Nanomagnetismo y espintrónica

(una descripción desde la experiencia personal)

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Gracias por la invitación

Disculpas: esta charla va a ser una visión muy parcial del tema, casi un relato de una experiencia personal

Outline

- Magnetoelectronics vs Spintronics
- A bit of history
- GMR
- TMR

Magnetoelectronics vs Spintronics (spin electronics)

New field of electronics which is not based on the conduction by electrons or holes as in semiconductor devices, but relies on the different transport properties of the majority and minority spin electrons.

ADD TO ELECTRONICS AN ADDITIONAL DEGREE OF FREEDOM: THE SPIN CHARACTER

Magnetoelectronics: Pasive elements (resistors).
Change in resistance upon application of a magnetic field.

Fully metallic (AMR, GMR), oxide (CMR, TMR) or metal oxide (TMR) structures.

Spintronics: Active elements (spin transistors).
Amplify a current rather than merely switching it on and off.

Metal (FM) - Semiconductor (non FM) or Semiconductor (FM) -Semiconductor (non FM) structures.

Driving force for the appearance of spin electronics

Computers get more powerful every day: faster, smaller and with more storage capacity.

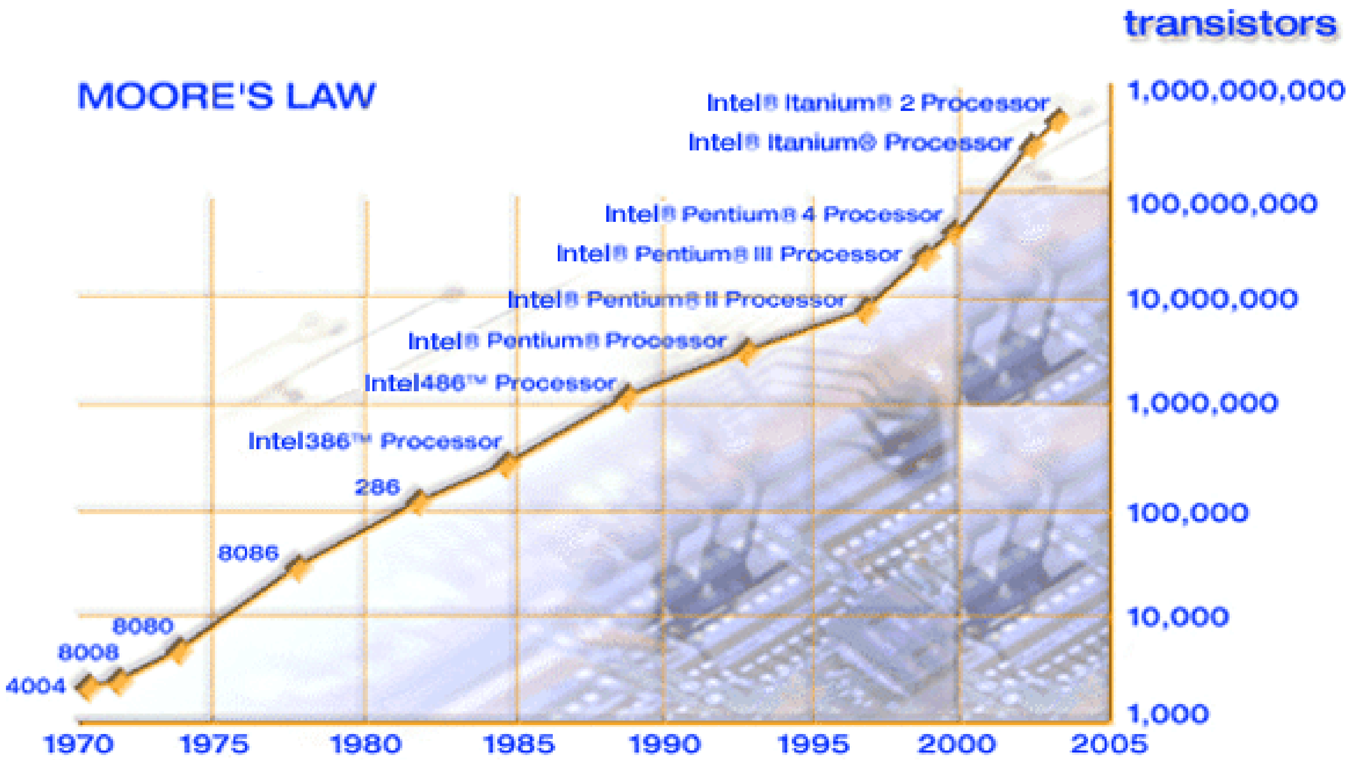
Parallel improvement of semiconductor and magnetic recording industries.
Information processing is performed using charges, and info storage using spins.

However: very little basic and technological overlap between the magnetic recording and semiconductor industries.

Both communities have been following their own “roadmaps”: documents that especify how and when certain developments will happen in each field, and what each industry needs to do to get there. Moore’s law for semiconductors and its equivalent for magnetic recording.

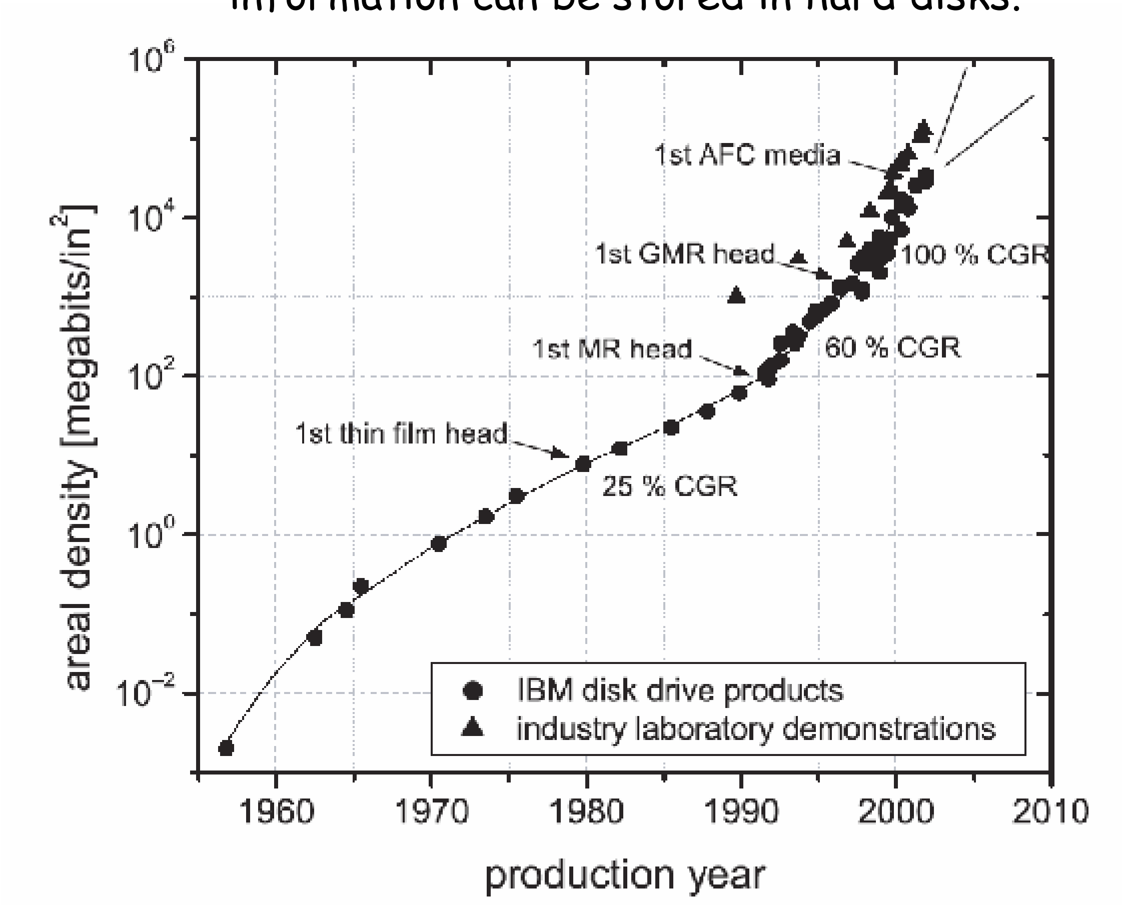
Moore's law: number of transistors per integrated circuit

Semiconductors: more and more transistors and capacitors can be stored into a silicon chip.



Magnetic recording equivalent to Moore's law: Areal density progress in magnetic recording since its invention

Magnetic recording: more and more information can be stored in hard disks.



So far magnetoelectronics is doing better than spintronics

Magnetic-recording industry has been the driving force behind magnetoelectronics, trying to investigate if magnetic materials (mainly in thin film form) can be used in electronic components and circuits, although semiconductor industry is starting to become involved.

Spin electronics in semiconductors: key factors

An obstacle for spintronics is that electronics companies are geared up to working with semiconductors, not metals.

An important goal is to make devices using semiconductors that are compatible with existing chip technology.

The problem is that conventional semiconductors used in integrated circuits are not magnetic.

This is why several research groups are exploring ways of turning these semiconductors into ferromagnetic materials.

Big problem: sustaining spin-polarized transport across the interfaces between the different materials. Interfaces between semiconductors and ferromagnetic metals present a Schottky barrier, leading to loss of spin polarization.

Ferromagnetic semiconductors

Injecting spin across the interface between two semiconductors (one of them ferromagnetic) should be easier because there is no Schottky barrier.

ZnSe dopped with Be and Mn, Co doped TiO_2, Mn doped SnO or Mn doped GaAs are candidates for FM SC.

Aim: fully switchable all-semiconductor spin valves, semiconductor spin transistors, which would amplify a current rather than merely switching it on and off.

Other spin electronic materials/phenomena

Oxides: rare earth manganites that exhibit Colossal MR (CMR).

