

# ***Introduction to Nanophysics***

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# What is the size for a “nano” ?

One (nm) equals to 1/1000000000 (10<sup>-9</sup>) meter

厘米 10<sup>-3</sup> m , **Macro**

微米 10<sup>-6</sup> m , **Micro**

奈米 10<sup>-9</sup> m , **Meso**

# R. Feynmann Already Knew about this !



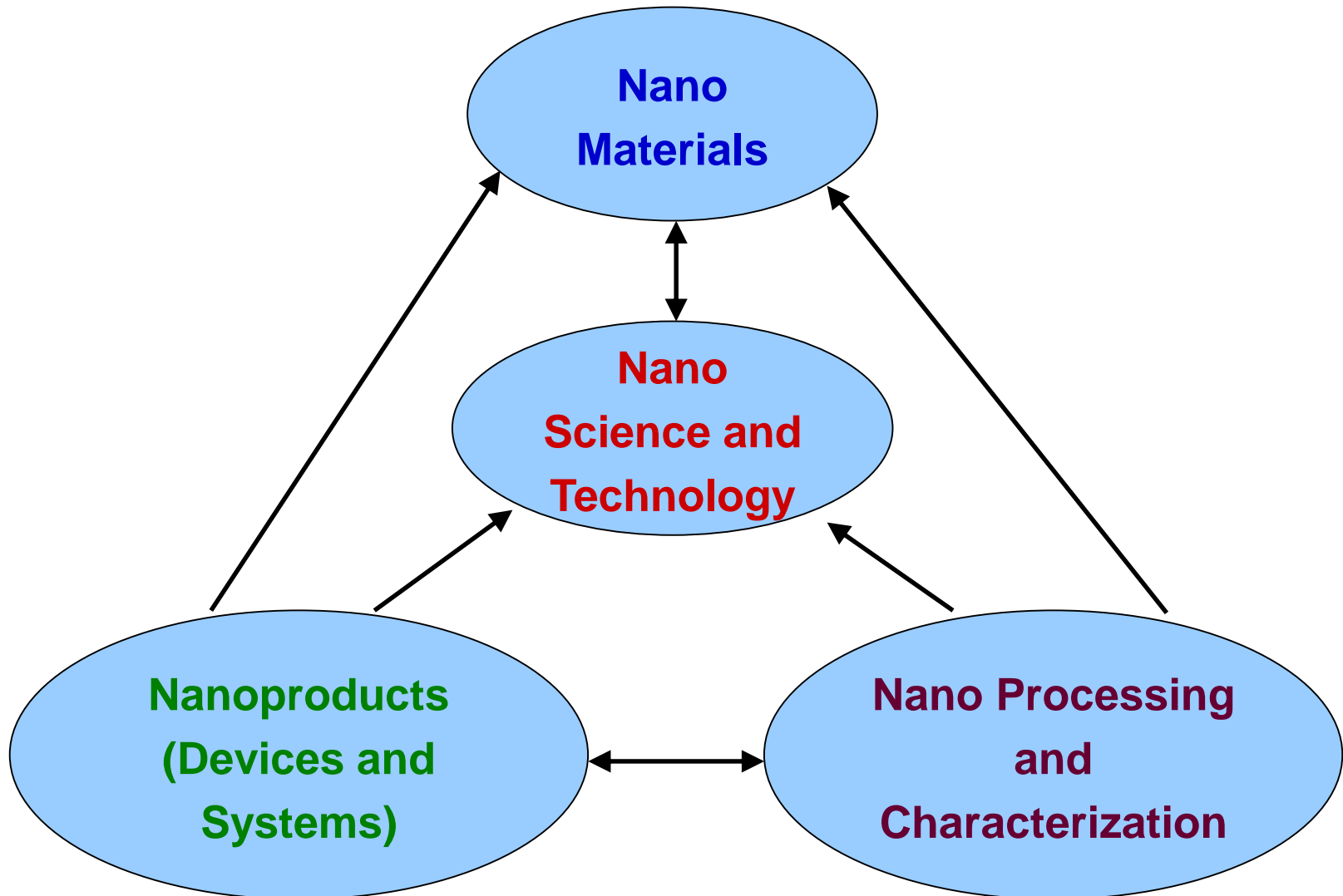
**“ There’s plenty of  
room at the bottom ! ”  
in 1959.**

# Physicists noticed the “Nano ” as early as .....

- 4th Century, Roman glassmaker: the color of glasses can be changed by mixing in metal particles
- In 1883, Films containing silver halides for photography were invented by George Eastman, founder of Kodak.
- 1908, Gustav Mie first provided the explanation of the size dependence of color.
- Vision from Feynman in 1959: “There is plenty room at the bottom”, and also recognized “there are plenty of nature-given nanostructures in biological systems”.
- 1950-1960, small metal particles were investigated by physicists.
- 1957, Ralph Landauer realized the importance of quantum mechanics plays in devices at small scales.
- Before 1997 => **mesoscopic** (or low dimensional) physics : quantum dots, wells, wires.....are known already.



# *Major Topics of Nanoscience and Technology*



# *What is the Nano Technology?*

➤ **Science and Technology Down scaling to size under 100 nm:**

**Via “Top-down” lithographic patterning:  
-- Moore’s law !**

➤ **Manipulate the atomic and molecular structures:**

**“Bottom-up” nano materials, growth and assembly.**

**Feymann: There’s plenty of room at the bottom**



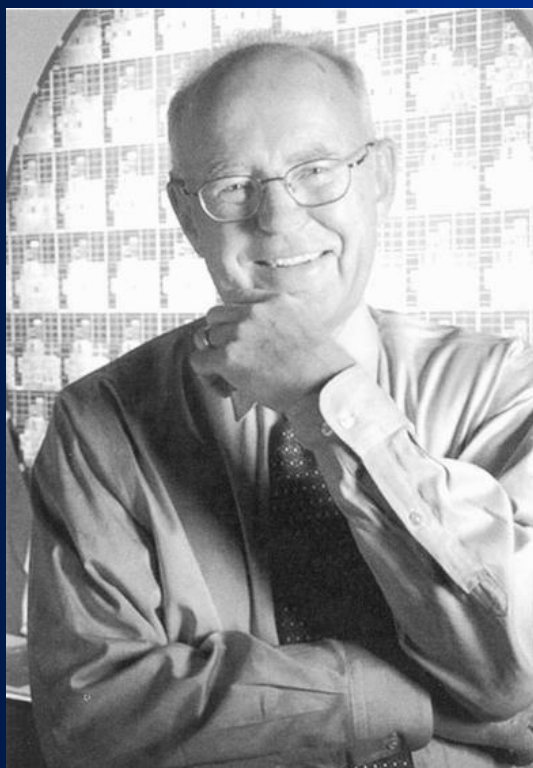
# 近來大力推動奈米科技的背景

## 來自微電子學可能遭遇瓶頸的考慮

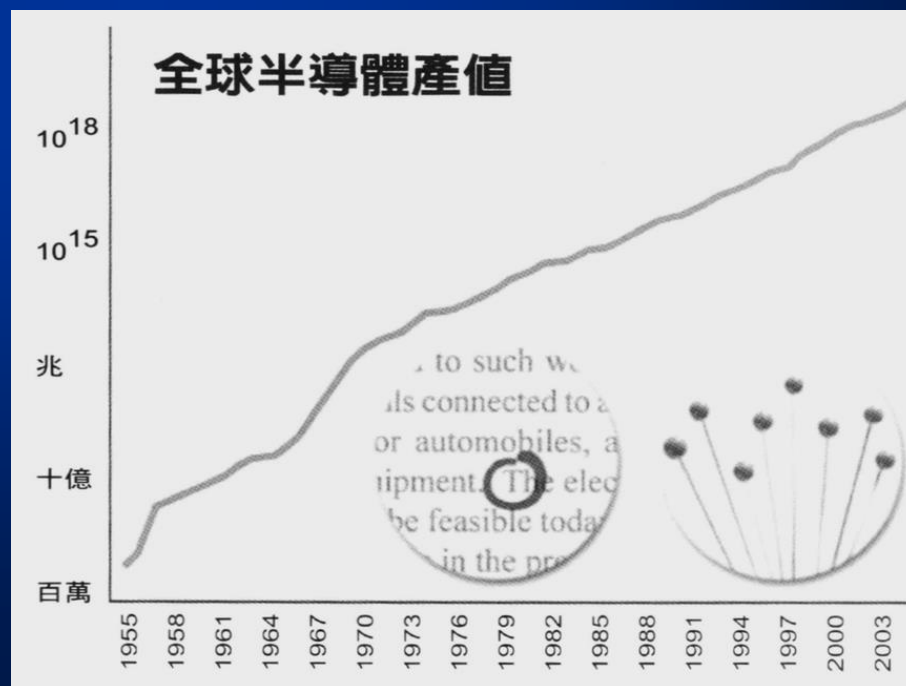
### Moore's Law : 摩爾定律

A 30% decrease in the size of  
printed dimensions every 1.5 years.

矽晶上電子原件數每1年半會增加一倍



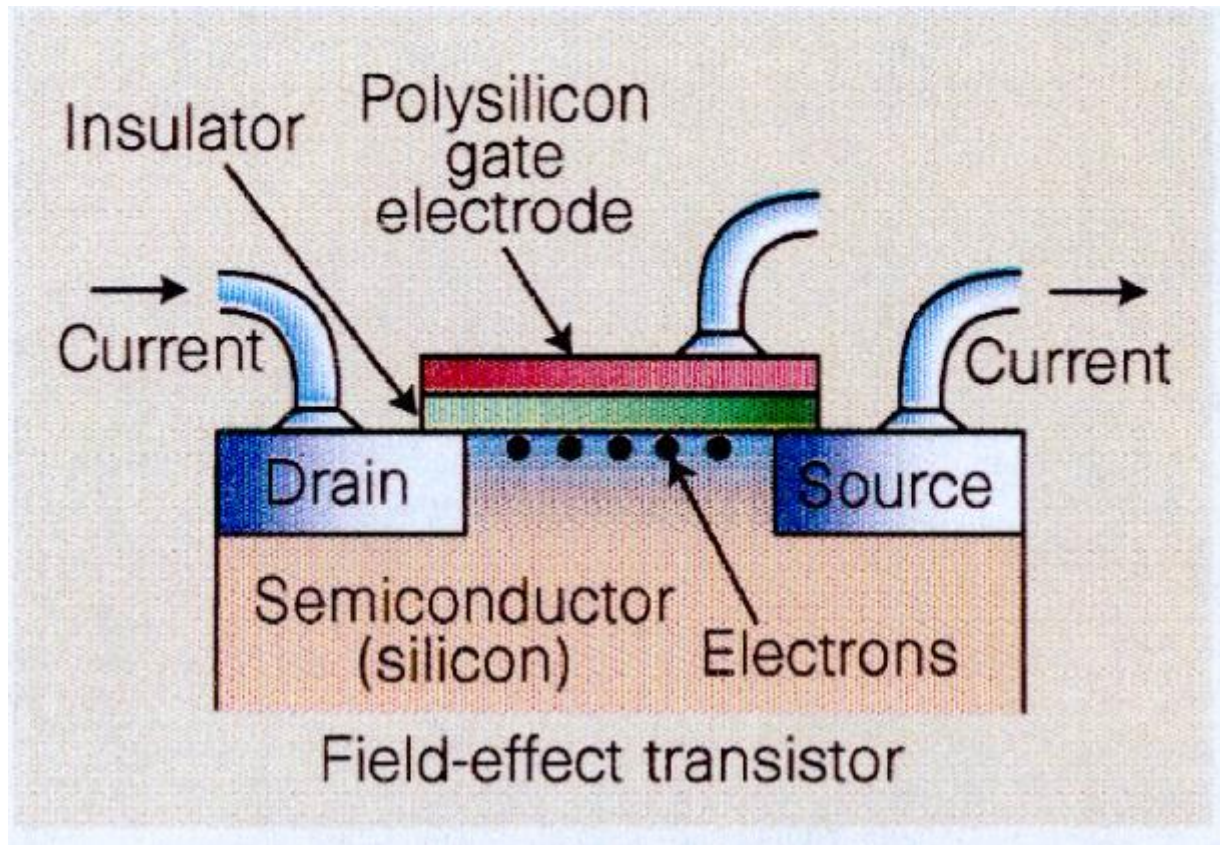
Gordon Moore



***Two basic modern electronic technologies  
in condensed matter physics field***

- ❑ MOSFET
- ❑ MRAM

# *Metal-Oxide-Field Effect Transistor (MOSFET)*

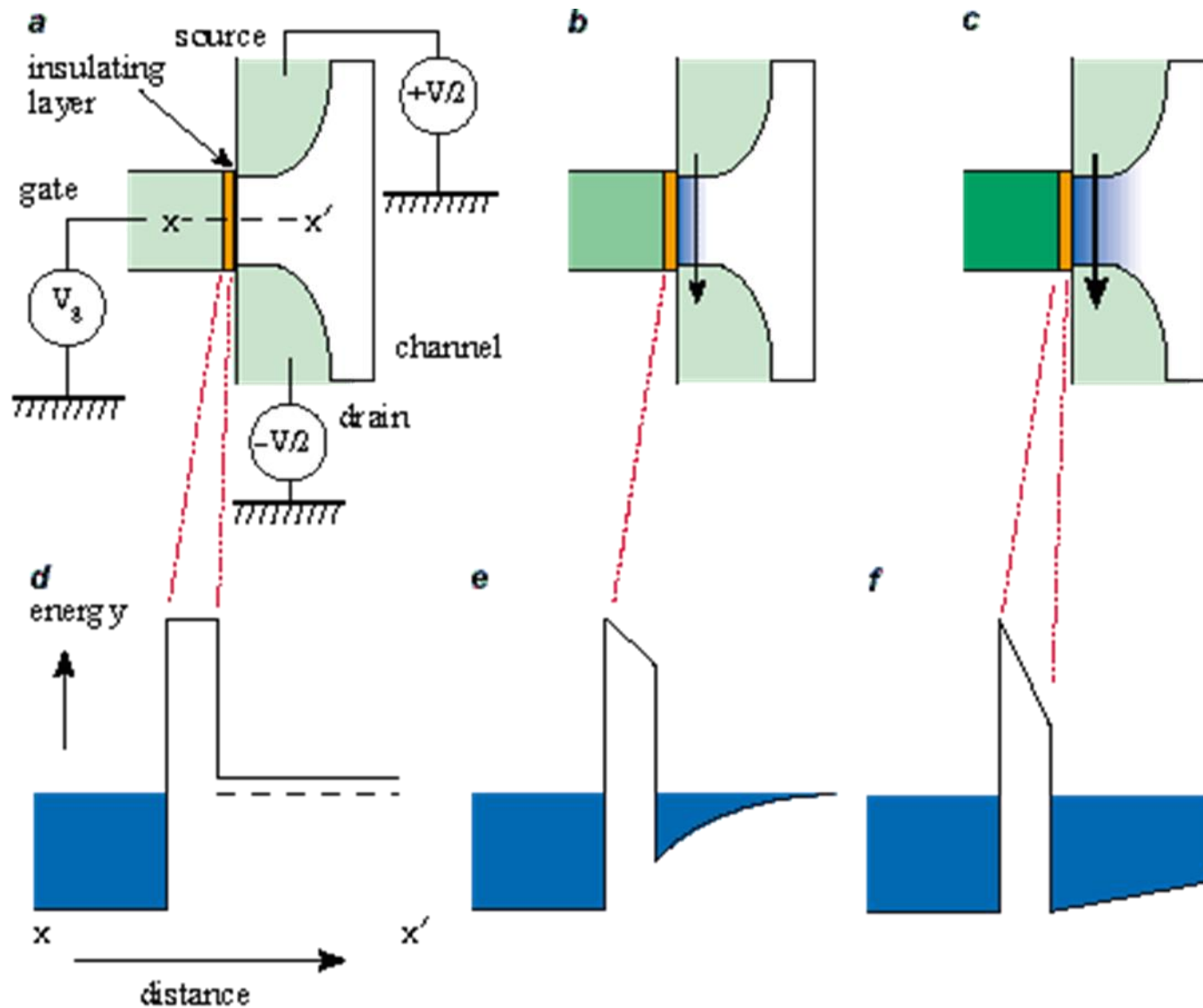


*1960 Kahng and Atalla, First MOSFET*

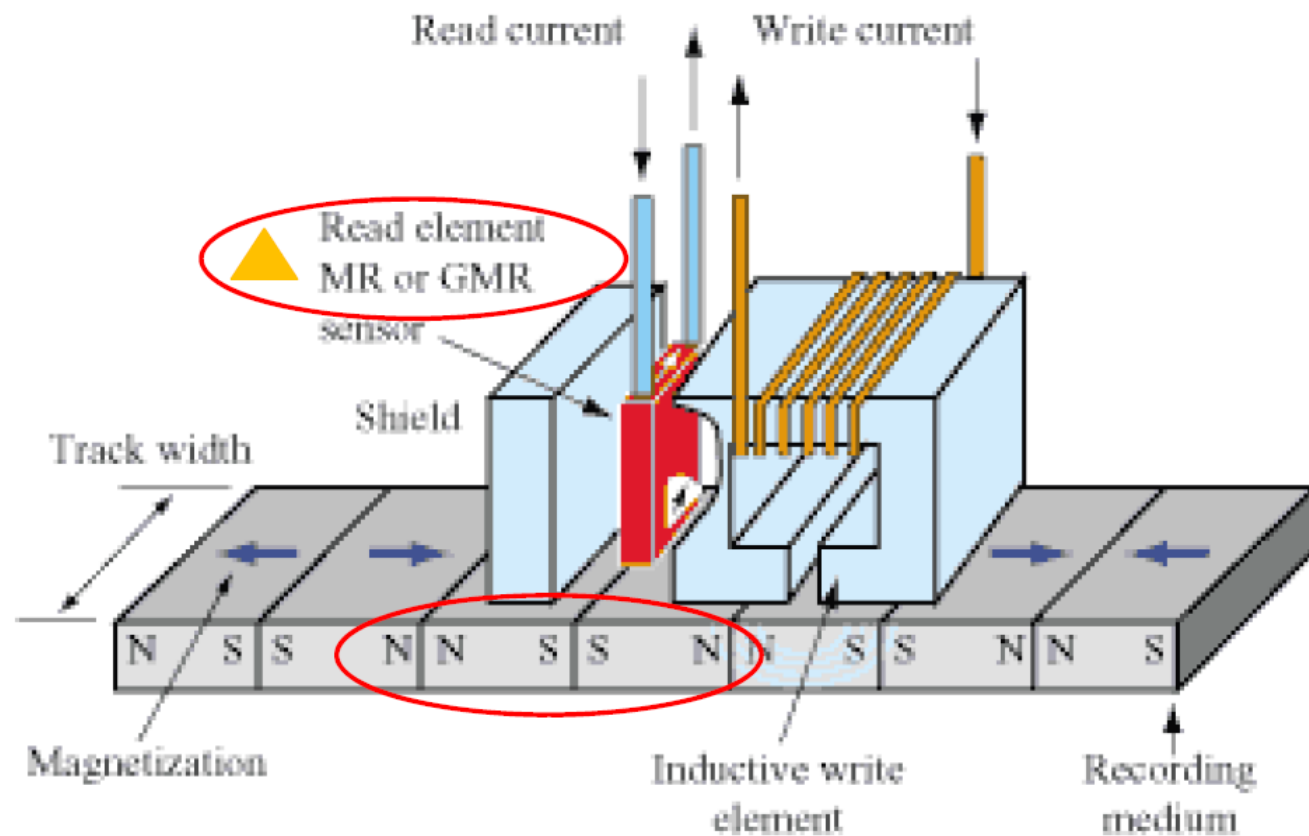
*1970 First IC, 1 kbit, 750 khz microprocessor*

# 電子科技之基礎--MOSFET

(metal-oxide-semiconductor field-effect transistor)



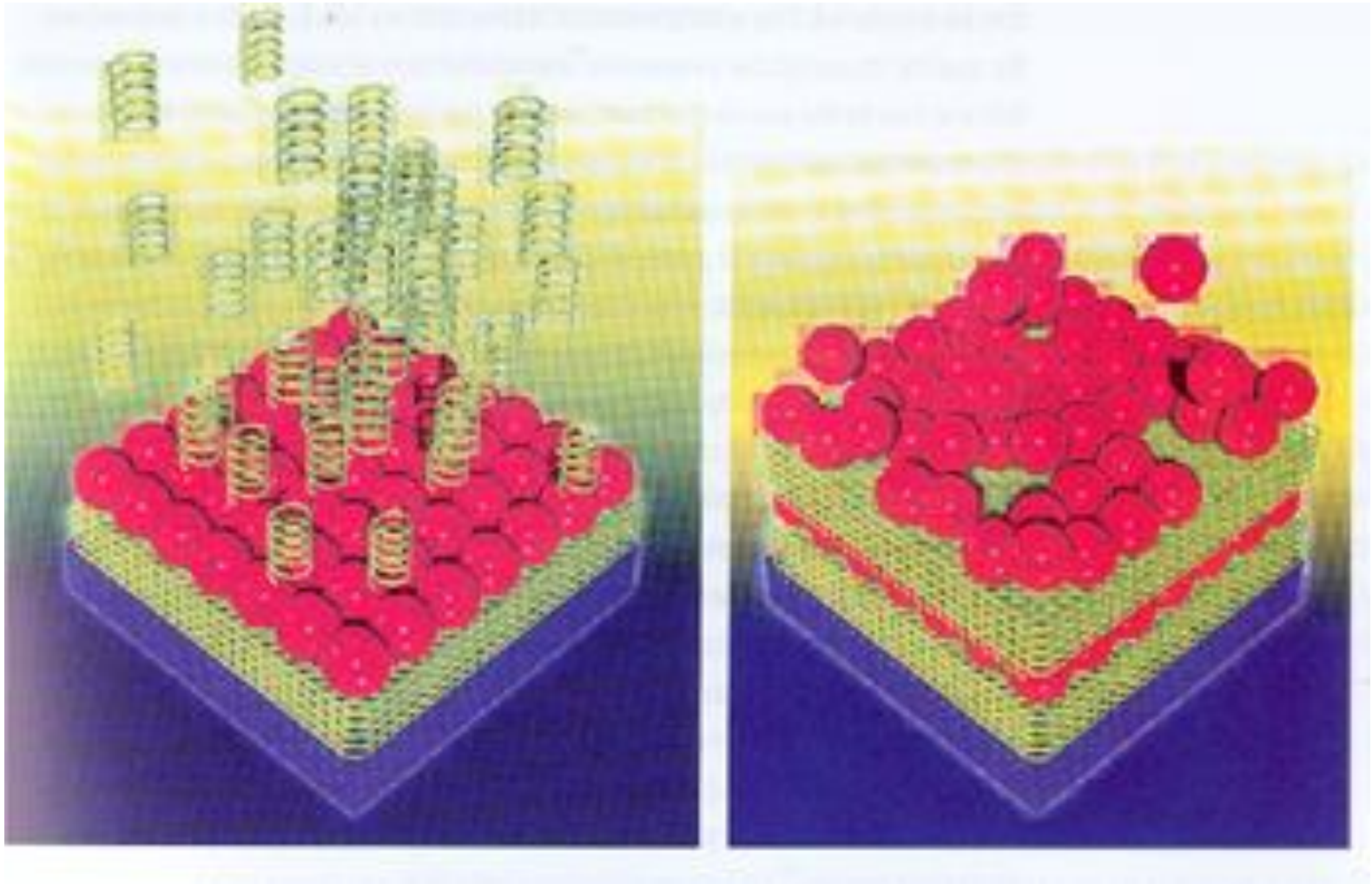
# 電子科技之基礎--磁記錄





# ***Bottom-up Nano systems & Self-Assembly***

enabling to design large molecules and nano materials



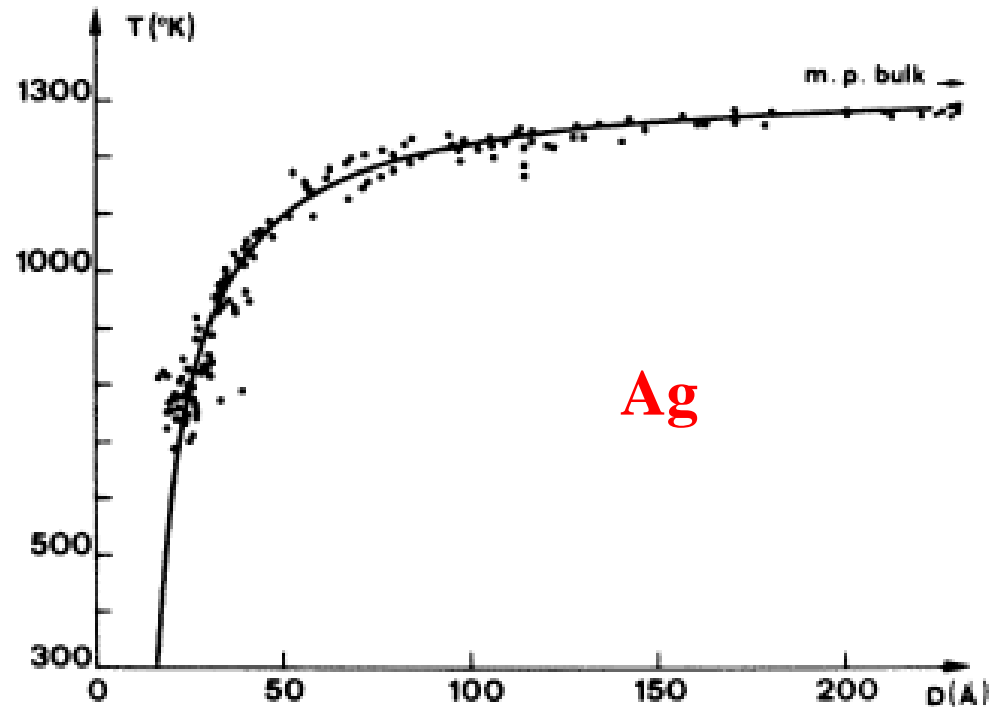


*Five major lessons  
that we have learned*

# **The First Lesson :**

## ***Bulk-to-nano Transition***

# Ex: size-dependence of melting temperature



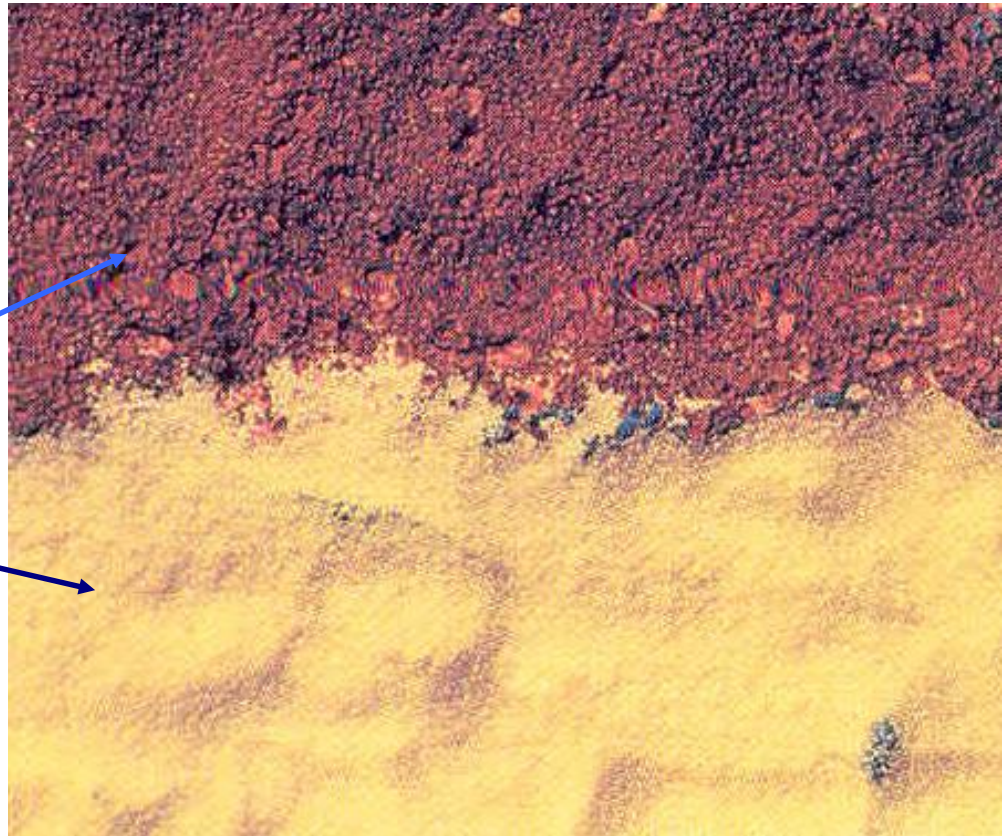
Ph. Buffat and J-P. Borel, Phys. Rev. A13, 2287 (1976)

# Ex: size-dependence of color

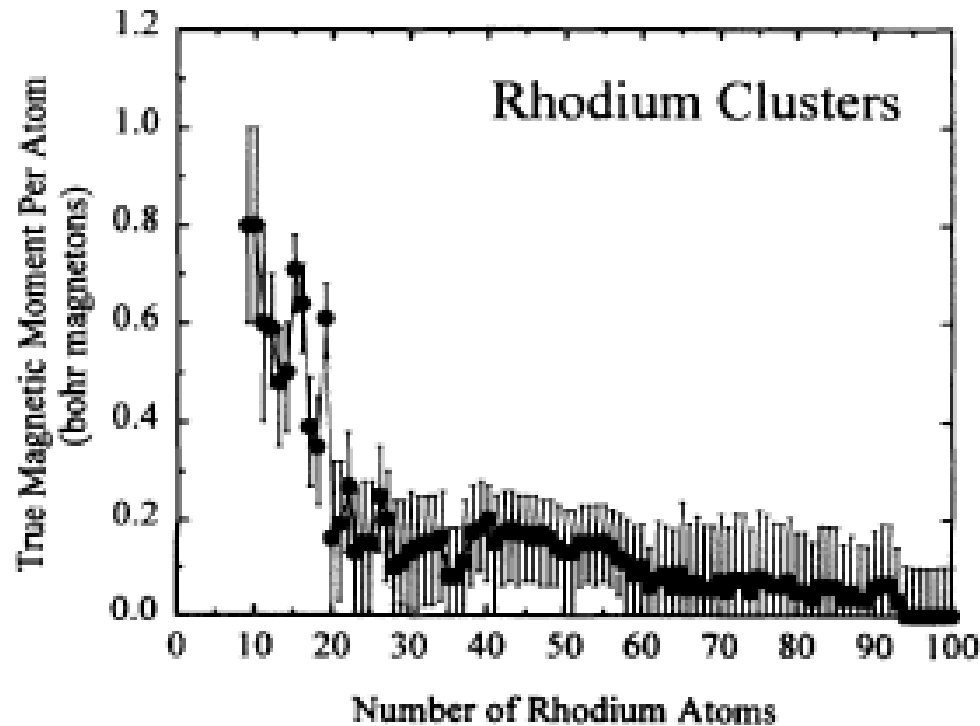
powered cadmium selenide (CdSe)

larger

smaller



## Ex: size-dependence of magnetism



A. J. Cox et al. Phys. Rev. B49, 12295 (1994)

# The Second Lesson :

## The Advent of Nano Era

- ❑ *The ability of growing the nano scale materials and structures*
- ❑ *The ability of detecting and manipulating on the nano scale*

## **(I) Advance in thin film growth:**

Such as molecular beam epitaxy (MBE), atomic layer deposition (ALD), laser MBE, etc...

