Perpendicular Recording

A Future Technology or a Temporary Solution?

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Seagate

Outline

- Overview
- Superparamagnetic limit and the need for a new technology
- Dodging the Superparamagnetic limit … The advantages of perpendicular recording?
- A new system component: soft underlayer challenges and design considerations
- Skew Angle Sensitivity
- Playback: new signal processing schemes
- New materials challenges
- How far perpendicular recording will take us and what will come next?

From RAMAC to Microdrive

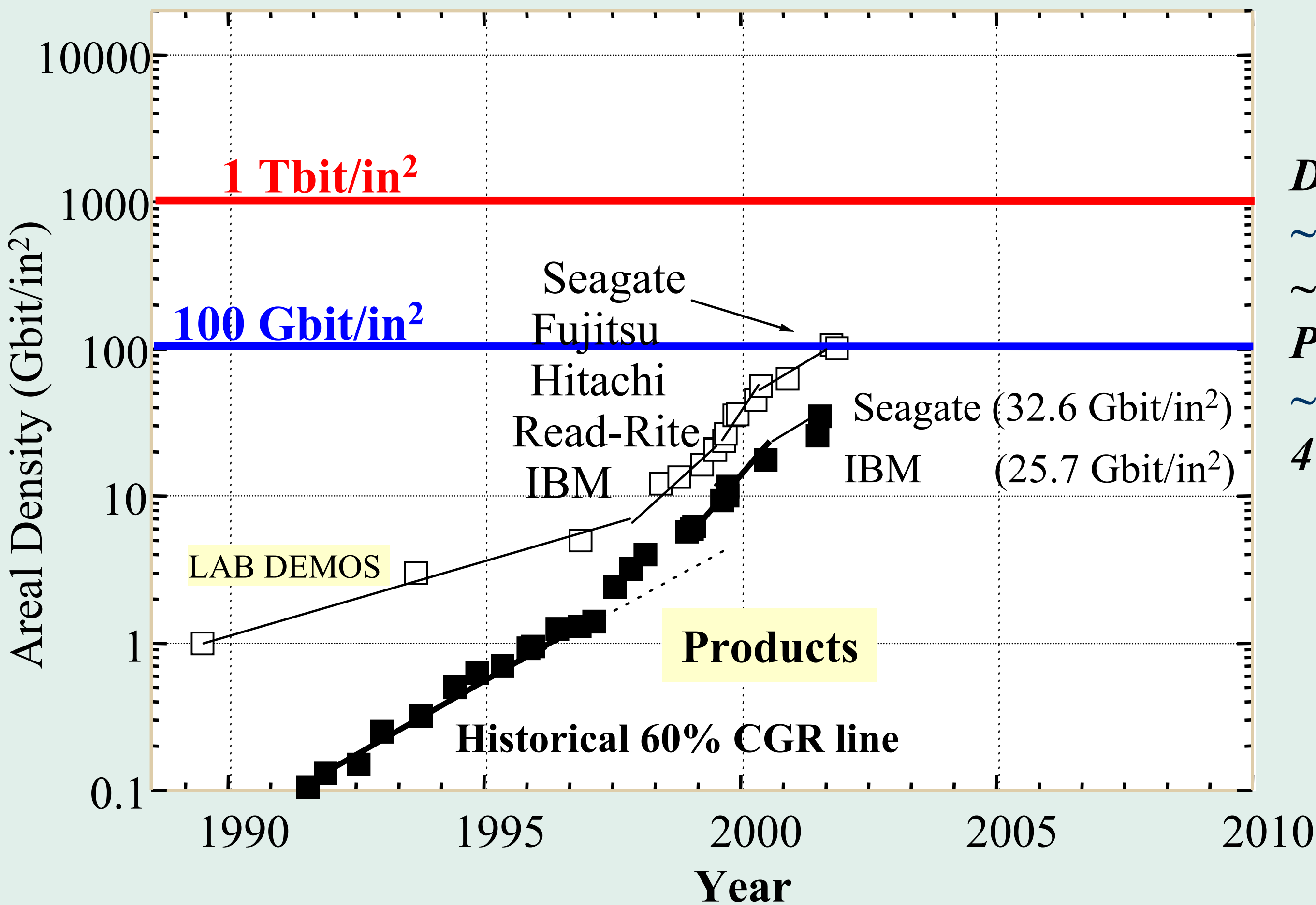
4.4 MB

70 kbit/s
IBM RAMAC 1955
2 kbits/in^2
50x24" dia disks

1 GB

32 Mbit/s
IBM Microdrive 2001
15.2 Gbits/in^2
1 x 1" dia disk

Progress in Magnetic Data Storage



Demos:
~100 Gbpsi long
~63 Gbpsi perp
Products:
~33 Gbpsi long
40 GB per disk

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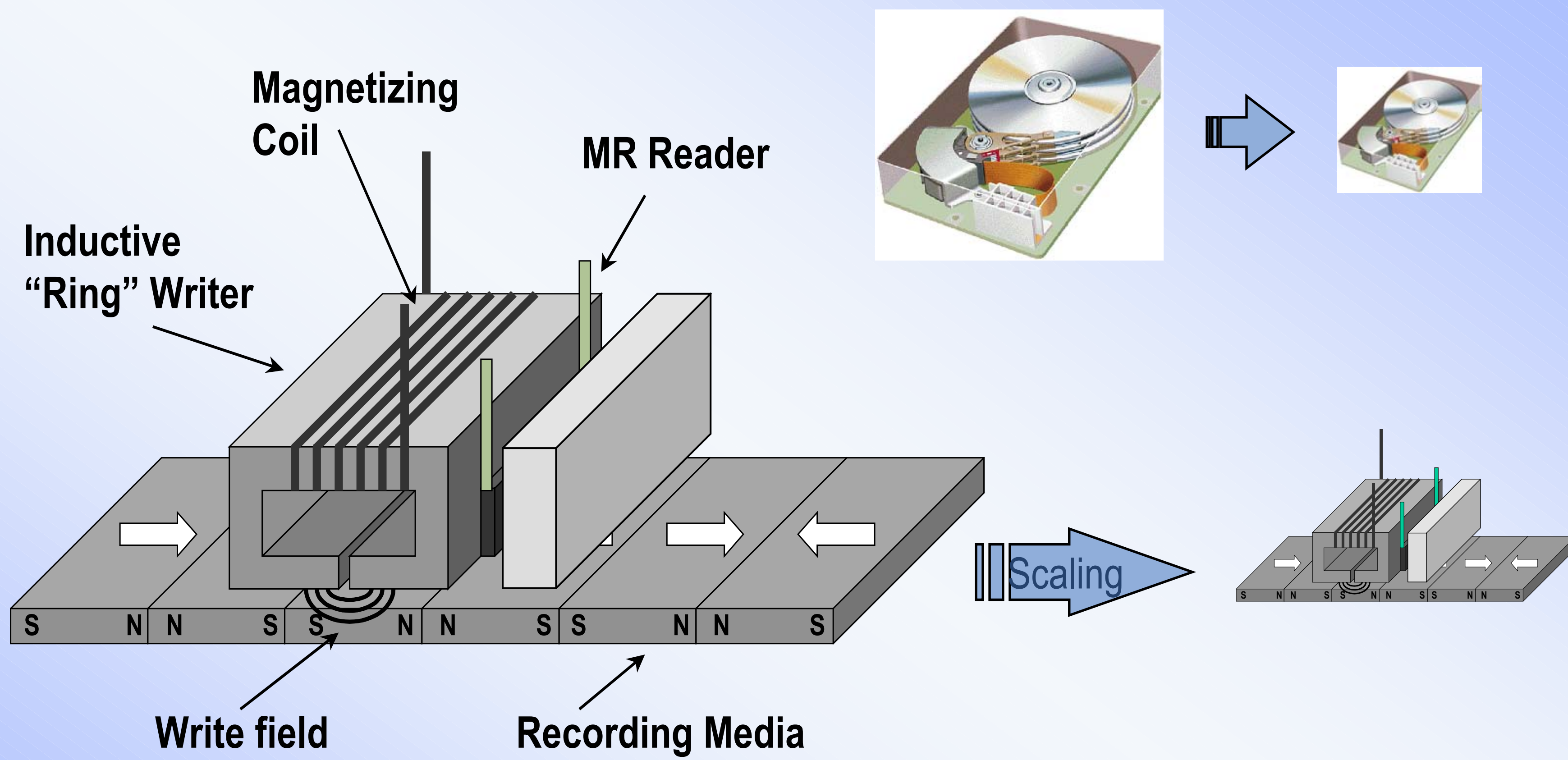
Scaling: Primary Technology Approach



- Longitudinal recording has been the underlying technology in the disk drive industry for the past several decades

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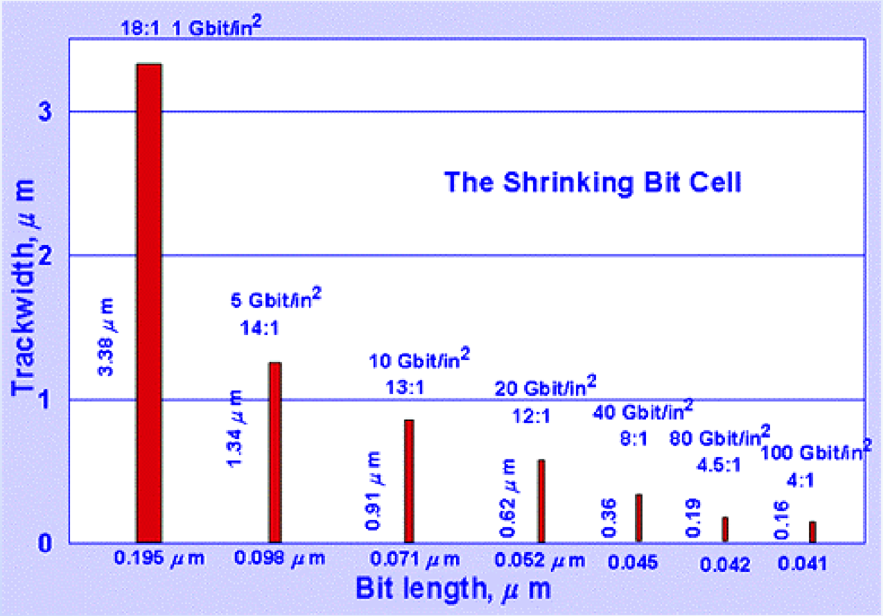
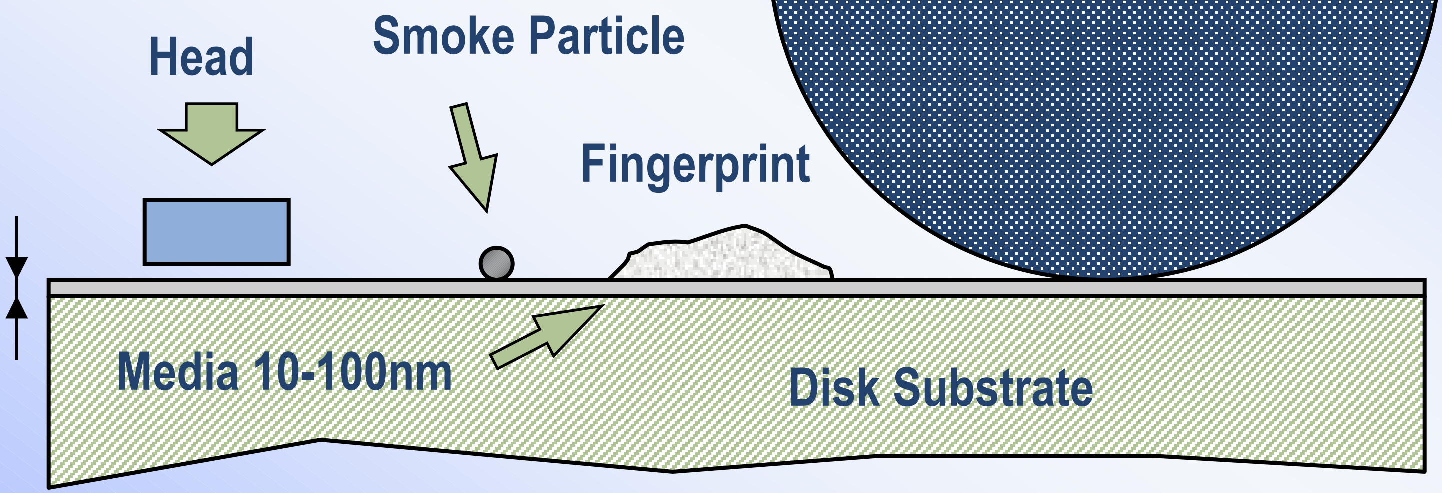
Scaling: Smaller heads, thinner media, lower fly heights





Superparamagnetic limit

- Overview of magnetic recording
- **Superparamagnetic limit** and the need for a new technology
- Dodging the Superparamagnetic limit … The advantages of perpendicular recording?
- A new system component: soft underlayer challenges and design considerations
- Skew Angle Sensitivity
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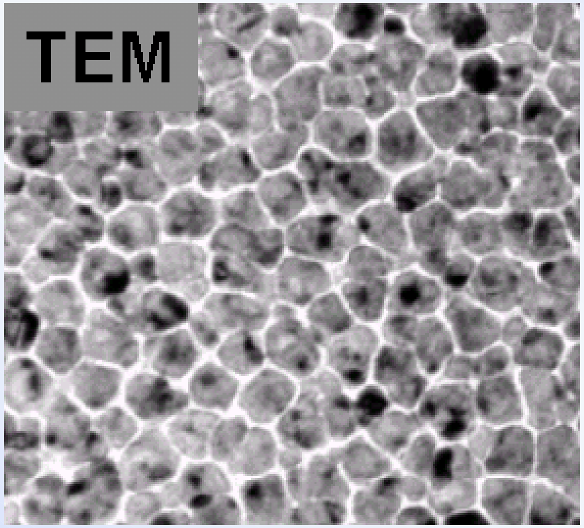
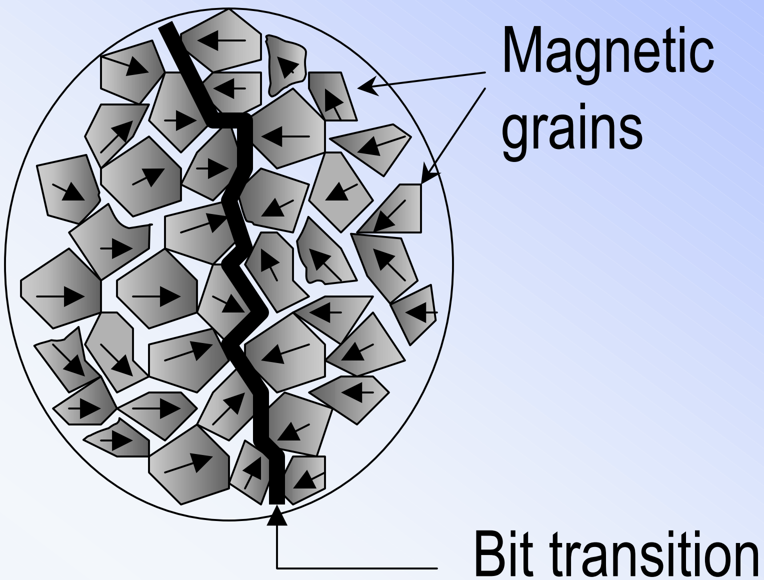
Media Microstructure, Scaling, and SNR





- SNR ~ log(N), N - number of grains per bit
- While scaling, need to preserve number of grains per bit to preserve SNR
- Grain size is reduced for higher areal densities: $a \sim \frac{1}{\sqrt{Areal\ Density}}$

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Media Stability

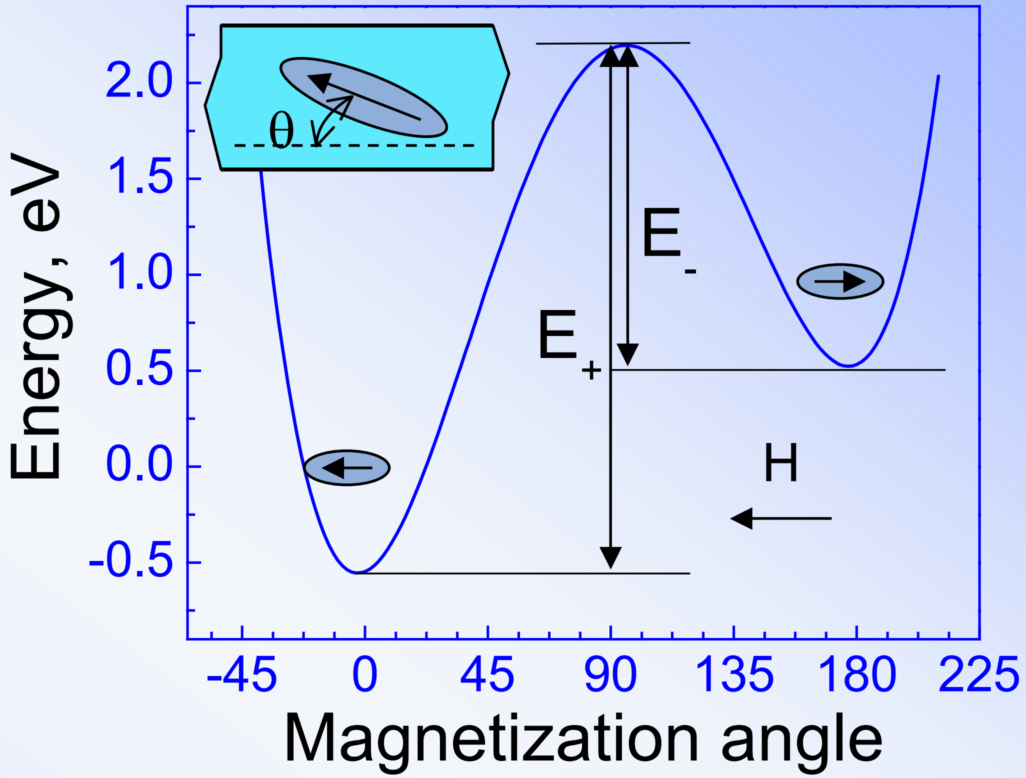
Probability of magnetization reversal due to thermal fluctuations:

$$f_{\pm} = f_0 \exp\left(-\frac{\Delta E_{\pm}}{k_B T}\right)$$

$$f_0 \sim 10^9 - 10^{12}, \Delta E_{\pm} \cong K_U V$$

K_U – anisotropy energy

V – grain volume



Thermally stable media: $\frac{K_U V}{k_B T} > 40 - 60$

Superparamagnetism

$$\frac{K_U V}{\mathrm{k_B} T} > 40-60 \Rightarrow V \cong a^3 \geq \frac{60\mathrm{k_B}T}{K_U}$$

$$a \sim \frac{1}{\sqrt{Areal\ Density}} \geq a_{\mathrm{minimum}} \cong \sqrt[3]{\frac{60\mathrm{k_B}T}{K_U}}$$

If $a<a_{minimum}$, medium becomes thermally unstable leading to severe deterioration of recorded data over time.

