# 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**

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## San Jose – January 21, 2014

# Topics

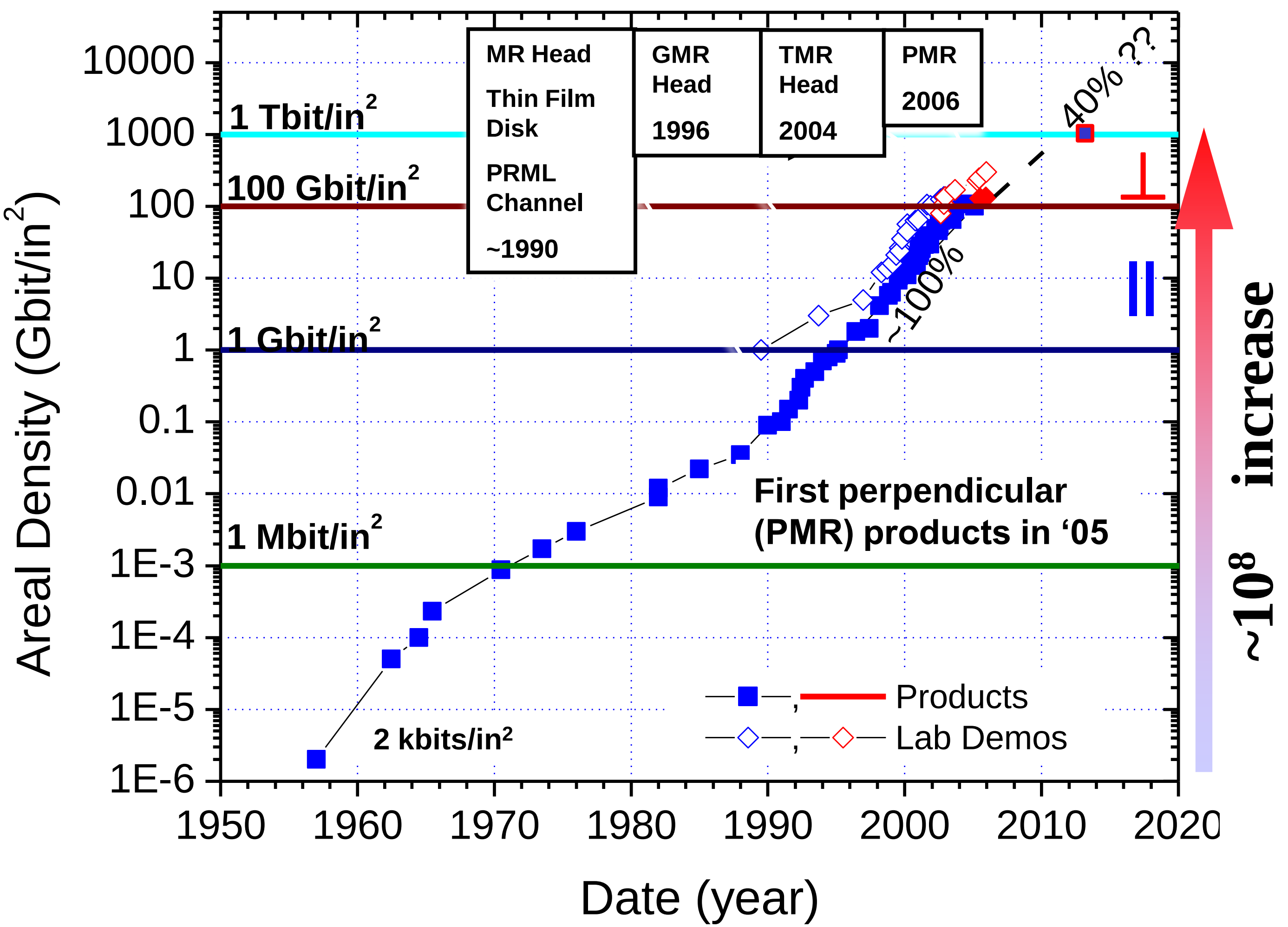
- **Introduction**
  - **Magnetic Recording Media background**
- **Chemically ordered $L1_0$ FePt media**
  - **Status and ongoing efforts**
  - **Key media parameters and requirements**
- **Thermal design**
  - **Recording time window**
  - **Modeling & Experiments**
- **Summary**
  - **Media Challenges**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

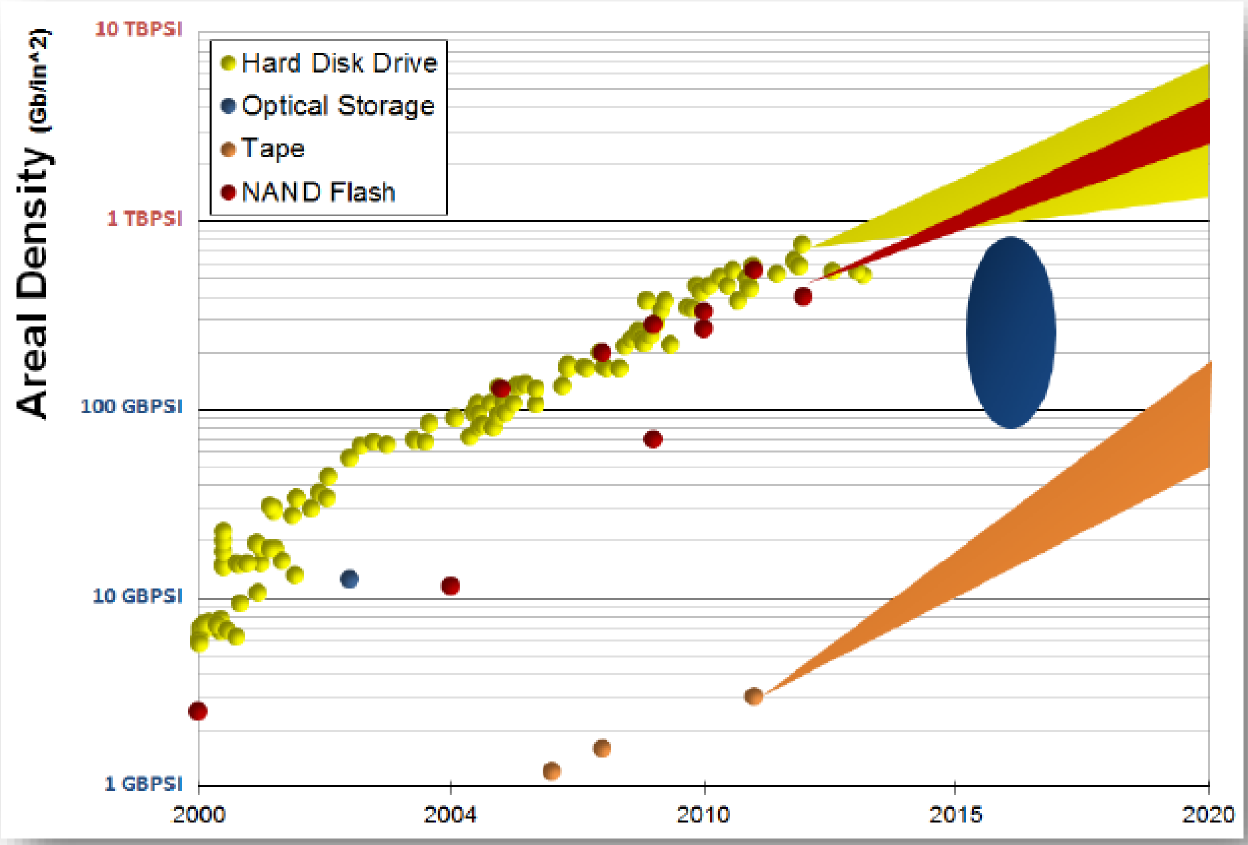
**Next Technology Transitions are hard**

## Hard Drive
***10% - 40% Growth Expected***

## Optical
Not clear on 4th Gen Technology

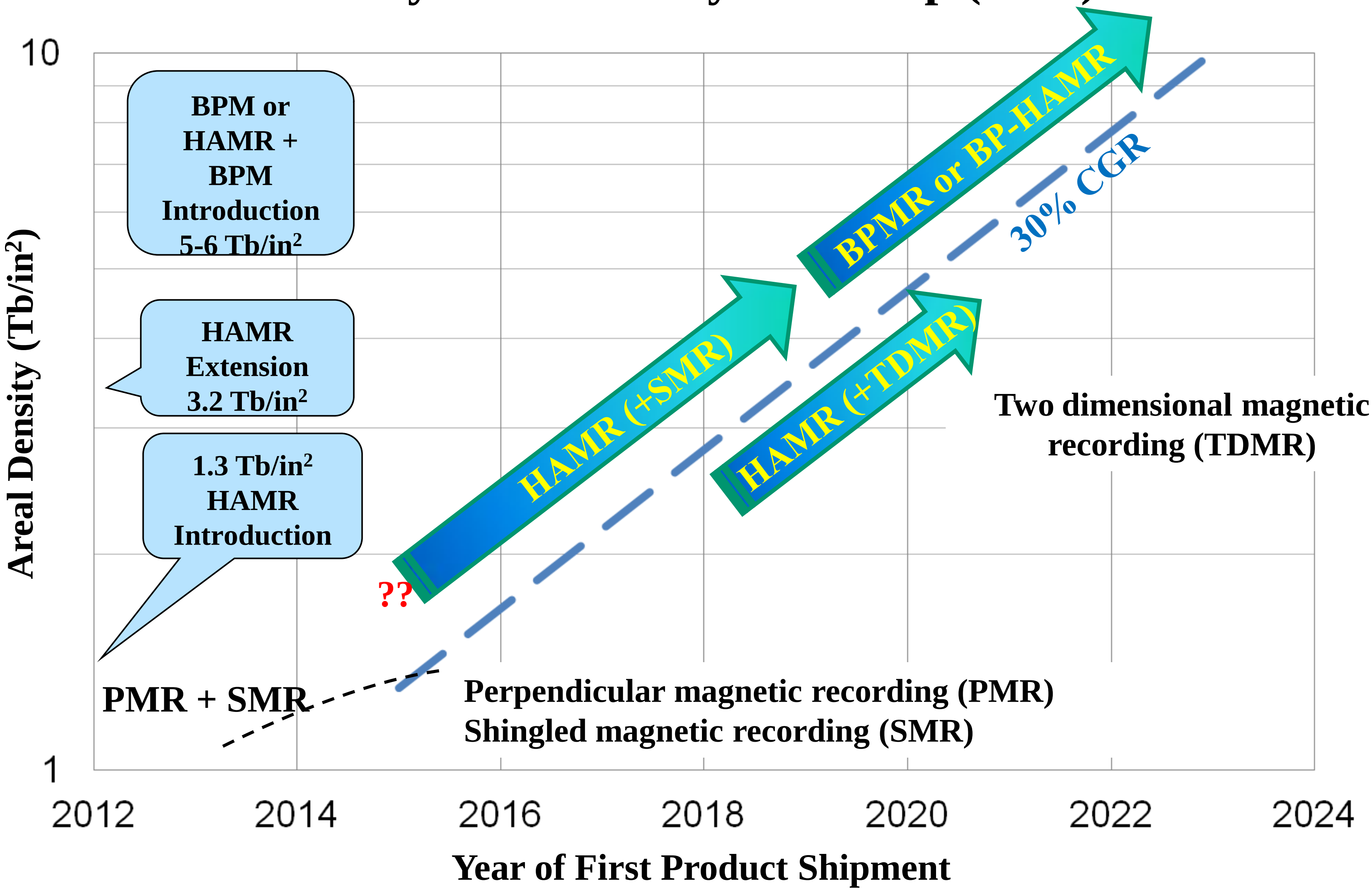
## Tape
***40% - 80% Growth Expected***

## Flash = SSD
***20% - 40% Growth Expected***

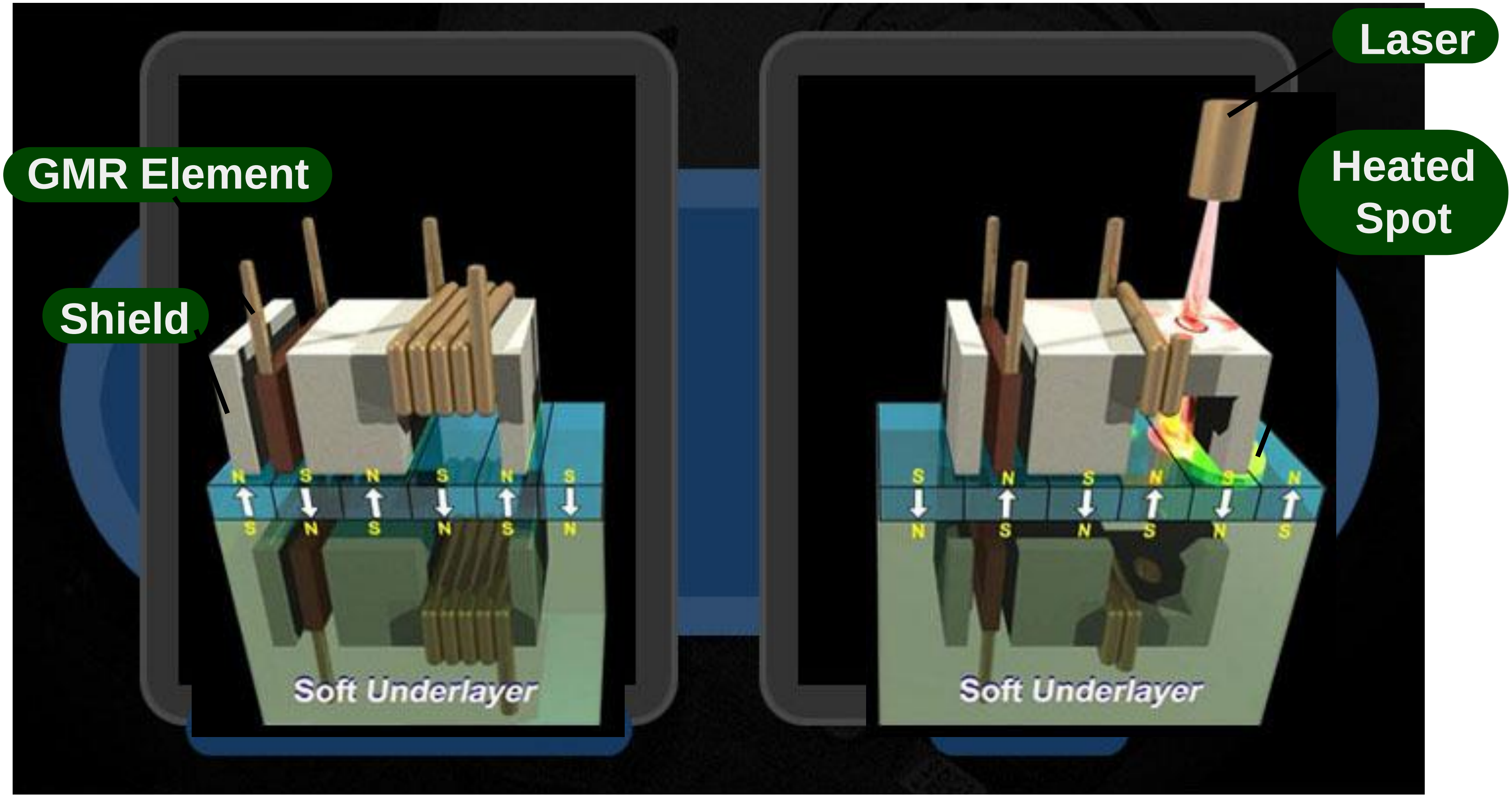



**Notes:**
Flash growth is flash in general and may not be representative of compute grade flash
Tape growth relies on them leveraging HDD areal density growth enablers which may not be possible

# Industry Areal Density Roadmap (2013)



# From PMR to Heat Assisted Magnetic Recording (HAMR)

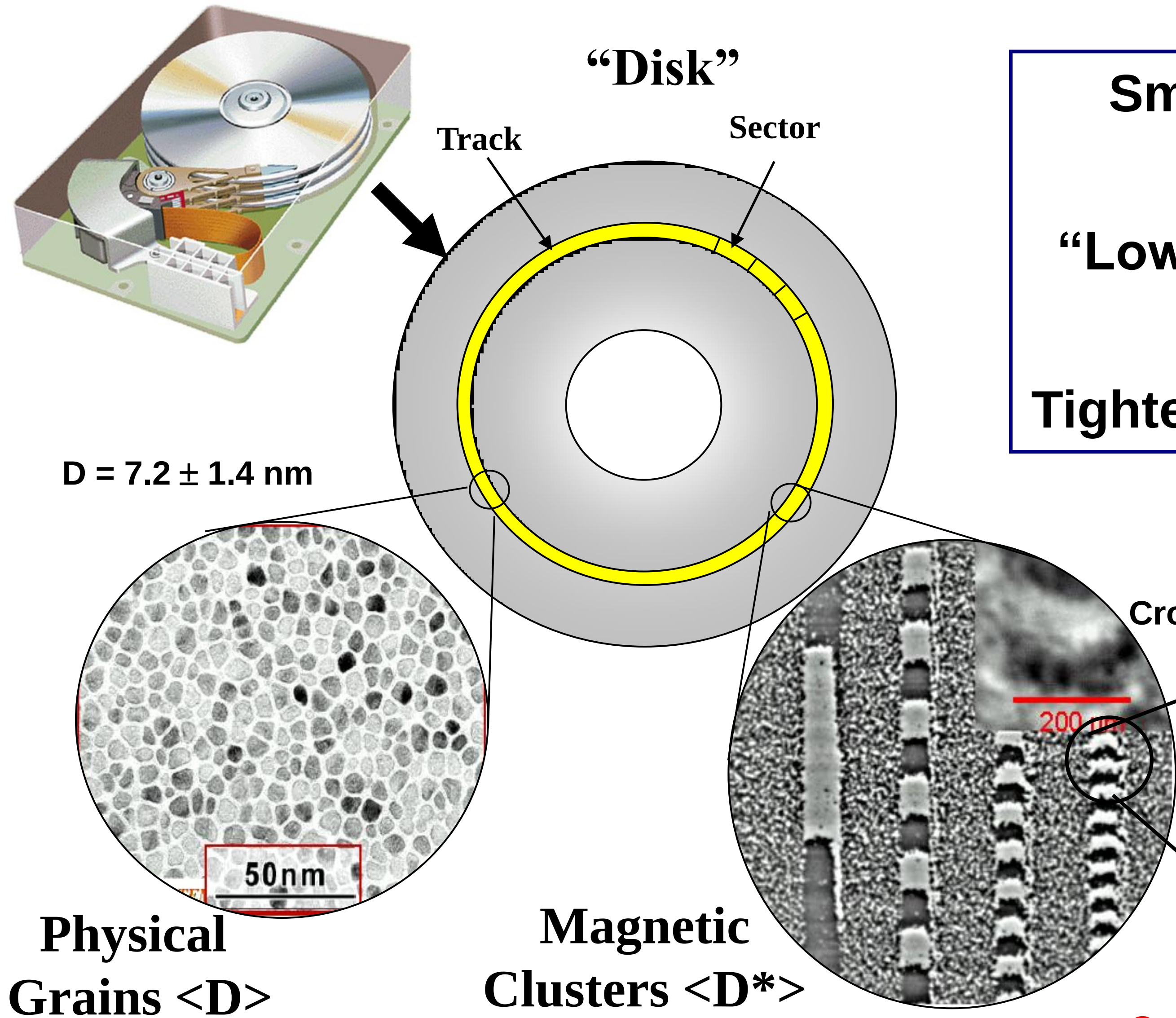



**Perpendicular Recording** **HAMR**

**Seagate 2002**

# Nanostructured Disks Suppress Noise

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




**Smaller grains**

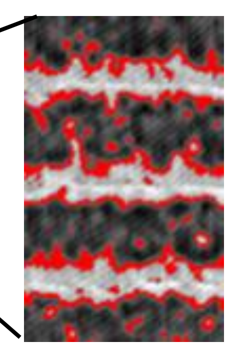
↓

**"Lower" exchange**

↓

**Tighter Distributions**

Cross track correlation ~ 25 nm



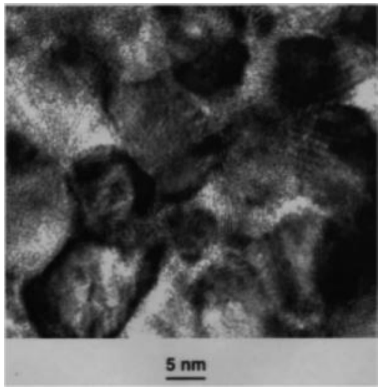
10 nm resolution MFM

Seagate 2004 J. Ahner, D. Weller

# Distribution Narrowing

← CoCrPt →

**1990 LMR**



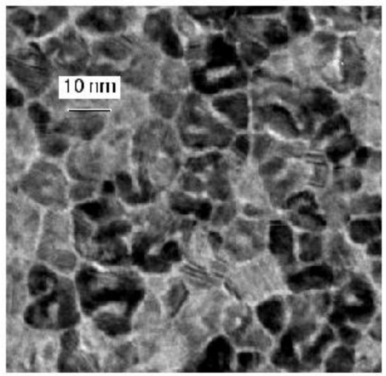

**10 Gbit/in$^2$**
**product media**

**12 nm grains**

**$\sigma_{area} \cong 0.9$**

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

**2000 LMR**



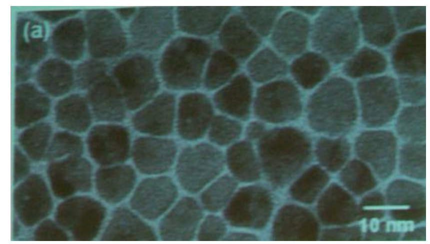

**35 Gb/in$^2$**
**prototype media**

**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**

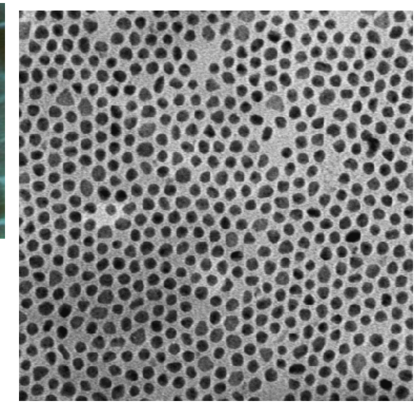
**8.5 nm grains**

**$\sigma_{area} \cong 036$**

**Tanahashi *et al.***
**TMRC 2008**

**FePt**
**SOMA**

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



**Nanoparticle arrays**

**4 nm particles**

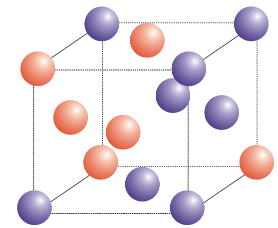
**$\sigma_{area} \cong 0.05$**

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

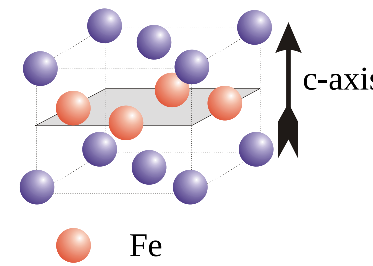
# FePt Nanoparticles – *fcc-fct* phase transformation