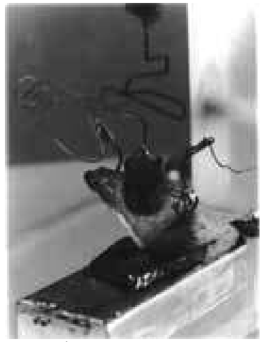
Drawback: CMR materials operate far below RT and lack from easy compatibility with semiconductor materials

Nitrides as spintronic materials? (Ga, Mn)N
Dietl, Phys. Stat. Sol. 240 (2003) 433.

This talk

I will rather center this talk in “magnetoelectronics”, mainly in fully metallic and metal-insulator heterostructures (just because of my ignorance on other issues, not because they are not interesting or relevant).

A bit of history

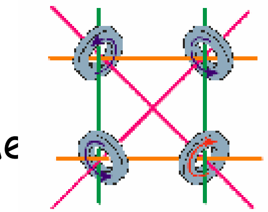


1857: Anisotropic Magnetoresistance - AMR (Bulk effect)
Thomson, W. Proc. R. Soc. **8** (1857) 546.

1947: Discovery of the transistor action in Ge.

1952: First commercial Ge transistors (5 years after discovery).

1950s - 1960s: ferrite core memories used as Magnetic Random Access Memories (MRAMs) in computers.
MRAMs replaced by Dynamic Random Access Me (DRAMs), essentially capacitors.



1975: Tunnel Magnetoresistance - TMR
Julliere, M. Phys. Lett. **54A** (1975) 225.

1979: IBM introduced thin film heads for read out from hard disks. Both write and read process were inductive, but the coil was made using thin film technology.

… a bit of (very recent) history….

1988-1990: Giant Magnetoresistance - GMR/Interlayer exchange coupling.
Baibich et al., Phys. Rev. Lett. **61** (1988) 2472.
Binasch et al., Phys. Rev. B **39** (1989) 4828.
Parkin et al., Phys. Rev. Lett. **64** (1990) 2304.

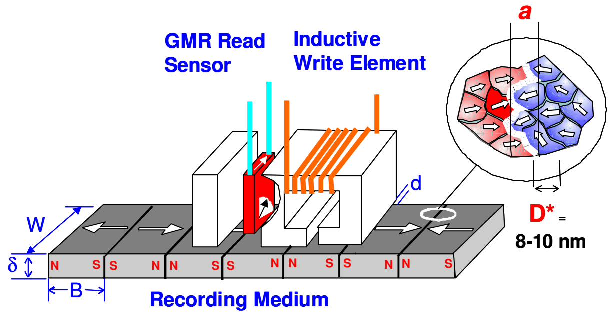
1991: IBM introduces the AMR effect for read out in hard-disk drives (HDD) (104 years after discovery). Even though AMR in permalloy is only 2%, it found its way in the field of applications.
This resulted in an annual growth rate of storage capacity of around 60%.

1991: Invention of the spin valve effect: the best way to obtain an antiparallel arrangement between two ferromagnetic layers separated by a non ferromagnetic one.
Dieny et al., Phys. Rev. B **43** (1991) 1297.

1994: First commercial product using GMR (a magnetic field sensor) (5 years after discovery)
Daughton et al., IEEE Trans. Magn. **30** (1994) 4608.

… a bit of history, till our days.

1995: Tunnel Magnetoresistance - TMR: Rediscovered
Miyazaki et al., JMMM **139** (1995) L231.
Moodera et al., Phys. Rev. Lett. **74** (1995) 3273.



1997: IBM introduces GMR for the sensors in HDD.
(8 years after discovery)
Wall Street Journal, 10 November 1997, p 88.

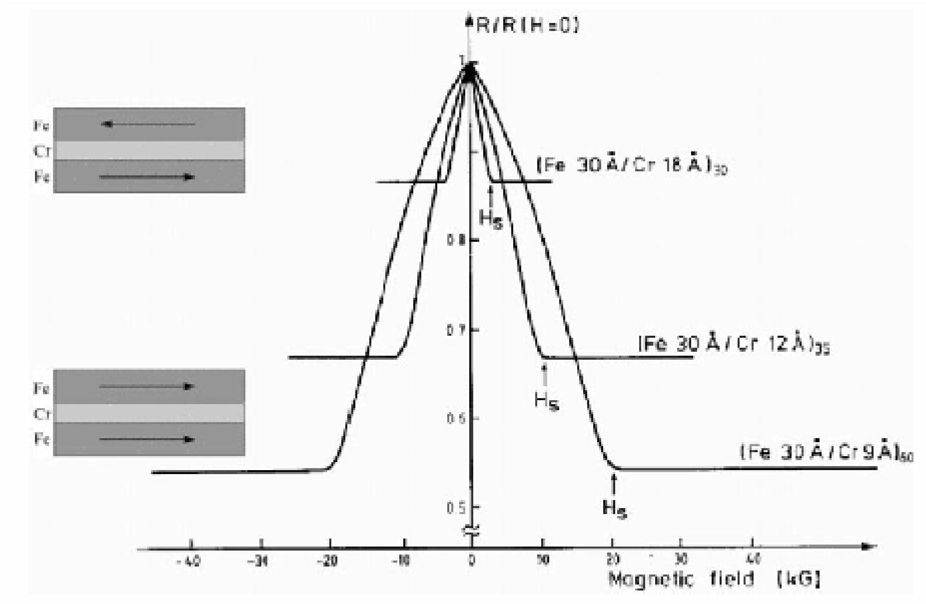
2004: Freescale Semiconductor [FSL] (Motorola spin-off company controlling all of its MRAM development): currently sampling a 4 Mb MRAM chip for back-up memory in industrial and military environments.

Near Future: MRAM production expected in 2005. The chip won't have the speed necessary for consumer products, but in settings where data loss cannot be afforded, the chip's non-volatility is in high demand.When they produce a 16Mb chip they will be able to penetrate the cell phone (in 2-3 years) and PC markets 3-4 years).

GMR

GMR in Fe/Cr(001) superlattices

Baibich et al., Phys. Rev. Lett. **61** november (1988) 2472.



Fe/Cr superlattices grown by MBE on GaAs(001).

Fe layers AF coupled for t_{Cr} < 30 Å

For t_{Cr} = 9 Å at 4,2 K, the resistivity was lowered by almost a factor of 2 in a magnetic field of 2T.

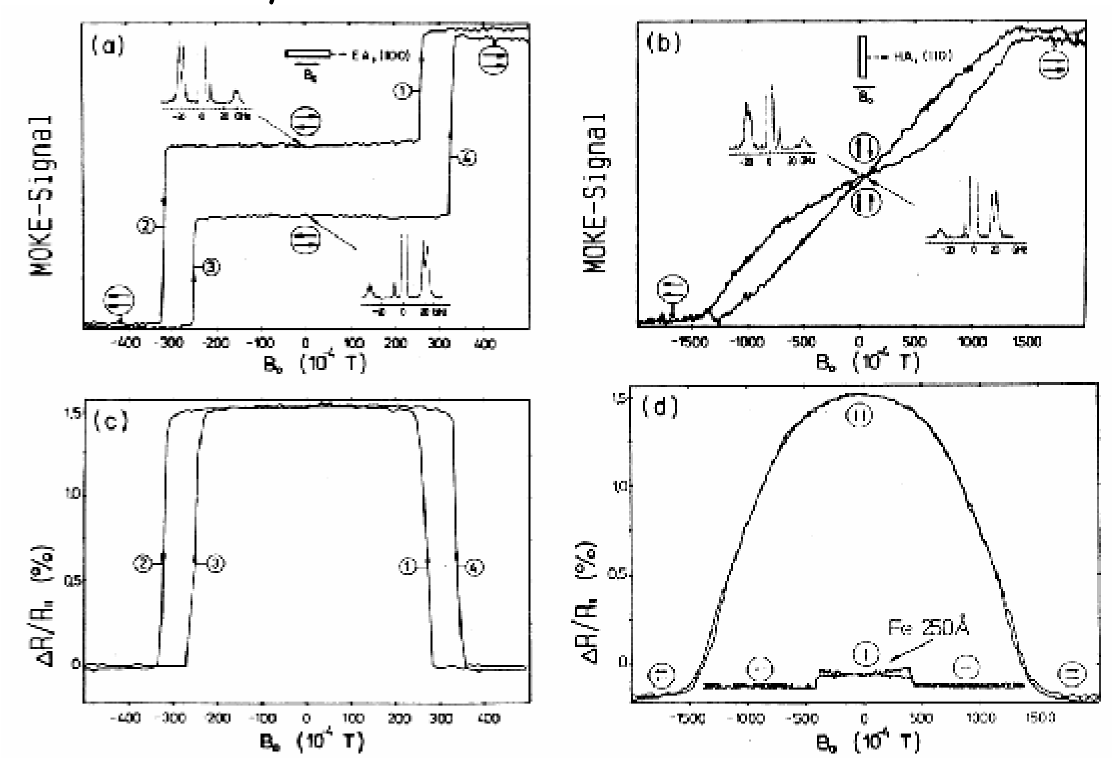
Giant magnetoresistance due to spin dependent transmission of the conduction electrons between Fe layers through Cr layers.

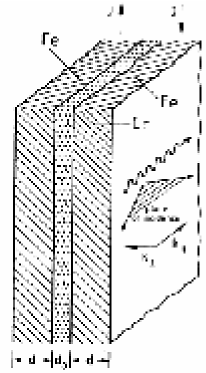
GMR in Fe/Cr/Fe trilayers

Binasch et al., Phys. Rev. B **39** march (1989) 4828.

Easy axis

Hard axis





Fe/Cr/Fe trilayers grown by MBE on GaAs(110).

Similar results to those from Baibich et al.

