Magnetic Materials

(especially magnetic recording)

NSF Workshop on Introducing Science Faculty to Materials Science and Engineering

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Outline of talk

- What is magnetism?
- How can materials be magnetic?
- What are some important properties of magnetic materials?
- Magnetic recording – an important application of nanomagnetism

Maxwell's equation (SI units):

$$\nabla \times \vec{D} = \rho \quad (Coulomb's\ law)$$

$$\nabla \times \vec{B} = 0 \quad (no\ magnetic\ monopoles)$$

$$\nabla \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0 \quad (Faraday's\ law)$$

$$\nabla \times \vec{H} - \frac{\partial \vec{D}}{\partial t} = \vec{J} \quad (Ampere's\ law)$$

ρ = charge density
J = current density
ε = permittivity
μ = permeability
E = electric field (intrinsic field)
D = displacement vector = εE (derived field)
B = magnetic induction (intrinsic field)
H = magnetic field = (1/μ)B (derived field)

Fields and Units

$\mathbf{D} = \varepsilon\mathbf{E} = \varepsilon_0\mathbf{E} + \mathbf{P}$, $\mathbf{P} = \Sigma\mathbf{p}/V = \chi\mathbf{E}$ = polarization

$\mathbf{H} = \mathbf{B}/\mu = \mathbf{B}/\mu_0 - \mathbf{M}$, or $\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{M})$,

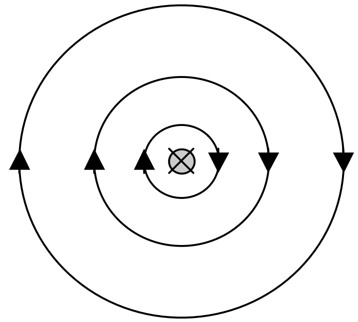
$\mathbf{M} = \Sigma\mathbf{m}/V = \chi_m\mathbf{H}$ = magnetization

- SI units: B in tesla (T), H in A/m, M in A/m
- Electromagnetic units (emu): a commonly used cgs system that works best for magnetism (not the same as the Gaussian system)

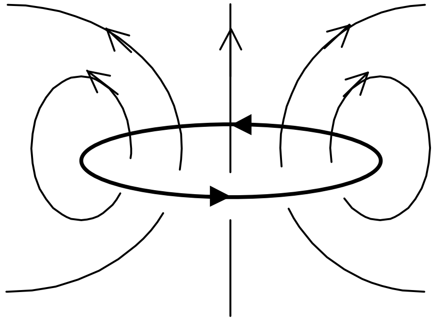
  emu system: $\mathbf{B} = \mathbf{H} + 4\pi\mathbf{M}$, B in gauss (G), H in oersted (Oe), M in Oe (= emu/cm^3)

Currents produce magnetic fields

Long, straight wire



current loop (**m** = I**A**)

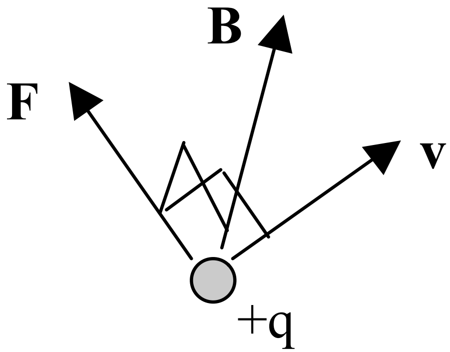


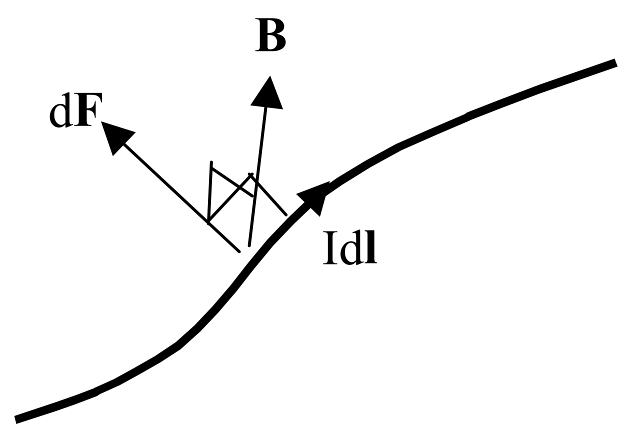
Magnetic fields exert forces on moving charges

F = q**v** x **B**

d**F** = I*d***l** x

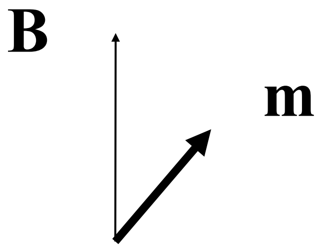
B





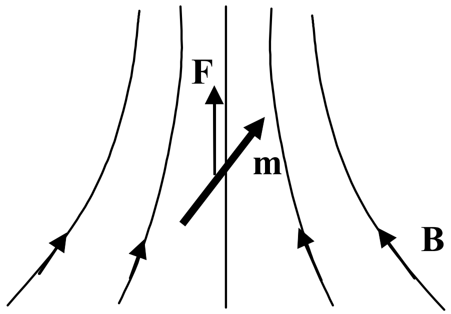
Interaction between a magnetic field and a magnetic dipole moment

A field exerts a torque on a magnetic dipole moment that tends to align the dipole in the field direction



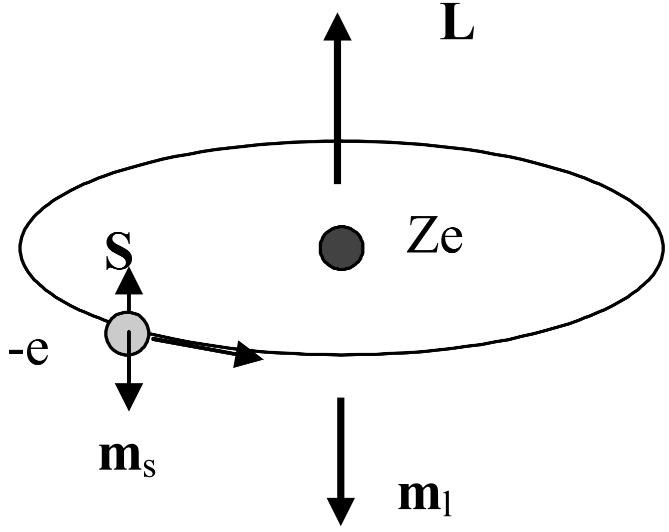
$\tau = \mathbf{m} \times \mathbf{B}$

A non-uniform field exerts a net force on a magnetic dipole moment.



F = -m(dB/dz)

Atomic origin of magnetism



orbital: $\mathbf{m}_l = -(e/2m)\mathbf{L}$

spin: $\mathbf{m}_s = -(e/m)\mathbf{S}$

Bohr magneton:

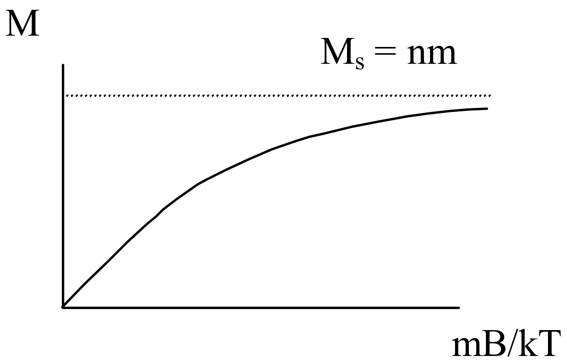
$$\beta = \frac{e\hbar}{2m} \ (= \mu_B)$$

Paramagnetism

Permanent atomic moments in thermal equilibrium (Boltzmann distribution) in an external magnetic field –

M = n<**m**>, N = no. atoms per unit volume

<**m**> = average moment of atom



U = -**m**·**B** = -mBcosθ = -m_zB

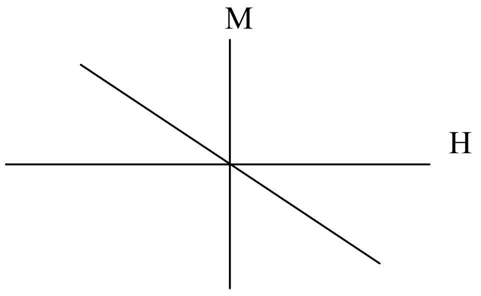
Classically,

$$\langle m_z \rangle = \frac{\int m \cos\theta \, e^{-U/kT} d(\cos\theta)}{\int e^{-U/kT} d(\cos\theta)}$$

(Quantum mechanics gives similar results.)

Diagmagnetism

Negative magnetic susceptibility exhibited by all substances.



