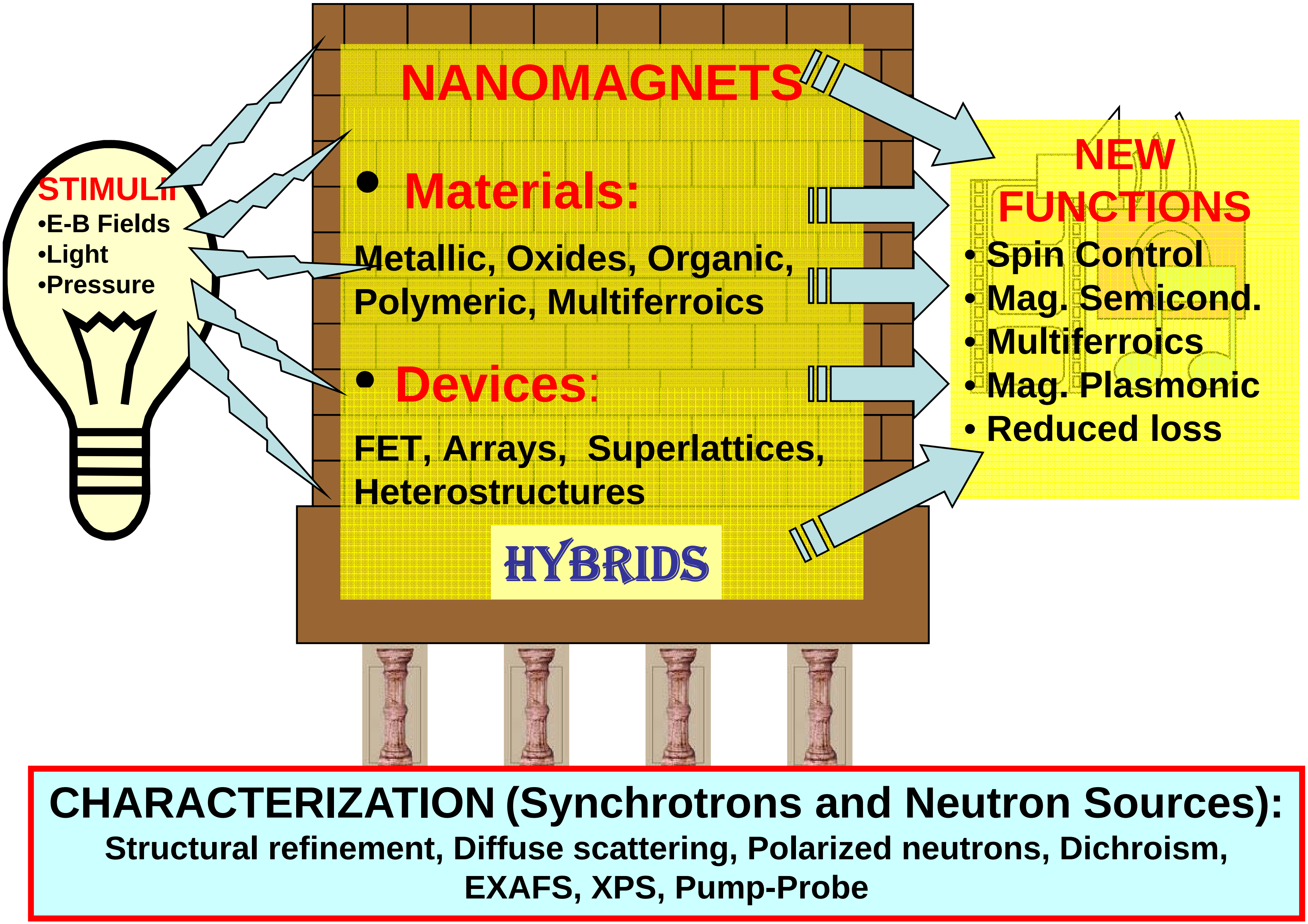
INTRODUCTION

ACS Nano January 2008

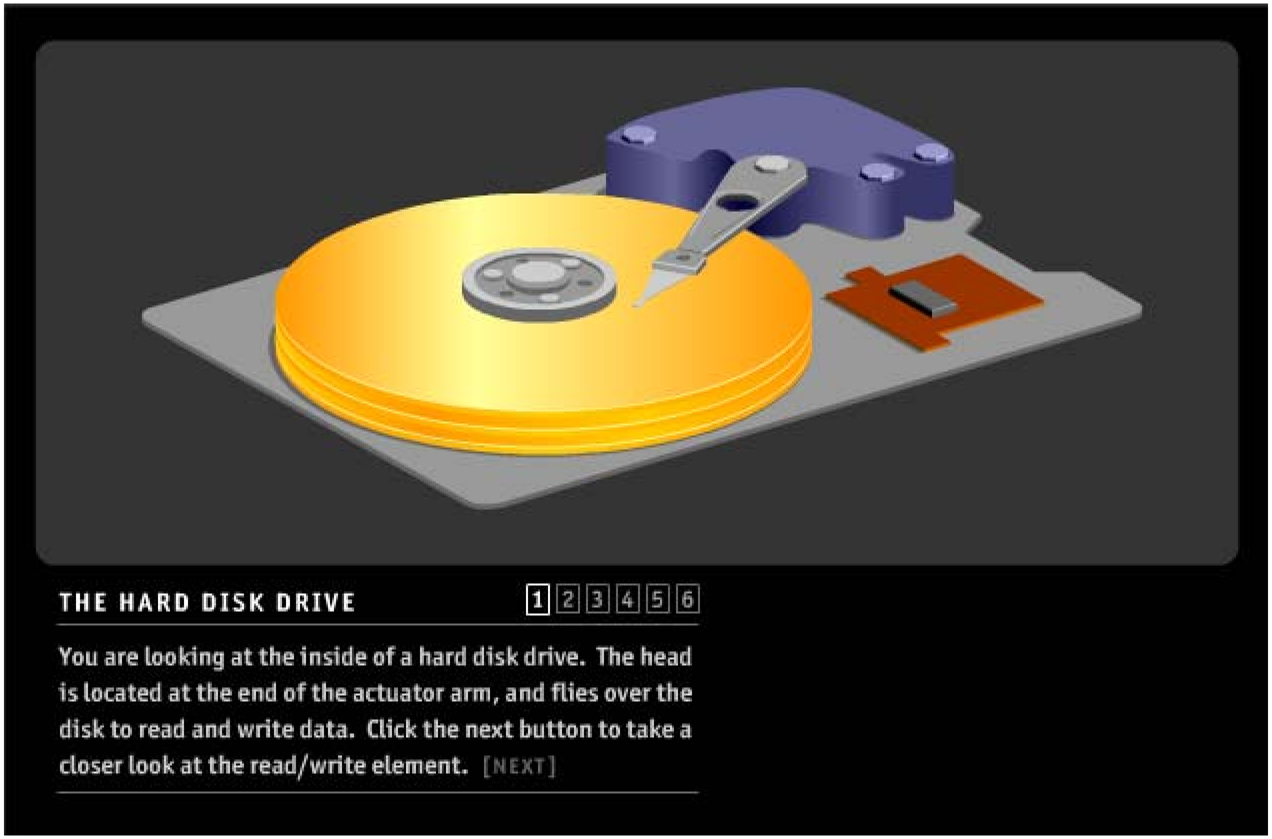
E. E. Fullerton and IKS


STIMULII
•E-B Fields
•Light
•Pressure
NANOMAGNETS
• Materials:
Metallic, Oxides, Organic, Polymeric, Multiferroics
• Devices:
FET, Arrays, Superlattices, Heterostructures
HYBRIDS
NEW FUNCTIONS
• Spin Control
• Mag. Semicond.
• Multiferroics
• Mag. Plasmonic
• Reduced loss
CHARACTERIZATION (Synchrotrons and Neutron Sources):
Structural refinement, Diffuse scattering, Polarized neutrons, Dichroism, EXAFS, XPS, Pump-Probe

2007 NOBEL PHYSICS

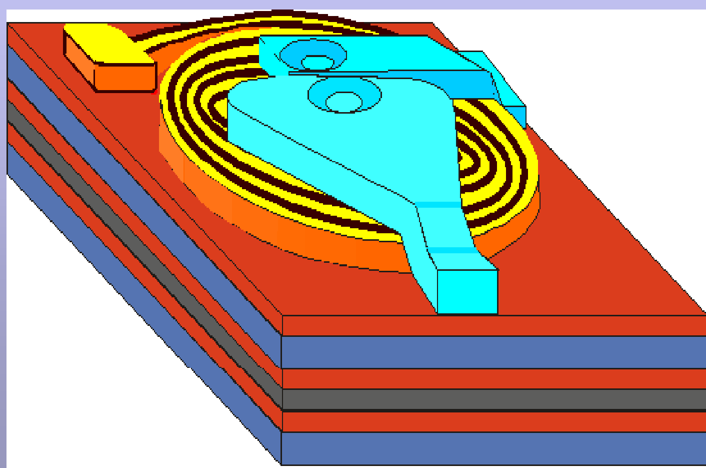
Grunberg

Fert



YOU USE IT

Read Head



iPOD

Basic Research
Where?

HISTORY

WHY DO ALL THIS ?

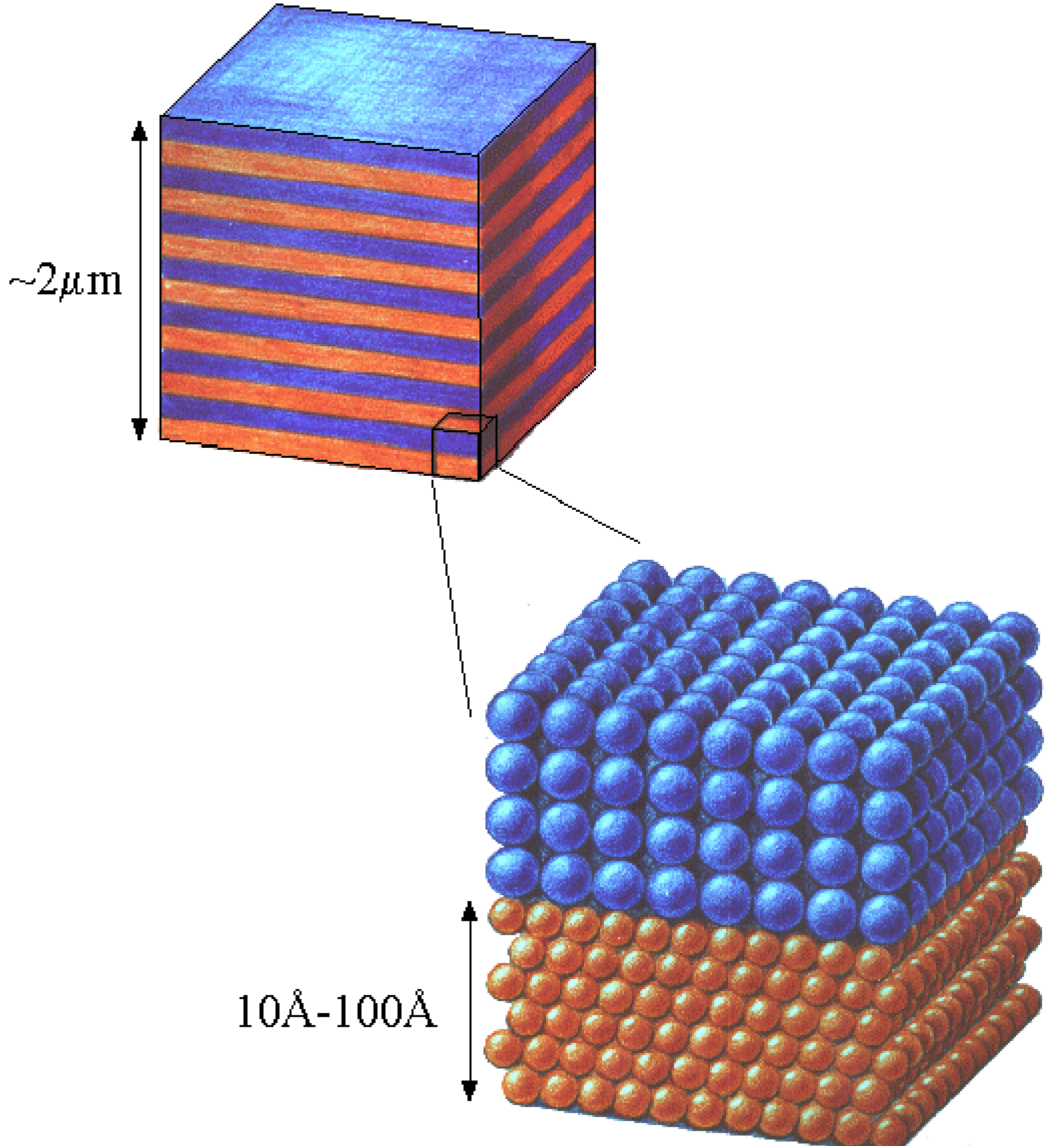
Many layers, N — Superlattice effects

Three layers — Coupling; Dimensional transitions; Spin Transmission

Two layers — Interfaces; Electron transfer; Strains; Negative pressure; Proximity effects

One layer — Disorder; Confinement; Lower dimensionality

SCIENCE DRIVEN RESEARCH



I.K.Schuller, Phys.Rev.Lett. 44, 1597(1980)

AIP Conference Proceedings
Series Editor: Hugh C. Wolfe
Number 53

MAGNETO-TRANSPORT

Modulated Structures—1979
(Kailua Kona, Hawaii)

Editors
J.M. Cowley, Arizona State University
J.B. Cohen, Northwestern University
M.B. Salamon, University of Illinois
B.J. Wuensch, Massachussetts Institute of Technology

American Institute of Physics
New York 1979

magnetoresistance shows anomalous behavior......

~ 20 %   MR

Giant MagnetoResistance- GMR

resistance is quadratic at low fields and then linear up to 70 kG. On the other hand the Hall coefficient (Figure 5) of all three samples is typical of that observed in pure nickel.[3,5,6,7]

In summary, we have measured the electric transport properties of Cu/Ni compositionally modulated alloys. The electrical resistivity and the magnetoresistance show anomalous behavior as a function of modulation amplitude. On the other hand, the thermopower and Hall coefficient show typical behavior of a ferromagnet. More detailed measurements are presently underway in order to clarify these points and their relationship to the anomalous elastic and magnetic properties.

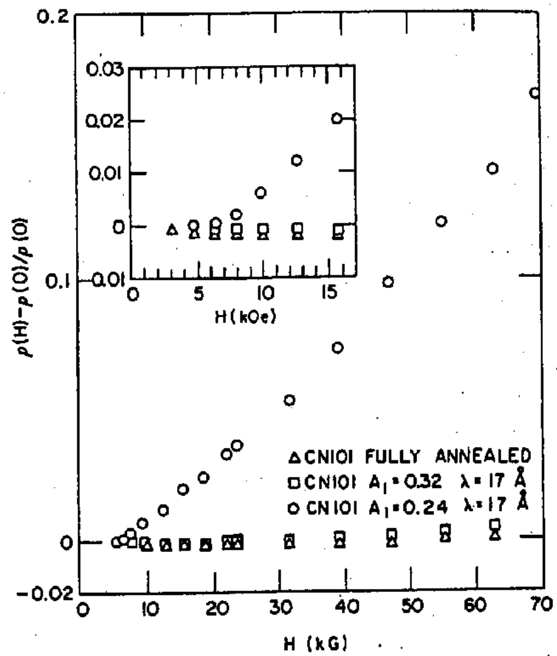
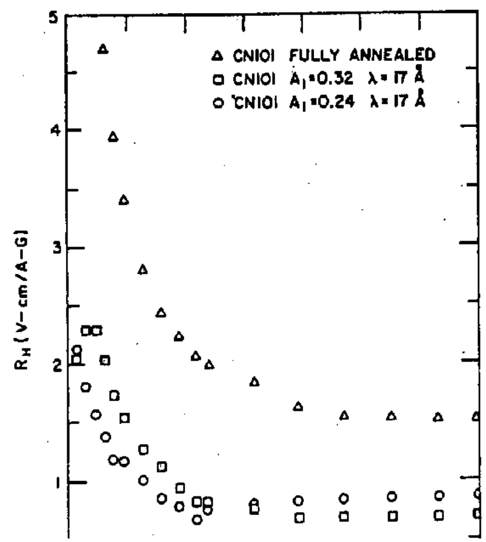


Fig. 4. Transverse magnetoresistance versus magnetic field. The inset shows in detail the low field behavior.



MAGNETIC COUPLING

Physica 108B (1981) 953-954
North-Holland Publishing Company

OD 6

INTERPLANAR MAGNETIC COUPLING IN Cu/Ni COMPOSITION MODULATED ALLOYS

Wen-Sheng Zhou,[†] H.K. Wong, J.R. Owers-Bradley and W.P. Halperin[‡]

Department of Physics and Astronomy and Materials Research Center
Northwestern University, Evanston, Illinois 60201

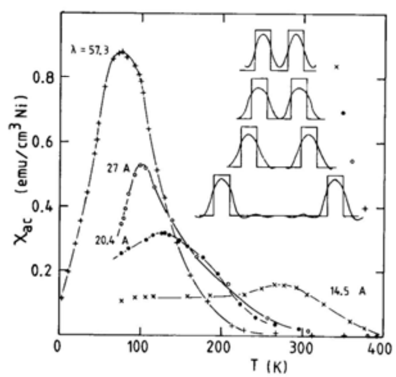
Measurements of the ac susceptibility of composition modulated structures of Cu/Ni have been performed as a function of temperature and magnetic field. A magnetic transition is clearly defined by a peak in the temperature dependence of the ac susceptibility. The peak temperature increases approximately linearly with increasing nickel plane thickness and decreases as the cubic power of the composition modulation wavelength.

There has been considerable interest recently[1-6] in composition modulated structures (CMS) both of semi-conductors and of metals. Two metals with suitably close lattice constants and the same crystal structure can be grown by alternate evaporation or sputtering techniques into thick films with excellent texture and a strong periodic variation in the composition, normal to the plane of the film. Layered metal films Au/Ni, Cu/Pd, Cu/Ni, Pd/Ag have shown startling enhancement[1] in the biaxial elastic modulus for particular composition periodicities. Enhancement in the magnetization of Cu/Ni structures above that of pure Ni was reported by Thaler et al.[2] which stimulated more extensive investigations[3-6] of the Cu/Ni system. This more recent work including electron-band theory, magnetization and neutron scattering experiments concur that there is no enhancement in the magnetization of Ni in Cu/Ni CMS and that likely the ferromagnetic resonance measurements of Thaler et al.[2] should be interpreted in terms of a large surface anisotropy constraining the magnetization to be in the plane of the film. Magnetization measurements[3] do not find evidence for superparamagnetism or magnetic clusters less than 10 x 200 x 200 (A). Other experiments[5,6] have been interpreted in terms of magnetic clusters but no magnetic experiments[3,5,6] have shown effects attributable to the composition modulation itself.

