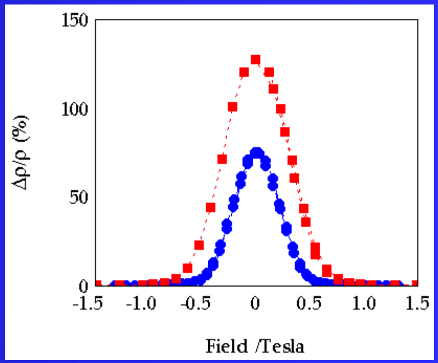
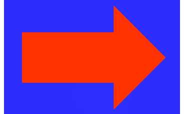
The Story of Giant Magnetoresistance (GMR)

From Laboratory to Hard Drive





Anne Reilly

Grants Development UHCL

Adjunct Professor of Physics

The Nobel Prize in Physics 2007

The Nobel Prize in Physics is awarded to ALBERT FERT and PETER GRÜNBERG for their discovery of Giant Magnetoresistance. Applications of this phenomenon have revolutionized techniques for retrieving data from hard disks. The discovery also plays a major role in various magnetic sensors as well as for the development of a new generation of electronics. The use of Giant Magnetoresistance can be regarded as one of the first major applications of nanotechnology.

Fert

Grunberg

Outline

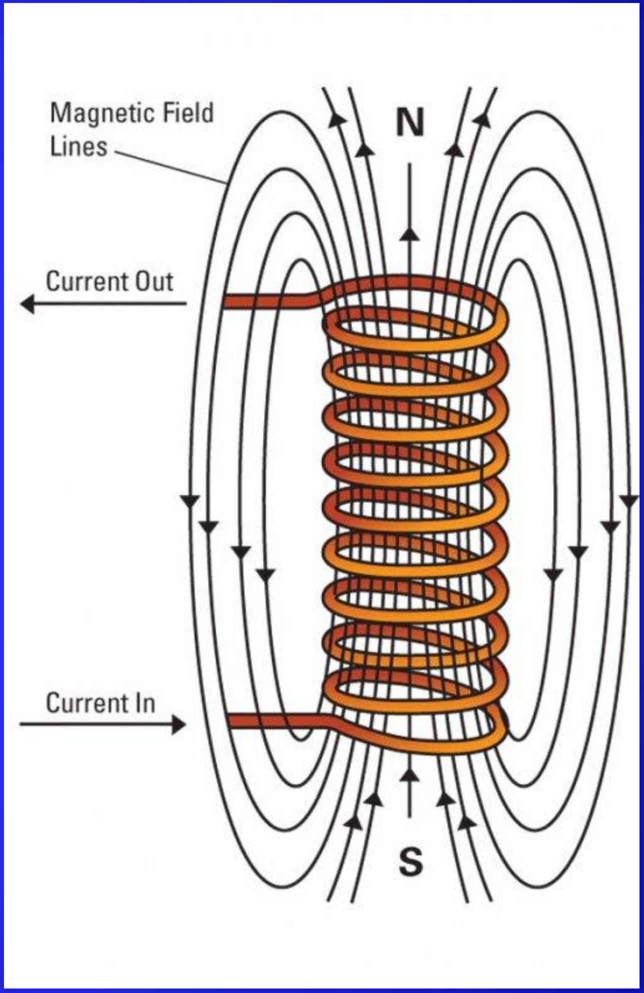
1. ***Magnetic Materials: Basic Properties***
    a. Source of Magnetism
    b. Types of Magnetism
    c. Domains and Hysteresis
    d. Spin-Dependent Transport

2. ***The Discovery of Giant Magnetoresistance***
    a. Atomically Engineered Structures
    b. Fe/Cr Multilayers and Antiferromagnetic Coupling
    c. Giant Magnetoresistance
    d. Advances to Applications

3. ***GMR and the Computer Hard Drive***

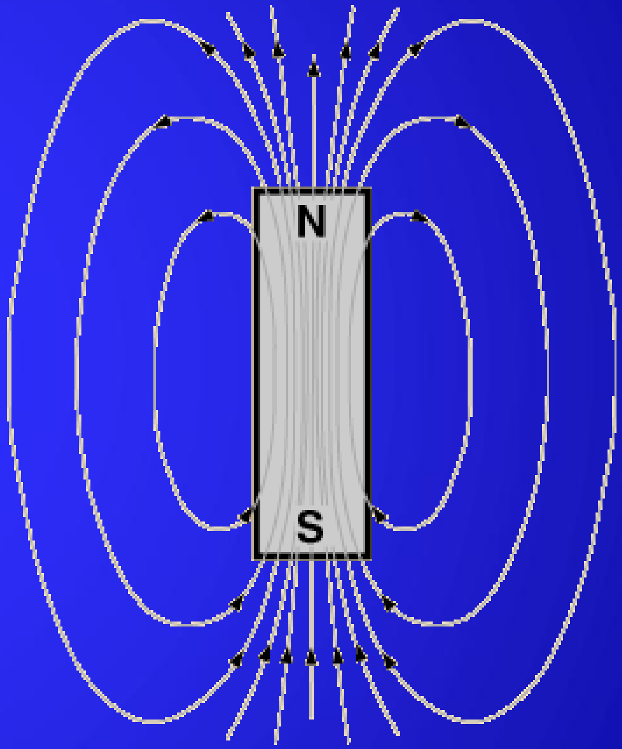
Magnetic Materials: Basic Properties

Source of Magnetism: Moving Electric Charge (Current)



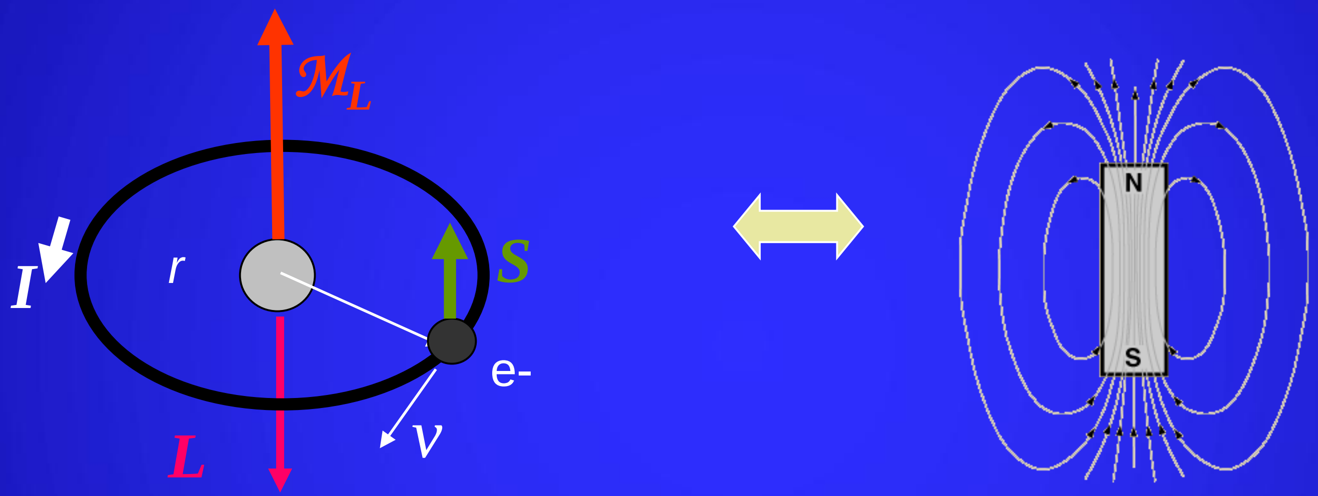
www.lanl.gov

Source of Magnetism: Moving Electric Charge (Current)



Source of Magnetism: Moving Electric Charge (Current)

Atomic Magnetism arises from electron angular momentum and spin



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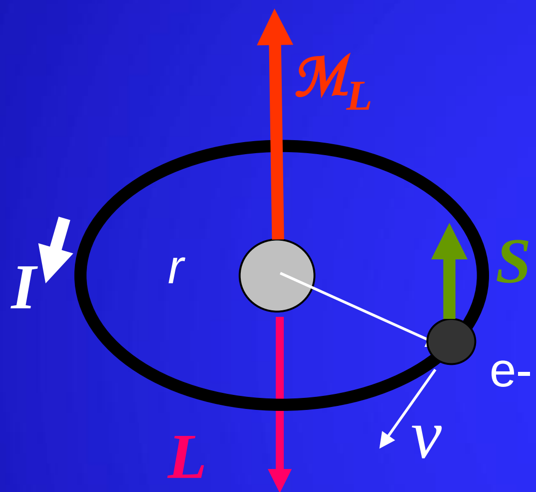
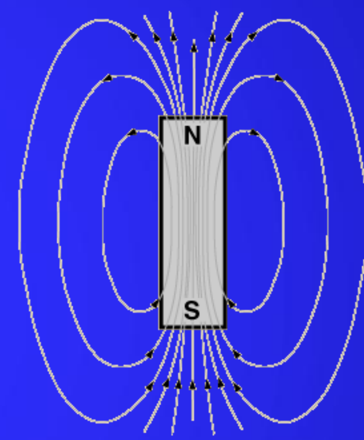




Atomic magnetic moment:

$$\vec{\mathcal{M}} = -\mu_B \vec{L} - g_e \mu_B \vec{S}$$

Angular momentum vector

Spin vector

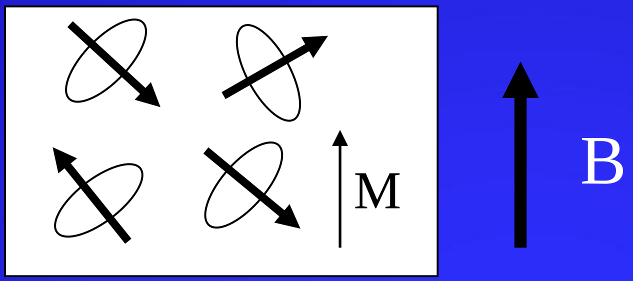
Bohr magneton

$$\mu_B = \frac{e\hbar}{2m}$$

Gyromagnetic ratio $g_e \sim 2$

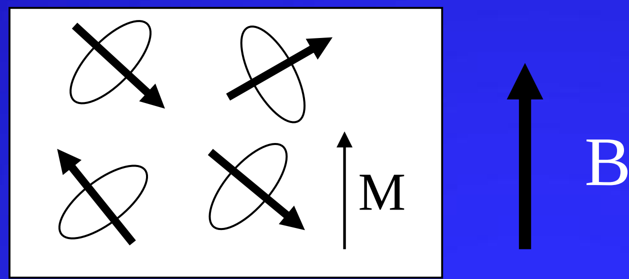
What happens in a solid?

