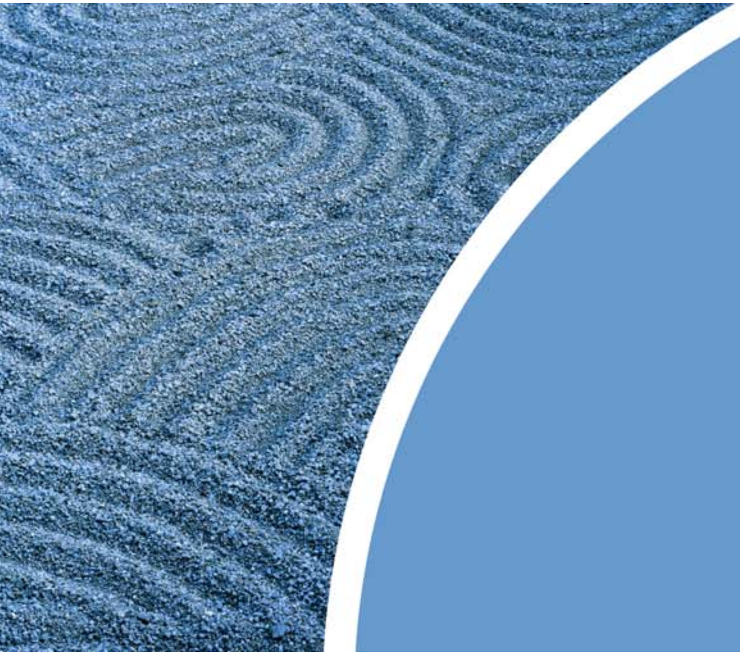

Materials, microstructure, magnetism and spin transport: the physics soup of magnetic recording

Olle Heinonen
Seagate Technology
March 2006

Seagate
We turn on ideas

Acknowledgements

I have benefited from working with and talking to many people, and also liberally stolen slides from

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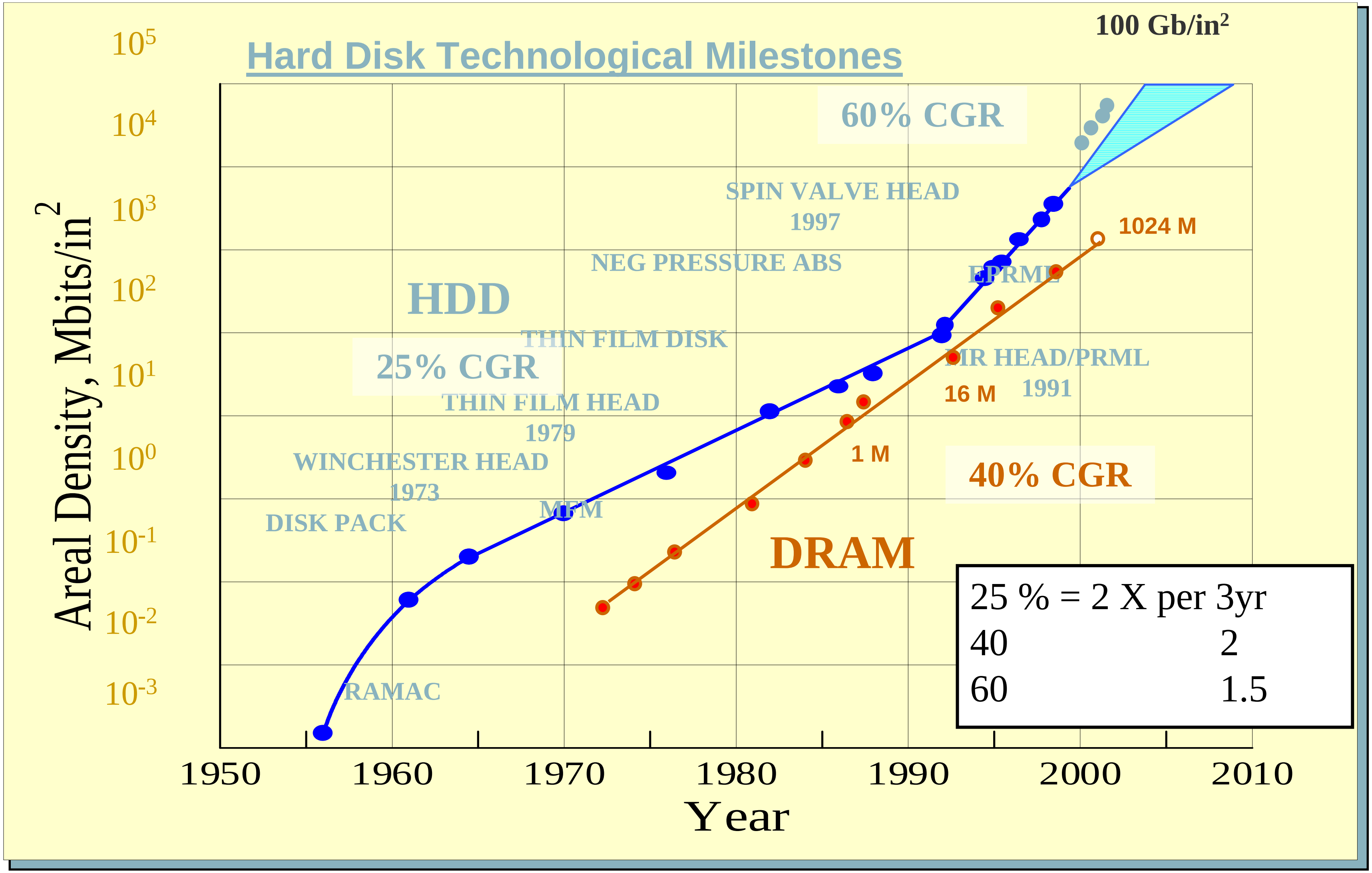
- **Bill Butler (Mint, U of Alabama), Xiaoguang Zhang (ORNL)**
- **Allan MacDonald, Paul Haney (U of Texas), Enrico Rossi (U of Chicago)**
- **Many others, too.**

Areal Density Growth Rates Disc Drives

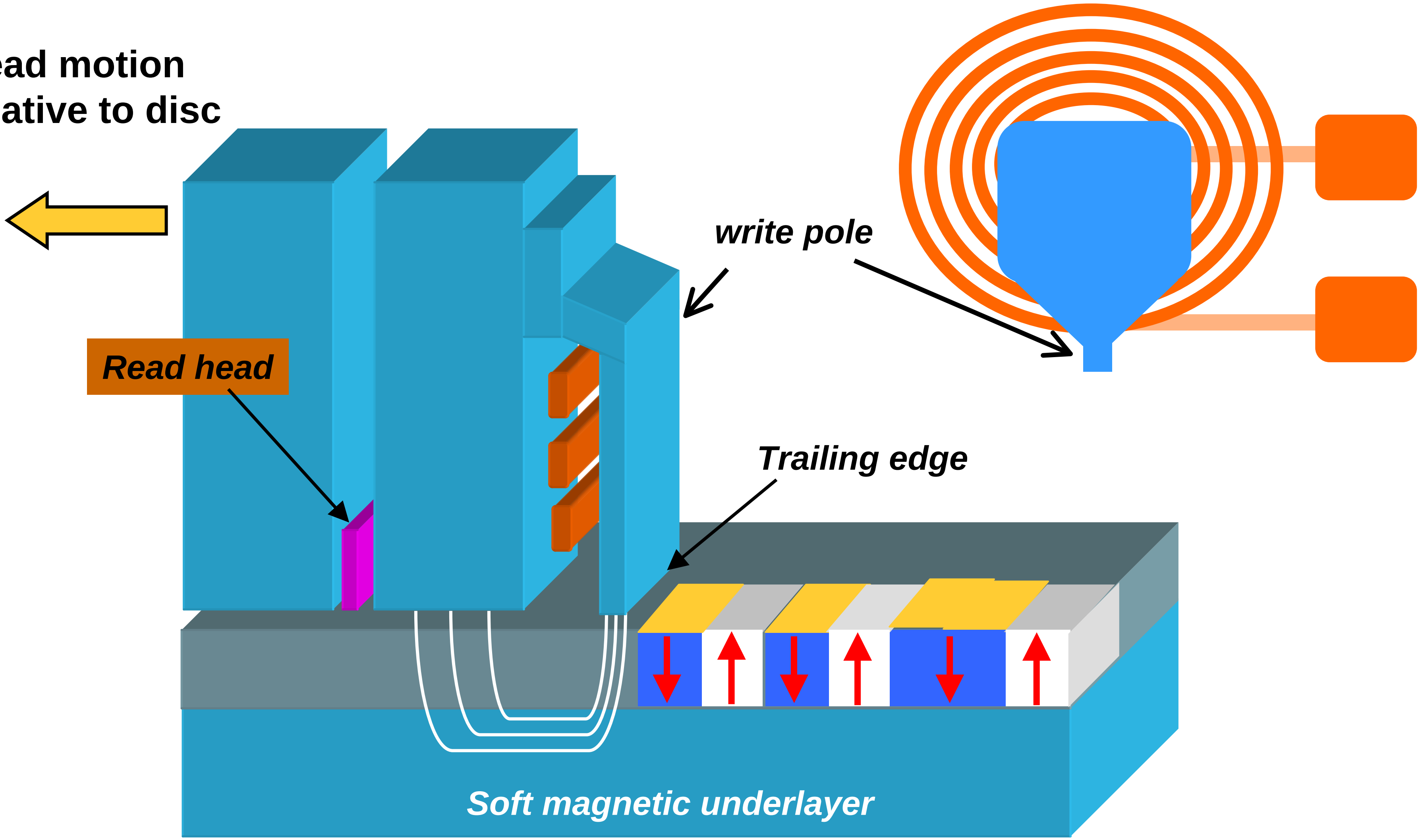


Hard Disk Technological Milestones

25 % = 2 X per 3yr
40 2
60 1.5

(Slide courtesy of M. Kief)

