Introduction to Nanophysics

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What is the size for a “nano” ?

One (nm) equals to 1/1000000000 (10^{-9}) meter

10^{-3} m , **Macro**

10^{-6} m , **Micro**

10^{-9} m , **Meso**

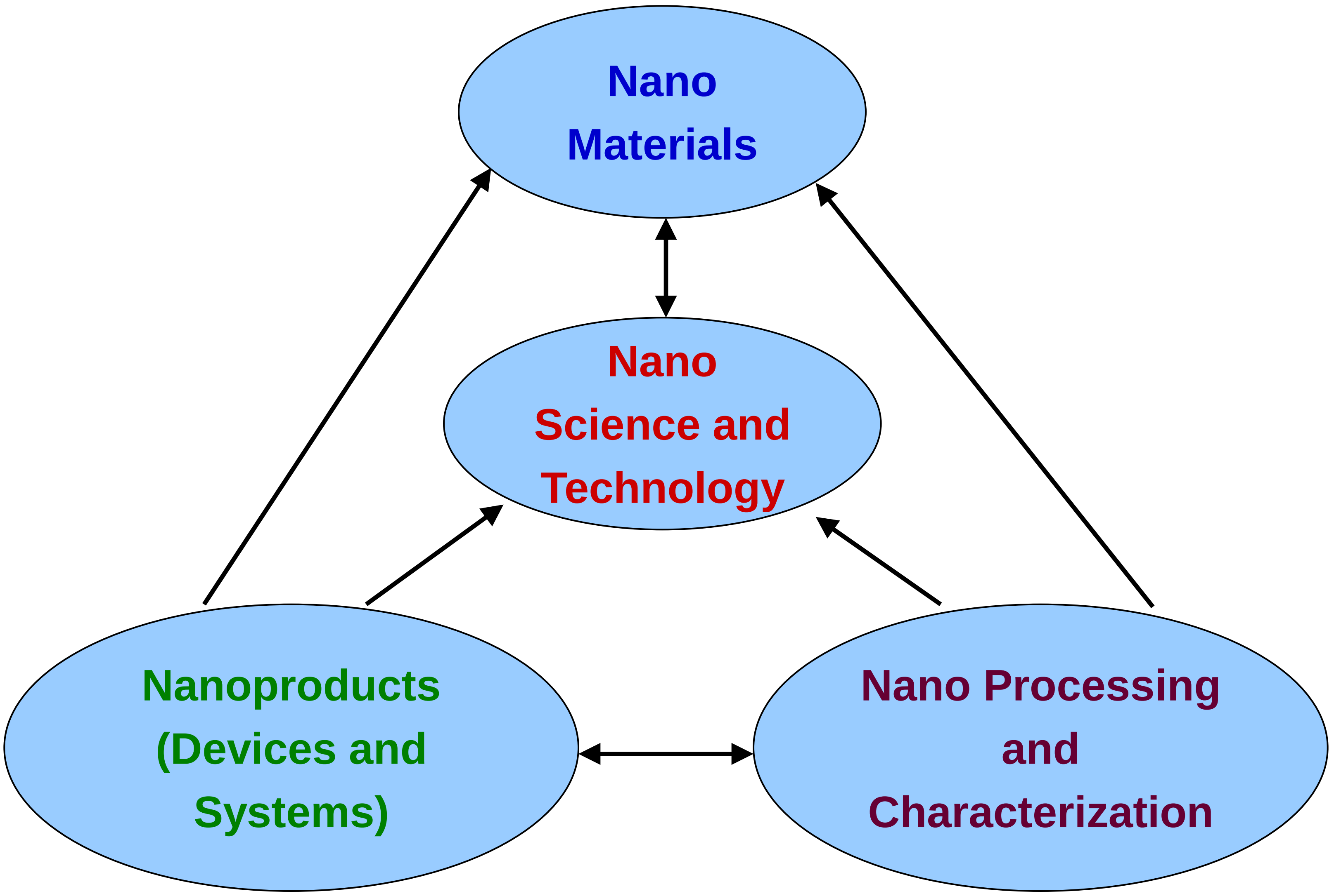
R. Feymann Already Knew about this !

" 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 Koda.
- 1908, Gustay 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 with 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?

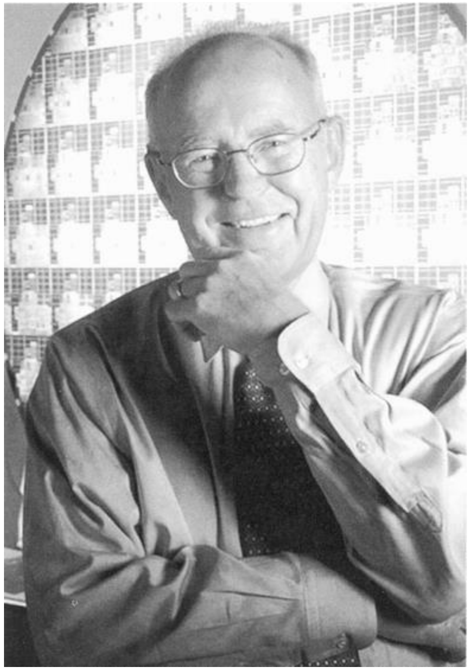
- **Science and Technology Down scaling to size under 100 nm:**

  Via "Top-down" lithographic pattering:
  -- Moore's law !

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

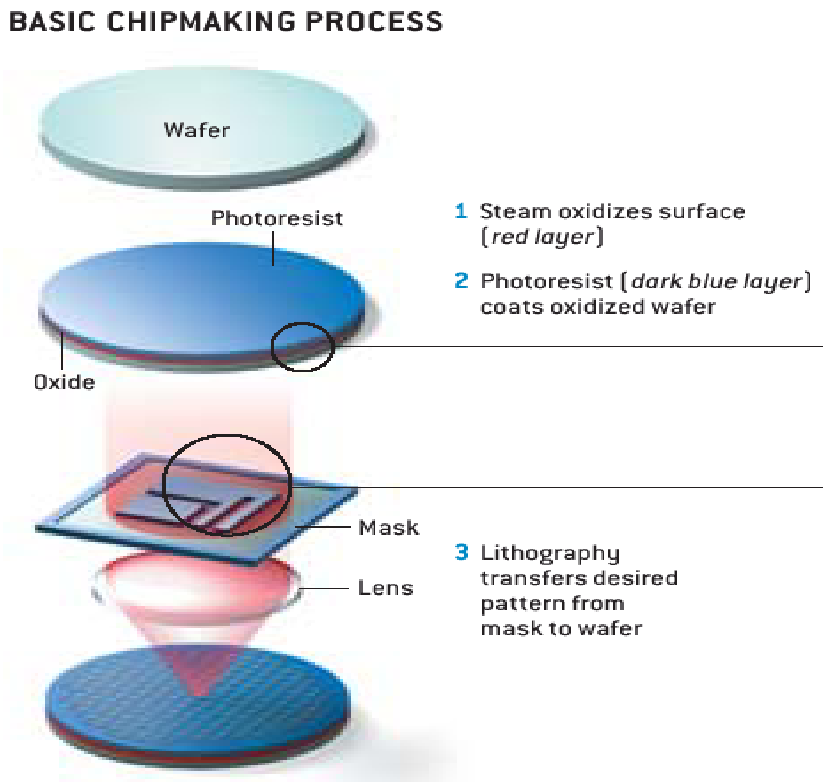
  "Bottom-up" nano materials, growth and assembly.
  Feymann: There's plenty of room at the bottom

Major Driving Force pushing for Nano Technology: Due to the bottle neck in Microelectronics



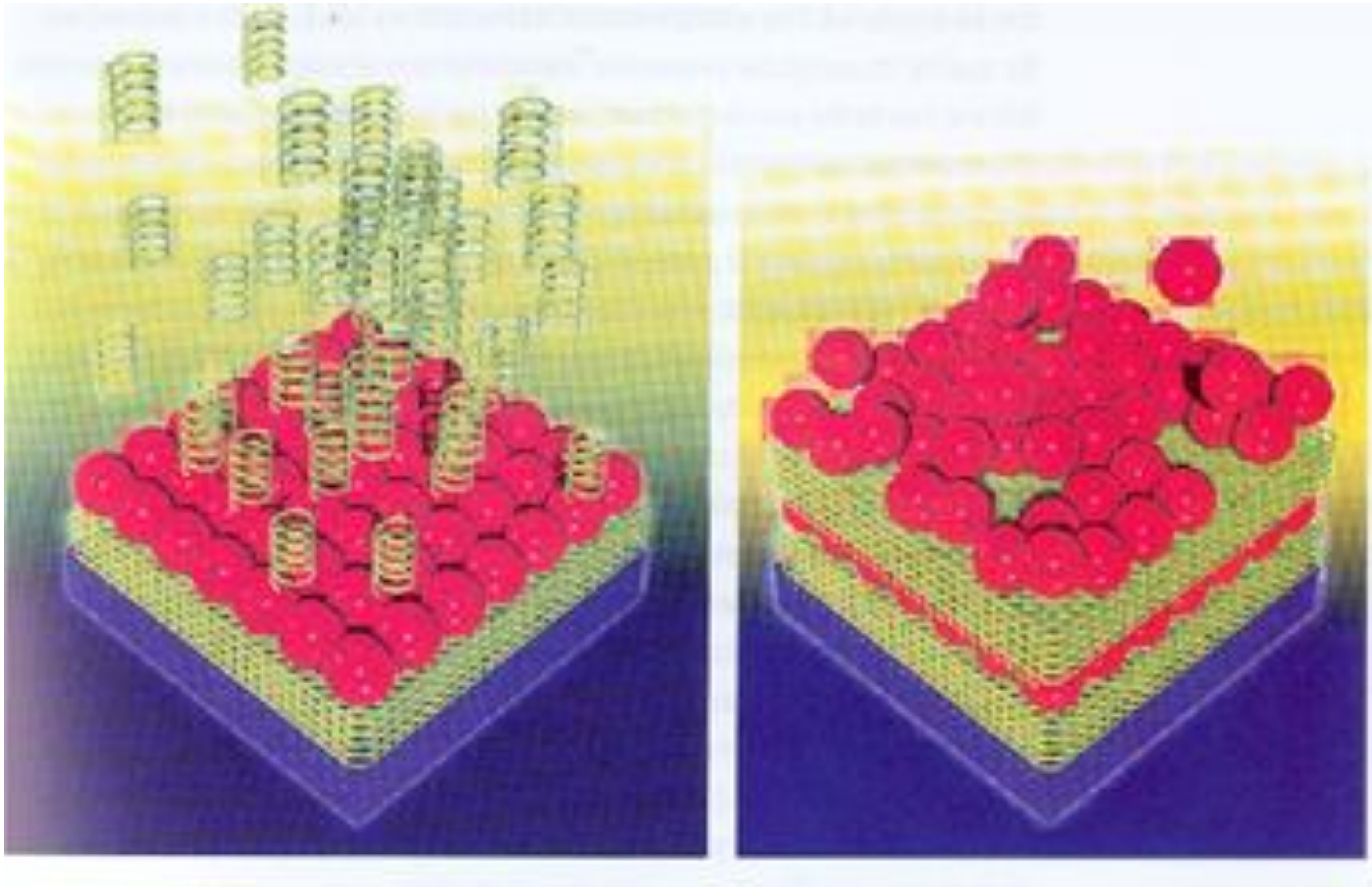
Moore's Law :