In this brief report we discuss our measurements of the low field ac susceptibility of Cu/Ni films where we have discovered a strong dependence of the magnetic transition temperature of the wavelength λ of the composition modulation.

The Cu/Ni samples were prepared using a dual electron-beam-gun system with a reciprocating shutter in vacuum of $\sim 10^{-6}$ torr. Evaporation was performed onto a cleaved mica substrate regulated near 300°C. The films were removed from the substrate and characterized by X-ray diffraction analysis before susceptibility measurements were conducted with the probe coil axis in the plane of the film. Measurements were taken from 1 K to 500 K at a frequency of 200 Hz and amplitude of 1 mT using a sample extraction technique. Some measurements were taken in magnetic fields up to 0.2 T.

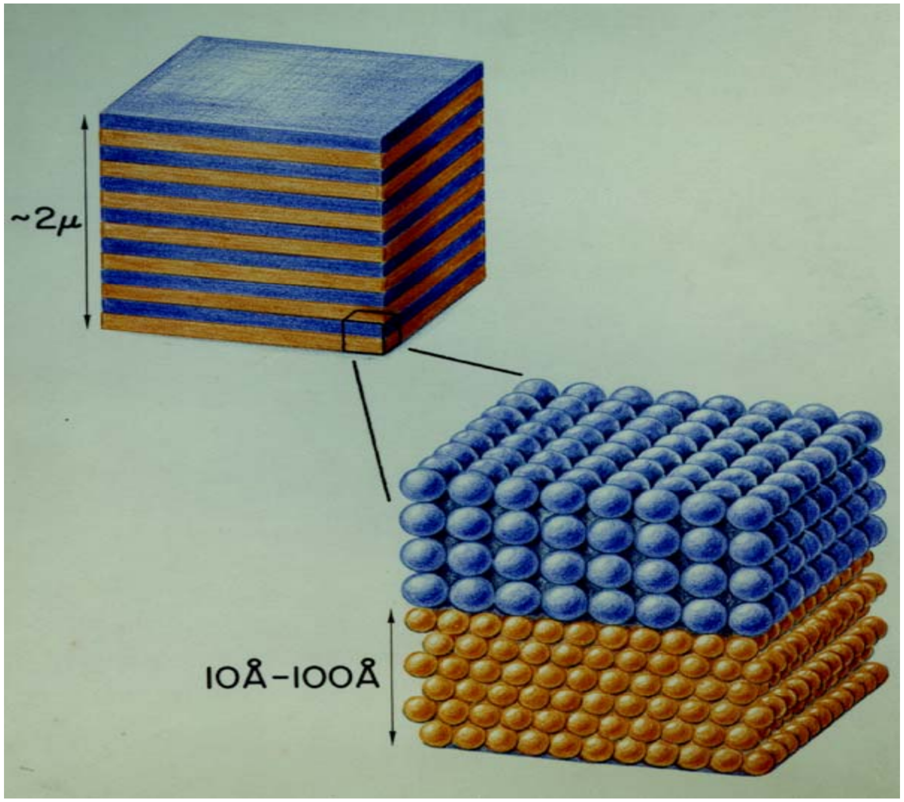
Our films can be thought of as having very strong nickel-rich planar regions, typically 80%, of thickness t_{Ni} separated by a thickness of copper, determined by λ the modulation wavelength. Standard X-ray diffraction experiments show a large Bragg peak skirted by satellites whose spacing fixes λ. Fourth order satellites were frequently observed and all of the satellite intensities are used[7] to determine the composition profile, Fig. 1. In this fugure the rectangular wave is the shutter waveform which sets the scale of Ni composition as displayed in the figure between zero and 100%. The composition as displayed in the figure between zero and 100%. The composition profiles found by X-ray experiments are shown superimposed. Four representative data sets are presented in the figure showing a clear signature of a magnetic transition through a peak[8] in the ac susceptibility as a function of temperature. We have intentionally construc-



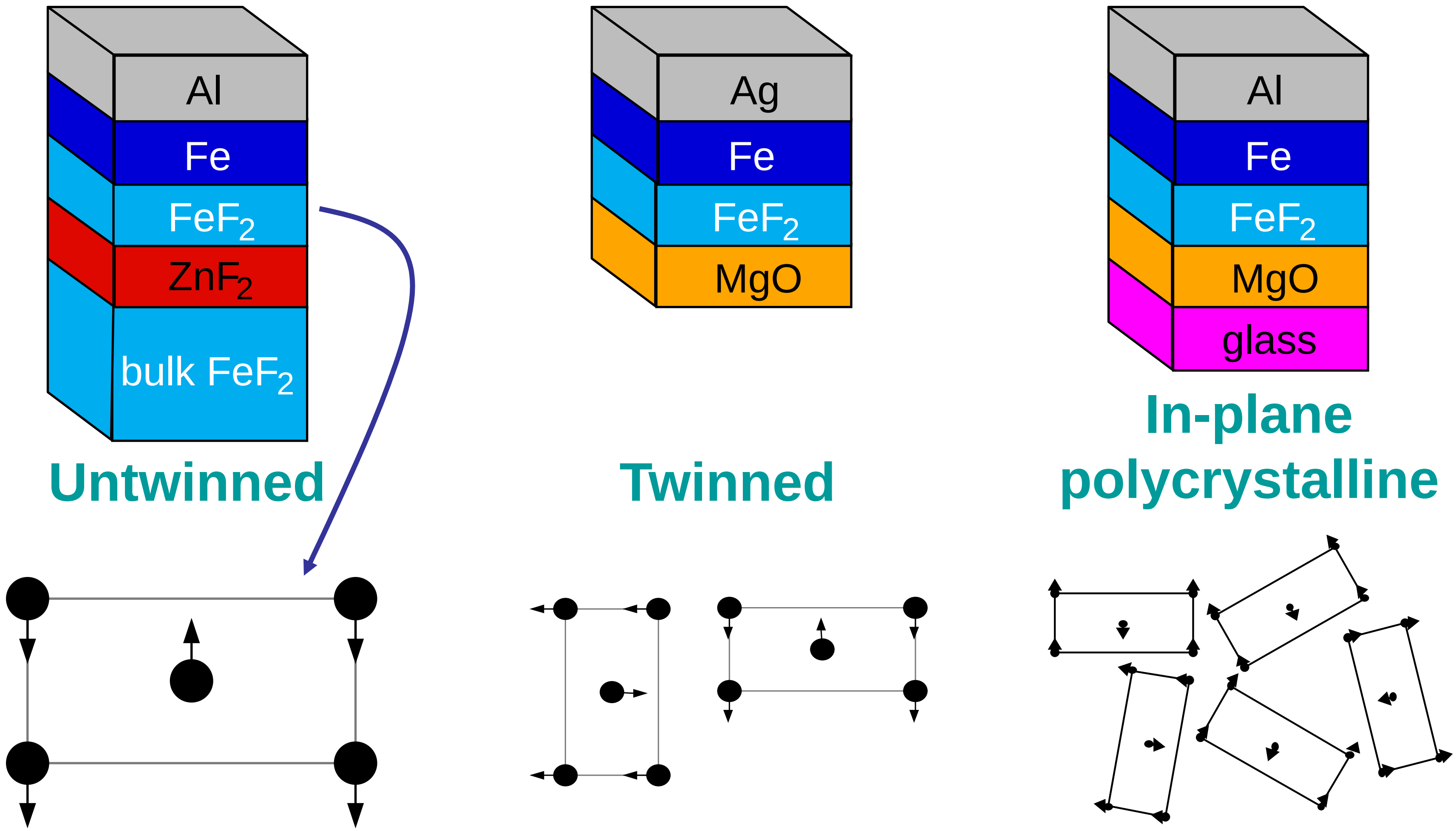
The ac susceptibility is presented as a function of temperature for four Cu/Ni CMS for which the composition profiles are shown adjacently and explained in the text.

STRUCTURE

Superlattice

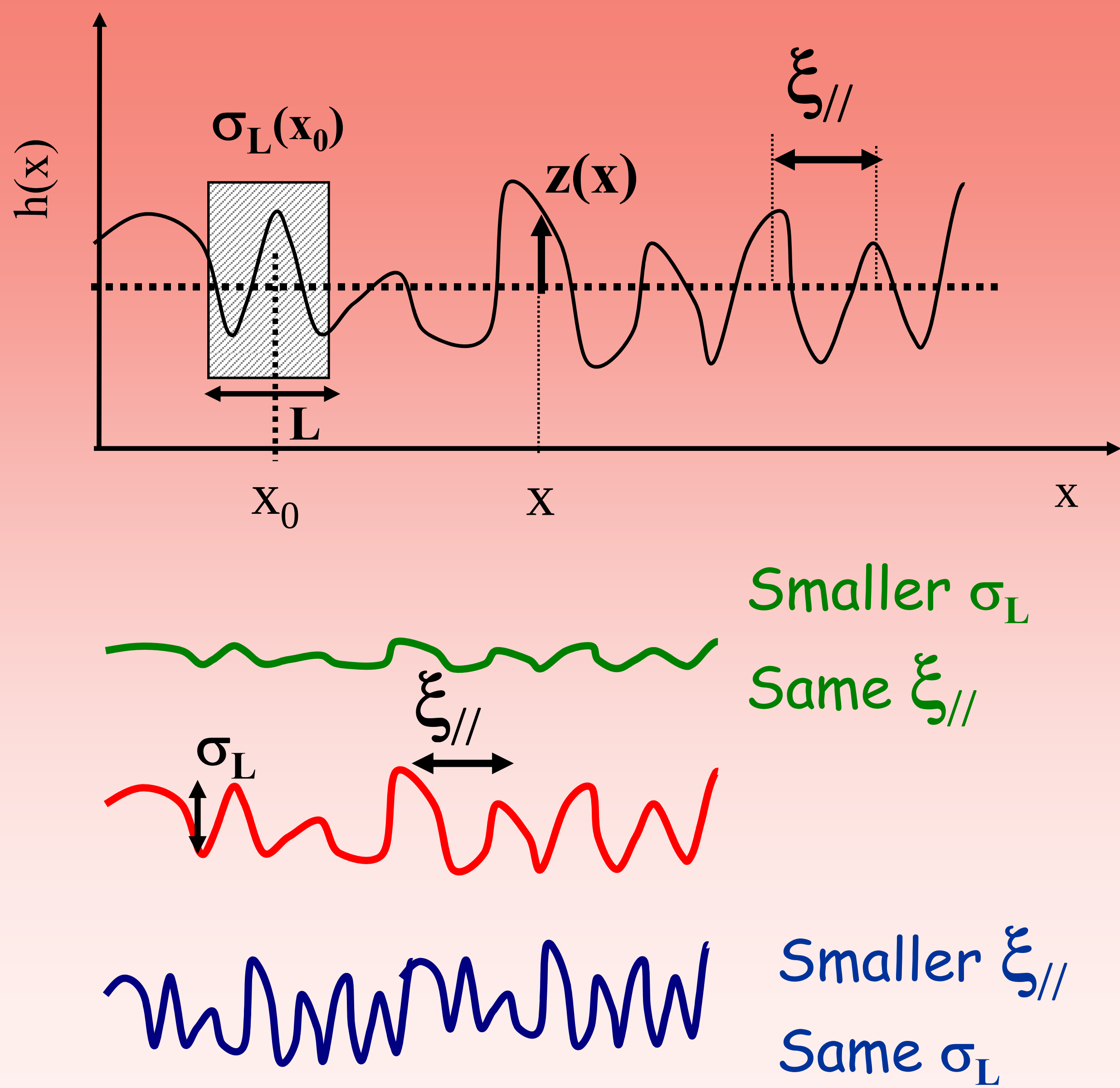


Structure-Complicated



110 FeF_2

Interfaces



$\xi_{//}$
$\sigma_L(x_0)$
z(x)
h(x)
L
x_0
x
x
Smaller σ_L
Same $\xi_{//}$
$\xi_{//}$
σ_L
Smaller $\xi_{//}$
Same σ_L

SCATTERING

$$I = \mathcal{F}(r) \times \mathcal{F}^*(r)$$

Fourier Transform of Composition Profile

Structural

Chemical

Magnetic

Problem

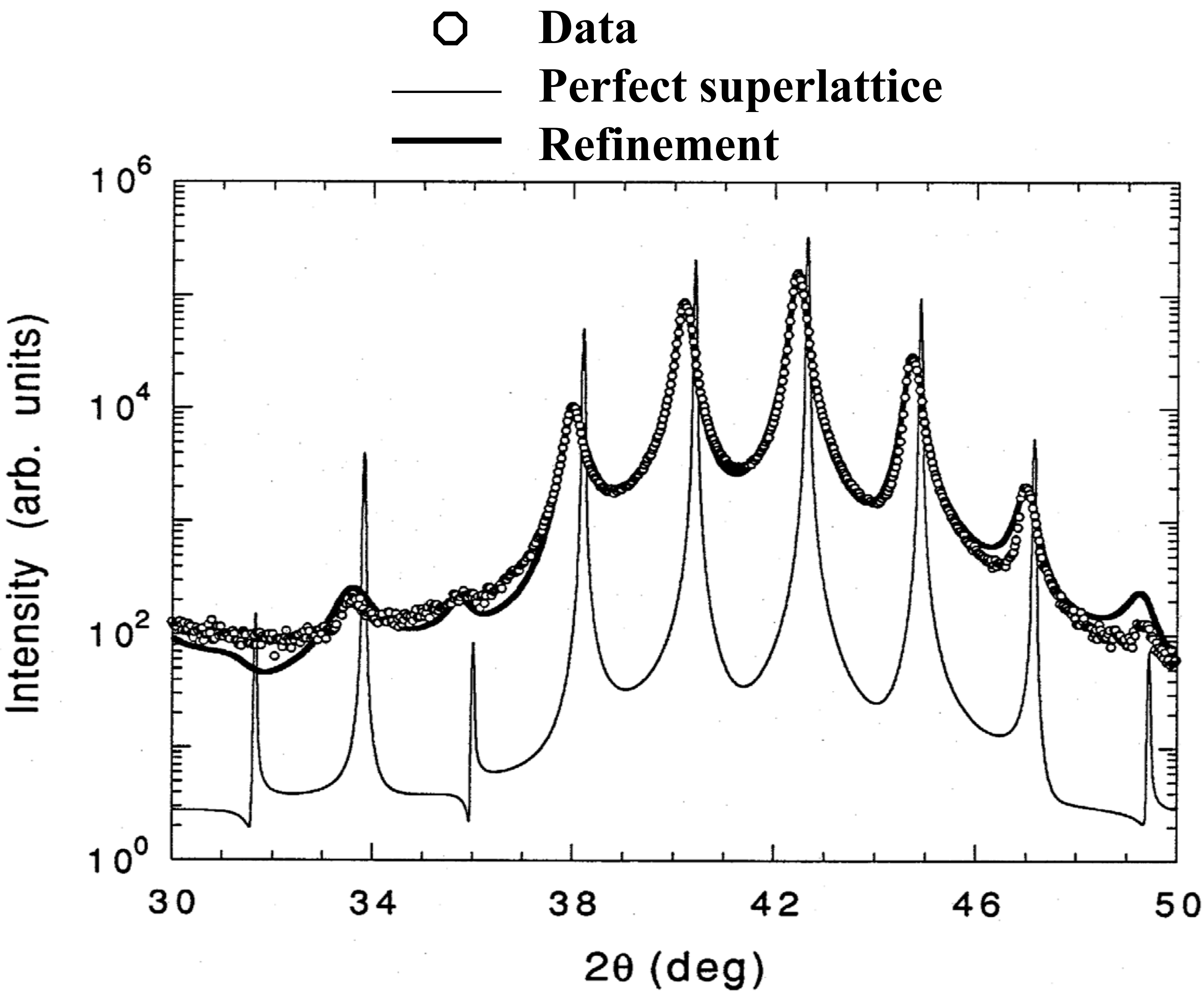
Phase lost: Inversion Impossible

Modeling Needed (**refinement**)

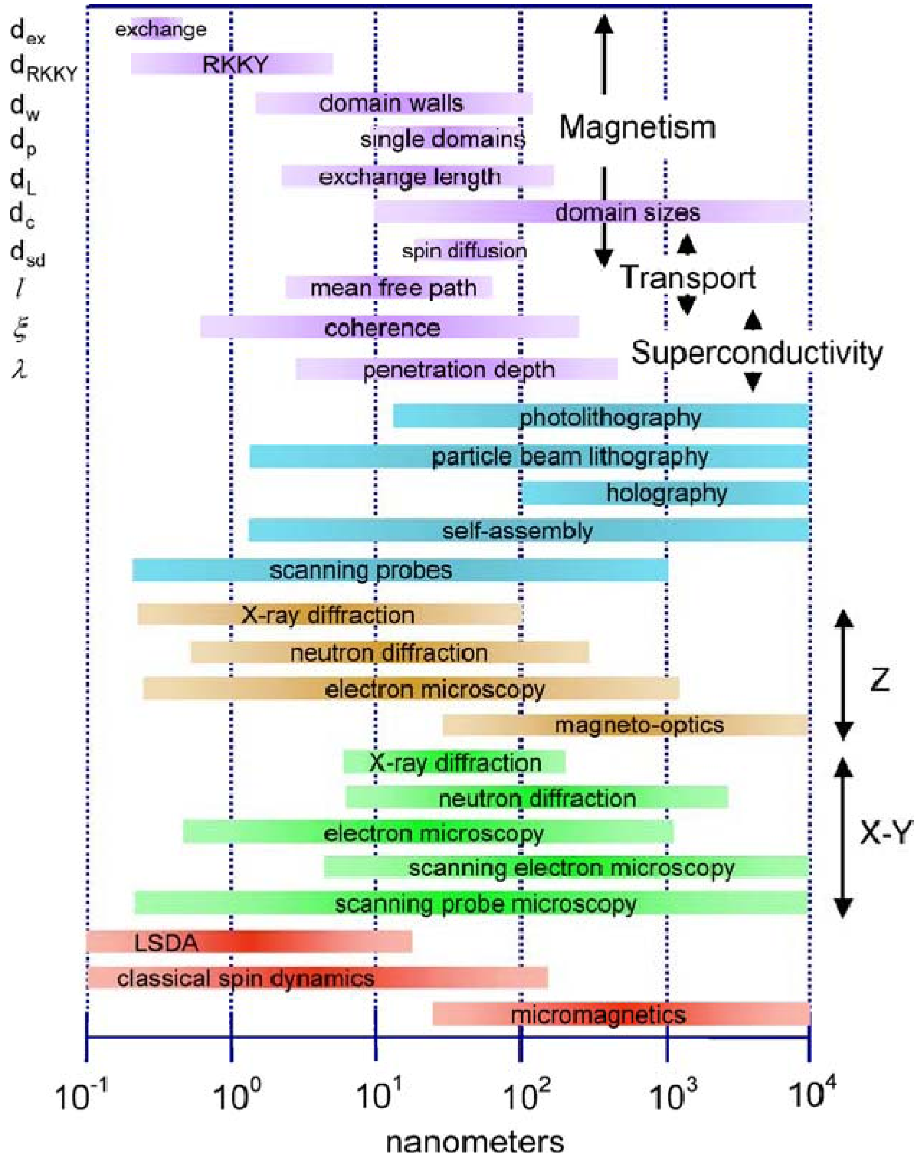
SUPREX at http://ischuller.ucsd.edu

E.E. Fullerton, I. K Schuller, H. Vanderstraeten, Y. Bruynseraede, Phys. Rev B45, 9292(1992)

REFINEMENT: Mo/Ni Superlattices



Scattering Techniques Measure All Relevant Phenomena in Nanomagnetism



Drivers of modern nanomagnetism research demand smaller, sensitive, and specific probes that can measure nanomagnetic structures whose physical dimensions compete with fundamental magnetic length-scales.

key length scales in magnetic structures, fabrication routes, scattering techniques and theory

-Length-scales relevant to different magnetic phenomena (purple)

-Nanofabrication techniques (blue)

-Tools suitable for probing magnetic structures across the thin dimension of a film (Z-structures) (brown)

-Tools that are applicable to studies of lateral inhomogeneities (X-Y plane) (green)

-Theoretical tools (red) are also available that can predict magnetic properties of nanometer-scale structures.