Individual atomic moments in solids are usually not aligned.



What happens in a solid?

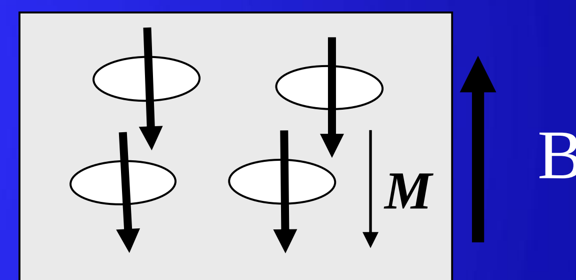
Individual atomic moments in solids are usually not aligned.



Diamagnetism

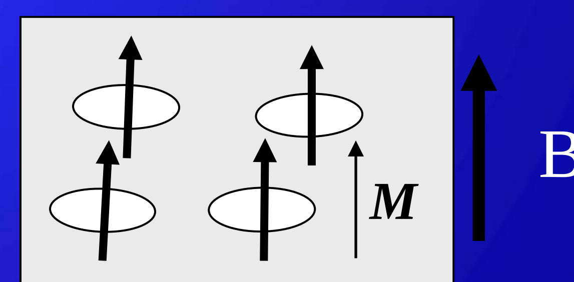
Induced moment is opposite of external field, B

(M_{dia} is very small, except in superconductors)



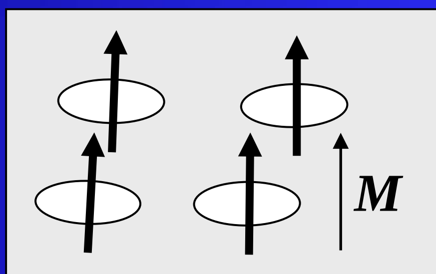
Paramagnetism

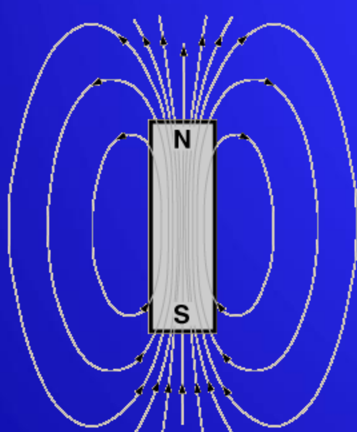
Induced moment is in same direction as field

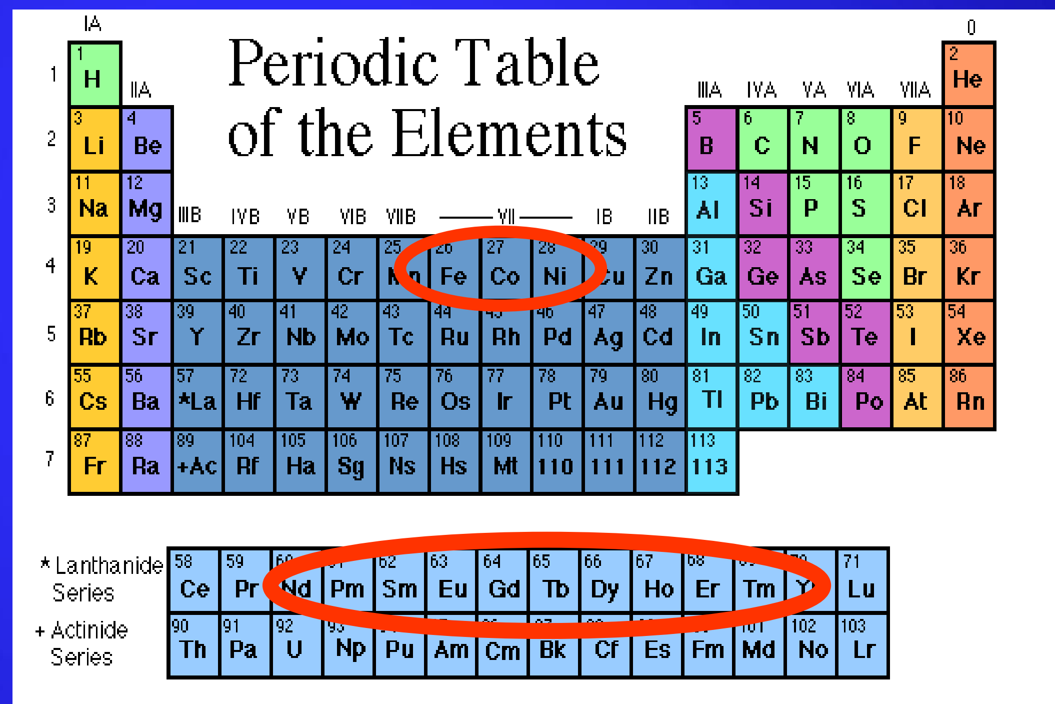


Ferromagnetism (3d and rare earth elements)

Occurs in materials we usually call ‘magnetic”. Interaction between electrons (exchange) causes moments to align *spontaneously*.







Exchange Interaction

- **Central for understanding magnetic interactions in solids**
- **A quantum mechanical effect, arises from Coulomb electrostatic interaction and the Pauli exclusion principle**

Coulomb repulsion energy high

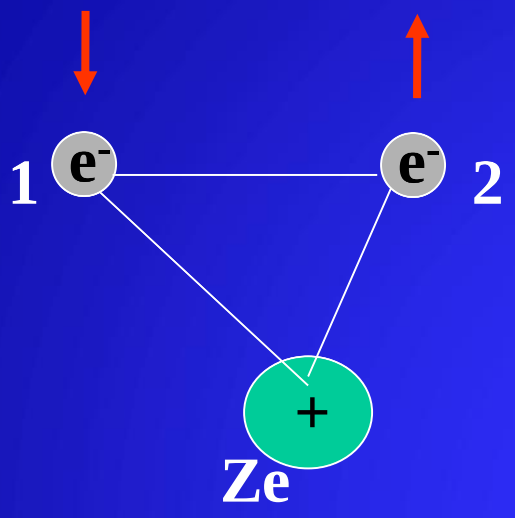
Coulomb repulsion energy lowered

$$U_C = \frac{e^2}{4\pi\varepsilon_0 r^2} \sim 10^{-18}\, J$$

(10^5 K !)

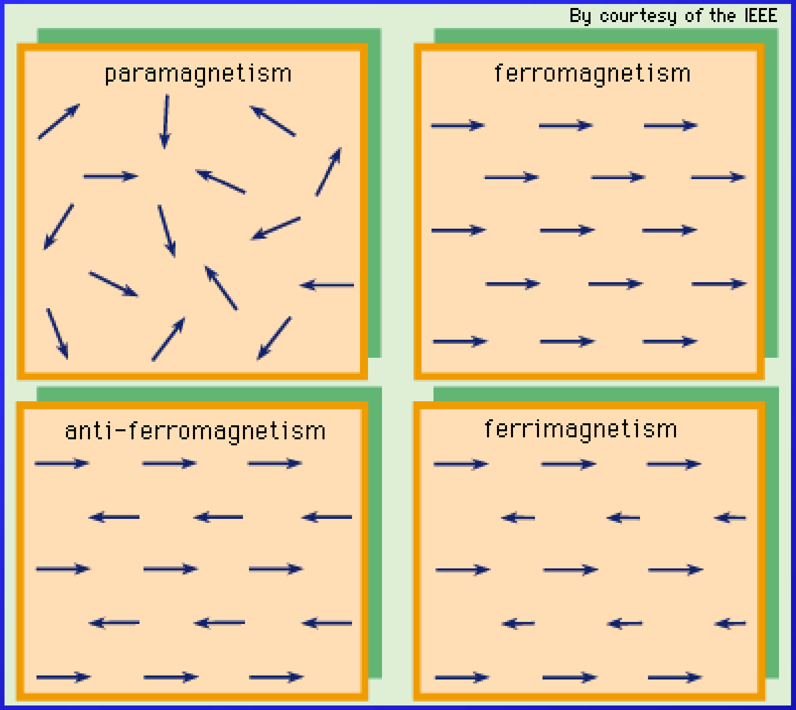
Natural Principle: Minimization of Energy

