Progress and Challenges in Magnetic Data Storage

Mark H. Kryder

Seagate
We turn on ideas

Invention of the Disk Drive - 1956

IBM 305 RAMAC

(Random Access Method of Accounting and Control)

5 Megabyte Capacity
50 disks, each 24 inches in diameter
2000 bits/in^2 storage density.

This drive could store 2000 pages of text with 2500 characters per page.

Cheetah 15K.5

Perpendicular Recording

First 300 Gbyte 15 Krpm disk drive.

1.4 Million Hour MTBF.

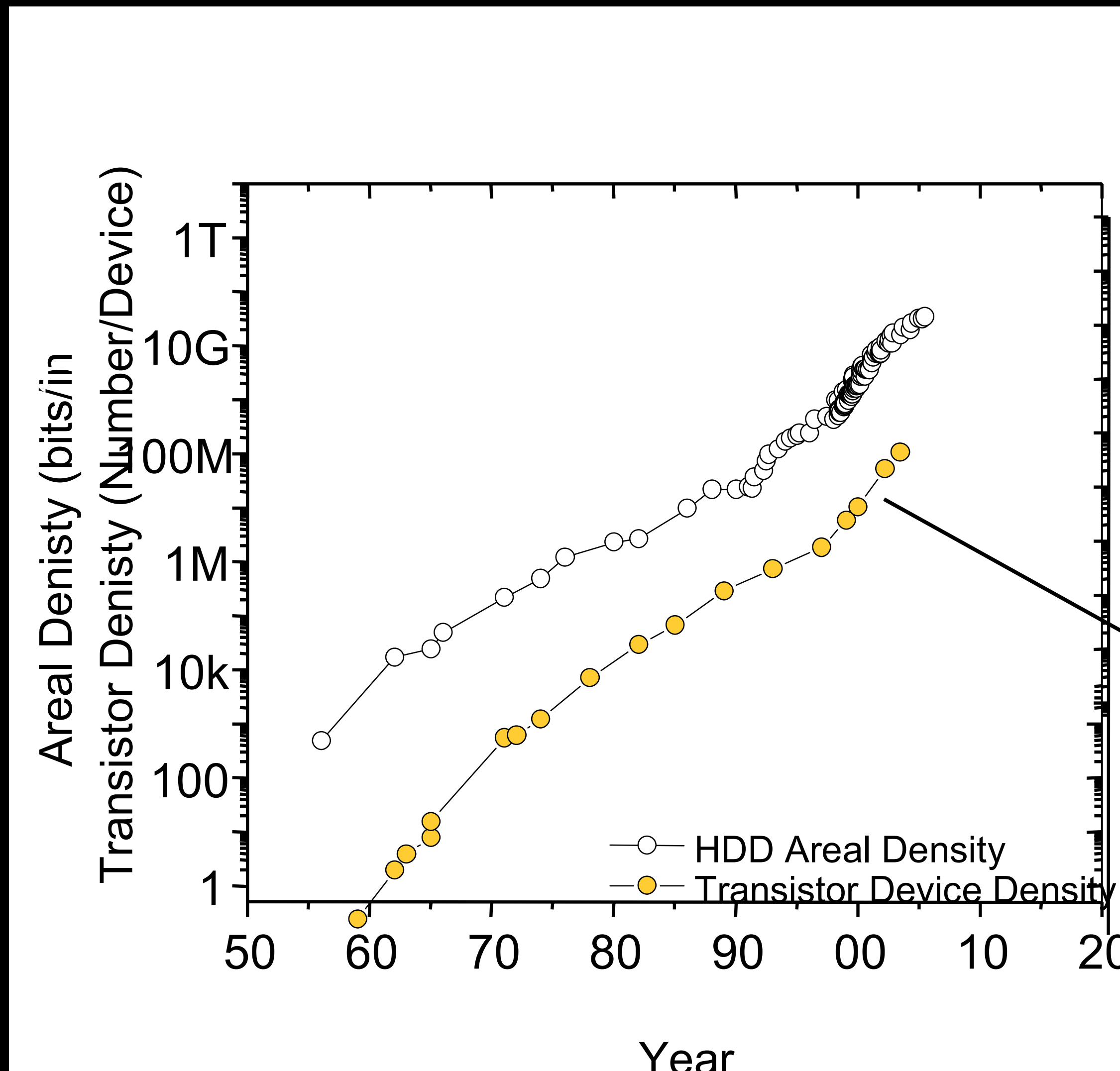
Nonrecoverable Read Error Rate: 1 sector per 10e16

Average R/W time: 3.5/4.0 msec

Latency: 2 msec

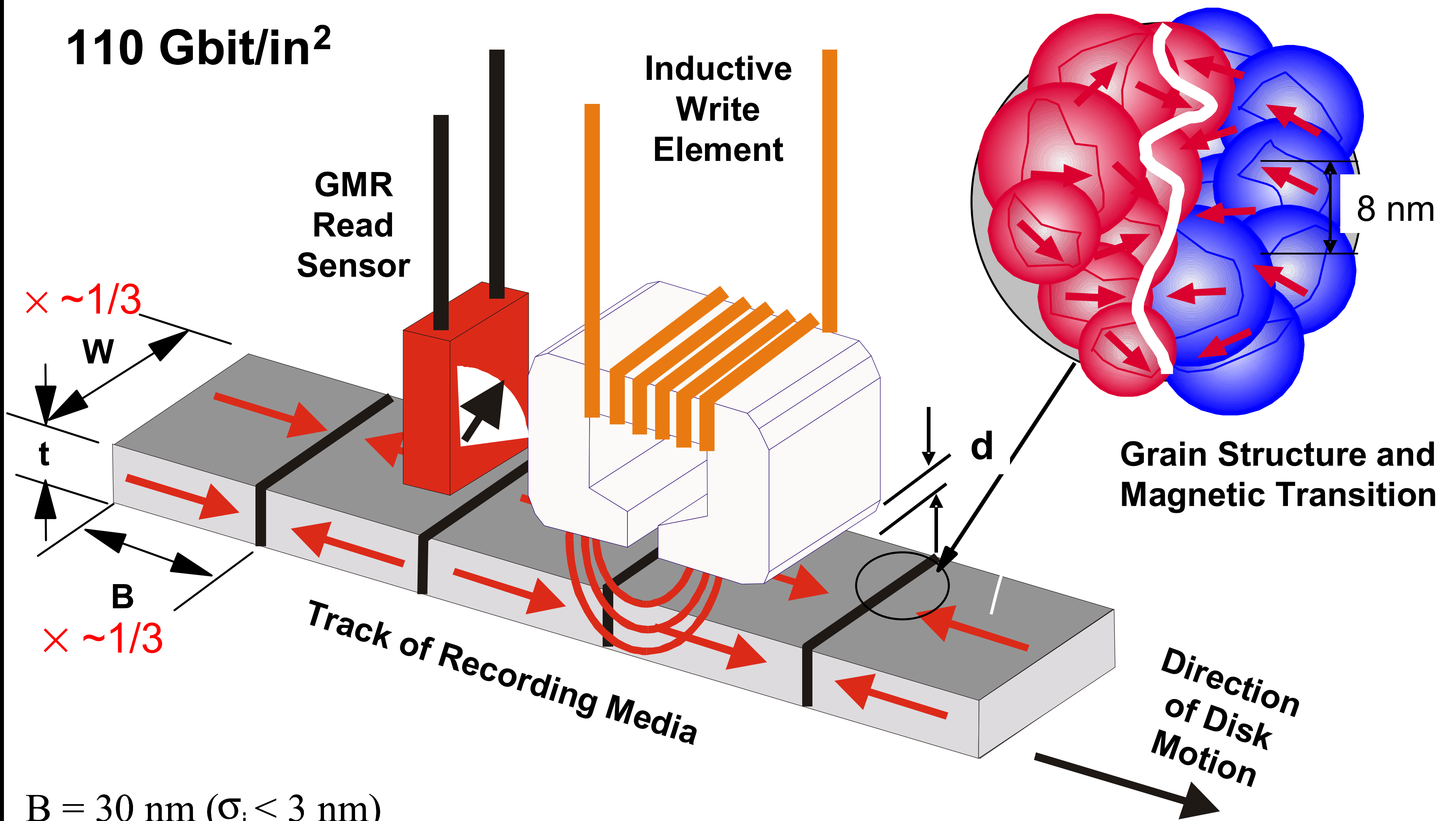
125 MB/s Sustained Transfer Rate

HDD Areal Density vs. Moore's Law



Note – chip size has grown over time

Recording Basics – Some Dimensions

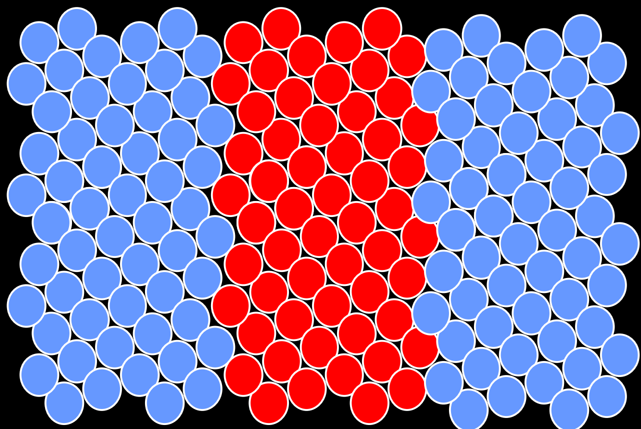


B = 30 nm ($\sigma_j < 3$ nm)

W=194 nm, t = 15 nm, d= 10 nm

Need $\sigma_j \sim$ 1nm at Tbpsi Densities

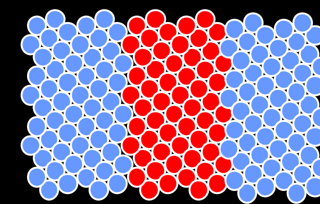
Superparamagnetism



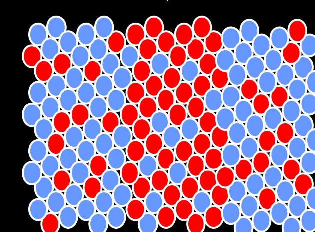
To preserve SNR, number of grains in a bit must be constant.

