奈米物理簡介

清華大學物理系
郭瑞年教授

何謂奈米？

奈米 (nm) 就是 1/1000000000 (10^{-9}) 公尺

10^{-3} m ，厘米 - **宏觀世界** **Macro**

10^{-6} m ，微米 - **微觀世界** **Micro**

10^{-9} m ，奈米 - **介觀世界** **Meso**

費曼的主張

「物理學的原理並未否決原子層次上製造器具的可能性，如果有朝一日人類可以隨意操控原子，讓每一位元資訊存在一百個原子上，全世界重要藏書的儲存僅需要一粒塵埃的空間就夠了。」

(“ There’s plenty of room at the bottom ”, 1959年)

物理學家很早就注意到奈米…

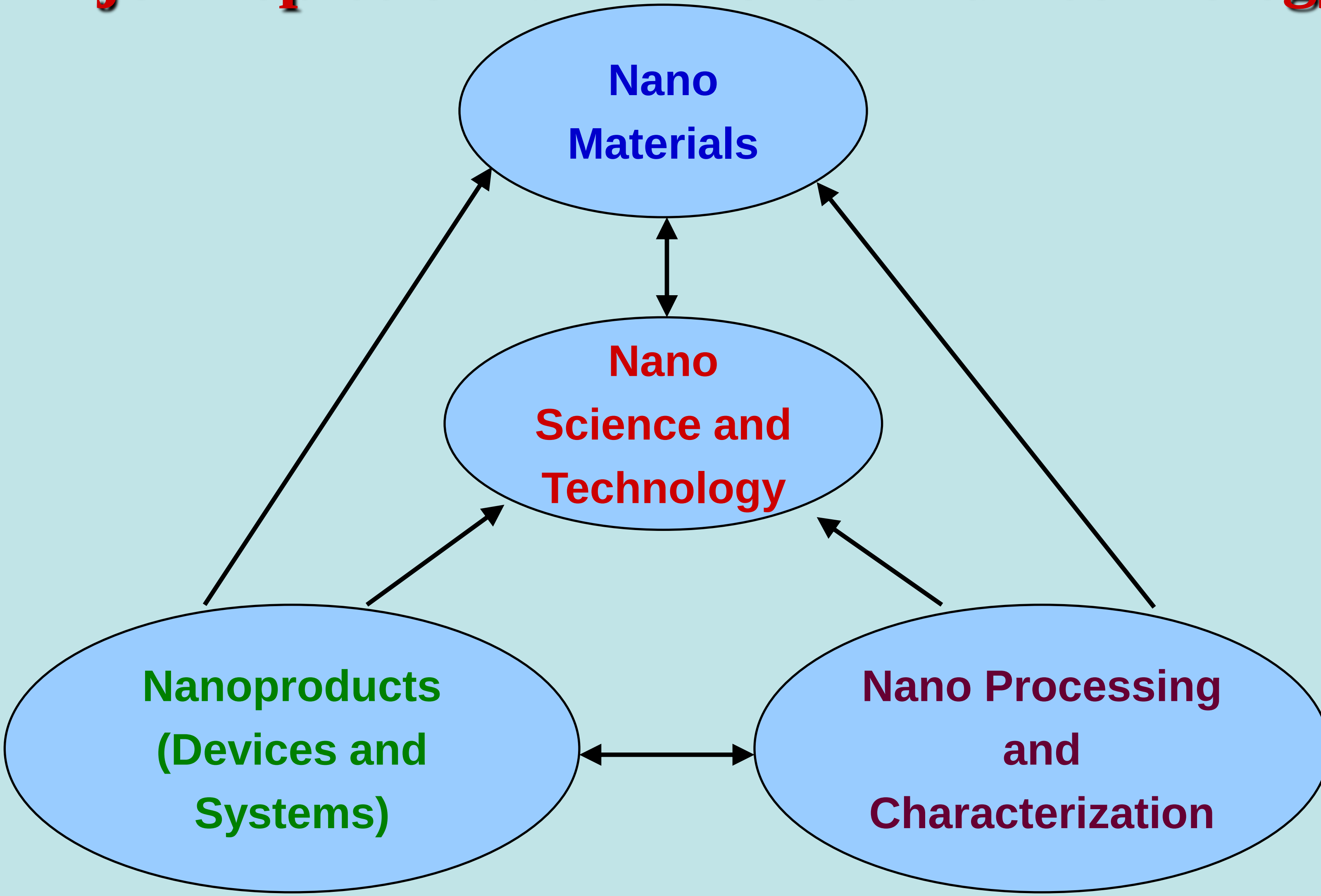
- 4th Century, Roman glassmaker: the color of glasses can be changed by mixing in metal particles
- 1883, Films containing silver halides for photography were invented by George Eastman, founder of Kodak
- 1908, Gustay Mie first provided the explanation of the size dependence of color
- Vision from Feynman 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

奈米科技的起源

1996-1998 年間,以美國 NSF 爲主要贊助者,由World Technology Evaluation Center (WTEC) 出面組織的委員對奈米尺度下之可能科技作了仔細的評估.

結論是奈米科技極具潛力，發展它可能會有重要且影響廣泛的技術突破. .

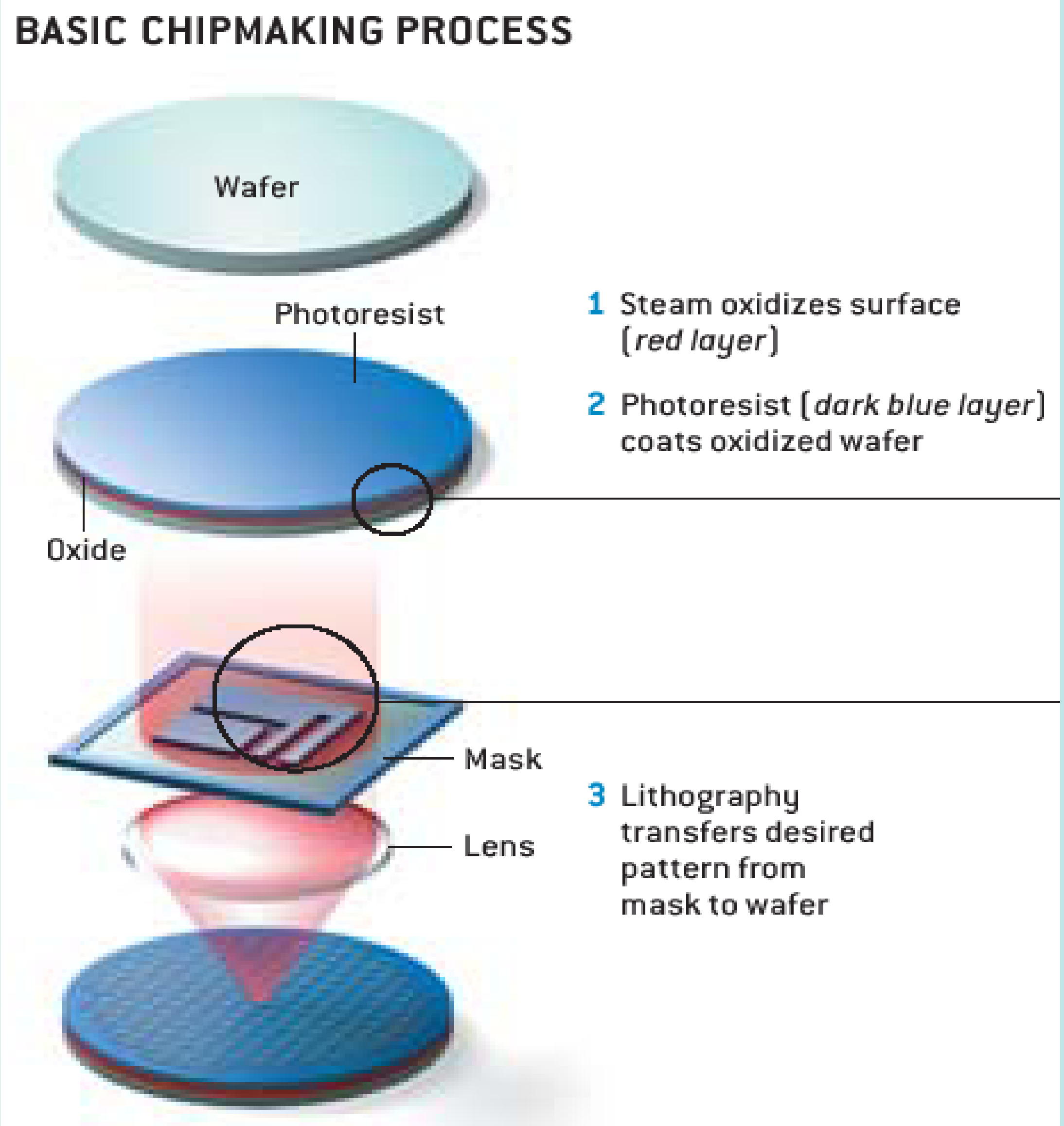
Major Topics of Nanoscience and Technology



甚麼是奈米科技？

- 縮小尺度至100 nm以內的科技：
  Top-down之奈米結構的雕刻細化
  莫爾定律(Moore's law－每2年縮小30%尺寸)
- 操控原子（分子）的科技：Bottom-up 之奈米體系的成長組裝
  費曼的主張－從底部作起，下面還有無限寬廣的空間
- 創物者的科技：以大自然為師
  創造生命物質的法則 － 奈米為生物體的構築單元尺度

縮小尺度至100 nm以內的科技：Top-down之奈米結構的雕刻細化



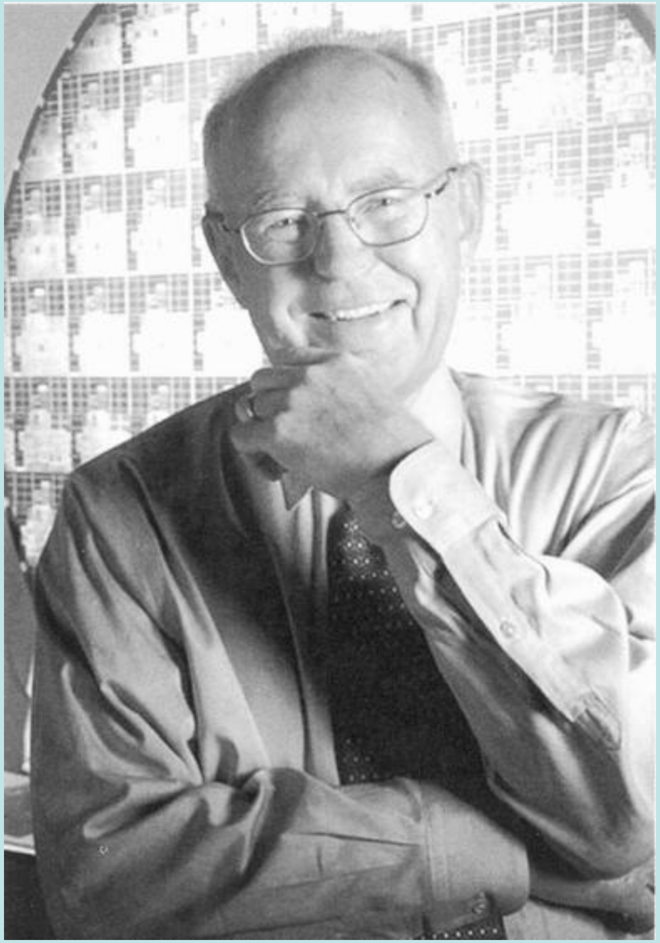
近來大力推動奈米科技的背景

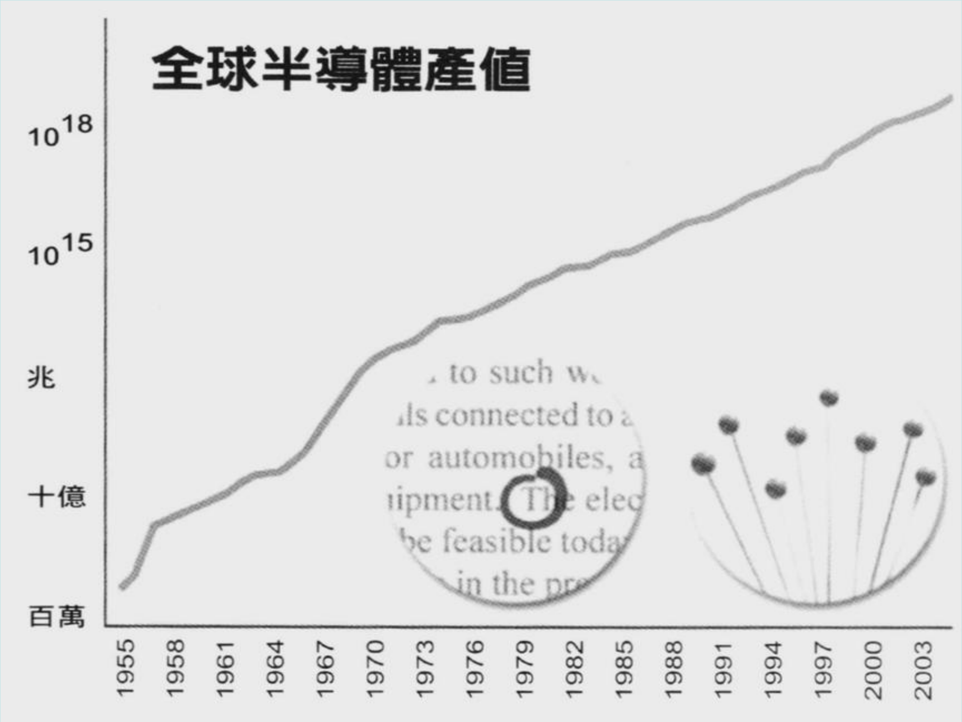
來自微電子學可能遭遇瓶頸的考慮

Moore's Law：摩爾定律

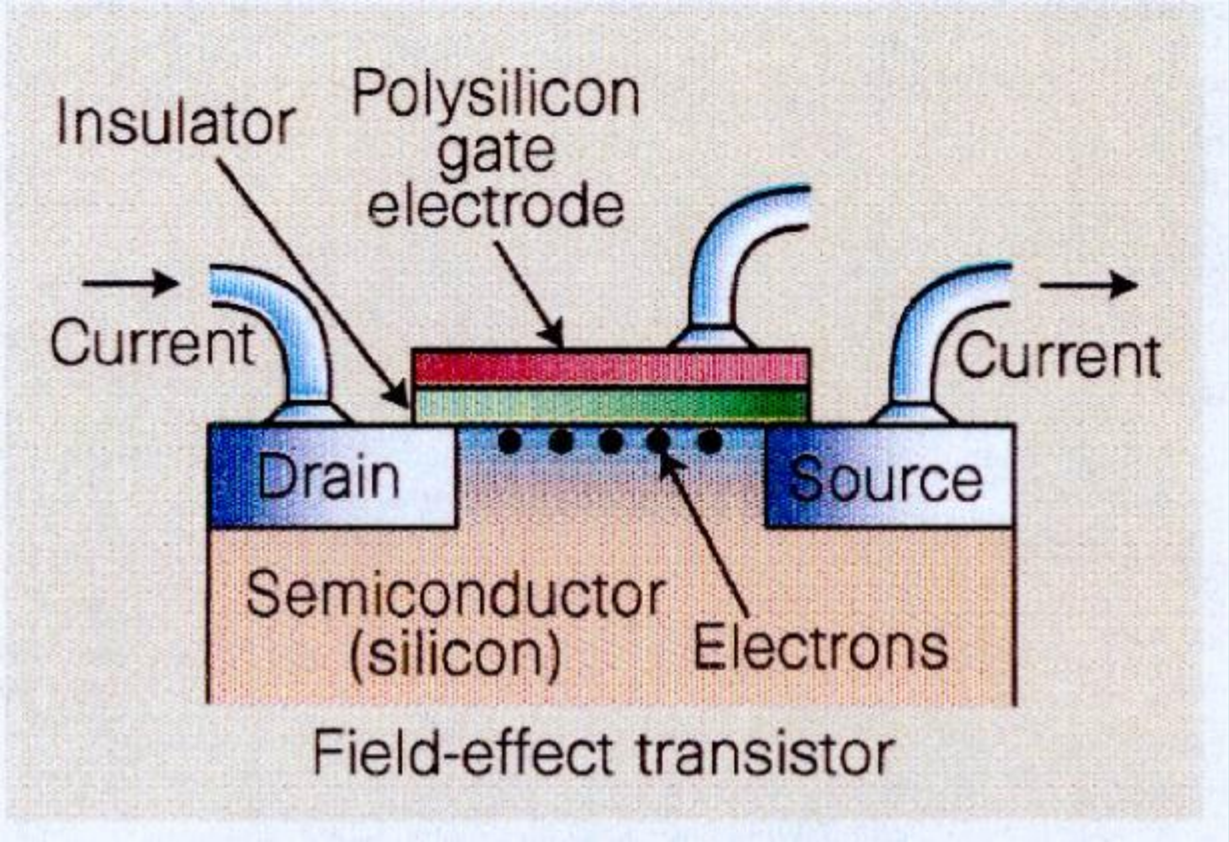
A 30% decrease in the size of printed dimensions every two years.