Exchange Interaction: A Quantum Mechanical Effect



$$E = \frac{\langle \Psi | \mathcal{H} | \Psi \rangle}{\langle \Psi | \Psi \rangle}$$

$$\mathcal{H}_{ex} = -2J\bar{S}_i \cdot \bar{S}_j$$



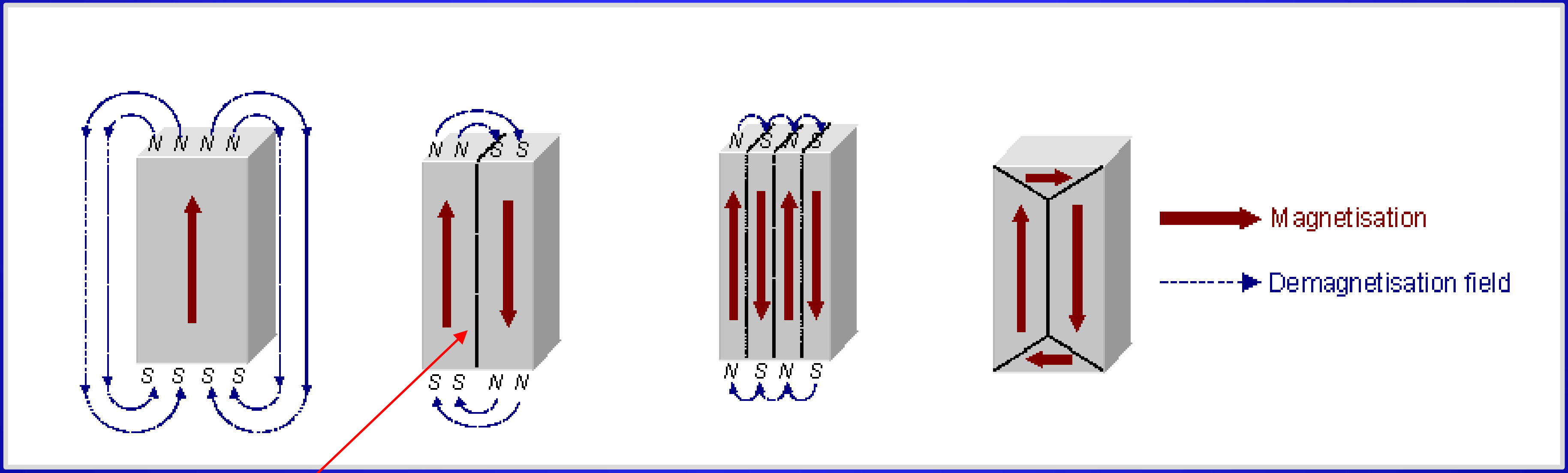
J>0

J<0

Domains

In ferromagnetic materials, exchange interaction leads to an alignment of atomic spins.

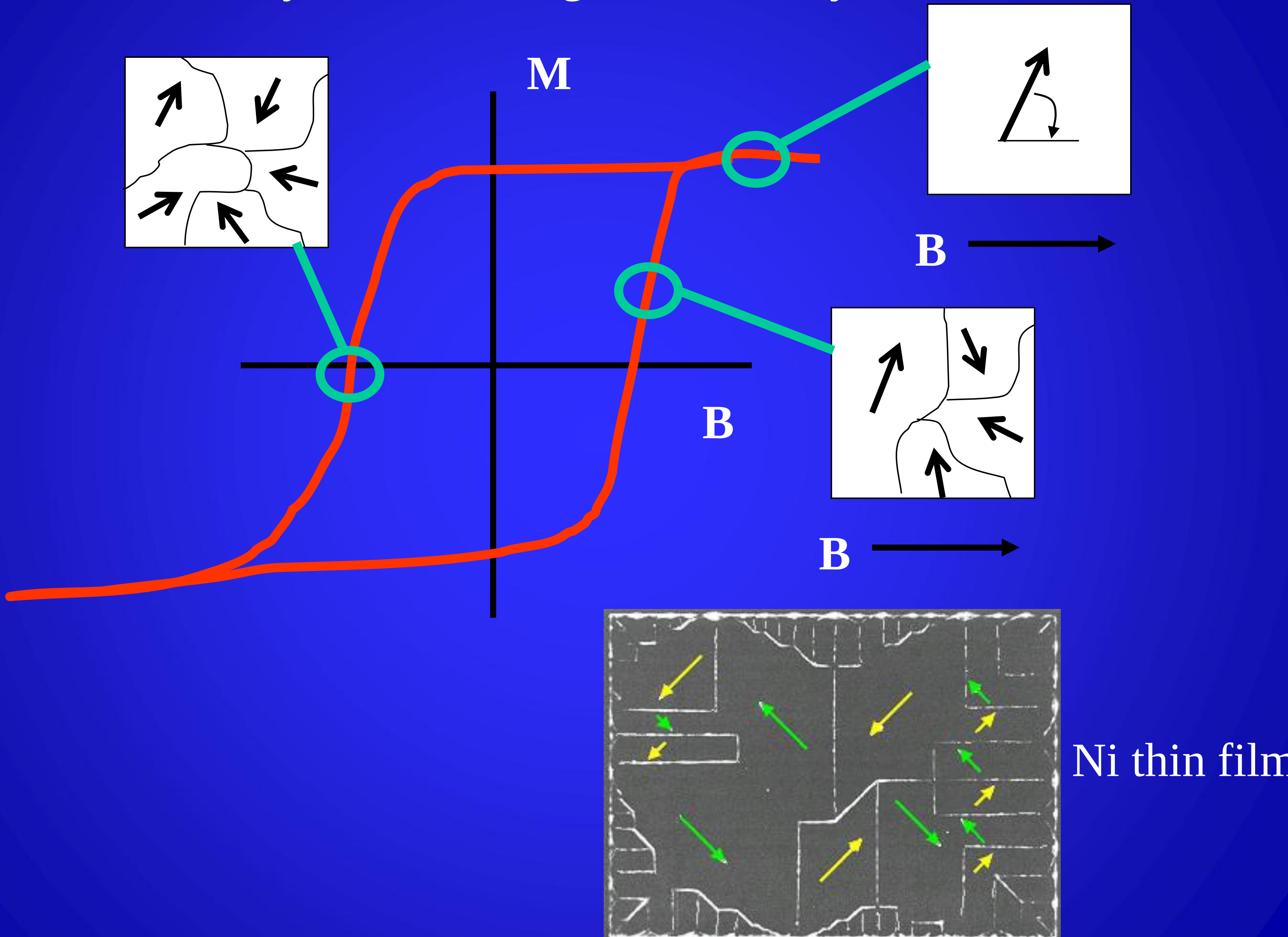
However, this leads to a large external and dipolar magnetic fields which will tend to demagnetize the material. Domains are formed to minimize this effect.



Domain wall

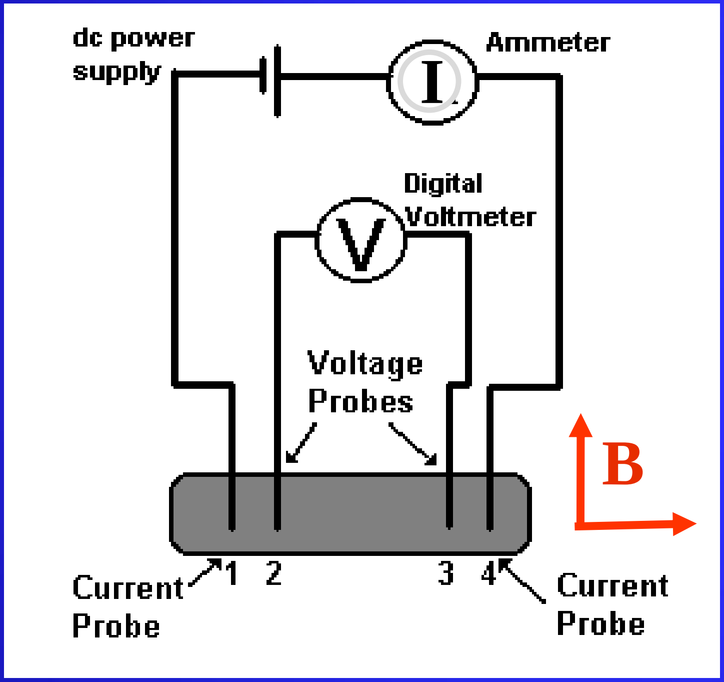
From http://www.aacg.bham.ac.uk/magnetic_materials

Hysteresis = Magnetic Memory

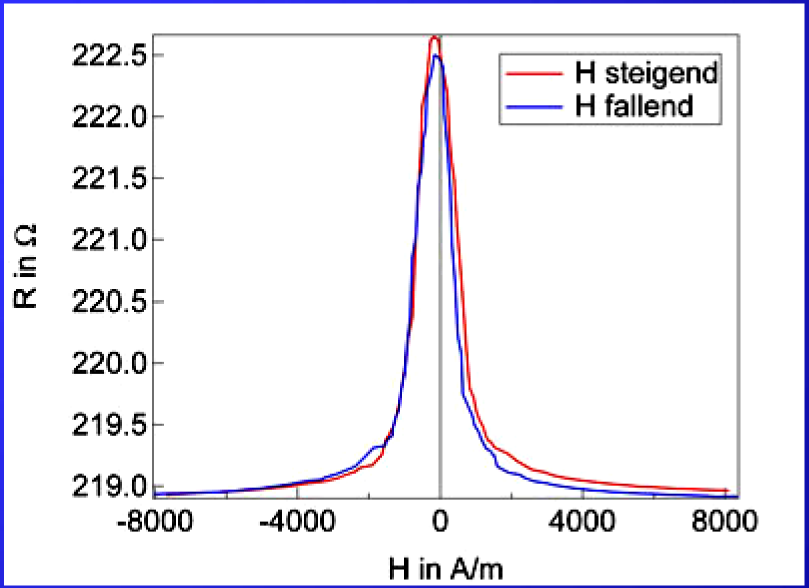


Spin-Dependent Transport and Ordinary (Anisotropic) Magnetoresistance (AMR)