Disc Drive 101 - Perpendicular Recording



Head motion relative to disc

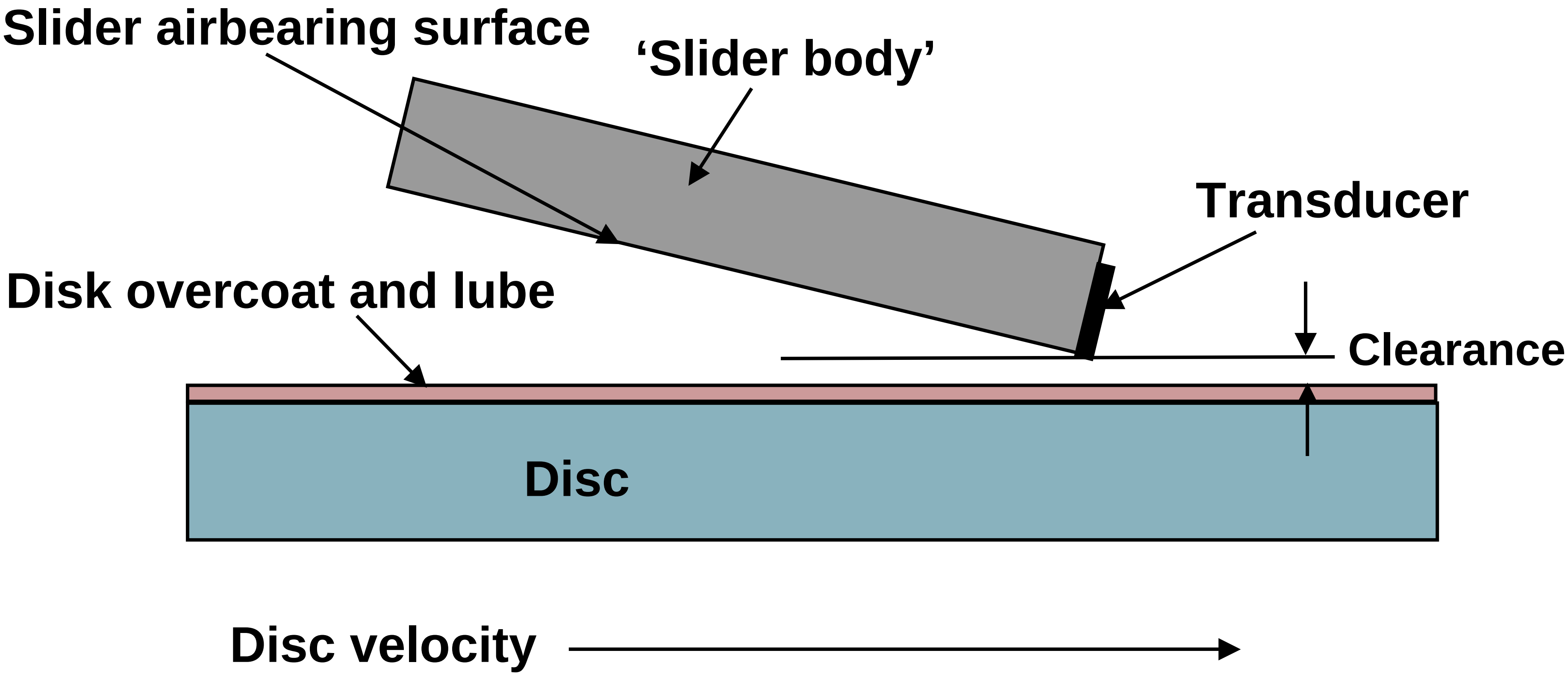
Read head

write pole

Trailing edge

Soft magnetic underlayer

Disc Drive 101 – slider cartoon



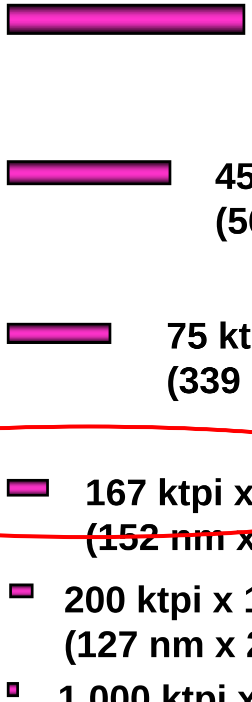
The airflow from the disc makes the slider fly above the disc surface. The clearance – space between transducer overcoat and disc lube and overcoat – is a few nanometers (!!!!)

Reader requirements

- **Must provide adequate signal and low enough noise (SNR is what matters at the end of the day) to the pre-amplifier and signal processing**
- **It can resolve bits along the track**
- **Interference from adjacent track and from other bits on the same track does not significantly degrade the SNR**
- **Low fly-height sensitivity**
- **It is manufacturable at low cost and high yield**
- **It is reliable (warranty on a Seagate drive is 5 years)**

For > 100 Gb/in2: Dimensions and Reader Technologies

Areal Density vs. Magnetic Bit Sizes



10 Gb/in^2 — **32 ktpi x 345 kbpi (794 nm x 74 nm)**

20 Gb/in^2 — **45 ktpi x 445 kbpi (564 nm x 57 nm)**

40 Gb/in^2 — **75 ktpi x 530 kbpi (339 nm x 48 nm)**

100 Gb/in^2 — **167 ktpi x 600 kbpi (152 nm x 39 nm)**

200Gb/in^2 — **200 ktpi x 1,000 kbpi (127 nm x 25 nm)**

1 Terabit/in^2 — **1,000 ktpi x 1,000 kbpi (25.4 nm x 25.4 nm)**

Experimental MR Effect

AMR (~2%)

↓

GMR (~20 %)

↓

TMR (20-230%)

CPP-GMR (up to 50%)

High MR ratio translates to High Signal– to–Noise ratio

(‘Borrowed’ from Sining Mao)

Industry First TMR Head Product

Seagate 2.5" Laptop Drive Momentus II

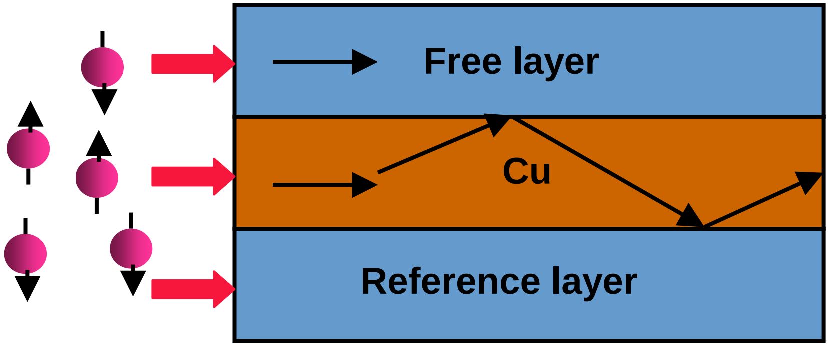
Sept. 2004

Other different product families starting at 80-100Gb/in^2

(‘Borrowed’ from Sining Mao)

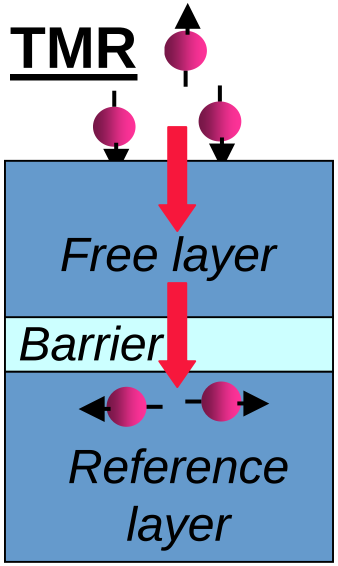
How Do GMR and TMR Work?

GMR



- Resistance of device depends on electrons undergoing spin-dependent scattering at interfaces and in the thin films
- Magnetoresistive ratio limited by magnitude of spin asymmetry in scattering, spin flip scattering, and shunting resistances (where there is no spin-dependent scattering)

TMR



- Resistance of device depends on electrons undergoing spin-dependent tunneling through the barrier layer
- Bandstructure (mis)match or symmetries can severely limit tunneling in one (minority) channel, giving rise to large magnetoresistance

Tunneling magnetoresistance

$$G = \frac{2\pi e^2}{\hbar} \sum_s \sum_{n_F,\vec{k}_F} \sum_{n_R,\vec{k}_R} \left| t\left(n_F,\vec{k}_F; n_R,\vec{k}_R; s\right) \right|^2 A^{\mathrm{F}}_{n_F,\vec{k}_F,s}\left(E^{\mathrm{F}}_{\mathrm{F}}\right) A^{\mathrm{R}}_{n_R,\vec{k}_R,s}\left(E^{\mathrm{R}}_{\mathrm{F}}\right)$$

In the absence of spin-flip scattering $A_{n,\vec{k},s}(E) = \delta\left(E_{n,\vec{k},s} - E\right)$