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



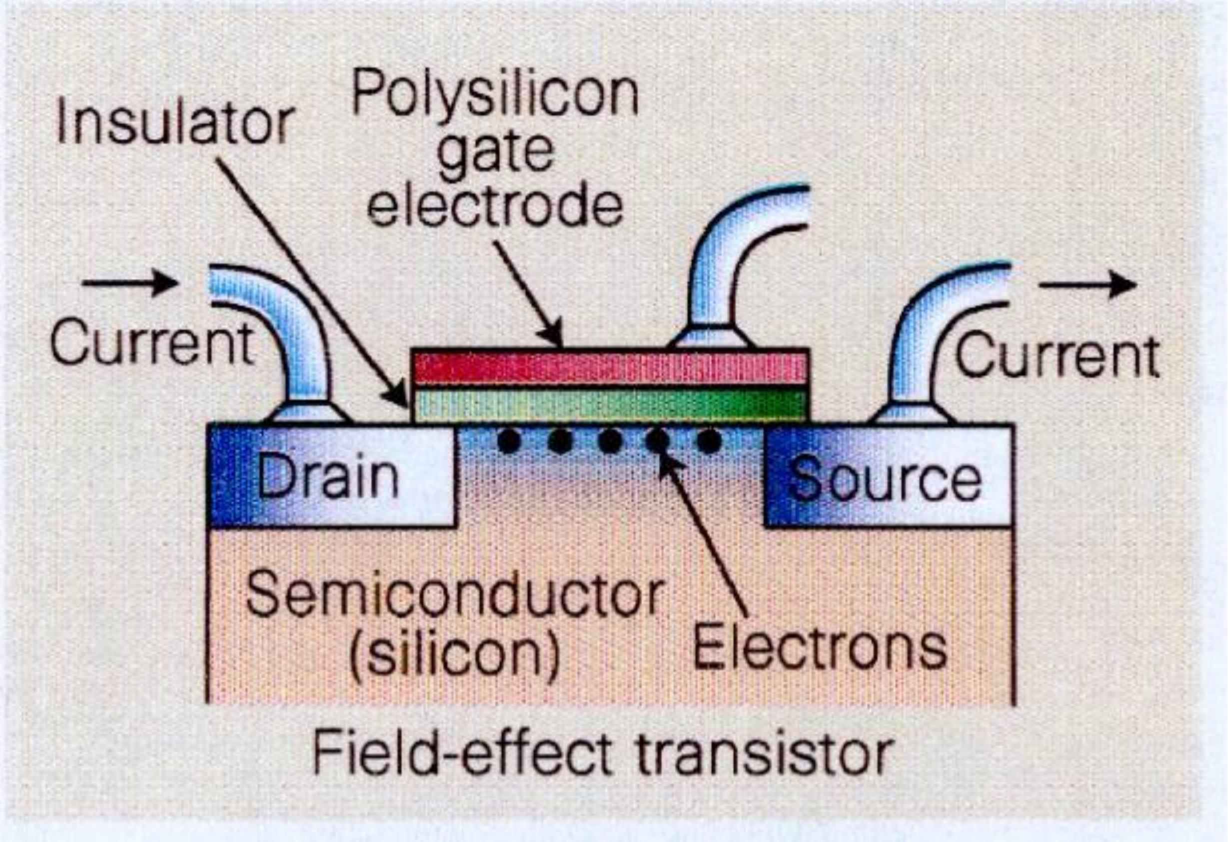
Bottom-up Nano systems & Self-Assembly

enabling of designing large molecules and nano materials



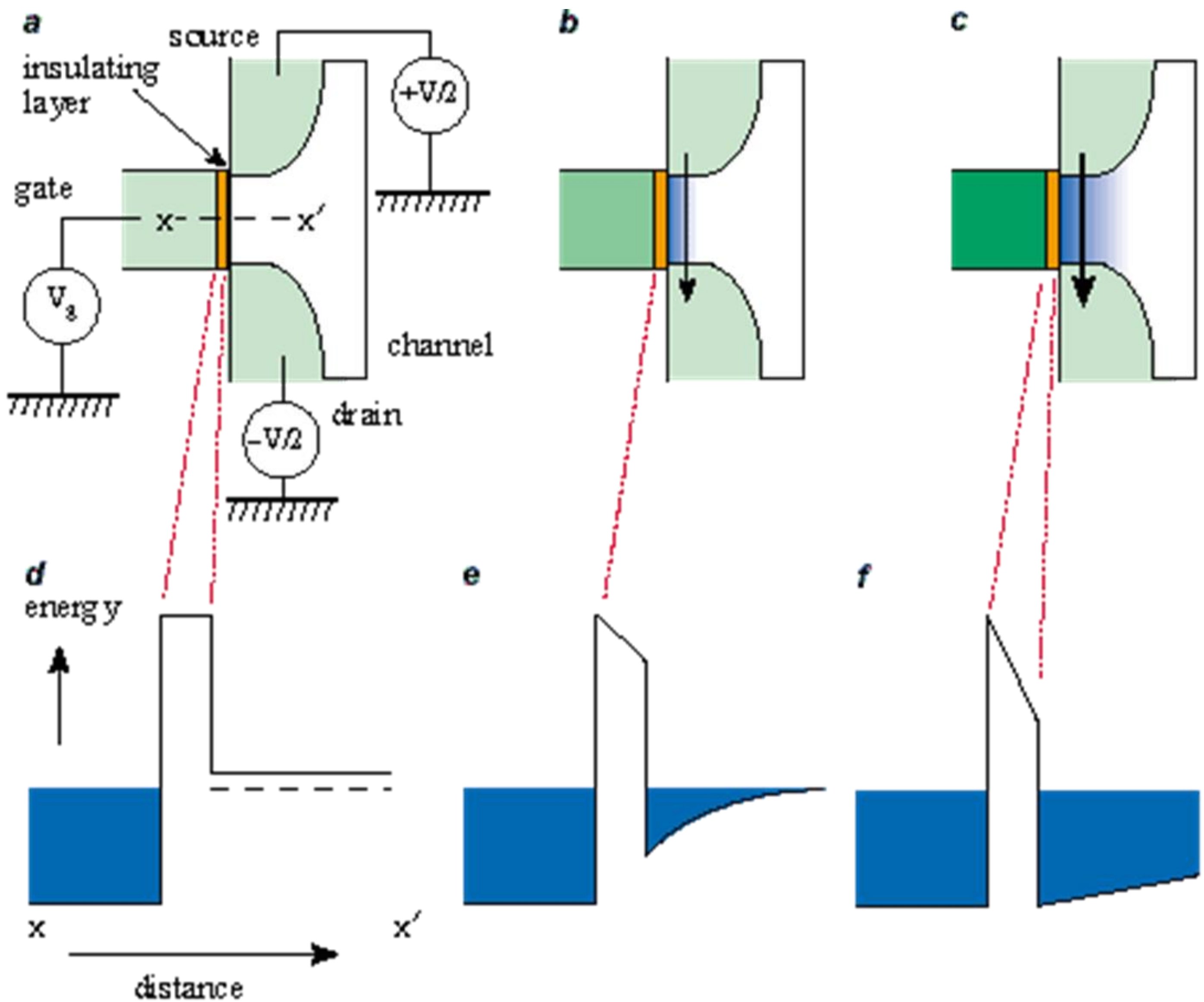
Two basic modern electronic technologies in Condensed Matter Physics Field

Metal-Oxide-Field Effect Transistor

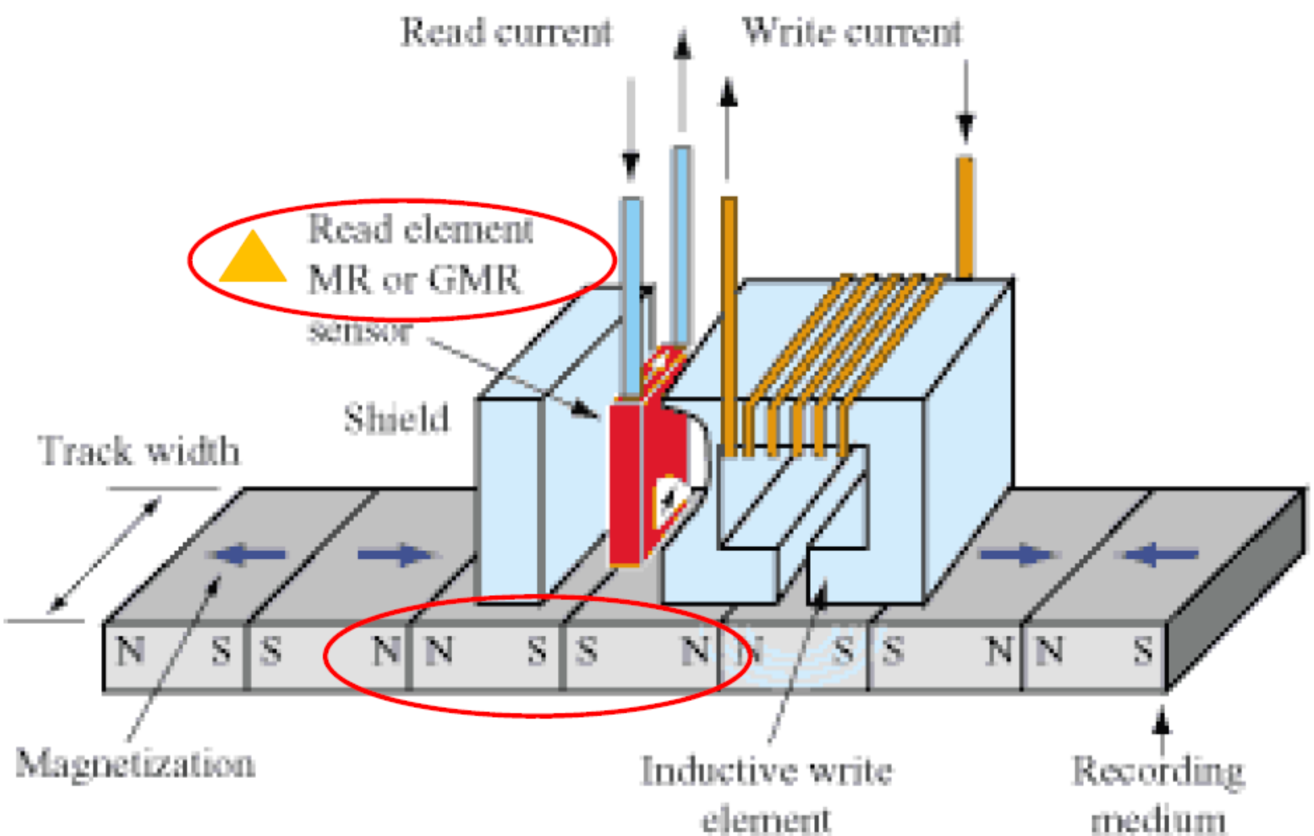


1960 Kahng and Atalla,   First MOSFET
1970 First IC, 1 kbit, 750 khz microprocessor

電子科技之基礎--MOSFET
(metal-oxide-semiconductor field-effect transistor)



電子科技之基礎--磁記錄



Read current
Write current
Read element
MR or GMR
sensor
Shield
Track width
N S S N N S S N N S S N N S
Magnetization
Inductive write
element
Recording
medium

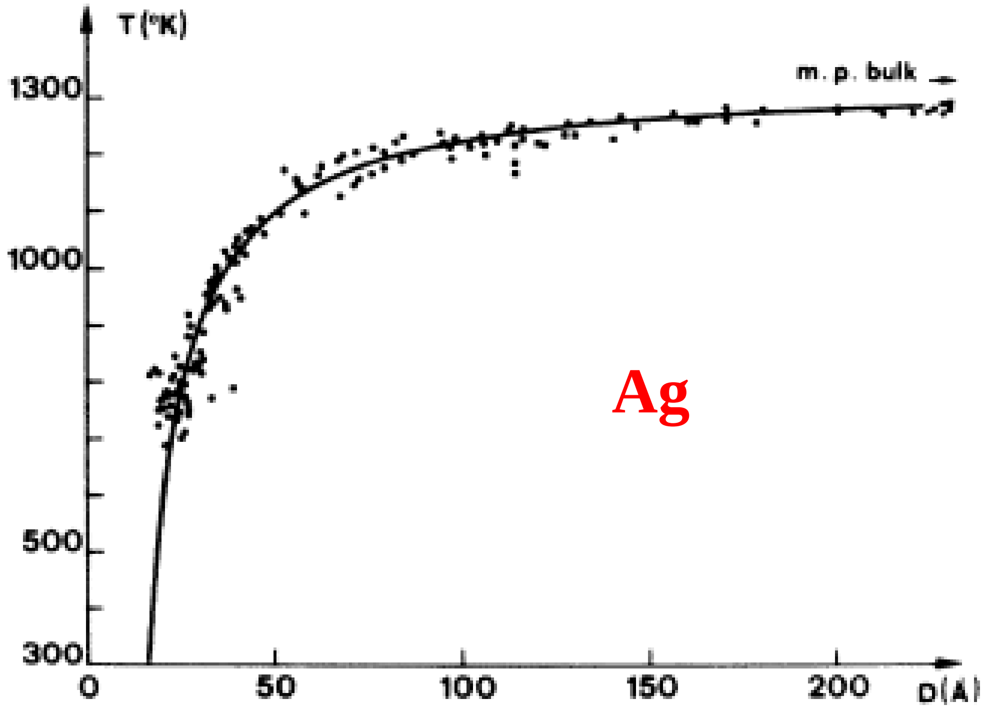
Five major lessons

that we have learned

The First Lesson :

Bulk-to-nano Transition

Ex: size-dependence of melting temperature



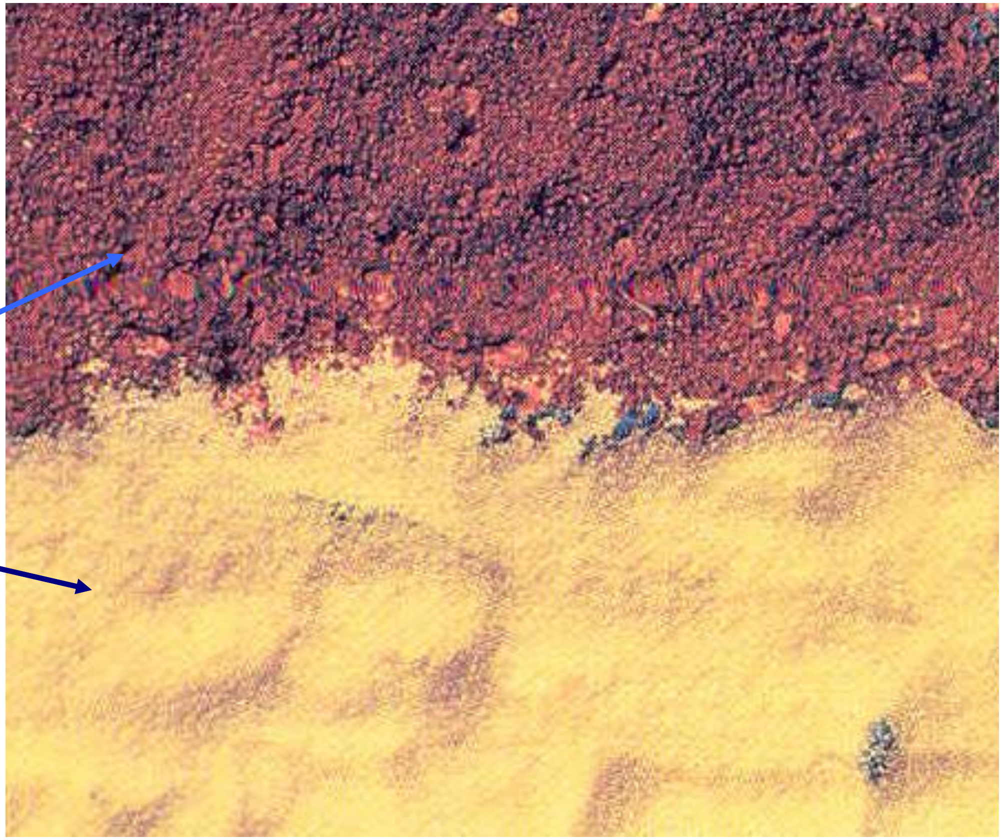
Ph. Buffat and J-P. Borel, Phys. Rev. A13, 2287 (1976)