$\mathbf{M} = \chi\mathbf{H}, \quad (\chi < 0)$

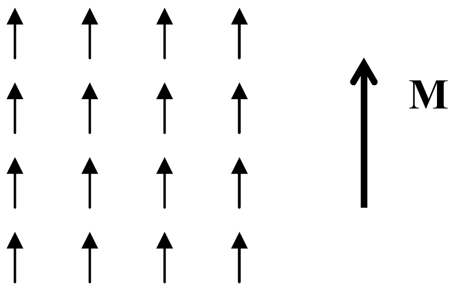
Based on Faraday's law: Electronic orbits change when magnetic field is applied to produce an opposing magnetic flux. Conduction electrons also exhibit diagmagnetism. χ is approximately independent of temperature.

Spontaneous magnetic ordering

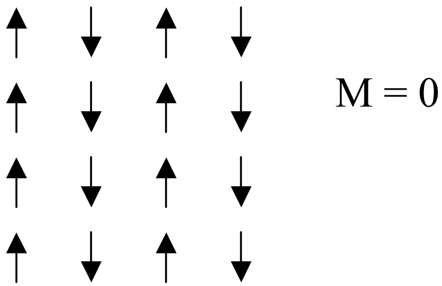
Caused by exchange interactions between atoms

Ferromagnetism:

e.g., Co, Fe, Ni, NiFe, CoPt

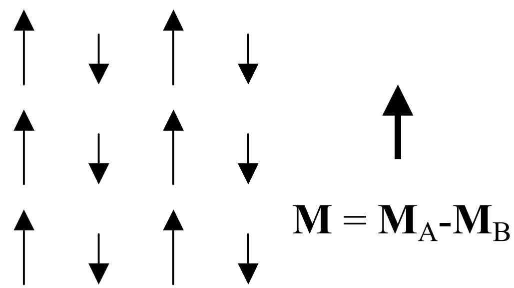


Antiferromagnetism



e.g., MnO, NiO, MnF_2, α-Fe_2O_3 (hematite)

Ferrimagnetism



e.g., Fe_3O_4 (magnetite), γ-Fe_2O_3 (maghemite), $BaFe_{12}O_{19}$, TbFeCo

Exchange interaction

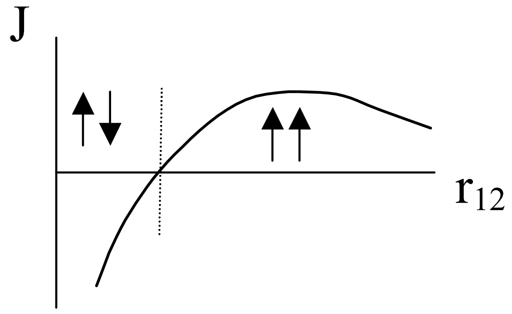
- Magnetic ordering is due to *exchange interaction* between atoms. Exchange energy is the difference between the Coulomb interaction for antiparallel and parallel electrons

$$E_{ex} = E_{\uparrow\uparrow} - E_{\uparrow\downarrow}$$

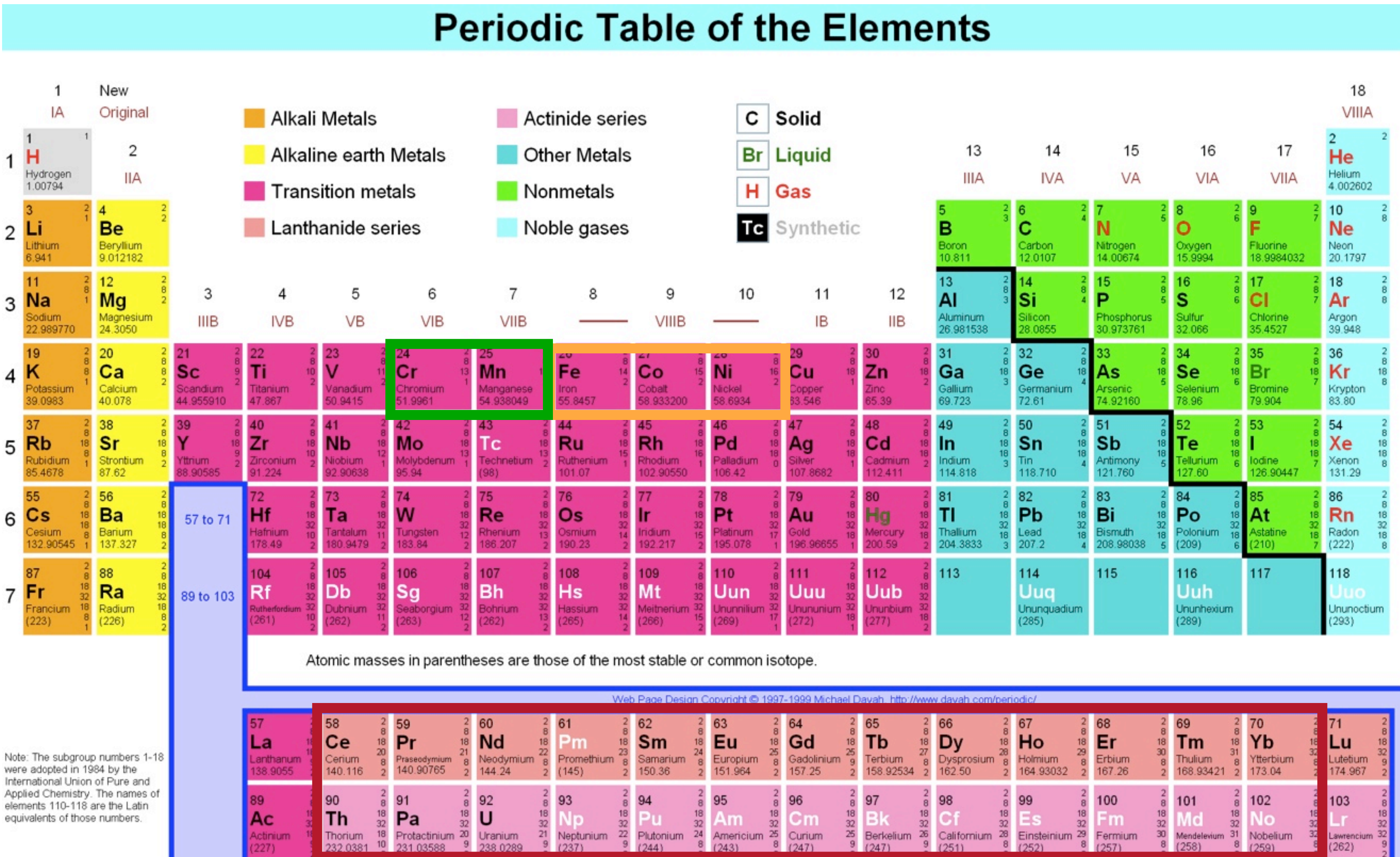
$$E_{ex} = -2J\mathbf{S}_1 \cdot \mathbf{S}_2,$$

J = exchange integral

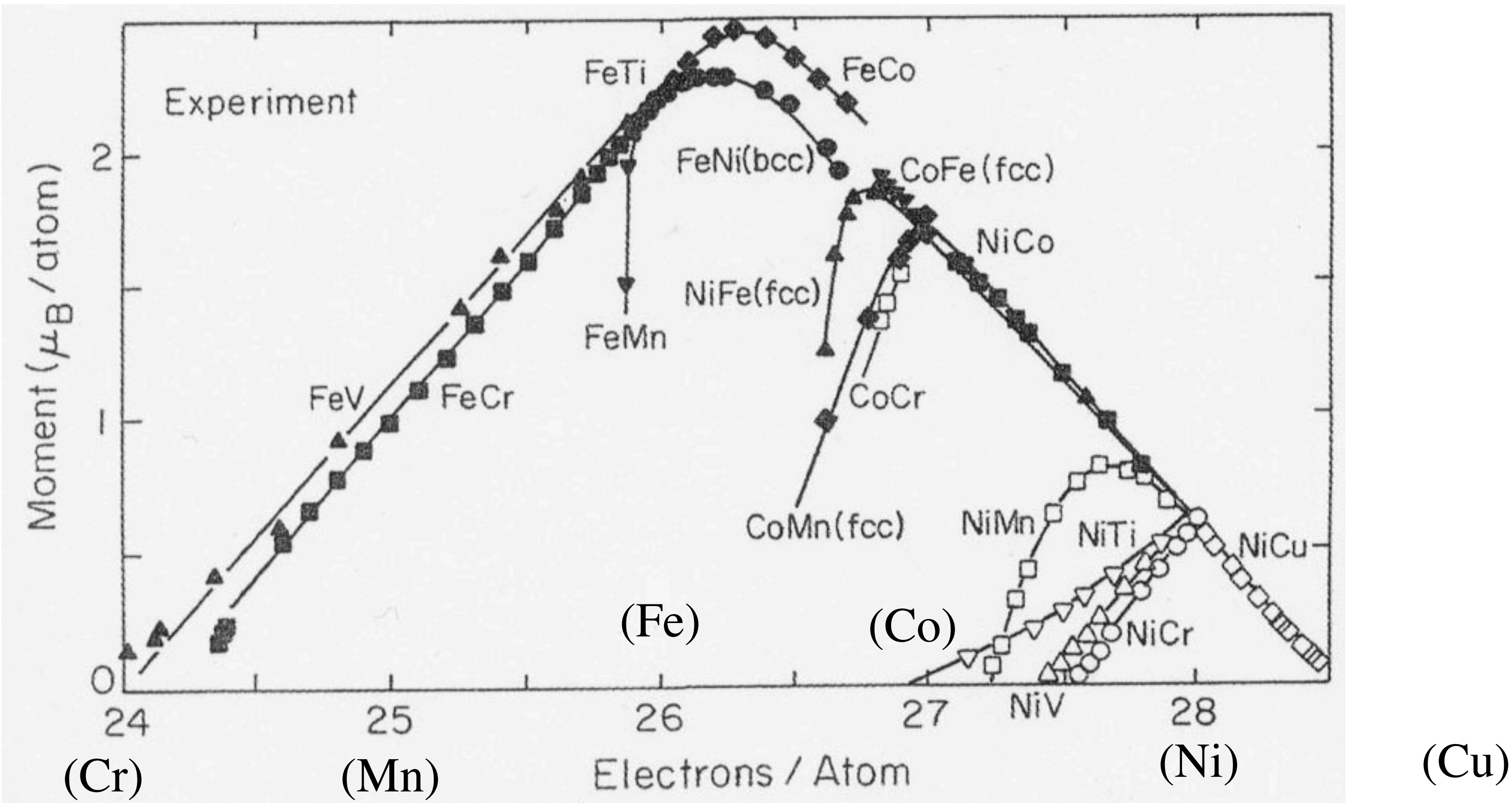
- Net wavefunction (spin times spatial) of two electrons must be antisymmetrical (Pauli exclusion principle). Thus, spatial wavefunction for parallel and antiparallel spin configurations must have different symmetry – further apart when parallel.