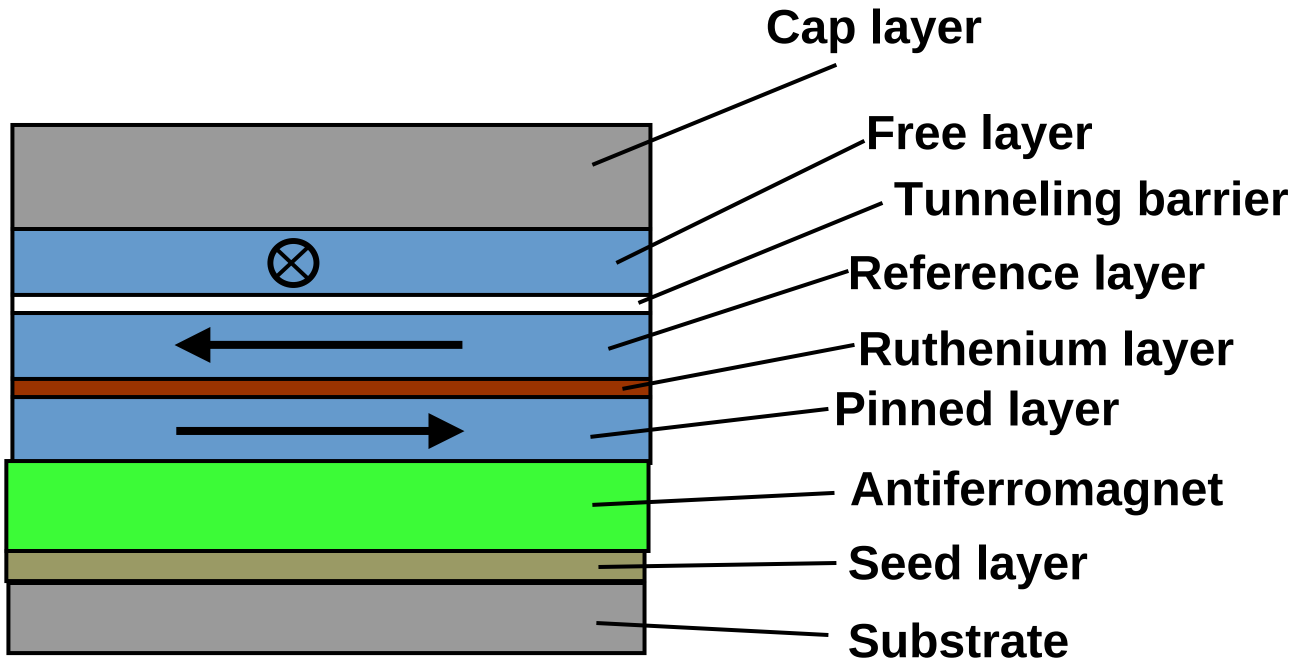
Assume $\left| t\left(n_F,\vec{k}_F; n_R,\vec{k}_R; s\right) \right|^2 \approx \left| t\left(n_F,\vec{k}_F, s\right) \right| \left| t\left(n_R,\vec{k}_R, s\right) \right|$ (does not hold for epitaxial Fe-MgO systems!)

Define for F and R sides $t_s N_s = \sum_{n,\vec{k}} \left| t_{n,\vec{k}} \right| \delta\left(E_F - E_{n,\vec{k},s}\right)$

Define polarization for F and R sides $P = \dfrac{t_\uparrow N_\uparrow - t_\downarrow N_\downarrow}{t_\uparrow N_\uparrow + t_\downarrow N_\downarrow}$

Julliere formula $\Delta G = \dfrac{2P^{\mathrm{F}}P^{\mathrm{R}}}{1 - P^{\mathrm{F}}P^{\mathrm{R}}}$

Tunneling magnetoresistive reader



- A very heterogeneous soup of materials: metals, dirty metals, insulators, antiferromagnets, ferromagnets with different thermal, mechanical, electrical and magnetic properties. Very difficult to develop processing for this heterogeneous mix.

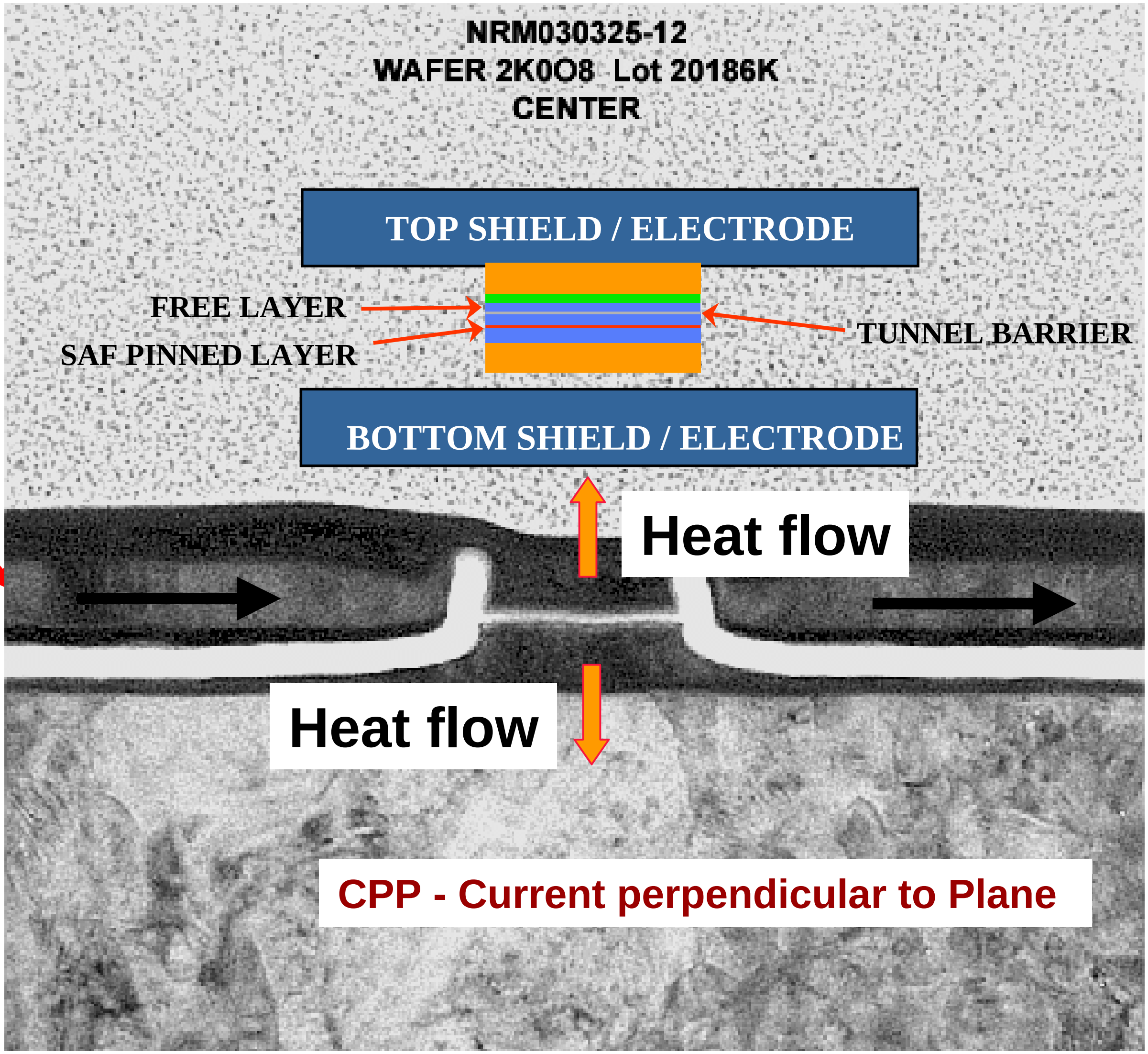
- Each material is chosen for a specific, unique and necessary property (eg magnetization density, exchange bias strength), but increasing this quality usually decreases another quality (eg magnetic anisotropy, thermal conductance, stress, magnetoresistance,…)

TMR Reader Design Structure

Seagate Unique Upper Shield Seed and PM cap layer
- **Needed to magnetically de-couple magnets and shield**

Permanent Magnet hard bias layer

Electrical Isolator
- **Needed to force current to flow through reader stack**

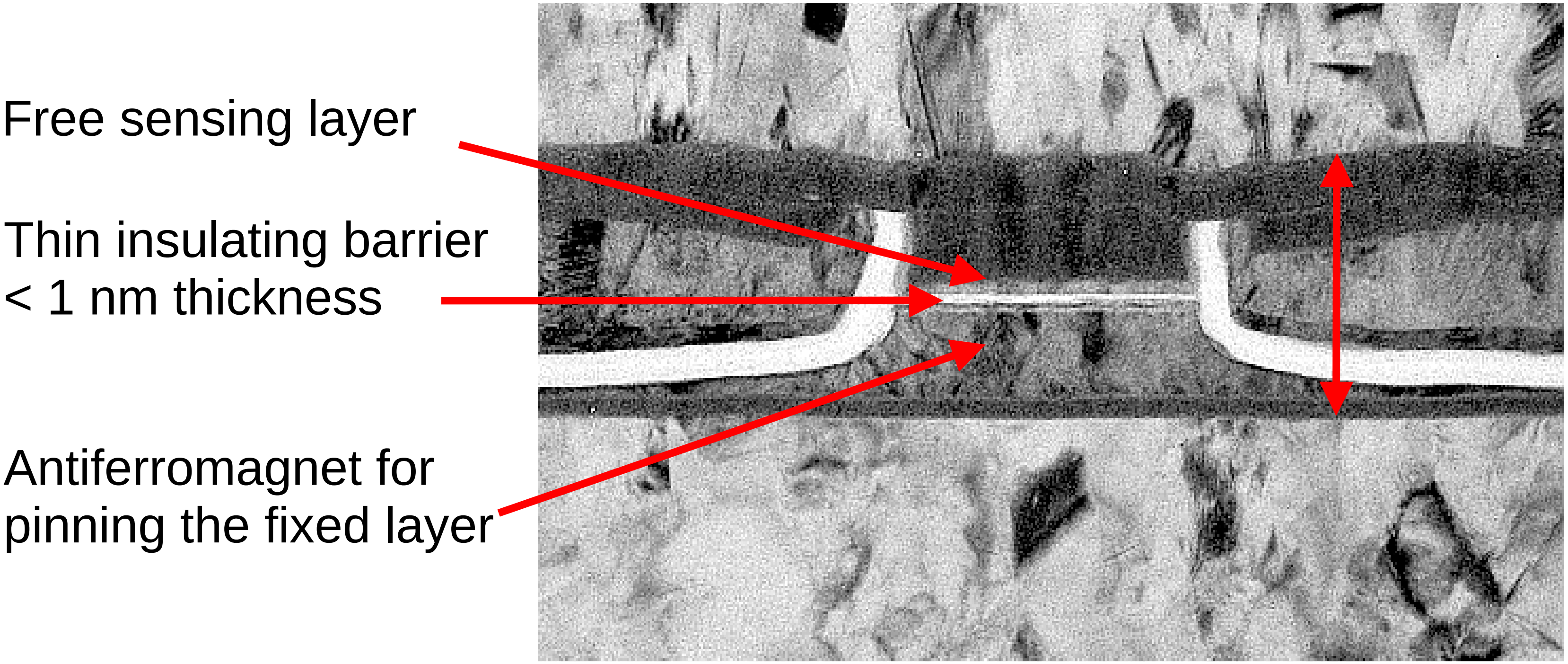


TMR runs cooler (vs. GMR) since heat conducts directly into top and bottom metal shields

