectroscopy
NFT: Near Field Transducer
LD: Laser Diode
TFC: Thermal Fluctuation Control
ATI: Adjacent Track Interference
MTO: Magnetic to Thermal Offset
NVM: Non Volatile Memory
LLB: Landau Lifschitz Bloch
Voronoi: A V-diagram is an ordered list of elements (tuple of cells)

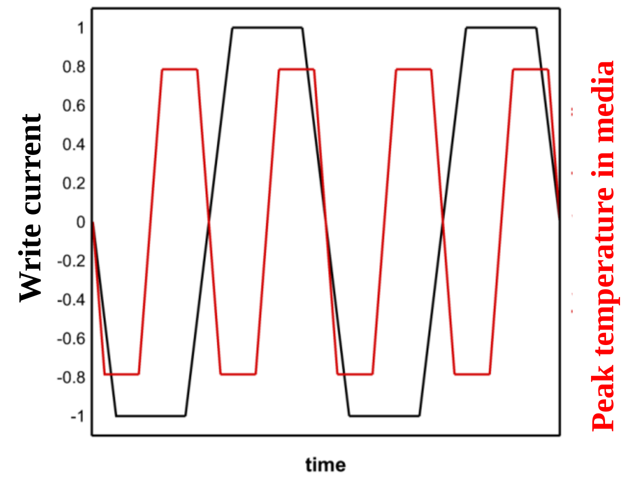
CMU: Carnegie Mellow University
ASTC: Advanced Storage Technology Consortium
IDEMA: International Disk Drive Equipment and Materials Association

Pulsed Recording on Spinstand – Phase Dependence Summary

Signal vs. Pulse Phase on Spinstand

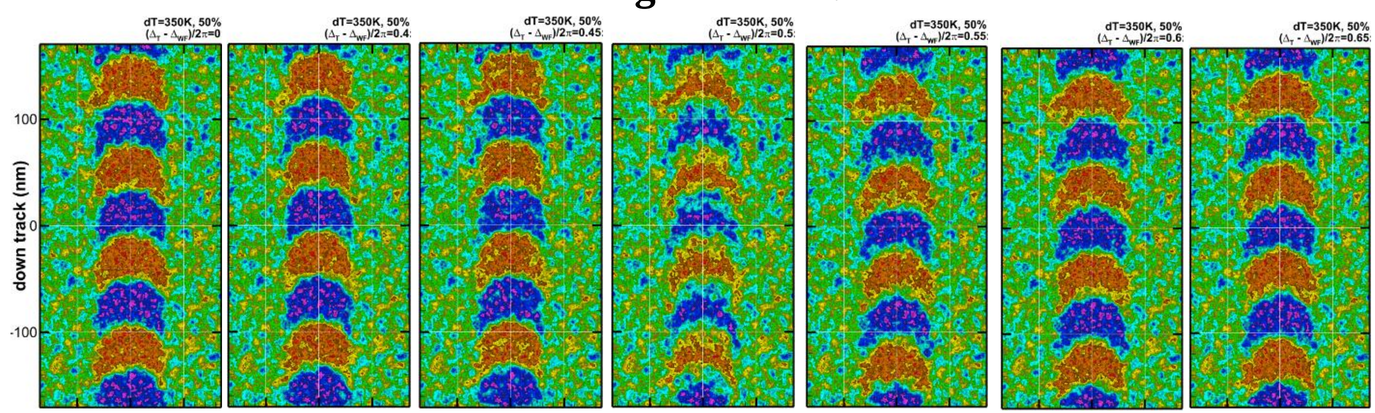


Timing for Worst Recording



Media:
τ = 1ns

Recording Model vs. Phase



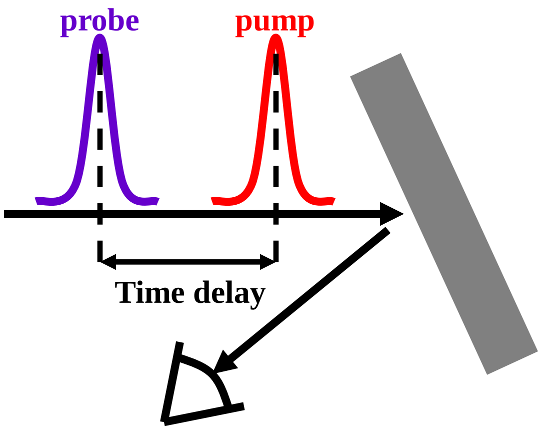
- **Poor recording occurs if grains freeze while applied field is slewing through zero.**
- **Also need to optimize frequency and pulse parameters for best recording.**