Where in the periodic table do we find magnetism?



Slater-Pauling Curve



FeCo has highest known magnetization

Some Important Properties of Ferro- and Ferri-Magnetic Materials

Intrinsic properties:

- Saturation magnetization – M_s (A/m, emu/cc)
- Magnetocrystalline anisotropy (J/m^3, erg/cc)
- Magnetostriction (unitless)

Extrinsic properties:

- Coercivity (A/m, T, Oe)
- Shape anisotropy (J/m^3, erg/cc)

Soft Magnetic Materials (low Hc)

- **Applications**: transformer cores, electromagnetic cores, read heads, …
- **Important properties**: Ms (usually want high), anisotropy (usually low), magnetostriction (usually small), frequency response (high), eddy current loss (low resistivity), …
- **Examples**: Iron and steel, NiFe, CoFe, amorphous alloys, ferrites, …
- Coercivity depends on both intrinsic properties and microstructure.

Hard Magnetic Materials (high Hc)

- **Applications:** permanent magnets, magnetic recording media
- **Examples:** $BaFe_{12}O_{19}$, $Fe_{14}Nd_2B$, Sm_2Co_{17}, CoPtCr, …
- **Energy product = $(BH)_{max}$**
- Coercivity depends on anisotropy and microstructure

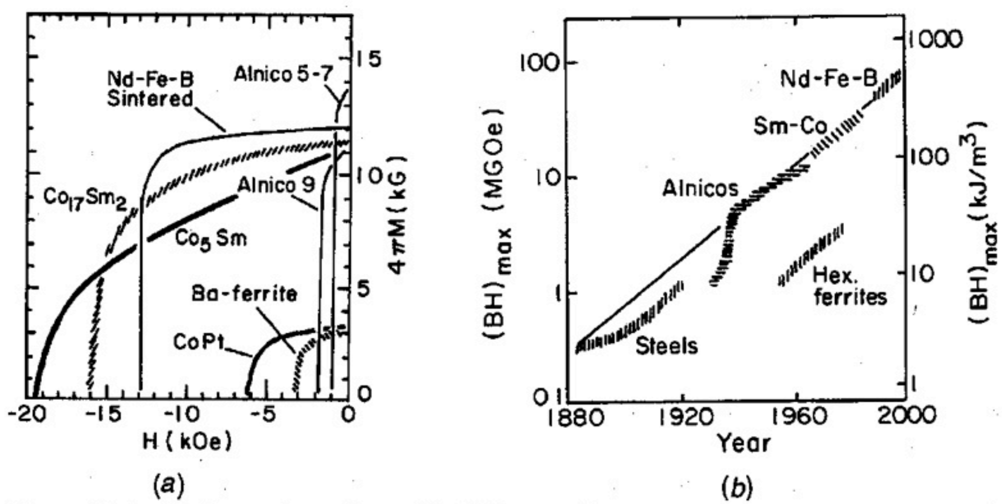
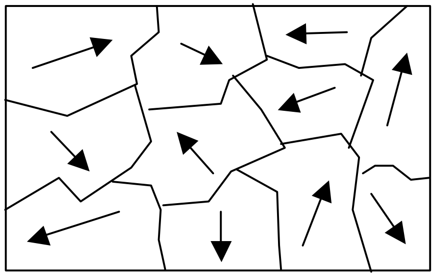


Figure 13.4 (*a*) Second quadrant *M*−*H* loops of some common permanent magnets. (*b*) Increase in $(BH)_{max}$ of permanent magnets over recent decades.

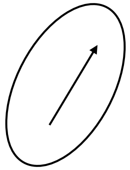
Magnetic domains

Large particles and films generally consist of uniformly magnetized regions (≥ 0.1 μm) called 'domains'.

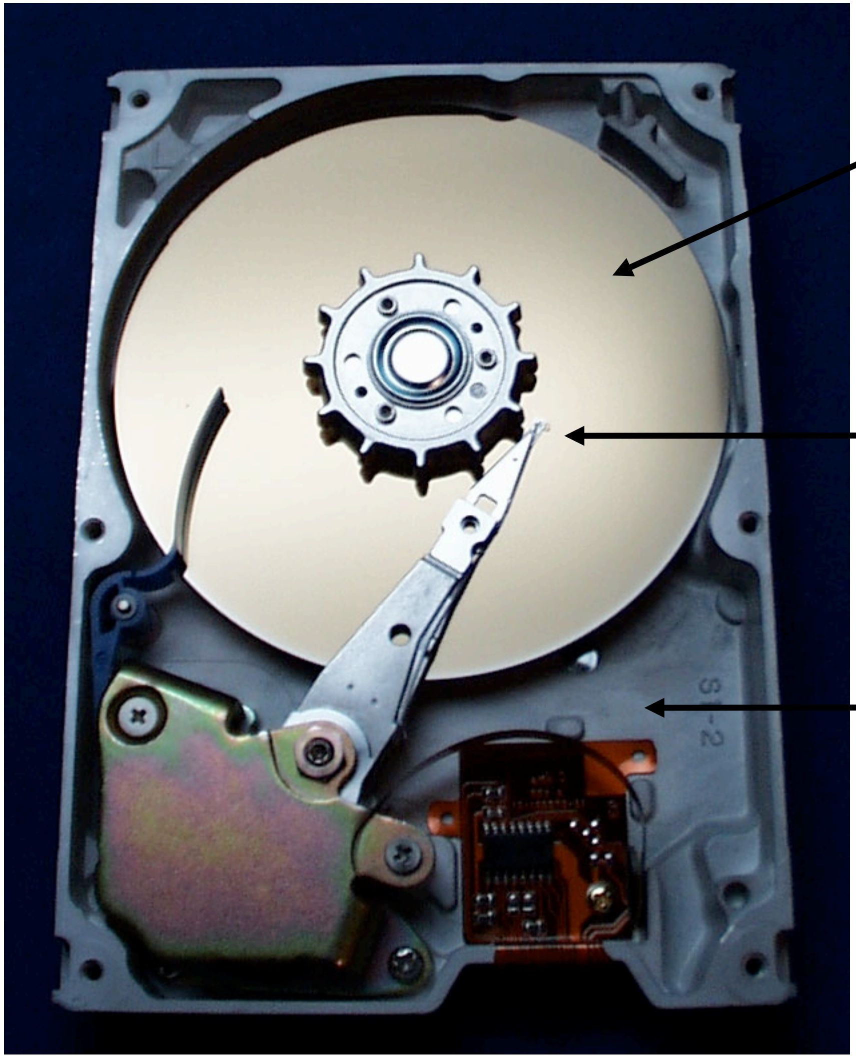


Domain walls can move under the influence of an applied magnetic field.

If particles are sufficiently small, then they are 'single domain'. Critical size depends on strength of exchange coupling, magnetic anisotropy energy, magnetization, particle shape. $D_C \sim 10–100$ nm.