FEM model: ~60 C

('Borrowed' from Sining Mao)

TMR Product ABS TEM Image



Free sensing layer

Thin insulating barrier
< 1 nm thickness

Antiferromagnet for
pinning the fixed layer

- Abutted junction layout with hard bias
- Reader width ~ 90-100nm and Shield spacing ~ 80nm

(Also ‘borrowed’ from Sining Mao)

Tunneling MR (TMR) Stack Limit

Low RA limit ---

How low RA and how high TMR?

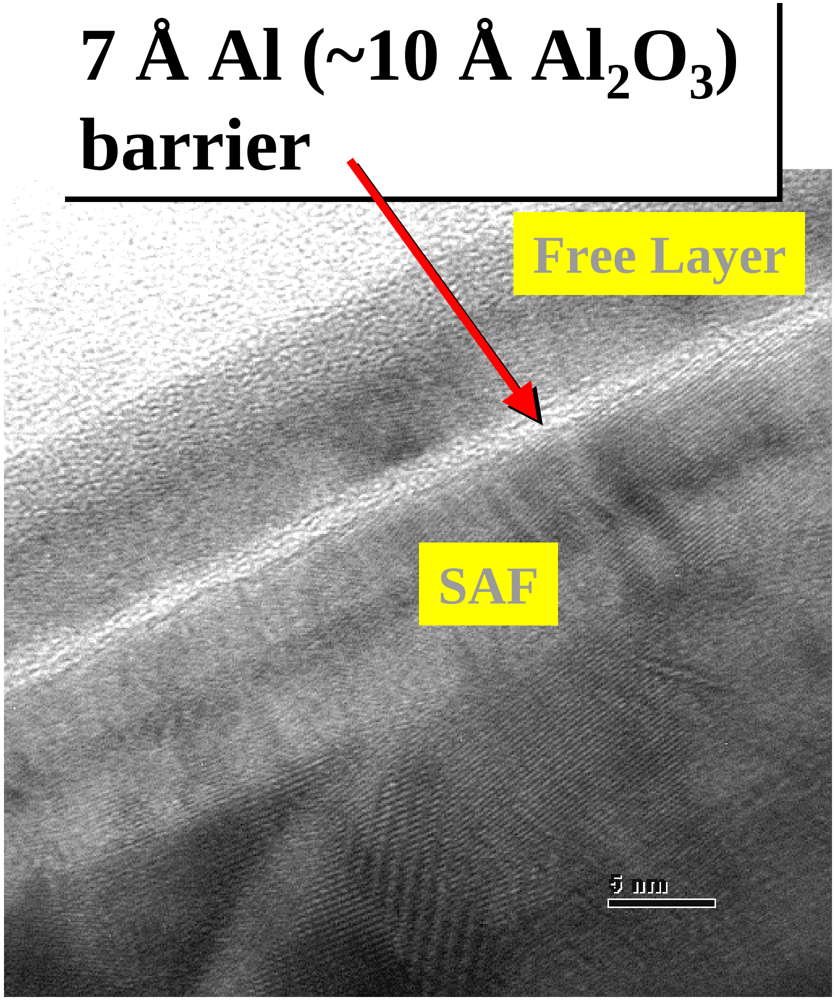
Materials

Pinhole Free/flat/dense/ homogenous oxidation

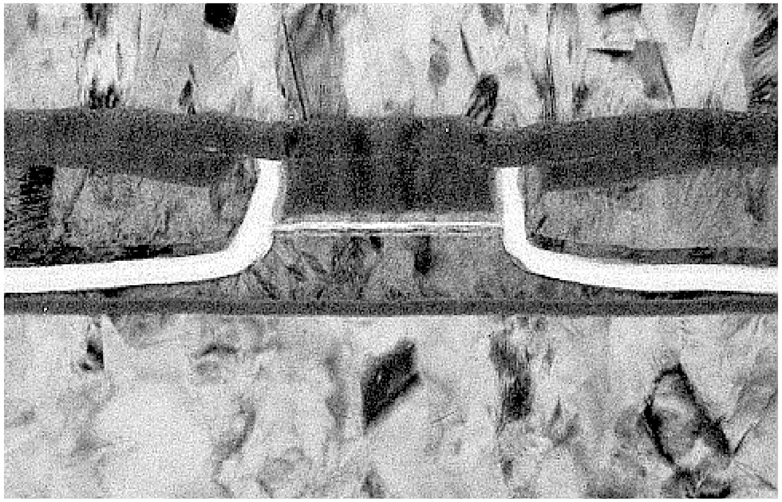
Physics:

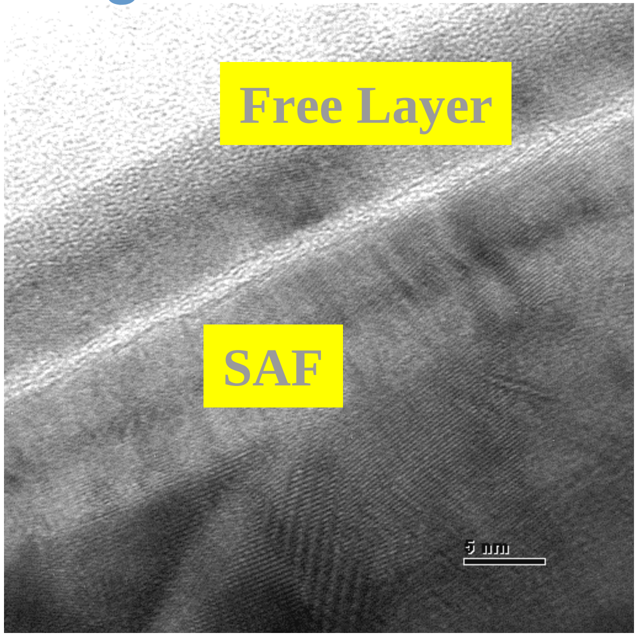
Two monolayer --- pseudogaps insulating if Al_2O_3 >4.6Å

(Jpn. J. Appl. Phys. vol. 39, pp479-481 (May, 2000))



Factors influencing the tunneling magnetoresistance





- Barrier formation: over-oxidation oxidizes electrodes and squashes TMR; under-oxidation leaves metallic pinholes which shunt current without signal (and lead to reliability issues)

- Barrier thickness: too thick -> too large resistance. Too thin -> defects and pinholes

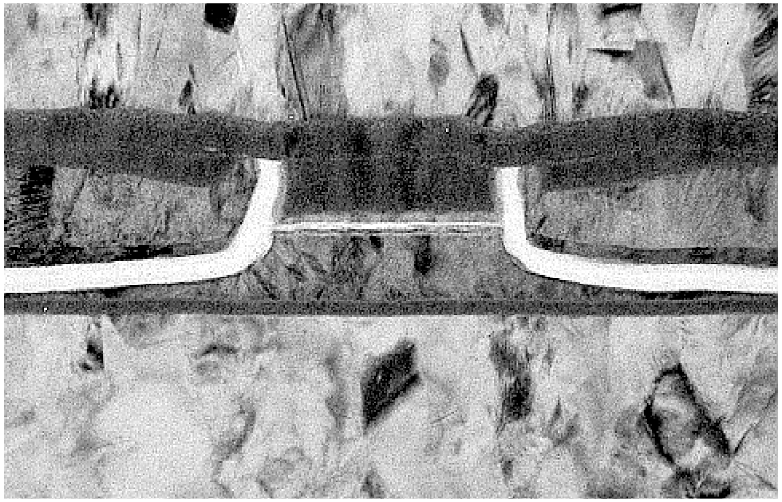
- Materials kinetics and thermodynamics: how does the barrier material wet the RL electrode? What are the kinetics and thermodynamics of the oxidation process? Does the barrier material form alloys with the electrodes?

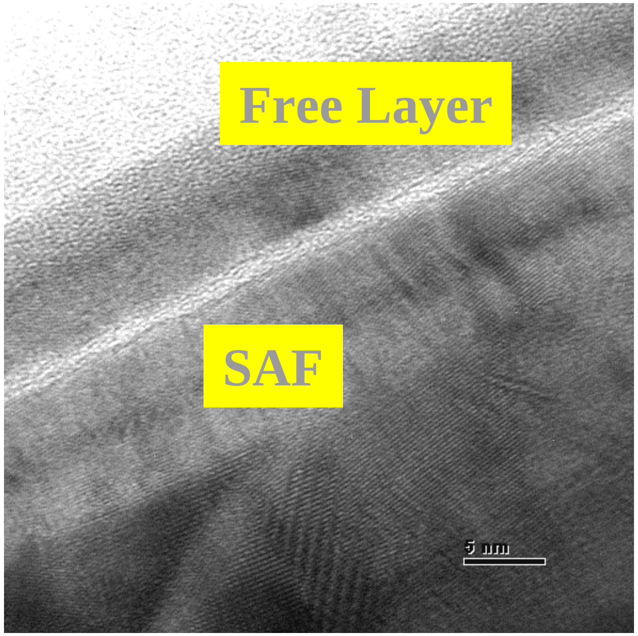
- Stack texture

- Electrode materials

- Grain size: large grains gives domed interfaces – difficult to make uniform barrier. Also affects diffusion of atomic species.