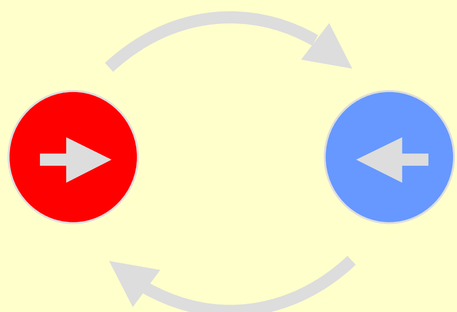
$$SNR \sim \log_{10}(N)$$

Therefore higher densities require smaller grains



The smaller bits have a higher probability of flipping and the data is unstable

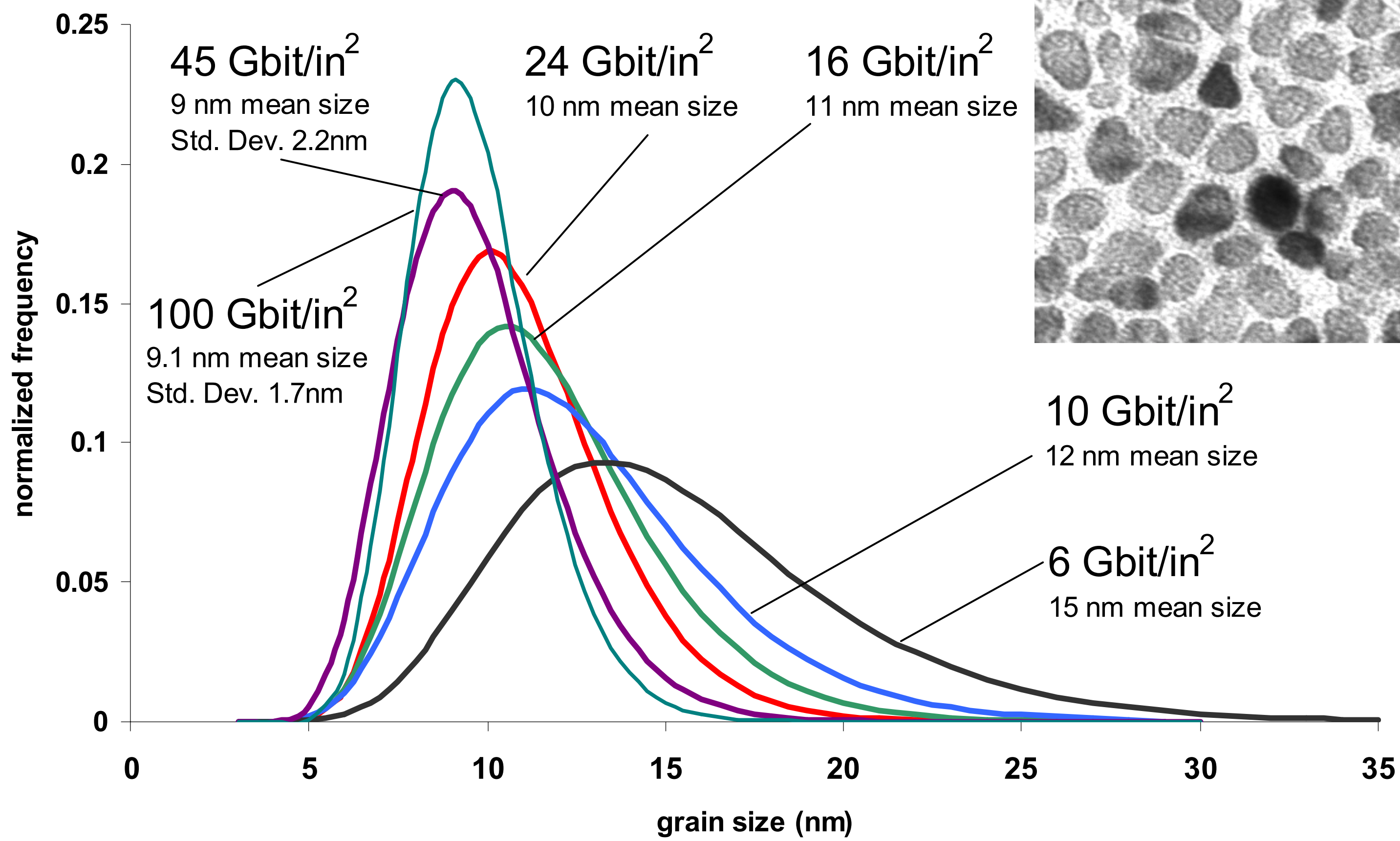




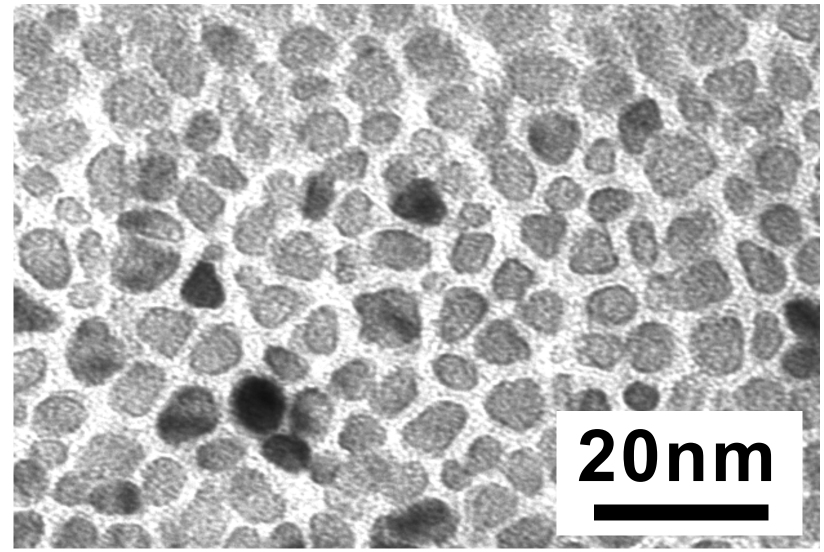
High areal density means small volume

$$\tau = \frac{1}{f_0} e^{\frac{K_u V}{k_B T}}$$

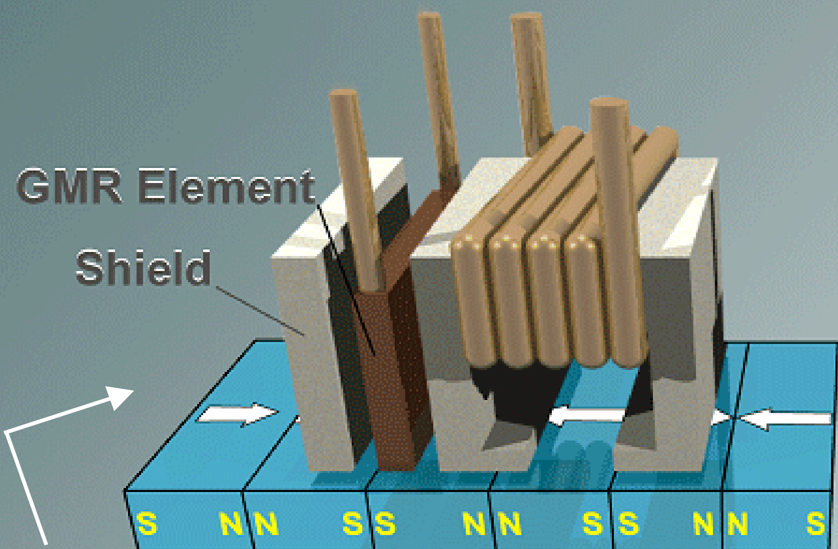
Magnetic Media Evolution



Physical grain size below 10 nm



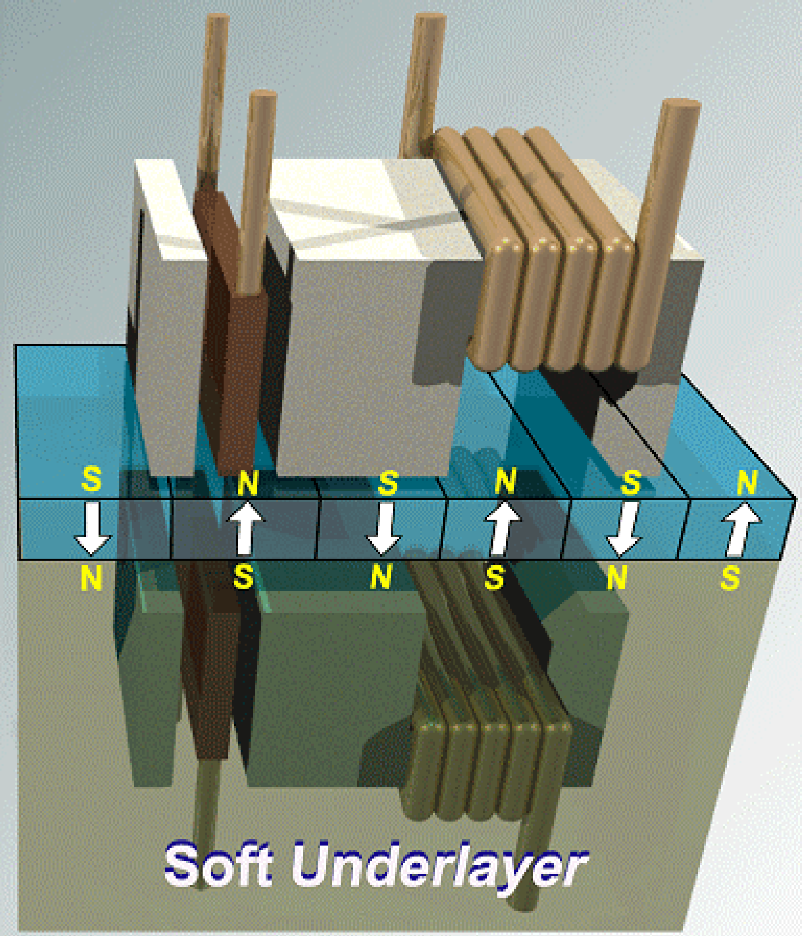
Longitudinal Recording



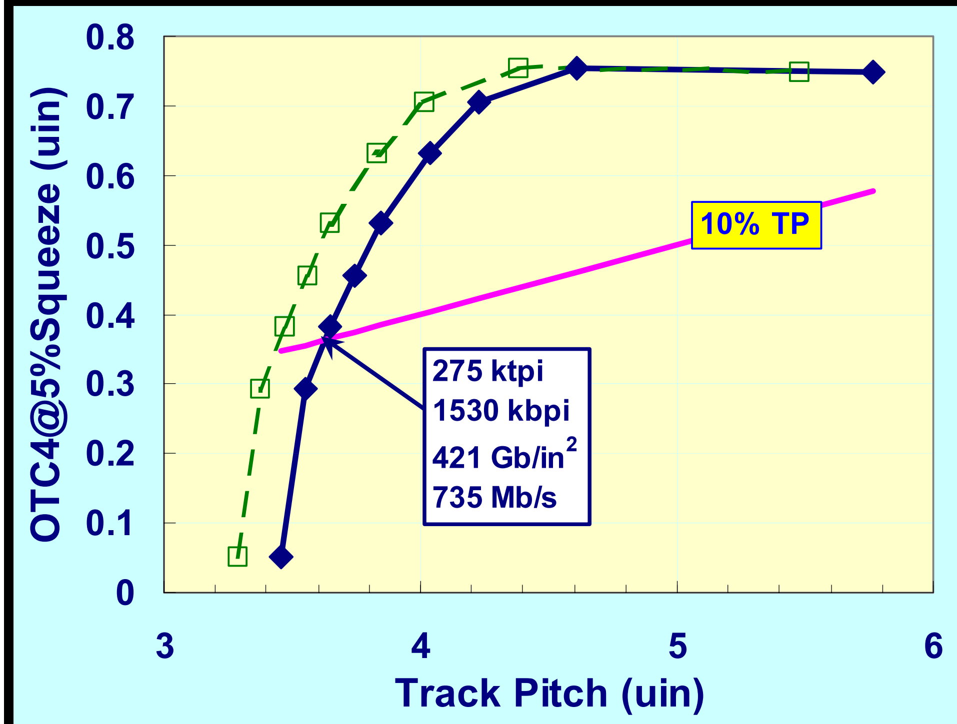
Magnetic domains oriented in the direction of travel of the head.

Soft underlayer "mirrors" write head and makes it possible to write domains much closer together.

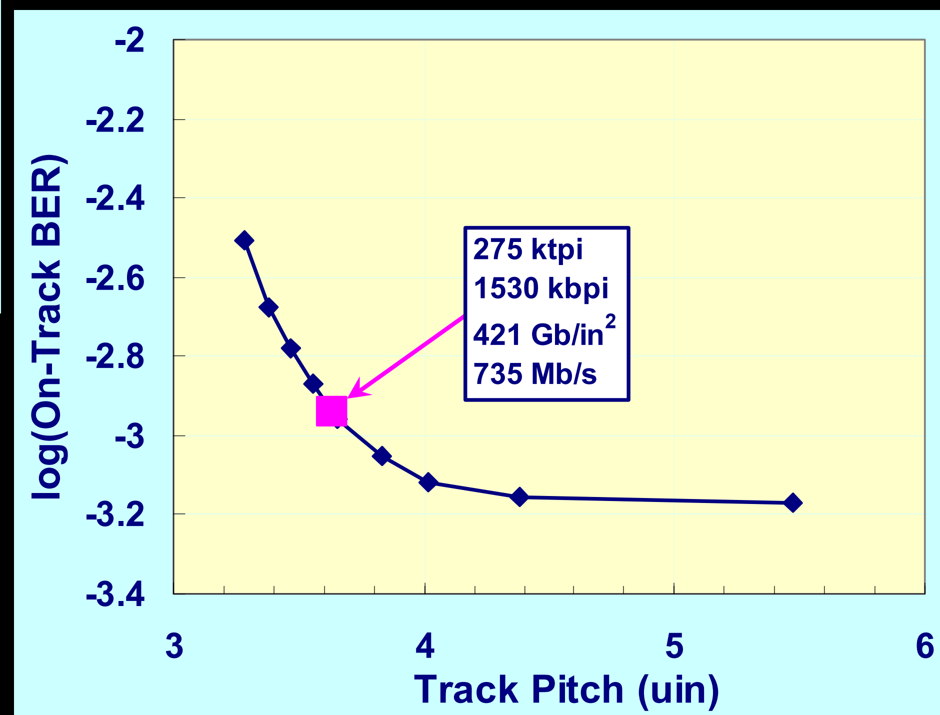
Perpendicular Recording



421 Gb/in² Areal Density Demo at OTC-w3GI

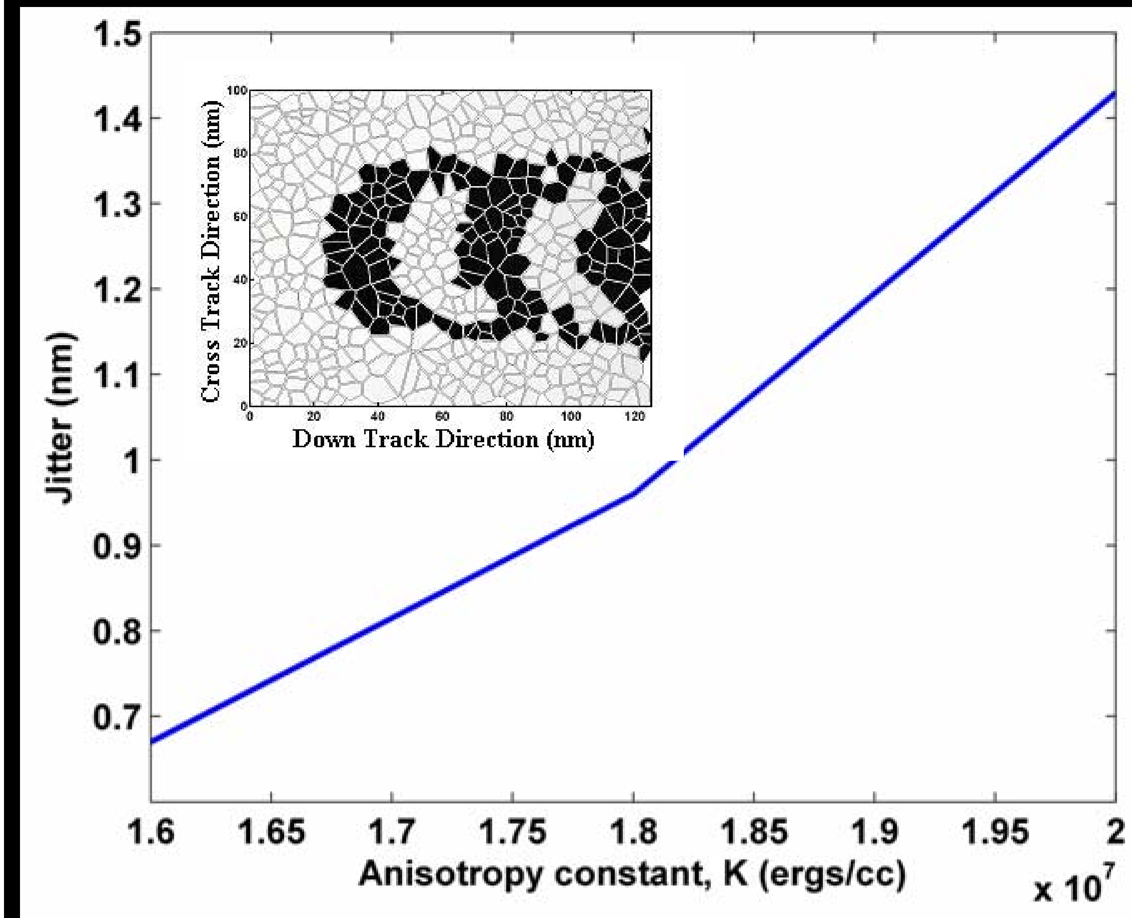


- Using OTC-w3GI criteria, areal density of 421 Gb/in² was achieved. On-track BER at nominal TP is $10^{-2.94}$ with no parity. PE Error Floor is $10^{-3.17}$ with no parity and $10^{-3.71}$ with parity. BAR = 5.6