CAPABILITIES

Capability	Neutrons	Synchrotron	Electron Micr	Scanning Probe
Magnetic structure	🙂	☺☺	🚫	🙂
Element specificity	🚫	🙂	☺☺	☺
Isotope sensitivity	🙂	☺	🚫	🚫
Energy tuning	🚫	🙂	☺☺	🚫
Inelastic	🙂	🚫	☺	🚫
Intensity	☺	🙂	☺☺	☺
Time dependence	☺☺☺	🙂	🚫	🚫

SAMPLE VIEWPOINT

Sample	Neutrons	Synchrotron	E- microscopy	Scanning Probe
Destructive	🙂	☺☺	🚫	🙂
Smallest size	☺	🙂	☺☺	🙂
Homogeneity	☺	🙂	🙂	☺☺
Environment	🙂	🙂	🚫	☺
Heating	🙂	🚫	🙂	🙂
Interfaces	🙂	☺	☺	🚫

STRUCTURE ISSUES

- Nothing is perfect
- Relevant length scales
- Limitations of characterization techniques

Interesting Physics and Applications
SPINTRONICS

Three layers

Coupling

Spin Transmission

Two layers

Interfaces

Proximity effects

PROXIMITY

- **Magnetic Proximity**

  Direct contact

•M. M. Kiwi and M. J. Zuckermann, in Magnetism and Magnetic Materials-1973 eds. R. E. Taylor and J. J. Rhyne, AIP Conf. Proc. No. 18, 1997, p347

•J. J. Akerman, I. Guedes, C. Leighton, M. Grimsditch, and I. K. Schuller, Phys. Rev B65, 104432, 2002

  Across a thin insulator

J. P. McGuire, C. Ciuti, L. J. Sham, Phys. Rev. B 69,115339(2004)

- **Exchange Bias**

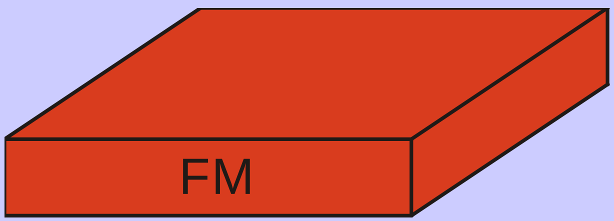
EXCHANGE BIAS

Ferromagnet coupled to

- Synthetic Antiferromagnet(SAF)
  (F-Ru-F)

- Antiferromagnet

EVERYTHING YOU WANTED TO KNOW ABOUT FERROMAGNETISM…….but …were afraid to ask



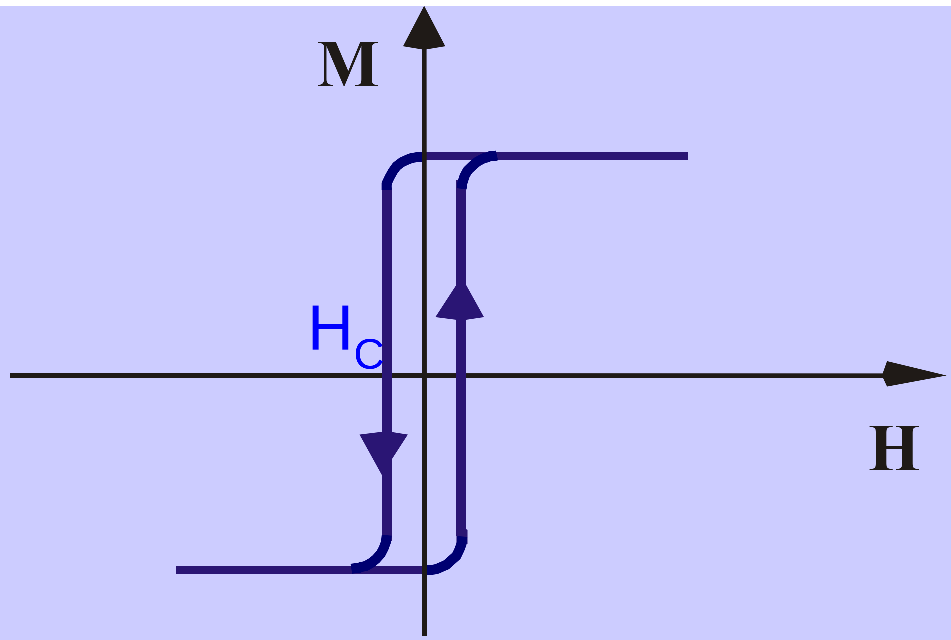
Free FM

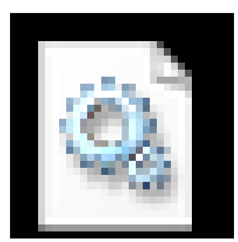
Small coercivity H_C

Exchange field H_E=0

Symmetric

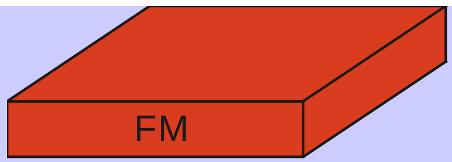
Uniform



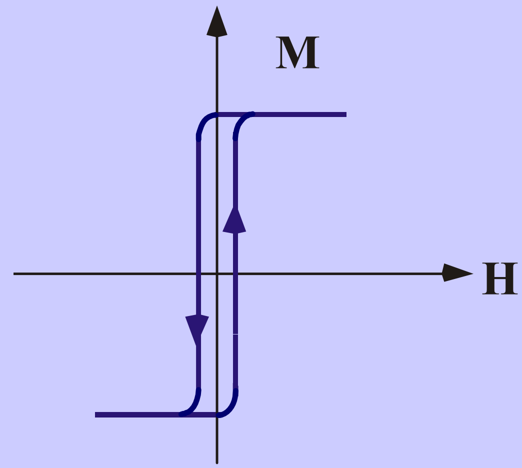


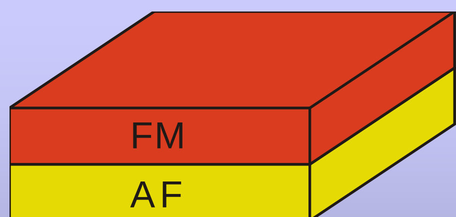
Reversal.exe

Exchange Bias

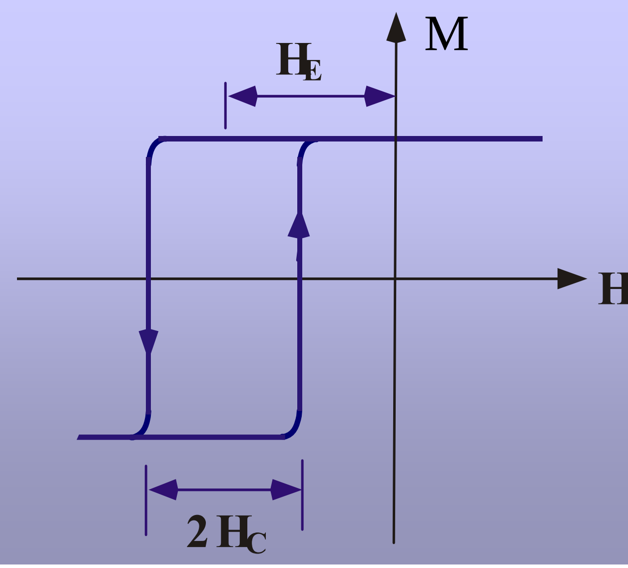


Free FM
Exchange field H_E=0
Small coercivity H_C
Symmetric
Uniform



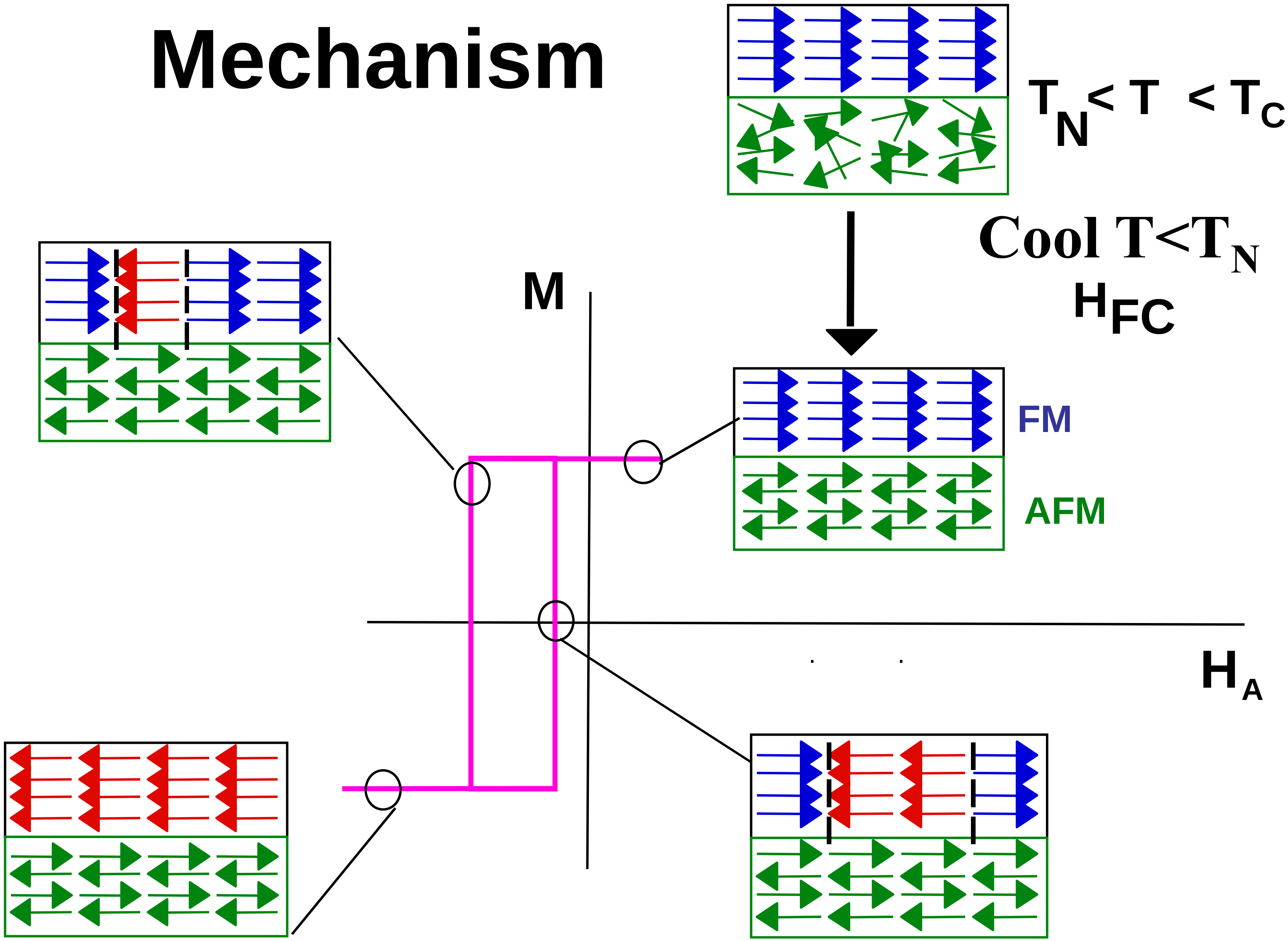


Pinned FM
Large H_E
Large H_C



Deceptively Simple

Mechanism

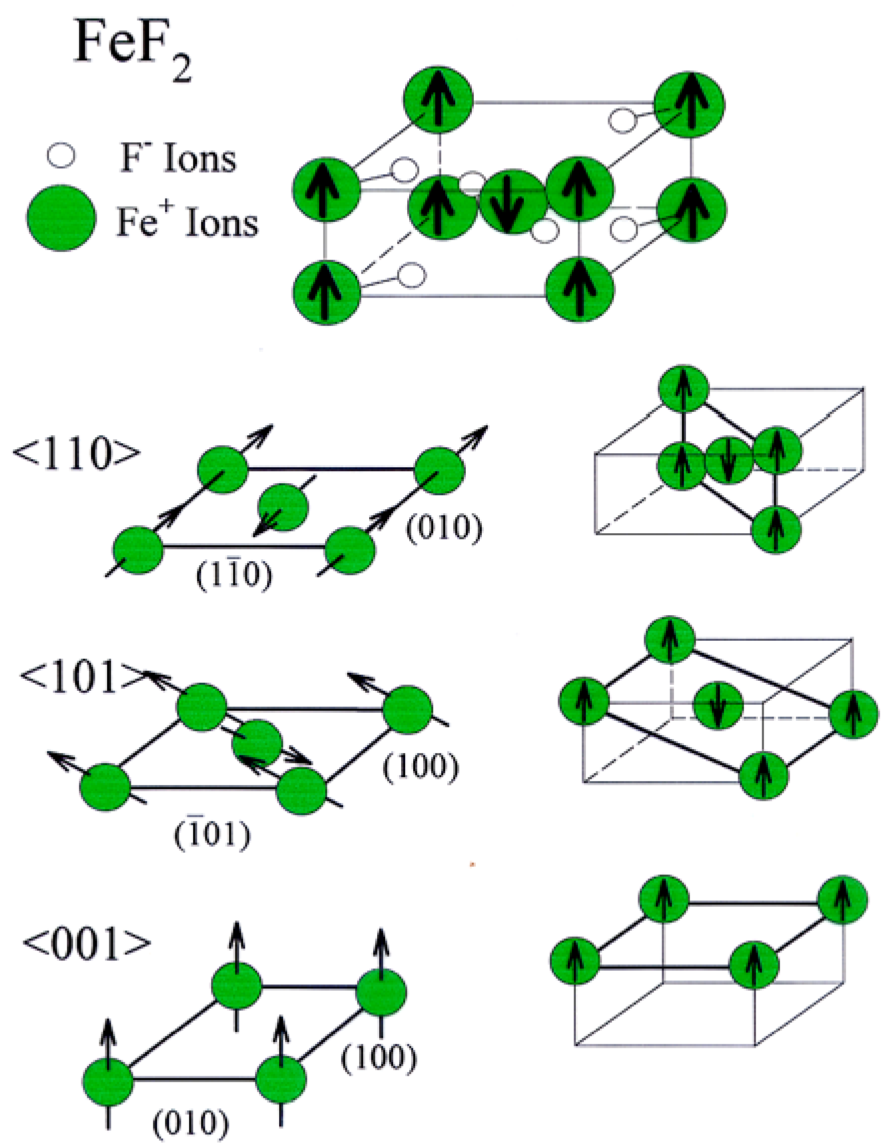


W.H. Meiklejohn, C.P. Bean, Phys. Rev., 105, 904(1957).

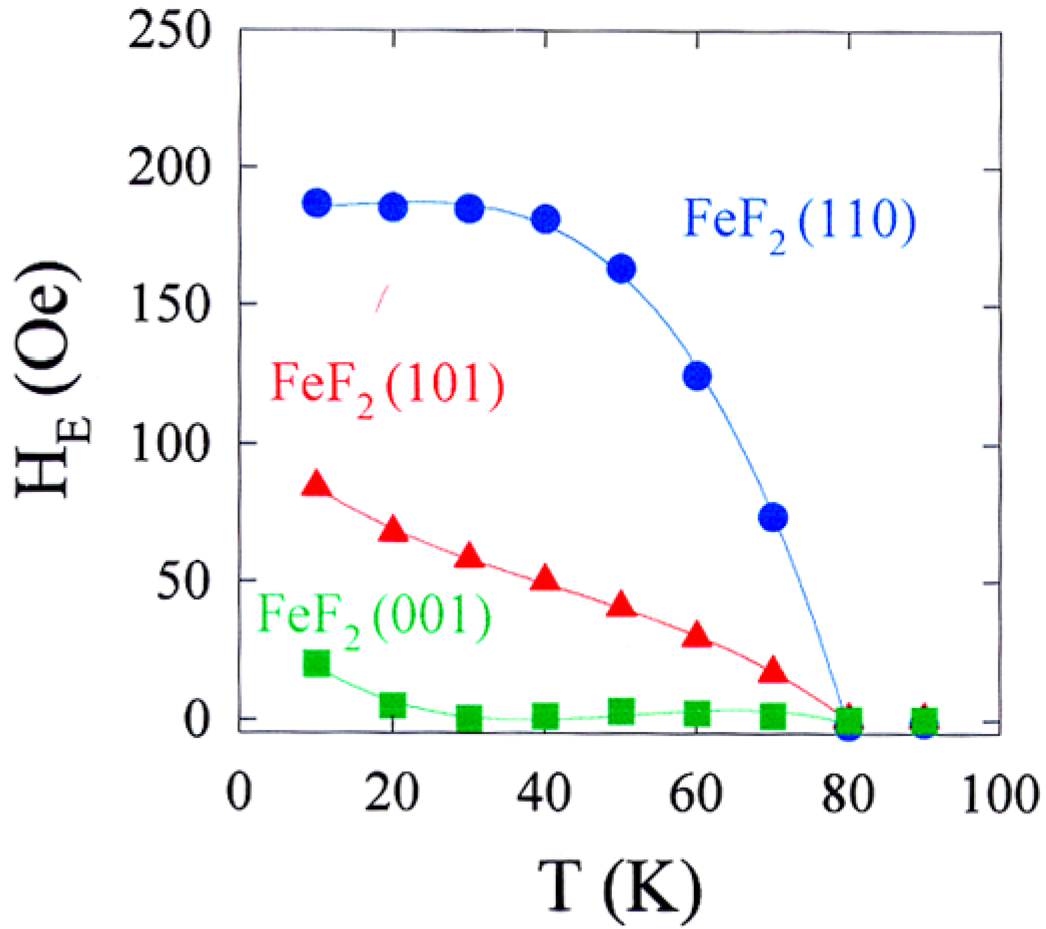
What to expect

- **Maximum Uncompensated Surfaces**
- **Zero for Compensated Surface**
- **Negative**
- **Reversal Symmetric**