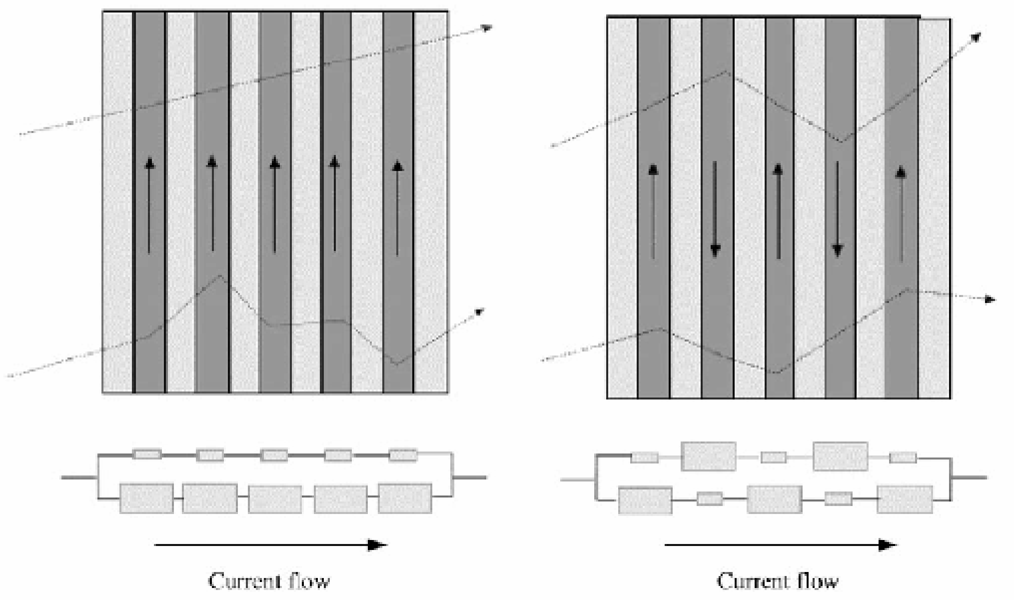
GMR interpretation:

Spin dependent scattering at the interface

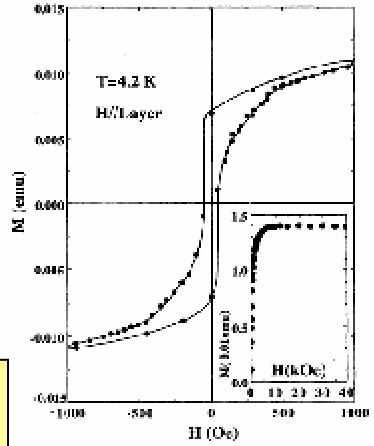
Two resistor model for GMR

Low resistance

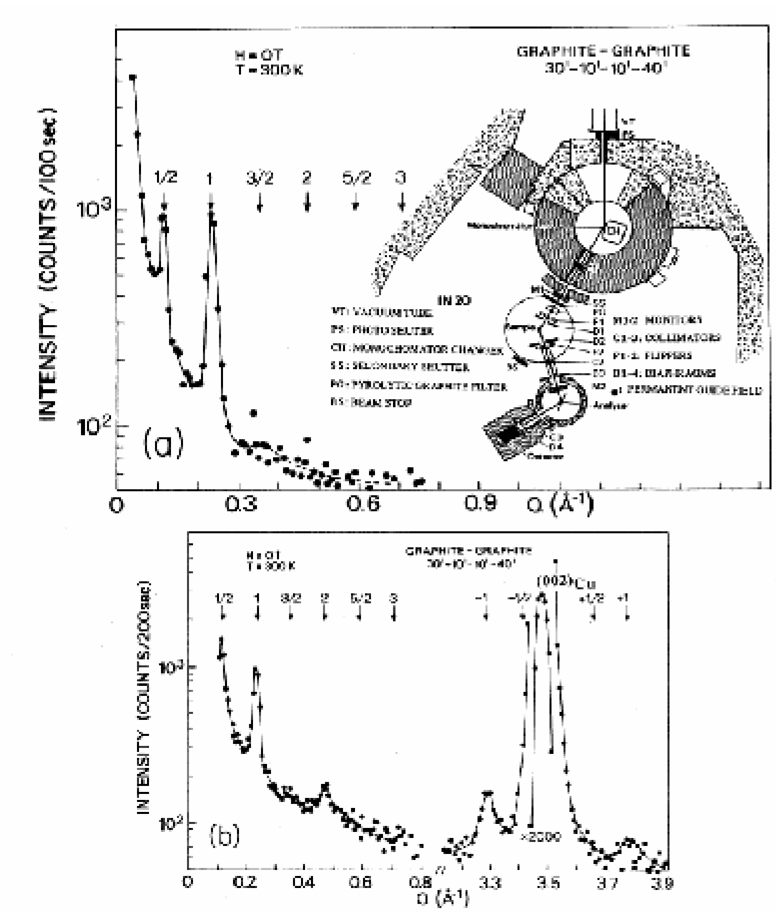
High resistance



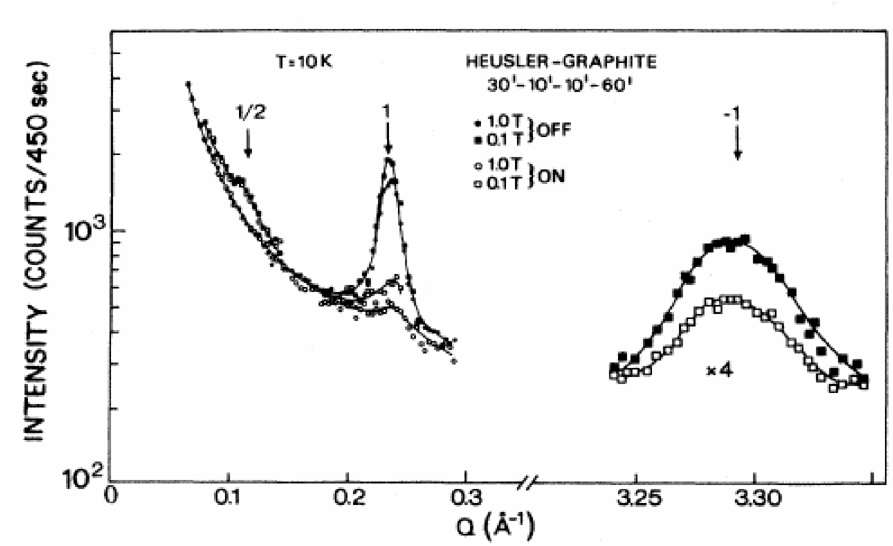
First epitaxial Co/Cu superlattices with AF coupling



Cebollada et al., Phys. Rev. B **39** (1989) 9726
One of the systems that would exhibit the largest GMR
In our case the superlattices where grown on Cu(100) metallic substrates: we could not measure magnetotransport.

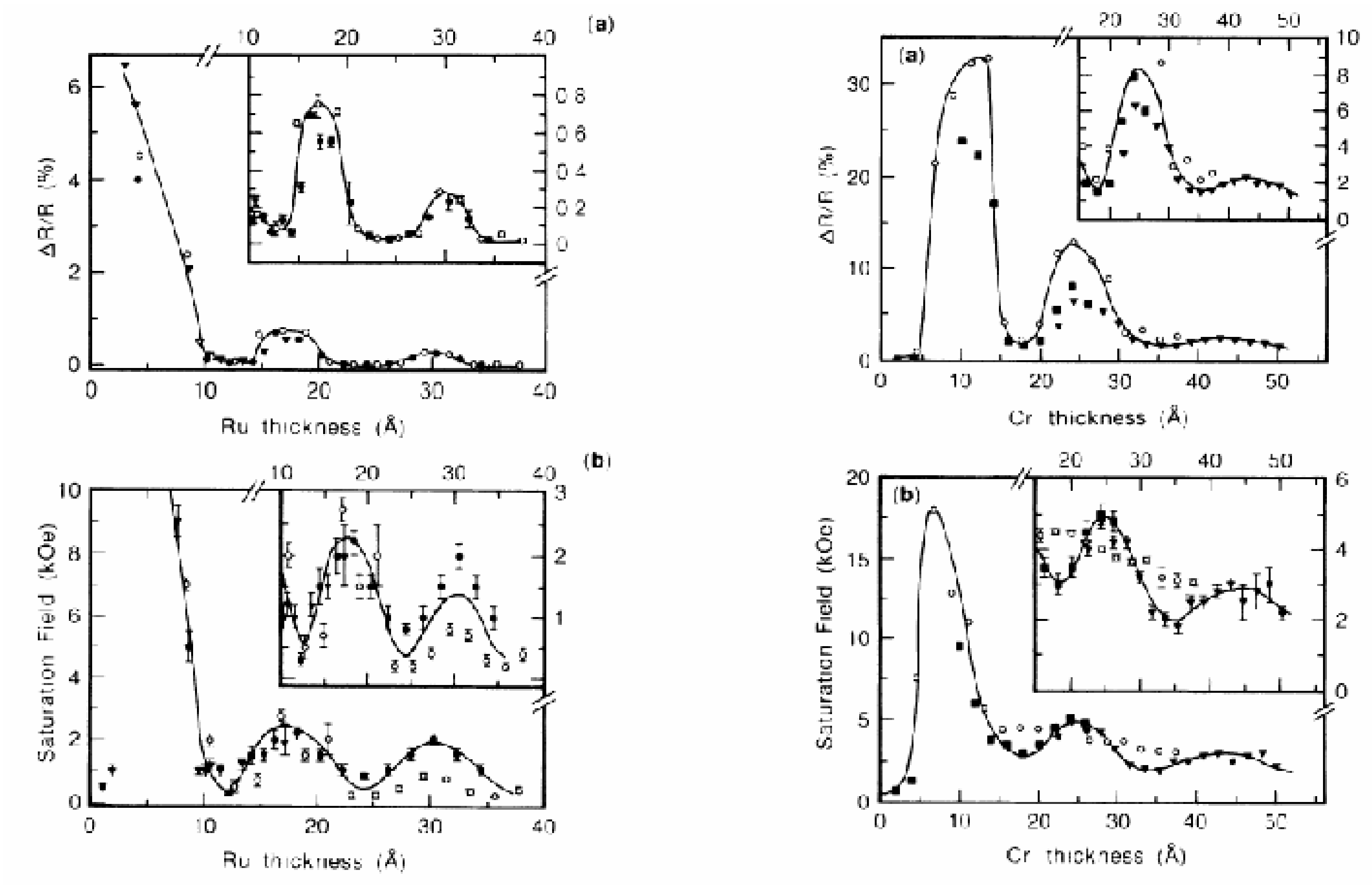


48 hours to grow a single superlattice in a home made "MBE" system



Oscillations in the exchange coupling: Co/Cr, Co/Ru, Fe/Cr

Parkin, More and Roche, Phys. Rev. Lett. **64** (1990) 2304
Multilayers grown by sputtering on Si(111).
Both the GMR and the saturation field oscillates