R. Victora et al., U. of Minnesota

Jitter: Recording at Tbit/in2



Media Parameters

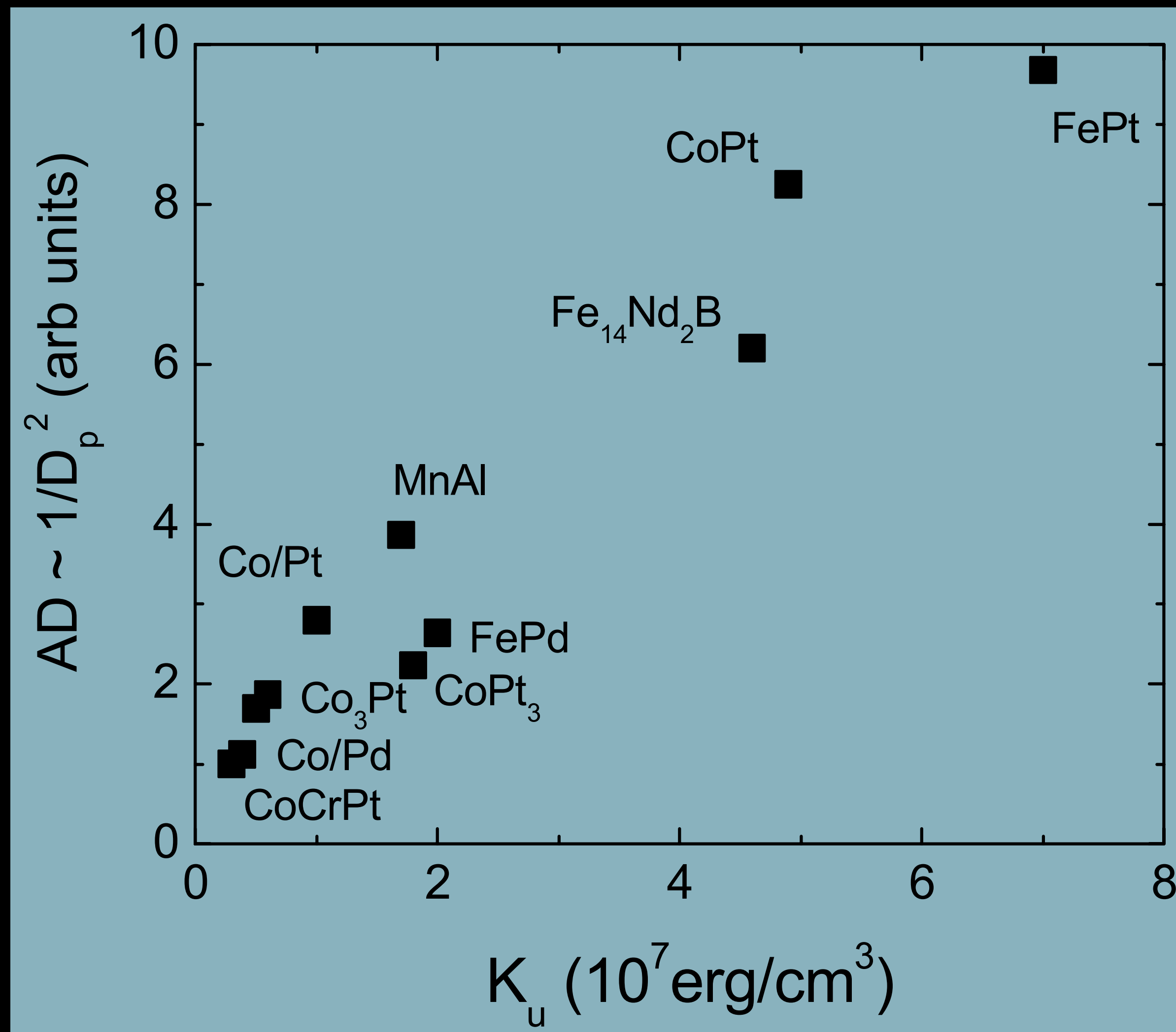
- Optimized ECC grain
- 3° Easy Axis Cone
- Bit length is 10 nm.
- K uniformly distributed with 5% stdev.

Thermal stability requires K= $2x10^7$ ers/cc. Therefore, this head and media combination requires signal processing to accommodate 14% jitter for Terabit/in^2.

Areal Density Potential of Media Candidates

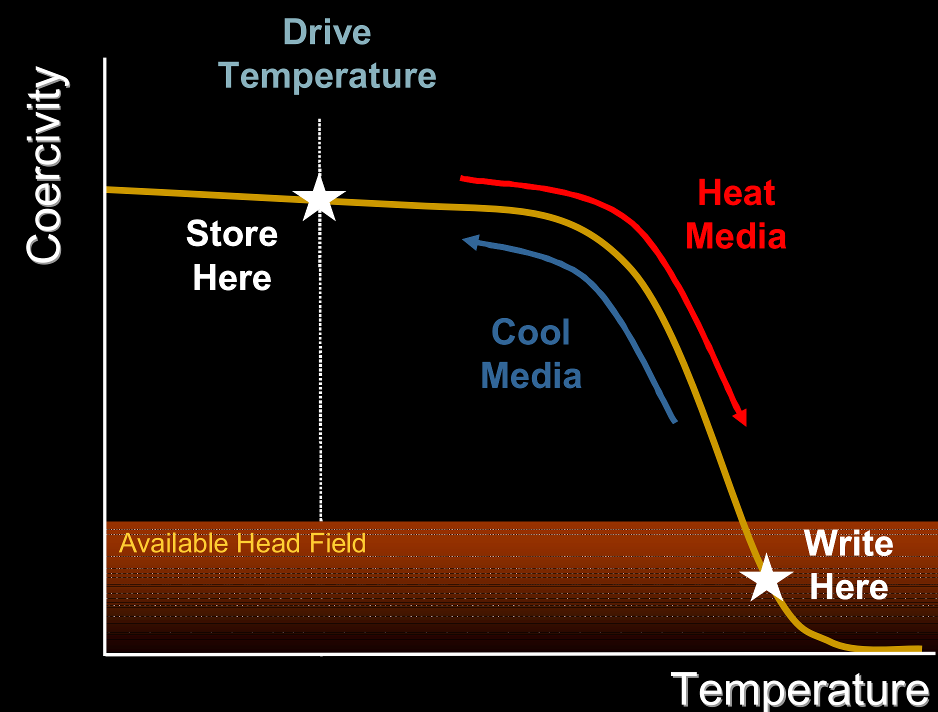
FePt and other high anisotropy materials offer areal density potential 10X that of CoCrPt materials used in perpendicular recording.

How to write on them?



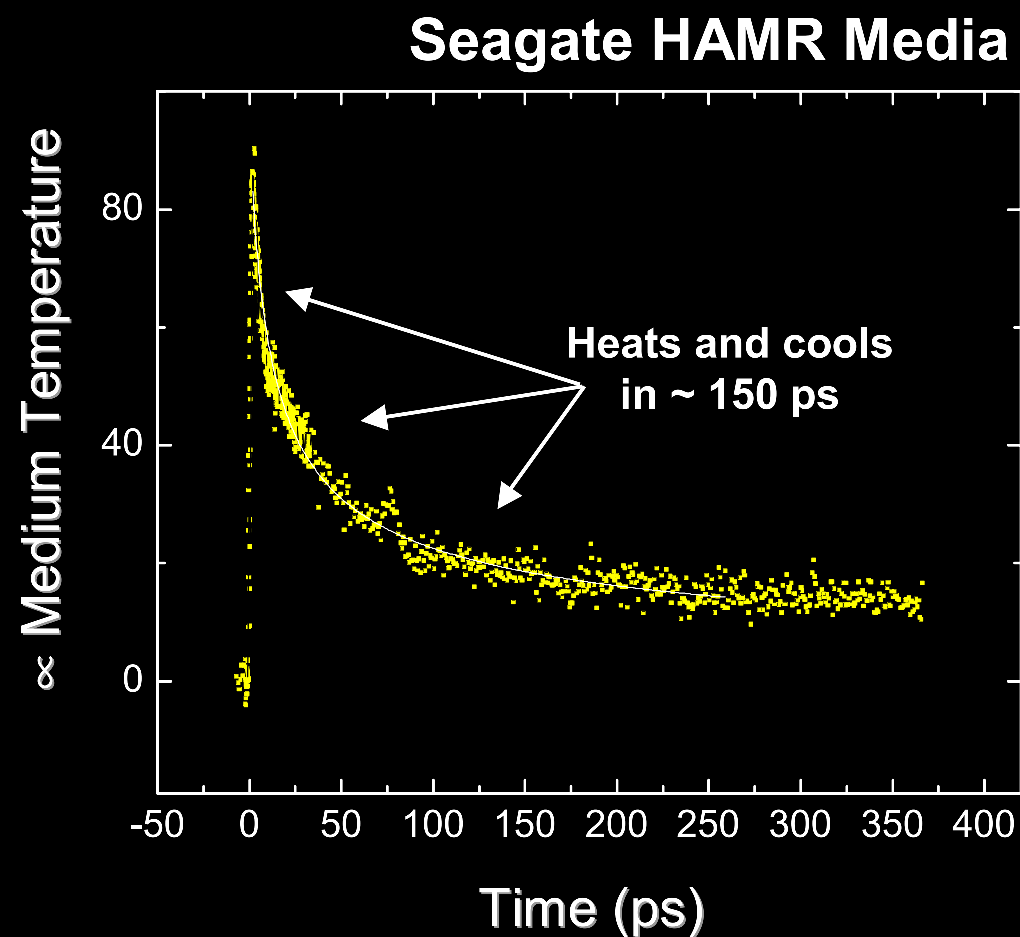
High Anisotropy Media

With HAMR we can write on high anisotropy media and extend the areal density growth curve