Factors influencing the magnetic behavior

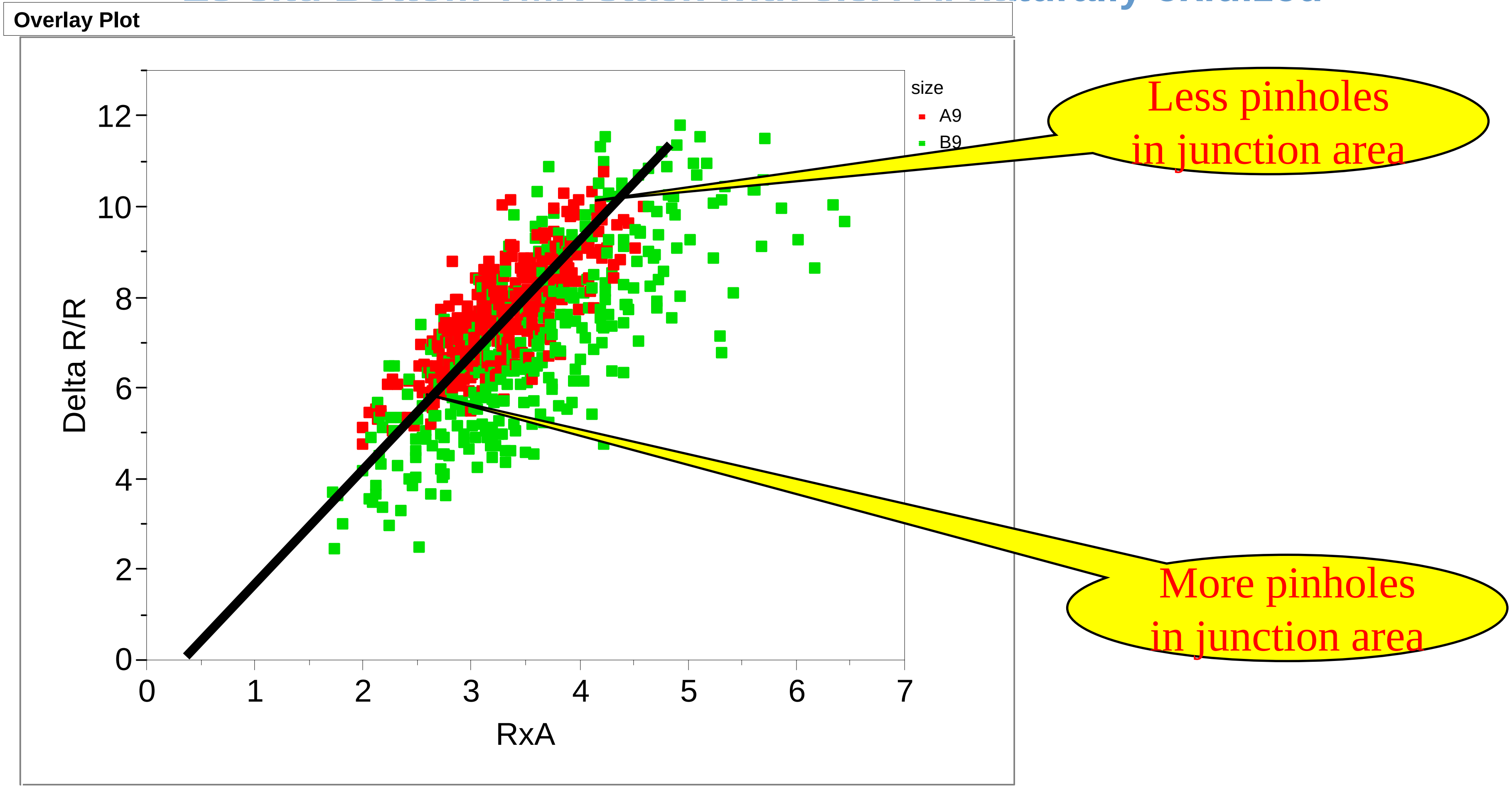




- **Magnetization density**
- **Anisotropy, grains size, texture**
- **Magnetostriction and stresses**
- **Permanent magnet material, thickness, distance to stack**
- **Current density**
- **Barrier defects and pinholes**
- **Spin momentum transfer effects**
- **Temperature**

Pinhole Physics-- Atomic Interface Engineering

Es-situ Bottom TMR stack with 5.5Å Al naturally oxidized

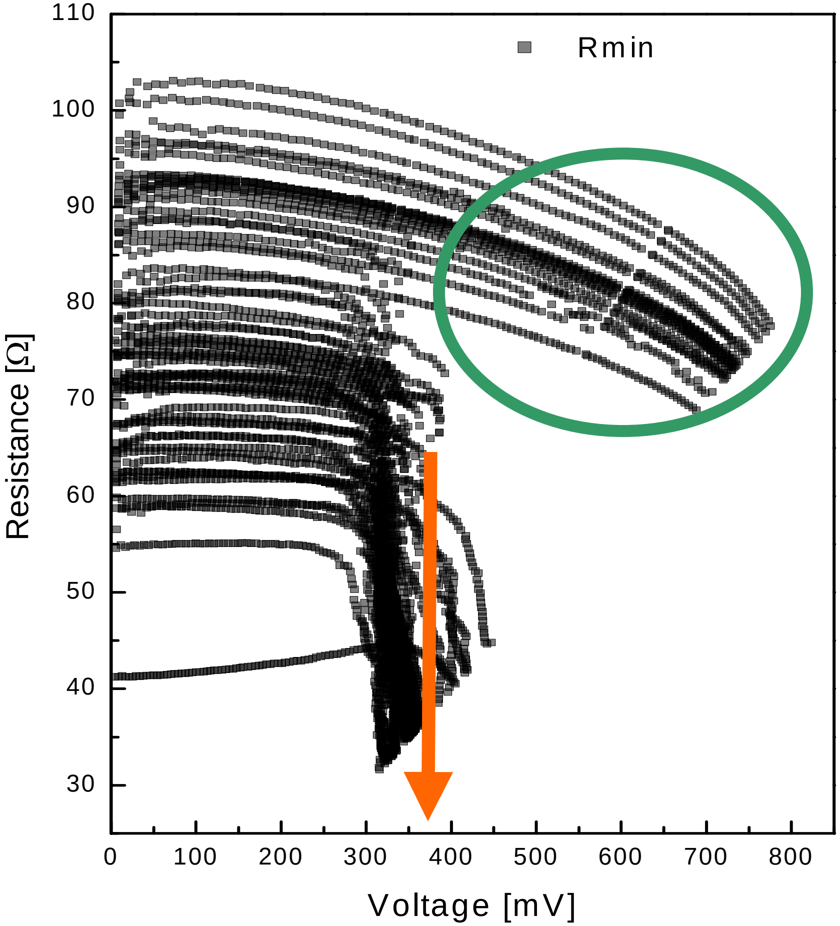


Less pinholes in junction area

More pinholes in junction area

Wide distributions of TMR ratio and RxA due to the pinholes in barrier (Janusz Nowak, Invited talk at M⁴, Ames, Iowa, May 16-17, 2002.)

How to identify pinhole presence? - Examine breakdown



(Janusz Nowak, Invited talk at M^4, Ames, Iowa, May 16-17, 2002.)

RxA~10 $\Omega\mu m^2$
For 64 examined devices
25% have $V_{breakdown}$>400mV (no pinholes)
75% devices have pinholes
existing pinhole begin to grow
at applied voltage ~330mV

- **Impact on reliability and ESD/EOS resistance**

Noise and scaling in tunneling readers

Poisson-limited shot noise voltage in tunneling readers:

Intrinsic!

$$v_{n,S} = \sqrt{2e\,|\,I\,|\,\Delta f}\,R = \sqrt{2eV_b R\Delta f} = \sqrt{2eV_b\left(RA\right)\Delta f / A}$$

Gets small!

Thermal magnetic noise in infrared limit* ($\omega << \omega_{FMR}$):

$$v_s \approx V_b \boxed{\frac{1}{R}\frac{dR}{dH}} \sqrt{\frac{4k_B T\alpha}{\mu_0 M_S V\gamma}} \quad V/\sqrt{Hz}$$

(all SI units)

Stiffness

A/m

Gets small!

m/(As)

Signal voltage: $V_s = V_b \frac{\Delta R}{R}\eta \approx V_b \frac{1}{R}\frac{dR}{dH}\boxed{H_{eff}}$

Effective field from media – gets smaller!

Reducing sensor size increases both shot noise and thermal noise – need to off-set by reducing (RA)-product while maintaining TMR, and by increasing the stiffness, while maintaining signal from smaller and smaller external fields

(*K.B. Klaassen, Xinzhi Xing, J.C.L. van Peppen, *IEEE Trans. Mag.*)

Outlook

Industry's first commercial tunneling reader introduced in 2004 – a tour-de-force in materials science, process engineering, device physics,….

You can now go and buy, for the price of a toaster, a piece of state-of-the-art nano-spintronics technology manufactured with sub-Angstrom precision.

Eventually, tunneling readers will run out of steam – SNR will degrade (shot noise). Likely candidates to supercede tunneling readers are metallic CPP spin valves (~replace tunneling barrier with band-matched normal metal).

Advantages:

- low RA-product ensures acceptable device resistance at small dimensions.