Systematic variation of the strength and oscillation period …

Ti (hcp)	V (bcc)	Cr (bcc)	Mn (complex cubic)	Fe (bcc)	Co (hcp)	Ni (fcc)	Cu (fcc)
No Coupling	9, 3	7, 7		Ferro-Magnet	Ferro-Magnet	Ferro-Magnet	8, 3
	0.1, 9	.24, 18					0.3, 10
2.89	2.62	2.50	2.24	2.48	2.50	2.49	2.56
Zr (hcp)	**Nb (bcc)**	**Mo (bcc)**	**Tc (hcp)**	**Ru (hcp)**	**Rh (fcc)**	**Pd (fcc)**	**Ag (fcc)**
No Coupling	9.5, 2.5	5.2, 3		3, 3	7.9, 3	No Coupling	No Coupling
	.02, *	.12, 11		5, 11	1.6, 9		
3.17	2.86	2.72	2.71	2.65	2.69	2.75	2.89
Hf (hcp)	**Ta (bcc)**	**W (bcc)**	**Re (hcp)**	**Os (hcp)**	**Ir (fcc)**	**Pt (fcc)**	**Au (fcc)**
No Coupling	7, 2	5.5, 3	4.2, 3.5		4, 3	No Coupling	No Coupling
	.01, *	.03, *	.41, 10		1.85, 9		
3.13	2.86	2.74	2.74	2.68	2.71	2.77	2.88

fcc bcc
hcp complex cubic

Element	
A_1 (Å)	ΔA_1 (Å)
J_1 (erg/cm²)	P (Å)
r_{ws} (Å)	

S.S.S.P.Parkin
Phys. Rev. Lett. 67 (1991) 3598

A_1: spacer thickness for first AF peak
ΔA_1: range of spacer thickness for first AF region
P: oscillation period
J_1: coupling strength

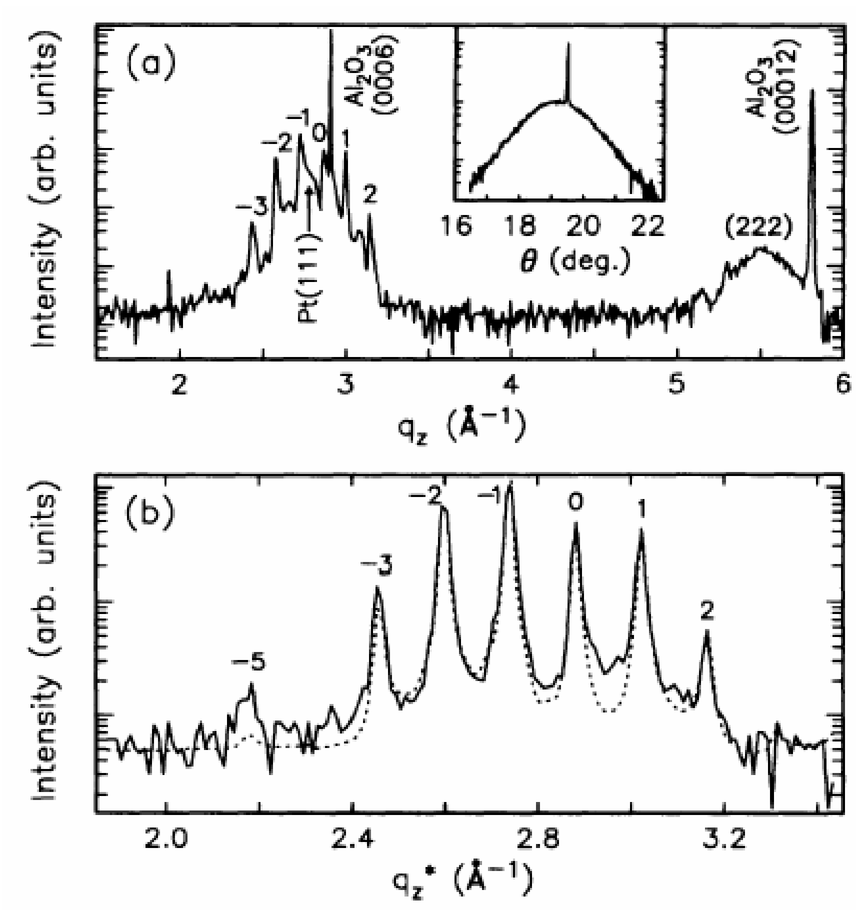
Interpretation: RKKY like coupling mediated by the conduction electrons of the spacers.

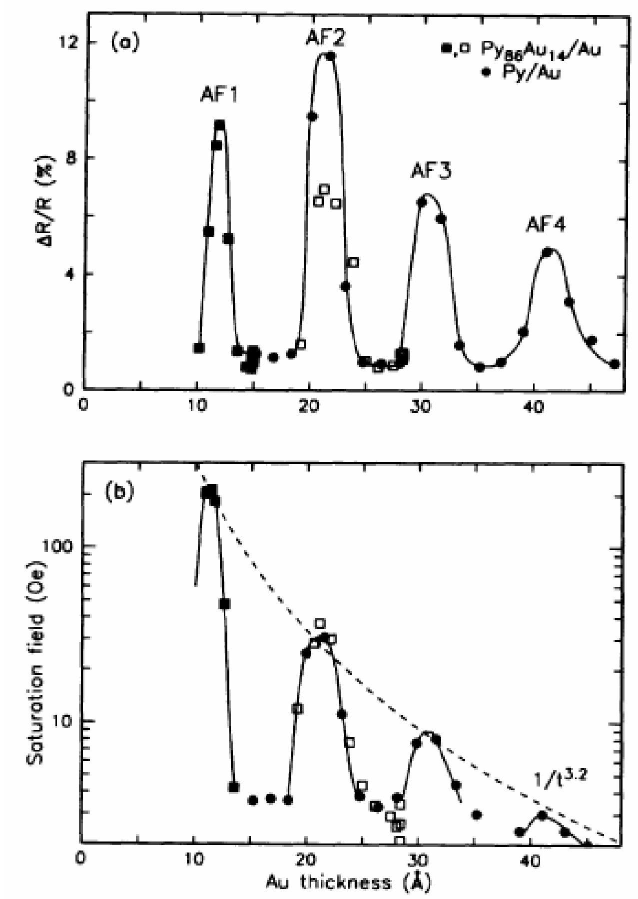
First observation of oscillatory coupling in Co/Cu/Co epitaxial systems:
A.Cebollada, et al. J. Magn. Magn. Mat. **102** (1991) 25.

GMR and oscillatory coupling in epi Permalloy/Au superlattices

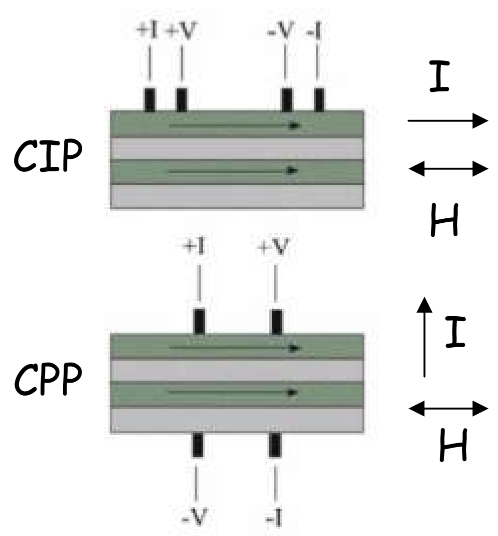
Parkin et al., Phys. Rev. Lett. **72** (1994) 3718

A whole series of superlattices grown in a raw in a commercial VG MBE system (IBM) and using a 6 cm long substrate + wedge technique





Further improvements in GMR: CIP vs CPP



Requirements for the observation of GMR:

Antiparallel vs parallel arrangement of magnetizations.

Electrons have long enough mean free path to sample at least two consecutive FM layers.

Electrons can undergo spin dependent scattering at the FM - non FM interfaces

CPP seems promising.