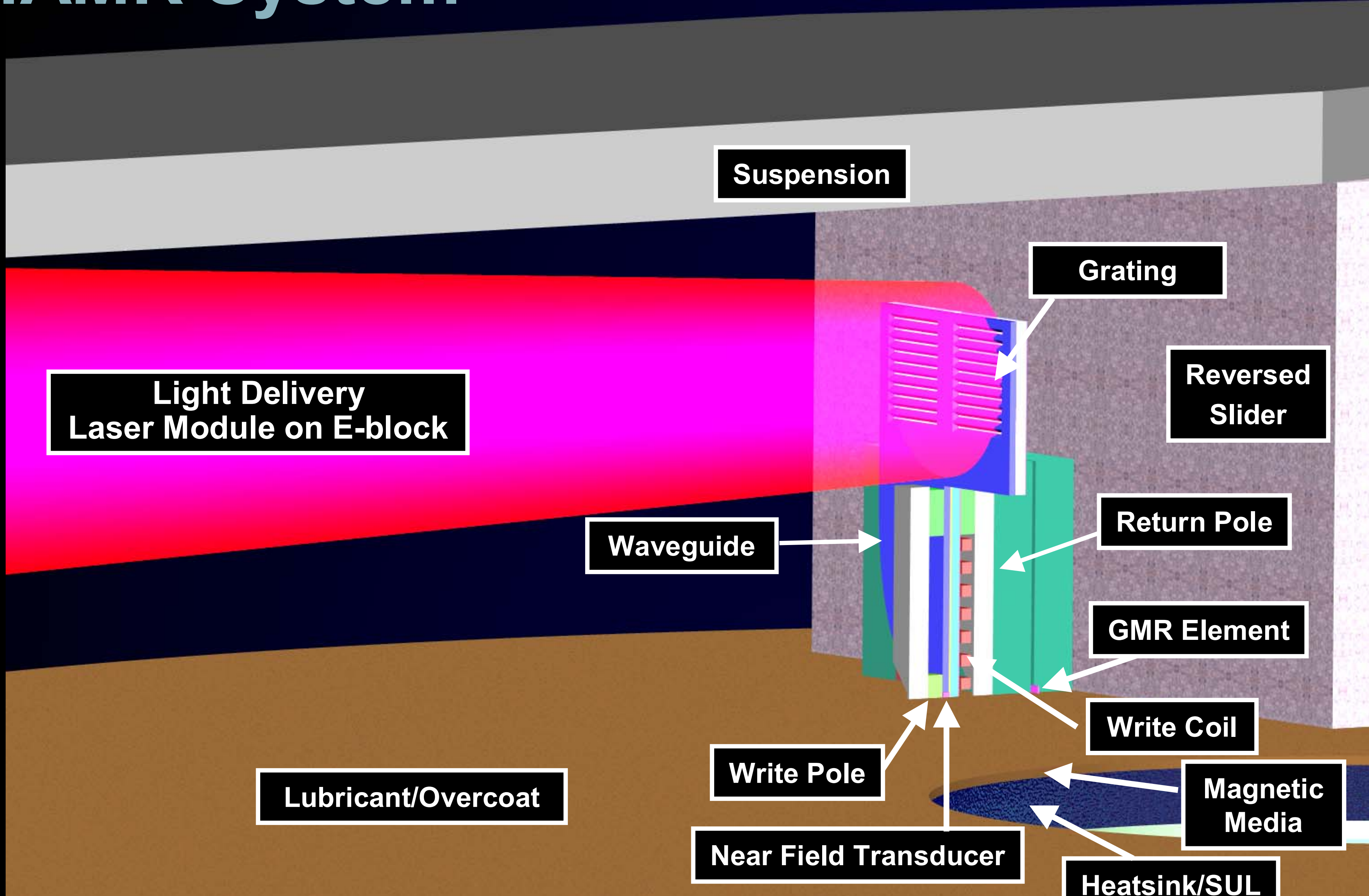
Fast Media Cooling

Media thermal response times are extremely fast when properly designed

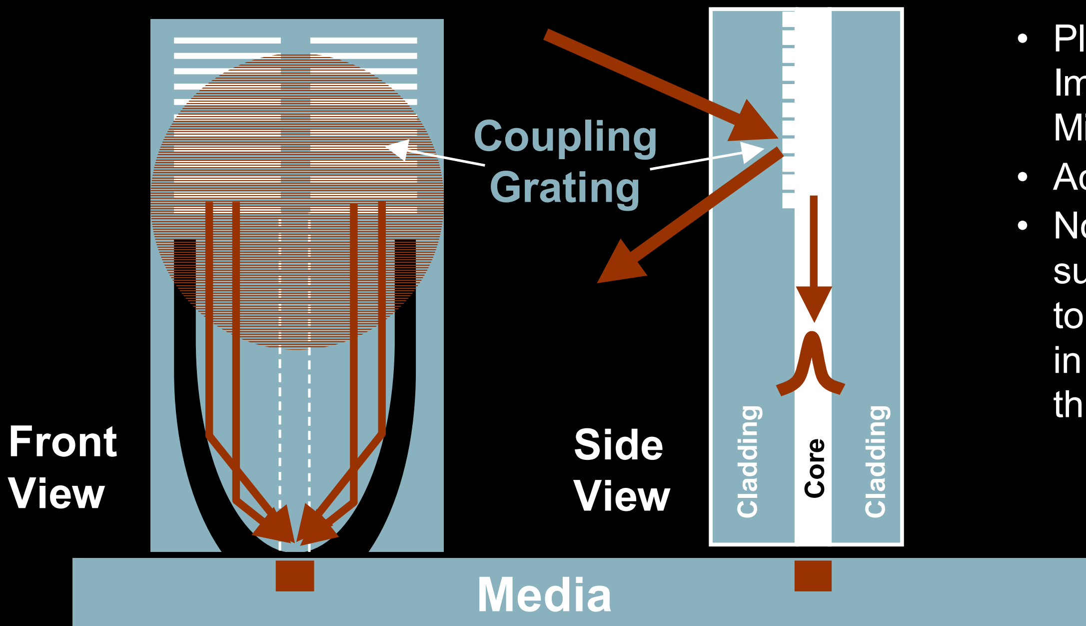


J. Hohlfeld

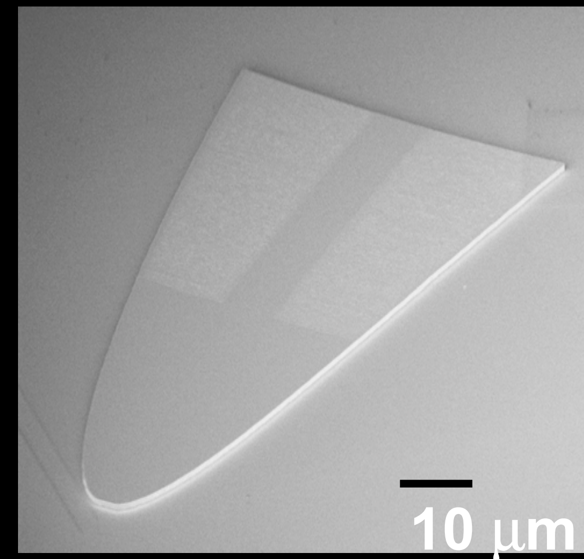
HAMR System


Suspension
Grating
Reversed Slider
Light Delivery
Laser Module on E-block
Waveguide
Return Pole
GMR Element
Write Coil
Write Pole
Lubricant/Overcoat
Magnetic Media
Near Field Transducer
Heatsink/SUL

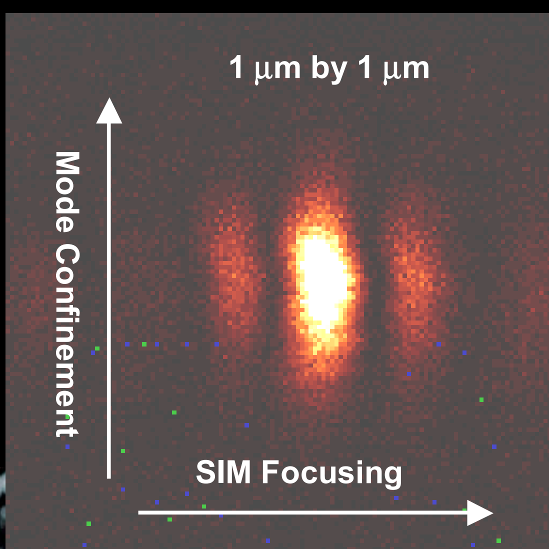
Near-Field Optical Waveguide

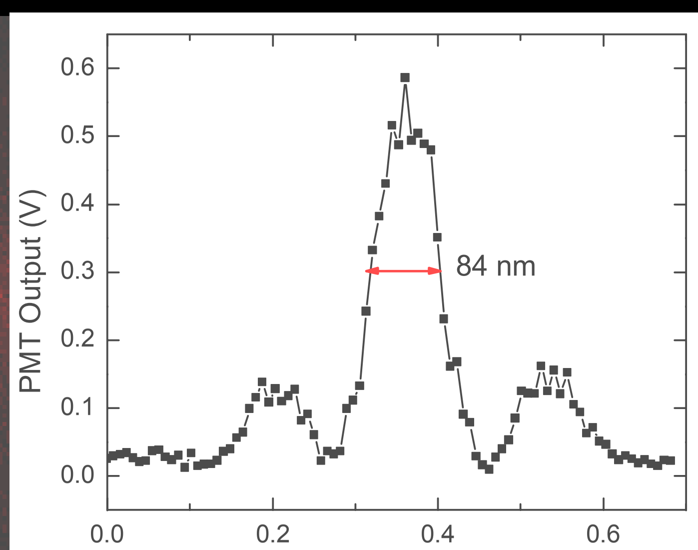


- Planer Solid Immersion Mirror (SIM)
- Achromatic
- Not susceptible to variations in film thickness



Solid Immersion Mirror





- Tantalum core layer sandwiched between two alumina cladding layers
- SNOM scans over focal plane
- At blue light (413 nm), full-width-half-max focused spot size < 90 nm

Optical Image & SNOM of ABS

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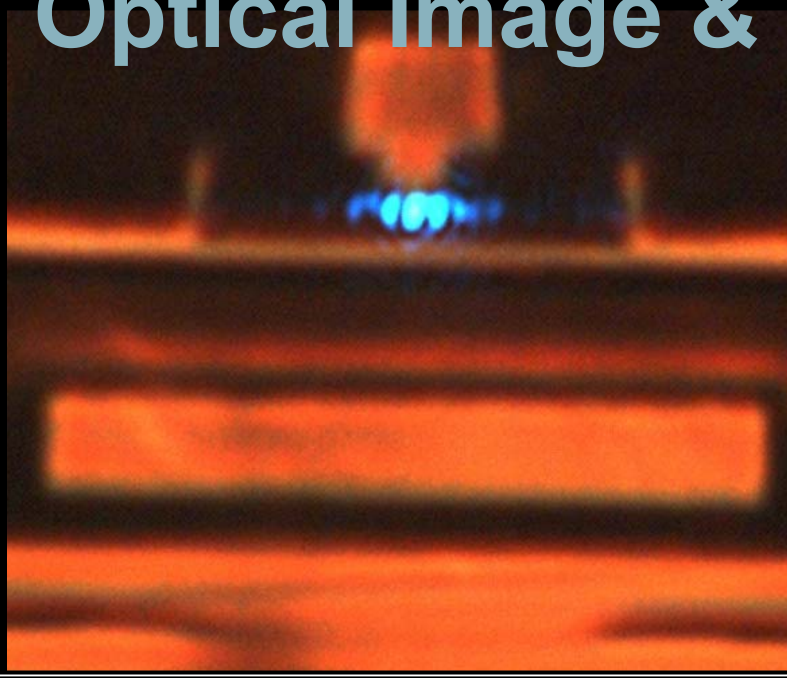
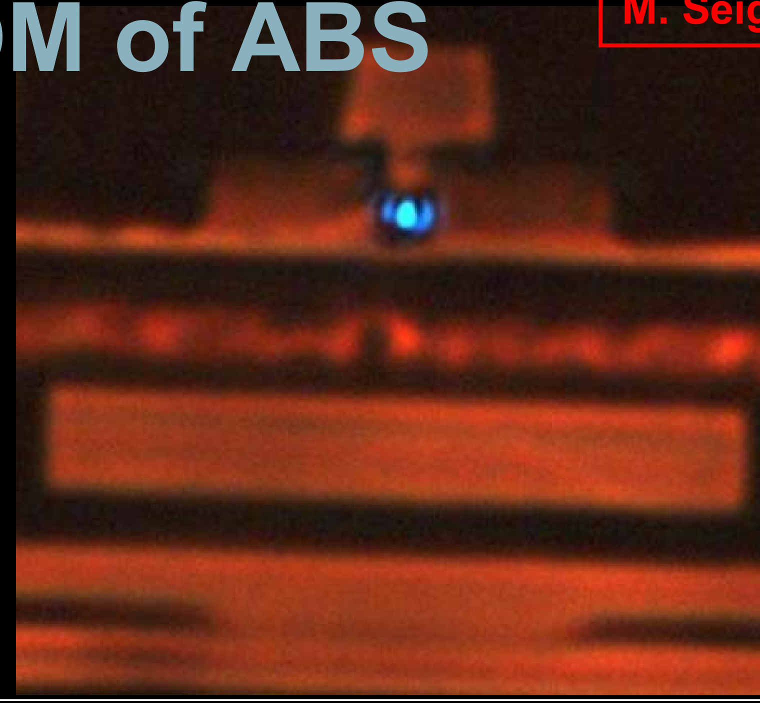
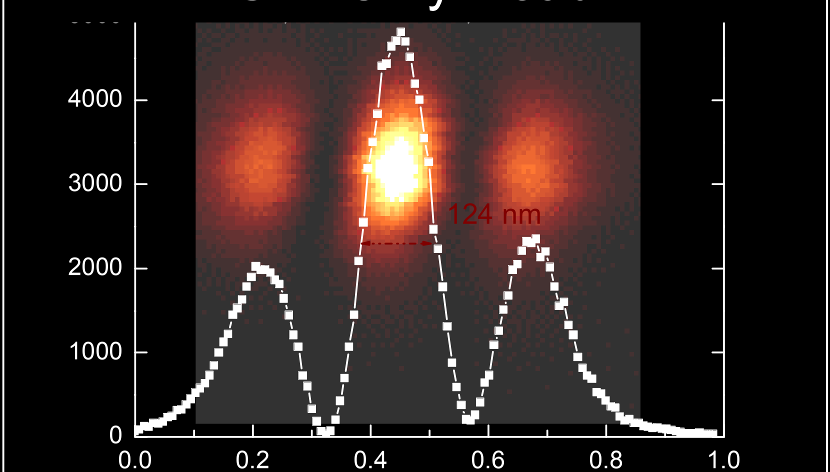
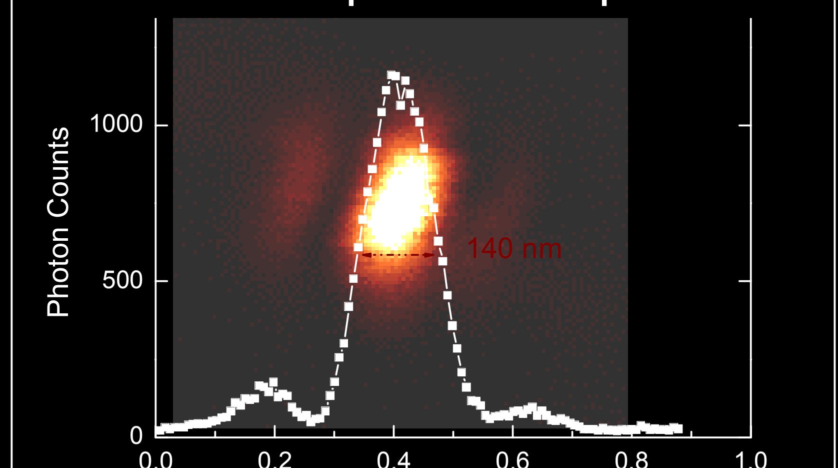