Approaches to avoid superparamagnetic instabilities:

- Decrease $a_{minimum}$ by increasing K_U
- Increase *a* by decreasing the number of grains per bit

Media Writability Limit

Stable media: $\frac{K_U V}{k_B T} \sim 40 - 60 \Rightarrow K_U \sim \frac{1}{V}$ or $K_U \sim \frac{1}{a^3}$

$$H_{write} > H_0 = \alpha \frac{2K_U}{M_S} - N_{eff} M_S \sim \frac{1}{a^3} \sim Areal\ Density^{3/2}$$

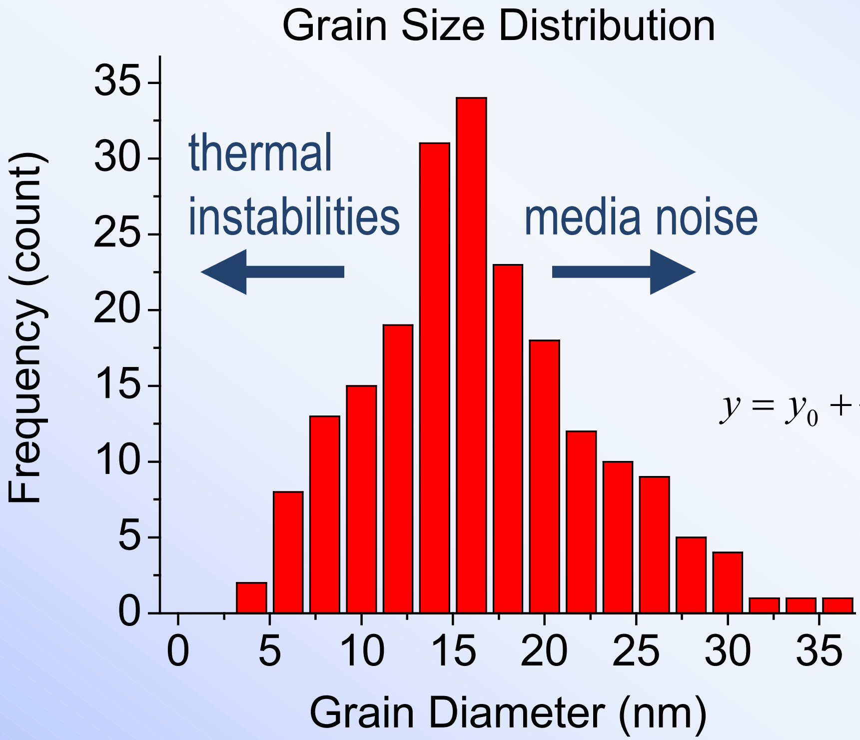
Higher areal density media requires higher write fields !!!

$H_{write} \sim M_S$ of the head material

Highest $4\pi M_S$ (=B_S) available today is ~26 kGauss (2.6Tesla)

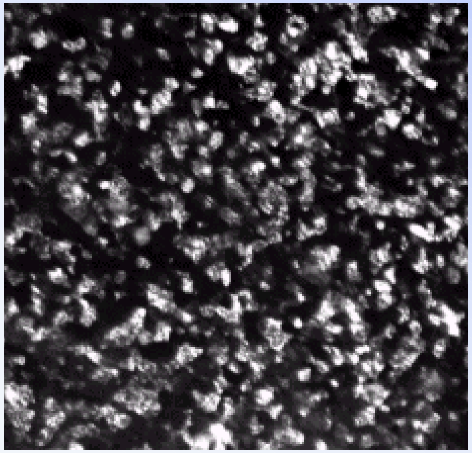
In longitudinal recording, the highest write field possible to generate is ~$2\pi M_S$!!!

Additional challenges: Grain Size Distribution



Grains in polycrystalline media are not uniform in size. The grain sizes are log-normally distributed

$$y = y_0 + \frac{A}{\sqrt{2\pi}wx}\exp\left[-\frac{\left[\ln\frac{x}{x_c}\right]^2}{2w^2}\right]$$



- Too small grains are thermally unstable ⇒ Unstable data
- Too large grains cannot be switched ⇒ Noise

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Advantages of Perpendicular Recording

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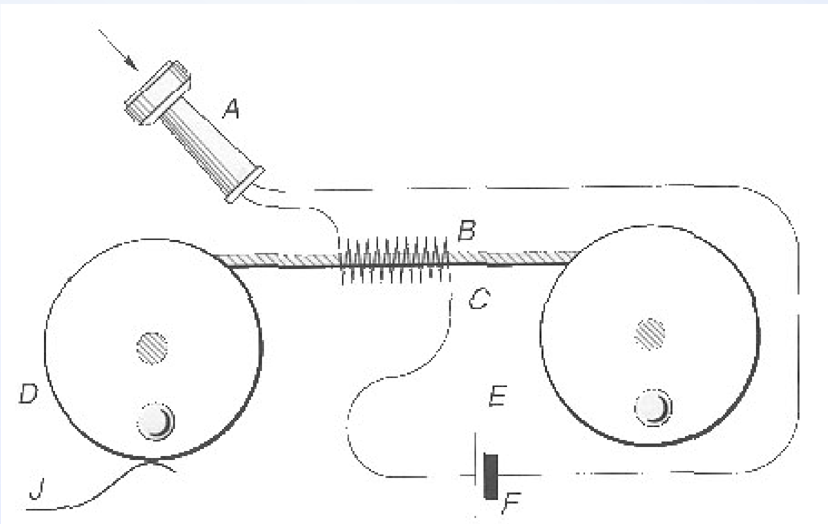
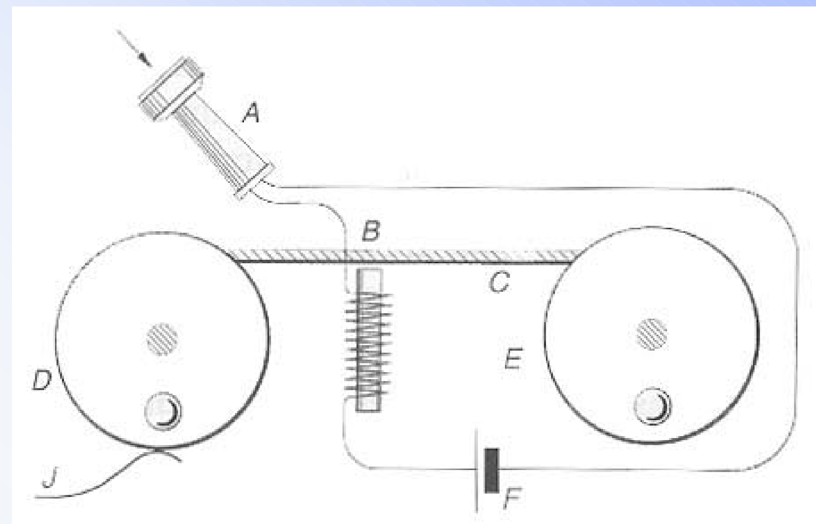
Origins of Perpendicular Recording

1878: Magnetic Recording: Oberlin Smith



Longitudinal Recording

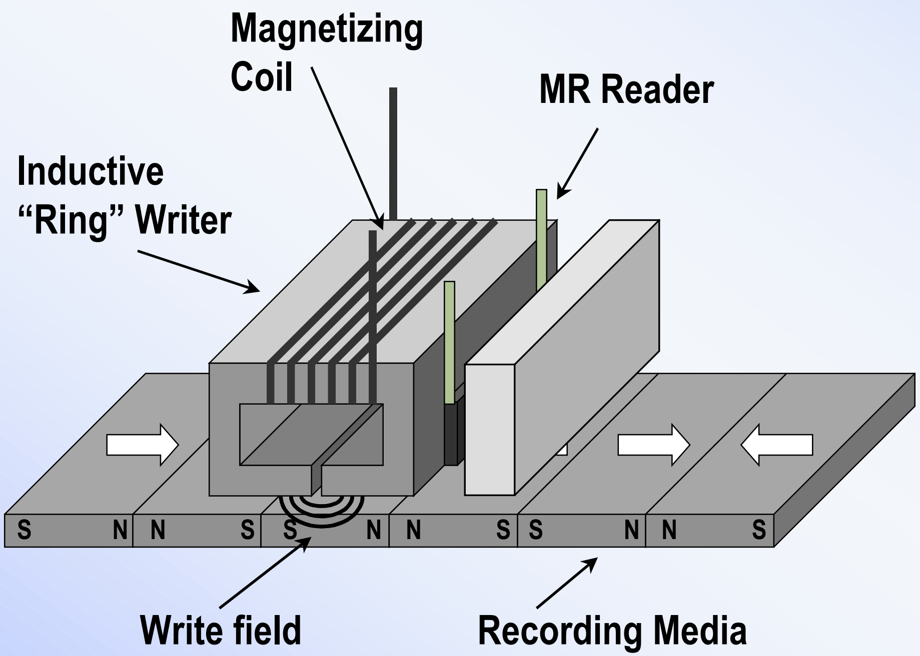


Perpendicular Recording

1960: G.Fan, *Ampex Corporation*

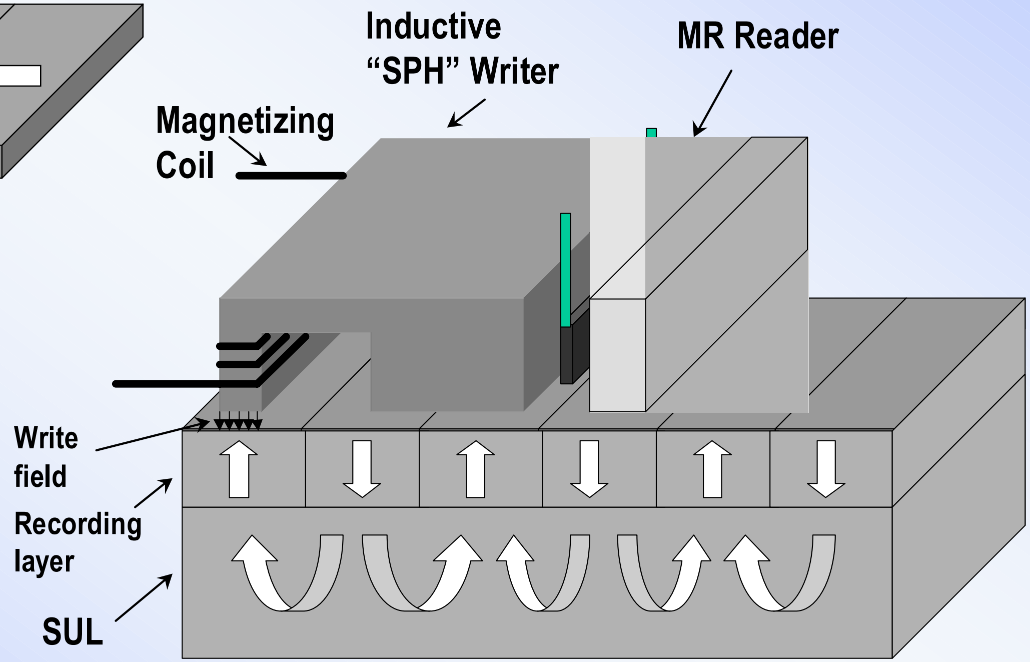
1977: S. Iwasaki, Magnetic Disk Perpendicular Recording Demo