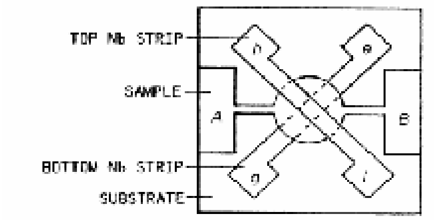
Problem:

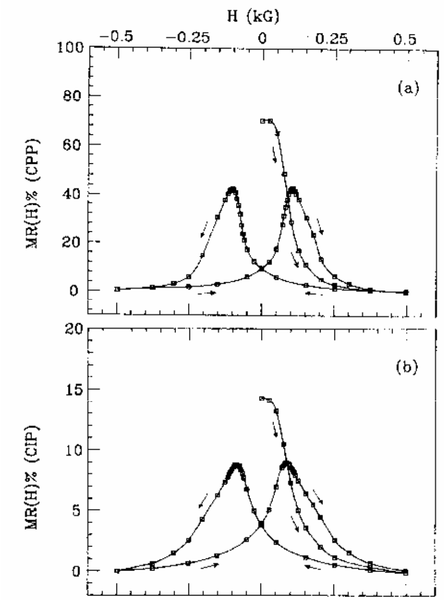
CIP: resistances of the order of 0,01 - 1 Ω

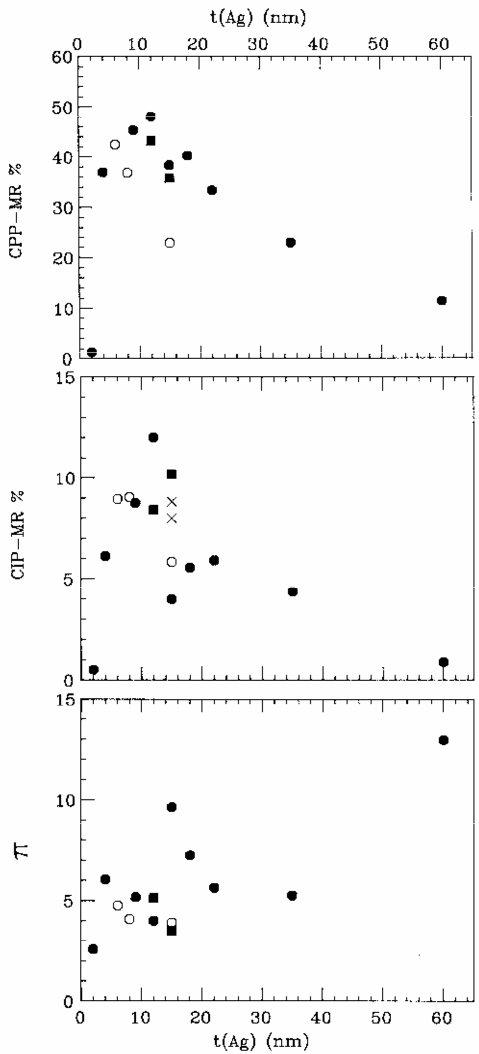
CPP: $1mm^2$ sample 1μm "long" is 10^{-7} - 10^{-8} Ω

GMR in CPP structures

Pratt et al., PRL **66** (1991) 3060
Ag/Co multilayers (uncoupled or FM coupled)
Grown on and capped with supercond. Nb
(two terminal technique)







CPP-MR: qualitatively same variation with t_{Ag} than CIP-MR.

MR does not oscillate with t_{Ag}: FM coupled or ouncoupled Co layers.

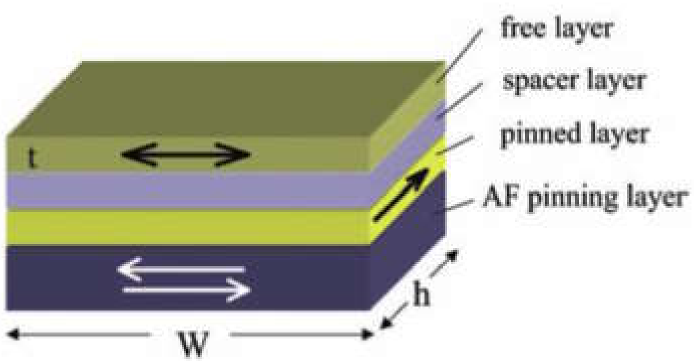
CPP-MR: max. value of 50%.

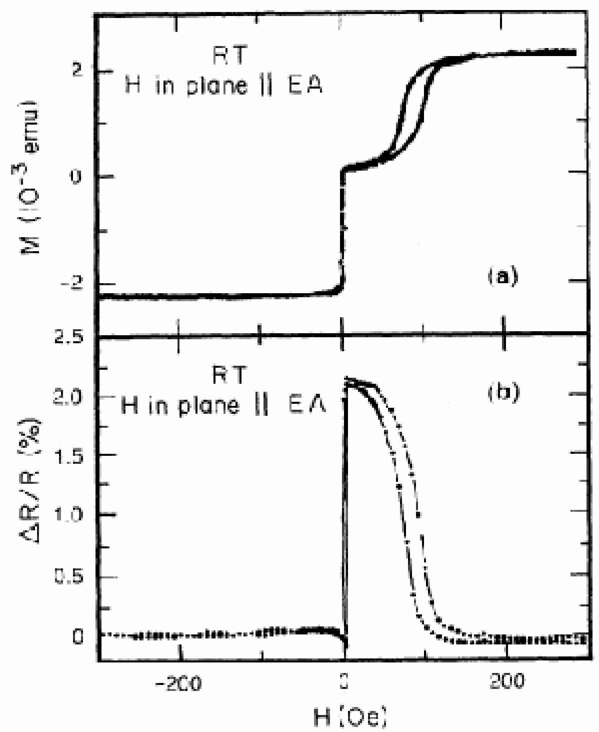
CPP-MR between 3 and 15 times larger than CIP-MR.

GMR in Spin Valves: SPIN VALVE EFFECT

Dieny et al., Phys. Rev. B 43 (1991) 1297.

GMR effect in uncoupled NiFe layers separated by Cu, Ag, Au.
Sputtered on Si substrates
Top NiFe layer magnetization pinned by exchange bias to antiferromagnetic FeMn.



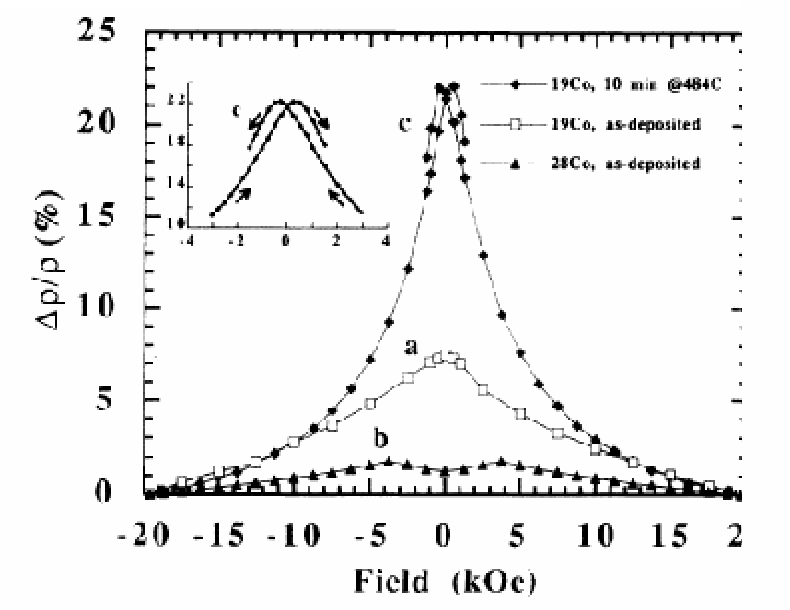


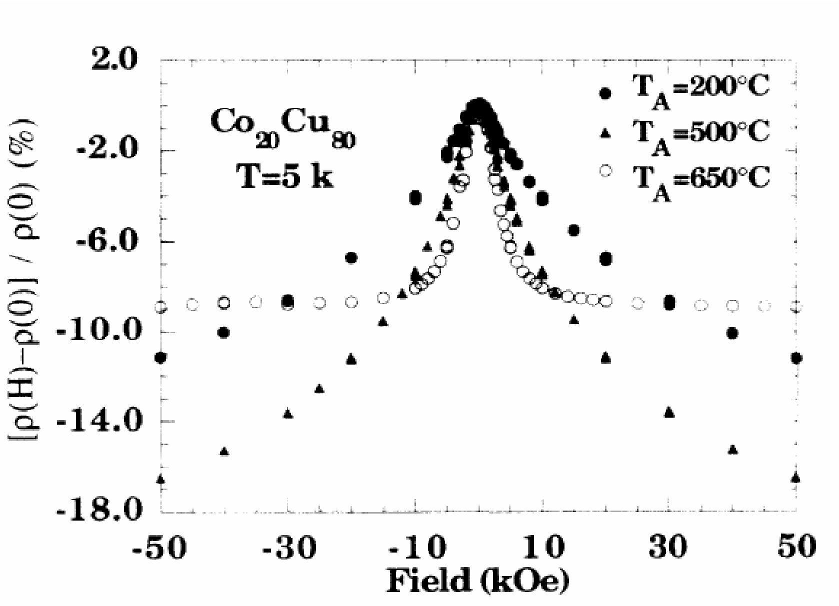
GMR: 5% in 10 Oe at RT
TECHNOLOGICALLY RELEVANT!

GMR in granular alloys

Berkowitz et al., PRL **68** (1992) 3745 and Xiao et al., PRL **68** (1992) 3749

One doesn't even need continuous films and/or multilayered structure.
Co-Cu: Excellent candidate. Very large GMR in multilayers + zero Co solubility in Cu.
Co nanoparticles embedded in a Cu matrix:Random magnetization orientation at zero field + spin dependent scattering at the particle-matrix interface

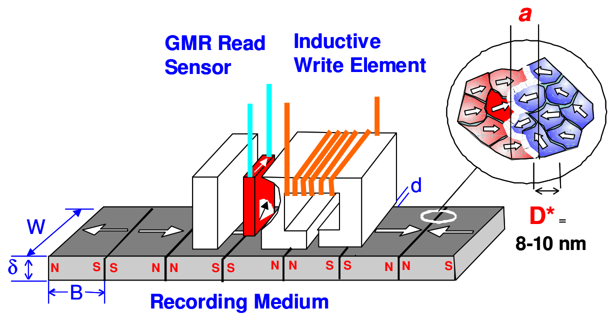




GMR: Applications

Benefits:	GMR	HALL	AMR
Physical Size	Small	Small	Large
Signal Level	Large	Small	Medium
Sensitivity	High	Low	High
Temperature Stability	High	Low	Medium
Power Consumption	Low	Low	High
Cost	Low	Low	High

Magnetoelectronics:
Hard disk drives



Non mangetoelectronic applications: Speed and Position detection. General Field Detection in Implantable Medical Devices• Wheel Speed Sensing for ABS Brake Applications• Transmission Gear Speed Sensing for Shift Control• Low Field Detection in Currency Applications• Current Sensing in PCB Traces and Wires• Overcurrent and Short Circuit Detection• Vehicle Detection for Traffic Counting Applications• Magnetic Encoder Detection for Secure Safe Applications• Position Sensing for Shock Absorber Feedback Control• Earth's Field Detection for Revolution Counting ….

TMR

TMR

Very similar effect to GMR in CPP geometry.