- Electronic noise is Johnson noise, which has better scaling properties than shot noise

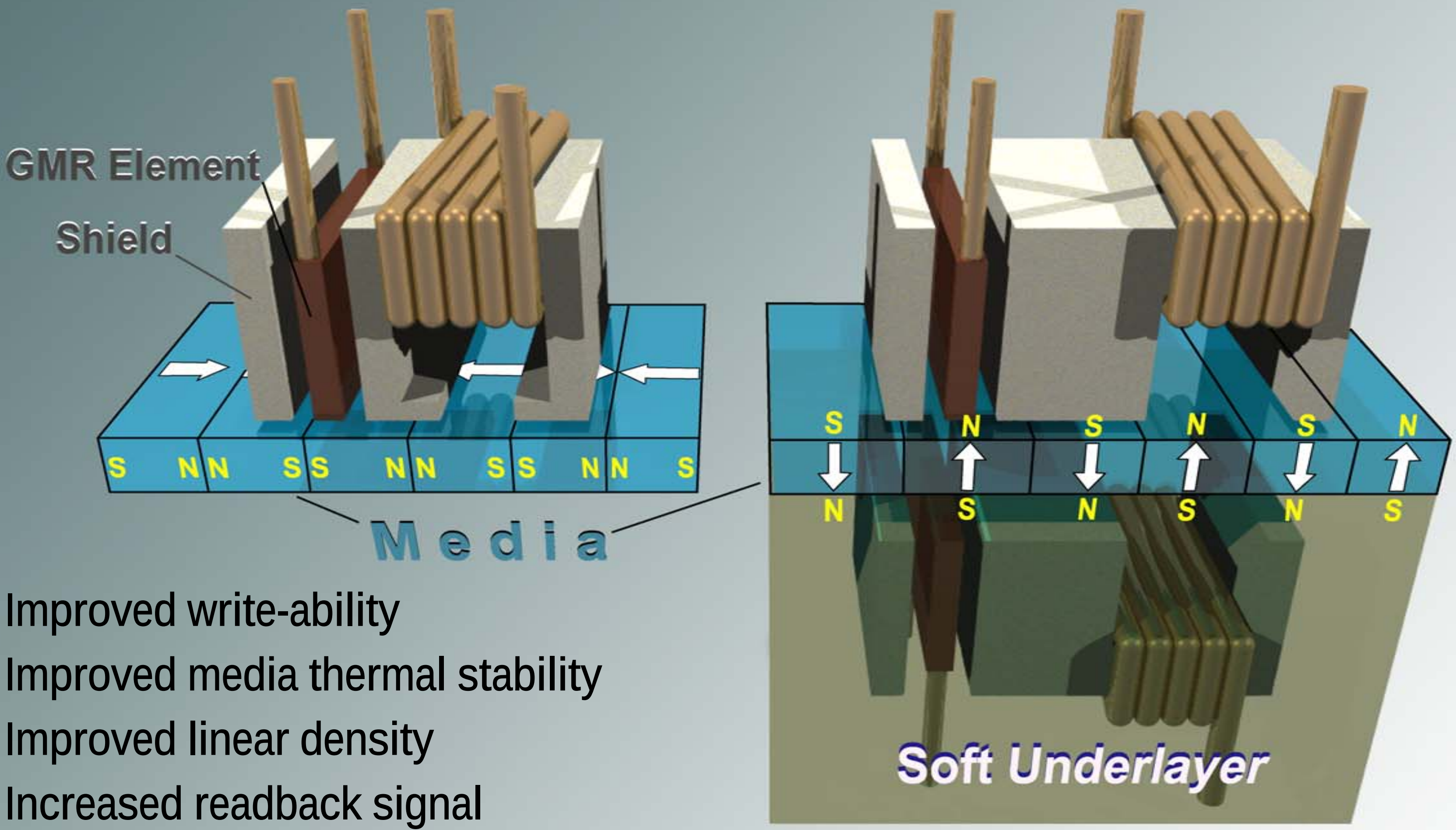
Disadvantages:

- Higher current densities -> the risk of more pronounced effects from spin momentum transfer

- Small magnetoresistive ratio (compared to best tunneling magnetoresistance)

Interesting direction: use engineered half metallic layers and engineered band-matched spacer layer for increased magnetoresistance

Longitudinal vs. Perpendicular Recording

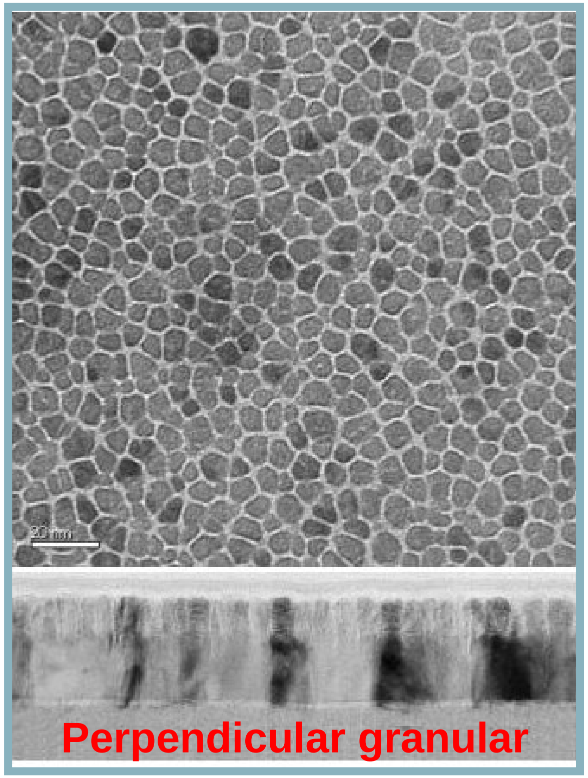


- Improved write-ability
- Improved media thermal stability
- Improved linear density
- Increased readback signal
- … but many new challenges

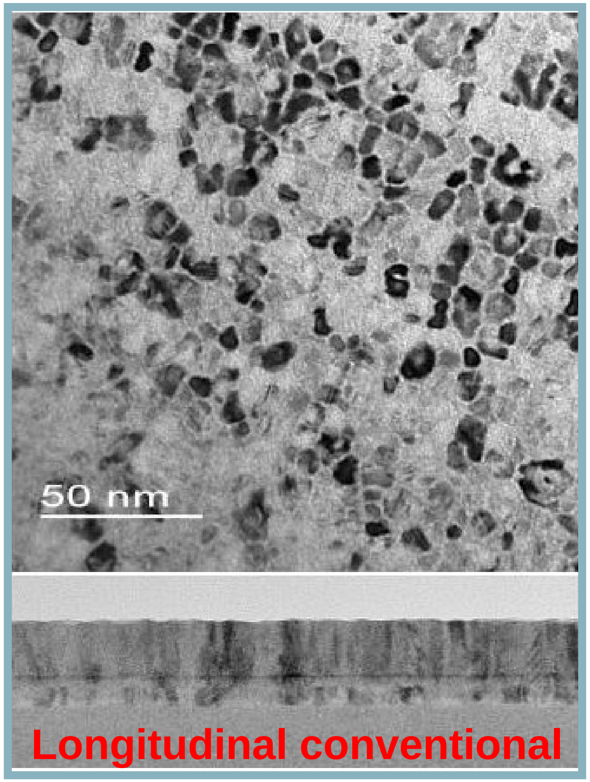
Media Constraints – The SPL

Superparamagnetic limit, where grains become susceptible to thermal fluctuations (at room temp!) and lose their magnetization (signal, data loss)

- Smaller media grains ➡ SNR improves ➡ Higher AD
- Smaller grains require higher anisotropy to maintain thermal stability
- Higher anisotropy requires more head write field to achieve SNR