➤ For nano electronics in metals, oxides, and semiconductors

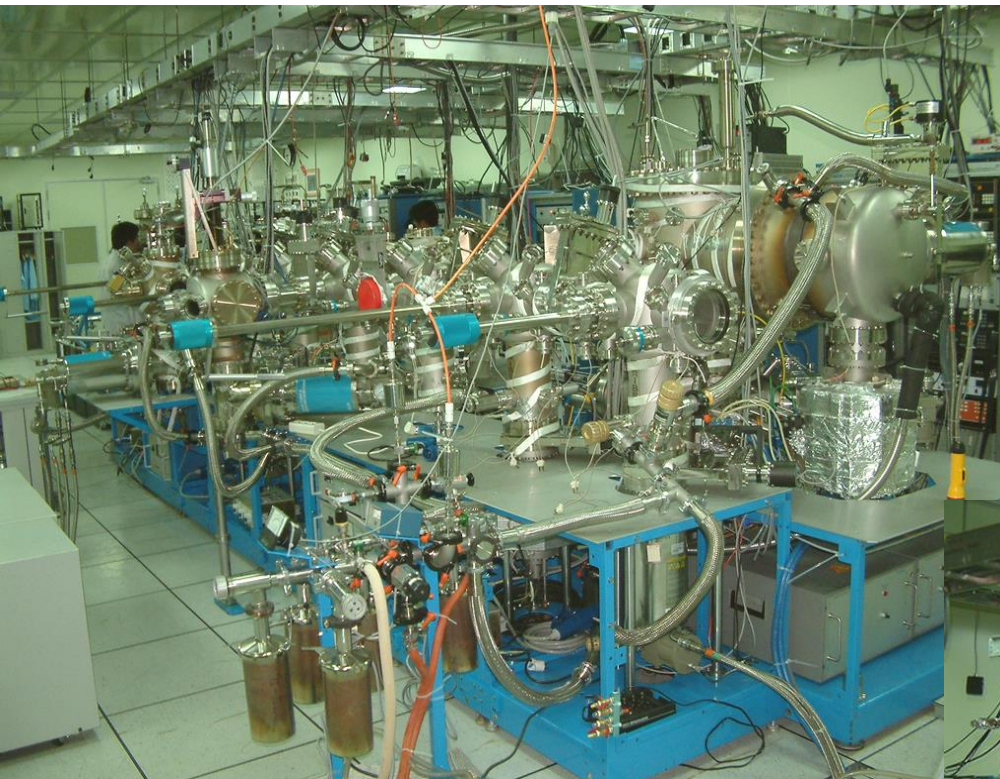
## **(II) Detection at nano scale: STM, AFM, MFM, STEM, Cs-TEM**

➤ In 1982, Binnig, and Rohrer in IBM invented scanning tunneling microscope (STM).

➤ In 1986, Binnig, Quate, and Gerber invented the atomic force microscope (AFM).



# Integrated MBE Multi-chamber System



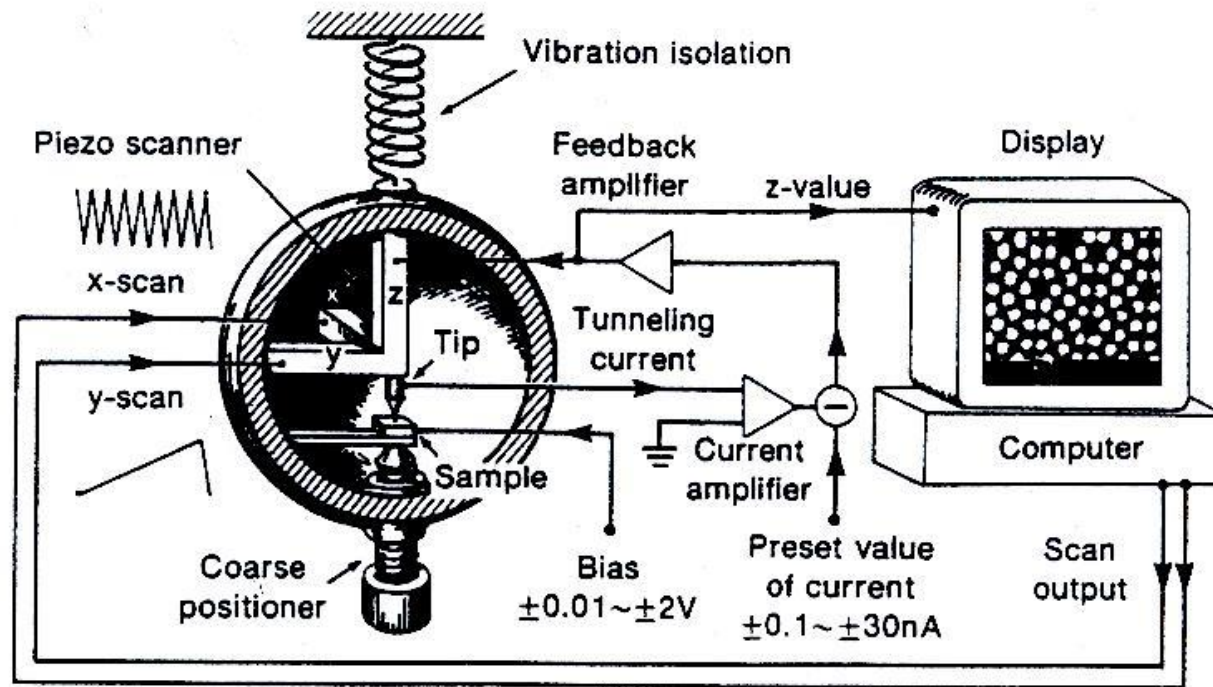
Now located at the Nano  
Science & Technology  
Center, ITRI, Hsin Chu,  
Taiwan

**For metals, oxides and  
semiconductor films  
on the nano scale**



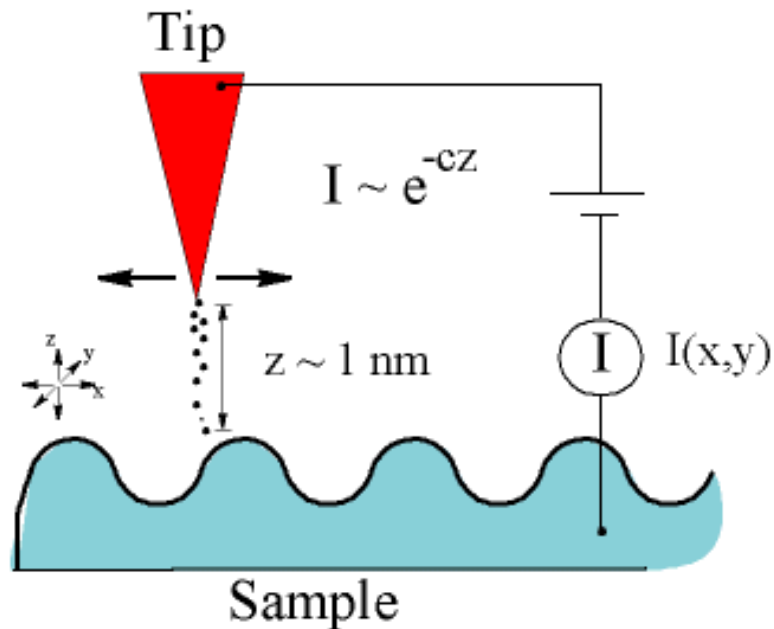


# Scanning Tunneling Microscope (STM)

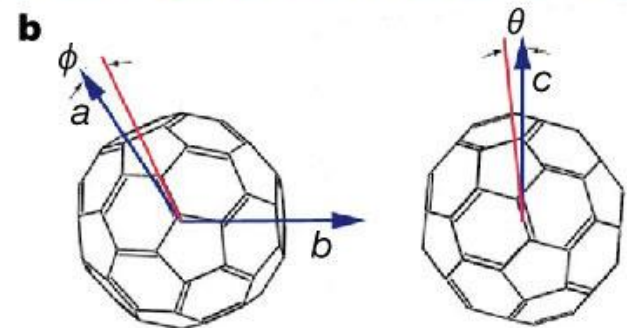
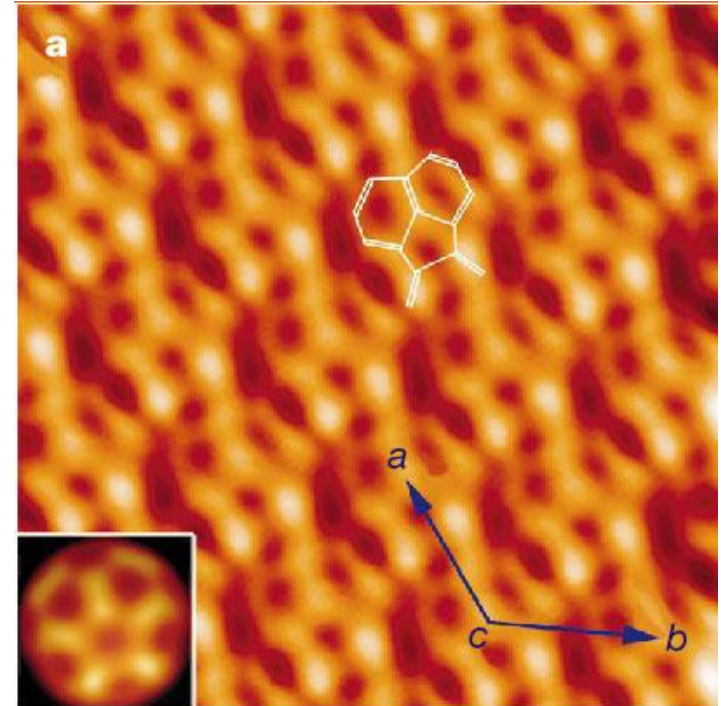


**Figure 1.10** Scanning tunneling microscope. (From C. Julian Chen, *Introduction to Scanning Tunneling Microscopy*, Oxford: Oxford University Press, 1993.)

# Scanning Tunneling Microscope (STM) – Physicist used to detect nano structures

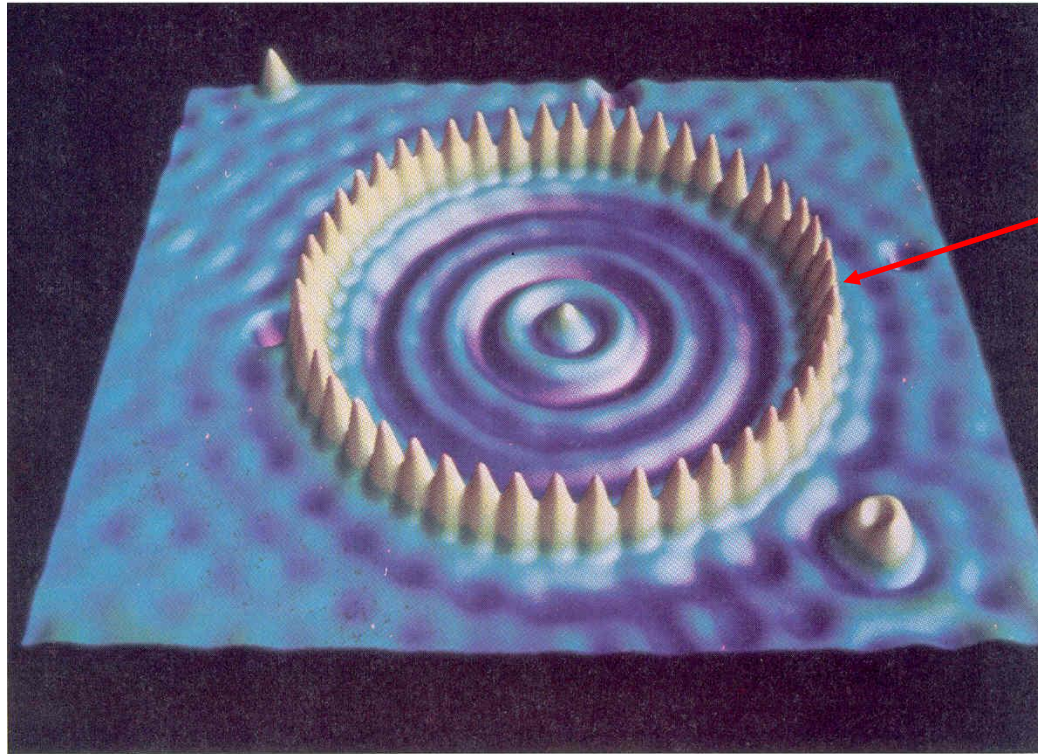


**Nature 409, 304 (2001)**



# Quantum Corral

of 7.13 nm radius, 48 Fe atoms on the Cu (111) surface



Fe

This STM image shows the direct observation of standing-wave patterns in the local density of states of the Cu(111) surface. These spatial oscillations are quantum mechanical interference patterns caused by scattering of the 2D electron gas off the Fe adatoms and point defects.

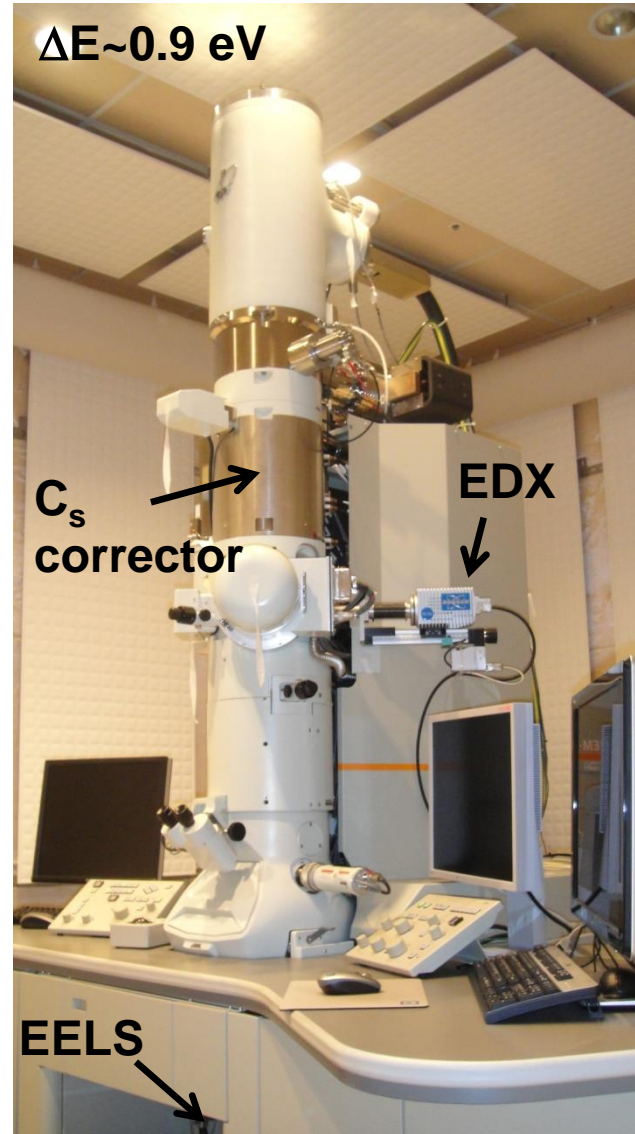


# Scanning Transmission Electron Microscopy

## 2-Å STEM



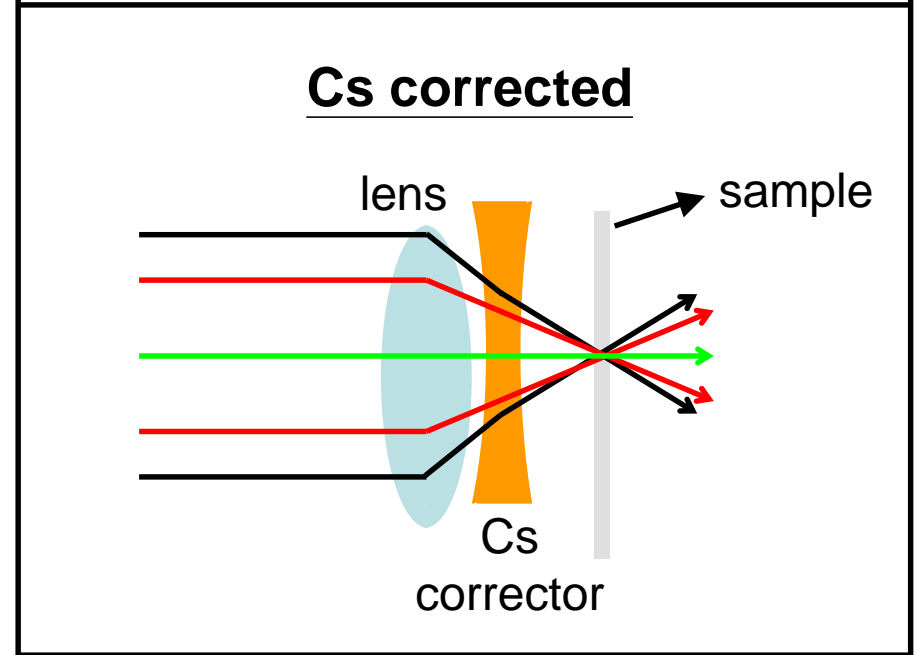
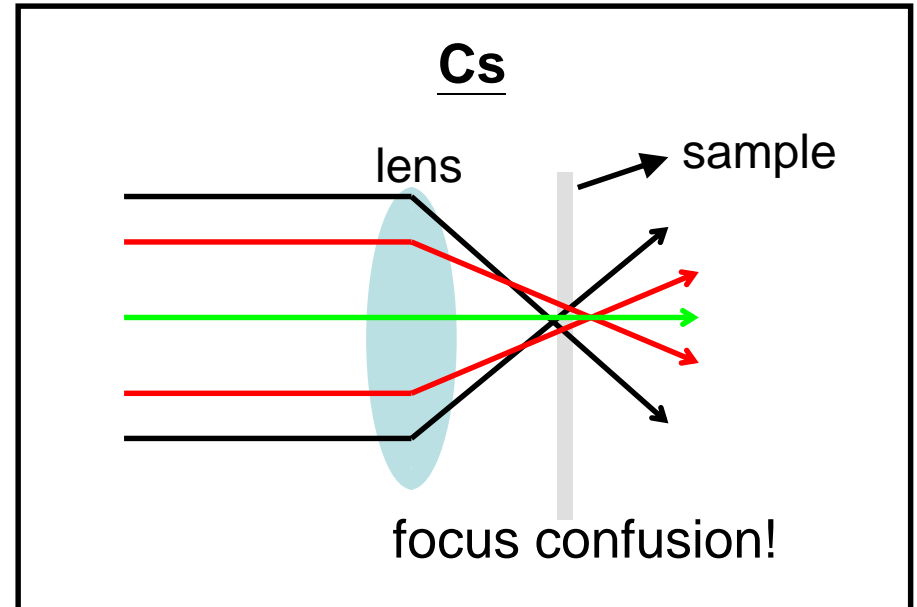
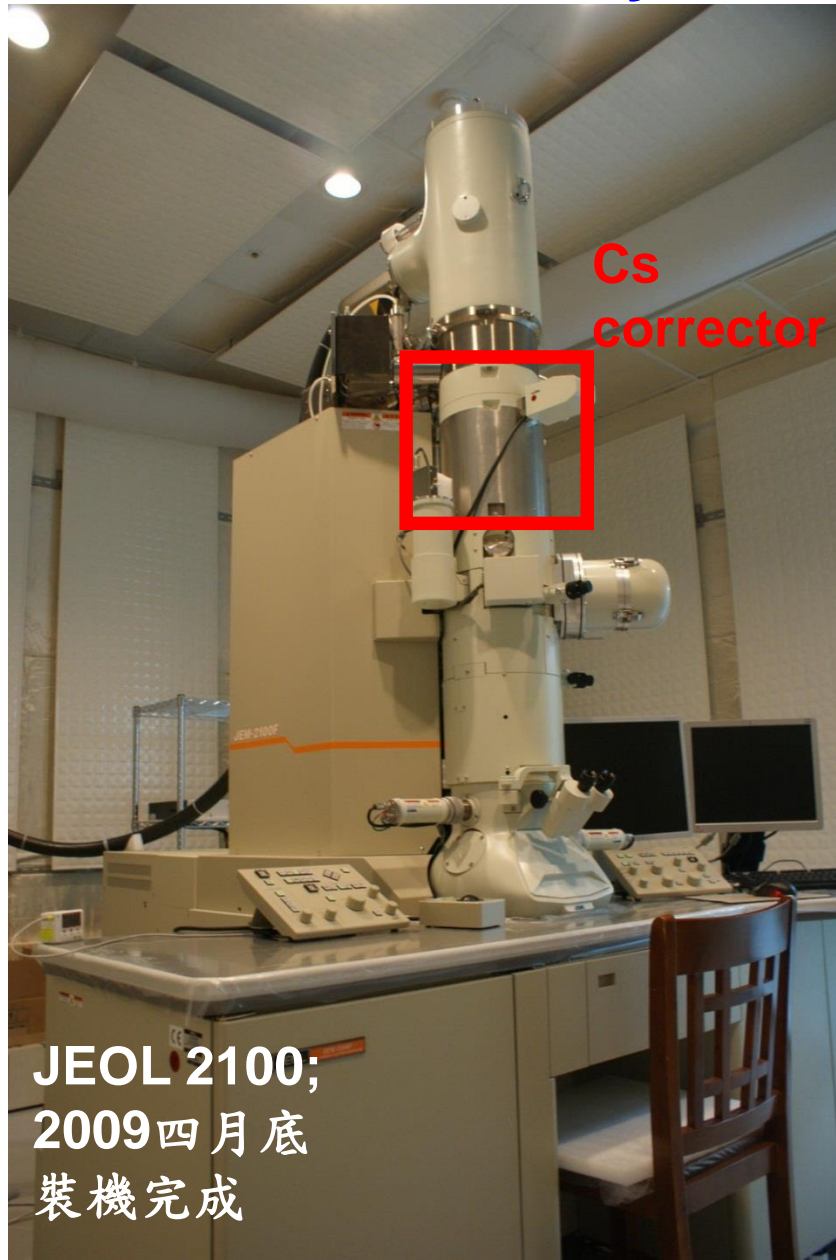
## 1-Å STEM



Prof. C. H. Chen and  
Dr. M.-W. Chu  
In CCMS/NTU.