矽晶上電子原件數每兩年會增加一倍





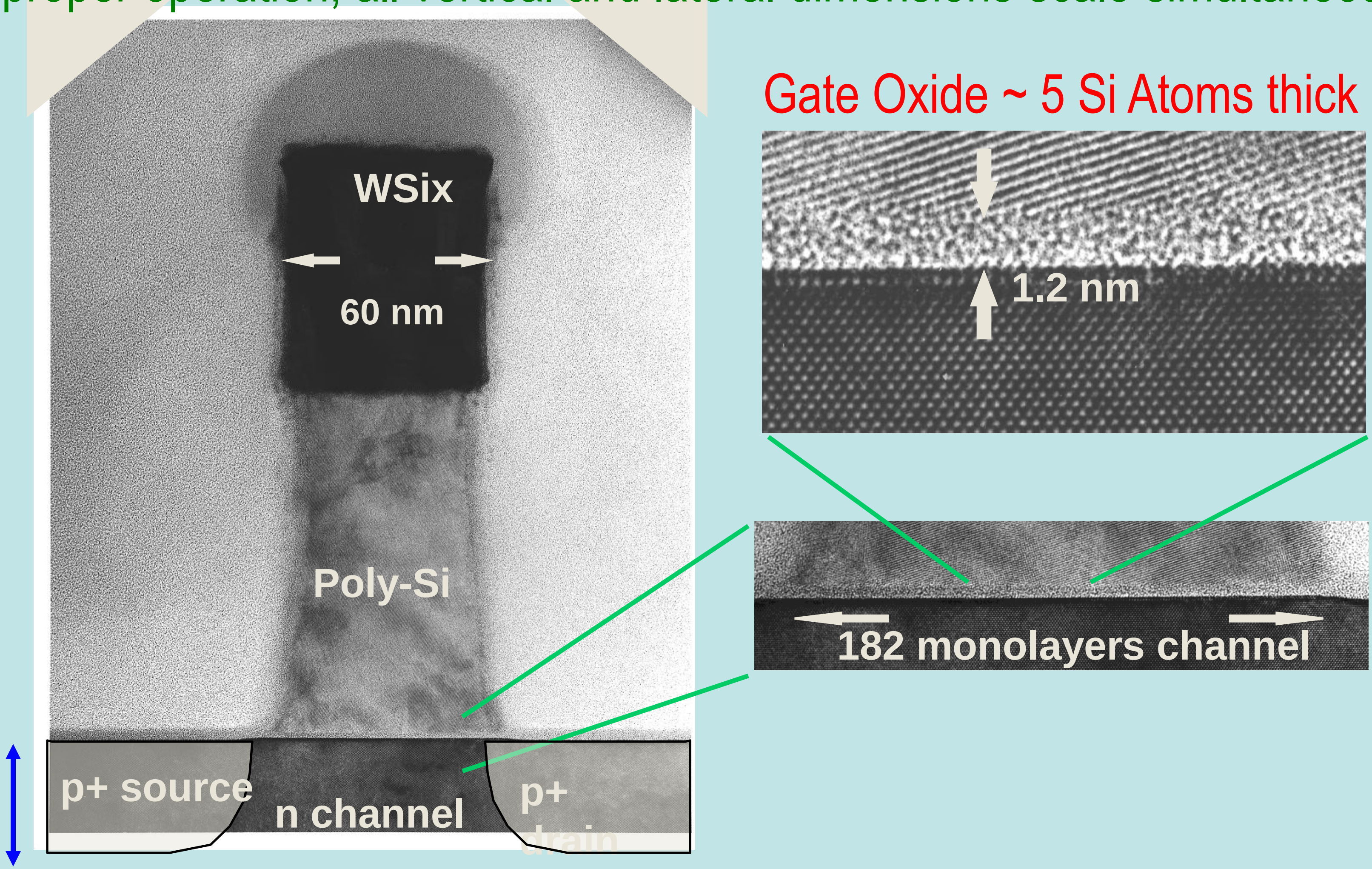
MOSFET (互補式金氧場效電晶體)



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

Scaling Limits to CMOS Technology

(For proper operation, all vertical and lateral dimensions scale simultaneously)



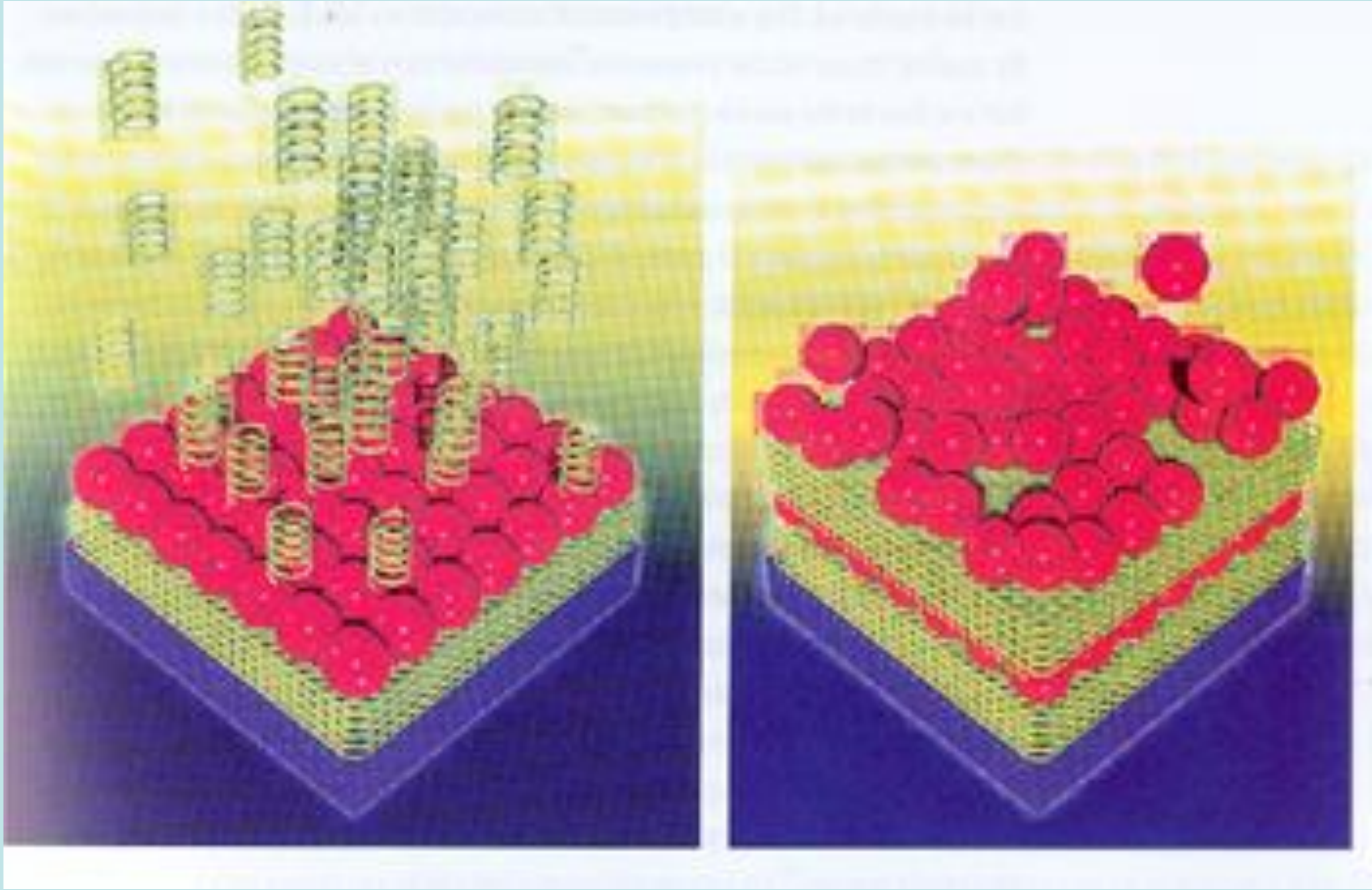
Shrinking the junction depth ⇨ increasing the carrier concentration

可能遭遇的問題

- 需要製造更小的 pattern 的技術 (advanced lithographic techniques, e-beam, x-ray..)
- 電子波動性和量子特性的重要
- ..etc.

Bottom-up 之奈米體系的成長組裝

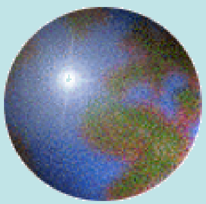
由原子、分子 由下而上之自組裝技術突破，使科學家們得以開始設計超大分子和各種嶄新奈米結構及材料。



百花齊放的奈米新世紀

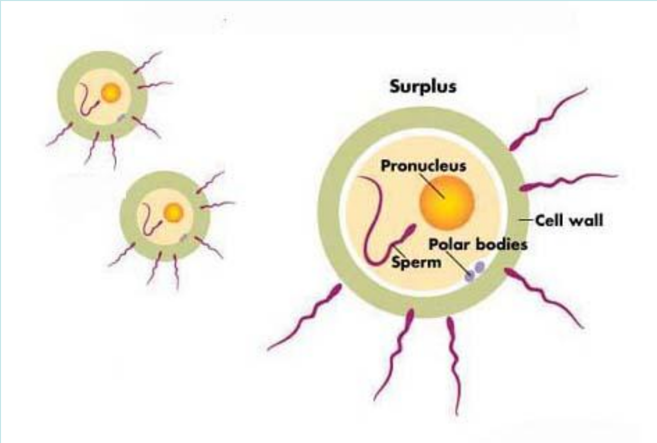
- 奈米物理
- 奈米化學

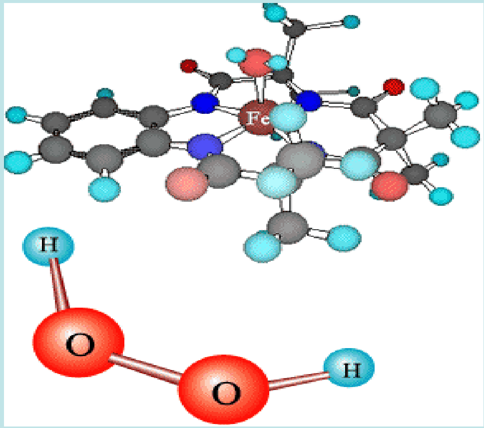
奈米材料



- 奈米機械
- 奈米電子
- 奈米生技
- 奈米醫學
- 奈米武器
- 奈米能源
- 奈米環保

跨領域最小單位逐漸重疊





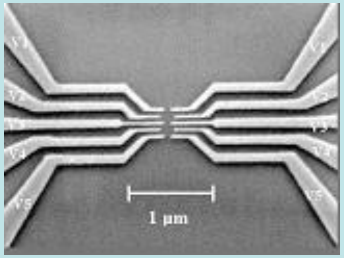
電機工程

光電

生物

材料

奈米

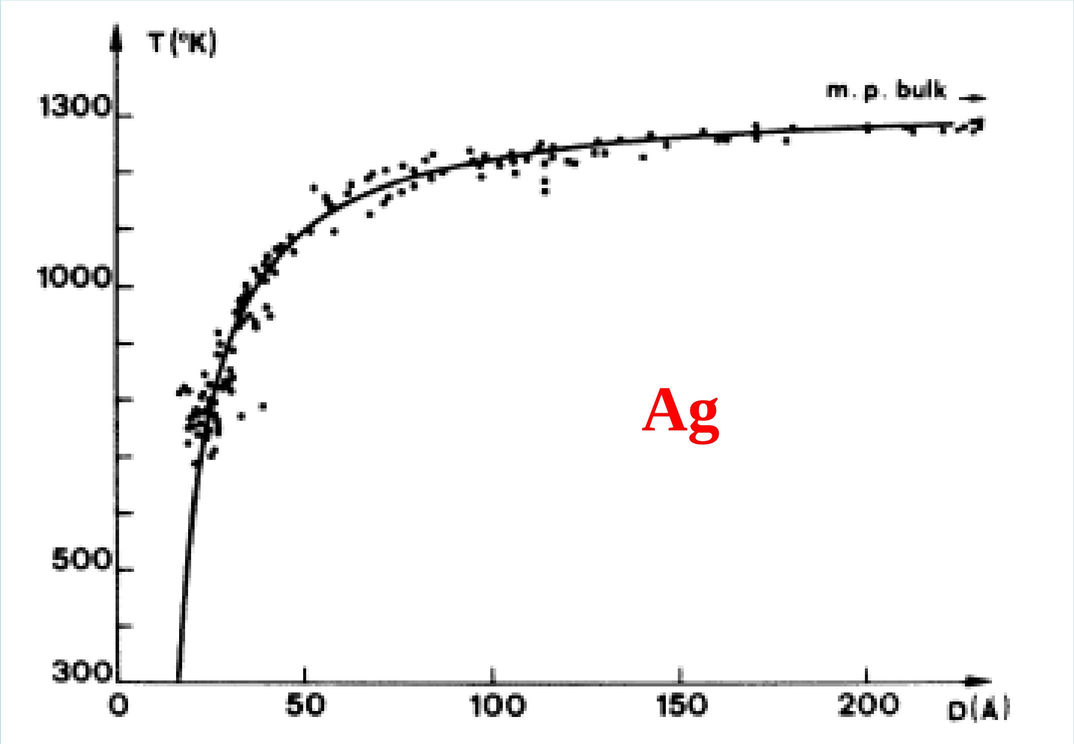


First Lesson :

塊材到奈米的轉變

(Bulk-to-nano Transition)