Closest Alternative Technology

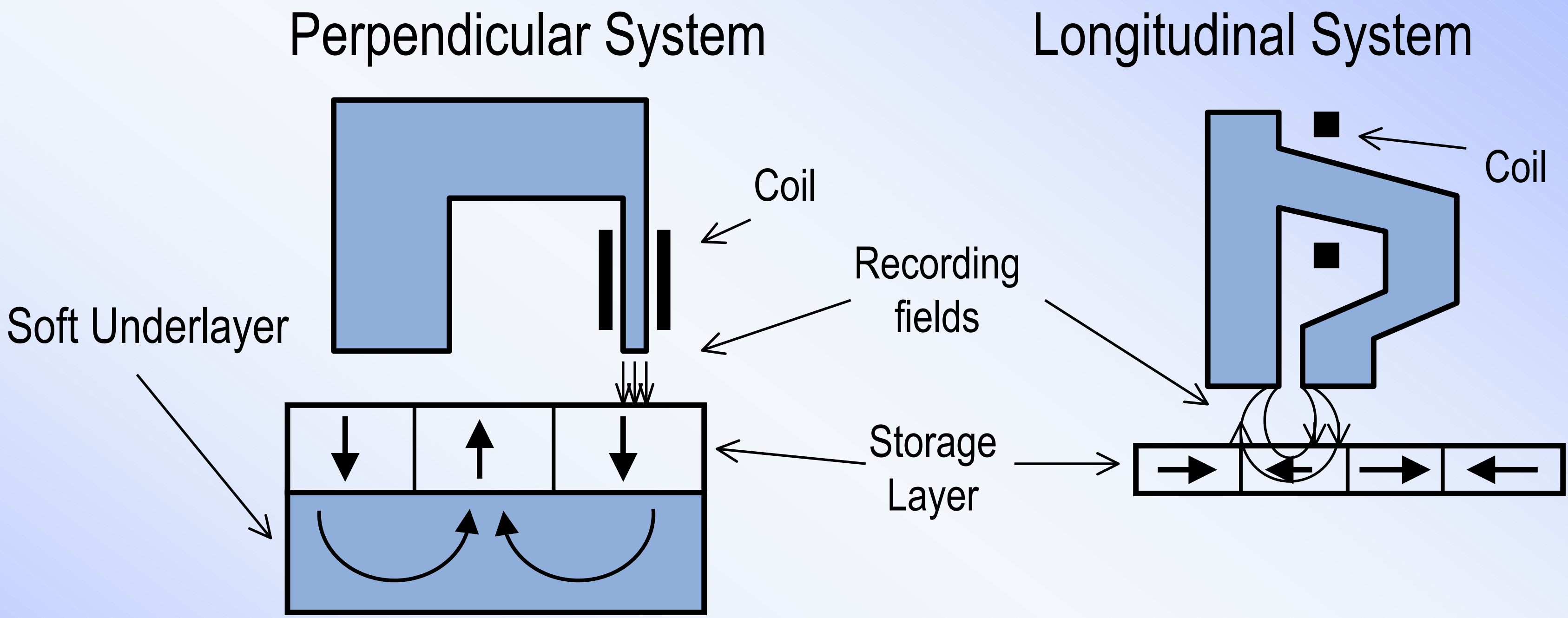


Longitudinal

Perpendicular

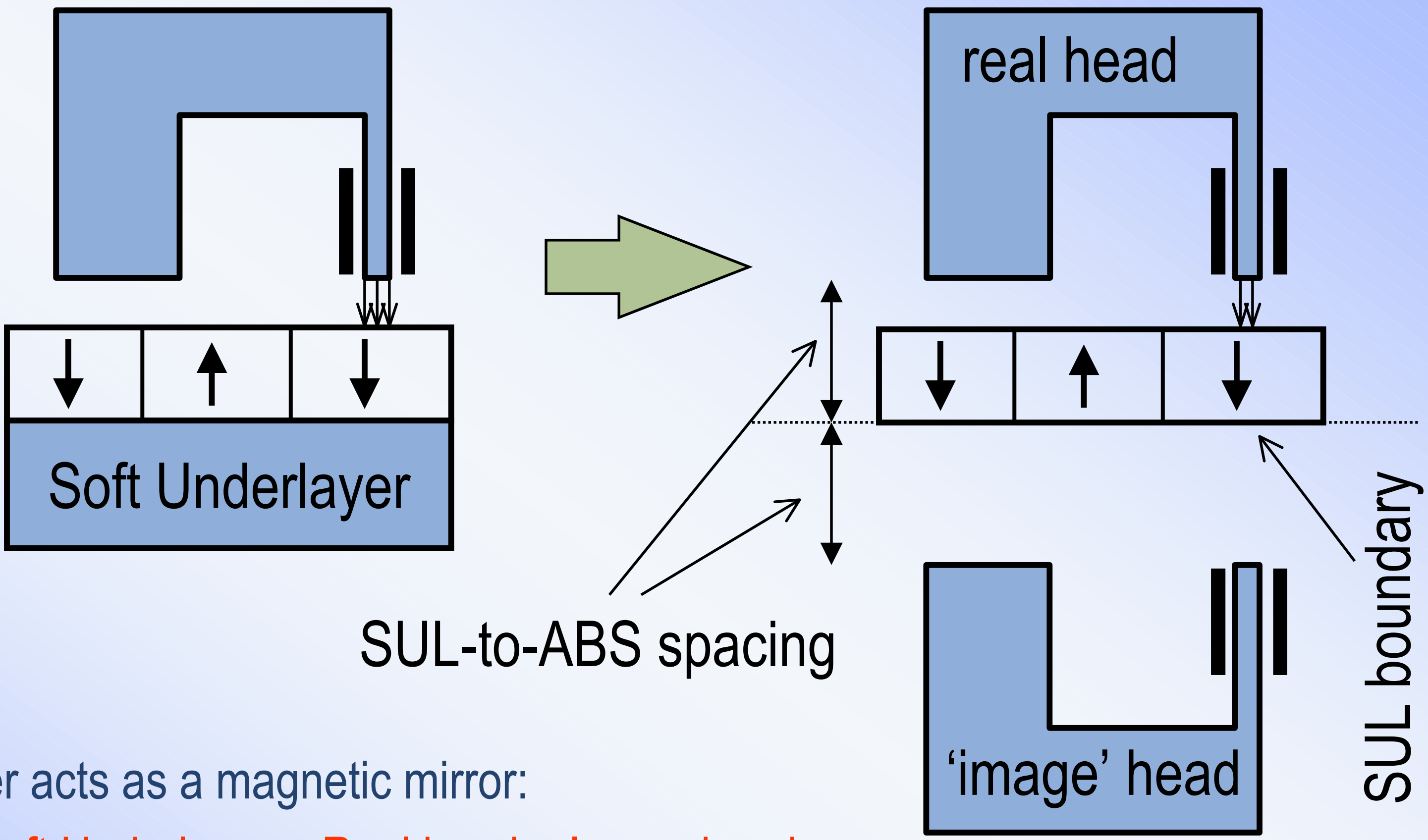


Perpendicular versus Longitudinal



Notice: Soft Underlayer (SUL) - a new system component

Soft Underlayer: Magnetic Imaging

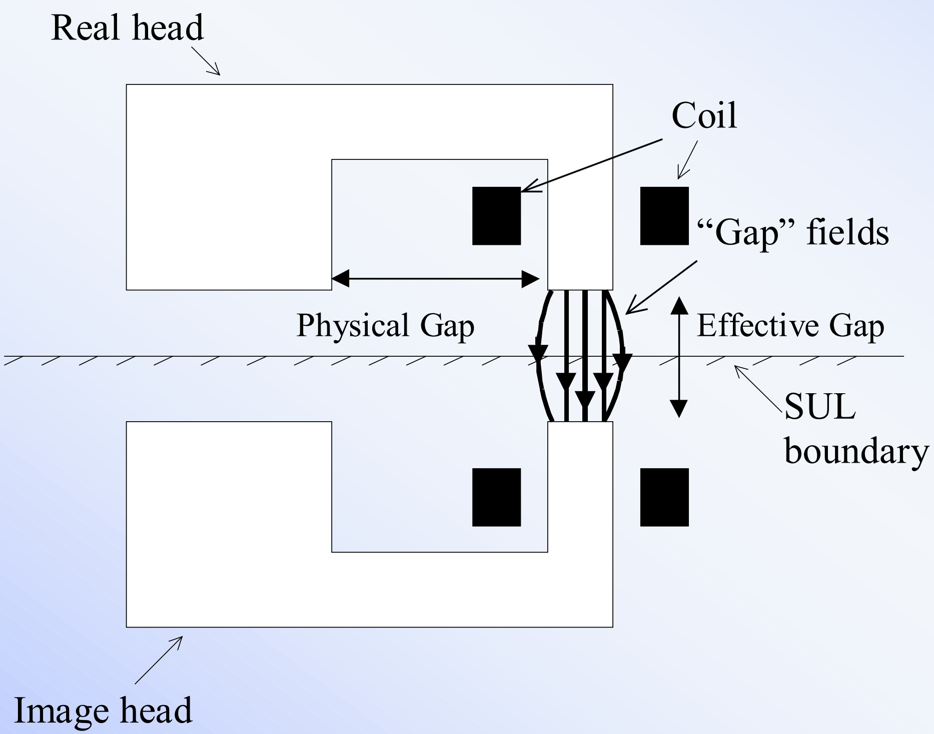


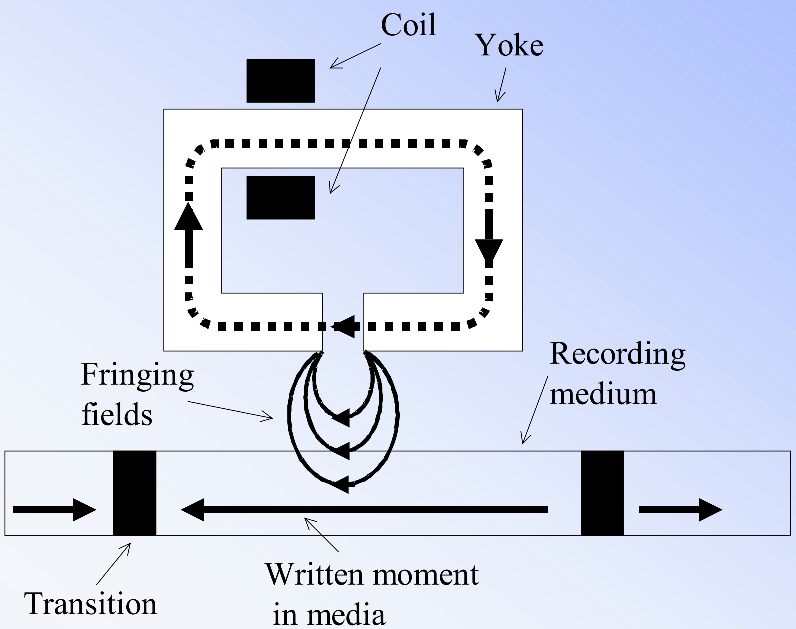
Soft underlayer acts as a magnetic mirror:

Real head + Soft Underlayer = Real head + Image head

Recording layer is sandwitched between real and 'image' write poles - writing in the gap (in longitudinal recording writing is done with fringing fields)

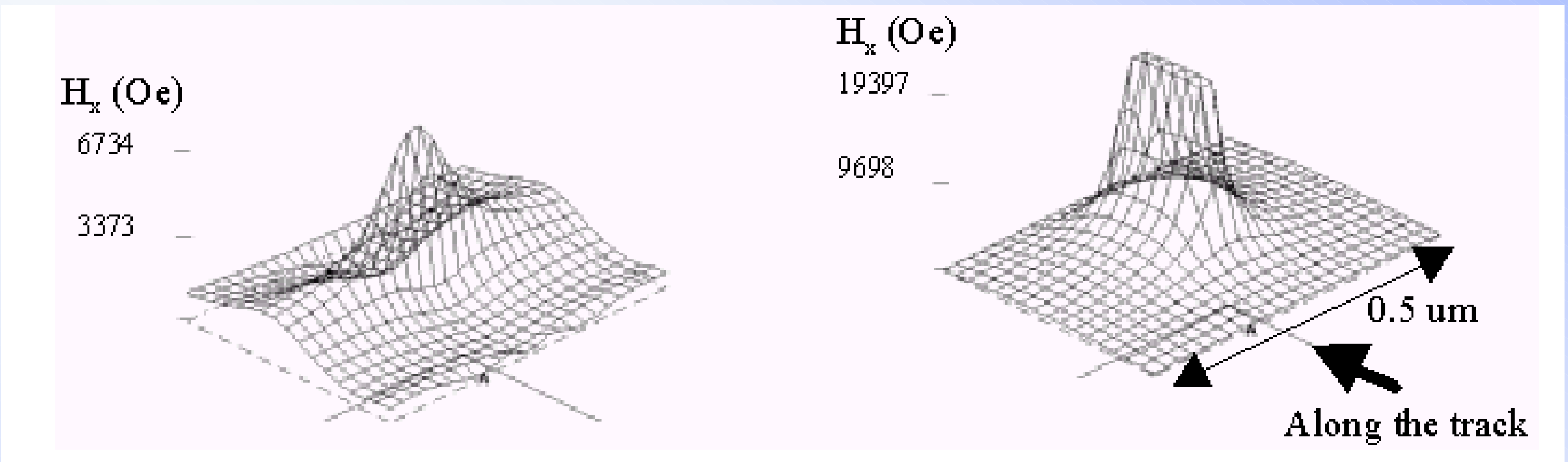
Gap versus Fringing Field Writing





- In perpendicular recording the write process effectively occurs in the gap (Write Field < $4\pi M_S$)
- In longitudinal recording the write process is done with the fringing fields (Write Field < $2\pi M_S$)

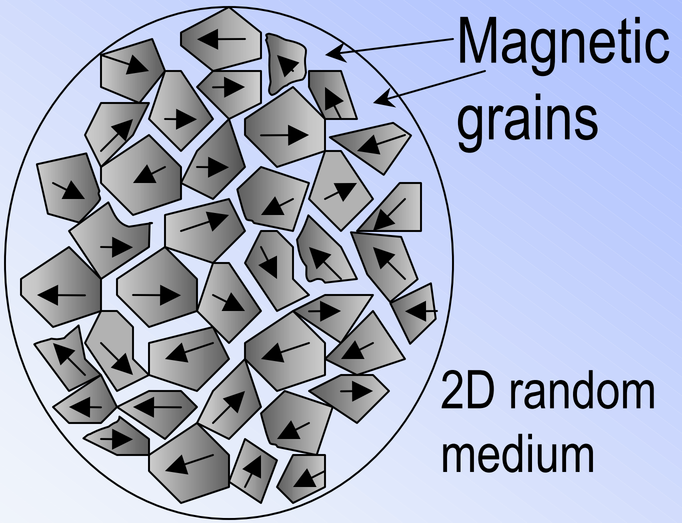
Write Field Comparison



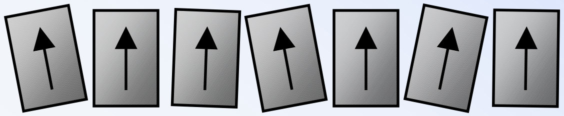
- **Twice as high write field amplitude:** can write on higher anisotropy media ⇒ better thermal stability
- **Substantially sharper field gradients:** less sensitive to grain anisotropy distribution ⇒ sharper bit transitions ⇒ higher areal density

Well-Aligned Recording Layers

In a typical longitudinal recording layer the magnetic anisotropy axes of individual grains are randomly oriented in the plane of the film



In perpendicular recording layer the anisotropy axis is relatively well aligned (<2-4 degrees) perpendicular to the plane of the film



Substantially relaxes the requirements for write field gradients

Can use thicker recording layer - better thermal stability !!!

(increased V in $K_U V/k_B T$ ratio)

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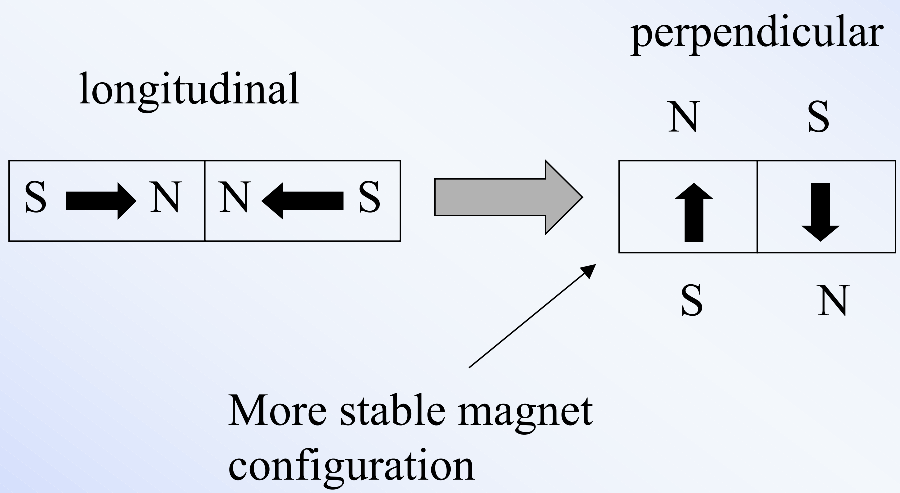
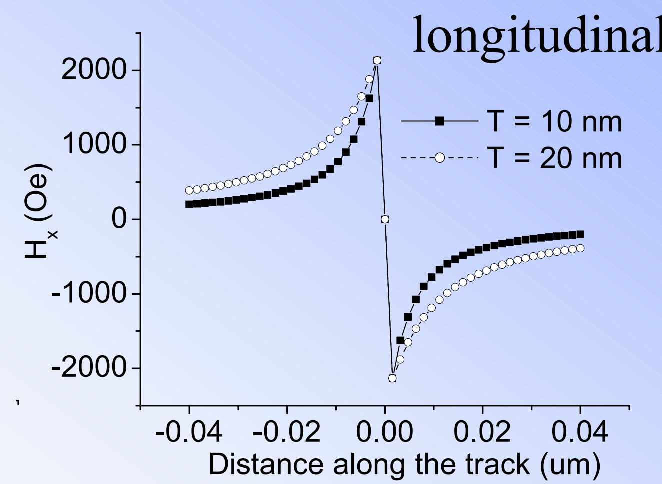
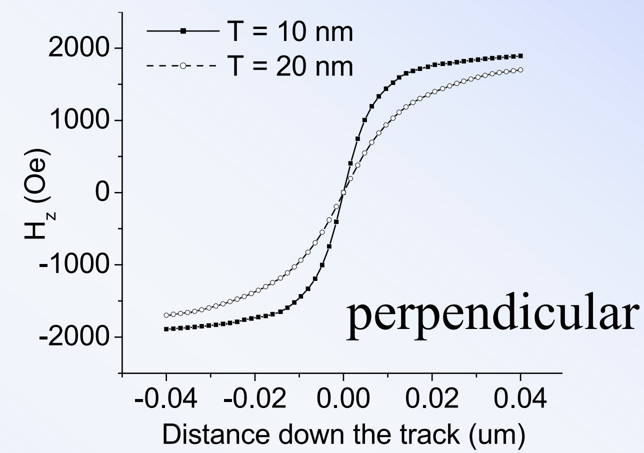
Demag Fields at Bit Transitions





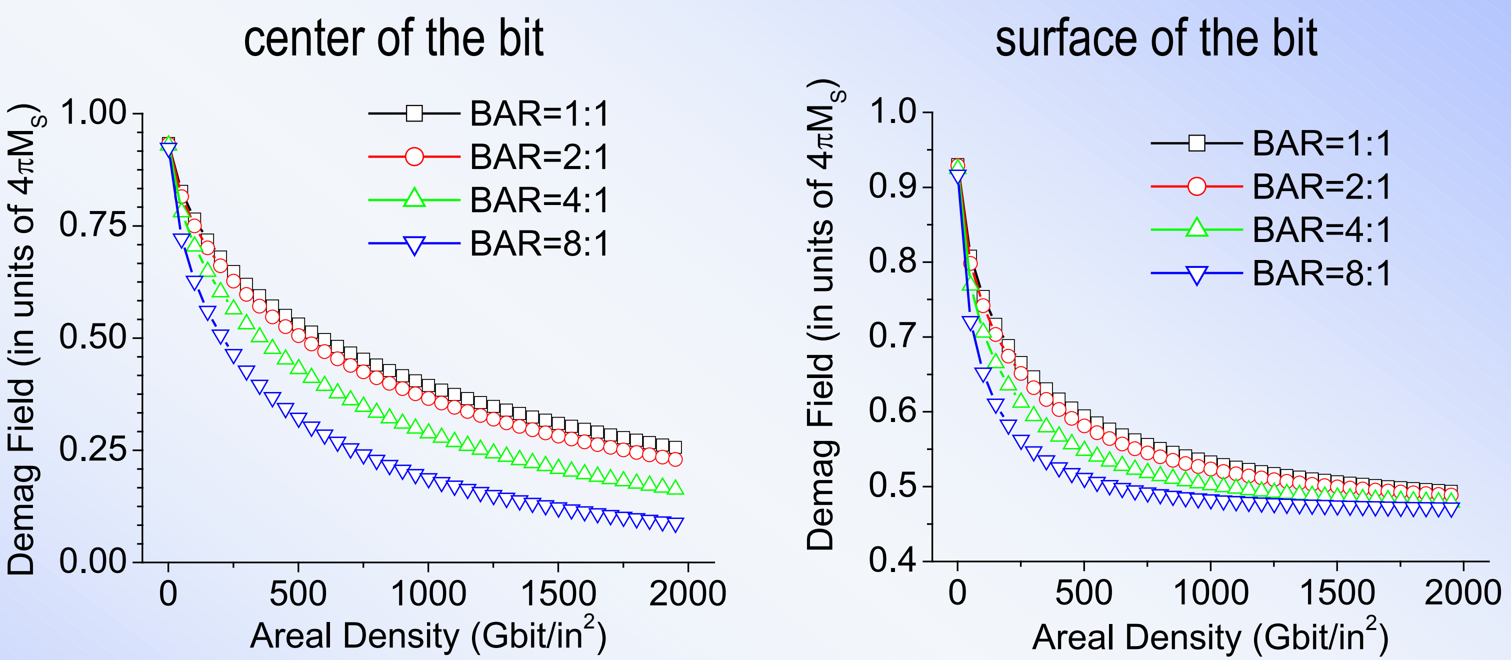


Demagnetizing fields destabilize recorded magnetization:

- **Increased transition width**
- **Contribute to thermal instabilities**

Perpendicular recording promotes higher areal densities !!!