Thermal properties by time-domain thermoreflectance

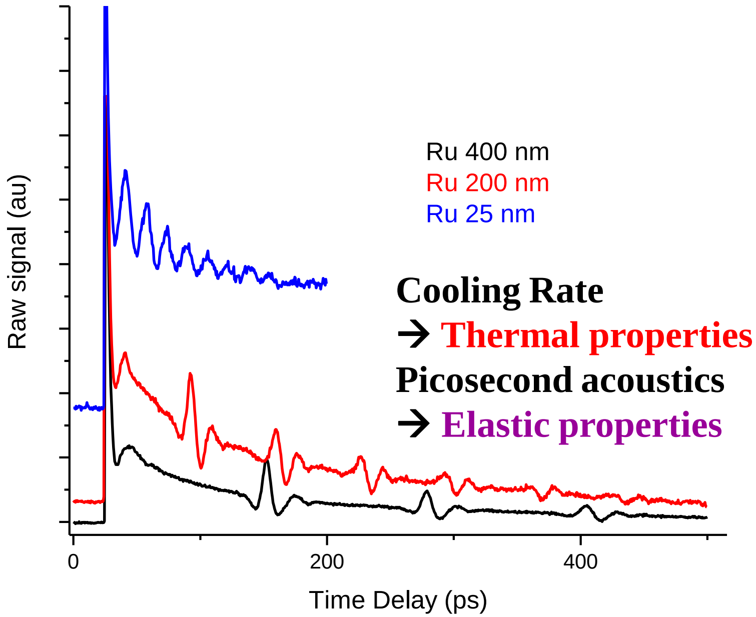
- **Measure cooling rate of the sample after a heat pulse**
- **Temperature measurement made by thermoreflectance**

$$\frac{\Delta R}{R} = \frac{1}{R}\frac{\partial R}{\partial T}\Delta T = C_{TR}\Delta T$$

- **Heat pulse provided by ultrafast laser pulse (~300 fs)**
- **Reflectance measured by a probe laser beam with ps resolution as function of time delay**



Time Domain Thermo-Reflectance Traces

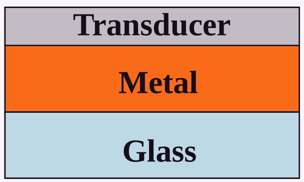


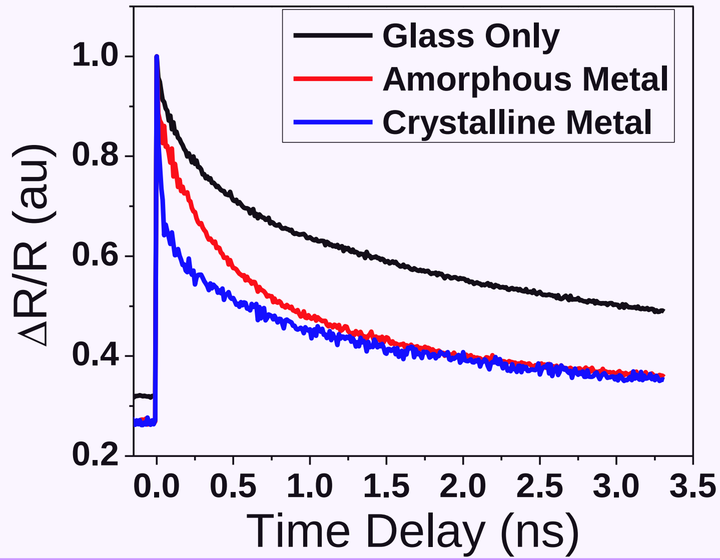
- **The technique is the most versatile for thin films**
- **Works for metals and dielectrics and multilayers**
- **Can quantify thermal conductivity Λ and interface thermal boundary conductance G**
- **Can be adapted to measure thermal anisotropy – normal sensitivity is out-of-plane**