# Spherical Aberration Corrected (球面相差)

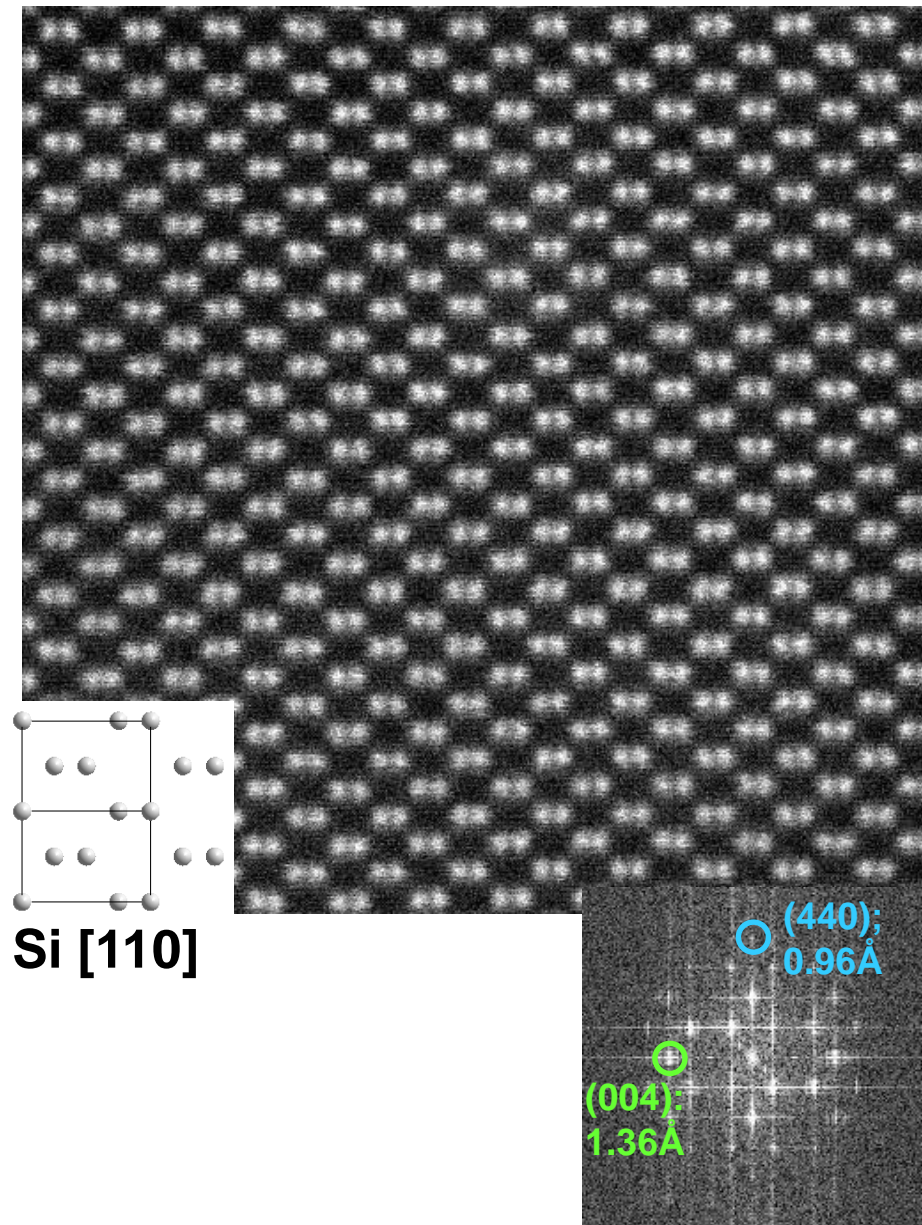
Cs-STEM by C. H. Chen at CCMS, NTU



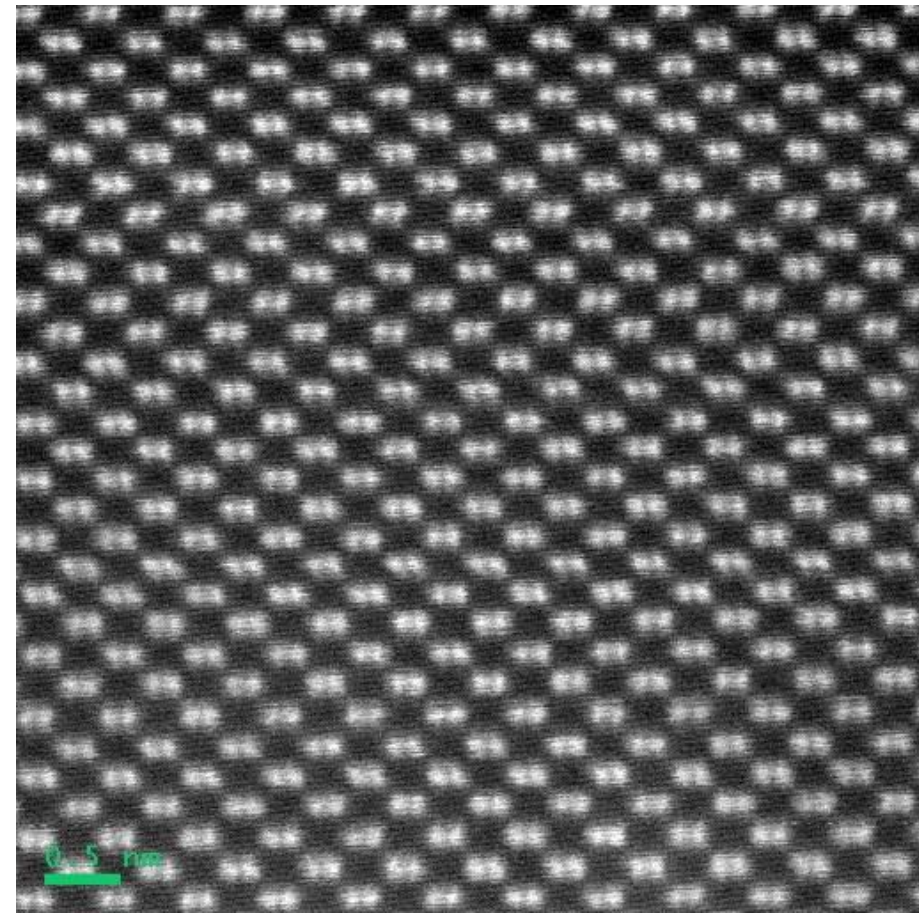


# High-Angle ADF: Si dumbbell, 1.36 Å spacing

15s exposure

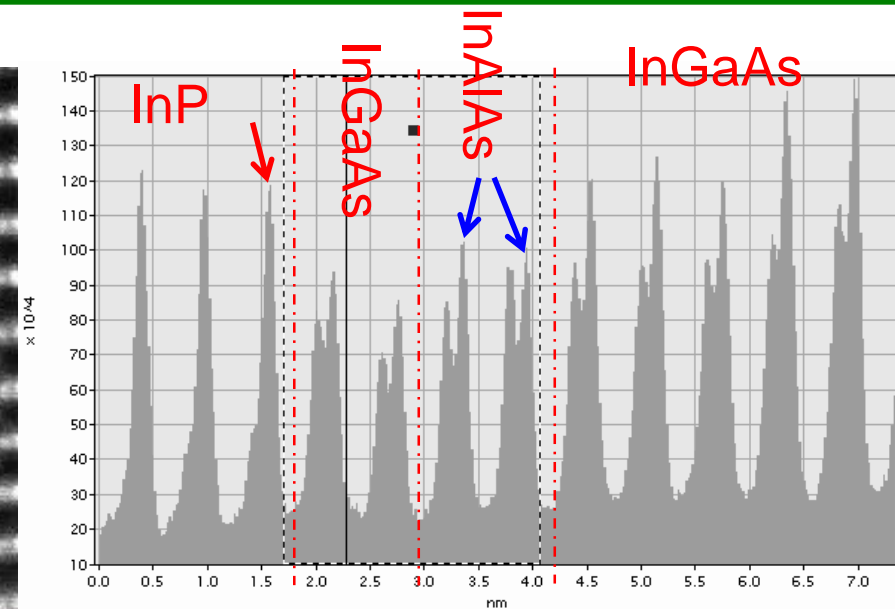
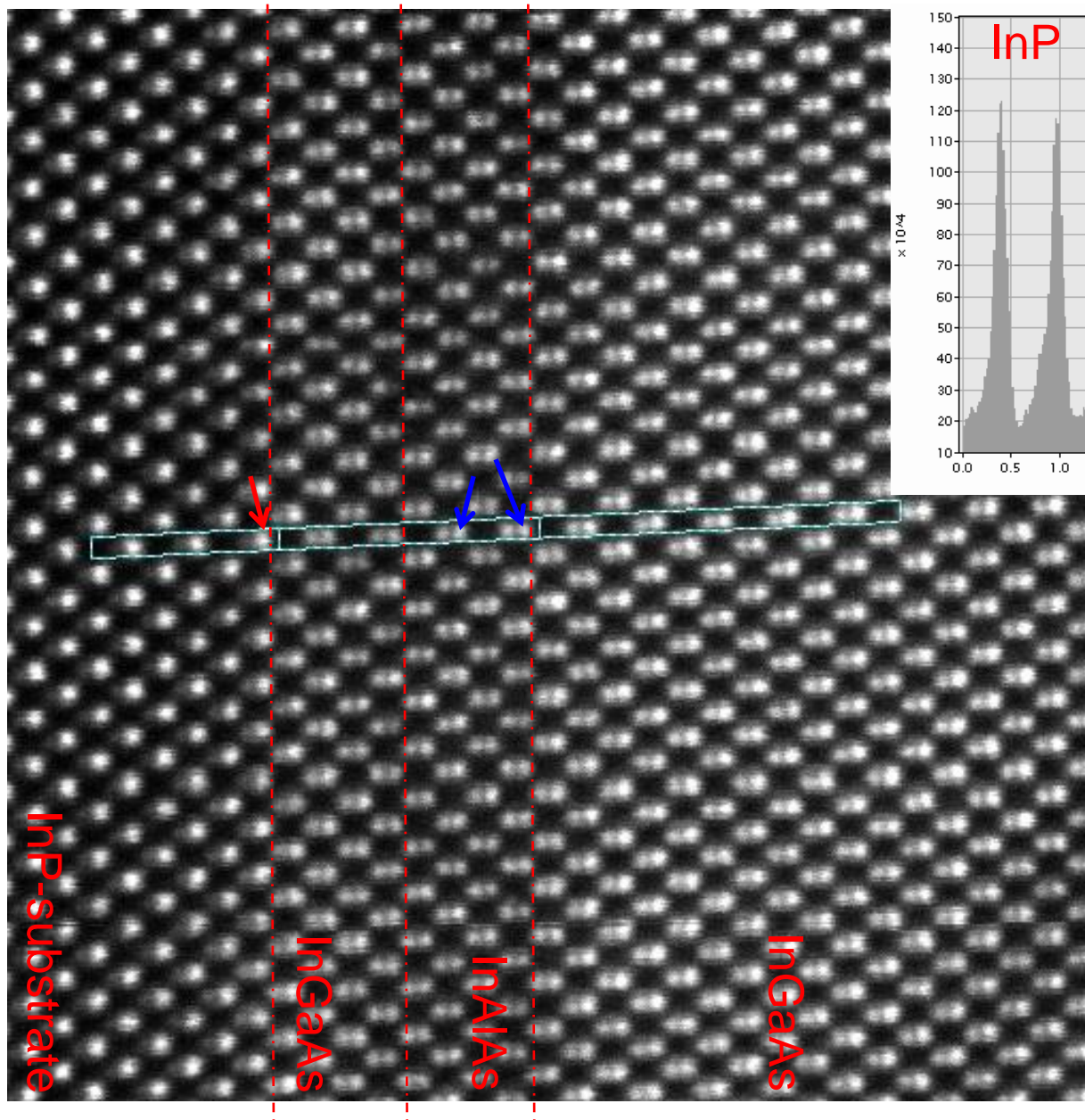


60s exposure



***Drift ~1Å/min !!***

# InGaAs/InAlAs superlattices on InP Substrate by MBE

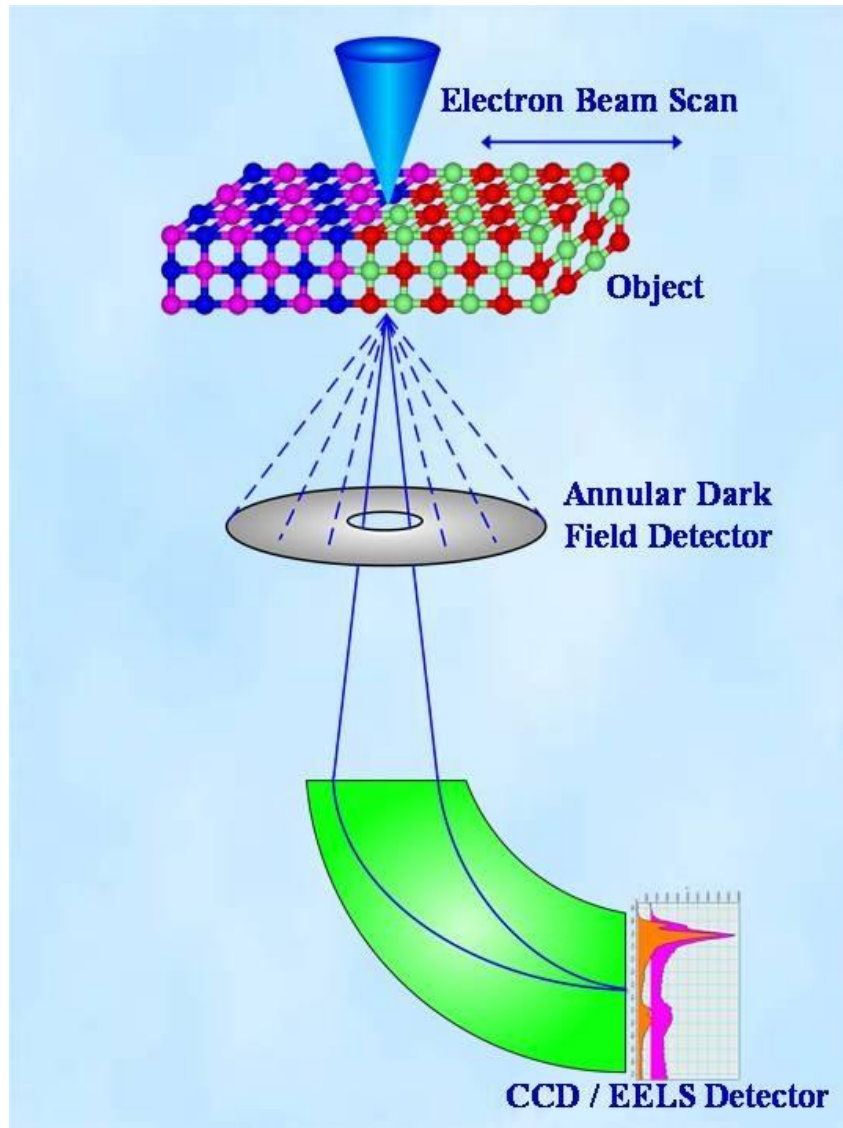


- Determining the interface location and sharpness is easy.
- The *In*-distribution seems to be inhomogeneous in the InAlAs layer (blue arrows).
- Note that InP substrate is In-terminated (red arrow).

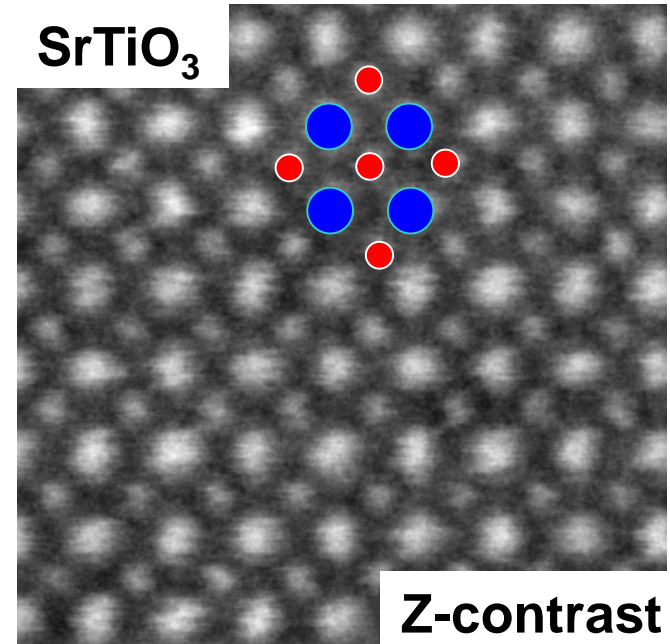


# Atomic Resolution STEM Imaging: Z-contrast

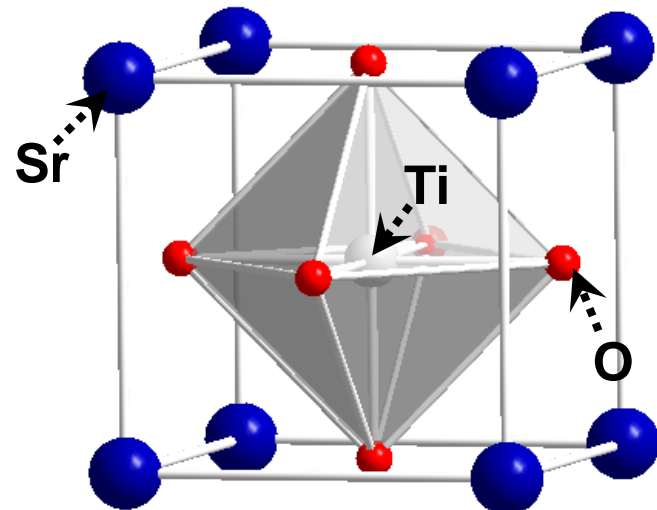
## 2-Å Electron Probe



$\text{SrTiO}_3$



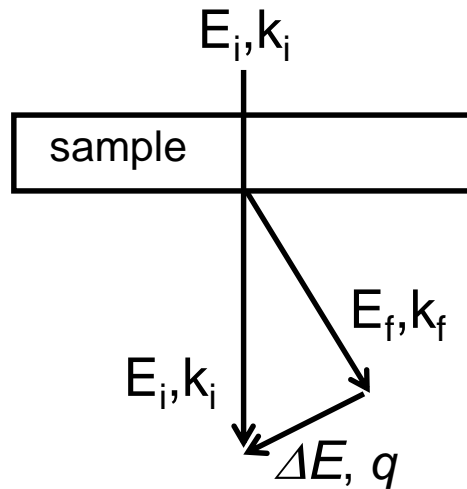
Z-contrast



cubic;  $a = 3.905 \text{ \AA}$



# Electron Energy-Loss Spectroscopy (EELS)



$$\Delta E = E_i - E_f$$

$$q = k_i - k_f$$

## Coulomb Interaction

$$v(r) = \sum_j \frac{e^2}{|r - r_j|}$$

$$= \sum_q v_q \rho_q e^{iqr}$$

, where  $\rho_q$  the electron density operator



## Inelastic Scattering ( $\Delta E$ ) Probability

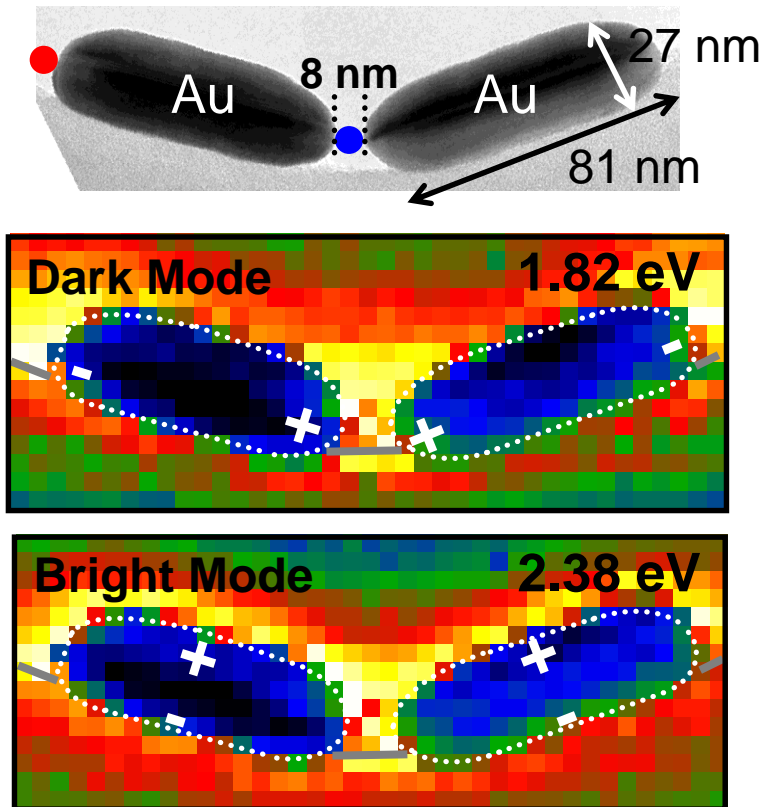
$$\frac{d^2\sigma}{d\Omega dE} \sim \sum_f \left| \langle \psi_f | v(q) | \psi_i \rangle \right|^2 \delta(E_i - E_f - \Delta E)$$

$$\sim \frac{1}{q^4} \cdot S(\omega, q) \longrightarrow \text{X-ray}$$

$$\sim \frac{1}{q^2} \cdot \text{Im} \left[ \frac{1}{\varepsilon(\omega, q)} \right] \longrightarrow \text{EELS}$$

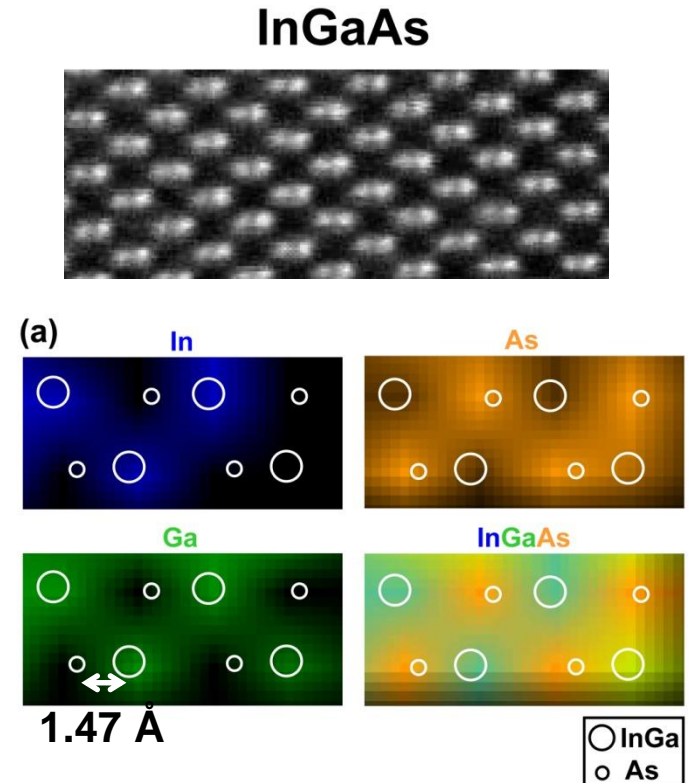
# Spectral Imaging at Ultimate Spatial Resolution

## Plasmonic Mapping: STEM-EELS (2-Å Probe)



M.-W. Chu *et al.*, Nano Lett. **9**, 399 (2009).

## Chemical Mapping: STEM-EDX (1-Å Probe)



M.-W. Chu *et al.*, Phys. Rev. Lett. **104**, 196101 (2010).

# **The Third Lesson:**

## ***The importance of Quantum Physics***

# The cause for variation of scaling

- Influence of Boundary
  - Increase of proportion of boundaries
  - Existence of surface / edge modes
  - Geometrical reconstruction
- Decrease of the number of particles  
decrease of confinement, increase of perturbation
- Different scaling for different physical entity

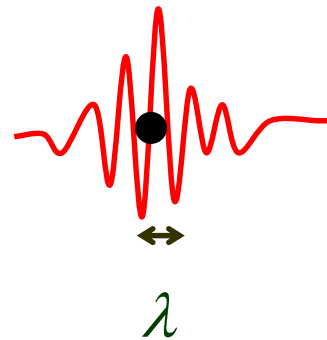
**Quantum Effect:**

**=> Most likely to have new breakthrough !**

# The connection of materials wave with mechanics

$h$  = Planck constant  
( $6.626 \times 10^{-34}$  joule-sec)

DeBroglie wave :  
 $\lambda = h/p$



Einstein:  
 $E = h\nu = p^2/2m$

Wave length

Free electrons

自由電子:  $\lambda_{th}(300K) = 6.2nm$

Semiconductors

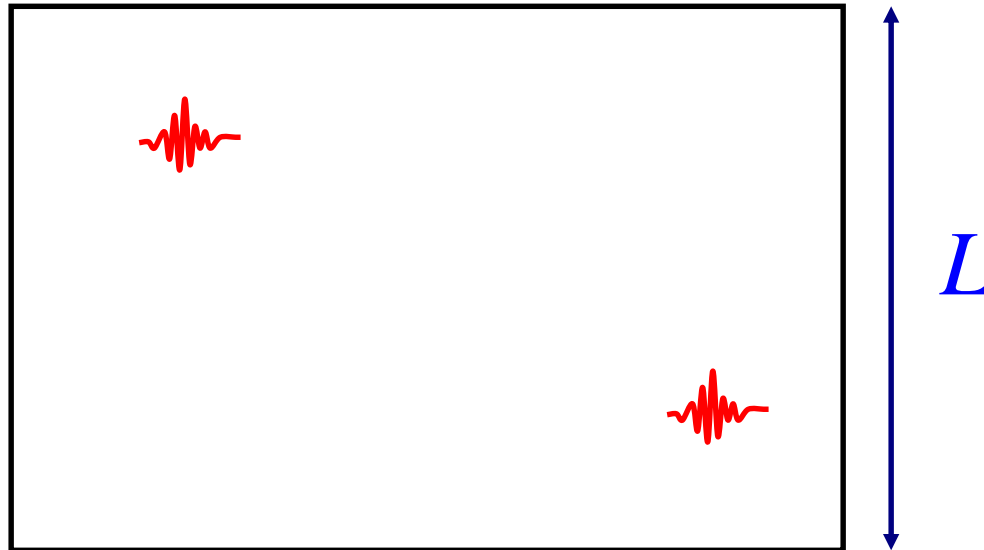
(半導體中  $10nm \leq \lambda \leq 100nm$ )