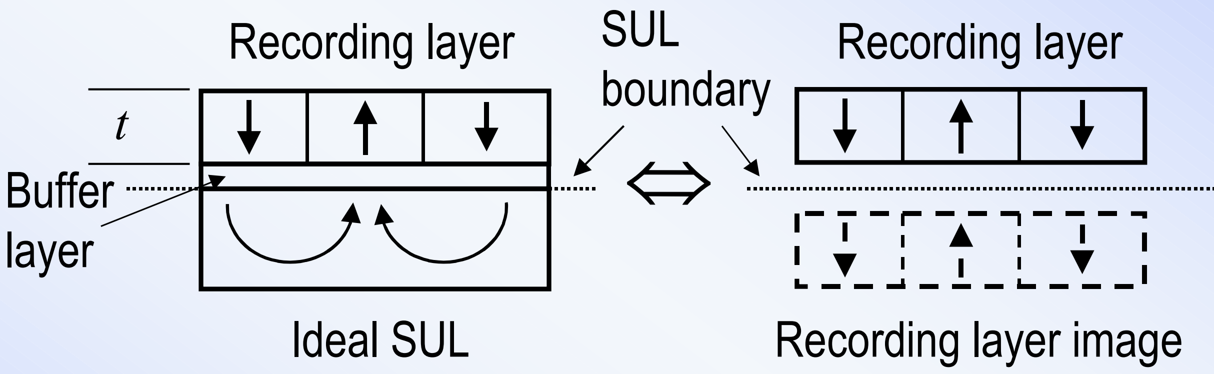
Reduced Demag Field at high BAR

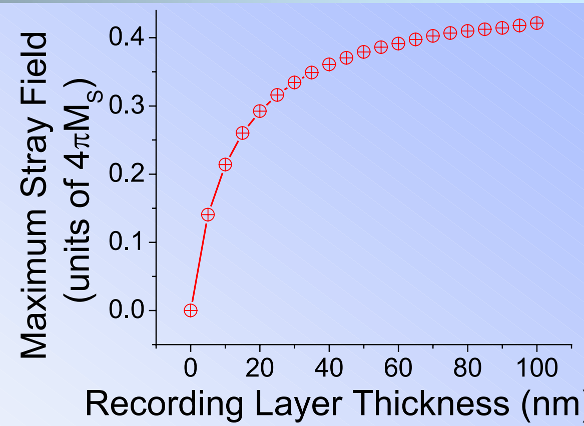


$$\text{BAR} = \frac{\text{track width}}{\text{bit length along the track}}$$

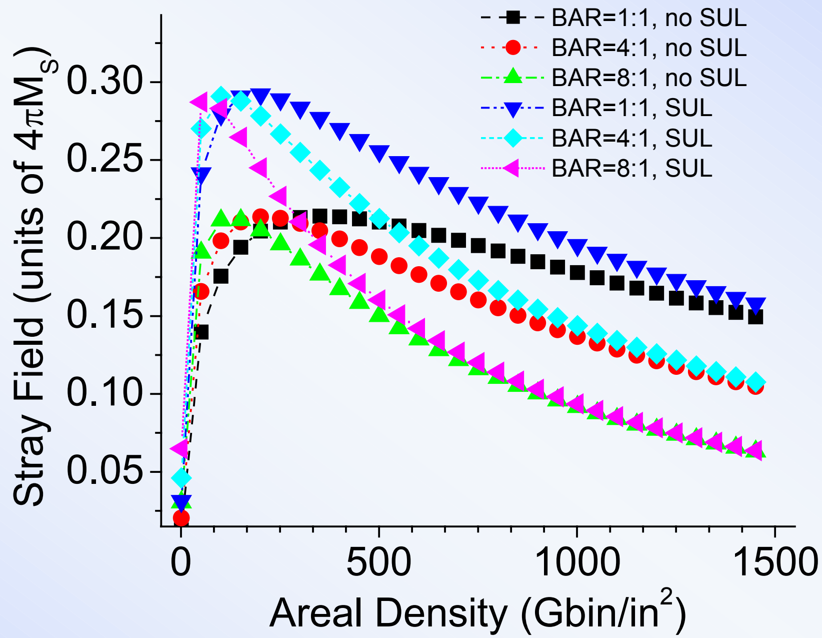
In contrast to longitudinal recording, in perpendicular recording higher bit aspect ratios (BAR) lead to reduce demagnetizing field - one of the major destabilizing factors leading to thermal instabilities

Enhanced Playback due to SUL





The magnitude of the stray fields (playback) is increased due to effective media thickness increase

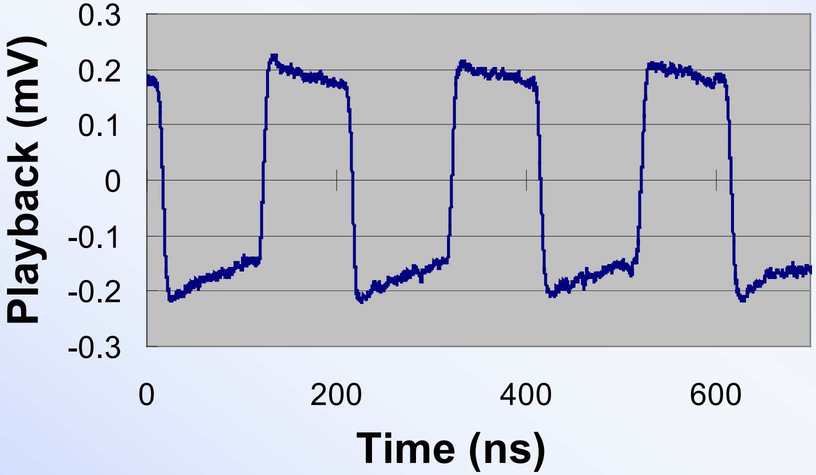


Summary of Advantages

- Higher write field amplitude - can use higher anisotropy media, better thermal stability
- Higher write field gradients and well aligned recording layers - thicker media, better thermal stability
- Zero demag at transitions - sharp bit transitions, more stable recorded data
- Decrease of demag with areal density increase - improved media stability at higher areal densities
- Higher playback amplitude - improved playback performance at higher areal densities

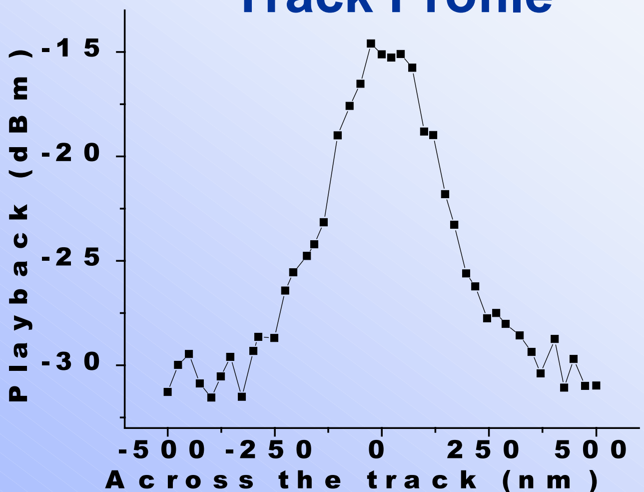
Narrow track recording

Waveform (200nm trackwidth)

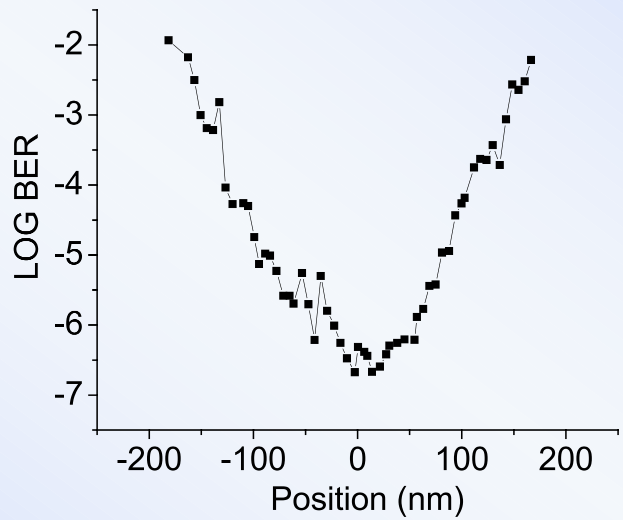


	1um track	.2um track
D50 (kfci)	200	190
acsn (1bit/pw50, dB)	21	19.5
Overwrite (dB)	40	40

Track Profile



Bathtub curve



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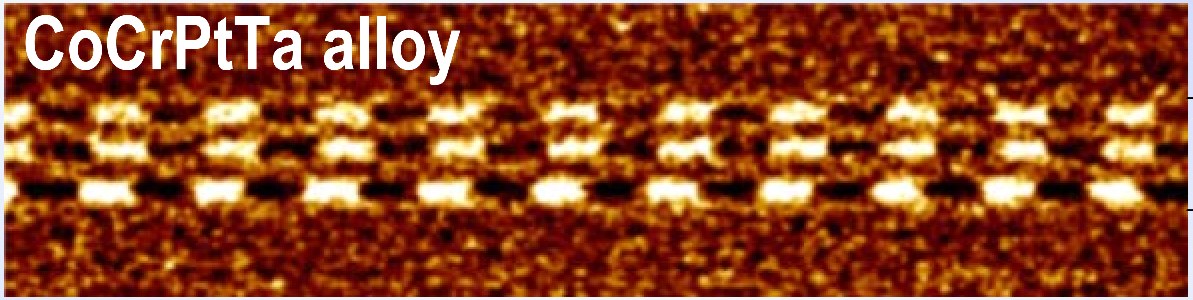
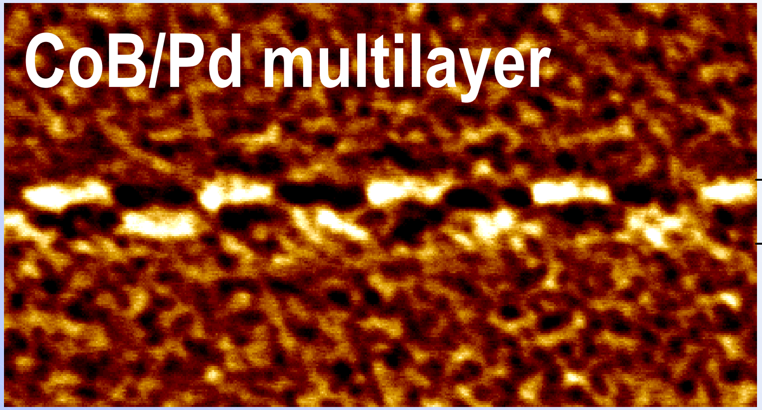
Narrow Track Recording

~190 ktpi

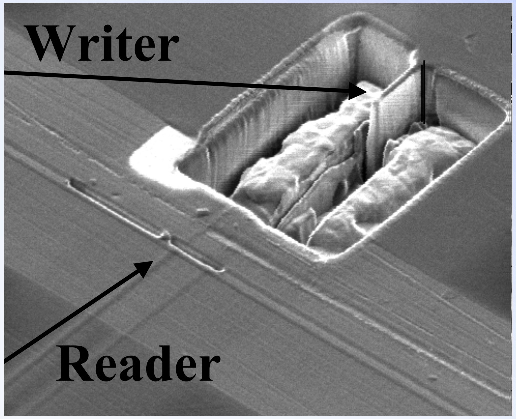


400 nm



~400 ktpi

130 nm



Current "state-of-the-art" longitudinal recording is <100ktpi

Soft Underlayer Challenges

- Overview of magnetic recording
- Superparamagnetic limit and the need for a new technology
- Dodging the Superparamagnetic limit … The advantages of perpendicular recording?
- **A new system component:** soft underlayer challenges and design considerations
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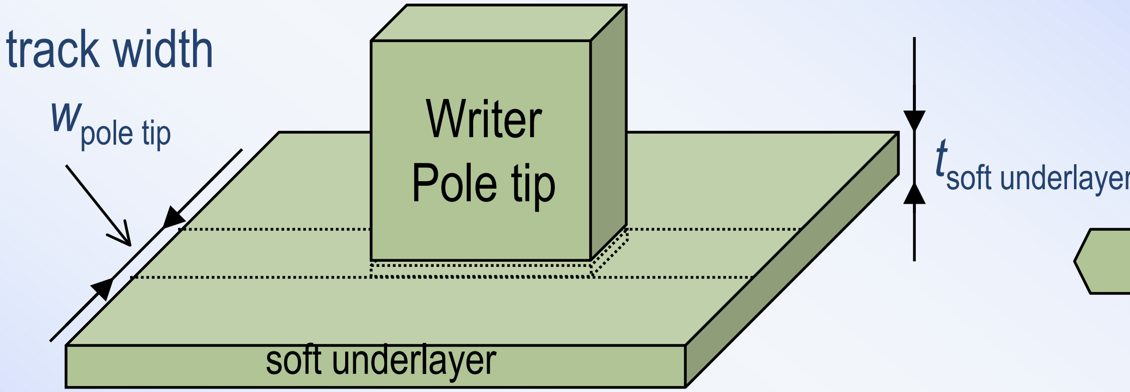
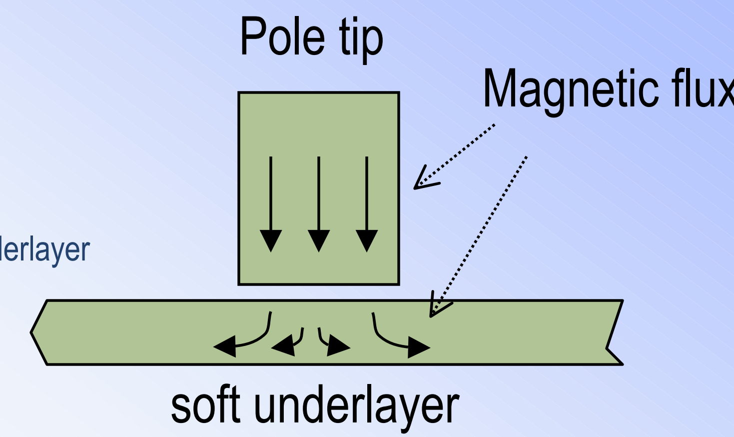
Soft Underlayer as a Flux Conductor





$\mathrm{div}\mathbf{B} = 0 \Rightarrow$ Magnetic flux should be conserved

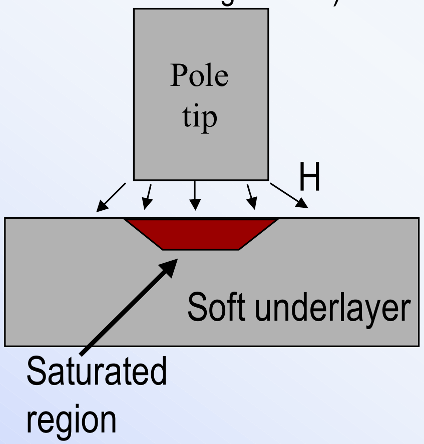
$$\mathbf{B}_{\text{into soft underlayer}} \times A_{\text{soft underlayer effective}} = \mathbf{B}_{\text{emanating from the pole tip}} \times A_{\text{ABS pole tip}}$$

In the limiting case, when the pole tip saturates (during writing):

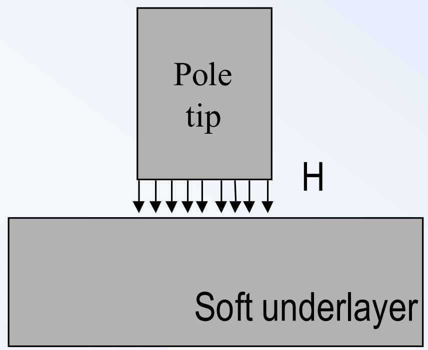
$$4\pi M_{\text{S soft underlayer}} \times A_{\text{soft underlayer effective}} \geq 4\pi M_{\text{S pole tip}} \times A_{\text{ABS pole tip}}$$

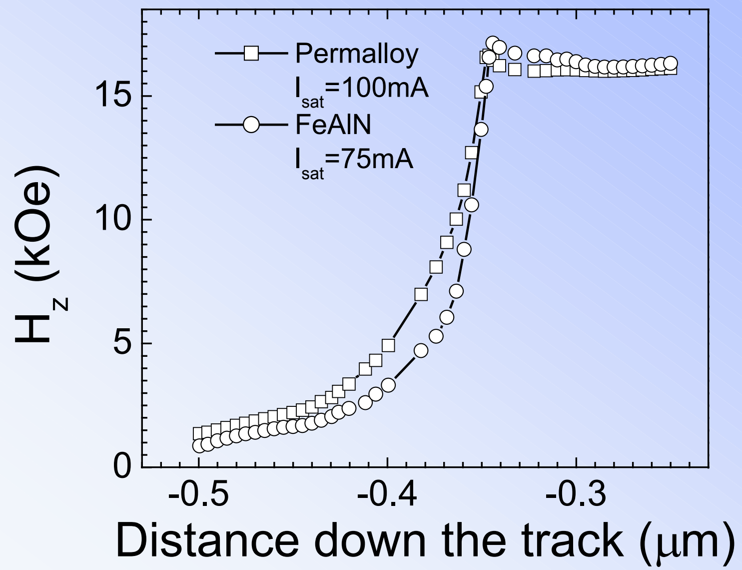
Soft Underlayer Moment

SUL $4\pi M_S$ < Head $4\pi M_S$
(saturated region under the pole tip deteriorates gradients)



SUL $4\pi M_S$ > Head $4\pi M_S$
(not saturated under the pole tip)



