

Anisotropie

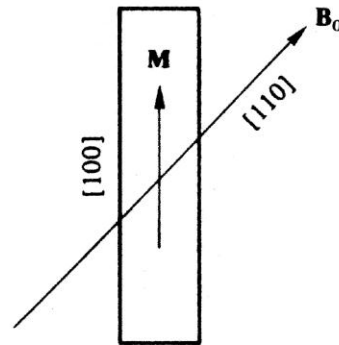


Fig. 11.36 When a single-crystal bar of Fe is magnetized in a 'difficult' direction, there is little hindrance to domain boundary movement to orient the domains in the most favourable [100] direction.

Anisotropie

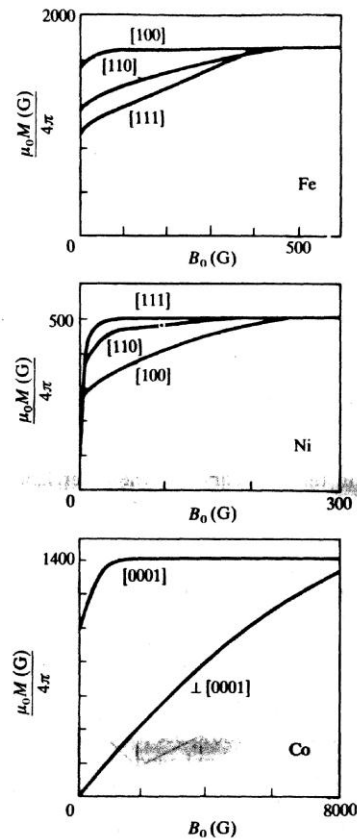


Fig. 11.31 Magnetocrystalline anisotropy as observed in Fe, Co and Ni. (After Honda and Kaya (1926).)

Ordres de grandeur:
« champs d'anisotropie »
0.01-1 Tesla pour 3d

Division en domaines

Domains and the magnetization process

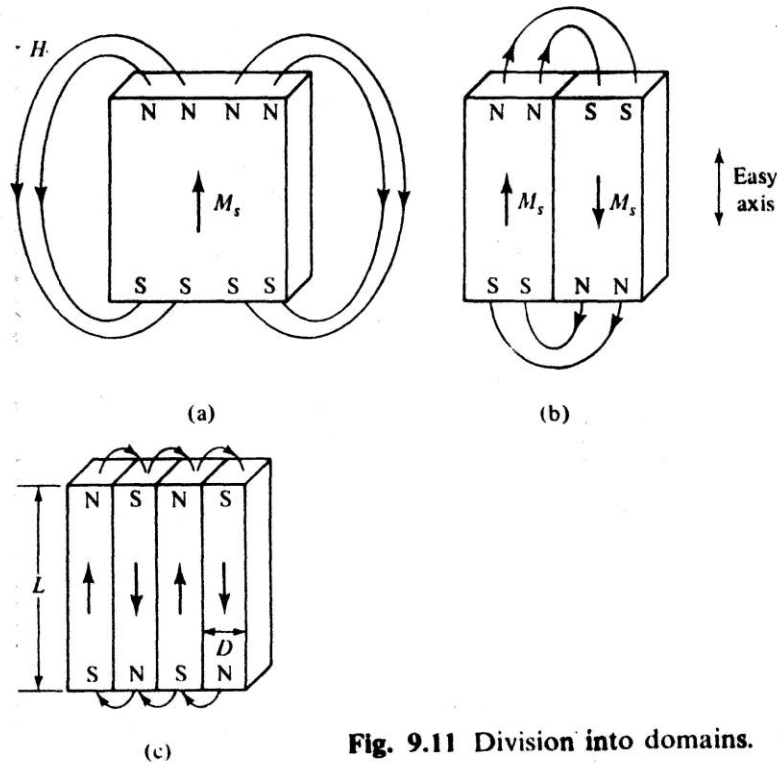
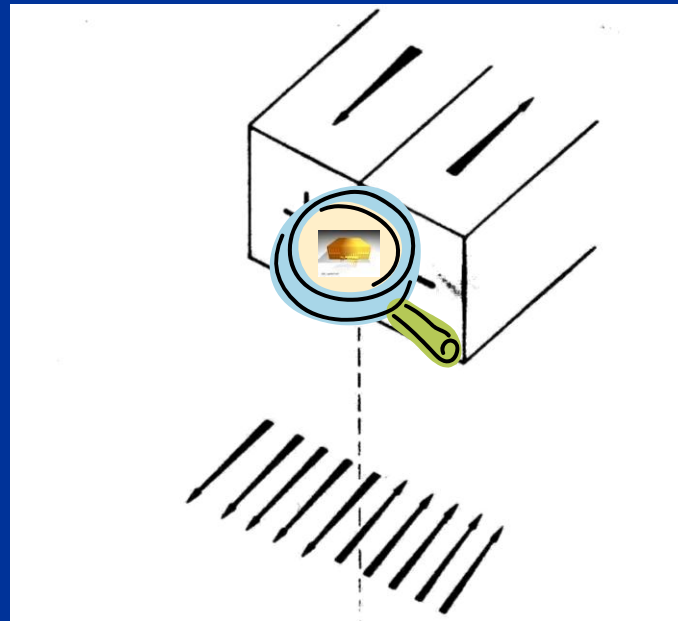
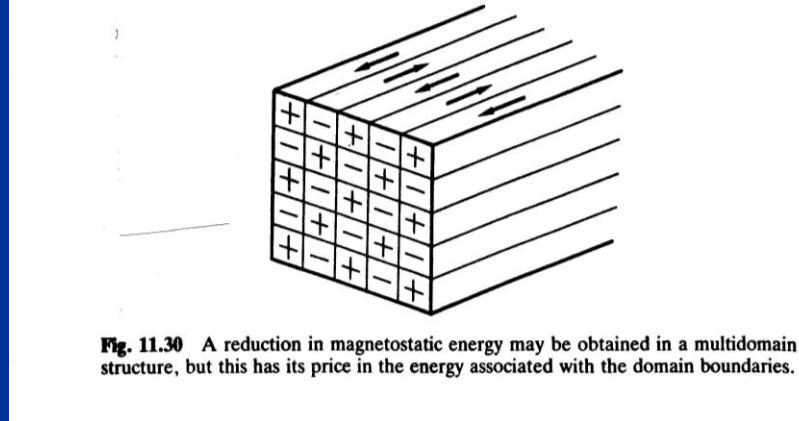
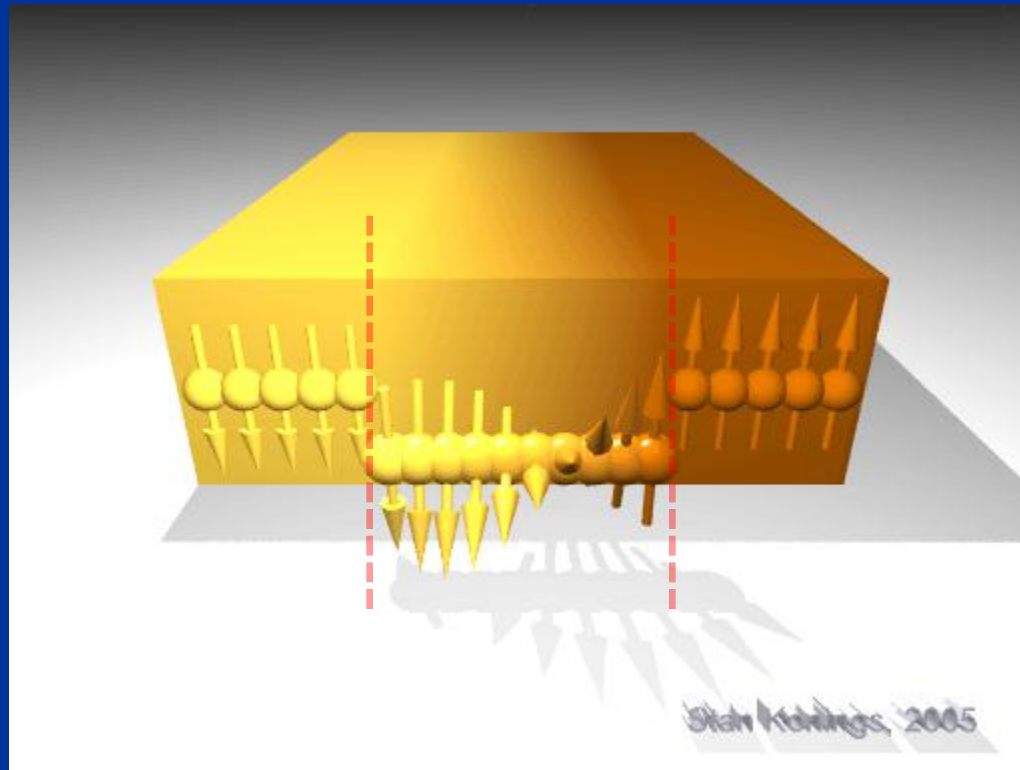


Fig. 9.11 Division into domains. (Internal H fields not shown.)

Domaines et parois



Paroi entre domaines



Division en domaines

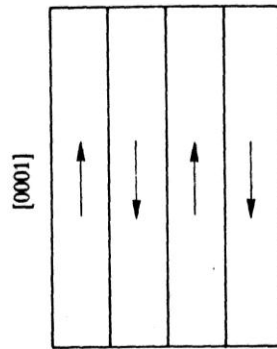


Fig. 11.34 In the highly anisotropic Co, a state of high magnetostatic energy may be preferable to one of higher energy of crystalline anisotropy.

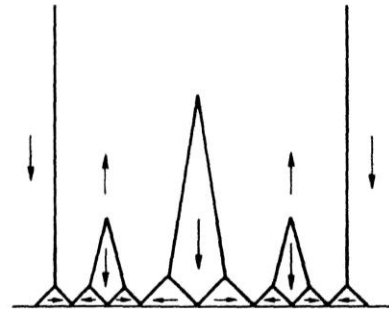


Fig. 11.35 If closure domains are to arise in Co, they must have the least possible size—the above arrangement has been suggested. (After Craik and Tebble (1965).)

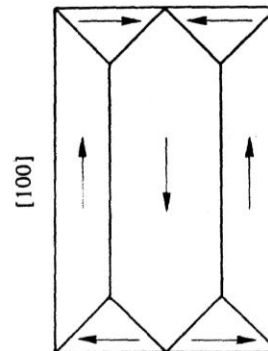
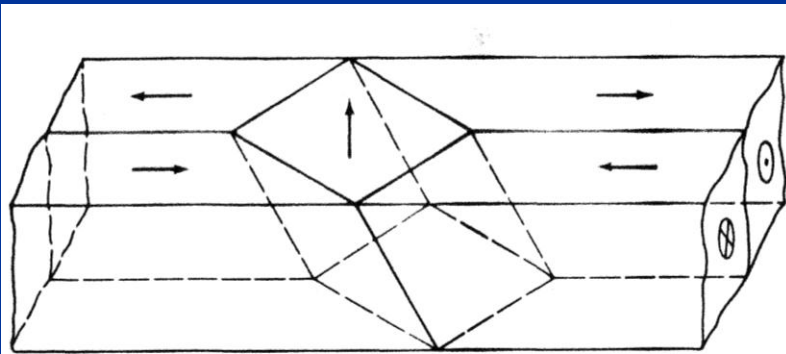
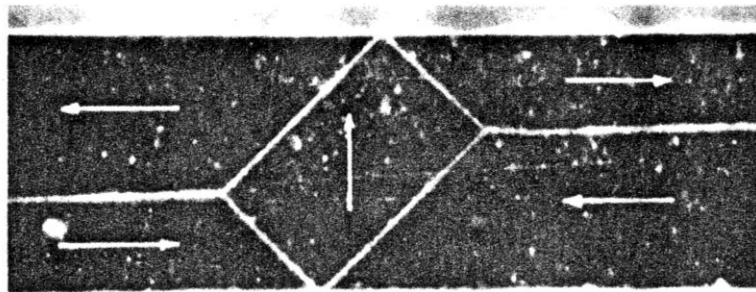


Fig. 11.33 An arrangement of closure domains that minimizes the magnetostatic energy of a single-crystal bar magnet of iron.