例：size-dependence of melting temperature



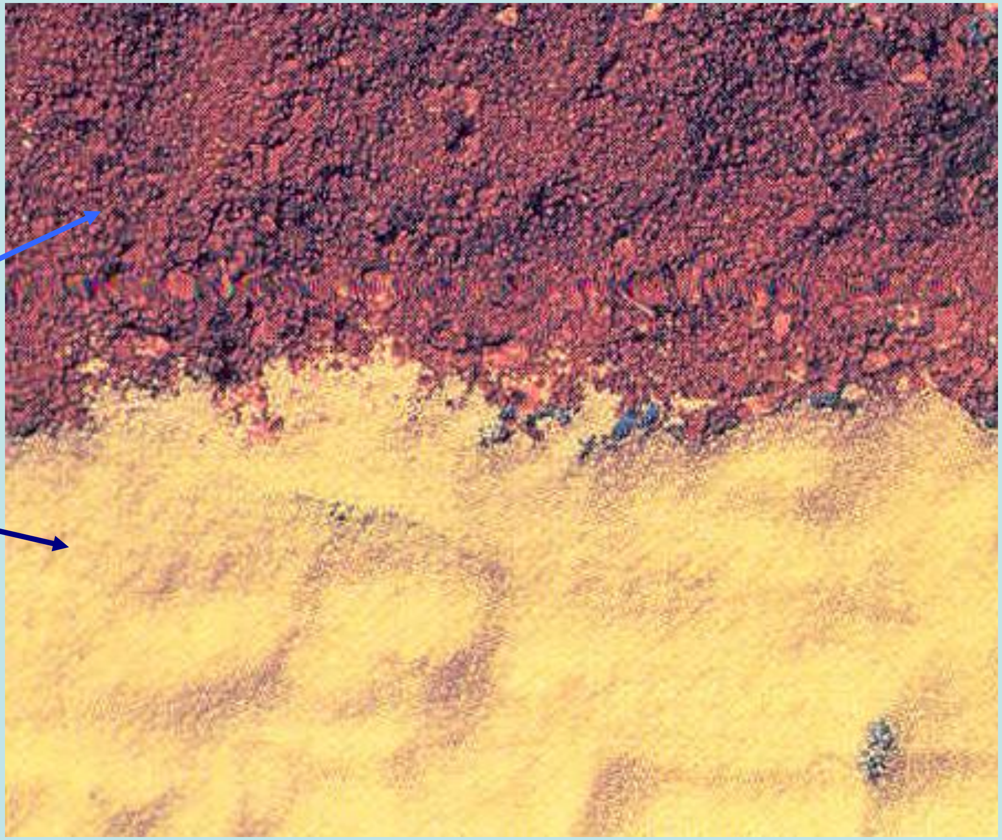
Ph. Buffat and J-P. Borel, Phys. Rev. A13, 2287 (1976)

例: size-dependence of color

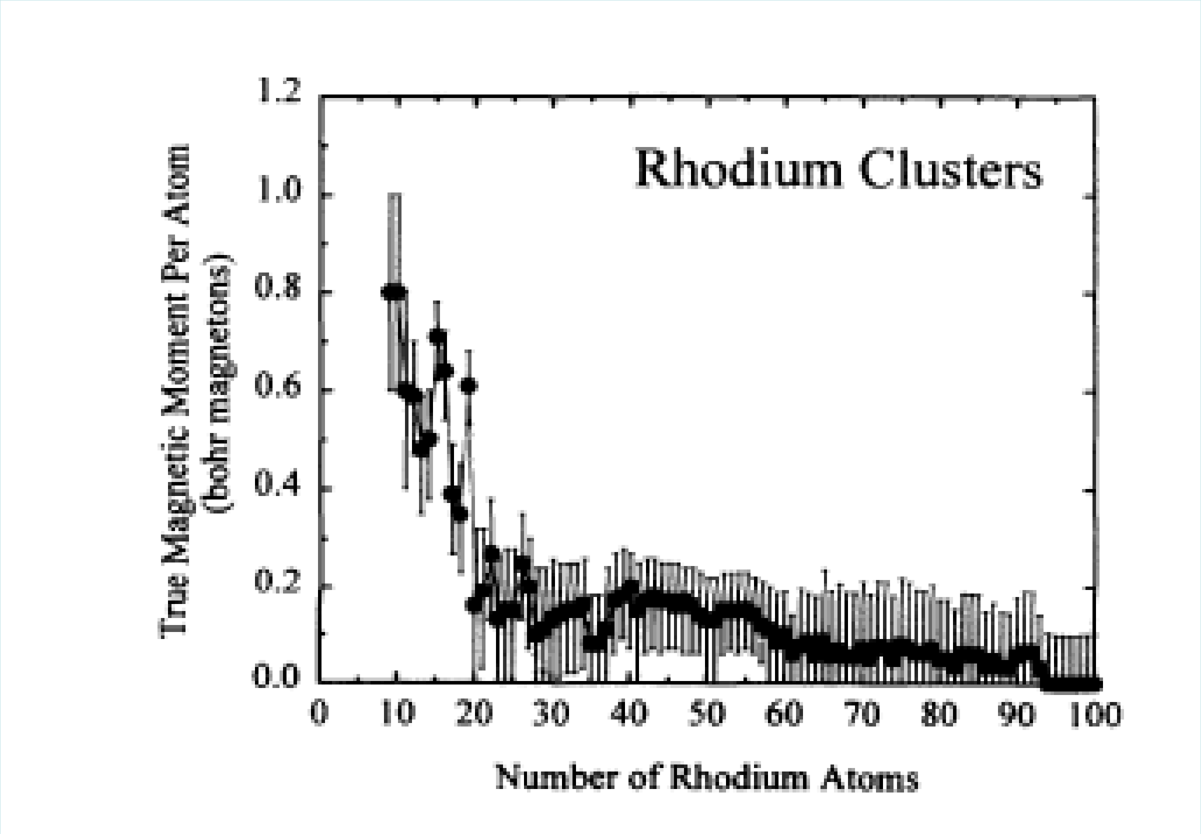
powered cadmium selenide

larger

smaller

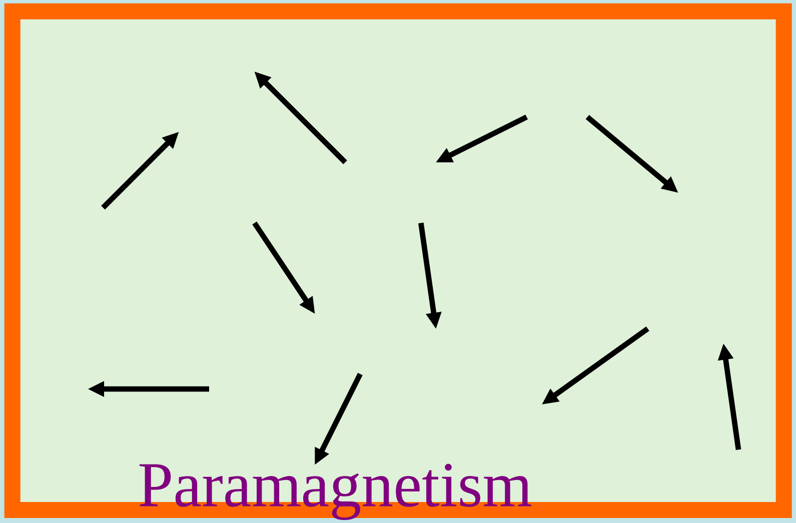


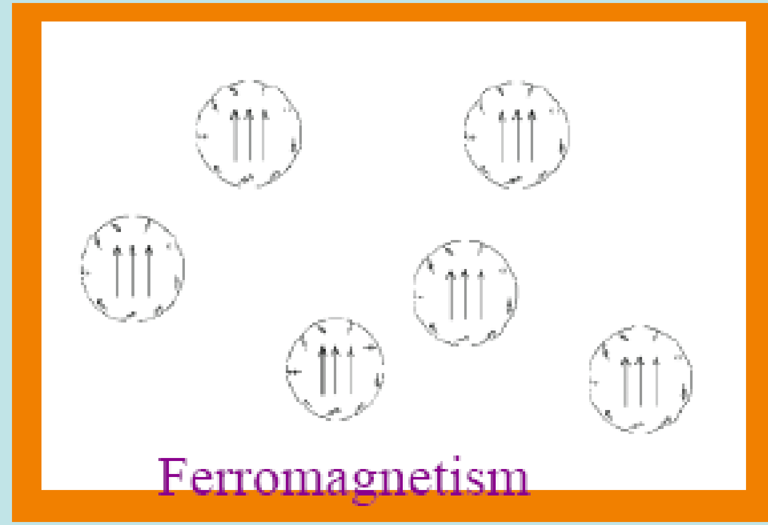
例: size-dependence of magnetism

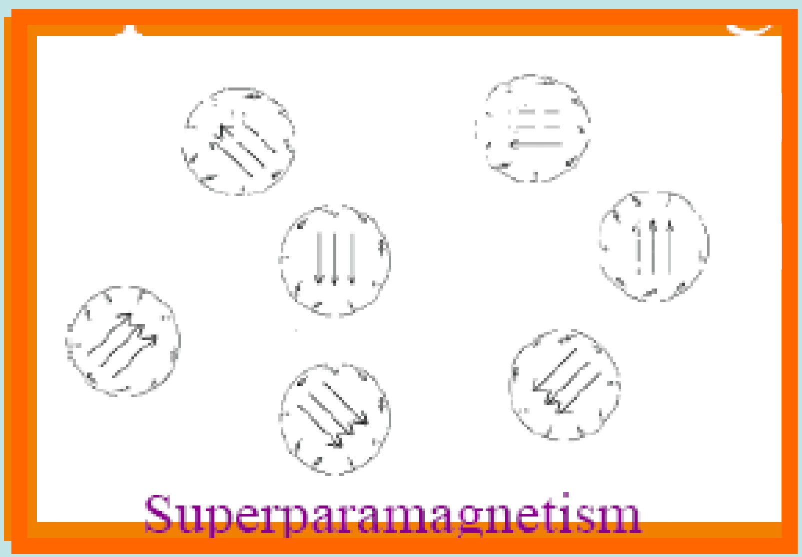


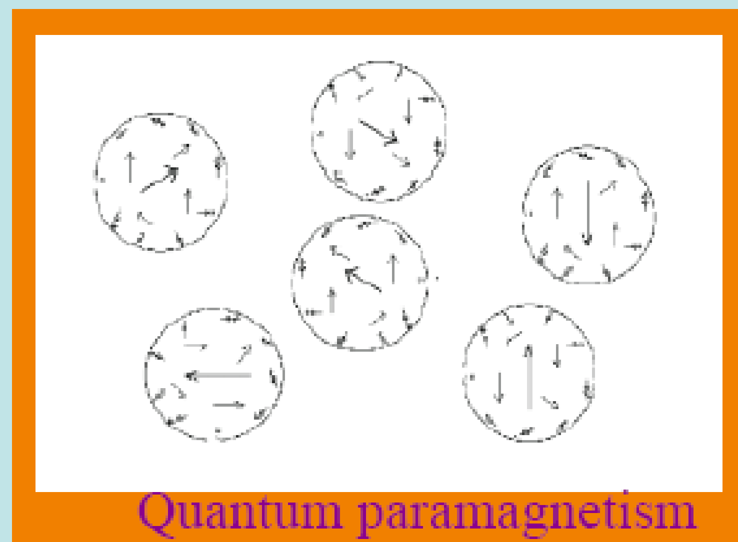
A. J. Cox et al. Phys. Rev. B49, 12295 (1994)

Diagram for Possible Magnetic order



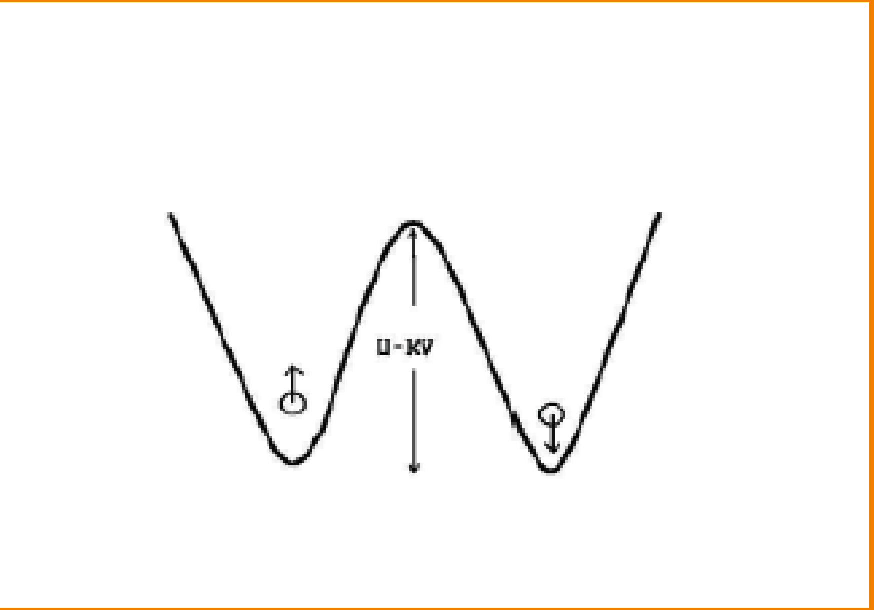






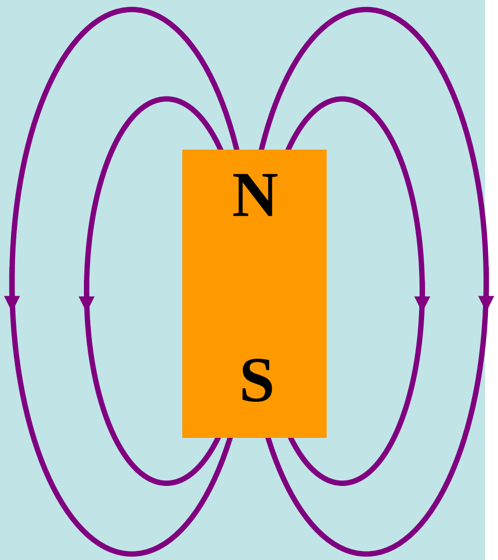
Superparamagnetism 超順磁現象 in Nano Particles

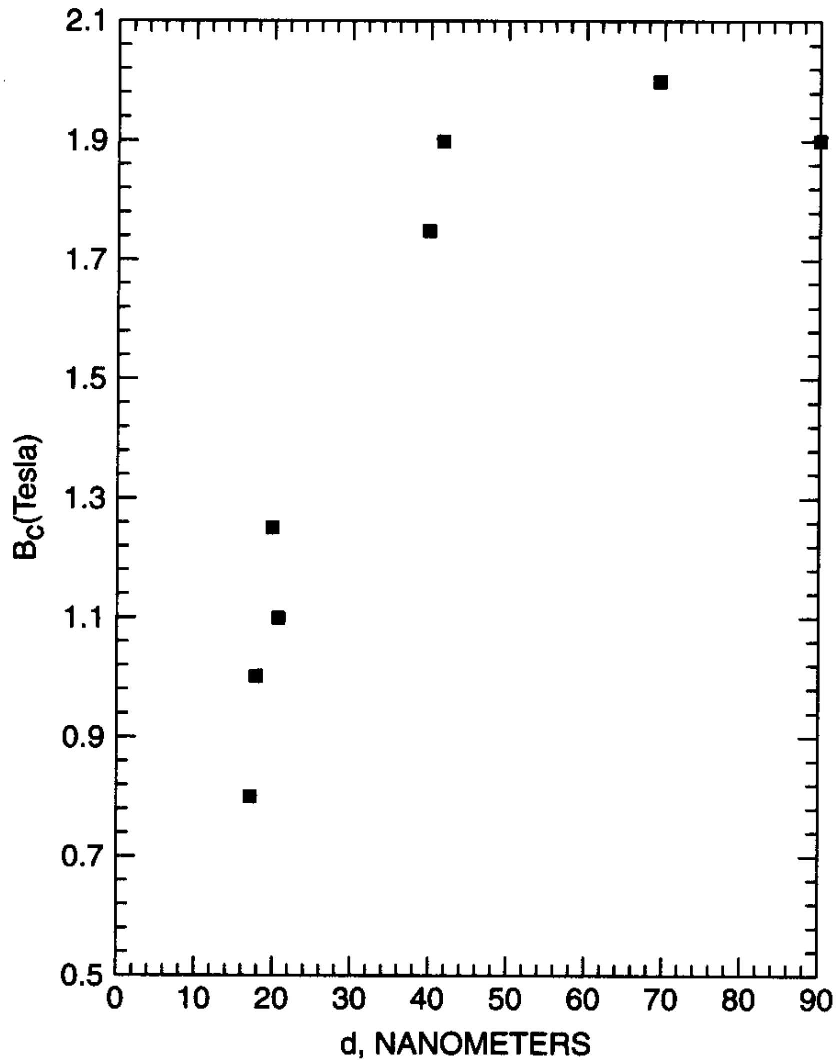
. Nanoparticles usually exhibit an uniaxial magnetic anisotropy



.As the size of nanoparticles decreases,when KV< $k_B T$, magnetic nanoparticles exhibit superparamagnetic relaxation, i.e., thermally fluctuations of the magnetization vector among the easy axis of magnetization.