Hard Disk Drive



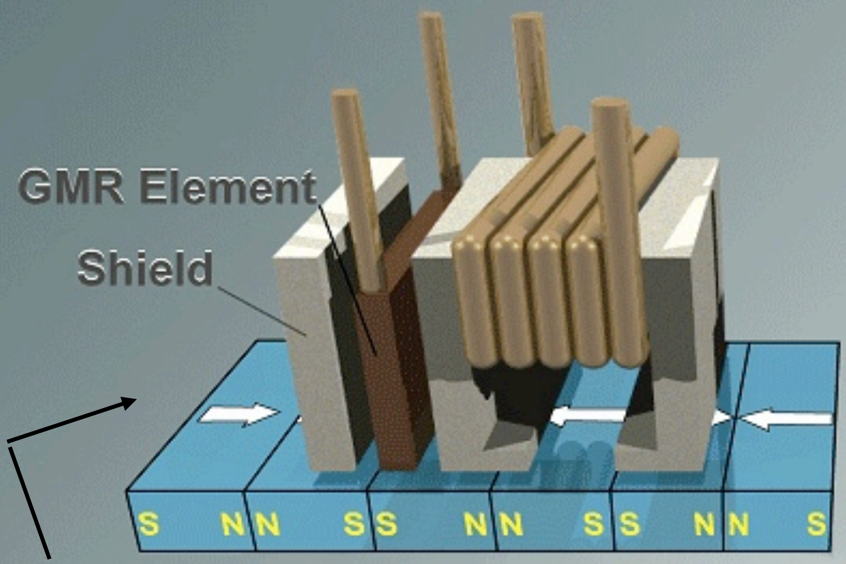
Magnetic film on which bits are stored.

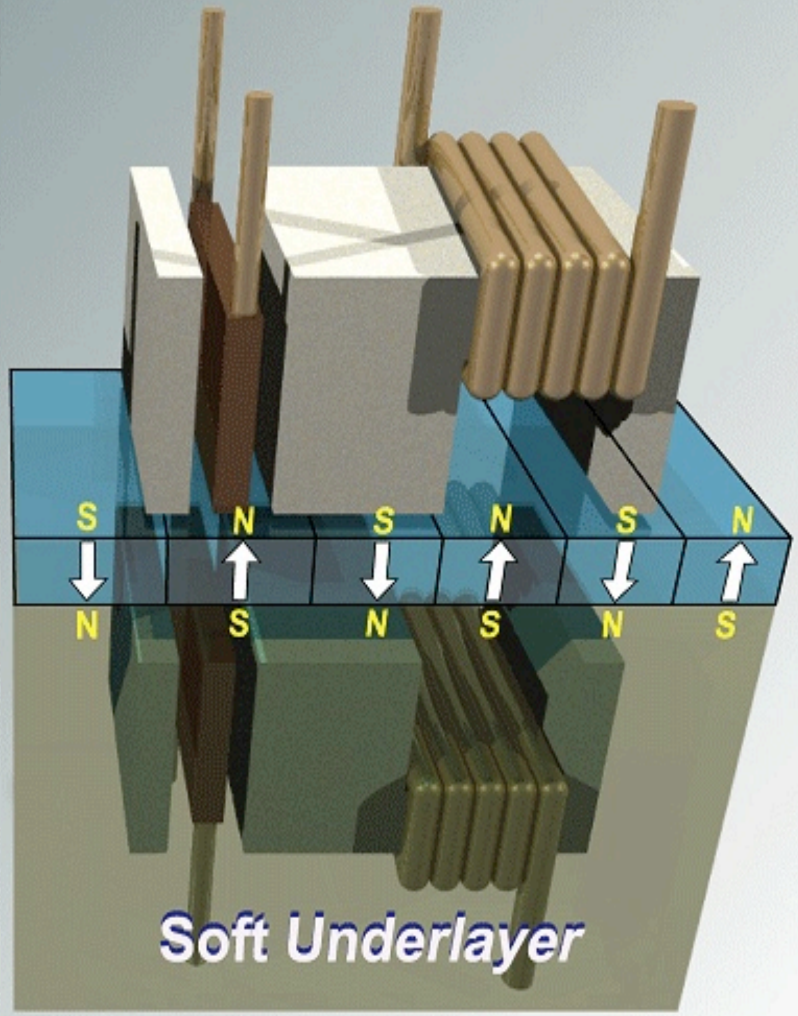
Head for writing and reading bits.

Servo system for positioning the head

Longitudinal Recording

Perpendicular Recording





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

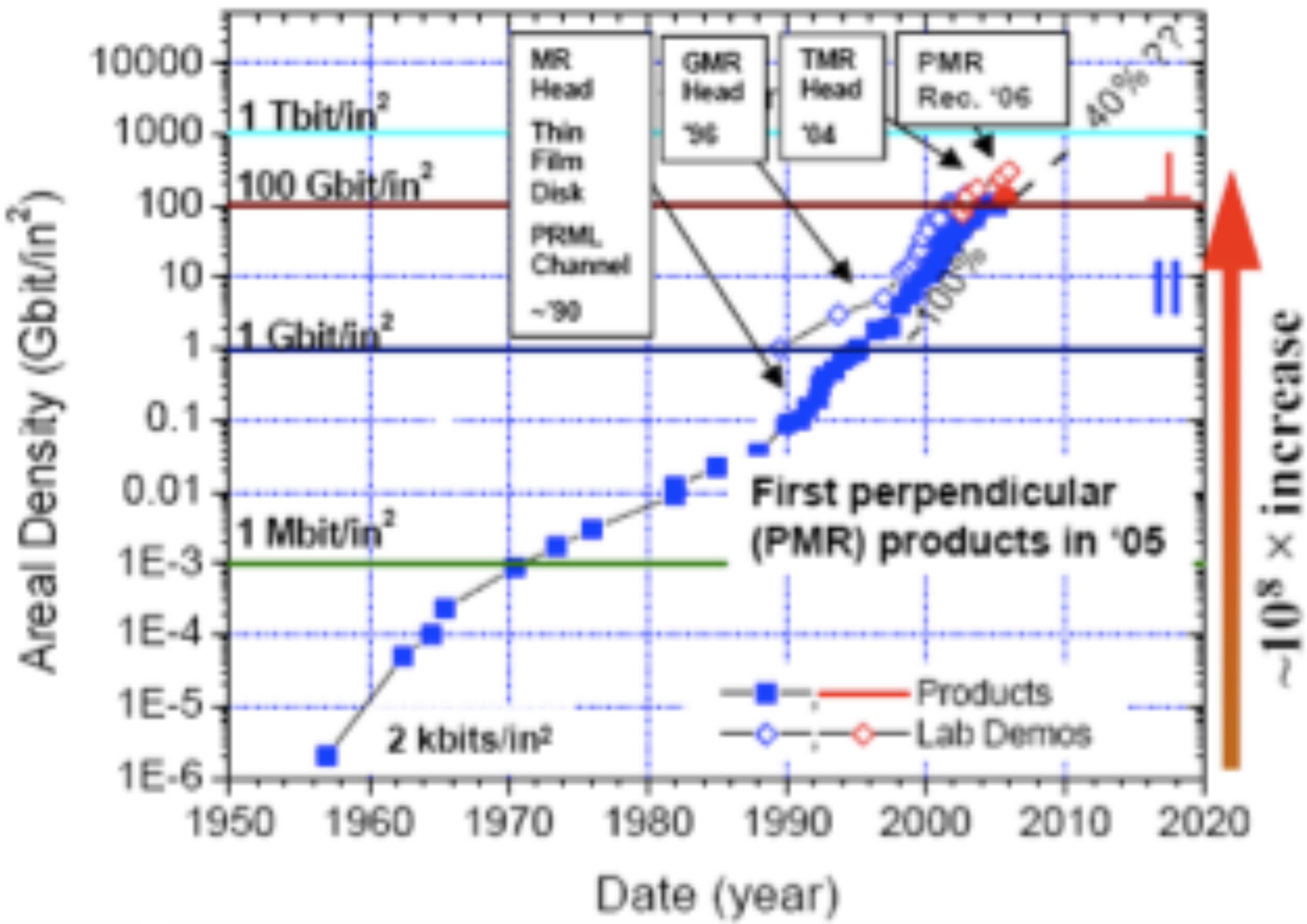
Soft underlayer "mirrors" write head and makes it possible to write domains much closer together.