CRYSTALLINE ORIENTATION

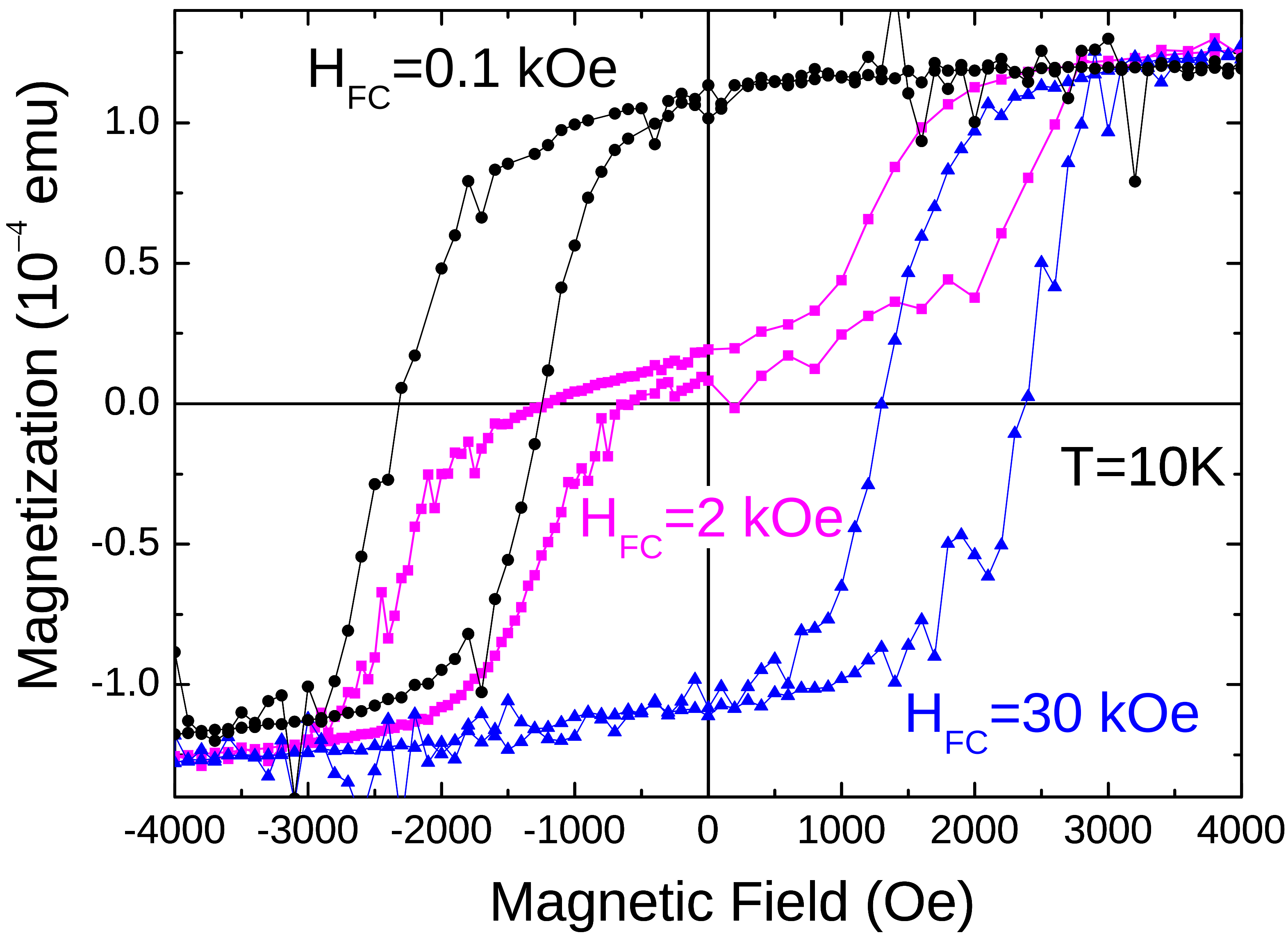


SURPRISE



250
200
150
100
50
0
0
20
40
60
80
100
H_E (Oe)
T (K)
FeF_2 (110)
FeF_2 (101)
FeF_2 (001)

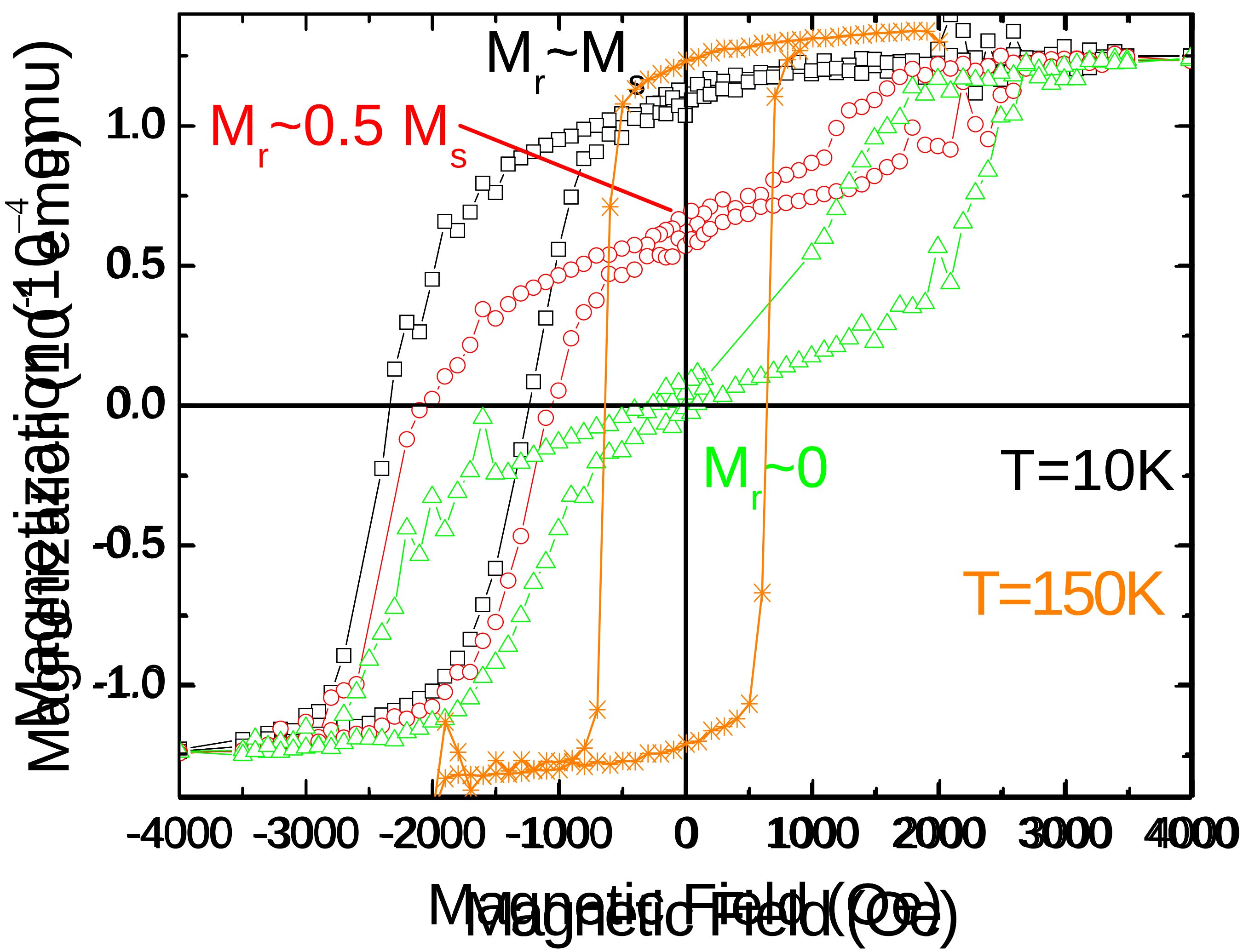
Field Cooling



(110)MgF_2/FeF_2(500Å)/Co(38Å)/Al(25Å)

Zero Field Cooling

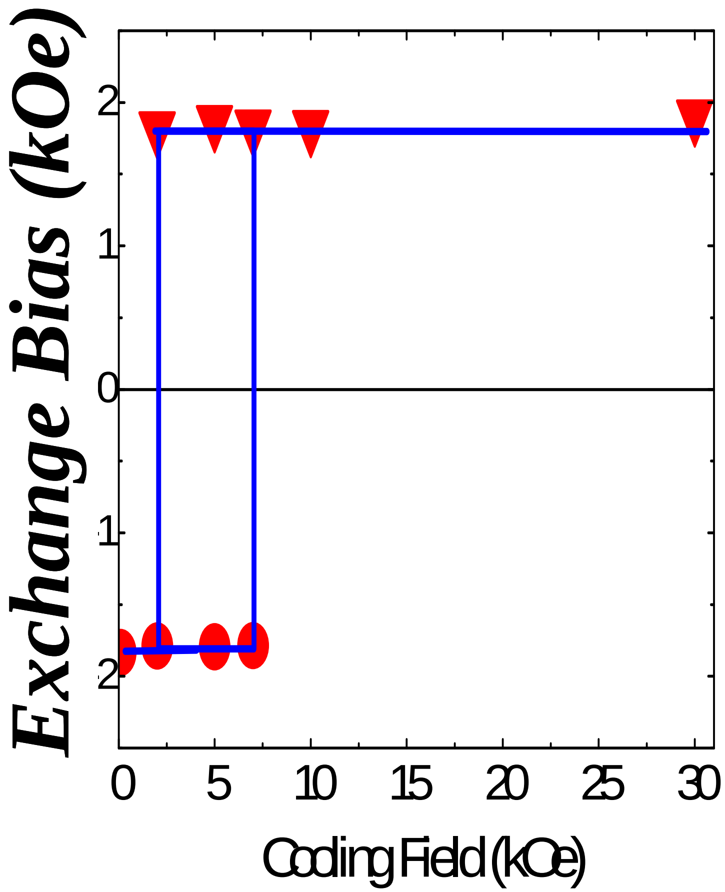
Imprinting Domains!

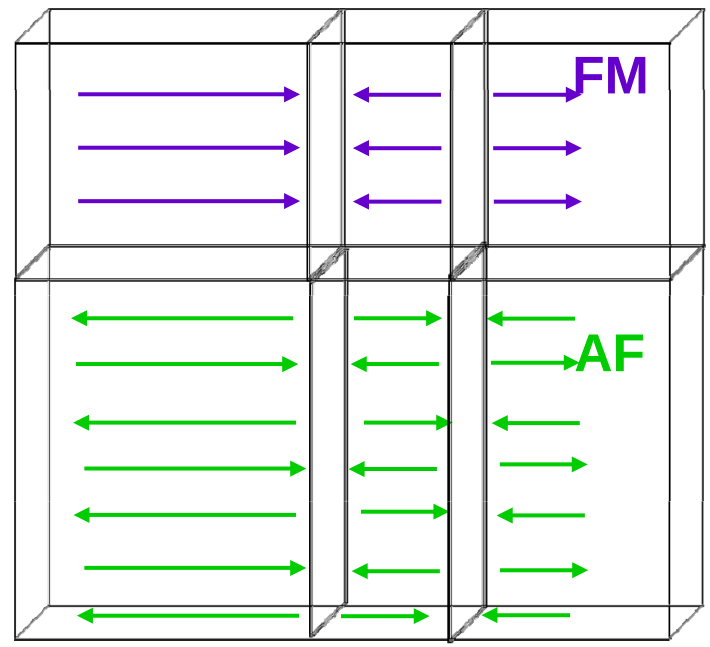


T_N = 78.4 K

(110)MgF_2/FeF_2(500Å)/Co(38Å)/Al(25Å)

Impression of Domains





FM-Domain > AF-Domain

EXCHANGE BIAS
RECENT ISSUES

- Bulk vs. Surface
- Unpinned Spins in the AFM
- Pinned Spins in the AFM
- Where are the spins ?

PROXIMITY ISSUES

- Magnetic Proximity
  - **Why is not observed ?**
- Exchange Bias
  - **Where are the spins**
  - **What determines the magnitude**

COUPLING

- Dipolar
  - L. Neel, Compt. Rend.255,1676(1962)
  - S. Demokritov, E. Tsymbal, P. Grunberg, W. Zinn, and I. K. Schuller. Phys. Rev. B49, 720(1994)

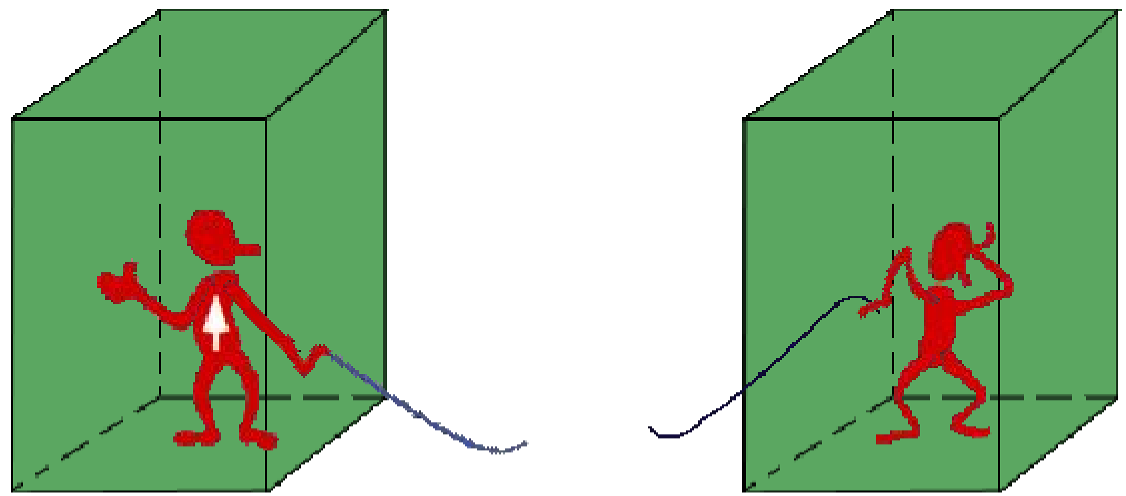
- Exchange
- Quantum Well States

J. E. Ortega, F. J. Himpsel, G. J. Mankey, R. F. Willis, Phys. Rev B47, 1540(1993)

- RKKY (Oscillatory)
  - K. Yosida and A. Okiji, Phys. Rev. B 14, 301(1965)
  - W.S. Zhou, H. K. Wong, J. R. Owers Bradley and W. P. Halperin, Physics B & C 108,953(1981)