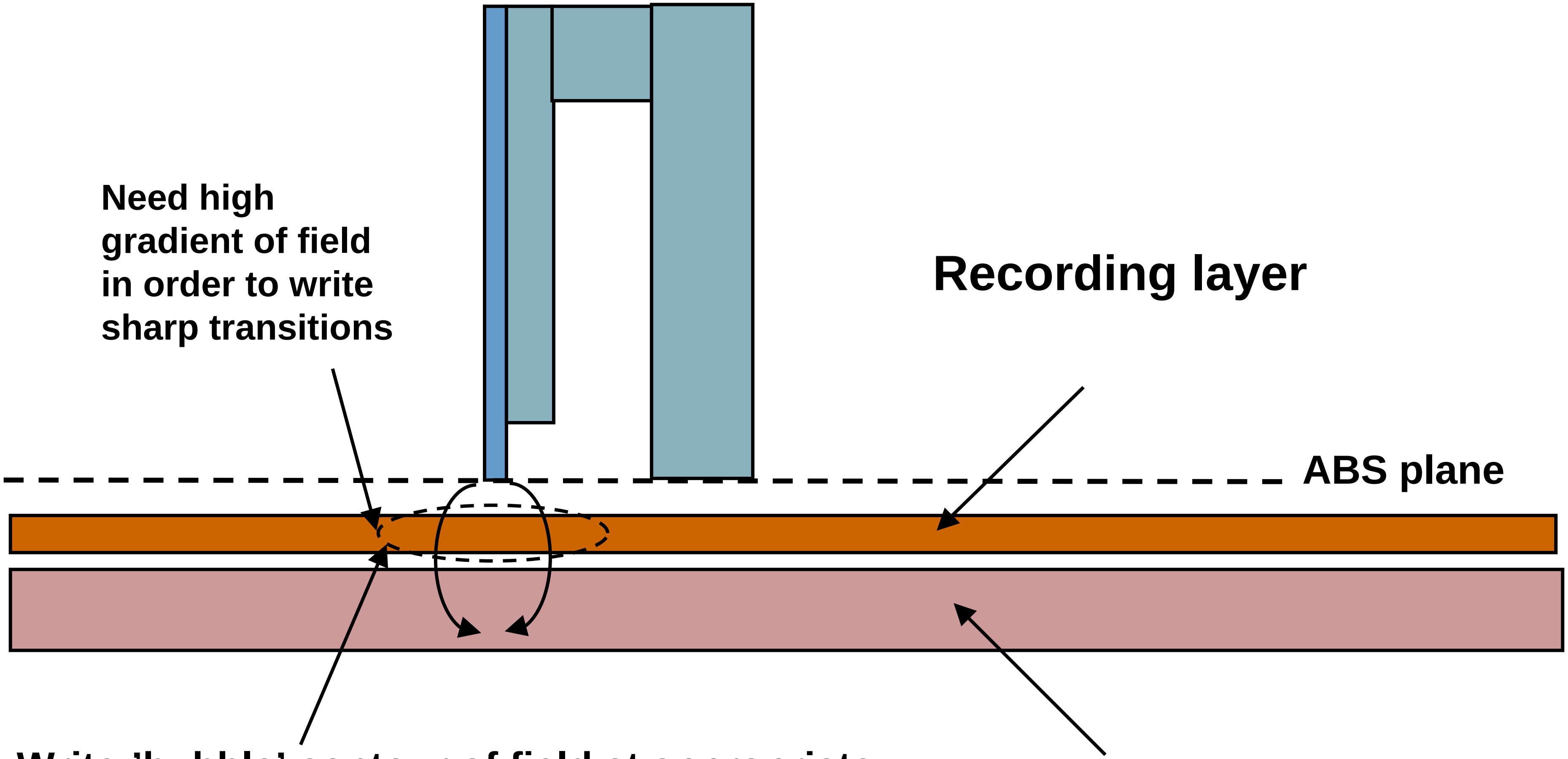
Perpendicular granular



Longitudinal conventional

(Stolen from Robert Lamberton)

Perpendicular writing



Need high gradient of field in order to write sharp transitions

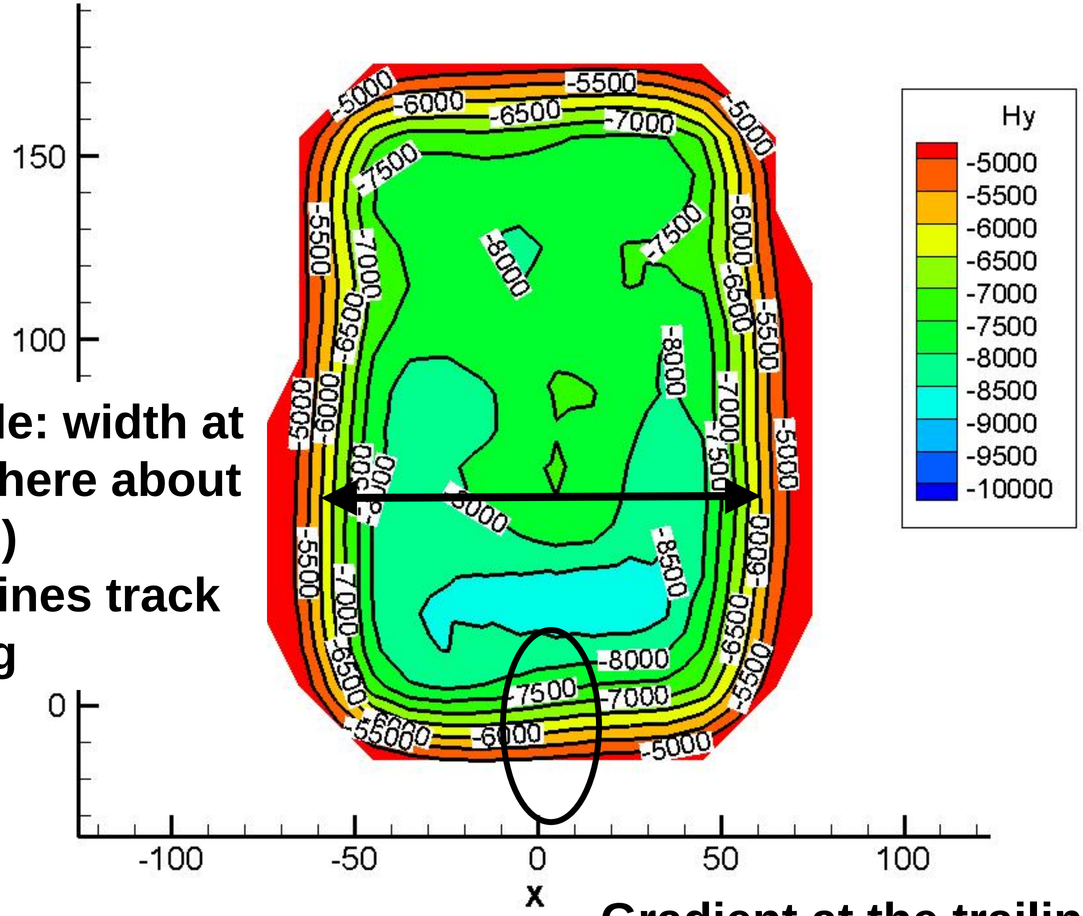
Recording layer

ABS plane

Soft underlayer

Write-’bubble’ contour of field at appropriate value (~H_c). Width of bubble determines track width

Ex: Contour map of perpendicular field



Example: width at 6 kOe (here about 118 nm) determines track spacing

Gradient at the trailing edge limits bit spacing

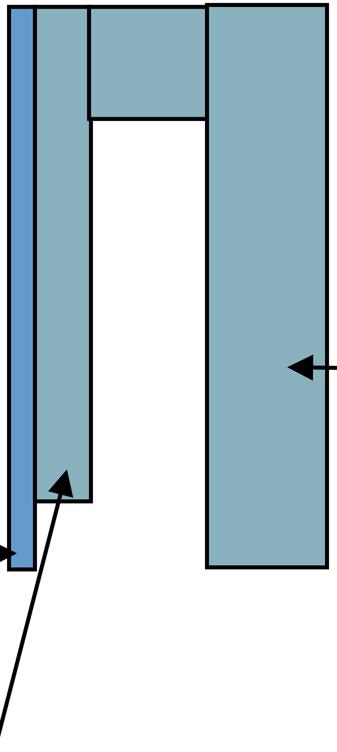
Perpendicular writing

To write well, we need

- **Large field magnitude -> enables high-coercivity media -> enables smaller grains with thermal stability**
- **Well confined field spatially -> narrow tracks and no unwanted erasure**
- **Large field gradient at the trailing edge -> enables sharp transitions -> enables high linear density.**
- **Manufacturable design at low cost and high yield.**

These requirements are not mutually compatible!

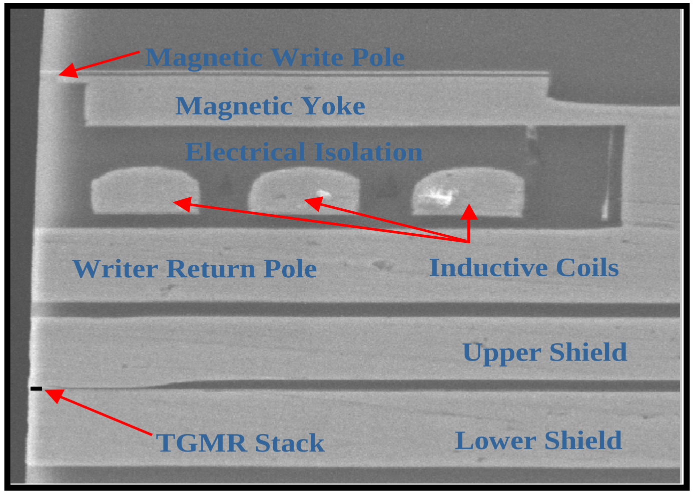
Writers – materials issues



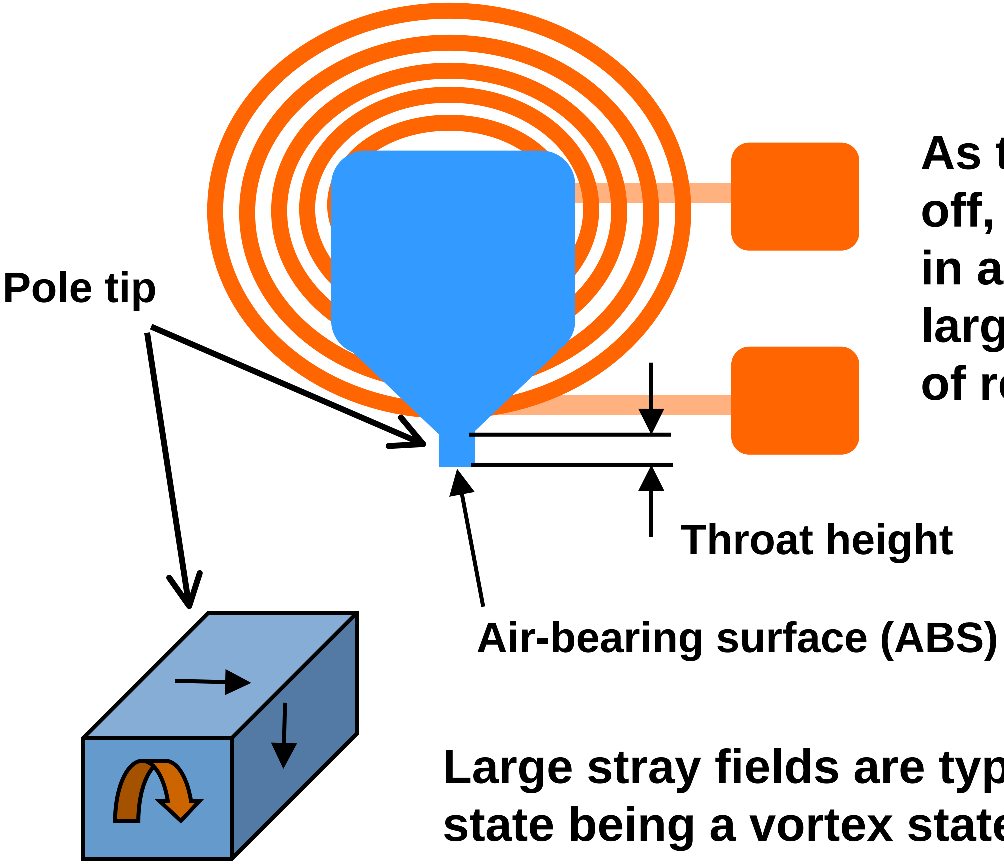
Top pole – the business end of the writer. Want maximum field strength -> largest possible saturation magnetization density. Unfortunately, 2.45 T is the largest available (Slater-Pauling curve)

Return pole. Need soft material, small stray fields to prevent unwanted erasure of written data.