Areal Density Progress (HDD)

Commercial products:
>100 Gbits/in², >160 GB/3.5" Platter

Demonstrations:
up to 421 Gbit/in²

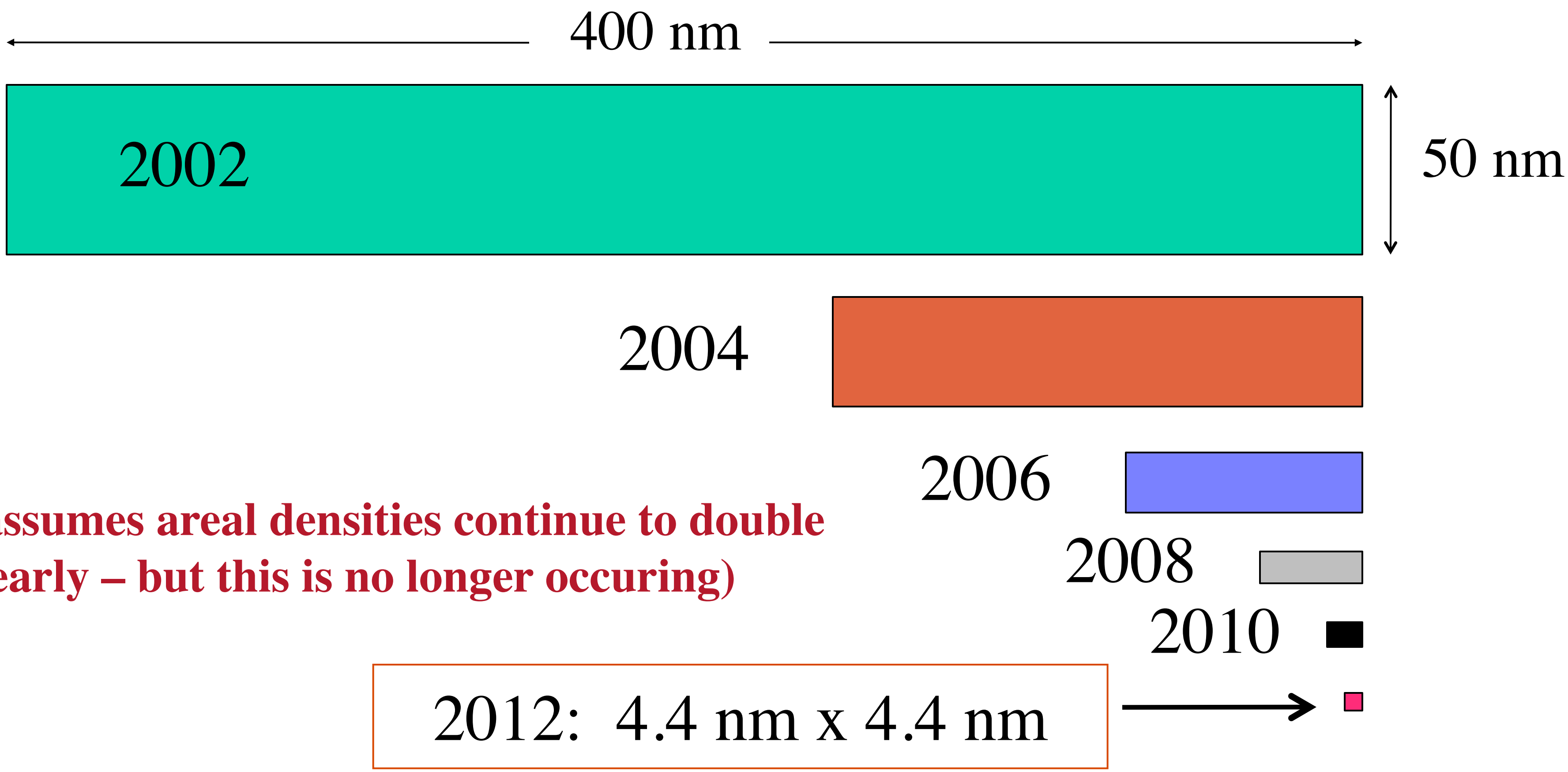
Research frontier:
≥1 Tbits/in²



Technology Options:
- Longitudinal Rec.
- Perpendicular Rec.
- Heat Assisted Rec.
- Discrete Track Media
- Bit Patterned Media
- Self Organized Media

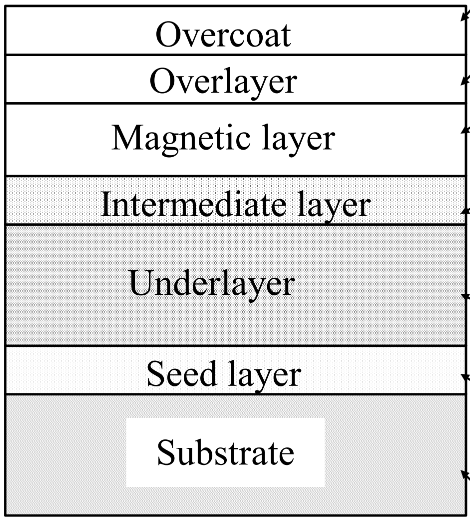
Industry is rapidly transitioning to Perpendicular Recording

The incredible shrinking bit!
Predicted Relative Sizes of HDD Storage Bits



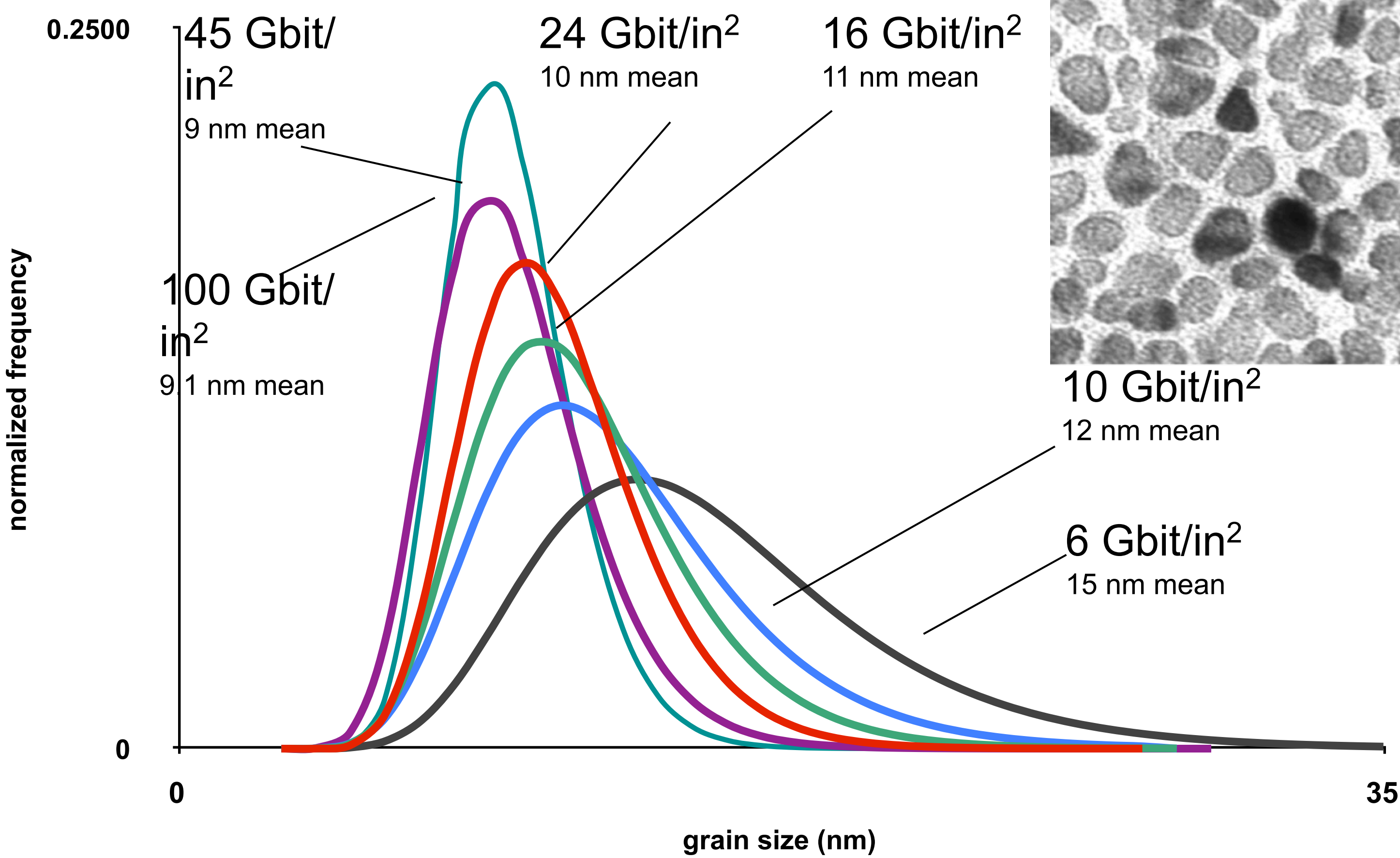
(assumes areal densities continue to double yearly – but this is no longer occuring)

Typical media layer structure

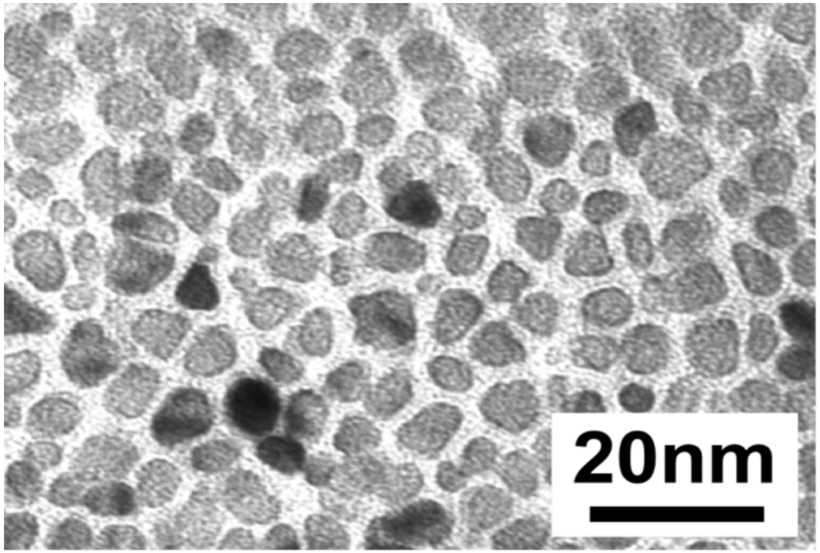


- lubricant
- diamond-like protection from wear and corrosion
- Co-alloy (CoPtCr, CoPtCrB, CoPtCrTa, …)
- Usually CrX. Helps improve epitaxial growth of magnetic layer, improves grain isolation by Cr diffusion from intermediate layer
- grain growth and texture (e.g., CrTi, CrTiB, NiAl)
- helps control grain growth and texture (CrX, e.g., CoCrZr)
- glass or NiP coated Al-Mg. Condition of NiP coating (oxidation, roughness) has some effect on grain size.

