Nanosciences et nanotechnologies
De la physico-chimie des surfaces
à
l'électronique de spin

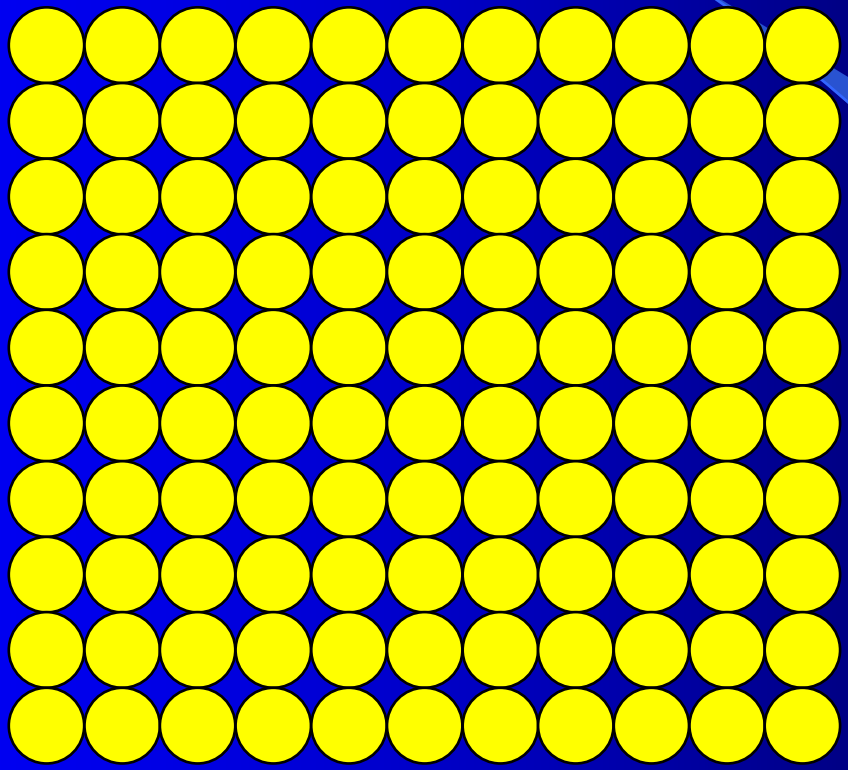
Patrick Alnot

Nancy-Université
Université Henri Poincaré

Sommaire

- De la science de surface aux « nanos »
  - Caractérisations de surfaces: les outils des physiciens au service des chimistes
  - La physico-chimie des surfaces
  - Les systèmes multi-couches: les outils des chimistes au service des physiciens
    - Les semiconducteurs
    - Les couches métalliques et l'électronique de spin
- Nanosciences et nanotechnologies: intérêts et enjeux
- Conclusions

Fabrication d'une surface

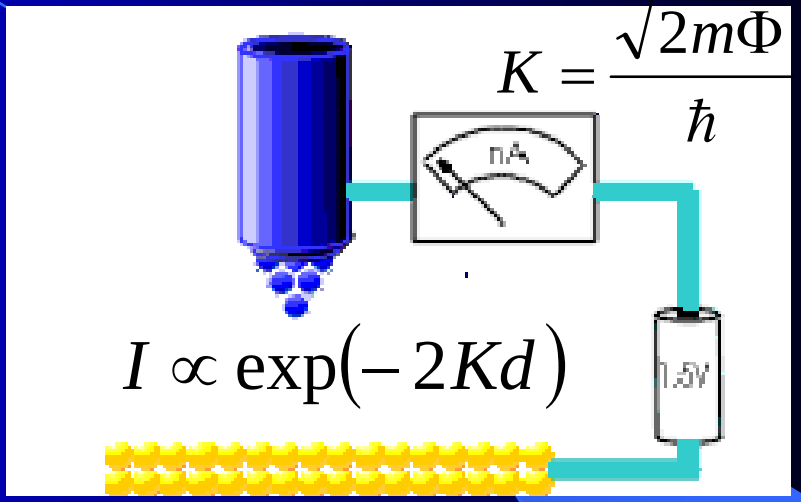


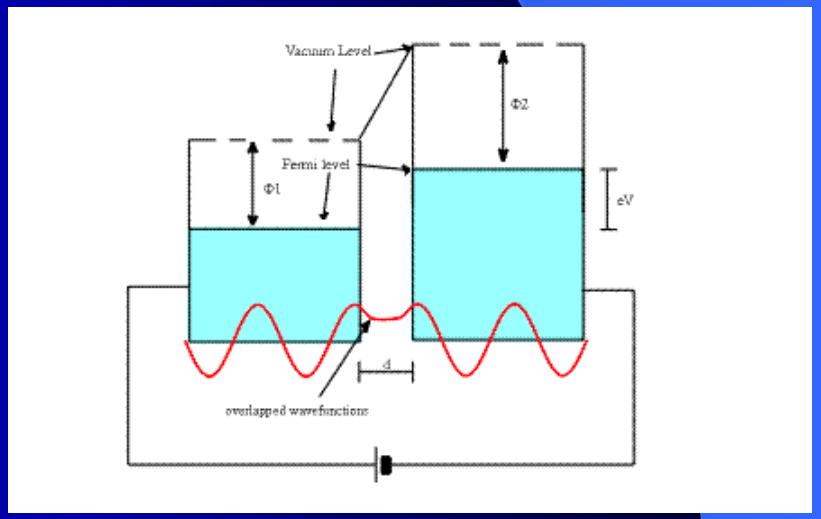
Le Microscope à effet tunnel
Prix Nobel de Physique 1986

Gerd Binnig
Heinrich Rohrer
IBM Zurich

$$K = \frac{\sqrt{2m\Phi}}{\hbar}$$

$$I \propto \exp(-2Kd)$$





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A major breakthrough in surface science occurred after the invention of the Scanning Tunneling Microscope (STM) in 1982 by Binnig et al. [5],[6]. The first atomically resolved STM imaging of Si(111)7x7 surface was achieved a year later [7].

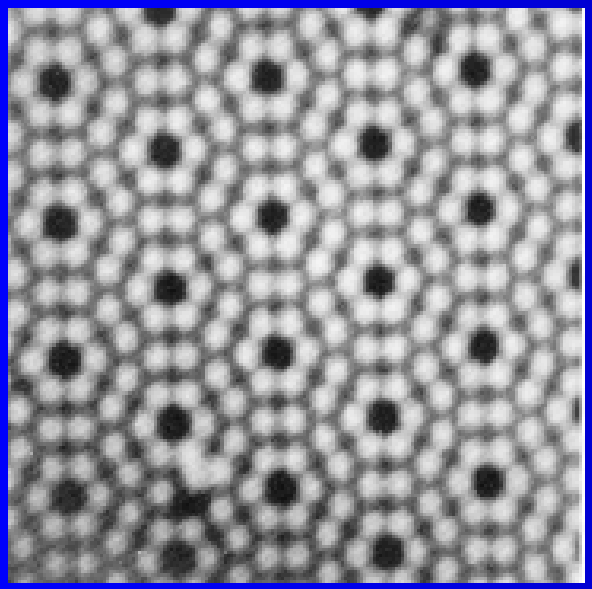

Fig. 5 Topographic image of Si(111)7x7 surface as recorded using Scanning Tunneling Microscope (STM) with a bias voltage of + 2 V [8].

Atomically resolved Atomic Force Microscope (AFM) imaging of Si(111)7x7 surface was the next powerful tool used for studying this surface [9].

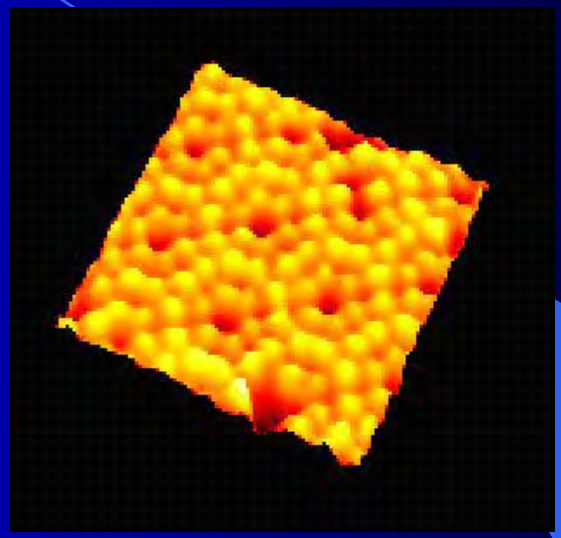

Fig. 6 A 3D image of ac-mode Atomic Force Microscope (AFM) data of the Si(111)7x7 surface [9].

5. Binnig,G., Rohrer,H., Gerber,Ch. And Weibel,E., Physica 107 A&B, 1335 (1982).
6. Binnig,G., Rohrer,H., Gerber,Ch. And Weibel,E., Appl. Phys. Lett. 40, 178 (1982)
7. Binnig,G., Rohrer,H., Gerber,Ch. And Weibel,E.,"7x7 Reconstruction on Si(111) Resolved in Real Space", Phys. Rev. Lett. 50, 120 (1983).
8. Wiesendanger,R., Tarrach,G.,Scandella,L. and Gunthererodt,H.-J., Ultramicroscopy 32, 291 (1
9. Erlandsson,R. and Olsson,L., Appl. Phys. A 66, S879 (1998).

Electrodynamique quantique
Prix Nobel de Physique 1965

Richard Feynman
Caltec USA

"The principles of physics, as far as I can see, do not speak against the possibility of maneuvering things atom by atom.

It is not an attempt to violate any laws; it is something, in principle, that can be done; but in practice, it has not been done because we are too big."

- Richard P. Feynman (1959)

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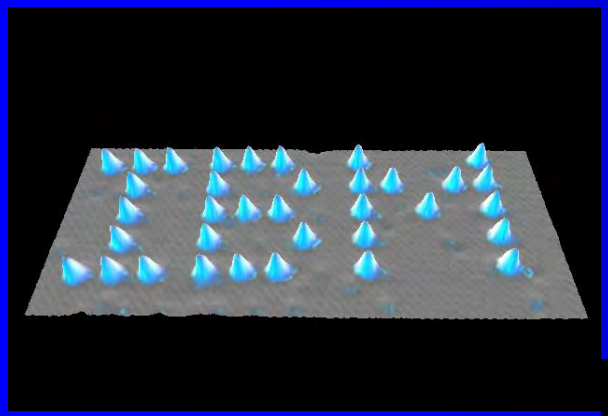
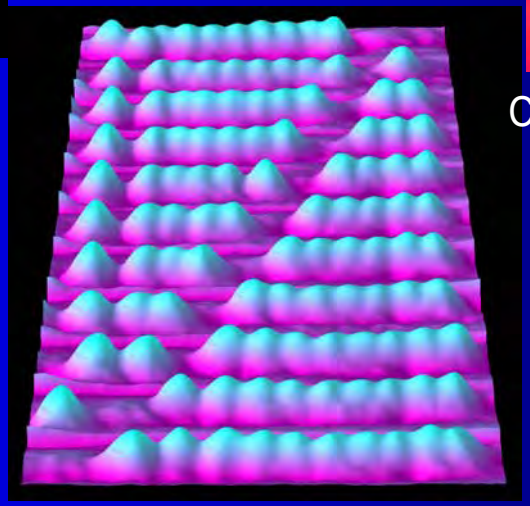
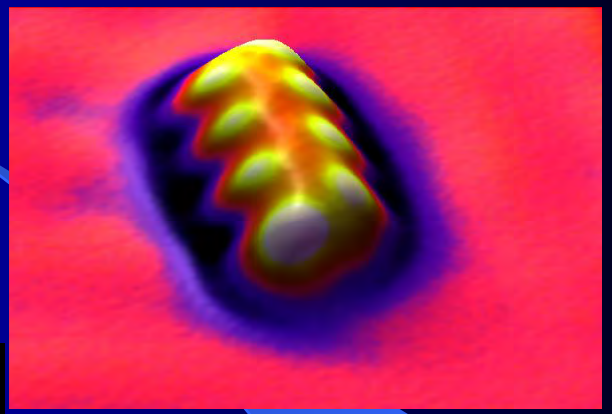
Manipulation d'atomes



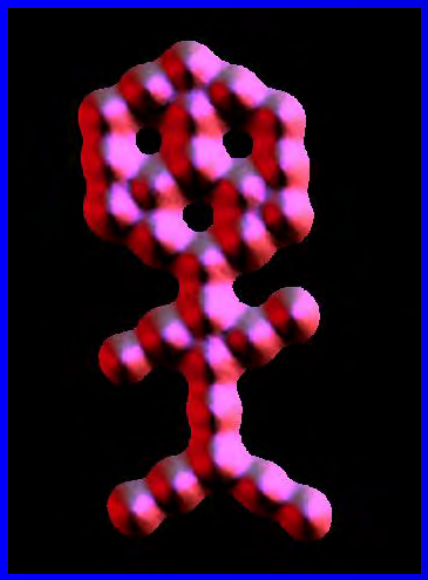
Xenon on Nickel (110)



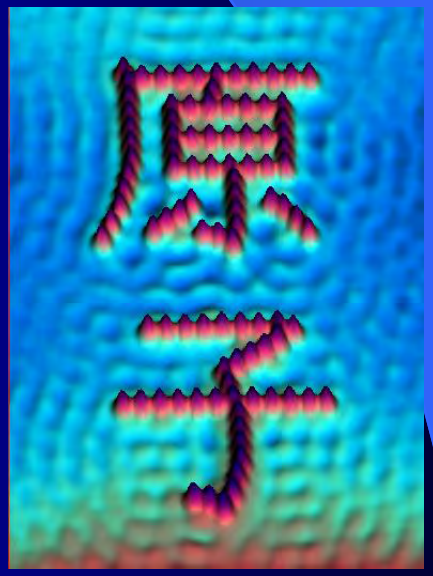
C_{60} on Copper



Cesium & Iodine on Copper (111)



Carbon Monoxide on Platinum (111)

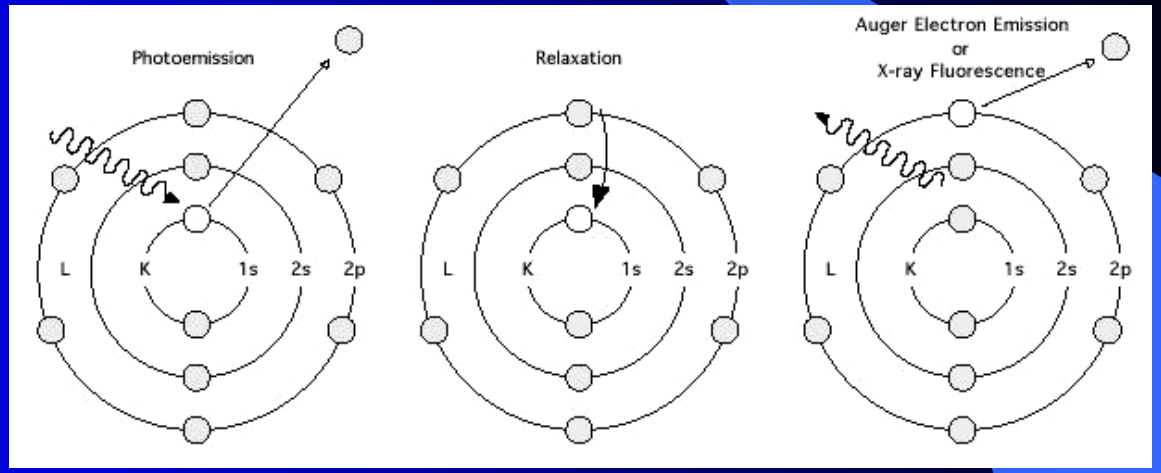


Iron on C

Electron Spectrocopy for Chemical Analyses

Prix Nobel de Physique 1981

Kai Siegbahn
Upssala University



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La photoemission induits par Rayons X