Magnet Magnet

Large Distance

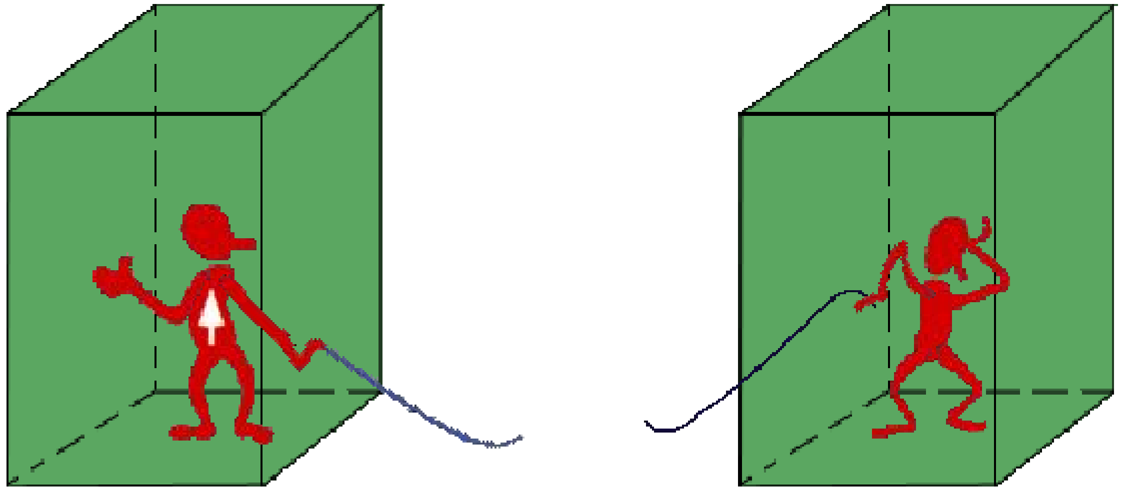


No comunication

Nano Distance

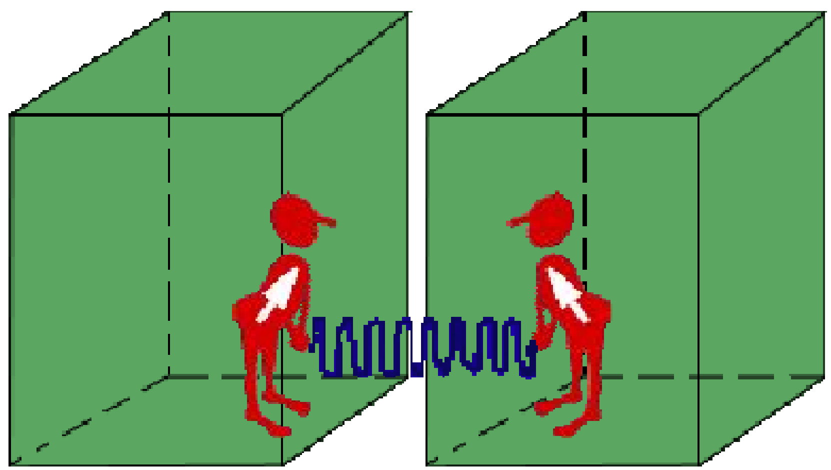
Magnet

Large Distance



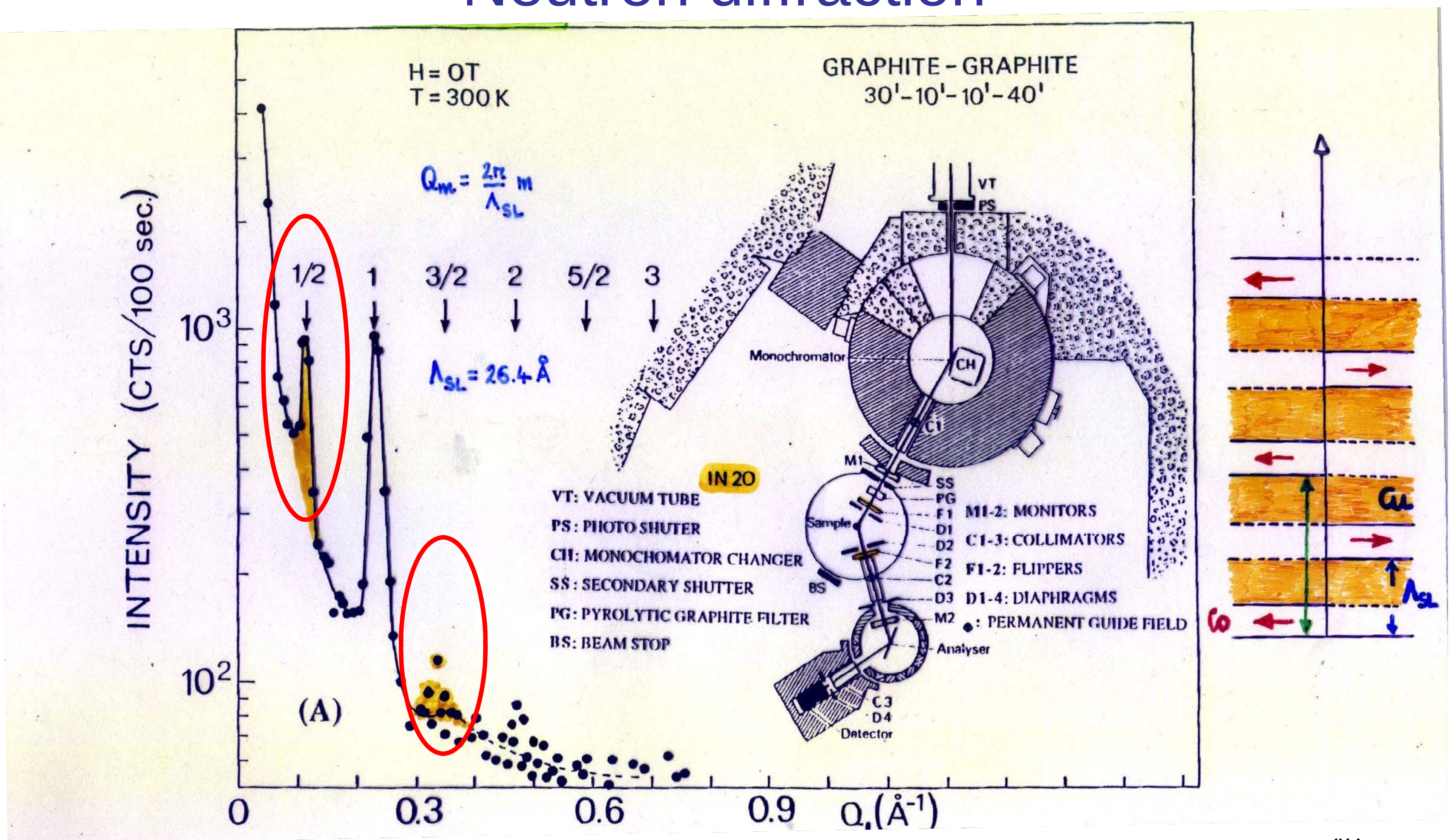
No comunication

Nano Distance



Comunication established

ANTIFERROMAGNETIC COUPLING
Neutron diffraction

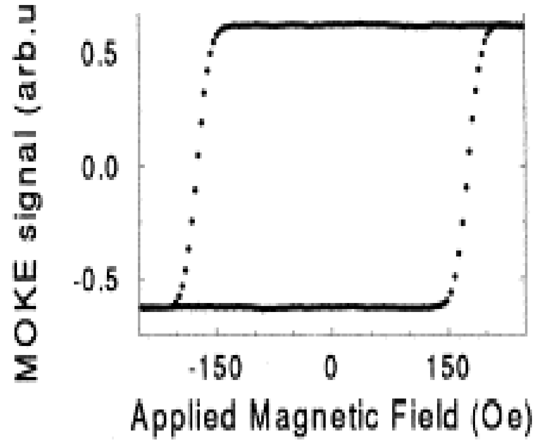


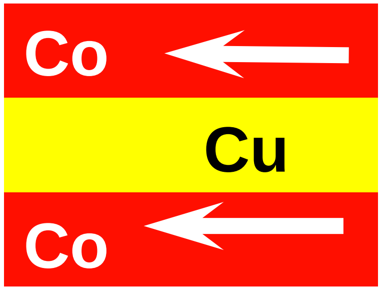
Alfonso Cebollada et al, Phys. Rev. B 39, 9726 (1989) .

Oscillatory Coupling

Miranda- U. Autonoma

8Cu/3Co/8Cu/3Co

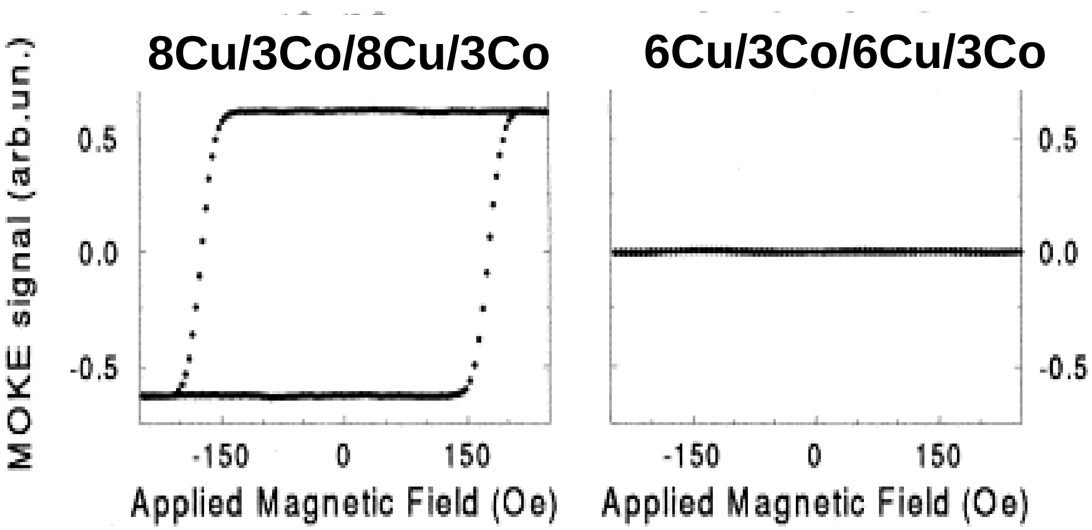


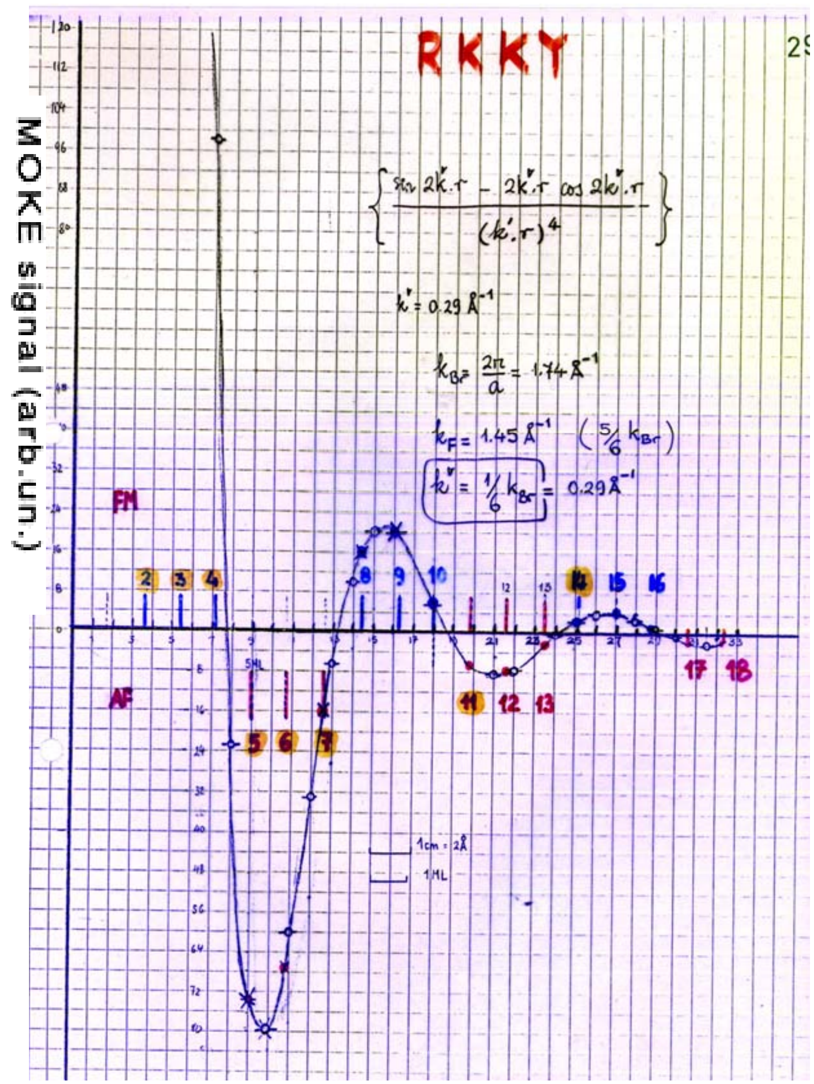


Alfonso Cebollada et al, Phys. Rev. B 39, 9726 (1989) .

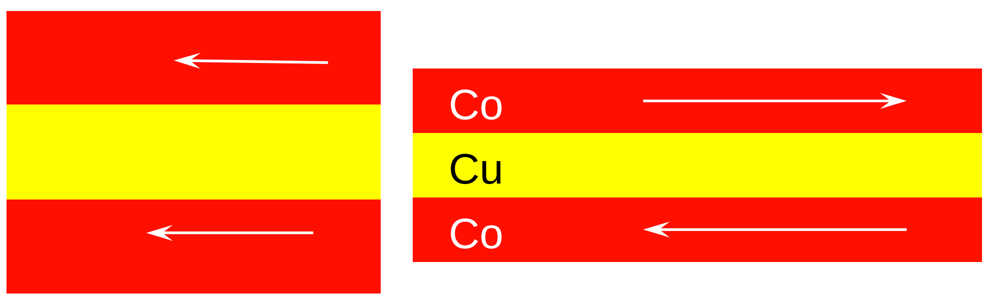
J.J. de Miguel et al, JMMM 93 (1991) 1, A. Cebollada et al, JMMM 102 (1991) 25

Oscillatory coupling





ANTIFERROMAGNETIC COUPLING



J.J. de Miguel et al, JMMM 93 (1991) 1

Lab notebook (1989)

A. Cebollada, Ph. D., UAM (1991) and A. Cebollada et al, JMMM 102 (1991) 25

SPIN PROPAGATION

- Natural Superlattices- CMR

  ~ 0.2 nm
- Metals- GMR

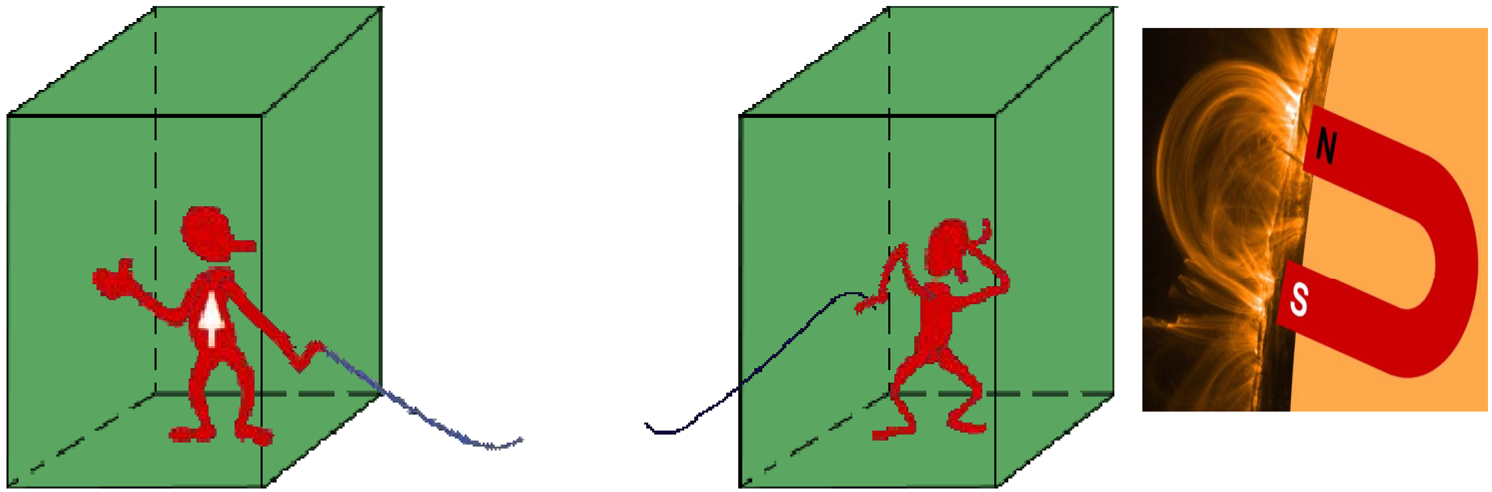
  > 20 nm
- Insulators-Oxides-TMR

  ~ 2 nm
- Semiconductors-”Spintronics”