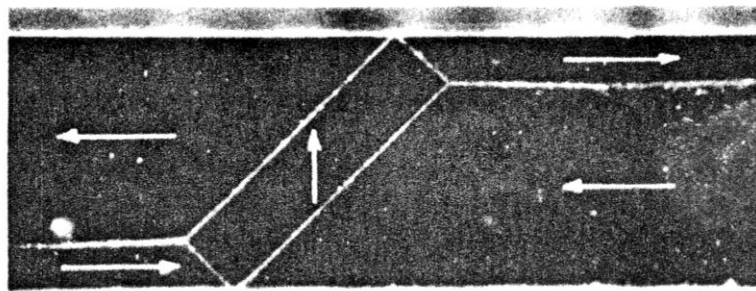
Visualisation des parois



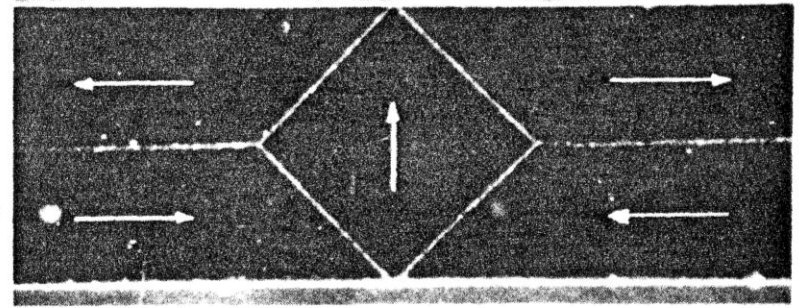
$H = 0$



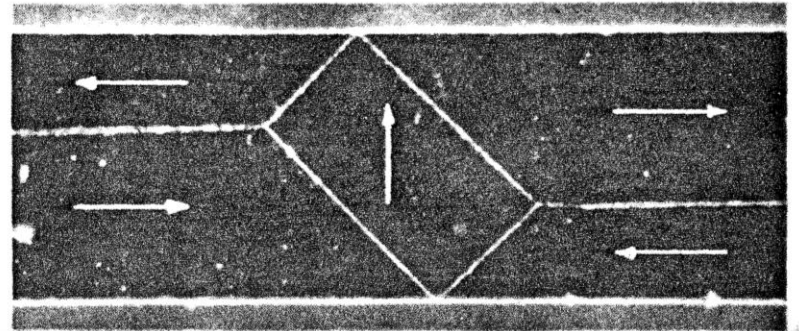
H



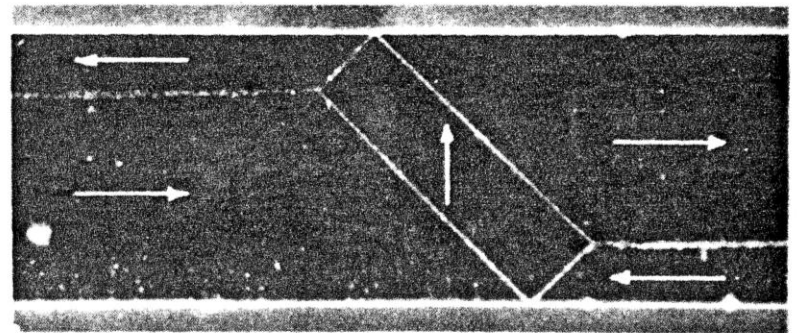
H



$H = 0$



H



H

Magnetic structures



macroscopic

atomic



permanent
magnets

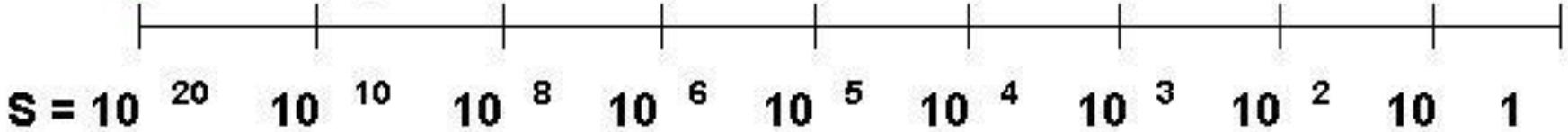
micron
particles

nanoparticles

clusters

molecular
clusters

atoms



multi - domains

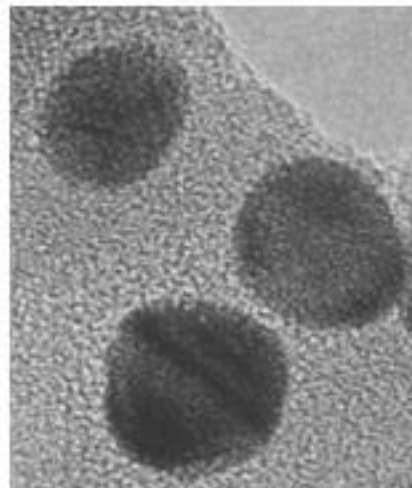
single - domains

spins

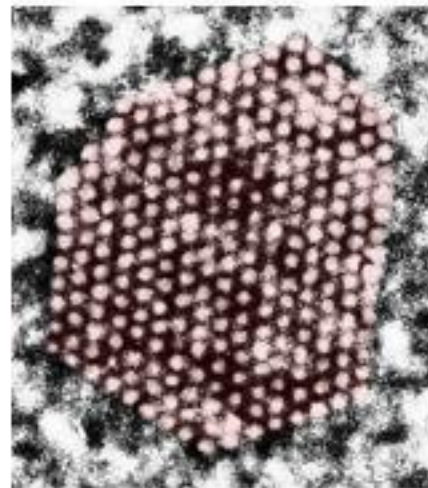
1 mm



20 nm



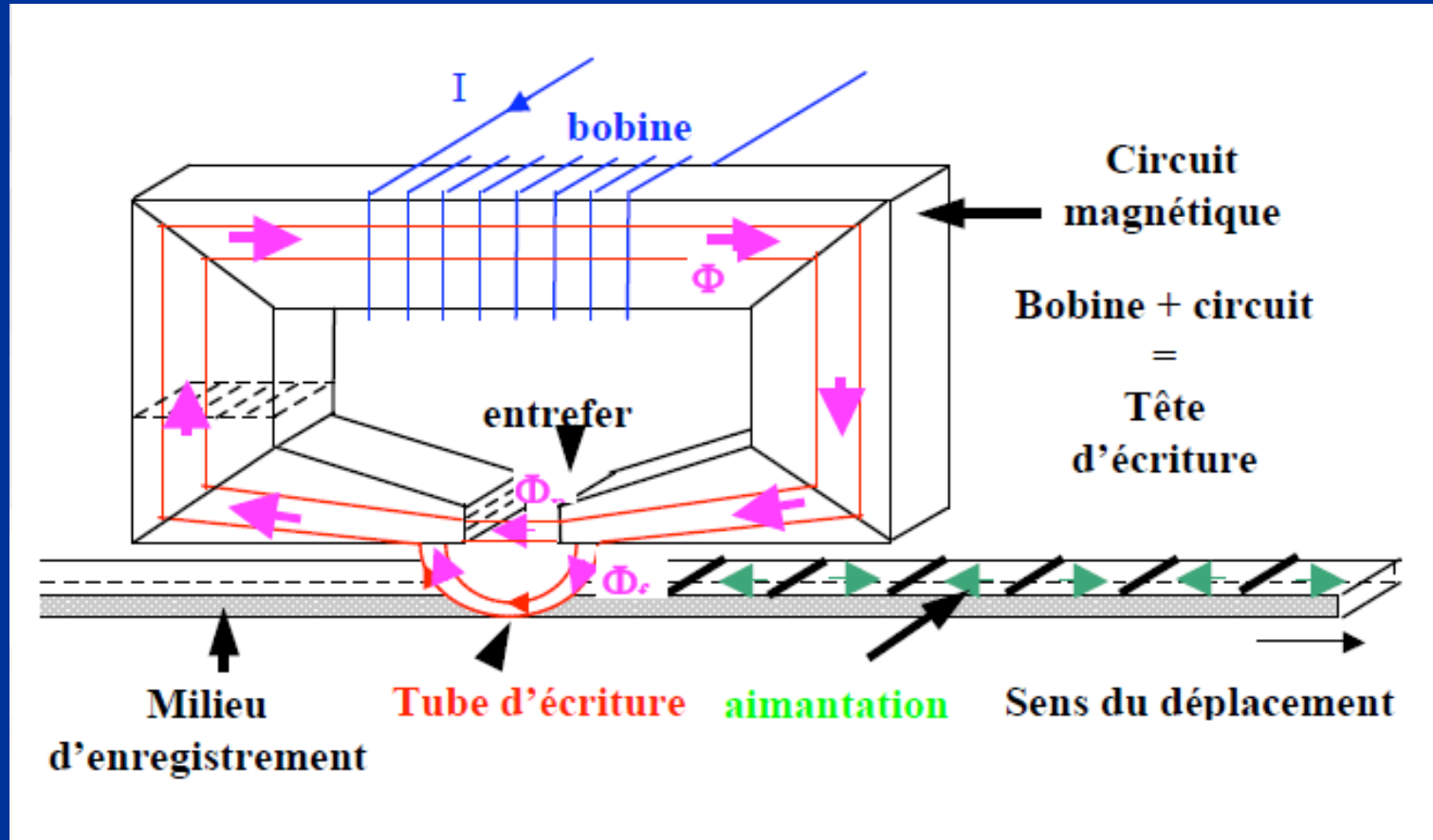
3 nm



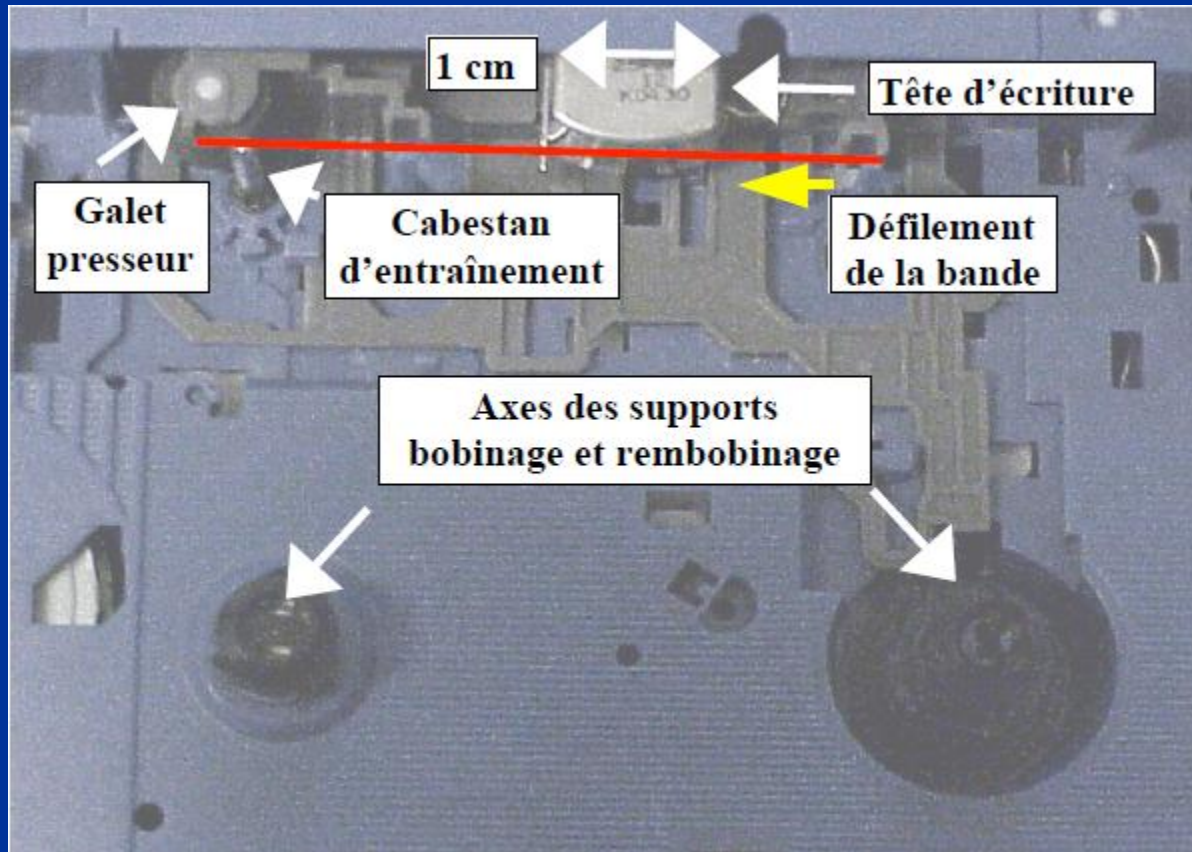
1 nm



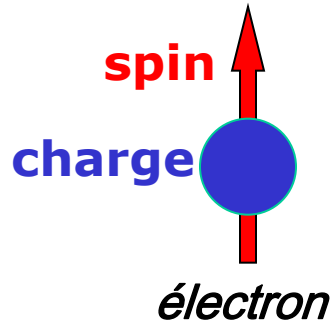
Enregistrement longitudinal



Magnétophone à cassette

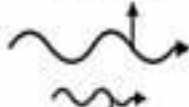


Spintronique: le spin s'invite en électronique, dans nos ordinateurs et dans nos téléphones



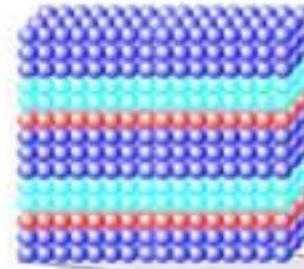
Influence du spin sur la mobilité des électrons

Électron spin up



Électron spin down

+ Nanostructures magnétiques

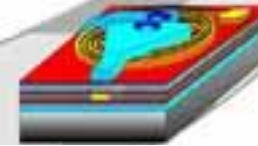
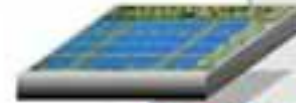


→ Spintronique



GMR, TMR, etc...