Ex: size-dependence of color

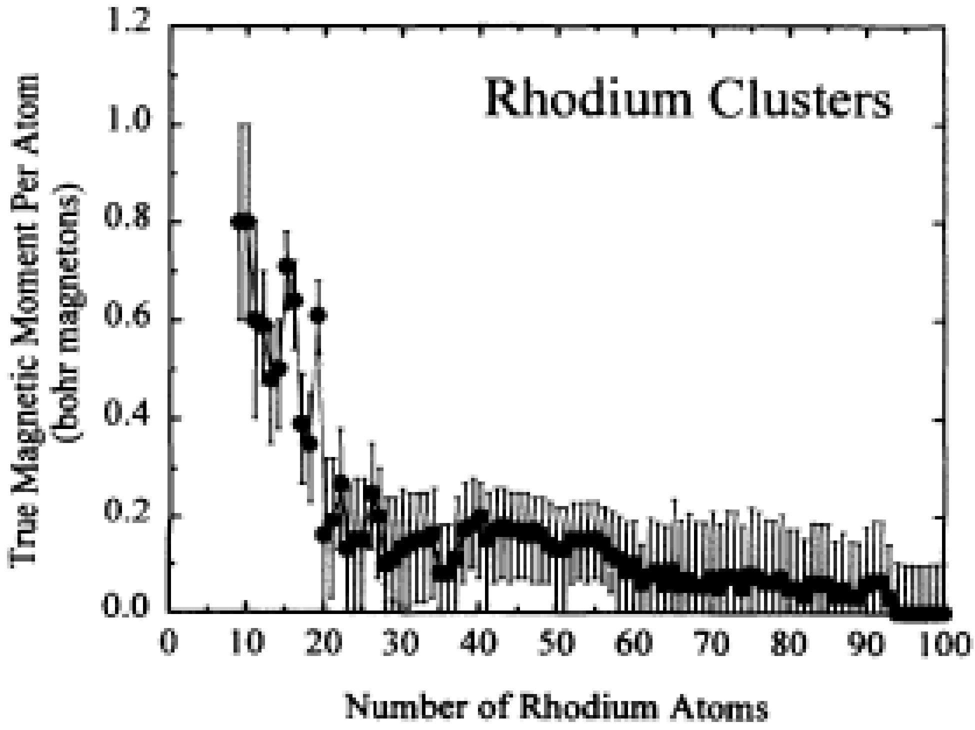
powered cadmium selenide

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:

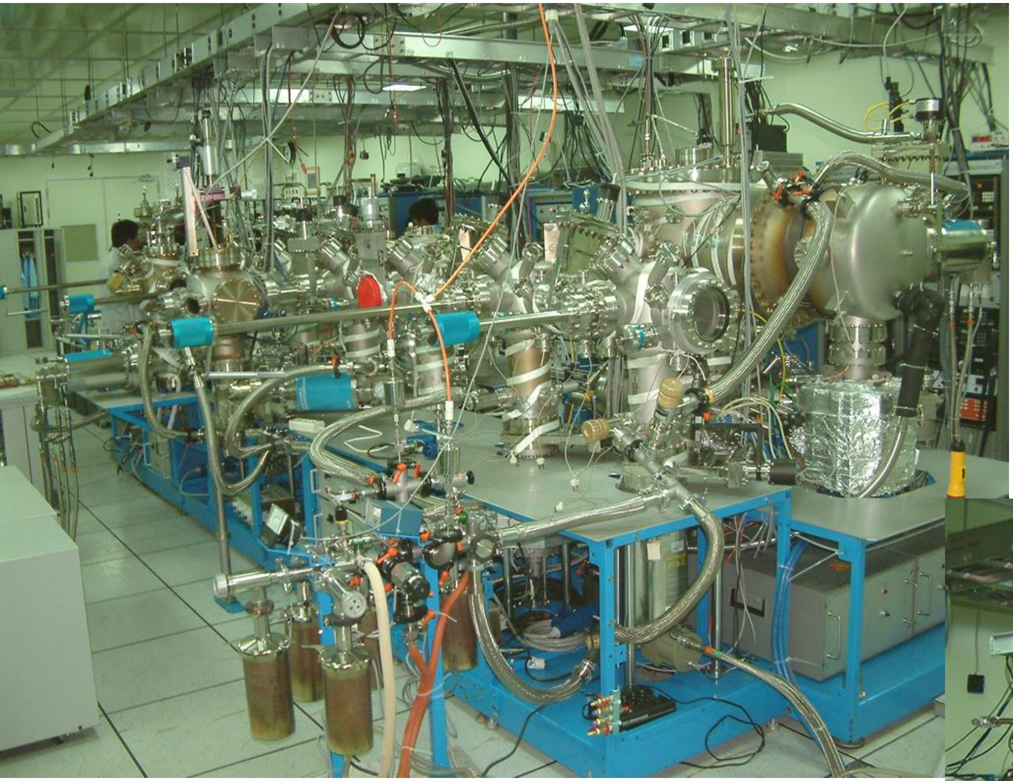
Such as Molecular Beam Epitaxy, atomic layer depostion, laser MBE, etc…

- For nano electronics in metals, oxides, and semiconductors

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

- In 1982, Binning, and Rohrer in IBM invented scanning tunneling microscope (STM).
- In 1986, Binning, Quate, and Gerber invented the atomic force microscope (AFM).

Integrated MBE Multi-chamber System



Now located in the Nano Technology Center, ITRI, Hsin Chu, Taiwan

For Metal, Oxide and Semiconductor Films On the Nano scale

Scanning Tunneling Microscope (STM)

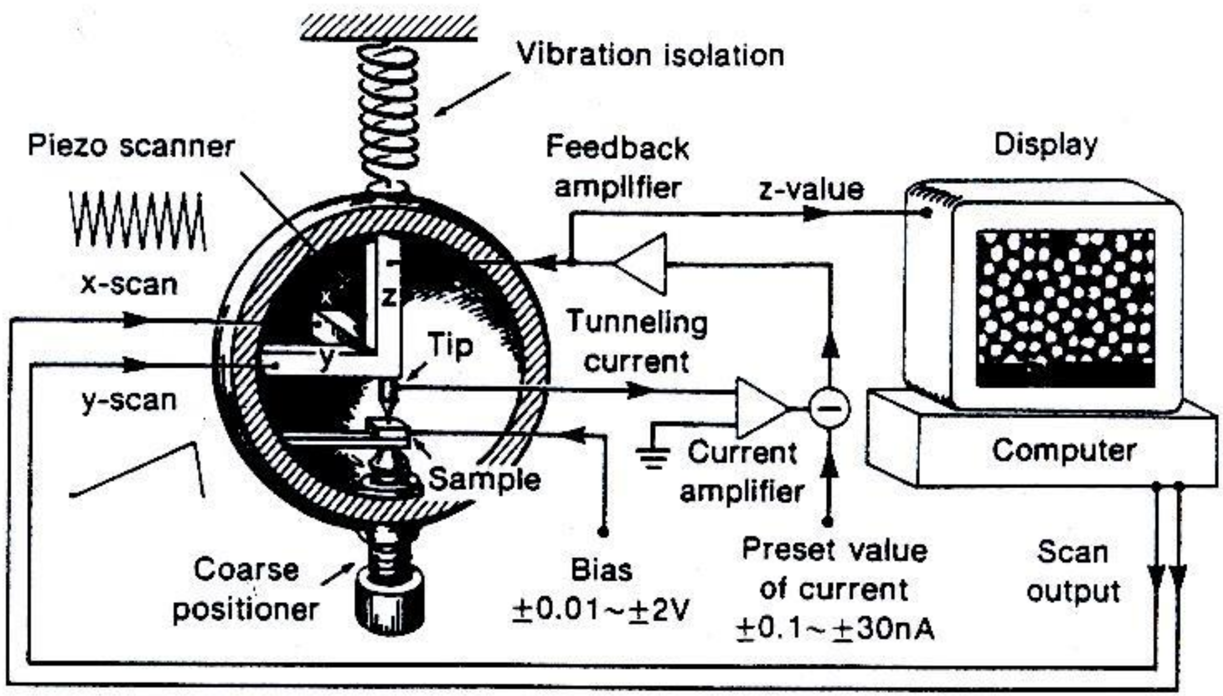
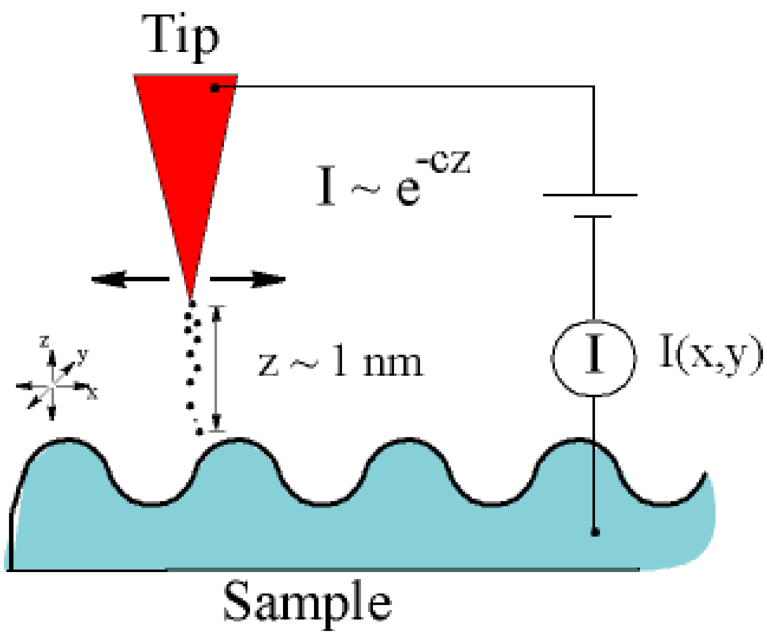
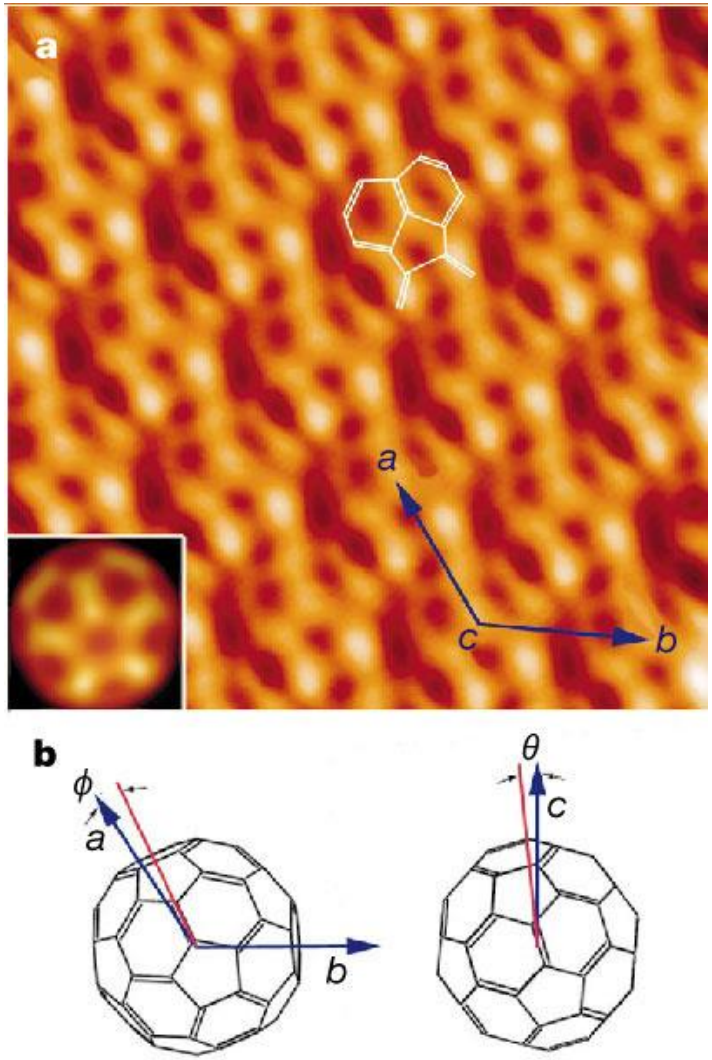


Figure 1.10 Scanning tunneling microscope. (From C. Julian Chen, *Introduction to Scanning Tunneling Microscopy*, Oxford: Oxford University Press, 1993.)

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

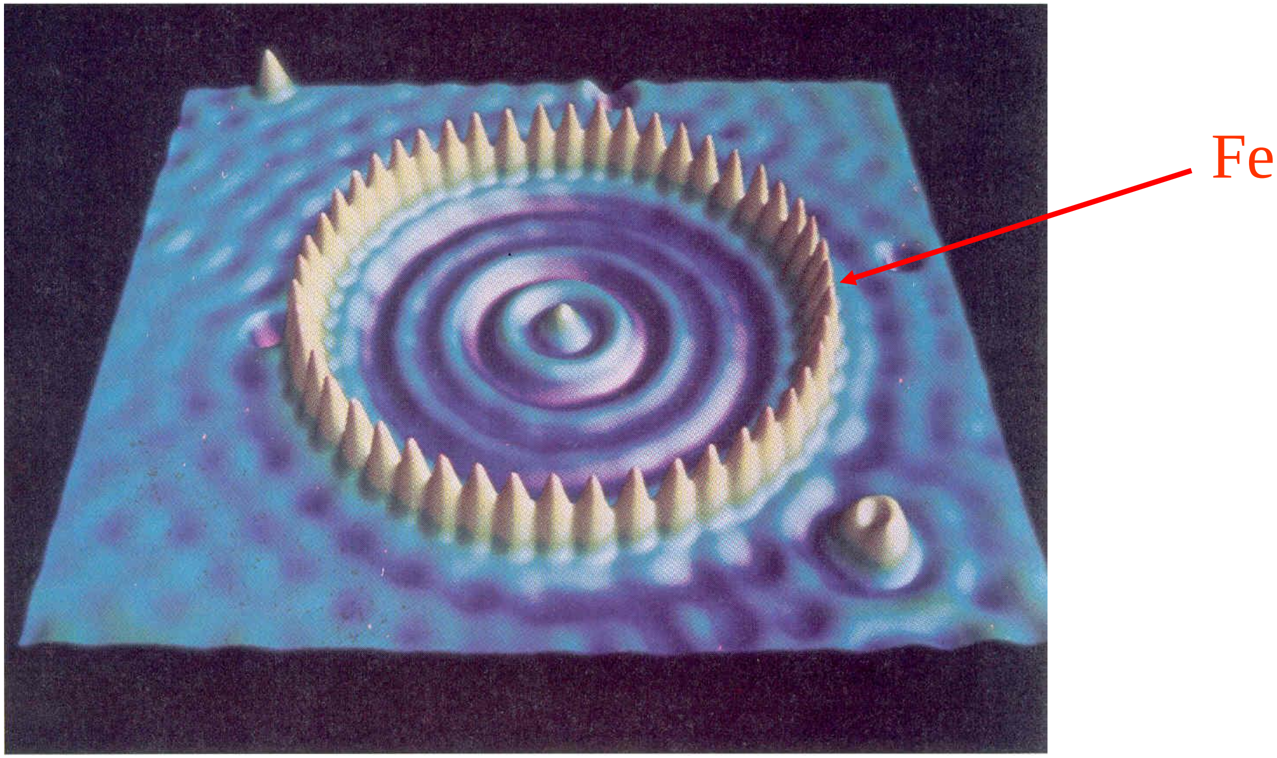


Nature 409, 304 (2001)