Observed when the interlayer is insulating and tunneling of electrons between the ferromagnetic ectrodes across the interlayer occurs: spin dependent tunneling.

Very challenging from the technical realization of the devices point of view.

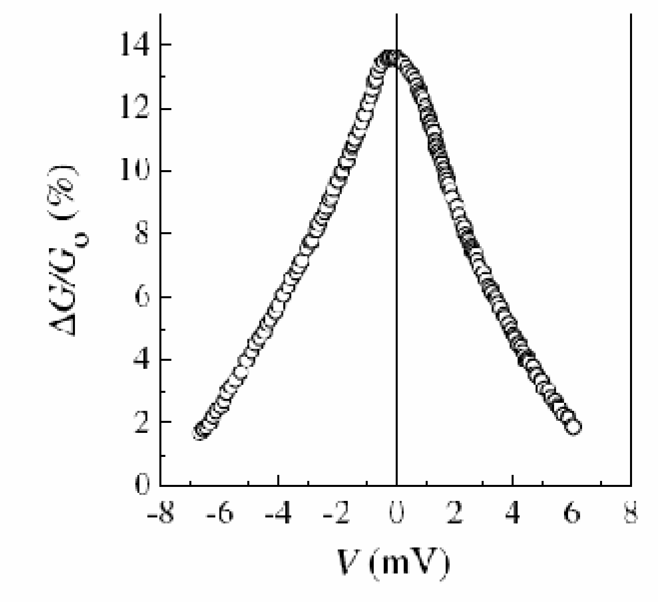
Basically two methods to fabricate tunnel junctions: shadow mask ("bottom up", more universal) and post growth lithography ("top down", more for epi systems)

No pinholes are allowed in the barrier: 1 single pinhole in the whole junction area and the device is shorted.

Mostly Al_2O_3 amorphous barrier used.

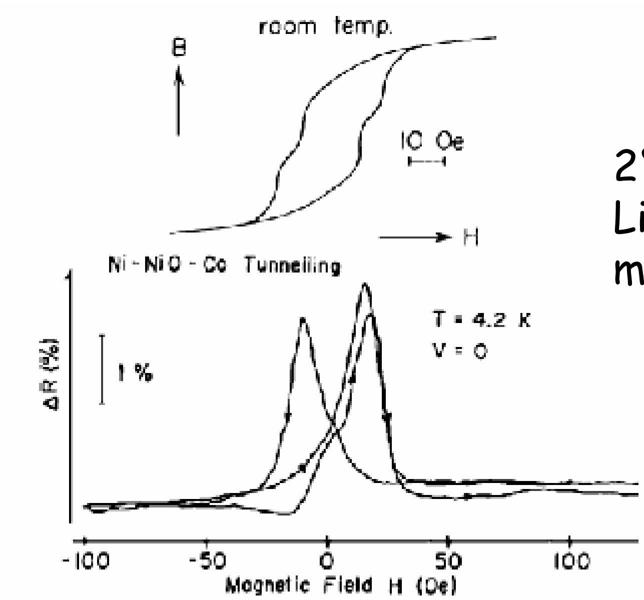
Julliere's experiment: The original demonstration of TMR effect

Julliere, M. Phys. Lett. **54A** (1975) 225.
14% TMR in Fe/Ge/Co at 4.2K
Oxidized amorphous Ge barrier



TMR: Maekawa and Gäfvert

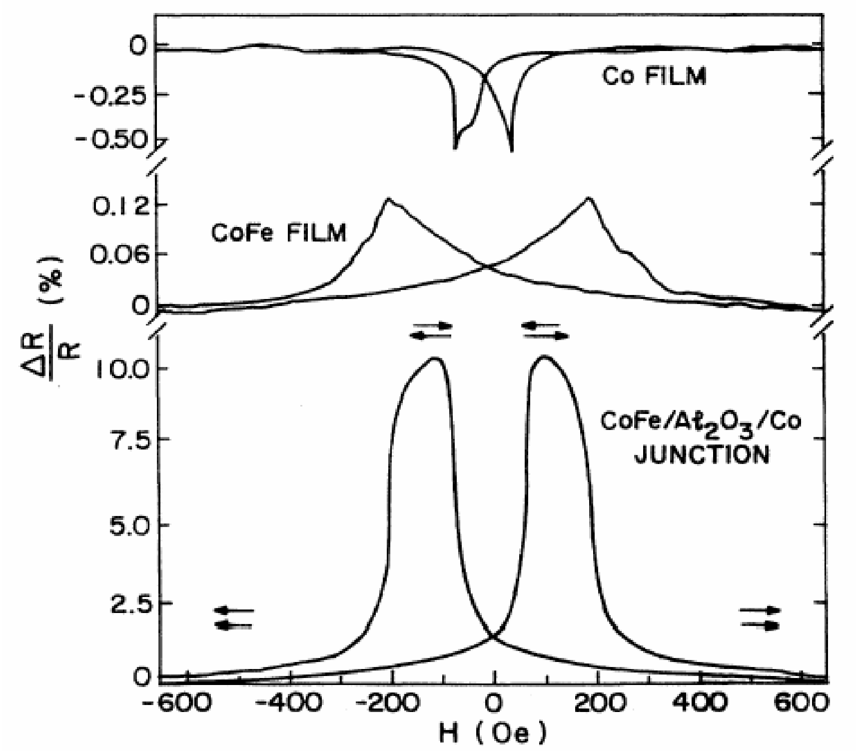
Maekawa and Gäfvert IEEE Trans. Magnet. 18 (1982) 707



2% TMR at 4.2 K
Link of the hysteresis behaviour of the magnetic electrodes with the observed MR

TMR rediscovered: Moodera

Moodera et al., Phys. Rev. Lett. 74 (1995) 3273.
First TMR result obtained for $CoFe/Al_2O_3/Co$ at RT



Electrodes sputter deposited.
Al at LN2 + oxidation for barrier formation.

TMR depends on barrier height,width and kind of material.

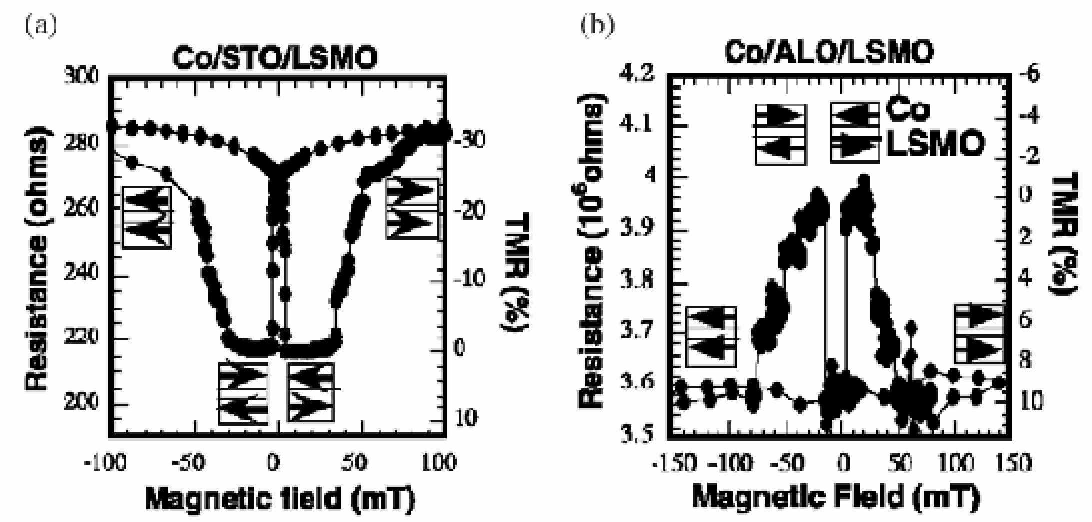
The higher the spin polarization of the tunneling electrons, the higher the TMR (half metallic materials have great potential relevance).

TMR: a myriad of works since Moodera's '95 paper

Parkin
Freitas
De Teresa
.....

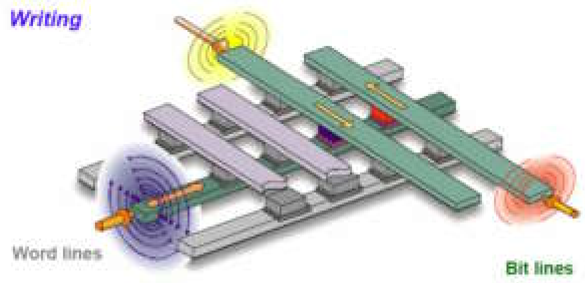
De Teresa et al, Science **286** (1999) 507

Tunneling effects are determined by the electronic structure at the intefaces



Main TMR application: MRAM
Magnetic Random Access Memory

Technological relevance of TMR: MRAM

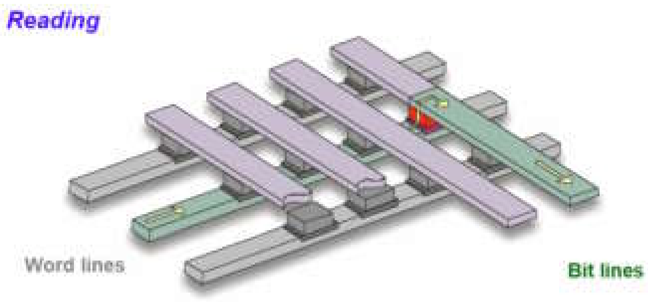


Fast, dense, non-volatile, cheaper universal memory. Projected by some to become a $50 billion industry by 2010.

Nearly every major tech company now has a hand in MRAM.

Each magnetic tunnel junction is a memory cell that stores a single bit of data.

To write in such a cell, one need only apply a magnetic field to flip the spin orientation of one of the layers.



www.forbesnanotech.com; november 2004, vol 4 #2.

Advantages of storing info with MRAM

RAM:

Use charge to represent data: need to be supplied with a constant flow of electricity.

In the event of a power outage or a system crash in a computer running regular RAM, the data is lost the second the electricity stops flowing.