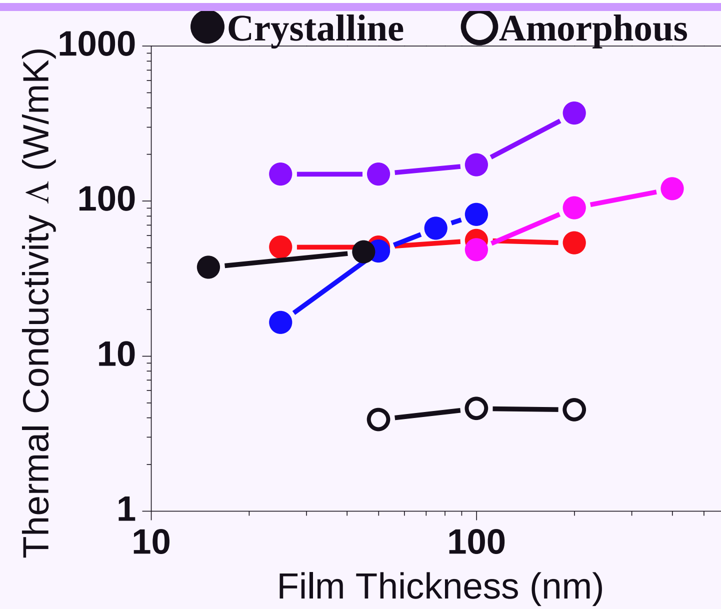
D.G. Cahill, Rev. Sci. Instrum. 75, 5119 (2004)
A.J. Schmidt et al, Rev. Sci. Instrum. 79, 114902 (2008)
P.E. Hopkins et al., J. Heat Transfer 132, 081302 (2010)