Atoms

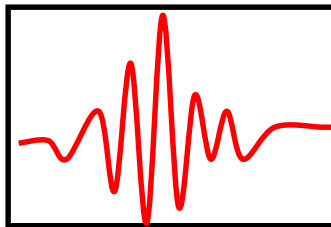
原子:  $\lambda_{th}(300K) \leq 0.2nm$

# Bulk Limit $\longleftrightarrow$ Nano Limit

For bulk  
materials  
 $\lambda \ll L$



For nano  
materials  
 $\lambda \sim L$



# Major Quantum Effects at the Nano Scale

- Interference
- Quantization
- Tunneling
- Quantum spin

# **(I) Interference**

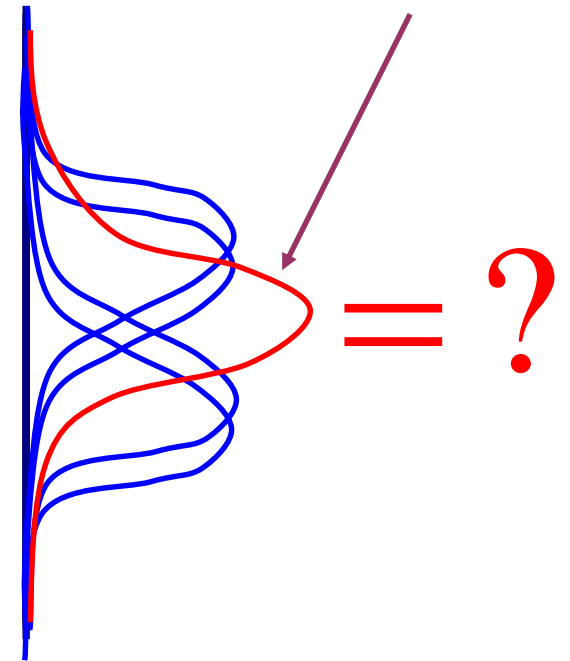


# The wonder of electron in waves

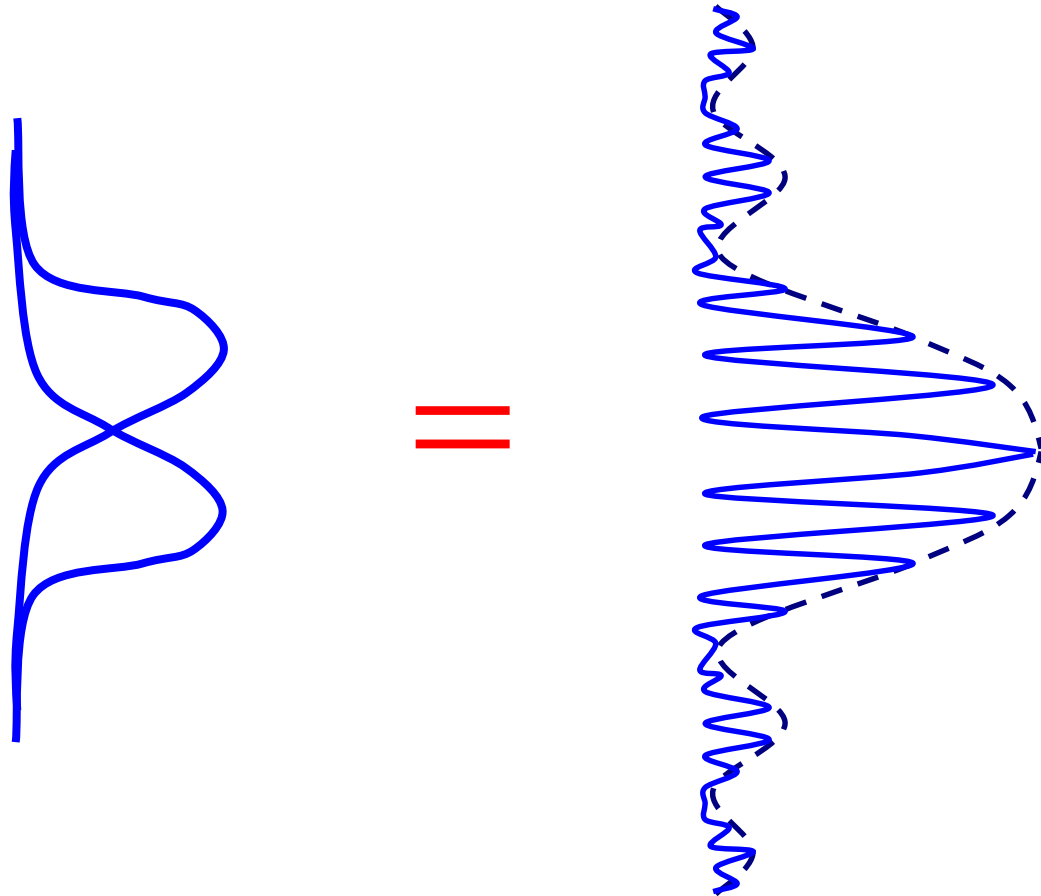
Electron source 



Classical mechanics

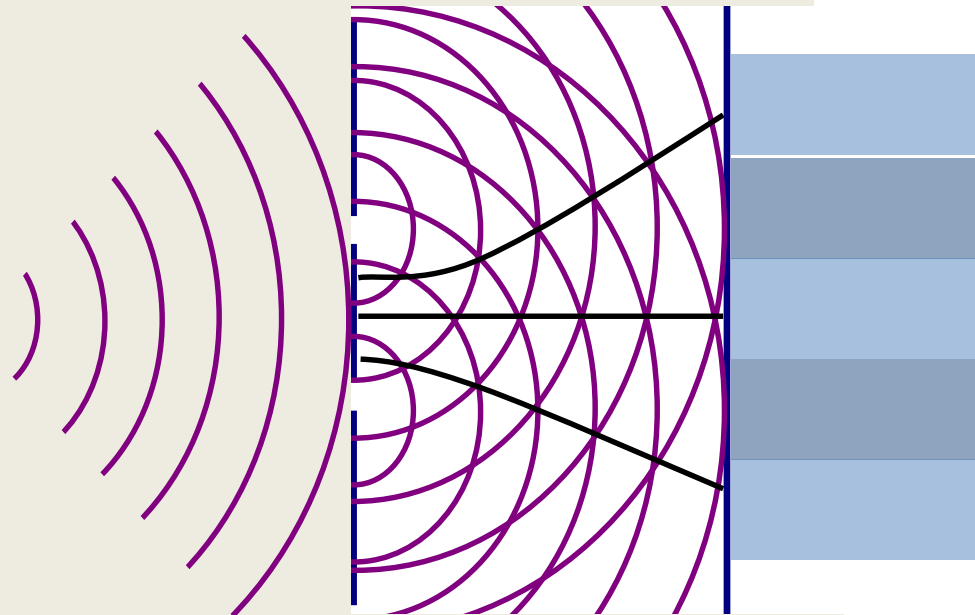


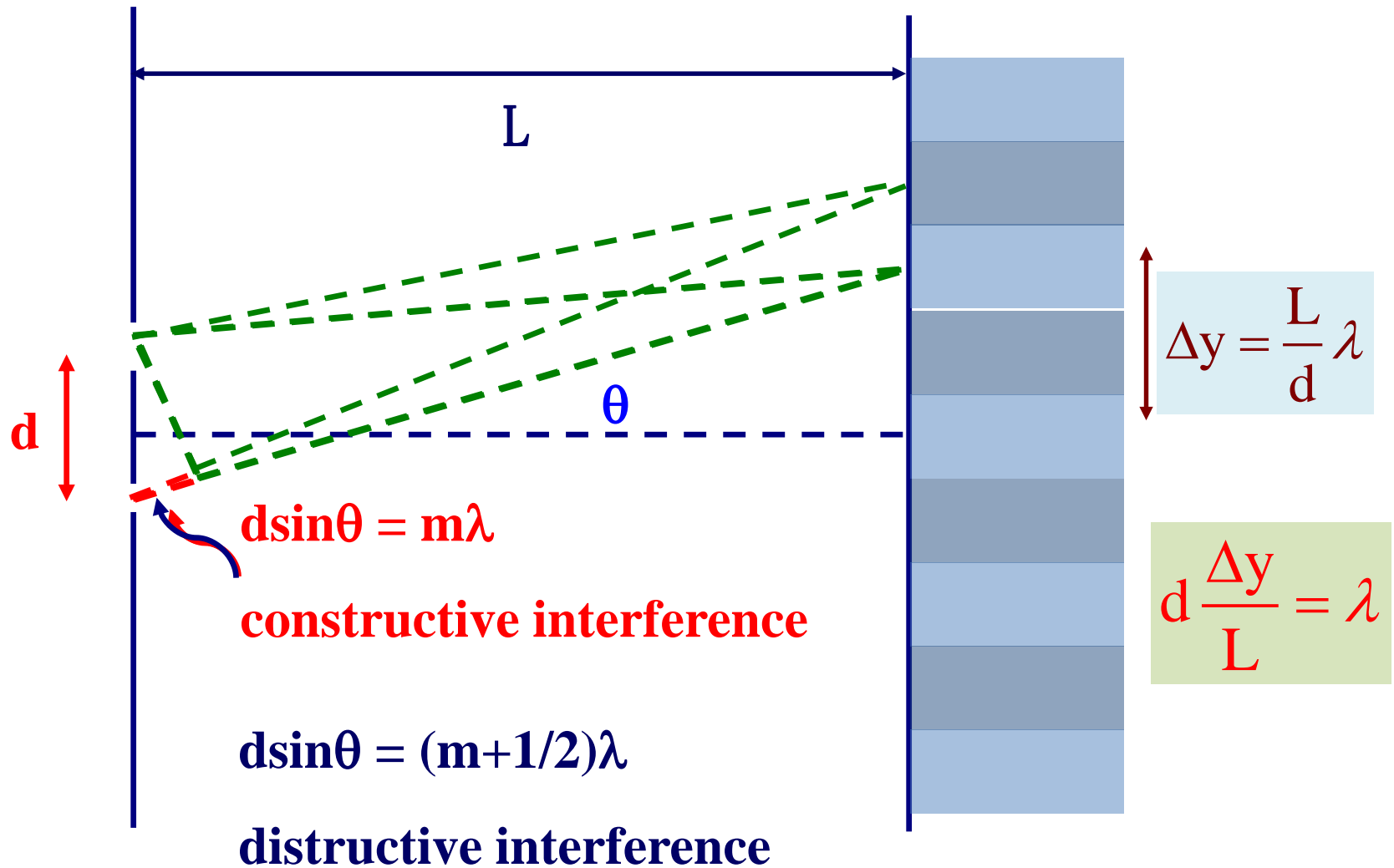
# The wave property of electrons

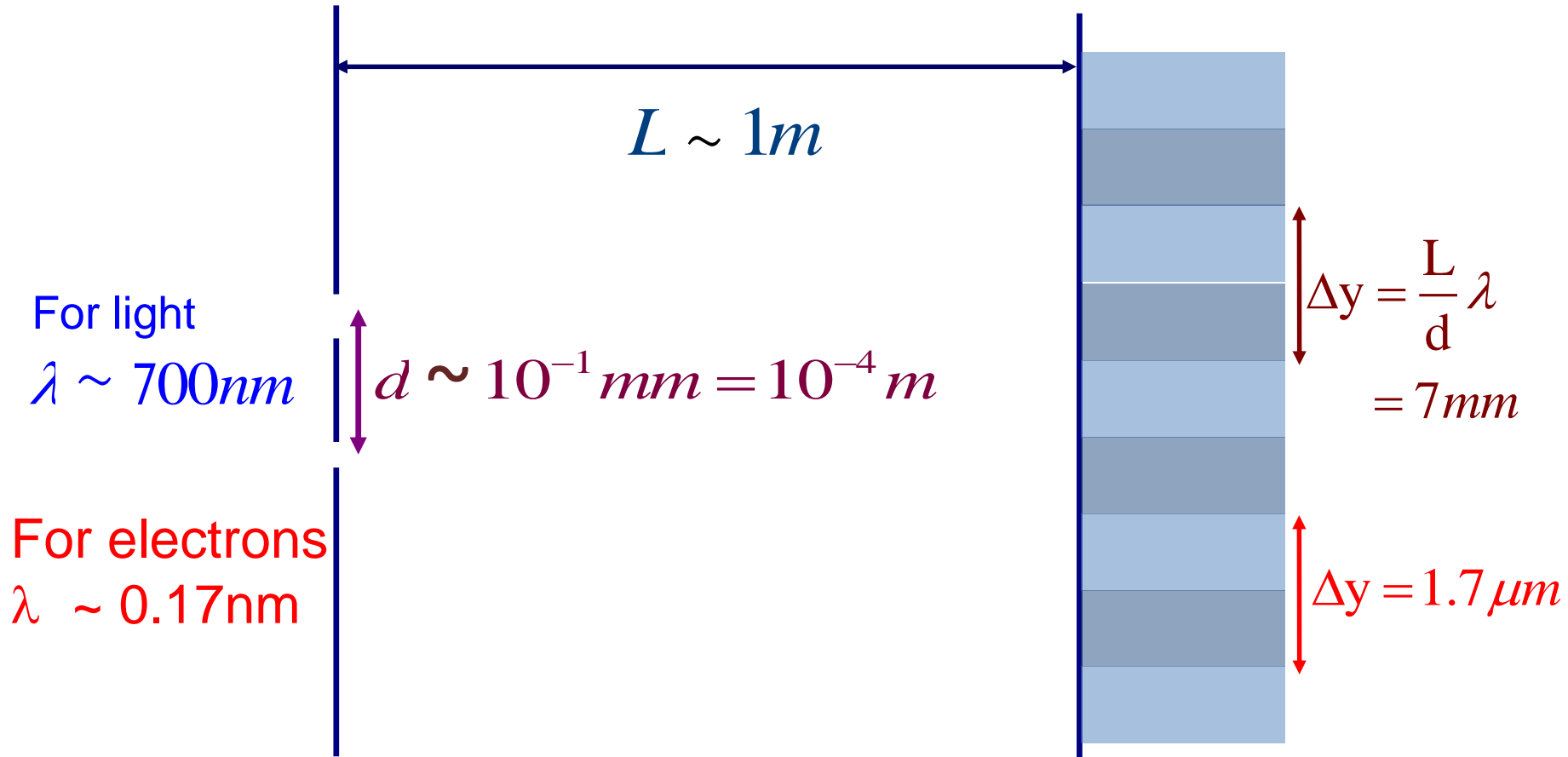


# Double Slit Interference of Electrons

Electron source







## **(II) Quantization**

**Confinement of the materials wave**



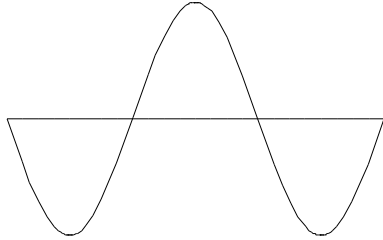
**Standing Wave**



**Quantizations**

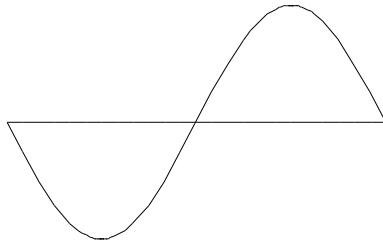
# The Quantization of Energy

$n = 3$



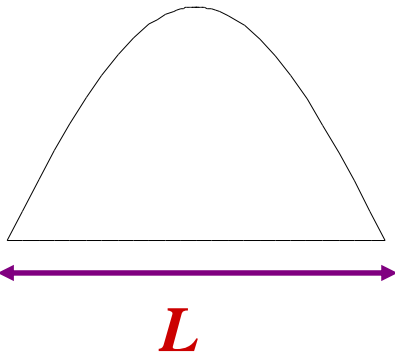
$$L = \frac{n}{2} \lambda$$

$n = 2$



$$p = \frac{h}{\lambda} = \frac{nh}{2L}$$

$n = 1$



$$\delta E \propto 1/L^2$$

$$E_n = \frac{p^2}{2m} = \frac{n^2 h^2}{8mL^2}$$



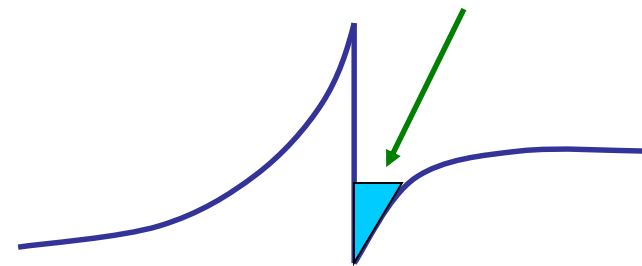
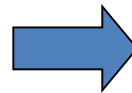
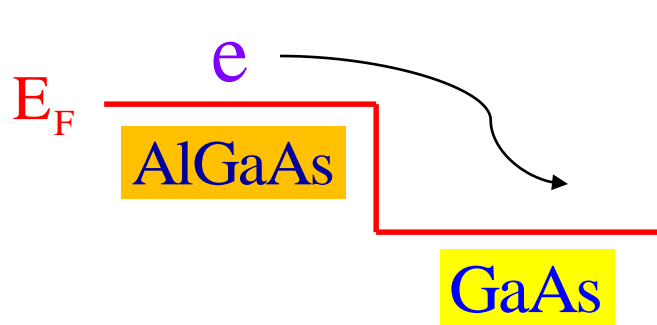
# Quantum well: 1D confinement

**MOSFET:**

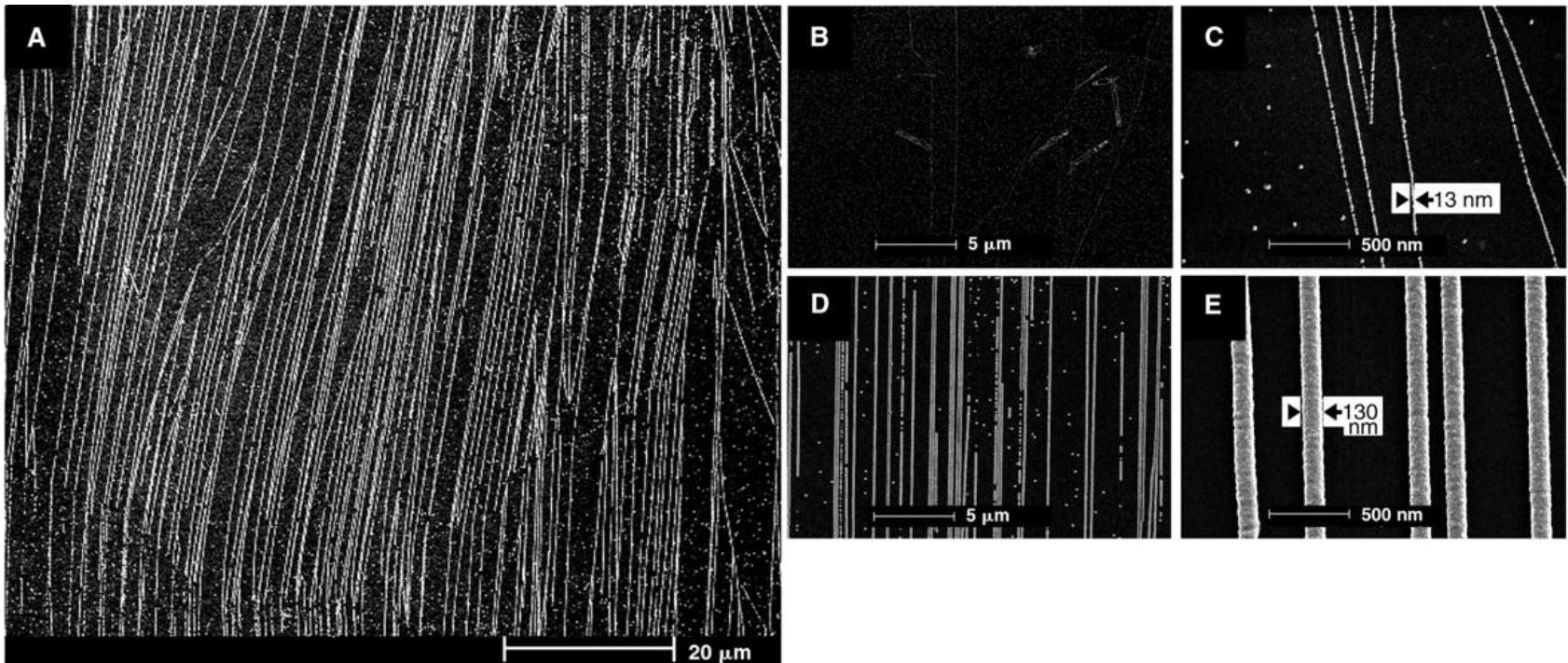


**2D electron Gas**

二維電子氣



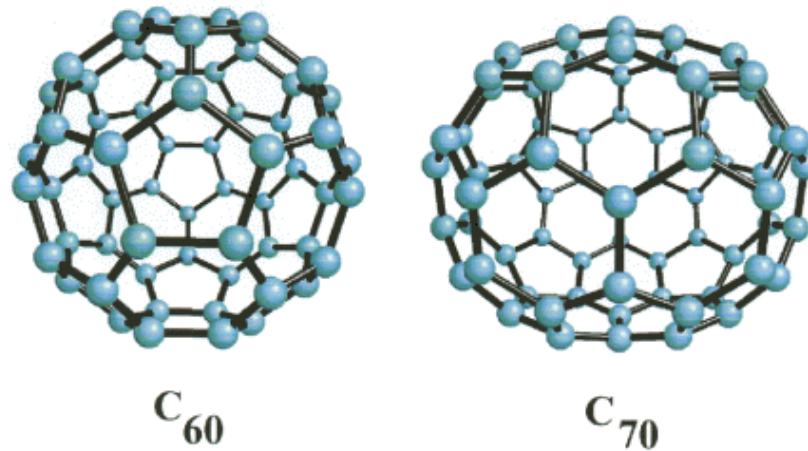
# Quantum wire: 2 D-Confinement



SEM images of MoO<sub>x</sub> nanowires on graphite surfaces

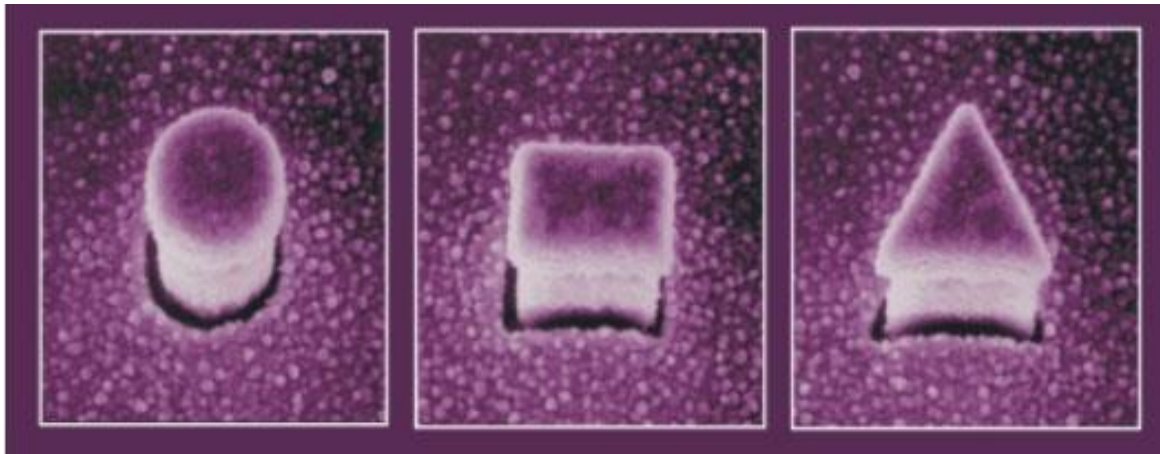
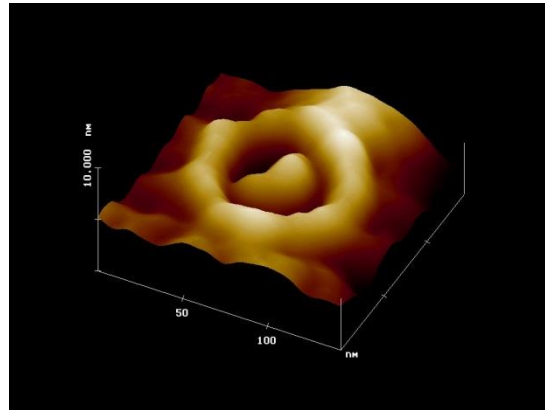
Science **290**, 2120-2123, (2000).

# Quantum dot: 3D - Confinement



Smalley et al, Rice Univ, (1985)

# Quantum Dots of various shape



Absorption in scattering  
from red to yellow



$$E = hc / \lambda \propto 1 / L^2$$

powdered CdSe (Cadium Selenide)

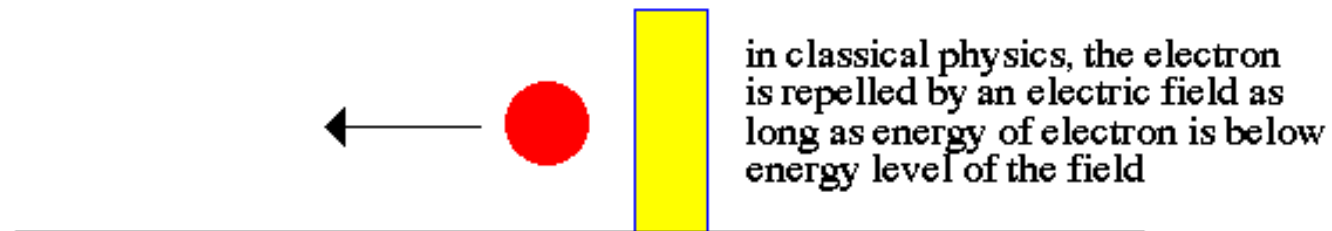
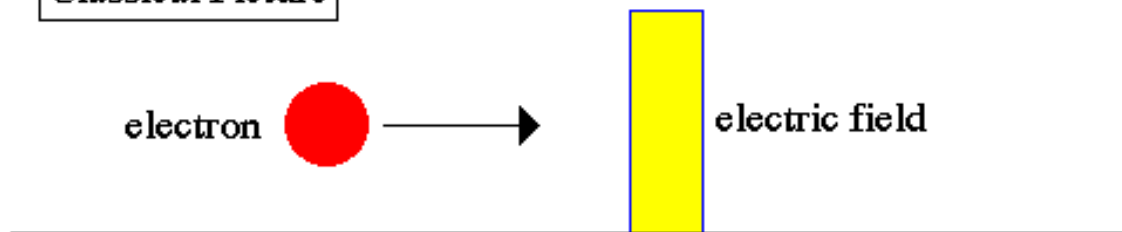
larger  
smaller



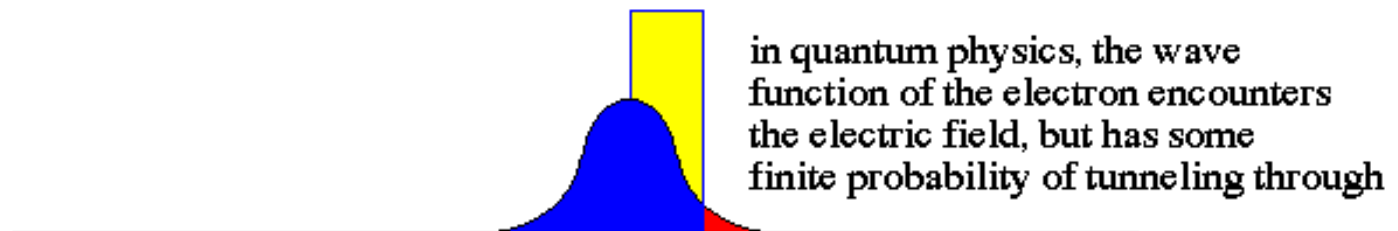
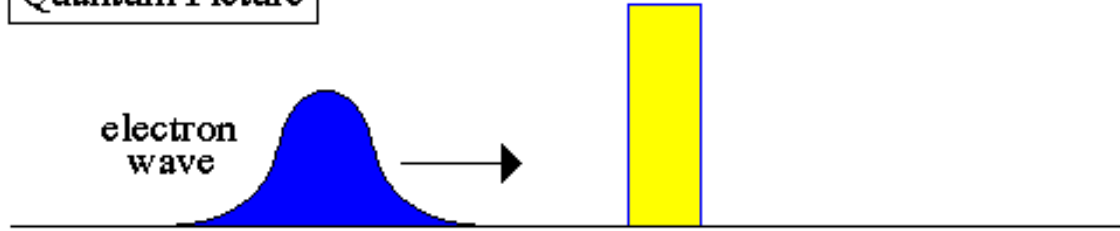
# **(III) Tunneling and Nano-electronics**



### Classical Picture

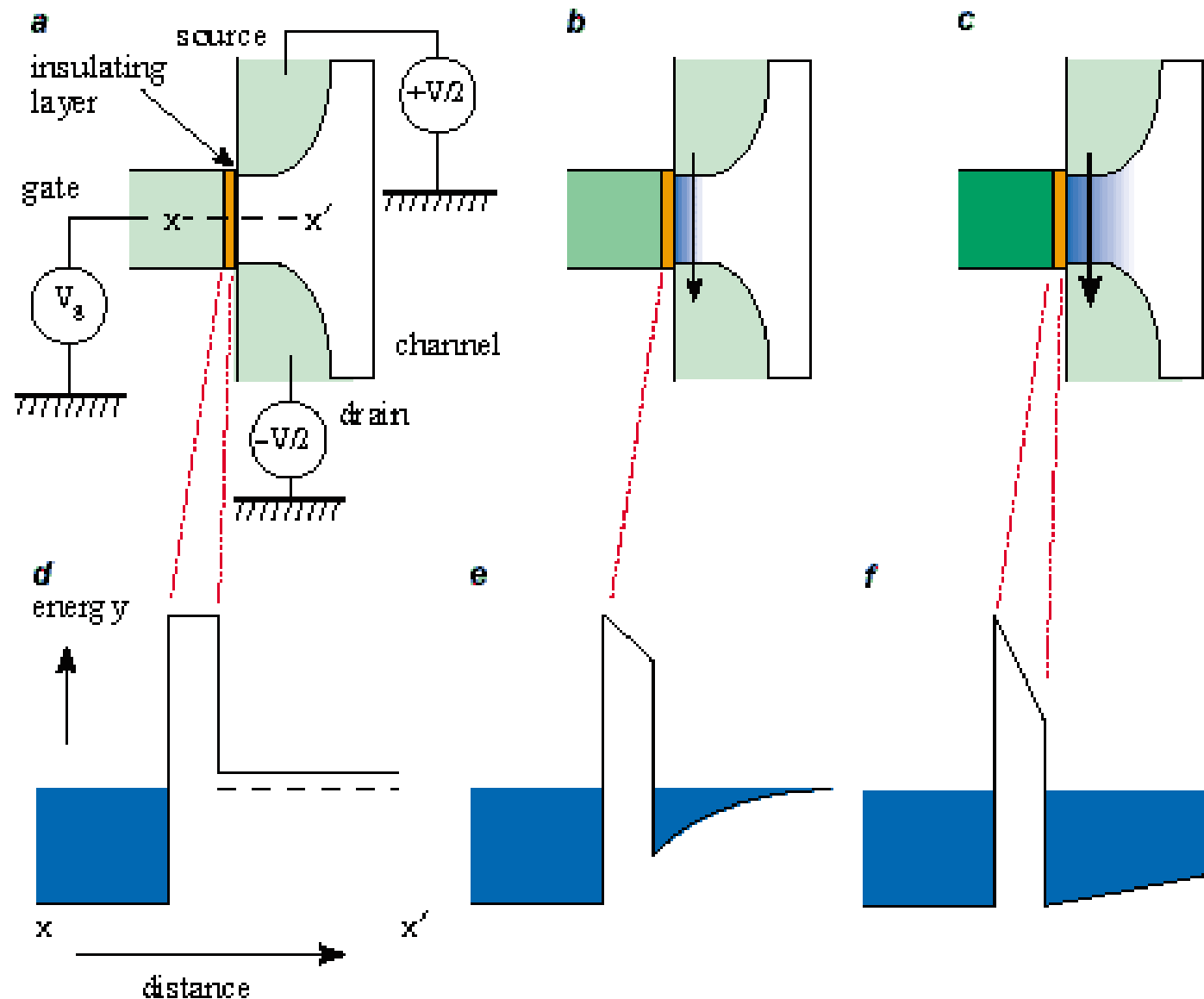


### Quantum Picture



nm

# Quantum tunneling is the major effect for the failure of transistor at nano scale







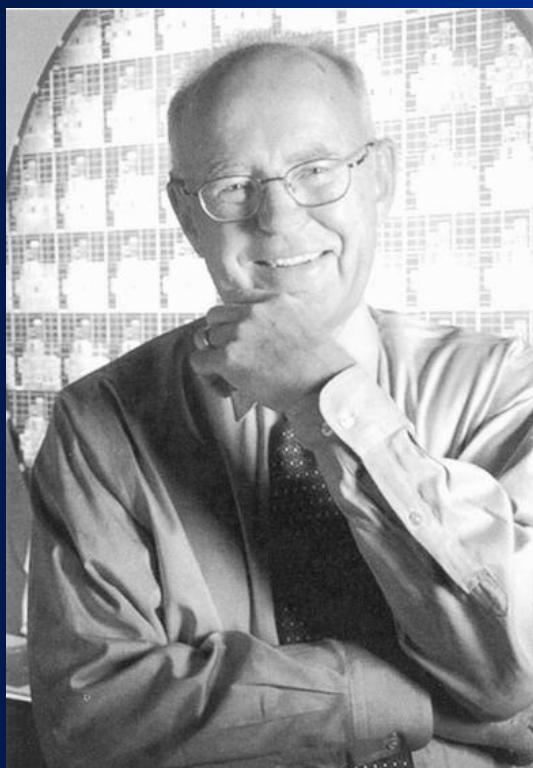
# 近來大力推動奈米科技的背景

## 來自微電子學可能遭遇瓶頸的考慮

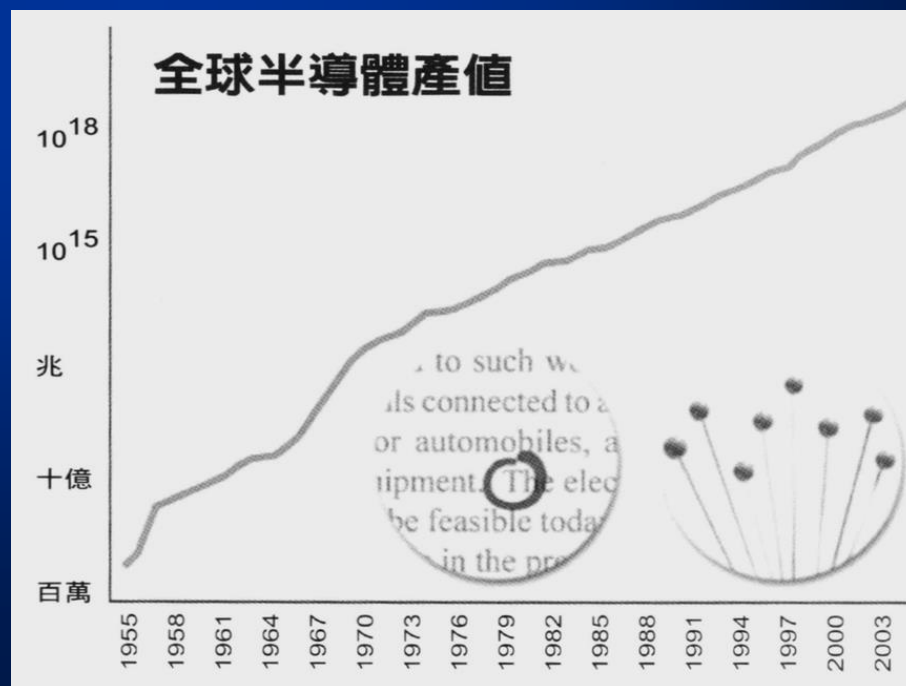
### Moore's Law : 摩爾定律

A 30% decrease in the size of  
printed dimensions every 1.5 years.

矽晶上電子原件數每1年半會增加一倍

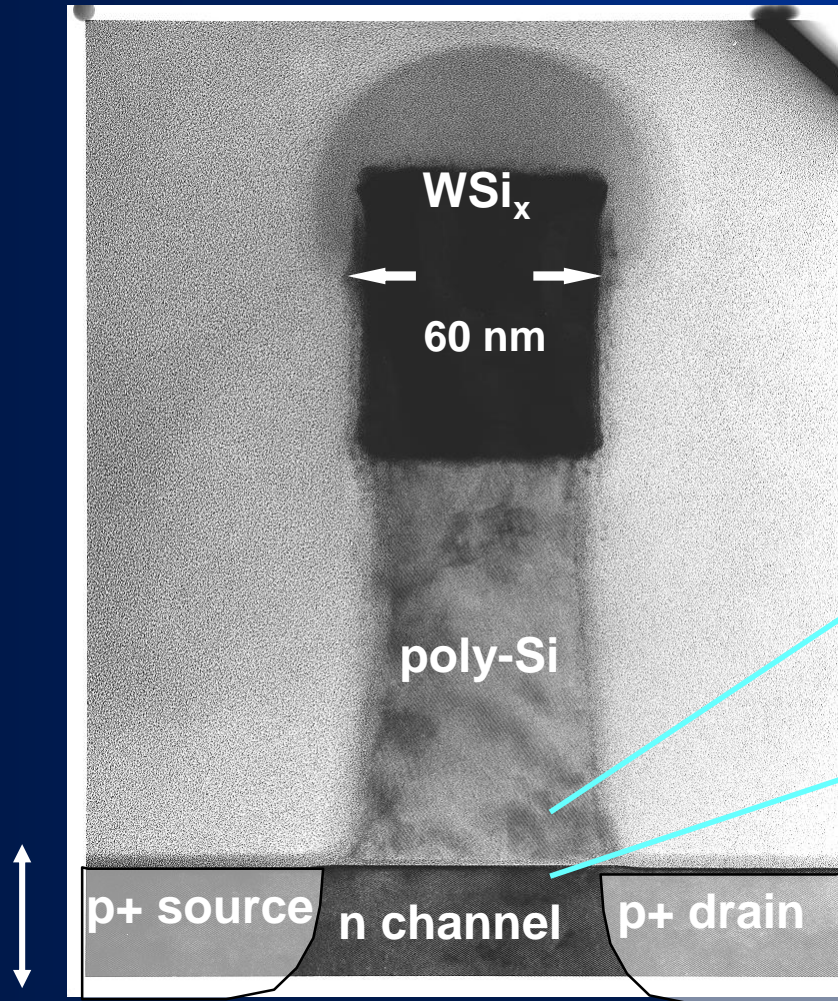


Gordon Moore

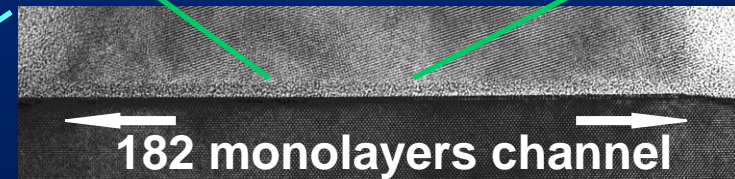
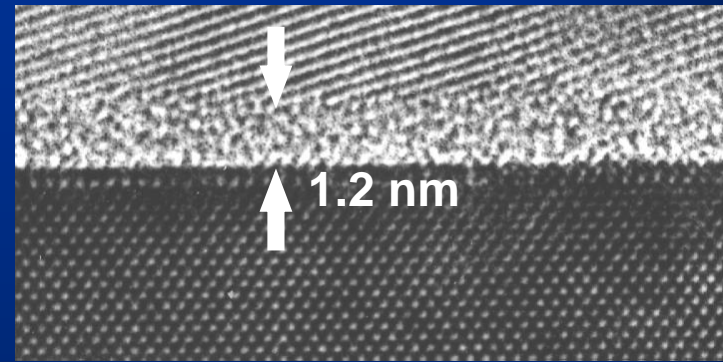




# Scaling Limits to CMOS Technology



Gate Oxide ~ 5 Si Atoms thick !