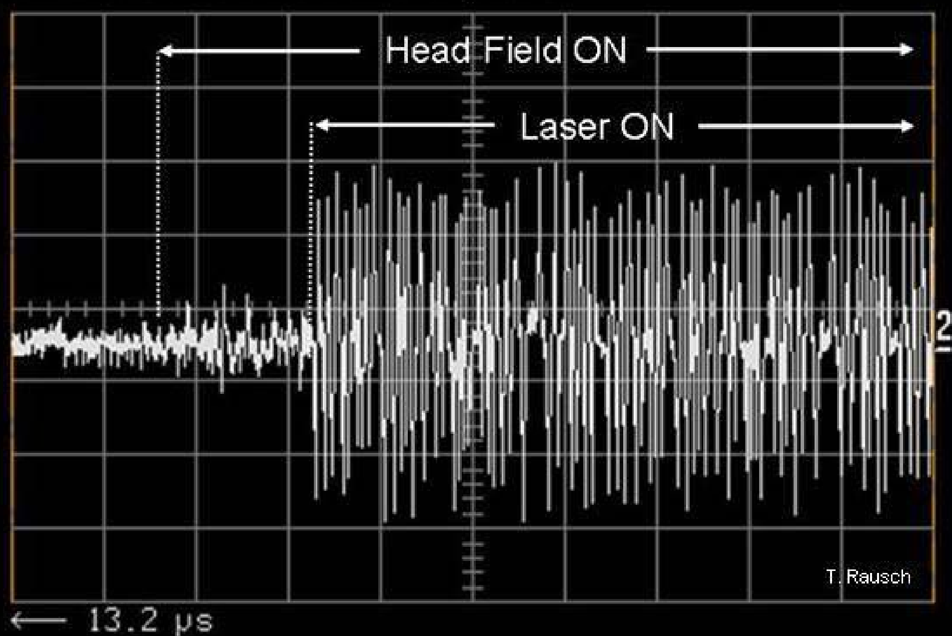




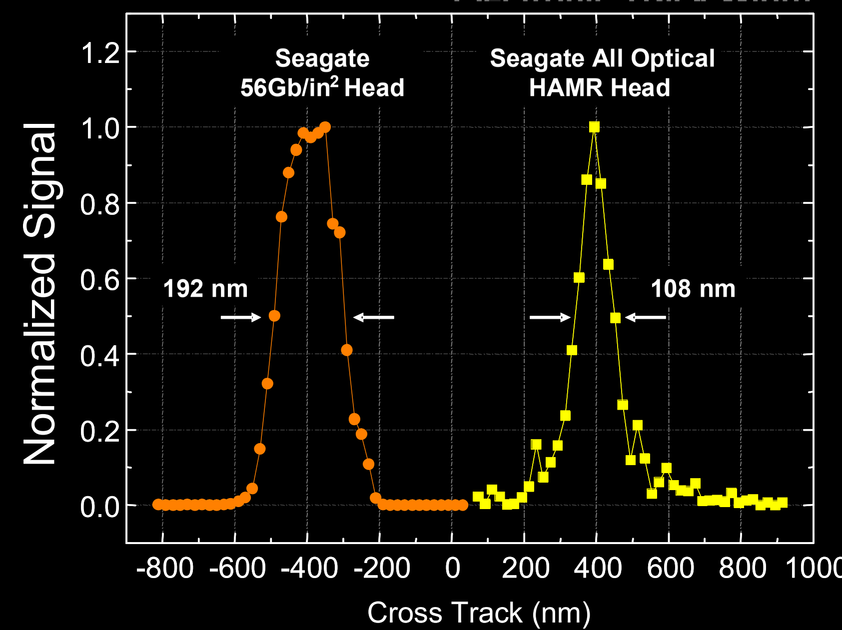


Spin Stand Recording – HAMR

127-bit Pseudo Random Sequence



Narrow Band Track Width



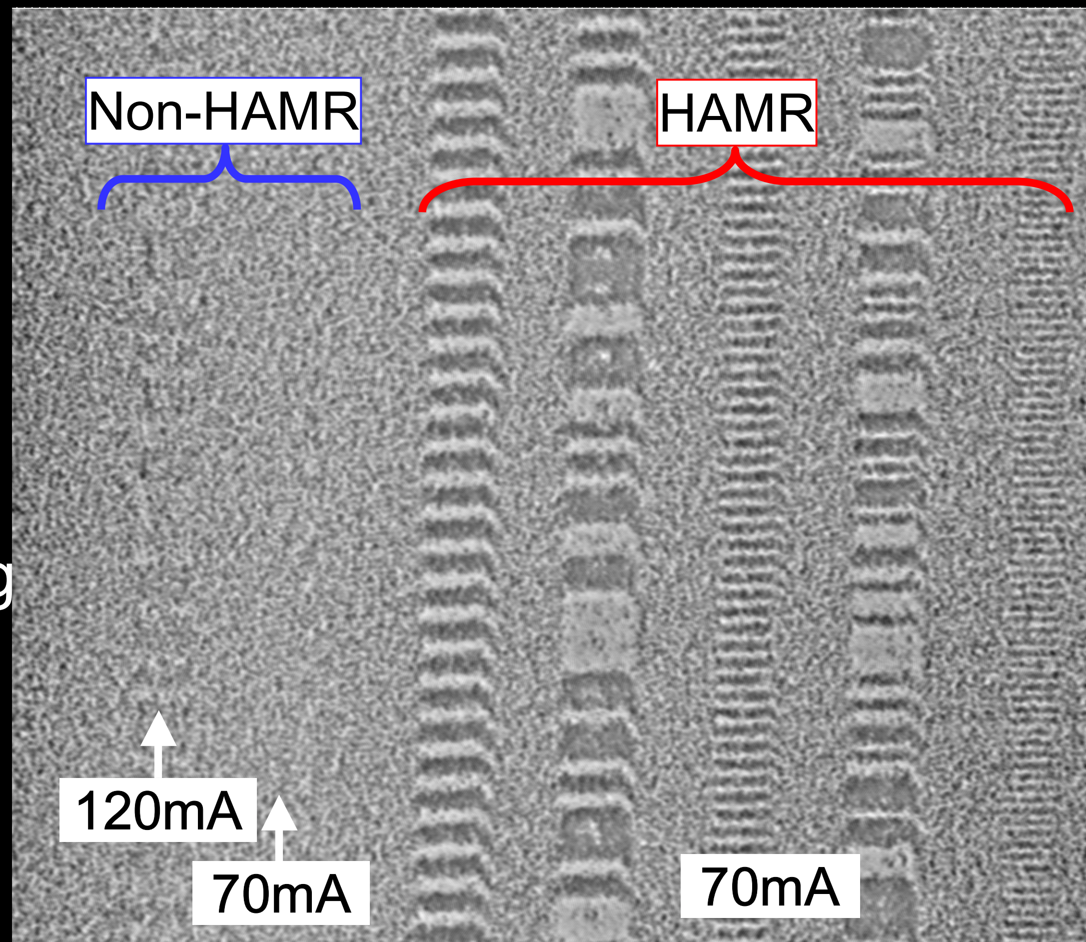
Recorded and Read back using typical recording conditions

MFM of Non-HAMR & HAMR Tracks (Fully Integrated HAMR Head)

Fully Integrated HAMR Head

HAMR Unique Media

- High Anisotropy
- Proper Heatsinking



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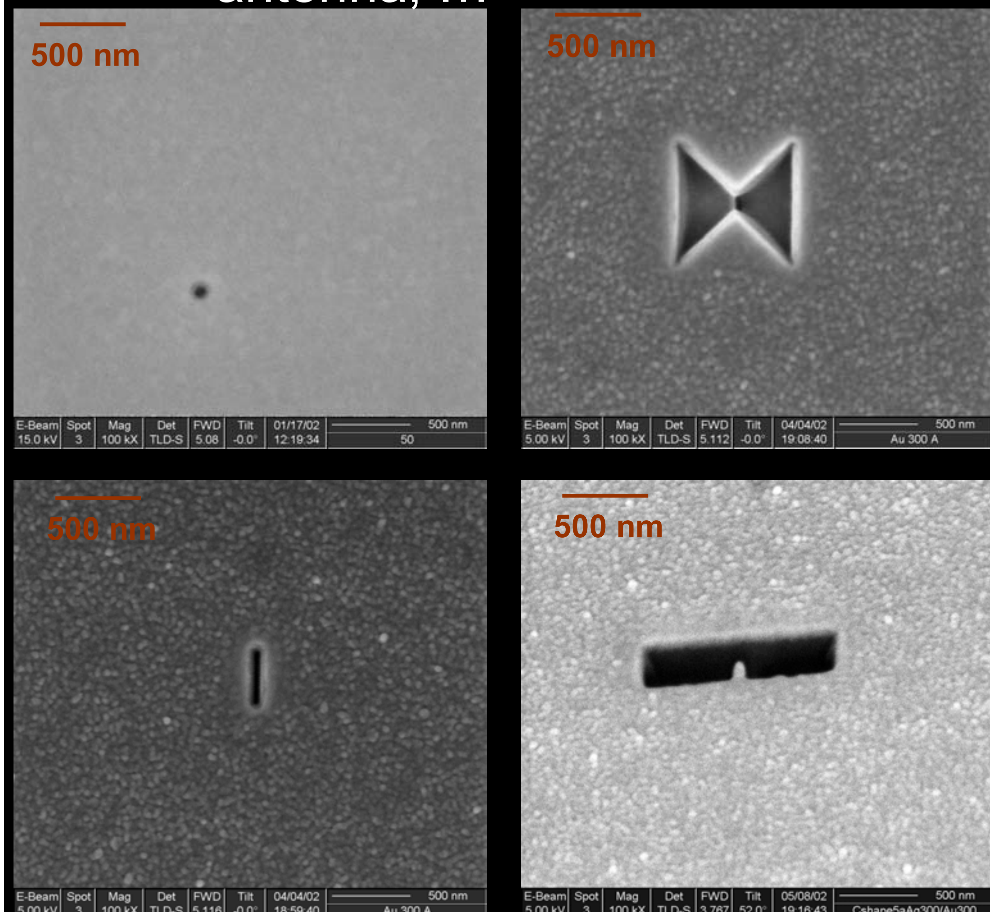
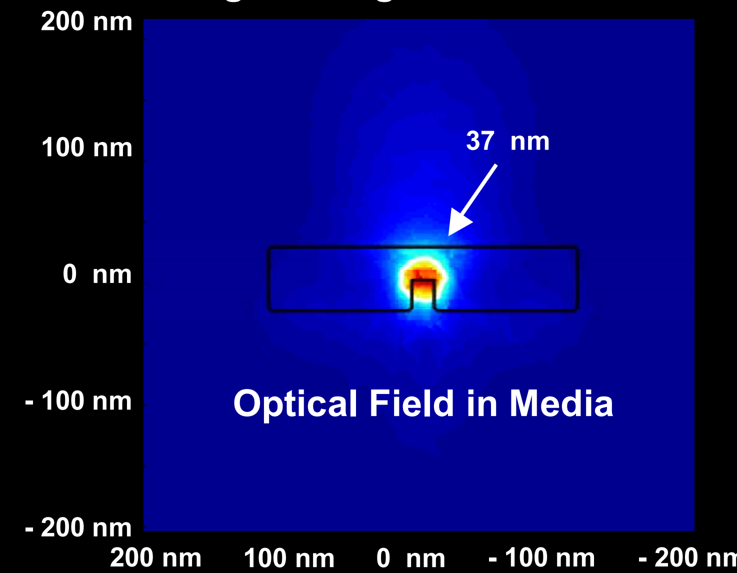
Near Field Transducers

NFT to reduce the optical spot size.

- Aperture, bowtie, ridge WG, beaked antenna, …



Ridge Waveguide



- Nano-Holes
  L.Yin et al., APL 85 (3), pp. 467-469 (2004).
  E. Popov, et al., *Appl. Opt.* 44, pp. 2332-2337 (2005).
- Rectangular Aperture
  Shi, et al, Jap. J. Appl. Phys. 41 (2002).
- Bowtie
  R. Grober, et al, APL 70, pp. 2368-2370 (1997).
- Hitachi - Beaked Antenna
  T. Matsumoto, et al, ISOM/ODS'05, (2005).
- Sharp - Smash Head
  S. Miyanishi INTERMAG (2005).
- Sony - SIL + Single Pole Head
  N. Kojima, et al, INTERMAG (2007).

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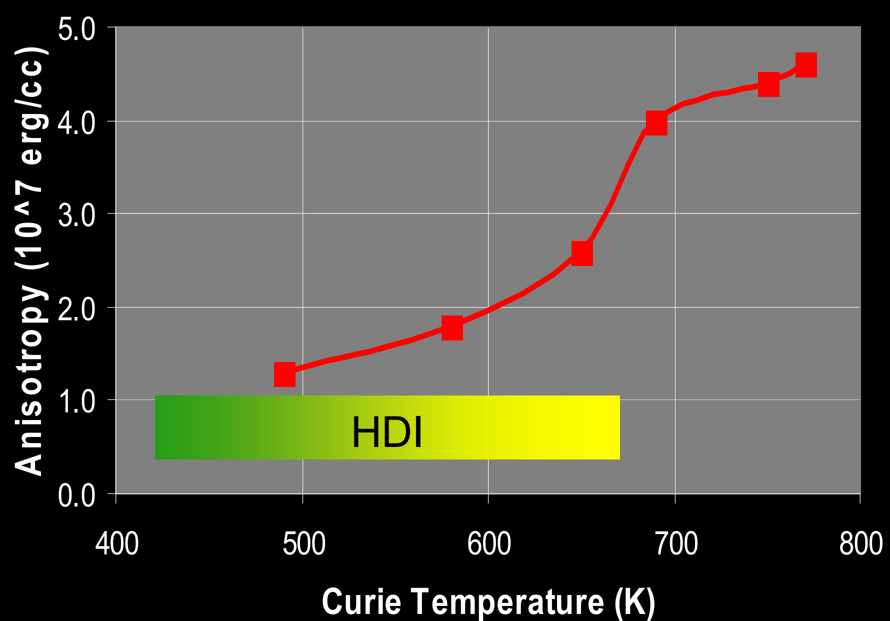
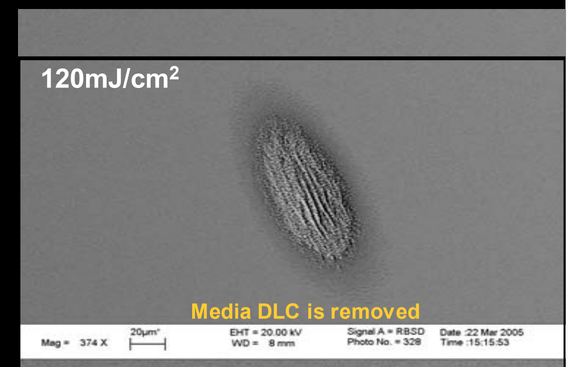
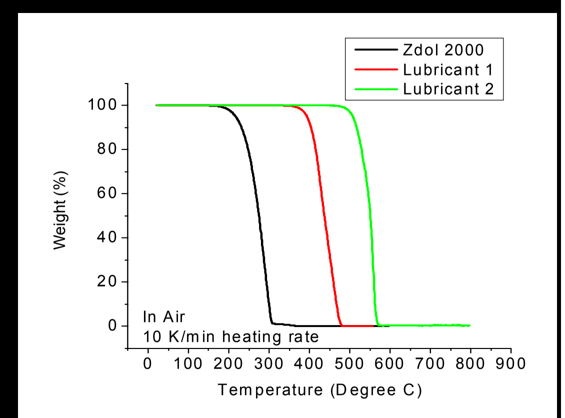
HAMR Head Disc Interface Material Needs