Discovered by Lord Kelvin in 1856.



$$V = IR$$



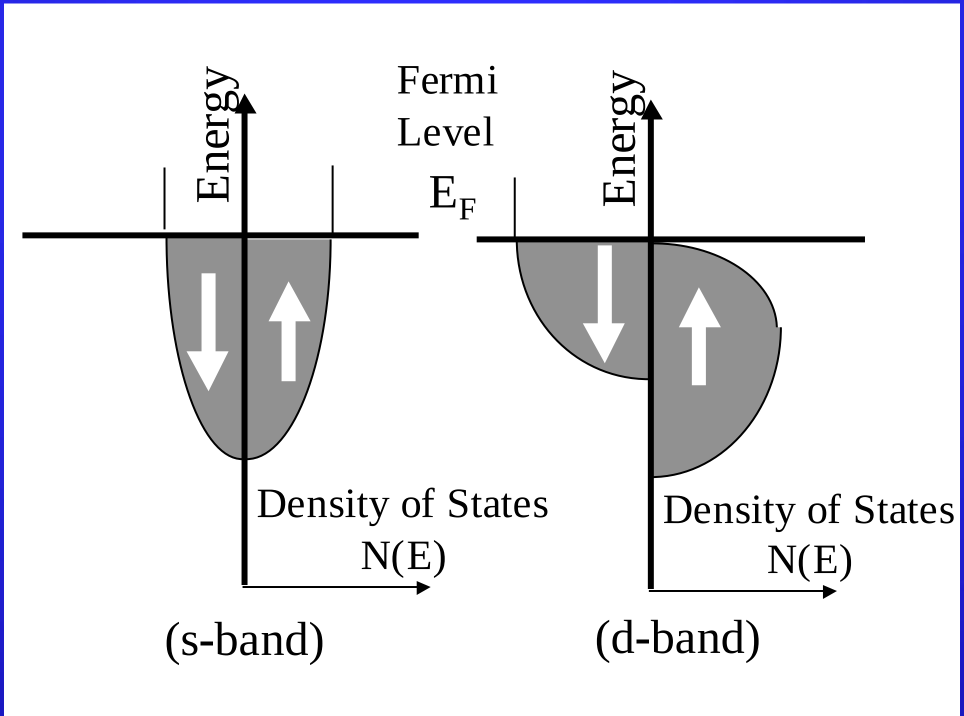
AMR~1-2%

www.emg.tu-bs.de

Spin Dependent Scattering

Resistance (R) and Resistivity (ρ) determined by scattering of electrons. In ferromagnets, because of the exchange interaction, one spin state is favored. This means that there are less energy states available for one spin than the other, and:

$\rho\downarrow > \rho\uparrow$ in ferromagnetic element metals



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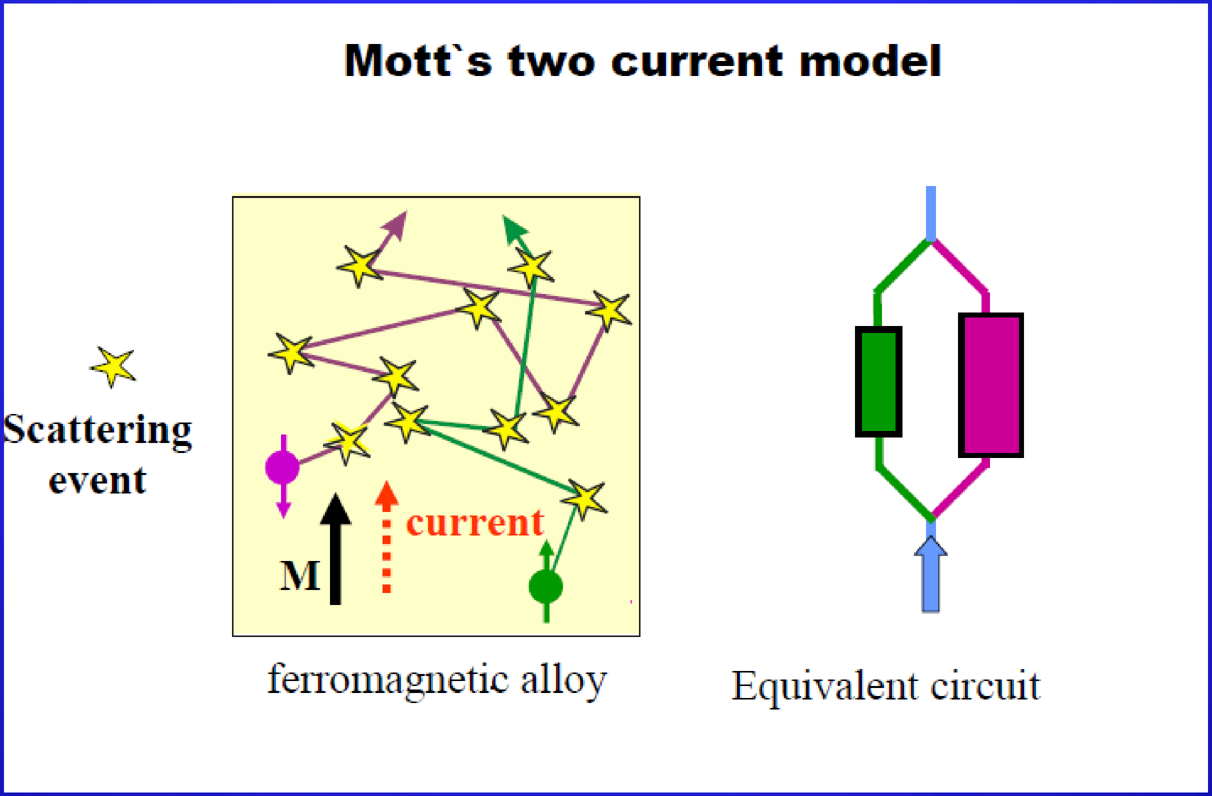