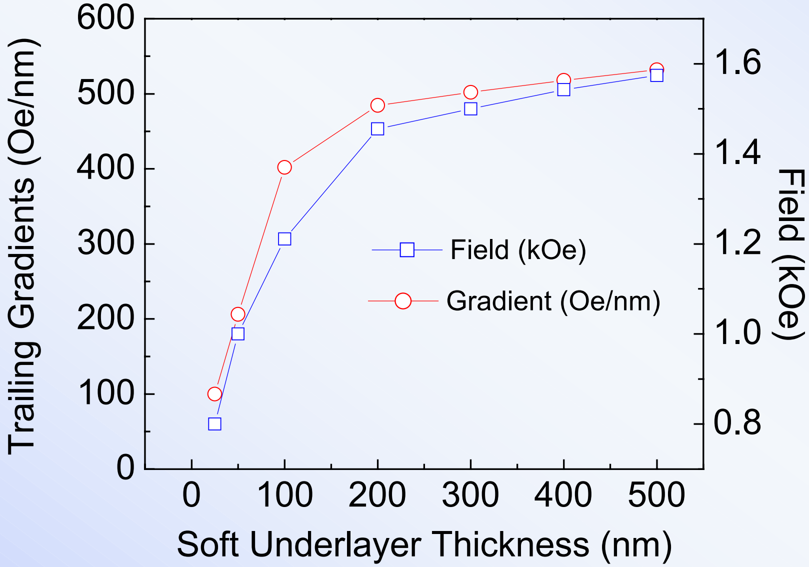


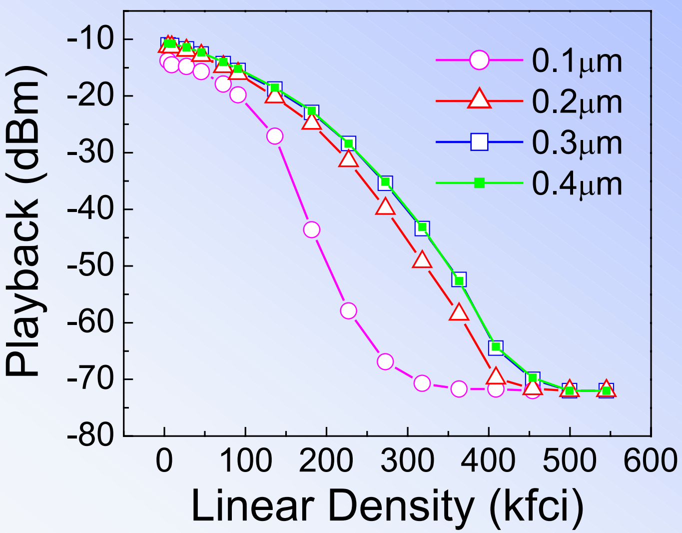
$$4\pi M_{S\,\text{soft underlayer}} \times A_{\text{soft underlayer effective}} \geq 4\pi M_{S\,\text{pole tip}} \times A_{\text{ABS pole tip}}$$

$$A_{\text{soft underlayer effective}} \cong A_{\text{ABS pole tip}} \Rightarrow 4\pi M_{S\,\text{soft underlayer}} \geq 4\pi M_{S\,\text{pole tip}}$$

Usage of lower moment soft underlayers can lead to the deterioration of the write field gradients

Soft Underlayer Thickness

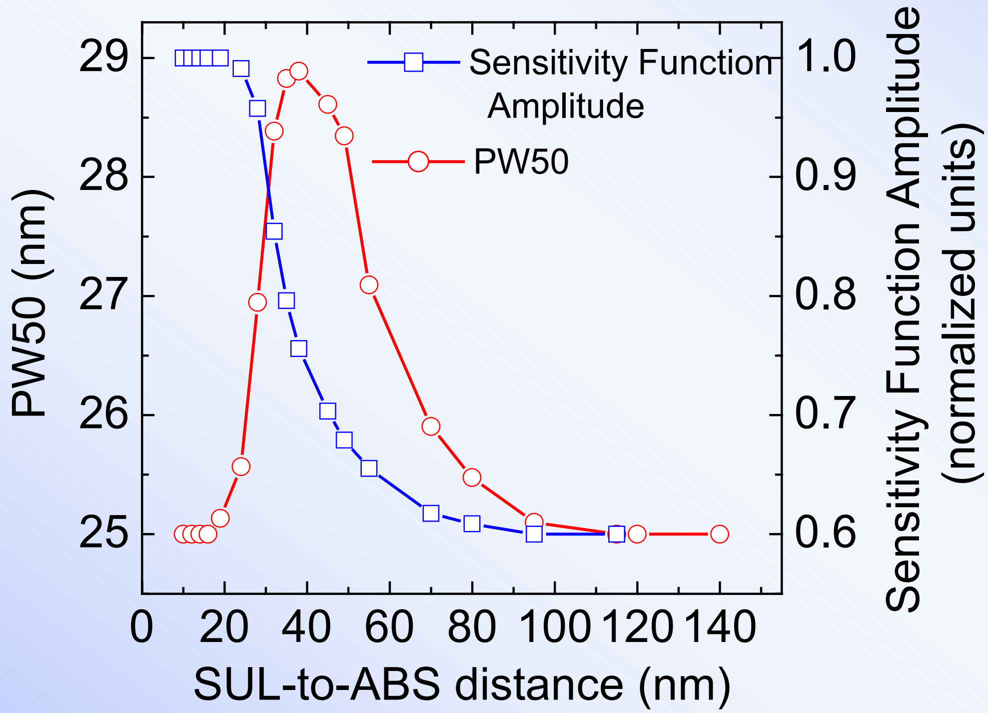


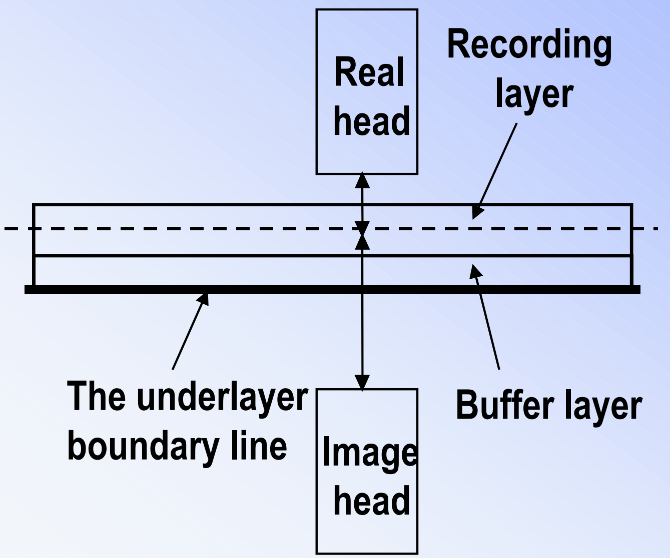


$$t_{\text{soft underlayer}} \geq \frac{1}{2}\frac{M_{\text{S pole tip}}}{M_{\text{S soft underlayer}}} w_{\text{pole tip}}$$

Both the write field amplitude and the write field gradient can deteriorate is too thin soft underlayer is used

Soft Underlayer and Playback Resolution



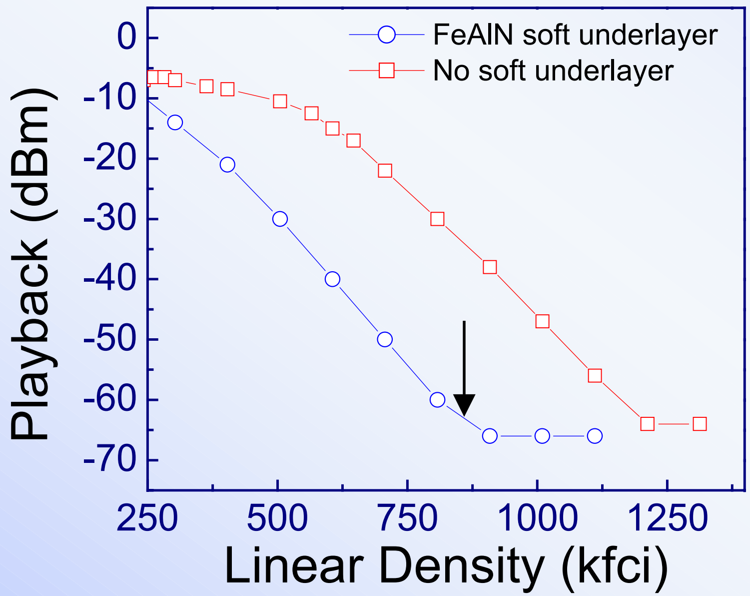


Soft underlayer introduces asymmetry into the playback system.

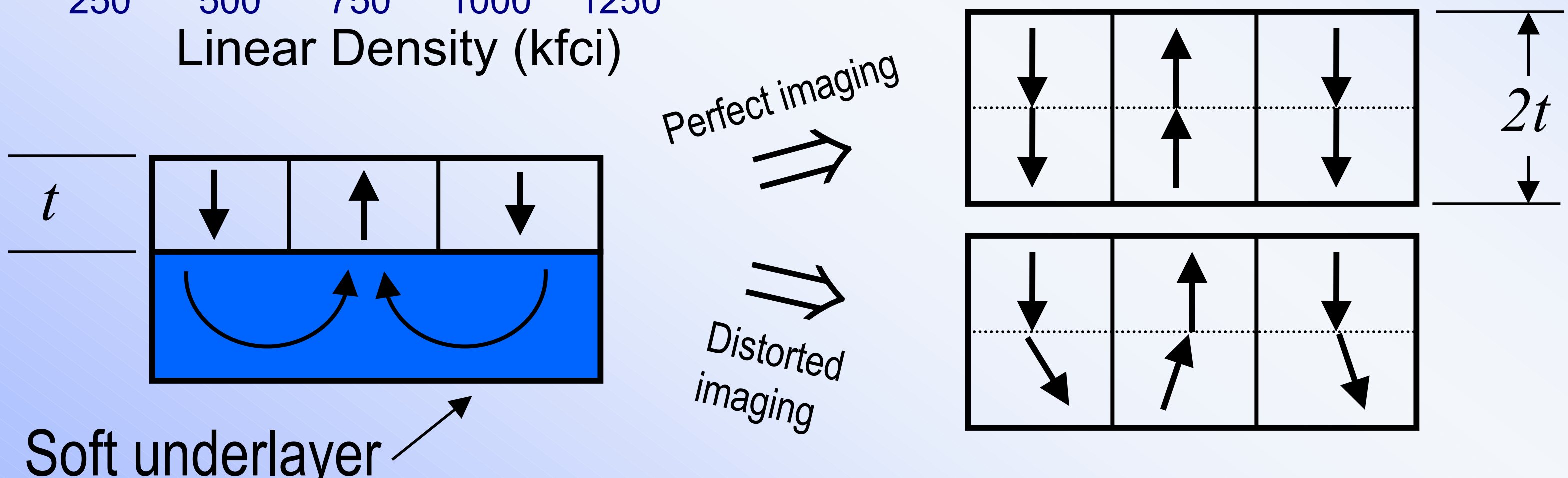
If not designed properly, can deteriorate system's resolution

Soft Underlayer Micromagnetics

CoCrPtTa recording layer



- CoCrPtTa alloy based recording layer is capable of recording densities well in excess of 600kfci.
- Further development is necessary to minimize noise and/or distortions caused by the presence of the soft underlayer



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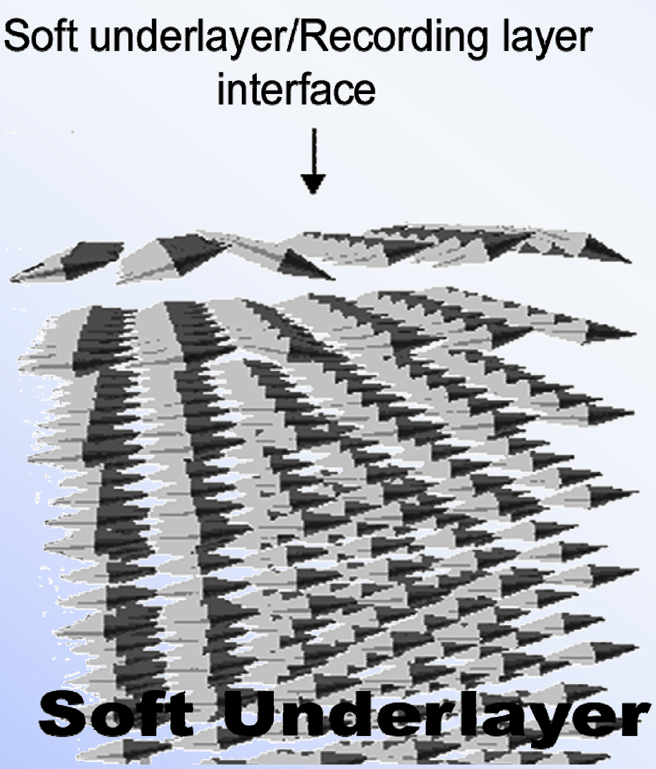
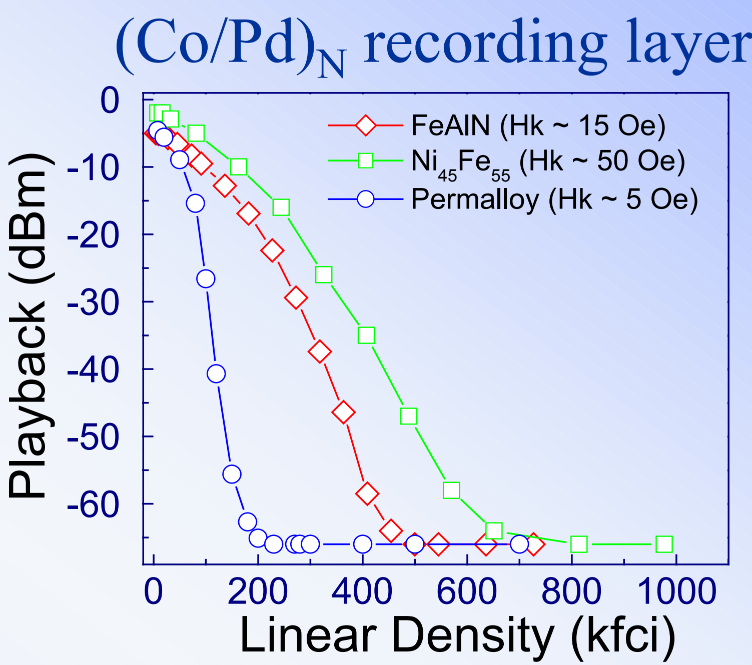
Micromagnetics and Playback Resolution

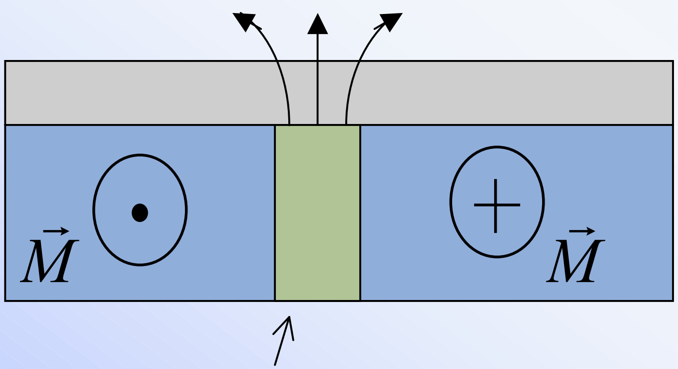




Material	Hk (Oe)	Ms (kGauss)	A x10E-6 (erg/cm) (*)	Delta (nm)	Linear Density (kfci)
Permalloy	5	10	~1.0	112	226
FeAlN	15	20	~1.7	60	421
Ni45Fe55	<50	16	~1.5	34	737
CoFe	100	24	~2.0	23	1099

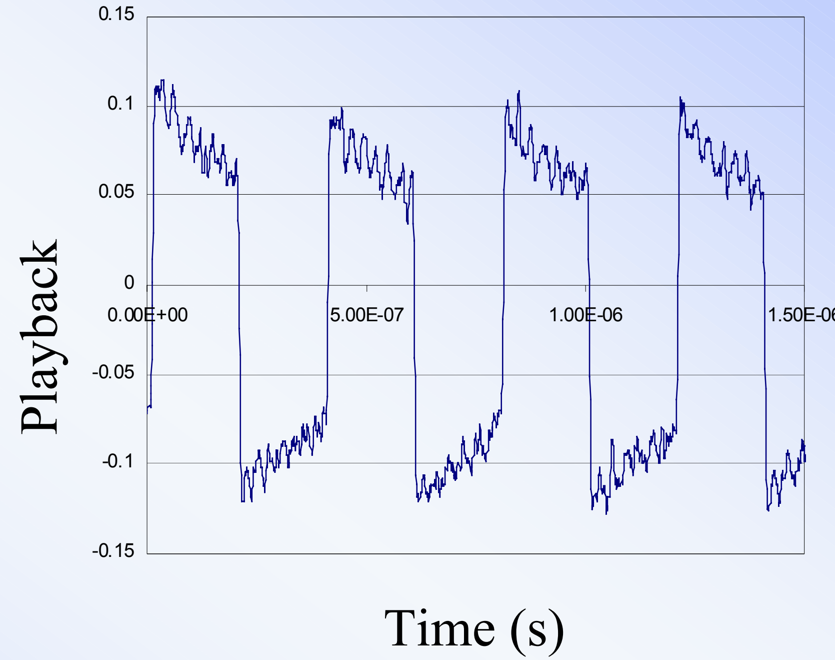
Soft Underlayer Noise

Fields from Wall (Source of Noise)



Domain wall
(source of "magnetic charges")

Ta/Permalloy/Pd/$(Co/Pd)_N$
(not biased soft underlayer)