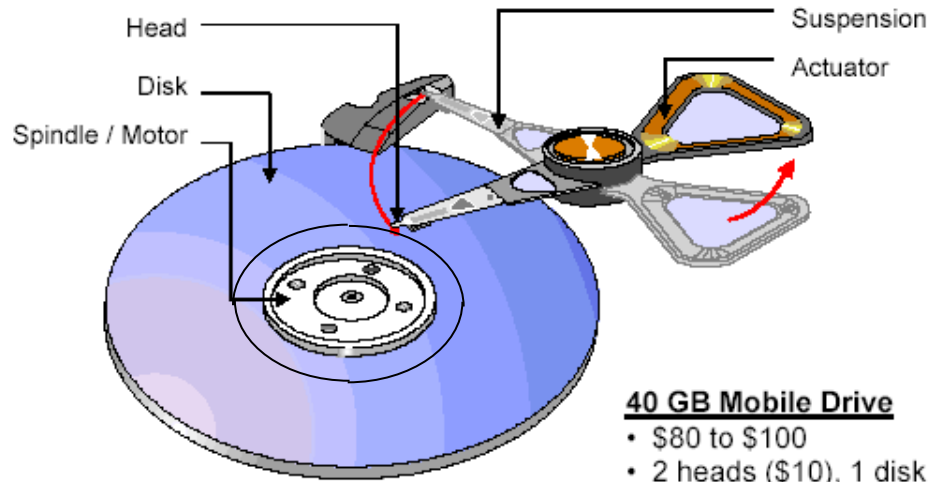
Memoire (M-RAM)



Têtes de lecture pour disque dur, capteurs, etc

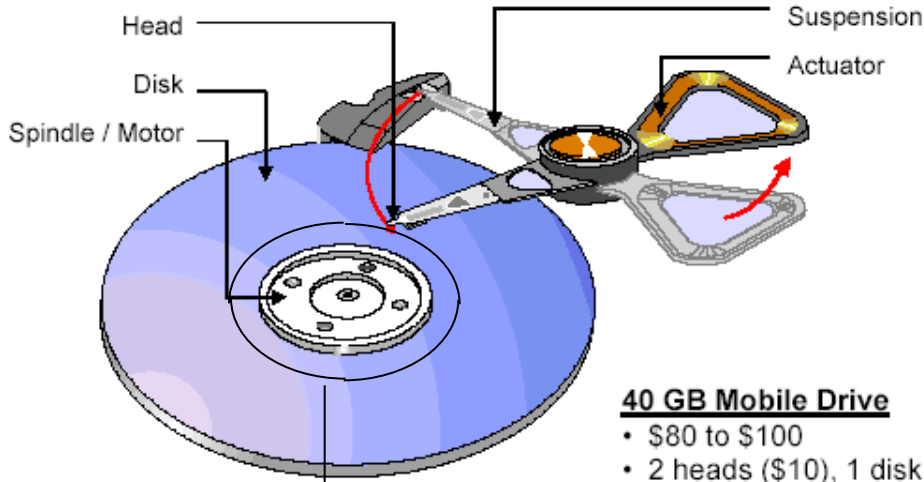
commutation magnétique et oscillations hyperfréquence par **transfert de spin**, spintronique avec **semiconducteurs**, spintronique **moléculaire**, etc

The Magnetic Recording System



40 GB Mobile Drive

- \$80 to \$100
- 2 heads (\$10), 1 disk (\$5)
- 40 Gbit/in² to 80 Gbit/in²

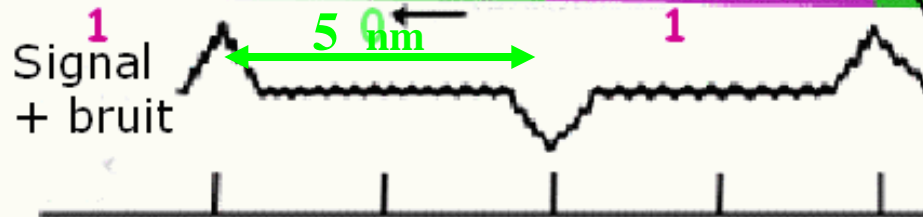
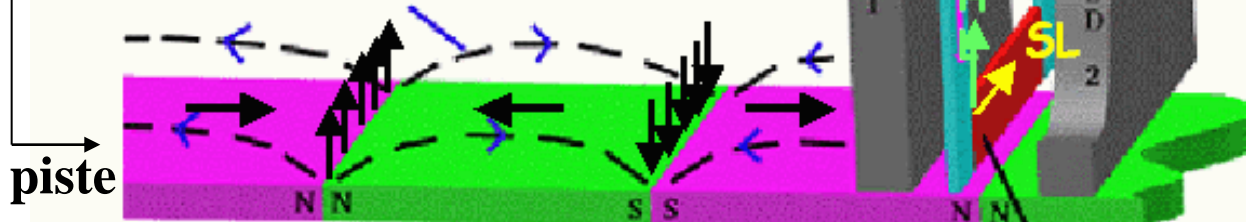


40 GB Mobile Drive

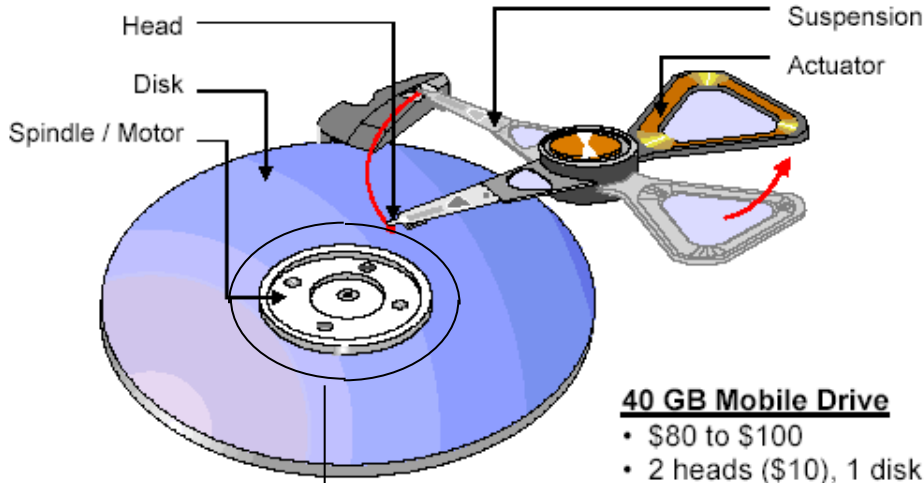
- \$80 to \$100
- 2 heads (\$10), 1 disk (\$5)
- 40 Gbit/in² to 80 Gbit/in²

**Tête de lecture
de disque dur**

Champ magnétique
créé par le média



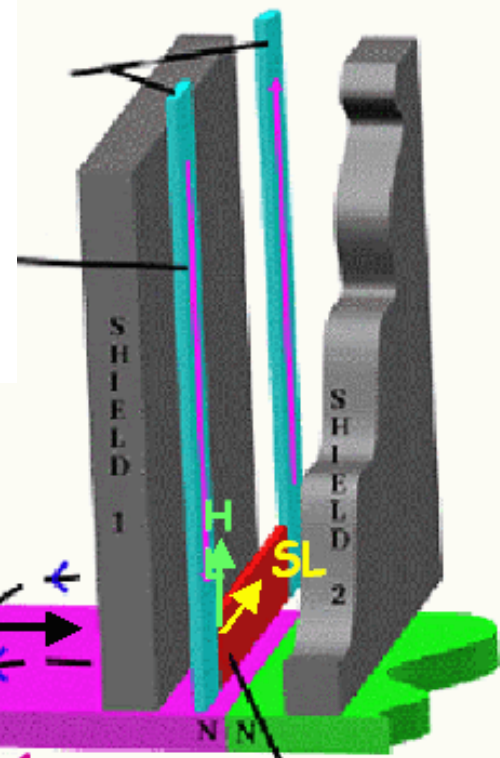
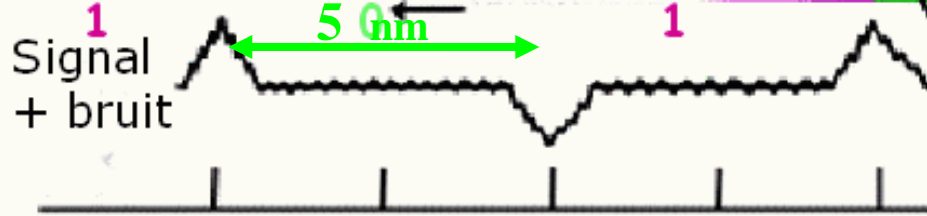
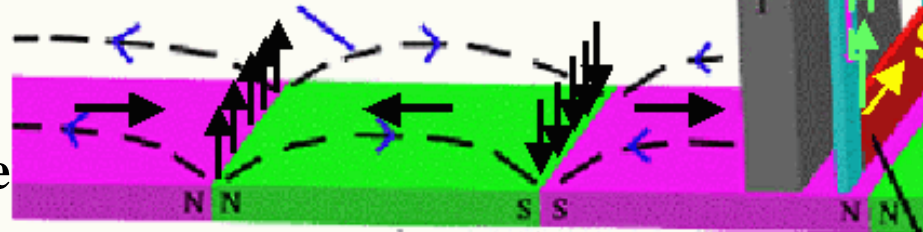
**Elément GMR
(multicouche
magnétique)**



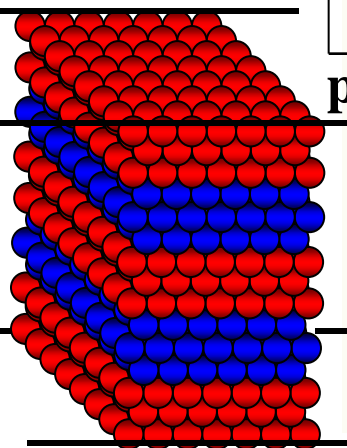
Tête de lecture de disque dur

- 40 GB Mobile Drive**
- \$80 to \$100
 - 2 heads (\$10), 1 disk (\$5)
 - 40 Gbit/in² to 80 Gbit/in²

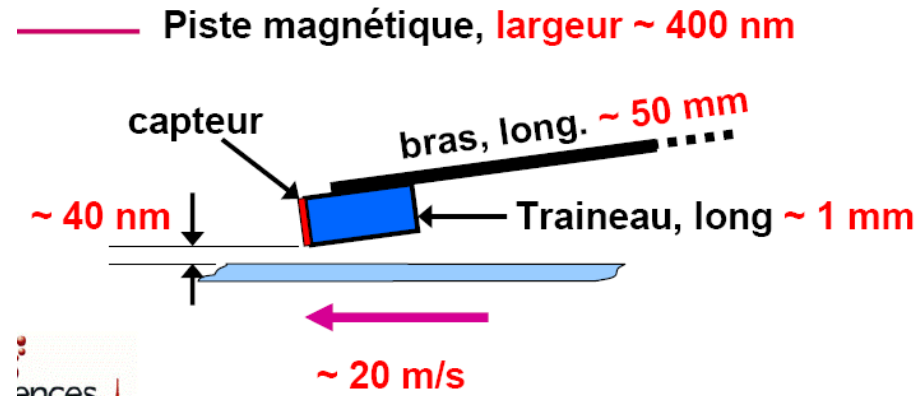
Champ magnétique créé par le média



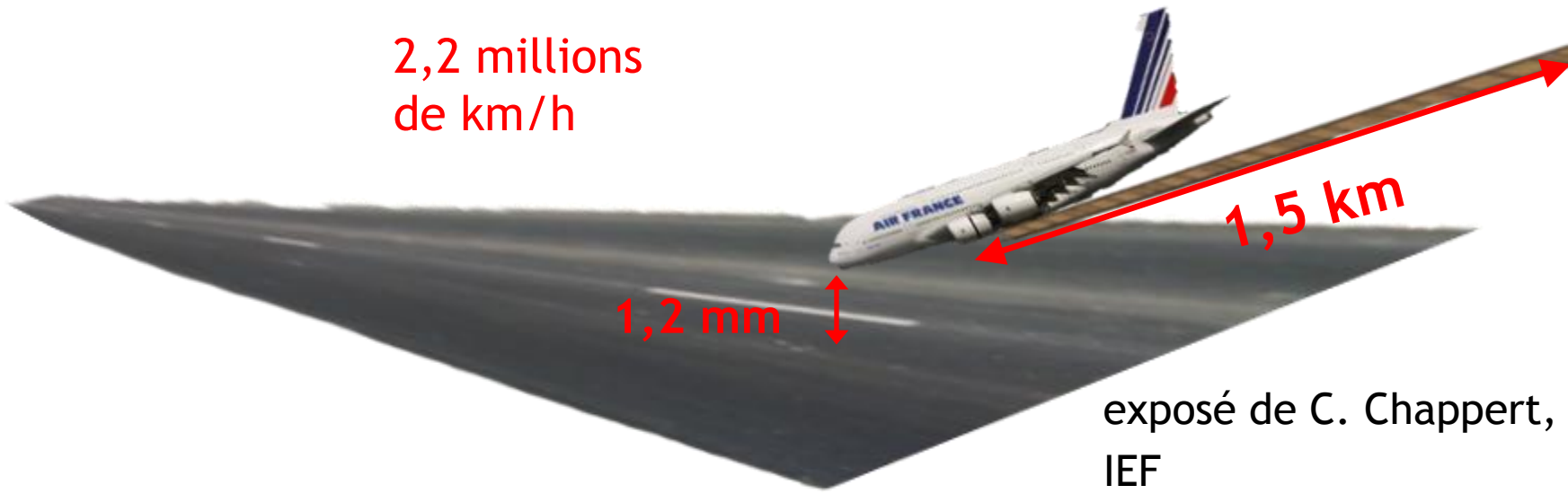
Elément GMR (multicouche magnétique)