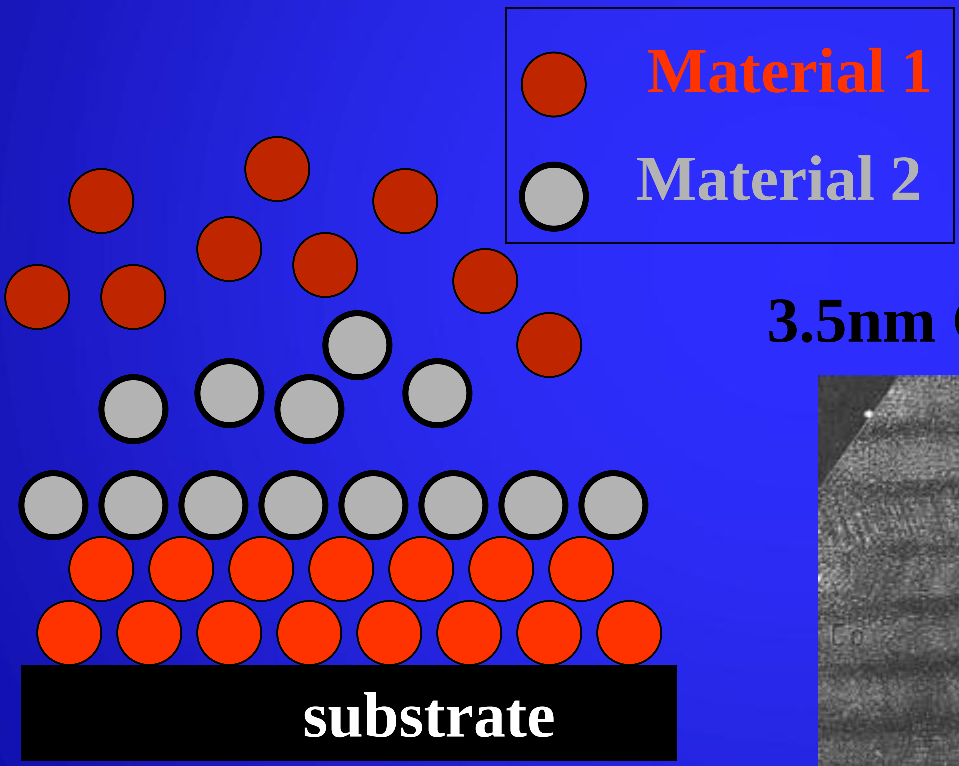
www.nobelprize.org

The Discovery of Giant Magnetoresistance

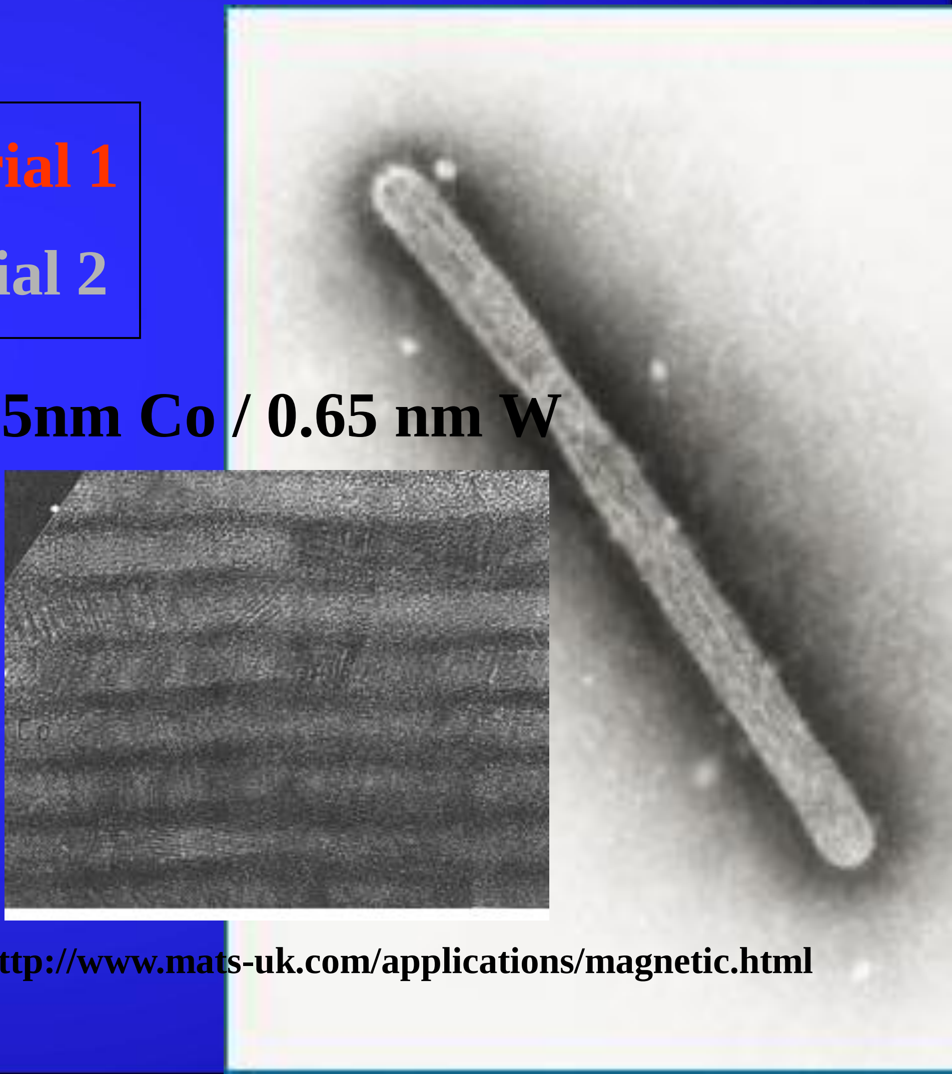
The 1980’s necessary technological advance:

Nanotechnology

“Atomically engineered structures”

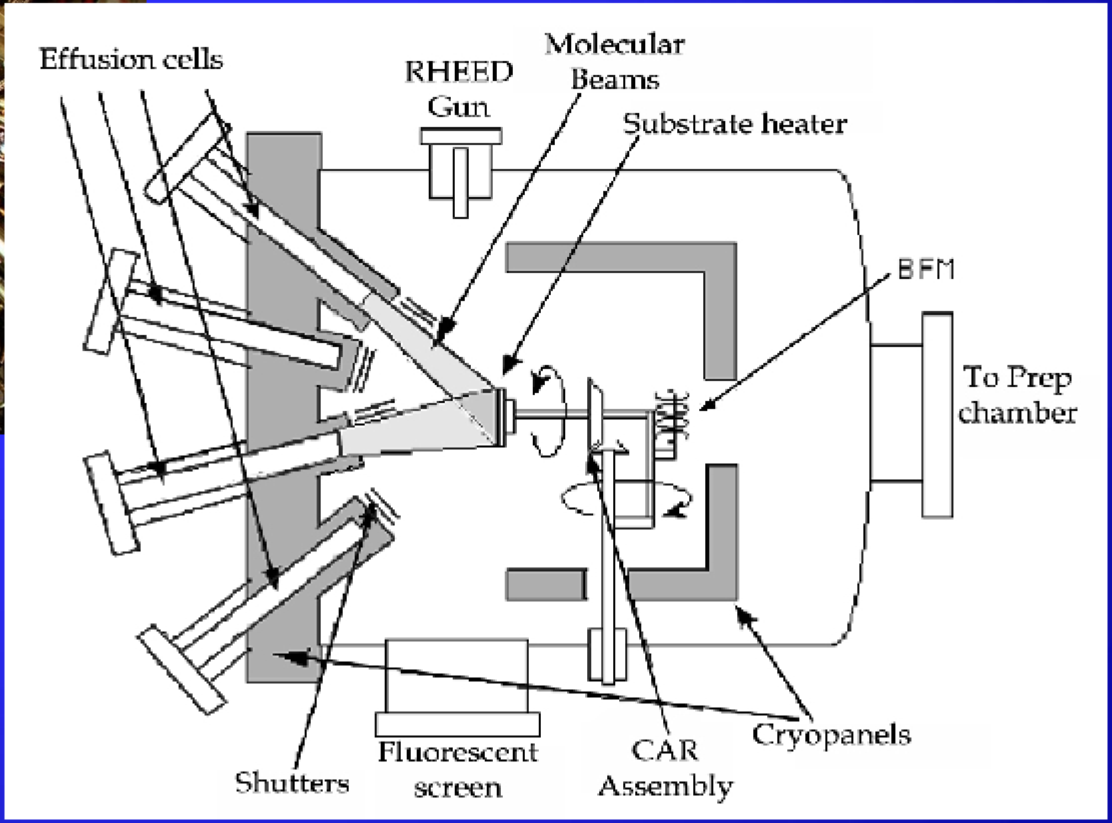


3.5nm Co / 0.65 nm W



http://www.mats-uk.com/applications/magnetic.html

Molecular Beam Epitaxy (MBE)

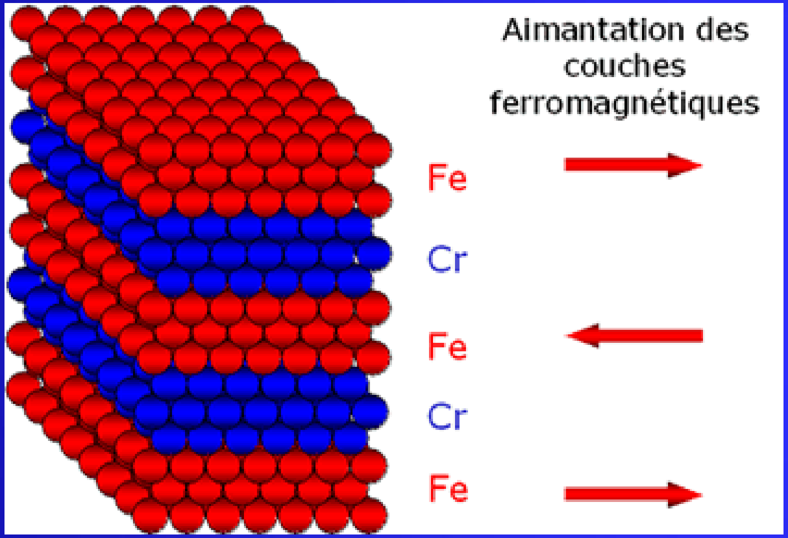


also, Sputtering

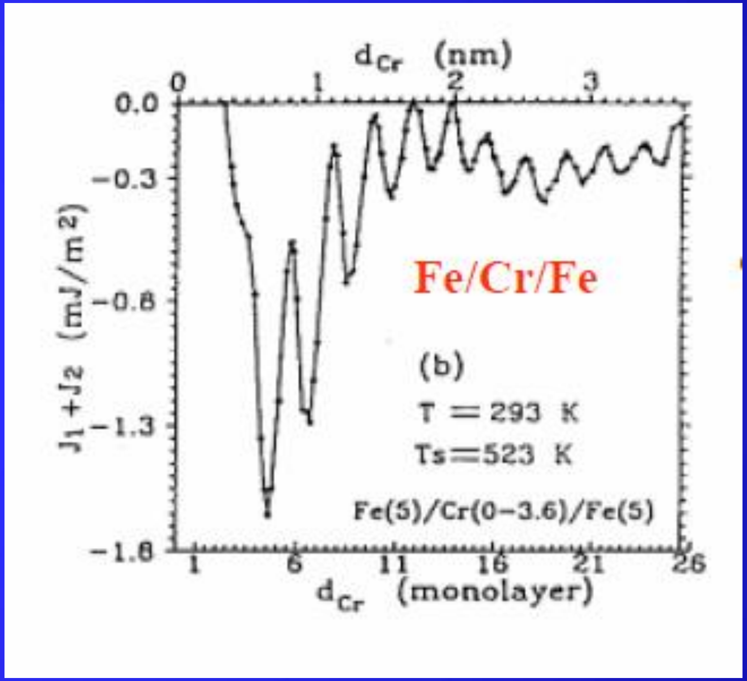
Physics.umn.edu

Peter Grunberg *et al.*, Discovery of AF coupling in Fe/Cr multilayers

"Layered Magnetic Structures: Evidence for Antiferromagnetic Coupling of Fe Layers across Cr Interlayers", Physical Review Letters, 57, 2442–2445 (1986)