Magnetic Media Evolution

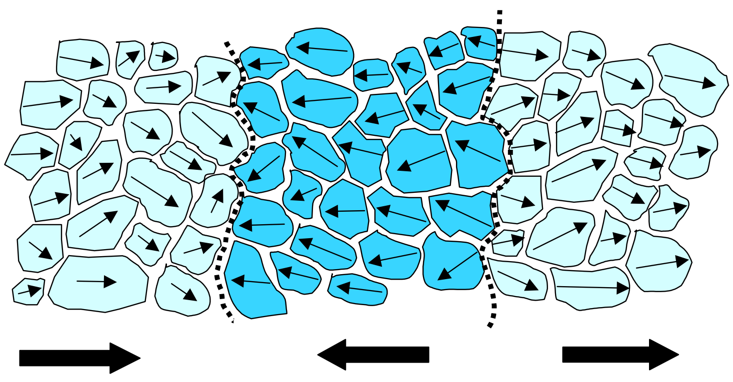


Physical grain size below 10 nm

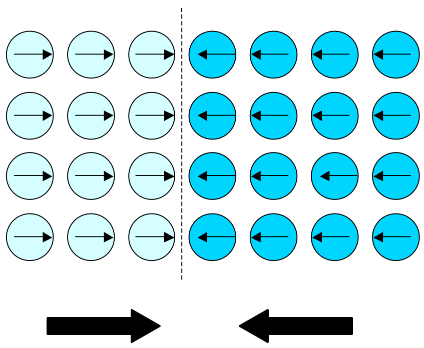


Ideal Media Structure

traditional



lithographically patterned, or self-assembled



- For high-density storage, media should have small, isolated, thermally stable magnetic grains.
- Small grain size ⇒ magnetization decay; large write versus store fields ⇒ magnetic anisotropy must be increased.

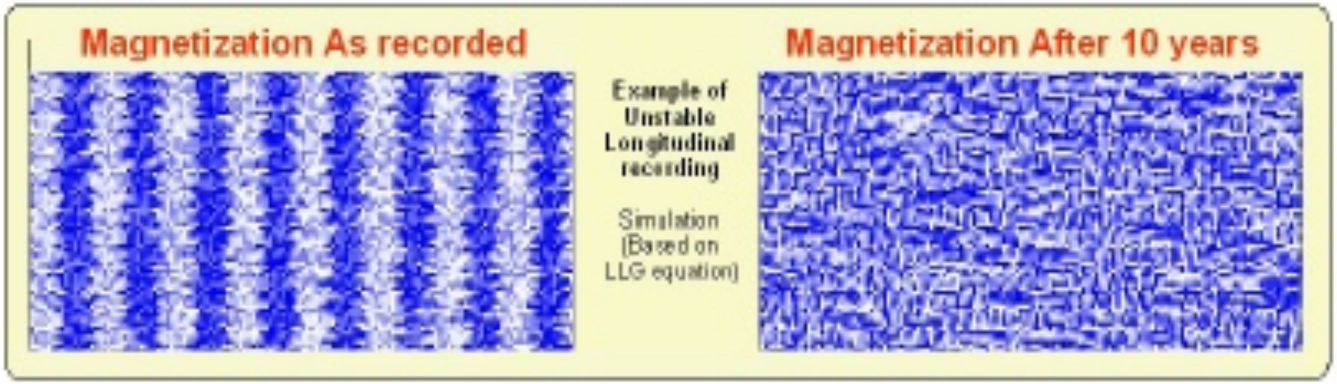
The problem with small magnets -

- Magnets no longer stay magnetized when they approach the nanometer size (superparamagnetism)
- Hard drive disks now made of cobalt alloy granular films. Small size limit is about 8 nanometers.
- One proposed solution for extending storage densities – Chemically synthesized *FePt nanoparticles*.

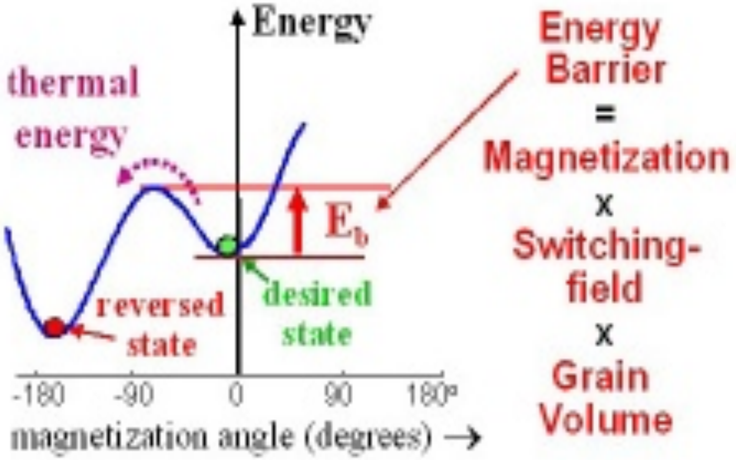
The Superparamagnetic Effect

HITACHI Inspire the Next

- Recording medium is made up of many very-small magnetic grains.
- Bits (±1) are written onto these grains. About 100 grains for each bit

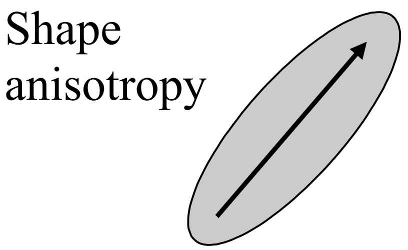


- For high areal-densities, the bits and the grains themselves have to be very small → it takes only tiny energy to flip them!
- If grains are too small they spontaneously reverse magnetization just from thermal energy at room temperature!

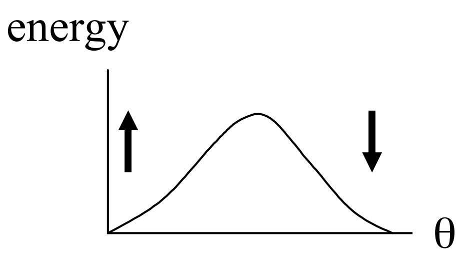


Magnetic anisotropy

Most materials have a preferred direction of magnetization. Usually, due to *crystalline* structure (cubic, hexagonal, etc.), *shape* (grains, films, etc.), or *stress*.