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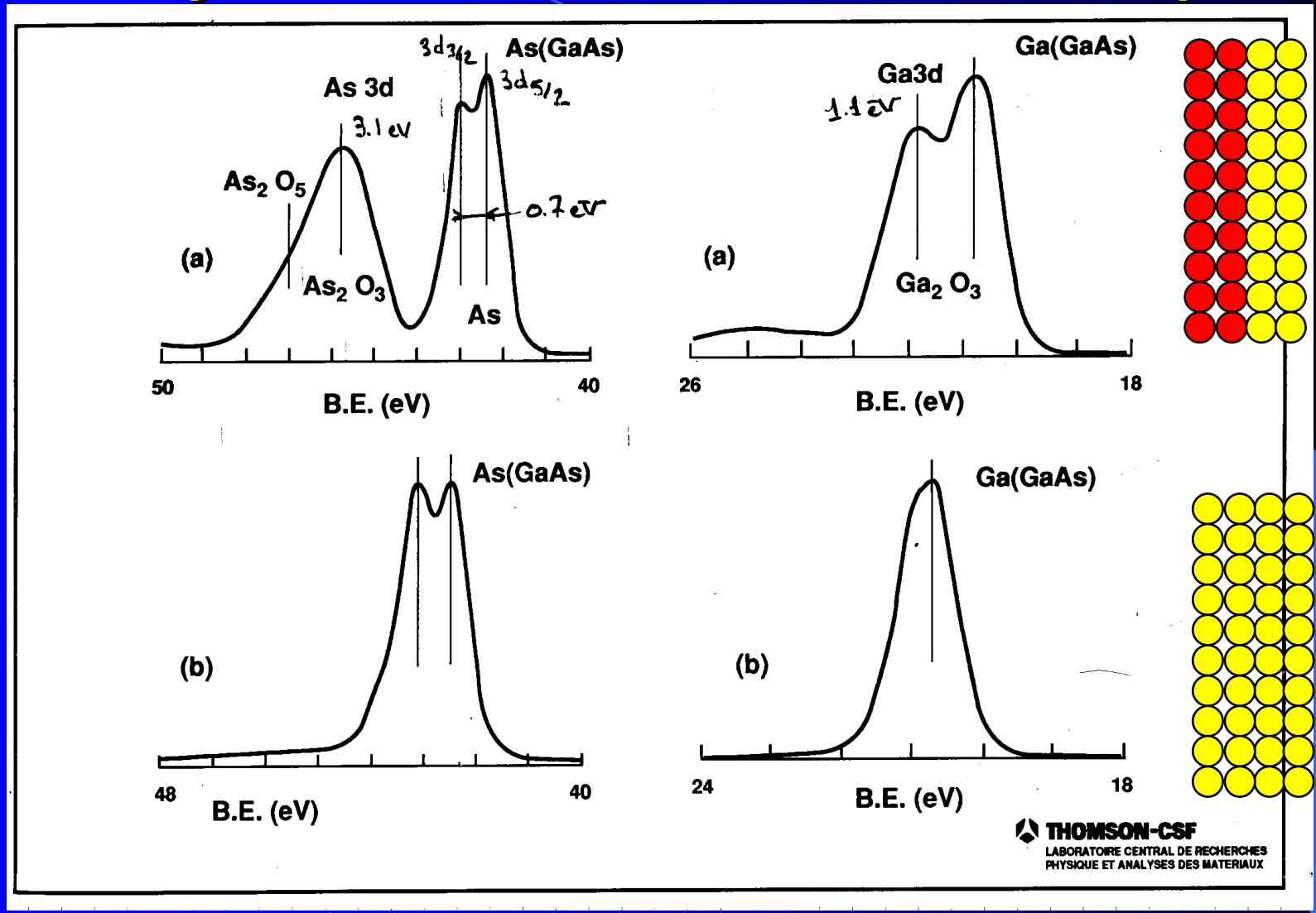
Analyse d'une surface de GaAs(100)



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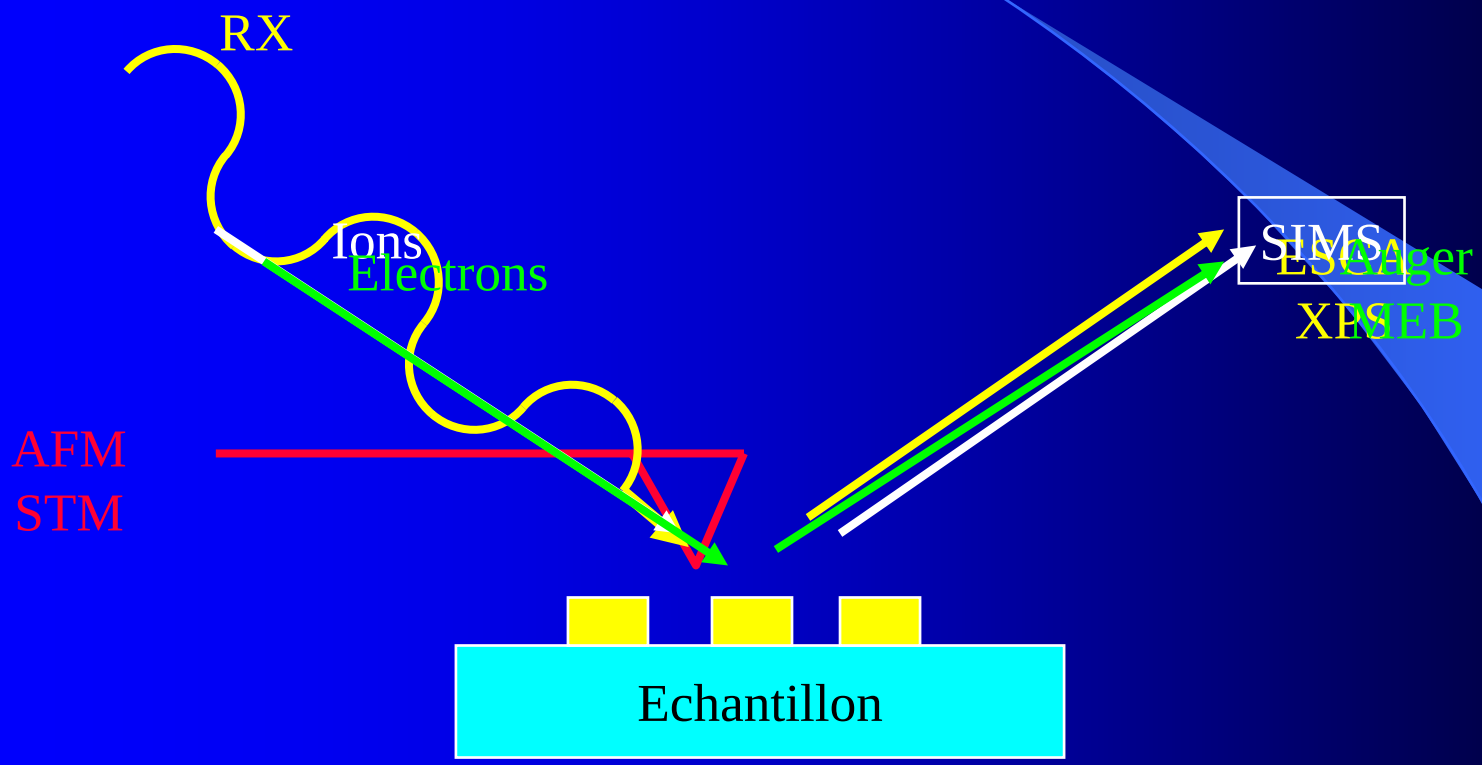
Caractérisations physico-chimique des matériaux et dispositifs



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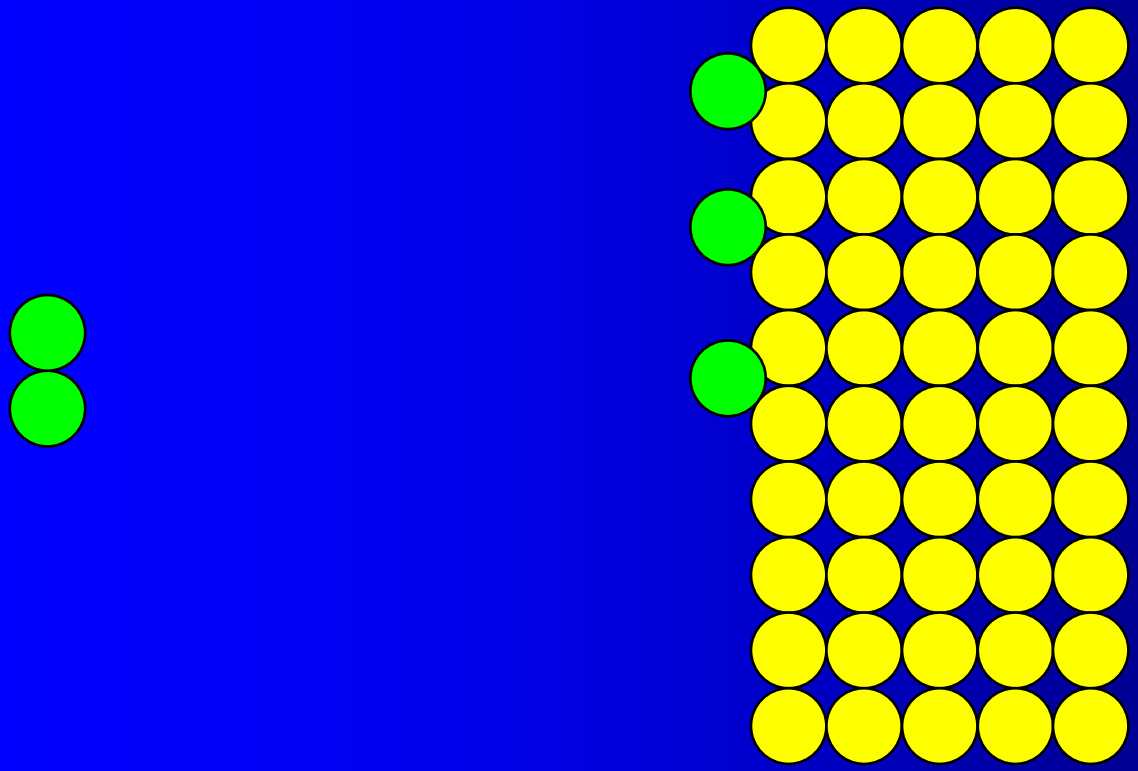
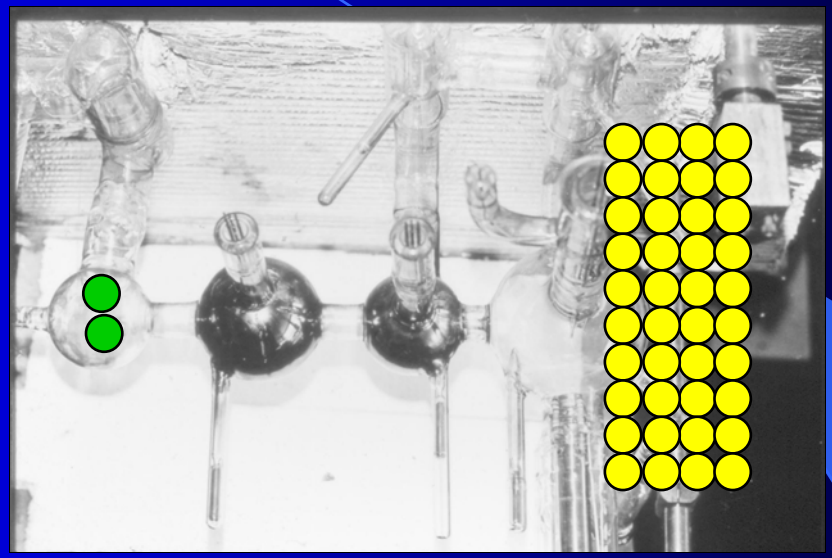
Physisorption et chimisorption

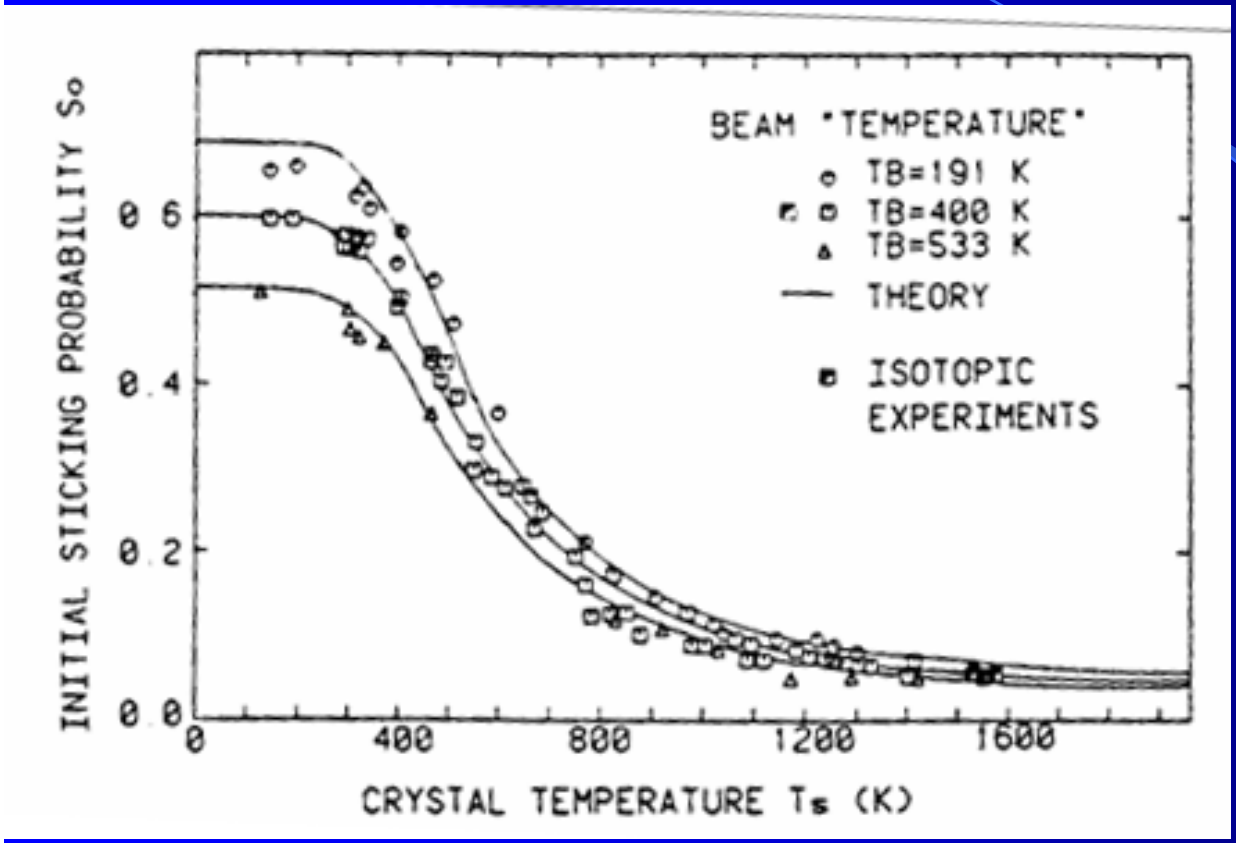


Les phénomènes d'adsorption

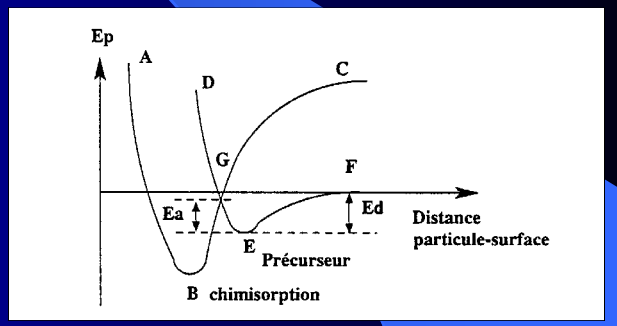
- D.A. King et A. Cassuto
  - Adsorption de molécules simples sur W(100)
  - Technique des faisceaux moléculaires
  - N_2/W(100)
  - H_2/W(100)
  - NH_3/W(100)



N_2/W(100)



$$S_0 = \alpha\left[1+\frac{\nu_d}{\nu_a}Exp\left(-\frac{E_d - E_a}{R.T_s}\right)\right]^{-1}$$



P. Alnot and D.A. King, *Trapping, sticking and reactive scattering in chemisorption: nitrogen isotopes on W(100)*. Surf. sci., 1982. **126**: p. 359.