Shrinking the junction depth  $\Rightarrow$  increasing the carrier concentration



# CMOS scaling, When do we stop ?

**Reliability:** ~~25~~ ~~22~~ ~~18~~ 16 Å ?

processing and yield issue

**Tunneling :** 15 Å

Design Issue: chosen for 1A/cm<sup>2</sup> leakage

$I_{\text{on}}/I_{\text{off}} \gg 1$  at 12 Å

**Bonding:**

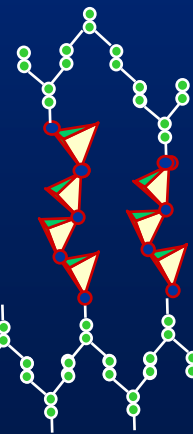
Fundamental Issues---

- how many atoms do we need to get bulk-like properties?  
EELS -- Minimal **4** atomic layers !!
- Is the interface electronically abrupt?
- Can we control roughness?

In 1997, a gate oxide was 25 silicon atoms thick.



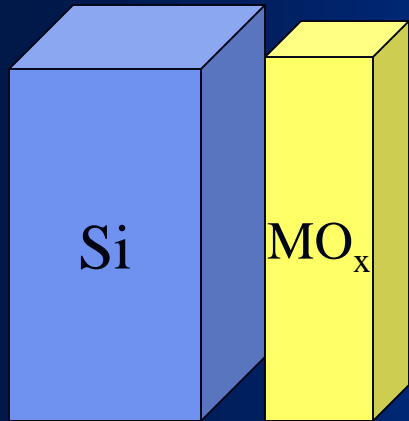
In 2007, a gate oxide will be **5** silicon atoms thick, if we still use SiO<sub>2</sub>



and at least 2 of those 5 atoms will be at the interfaces.



# Fundamental Materials Selection Guidelines



- Thermodynamic stability in contact with Si to 750°C and higher. **(Hubbard and Schlom)**  
**Alkaline earth oxide, IIIB, IVB oxide and rare earth oxide**
- Dielectric constant, band gap, and conduction band offset
- Defect related leakage, substantially less than SiO<sub>2</sub> at  $t_{eq} < 1.5$  nm
- Low interfacial state density  $D_{it} < 10^{11}$  eV<sup>-1</sup>cm<sup>-2</sup>
- Low oxygen diffusivity
- Crystallization temperature >1000°C



$t_{eq}$  : equivalent oxide thickness (EOT) to be under 1.0 nm

$$t_{eq} = t_{ox} \kappa_{\text{SiO}_2} / \kappa_{ox}$$





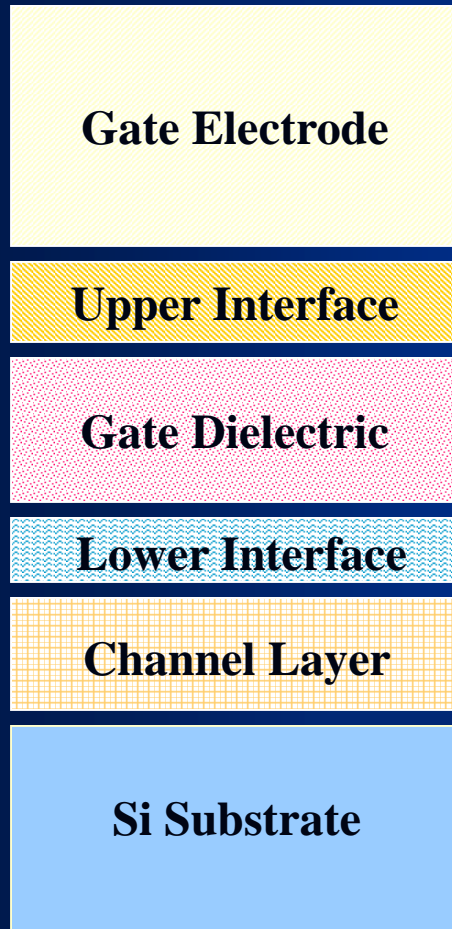
# Basic Characteristics of Binary Oxide Dielectrics

Dielectrics	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Y <sub>2</sub> O <sub>3</sub>	HfO <sub>2</sub>	Ta <sub>2</sub> O <sub>5</sub>	ZrO <sub>2</sub>	La <sub>2</sub> O <sub>3</sub>	TiO <sub>2</sub>
Dielectric constant	3.9	9.0	18	20	25	27	30	80
Band gap (eV)	9.0	8.8	5.5	5.7	4.5	7.8	4.3	3.0
Band offset (eV)	3.2	2.5	2.3	1.5	1.0	1.4	2.3	1.2
Free energy of formation MO <sub>x</sub> +Si <sub>2</sub> → M+ SiO <sub>2</sub> @727C, Kcal/mole of MO <sub>x</sub>	-	63.4	116.8	47.6	-52.5	42.3	98.5	7.5
Stability of amorphous phase	High	High	High	Low	Low	Low	High	High
Silicide formation ?	-	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hydroxide formation ?	-	Some	Yes	Some	Some	Some	Yes	Some
Oxygen diffusivity @950C (cm <sup>2</sup> /sec)	2x 10 <sup>-14</sup>	5x 10 <sup>-25</sup>	?	?	?	10 <sup>-12</sup>	?	10 <sup>-13</sup>



# Integration Issues for High $\kappa$ Gate Stack

## FET Gate Stack



## Critical Integration Issues

- Morphology dependence of leakage  
*Amorphous vs crystalline films?*
- Interfacial structures
- Thermal stability
- Gate electrode compatibility
- Reliability

## Fundamental Limitations

- Fixed charge
- Dopant depletion in poly-Si gate
- Dopant diffusion
- Increasing field in the channel region

# Si CMOS Device Scaling – Beyond 22 nm node

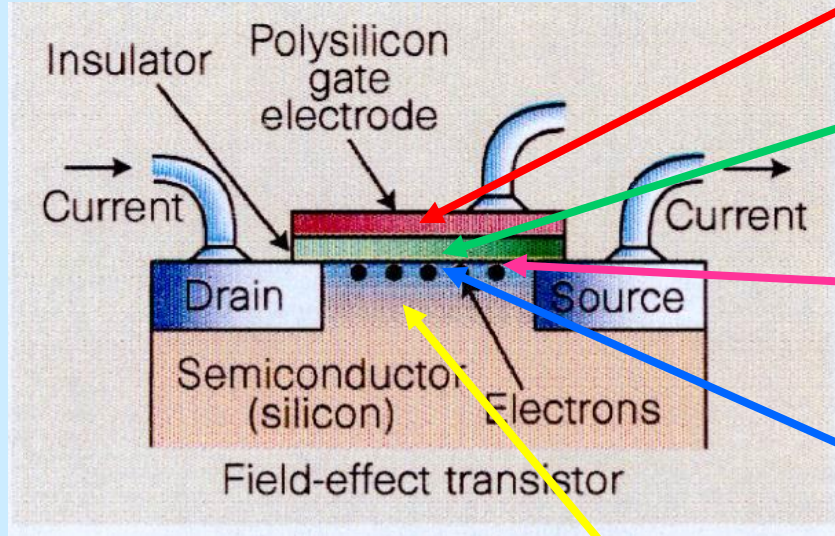
## High $\kappa$ , Metal gates, and High mobility channel

### 1947 First Transistor



The Transistor  
50th Anniversary: 1947–1997

### 1960 First MOSFET



**Metal Gate**

**High  $\kappa$  gate dielectrics**

**Oxide/semiconductor interface**

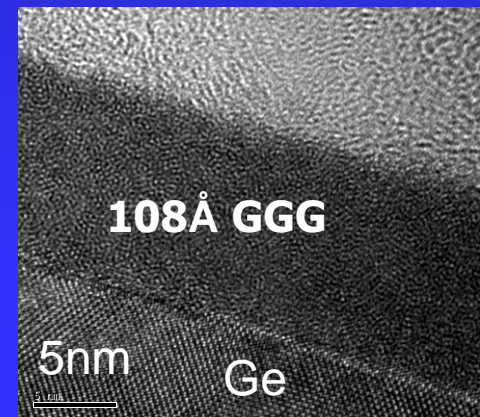
**High mobility channel**

**Integration of Ge, III-V with Si**

**Moore's Law: The number of transistors per square inch doubles every 18 months**

Shorter gate length  $L$   
Thinner gate dielectrics  $t_{ox}$

**Driving force :**  
**High speed**  
**Low power consumption**  
**High package density**



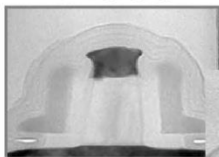


# Intel Transistor Scaling and Research Roadmap

## Transistor Scaling and Research Roadmap

90nm Node

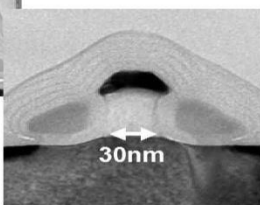
2003



50nm Length  
(Production)

65nm Node

2005



30nm Length  
(Development)

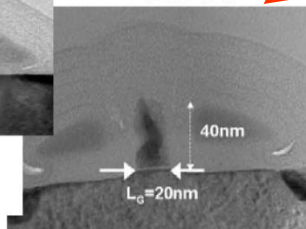
Uniaxial  
Strain

SiGe S/D PMOS

1.2nm Ultra-thin SiO<sub>2</sub>

45nm Node

2007

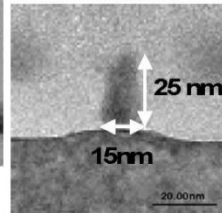


20nm Length  
(Development)

High-K &  
Metal-Gate  
Options

32nm Node

2009

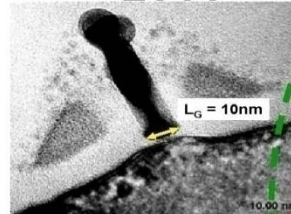


15nm Length  
(Research)

Non-planar Tri-Gate  
Architecture Option

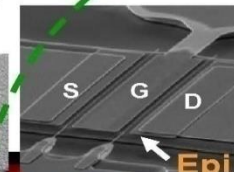
22nm Node

2011



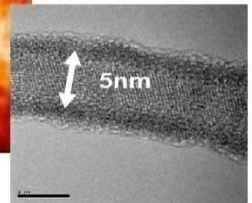
10nm Length  
(Research)

2015-2019  
Research



III-V Device  
Prototype  
(Research)

C-nanotube  
Prototype  
(Research)



Nanowire  
Prototype  
(Research)

Robert Chau, Intel, ICSICT 2004

*More non-silicon elements introduced*



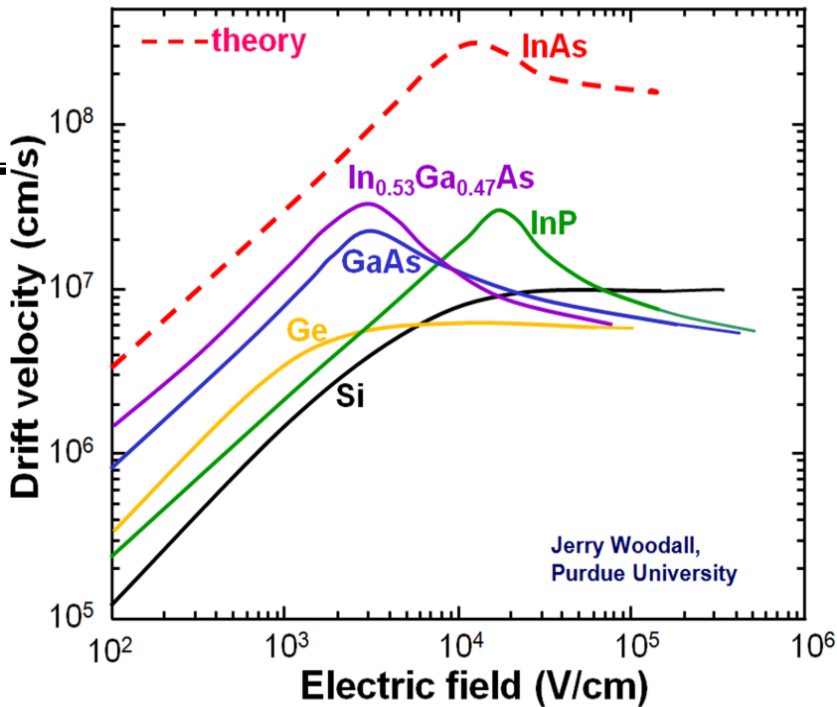


## Intel R&D PIPELINE



*Innovating for the Next Decade of Computing*

# Why III-V MOSFETs?



## III-V semiconductors

- ✓ high electron mobility/drift velocity
- ✓ sophisticated band-gap engineering
- improved power/performance tradeoff
- ✓ high frequency or optical applications
- ✓ substantial manufacturing experience

## High- $\kappa$ / III-V MOSFETs

- ◆ Schottky gate (MESFET/HEMT) → MOS gate
- reduced gate leakage

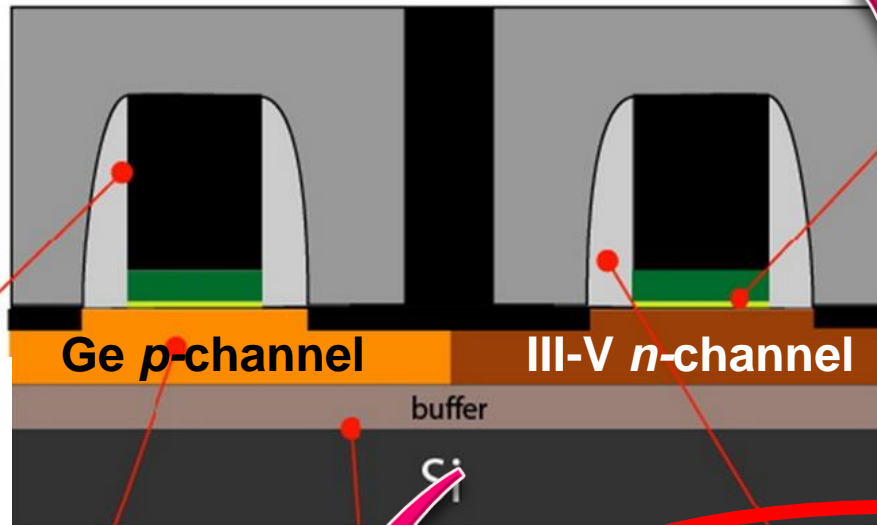
	IV		III-V				
	Si	Ge	GaAs	In <sub>0.53</sub> Ga <sub>0.47</sub> As	InAs	GaSb	InSb
Electron Mobility (cm <sup>2</sup> /V·s)	1,400	3,900	8,500	12,000	40,000	3000	77,000
Hole mobility (cm <sup>2</sup> /V·s)	450	1,900	400	450	500	1000	850
Bandgap (eV)	1.11	0.67	1.42	0.74	0.36	0.72	0.17

# The Grand Challenges for III-V/Ge CMOS

J. A. del Alamo

IEDM 2007 Short Course:  
Emerging Nanotechnology  
and Nanoelectronics

non-planar  
device architecture



high- $\kappa$  dielectric  
gate insulator

- ✓ low gate leakage
- ✓ EOT < 1 nm
- ✓  $D_{it} \leq 10^{11} \text{ cm}^{-2} \text{ eV}^{-1}$

Ge p-channel  
MOSFETs

scalable, self-aligned,  
E-mode device architectures

III-V epitaxy on  
large-area Si wafers

# Science and Technology of Ultimate CMOS

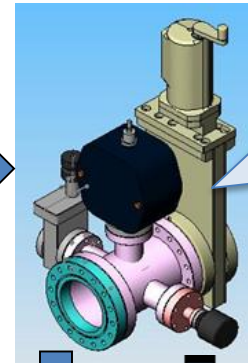
## The Ultimate CMOS – End of road map

**To achieve higher speed and lower power consumption**

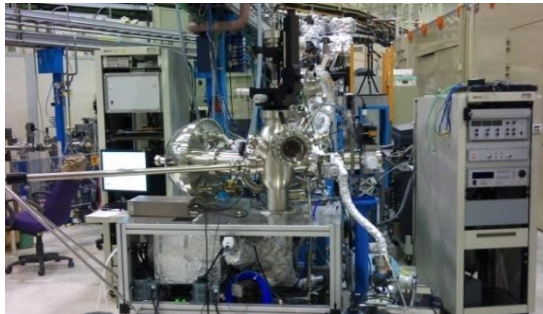
R&D of III-V InGaAs MOSFET *state-of-art* technology below 5 nm node,  
by combining advanced analysis of spectroscopy/microscopy/quantum transport/theoretical modeling



- In-situ ALD of oxide integrated with MBE at ITRI Nano center
- Controlled chemical reaction route and species at surface



Portable UHV chamber for transfer 2" wafers in  $3 \times 10^{-10}$  torr for ARPES, PES and STM analysis

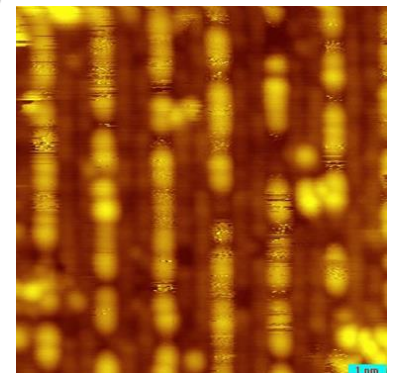


High resolution synchrotron radiation photoemission spectroscopy in NSRRC by Dr. T.W. Pi.

RT and LT STM/STS study by Dr. W. W. Pi at CCMS/NTU



InGaAs surface reconstructed at 77K

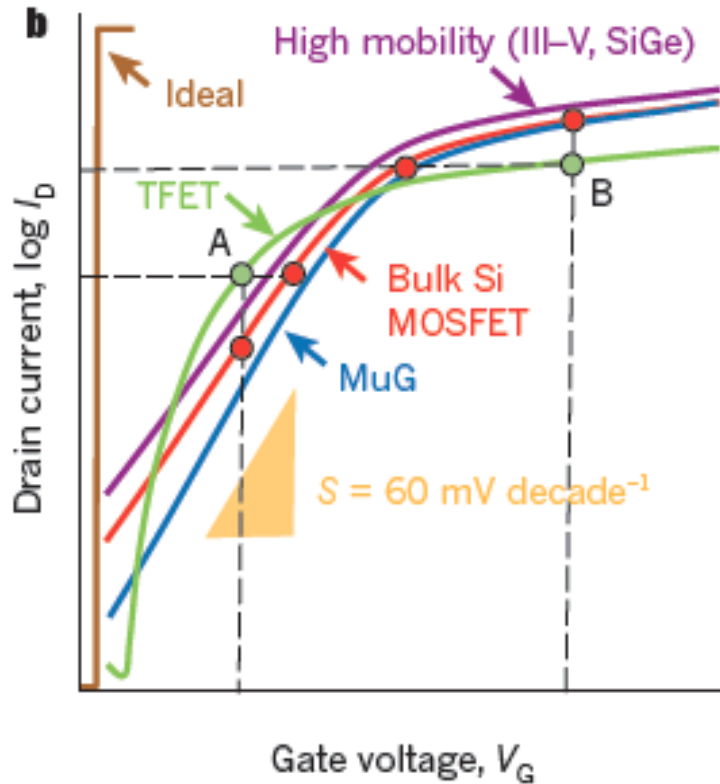


# Tunneling-FETs offer sharper turn-on devices compared to MOSFETs

Lower  $V_{DD}$  to lower switching energy ( $P_{active} \sim C \cdot V_{DD}^2$ )

Better performance for ultra low-power applications

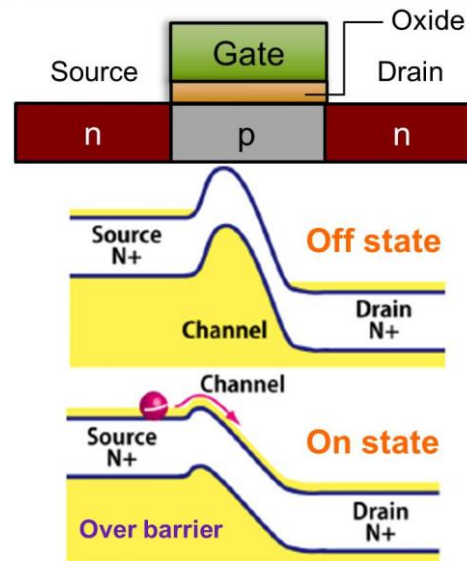
## Atomic Model Prediction



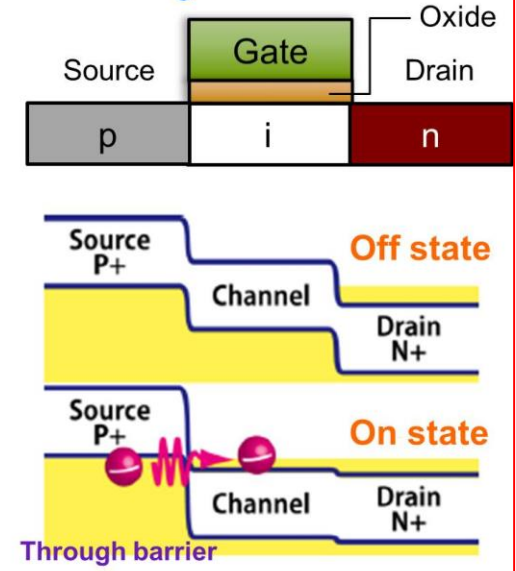
Much smaller subthreshold swing !

A. M. Ionescu et al.,  
*Nature* **479**, 329 (2011).

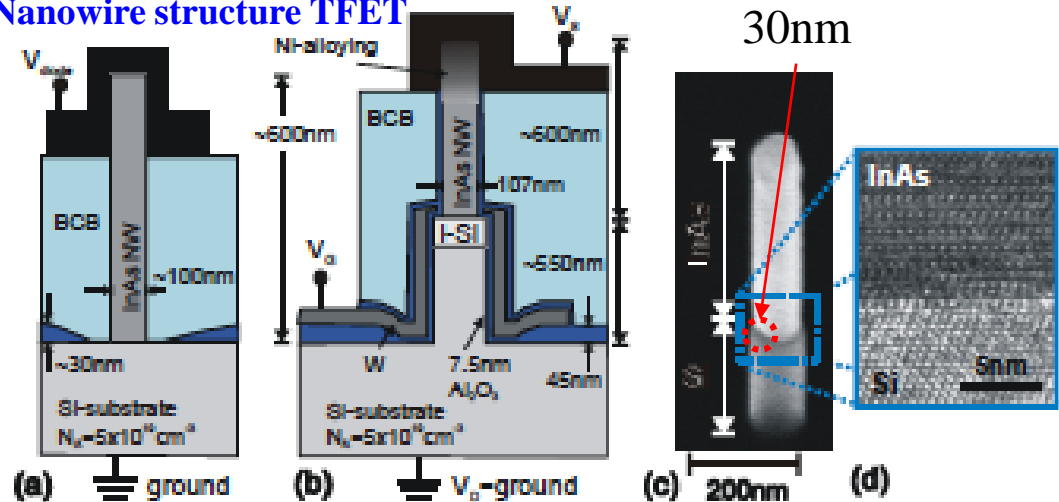
### Conventional MOSFET



### Tunneling FET



### Nanowire structure TFET



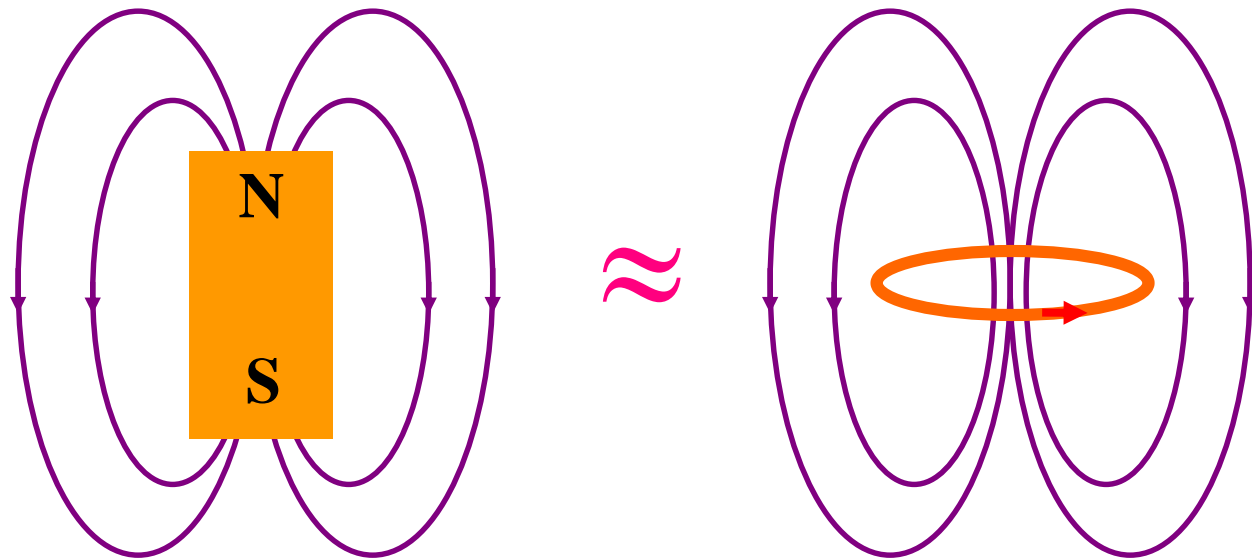
H. Riel et al., *IEDM* 391 (2012).

# **(IV) Quantum Spin**



# Spin and Nano technology

**Electron Spin is the smallest unit of magnetism,  
came from Quantum Mechanics**



**Often being used for  
magnetic recording  
~30 billion market**

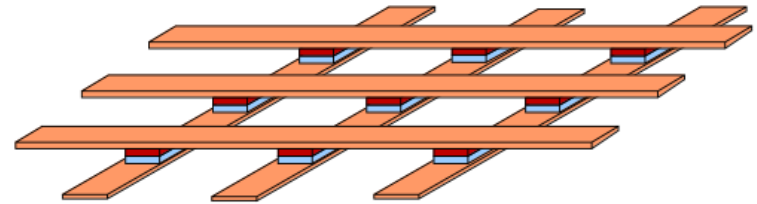
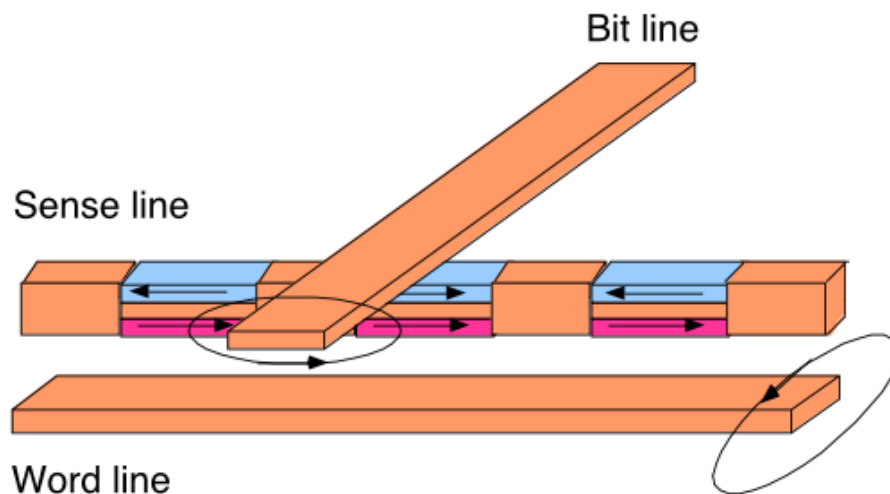


Well read: spintronics has dramatically increased data storage densities in hard drives.