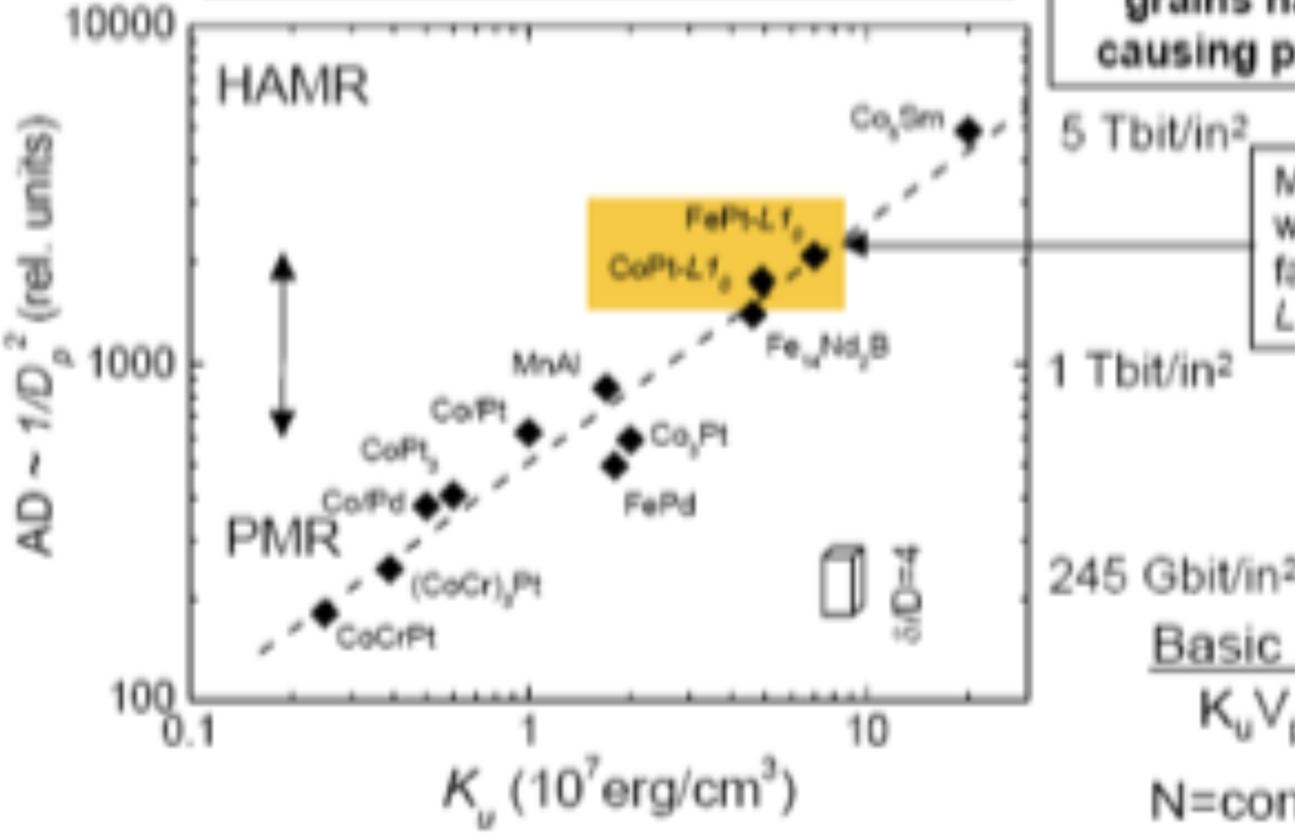
Anisotropy energy = energy difference between "easy" and "hard" directions.



High Ku Media Potential

$$AD_{max} \propto K_u \ @ \ T_S = 350K$$

Plot is based on bulk materials properties (Ku, Ms); small grains have a lot of surface causing properties to change!



Major efforts worldwide to fabricate such $L1_0$ structures

<u>Basic assumptions:</u>

K_uV_p/k_BT~const

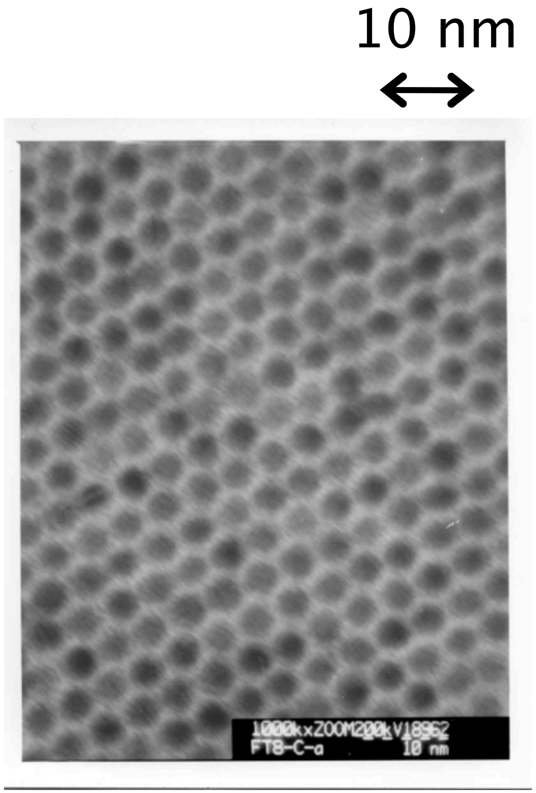
N=const (grains/bit)

Scaling strategy: tall grains with small core size D_p!
Grain aspect ratio of δ/D=4 optimizes thermal stability!

D. Weller, et al., IEEE Trans. Magn. 36, 10(2000).

Self-organized FePt nanoparticles

- First reported by Sun et al. [Science, **287**, 1989 (2000)] – one of "Chemistry Highlights" of 2000.
- Synthesis – reduction of $Pt(acac)_2$ in a diol and decomposition of $Fe(CO)_5$ in presence of surfactant stabilizers at high temperature.
- Self-assembly – slow evaporation of particle dispersion on substrate.



3.5 nm FePt particle array – M. Chen and D.E. Nikles

High Anisotropy FePt Nanoparticle Arrays

- As prepared particles are superparamagnetic.
- Anneal at T ~ 550 ^{o}C to produce chemically ordered high-anisotropy $L1_0$ fct phase.
- Particles ≥ 3 nm thermally stable for > 10 years.
- Potential storage density > 1 Tb/in^2 as conventional medium using heat assisted recording.
- Potential storage density ~ 50 Tb/in^2 if 1 bit/particle recording can be achieved.
- Sintering of particles at the high annealing temperatures required for chemical ordering is a major problem.

50 terabits per square inch on a half dollar size disk

- **Over 3.4 million high-resolution photos, or …**
- **2,800 audio CDs, or…**
- **1,600 hours of television, or …**

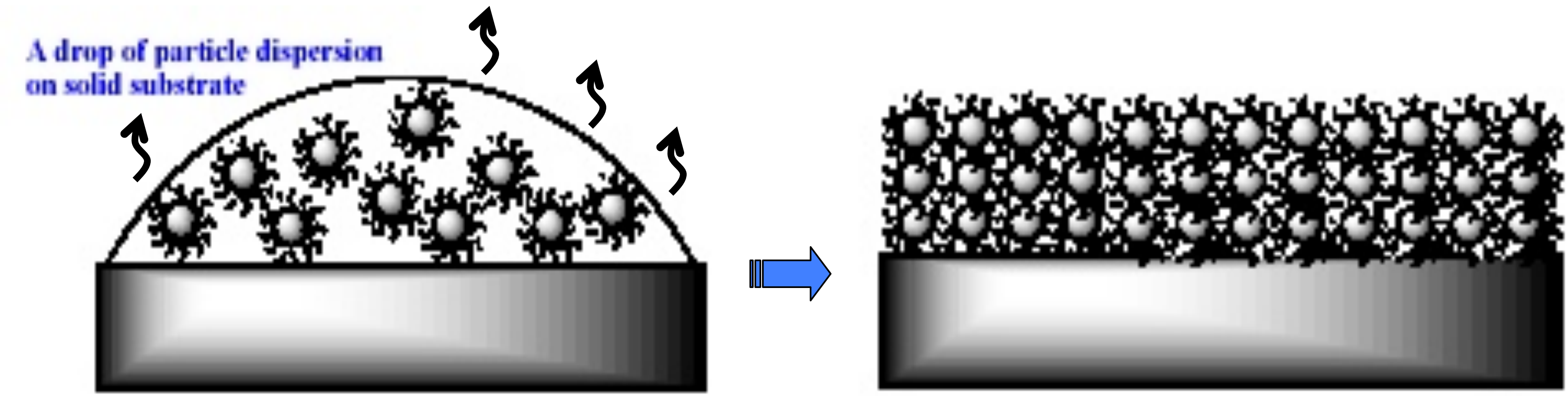
- **the entire printed collection of the U.S. Library of Congress**

Library of Congress, Jefferson building

Synthesis of FePt Nanoparticles

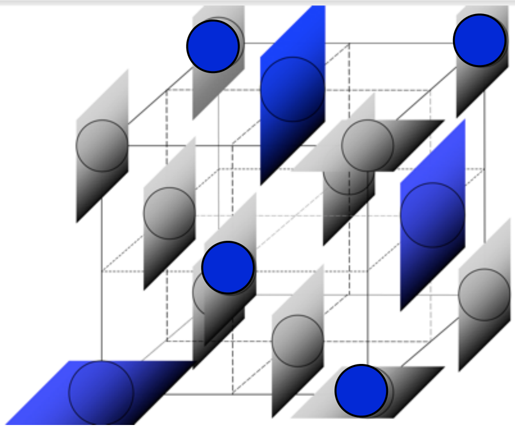
Courtesy of Hao Zeng (IBM)

Self-Assembly



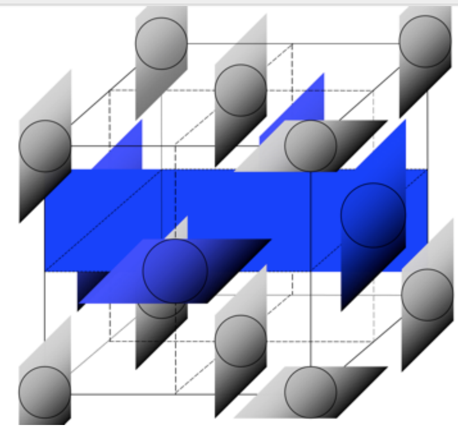
Structural Transition of FePt Nanoparticles

Chemically Disordered Structure



annealing

Chemically Ordered Structure



K_u: ~$7x10^{7}$erg/cc

fcc structure

Only Fundamental Peaks

(111), (200), ...