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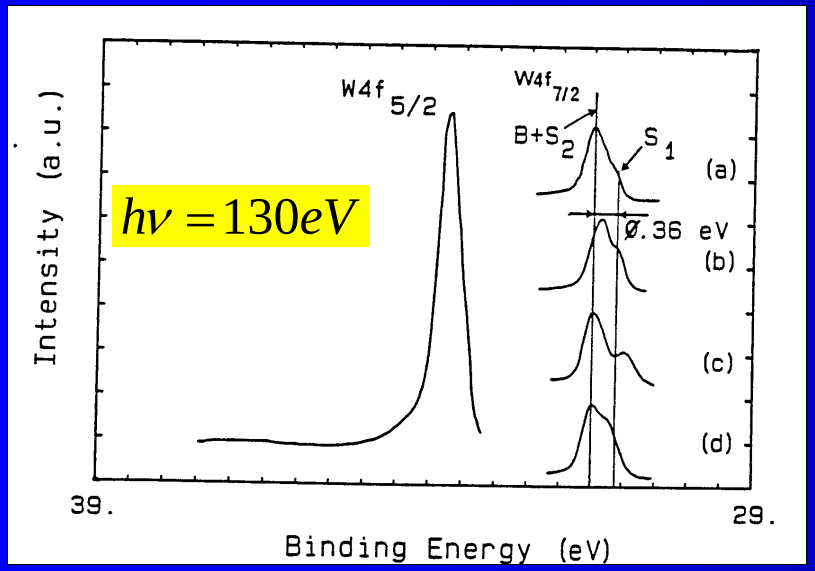
O_2 / W(100)

SSRL Palo-Alto CA



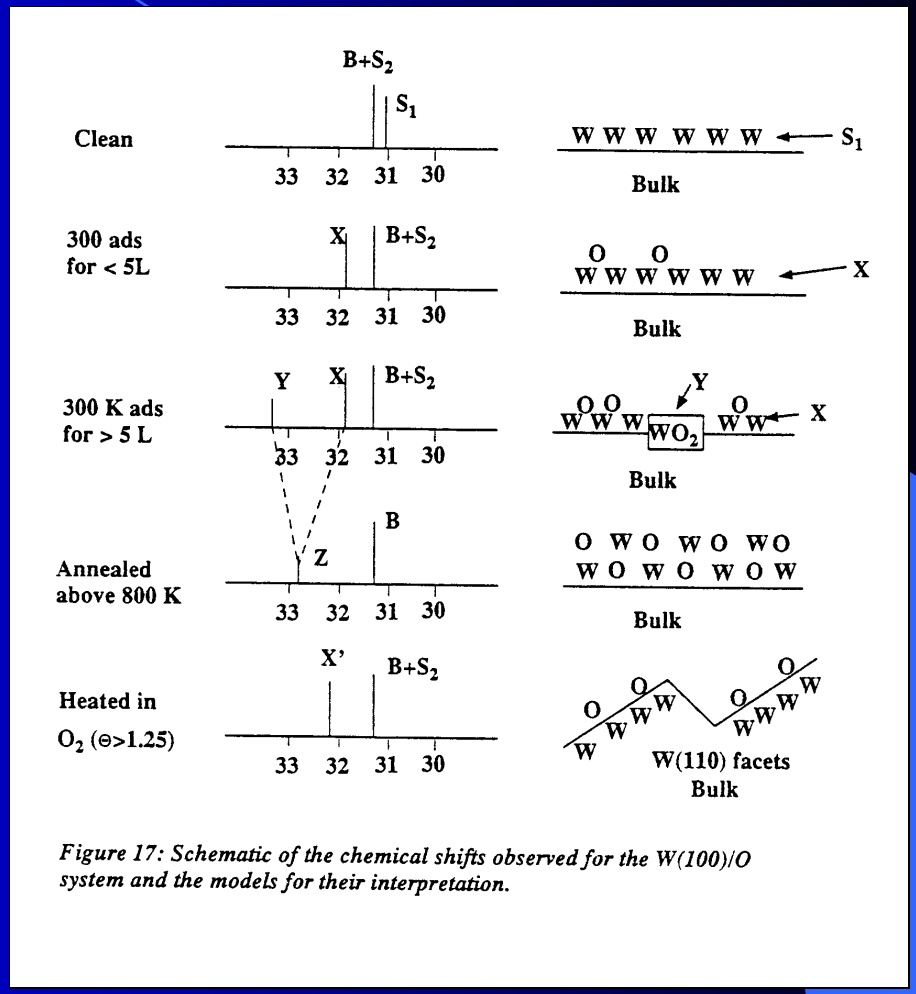
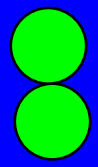
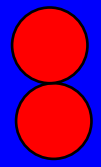


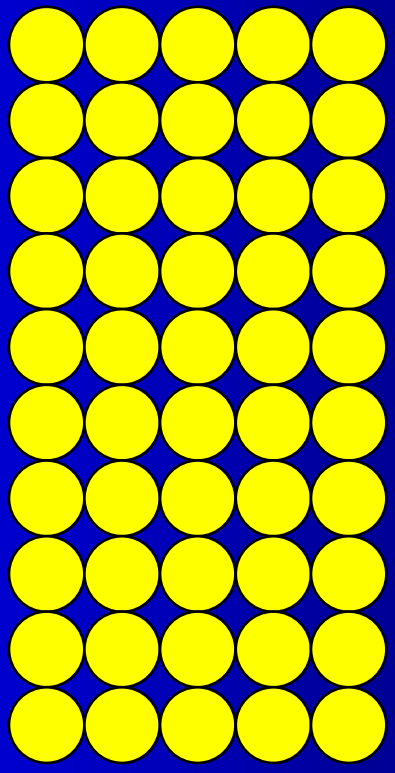
Figure 17: Schematic of the chemical shifts observed for the W(100)/O system and the models for their interpretation.

Alnot, P., C.R. Brundle, D.A. Auerbach, **J.R. Behm**, and A. Viescas, *A surface core-level shift photoemission study on the interaction of oxygen with W(100).* Surf. Sci., 1989. **213**: p. 1.

Adsorption, réaction et désorption

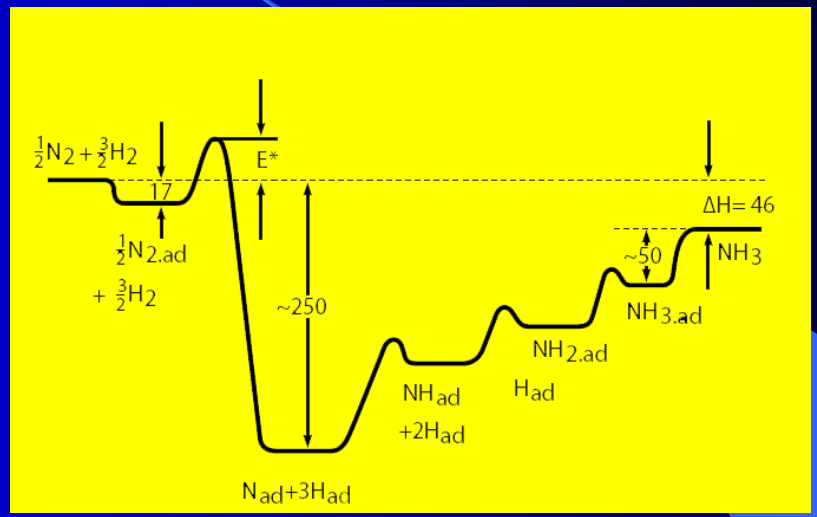


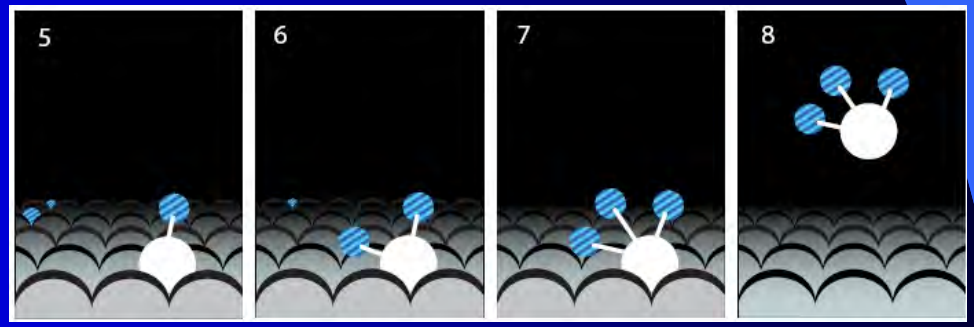




Réactions chimiques en sciences des surfaces
Prix Nobel de chimie 2007

Gerhardt Ertl
Fritz Haber Institute
Berlin





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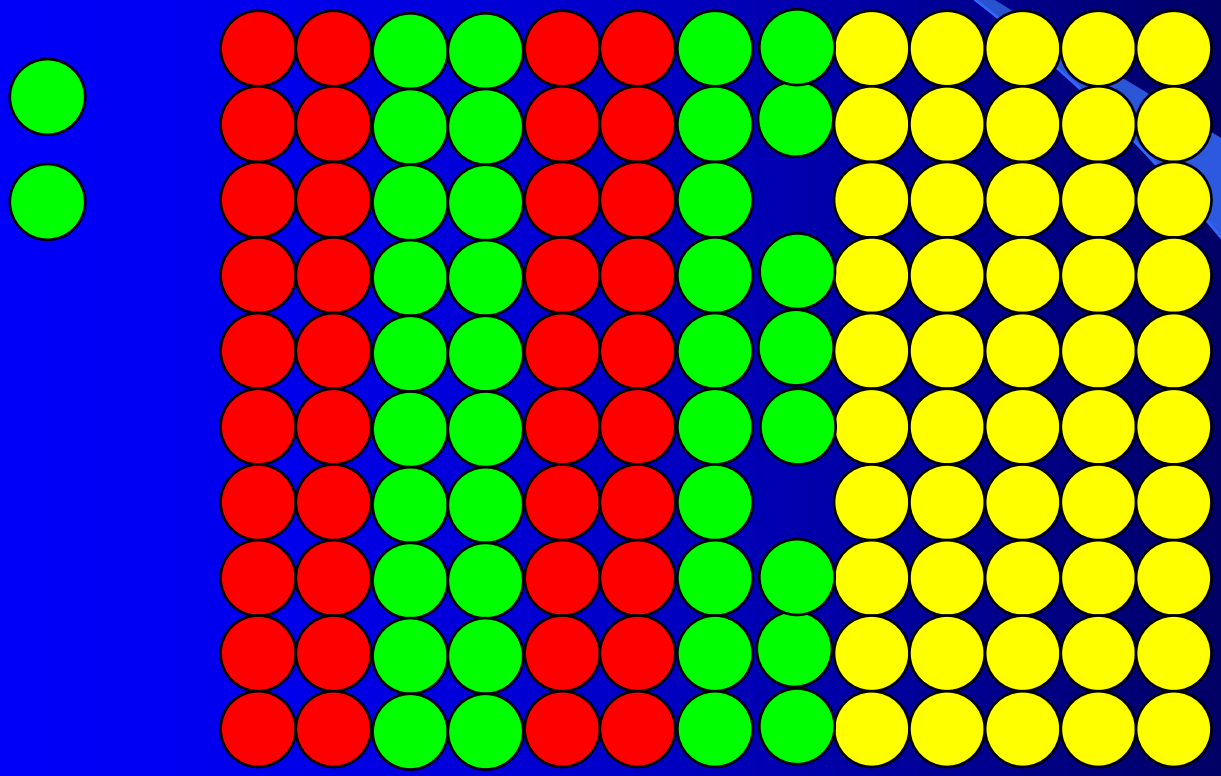
Une brève histoire de la science des surfaces