  > 200 nm

Magnet

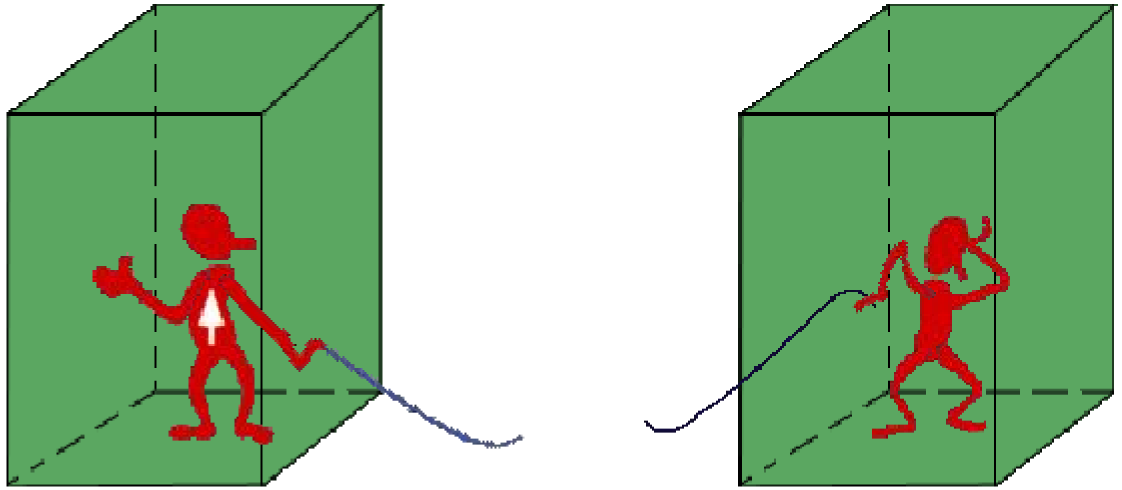
Large Distance



Electrical Resistance Doesn’t Change

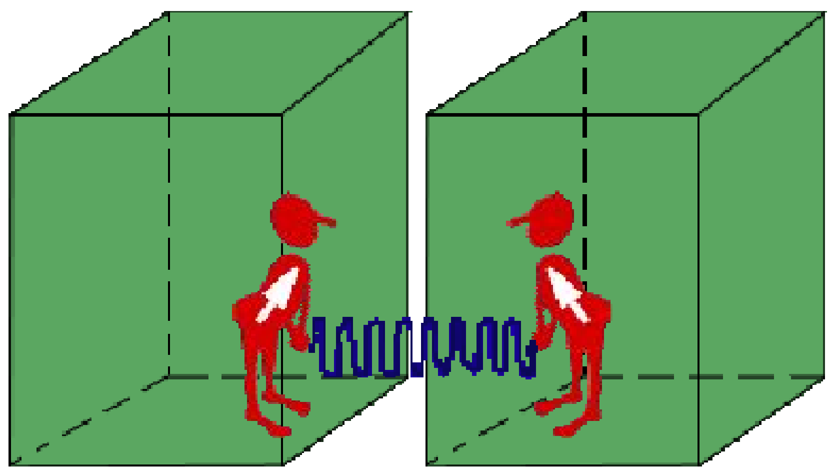
Magnet

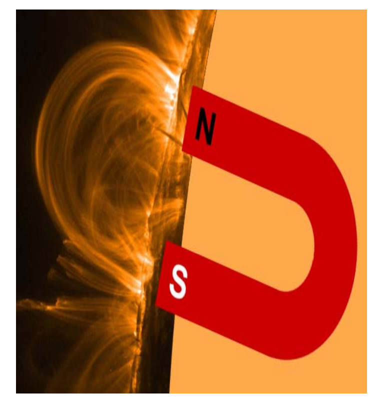
Large Distance



Electrical Resistance Doesn’t Change

Nano Distance



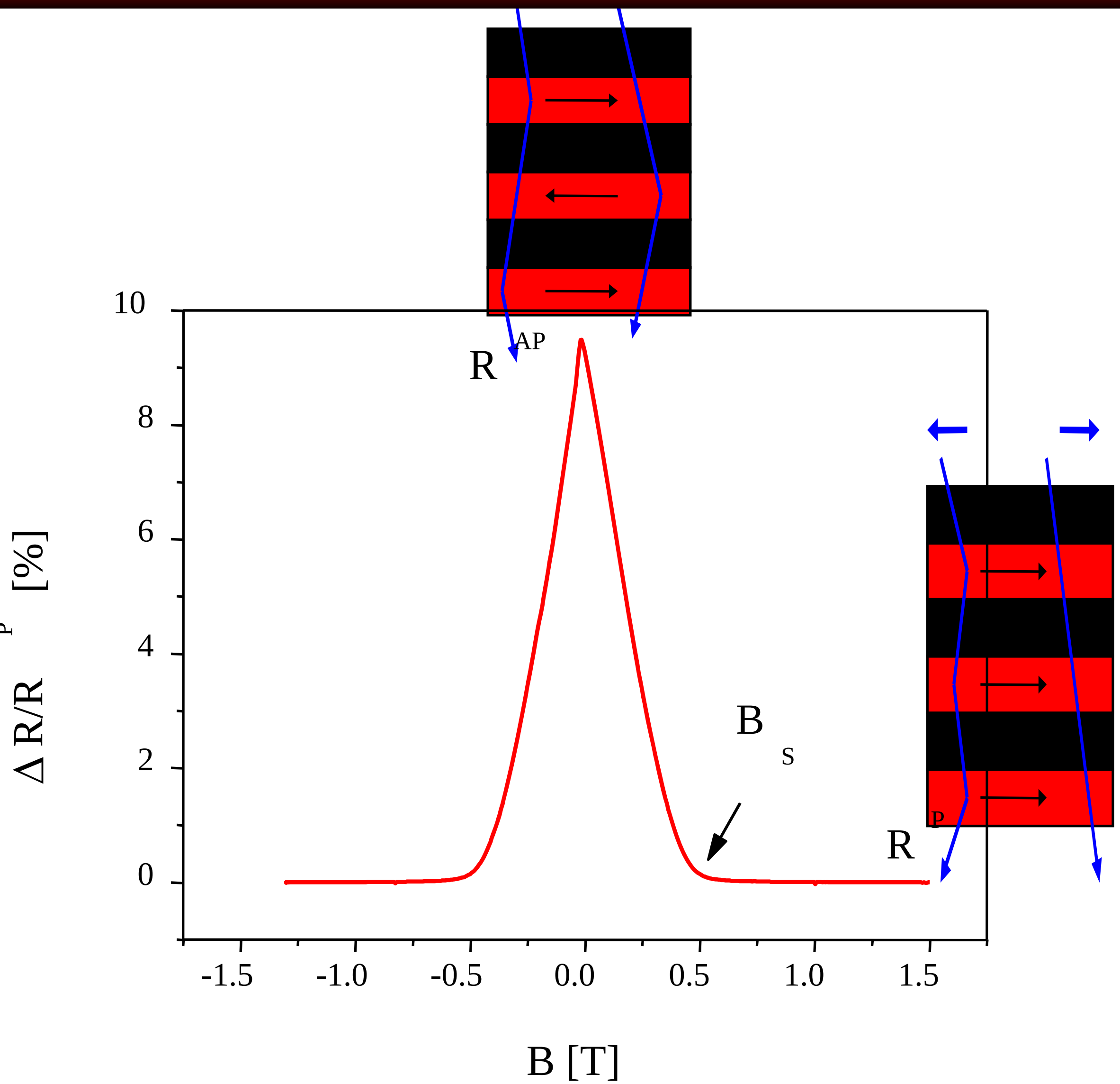


Large Change in Electrical Resistance

Giant Magneto Resistance

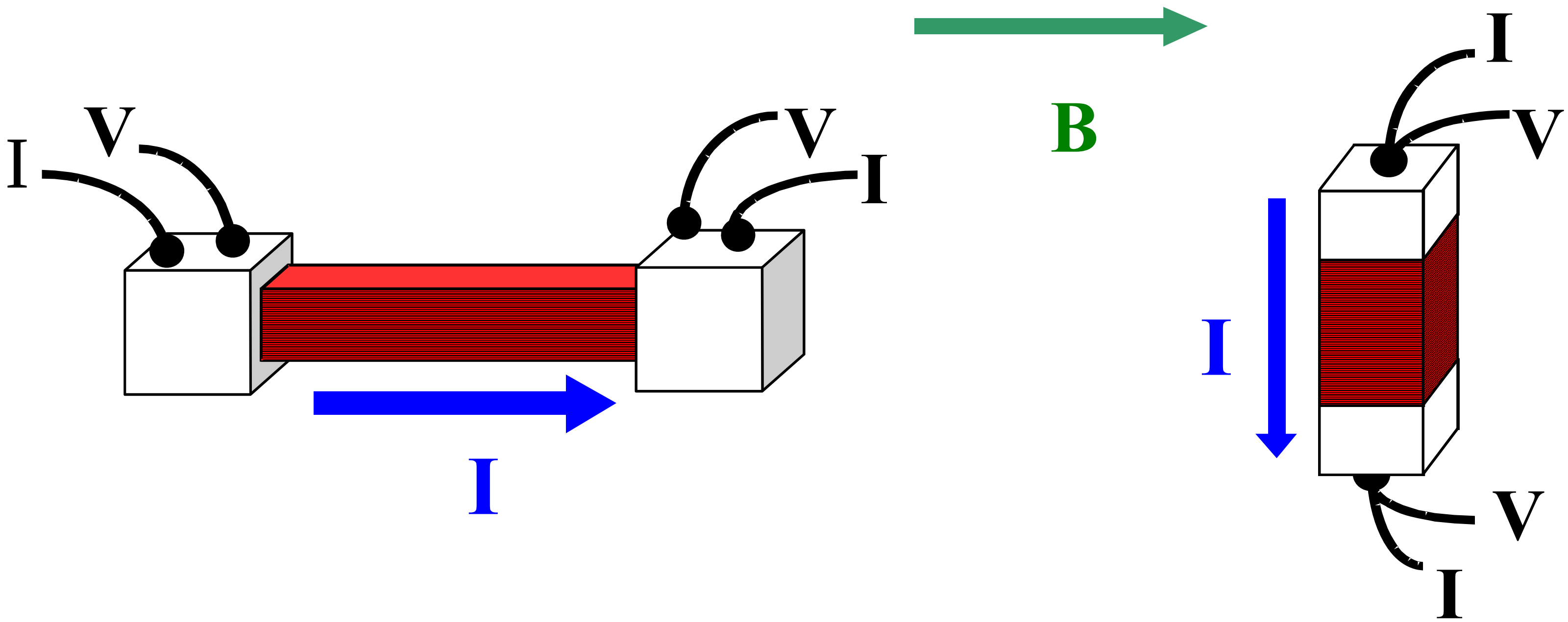
in [Fe/Cr] superlattices

GMR in Fe/Cr superlattices



M. N. Baibich et al Phys. Rev. Lett.61, 2472 (1988)

Transport : CIP vs CPP



CIP

CPP

(Current in Plane)

R large, easy

Model complicated

(Current Perpendicular to Plane)

R small, dificult

Model simple

Valet-Fert, PRB 48, 7099 (1993)

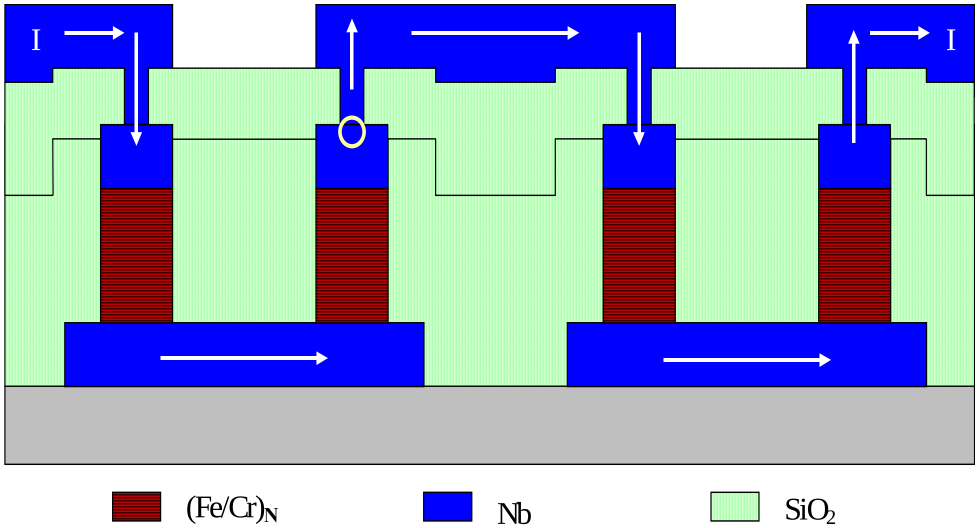
CONTACT RESISTANCE

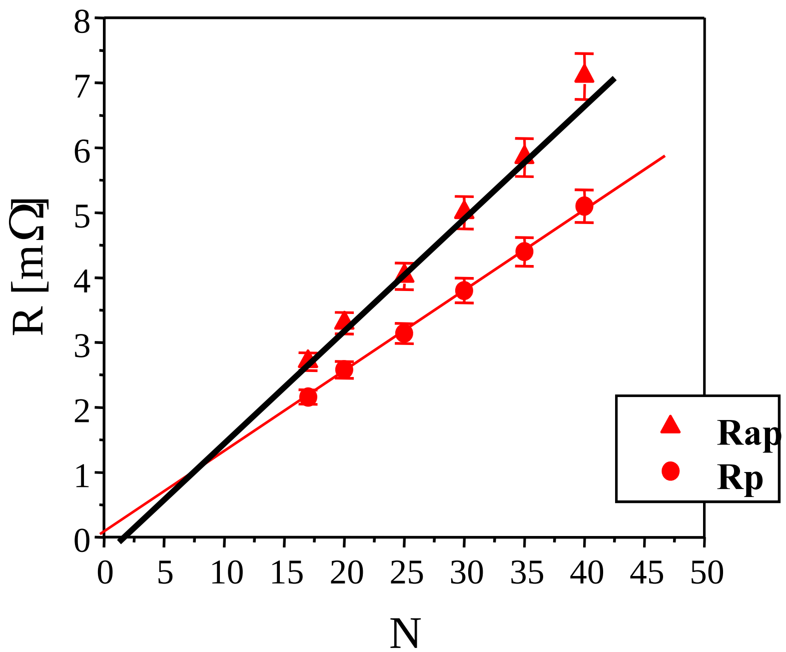
Lithography

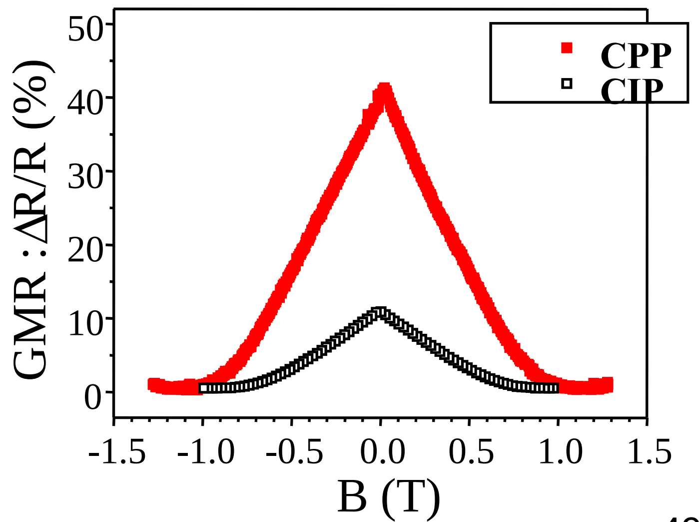
Superconducting electrodes

Perpendicular resistance

$[Fe_{30Å}Cr_{12Å}]_N$



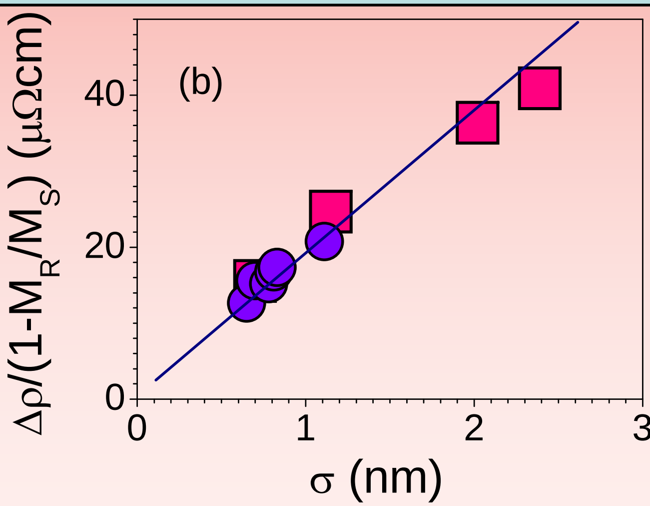




CPP GMR >> CIP GMR

Roughness is KEY in Fe/Cr GMR!!!!

J. Santamaria , M-E Gomez, M-C Cyrille, C. Leighton, K. K. Krishnan,IKS
Phys. Rev.B65, 012412(2002)

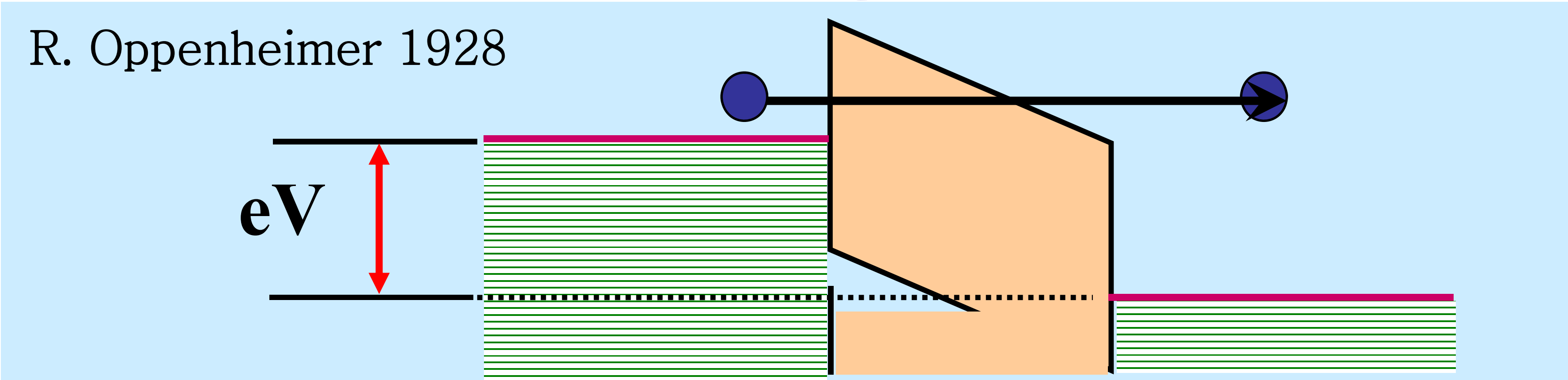


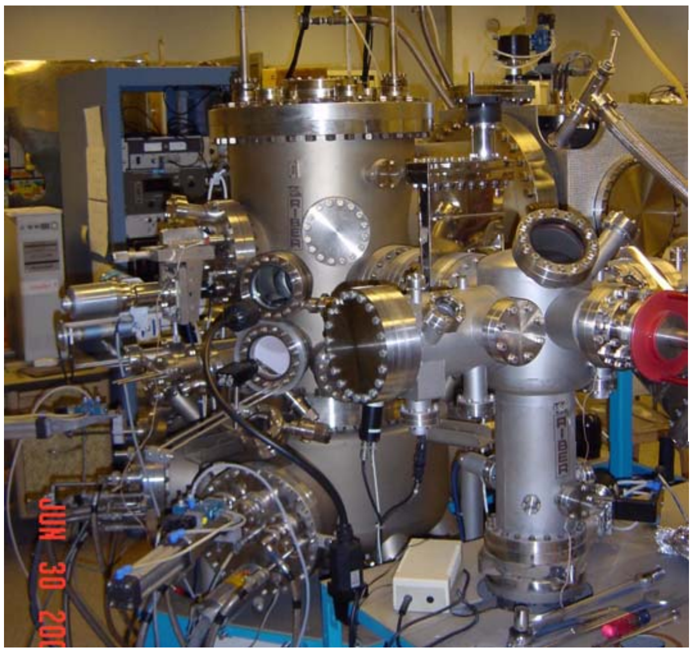
■ **Pressure**

● **Number of bilayers**

MAGNETIC TUNNELING

CONCEPT





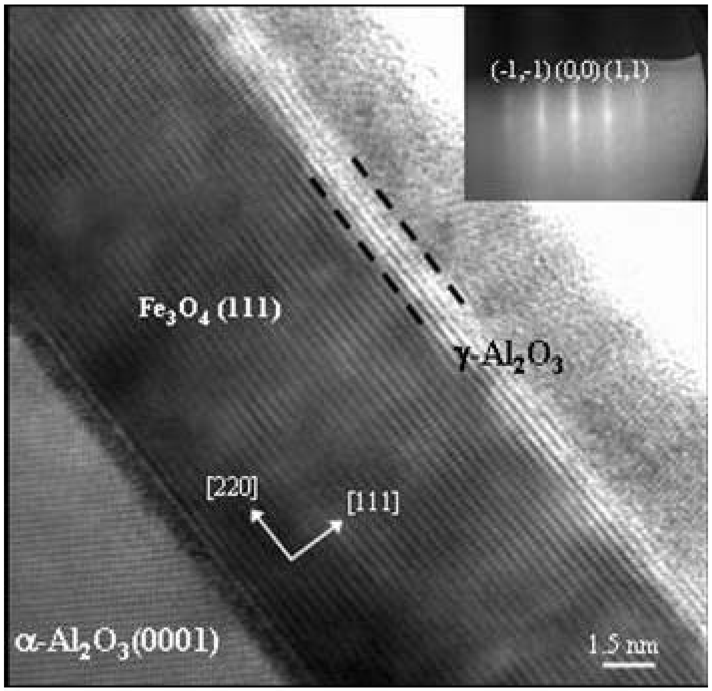
F Metal	Insulator ~ 10 A	F Metal

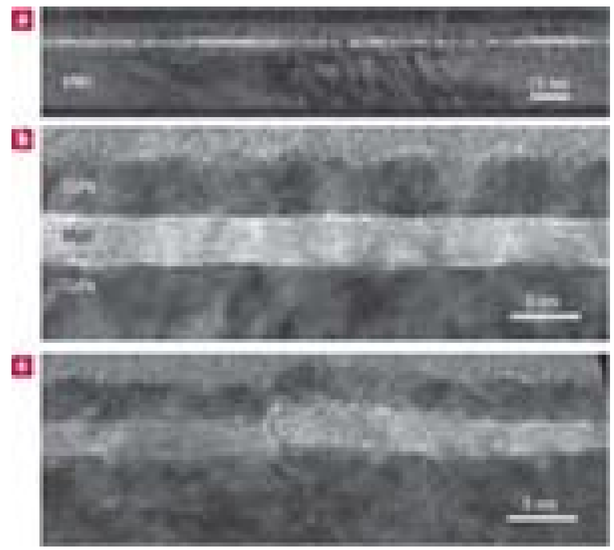
I. Giaver 1960

USE

MOLECULAR BEAM EPITAXY (MBE)

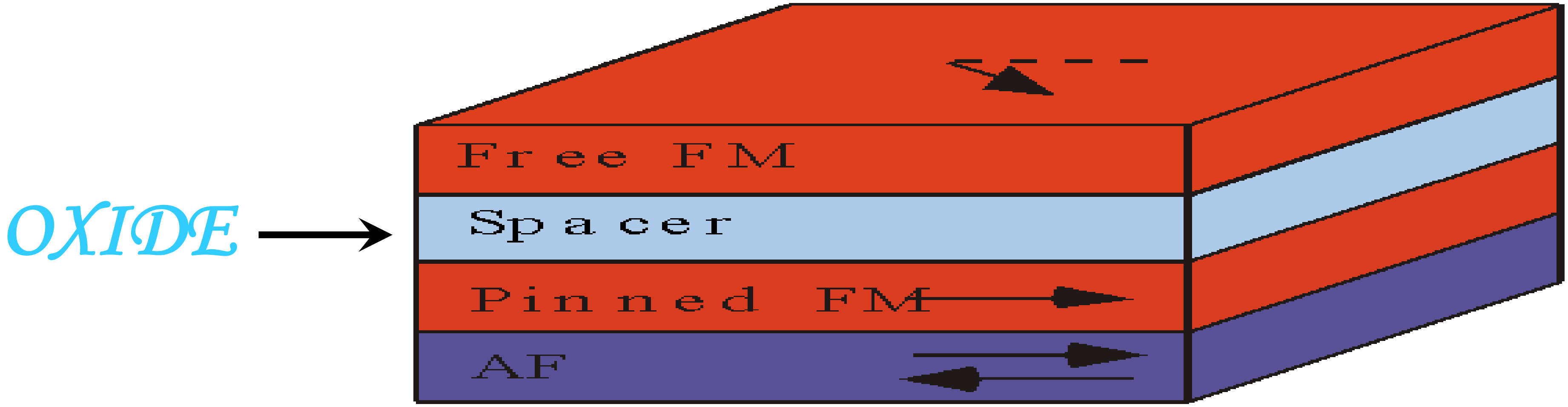
Don't be afraid to ask





DEPOSITION AND OXIDATION

KEY



It is much easier to conceive than to deliver.