例:超順磁現象 (Superparamagnetism)





Dependence of the coercive field B_c (i.e., H_c) on the granular particle size *d* of a Nd–B–Fe permanent magnet. [Adapted from A. Manaf et al., *J. Magn. Magn. Mater.* **101**, 360 (1991).]

Second Lesson :

發展奈米結構製成的能力，並可作奈米尺度精準的原子操控

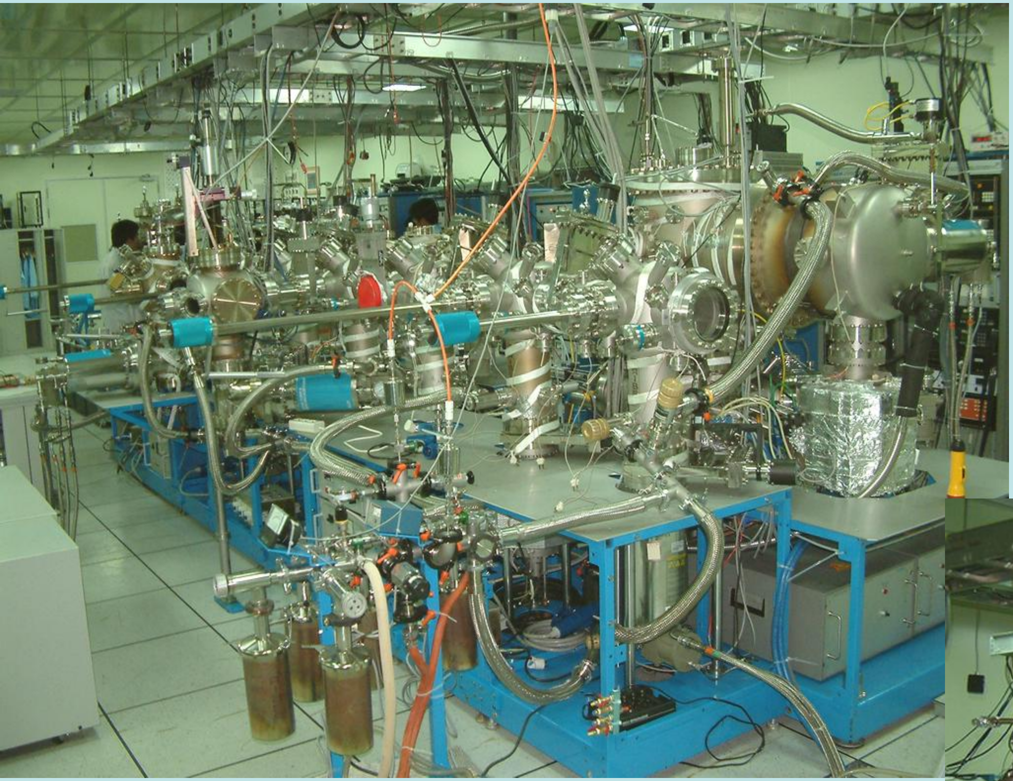
(I) 原子分子磊金術 (MBE)

- For Nano electronics in metals, oxides, and semiconductors

(II) 奈米尺碼之探測 : STM, AFM, MFM

- 1982年 IBM公司之**Binning** 與 **Rohrer** 發明掃瞄穿隧顯微鏡（STM）.
- **1986**年 **Binning**、**Quati** 與 **Gerber** 發明原子力顯微鏡（AFM）.

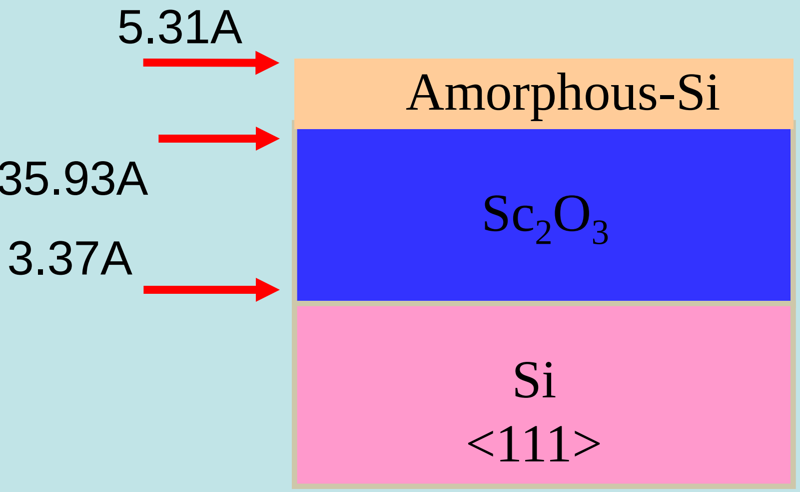
Integrated MBE Multi-chamber System

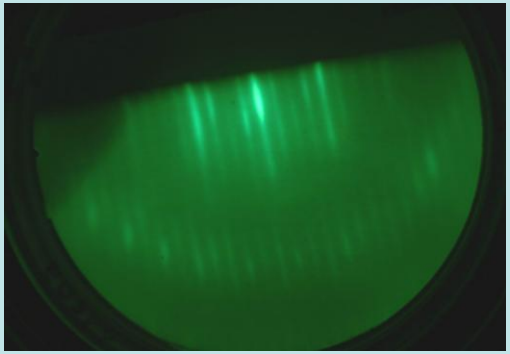


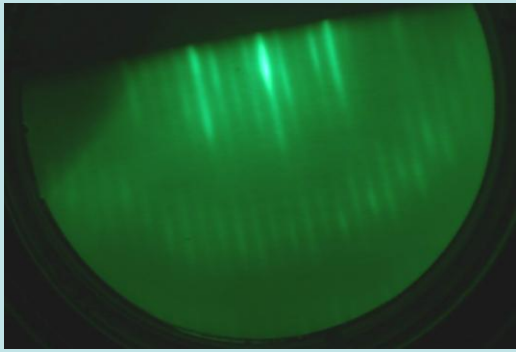
Now located in the Nano Technology Center, ITRI, Hsin Chu, Taiwan

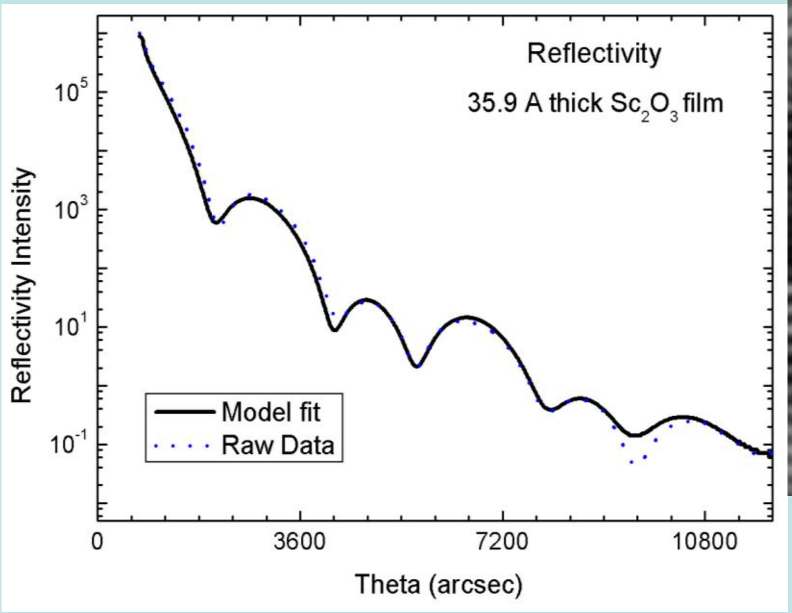
For Metal, Oxide and Semiconductor Films On the Nano scale

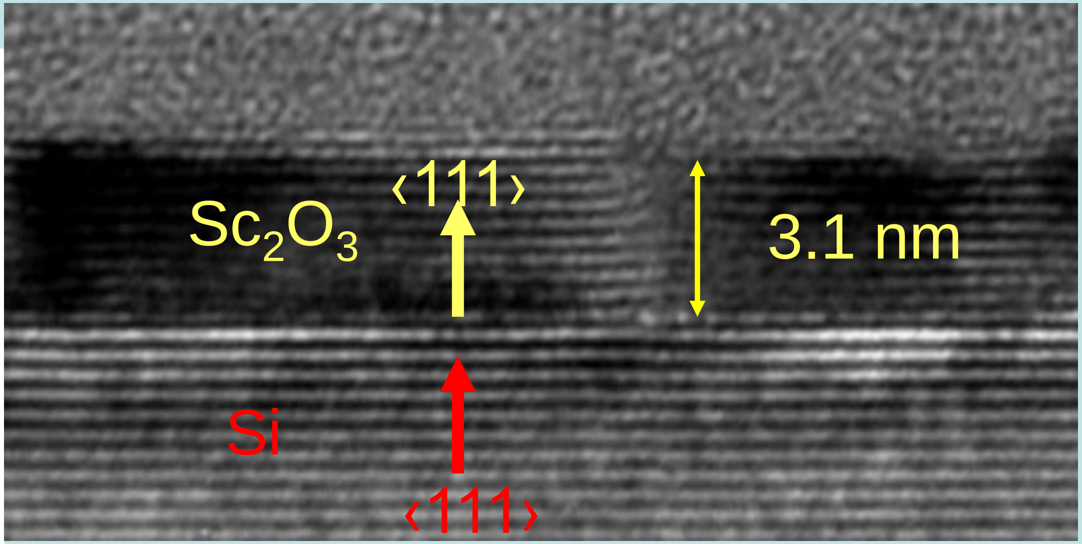
Single Crystalline (111) Sc_2O_3 Film on (111) Si











Hong and Kwo et al

掃瞄穿隧顯微鏡 (STM)

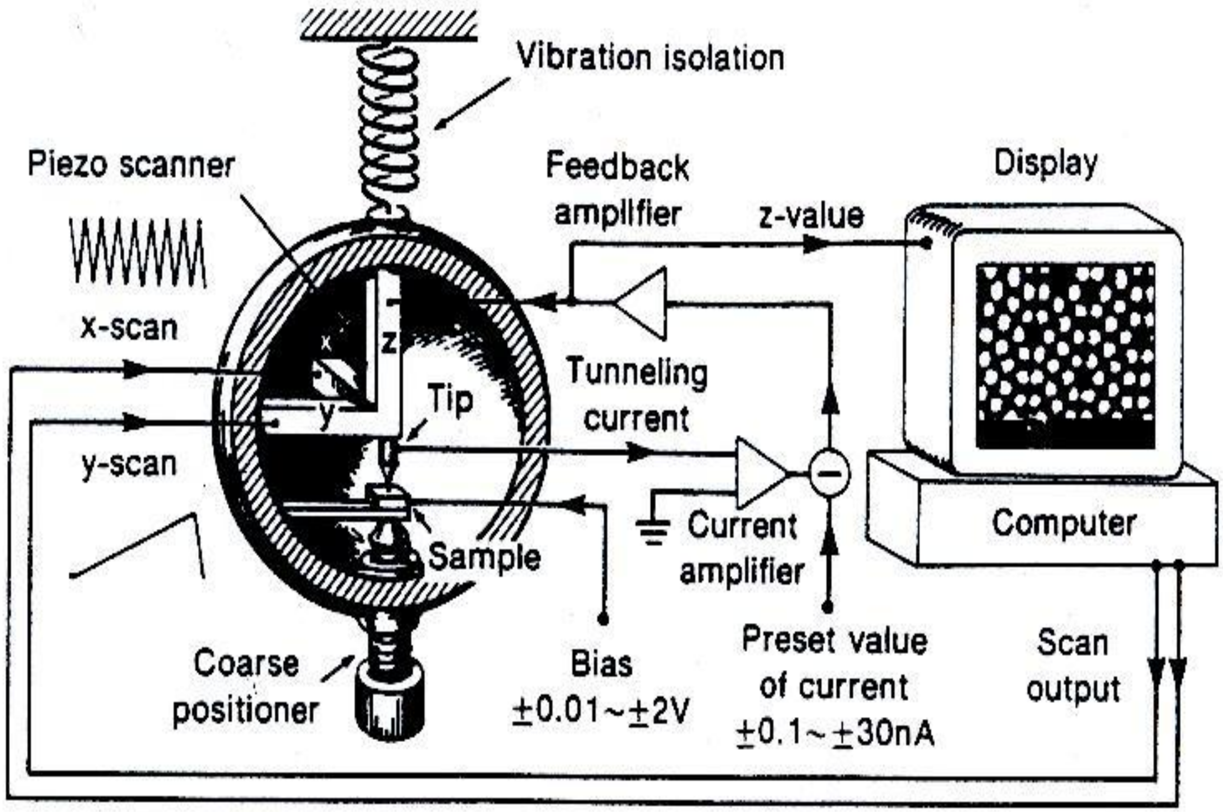
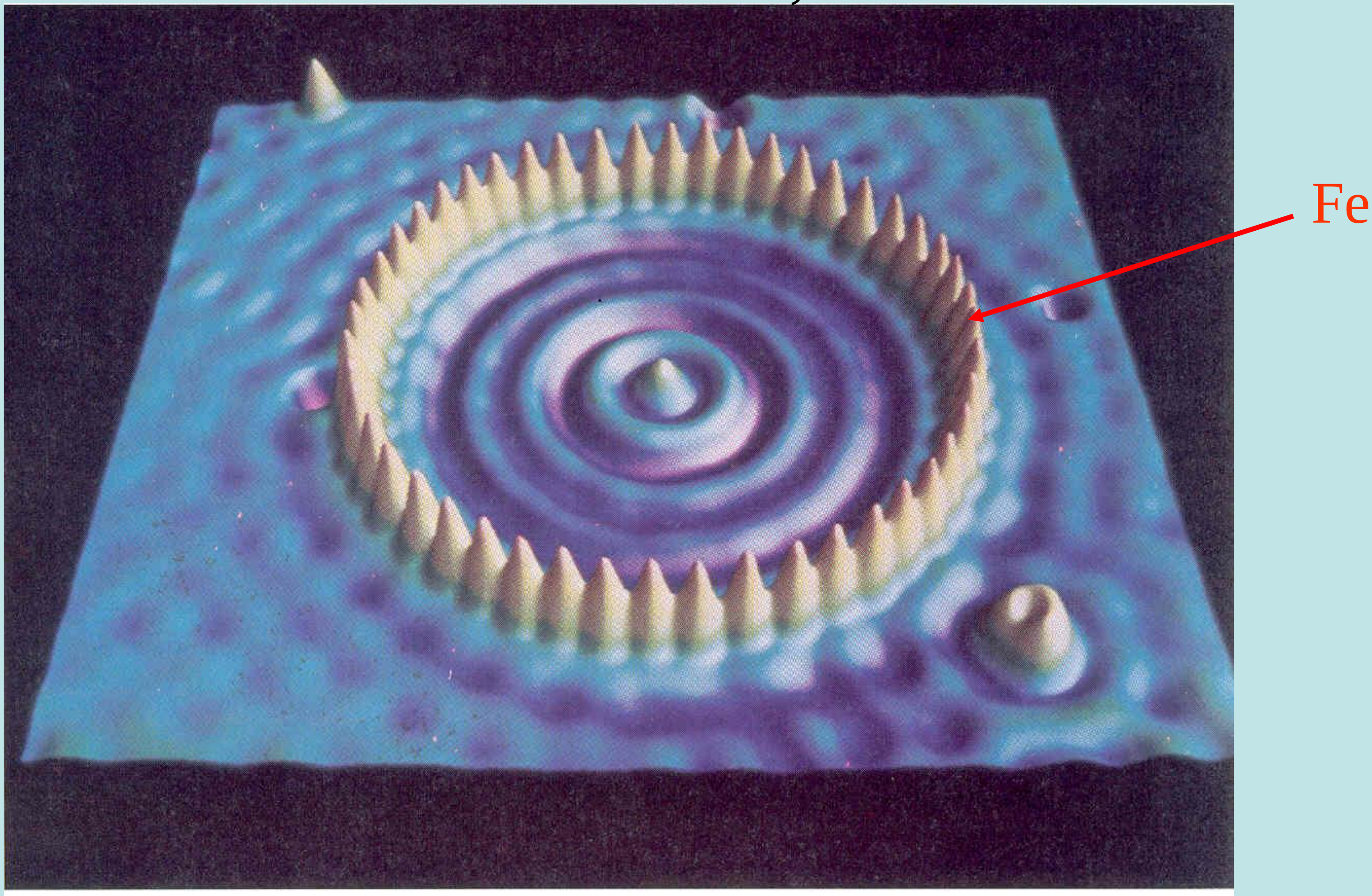


Figure 1.10 Scanning tunneling microscope. (From C. Julian Chen, *Introduction to Scanning Tunneling Microscopy*, Oxford: Oxford University Press, 1993.)