**Spintronics  $\Leftrightarrow$  Electronics**

# New generation of computer

Computation and storage  
in one shot

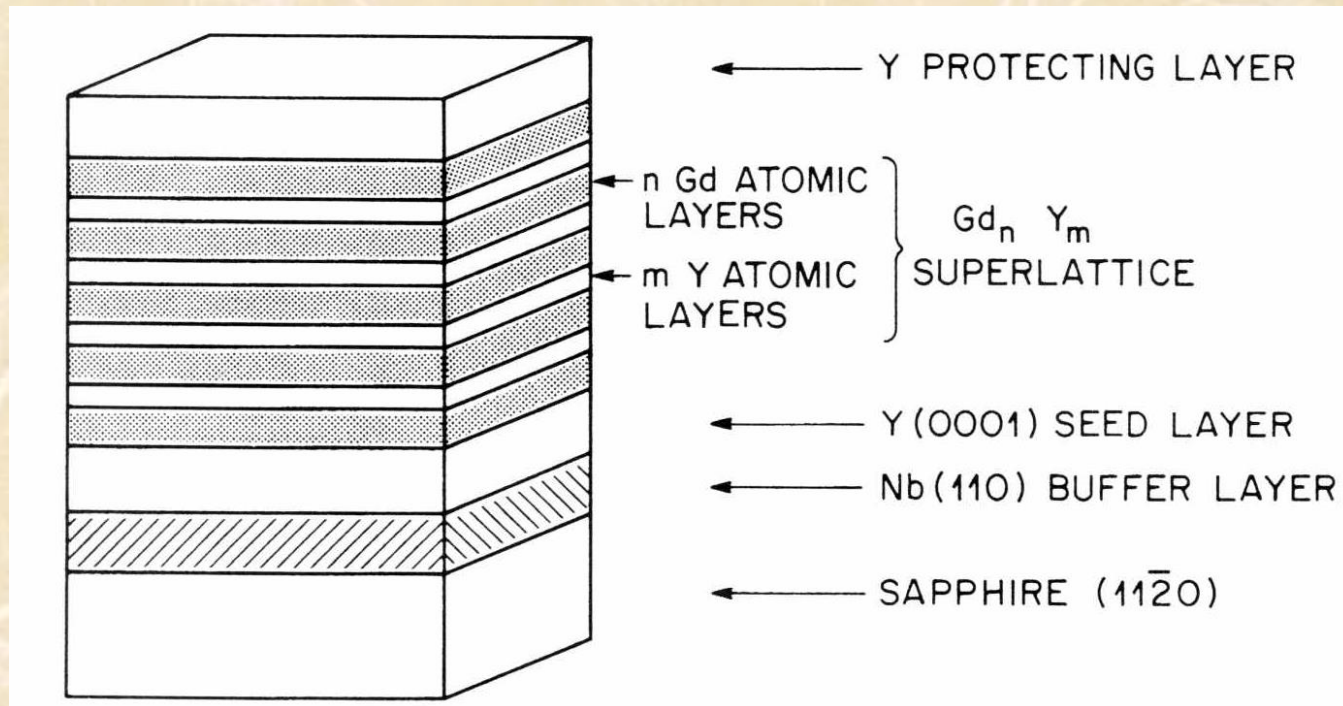


**Fig. 7.** A schematic representation of RAM that is constructed of magnetic tunnel junctions connected together in a point contact array. The conducting wires provide current to the junctions and permit voltage measurements to be made. They also enable the manipulation of the magnetization of the elements by carrying currents both above and below the magnetic junctions to create magnetic fields.

When turn-on,  
it is ready!

# Artificial Superlattice

- Matching the structural periodicity with physical length scale of **superconductivity and magnetism**
- **Modulation of physical properties**



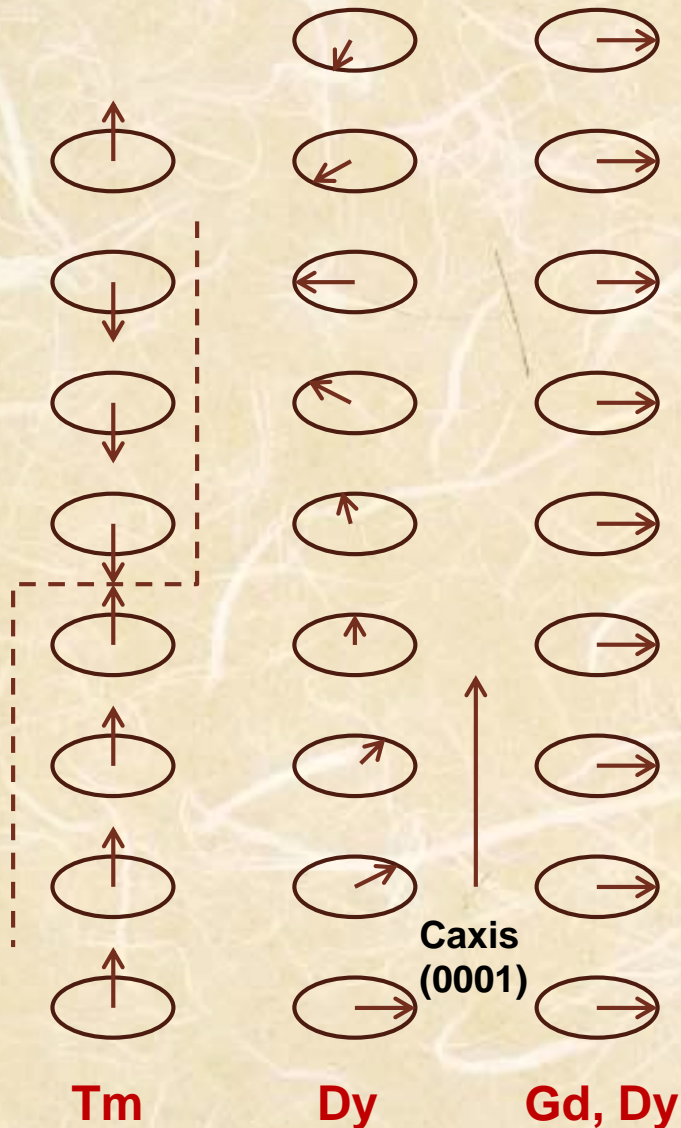
## Invention of metal molecular beam epitaxy in 1981

- Single crystal epitaxial superlattices with atomically abrupt interfaces



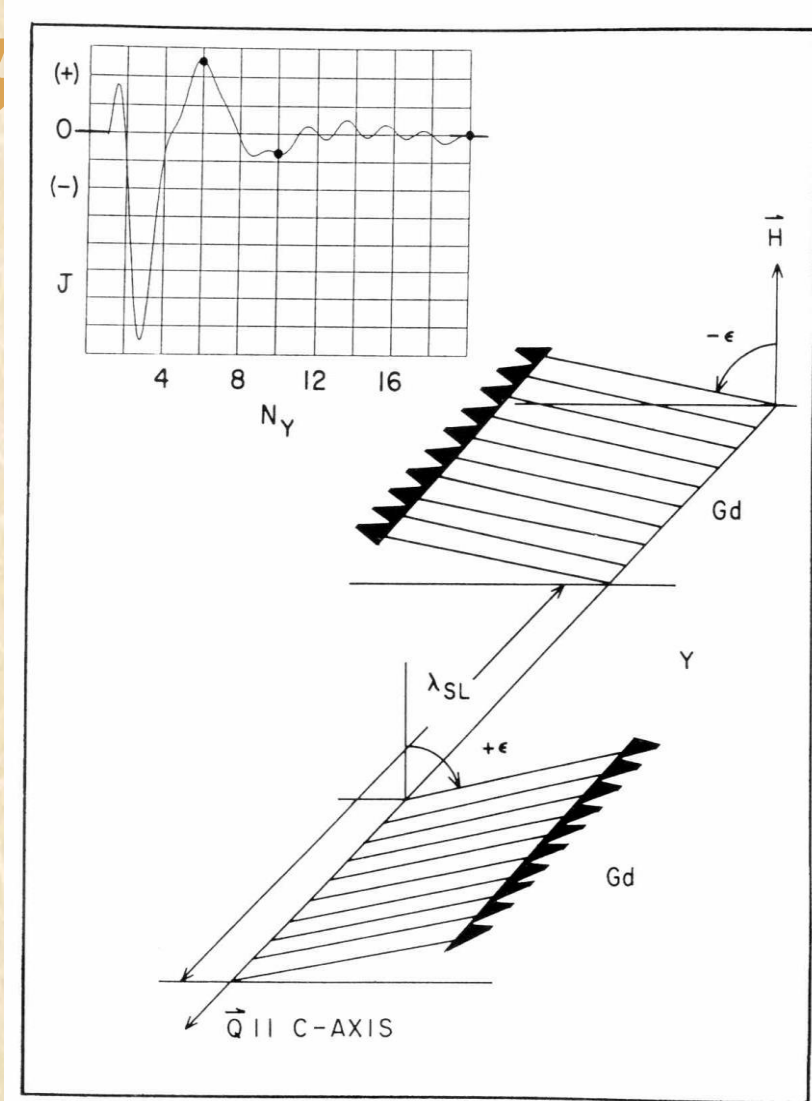
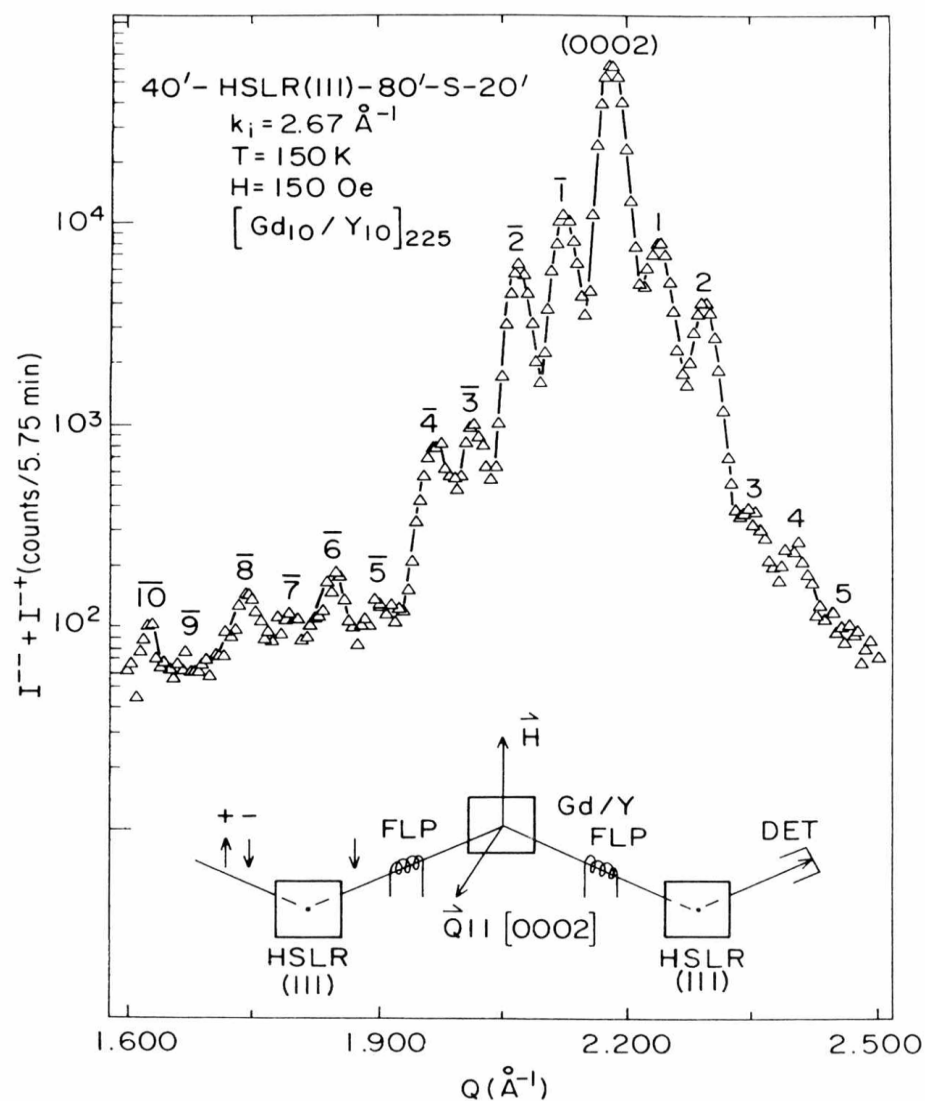
# HCP crystal structure

- Similar crystal- chemical nature of rare earths form coherent superlattices
- Metallic superlattice effect
  - Long range nature of the indirect exchange interaction
  - Magnetic coupling of magnetic rare earth through non – magnetic Y, Lu
  - Modulation of magnetic properties of Gd - Y Superlattices
  - Spin structure modification of Tm - Y, Dy - Y Superlattices
- 2-dimensional magnetism
- Interfacial magnetism



Spin structures of heavy rare - earths

# Neutron Diffraction Studies of the $\text{Gd}_{10}\text{-Y}_{10}$ Magnetic Superlattice Antiferromagnetically coupled below 200K



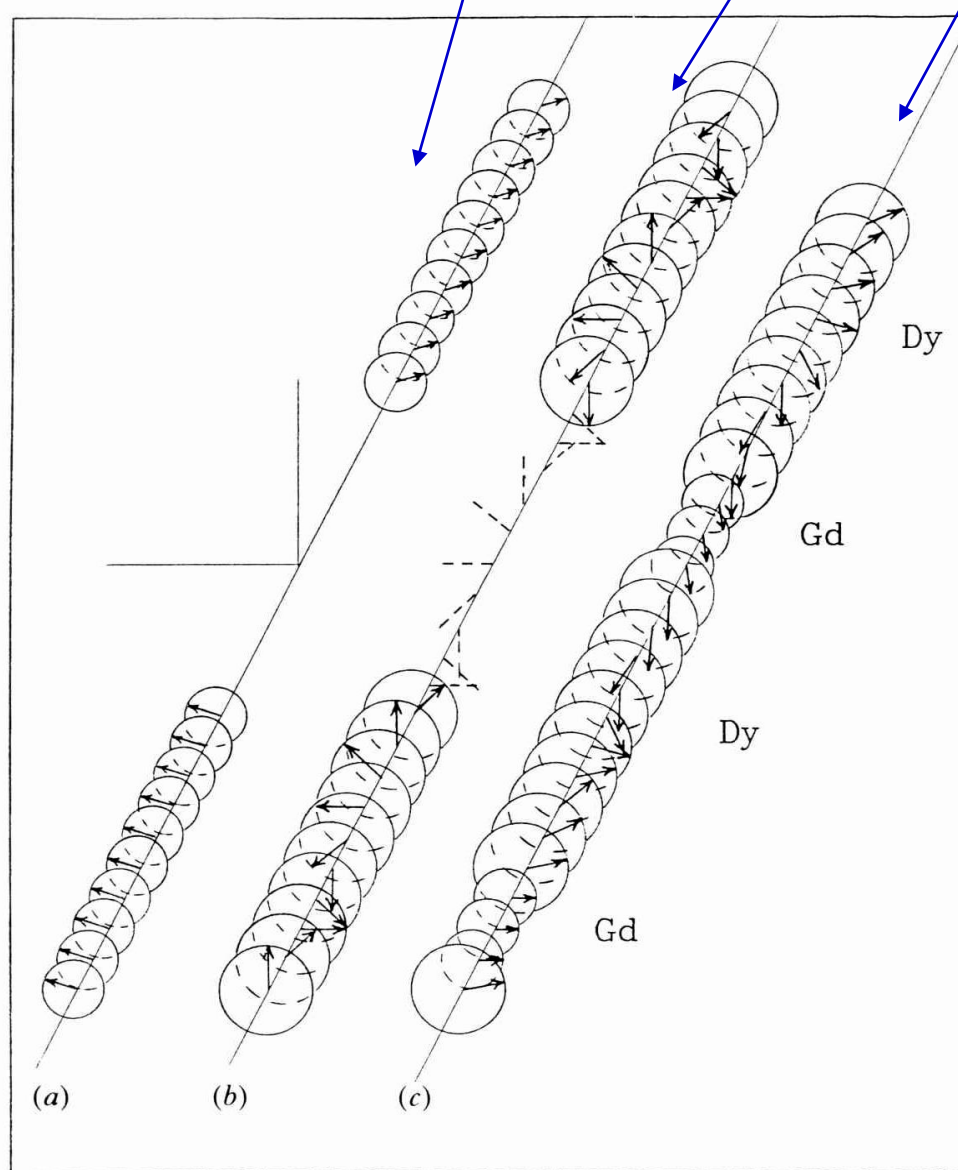


# Spin Structure Tailoring in artificial Superlattices

**Gd-Y**

**Dy-Y**

**Gd-Dy**



Year 1984-1989



# Giant Magnetoresistance (GMR)

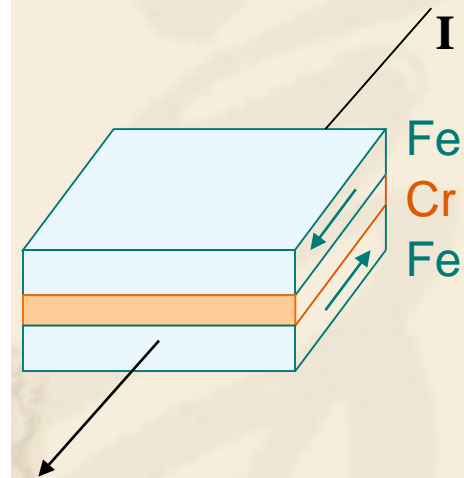
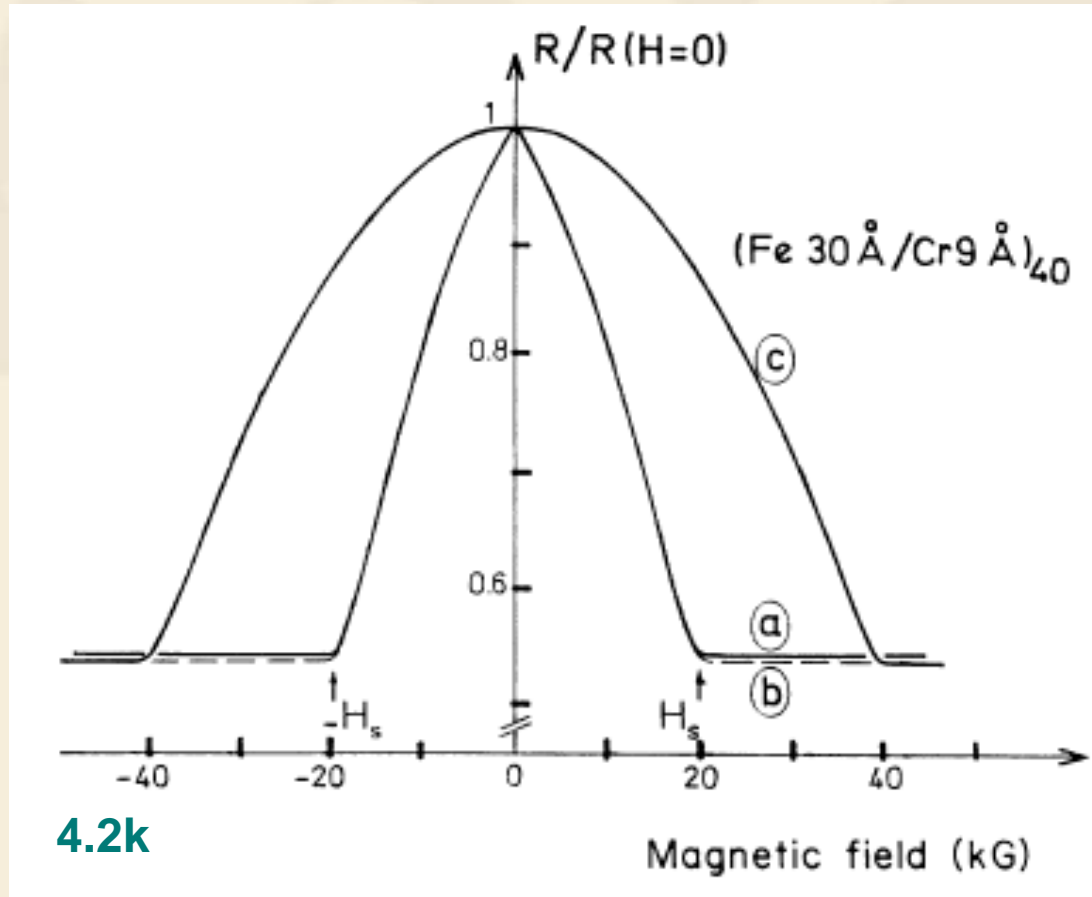
## ❖ What is GMR?

- ✦ GMR is a very large change in electrical resistance that is observed in a ferromagnet/paramagnet multilayer structure.
- ✦ Resistance change occurs when the relative orientations of the magnetic moments in alternate ferromagnetic layers change as a function of applied field.
- ✦ The total resistance of this material is lowest when the magnetic orientations of the ferromagnetic layers are aligned, is highest when the orientations are anti-aligned.

Ferro.
Para.
Ferro.
Ferro.
Para.
Ferro.
Para.
Ferro.

M. N. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, and F. Petroff,  
*Phys. Rev. Lett.*, **61**, 2472 (1988).

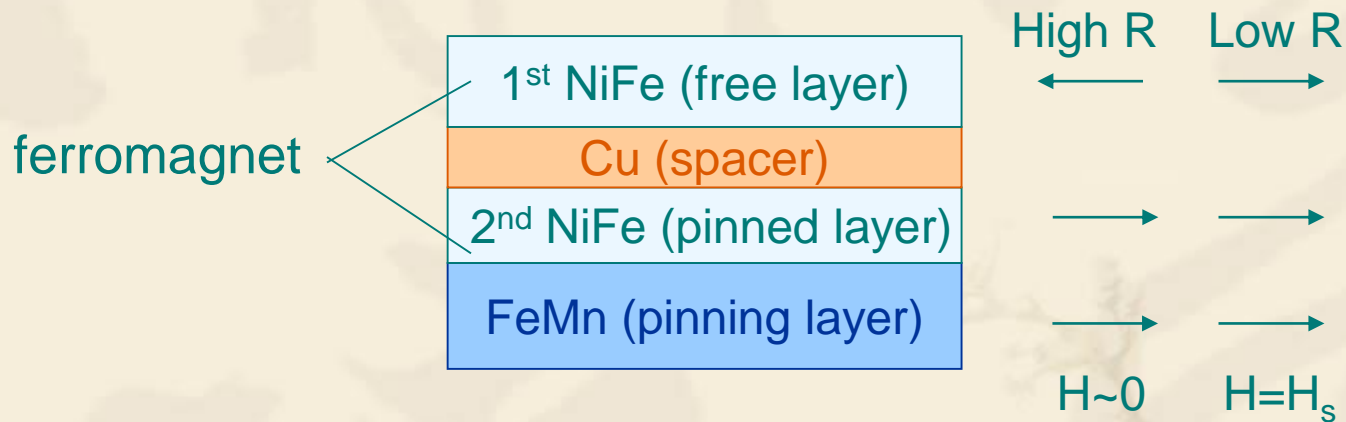
# First Evidence of GMR



$H_s$  corresponds to the field at which all layer magnetizations point along the field direction.

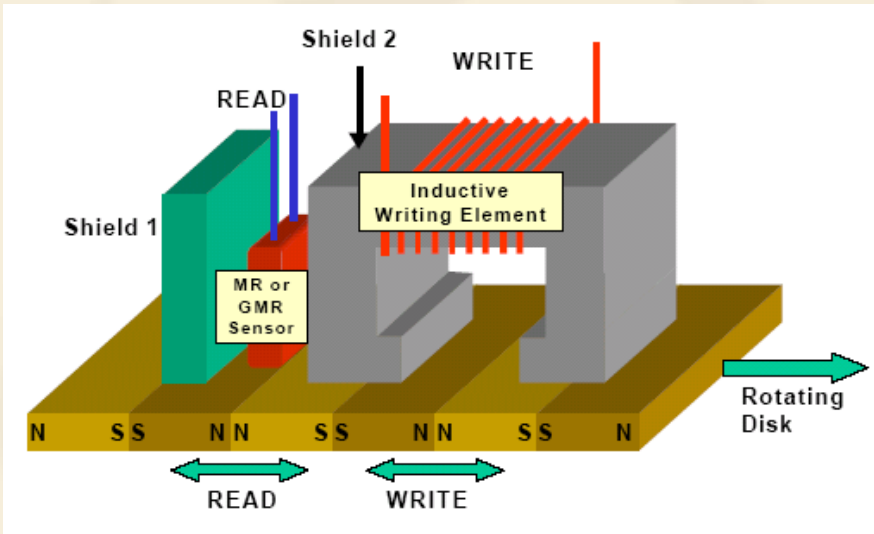
# Spin-Valve GMR

- ✦ The simple structure of Spin-valve GMR :

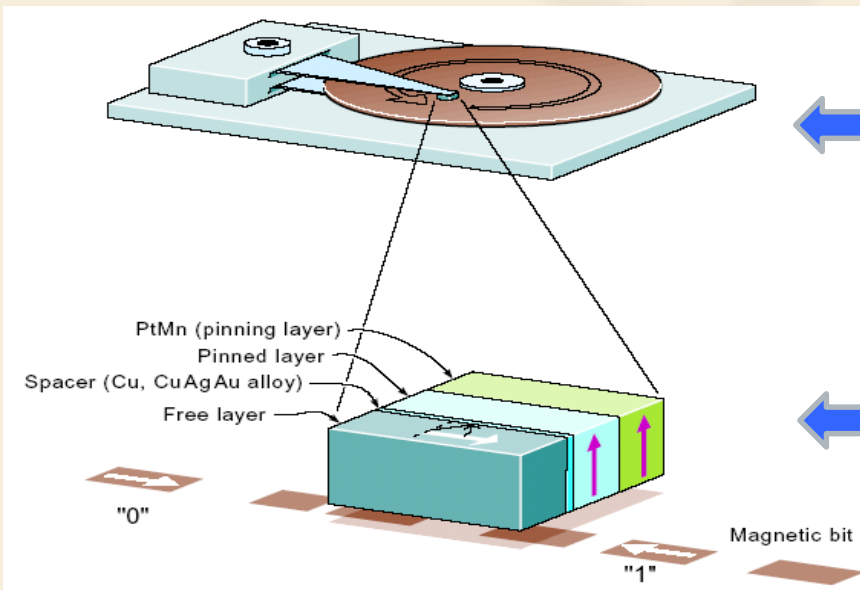


- ✦ The magnetization of the top permalloy layer is free to rotate as the field is varied. The second permalloy layer is fixed due to its exchange interaction with the FeMn layer.

# GMR Spin Valve Reading Head



✦ Magnetization is stored as a “0” in one direction, and as a “1” in the other. This is the magnetic field sensed by the GMR head.

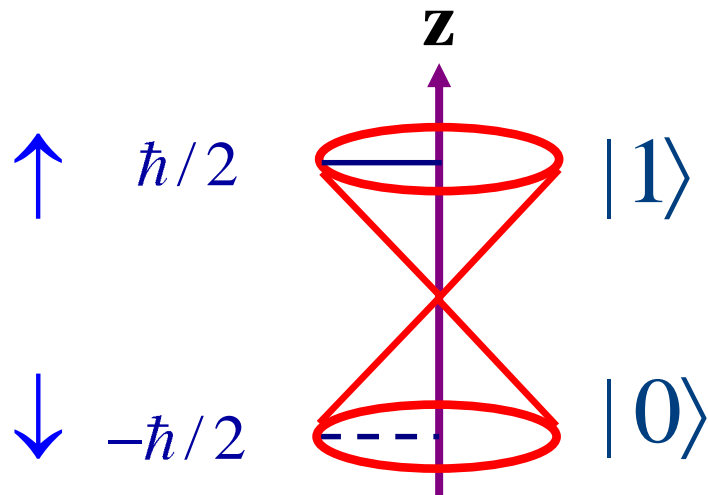


✦ When the head passes over these magnetic bits, the magnetization direction of the free layer in the head responds to the field in each bit by rotating either up or down.

✦ The resulting change in the resistance is sensed by the voltage across the GMR head (current passing through the GMR element is constant).