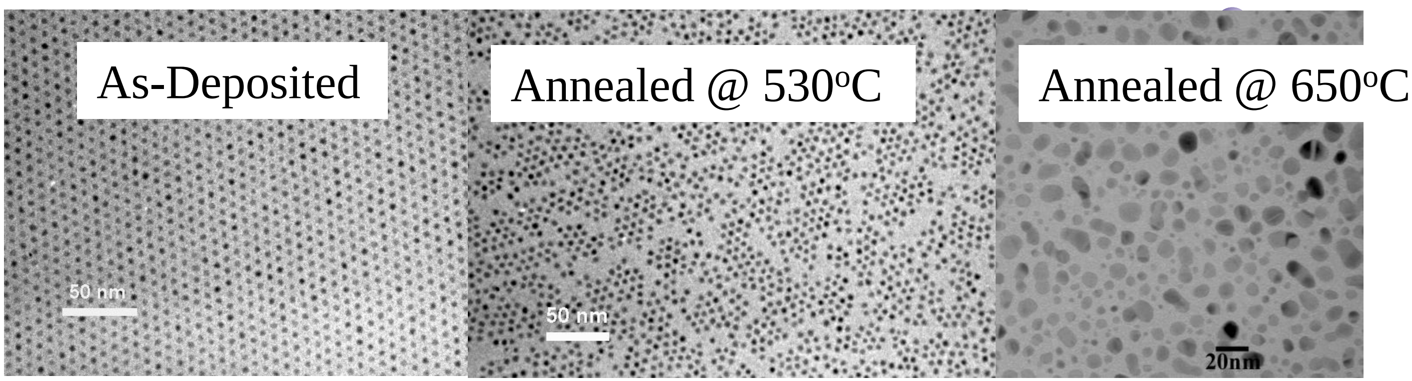
- Annealing leads to formation of ordered, high-$K_U$ ferromagnetic phase,
- unfortunately it also leads to particle agglomeration & disorder in the array


chemically disordered
fcc structure
superparamagnetic



chemically ordered
fct structure
ferromagnetic

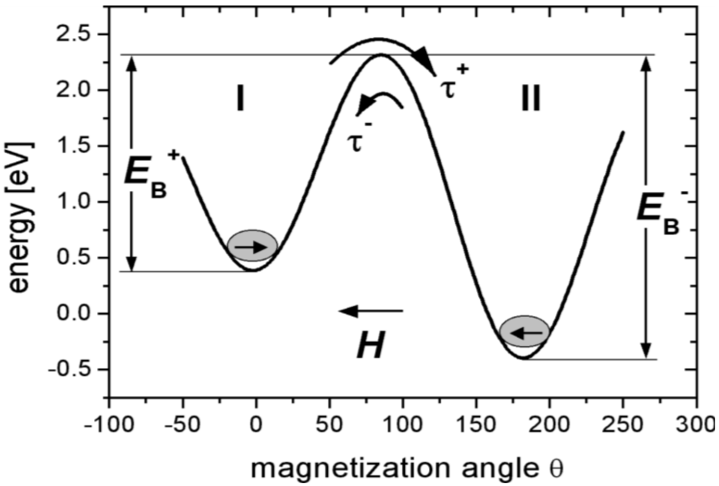



TEM from D. Weller (Seagate), presentation CC-03, Intermag '03 (Jan Thiele)

**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)**

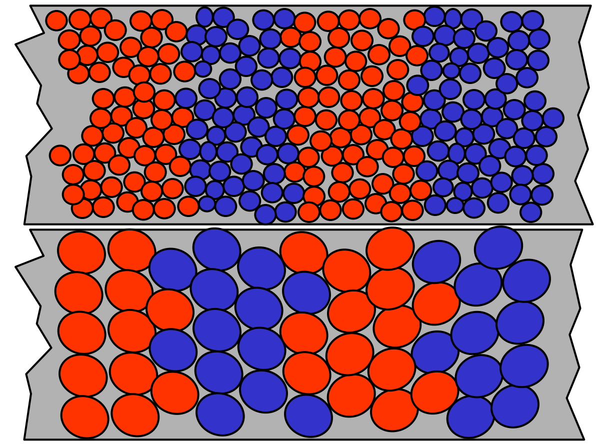
# Media Design Constraints – “Trilemma”

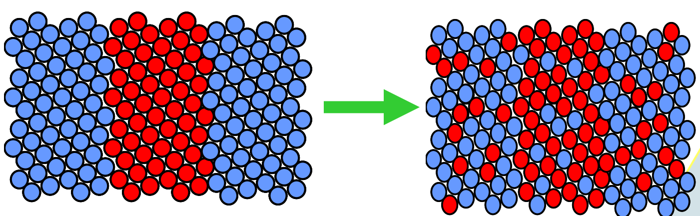


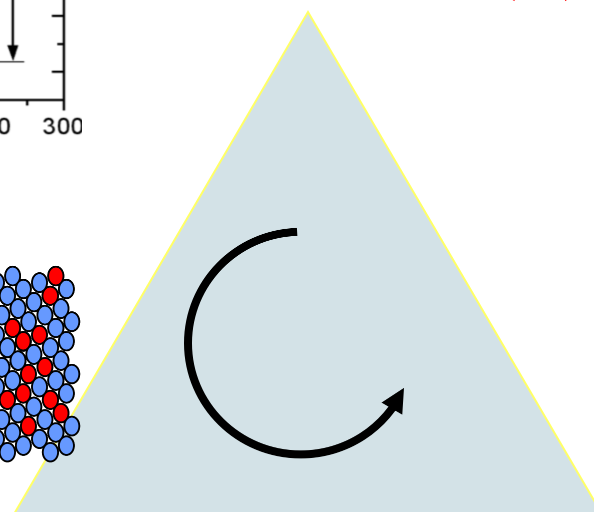

**Media SNR**

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

**Small Grains (V)**







**Thermal Stability**

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

**$K_u V = 40\text{-}60\ k_B T$**

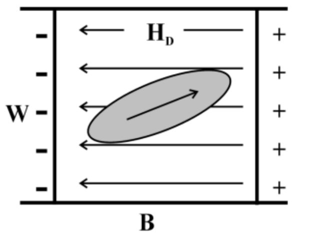
**Writability**

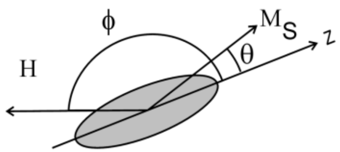
$$H_0 = \alpha \frac{2K_u}{M_s} - N_{eff} M_s$$

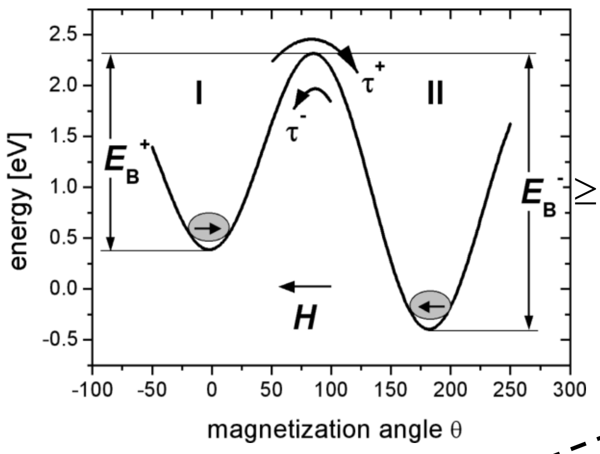
**$H_0$ < Head Field**

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

# Smallest thermally stable grain size - details




$\geq$1.2 eV

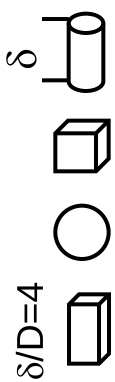
$$\tau = f_0^{-1} e^{E_B / k_B T_S}$$

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

$f_0$: 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

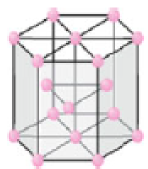
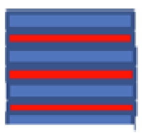
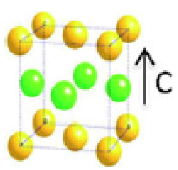
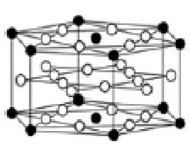
n=1/3, k=6/π for spheres

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)**

| | alloy system | material | $K_u$ ($10^7$ erg/cm$^3$) | $M_S$ (emu/cm$^3$) | $T$ = 350 K: $H_K$ (kOe) | $T$ = 350 K: $T_C$ (K) | δ=10 nm: $D_p$ (a) (nm) | $D_p$ (b) (nm) | $D_p$ (c) (nm) | δ/<D> =2: $D_p$ (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 |
| | $L1_0/L1_1$ | 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 |

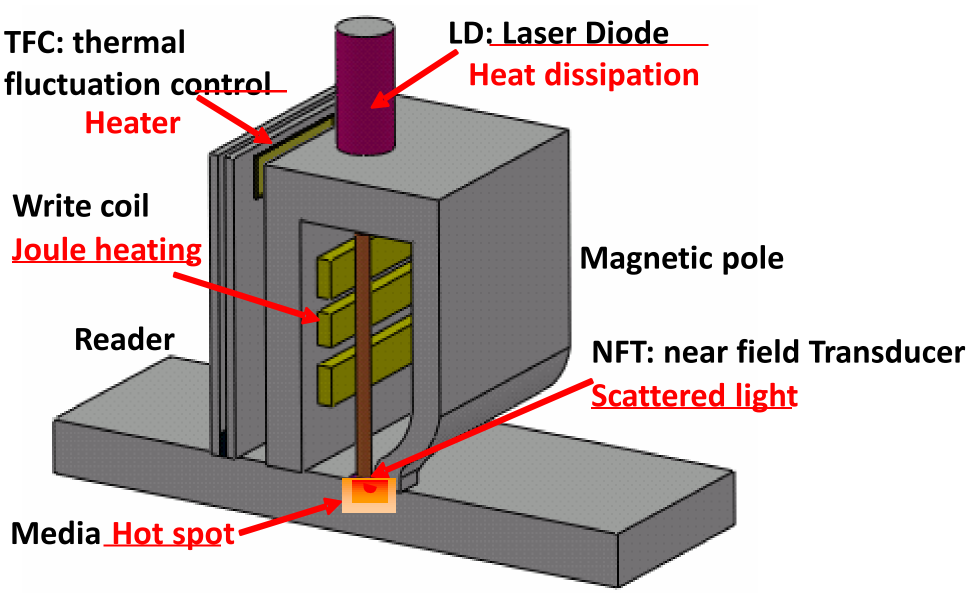
~10x higher Ku — "low" Tc — 2x smaller grain dia

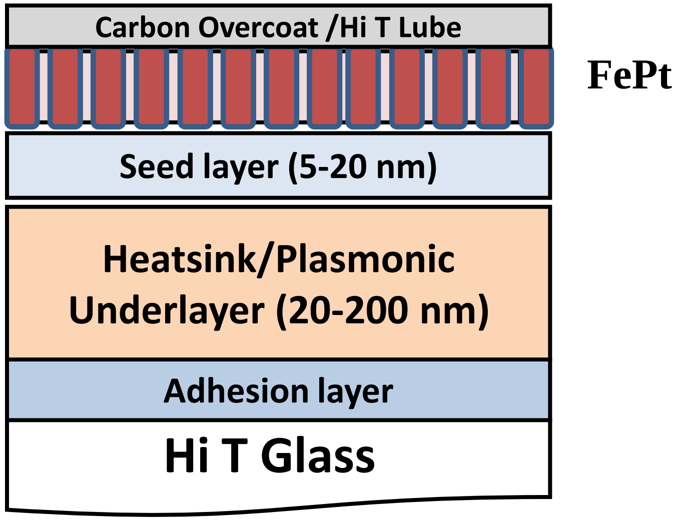
$D_p$ is the average thermally stable grain diameter assuming $KV/k_BT = 60$ and $T = 350$ K, $k_B = 1.3807 \times 10^{-16}$ erg K$^{-1}$ and volumes (a) $V = \pi/4 \times D^2 \times 10$ nm (cylinders), (b) $V = D^3$ (cubes), (c) $V = 4/3 \times \pi \times (D/2)^3$ (spheres) and (d) $V = \pi/4 \times D^2 \times \delta$ (cylinders with $\delta/D = 2$). The thickness $\delta$ 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

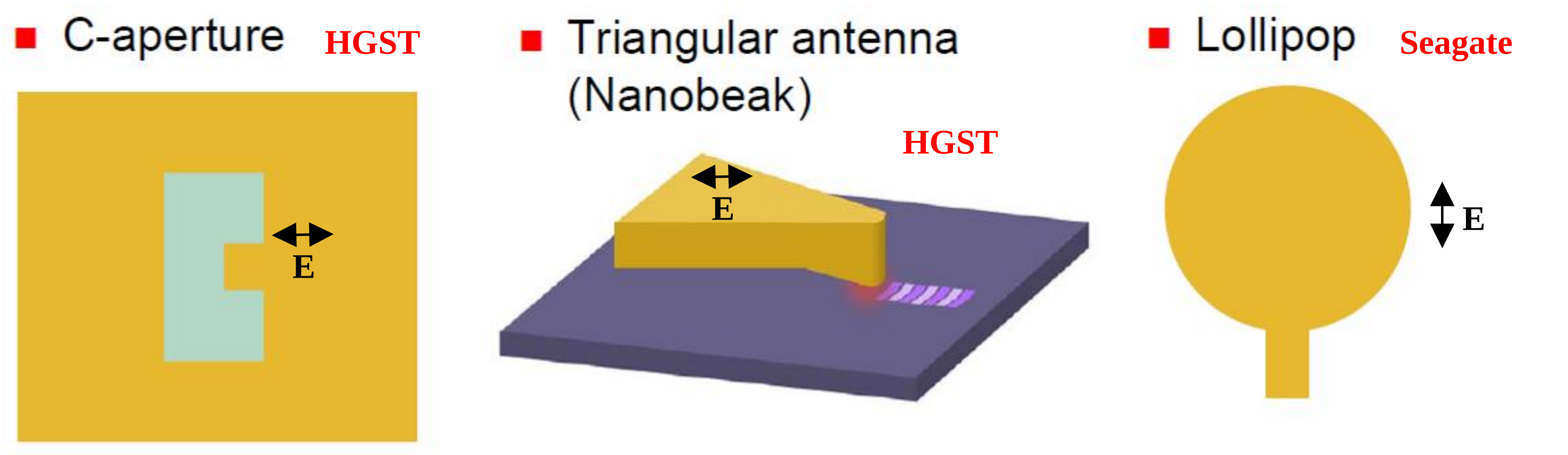



1. **Chemically ordered and textured $L1_0$ FePtX-Y (001) granular media for high areal density heat-assisted magnetic recording (HAMR)**

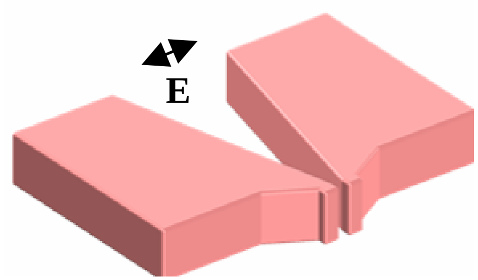
2. **Thermal design to improve the recording time window down to < 1 ns and increase the areal density beyond $1 Tb/in^2$**

# HAMR heads (brief): Multiple Near Field Transducer Designs




- Waveguide/Needle

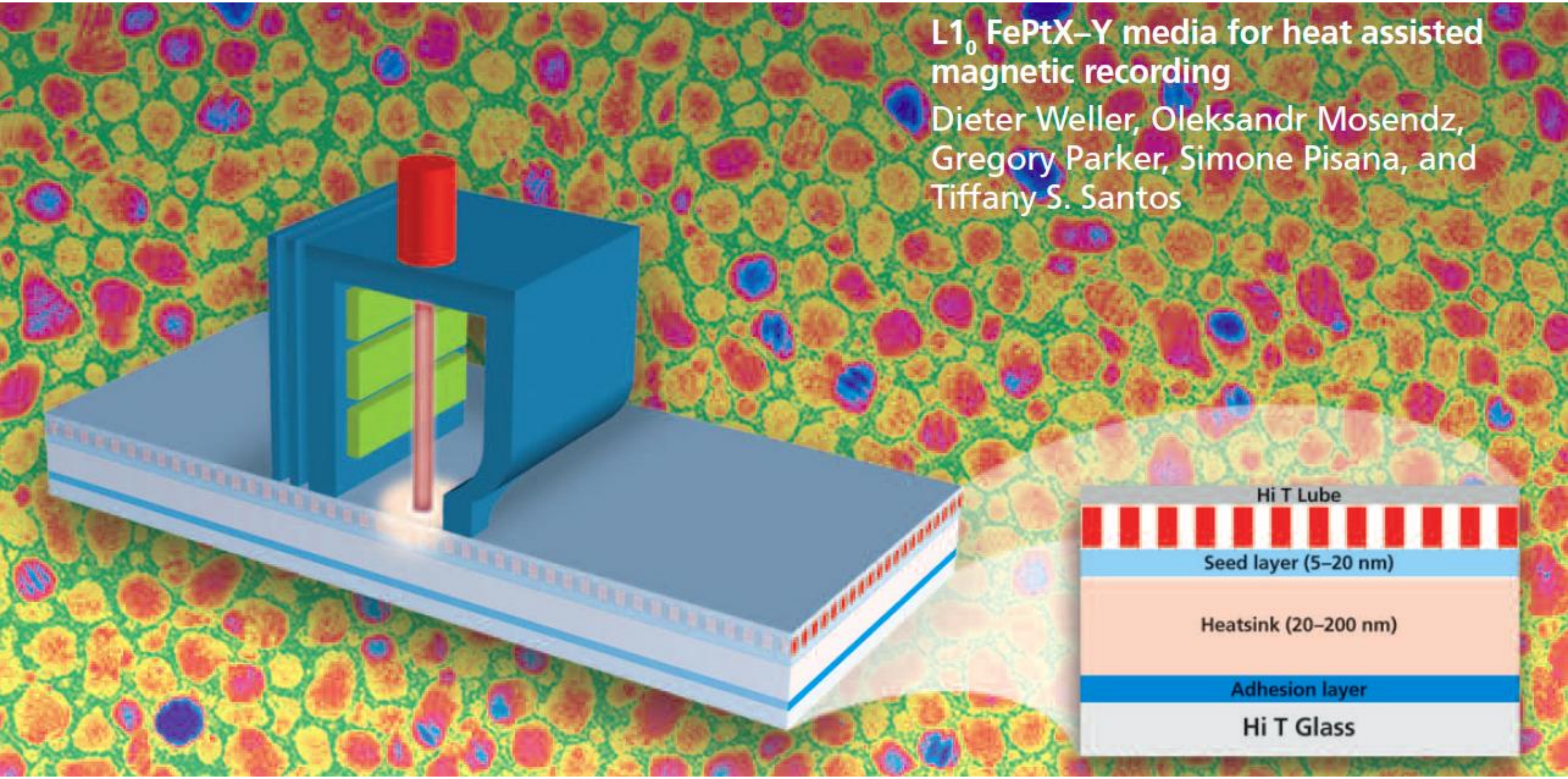
Berkeley, CMU



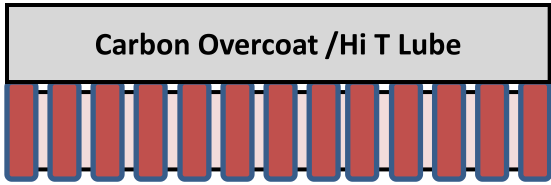

**All transducers can produce very small heat spots**
**Common challenge is reliability**

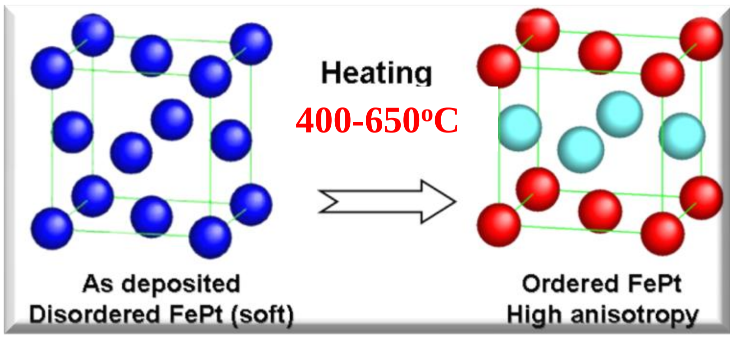
**Barry Stipe**

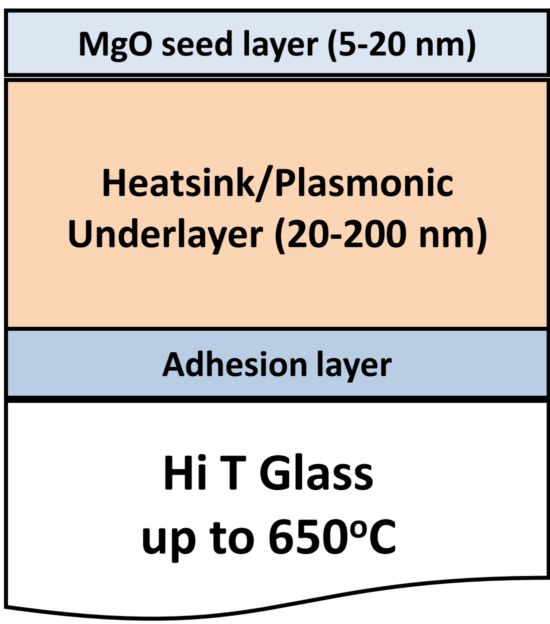
# pss – physica status solidi A **210**, 1245-1260 (2013) paper



# 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

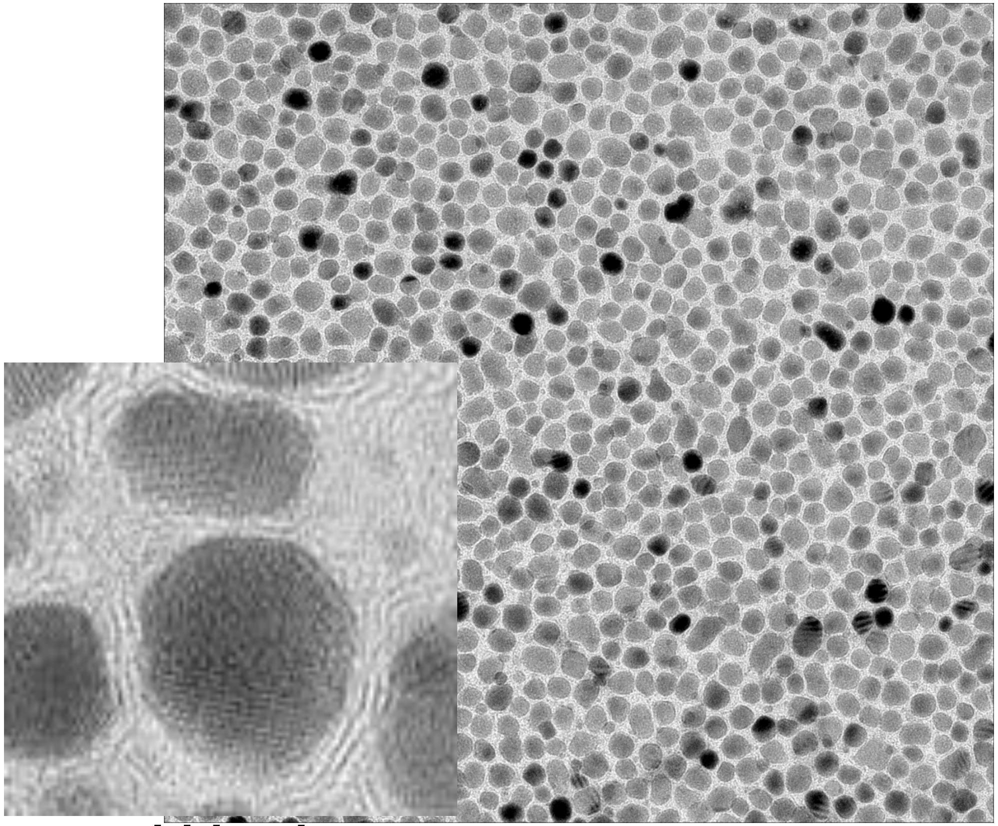
Examples: **AgX, AlX, CuX, CrX, AuX, etc.**