Quantum Corral

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



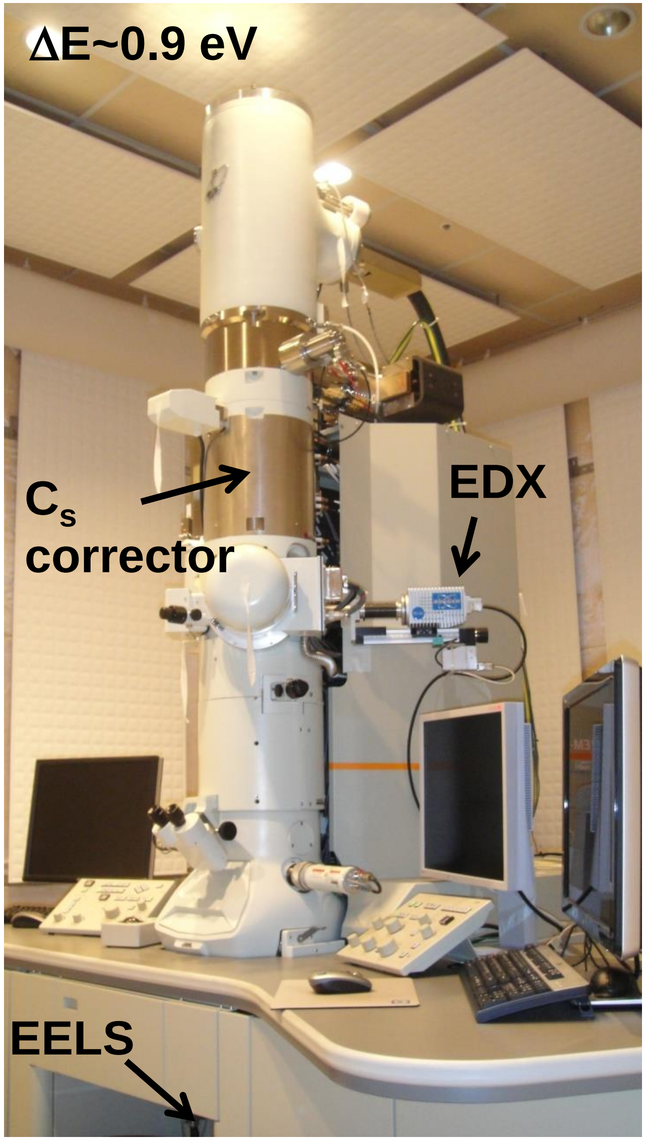
This STM image shows the direct observation of standing-wave patterns in the local density of states of the Cu(111) surface. These spatial oscillations are quantum mechanical interference patterns caused by scattering of the 2D electron gas off the Fe adatoms and point defects.

Crommue, Luts, and Eigler, Science 262, 218-220, 1993

Scanning Transmission Electron Microscope Laboratory

2-Å STEM

1-Å STEM

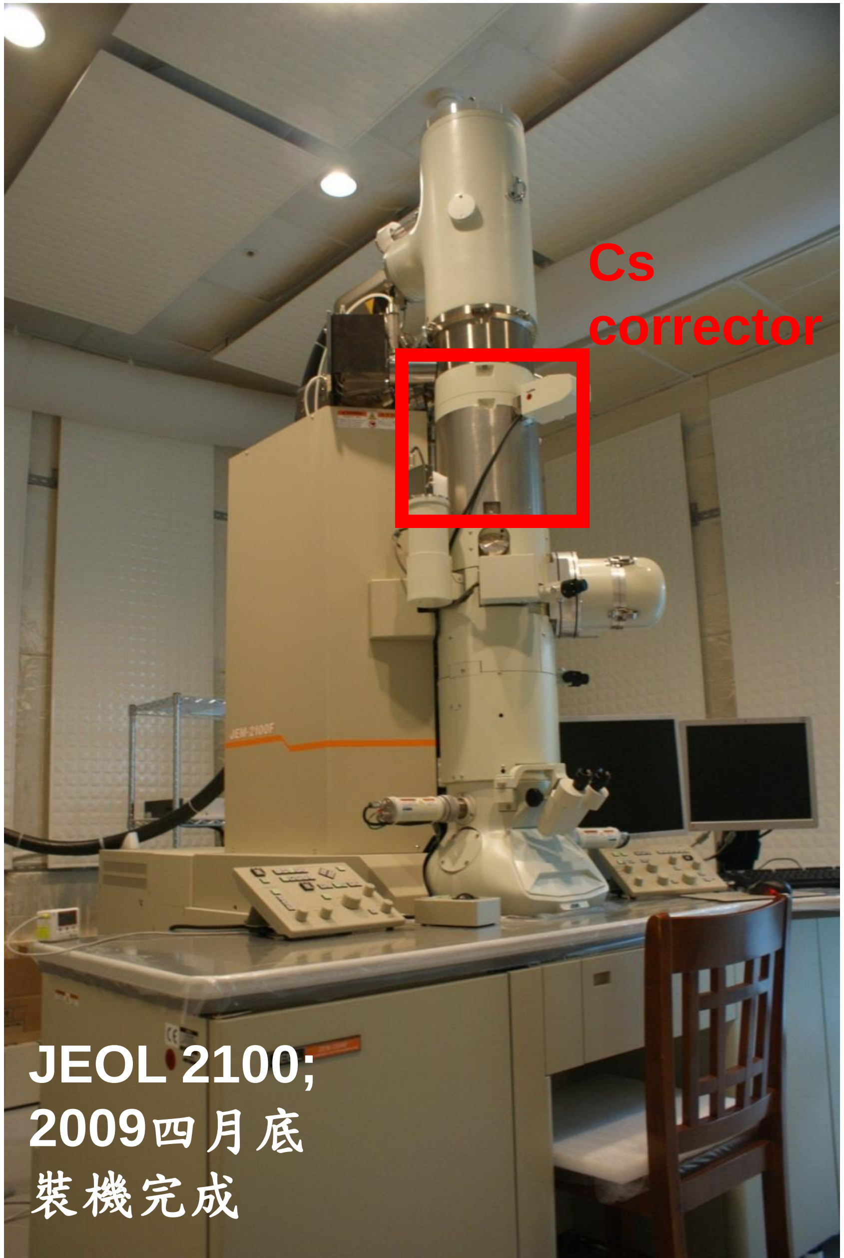


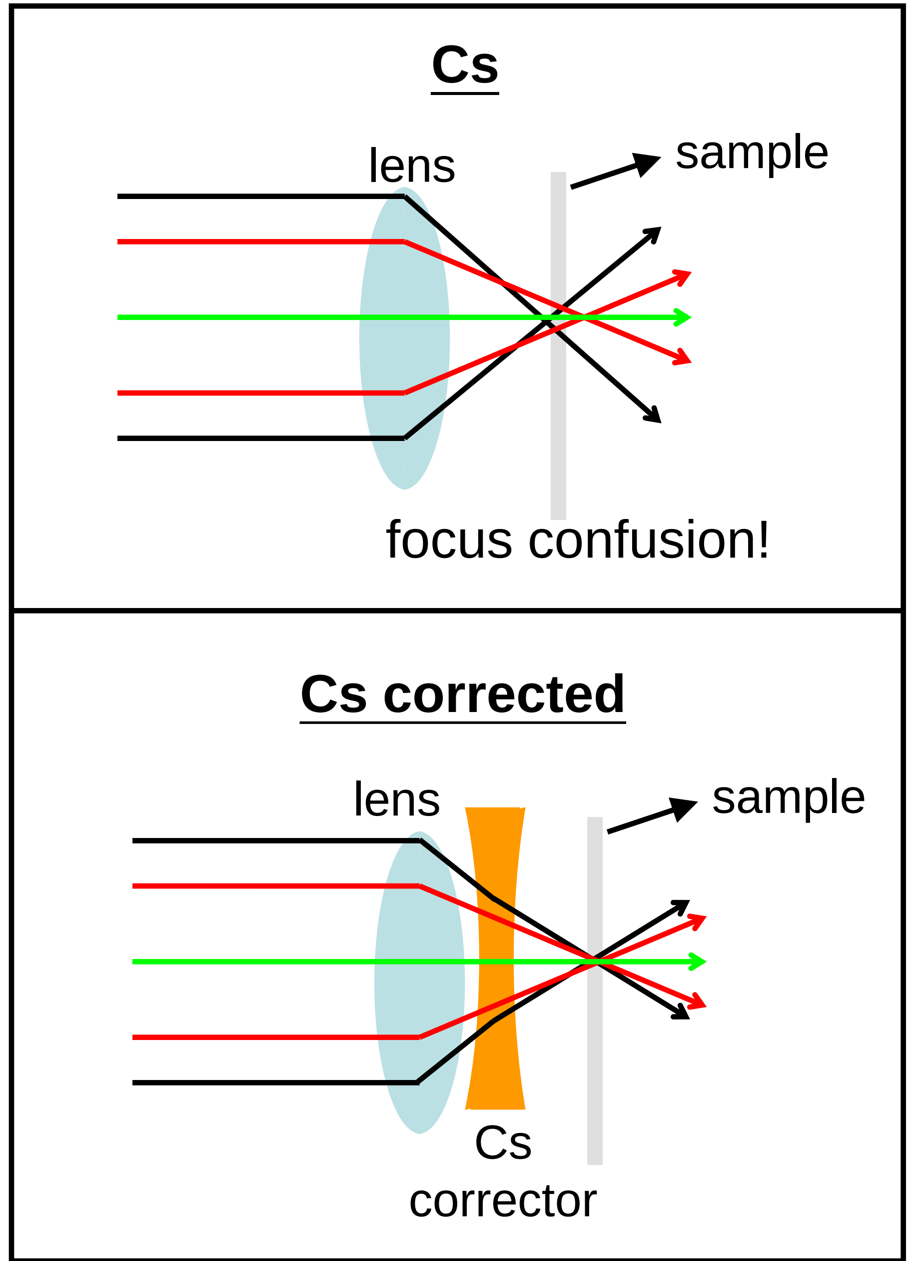
Prof. C. H. Chen and

Dr. M.-W. Chu

In CCMS/NTU.

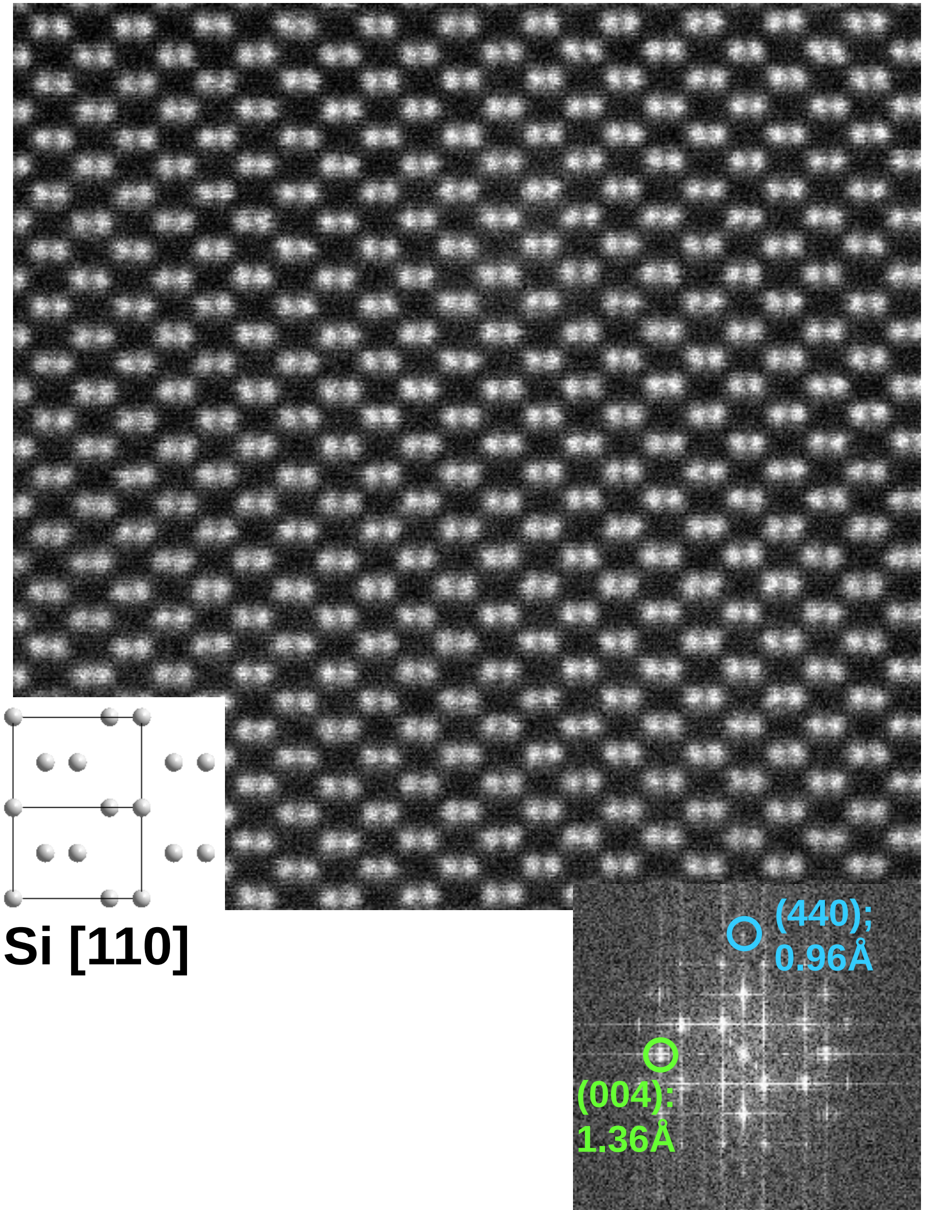
Spherical Aberration Corrected (球面相差)
Cs-STEM by C. H. Chen at CCMS, NTU