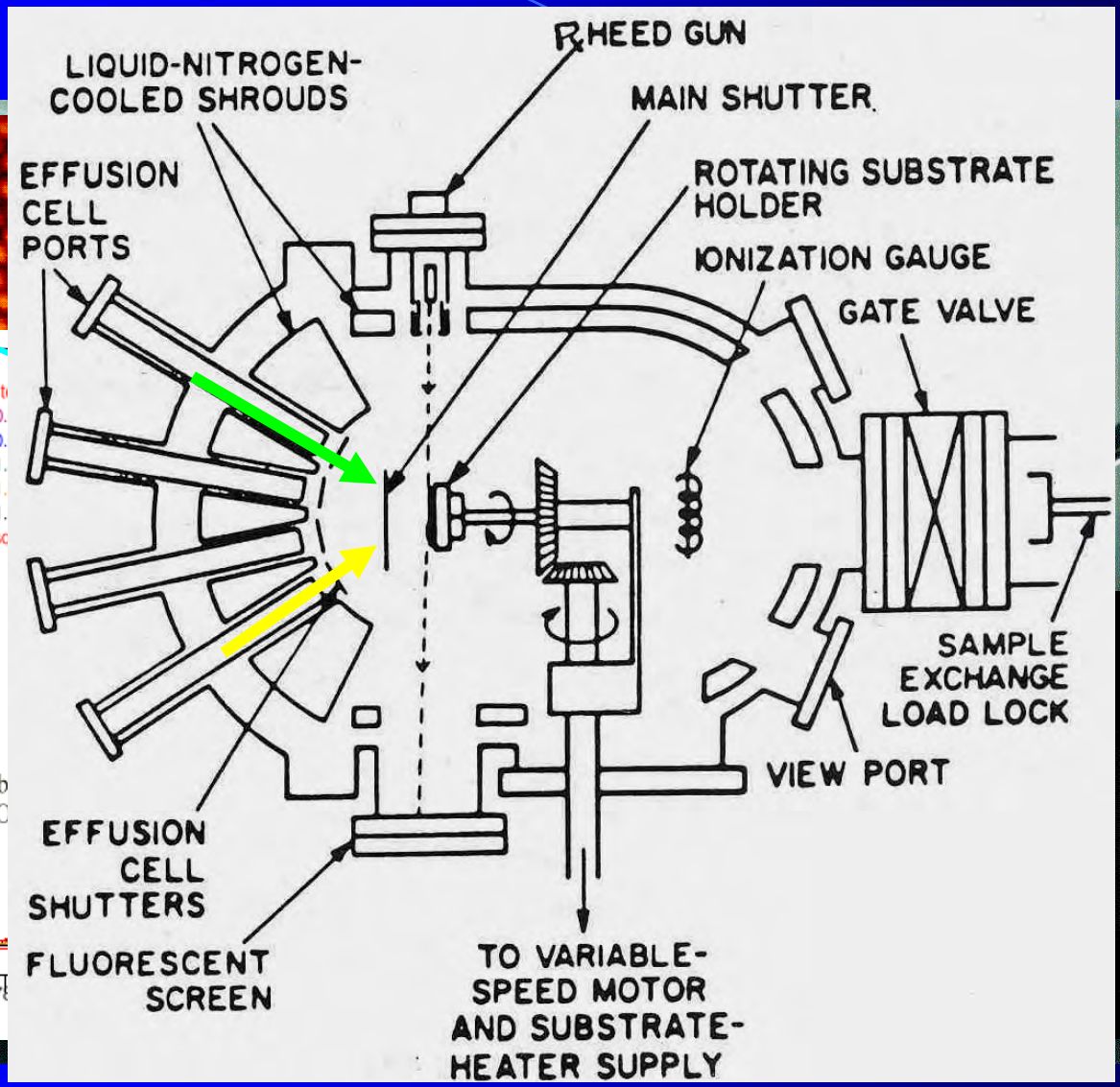
Université Henri Poincaré

Fabrication de multicouches

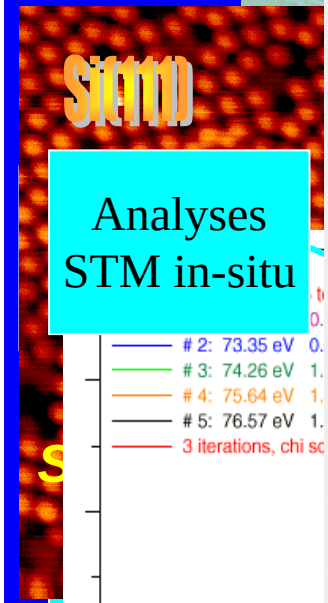


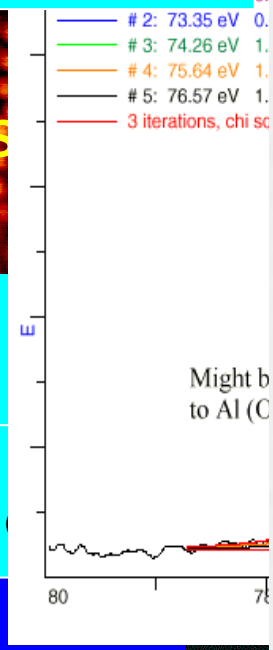
Epitaxie par jets moléculaires

L. P. M.



Analyses STM in-situ





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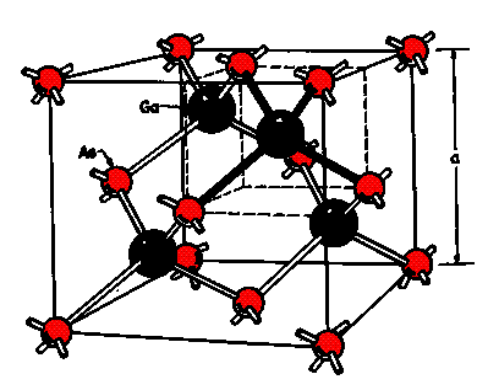
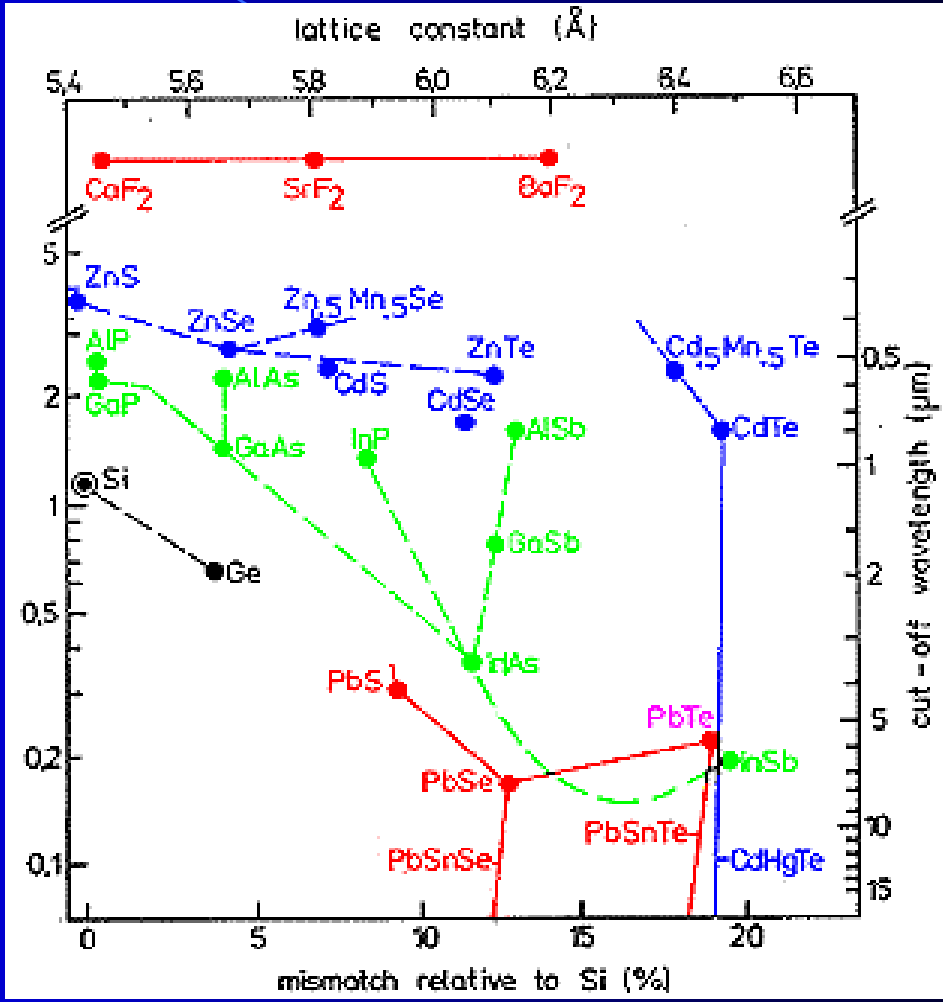
Semiconducteurs III-V





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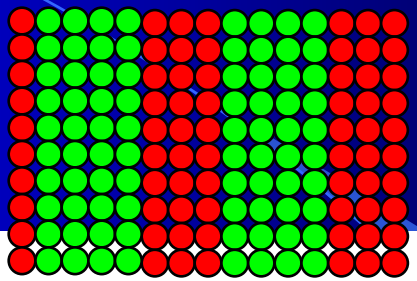
Effet tunnel dans les MPQ, SS
Prix Nobel de Physique 1973

Leo Esaki
IBM Yorktown Heights USA



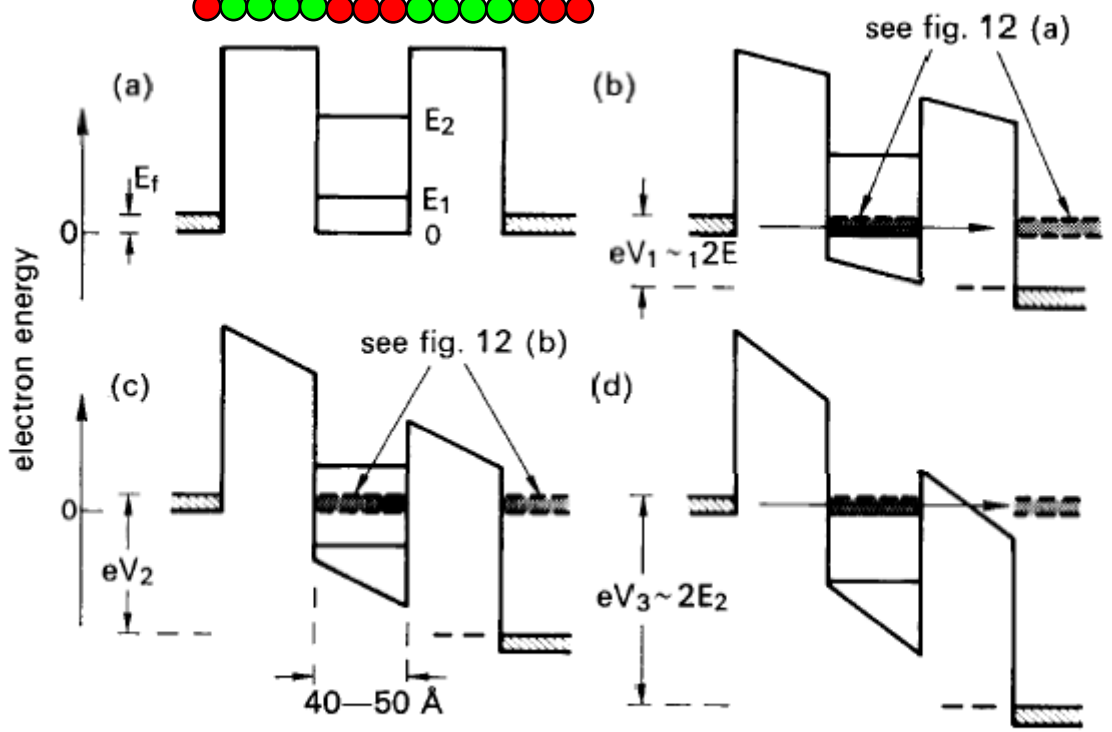
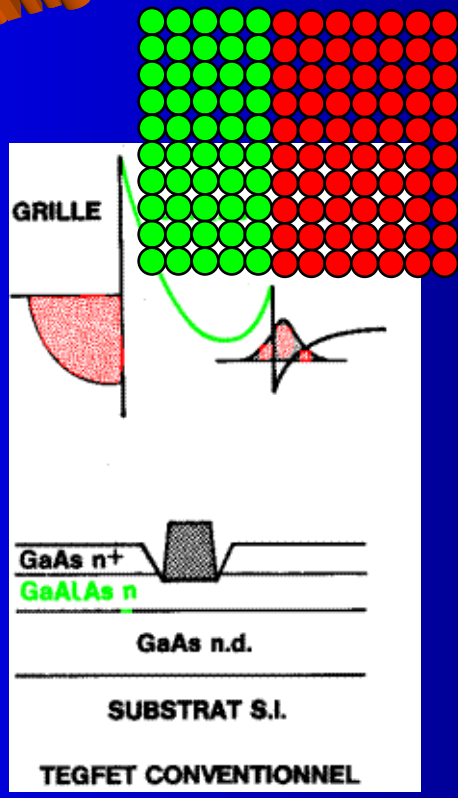
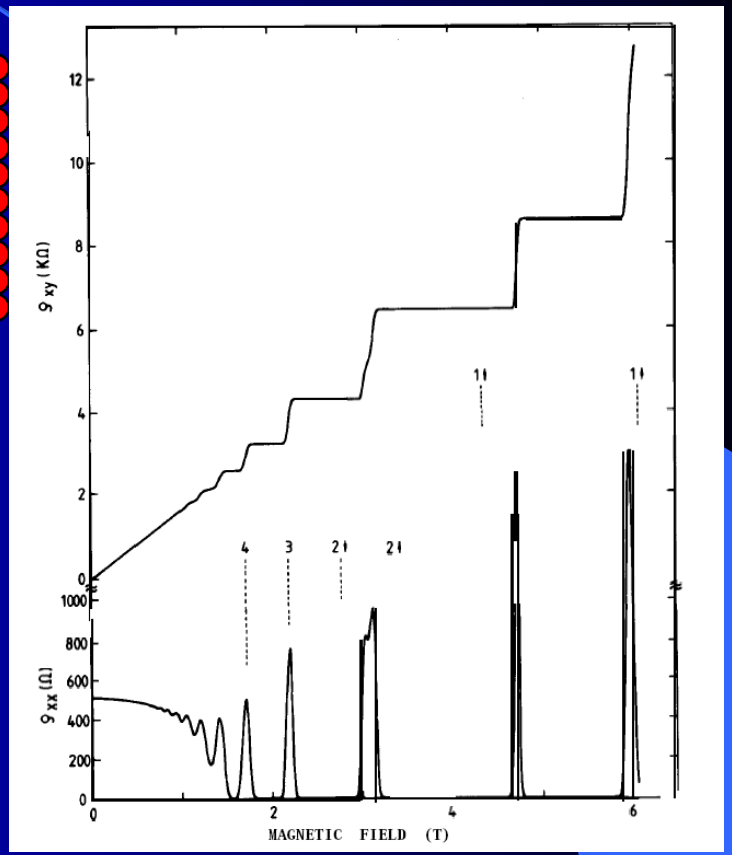


Fig. 9. Energy diagrams at varying bias-conditions in a double-barrier tunnel junction, indicating the resonant transmission in (b) and (d).