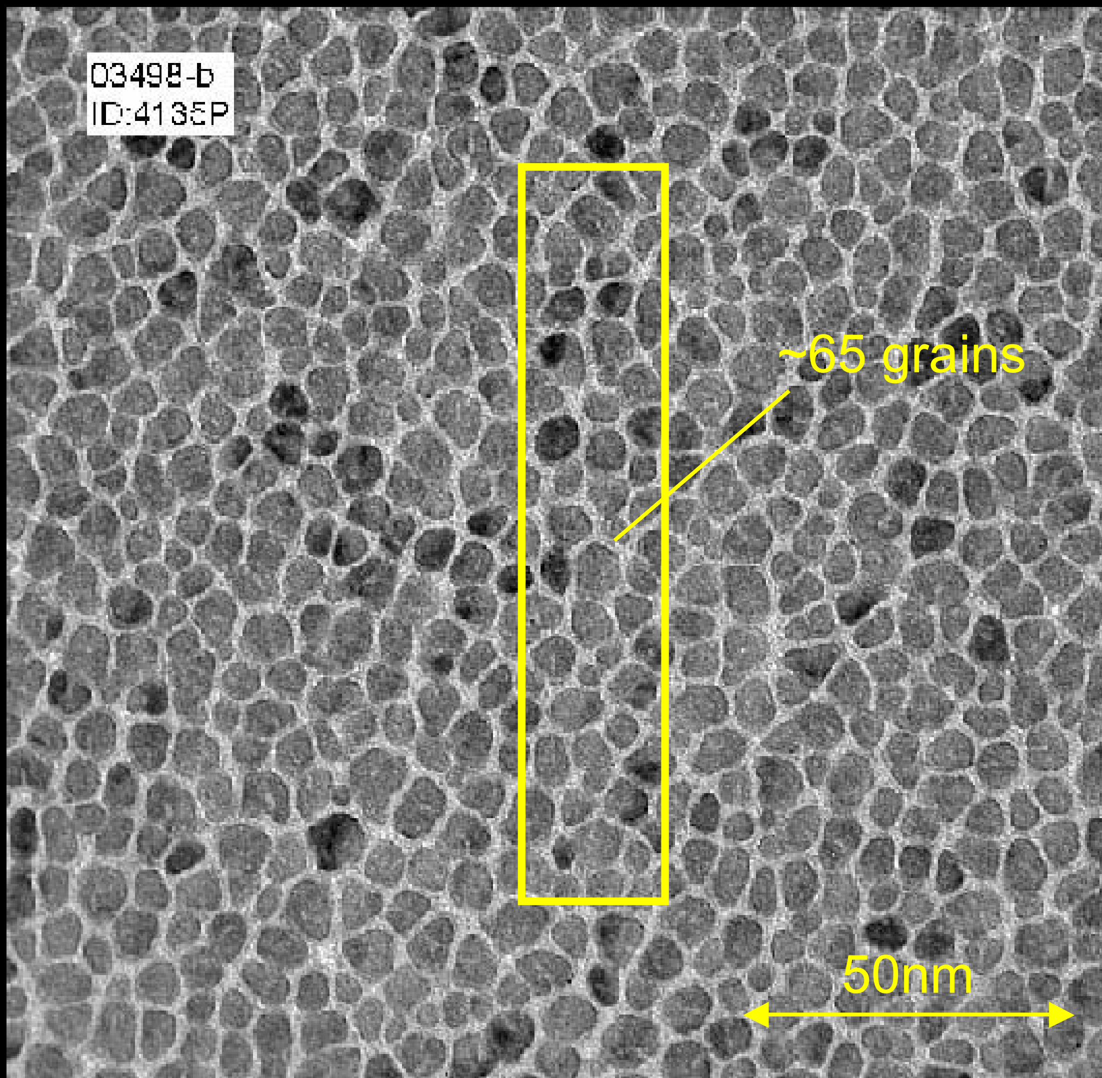
- Media Overcoat (< 2 nm) and Lubricant must be able to withstand the repeated exposure to the high writing temperature.
- New media overcoat materials will be needed.
  - Carbon overcoat can be damaged and/or graphitized at much lower temperature than its 560°C oxidation temperature.
- New Disc Lubricant materials will be required.







The Argument for Bit Patterned Media



Dimensions at left correspond to 240 Gb/in^2 recording.

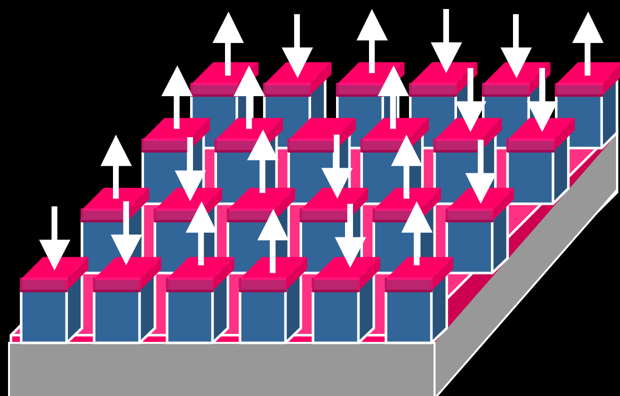
Too small grains become thermally unstable.

So why not make one grain per bit?

The density could then, possibly, increase by a factor of 65!

Bit Patterned Media
Lithography vs. Self Organization

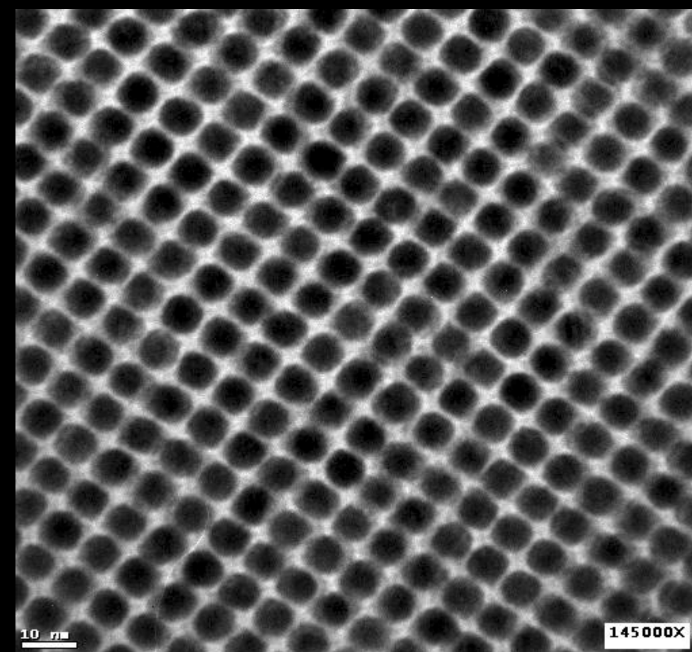
Lithographically Defined



Major obstacle is finding low cost means of making media

- At 1 Tbpsi, assuming a square bit cell and equal lines and spaces, 12.5 nm lithography would be required
- Semiconductor Industry Association roadmap does not provide such linewidths within the next decade

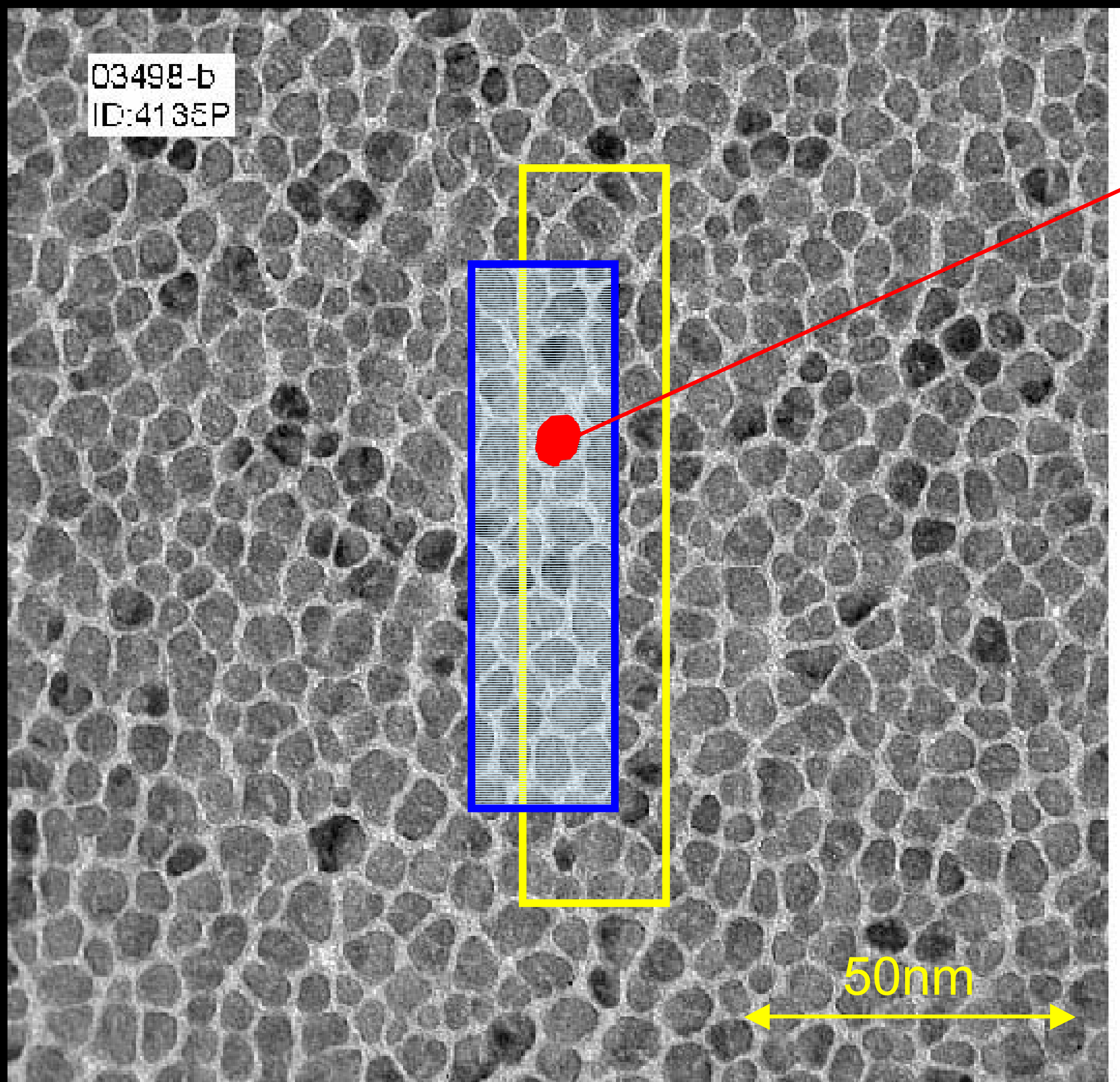
FePt Self-Organized Media



•6.3+/-0.3 nm FePt particles

$s_{Diameter}$@0.05

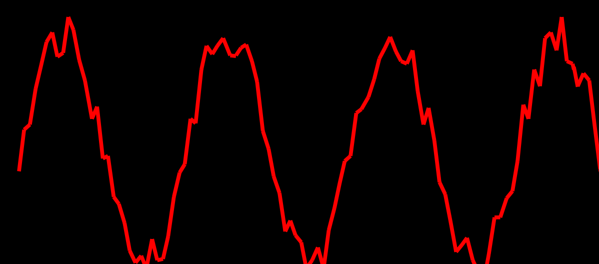
Poorly Written Conventional Recording



one grain/bit wrongly recorded

Read head sees ~ 50 grains

Read signal is then 96%, not 100% – hardly noticed



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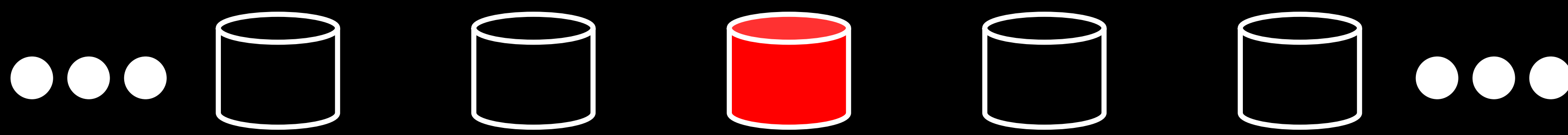
Poorly Written BPM Recording

Same assumption: 2% of the dots wrongly recorded



1 out of 50 dots not written

That is: 1 out of 50 dots potentially wrongly recorded

That is: Bit-error rate is 0.01 = 10^{-2} (poor!)

Increasing SNR or reading once again does not help!

Too much deviation from ideality is fatal!

Distributions are absolutely critical in BPM recording

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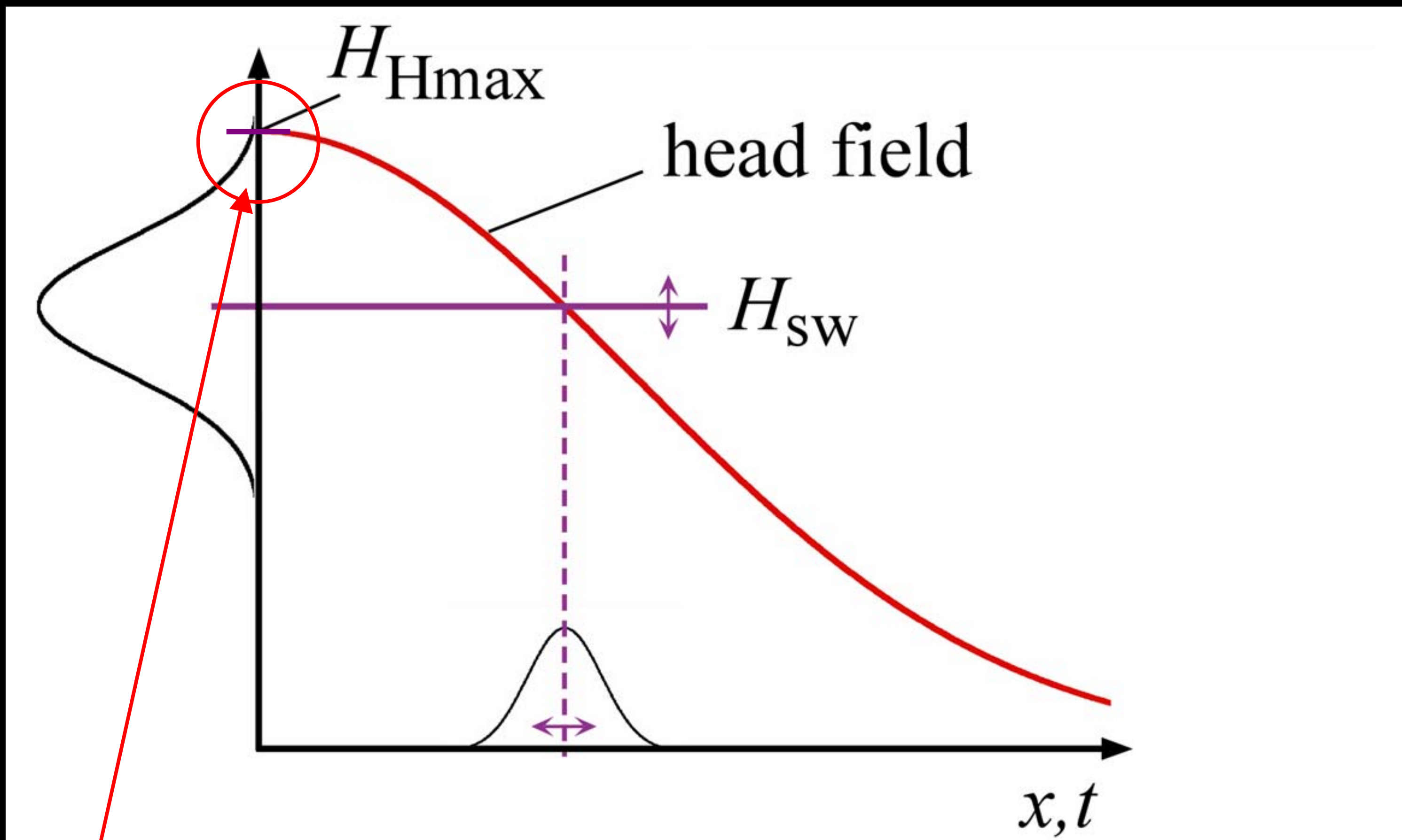
Presented at the PITP/SpinAps Asilomar Conference in June 2007