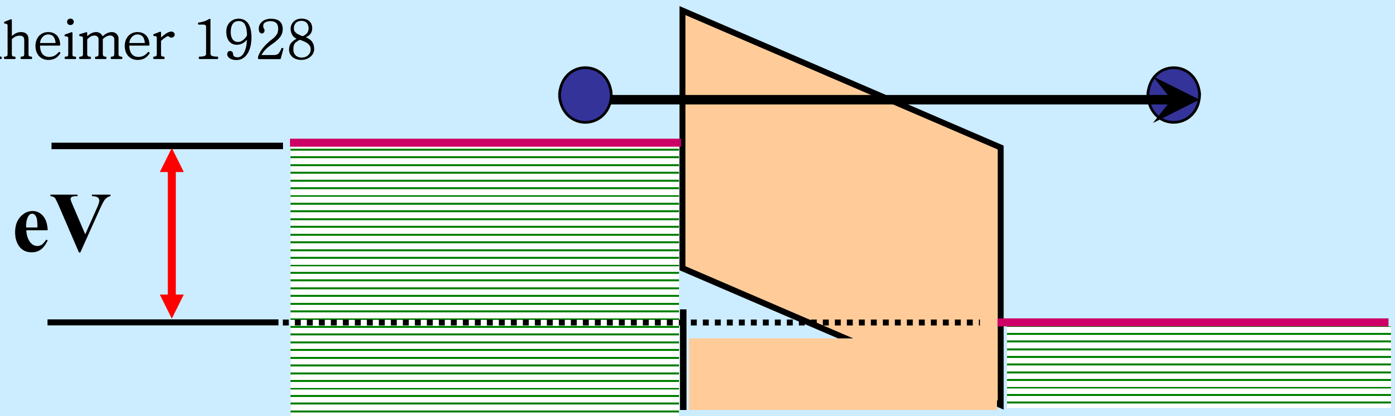
Jackie Schuller

There is oxide formation in other places besides where there is oxide deposited

X. Batlle et al, JMMM, 260, 77(2003)

CONCEPT

R. Oppenheimer 1928



I. Giaver 1960

IN SPITE OF

MOLECULAR BEAM EPITAXY (MBE)

But we used MBE !!!!!
so it must be right

Just because you spent

$ 1,000,000

on a machine it doesn't mean that

it suddenly became a

magic tool

Characterize with right tools

Microscopy vs. Transport

Pinhole – needle in a haystack

Junction RA
10^3-10^5 $\Omega\mu m^2$

Short RA
~10^{-3} $\Omega\mu m^2$

1 in 10^6-10^8
$1Å^2$-$1nm^2$ in $1\mu m^2$

Microscopy

Search for sub-nm features over µm range

Transport

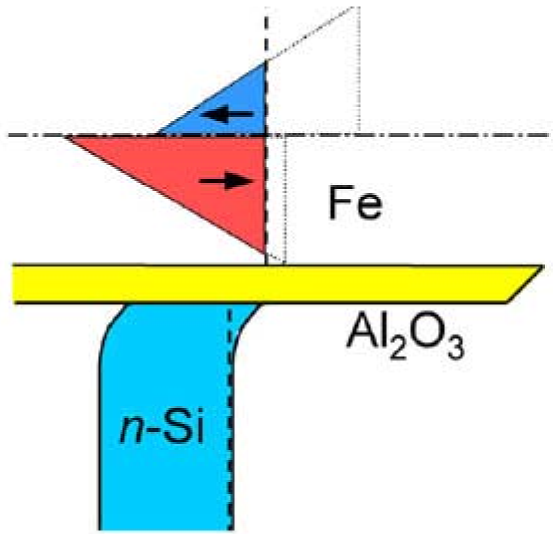
Direct measurement on final device

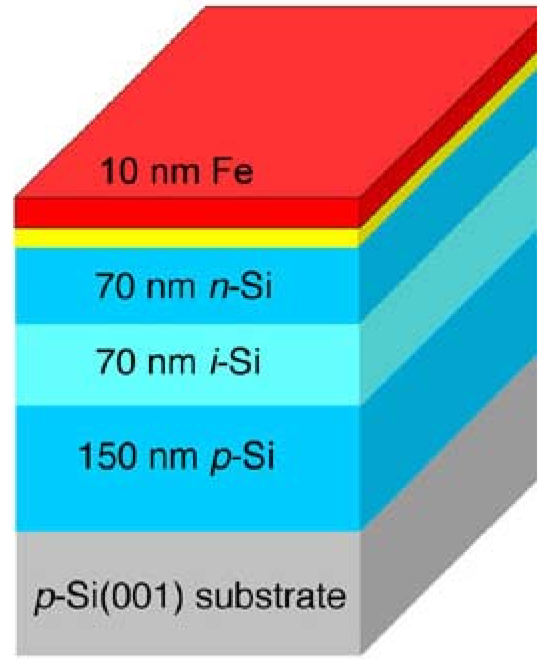
Tunneling
Issues

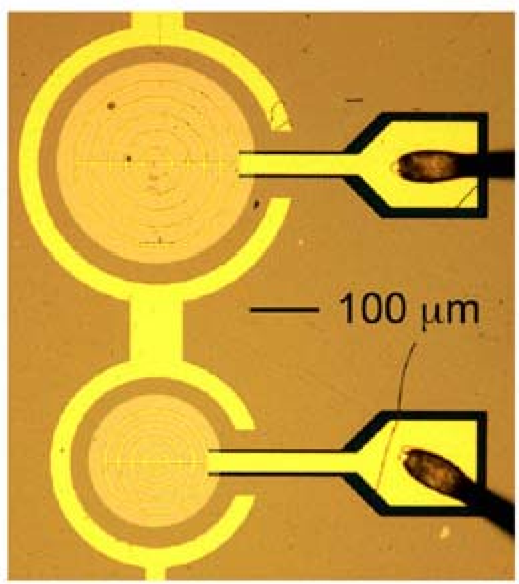
Mechanism ?

- **Temperature Dependence**
- **Different Oxides**
- **Spin Injection**

Spin Injection into Si







SPIN PROPAGATION RECENT ISSUES

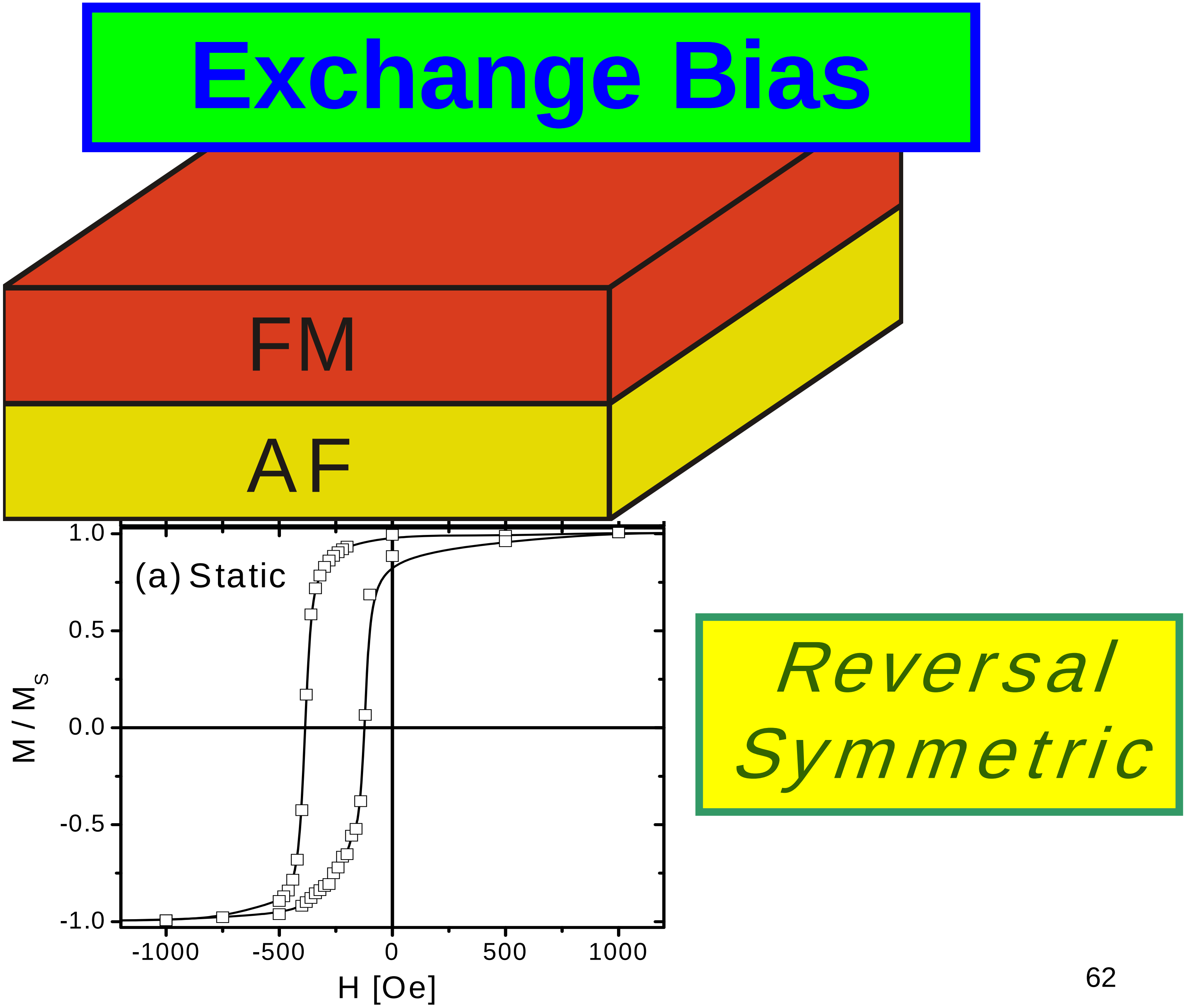
- Metals- GMR

  Non Local Spin Transmission
- Insulators-Oxides-TMR

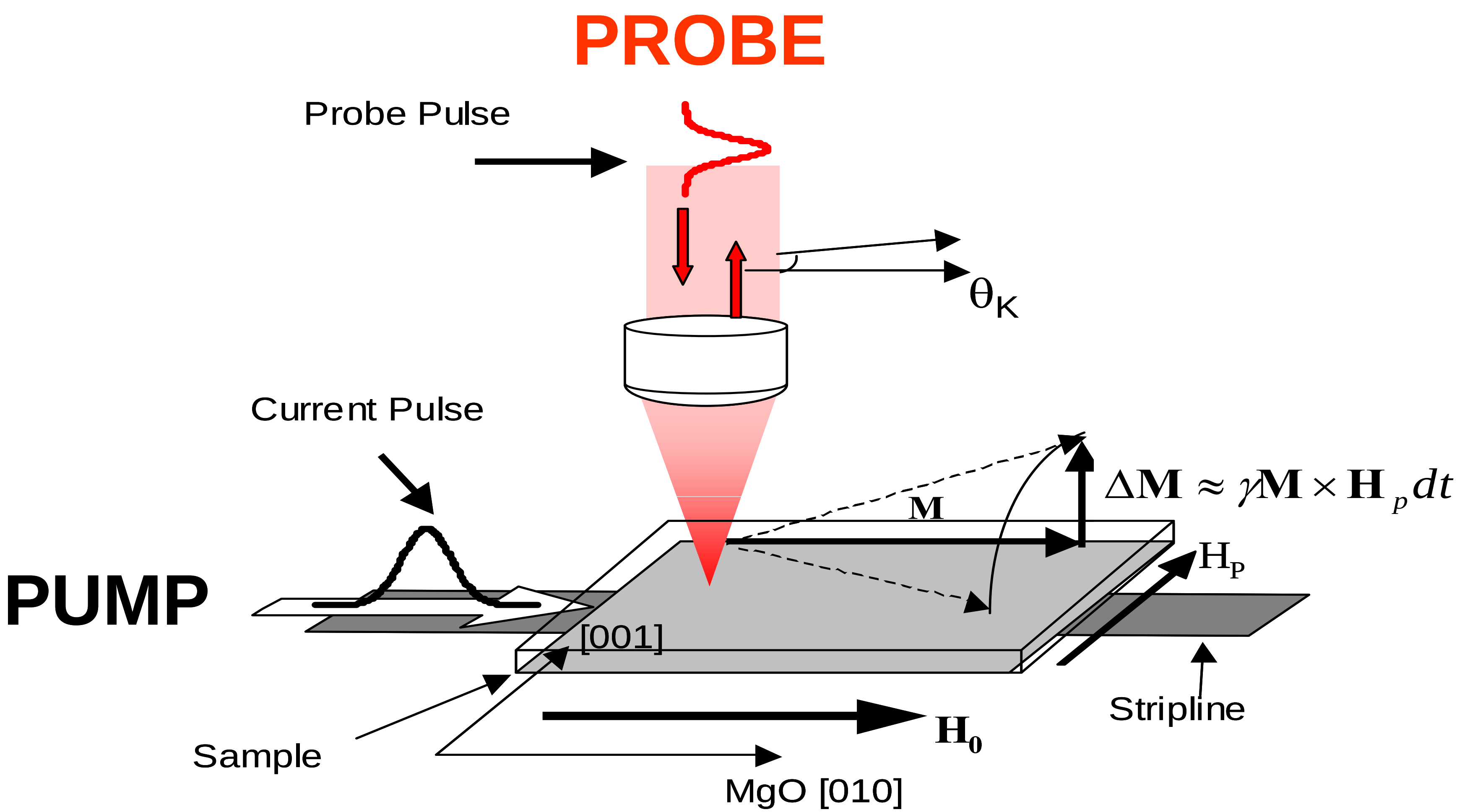
  Pin Hole-BMR
- Semiconductors-"Spintronics"

  Conductivity Missmatch

TIME DEPENDENCE

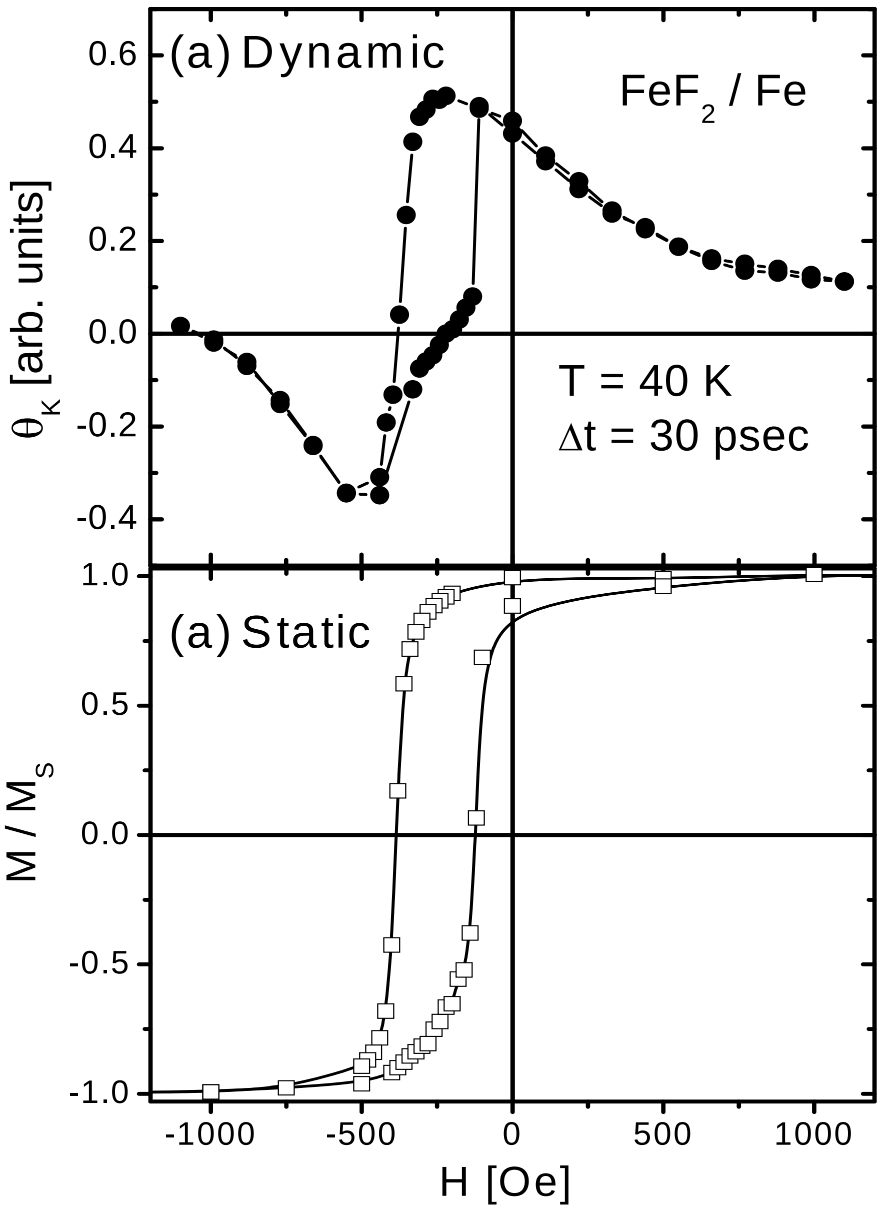

Exchange Bias
FM
AF
(a) Static
M / M_S
1.0
0.5
0.0
-0.5
-1.0
-1000
-500
0
500
1000
H [Oe]
Reversal
Symmetric