Le disque dur



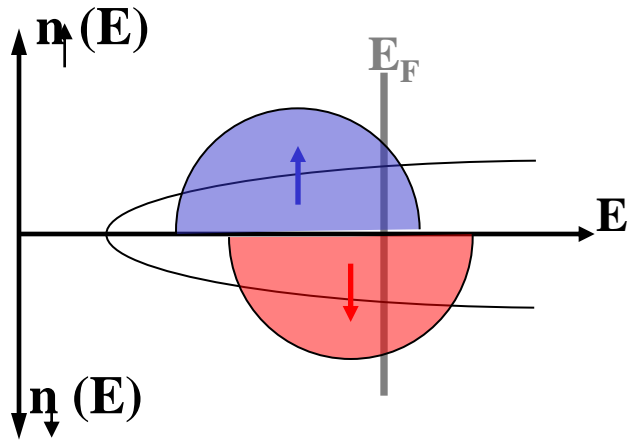
2,2 millions
de km/h



exposé de C. Chappert,
IEF

Influence du spin sur la mobilité des électrons dans les conducteurs magnétiques

(proposition de Mott en 1936 et mise en évidence en 1968)

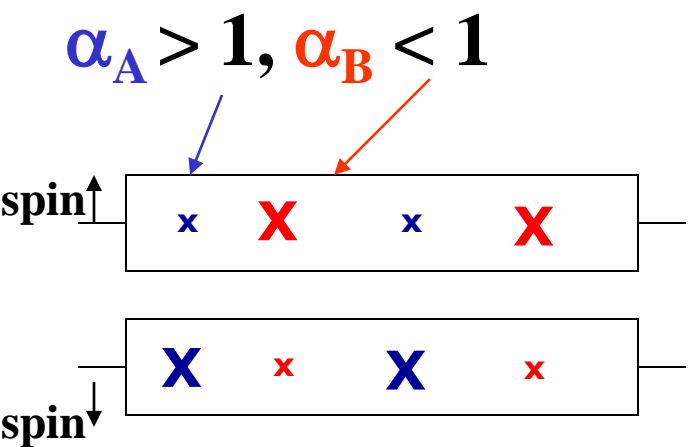


Décalage des bandes d'énergie des électrons de spin \uparrow (majoritaires) et \downarrow (minoritaires) dans un métal ferromagnétique comme le fer ou le nickel

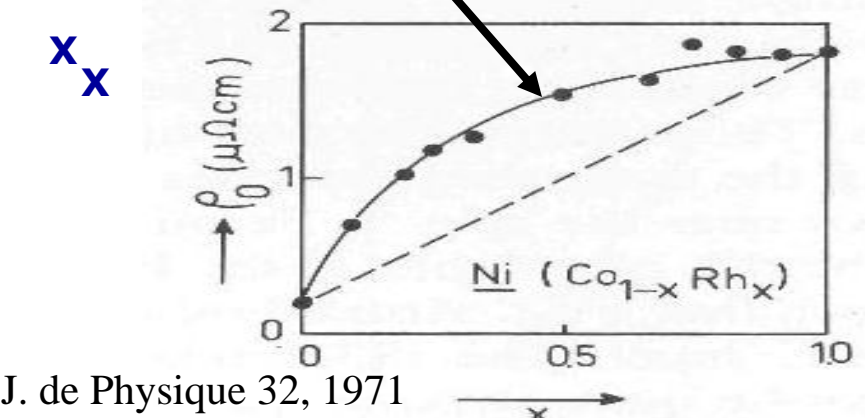
Alliages avec impuretés A and B d'asymétrie en spin opposée ou semblable : le pré-concept de la GMR

Exemple: Ni + impuretés A and B (Fert-Campbell, 1968, 1971)

1er cas



$\rho_{AB} \gg \rho_A + \rho_B$



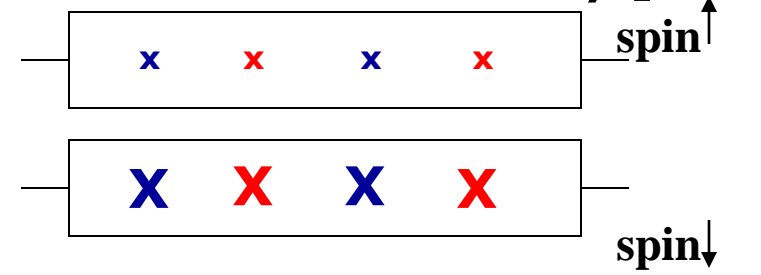
$\alpha = \rho_{\downarrow} / \rho_{\uparrow}$

X = obstacle

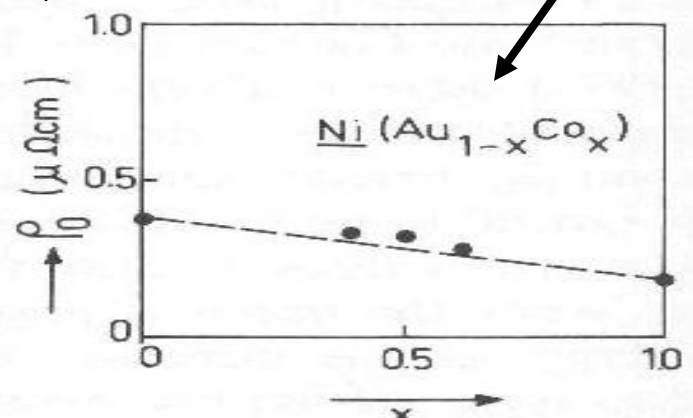
2ème cas

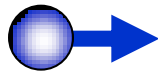
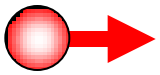
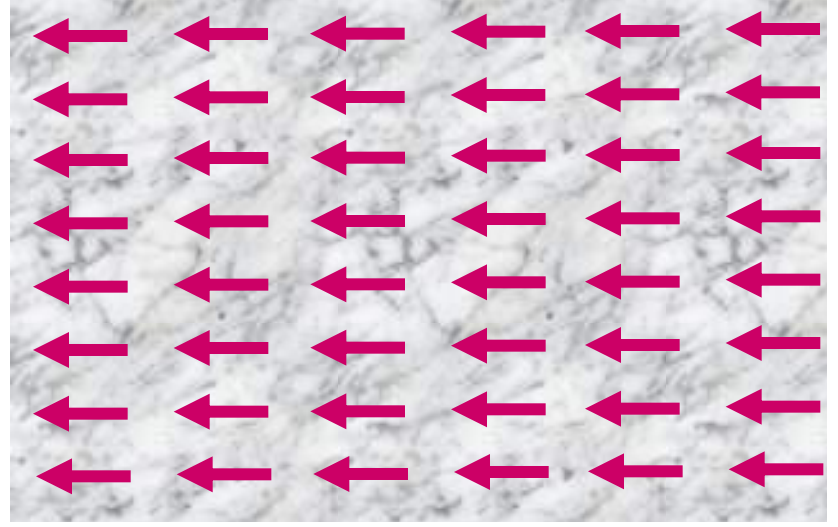
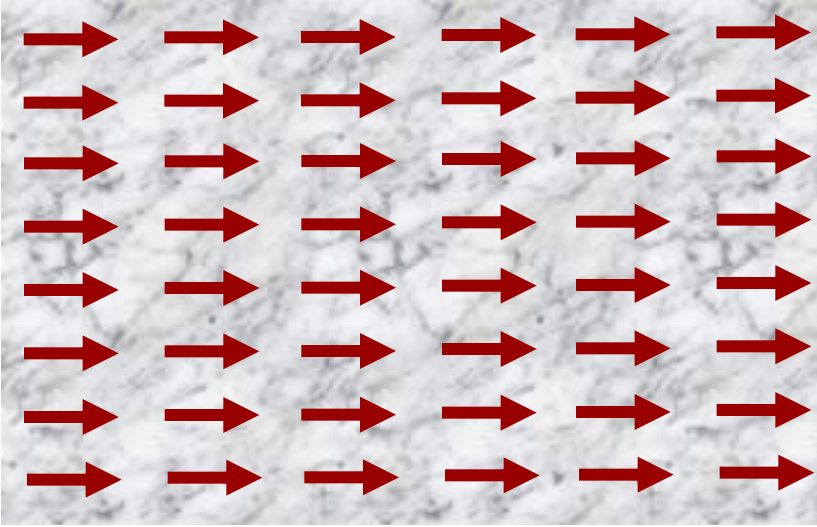
α_A and $\alpha_B > 1$

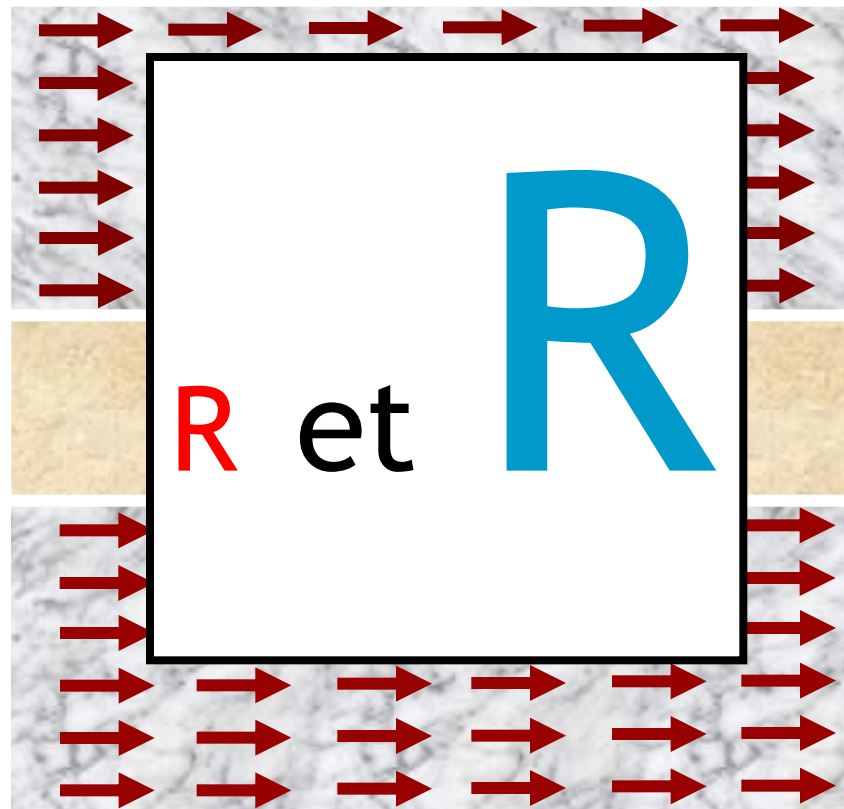
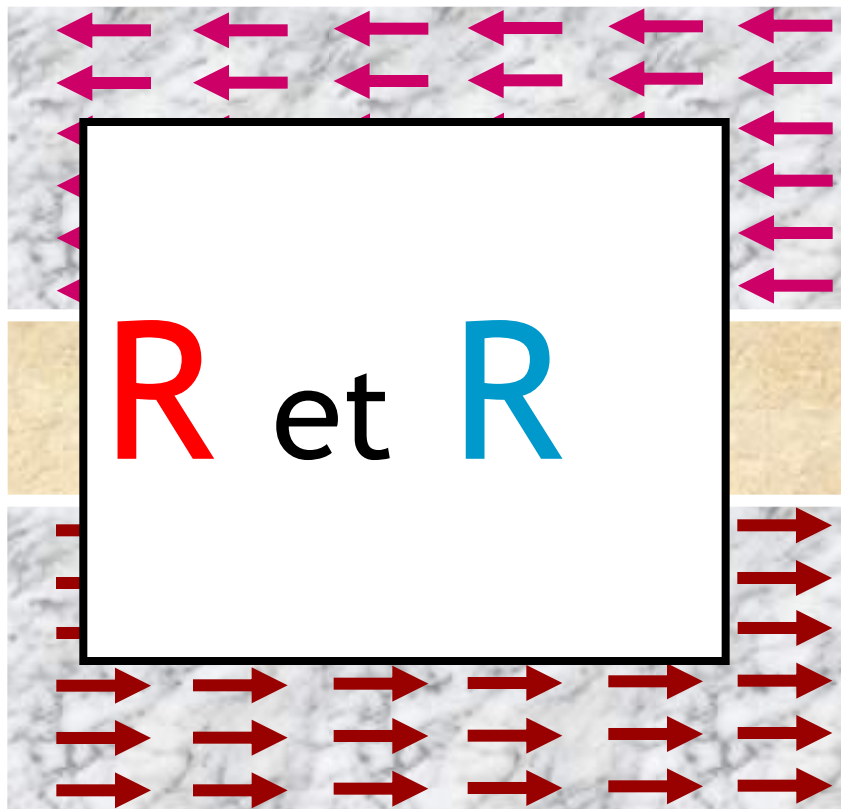
Canal de haute mobilité → ρ petit