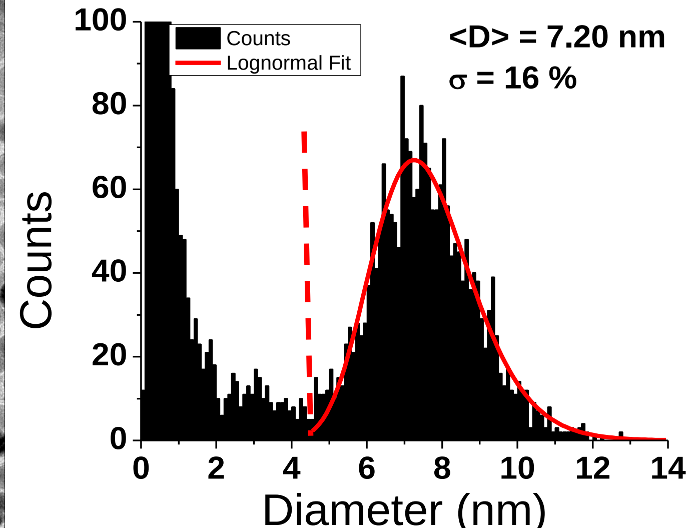
**Adhesion layer**

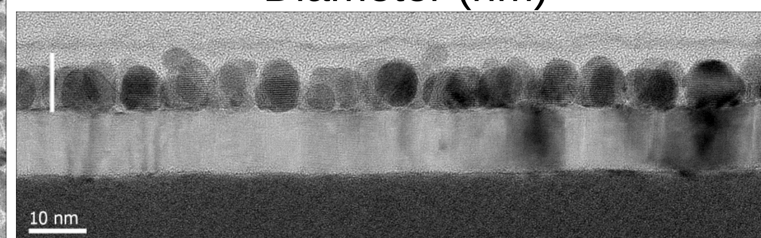
Example: **NiTa**

# “Early” FePt HAMR media microstructure – spherical grains

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






**Graphitic Sheets**

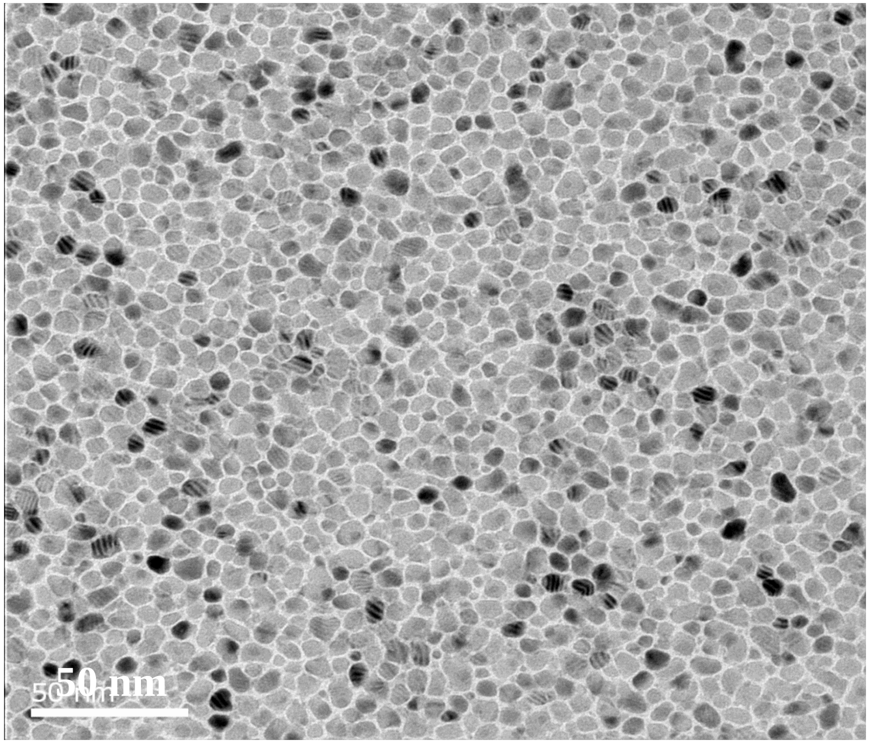
- **Used a new Lean 200 sputter tool w/ 20 chambers**
- **Low thickness δ ~ 7 nm and relatively high roughness**
- **Average grain size <D>~7.2 nm, grain pitch <P>~9 nm**
- **grain aspect ratio δ/D~1**
- **many small grains D<3 nm (thermally unstable)**

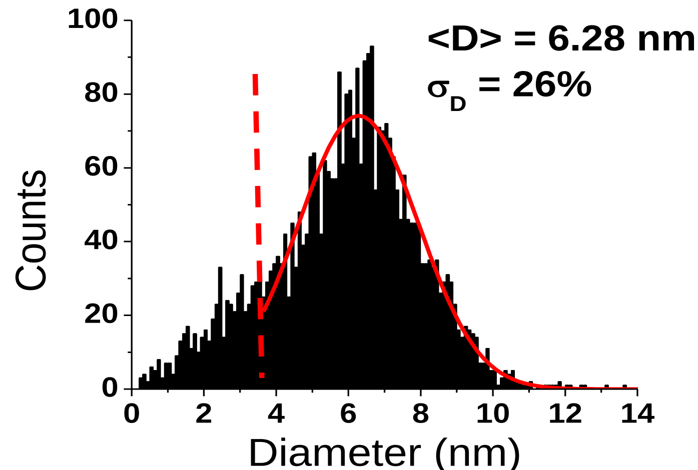


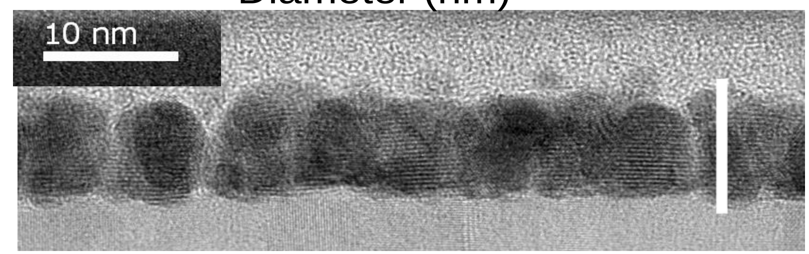
**O. Mosendz**, et al., J.Appl. Phys. 111, 07B729 (2012)

# "More recent" FePt media – dual layers w/ more cylindrical grains

**Granular FePtX-Y media grown at ~620°C 2012**



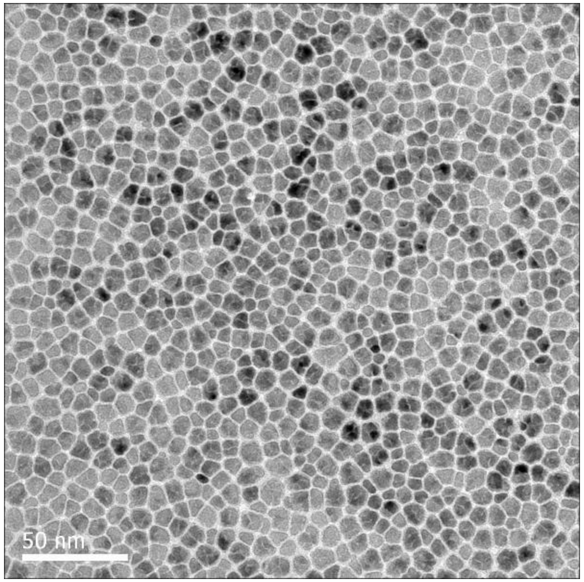




- **higher thickness δ ~ 10 nm → improved read back signal**
- **average grain size <D>~6.3 nm, grain pitch~ <P>~7.3 nm**
- **grain aspect ratio δ/D~1.6**
- **less grains with D < 3.5 nm**
- **smoother surface**
- **BUT: worse grain size distribution**

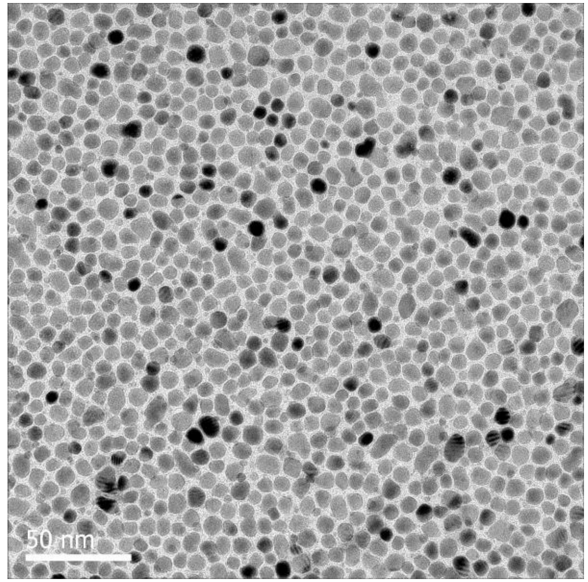
D. Weller et al., Phys. Status Solidi **A 210**, 1245 (2013)

# Grain Size and Microstructure from CoCrPt PMR to FePt HAMR 2013

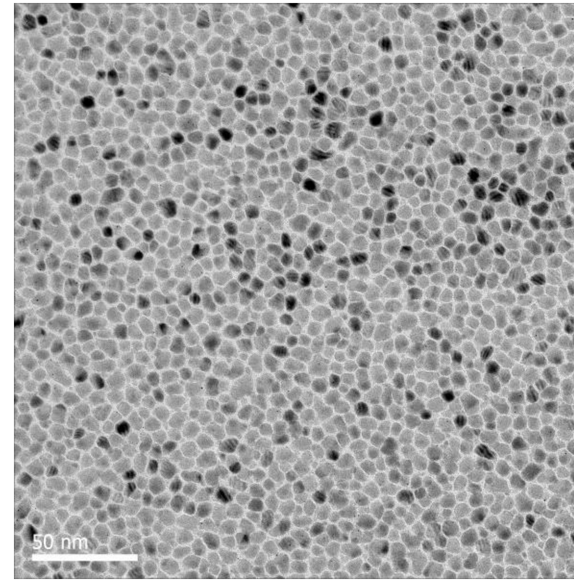
**Typical PMR**



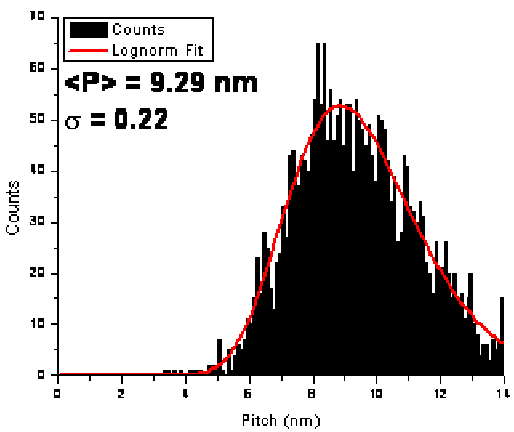

HAMR Media

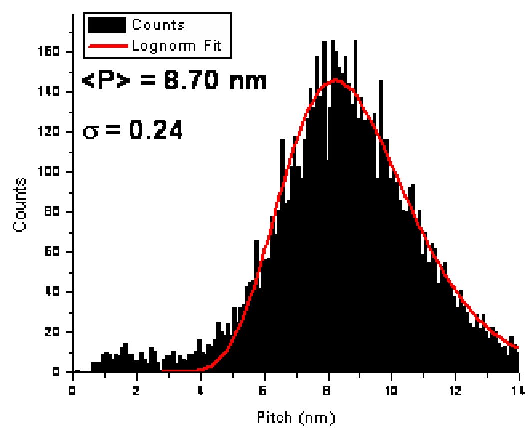


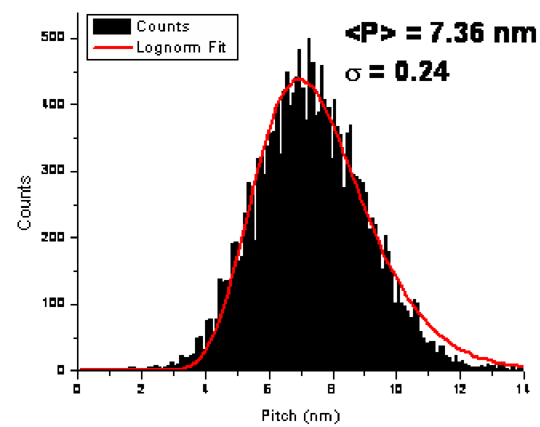

HAMR: more Voronoi and columnar




## Improved Grain Size (Pitch) & Distributions

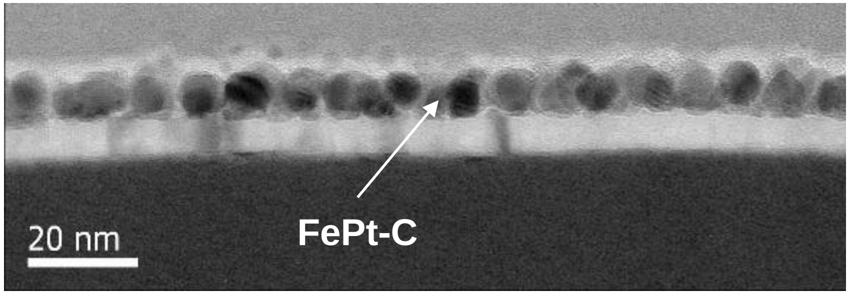


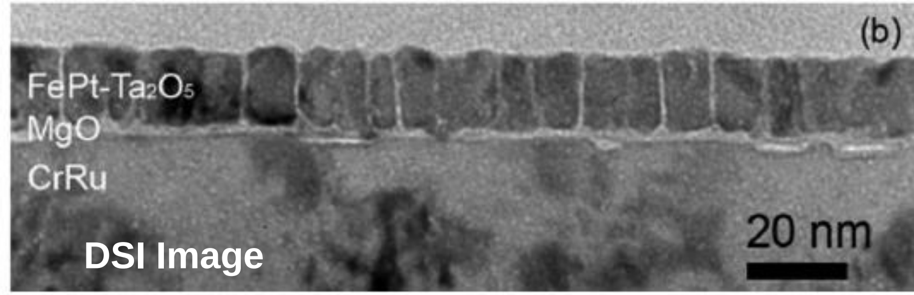



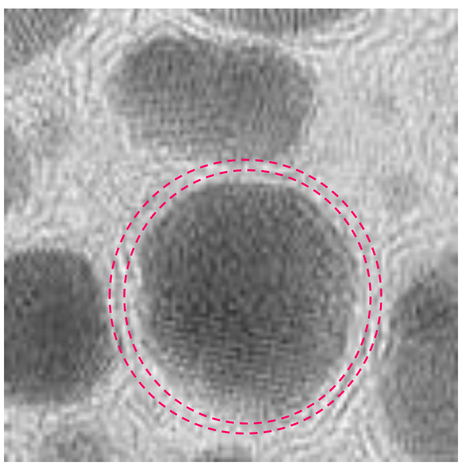
# Importance of Columnar Grains

**Spheres** *VS.* **Columns**




**Graphitic Sheets**

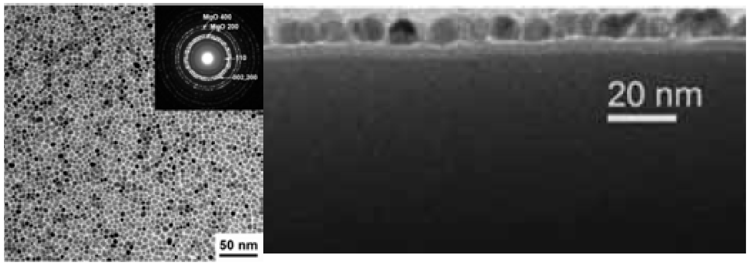


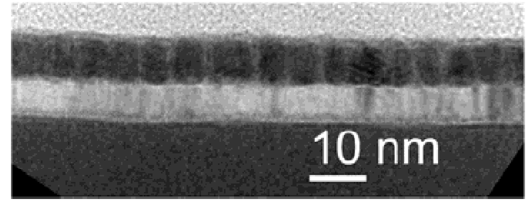
***Advantages of columnar grain growth:***

- **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.**

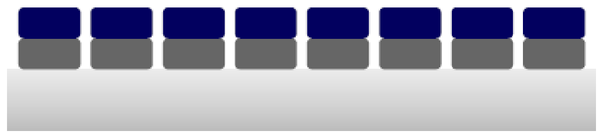
# K. Hono - Nat'l Institute of Materials Science Japan (NIMS)

FePt-C as template + $FePt\text{-}TiO_2$ for columnar growth

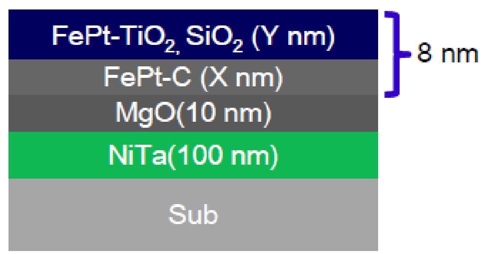



**K. Hono**
**2013 ASTC**
**presentation**




dual mag layers




@ 600 oC

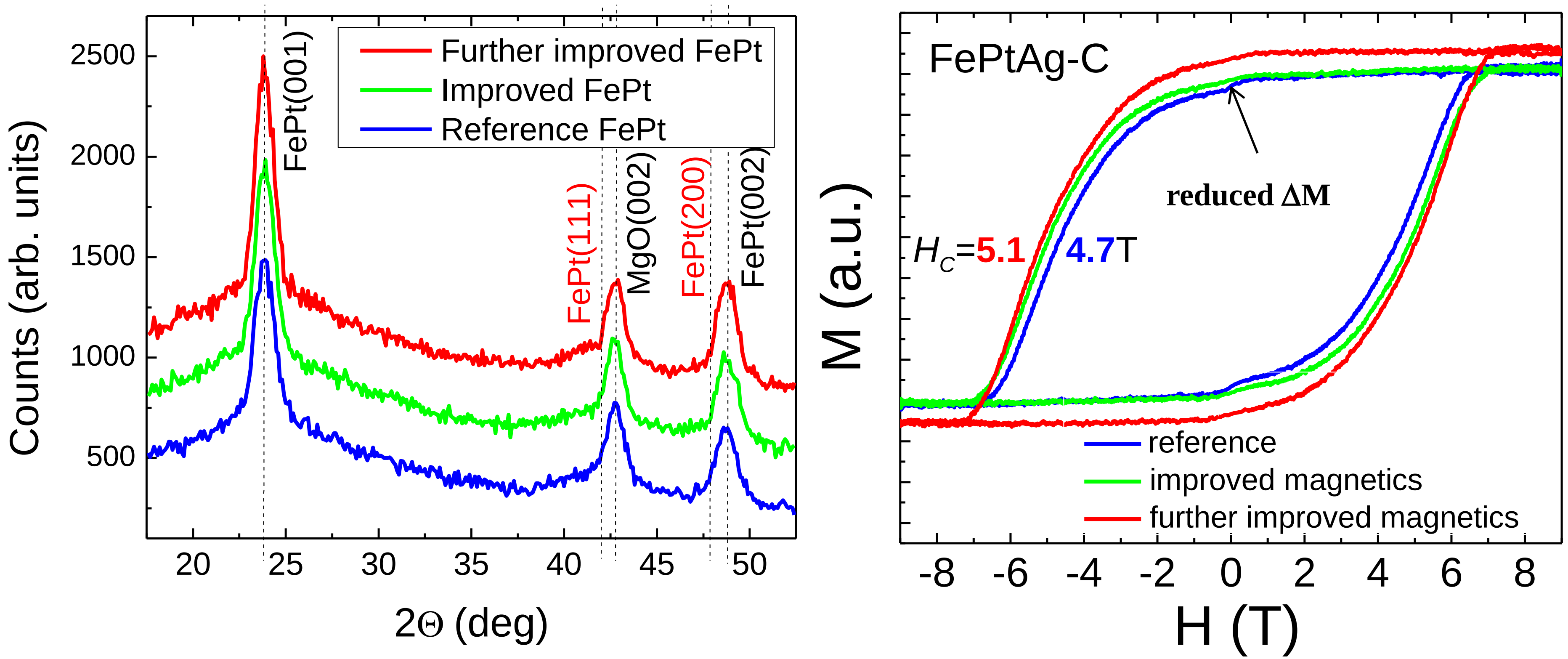
@RT

| 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**

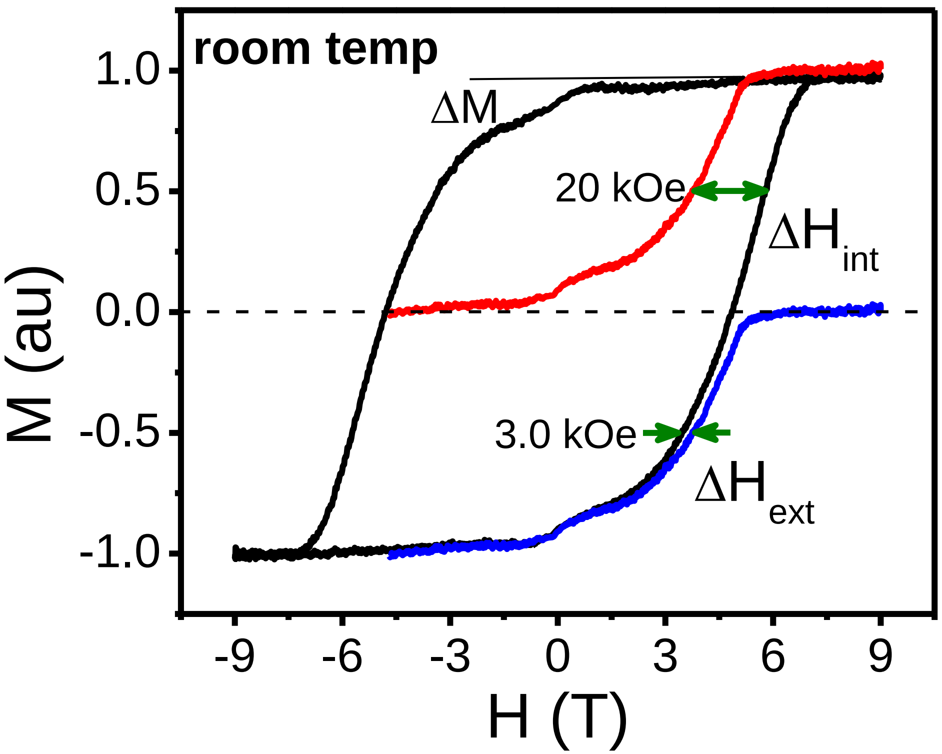
# XRD and MOKE hysteresis of improved media 2013