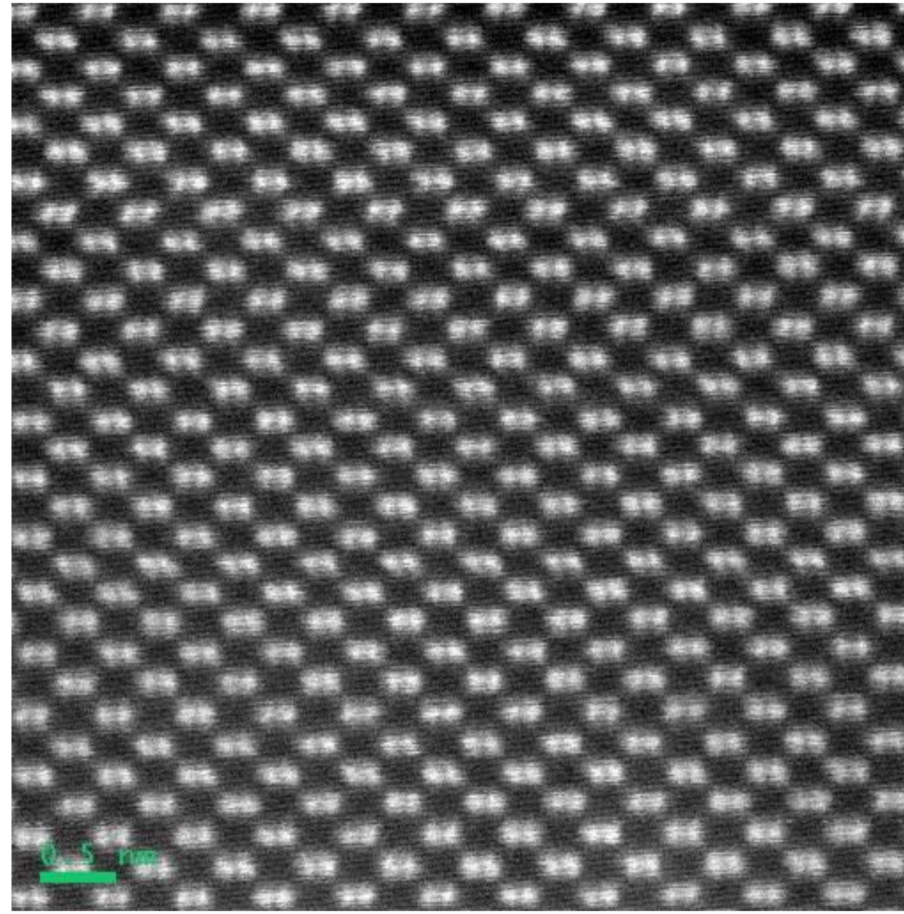


High-Angle ADF: Si dumbbell, 1.36 Å spacing

15s exposure

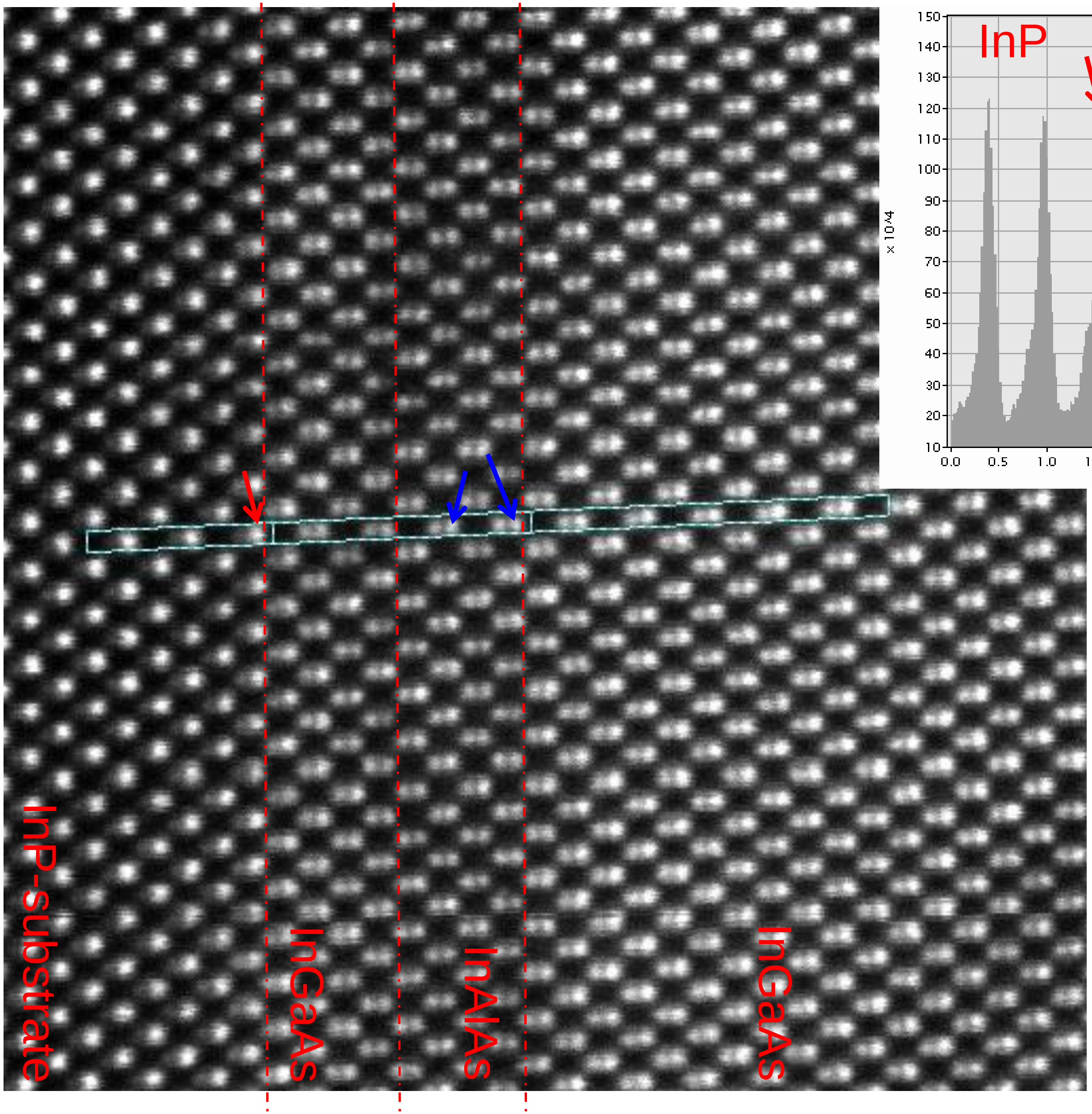


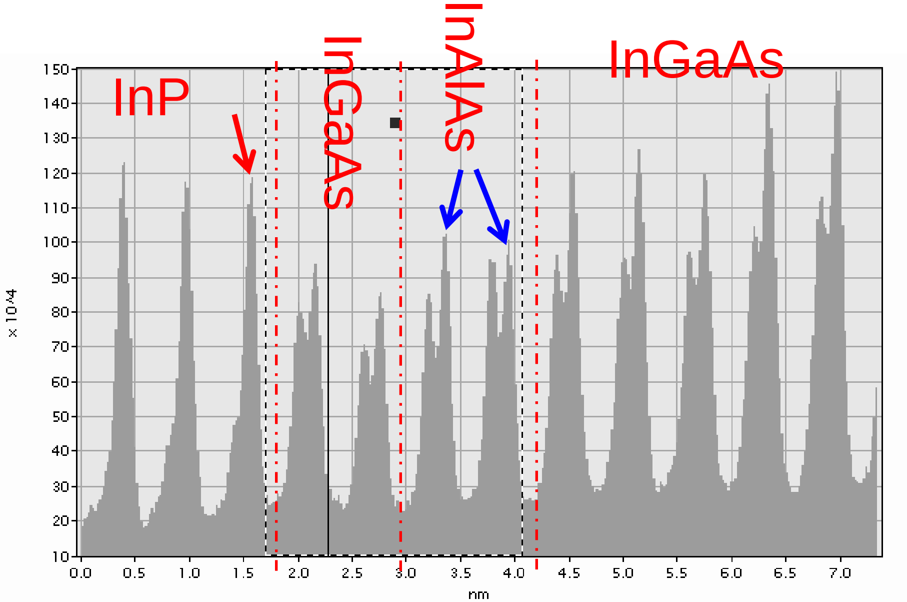
60s exposure



Drift ~1Å/min !!

InGaAs/InAlAs superlattices on InP Substrate

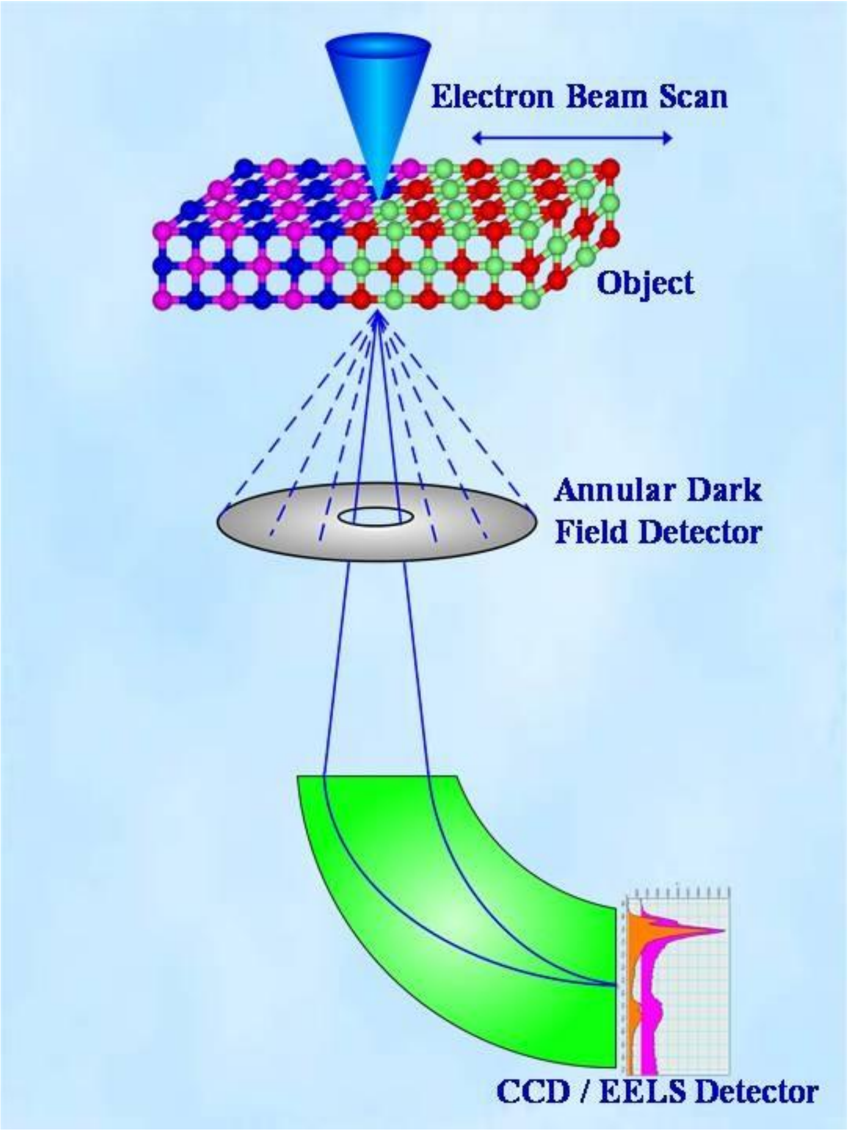


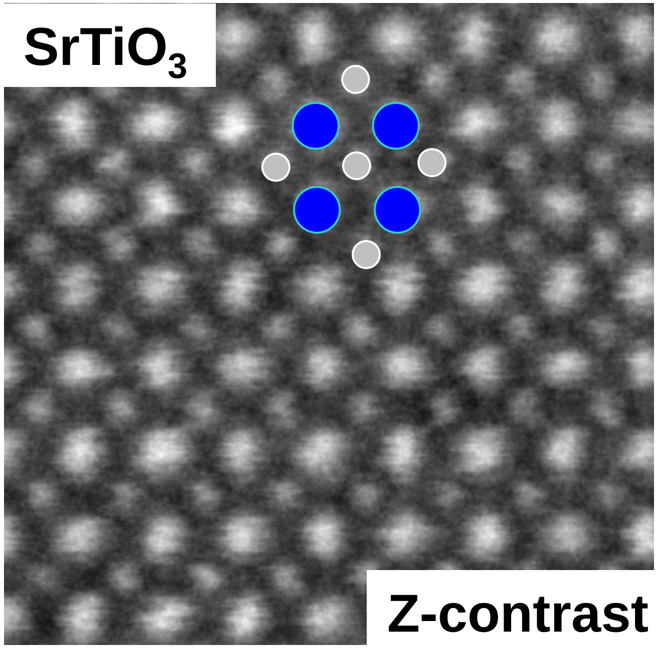


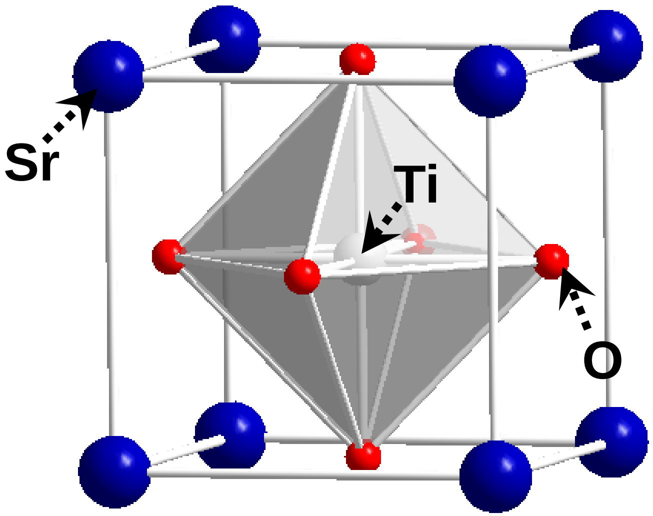
- Determining the interface location and sharpness is easy.
- The In-distribution seems to be inhomogeneous in the InAlAs layer (blue arrows).
- Note that InP substrate is In-terminated (red arrow).