Memory cells need to be refreshed thousands of times per second, which uses up a significant amount of electrical power.

MRAM:

Spin is much more stable (once the spins are aligned, they stay that way unless you apply a magnetic field to flip them): Non volatile.

Spin orientation, on the other hand, stays put, so an MRAM computer doesn't lose data.

Therefore a computer running on MRAM uses much less power. Specially advantageous in portable electronic devices.

MRAM vs other volatile or non volatile memories

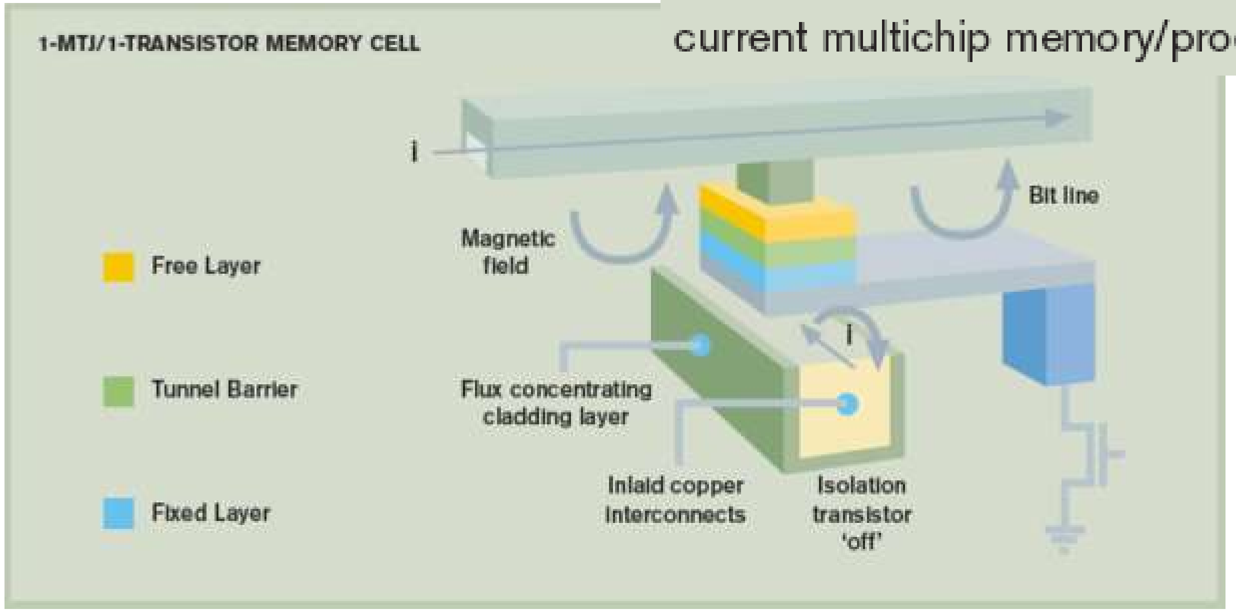
MRAM is expected to offer other significant performance advantages over existing memory technologies. It is expected to have better write characteristics because it does not require high-voltage programming while Flash memory does. It could eliminate the lengthy boot-up times for computers and other electronic devices. MRAM is expected to substantially reduce the battery power drain for portable electronic devices because it does not require the background refreshing of DRAM.

Boot-up process unnecessary: "computers that turn on and off as quickly and easily as a light switch.

Launched by Motorola
freescale™ semiconductor

MRAM: ready integration

Because MRAM is readily integrated with conventional complimentary metal-oxide semiconductor (CMOS) processes, single-chip solutions can considerably reduce the cost of current multichip memory/processor applications.



MRAM cell is based on a single transistor and magnetic tunnel junction (MTJ) structure. The MTJ structure is integrated on top of the transistor to achieve a small cell size.

<u>MRAM vs other non volatile memories</u>

Nonvolatile memories, such as hard disk and Flash, store instructions and data from operating systems and individual programs, and transfer them to the processor when needed. This transfer can become a bottleneck and hinder the processor performance. MRAM stores this same information, but with the capability to deliver it directly to the microprocessor without creating a bottleneck.

Launched by Motorola
freescale™
semiconductor

Overall comparison

COMPARISON OF EXPECTED MRAM FEATURES WITH OTHER MEMORY TECHNOLOGIES				
	SRAM	**DRAM**	**Flash**	**MRAM**
Read Time	Fast	Moderate	Moderate	Moderate-Fast
Write Time	Fast	Moderate	Slow	Moderate-Fast
Nonvolatile	No	No	Yes	Yes
Refresh	N/A	Yes	N/A	N/A
Minimum Cell Size	Large	Small	Small	Small
Low Voltage	Yes	Limited	No	Yes

Launched by Motorola freescale™ semiconductor

Companies working on MRAM production

Alliances involving multi-billion dollar companies:

Freescale - Philips - STMicroelectronics (chipmaker company)

IBM - Infineon (Germany-based): commercialize MRAM through a new company called Altis Semiconductor.
(the first mass-produced spintronic device was developed by IBM)

IBM - Stanford University : IBM-Stanford Spintronic Science and Applications Center.

NEC - Toshiba.

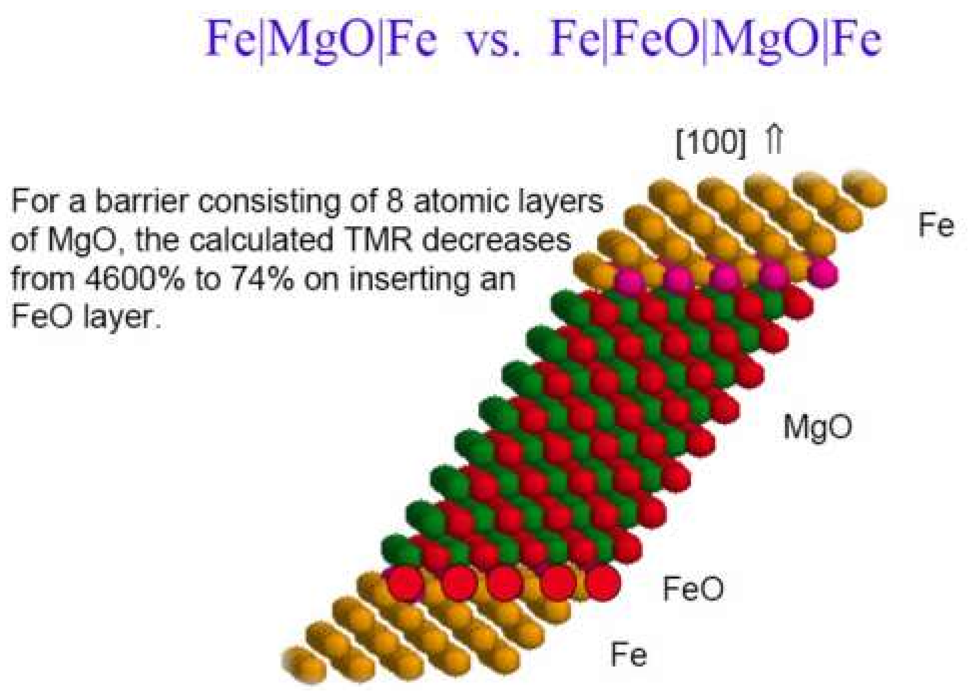
Hewlett-Packard - Samsung - Sony - Renaissance - Intel.

TMR: technological impact; but can we go any further?

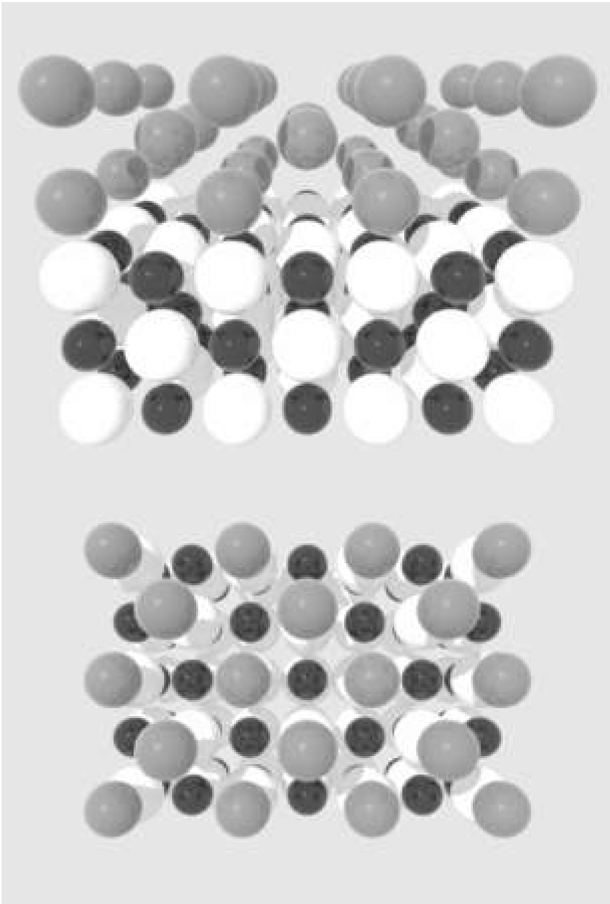
Amorphous Al_2O_3: most commonly used barrier
Max. TMR at RT < 70%
It doesn't seem to go much higher.

TMR: can we go any further?