**(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)




At room temperature

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

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

**$\sigma_{int}$ = 15 kOe (VSM)**

Grain volume distribution: **$\sigma_{vol}$ = 3.7 kOe**

- from TEM grain size analysis

Grain texture distribution: **$\sigma_{axis}$ = 6.6 kOe**

- from rocking curve width, XRD

Anisotropy distribution: **$\sigma_{Hk}$=12.9 kOe**

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

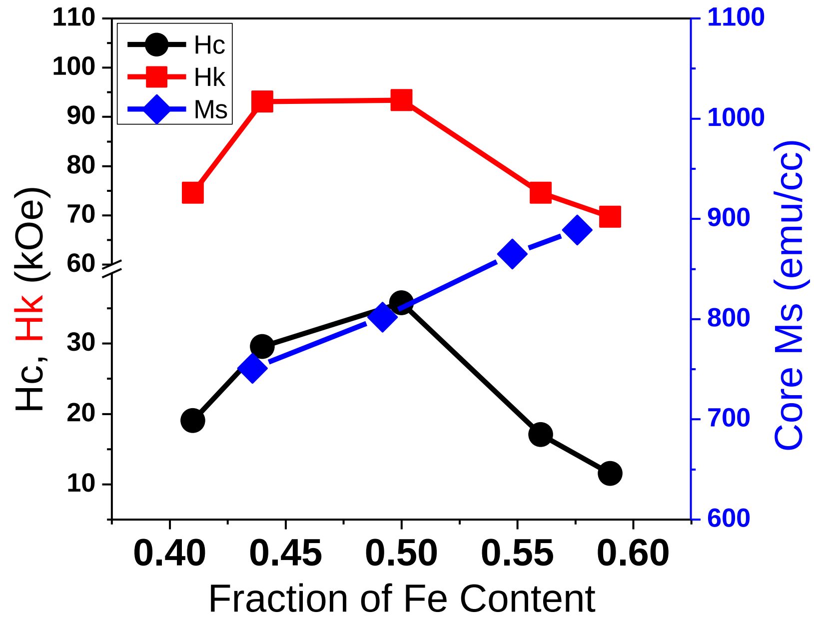
***What is iSFD at the recording temperature, near Tc ?***

***Micromagnetic model needed to go beyond these estimates***

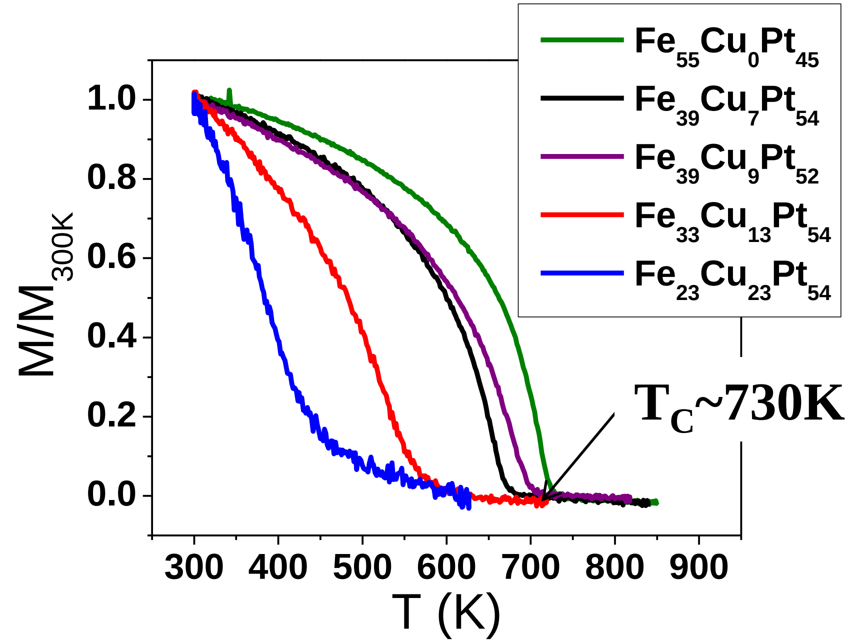
S. Pisana, et al., J. Appl. Phys. 113, 043910 (2013)

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

## granular




## continuous



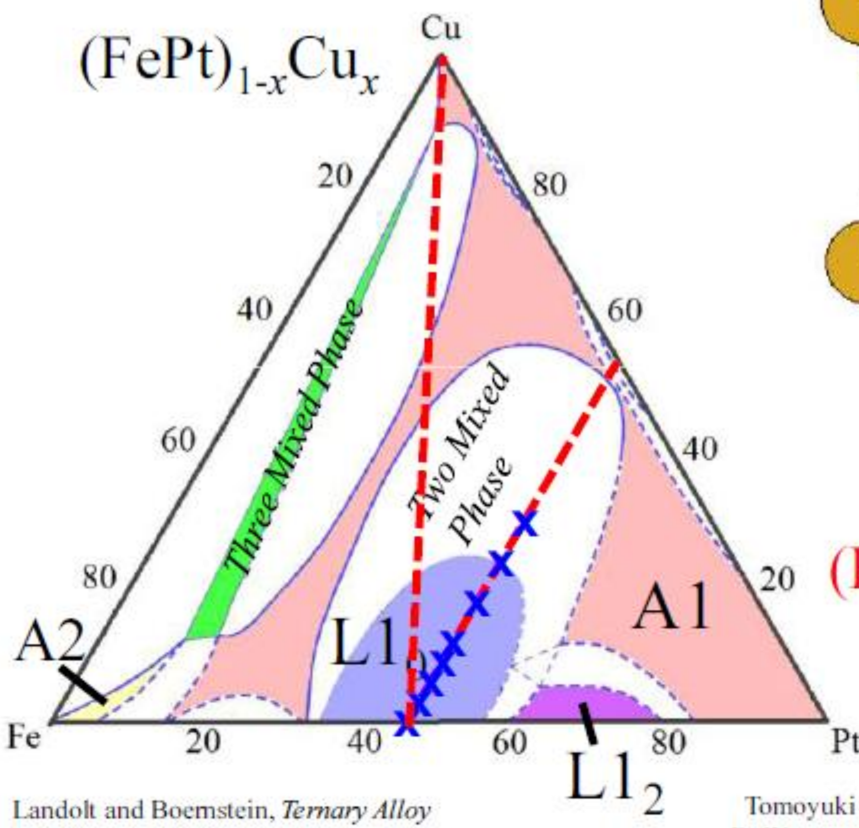

**Optimal values of coercivity and anisotropy at x=50%**

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

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

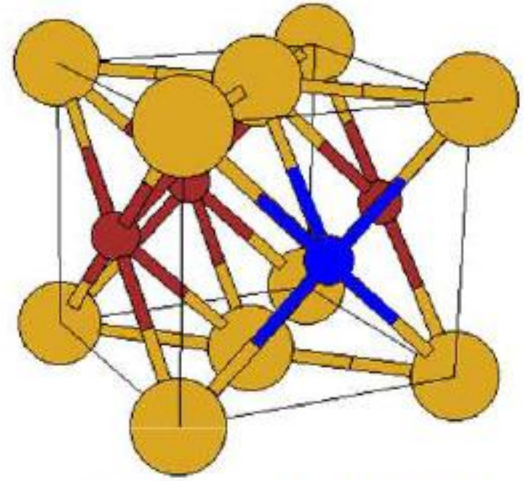
# Forming ternary alloys to improve ordering

## FePtCu




$(Fe_{1-x}Cu_x)_{55}Pt_{45}$

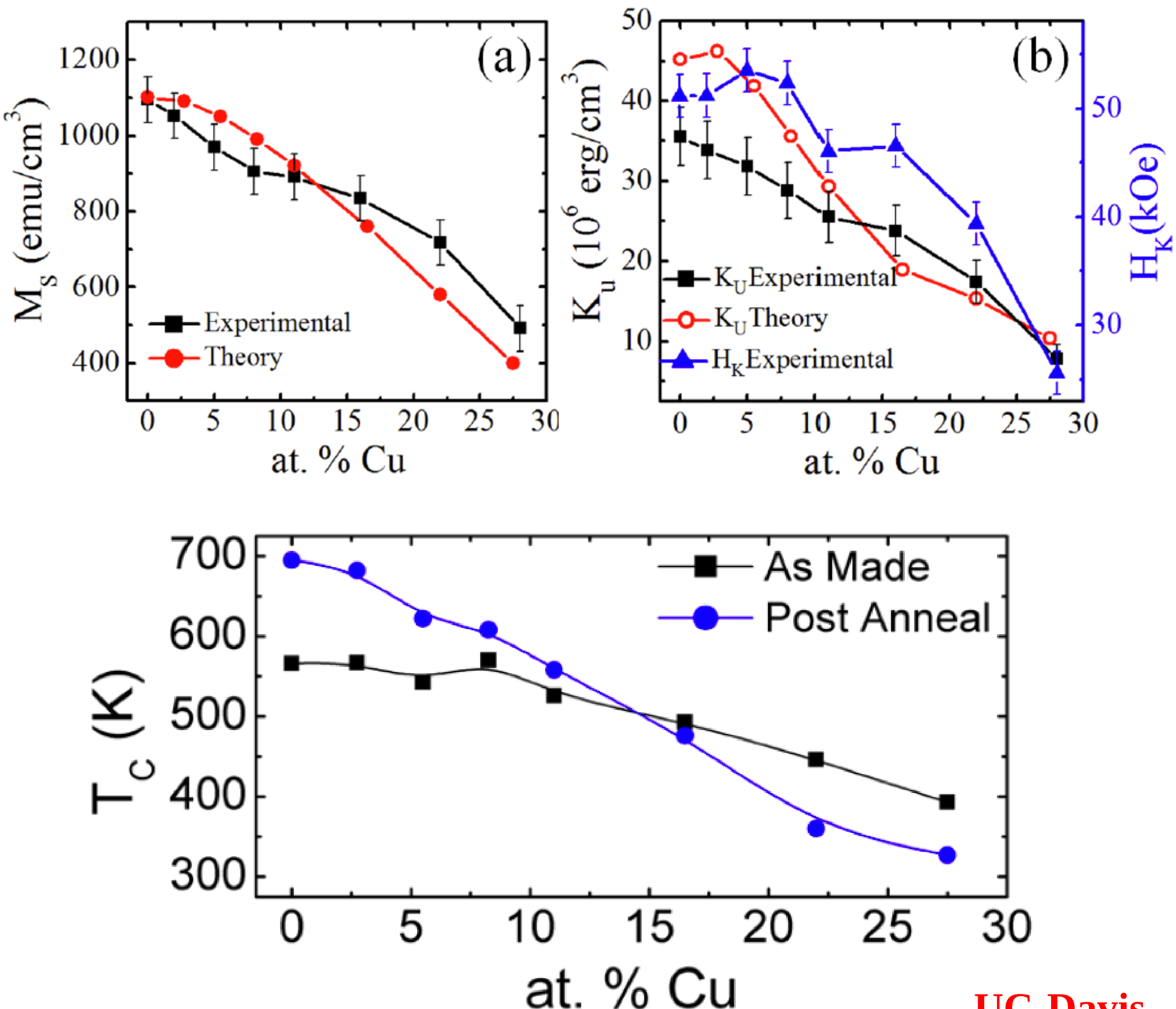
Landolt and Boernstein, *Ternary Alloy Systems*. (Springer-Verlag Berlin, 2008)



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)

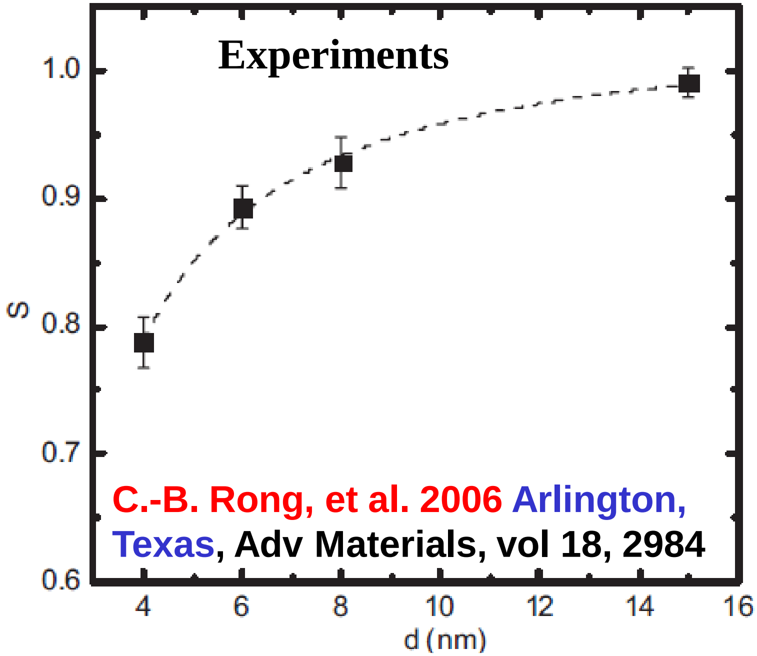
**UC Davis – Seagate**

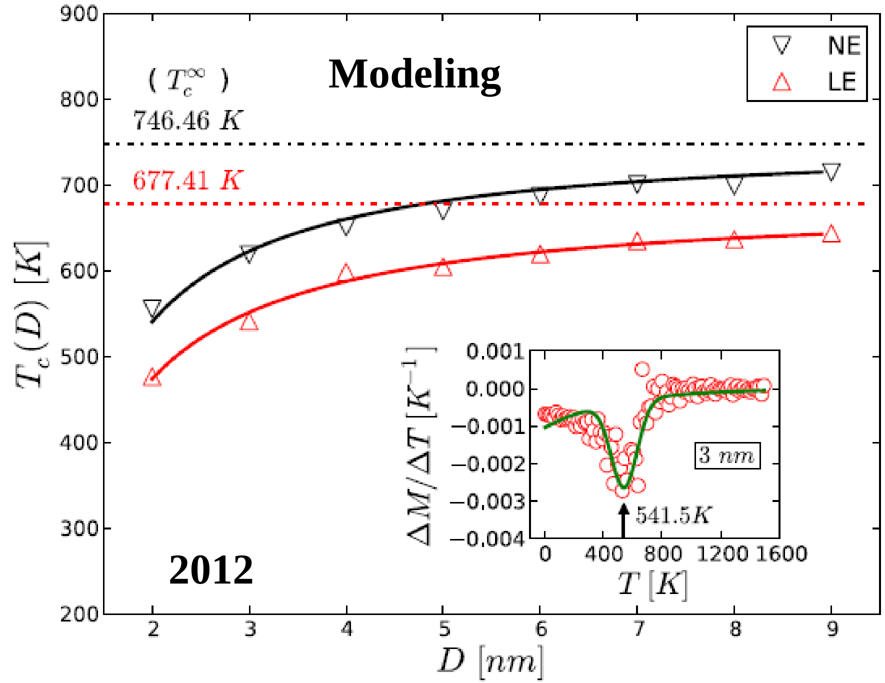


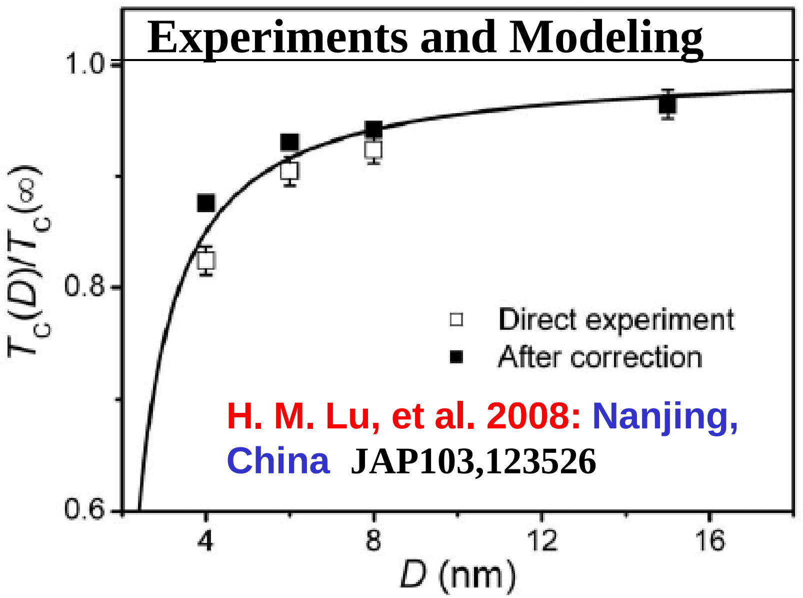

**UC-Davis - Seagate**

D.A. Gilbert, et al., Appl. Phys. Lett. 102, 1324006 (2013)

# Chemical ordering *S* and Curie temperature $T_C$ vs grain size



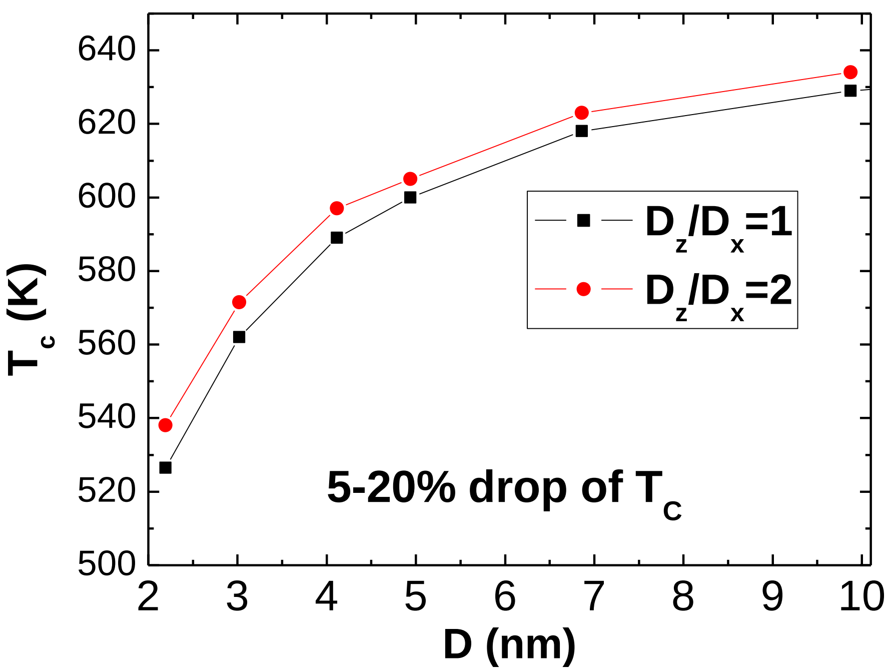



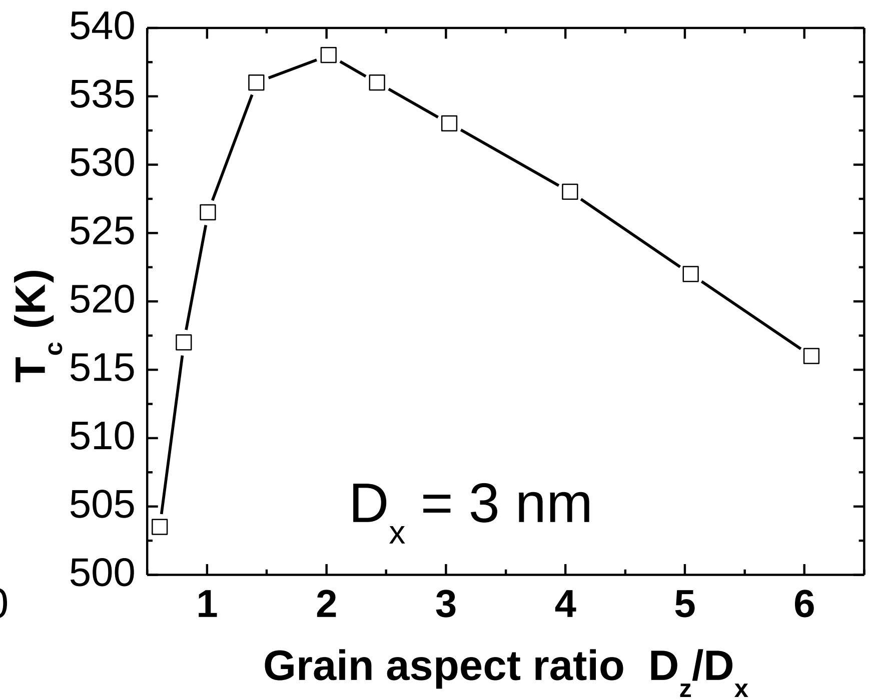




**O. Hovorka, ….., G. Ju, R. W. Chantrell, 2012: "The Curie temperature distribution of FePt granular magnetic recording media", APL 101, 052406 York U. - Seagate**