# Quantum behavior of ferromagnets

## -Spin as a quantum qubit

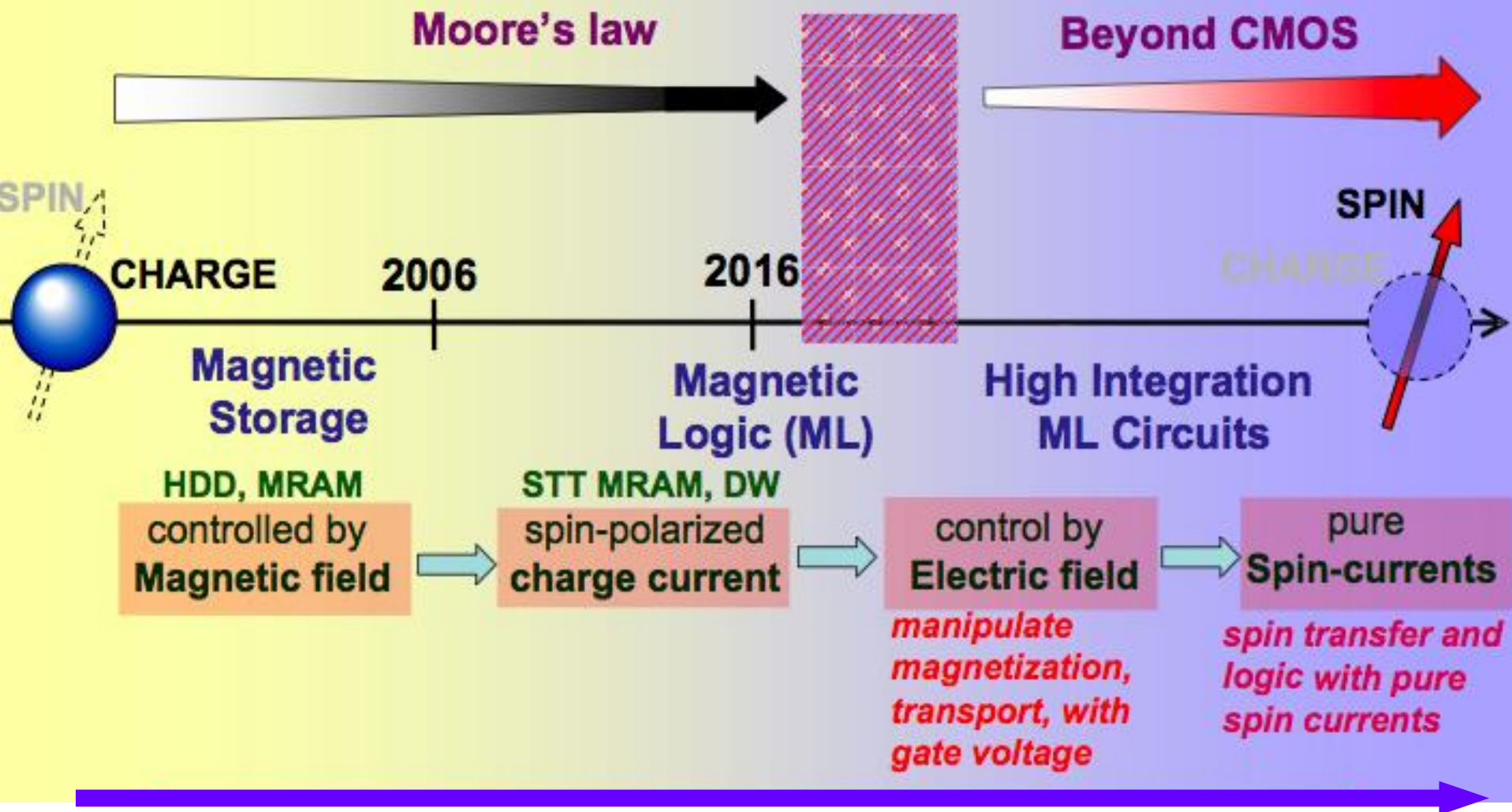


$$\text{qubit} = \alpha |0\rangle + \beta |1\rangle$$

**Due to superposition  
More information!**



# Tentative roadmap



**Can we take the “charge” out of Spintronics ?  
To generate pure spin current !**

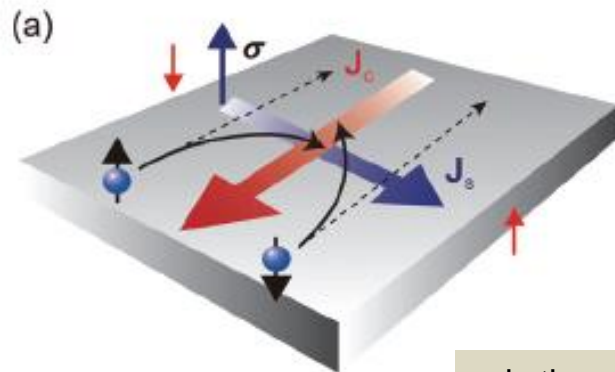
# Reciprocal conversion between spin and charge currents

## Spin Hall effect (2004)

**Charge Current**



**Transverse  
Spin Imbalance**



**Spin Orbit Interaction  
without magnetic field**

$$\mathbf{J}_s = \theta_H \hat{\boldsymbol{\sigma}} \times \mathbf{J}_c$$

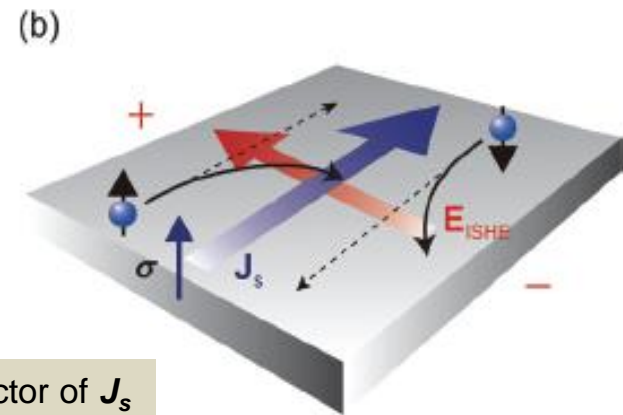
**Generate the spin current**

## Inverse Spin Hall effect (2006)

**Spin Current**



**Transverse  
Charge Imbalance**



$$\mathbf{J}_c = \theta_H \hat{\boldsymbol{\sigma}} \times \mathbf{J}_s$$

**Detect the spin current**



# Spintronics vs Electronics

- ✓ Reducing the heat generated in traditional electronics is a major driving force for developing spintronics.
- ✓ Spin-based transistors do not strictly rely on the raising or lowering of electrostatic barriers, hence it may overcome scaling limits in charge-based transistors.
- ✓ Spin transport in semiconductors may lead to dissipationless transfer of information by pure spin currents.
- ✓ Allow computer speed and power consumption to move beyond limitations of current technologies.

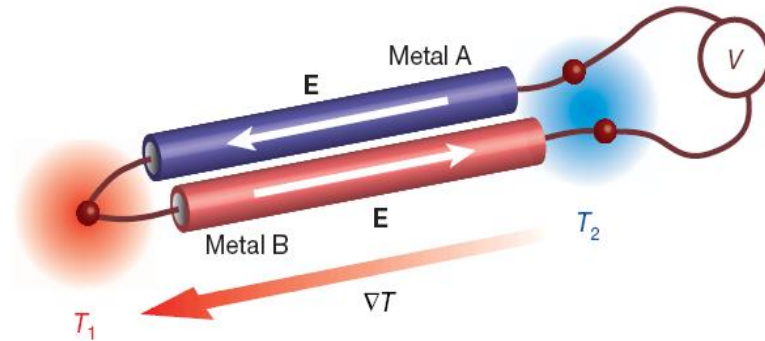
# Reliable generation of pure spin currents !

- ✓ Spin Hall effect (2004)
- ✓ Spin Pumping (2006)
- ✓ Inverse Spin Hall effect (2006)
- ✓ Spin Seebeck effect (2008)
- ✓ Spin Caloritronics (2010)

# Thermoelectric effect

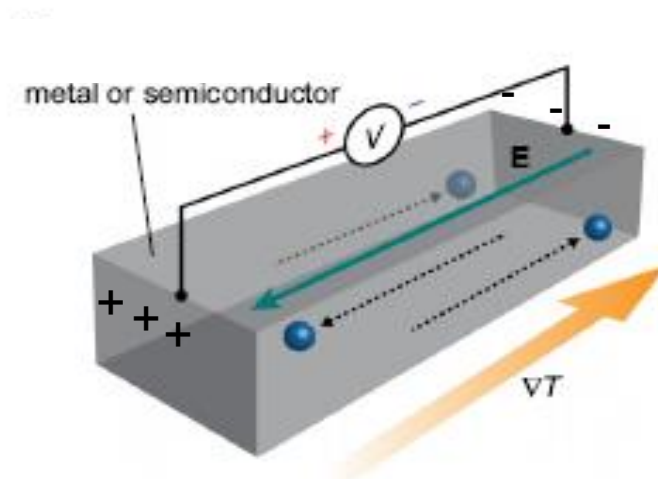
- The interplay between charge currents and heat
- To convert temperature differences  $\Delta T$  to electric voltage  $\Delta V$

## 1. Thermocouple



$$\Delta V = S \Delta T$$

## 2. Seebeck effect (1821)

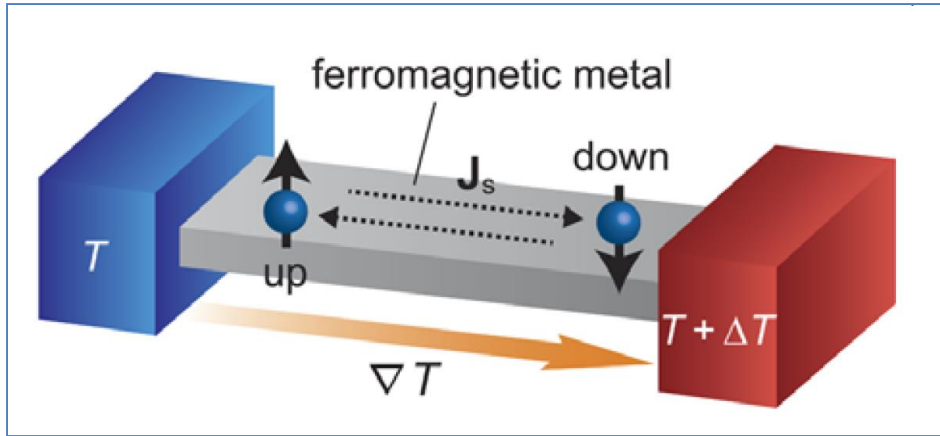


$$\Delta T \rightarrow V$$

$$S = \Delta V / \Delta T$$

**S:** Seebeck Coefficient

# Spin Seebeck effect: the interplay between spin current and heat



Generation of a “spin voltage” as a result of a temperature gradient in magnetic materials

$$\delta V_{spin} = S_{spin} \delta T$$

$\nabla T \Rightarrow$  a spin imbalance

- The up- spin and down-spin conduction electrons of a FM metal have **different chemical potential  $\mu$** , with **different scattering rate and density**, thus result in  $J_{\uparrow}$  and  $J_{\downarrow}$  of different amount.

$$S_{spin} = (1/e)[\partial\mu_{\uparrow}/\partial T - \partial\mu_{\downarrow}/\partial T]$$

- $J_{\uparrow}$  and  $J_{\downarrow}$  flow **in opposite directions** along  $\nabla T$ , and lead to a net  $J_s$

$$j_s = j_{\uparrow} - j_{\downarrow} = (\sigma_{\uparrow} S_{\uparrow} - \sigma_{\downarrow} S_{\downarrow})(-\nabla T)$$

- This pure **spin current** flows **without charge current** in open-circuit condition.

**Use heat to generate the spin current  $\rightarrow$  Spin Caloritronics !**

# Major Quantum Effect at the nano scale

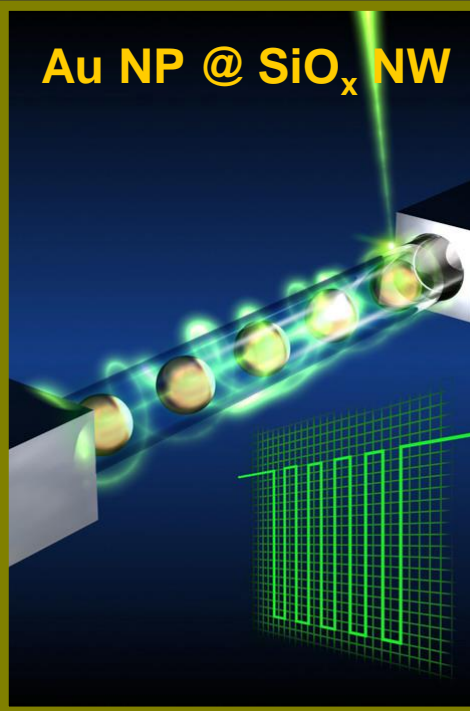
- Interference
- Quantization
- Tunneling
- Quantum Spin

# **The Fourth Lesson:**

*Innovations of  
nano structures and  
nano materials  
for various applications*

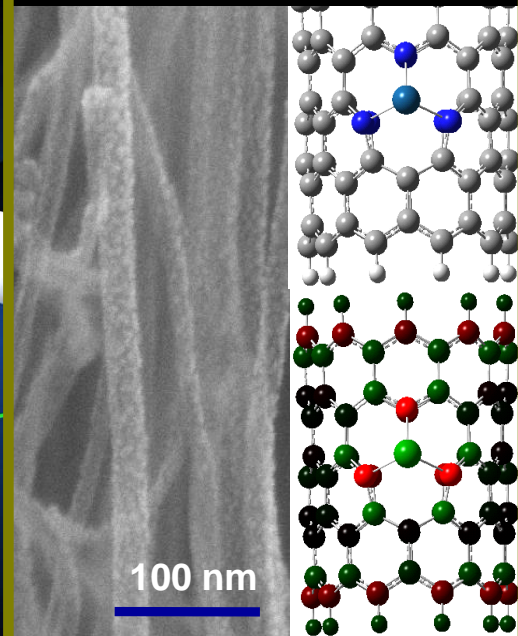
# Overview of Advanced Materials Laboratory

**Au NP @ SiO<sub>x</sub> NW**



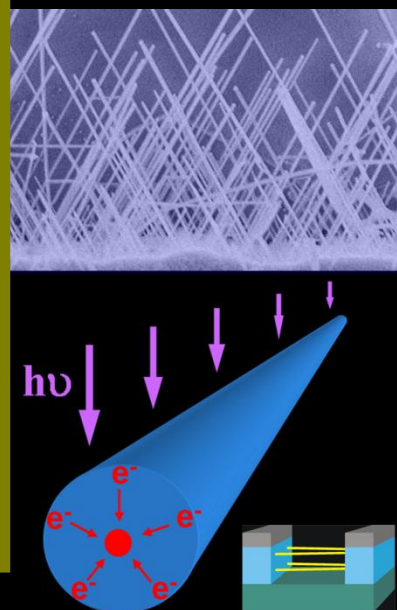
Color-selective Optical Switch, SPR-enhanced Sensor

**Pt-Ru NP on CN<sub>x</sub> NT**



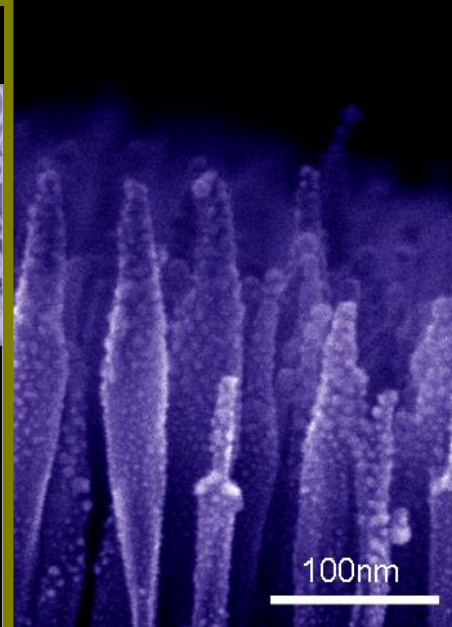
Fuel Cells, Supercapacitors

**GaN Nanobridge**



High-gain Photo-detector, Solar Cells, Bio-sensor

**Ag NP on Si NT**



SERS: Molecule/Bio-sensing

Li-Chyong Chen

Center for Condensed Matter Sciences

National Taiwan University



# The Nano-world at CCMS-AML:

## a Fruitful Research Field with Technology Implications

*JACS* 123, 2791 (2001)

*APL* 81, 22 (2002)

*JACS* 127, 2820 (2005)

*APL* 88, 241905 (2006)

*APL* 90, 213104 (2007)

*Adv. Func. Mater.* 18, 938 (2008)

*Small* 4, 925 (2008)

*Analytical Chem.* 81, 36 (2009)

*APL* 79, 3179 (2001)

*APL* 81, 4189 (2002)

*Adv. Func. Mater.* 12, 687 (2002)

*APL* 86, 203119 (2005)

*Chem. Mater.* 17, 3749 (2005)

*JACS* 128, 8368 (2006)

*PRB* 75, 195429 (2007)

*JACS* 130, 3543 (2008)

Chapter 9, pp. 259-309,  
*Nanowires and nanobelts*, Z.L.

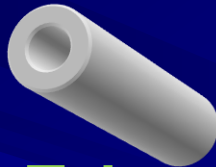
Wang Ed., Kluwer (2004)

*Adv. Func. Mater.* 16, 537 (2006)

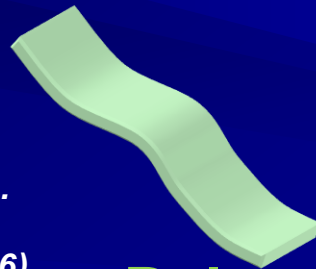
*APL* 90, 123109 (2007)

*Adv. Mater.* 19, 4524 (2007)

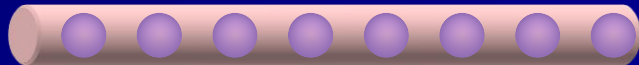
**Wire/Rod**



**Tube**



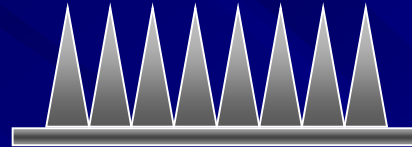
**Belt**



**Peapod**

*Adv. Mater.* 14, 1847 (2002)

*Nature Mater.* 5, 102 (2006)



**Nanotip**

*APL* 83, 1420 (2003)

*Nano. Lett.* 4, 471 (2004)

*Chem. Mater.* 17, 553 (2005)

*Adv. Func. Mater.* 15, 783 (2005)

*APL* 86, 203119 (2005)

US Patent 6,960,528,B2

*APL* 89, 143105 (2006)

*Nature Nanotech.* 2, 170 (2007)

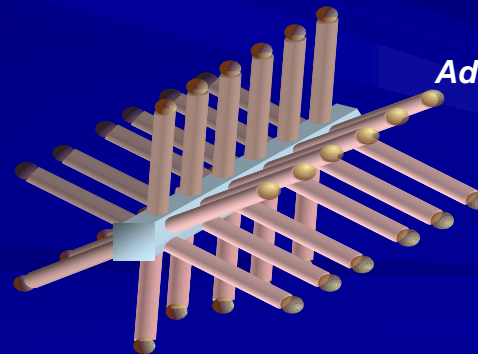
*Nano Lett.* 9, 1839 (2009)



**Core-shell**

*APL* 81, 1312 (2002)

*Nano. Lett.* 3, 537 (2003)



**Brush**

*Adv. Func. Mater.* 14, 233 (2004)

**Other Thin Films:**

*APL* 86, 21911 (2005)

*APL* 86, 83104 (2005)

*APL* 86, 161901 (2005)

*APL* 87, 261915 (2005)

*JVST B* 24, 87 (2006)

*APL* 88, 73515 (2006)

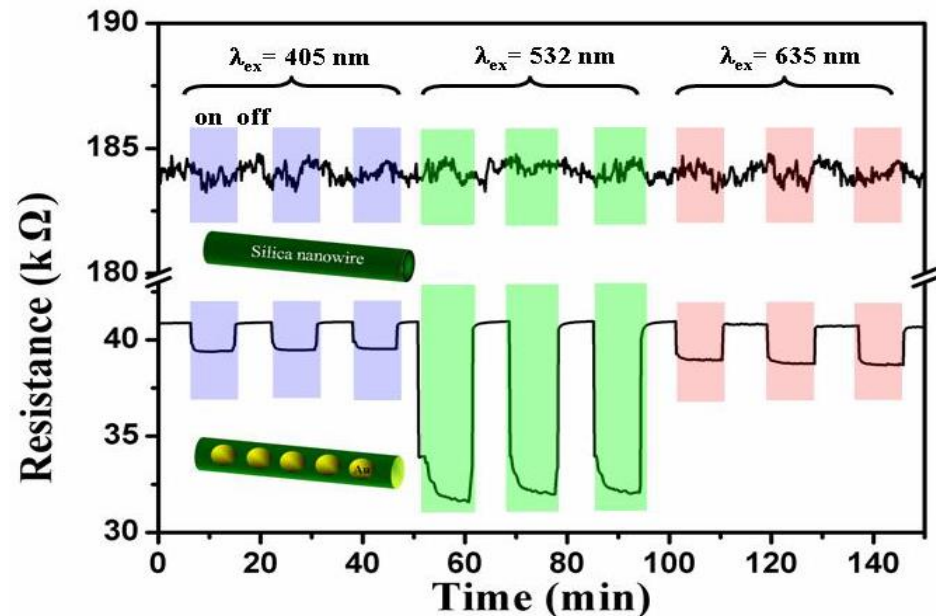
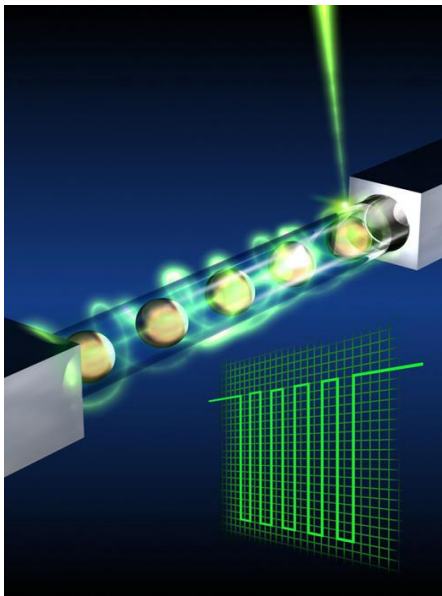
*Adv. Mater.* 21, 759 (2009)

# A Color-selective Nanoswitch

## Photosensitive Gold Nanoparticle-embedded Dielectric Nanowires

*M. S. Hu, et al., Nature Materials 5, 102-106 (2006)*

### A Fast Breaking Paper



In ancient Arabian story of “Ali Baba and the Forty Thieves”, the treasure is in a cave, of which the mouth is sealed by magic. It opens on the words "Open Sesame" and seals itself on the words "Close Sesame".

The nanopeapod (i.e., gold nanoparticle-embedded dielectric nanowire) will open to green light, but shut for lights of other colors.

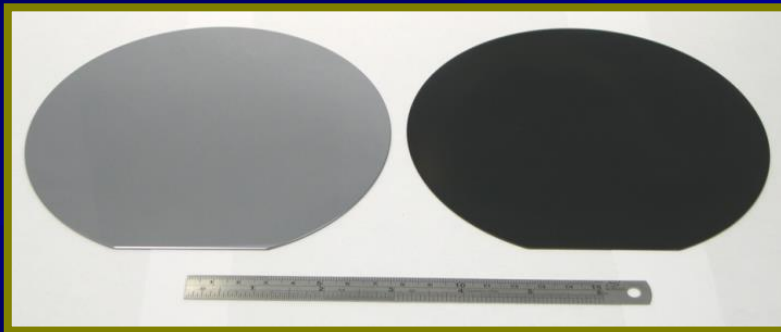
# Si Nanotips-Array and their Hetero-junctions: On-chip, IC-compatible

## \* Antireflection:

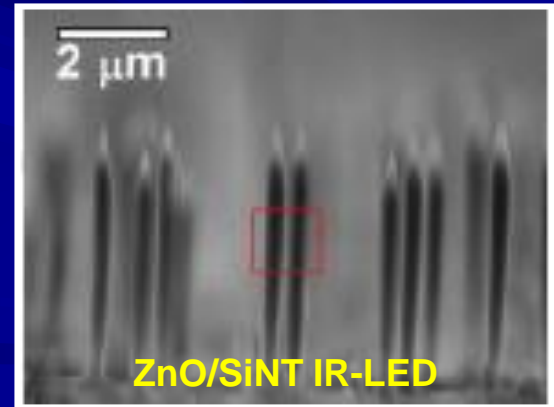
Broadband (uv-terahertz), Omnidirectional ( $>70^\circ$ )

## \* Electroluminescence in ZnO/SiNTs:

IR emission, x10 higher; turn-on  $\sim 3\text{V}$ , x2 lower than film



Nature-Nanotechnology  
2 (2007) 770



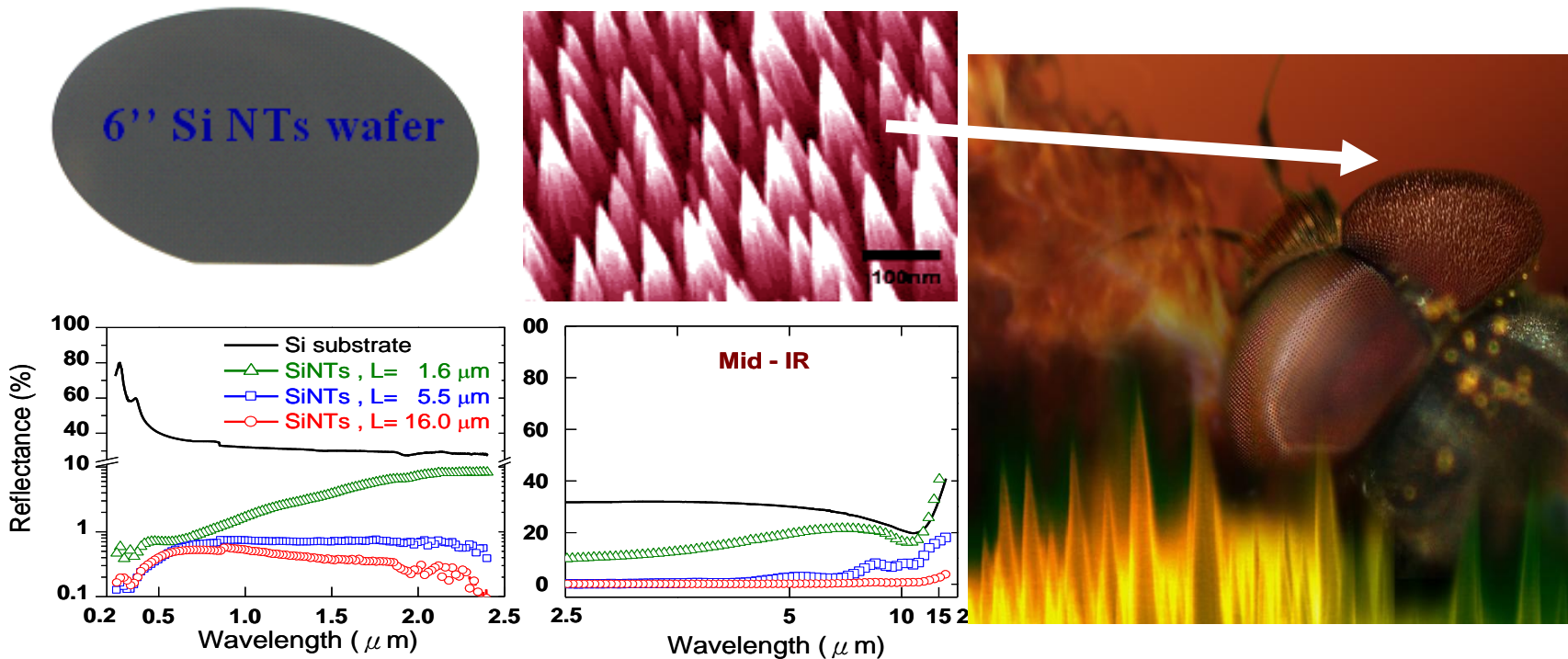
Nano Letters 9 (2009) 1839

# A Man-made Moth Eye

## Broadband and quasi-omni-directional, anti-reflection Properties with biomimetic Silicon nanostructure

Y. F. Huang, et al., *Nature Nanotechnology* 2, 770-774 (2007) & US Patent 2005

Featured by NPG Asia Materials, March 2008



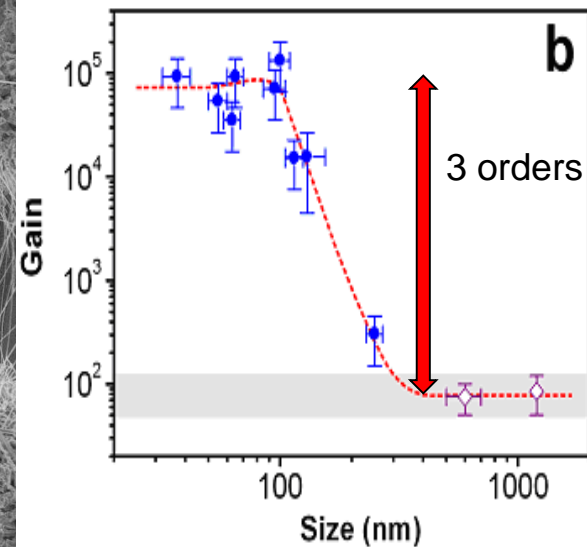
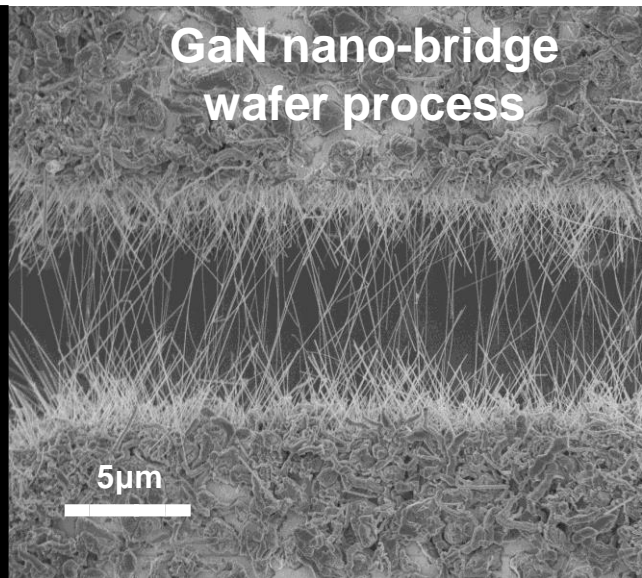
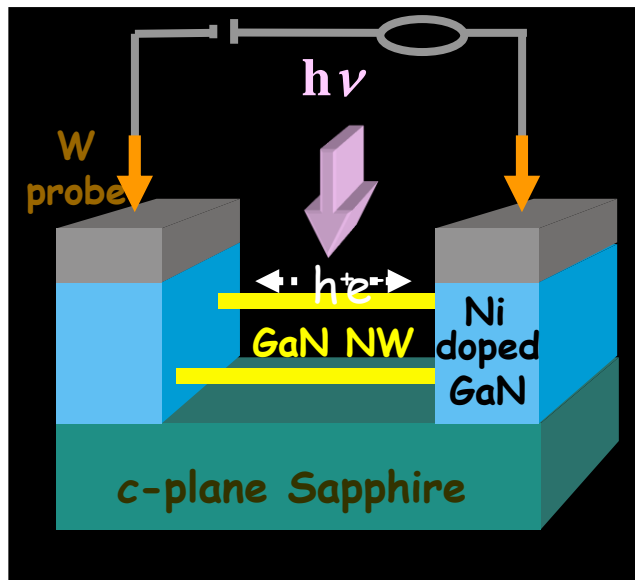
Many plants and animals have tiny surface structures that absorb certain wavelengths of light. These naturally formed nanostructures provide the colors in butterfly wings, camouflage for cicadas and enable moths to capture as much light as possible when flying at night. Now, we have created nanostructure surfaces which mimic moth eye and surpass its function in **anti-reflection** in that they absorb almost all incident light.