Thermal properties by time-domain thermoreflectance

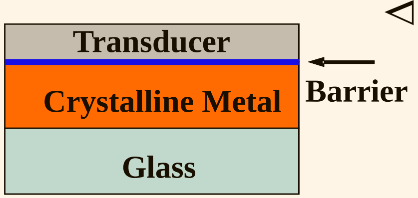
Determination of Thermal Conductivity Λ

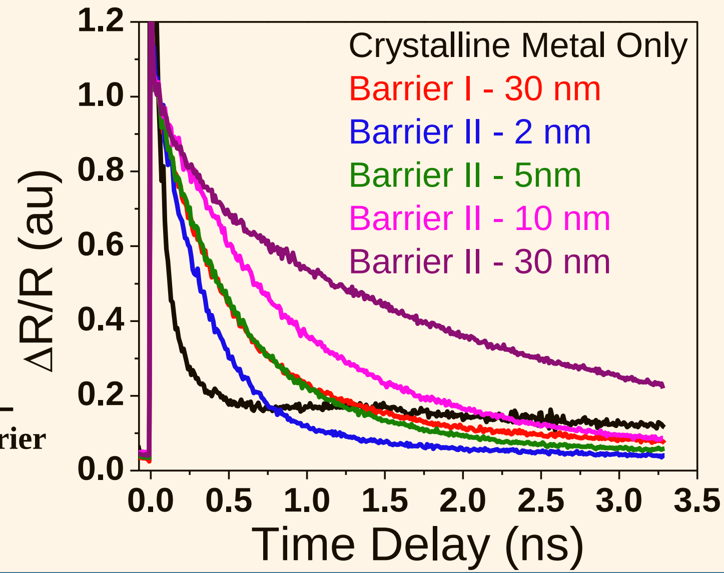


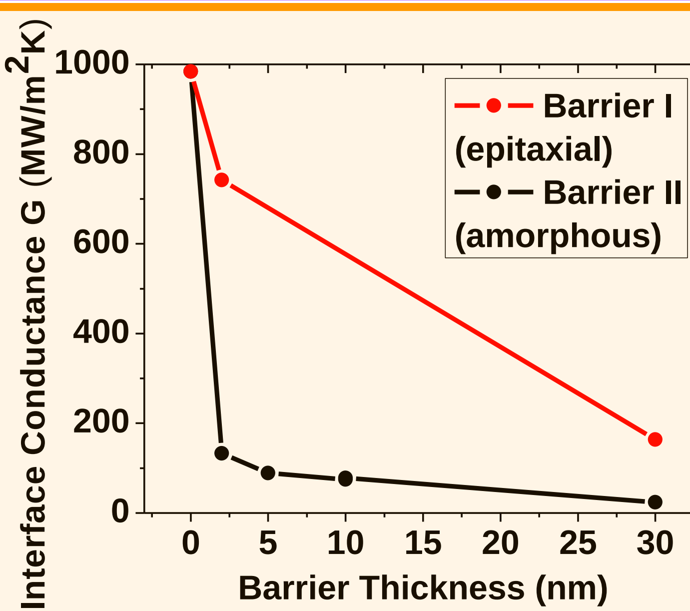




Determination of Interface Thermal Conductance G

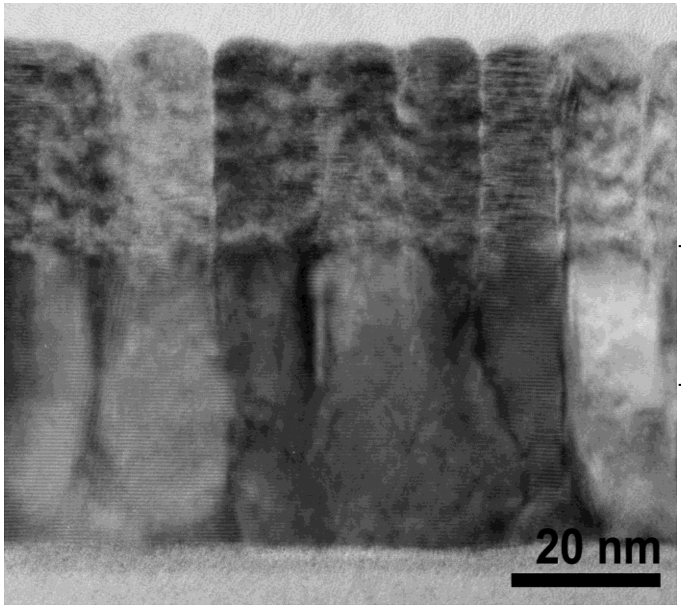






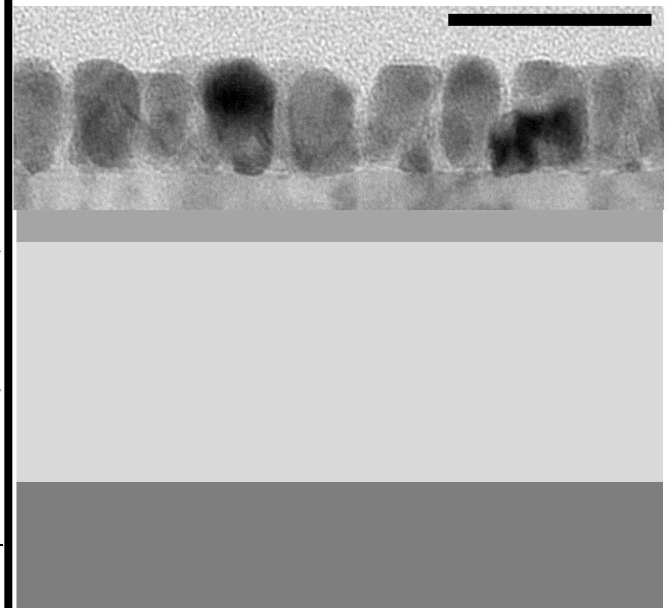
PMR versus HAMR media structure

PMR-media



- all RT deposition process
- minimum level of inter-diffusion
- step by step structure built up
  - grain orientation
  - grain size
  - grain isolation