量子柵欄 (Quantum Corral)

Of 7.13 nm radius, 48 Fe atoms



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

Third Lesson:

量子物理的重要！

尺度變化的起源

- 邊界的影響
  - 邊界佔有比例的增加
  - 邊界態 (surface / edge modes) 的存在
  - 幾何結構的重整

- 粒子數的減少
  (束縛減弱 , 擾動增加 , 連續性的不適用..)

- 不同物理量有不同的尺度變化

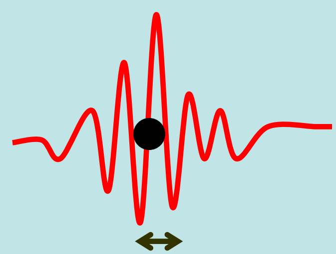
=> 最有可能產生新的突破

- 量子效應

物質波與力學性質的聯繫

h = Planck constant
$(6.626\times10^{-34}$ joule-sec)

DeBroglie:
$\lambda = h/p$



λ

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

波長

自由電子: $\lambda_{th}(300K) = 6.2nm$

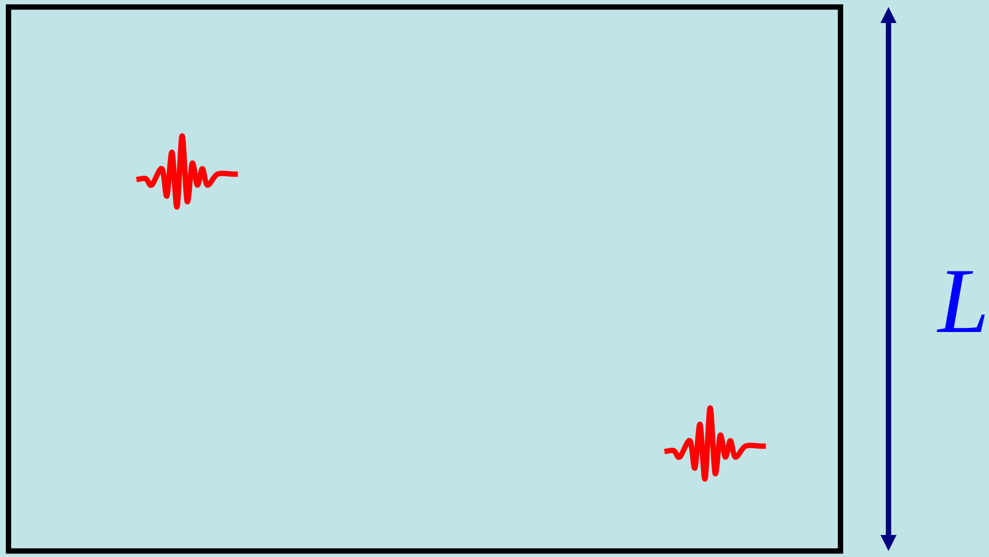
(半導體中$10nm \le \lambda \le 100nm$)

原子: $\lambda_{th}(300K) \le 0.2nm$

塊材極限 ⇔ 奈米極限

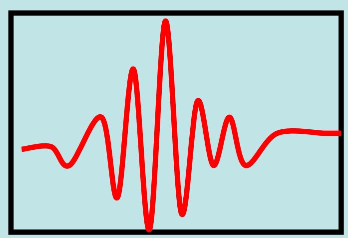
塊材

$\lambda \ll L$



奈米

$\lambda \sim L$

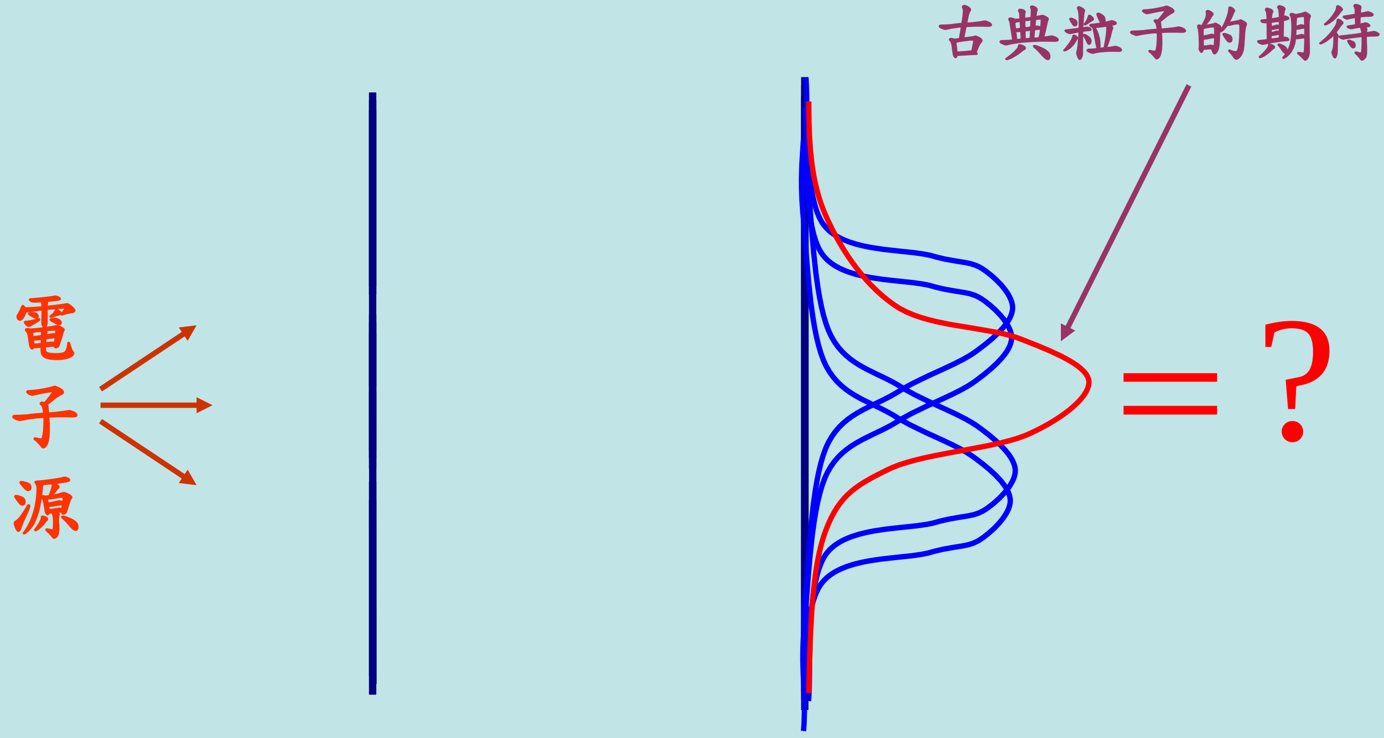


奈米尺度的主要量子效應

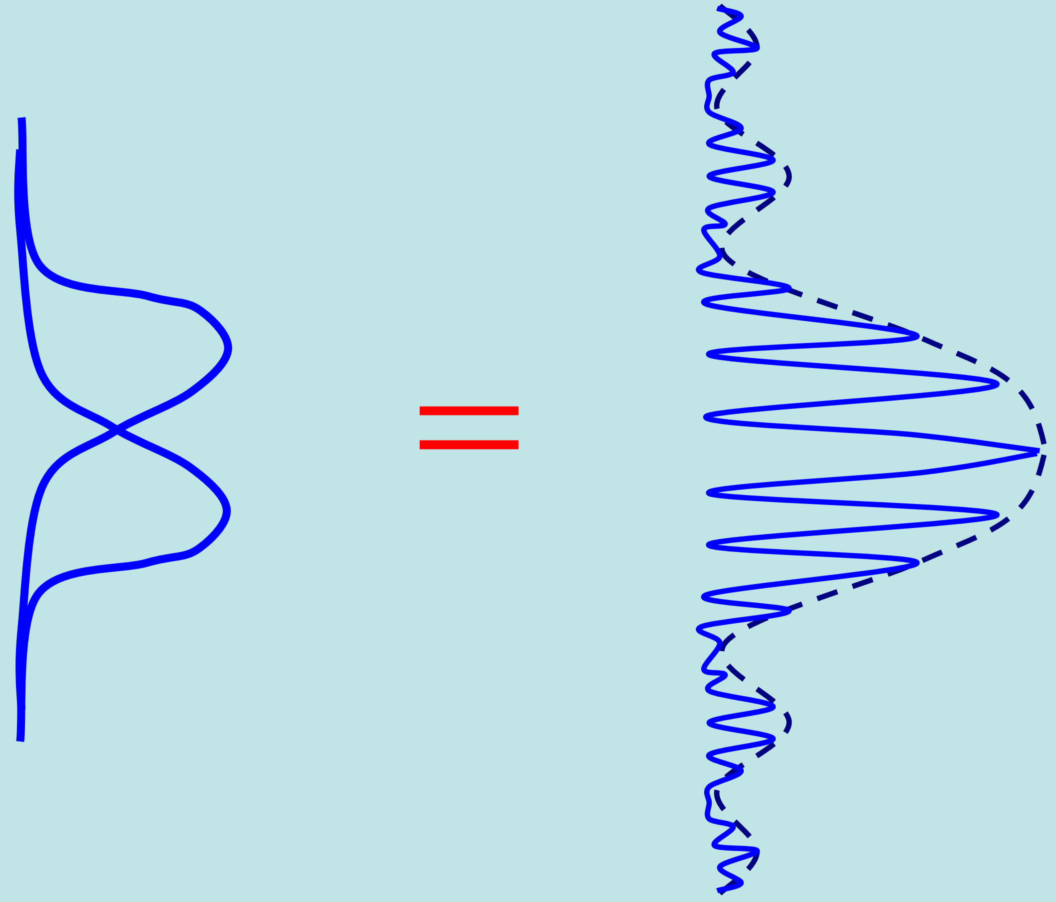
- Interference
- Quantization
- Tunneling
- Quantum Spin

(I) 干涉 (Interference)