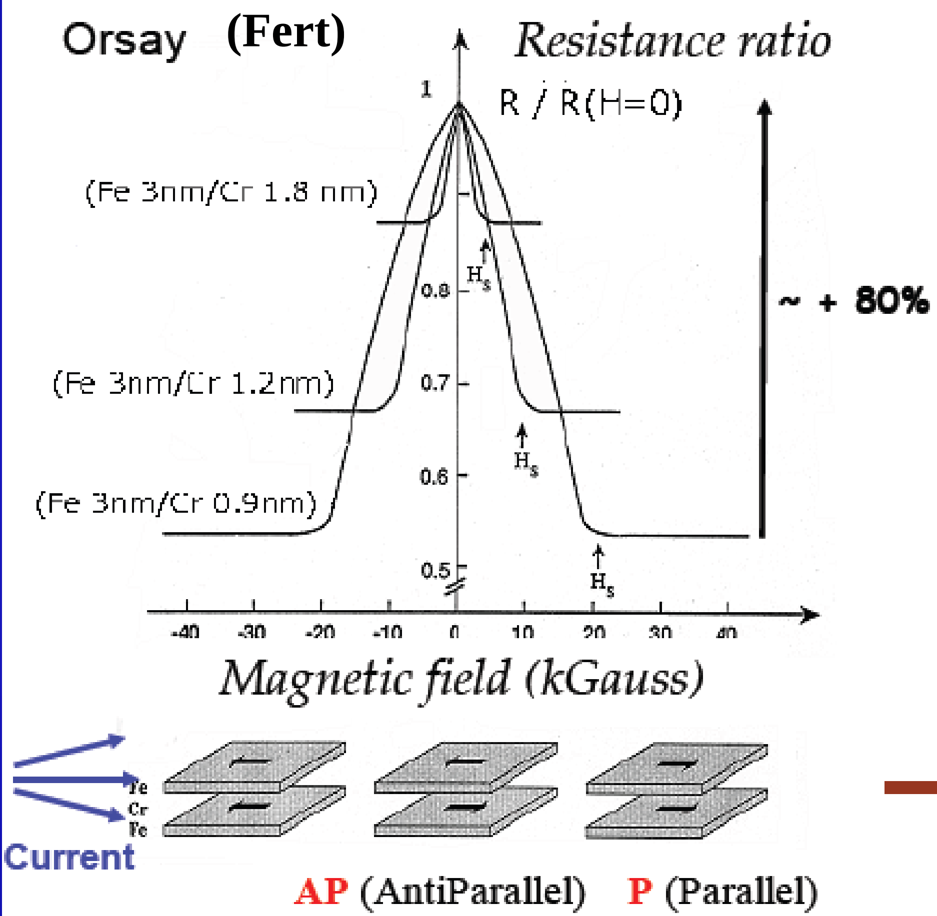


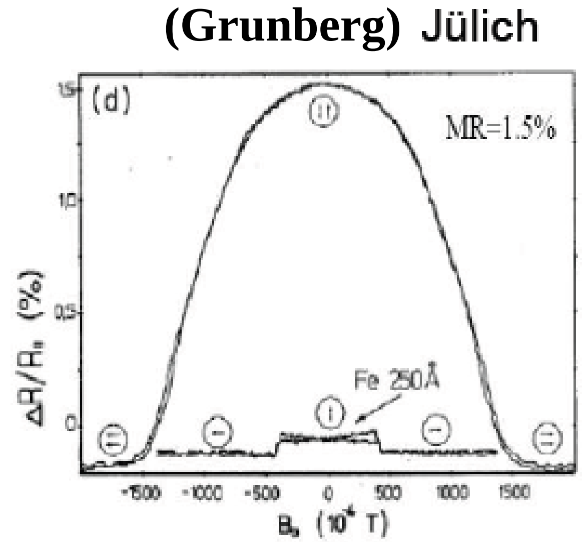
www.cnrs.fr

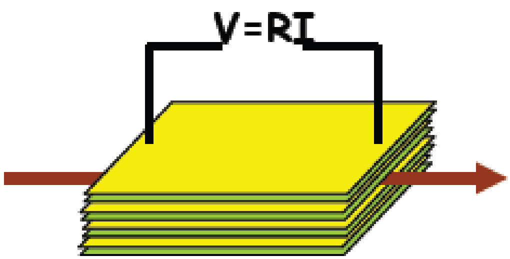


• Giant Magnetoresistance (GMR)

(Orsay, 1988, Fe/Cr multilayers, Jülich, 1989, Fe/Cr/Fe trilayers)



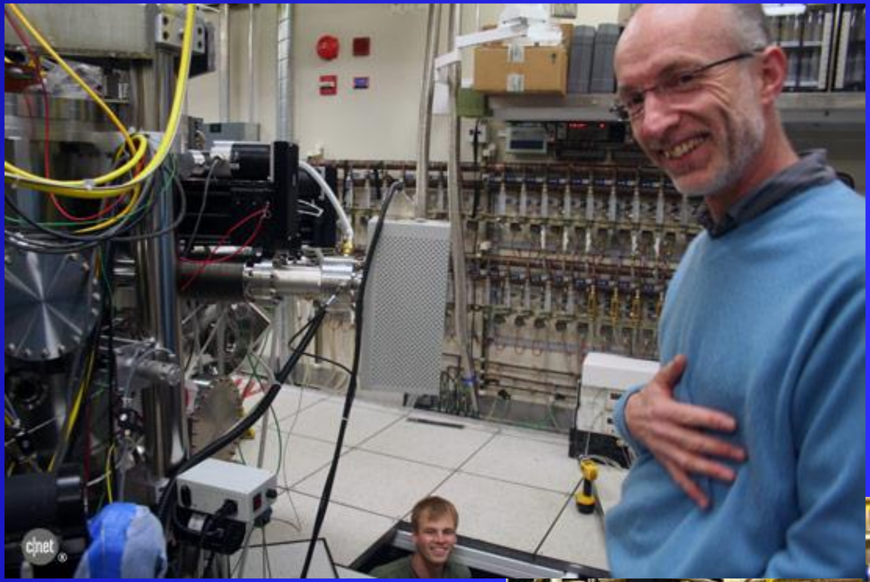


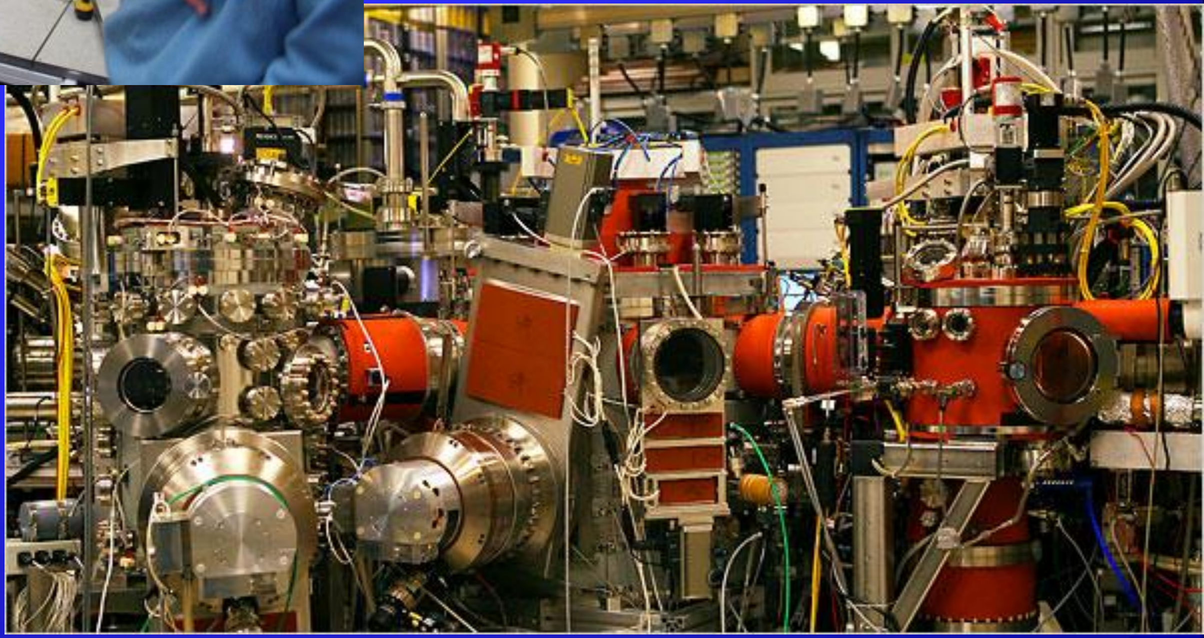


www.nobelprize.org

Phys. Rev. Lett. 61, 2472 (1988); Physical Review B 39, 4282 (1989)