Yoke – helps improve efficiency. Need moderately high magnetization density, but soft material to prevent goofy remanent states



Background – pole lamination and remanent erasure



As the current to the coil is turned off, the writer top pole can be stuck in a magnetic remnant state with large stray fields, leading to erasure of recorded data.

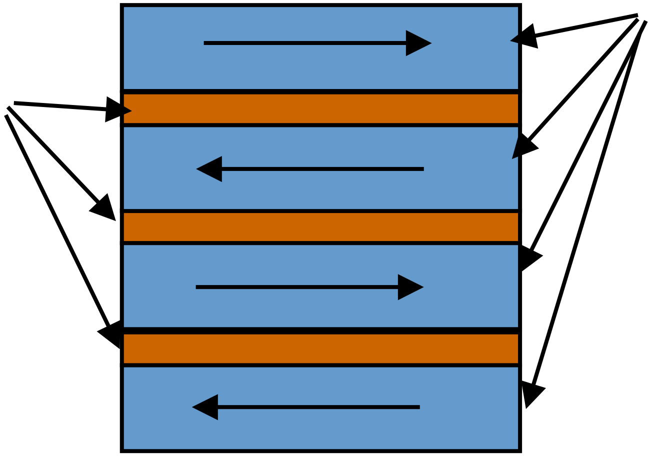
Large stray fields are typically due to the remnant state being a vortex state in the tip of the top pole.

Vortex formation is also not desirable from a dynamics point of view: reversal of vortices can be slow.

Lamination of top pole

Earlier work suggested lamination of the top pole as a way to eliminate remnant states with large stray fields (see, for example, N. Nakamoto et al., IEEE Trans. Mag. vol. 40, pp290 – 294, (2004)).

Micromagnetic modeling of poletips also showed periodic laminations to be effective in eliminating the vortex remnant state (see, for example, M. Mochizuki et al, J. Mag. Mag. Mat. vol. 287, pp372 – 375 (2005)). Lamination can force the magnetization into a synthetic antiferromagnetic arrangement with low stray fields.



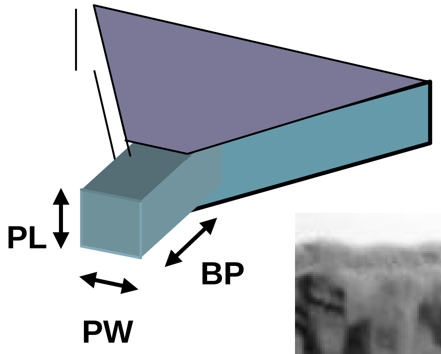
Non-magnetic spacer

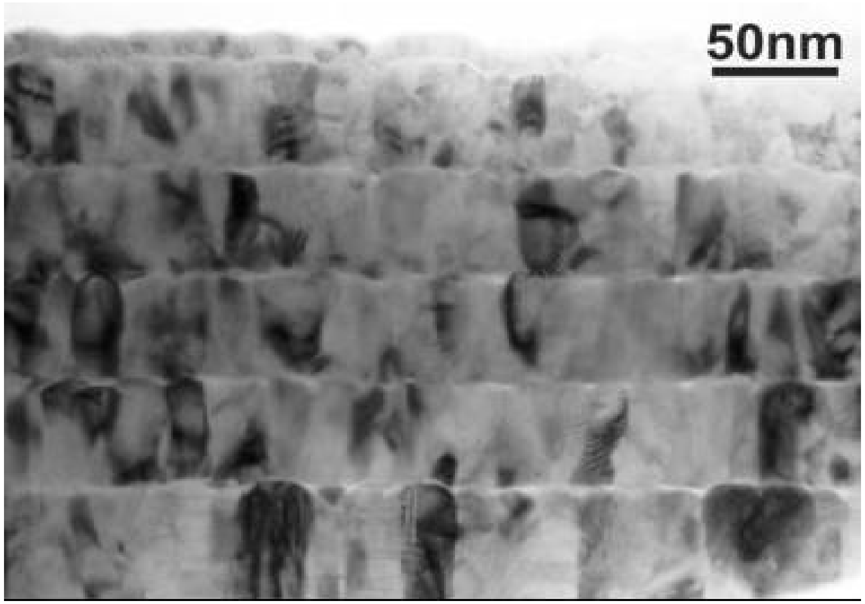
Ferromagnetic material

The cost of eliminating remnant erasure fields through lamination can be reduced writer efficiency, requiring large currents to excite the writer.

Bottom view of pole tip

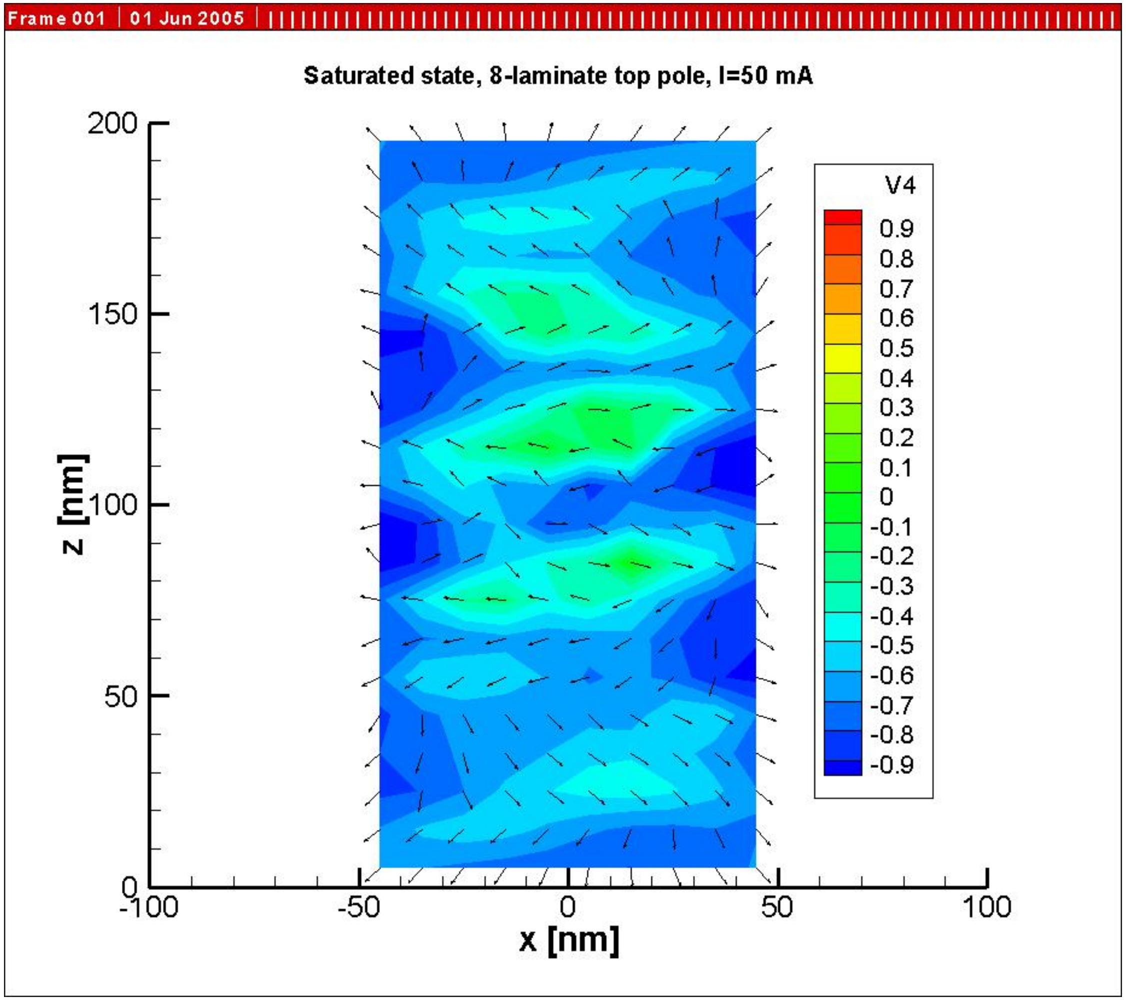
Actual TEM micrograph





(This slide too stolen from Robert Lamberton)

ABS view of poletip magnetization, eight-laminate pole



Saturated state of eight-laminate pole has clear zig-zag structure due to anti-ferromagnetic coupling between adjacent laminates

Color-coded normalized perp. component of poletip magnetization.

Challenges / Potential Research Areas

Writer Design

- Write field enhancement
  - Assist technologies (Field, Heat)
  - Gradient Control (downtrack / cross track directions)
- Write pole material domain control
  - Micromagnetic modelling / Novel material solutions

Future Storage Architectures (beyond 1 Tb/in^2)

- Bit patterned media / Heat-Assisted Magnetic Recording
- Probe Storage
- Semi-conductor & magnetic (spintronic) structures → Nano-magnetoelectronics
- Stuart Parkin’s race track storage….(?)