Atomic Resolution STEM Imaging: Z-contrast

2-Å Electron Probe

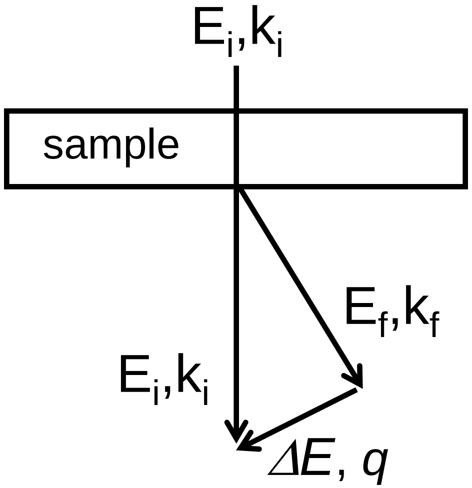






cubic; *a* = 3.905 Å

Electronic Exc.: Electron Energy-Loss Spectroscopy (EELS)



$$\Delta E = E_i - E_f$$

$$q = k_i - k_f$$

Coulomb Interaction

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

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

, where ρ_q the electron density operator

Inelastic Scattering (ΔE) Probability

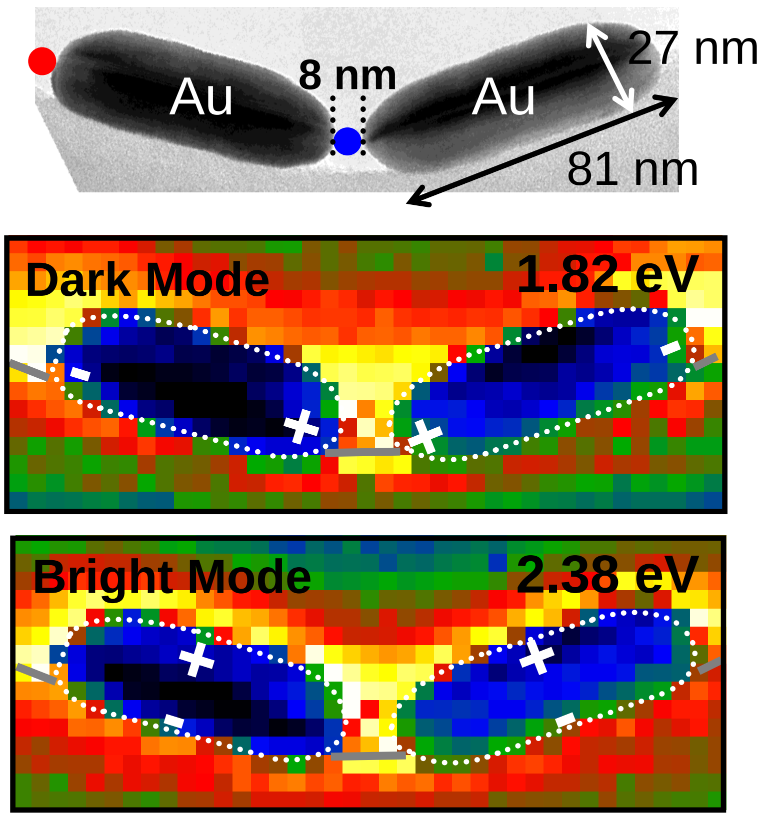
$$\frac{d^2\sigma}{d\Omega d\Delta E} \sim \sum_f \left| \langle \psi_f \left| v(q) \right| \psi_i \rangle \right|^2 \delta(E_i - E_f - \Delta E)$$

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

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

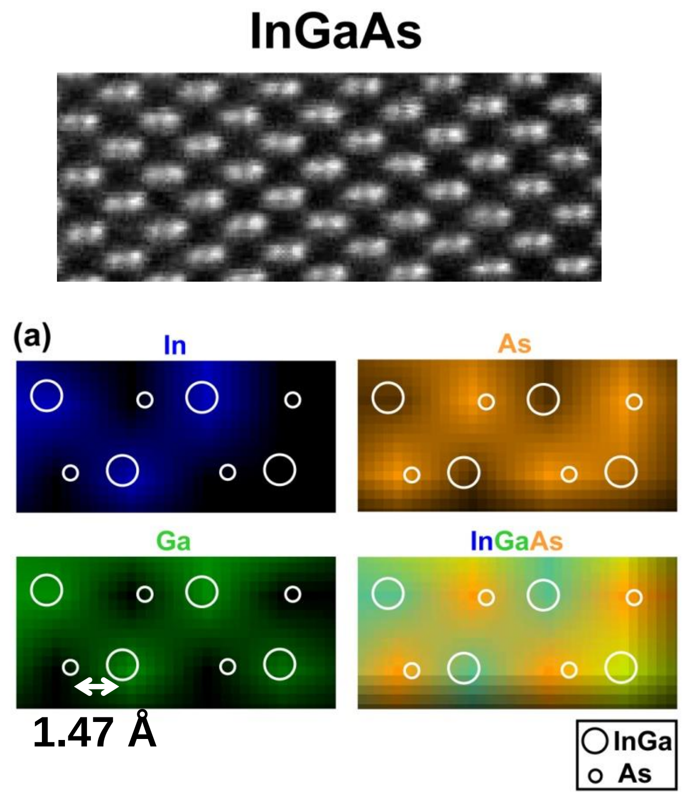
Spectral Imaging at Ultimate Spatial Resolution

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 purturbation

- Different scaling for different physical entity

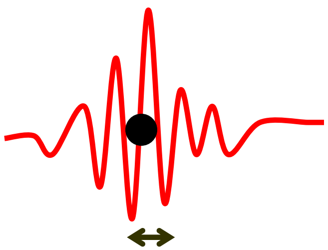
Quantum Effect:

=> Most likely to have new breakthough !

The connection of materials wave with mechanics

h = Planck constant (6.626×10^{-34} joule-sec)

DeBroglie:
$\lambda = h/p$



λ

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

Wave length

Free electrons $\lambda_{th}(300K) = 6.2nm$

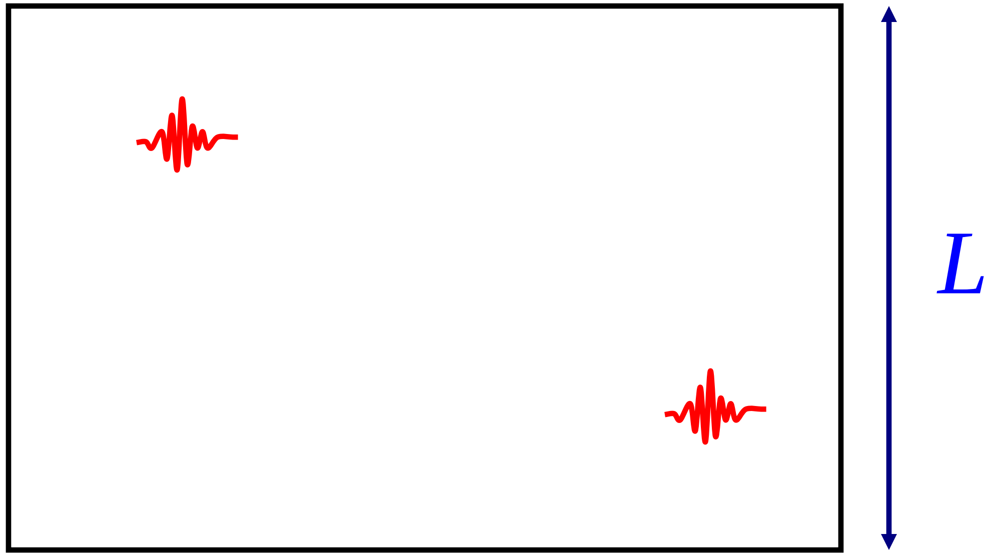
Semiconductors $10nm \le \lambda \le 100nm)$

Atoms $(300K) \le 0.2nm$

Bulk Limit ⇔ Nano Limit

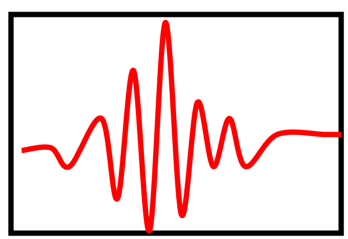
Bulk materials

$\lambda << L$



Nano

$\lambda \sim L$

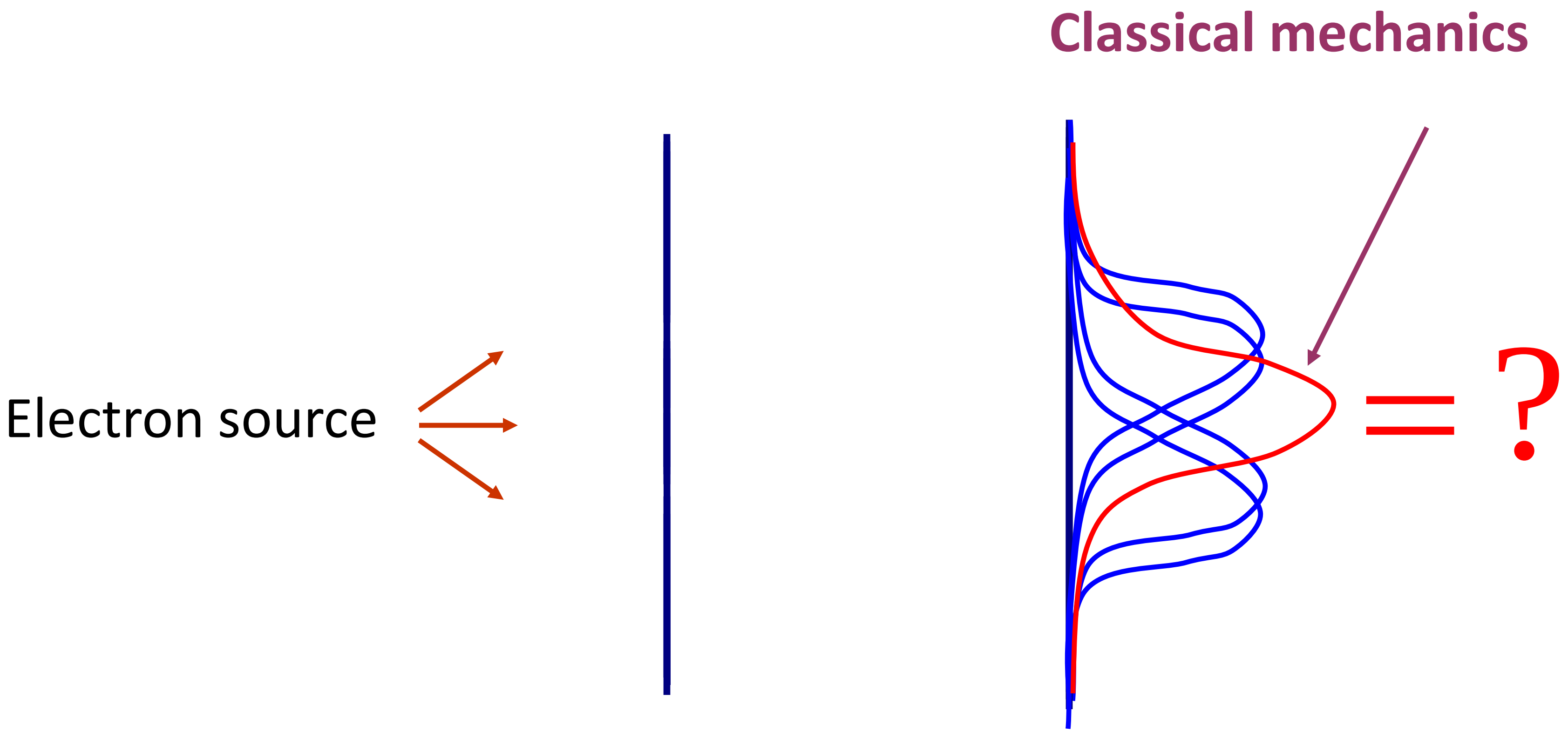


Major Qauntum Effect at the nano scale

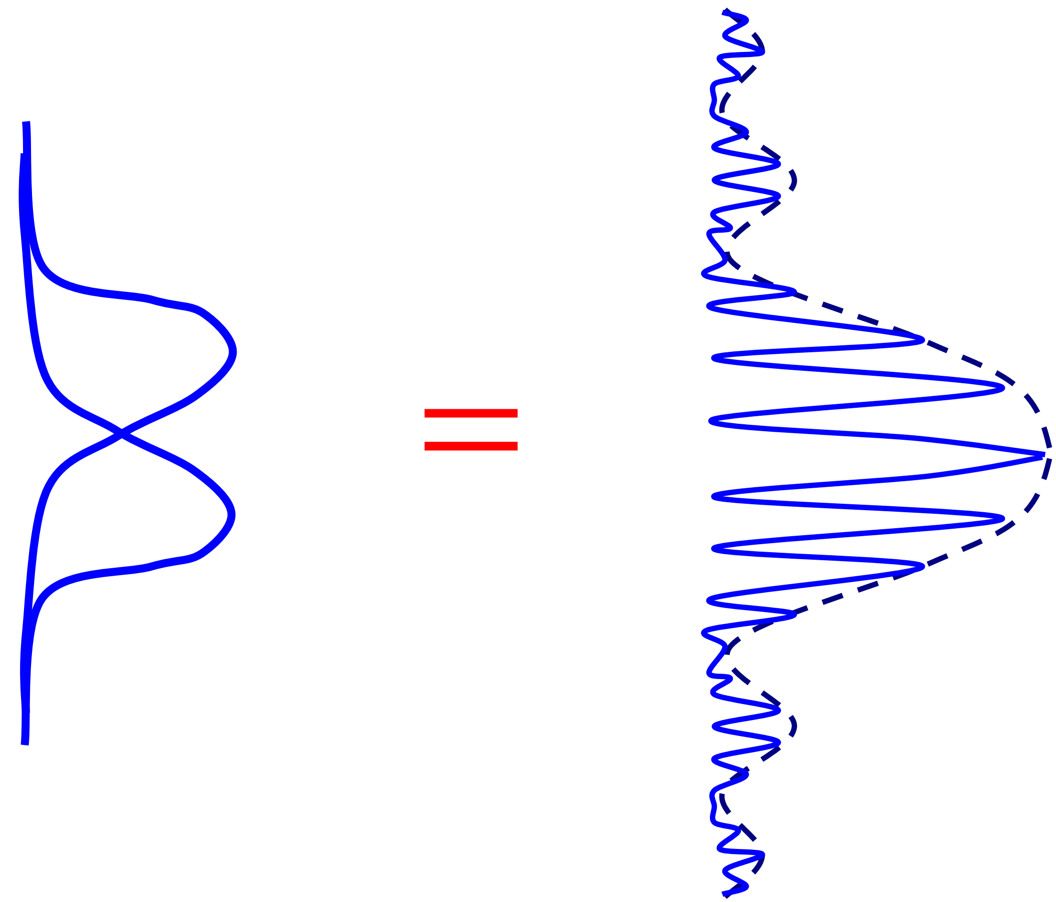
- Interference
- Quantization
- Tunneling
- Quantum Spin