Fully epitaxial Fe/MgO/Fe.
Theoretical predictions:
Butler et al., PRB 63 (2001) 054416
Mathon et al., PRB 63 (2001) 220403R



Fe/MgO/Fe(001) : a model system



Fe: bcc; a = 2.866 Å
MgO: NaCl; a = 4.213 Å

-3.8% mismatch upon 45° in plane lattice rotation

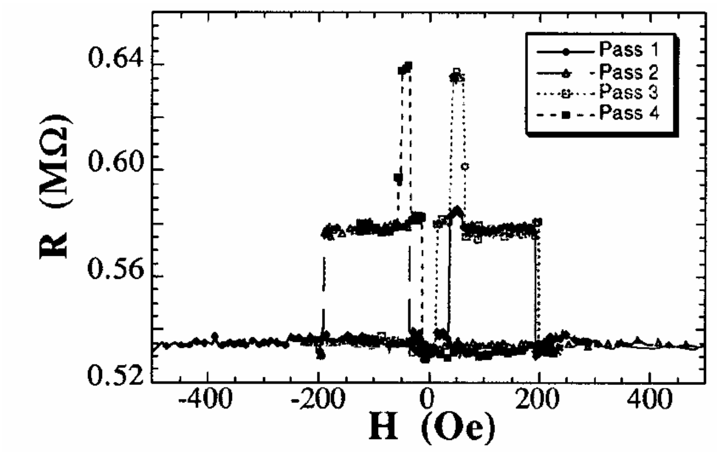
Epitaxial relations:

Fe(001)[110] // MgO(001)[100]

Fe atoms sit on top of O ions (4 Mg ions as next nearest neighbours)

TMR with MgO barriers

First results on Fe/MgO/Co policrystalline structures.
10-30 nm barrier thickness needed (pinholes)
Platt, Dieny and Berkowitz, J. Appl. Phys. **81** (1997) 5523



Fully epitaxial MTJs: our contribution

"Magnetorresistencia de uniones túnel basadas en metales ferromagnéticos de transición y óxidos epitaxiales". (Accion Integrada Hispano-Francesa)
IMM-UNR CNRS Thomson (Thales). 2000-2001

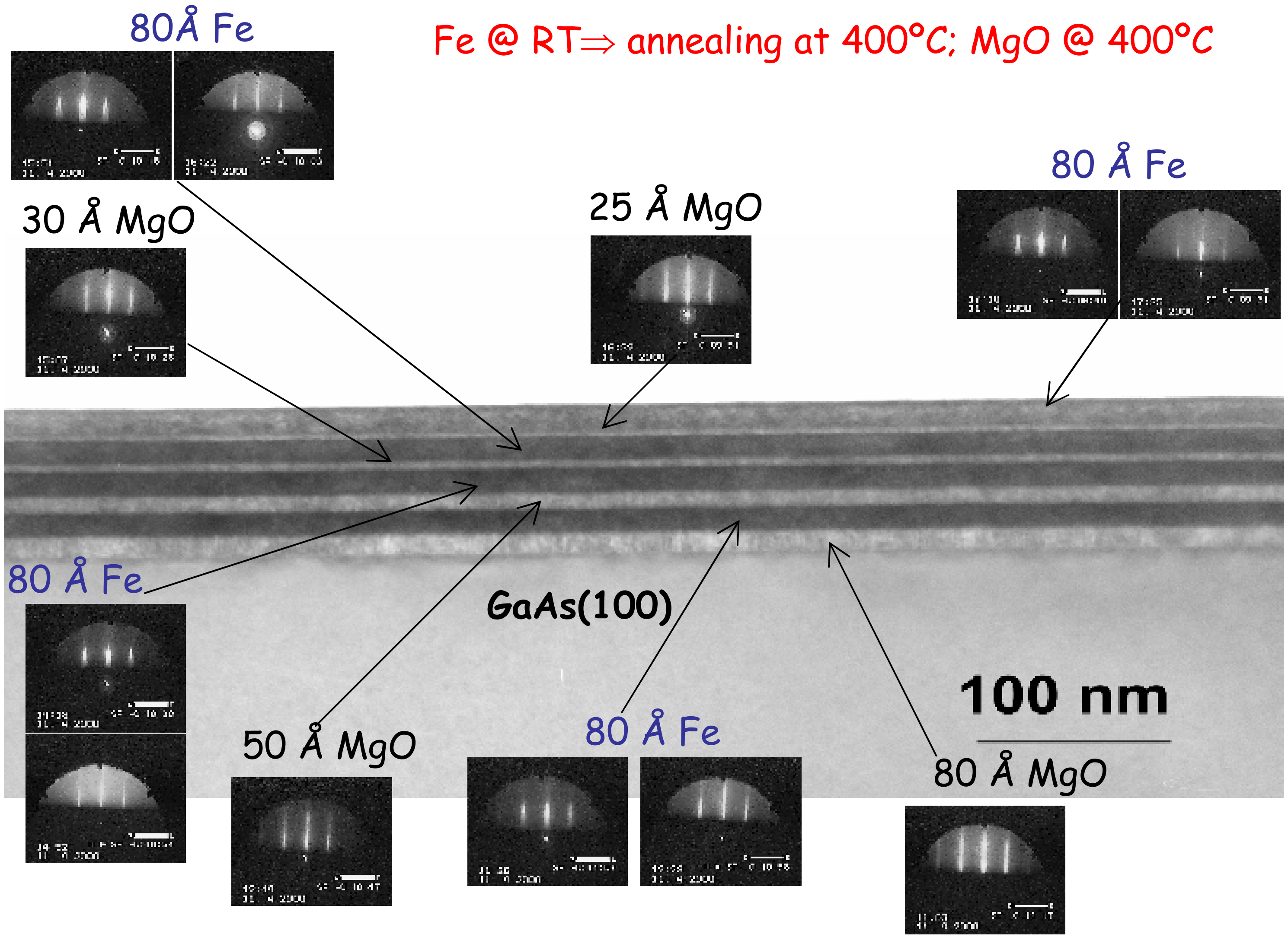
"Heteroestructuras híbridas con aplicaciones en magnetoelectrónica". MAT2000-1290-C03. 2001-2003.
IMM, Univ. Zaragoza, ICMAB

Tesis Carlos Martínez Boubeta.
U. Complutense Madrid (Oct. 2003)

Epitaxy

How to grow Epitaxial Fe/MgO superlattices on GaAs

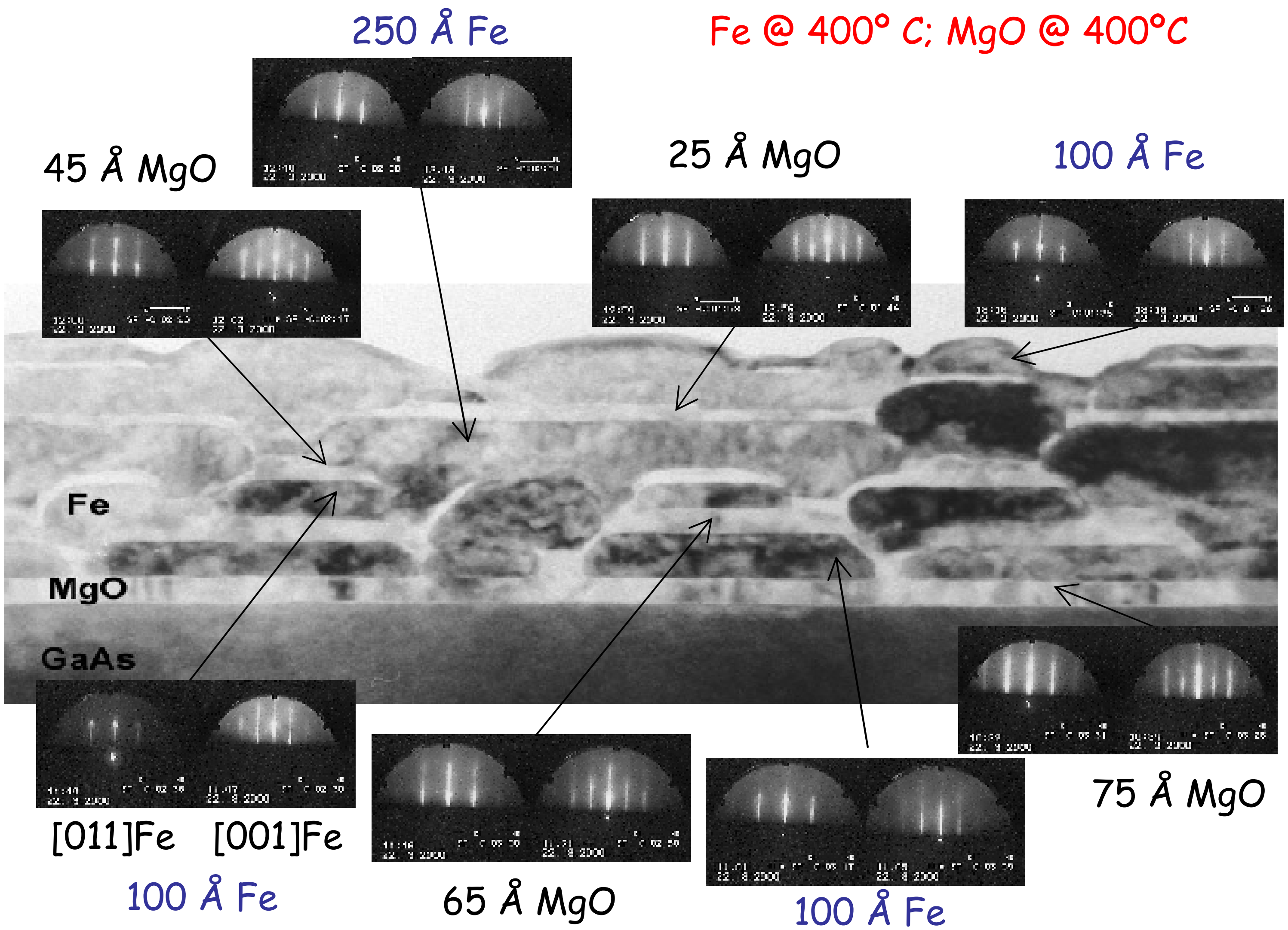
Fe @ RT ⇒ annealing at 400°C; MgO @ 400°C



C.Martínez Boubeta et al.; J. Cryst. Growth, **226 (2-3)** (2001) 223

C.Martínez Boubeta et al.; J.Phys. Cond. Mat. Topical Review **15** (2003) R1123

How NOT to grow Epitaxial Fe/MgO superlattices on GaAs



Magnetization reversal in an Epitaxial FeCo/MgO/Fe trilayer