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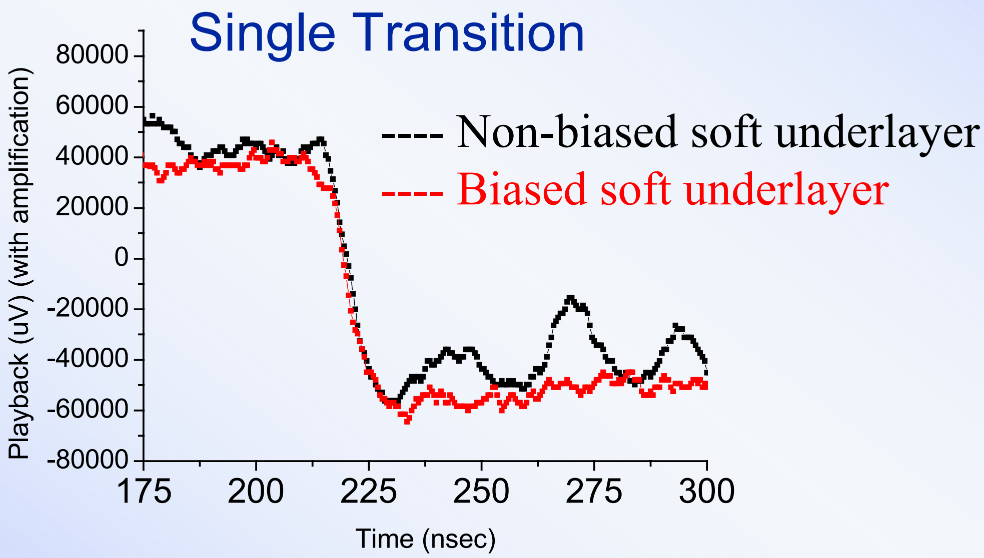
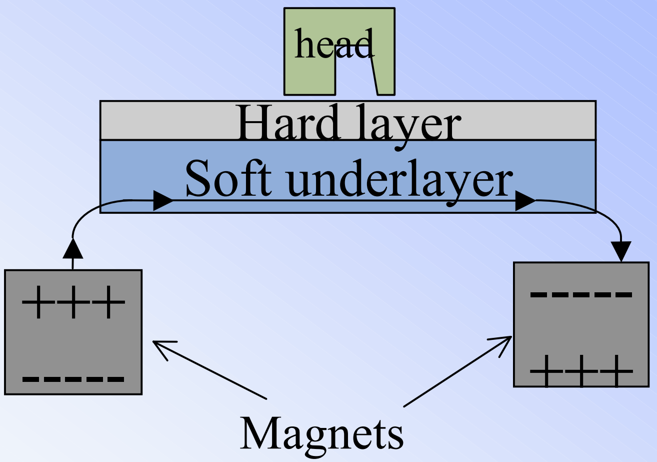
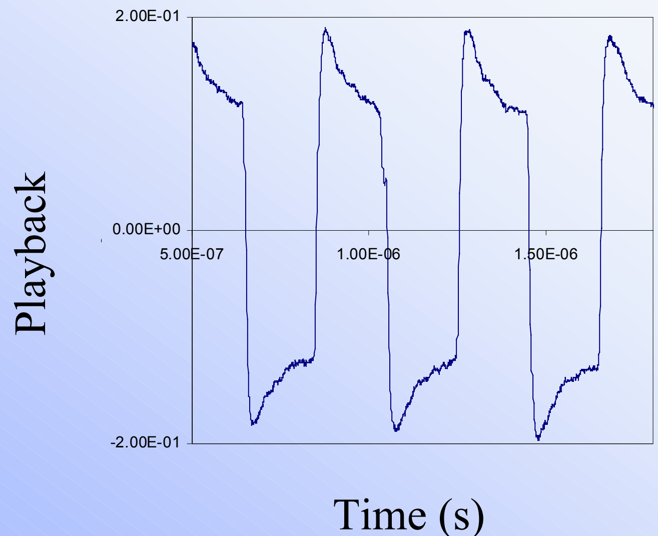
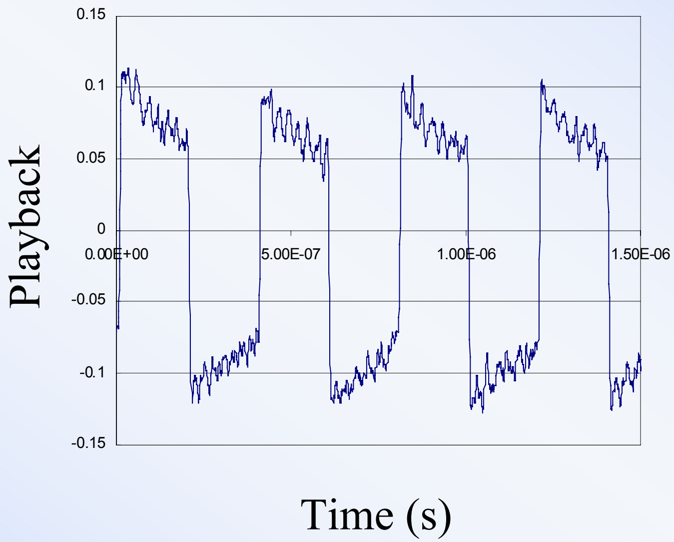
Soft Underlayer Biasing







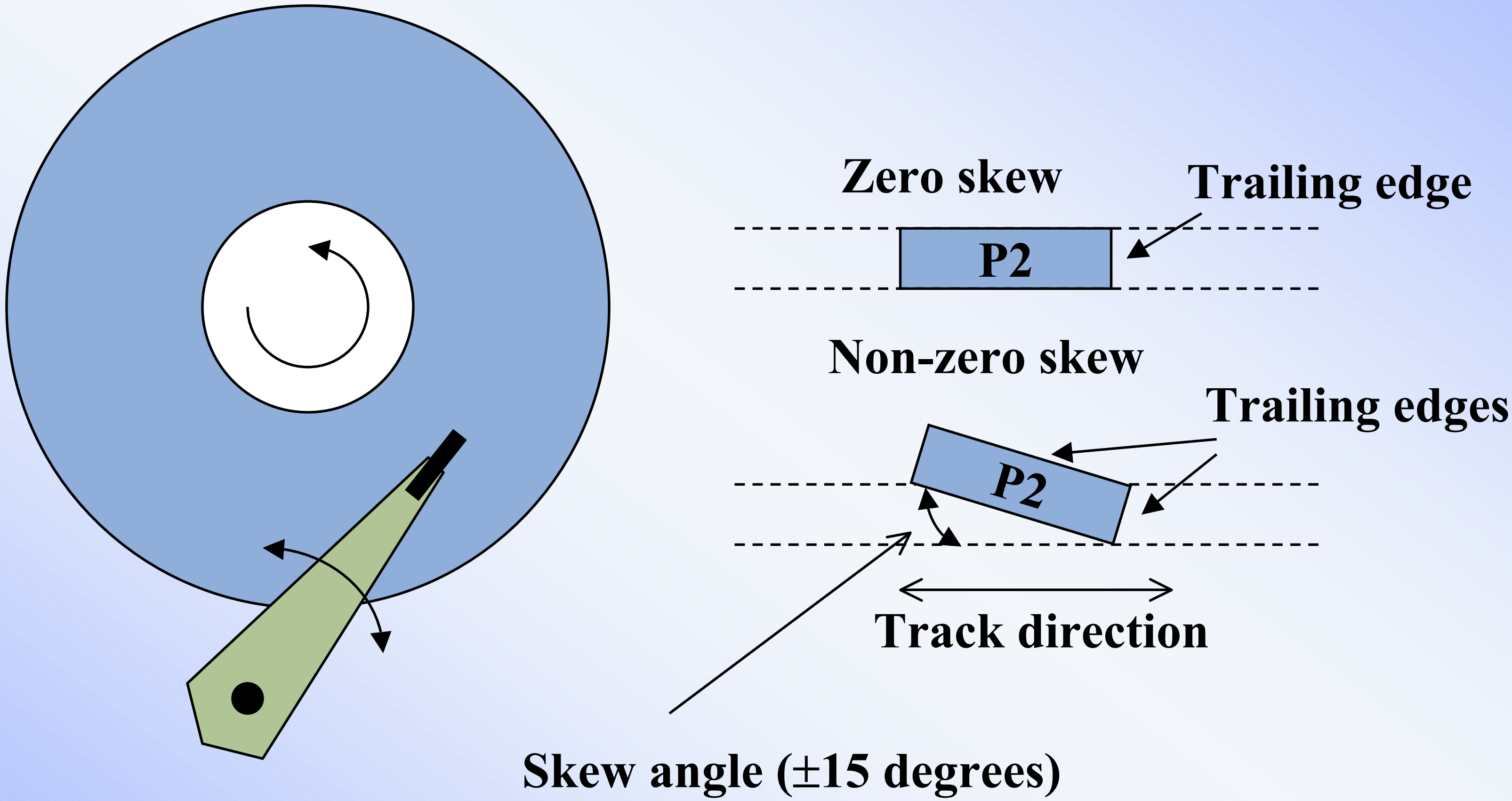
⇒



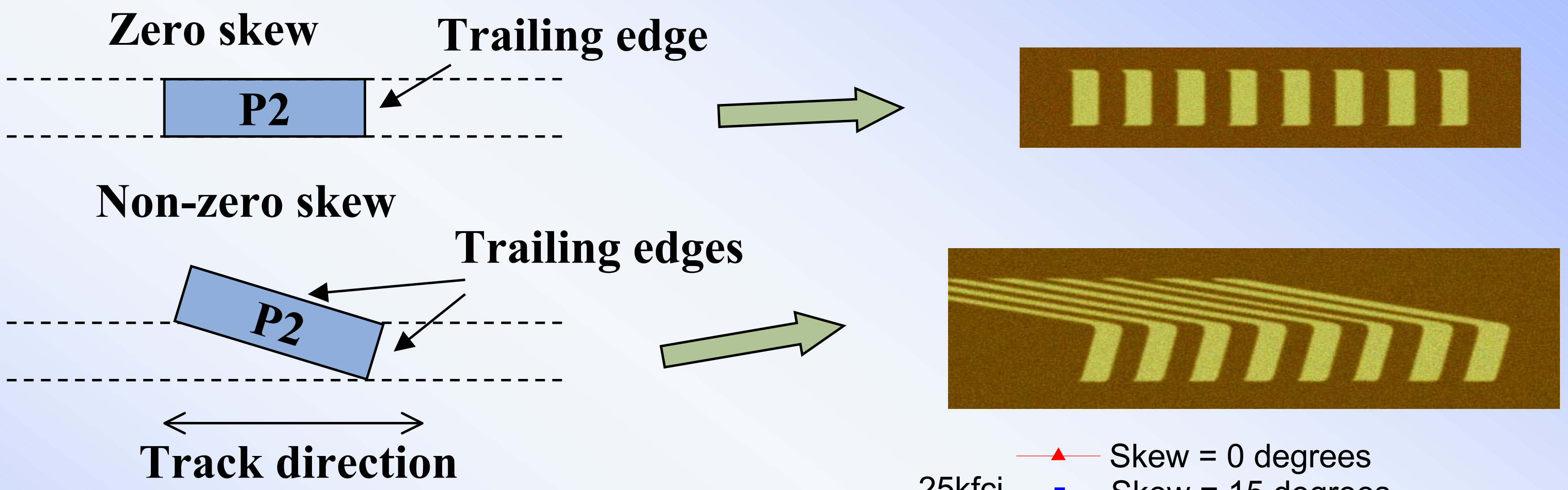
Skew Angle Sensitivity

- ❑ Overview of magnetic recording
- ❑ Superparamagnetic limit and the need for a new technology
- ❑ Dodging the Superparamagnetic limit … The advantages of perpendicular recording?
- ❑ A new system component: soft underlayer challenges and design considerations
- ❑ **Skew Angle Sensitivity**
- ❑ Playback: new signal processing schemes
- ❑ New materials challenges
- ❑ How far perpendicular recording will take us and what will come next?

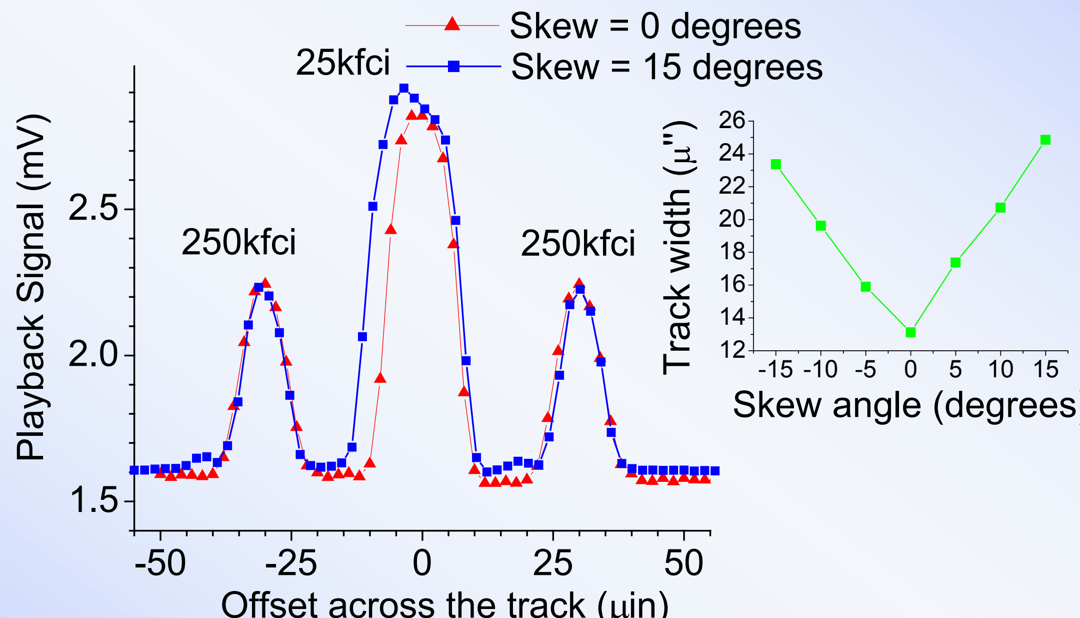
Skew angle


Zero skew
Trailing edge
P2
Non-zero skew
Trailing edges
P2
Track direction
Skew angle (±15 degrees)

Skew Angle Sensitivity



- **Track width increases**
- **Have to decrease the track density at higher skew angles**
- **Loss in areal density**



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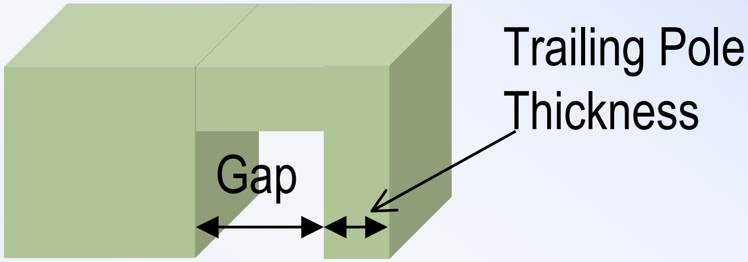
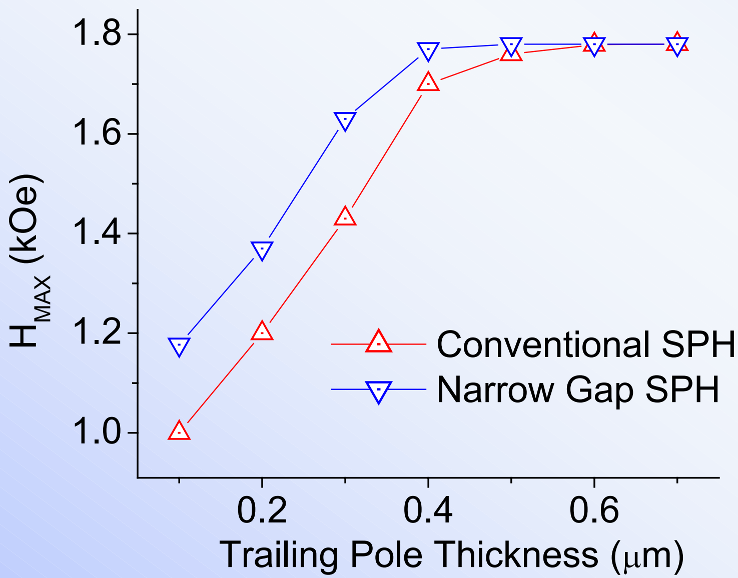
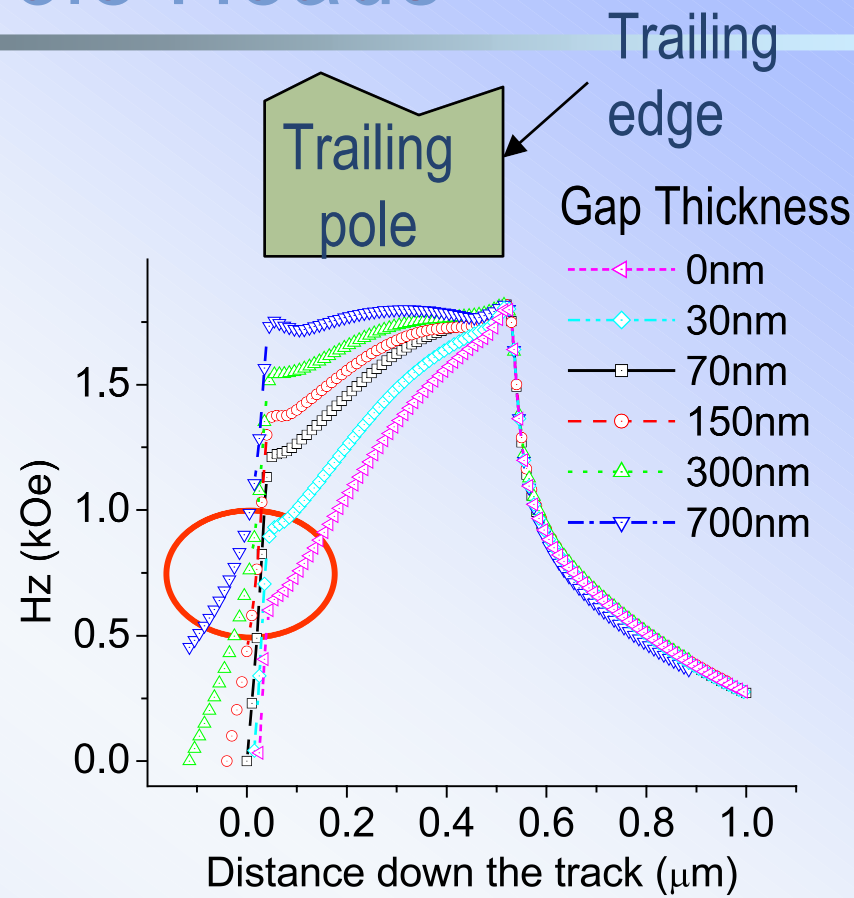
Narrow Gap Single Pole Heads