HAMR-media

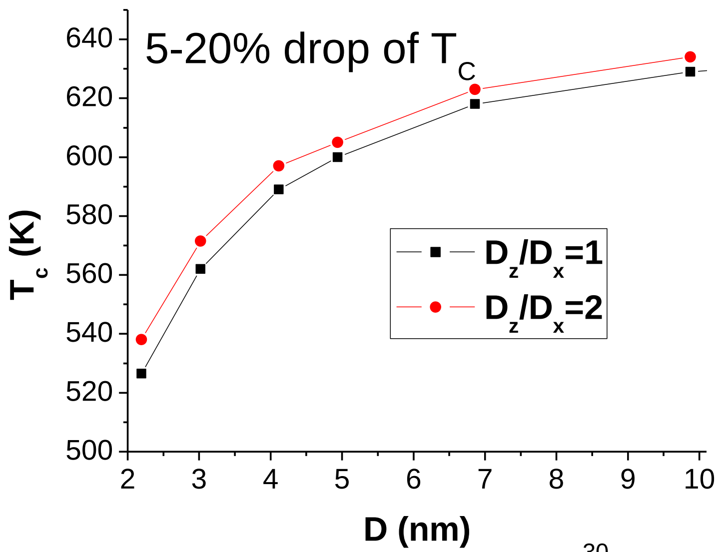


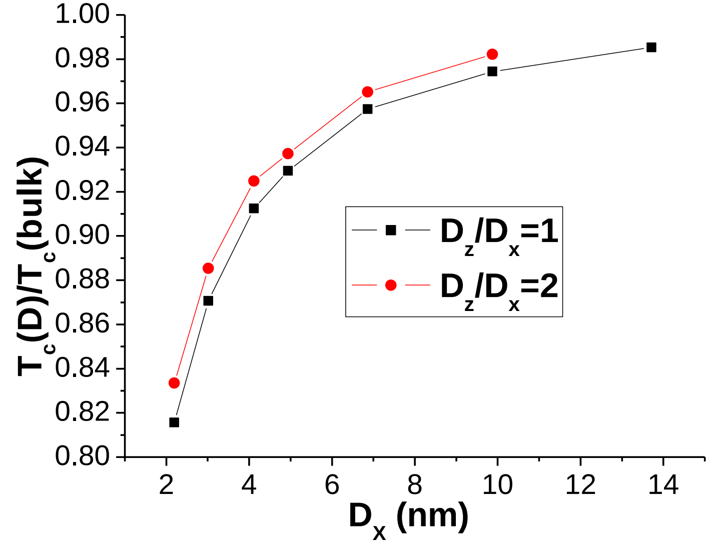
crucial interface: seed ➔ FePt grains

- RT ➔ high temperature (L1_0-order)
- oxide ➔ metal grains in segregant matrix
- continuous grains ➔ isolated grains
- epitaxy sets grain orientation, easy axis
- thermal contact sets grain cooling rate

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, …

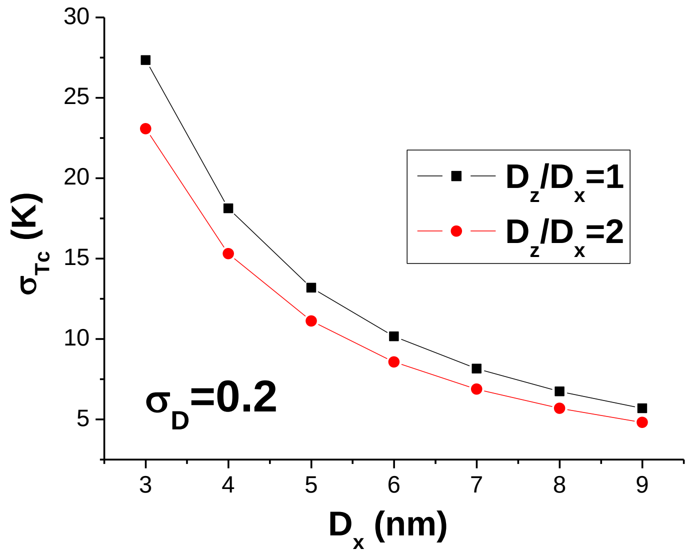
Andreas Lyberatos Modeling - 2012 & 2013