**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 $T_C$



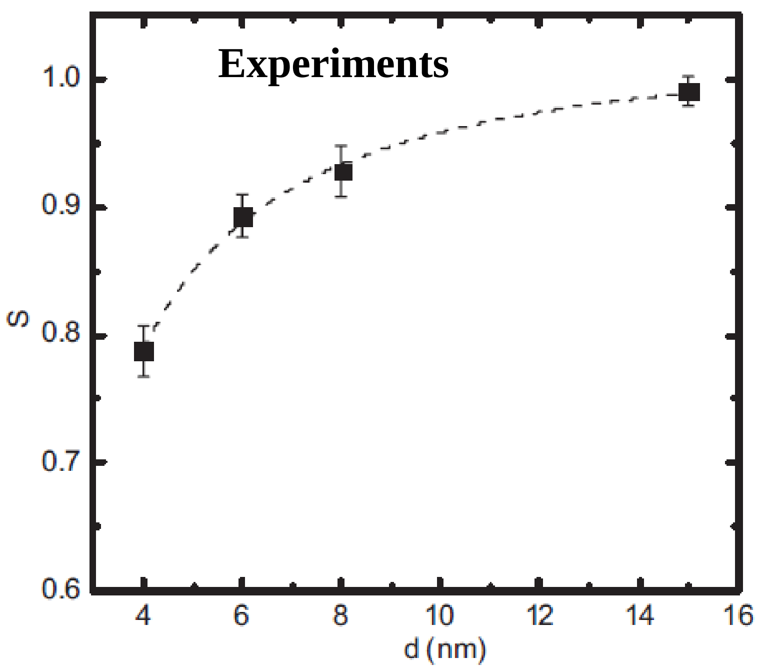

**Finite size scaling theory** $$T_c(D) = T_c(\infty)\left(1 - x_o D^{-1/\nu}\right)$$ **ν~0.7+/–.09**

- **$T_C$ 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**

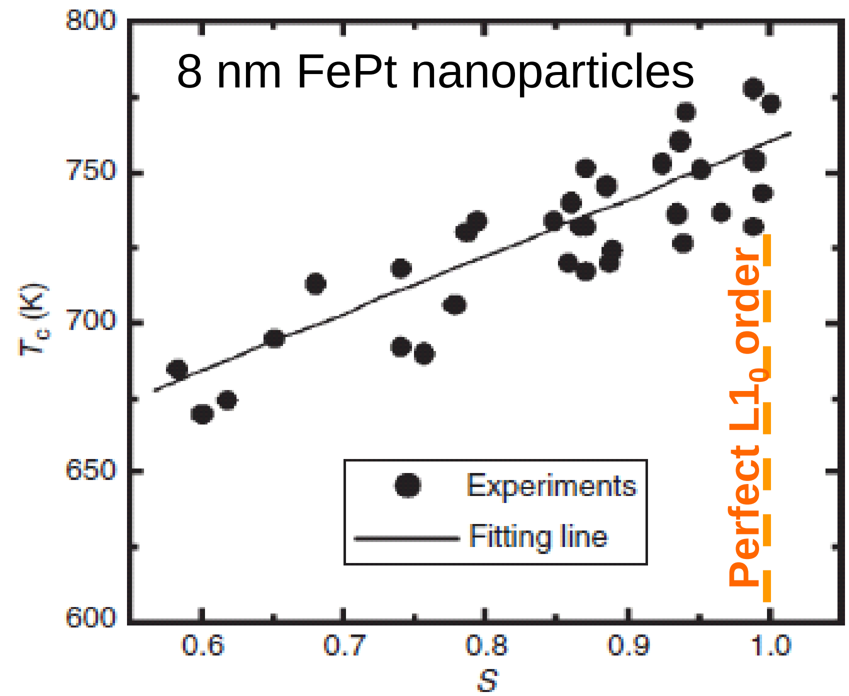
**A. Lyberatos**, D. Weller, G. Parker, "Finite size effects in *L1₀*-FePt nanoparticles" J. Appl. Phys. **114**, 233904 **(2013)**

# $L1_0$ Chemical Order Parameter & Curie temperature

**$L1_0$ Order Parameter vs grain size**



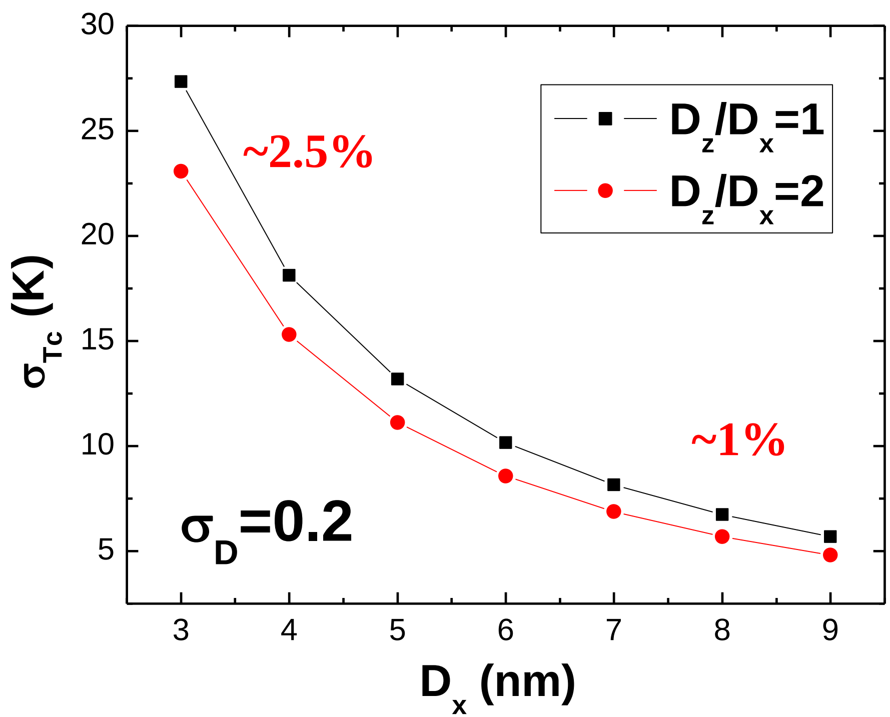

**Curie temperature vs $L1_0$ Order Parameter**




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**

# $\sigma_{TC}$ 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 $\sigma_{Tc}/T_C$ 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)**

**Buschow "Handbook of Magnetic Materials", Elsevier 2011, J. Lyubina, B. Rellinghaus, G. Gutfleisch, M. Albrecht**

# "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 $\delta_w$, 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$^3$) | $\delta_w$ (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**

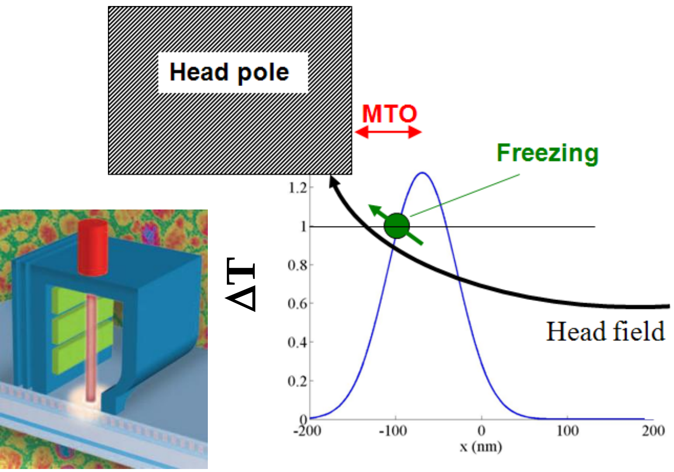
[a] fcc ($A1$) $Fe_3Pt$ starts to transform to a bcc martensite already at room temperature (Sumiyama et al., 1983).

**Strong dependence of $T_C$ on chemical ordering A1 → $L1_0$ ($\Delta T_C$ =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

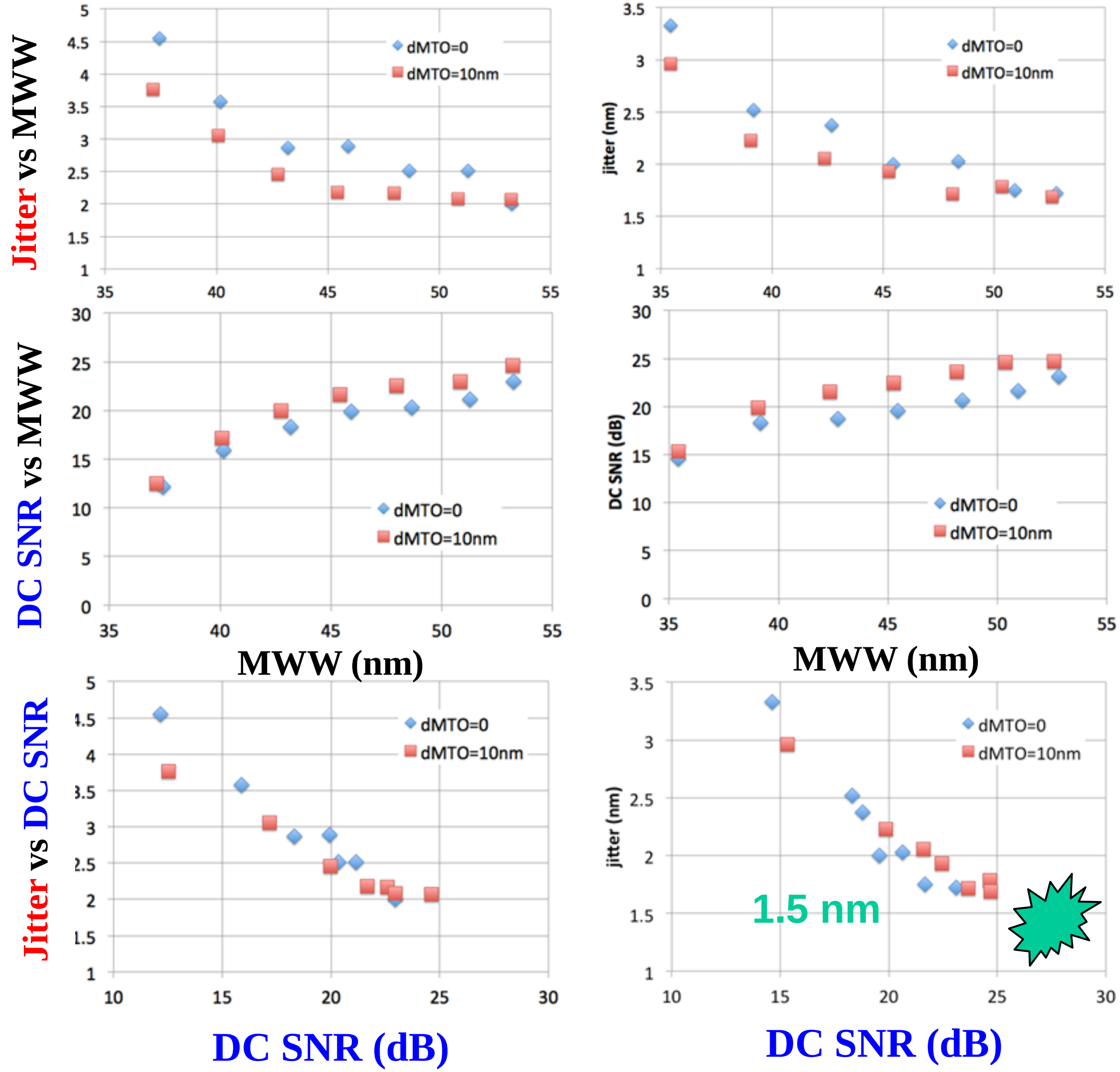
### Thermal and Field Contours



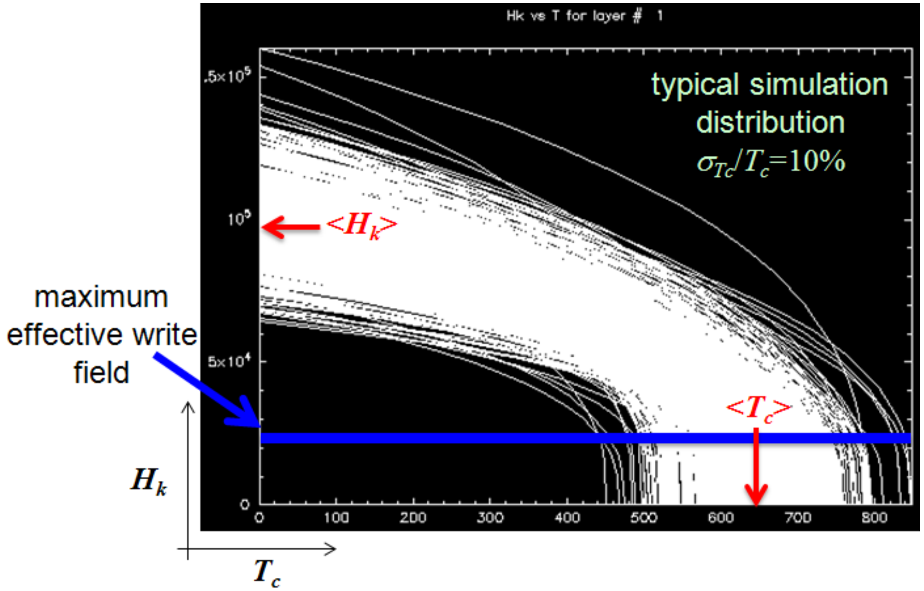

**MTO=magnetic field temperature offset**

- 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.

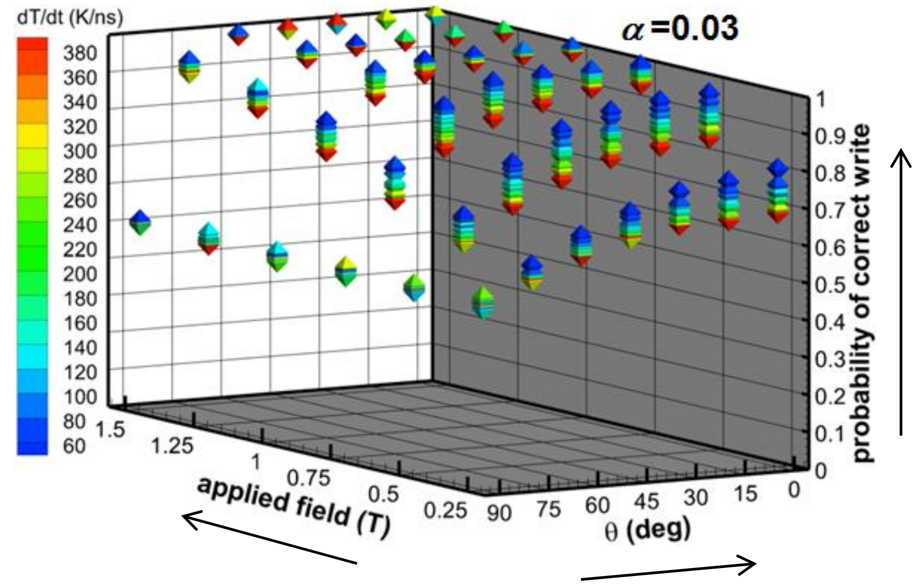
## Sigma $T_C$ = 5.1% | Sigma $T_C$ = 2.8%



# Grain Model and Field Cooling




dT/dt (K/ns)




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

- $\beta$=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.**

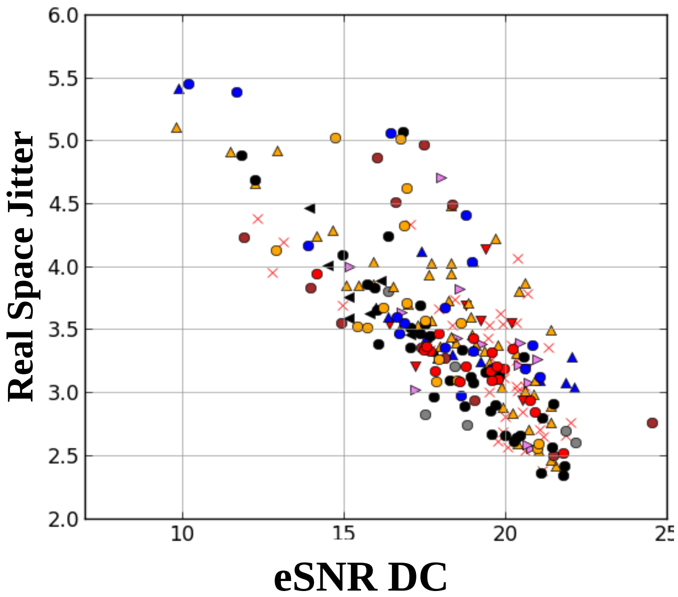


HGST a Western Digital company

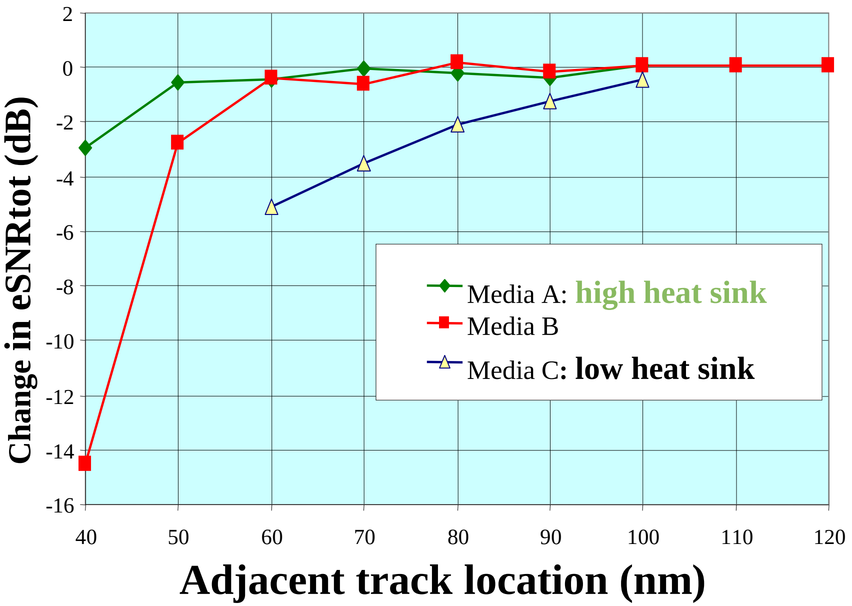
HGST
a Western Digital company

# Jitter, DC SNR, and Squeeze experiments

## Data for Various Integrated Heads and Recording Conditions




## Squeeze vs. Heatsink using an Integrated Head



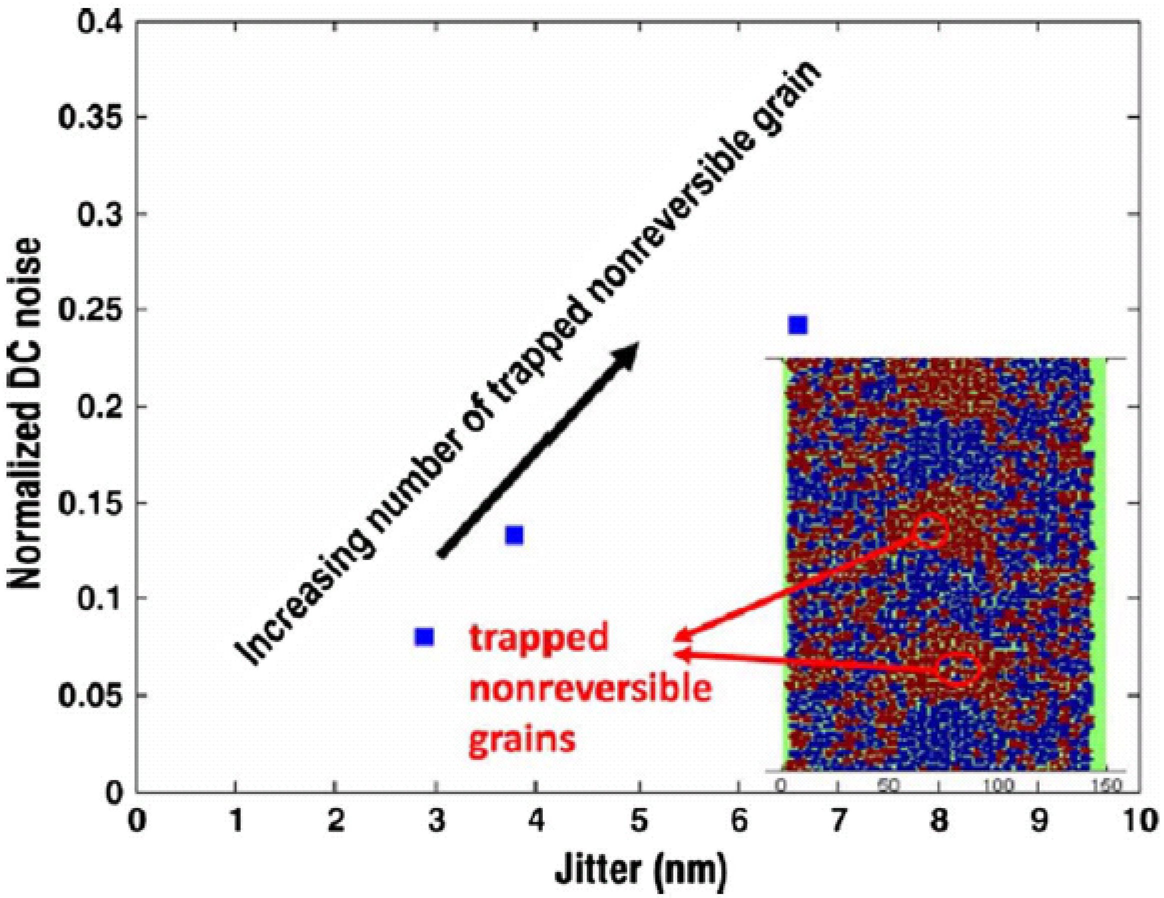

- Jitter and DC noise tend to be correlated but gradient and sigma $T_c$ mostly affect jitter.
  - **Best jitter still significantly behind PMR**. Easy to match or beat PMR on track pitch.
- **Head:** need high gradient, small **MTO**, high field angle.
- **Media:** need high gradient, columnar grains, 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**



**S. Pisana et. al**. AB-12, Intermag 2013

# DC noise vs jitter (model)

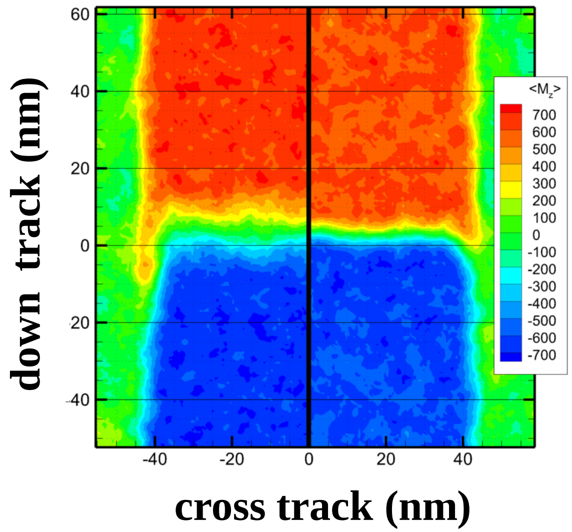



Xiaobin Wang, Kaizhong Gao, Hua Zhou, Amit Itagi, Mike Seigler, Edward Gage, "HAMR Recording Limitations and Extendibility" IEEE Trans Mag. 49, (2013) 686

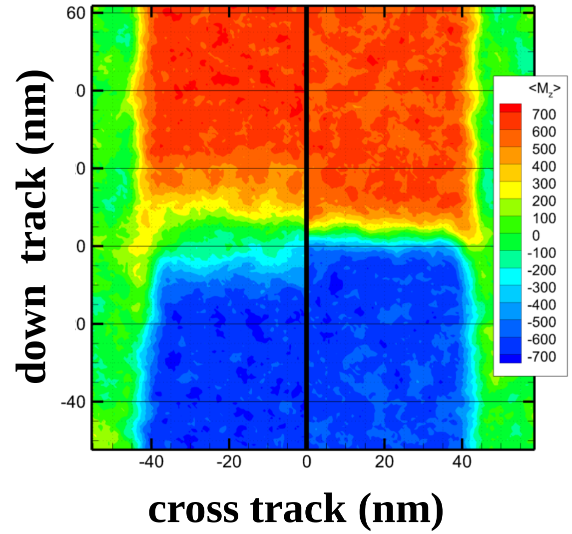
D. Weller, G. Parker, O. Mosendz, E. Champion, B. Stipe, X. Wang, T. Klemmer, G. Ju, A. Ajan, "A HAMR Media Technology Roadmap to an Areal Density of 4 Tbpsi" IEEE Trans Mag 50 (2014) 3100108