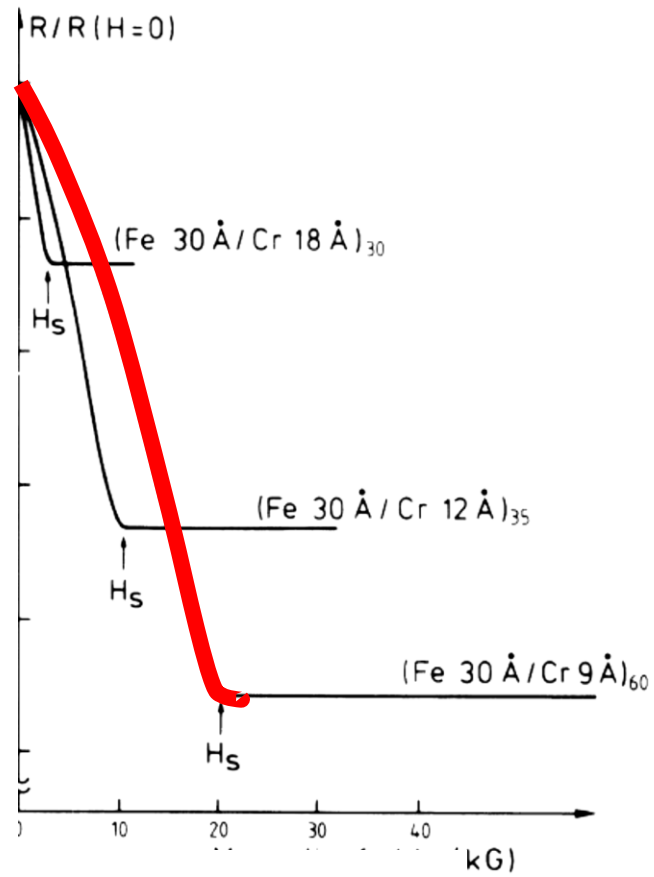
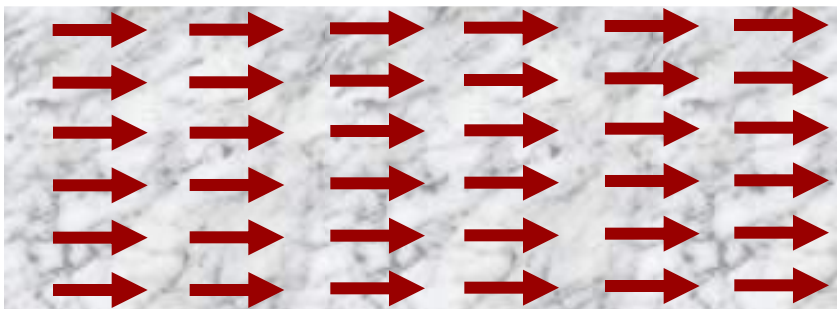
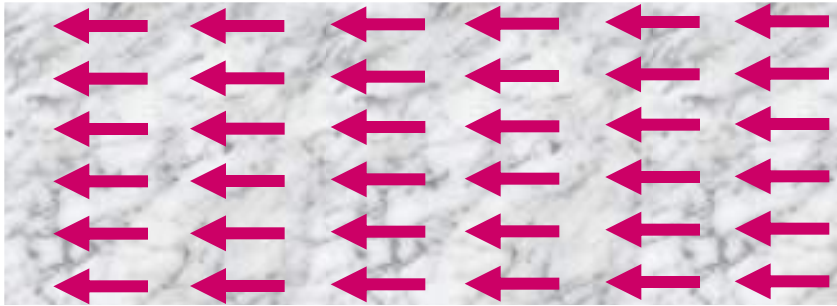
$\rho_{AB} \approx \rho_A + \rho_B$



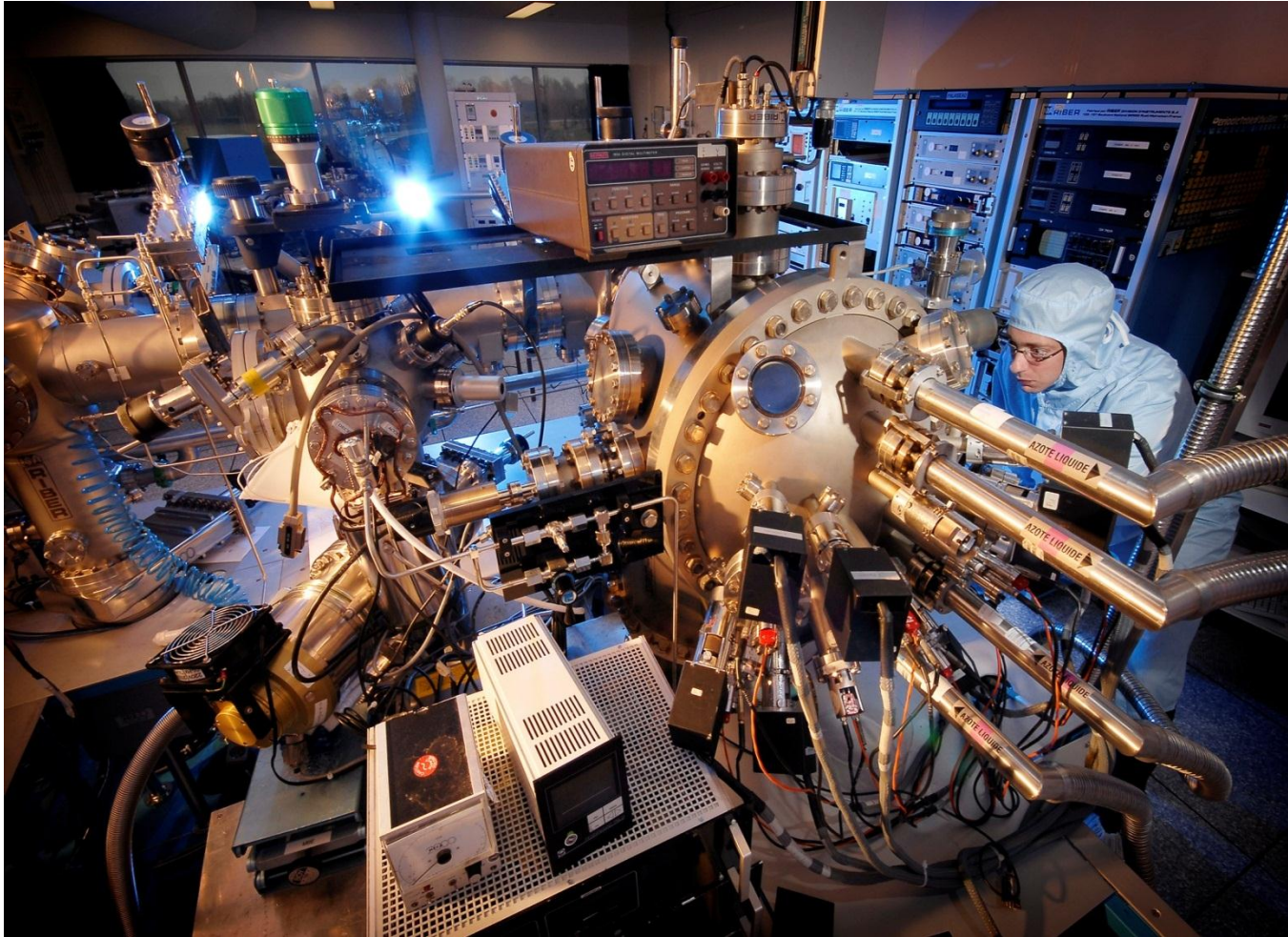




Resistance

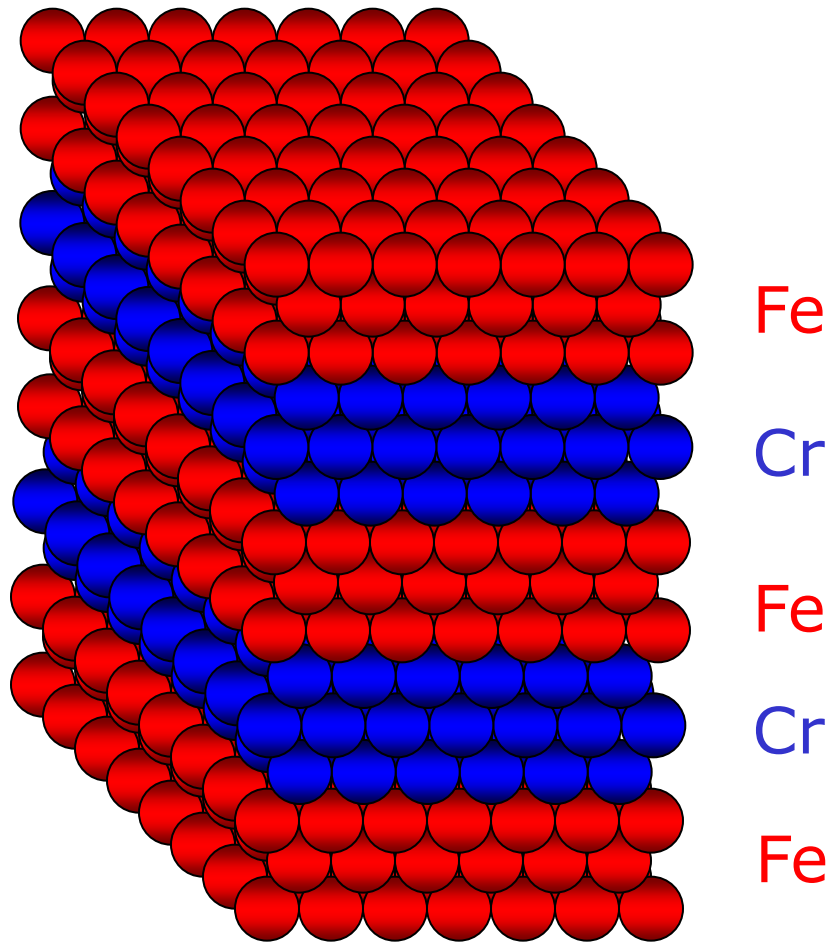


Champ magnétique



Bâti d'Epitaxie par Jets Moléculaires permettant la croissance de multicouches métalliques magnétiques (cliché CNRS/Thales)

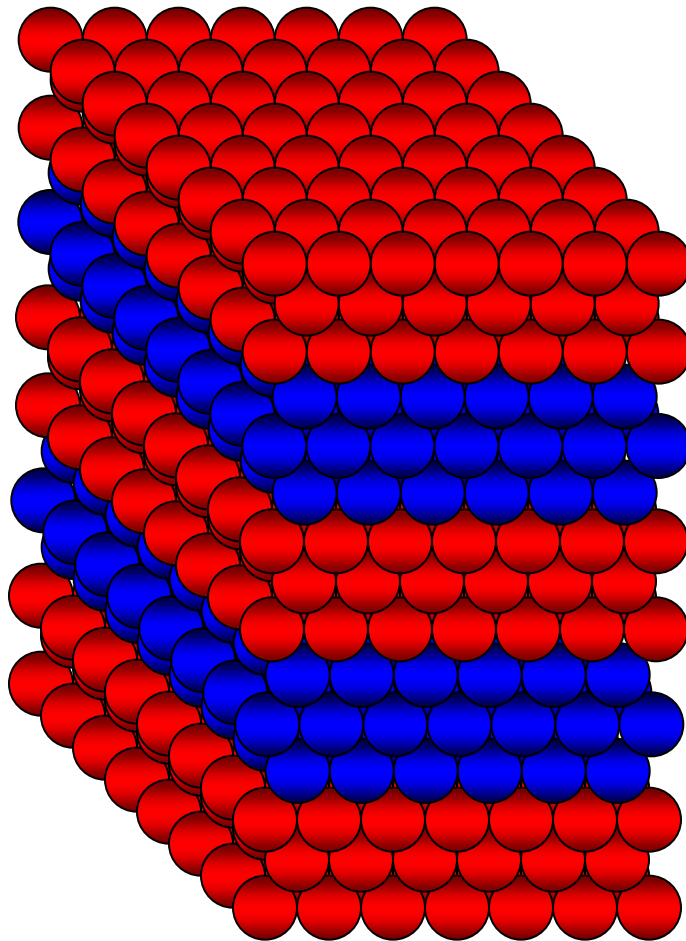
- **Multicouches magnétiques**



- **Multicouches magnétiques**

Aimantations des couches ferromagnétiques à champ magnétique nul:

état de forte résistance électrique



Fe



Cr

Fe




Cr

Fe

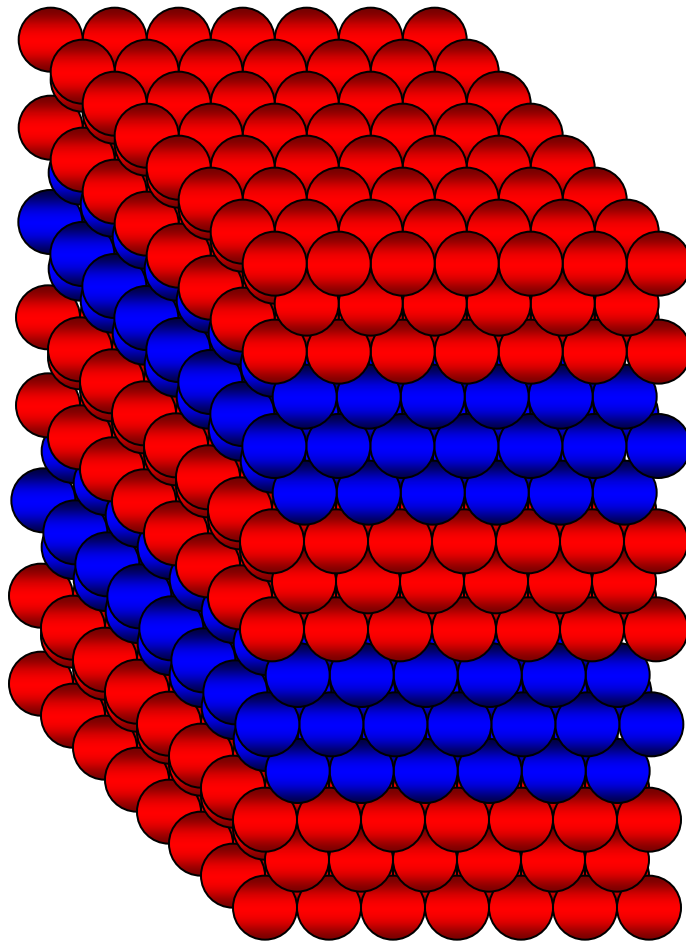


P. Grünberg, 1986 → couplage antiferromagnétique entre couches

• Multicouches magnétiques

Aimantations des couches ferromagnétiques en présence d'un champ magnétique 

: **état de faible résistance électrique**



Fe 

Cr

Fe 

Cr

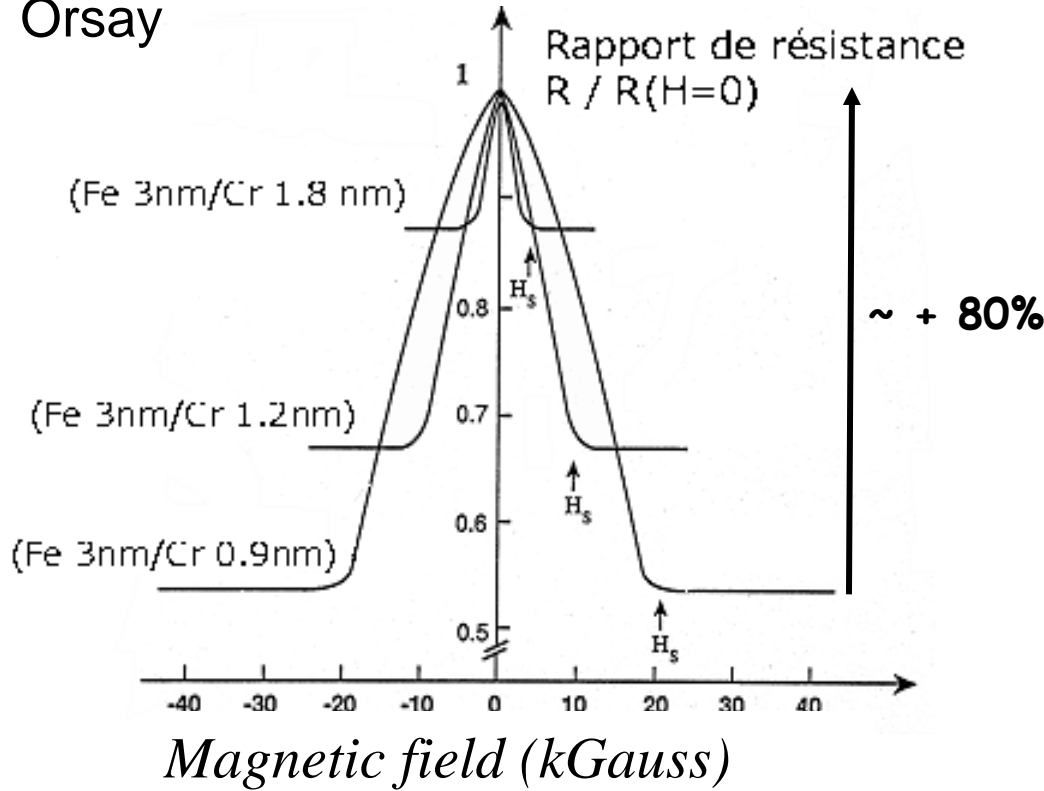
Fe 

P. Grünberg, 1986 → couplage antiferromagnétique entre couches

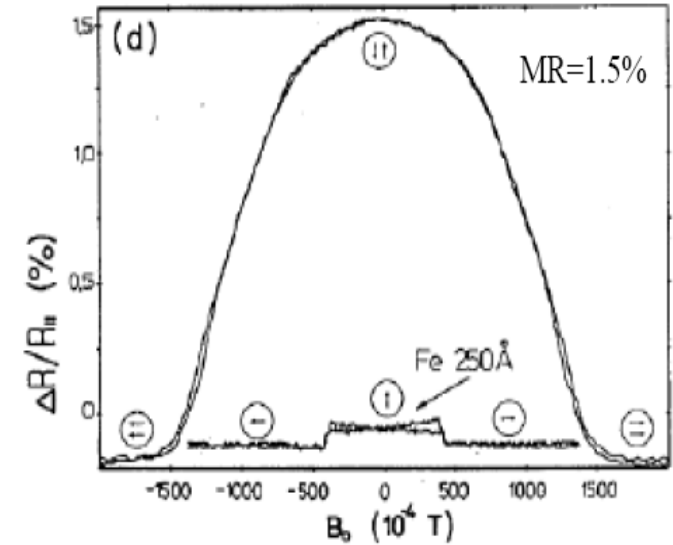
• MagnetoResistance Géante (GMR)

(Orsay, 1988, multicouches Fe/Cr, Jülich, 1989, tricouches Fe/Cr/Fe)

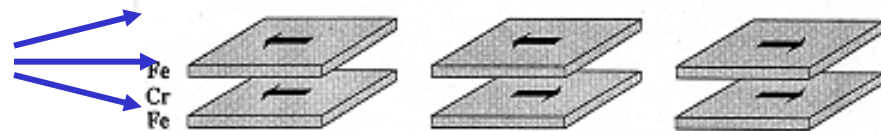
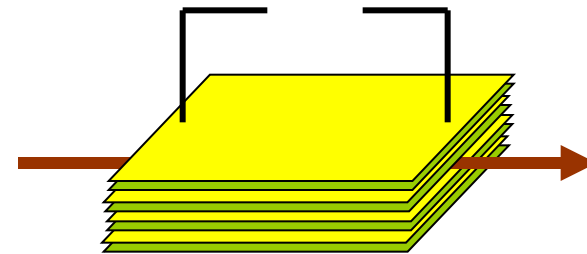
Orsay



Jülich



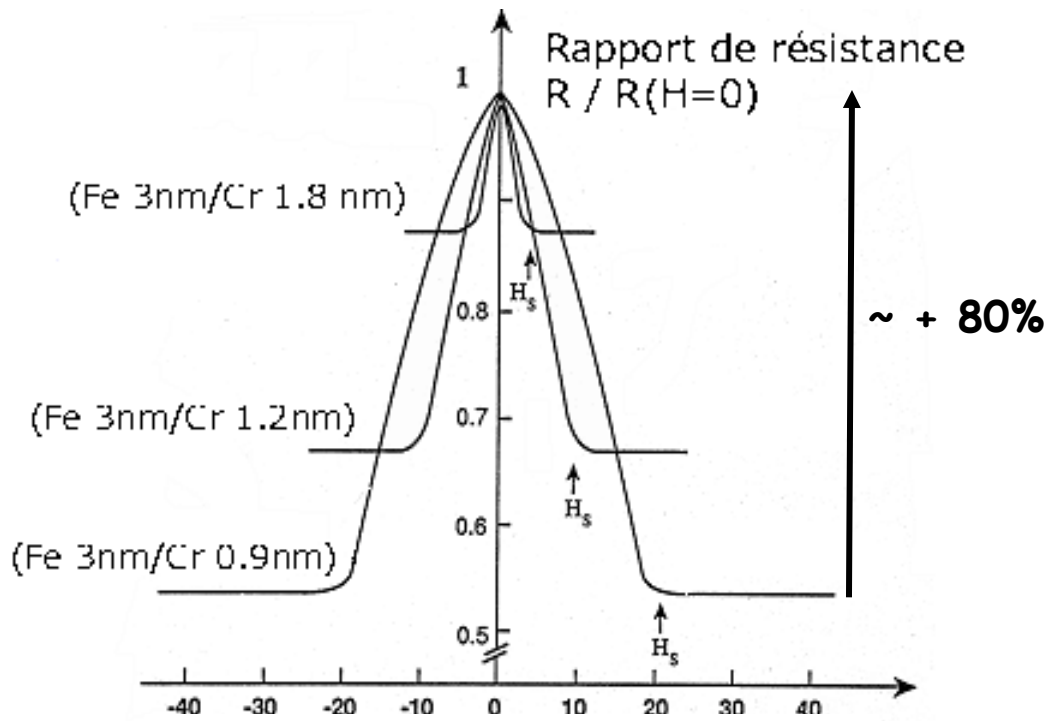
$$V=RI$$



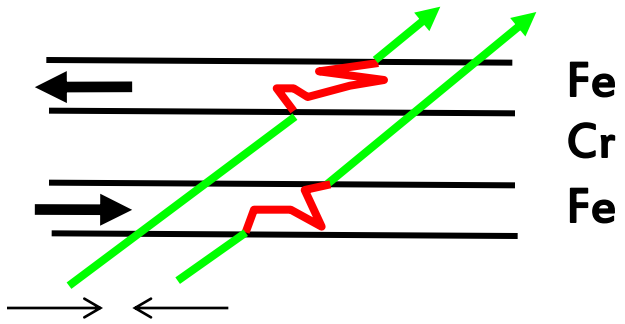
AP (AntiParallèle) P (Parallèle)

• Magneto-resistance Géante (GMR)

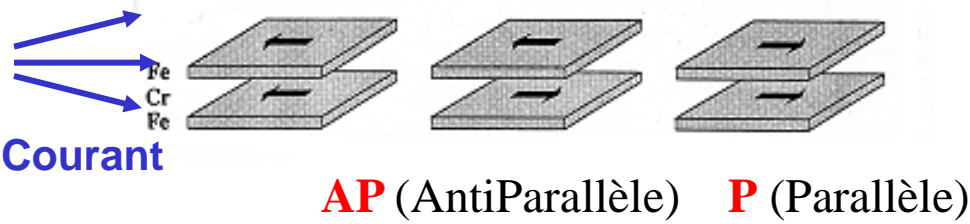
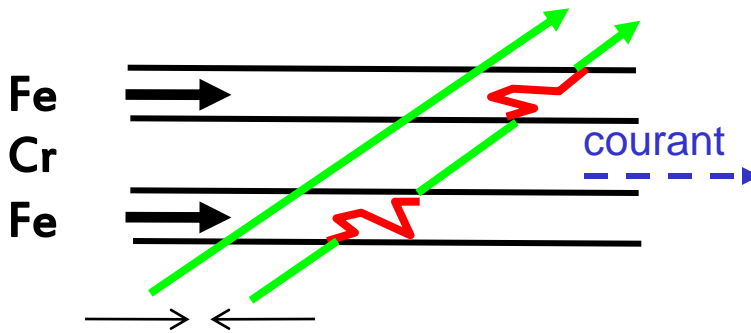
(Orsay, 1988, multicouches Fe/Cr, Jülich, 1989, tricouches Fe/Cr/Fe)



Aimantations **anti-parallèles** (champ nul, **forte** résistance)



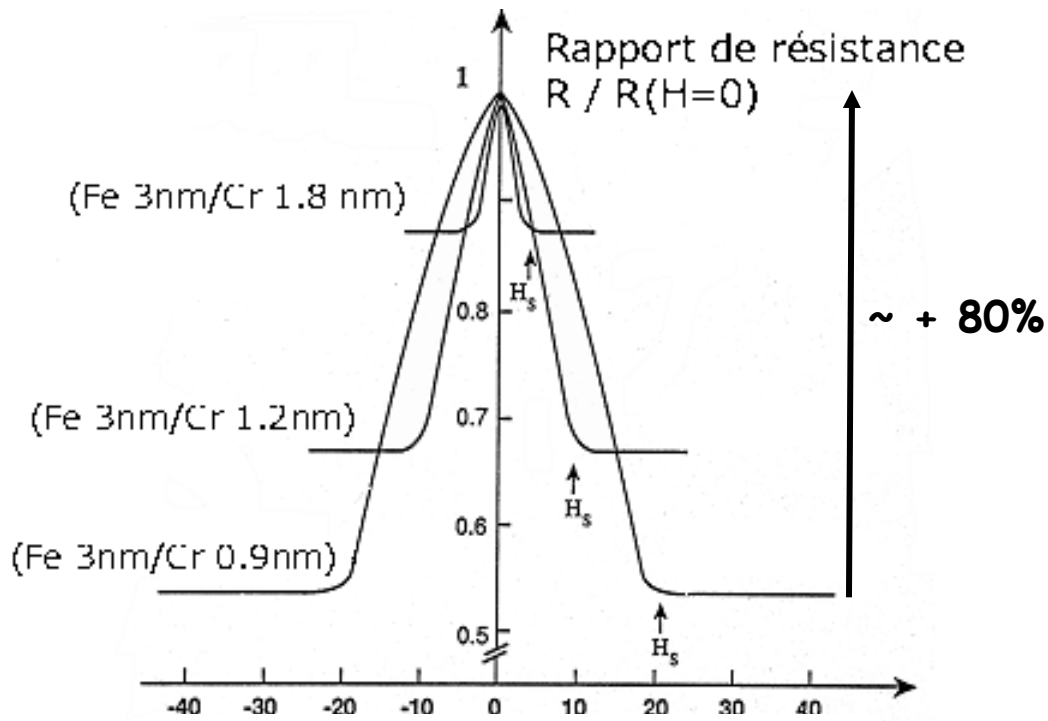
Aimantations **parallèles** (champ appl., **petite** resist.)