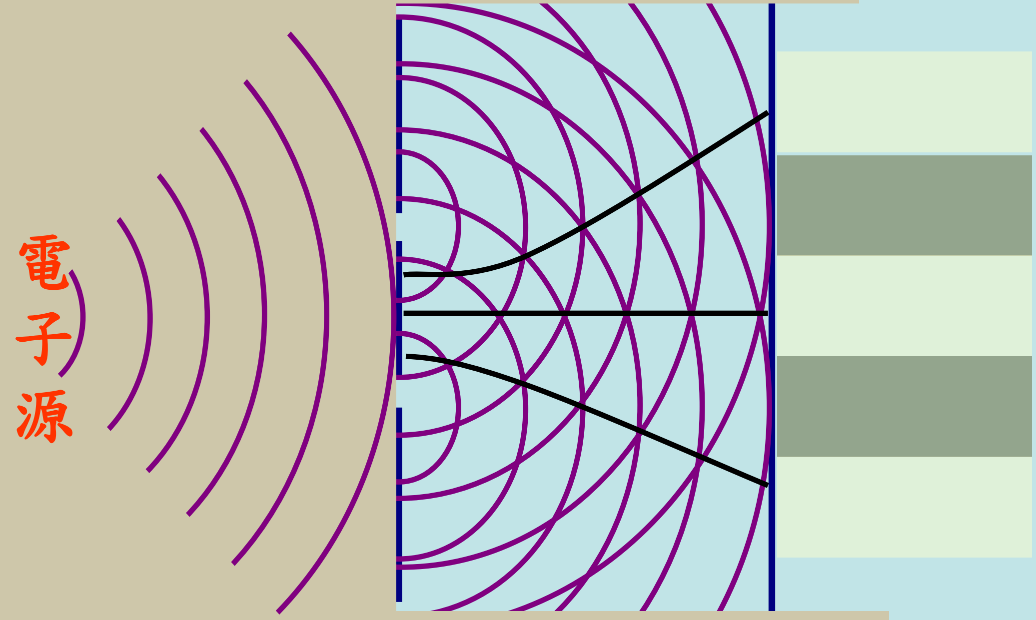
神奇的電子波動性

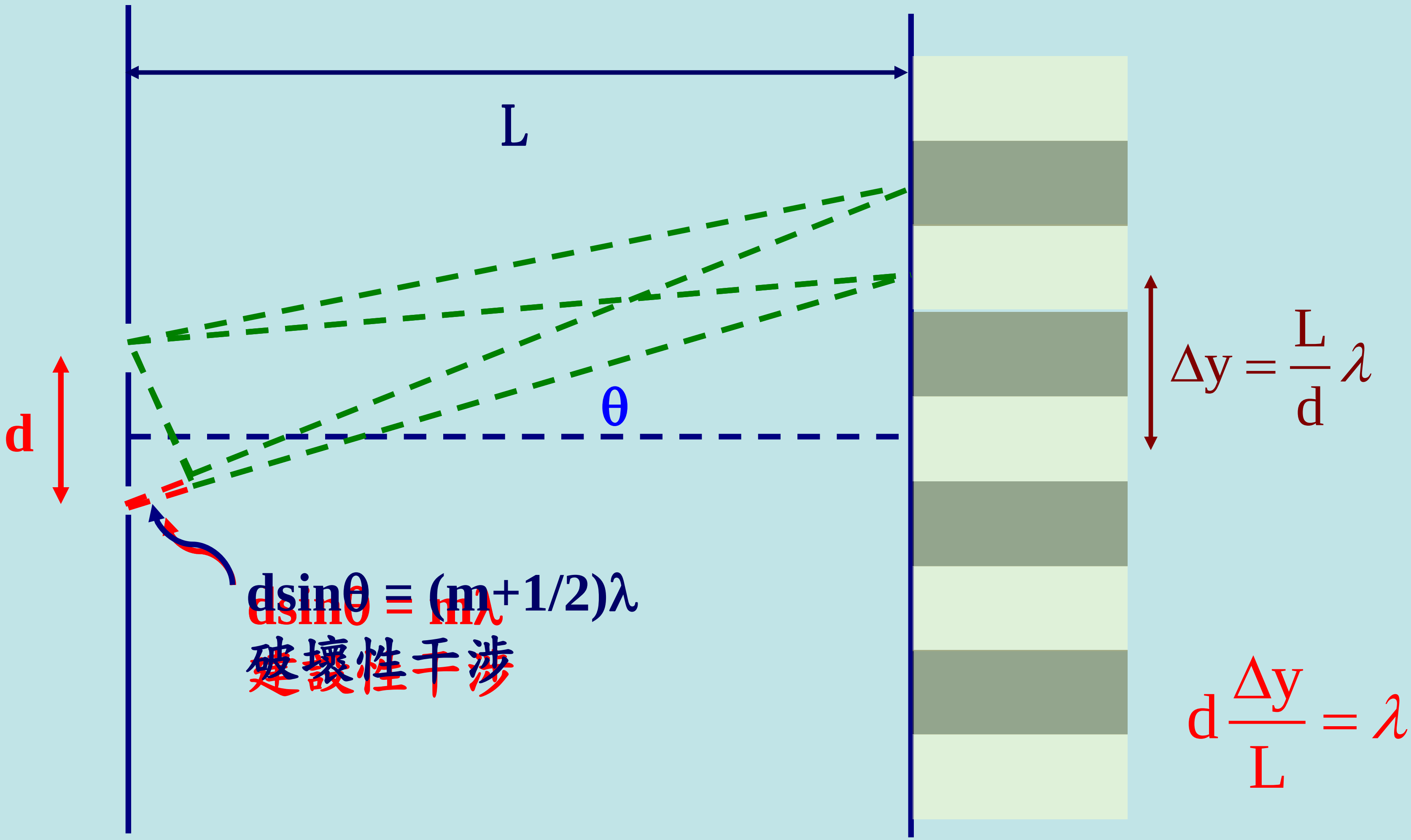


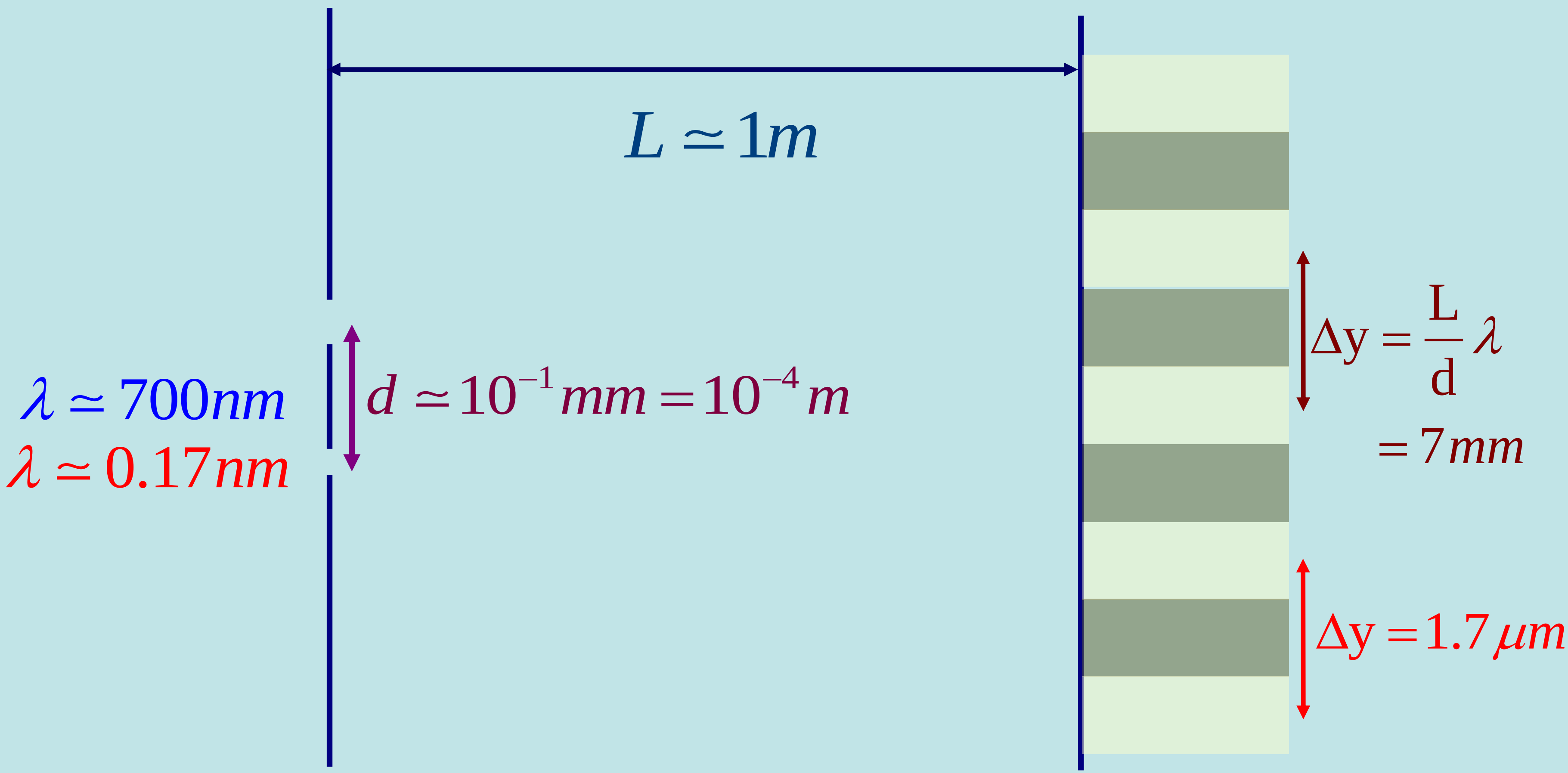
電子波動性



電子的雙狹縫干涉




L
θ
d
$\Delta y = \frac{L}{d}\lambda$
dsinθ = (m+1/2)λ
dsinθ = mλ
破壞性干涉
建設性干涉
$d\frac{\Delta y}{L} = \lambda$


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

(II) 量子化

(Quantization)

物質波的束縛

⬇

駐波

⬇

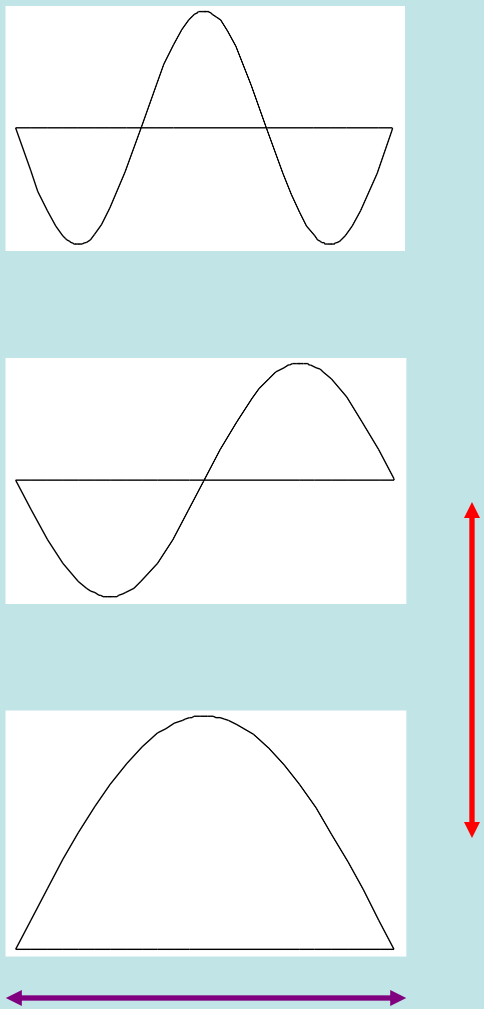
量子化

能量的量子化

$\mathrm{n}=3$

$\mathrm{n}=2$

$\mathrm{n}=1$



L

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

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

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

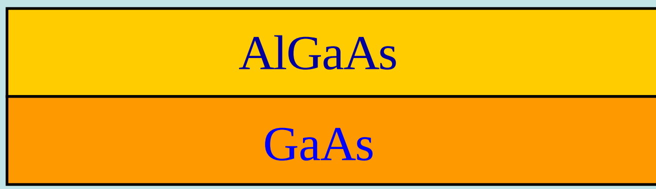
$$E_n=\frac{p^2}{2m}=\frac{n^2h^2}{8mL^2}$$

束縛結構的分類

依被束縛方向的數目分類:

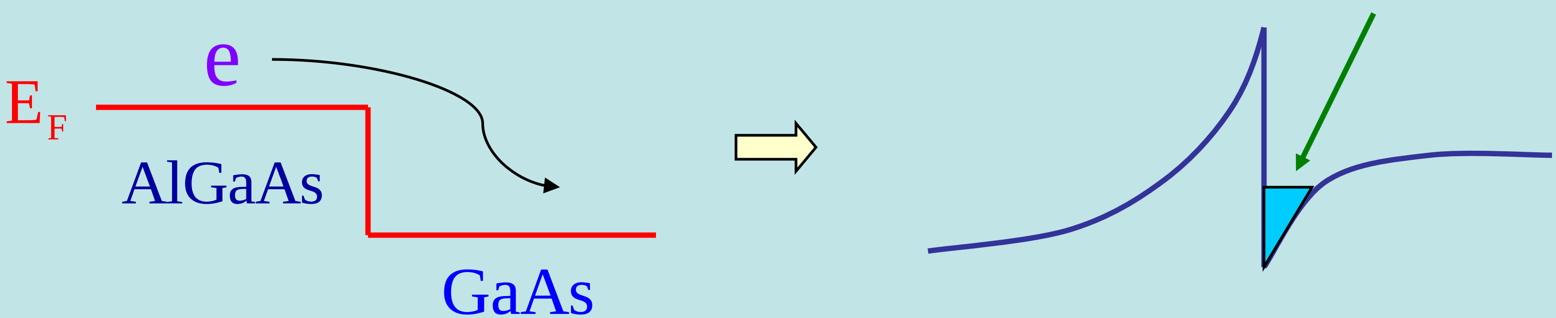
量子井 (quantum well): 1個束縛方向

MOSFET:

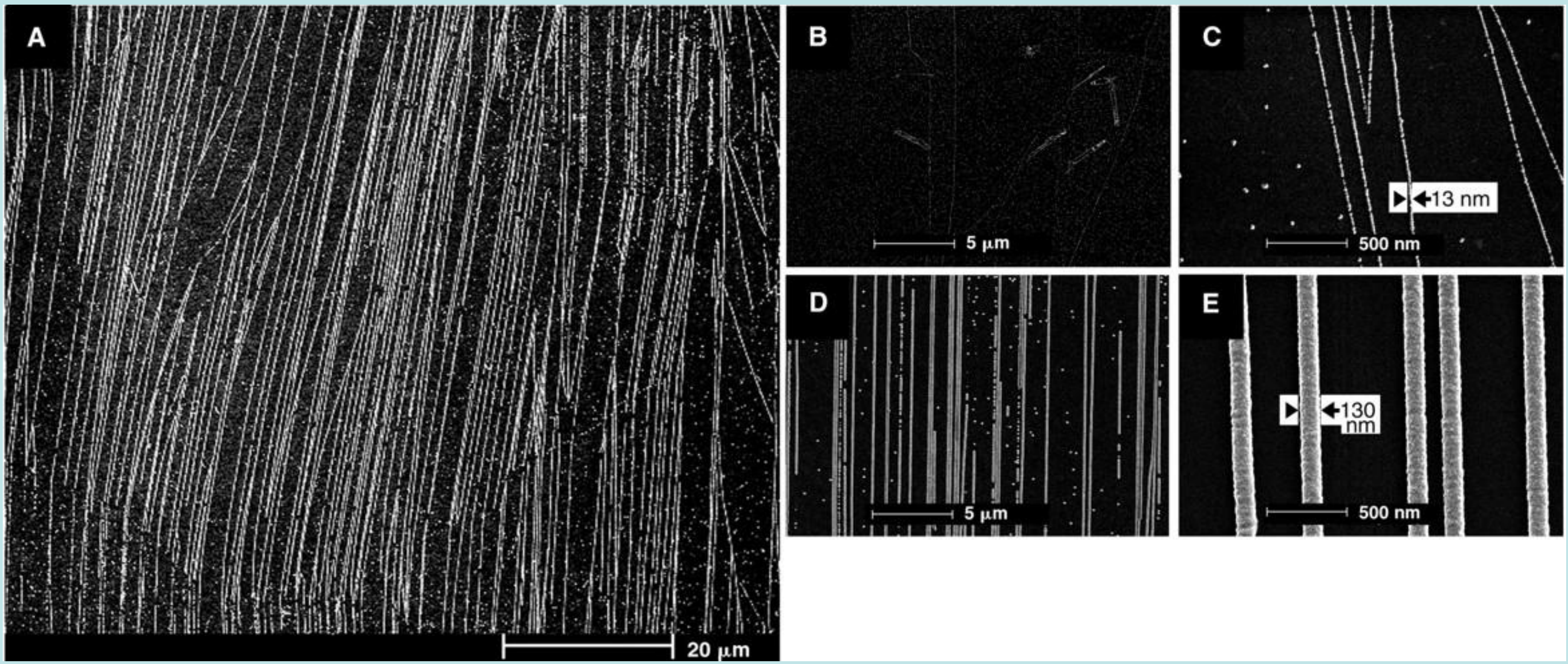


2D electron Gas

二維電子氣



量子線 (quantum wire): 2 個束縛方向



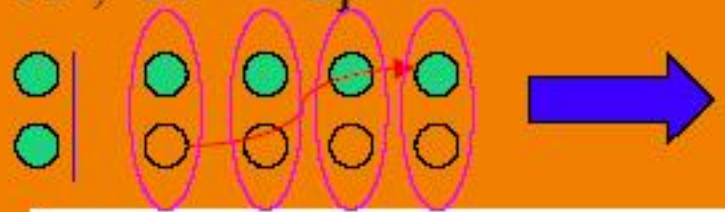
SEM images of MoO_x nanowires on graphite surfaces