# dT/dx gradient and $\sigma_{TC}$ effect on writing – model + experiments

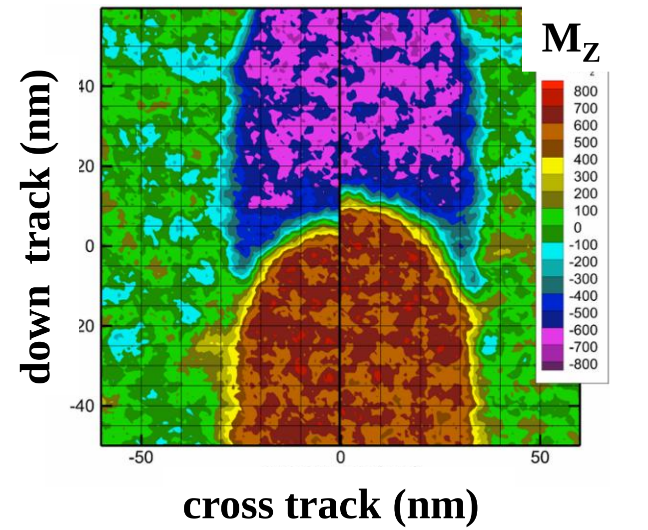
**Lower Sigma Tc (2.8%)**
3 K/nm 9 K/nm



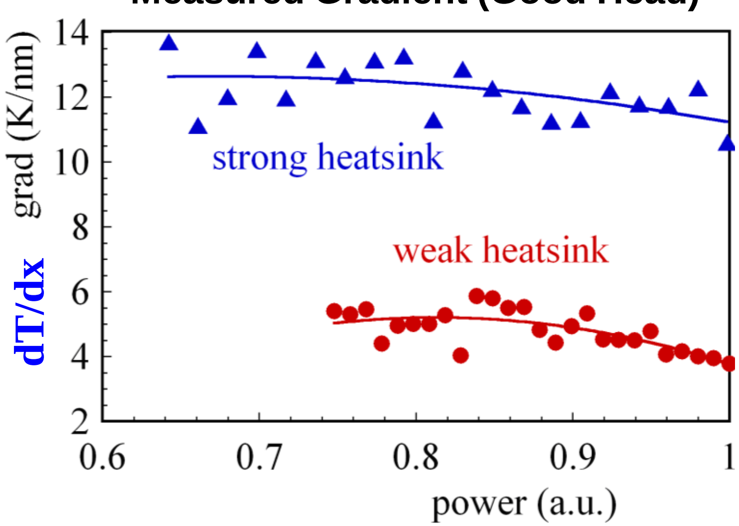

**Higher Sigma *Tc* (5.1%)**
3 K/nm 9 K/nm




**Effect of Power Modulation**
P 1.1 x P

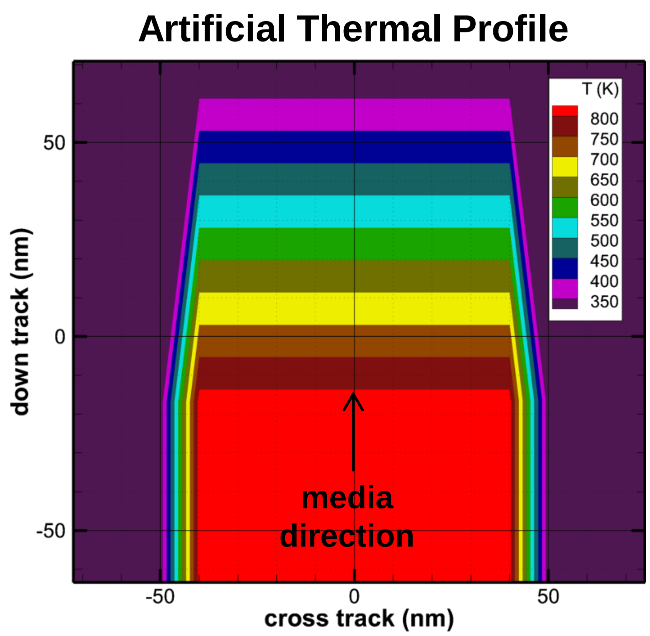


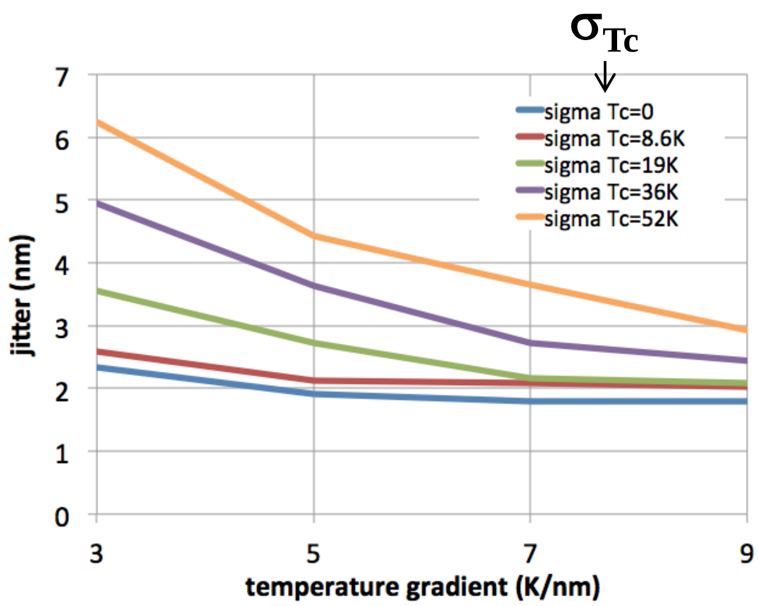

**Measured Gradient (Good Head)**

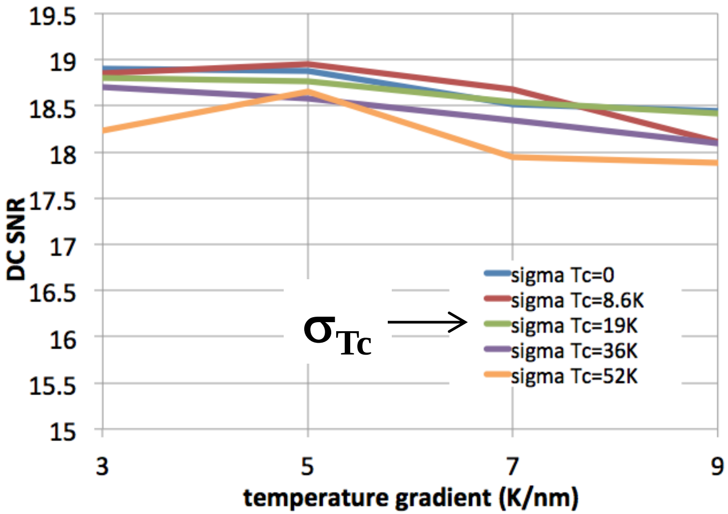



- **Down-track thermal gradient can be determined by transition shift or jitter method.**
  - Cross-track gradient from MWW with assumptions.
- **Gradient is given by: ΔT(write) x power modulation/transition shift.**
- **Media heat-sinking strongly modulates thermal gradients and improves track-squeeze 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



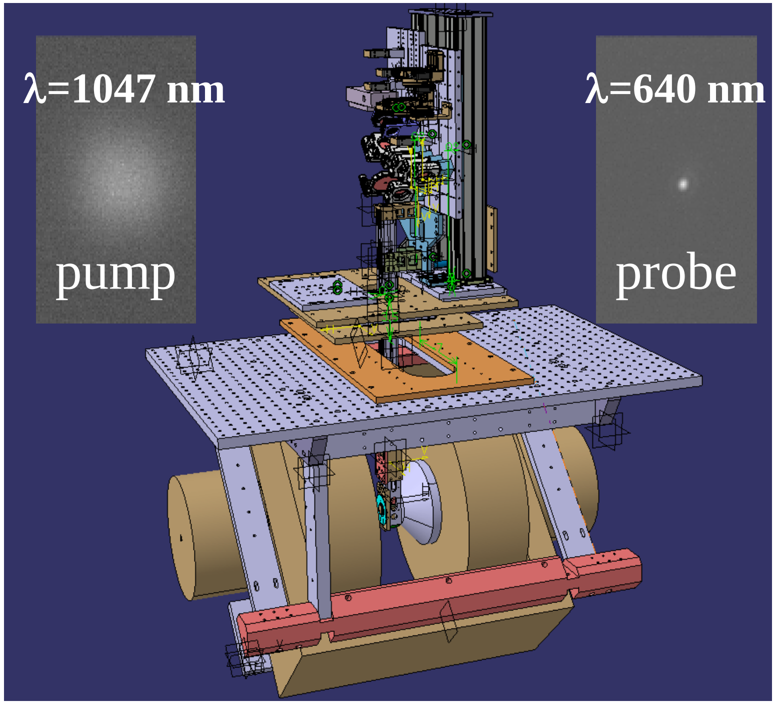




- Simplified writing:
  - **Apply constant themal gradient *dT/dx*.**
  - **Apply uniform write field.**
  - **Switch write field polarity.**
- Perpendicular write field magnitude (7kOe), write field **linear ramp in 0.4 ns** and non-Gaussian $T_c$ - distribution used.
- **Jitter strongly depends on 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/e[2])
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

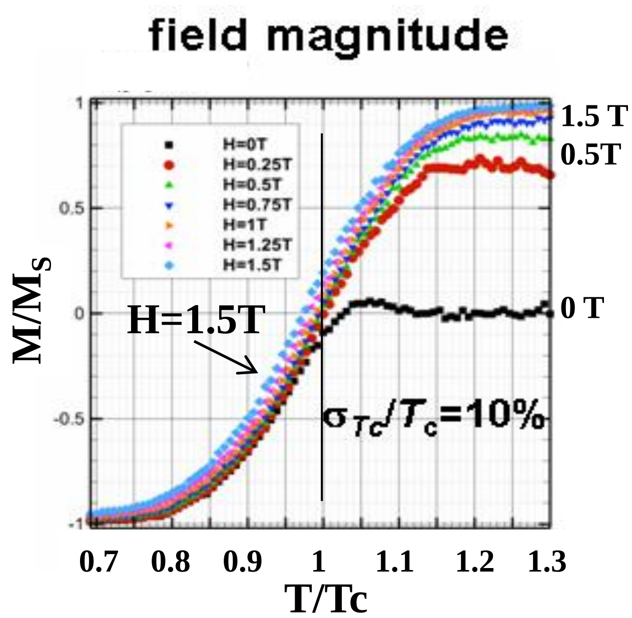
- Tool measures thermal remanence after nanosecond laser pulse in known applied field
  - Short pulse ensures fast cooling and 1D heat flow
- Remanence vs. field and angle can be used to characterize grain freezing effects
- **Remanence vs. pulse power can be used to measure sigma-$T_c$**

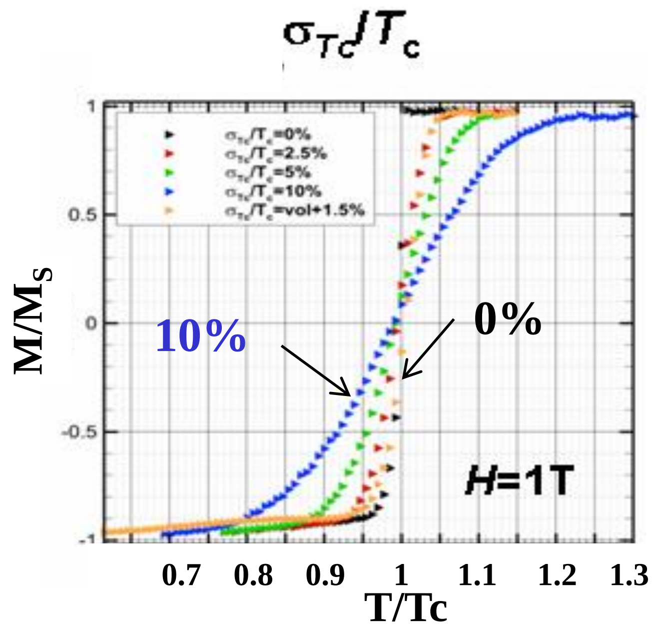
**S. Pisana**, S. Jain, J.W. Reiner, G.J. Parker, C.C. Poon, O. Hellwig and B.C. Stipe "Measurement of the Curie temperature distribution in FePt granular magnetic media" to be published

# Remanence vs. pulse power to measure sigma $T_C$

**modeling**

**1 ns pump pulse**

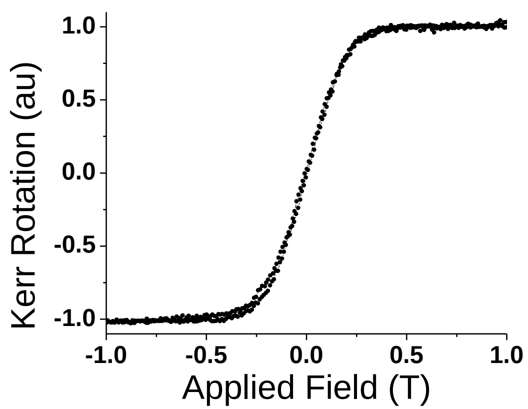


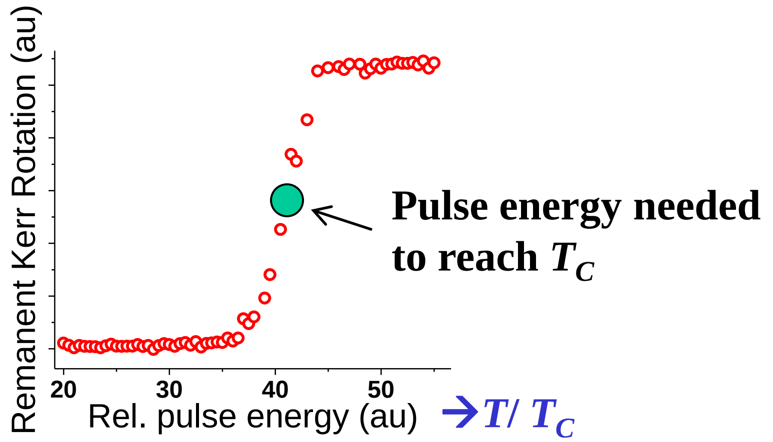




**experiments**

**5 ns pump pulse**

**measure several ms after pump @ each point**

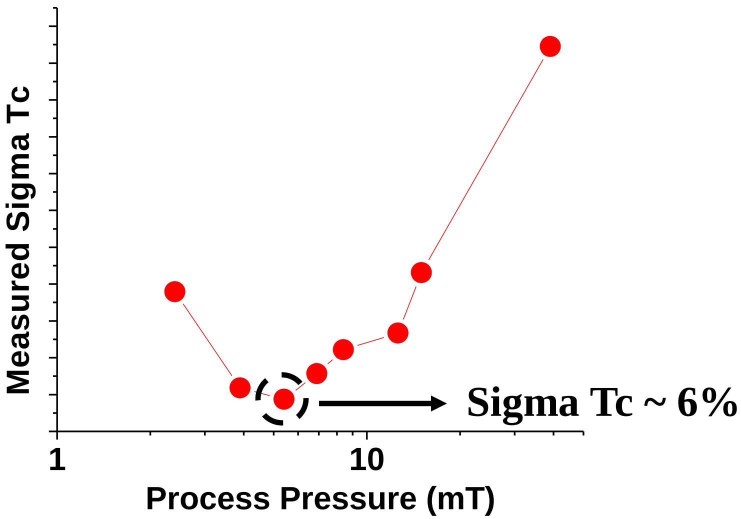


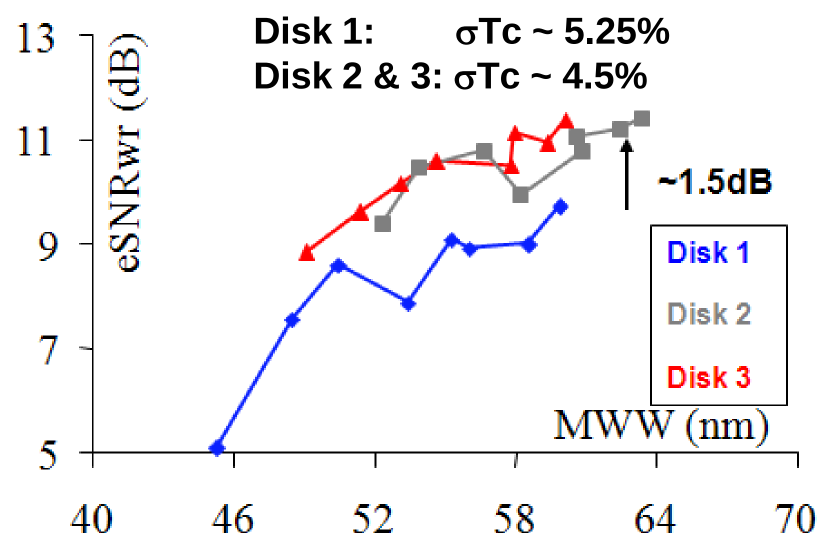

**S. Pisana**, S. Jain, J.W. Reiner, G.J. Parker, C.C. Poon, O. Hellwig and B.C. Stipe "Measurement of the Curie temperature distribution in FePt granular magnetic media" to be published 2014

# Curie Temperature Distribution $\sigma_{TC}$ and Performance

**Sputter Optimization**



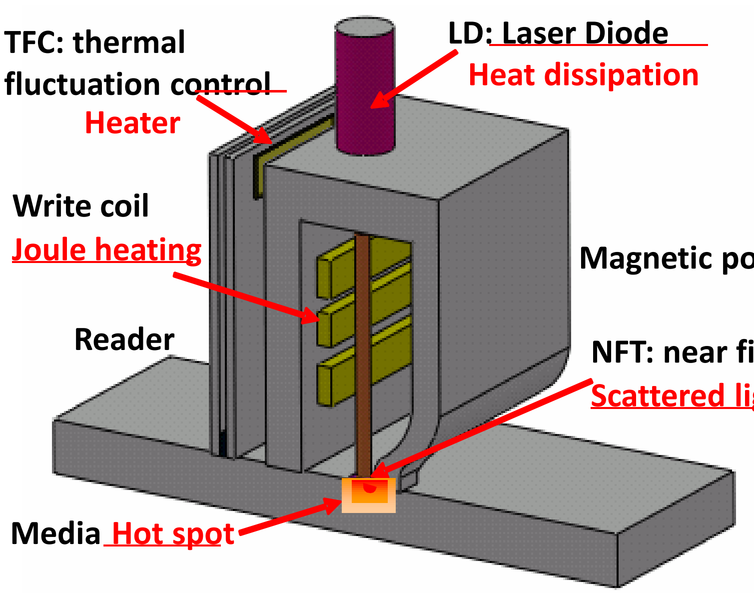

**Segregant Optimization**

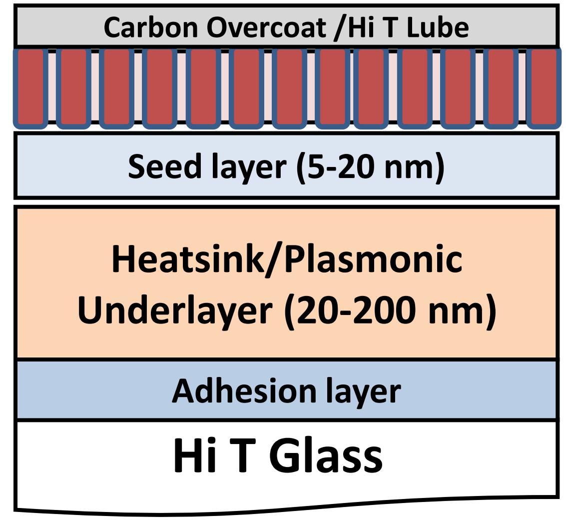



**MWW=Magnetic Write Width**

- **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**

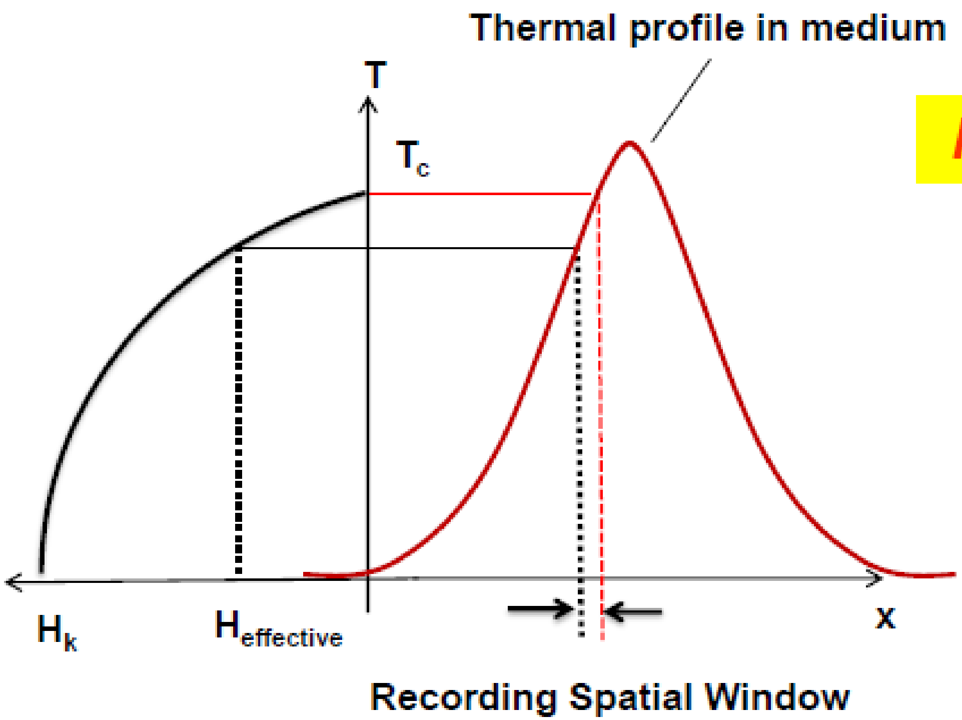
# Recording Time window




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 - Jimmy Zhu / CMU Pittsburgh