# Building a Nano-scale Bridge On-chip

## On-chip Fabrication of Well Aligned and Contact Barrier-Free GaN Nanobridge Devices with Ultrahigh Photocurrent Responsivity

*R. S. Chen, et al., Small 4, 925-929 (2008)*



- Nanowire: Naturally formed core-shell structure, 1D electron gas-like property
- On-chip process for building GaN nanobridge devices, which provide a large surface area, short transport path, and high responsivity for next-generation sensors and detectors

# **The Fifth Lesson:**

*Nano photonics*

*and*

*Bio-applications*

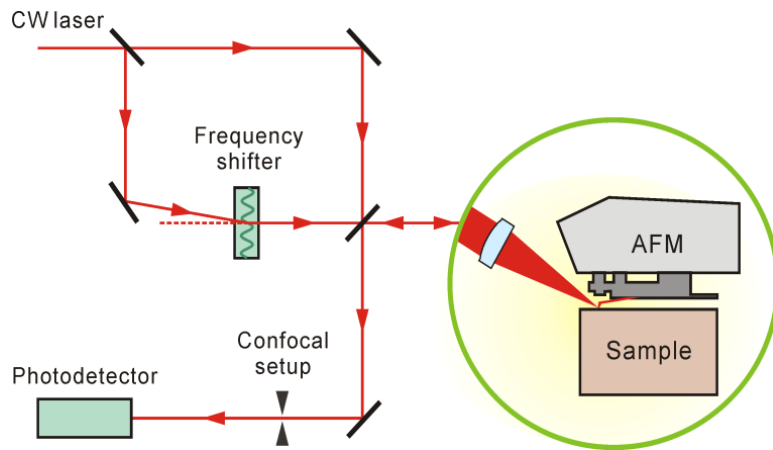


# Nano-photonics and Plasmonics

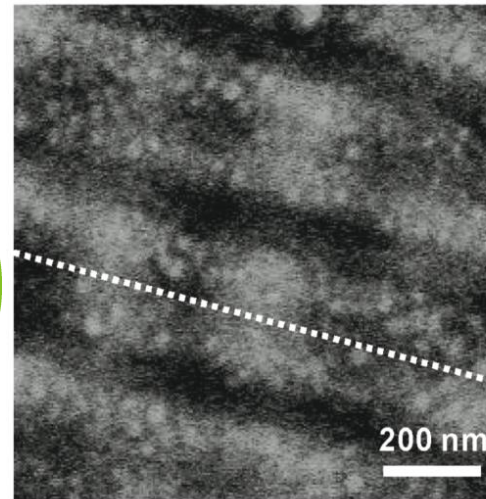
## Near-field examination of blue-ray discs

Dr. Juen-Kai Wang, CCMS, NTU

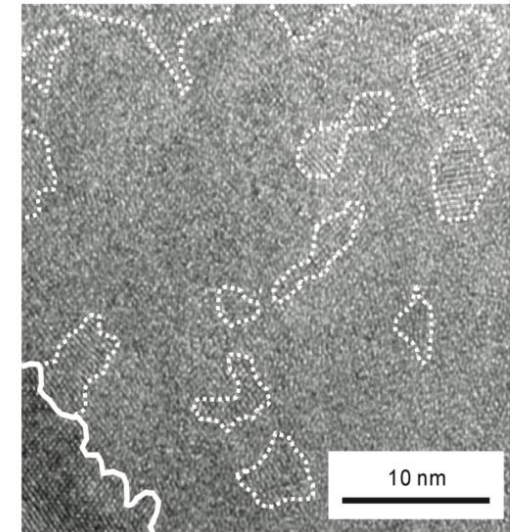
### S-SNOM setup



Near-field image of recorded disc

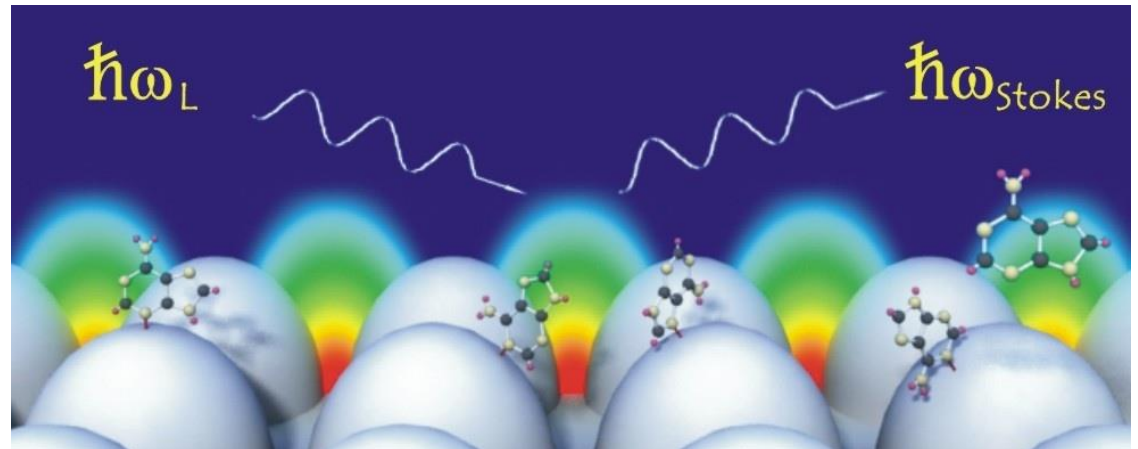
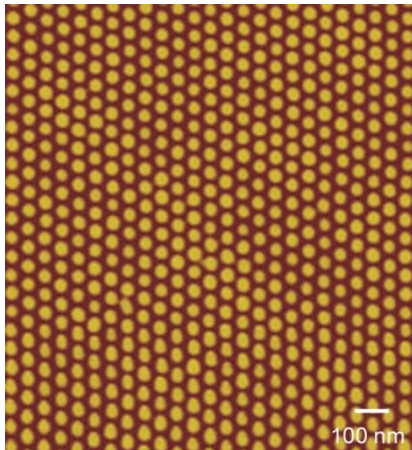
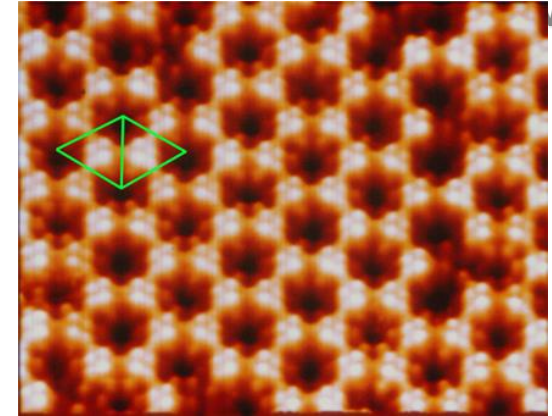
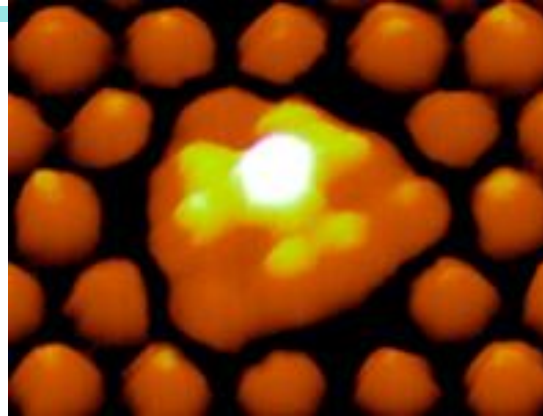
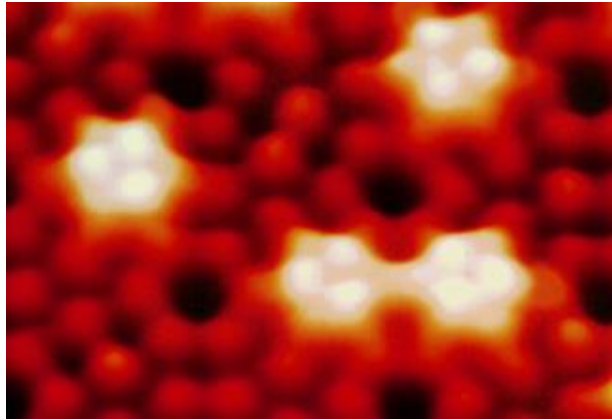


TEM image of recorded mark



- **Scattering-type SNOM reveals sub-10 nm optical signature.**
- The optical contrasts of the dark and the bright regions in near-field image of phase-change layer correspond to amorphous and polycrystalline AgInSbTe, respectively.
- Small bright spots with a size of ~30 nm emerge within the dark region, corresponding to the nano-sized ordered domains in the TEM image.
- **s-SNOM provides a direct optical probe in nanometer scale for high density optical storage media.**

# Creating Monodispersed Ordered Arrays of Surface-Magic-Clusters and Anodic Alumina Nanochannels by Constrained Self-organization

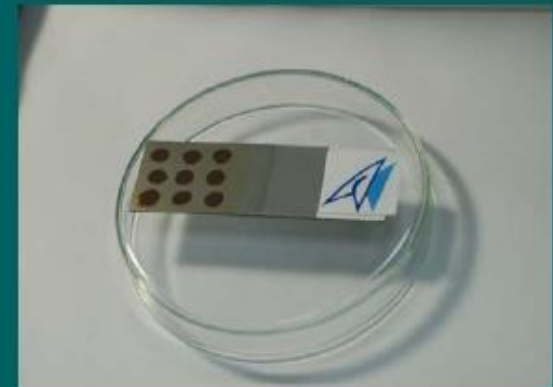
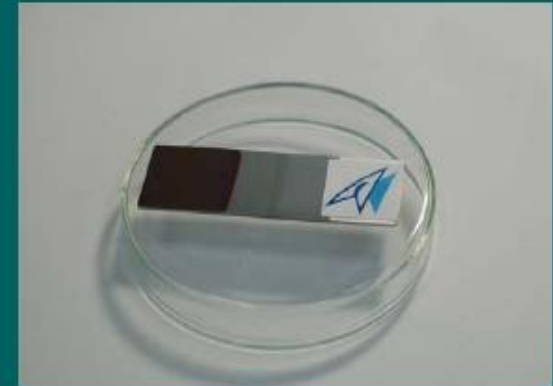
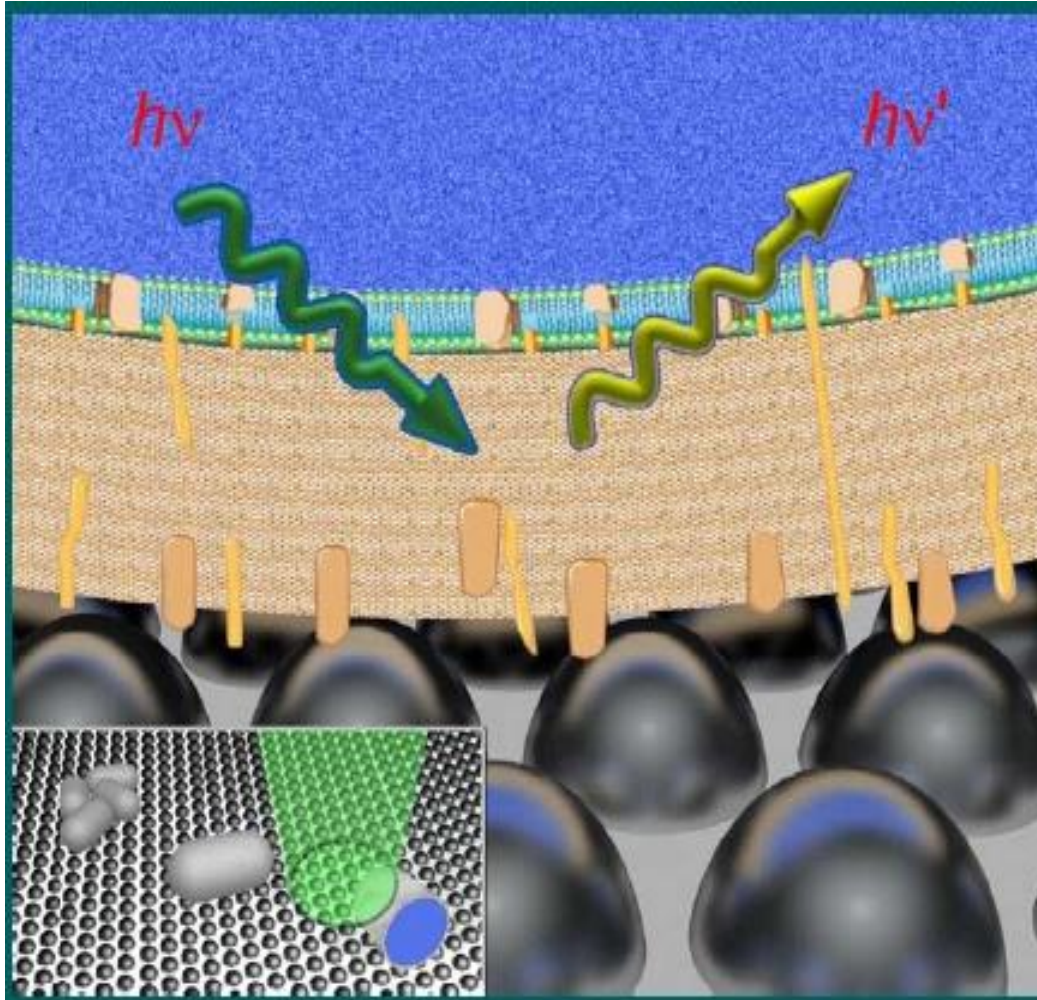


Prof. Yuh-Lin Wang 王玉麟  
IAMS Academia Sinica, Taiwan



# A High Sensitivity and High Speed Biomedical Diagnostic Technology with **Surface Enhanced Raman Scattering (SERS)**

Dr. Juen-Kai Wang, CCMS, NTU

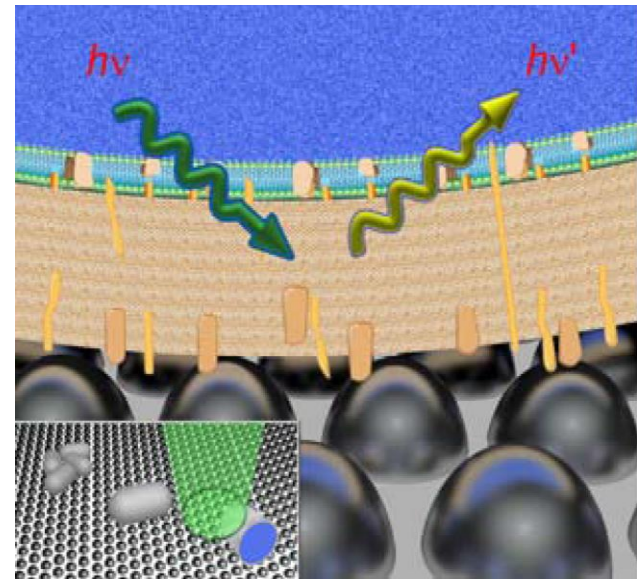
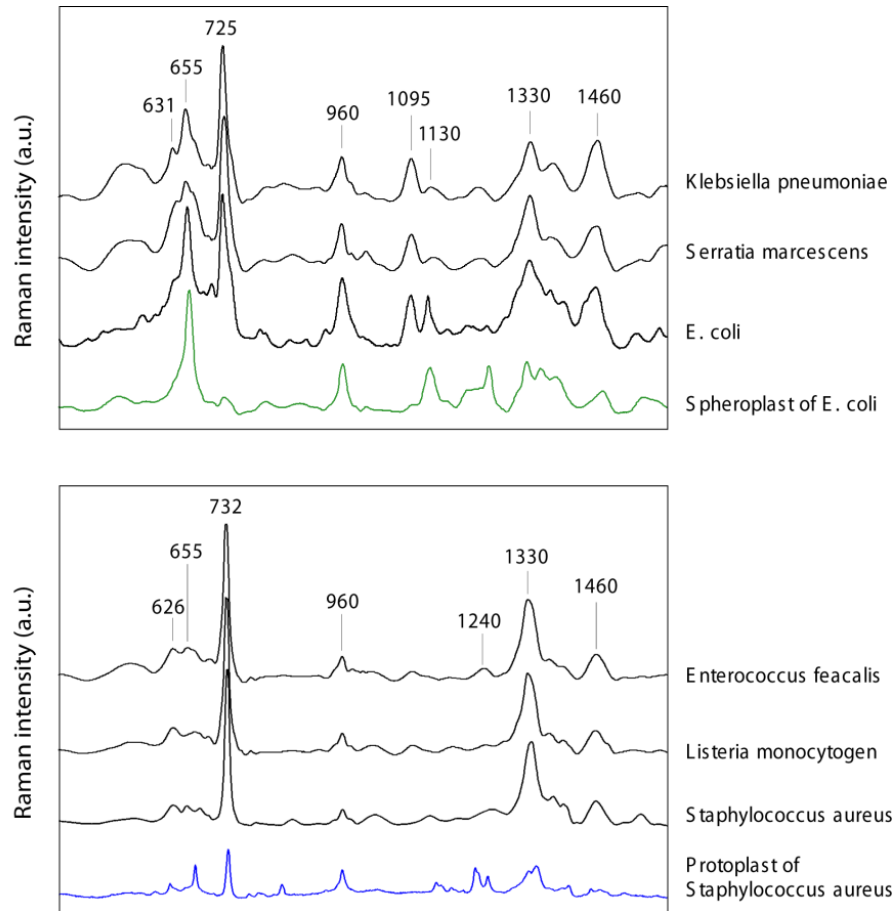


中央研究院  
原子分子科學研究所  
Institute of Atomic and Molecular Sciences  
Academia Sinica

Prof. Yuh-Lin Wang 王玉麟  
IAMS Academia Sinica, Taiwan

# SERS detection of bacterial cell wall

Dr. Juen-Kai Wang, CCMS, NTU



- Sensitive and stable SERS profiles based on our substrates readily reflect different bacterial cell walls found in Gram-positive, Gram-negative, and mycobacteria group.
- Characteristic changes in SERS profile are recognized in the *drug-sensitive* bacteria to antibiotic exposure, which could be used to differentiate them from the *drug-resistant* ones.

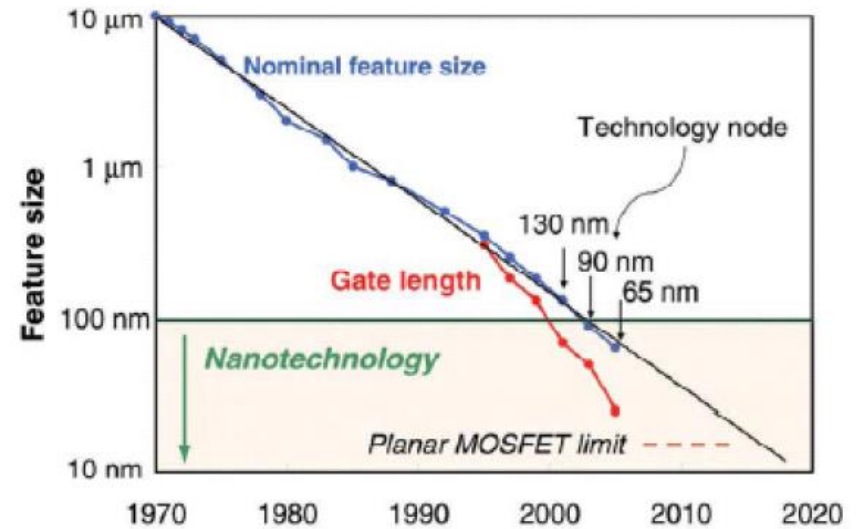
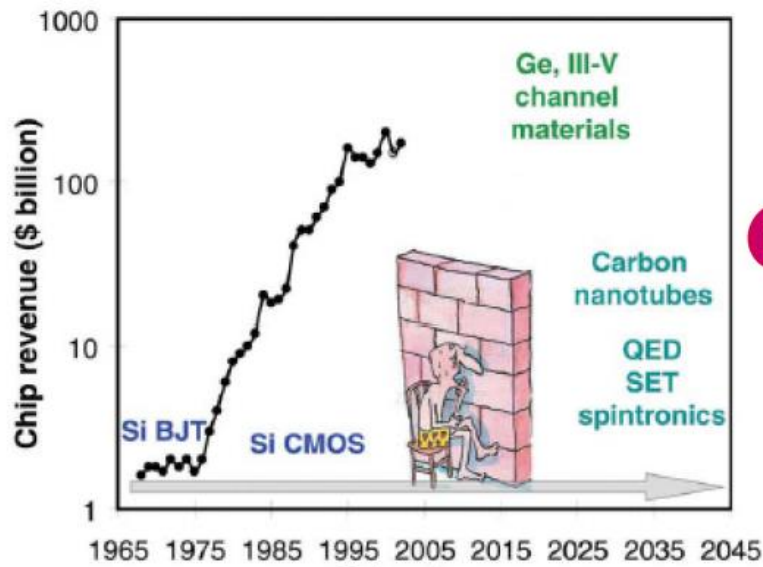
# The Advent of Carbon Era ?

The Physics of Graphene:

- Possibility of relativistic electronics and spintronics

# Background for search new platform

## Scaling limit of Si MOSFET & superparamagnetism



Carbon era?

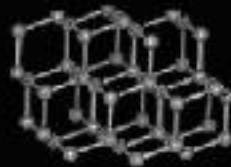
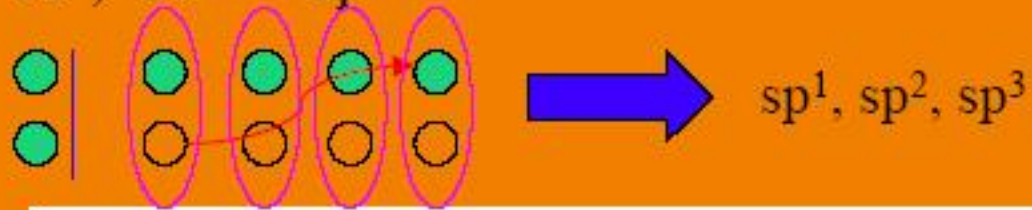
Thompson and Parthasarathy,  
Materialstoday 9, 20, 2006



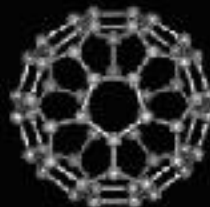
# Carbon Nanotube

+ Structure of carbon nanotubes

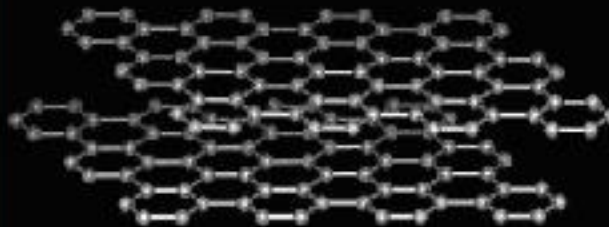
Carbon:  $1s^2, 2s^1, 2p^3$



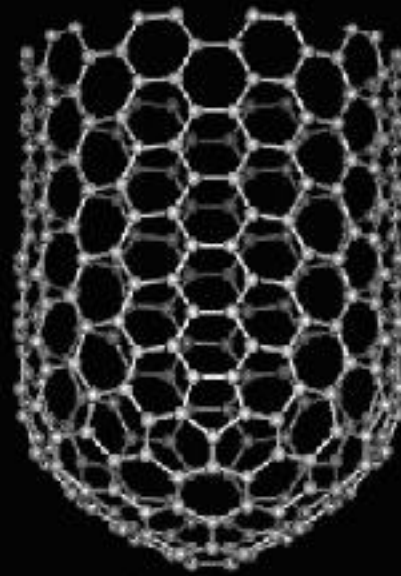
Diamond



C<sub>60</sub>  
Buckyball



Graphite



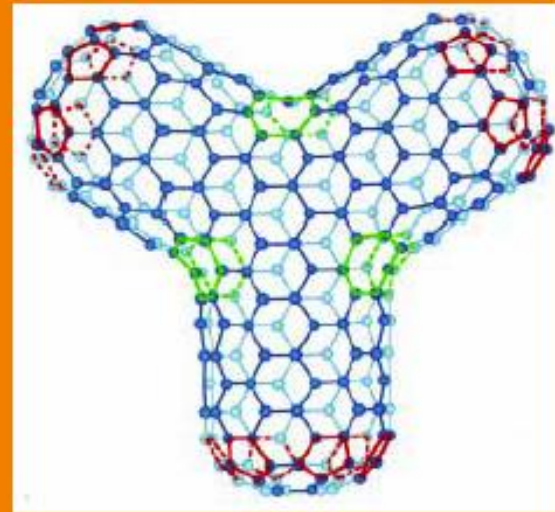
Nanotube

# Carbon Nanotube

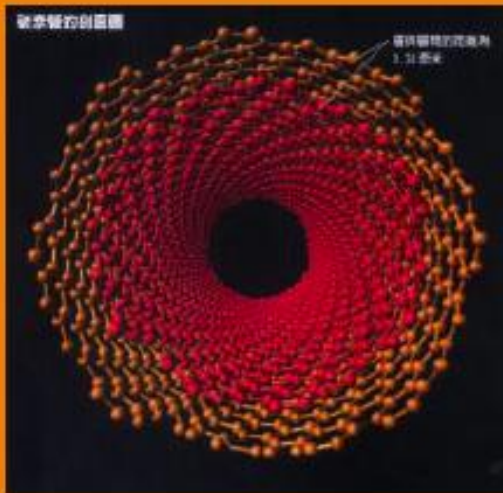


*Sumio Iijima*

Single-walled carbon nanotube, SWCNT



Multi-walled carbon nanotube, MWCNT



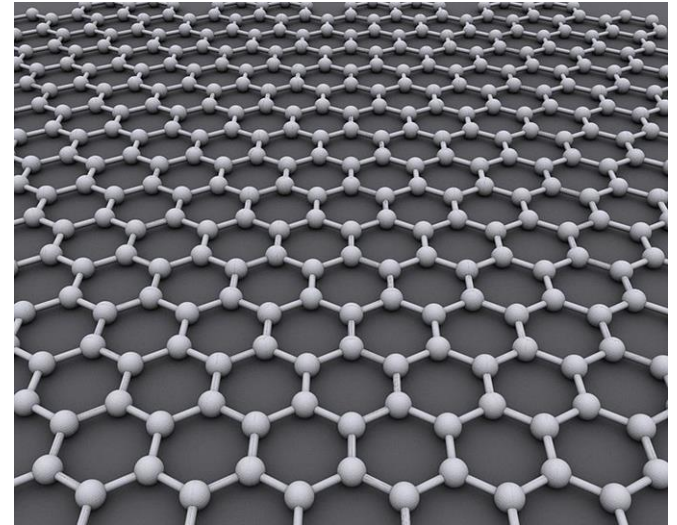
**Carbon Nanotube based Transistors / Electronics**

# Unexpected realization of graphene sheet

(



mechanically exfoliated graphene sheets



AFM image of single-layer graphene on  $\text{SiO}_2$   
K.S. Novoselove et al., Science 306, 666 (2004)

# Twisted (bilayer) Graphene

- ❑  $\theta = 1.1^\circ$
- ❑ Superconductivity
- ❑ Magnetism

Twistronics ?

# Papers to read

- “Observation of a Magnetic Antiphase Domain Structure with Long-Range Order in a Synthetic Gd-Y Superlattice”, C. F. Majkrzak, J. W. Cable, J. Kwo, M. Hong, D. B. McWhan, Y. Yafet, J. V. Waszczak, and C. Vettier, *Phys. Rev. Lett.* **56**, 2700, (1986).
- M. N. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, *Phys. Rev. Lett.*, **61**, 2472 (1988).
- “High k gate dielectrics  $\text{Gd}_2\text{O}_3$  and  $\text{Y}_2\text{O}_3$  for Si”, J. Kwo\*, M. Hong, A.R. Kortan, K. T. Queeney, Y. J. Chabal, J. P. Mannaerts, T. Boone, J. J. Krajewski, A. M. Sergent, and J. M. Rosamilia, *Appl. Phys. Lett.*, **77**, 130, (2000).
- “Epitaxial Cubic  $\text{Gd}_2\text{O}_3$  as a Dielectric for GaAs Passivation”, M. Hong, J. Kwo, A. R. Kortan, J. P. Mannaerts, and A. M. Sergent, *Science*, **283**, 1897, (1999).
- “Observation of the Spin Hall Effect in Semiconductors”, Y. K. Kato, R. C. Myers, A. C. Gossard, D. D. Awschalom\*, *Science* **306**, 1910 (2004).
- “Tunnel field-effect transistors as energy-efficient electronic switches”, A. M. Ionescu, and H. Riel, *Nature*, **479**, 329 (2011).