Brought to you by PITP (www.pitp.phas.ubc.ca)

Modeling of Write-Miss Errors



Finite probability some dots are not switched at all

Variance Analysis: Write Margin

Probability of a "write-miss":

$$P_w = \frac{1}{2}\left(1 - \mathrm{erf}\left(\frac{H_{H\max} - H_{sw0}}{\sigma_H \sqrt{2}}\right)\right)$$

$$\sigma_H = \sqrt{(\sigma_{Hsw})^2 + (\sigma_{Hd})^2}$$

H_{Hmax}: max eff. head field

H_{sw0}: mean switching field

Switching field distribution (anisotropy field distribution)

Interaction field distribution (surrounding dots)

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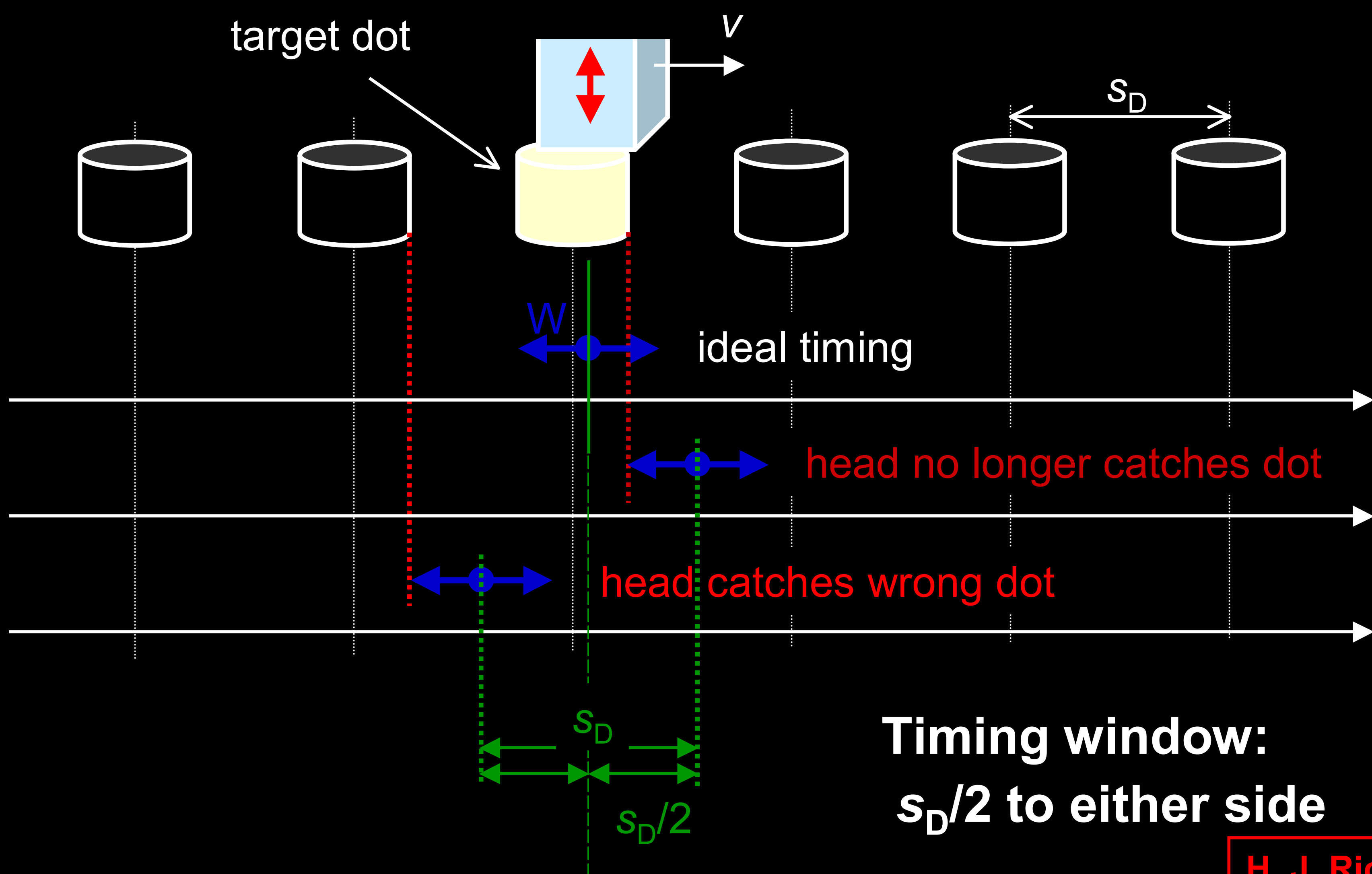
Another Source of Written-in Errors: Timing



Timing window:
$s_D/2$ to either side

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Variance Analysis: Timing

Probability of a timing error
(all Gaussians)

$$P_t = 1 - \mathrm{erf}\left(\frac{B/2}{\sqrt{2}\sigma_x}\right)$$

$$\sigma_x = \sqrt{\left(\sigma_x^{Hsw}\right)^2 + \left(\sigma_x^{Hd}\right)^2 + \left(\sigma_x^{pos,x}\right)^2}$$

Switching field distribution (anisotropy field distribution)

Interaction field distribution (surrounding dots)

Distribution due to dot spacing fluctuations

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Importance of Bit-Aspect Ratio (BAR)

BAR	BL (nm)	t_P (nm)	5% (nm)
1	25.4	25.4	1.3
2	18	35.9	0.9
4	12.7	50.8	0.6
8	9.0	71.8	0.4

Numbers for 1Tb/inch^2

Performance (data rate, etc)

Lithography requirements

Mechanical requirements

Head

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Areal Density Potential of BPM

- Assume elliptical dots
- Neglect all distributions: $\sigma_D/D = \sigma_{HA}/H_A = \sigma_{sD}/s_D = 0.05\%$
- Two configurations:

  pole head, SUL + storage layer

  ring head + storage layer
- Two hard layers:

  conventional

  composite with optimized coupling
- Limiting condition:

  20 kT minimum energy barrier at adjacent track

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Results (Elliptical Dots)

AD (Tb/in^2)	W (nm)	g (nm)	d (nm)	s_D (nm)	D (nm)	$AR \cdot D$ (nm)	H_A (kA/m)	M_{s1} (kA/m)	δ_1 (nm)	δ_{IL} (nm)	M_{s2} (kA/m)	δ_2 (nm)	BER$_w$ (dec)	BER$_t$ (dec)	BER (dec)
1	42	na	7.5	12.7	8.5	34	1716	1300	2	1	na	na	<-13.4	<-15	<-13.4
2	30	na	3.97	8.98	7.5	30	1572	1300	3	1	na	na	-2.1	-3.2	-2.0
3	29	na	3.24	7.33	6.5	26	3184	400	3	0.5	1200	1	-12.7	-9.5	-9.5
3	26	na	3.24	7.33	6.3	25	3137	600	1.75	0.5	600	4	-7.4	-8.2	-7.3
4	23	na	2.24	6.35	6	24	3279	400	2.75	0.5	1200	1	-5.5	-6.5	-5.5
5	20	na	1.75	5.66	5.5	22	3431	400	2.75	0.5	1200	0.75	-2.4	-5.2	-2.4
1	55	25	7.5	12.7	8	32	1388	700	2.5	na	na	na	<-15	<-15	<-15
2	32	17	3.97	8.98	7.5	30	1622	1300	2	na	na	na	-7.5	-9.5	-7.5
3	33	18	3.24	7.33	6.3	25	2583	400	2.75	na	1200	1	-5.6	-5.7	-5.4
1	21	na	7.5	25.4	16	16	1032	1300	6	1	na	na	-1.0	-11.3	-1.0
1	24	21	7.5	25.4	16	16	1037	1300	5	na	na	na	-4.3	<-15	-4.3

Pole head/SUL about equivalent to ring head

Pole head/SUL + composite is best

BAR = 1 is not good

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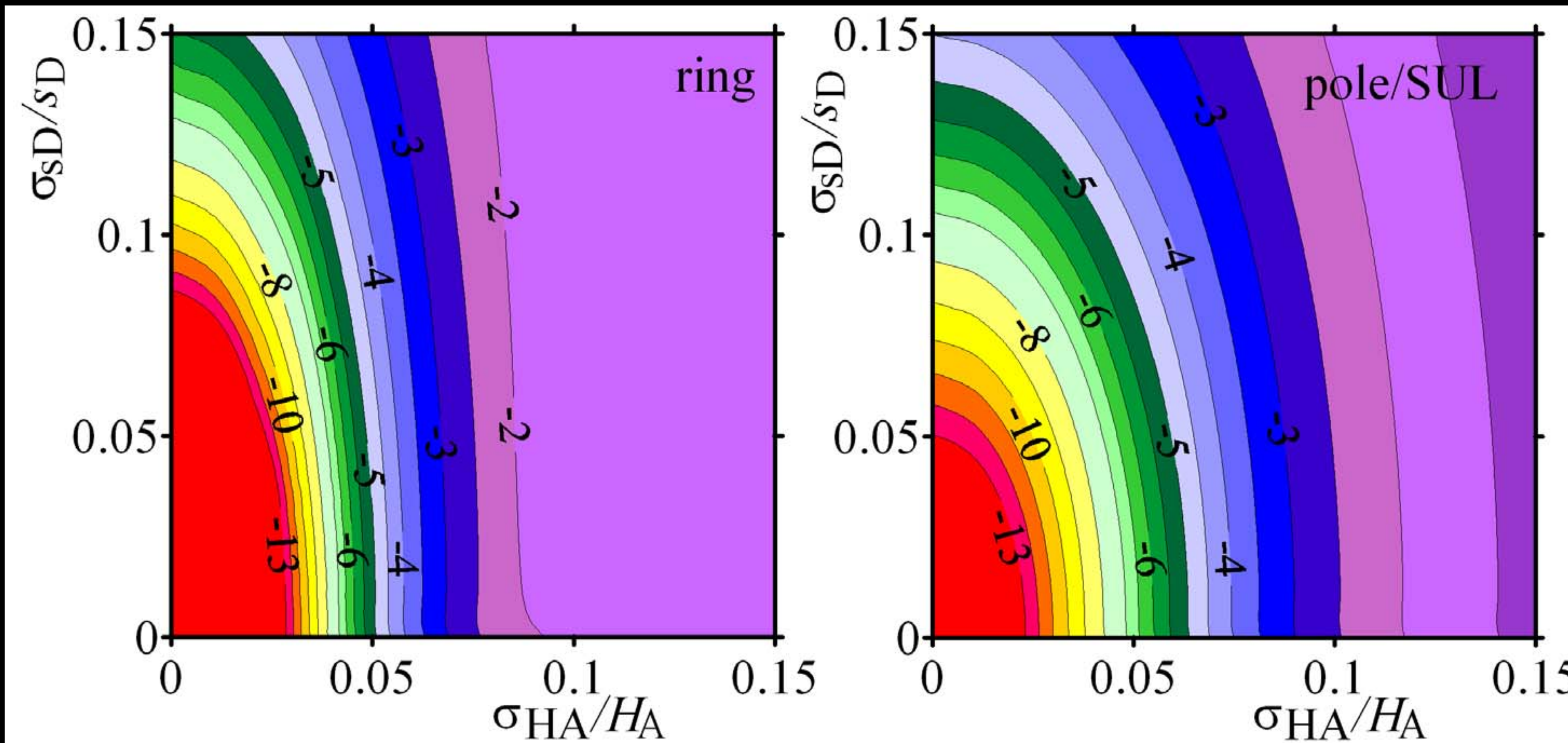
Distribution Effects (1Tb/in^2)

Contours of written-in error rates due to timing errors



Reasonable error rates require distributions of ~ 5%

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BPM Conclusions

- **BPM recording beyond 1 Tb/in^2 should be possible**
- **The three take-aways:**

Written-in bit errors dominate performance

Narrow distributions are key (< 5%)

Bit aspect ratio of 1 (bit length = track width) will not happen

Recent papers:

Appl. Phys. Lett, vol. 88, 222512 (2006).