L'effet Hall quantique
Prix Nobel 1985

Klaus Von Klitzing
Marx Planck Institute Stuttgard





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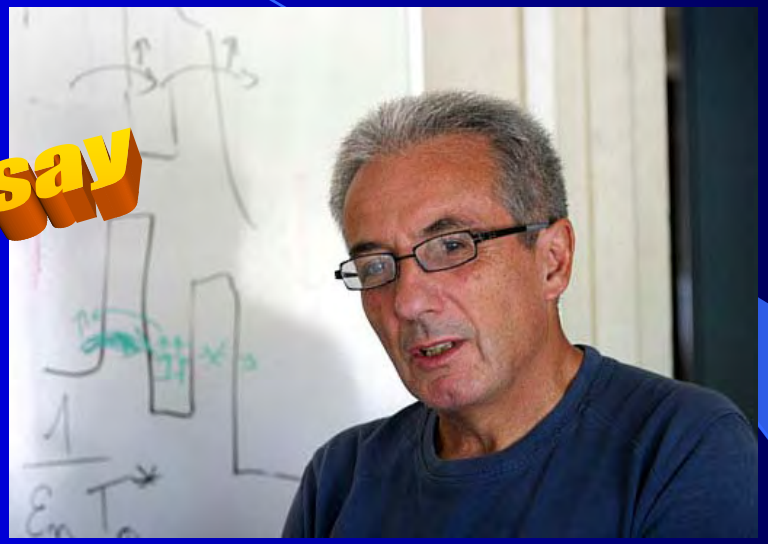
La magnétorésistance Géante
Prix Nobel de Physique 2007



Albert Fert
CNRS/THALES Orsay

Peter Grünberg
Forschungszentrum Jülich

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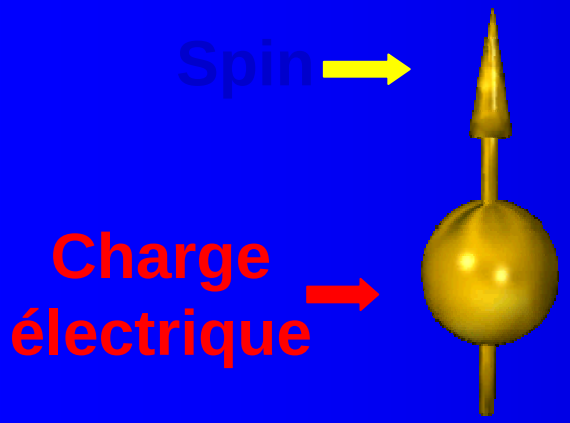
Le spin s'invite en électronique

Electron



Electronique: électrons mis en mouvement (courant) par action sur la charge

Spintronique: Mouvement par action sur le spin !
Générer, manipuler et détecter des courants de spin

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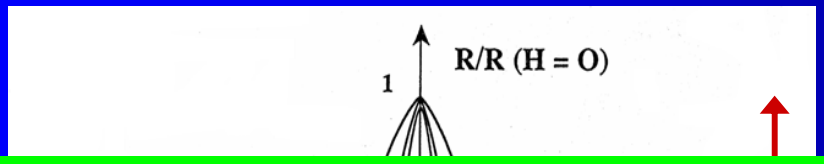
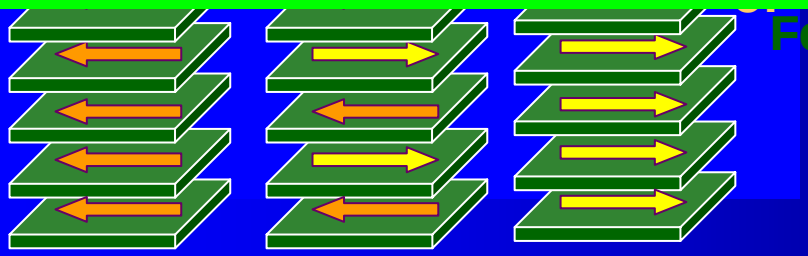
Nanomagnetisme et Electronique de Spin

La magnétorésistance géante des multicouches (Fert et al, Orsay, 1988)



géométrie CIP

M.N. Baibich, J.M. Broto, A. Fert, F. Nguyen van Dau, F. Petroff, P. Eitenne, G. Creuzet, A. Friederich, and J. Chazelas, "Giant Magnetoresistance of (001)Fe/(001)Cr Magnetic Superlat-tices", Phys. Rev. Lett. **61**, 2472 (1988).



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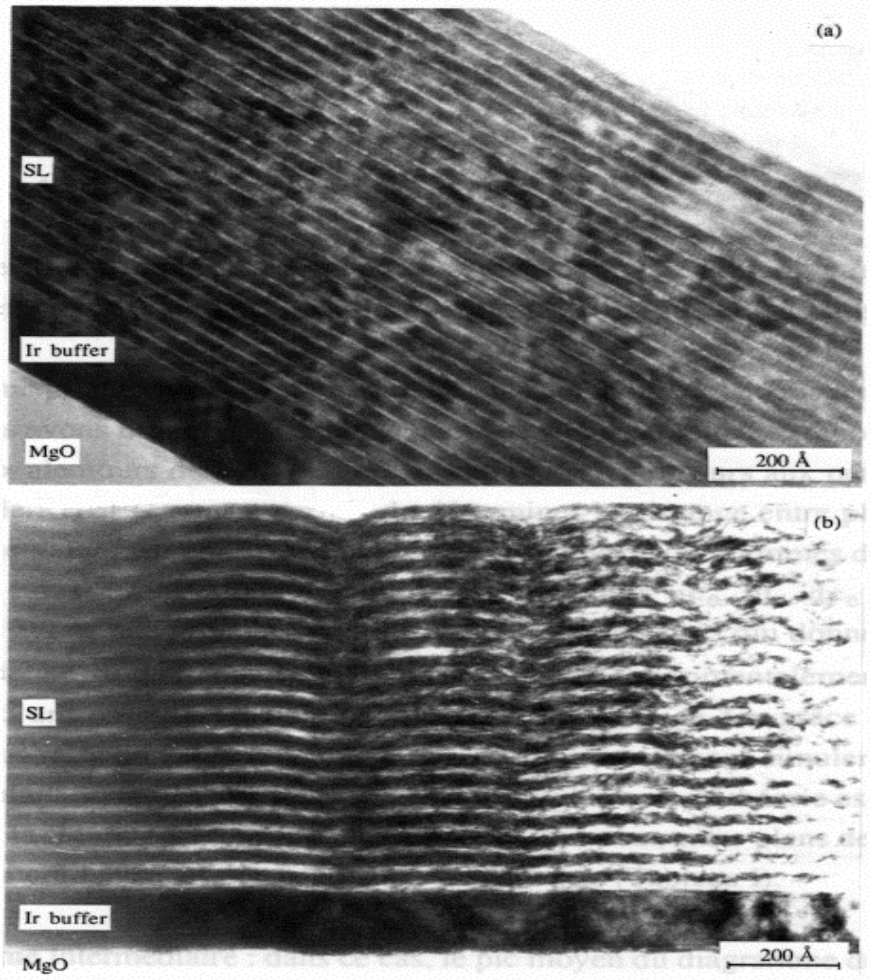
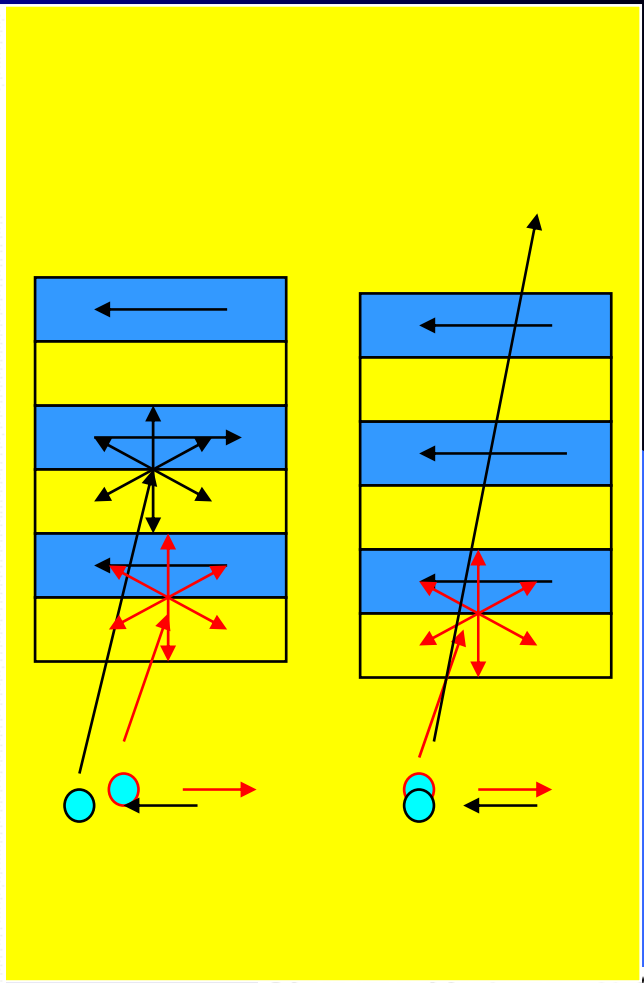
Magnétorésistance géante: vanne de spin

L. P. M.





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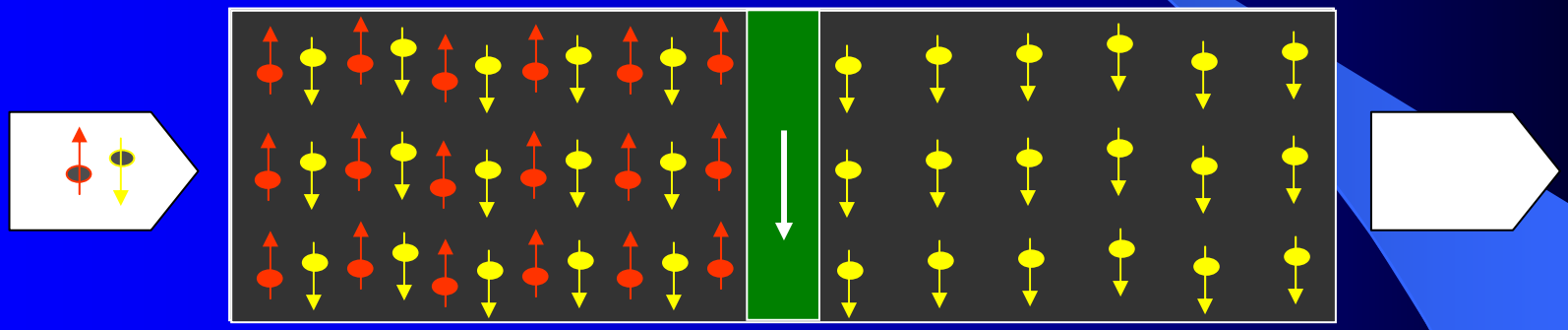
Magnéto-résistance Géante

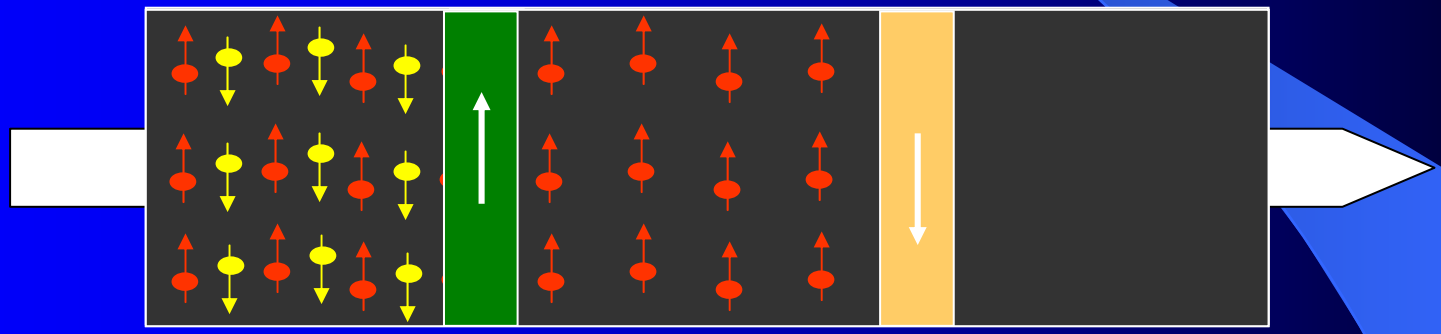
A. Fert, Prix Nobel 2007



→ Polariseur

Magnéto-résistance Géante

A. Fert, Prix Nobel 2007



→ Polariseur → Analyseur

L'enregistrement magnétique

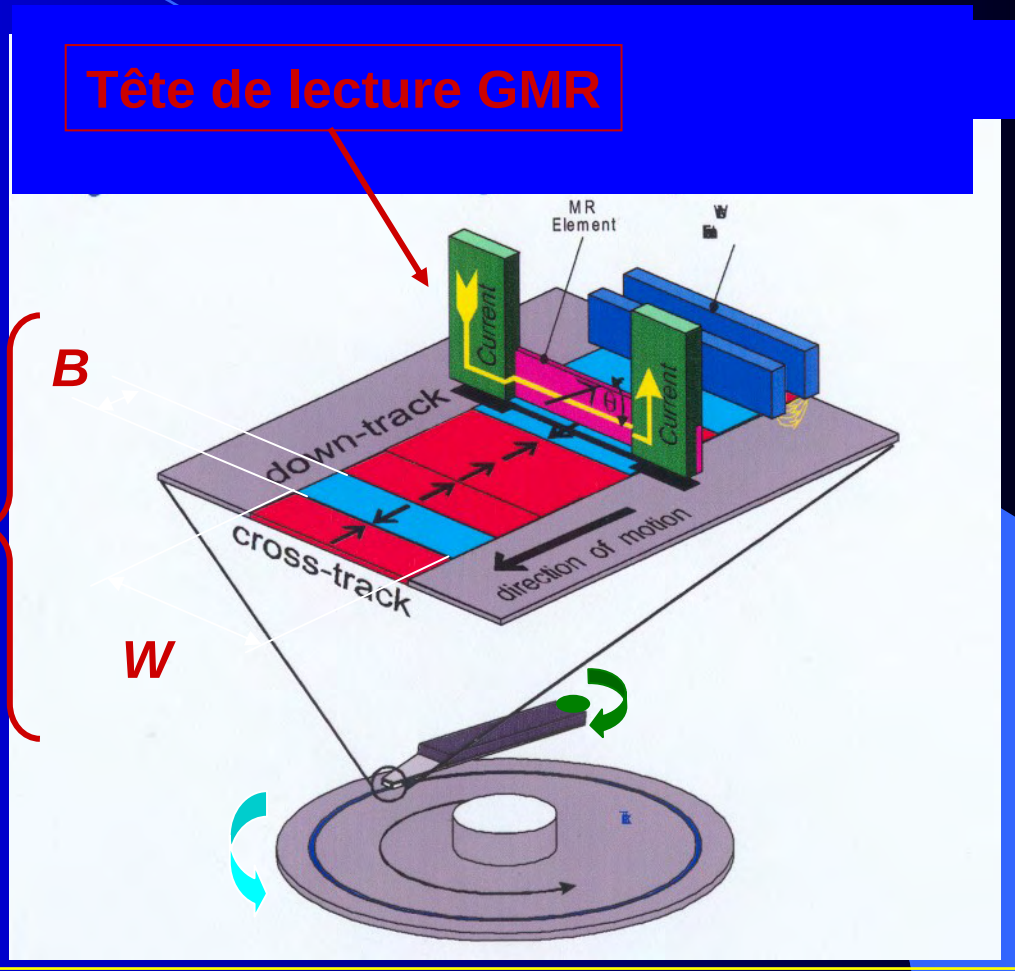
Ex: le disque dur

l'information est stockée sous forme de domaines magnétiques orientés « tête-bêche » le long de pistes circulaires

Produit 2002 :

B = 40 nm, W = 400 nm

Épaisseur film ~ 10 nm



Tendance: la densité d'enregistrement des produits double chaque année !!!