**Recording Time Window**

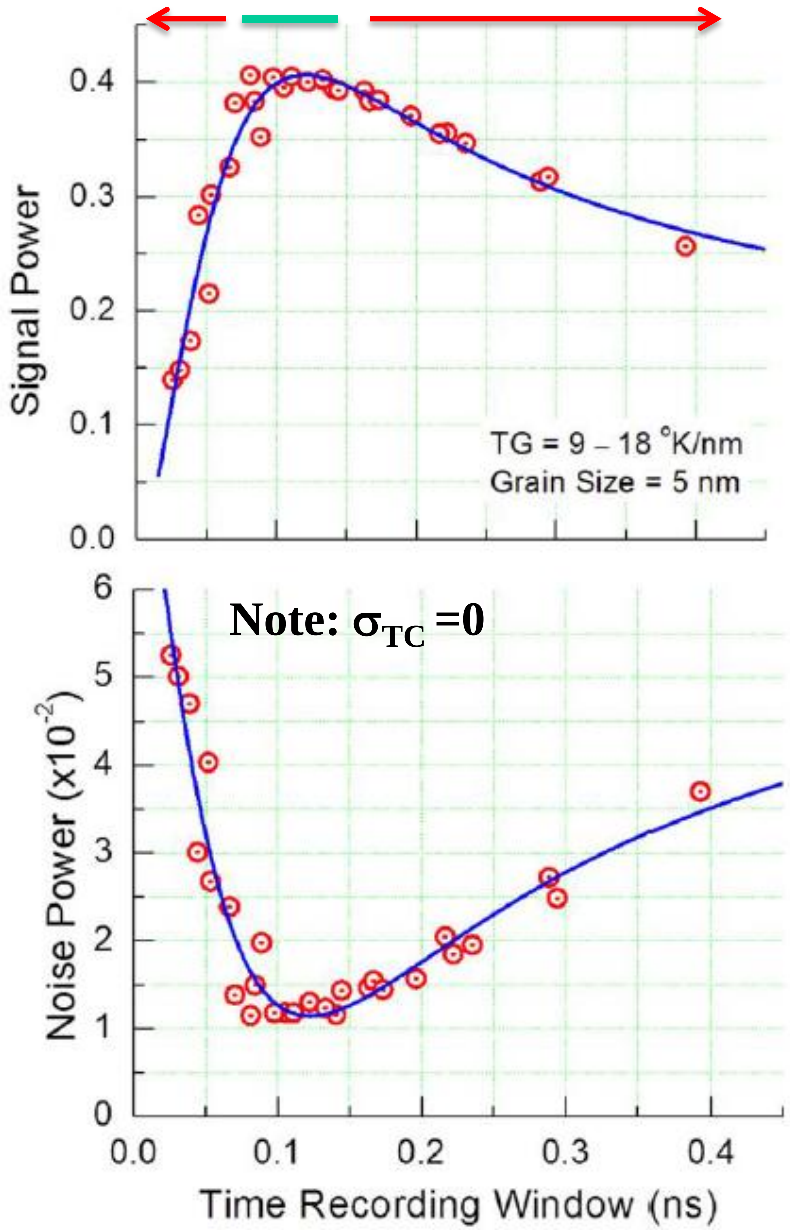
$$\Delta t = \frac{T_c - T_{rec}}{\frac{dT}{dx} \cdot v}$$

**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.

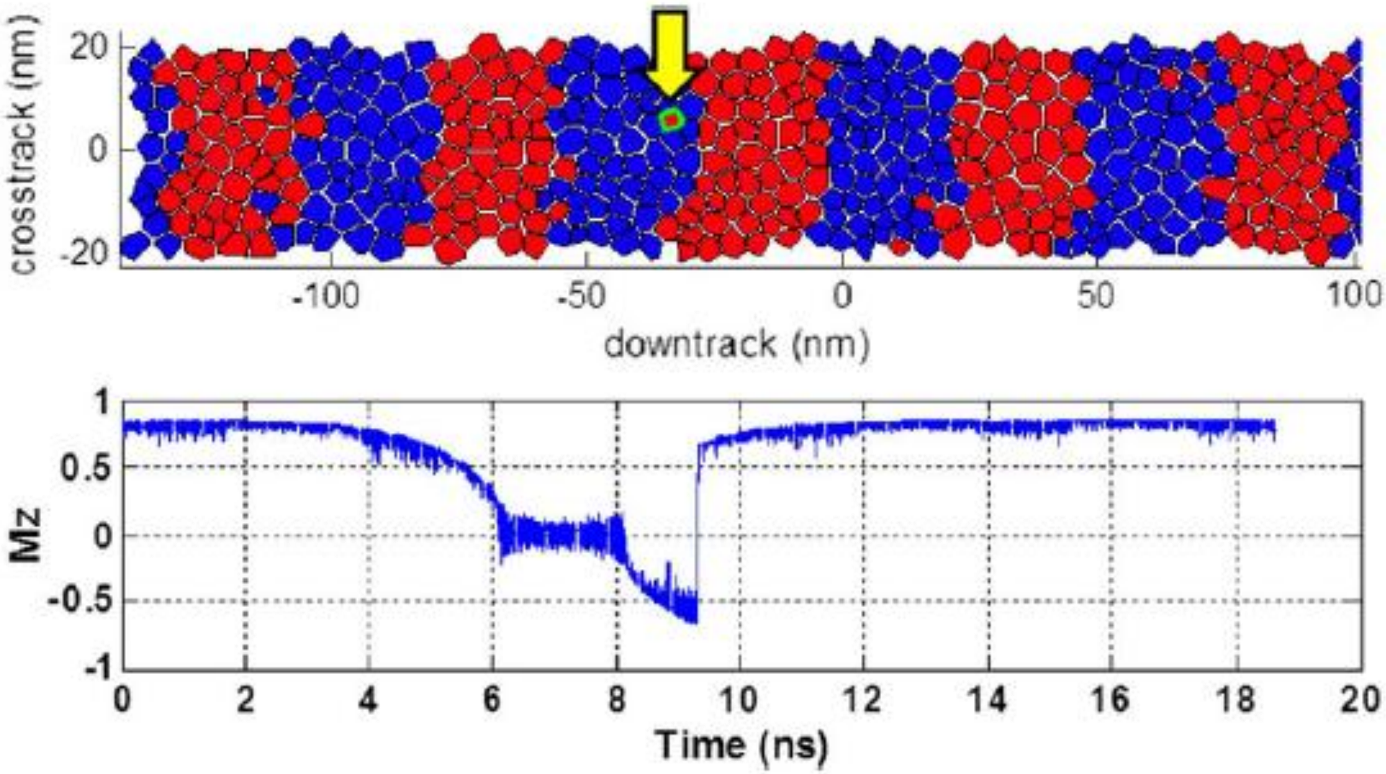
•Tight correlation between signal and noise in the recording time window

•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

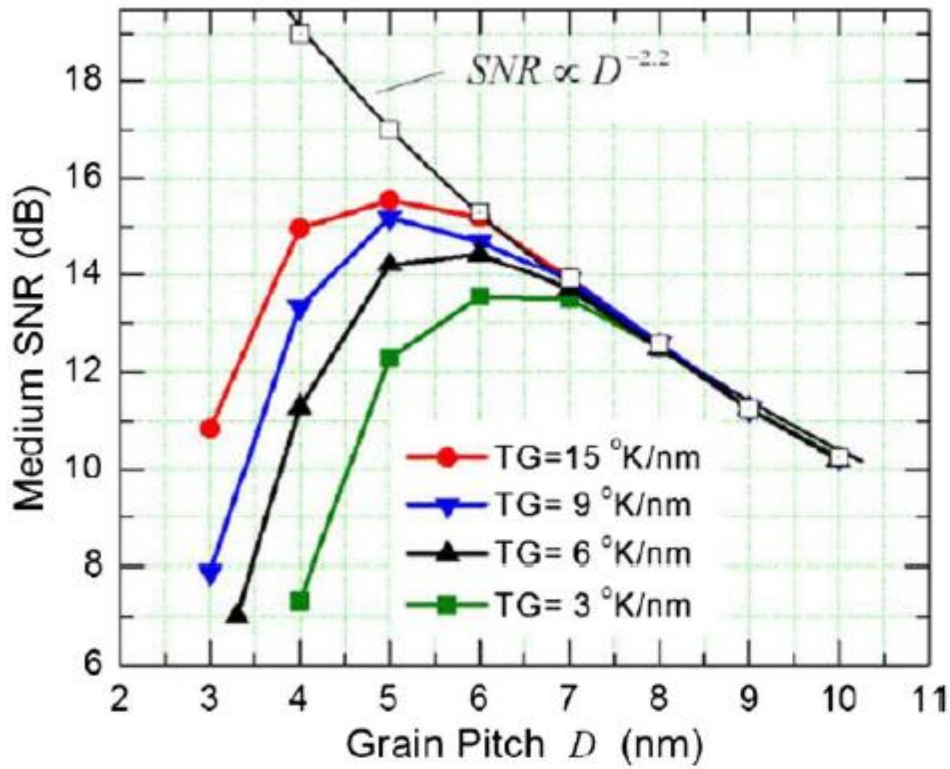
$$\Delta t = \frac{T_C - T_{rec}}{\frac{dT}{dx} \cdot v}$$

| | 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 **$\Delta t$ ~ 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 **$\Delta t$ ~ 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, $\sigma_{HK}$ = 10%, $\sigma_{Tc}$ = 0% and $dH_K/dT \sim 600$ Oe/K.

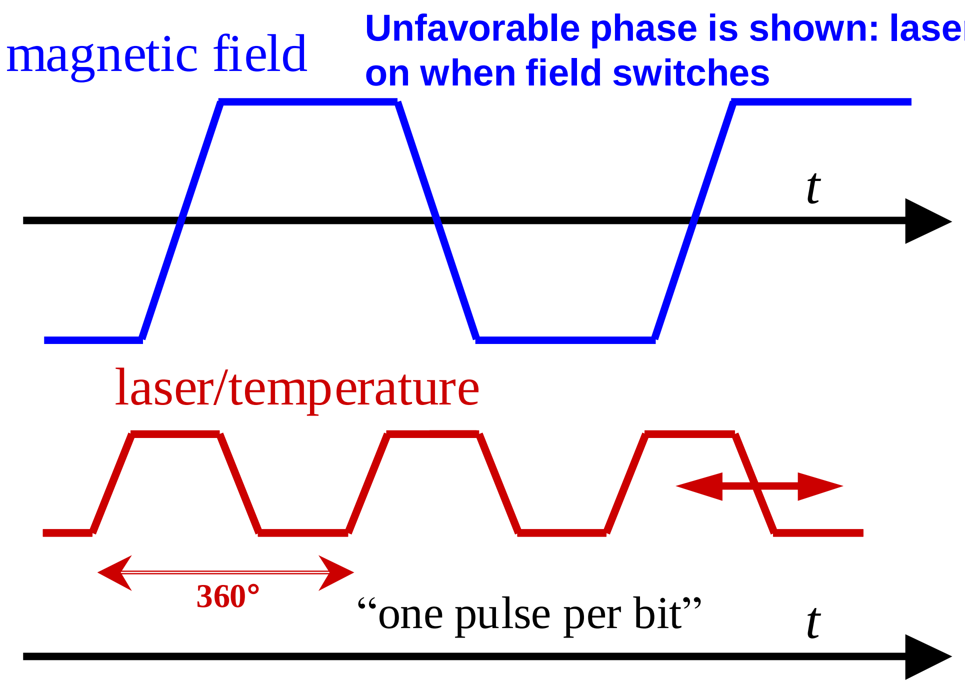

**Jian-Gang Zhu** and Hai Li, "Understanding Signal and Noise in HAMR" IEEE Trans Mag 49, 765 (2013)
**D. Weller**, G. Parker, O. Mosendz, E. Champion, B. Stipe, X. Wang, T. Klemmer, G. Ju, A. Ajan, "A HAMR Media Technology Roadmap to an Areal Density of 4 Tbpsi" IEEE Trans Mag 50, 3100108 (2014)

# Pulsing the Laser in HAMR Recording

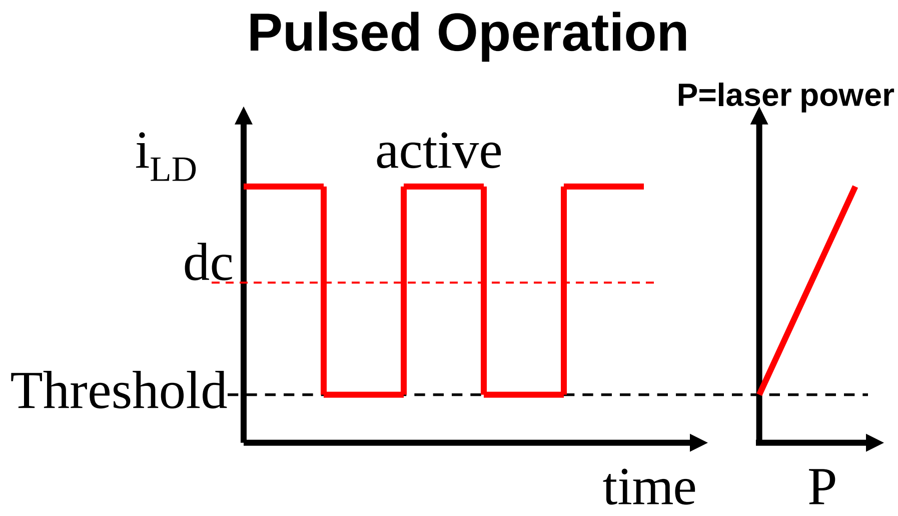
- **Why Pulsing?**
- **Reason #1**
  - **Laser only switched on when needed**
  - **Can lead to lower mean temperatures of the NFT => longer head life**
    - **Head life is a known problem for HAMR**
- **Reason #2:**
  - **Increased temperature gradient can lead to improved recording performance**
-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



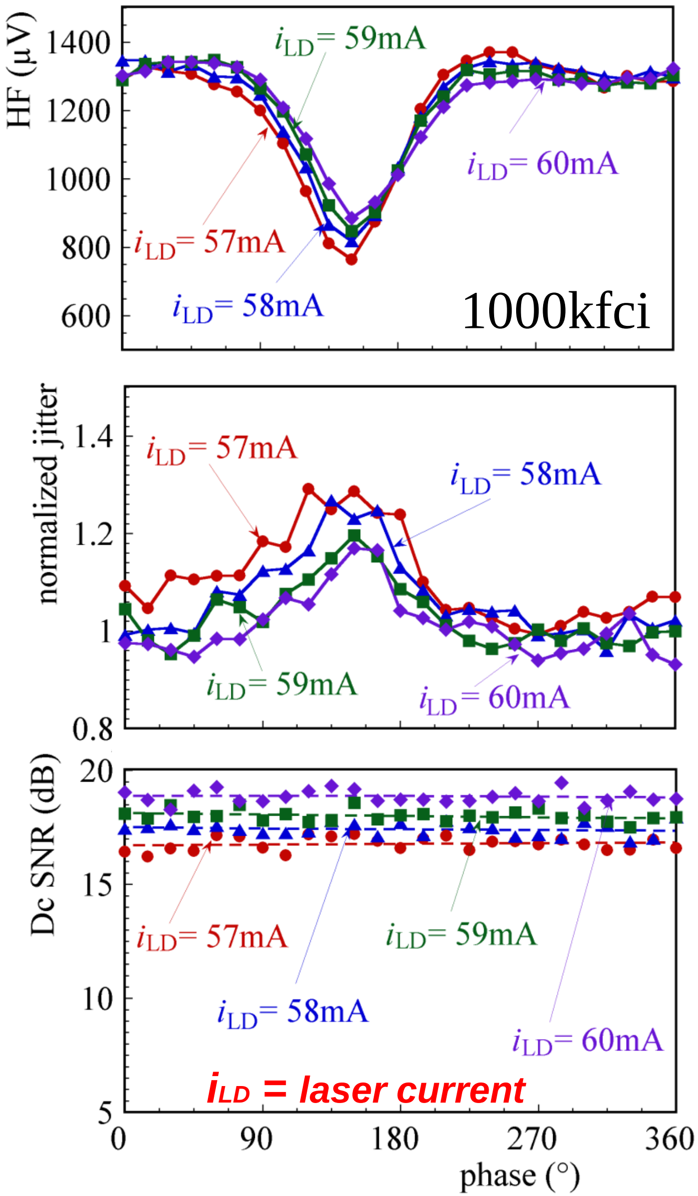

$i_{LD}$=threshold current the laser needs to turn on




- **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

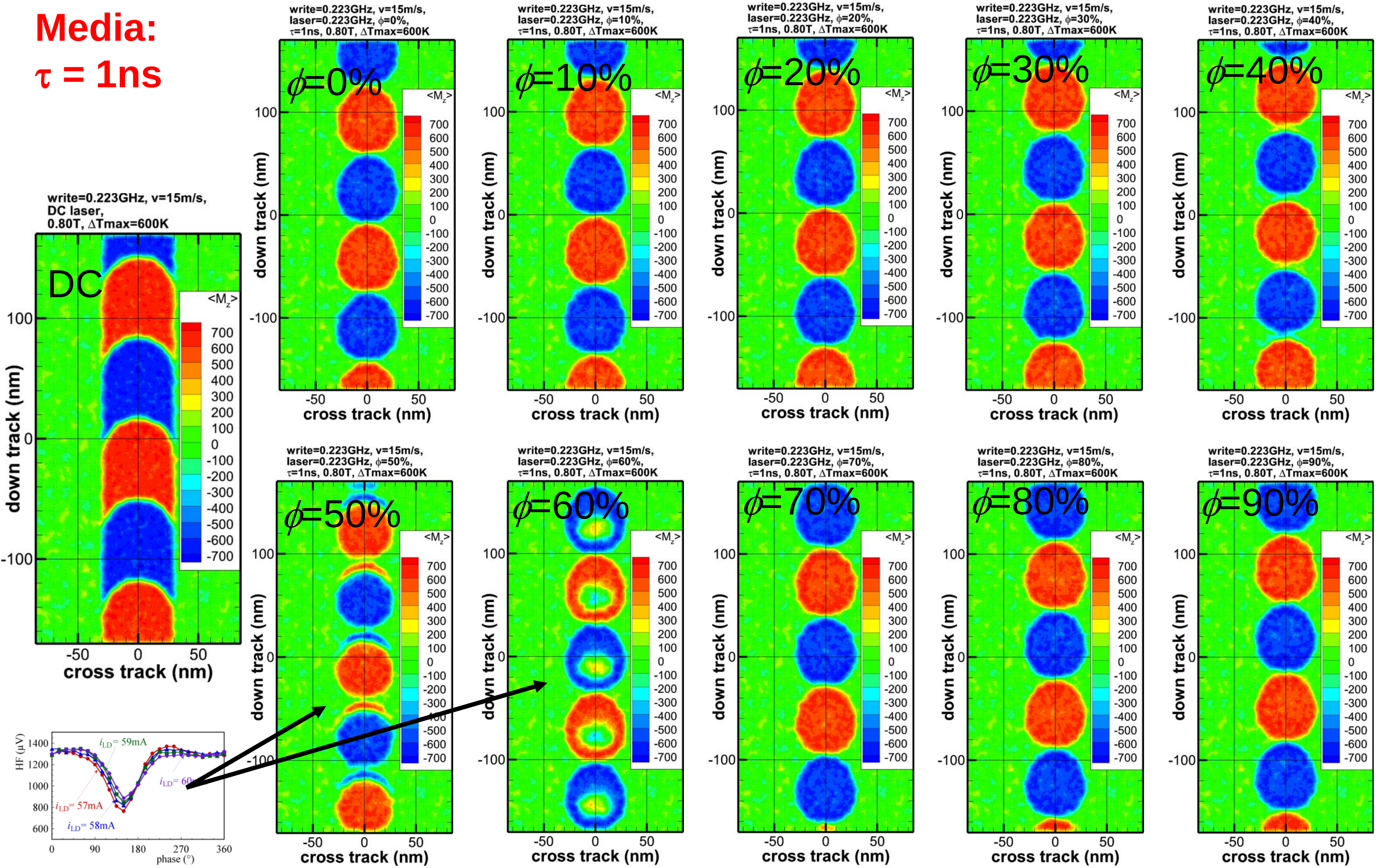



- **High frequency amplitude (HF) shows a dip**
- **The jitter deteriorates when the phase between the write field and the laser pulse is not optimized**
- **DC SNR is not affected by phase**
  - **(Note: multiple pulses per "long bit")**
  - **Confirms that phase of laser pulses affect only transitions**

**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:**
**$\tau$ = 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 |
| $\sigma_{HK}/H_K$ (%) | 5.0-10.0 | 5.0-10.0 |
| $T_C$ (K) | <=750 | 700 - 750 |
| $\sigma_{Tc}/T_C$ (%) | 2.0 | 2.0 |
| $\sigma_\theta$ (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 $\sigma_{Tc}$/Tc ~ 2% requirement | improved sputter conditions, seed layers, growth temperature and optimized exchange coupling | new characterization techniques, correlation of $\sigma_{Tc}$/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 |



D. Weller et al. IEEE Trans Mag 50, 3100108 (2014)

# Summary and Future Statements

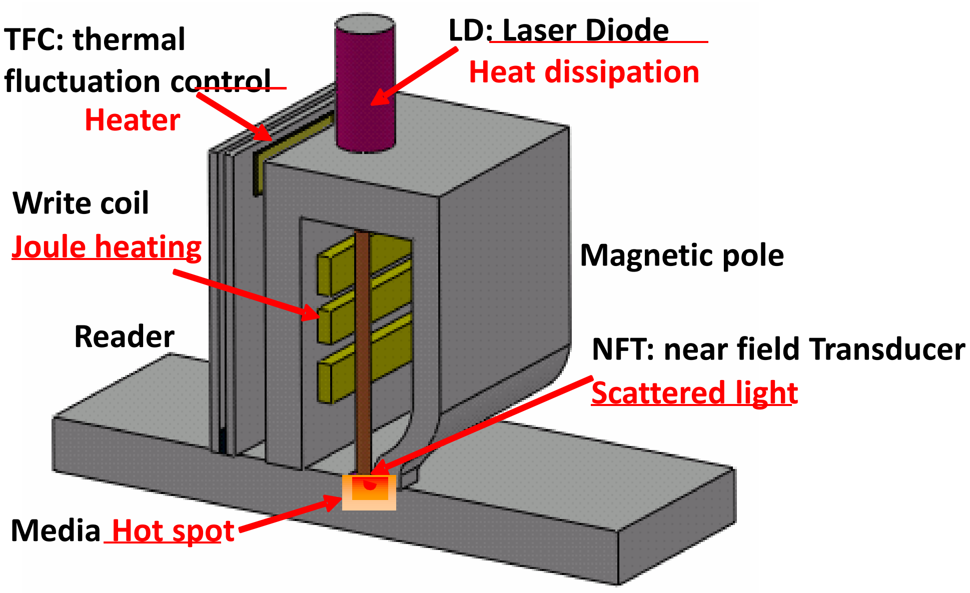
**A better understanding of HAMR recording has been achieved**
**- much improved granular $L1_O$ FePtX-Y media**
**- better heads and optimized recording time ~1ns aiming toward ~0.2-0.4 ns**
**- many challenges are focused on**