- In a narrow gap single pole heads, the write field is reduced towards the leading edge, thus, minimizing the skew angle sensitivity
- Can minimize the loss in track density from 25% to less than 5%

Perpendicular Playback

- Overview of magnetic recording
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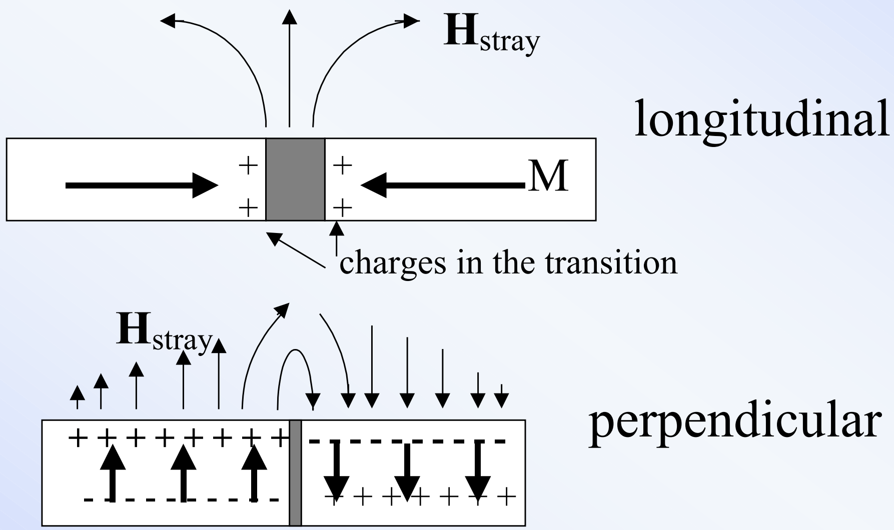
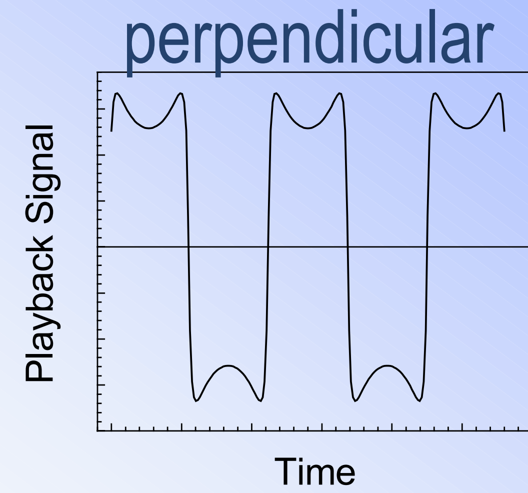
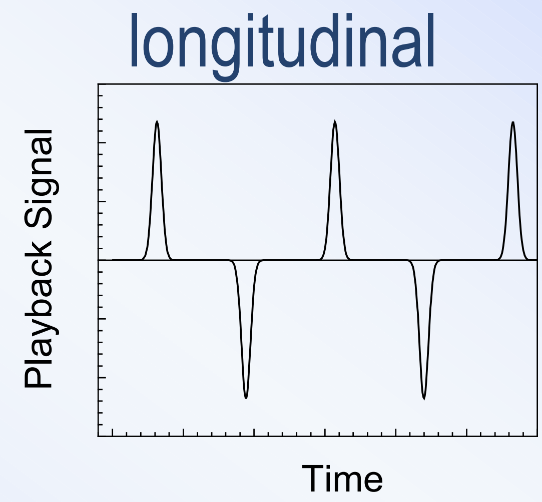
- Skew Angle Sensitivity
- **Playback:** new signal processing schemes
- New materials challenges
- How far perpendicular recording will take us and what will come next?

Perpendicular vs. Longitudinal Playback





- If a conventional reader is used, the channel sees the playback signal of different shape
- Can differentiate, however, part of the information is lost



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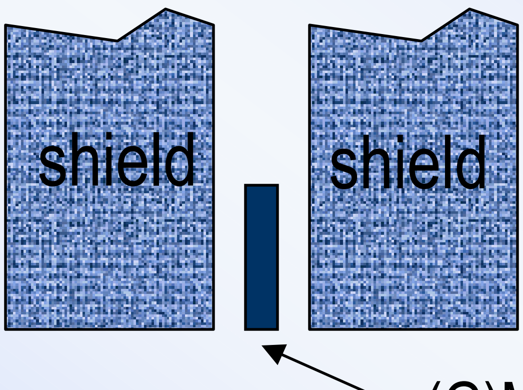
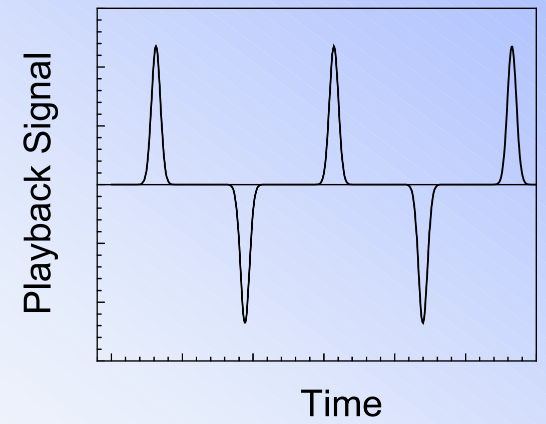
Equivalent Perpendicular Reader

Conventional shielded reader



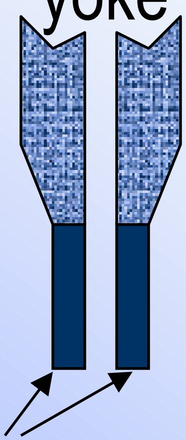
(G)MR element

Longitudinal media



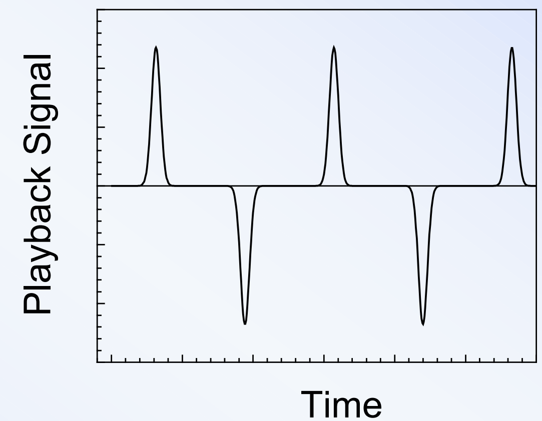
yoke

Differential reader



(G)MR elements

Perpendicular media



Materials Challenges

- Overview of magnetic recording
- Superparamagnetic limit and the need for a new technology
- Dodging the Superparamagnetic limit … The advantages of perpendicular recording?
- A new system component: soft underlayer challenges and design considerations
- Skew Angle Sensitivity
- Playback: new signal processing schemes
- **New materials challenges**
- How far perpendicular recording will take us and what will come next?

Perpendicular Media Materials

Overcoat

STORAGE LAYER :
- High squareness
- Exchange de-coupling
- Grain size control

Seed/Exchange de-coupling layer

SOFT UNDERLAYER :
- Efficiency of the recording system
- Soft underlayer noise

Buffer layer

Substrate

Composition
&
Microstructure

↓

Magnetic
Properties

↓

Performance

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Recording layers: Higher K_u Materials

Alloy System	Material	Anisotropy K_u (10^7erg/cc)	Saturation Magnetization M_s (emu/cc)	Anisotropy Field H_k (kOe)	Minimum stable grain size a (nm)
	CoCrPtX	0.20	200-300	15-20	8-10
Co-alloy	Co	0.45	1400	6.4	8.0
	Co_3Pt	2.00	1100	36	4.8
	FePd	1.8	1100	33	5.0
$L1_0$-phase	FePt	6.6-10	1140	116	2.8-3.3
	CoPt	4.9	800	123	3.6
	MnAl	1.7	560	69	5.1
Rare Earth	$Nd_2Fe_{14}B$	4.6	1270	73	3.7
	$SmCo_5$	11-20	910	240-400	2.2-2.7

Minimum thermally stable grain size: $$a \cong \sqrt[3]{\frac{60 \cdot k_B T}{K_u}}$$

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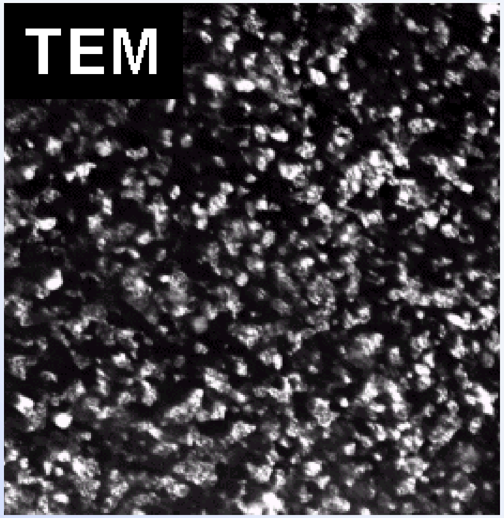
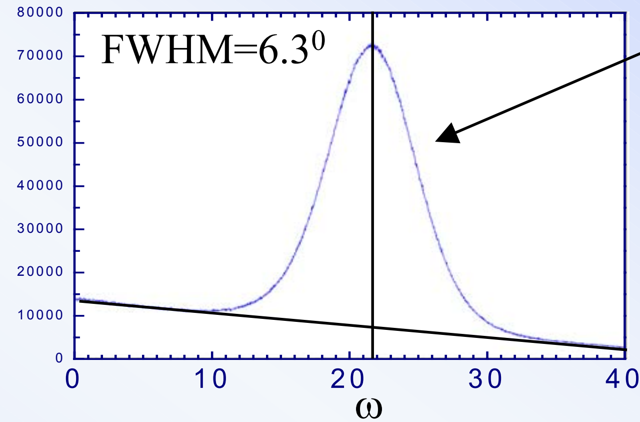
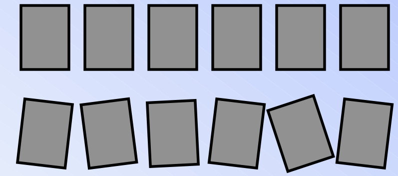
Microstructure of Recording layers



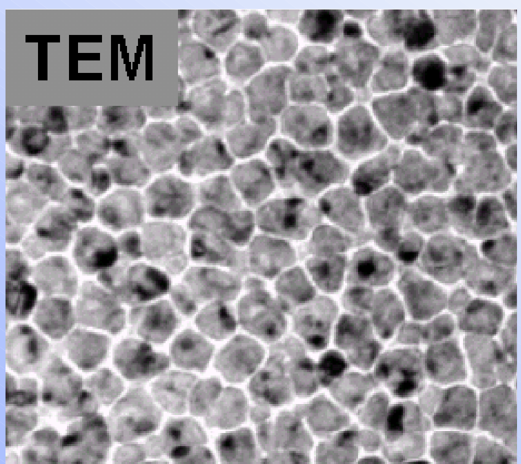
CoCrPtTa on Ti



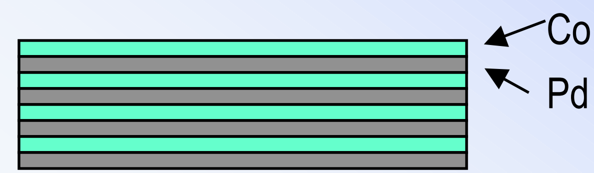
X-ray rocking curve

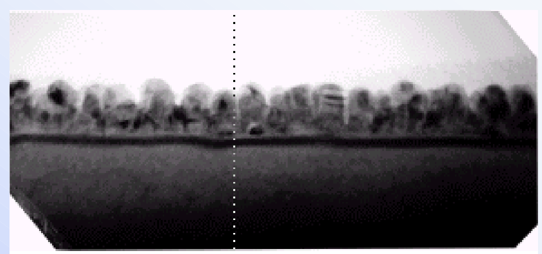


- Average grain size ~ 13nm
- (00_2) fiber-like texture with texture spread of 6.3^0



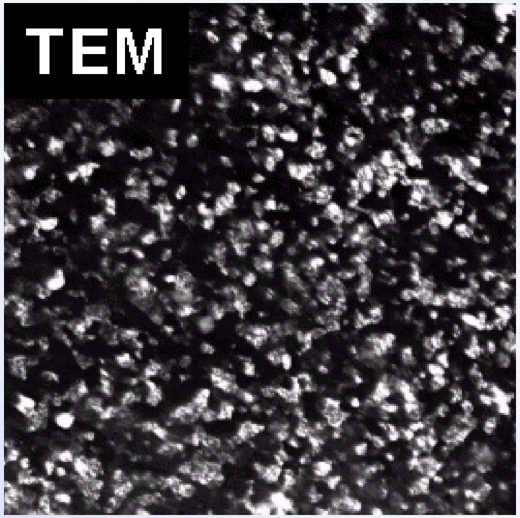
CoB/Pd multilayer on ITO

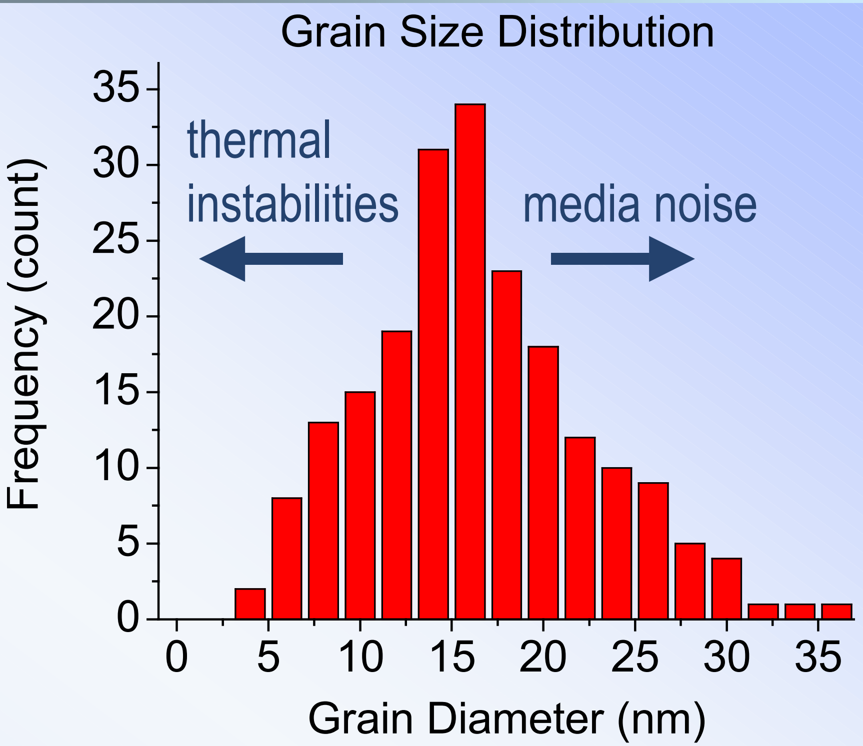




- Average column size ~ 20nm
- Randomly oriented

Grain Size Distribution Control





$$y = y_0 + \frac{A}{\sqrt{2\pi}wx}\exp\left[-\frac{\left[\ln\frac{x}{x_c}\right]^2}{2w^2}\right]$$

Narrowing the grain size distribution improves SNR and media stability

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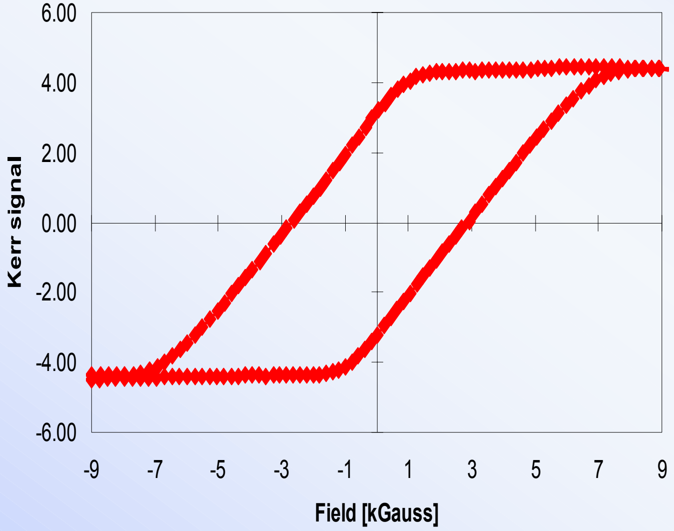
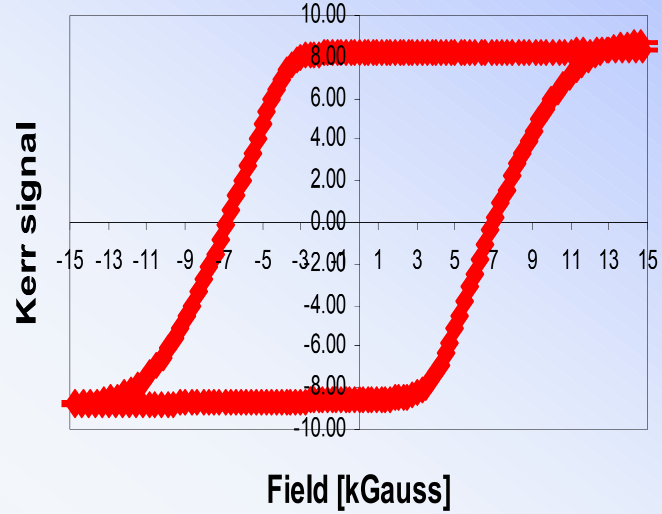
Magnetics of Recording Layers