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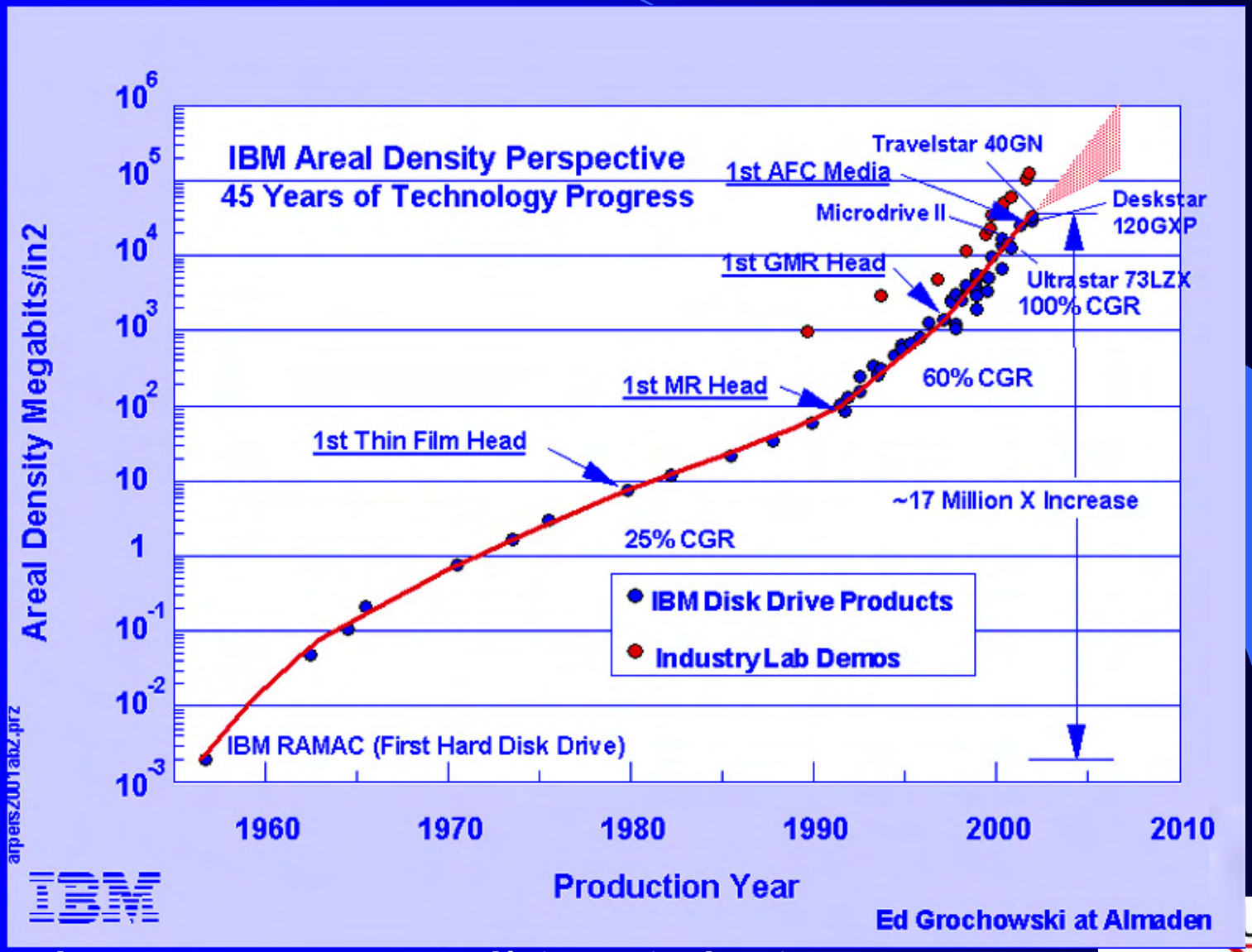
Enregistrement magnétique



Magnéto-résistance Géante

Matériaux nécessaires

Techniques expérimentales

L. P. M.

Complexe MPGA, LPM, Nancy

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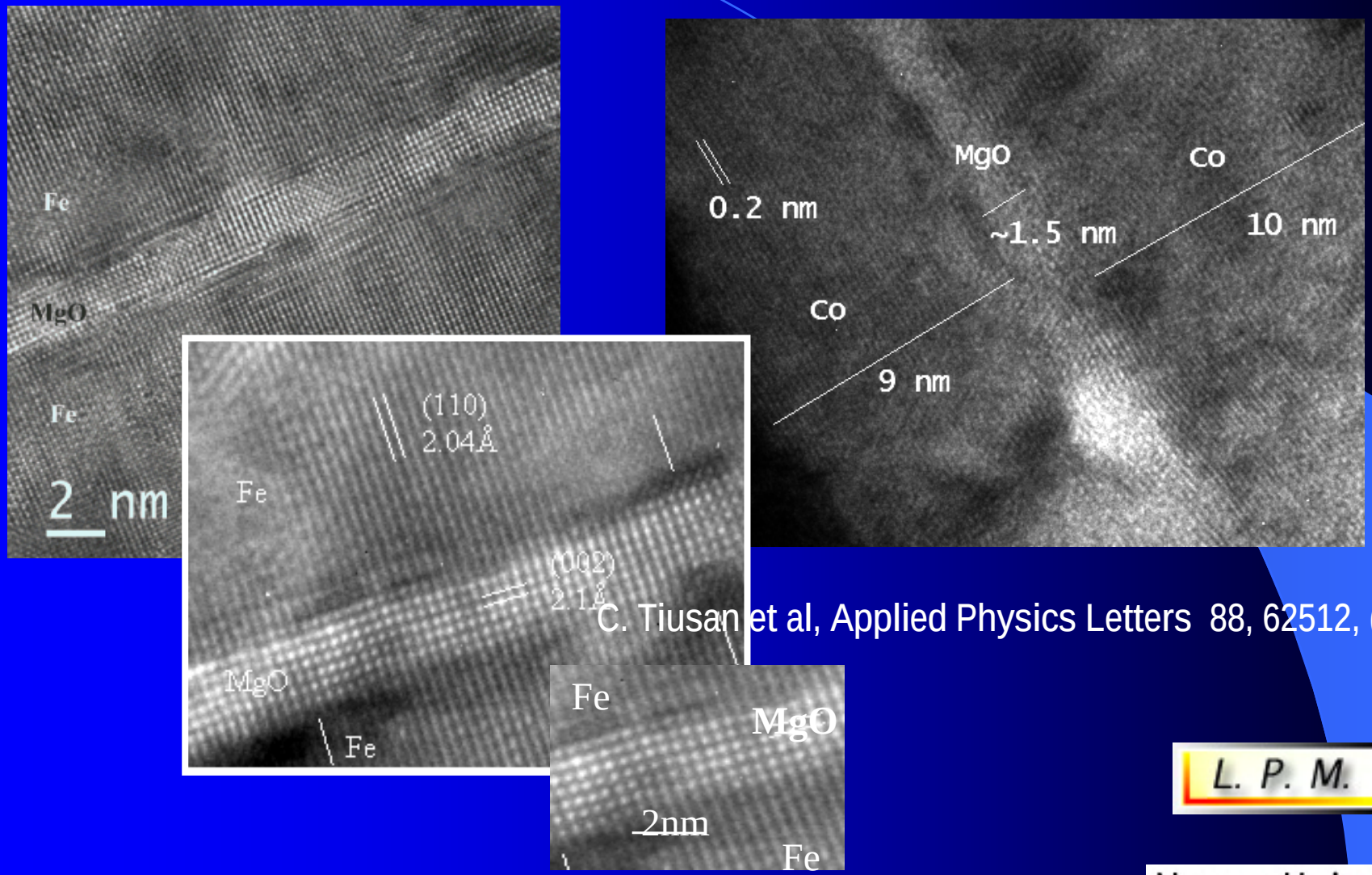
Magnéto-résistance Tunnel

Remplacer le métal par un isolant



C. Tiusan et al, Applied Physics Letters 88, 62512, (2006).

L. P. M.

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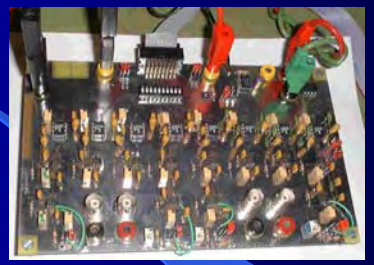
Utilisation d'un dispositif à électronique de spin pour la réalisation de capteurs de champ magnétique innovants



Contrats :

2001 - 2004 – Thèse G. Malinowski (CIFRE SNR) : démonstration

2005 – Dépôt ANR

2007 – ANR Transfert en milieu industriel avec Sensitec

NanoSciences GRAND-EST

Programme Grand Est de Recherche en Nanosciences – Bilan 2008

Transport dépendant du spin et nanomagnétisme : vers une électronique de spin

Michel HEHN

Membre Junior de l'Institut Universitaire de France 2008

LPM, Nancy-Université, CNRS, Boulevard des Aiguillettes B.P. 239

F-54506 Vandœuvre lès Nancy France

NanoSciences GRAND-EST

Programme Grand Est de Recherche en Nanosciences – Bilan 2008

Transfert de spin : Une autre façon de retourner l'aimantation

Stéphane Mangin

Membre Junior de l'Institut Universitaire de France 2007

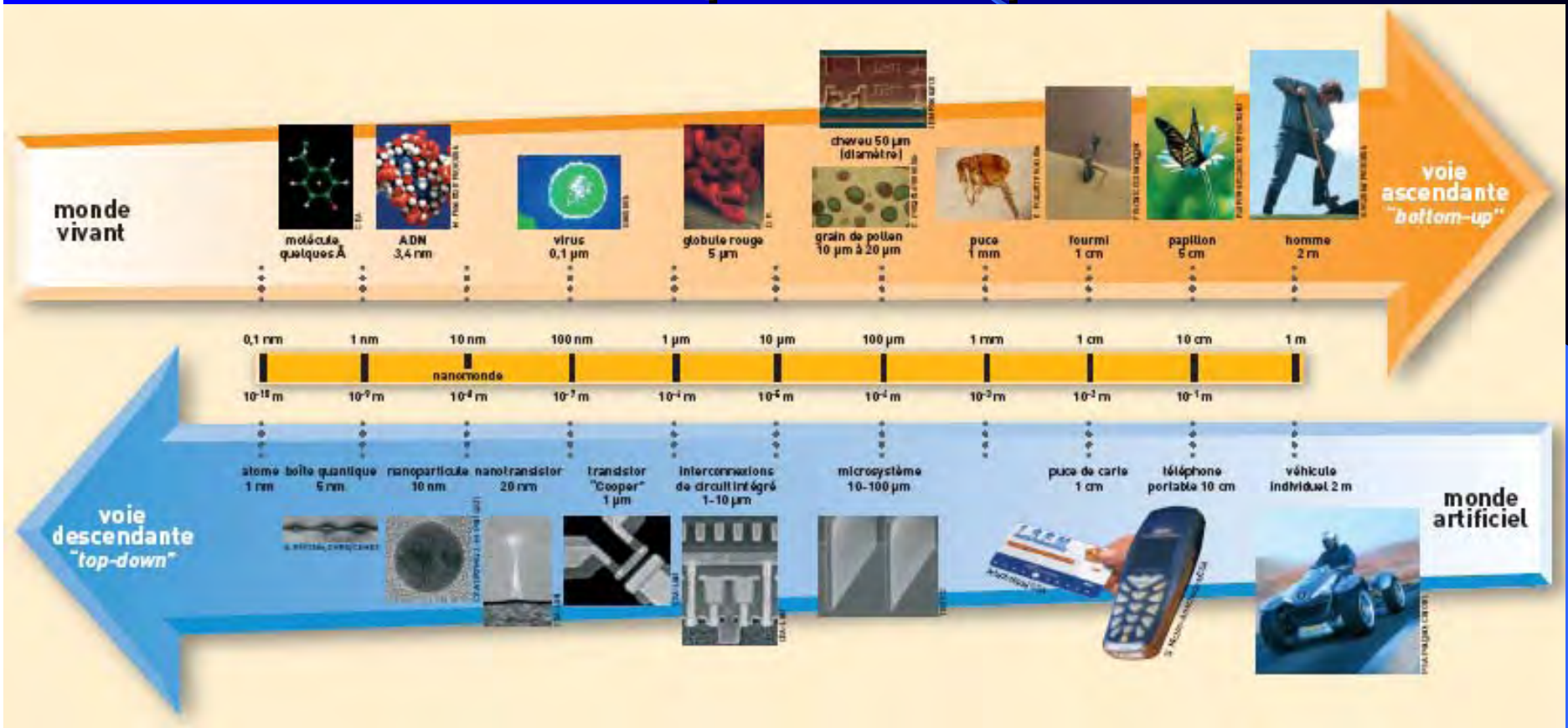
LPM, Nancy-Université, CNRS, Boulevard des Aiguillettes B.P. 239

F-54506 Vandœuvre lès Nancy FRANCE

Définitions

- **les *nanotechnologies***
  - champ de recherches impliquant la fabrication de structures, de dispositifs et de systèmes au niveau atomique, moléculaire ou supra moléculaire
  - *échelles caractéristiques* comprises approximativement entre 1 et 100 nanomètres
- **Les *nanosciences***
  - développement de champs scientifiques nouveaux qui explorent les phénomènes qui apparaissent à l'échelle nanométrique.

Les deux voies ascendante et montante Bottom-up et Top-Down



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Nanosciences et nanotechnologie une thématique transversale des technologies diffusantes

- Micro et nanoélectronique
  - Micro et Nanoelectronique CMOS
  - Electronique moléculaire
  - Electronique de spin
  - MEMS et NEMS
  - Photonique et optoélectronique
  - Composants quantiques
    - Ordinateur quantique
    - Information quantique
  - …….
- Nanobiotechnologies
  - Nano-Bio-Info-Cognitif NBIC
- Nanomatériaux et chimie
  - Chimie et assemblage moléculaire
- Métrologie et instrumentation

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World market forecast

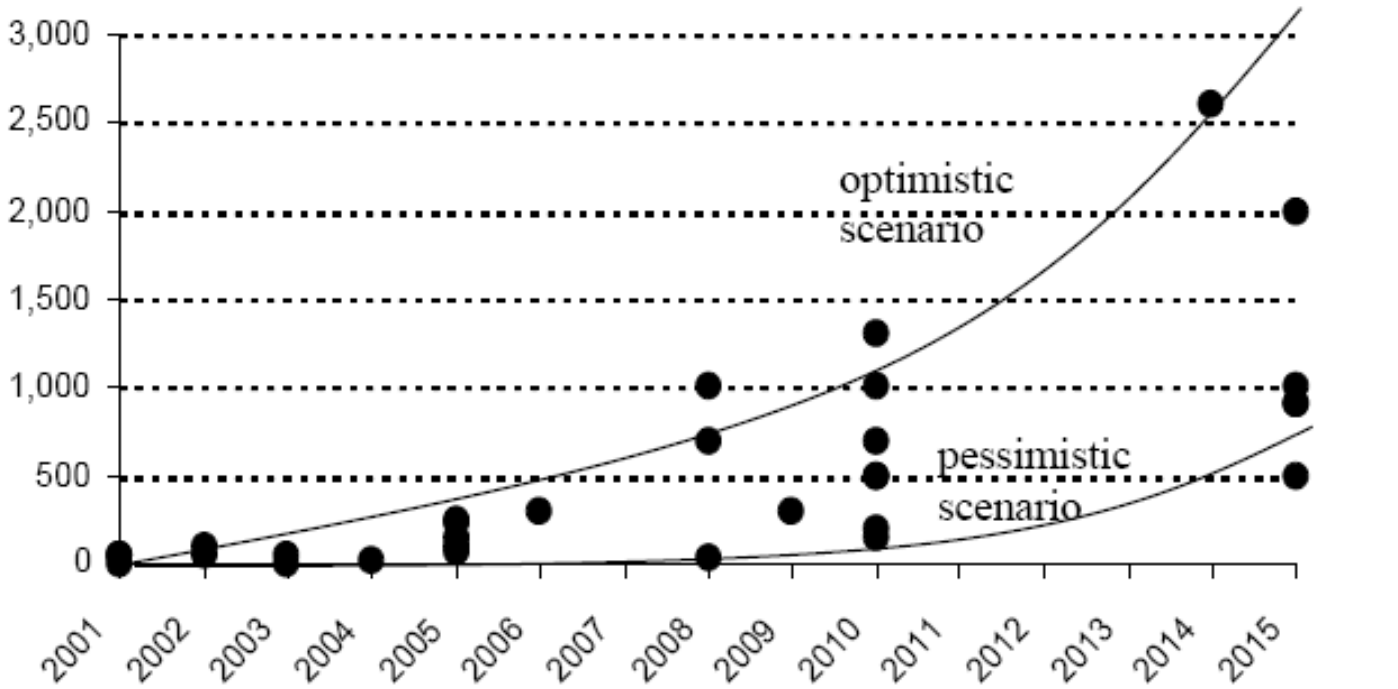

Figure 1: World market forecasts for nanotechnology in billion US Dollar. Diverse sources[1]