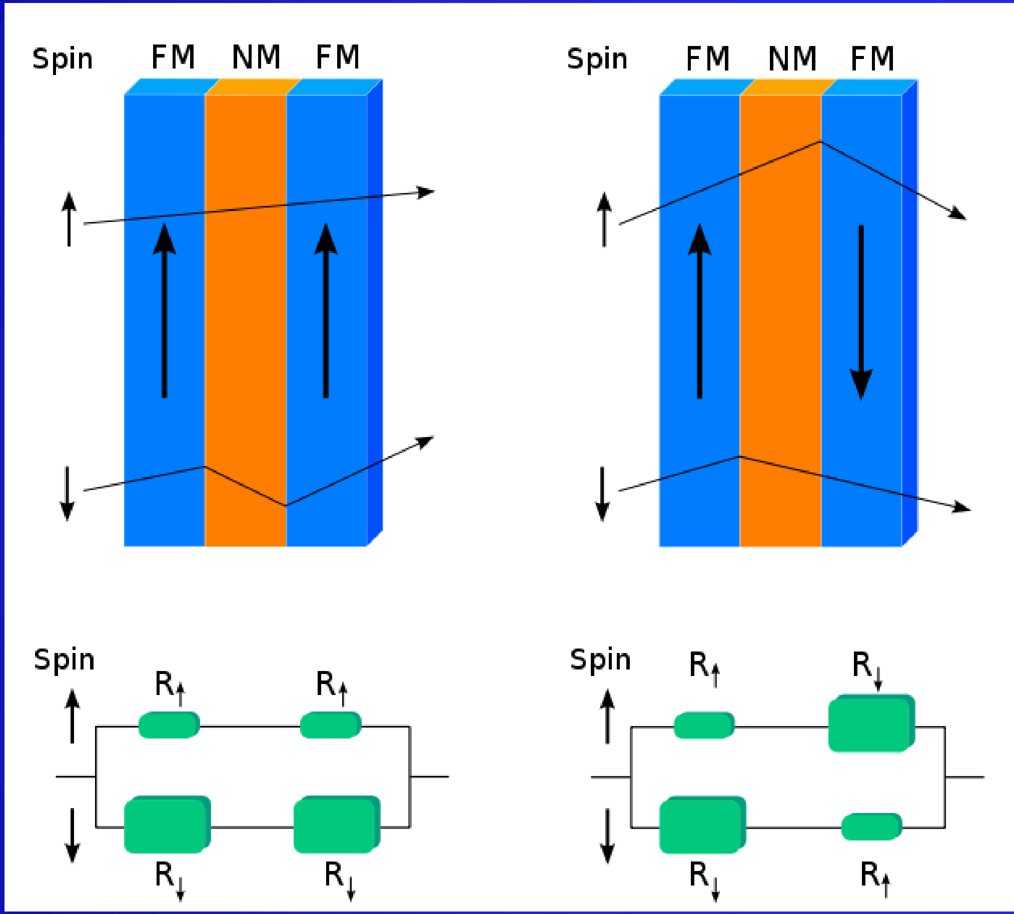
Stuart Parkin and IBM:
Understanding and Maximizing Effect for Application

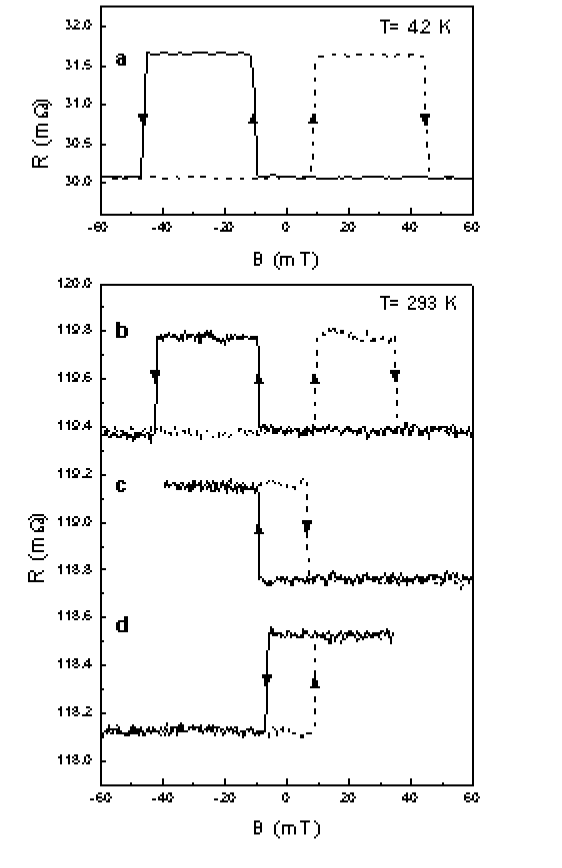




nytimes.com

Major Step: Invention of Spin Valve





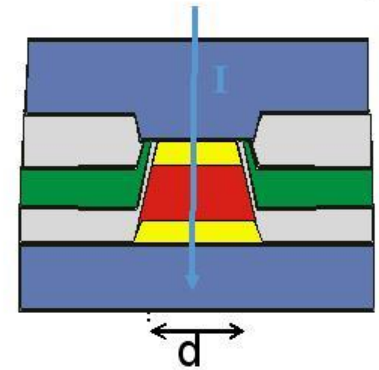
Dieny, Parkin (IBM)

rug.nl

Major Step: Current Perpendicular to the Plane (CPP) GMR

Jack Bass, William Pratt, Peter Schroeder
Michigan State University

CPP (Current Perpendicular to sensor Plane)



Area $A \sim d^2$

$R_{SENSOR} = R_j\ (\Omega\text{-}\mu m^2) / A$

Zdnet.com

IEEE TRANSACTIONS ON MAGNETICS, VOL. 34, NO. 4, JULY 1998 939

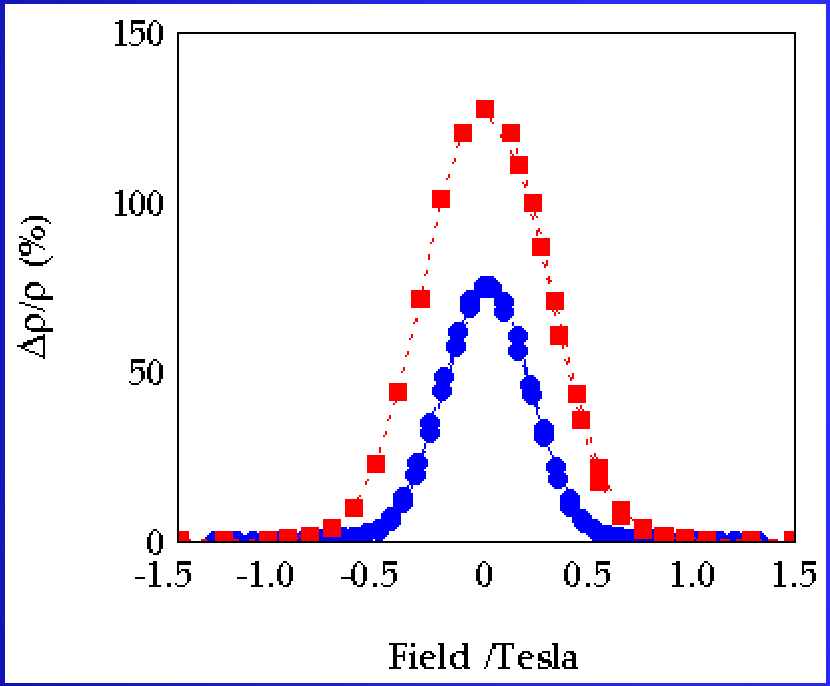
Giant Magnetoresistance of Current-Perpendicular Exchange-Biased Spin-Valves of Co/Cu.

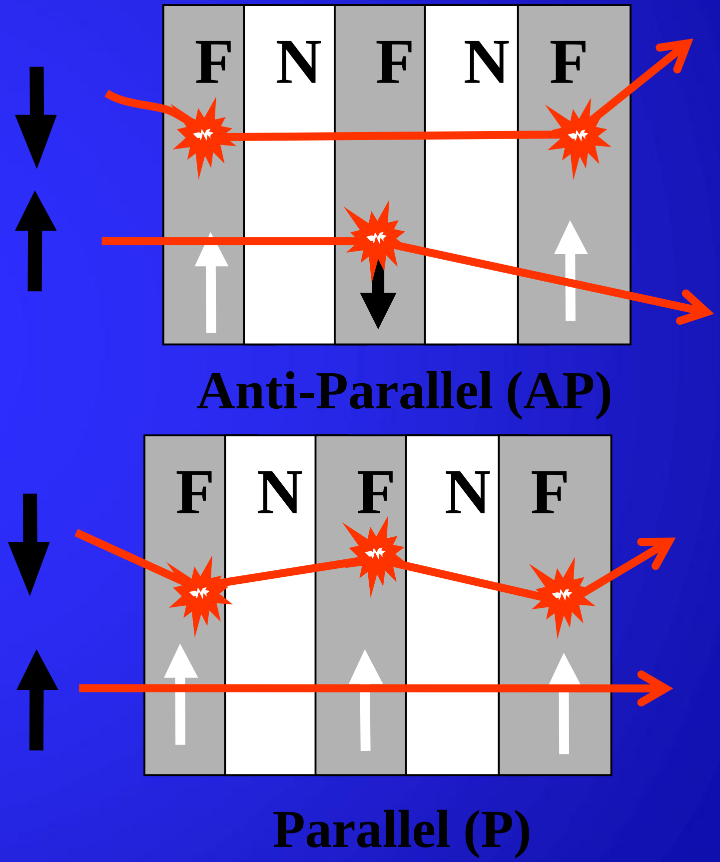
A. C. Reilly, W.-C. Chiang, W. Park, S. Y. Hsu*, R. Loloee, S. Steenwyk**,W. P. Pratt, Jr., J. Bass,

Department of Physics and Astronomy, Center for Fundamental Materials Research, and NSF MRSEC Center for Sensor Materials, Michigan State University, East Lansing, MI 48824-1116.
*Present Address: Department of Electrophysics, National Chiao Tung University, Hsinchu, Taiwan
**Permanent Address: Physics Department, Calvin College, Grand Rapids, MI 49546