Al/NiP/Ti(5nm)/$CoCr_{18}Pt_{10}Ta_3$(50nm); Hc=2.77 kOe



ITO(5nm)/(Co3/Pd10)x20; Hc=6.9kOe

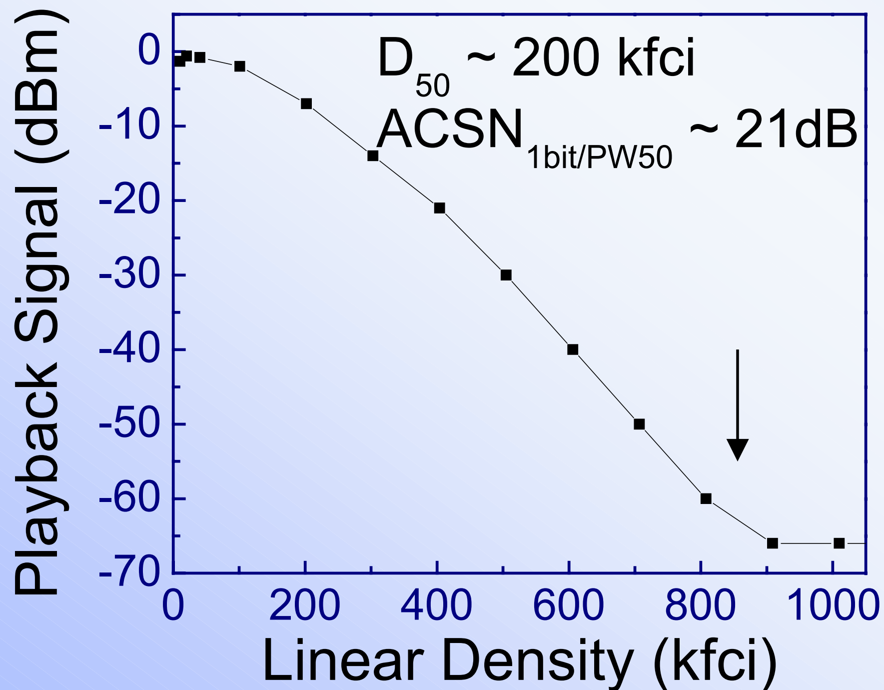


- Typically S=Mr/Ms < 1 ⇒ Thermal stability? DC noise

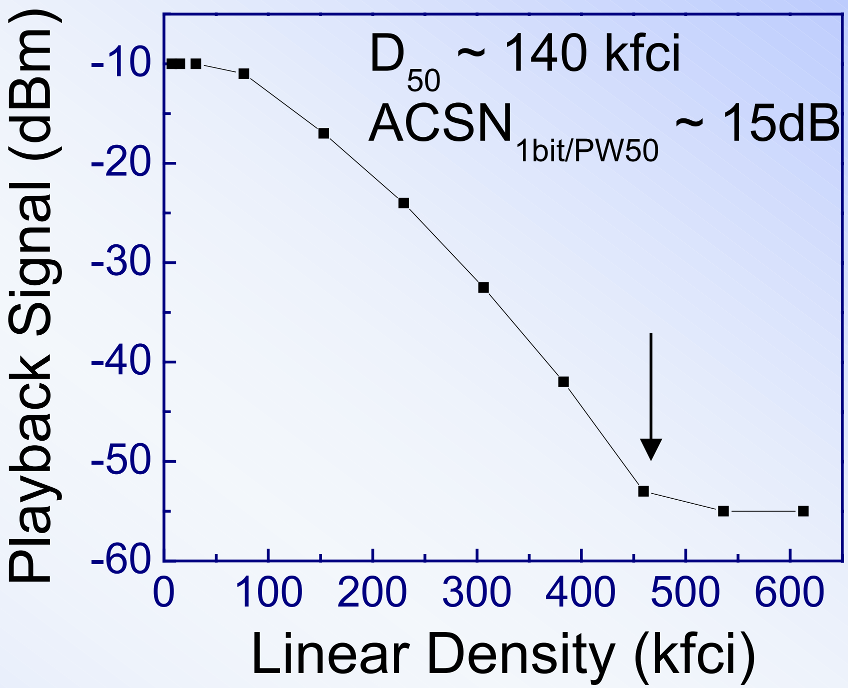
- S=1 ⇒ No DC noise; Thermally stable
- Extremely thin ITO buffer is sufficient to promote high Hc
- By adjusting thicknesses of Co and Pd in a bi-layer structure can make films with Hc > 10,000 Oe

Roll-off Curves / Media Noise

CoCr-alloy recording layer / FeAlN/Ta/NiFe soft underlayer / Single pole head



$(CoB/Pd)_N$ on ITO recording layer / FeAlN/Ta/NiFe soft underlayer / Single pole head



Overwrite > 39dB

Future of Magnetic Recording

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- Playback: new signal processing schemes
- New materials challenges
- **How far perpendicular recording will take us** and what will come next?

Perpendicular System at 1 Tbit/in^2 (NSIC)

- Superparamagnetic behavior is not avoided but delayed
- It is believed that ~1Tbit/in^2 is possible to achieve with perpendicular magnetic recording (~ 10x gain from longitudinal recording)

A 1Tbit/in^2 design:

Medium:

Perpendicular polycrystalline with SUL: Hc=12,000 Oe; Ms=6360 Gauss; Thickness = 9nm; Grain-diameter: 8nm with σ=1nm

Read Head:

Read-width: 30 nm, Sensitivity:1 mV peak-peak; Resistance: 50 ohms

Write Head:

Write-width: = 37nm; Saturation: 4πMs = 20,000 Gauss

Head/Disk Interface:

Magnetic Spacing: 6.5nm to top of medium; 1nm overcoat

What comes next?

Main driving force: to further delay the superparamagnetic limit

Thermally assisted writing

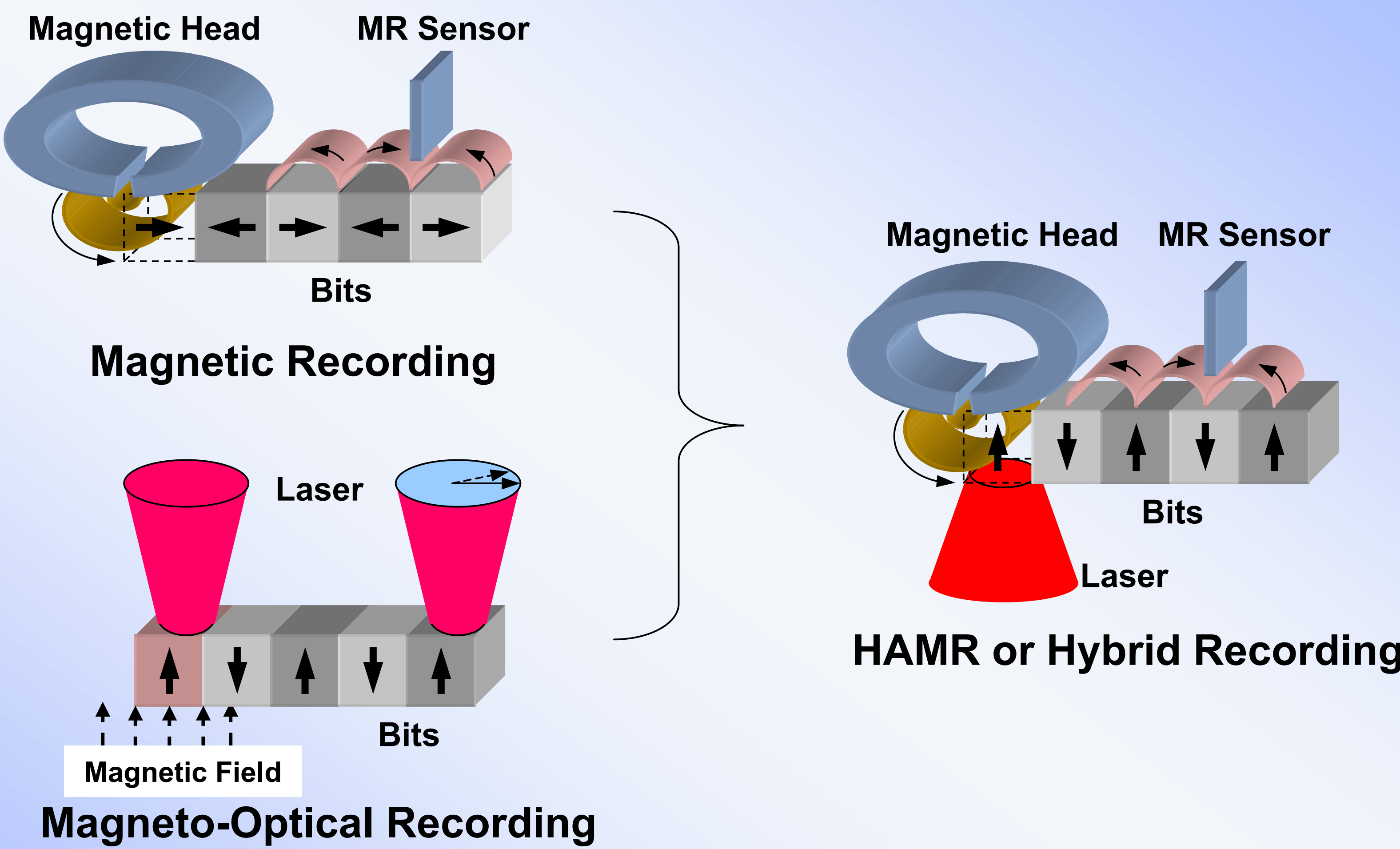
Patterned media

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

Change k_B?...

Cryo-drive

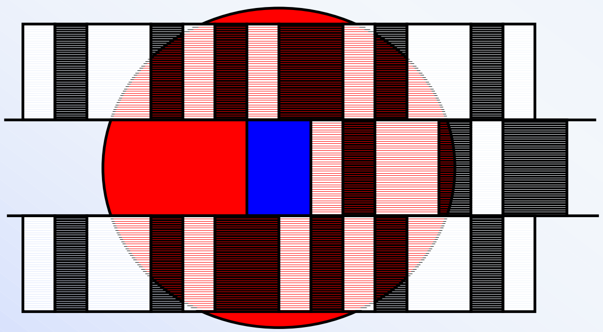
HAMR - Heat Assisted Magnetic Recording



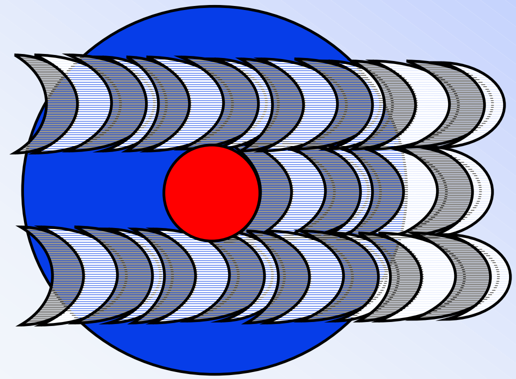
~ 10Tbit/in^2 is conceivable with HAMR + polycrystalline medium (10x gain)

Different Approaches to HAMR

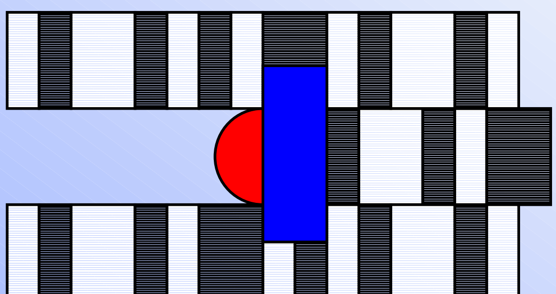
Far Field Light Delivery System:



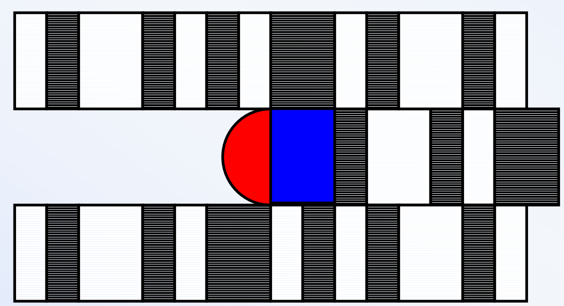
Near Field Light Delivery System with Global Magnetic Field:



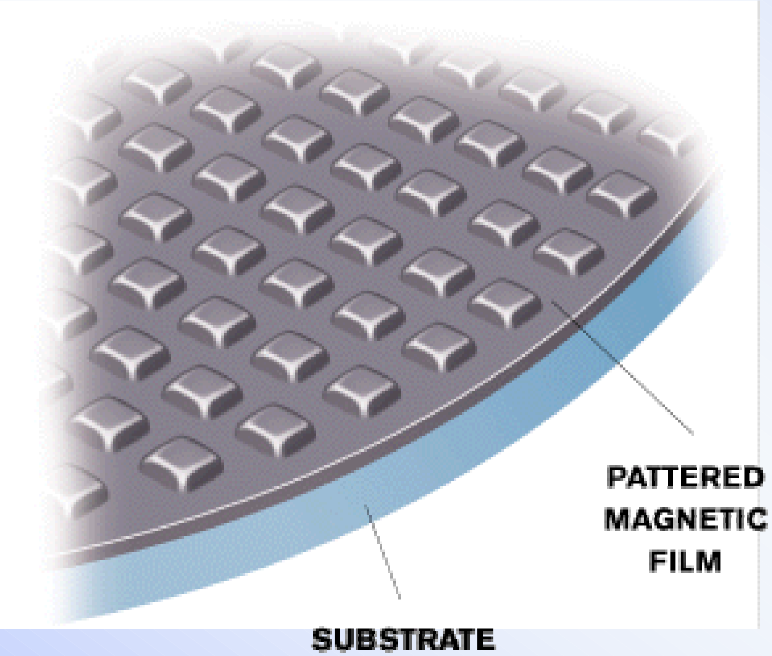
Near field light delivery system defines track-width; magnetic head defines bit length:

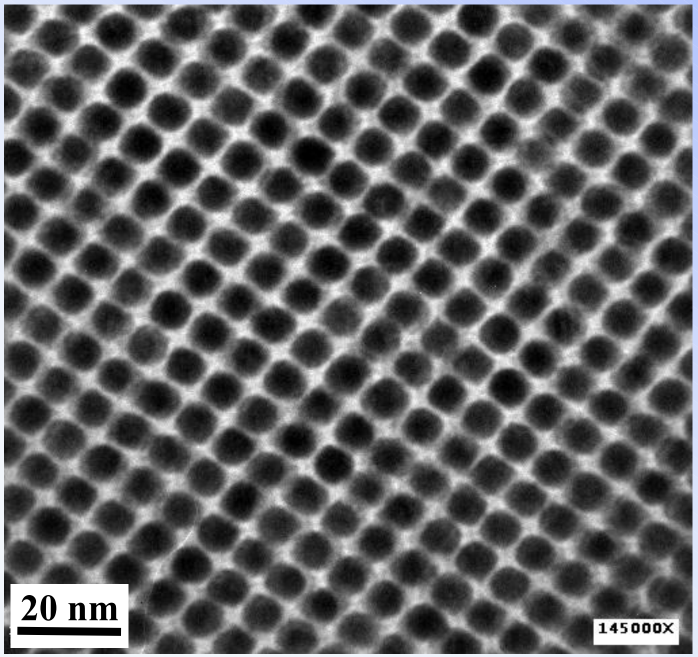


Near field light delivery system and magnetic head co-located to define bit and track:



Patterned Media/Self-Ordered Magnetic Arrays





S. Sun, Ch.Murray, D. Weller, L. Folks, A. Moser, Science, 287, 1989 2000

6.3 ± 0.3 nm FePt particles

Nanoparticle arrays – 9 "Tbit/in^2"

- Major challenge is finding low cost means of making media
- Above 50Tbit/in^2 is conceivable with HAMR + Patterned Medium (5x gain)

Future of Perpendicular Recording

It is believed that future generations of magnetic recording technologies are likely to be based on perpendicular recording due to advantageous nature of perpendicular recording with respect to high areal densities:

- higher write fields
- high trailing and side write field gradients
- well aligned medium
- absence of demagnetizing fields at bit transitions
- higher amplitude playback signal

Summary: Technology Options

Superparamagnetism - fundamental problem !

1. Shift to smaller grains without increasing Ho **(~2x gain)**
   - **AFC media**
2. Enhance Write Efficiency **(5-10x gain)**
   - **Perpendicular Magnetic Recording**
3. Use smaller Grains&Deal with Write Field Problem **(~10x gain)**
   - **Heat Assisted Magnetic Recording (HAMR)**
4. Single Grain per Bit Recording combined with HAMR **(~5x gain)**
   - **Self Ordered magnetic Array media (SOMA)**

150 gbit/in²

1 Tbit/in²

10 Tbit/in²

50 Tbit/in²

Ultimate Recording Density > 50 Tbit/in² conceivable