Source: nanoarticle_hullmann_nov2006.pdf (commission EU)

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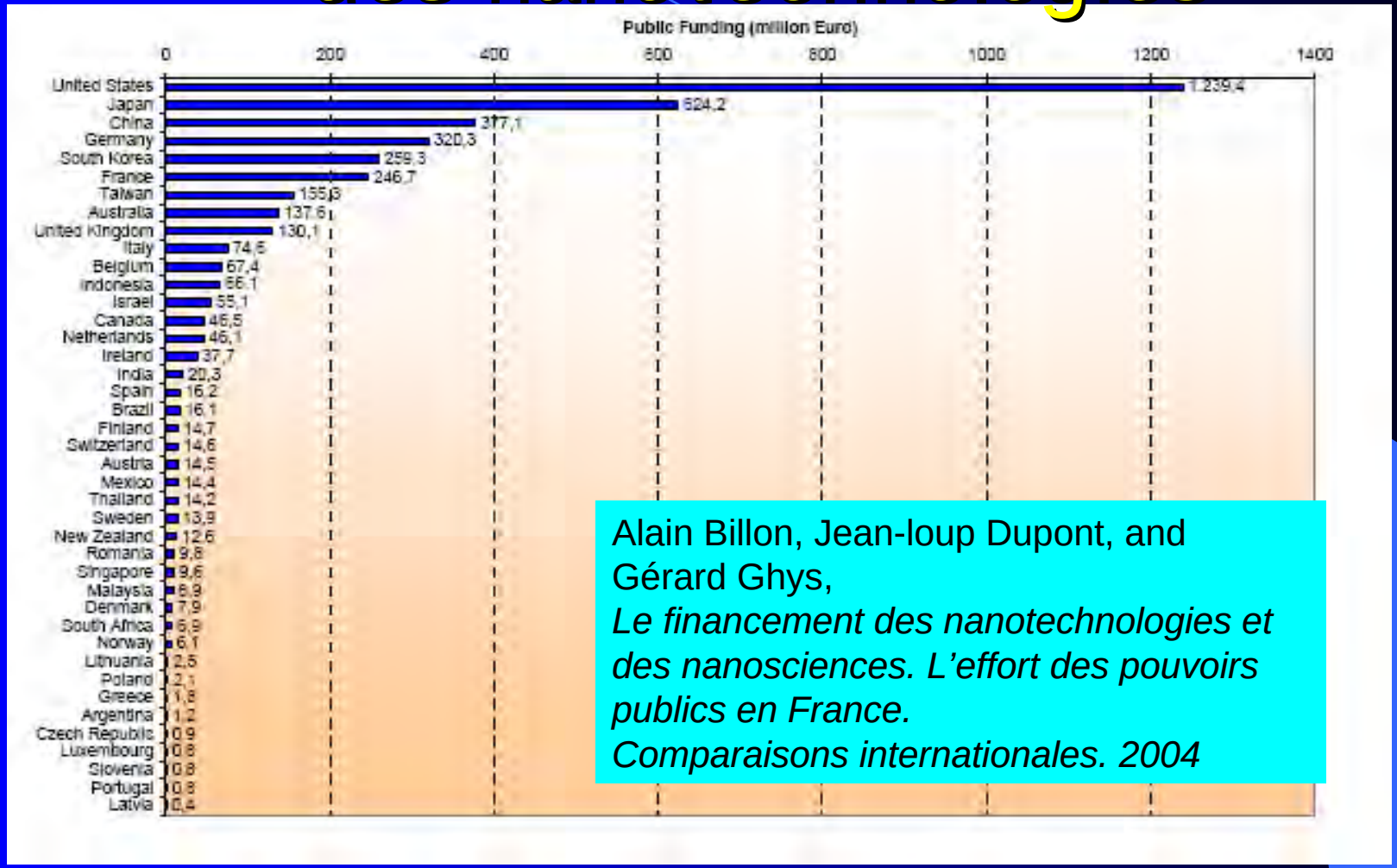
Financements publics R&D des nanotechnologies



Alain Billon, Jean-loup Dupont, and Gérard Ghys,
Le financement des nanotechnologies et des nanosciences. L'effort des pouvoirs publics en France.
Comparaisons internationales. 2004

Renzo Tomellini, *Some Figures about Nanotechnology R&D in Europe and Beyond.* 2005.
ftp://ftp.cordis.europa.eu/pub/nanotechnology/docs/nano_funding_data_08122005.pdf

NMP PCRD 6 – domaines R&D couverts

EUROPEAN COMMISSION

En vert: IP- SMEs

Gras: budgets élevés

Financement CE, € millions / Nombre de projets

PCRD 6 Grand total

1 426 / 386

Syst./instrum/equipment – diagnosis/surgery
Tissue engineering, bio-mimetic, bio-hybrid
Sensors, actuators – health, safety, security
Industrial bio-technol., Environmental technol.
Nanos for security systems

Size-dependent phen.
Self-organisation & assembly
Standardisation for nanos
Mol & bio molecular mechanisms & engines
Molecular motors
Interfaces bio / non-bio & applications
Nature as model
Nanotubes

NANO: 320 / 109

Nanostructures surfaces
3-D nano / no-carbon
Handling-control instrumentation
Devices, techniques
Nanoparticles in the living world
Nano drug delivery
Impact on health & environment
Ethical, legal, social aspects
Nano-photonic/electronic devices
Bio-sensors - diagnostics and health care
Roadmaps for Nanotechnologies

INTEGR 250 / 41

Multi-funct mat – factory of the future
Biomaterials for implants
Multi-funct technical textiles
Components for transport
Chemicals – eco-efficient processes
Safe, efficient construction
New construction products & proc.

Factory of the future through N-M-P
Knowl-based communities in prod. techn.
Knowl-based techn. in traditional Industries
(Machine tools, hydraulics, pigments, materials, stones, metals, textiles, plastics, wood, non-destructive testing)
Concepts for global delivery
Mapping and foresight

PROD: 437 / 97

Radical changes in the "basic" materials indus.
Waste mangt. Hazard reduction in plant & storage
Knowl-based, sust. proc., eco-innovation
Public awareness, sust. consumption
Safety, environmental technol.
Fast & Flexible manufacturing Enterprise

Understanding materials phen.
Modelling and design
Inrefacial phen. in materials
New tools for adv. mat.
New processing pathways

MAT: 390 / 120

Production of nanoparticles
Intelligent bio-materials
Tribology – surface engineering
Nanostructures porous materials
Ceramic thin films
New materials by design
High-perfo mat - macro-scale applic.
Bio-inspired, org/inorganic hybrid mat.
Solid-state ionics
Computational materials
Mapping & foresight activities

Clean **STEEL** production **20 / 1**

DG RTD-G / Technologies Industrielles / IA – Orsay, 15 Novembre

7

Liberté • Égalité • Fraternité
RÉPUBLIQUE FRANÇAISE

MINISTÈRE
DE L'ENSEIGNEMENT SUPÉRIEUR
ET DE LA RECHERCHE

Elaboration des stratégies nationales

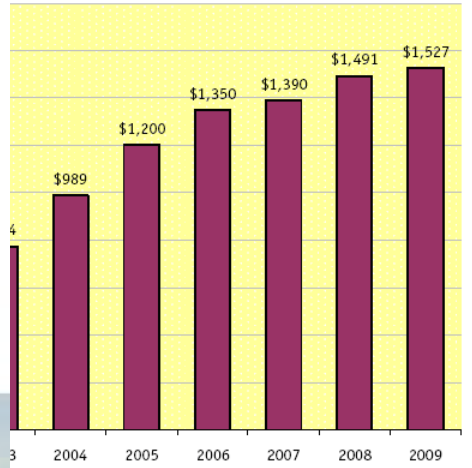
Table 1. Relationships betwe

PCA	GOAL: Goal 1: Advance a world-class nanotechnology research and development program
Fundamental Nanoscale Phenomena & Processes	critical
Nanomaterials	critical
Nanoscale Devices & Systems	primary
Instrumentation Research, Metrology, & Standards	secondary
Nanomanufacturing	primary
Major Research Facilities & Instrumentation Acquisition	secondary
Environment, Health, & Safety	primary
Education & Societal Dimensions	secondary

Relevance: critical, primary, secondary

Federal Ministry of Education and Research

Nano-Initiative – Action Plan 2010



ency funding (in millions of dollars) reported since
2008 figure is estimated; the 2009 figure is

Enjeux Scientifiques et Technologiques des nanosciences et nanotechnologies

- Développer les sciences et technologies de l'information, clés de la croissance
- Faciliter la convergence des STIC, de la physique, des sciences du vivant et des nanosciences
- Maîtriser la matière à l'échelle nanométrique
- Intégrer les apports de la modélisation et de la simulation

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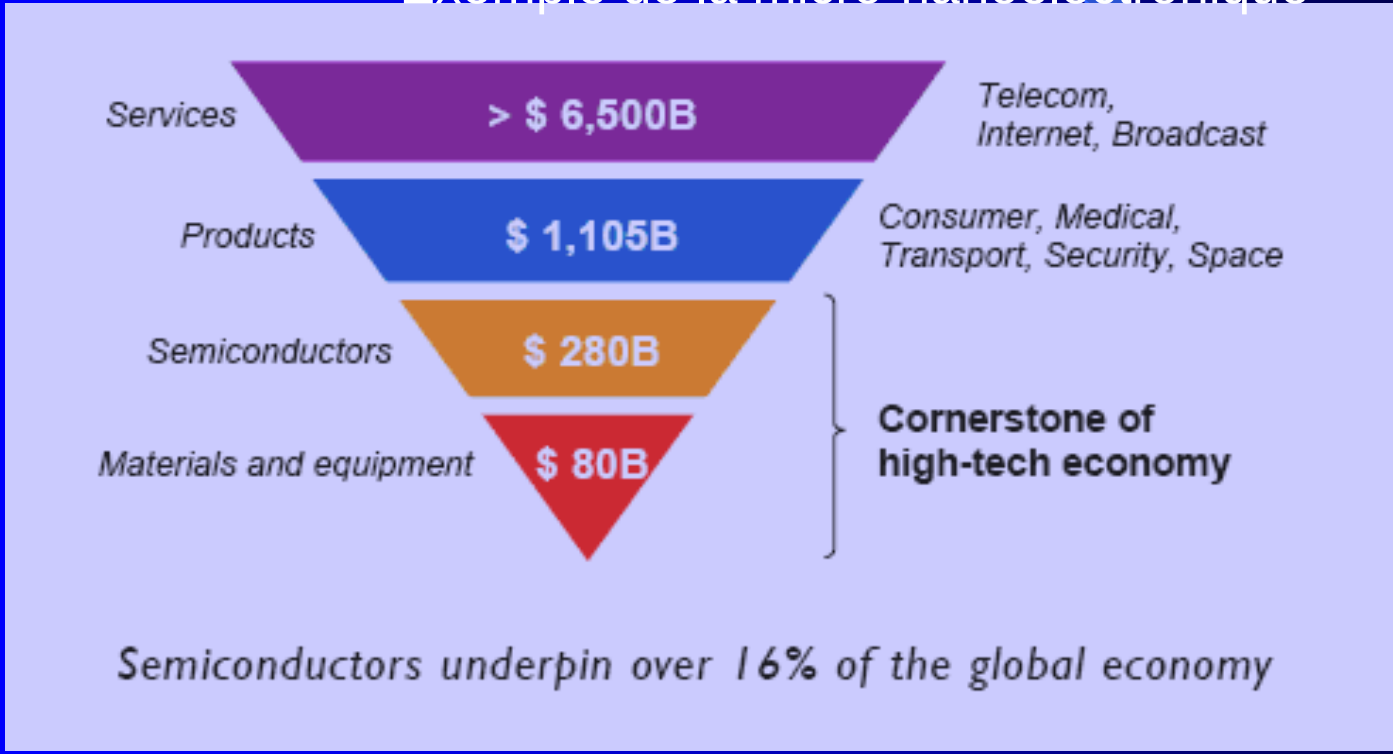
Les grands enjeux micro-nano
Augmentation de la compétitivité des entreprises

Exemple de la micro-nanoélectronique



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La micro-nanoélectronique et les technologies associées

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Innovation-Enabled Technology Pipeline

90 nm
2003

65 nm
2005

45 nm
2007

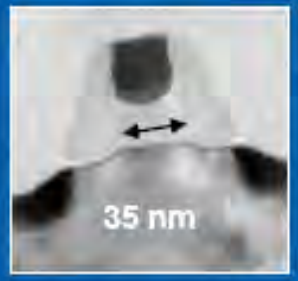
32 nm
2009

2011+

Manufacturing → Development → Research

SiGe S/D

Strained Silicon



SiGe S/D

Strained Silicon

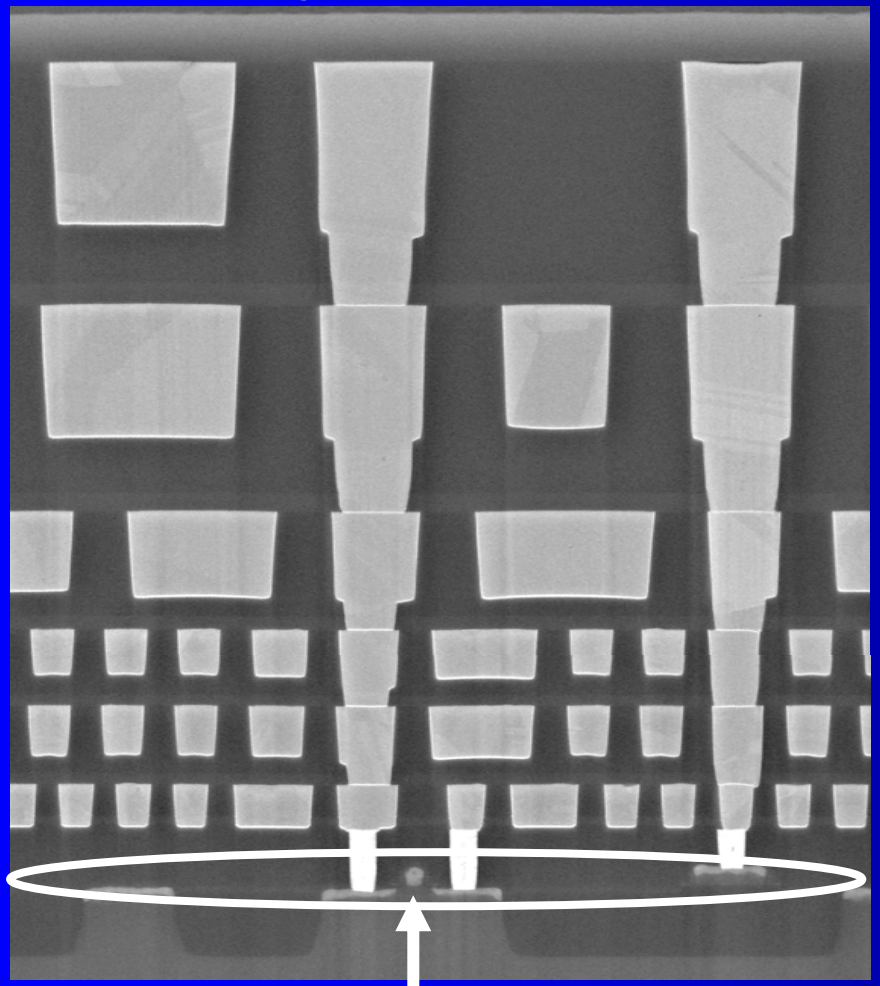
Future options subject to change

Intel Developer FORUM

intel

Building an Integrated Circuit

~ 60 days to manufacture



- Precision at the molecular and atomic levels.
- 23 masking layers.
- Some layers are thinner than a virus.