PUMP-PROBE



D. Engebretson, P. A. Crowell, C. Leighton, W.A.A. Macedo, I. K. Schuller
Phys. Rev. B71, 1884412(2005)

SURPRISE



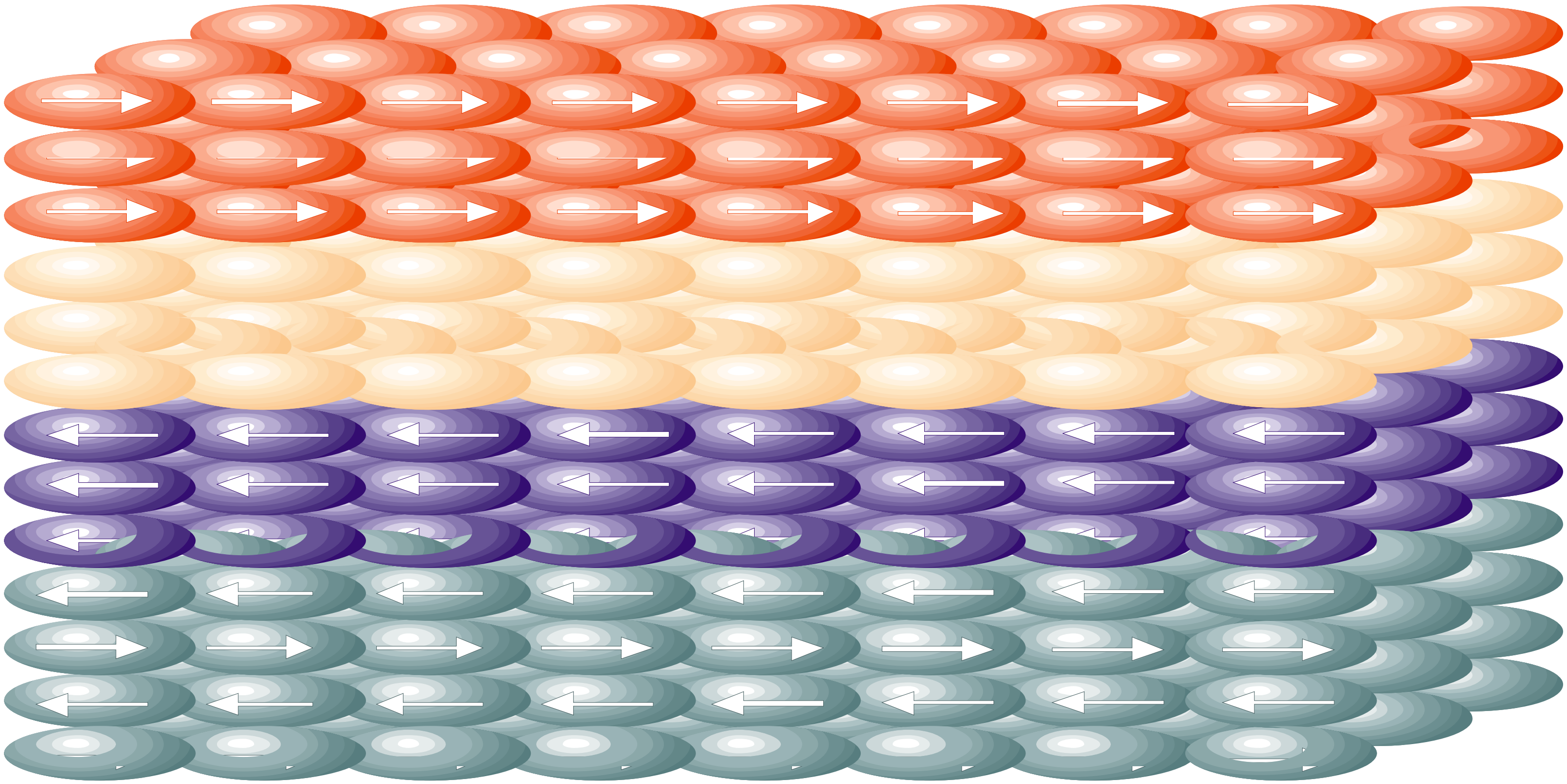
Reversal
NOT
Symmetric

Reversal
Symmetric

Time Dependence Issues

- Pump-Probe
- Single shot ?

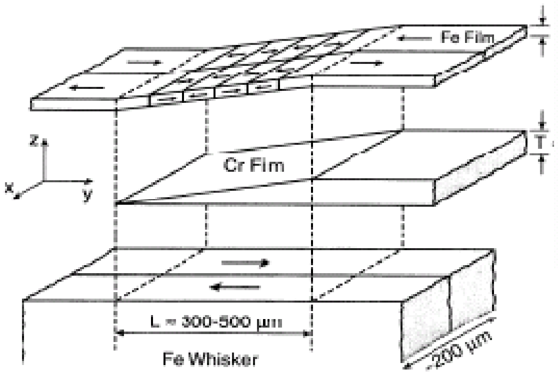
Spin Valve



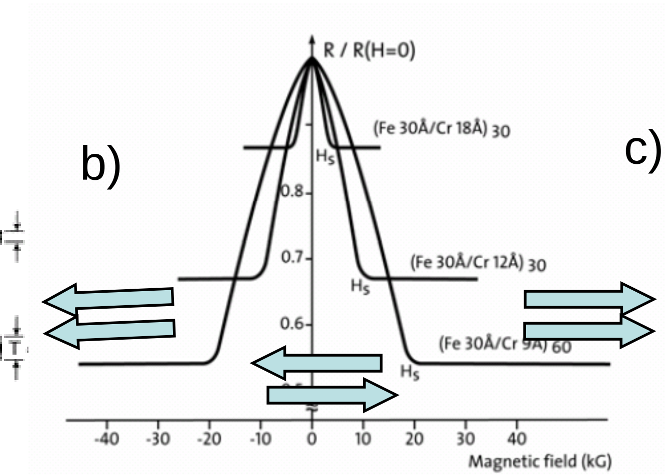
DIENY B, SPERIOSU VS, GURNEY BA, PARKIN SSP, WILHOIT DR,
ROCHE KP, METIN S, PETERSON DT, NADIMI S Source: J. Mag. Mag. Mat. 93,101(1991)

Science

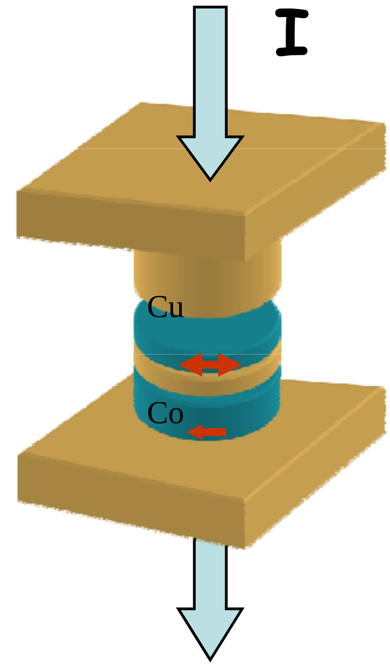
a)

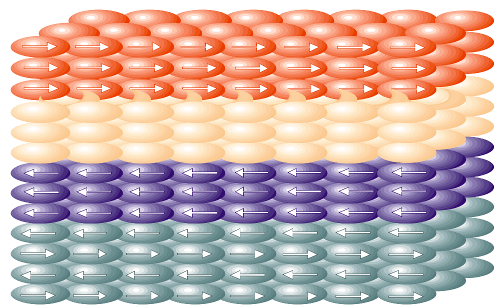


b)



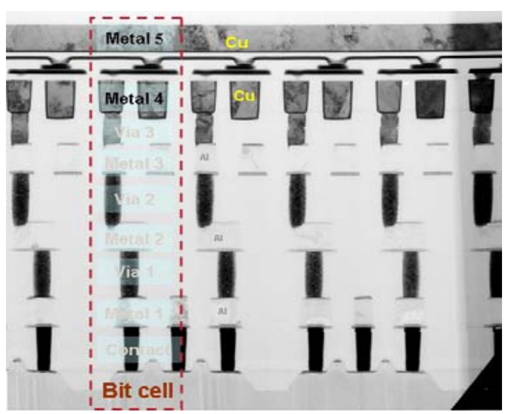
c)



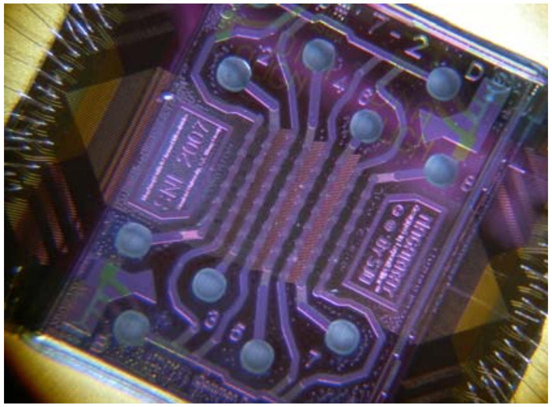


Applications

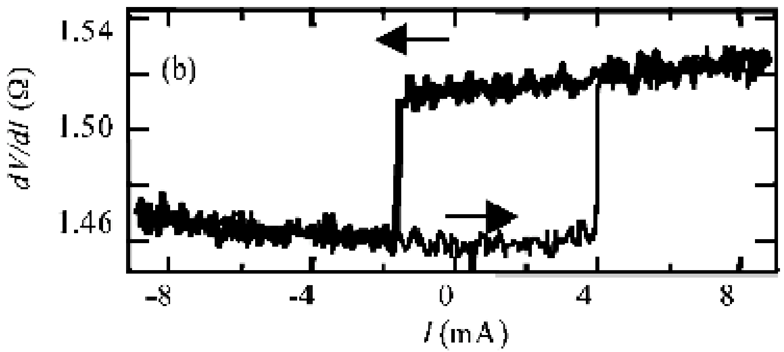
Hard disk drives



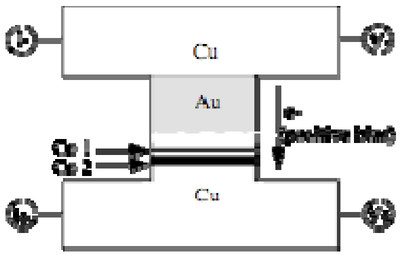
MRAM



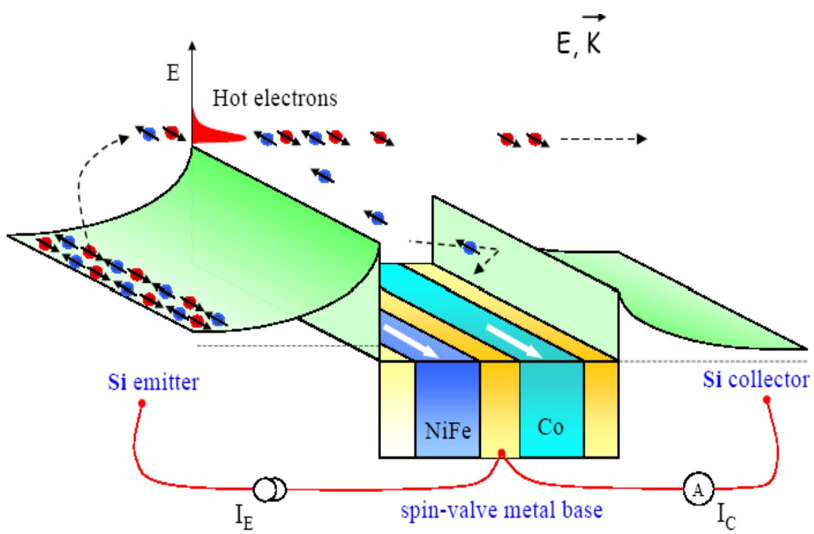
Sensors



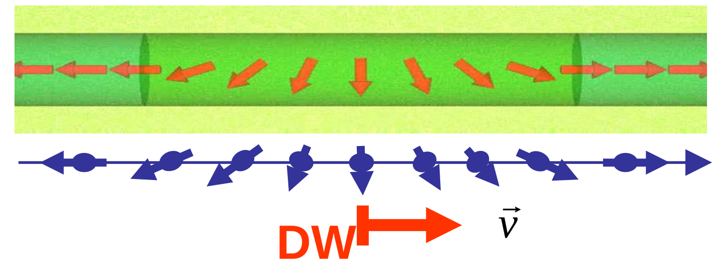
(b)
1.54
1.50
1.46
dV/dI (Ω)
-8
-4
0
4
8
I (mA)



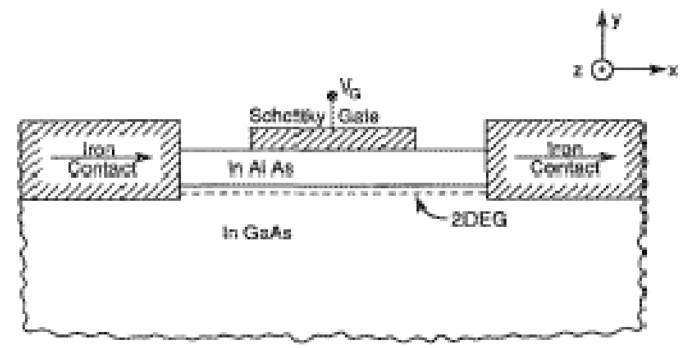
Cu
Au
Cu



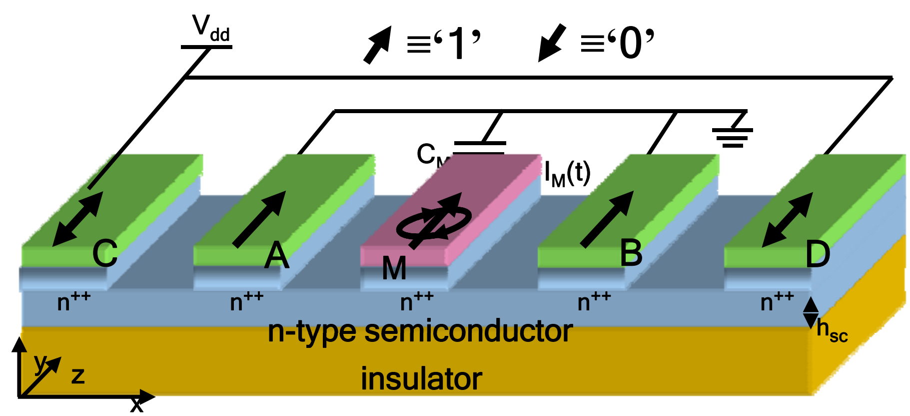
E, K
E
Hot electrons
NiFe
Co
Si emitter
Si collector
spin-valve metal base
I_E
I_C
A



DW
$\vec{v}$



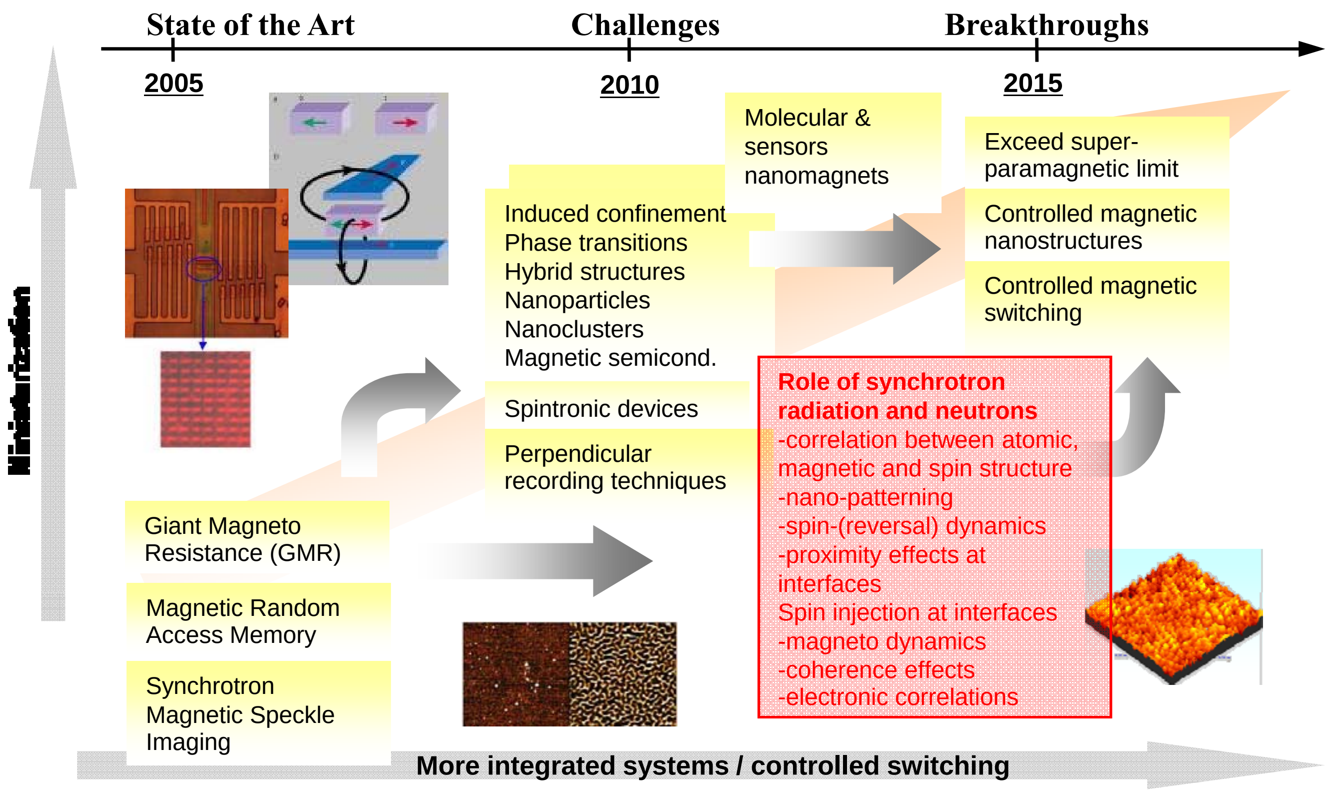
y
z
x
V_G
Schottky Gate
Iron Contact
In Al As
Iron Contact
2DEG
In GaAs



V_{dd}
≡'1'
≡'0'
C_M
$I_M(t)$
C
A
M
B
D
n++
n++
n++
n++
n++
h_{sc}
n-type semiconductor
insulator
y
z
x

GENERAL ISSUES

- Atomic scale characterization magnetism
- Spin Injection and Detection in Semiconductors
- Time dependence
- Integration of Devices



State of the Art
Challenges
Breakthroughs
2005
2010
2015
Miniaturization
Giant Magneto Resistance (GMR)
Magnetic Random Access Memory
Synchrotron Magnetic Speckle Imaging
Induced confinement
Phase transitions
Hybrid structures
Nanoparticles
Nanoclusters
Magnetic semicond.
Spintronic devices
Perpendicular recording techniques
Molecular & sensors nanomagnets
Exceed super-paramagnetic limit
Controlled magnetic nanostructures
Controlled magnetic switching
Role of synchrotron radiation and neutrons
-correlation between atomic, magnetic and spin structure
-nano-patterning
-spin-(reversal) dynamics
-proximity effects at interfaces
Spin injection at interfaces
-magneto dynamics
-coherence effects
-electronic correlations
More integrated systems / controlled switching

PROXIMITY EFFECT

COMPETITION
OF
LENGTH SCALES