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

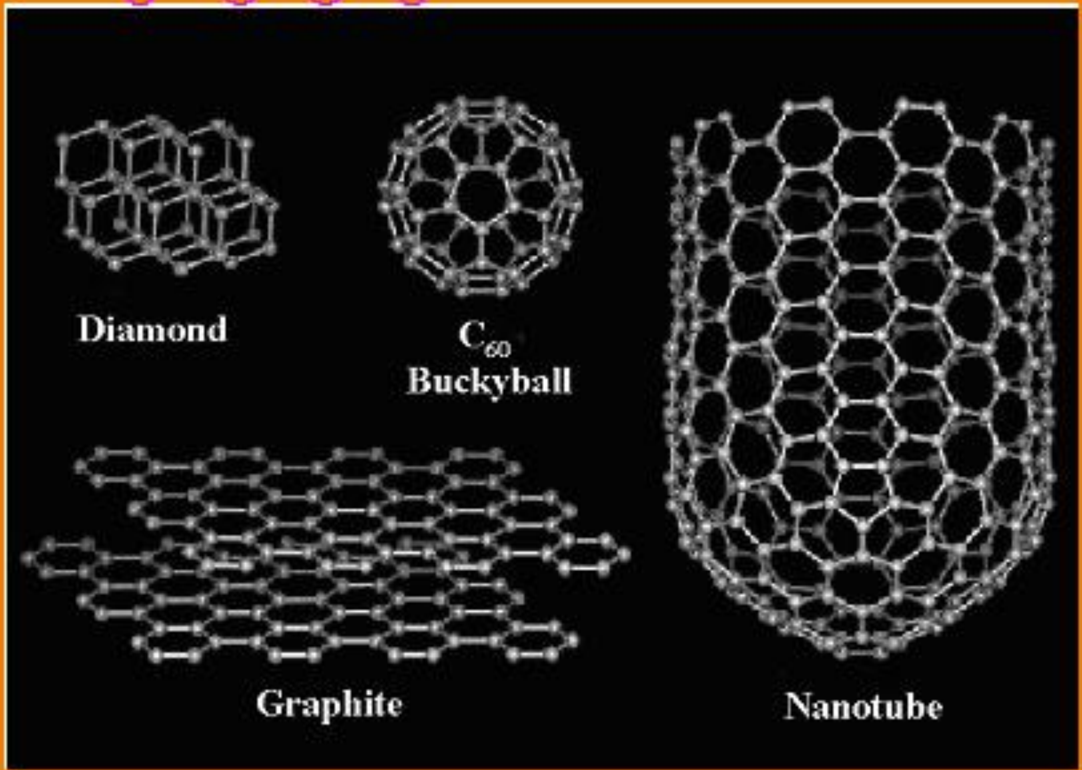
Carbon Nanotube

- Structure of carbon nonatubes

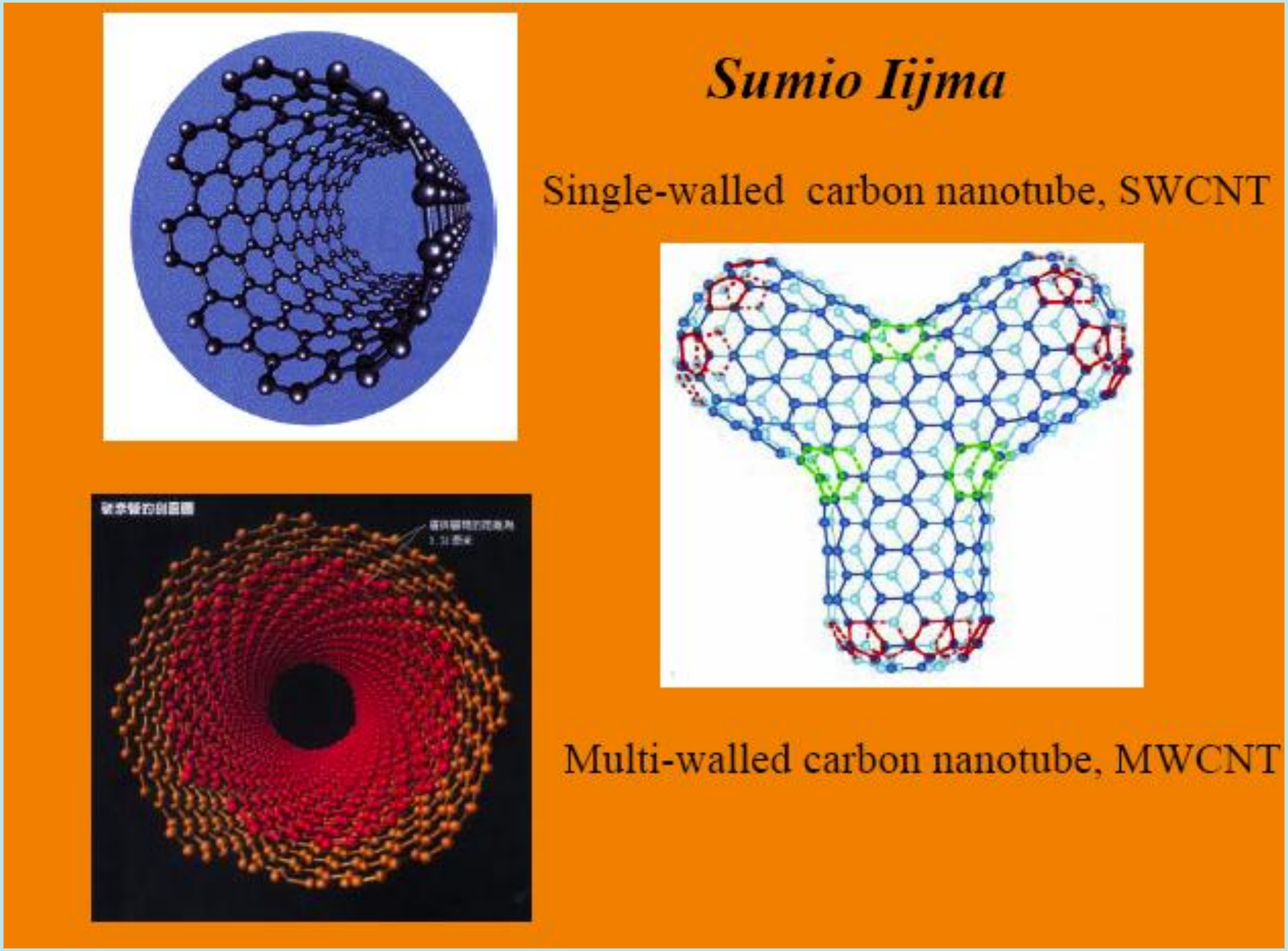
Carbon: $1s^2$, $2s^1$ $2p^3$



sp^1, sp^2, sp^3

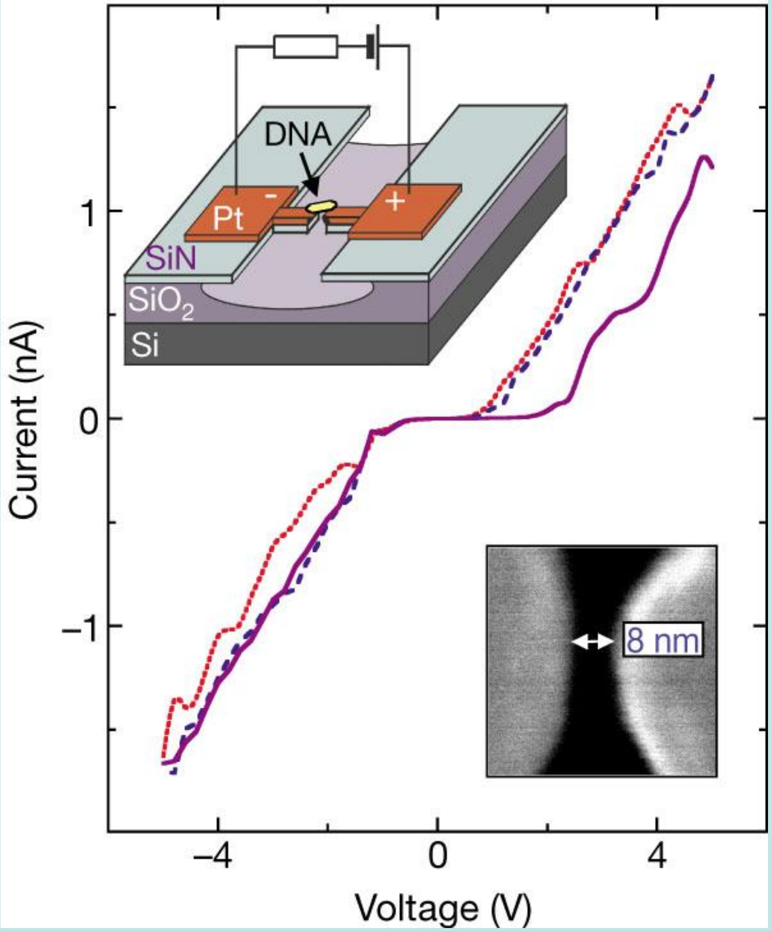


Carbon Nanotube



Carbon Nanotube based Transistors / Electronics

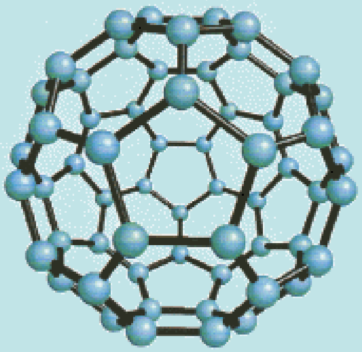
DNA線



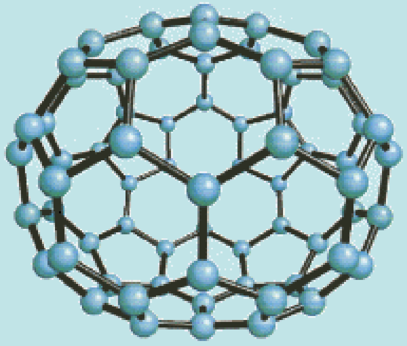
DNA 可以拿來當電線嗎？

To make new transistors?