(I) Interference

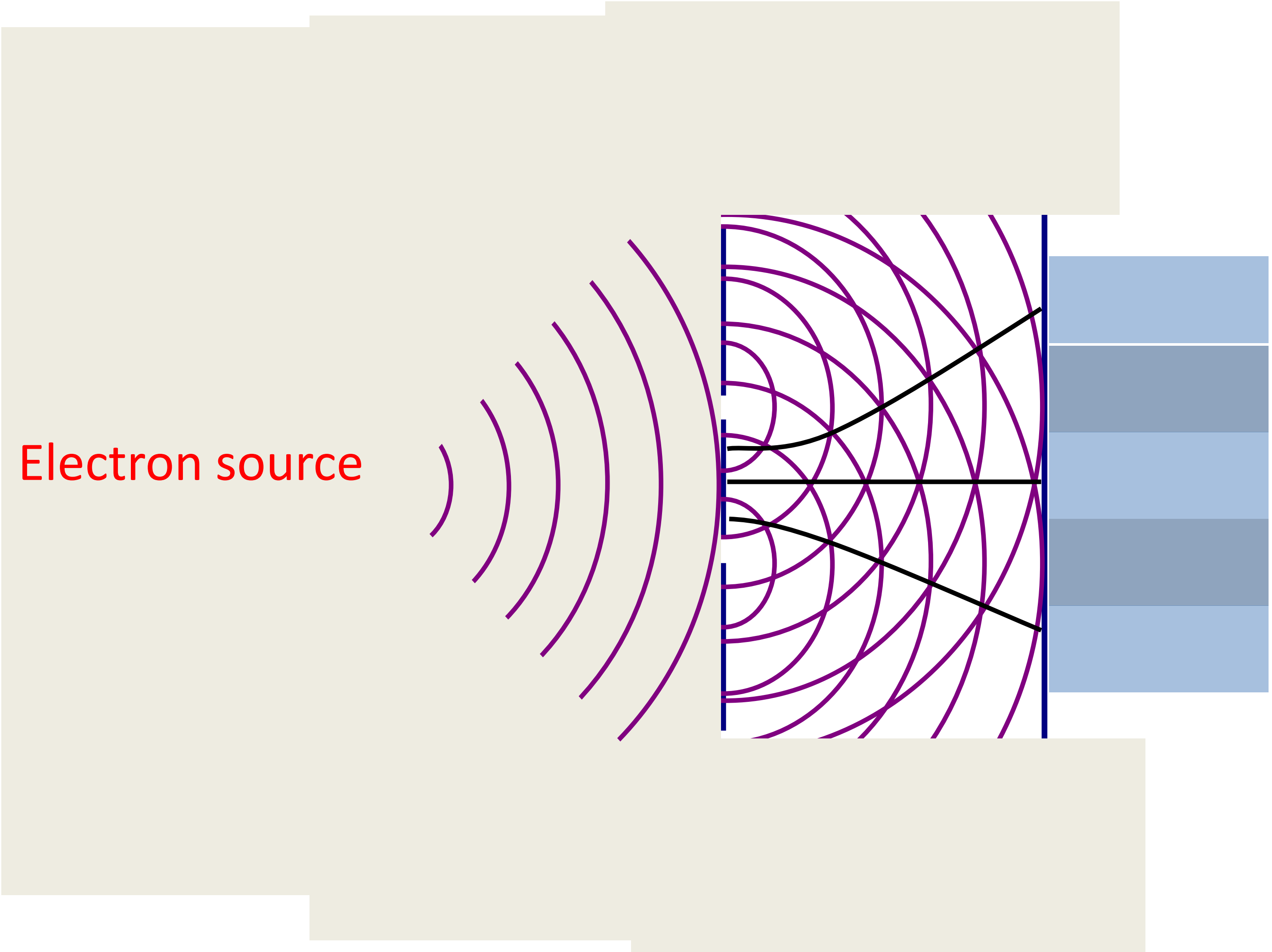
The wonder of electron in waves

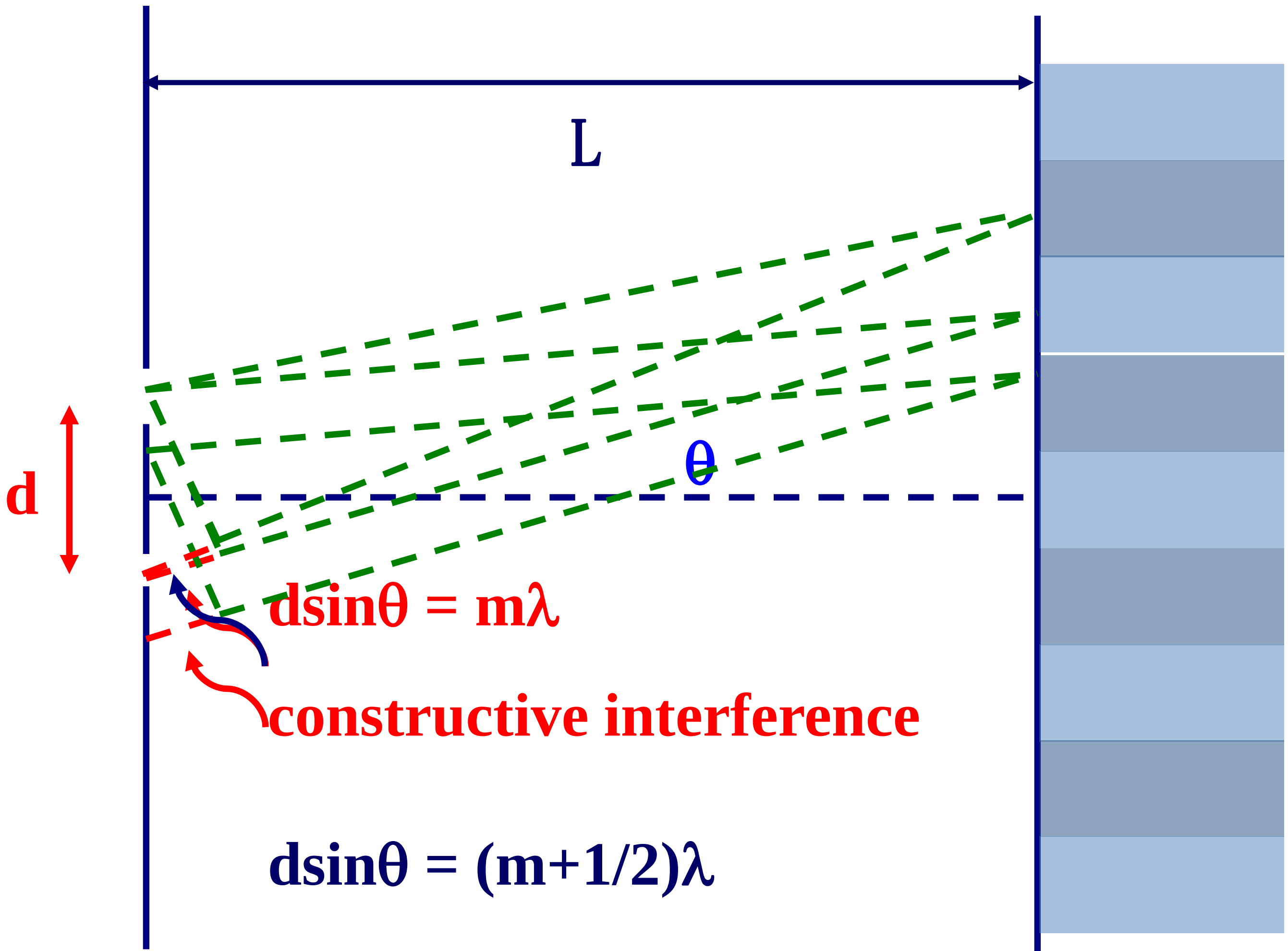


The wave property of electrons



Double Slit Interference of Electrons





$$\Delta y = \frac{L}{d}\lambda$$

$d\sin\theta = m\lambda$

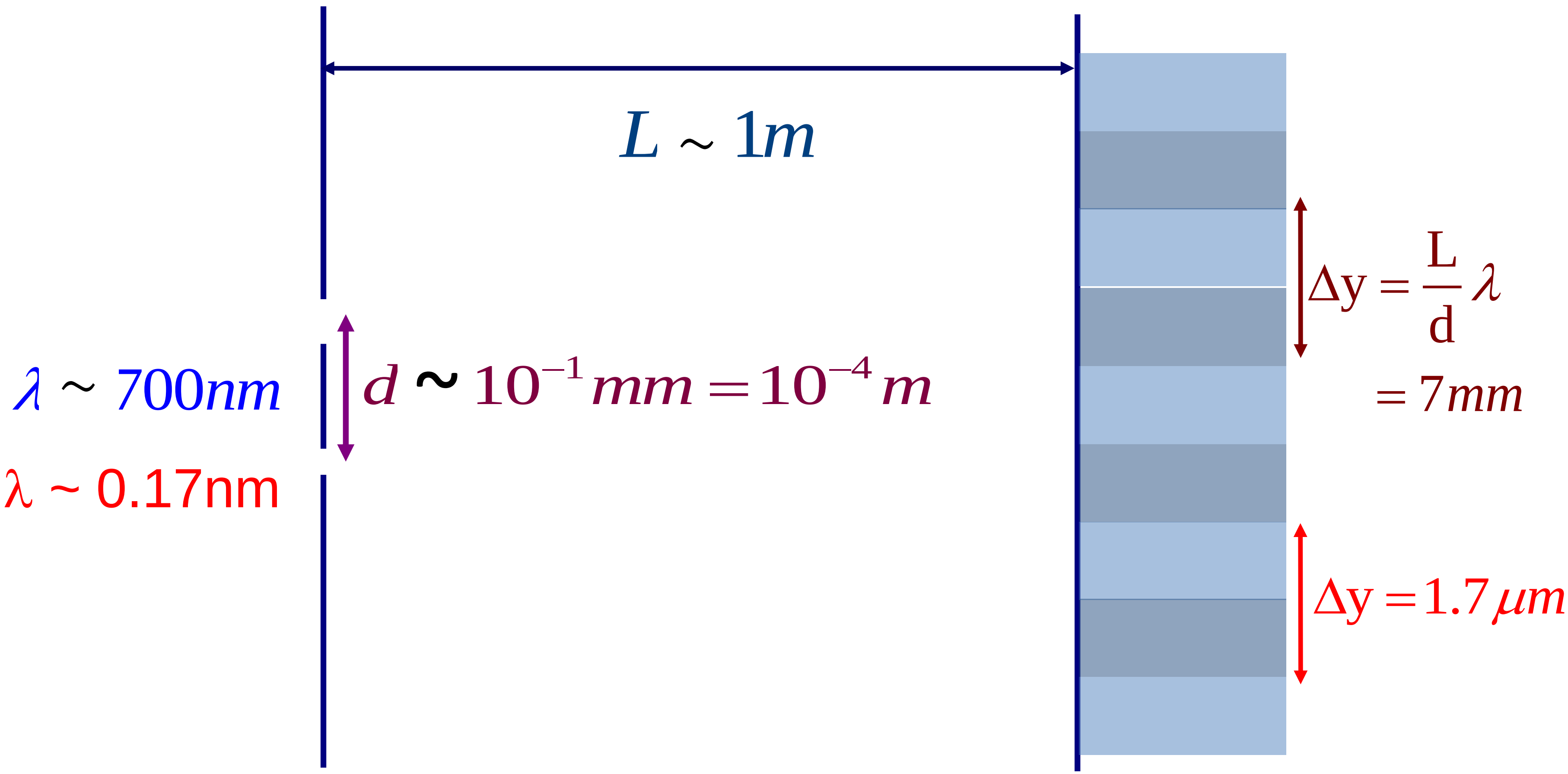
constructive interference

$d\sin\theta = (m+1/2)\lambda$

distructive interference

$$d\frac{\Delta y}{L} = \lambda$$

~



$L \sim 1m$
$\lambda \sim 700nm$
$\lambda \sim 0.17$nm
$d \sim 10^{-1}mm = 10^{-4}m$
$\Delta y = \frac{L}{d}\lambda$
$= 7mm$
$\Delta y = 1.7\mu m$