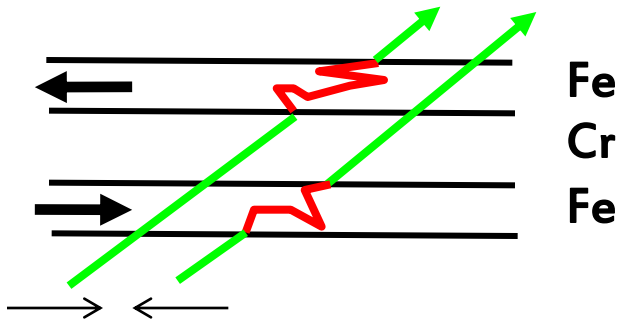
Condition pour GMR:
épaisseurs \approx nm

• Magneto-resistance Géante (GMR)

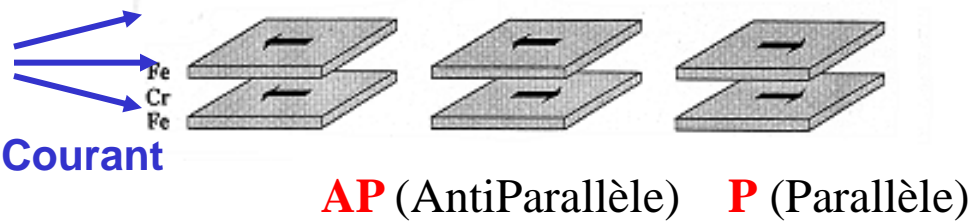
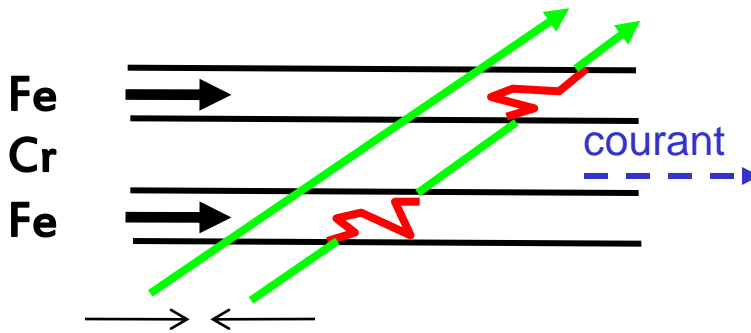
(Orsay, 1988, multicouches Fe/Cr, Jülich, 1989, tricouches Fe/Cr/Fe)



Aimantations **anti-parallèles** (champ nul, **forte** résistance)

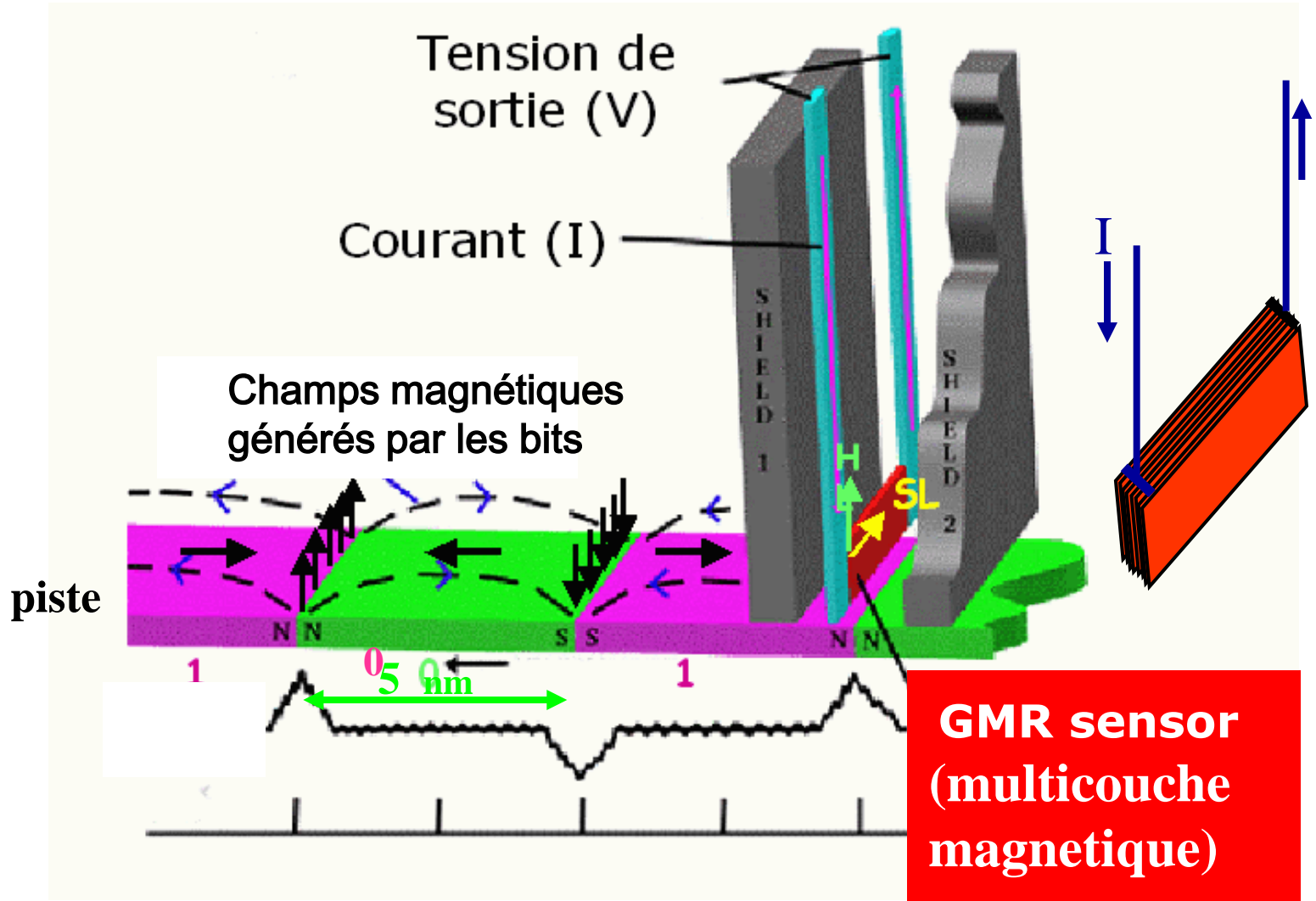


Aimantations **parallèles** (champ appl., **petite** resist.)



Condition pour GMR:
épaisseurs \approx nm

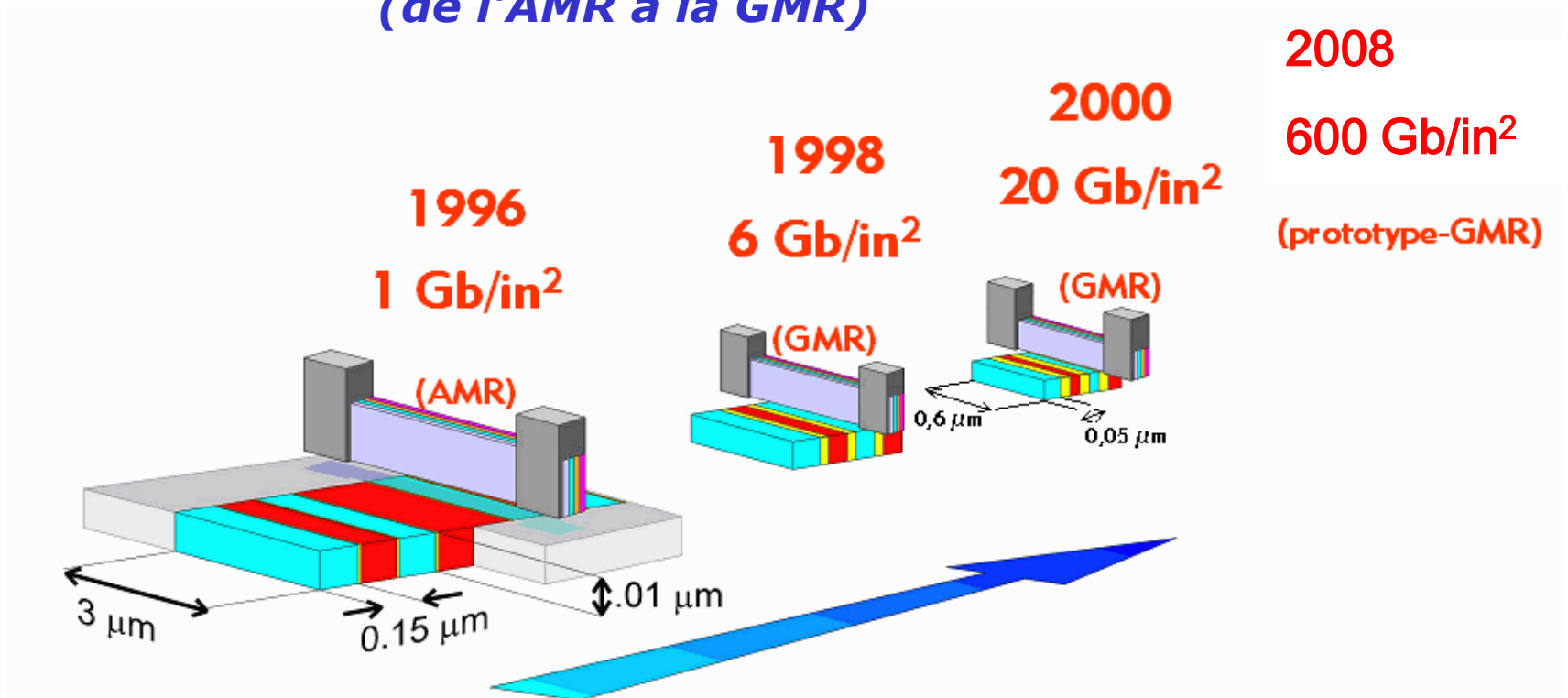
Tête de lecture de disque dur



GMR = Giant MagnetoResistance

• Enregistrement magnétique:

➤ évolution des densités surfaciques (de l'AMR à la GMR)



1 disque dur de 400 Giga-octet peut contenir une information équivalente à environ **800.000 livres** (format livre de poche)
ou à **1 million de photographies** (de définition moyenne)
ou à **8000 CD audio** (compression MP3)
ou à **300 heures video**, ou **36 heures video haute def.**

Extension de la technologie disque dur à l'électronique nomade



➤ *Micro-disque 4 GB*



Disque dur de 100 Go (Toshiba)
bientôt dans les Ipods ..

Giant Magnetoresistance of (001)Fe/(001)Cr Magnetic Superlattices

M. N. Baibich,^(a) J. M. Broto, A. Fert, F. Nguyen Van Dau, and F. Petroff
Laboratoire de Physique des Solides, Université Paris-Sud, F-91405 Orsay, France

P. Eitenne, G. Creuzet, A. Friederich, and J. Chazelas
Laboratoire Central de Recherches, Thomson CSF, B.P. 10, F-91401 Orsay, France
(Received 24 August 1988)

We have studied the magnetoresistance of (001)Fe/(001)Cr superlattices prepared by molecular-beam epitaxy. A huge magnetoresistance is found in superlattices with thin Cr layers: For example, with $t_{\text{Cr}}=9 \text{ \AA}$, at $T=4.2 \text{ K}$, the resistivity is lowered by almost a factor of 2 in a magnetic field of 2 T. We ascribe this giant magnetoresistance to spin-dependent transmission of the conduction electrons between Fe layers through Cr layers.