XRD

fct structure

Fundamental & Superstructural Peaks

(111), (200), (002), ...; (001), (110), ...

Fe atom   Pt atom

Beyond Conventional Recording

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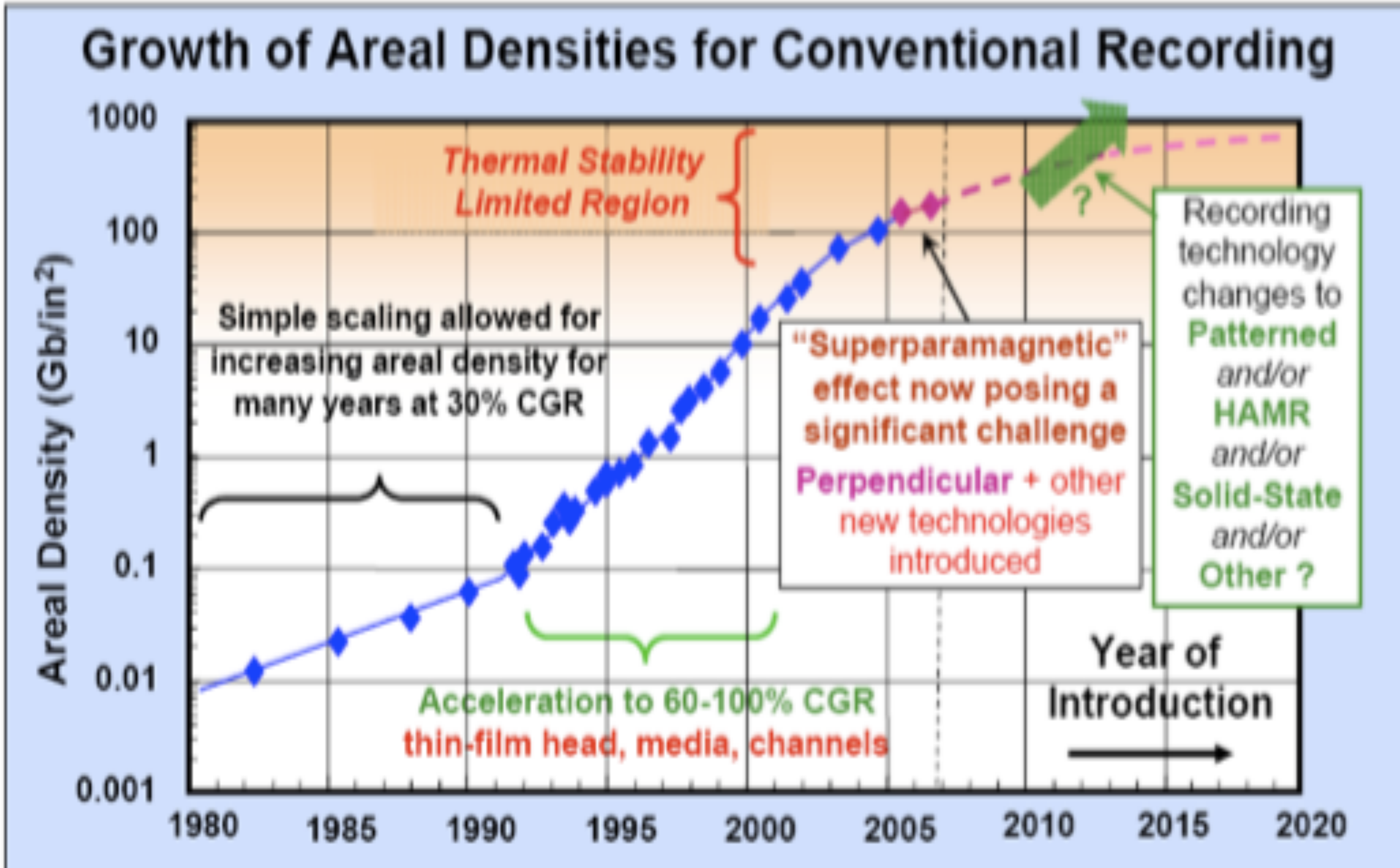

Rate of increase in areal density has slowed significantly. For conventional recording technology, fundamental issues force trade-off between: "Writability", "Signal-to-Noise", "Thermal Stability".

Beyond Conventional Recording

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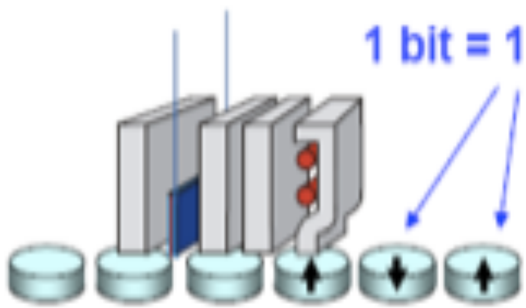
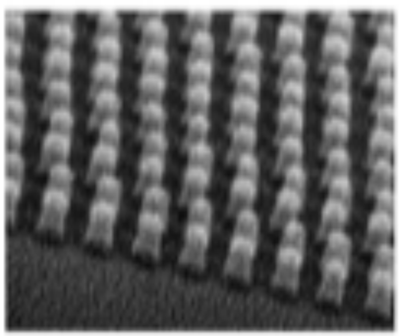
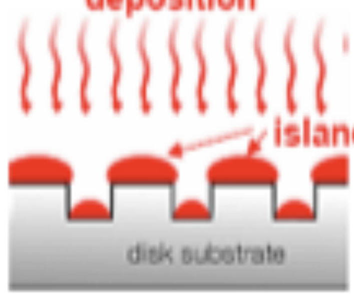
Two favorite technology options to extend thermal limit

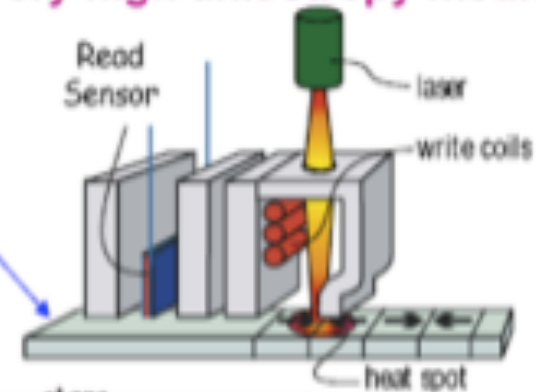
Patterned Media (increased V, utilizing 1 large "grain" per bit)

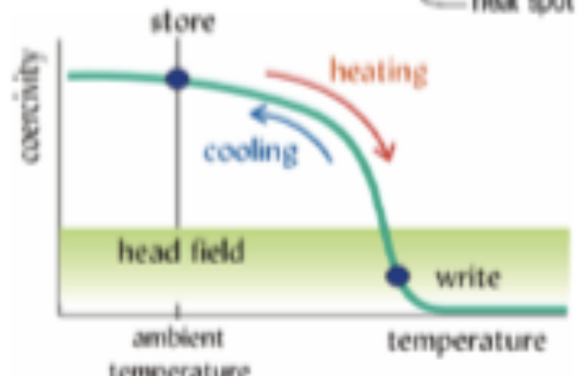






Thermal Assist (increased K_u, utilizing very high anisotropy media)





Challenges: *Disk Manufacture*
Lithography/Stamping

Challenges: *Head Integration*
New Media Development

... plus all the engineering challenges of scaling dimensions for >Terabit/in^2 !

Anisotropy Graded Media

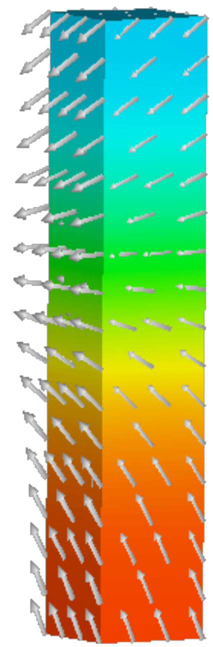
A new concept for extending storage densities

Suess et al., APL ***87****, 012504 (2005).*

In *conventional media*, anisotropy is uniform and reversal occurs by coherent rotation (Stoner-Wohlfarth model). Required switching field increases with increasing anisotropy.

In *anisotropy graded media*, composition and anisotropy vary uniform from bottom to top of grain. Magnetization reversal occurs by nucleation of domain at soft end and propogation through hard end.

Required switching field to stability ratio can be significantly lower than for uniform anisotropy grains.



Summary

- Magnetization of materials has atomic origin
- Properties of magnetic materials depend on both intrinsic and extrinsic factors
- Magnetic materials have broad technological applications
- Continued success of magnetic recording requires new materials and processes at the nanoscale