Source of GMR: Spin Dependent Scattering

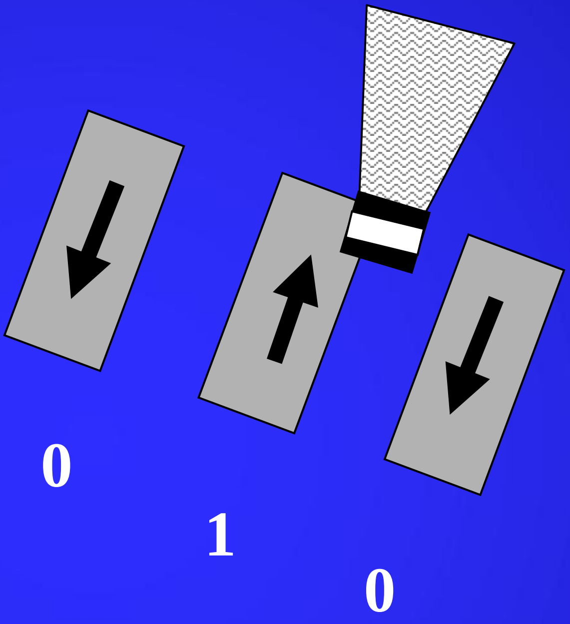
ρ↓ > ρ↑ in ferromagnetic element metals





Applications:
Computer Hard Drive Read Sensors

How your hard drive stores data



U 01010101
H 01001000
C 01000011
L 01001100

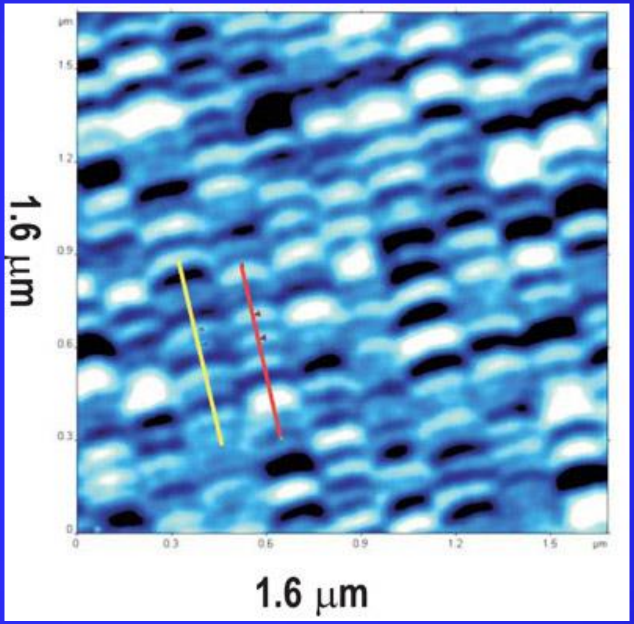
Binary code

With more sensitive sensors,

bits can get smaller = higher storage density

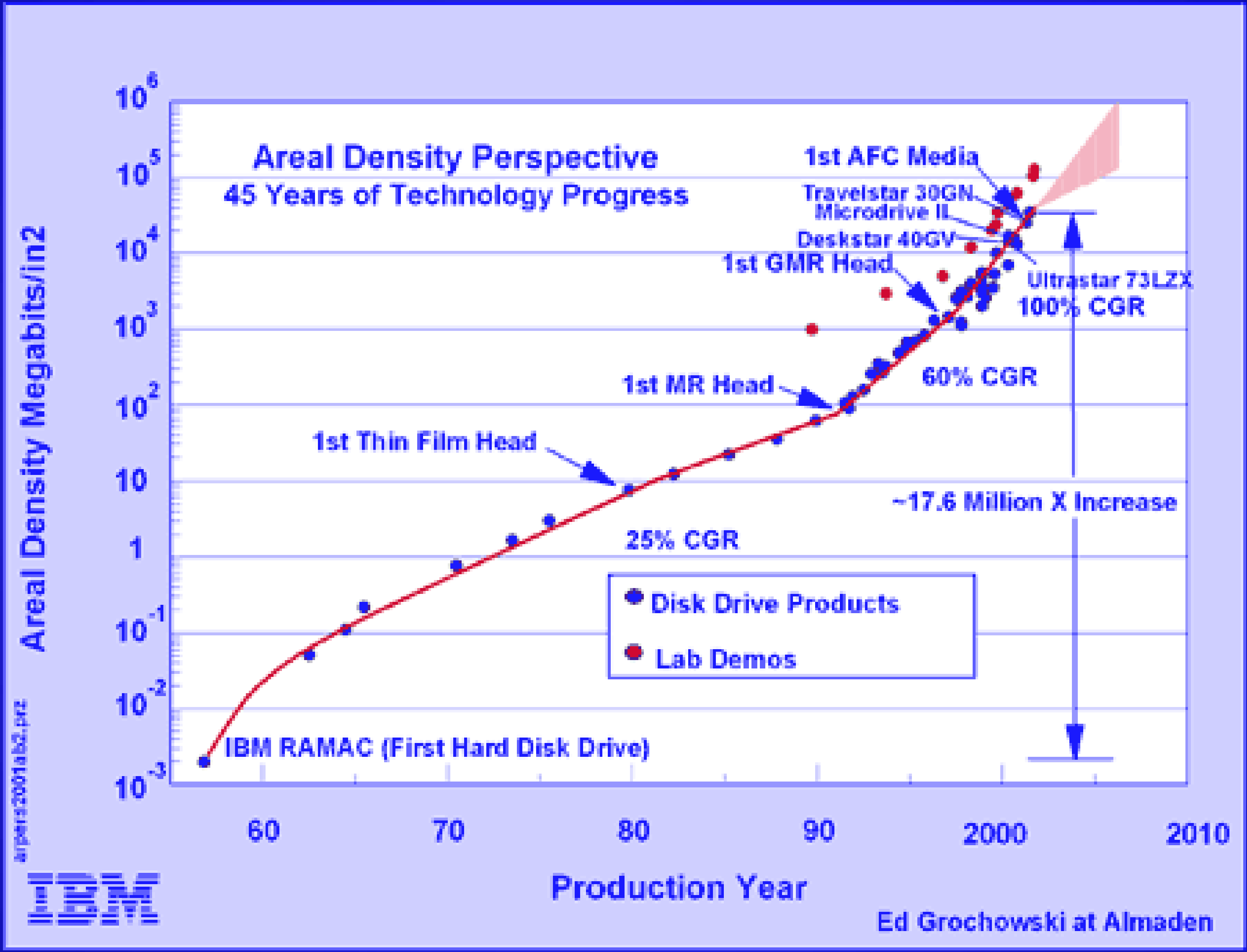
How your hard drive stores data

www.dmphotonics.com



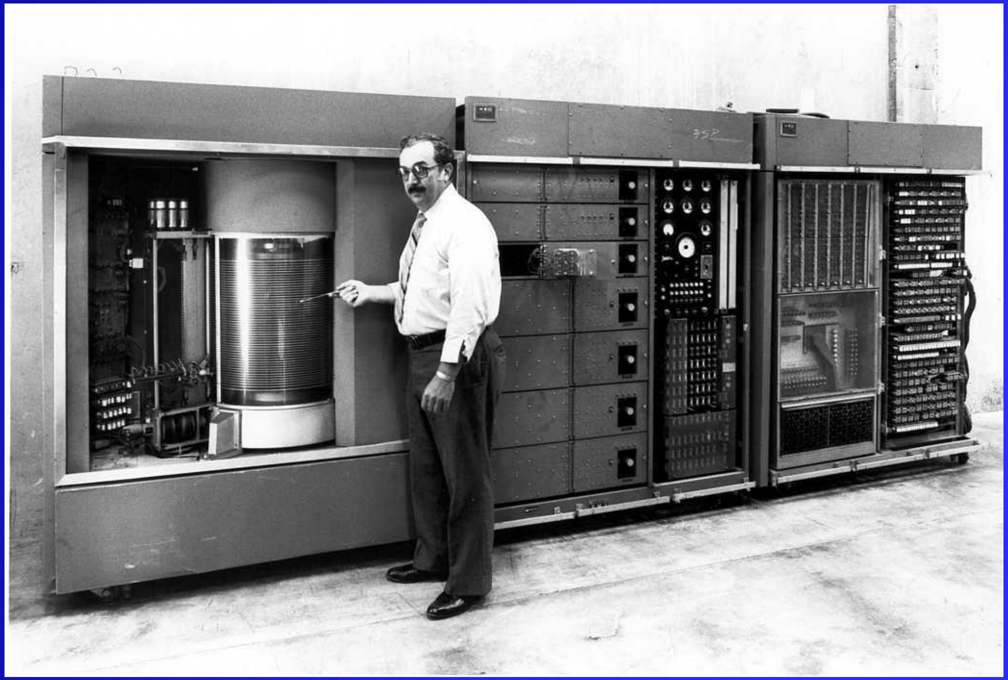
High resolution MFM image of Seagate Barracuda 750Gb Hard Drive, ST3750640AS

Evolution of the Hard Drive



Evolution of the Hard Drive

IBM 305 RAMAC, 1956



4.4 MB = 50 24-inch diameter disks.
Leased $3200 month

Evolution of the Hard Drive

2004: GB on the size of a quarter!

Links to See:

http://www.research.ibm.com/research/gmr.html

http://nobelprize.org/mediaplayer/index.php?id=797

The End… Questions?