**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

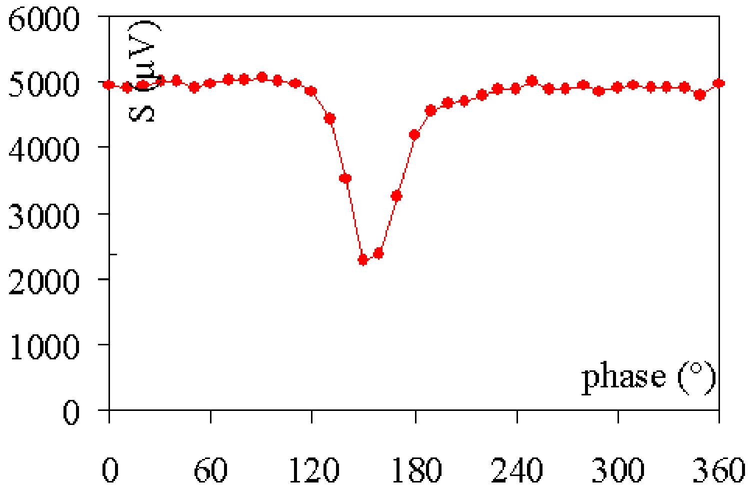
# Abbreviations

| | |
|---|---|
| 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) |

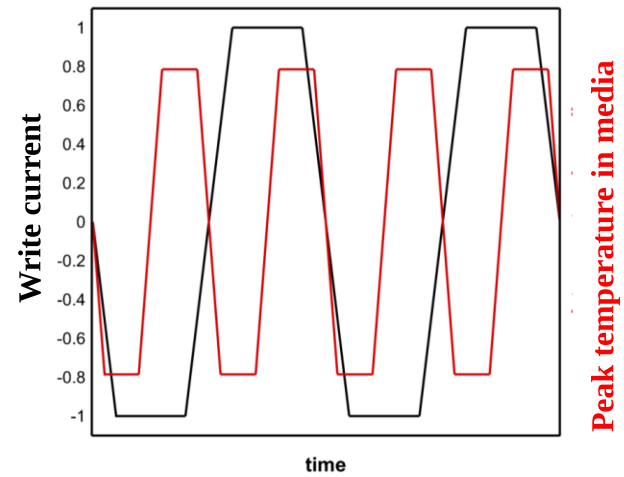
| | |
|---|---|
| CMU: | Carnegie Mellow University |
| ASTC: | Advanced Storage Technology Consortium |
| IDEMA: | International Disk Drive Equipment and Materials Association |

# Pulsed Recording on Spinstand – Phase Dependence Summary

**Signal vs. Pulse Phase on Spinstand**

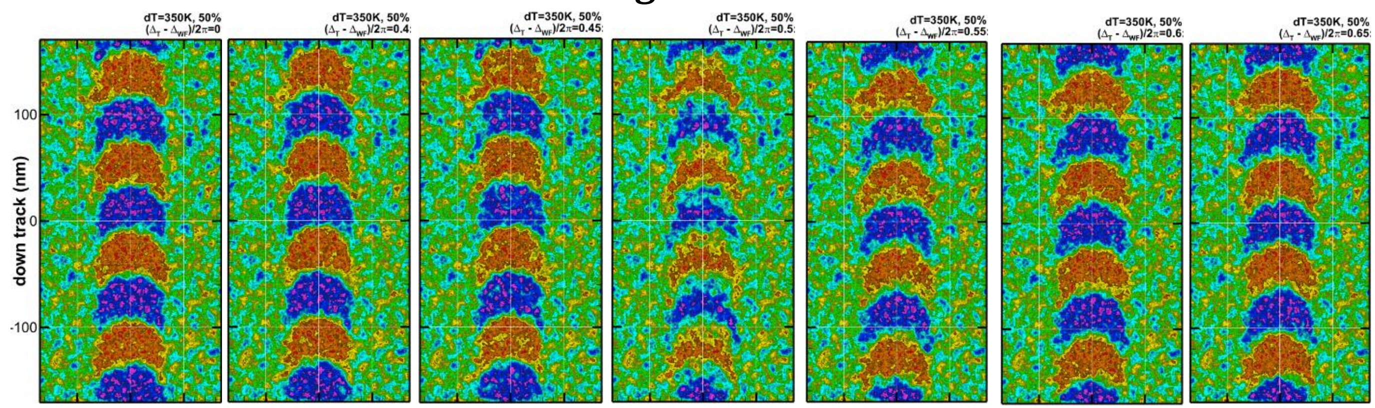



**Timing for Worst Recording**




**Media:**
**τ = 1ns**

**Recording Model vs. Phase**



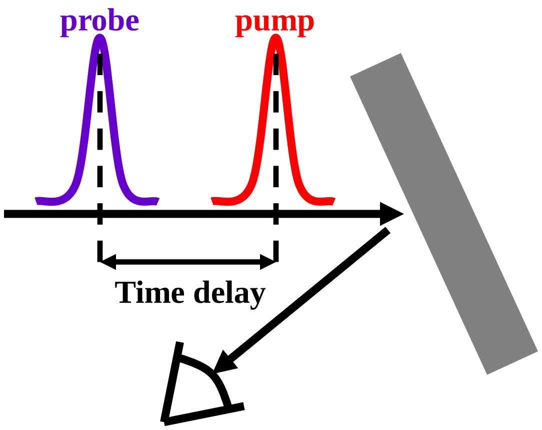

- **Poor recording occurs if grains freeze while applied field is slewing through zero.**
- **Also need to optimize frequency and pulse parameters for best recording.**

# Thermal properties by time-domain thermoreflectance

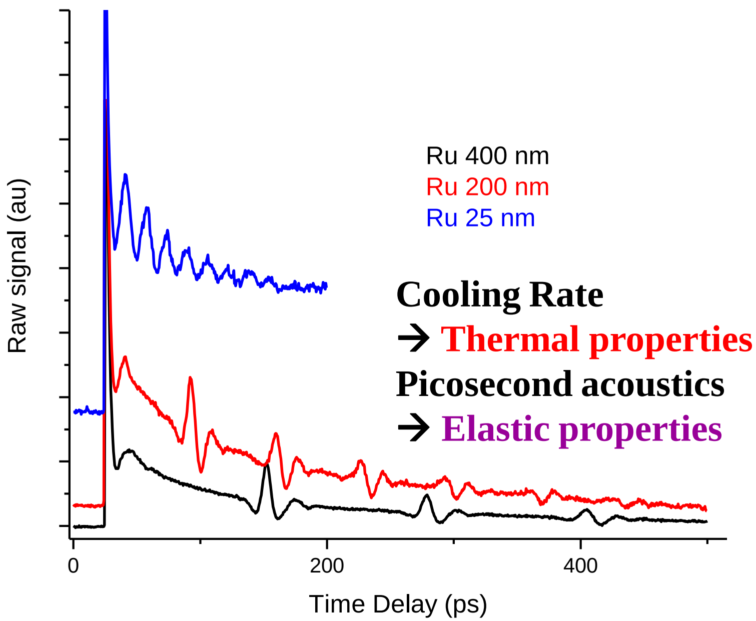
- **Measure cooling rate of the sample after a heat pulse**
- **Temperature measurement made by thermoreflectance**

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

- **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**

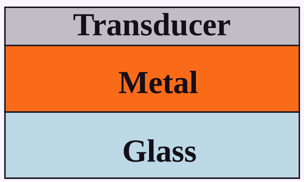


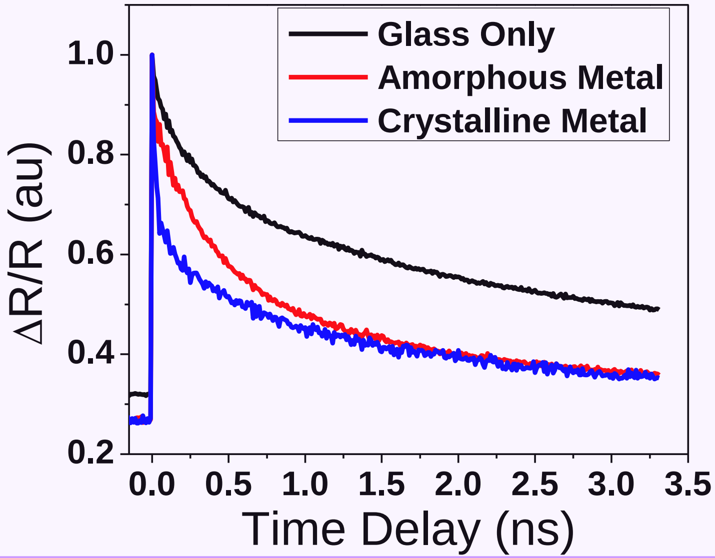

- **The technique is the most versatile for thin films**
- **Works for metals and dielectrics and multilayers**
- **Can quantify thermal conductivity Λ and interface thermal boundary conductance G**
- **Can be adapted to measure thermal anisotropy – normal sensitivity is out-of-plane**

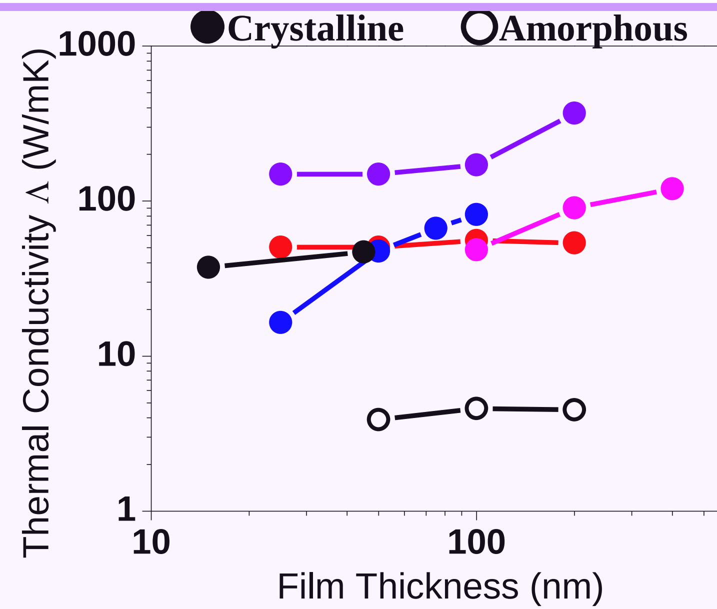
**D.G. Cahill, Rev. Sci. Instrum. 75, 5119 (2004)**
**A.J. Schmidt et al, Rev. Sci. Instrum. 79, 114902 (2008)**
**P.E. Hopkins et al., J. Heat Transfer 132, 081302 (2010)**

# Thermal properties by time-domain thermoreflectance

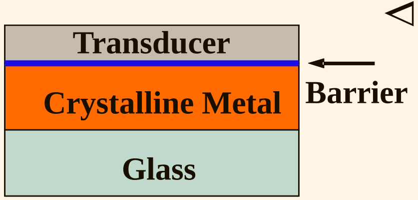
**Determination of Thermal Conductivity Λ**

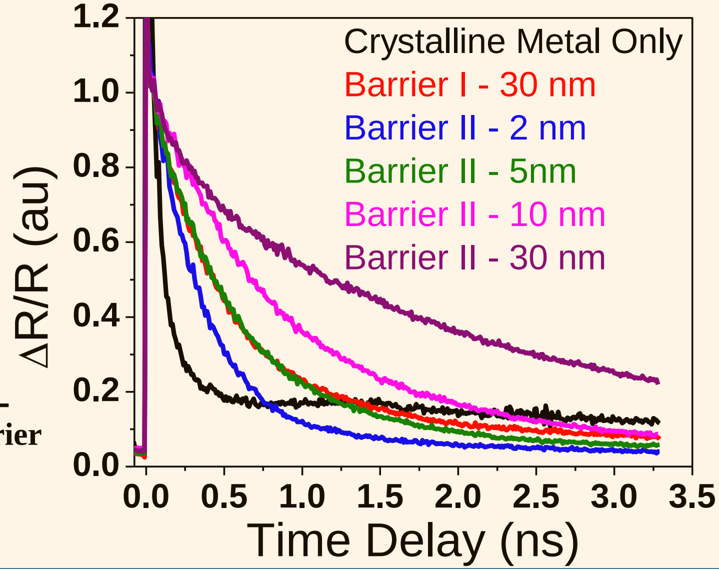


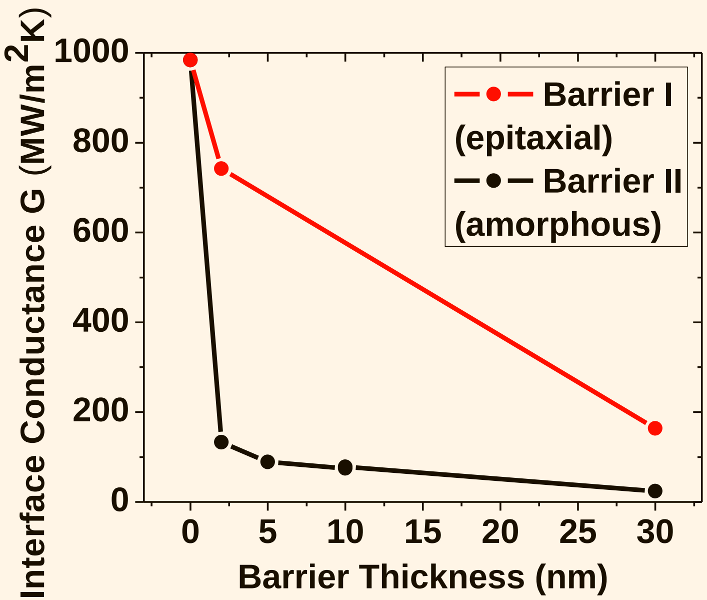




**Determination of Interface Thermal Conductance G**

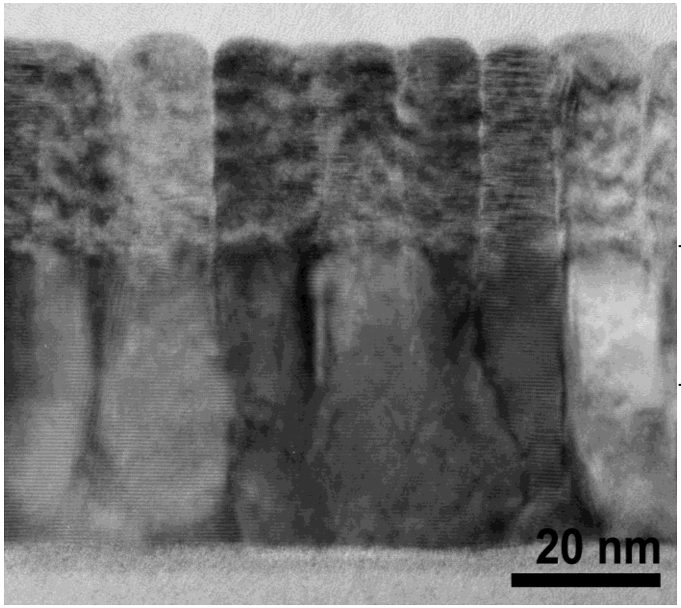


# PMR versus HAMR media structure

## PMR-media




**CoCrPt media**
(RT, columnar)

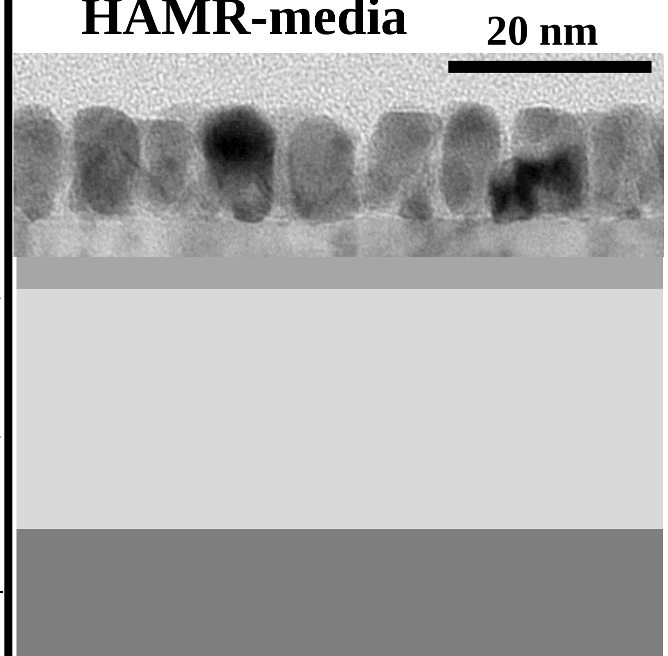
**Ru (hp)**
(set grain isolation)

**Ru (lp)**
(set grain size)

(set orientation)

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

## HAMR-media




**FePt-$L1_0$ + segregant**
(high temp.)

**MgO seed**
(diff. barrier)

**heat sink**
(set texture)

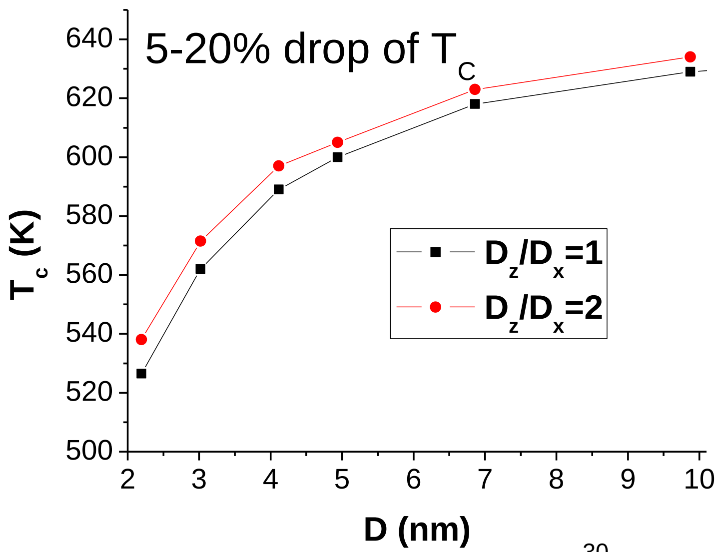
**heat sink seed and adhesion**

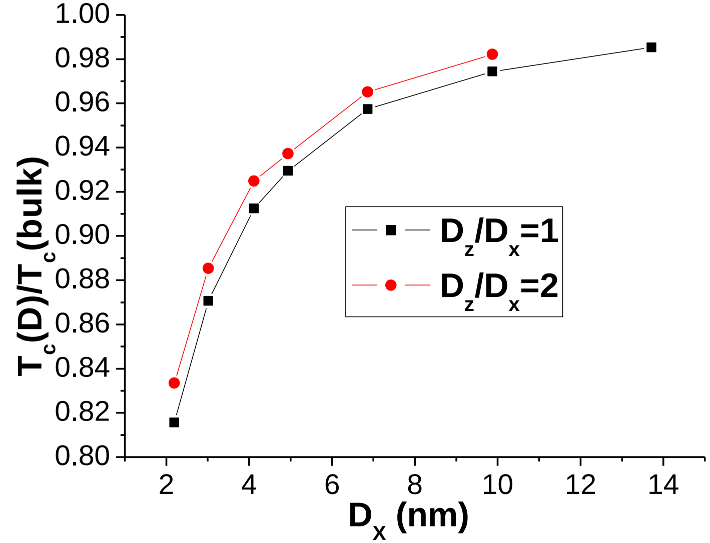
crucial interface: seed ➔ FePt grains

- 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, …**

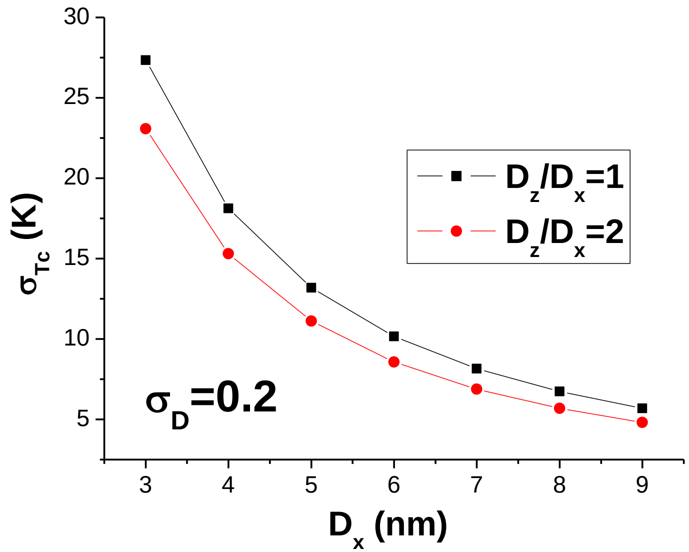
# Andreas Lyberatos Modeling - 2012 & 2013




D=8nm → $\sigma_{Tc}$~1%

D=4nm → $\sigma_{Tc}$~2.5%




**Modeling details (see papers*)**

$\sigma = T_{cxo}/n*D_x/a\wedge(-1/n)*\sigma_L$

$D_z/D_x=1$, $x_o=2.37$, $n=0.7$

$D_z/D_x=2$, $x_o=2$, $n=0.7$

$T_c=750K$, $\sigma_L=0.2$

**<u>Key statement:</u>**

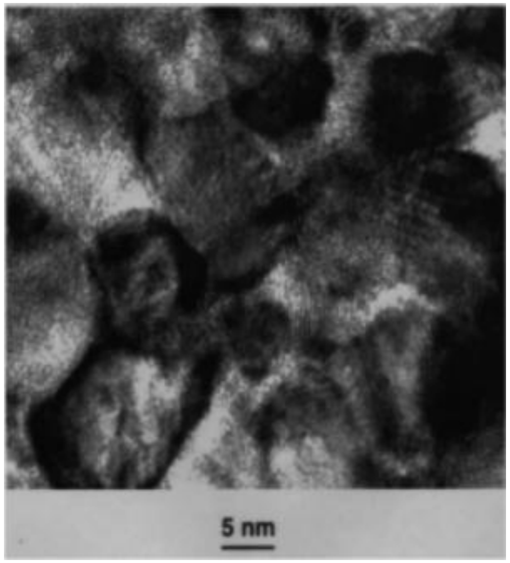
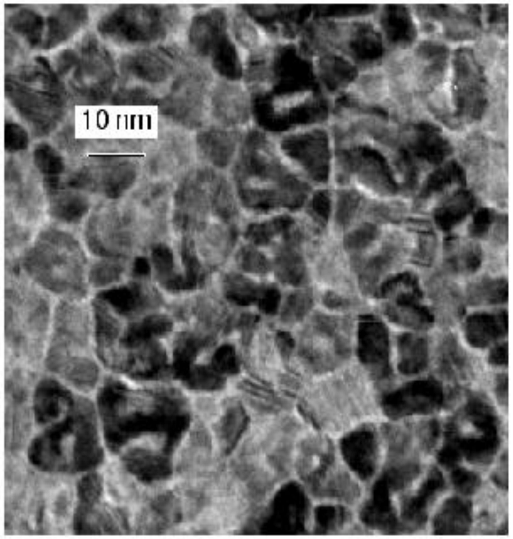
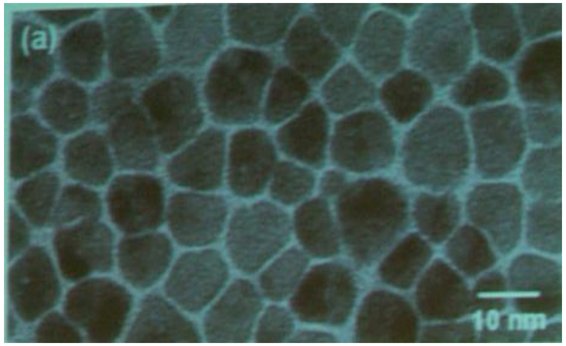
**Reducing D increases $\sigma_{Tc}$**

**Need to reduce $\sigma_D$**

*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 | 2000 LMR | 2012 PMR |
|---|---|---|
|  |  |  |



| | | |
|---|---|---|
| 10 Gb/in$^2$ product media grains, $\sigma_{area}$ ~ 0.9 | 35 Gb/in$^2$ prototype media 8.5 nm grains, $\sigma_{area}$ ~ 0.6 | 750 Gb/in$^2$ prototype media 12 nm 8.5 nm grains, $\sigma_{area}$ ~ 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/in$^2$**