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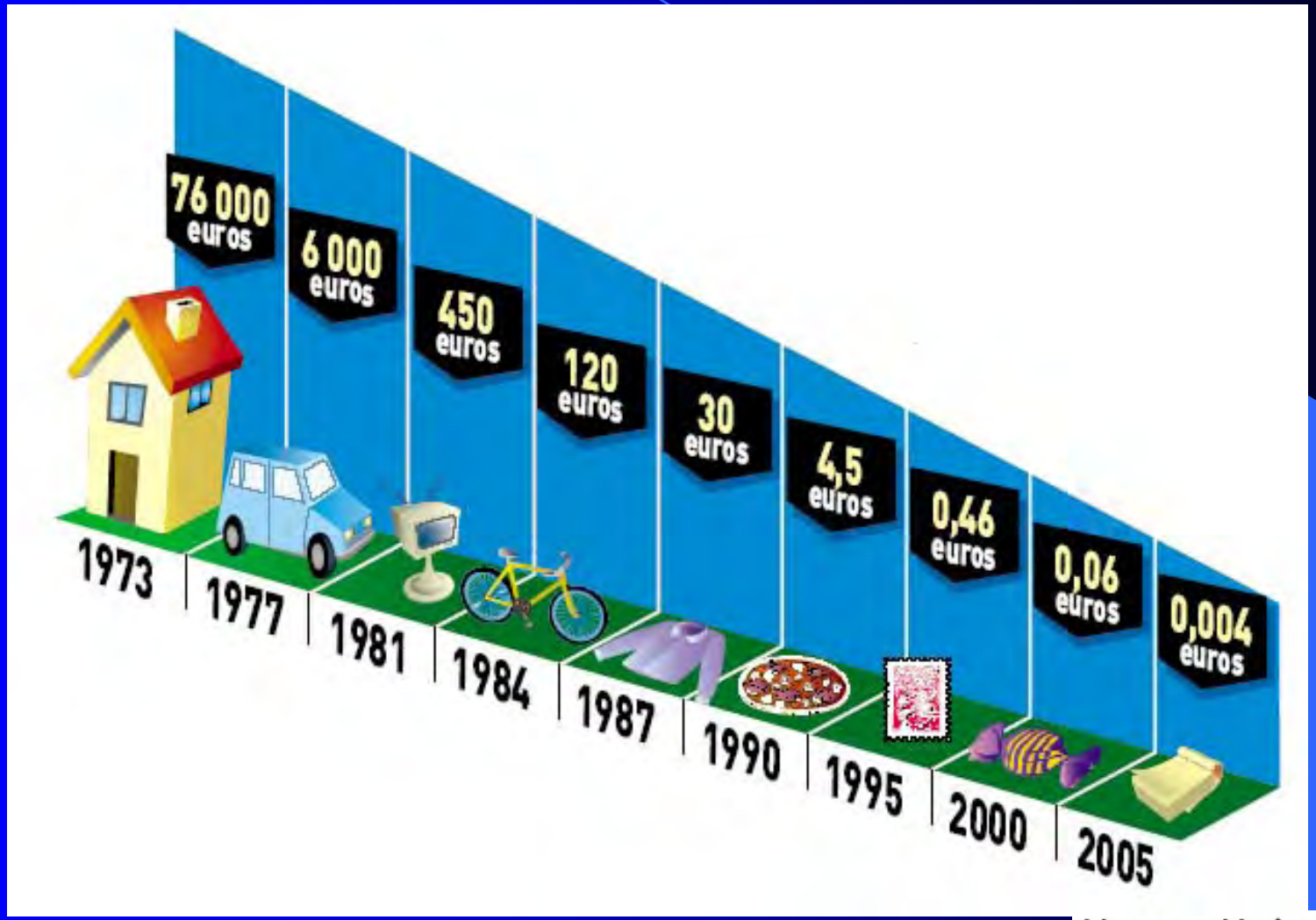
Coût 1 Million de transistor intégrés



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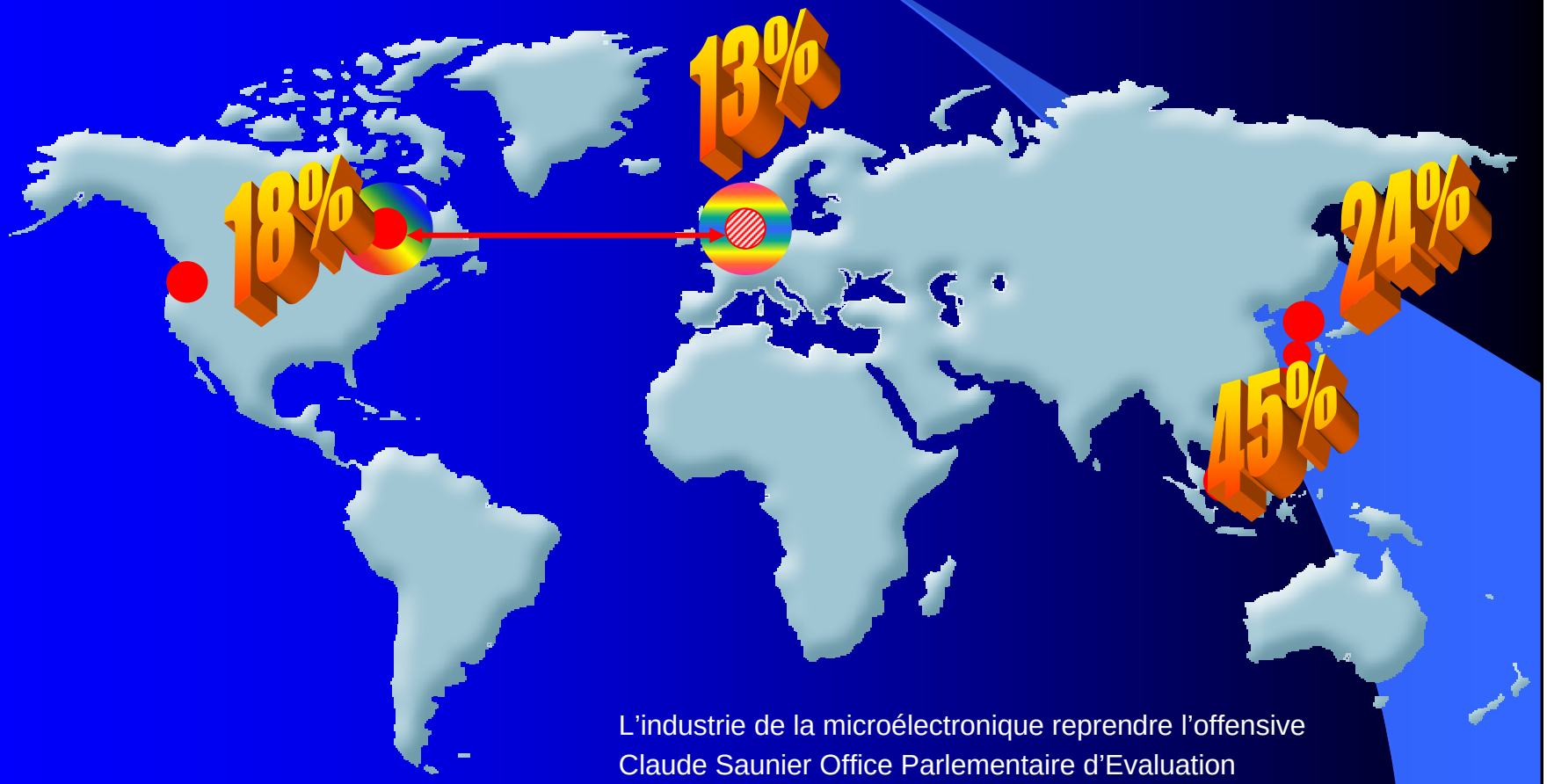
‘Cœur CMOS’
Les industriels leaders en R&D



L’industrie de la microélectronique reprendre l’offensive
Claude Saunier Office Parlementaire d’Evaluation
des Choix Scientifiques et Technologiques
25 juin 2008 http://www.senat.fr/rap/r07-417/

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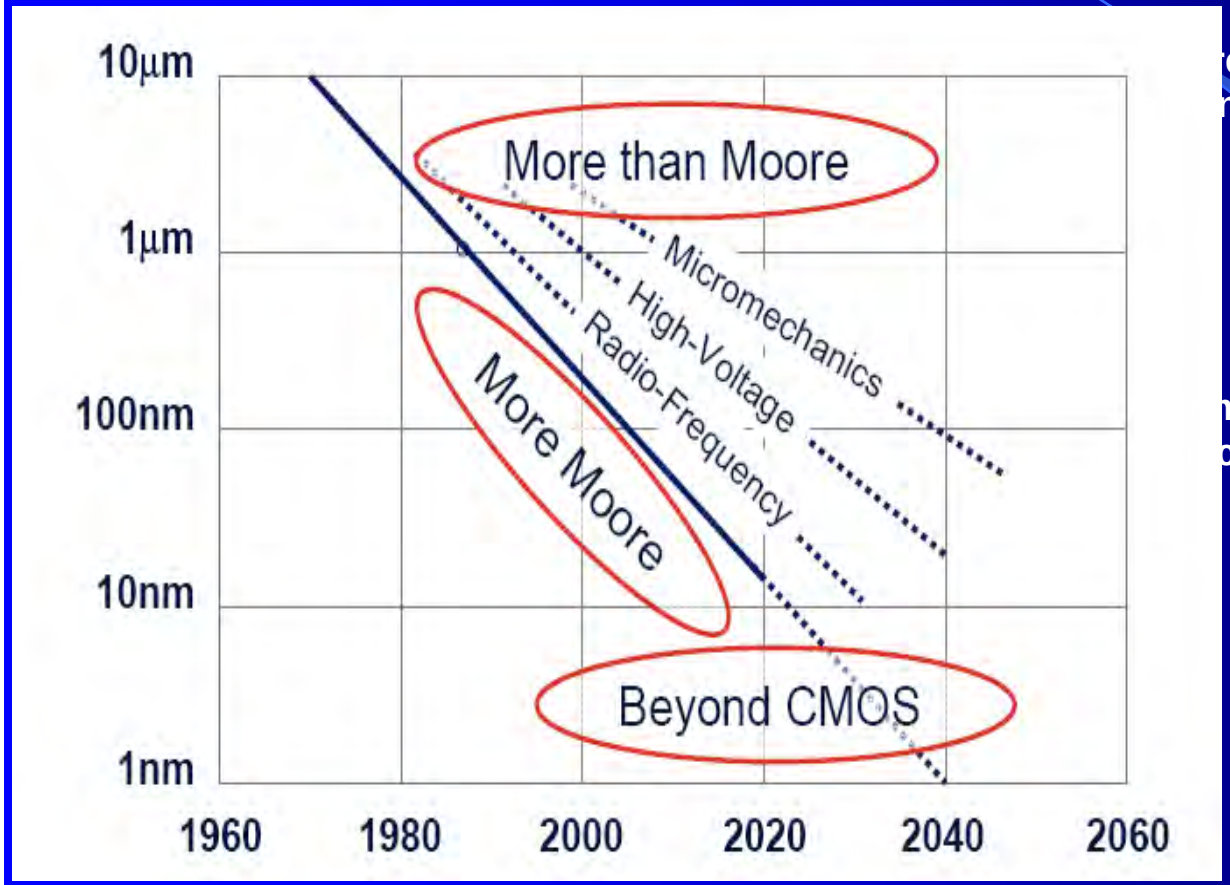
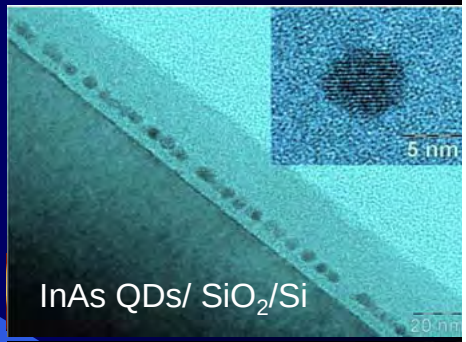
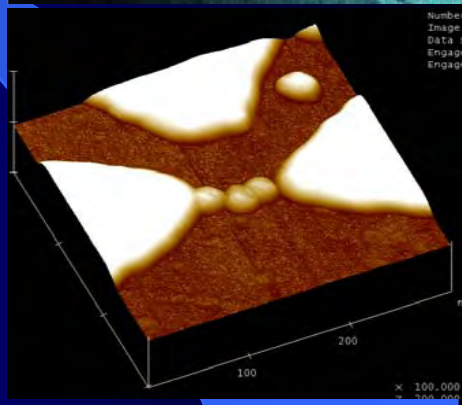
Les différentes stratégies en électronique

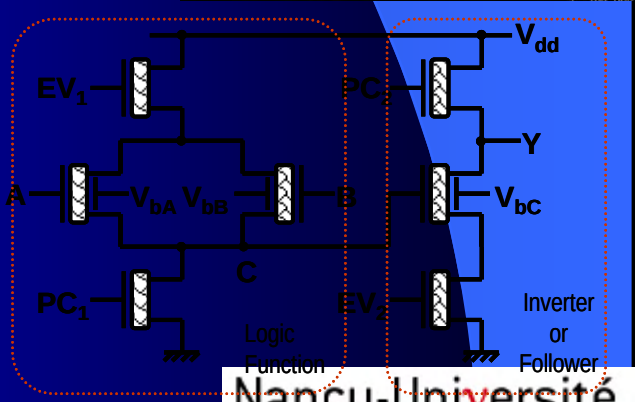


res Matériaux
nales



mposants
crets





Conception
Prédictive de circuits

Cellule reconf. à 8-Fonct

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conclusions

- Liens entre disciplines
  - Frontières et certitudes n'existent pas
- Les nanotechnologies et nanosciences
  - Petit objet mais vaste sujet
  - Thématiques transverses
  - Thématiques diffusantes
- Enjeux économiques importants
  - Electronique
  - Maitrise de l'énergie
  - Développement durable
  - Médecine et santé
- Développement responsable des nanosciences et nanotechnologies