D=8nm → σ_{Tc}~1%
D=4nm → σ_{Tc}~2.5%

Key statement:
Reducing D increases σ_{Tc}
Need to reduce σ_D



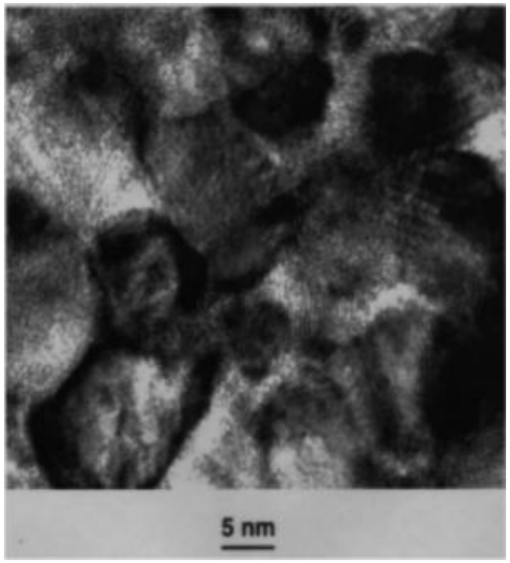
Modeling details (see papers*)

$\sigma=T_{cxo}/n*D_x/a$^(-1/n)*σ_L
$D_z/D_x=1$, $x_o=2.37$, $n=0.7$
$D_z/D_x=2$, $x_o=2$, $n=0.7$
$T_c=750K$, $\sigma_L=0.2$

*A. Lyberatos, D. Weller, G. Parker, B.C. Stipe, "Size dependence of Tc of $L1_0$-FePt nanoparticles" J. Appl. Phys.. 112, 113915 (2012)
*A. Lyberatos, D.Weller, G. Parker, "Finite size effects in $L1_0$-FePt nanoparticles" J. Appl. Phys.114, 233904 (2013)

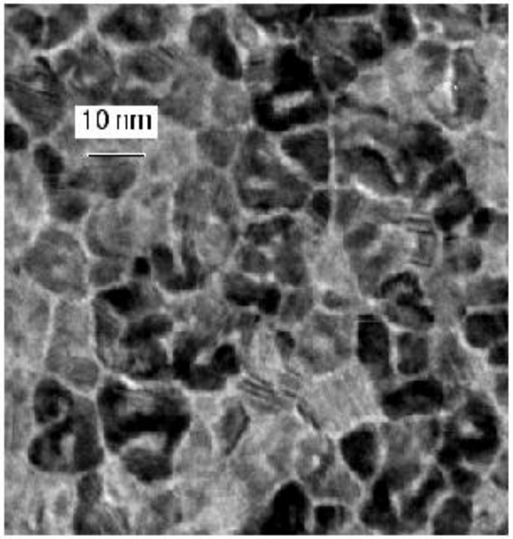
Background: CoCrPt based LMR → PMR media

1990 LMR



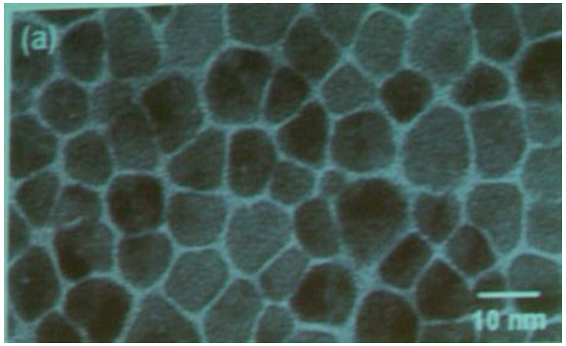
10 Gb/in² product media grains, σ_{area} ~ 0.9

2000 LMR



35 Gb/in² prototype media 8.5 nm grains, σ_{area} ~ 0.6

2012 PMR



750 Gb/in² prototype media 12 nm 8.5 nm grains, σ_{area} ~ 0.36

TEM images of progress in CoCrPtX granular media in longitudinal (LMR) and perpendicular magnetic recording (PMR)

Current product densities are ~ 700-750 Gb/in²