La découverte de Fert et Grünberg



DEUTSCHLAND



DEUTSCHES
PATENTAMT

⑫ **Patentschrift**
⑪ **DE 3820475 C 1**

⑳ Aktenzeichen: P 38 20 475.4-53
㉑ Anmeldetag: 16. 6. 88
㉒ Offenlegungstag: —
㉓ Veröffentlichungstag
der Patenterteilung: 21. 12. 89

⑤① Int. Cl. 4:
G 11 B 5/39
H 01 F 10/12
H 01 F 10/14

DE 3820475 C 1

Innerhalb von 3 Monaten nach Veröffentlichung der Erteilung kann Einspruch erhoben werden

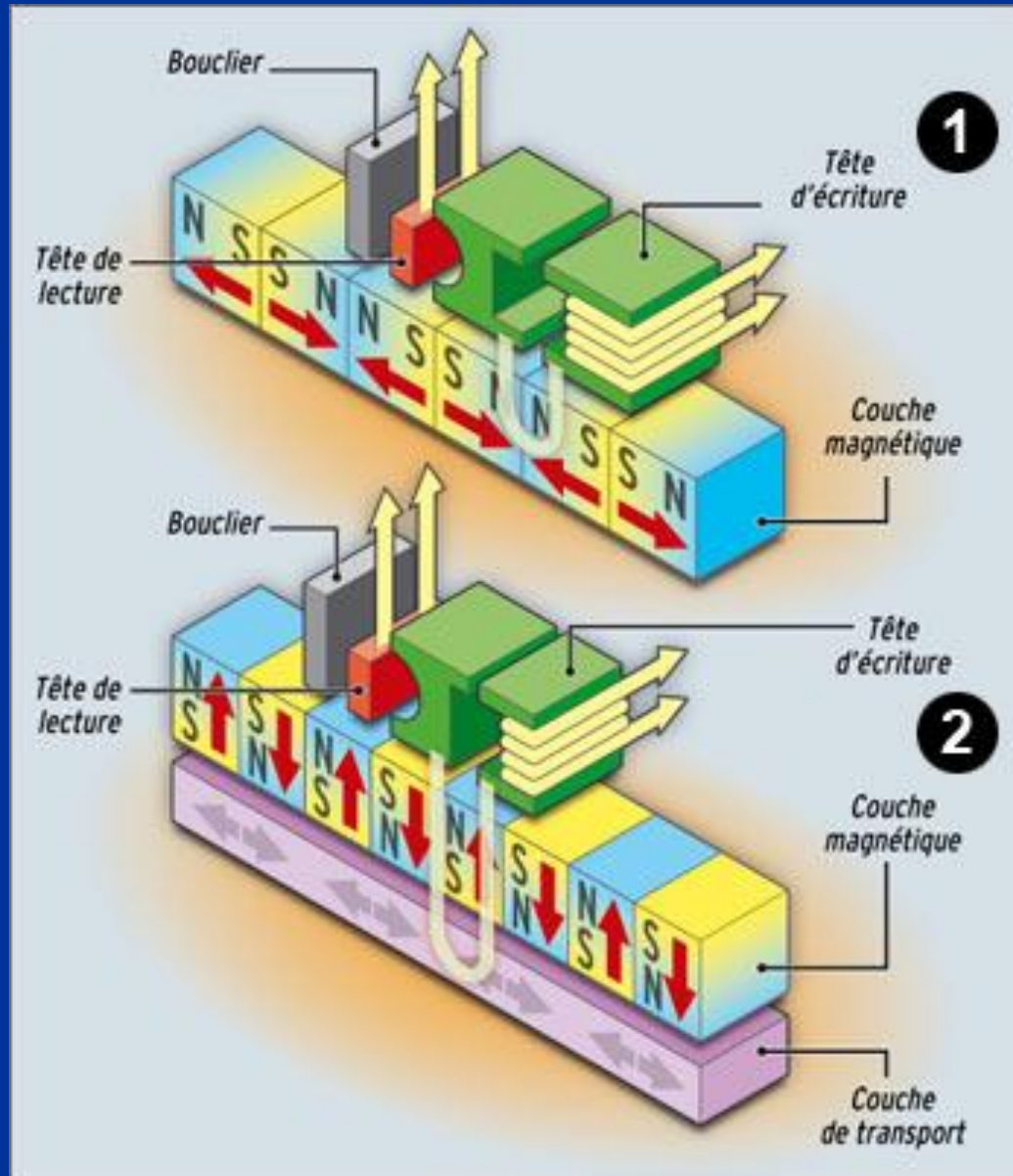
⑦③ **Patentinhaber:**
Kernforschungsanlage Jülich GmbH, 5170 Jülich, DE

⑦② **Erfinder:**
Grünberg, Peter, Dr. Dipl.-Phys., 5170 Jülich, DE

⑤⑥ **Für die Beurteilung der Patentfähigkeit
in Betracht gezogene Druckschriften:**

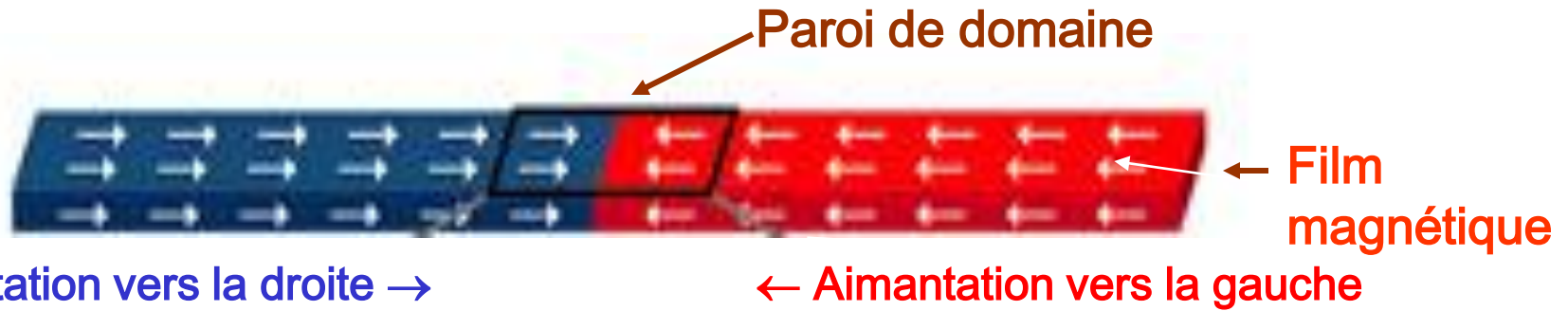
DE 34 04 273 A1
EP 02 21 540 A2

Enregistrement perpendiculaire

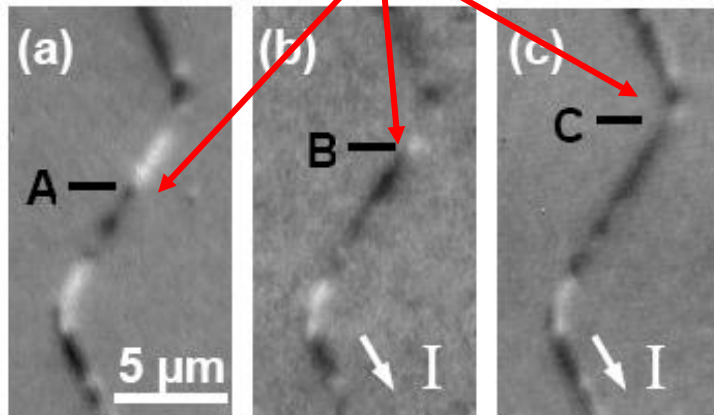


Un autre phénomène de transfert de spin:

le déplacement de paroi entre domaines magnétiques



Positions successives de parois après impulsions de courant de 5 ns

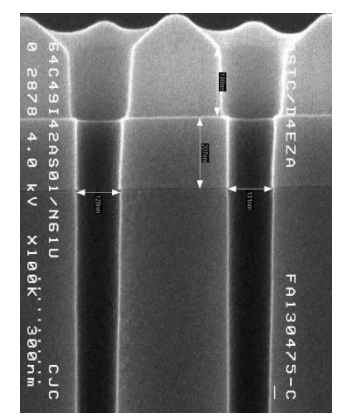
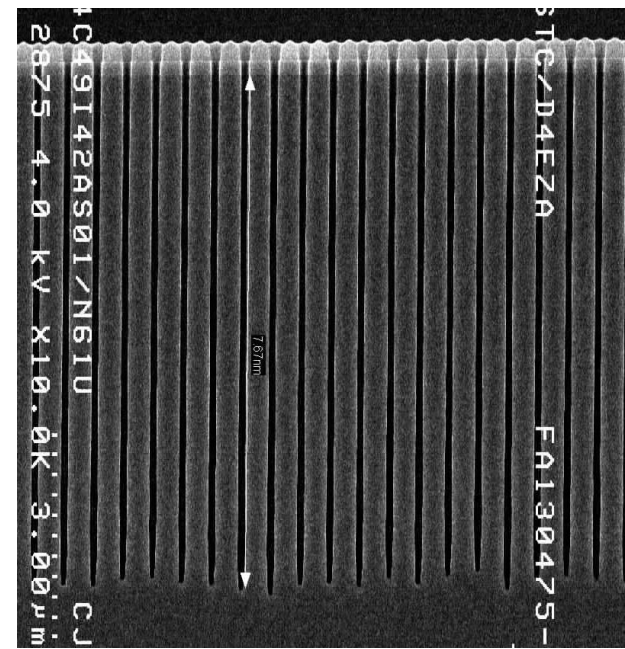
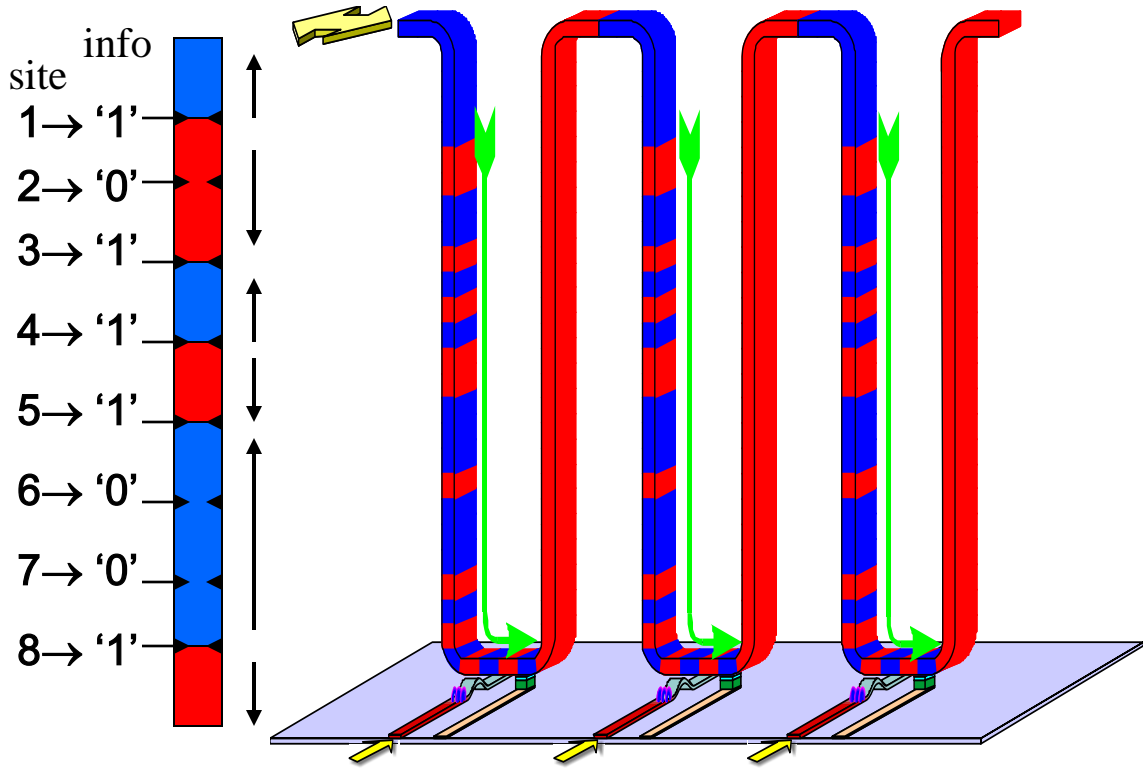


Experiences de microscopie en photo-émission d'électrons avec X polarisés circulairement (XMCD-PEEM) à l'ESRF:

Déplacement de paroi de domaine dans un nano-ruban magnétique: vitesse élevée (150m/s) obtenue avec faible densité de courant (10^6 Amp/cm²)

Image: des impulsions de courant de 5 ns déplacent une paroi de A à B, puis de B à C, etc

Train de parois dans un nano-ruban magnétique pour les mémoires de masse du futur ? (projet IBM, remplacement des disques durs ?)



Information stockée dans un train de parois situées à des encoches périodiques:
Pas de paroi = "0", paroi = "1"

A photograph of an adult elephant and a smaller calf walking across a golden-brown savanna. In the background, there are blue mountains under a clear sky. The word "ELECTRONIQUE" is written in pink across the adult elephant's body, and "SPINTRONIQUE" is written in green across the calf's body.

ELECTRONIQUE

SPINTRONIQUE