IEEE Trans. Magn., vol. 42, pp. 2255-2260, (2006)

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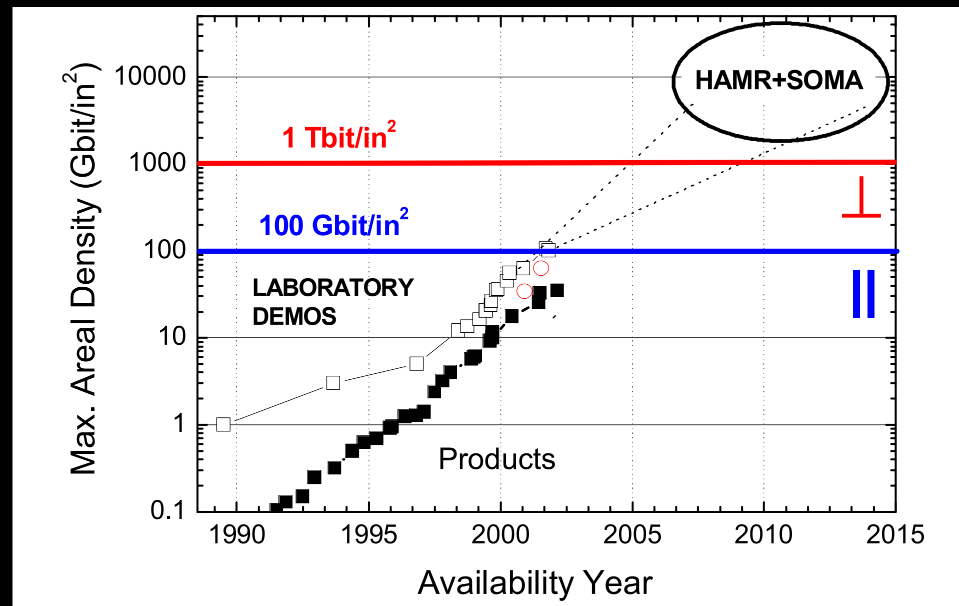
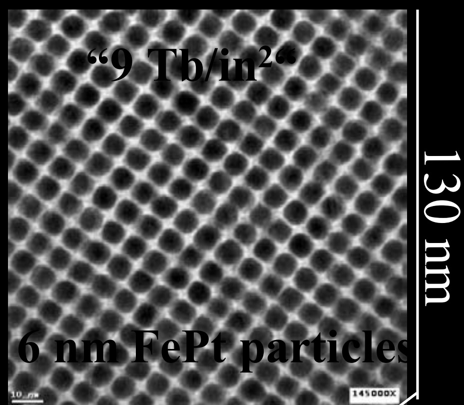
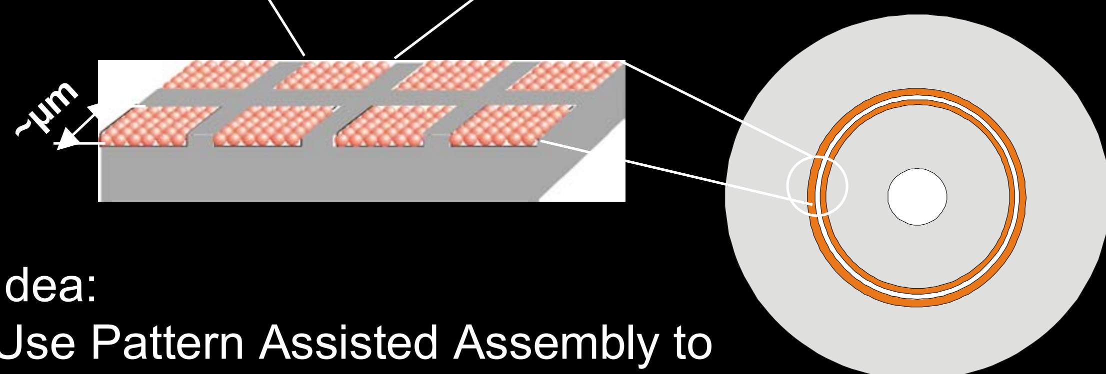
Ultimate Limits?

Single Particle Stability Limit ~40-50 Tb/in²



FePt Self-Organizing Media

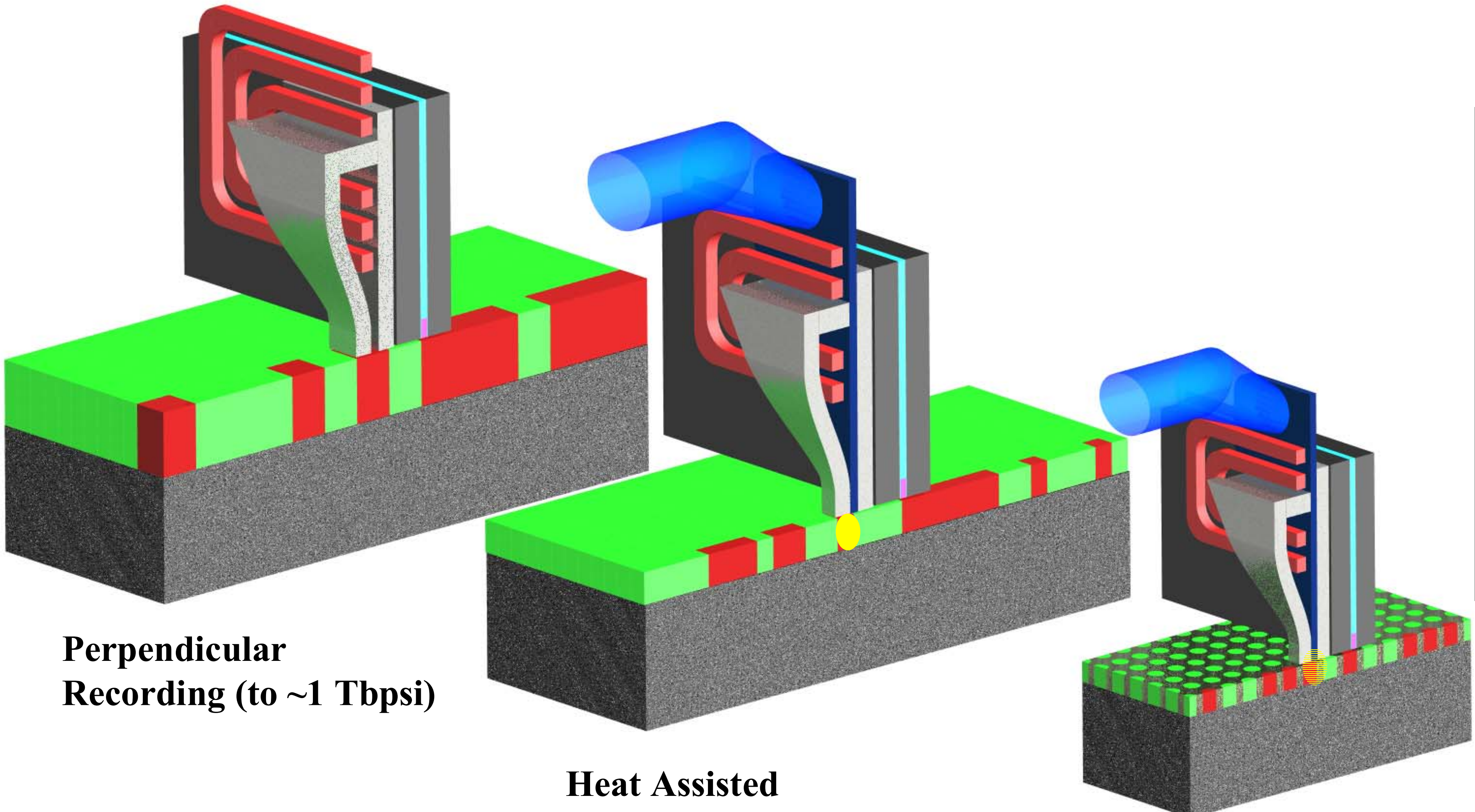




Idea:

Use Pattern Assisted Assembly to establish circumferential tracks on discs

Revolution in Magnetic Recording



Perpendicular Recording (to ~1 Tbpsi)

Heat Assisted Magnetic Recording (HAMR) to ~10 Tbpsi

HAMR on Bit Patterned Media (to 50 Tbpsi?)

Conclusions

Areal density growth on track at 40% per year

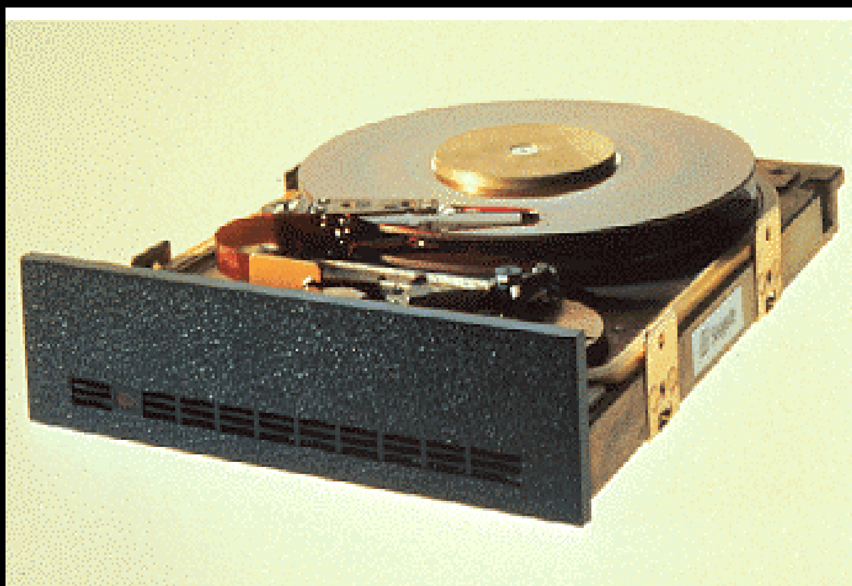
- Conventional perpendicular recording appears limited to 500-1000 Gbpsi.
- HAMR could extend the areal density by an order of magnitude.
- Bit patterned media/SOMA, combined with HAMR could, in principle, extend the areal density to perhaps 50 Tbpsi.
- Major unknown is magnetic head-media spacing.

Questions?

Seagate
We turn on ideas

Small Form Factor 5.25” Drive – 1979

Seagate ST506



This 3,600 RPM drive has a storage capacity of 5 Mbytes

Can read or write more than 12 records, spread randomly over the disc, in less than a second

12 GB Capacity One-Inch Hard Drive for Mobile Devices

Key Advantages

- Leading **12GB capacity** for handheld systems—delivers maximum storage for high-fidelity music, high-resolution video, and digital photos in portable music and video devices, including mobile phones
- New small footprint—**40x30x5 mm** size delivers large capacity in a tiny space, enabling smaller HDD-based systems
- Optional **drop sensor technology** improves shock tolerance to 2000 Gs by sensing and protecting against day-to-day drops and dings when properly installed in mobile devices
- **Uses 30% less power** than its predecessors
- **RunOn Technology** improves HDD performance while in a high-vibration environment such as jogging, helps prevent media skipping
- **One-second time-to-ready** helps handheld devices start up faster
- **RoHS-compliant** in line with international environmental regulations
- **Fluid dynamic bearing motors** deliver near-silent performance
- **Perpendicular recording technology** promises rapid capacity growth for years to come
- Supports **low-power modes** for increased battery life in appropriately equipped host systems

Specifications

Physical Dimensions (mm)	40x30x5
Weight (g)	14
Nonoperating Shock (Gs, 1 msec)	2000
Operating Shock (Gs, 1 msec)	2000
Power-On to Ready (sec, typical)	1.0
Write Average Current (mA)	240
Low Power Idle Average (mA)	77
Operating Temperature (°C)	0 to 70
Nonoperating Temperature (°C)	–40 to 70
Operating Humidity (%)	5 to 90
Nonoperating Humidity (%)	5 to 95

Disc Drives Today Cover the Widest Range of Users and Systems Ever

Some Perpendicular Products introduced in 2006

Product Name	Application	Disc Diameter (in.)	Areal Density (Gb/In^2)	Linear Density (Kbpi)	Track Density (Ktpi)	Drive Capacity (GB)	Disc Capacity (GB)
ST1.3	Handheld	1	133	940	140	12	12
Barracuda 7200.10	Consumer	3.5	133.3	939	142	750	187.5
Momentus 5400.3	Notebook	2.5	130.5	870	150	160	80
Cheetah 15K.5	Enterprise	3.5	108	865	125	300	75

HDD Performance Trends

3.5 inch Consumer	2006 (Perp)	2010 (Perp)
Drive Capacity (GB)	750	3,000
Number of Discs	4	4
Capacity (GB/disc)	187	750
Product Areal Density (Gbpsi)	133	500
Transfer Rate (Mb/sec)	930	2,000
RPM	7,200	7,200
3.5 inch Enterprise	**2006 (Perp)**	**2010 (Perp)**
Drive Capacity (GB)	300	1200
Number of Discs	4	4
Capacity (GB/disc)	75	300
Product Areal Density (Gbpsi)	108	400
Transfer Rate (Mb/sec)	975	2,000
RPM	15,000	15,000
1.0 inch Handheld	**2006 (Perp)**	**2010 (Perp)**
Drive Capacity (GB)	12	50
Number of Discs	1	1
Capacity (GB/disc)	12	50
Product Areal Density (Gbpsi)	133	500
Transfer Rate (Mb/sec)	145	300
RPM	3,600	4,200

In 3 Years, perpendicular recording will be approaching its superparamagnetic limit, but capacities will be high by today's standards.

HDD Performance Trends

3.5 inch Consumer	2006 (Perp)	2010 (Perp)	2014 (HAMR or BPM)
Drive Capacity (GB)	750	3,000	12,000
Number of Discs	4	4	4
Capacity (GB/disc)	187	750	3000
Product Areal Density (Gbpsi)	133	500	2000
Transfer Rate (Mb/sec)	930	2,000	4,000
RPM	7,200	7,200	7,200
3.5 inch Enterprise	**2006 (Perp)**	**2010 (Perp)**	**2014 (HAMR or BPM)**
Drive Capacity (GB)	300	1200	5,000
Number of Discs	4	4	4
Capacity (GB/disc)	75	300	1,200
Product Areal Density (Gbpsi)	108	400	1,600
Transfer Rate (Mb/sec)	975	2,000	4,000
RPM	15,000	15,000	15,000
1.0 inch Handheld	**2006 (Perp)**	**2010 (Perp)**	**2014 (HAMR or BPM)**
Drive Capacity (GB)	12	50	200
Number of Discs	1	1	1
Capacity (GB/disc)	12	50	200
Product Areal Density (Gbpsi)	133	500	2,000
Transfer Rate (Mb/sec)	145	300	750
RPM	3,600	4,200	5,400

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