(II) Quantization

Confinement of the materials wave

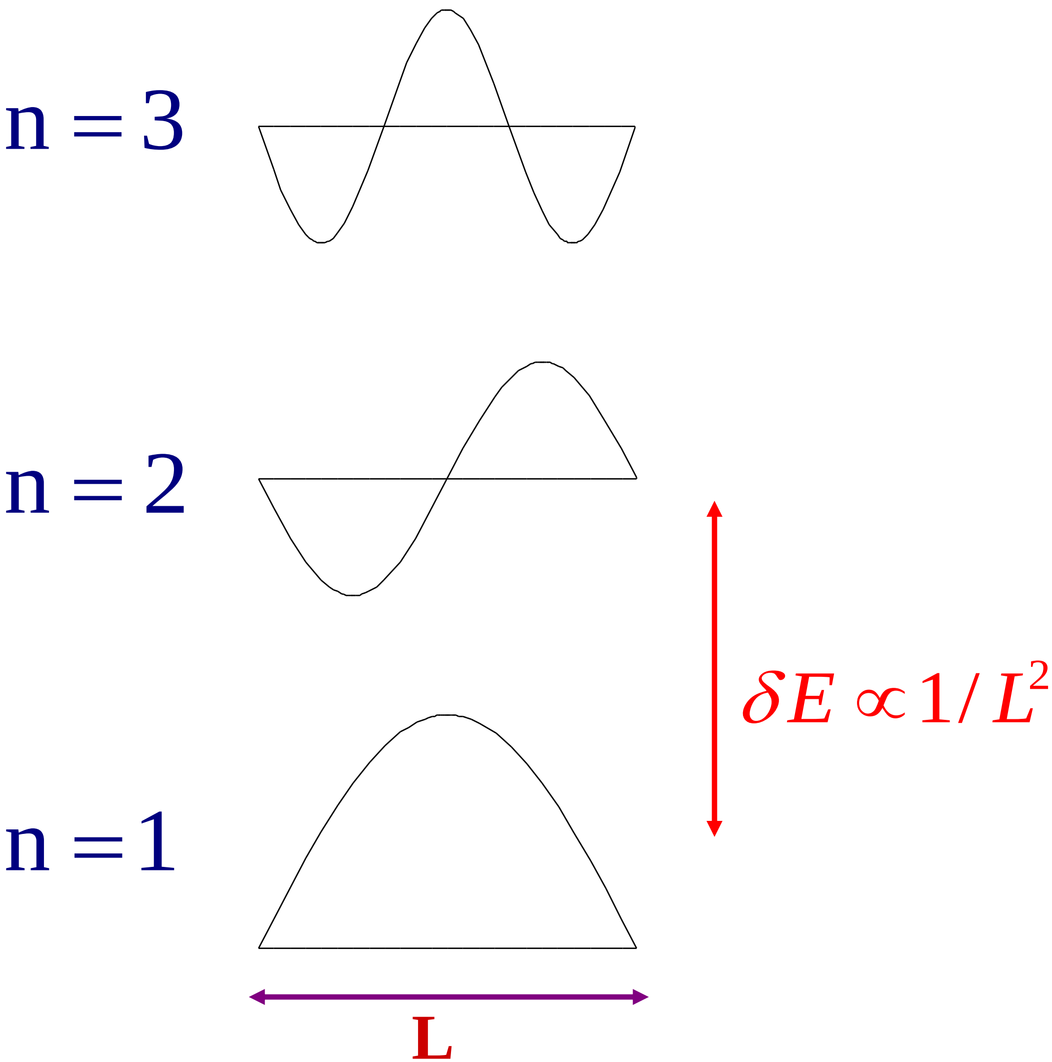
$\Downarrow$

Standing Wave

$\Downarrow$

Quantizations

The Qauntization of Energy

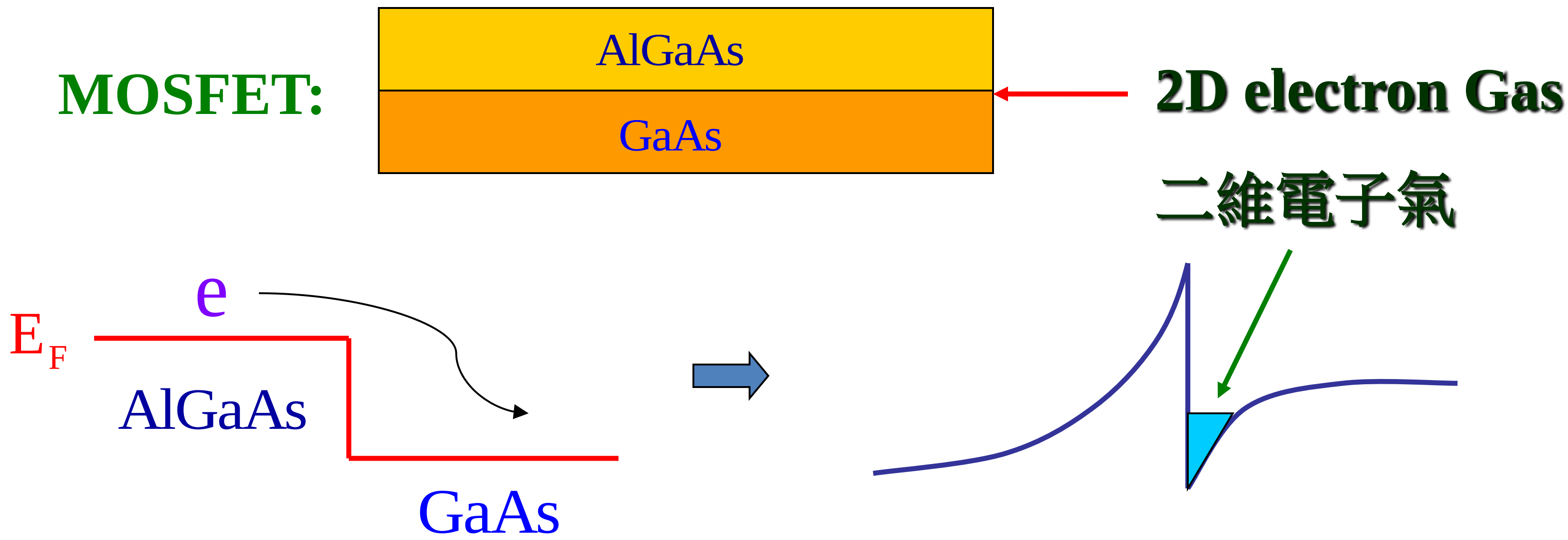


$$L = \frac{\mathrm{n}}{2}\lambda$$

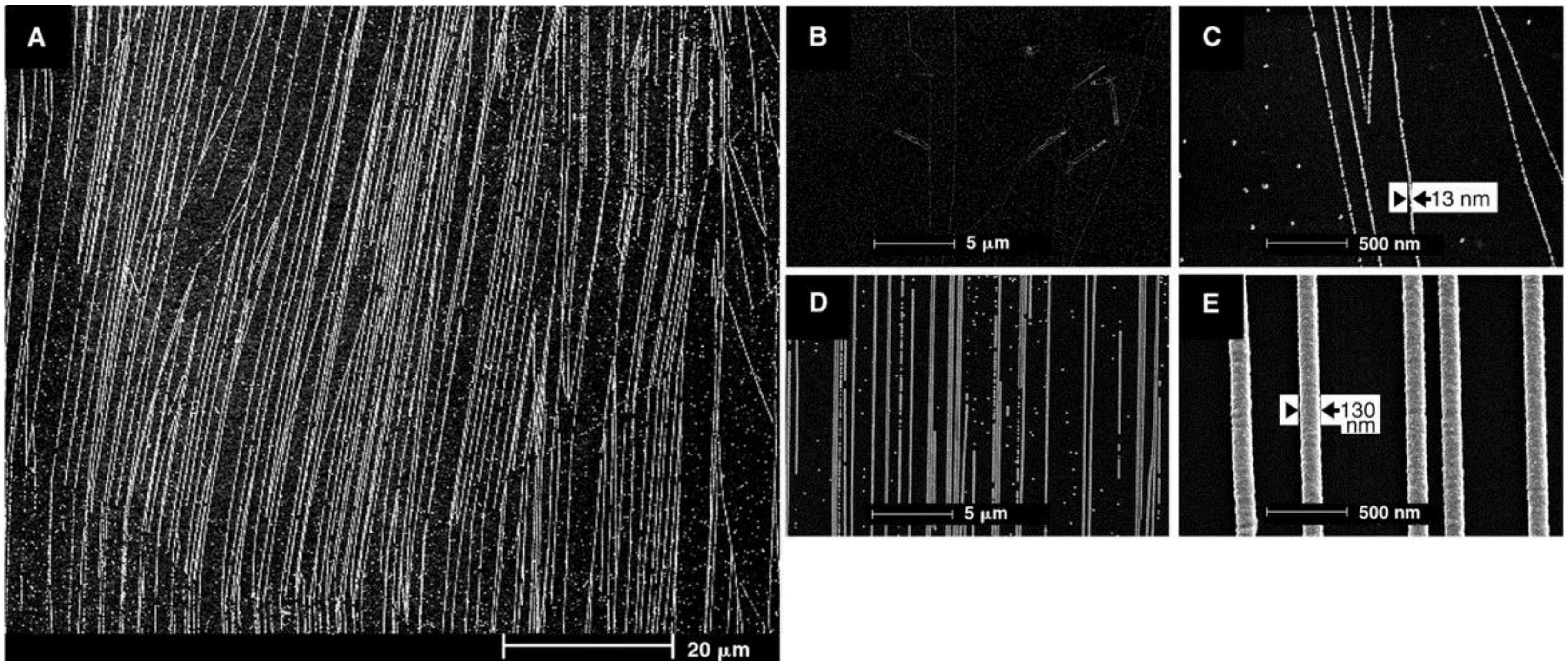
$$p = \frac{h}{\lambda} = \frac{nh}{2L}$$

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

Quantum well: 1D confinement



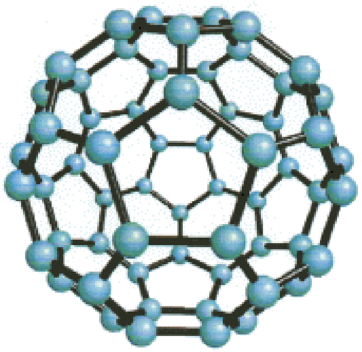
Quantum wire: 2 D-Confinement



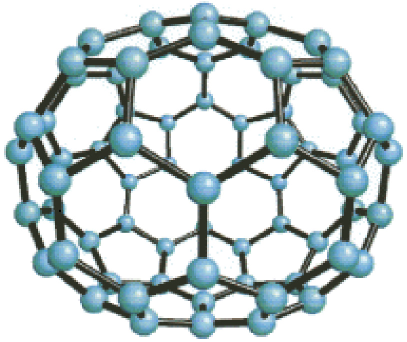
SEM images of MoO_x nanowires on graphite surfaces

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

Quantum dot: 3 D - Confinement

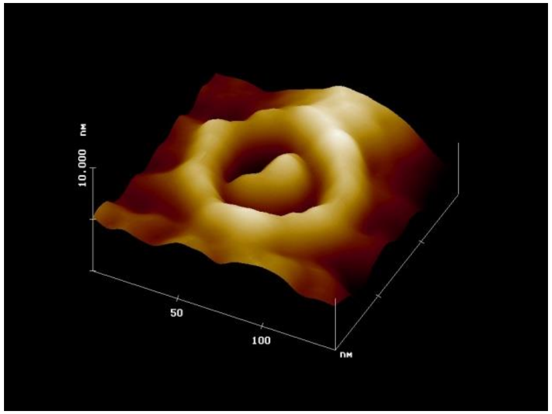


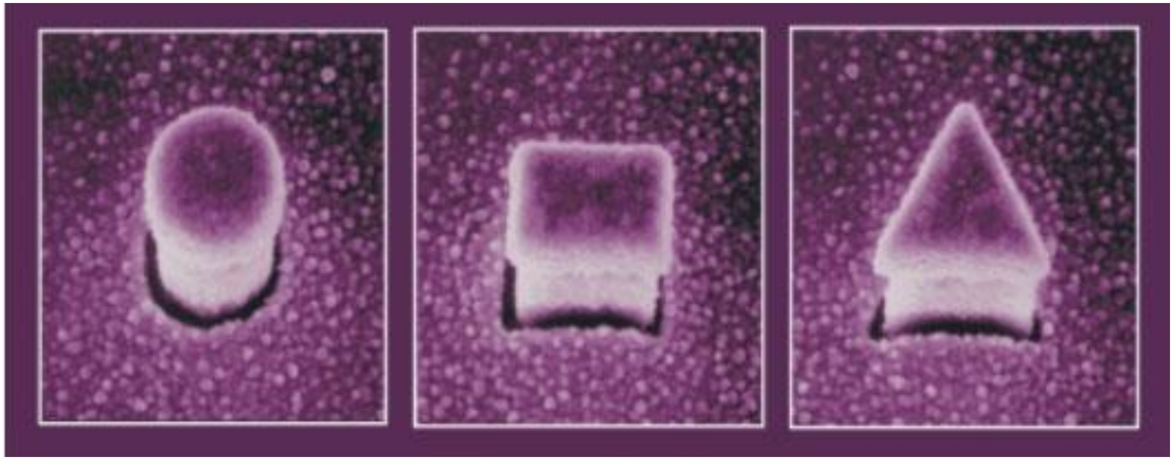
C_{60}



C_{70}

Quantum Dots of various shape





Absorption in scattering
From red to yellow

larger λ_0

λ $E = hc/\lambda \propto 1/L^2$

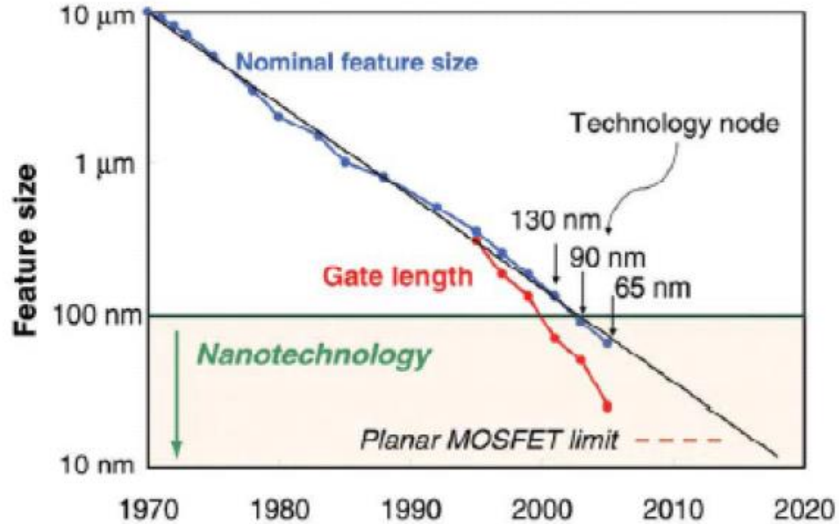
powdered Cadmium Selenide

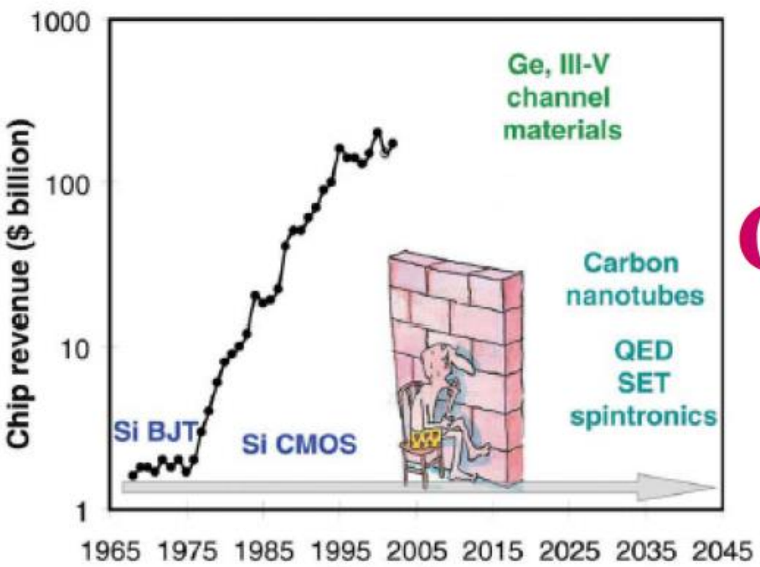
larger

smaller

Background for search new platform

Scaling limit of Si MOSFET
& superparamagnetism





Carbon era?

Thompson and Parthasarathy,
Materialstoday 9, 20, 2006