量子點 (quantum dot): 3 個束縛方向

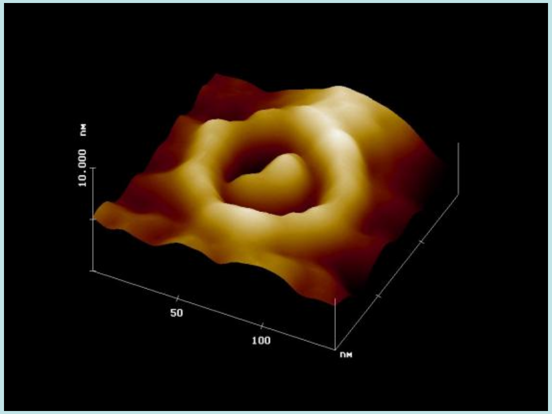


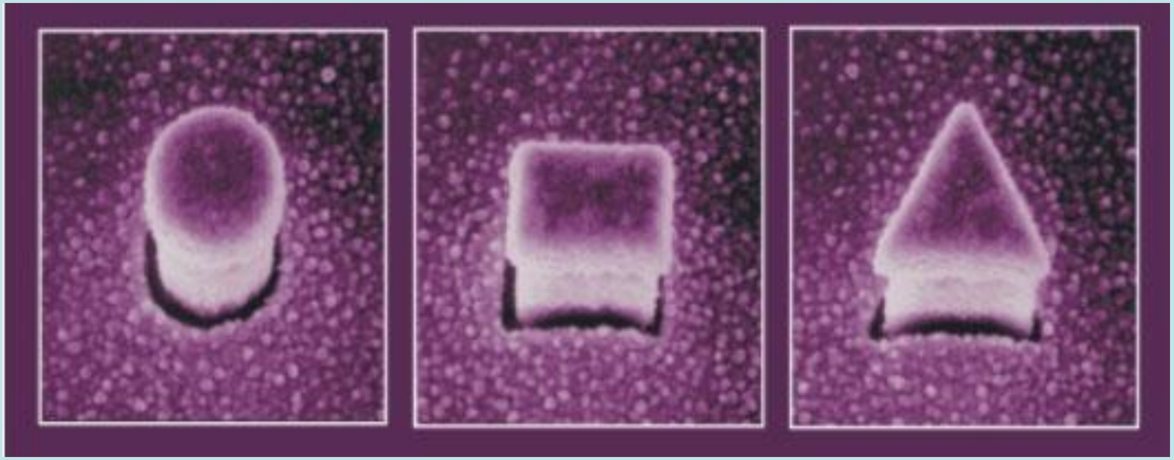
C_{60}



C_{70}

不同形狀的量子點

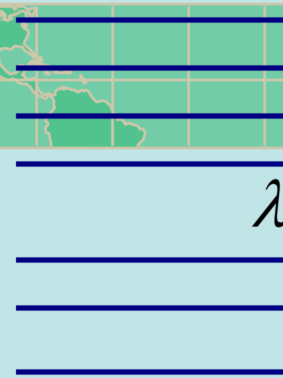




黃 紅

吸收 散射

λ_0

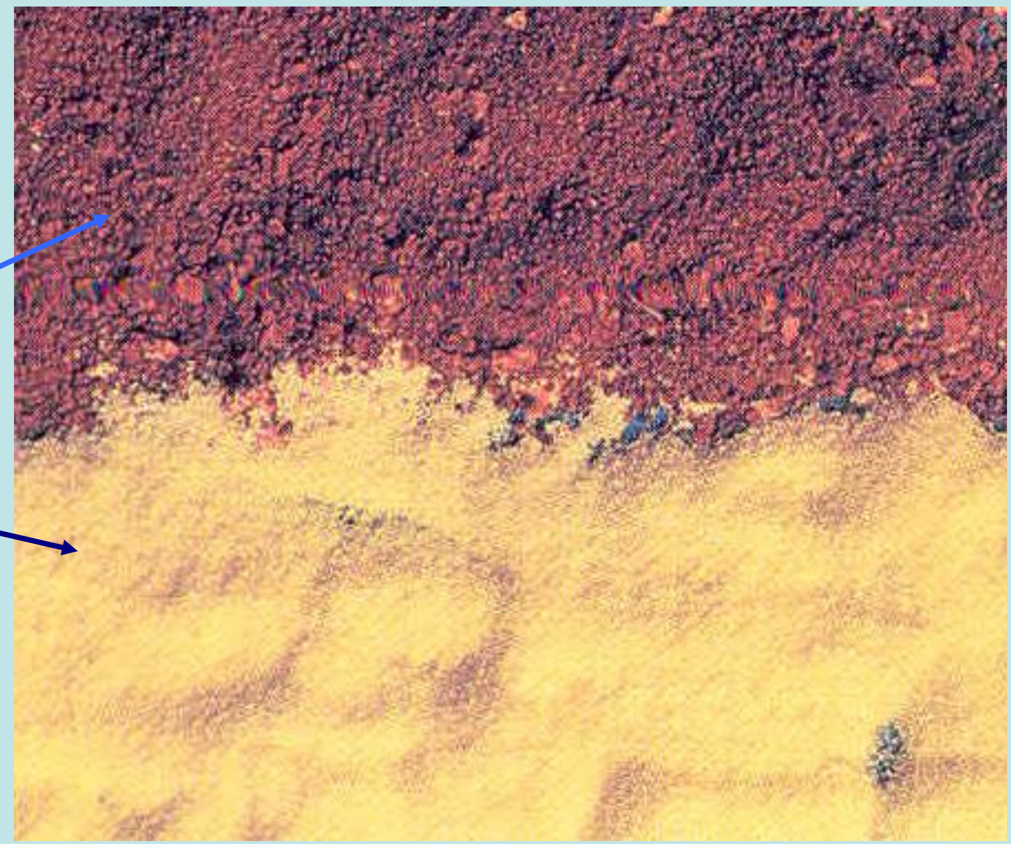


$$E = hc/\lambda \propto 1/L^2$$

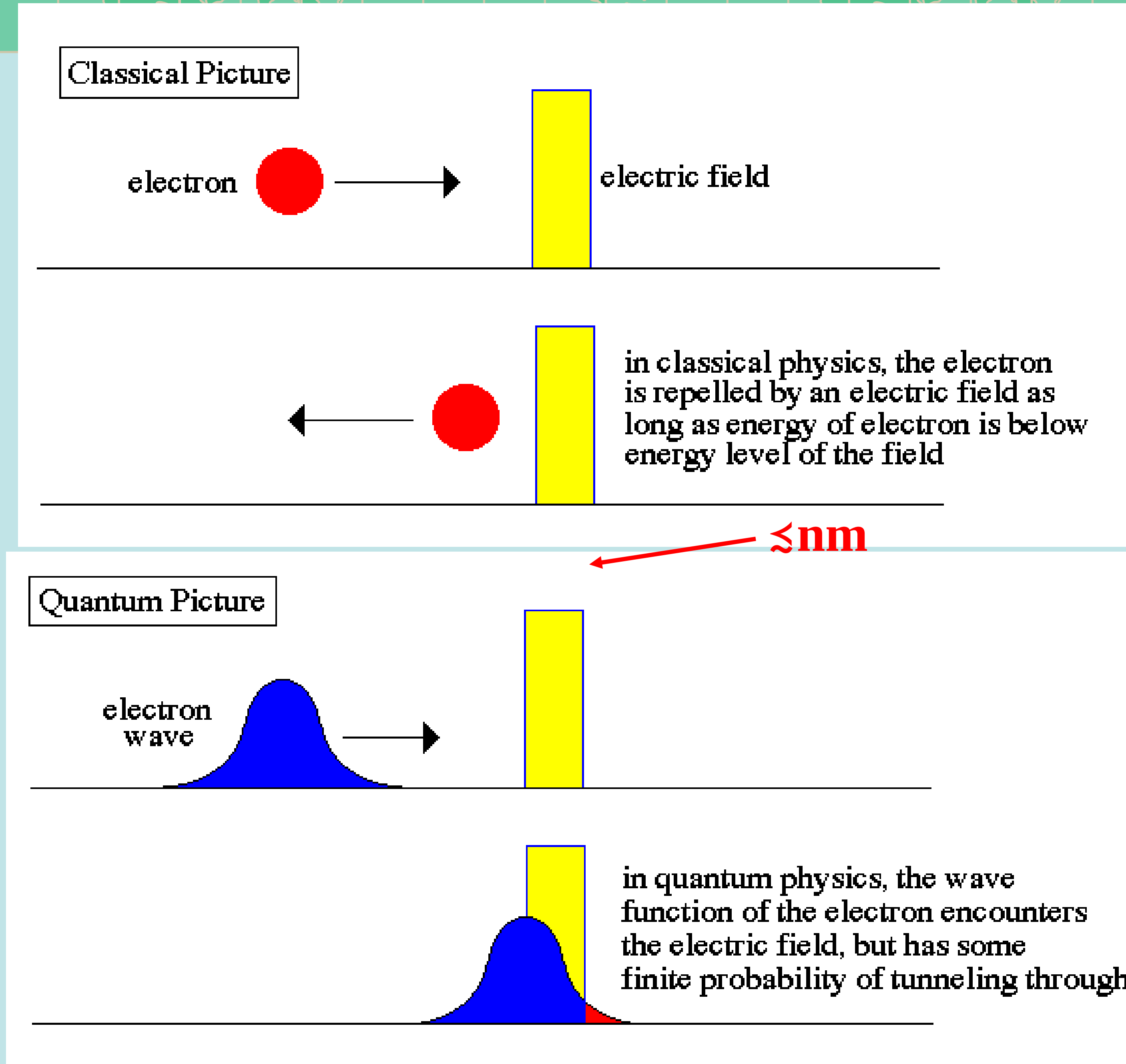
powdered Cadmium Selenide

larger

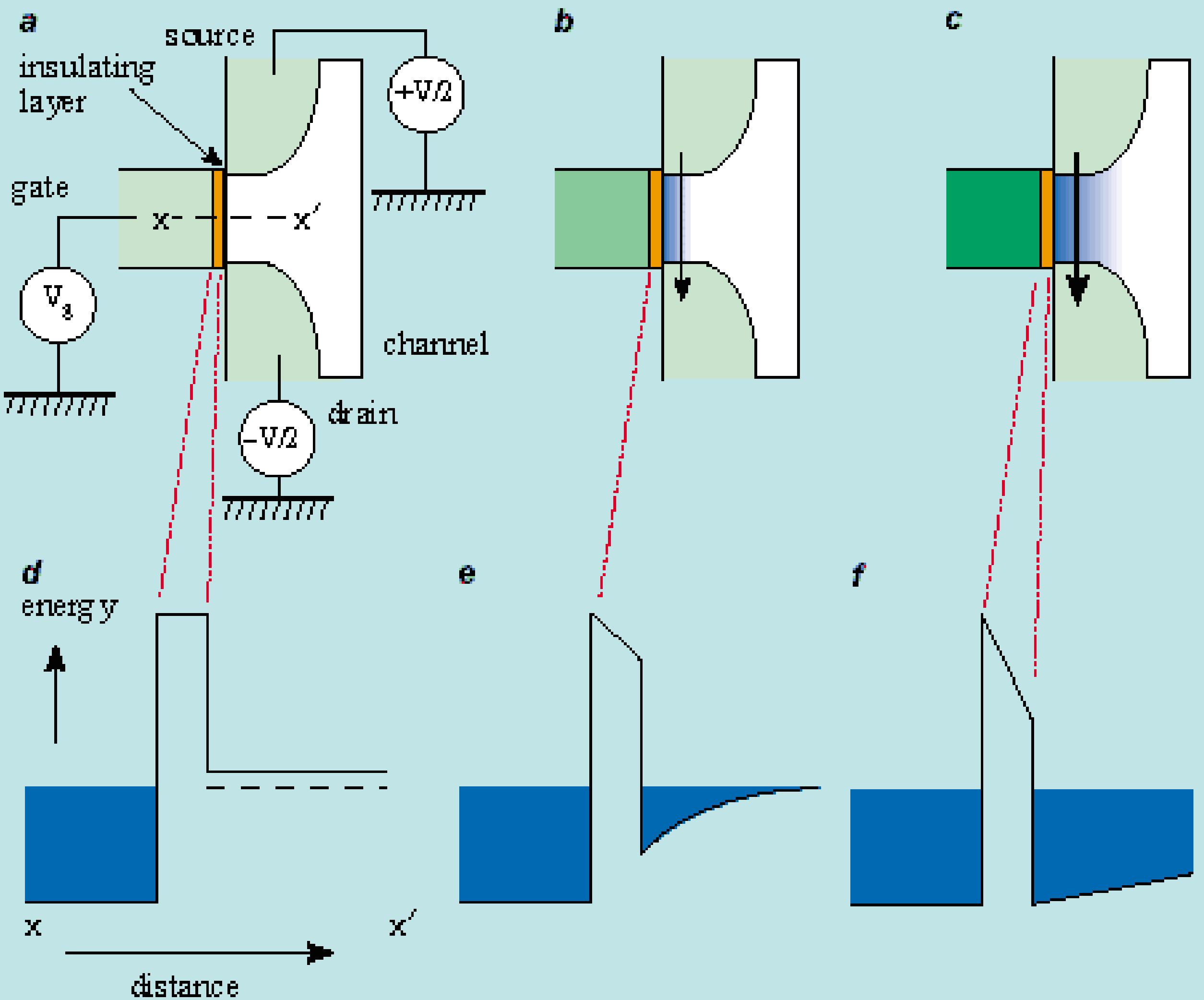
smaller



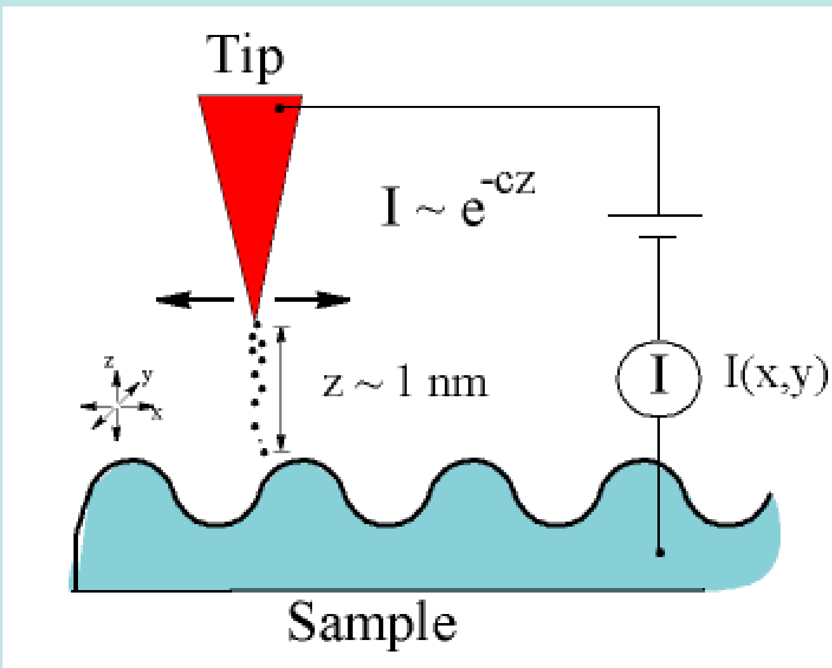
(III) 穿隧效應 (Tunneling)

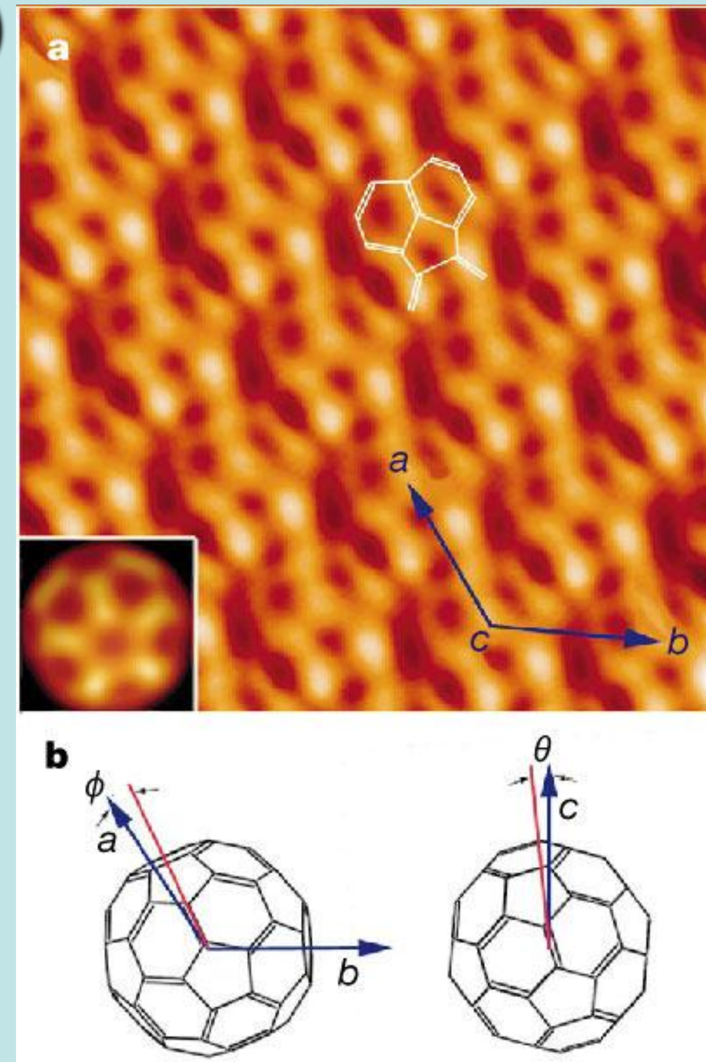

Classical Picture
electron
electric field
in classical physics, the electron
is repelled by an electric field as
long as energy of electron is below
energy level of the field
≲nm
Quantum Picture
electron
wave
in quantum physics, the wave
function of the electron encounters
the electric field, but has some
finite probability of tunneling through

穿隧效應是電晶體尺寸變小時可能失敗的主因



穿隧效應卻被物理學家用以探測奈米結構 Scanning Tunneling Microscope (STM)



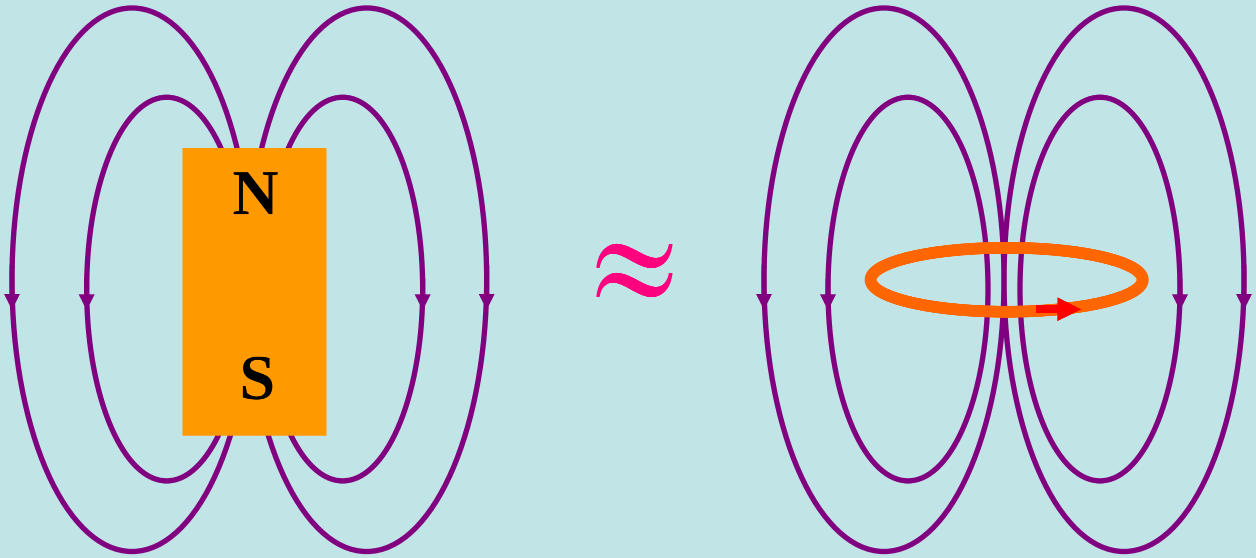


Nature 409, 304(2001)

(IV) 自旋 (Quantum Spin)

自旋(spin)與科技的關係

自旋爲磁性的最小單位，源自於量子力學



以往主要被用來作記憶使用
如硬碟 **(magnetic recording)**
~有300億市場.

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

現在的努力重點是希望能以自旋的組態作控制:

Spintronics ⇔ Electronics

自旋電子學!

新一代電腦

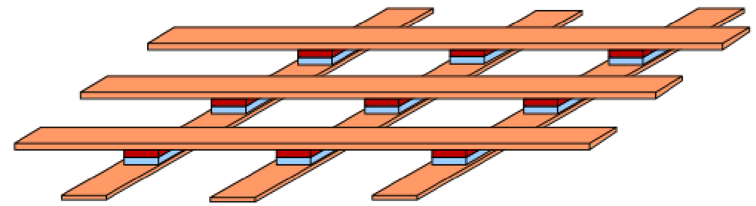
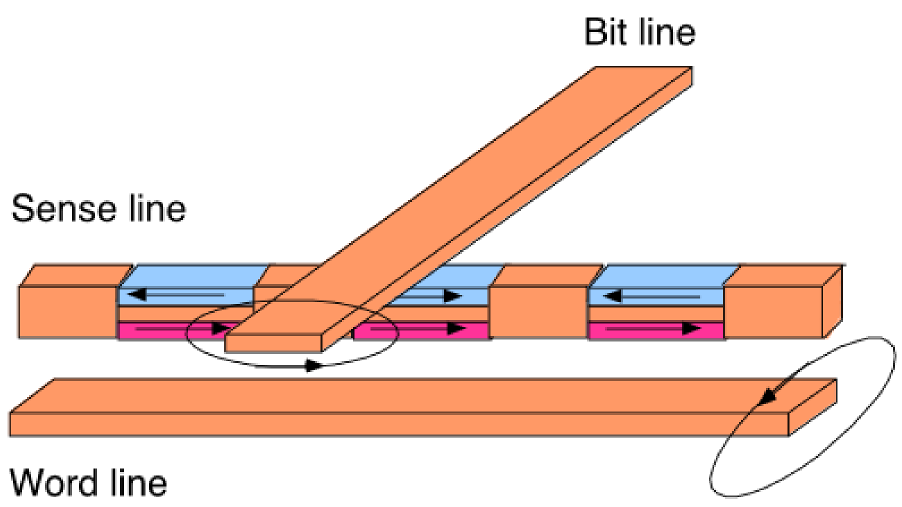


Fig. 7. A schematic representation of RAM that is constructed of magnetic tunnel junctions connected together in a point contact array. The conducting wires provide current to the junctions and permit voltage measurements to be made. They also enable the manipulation of the magnetization of the elements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

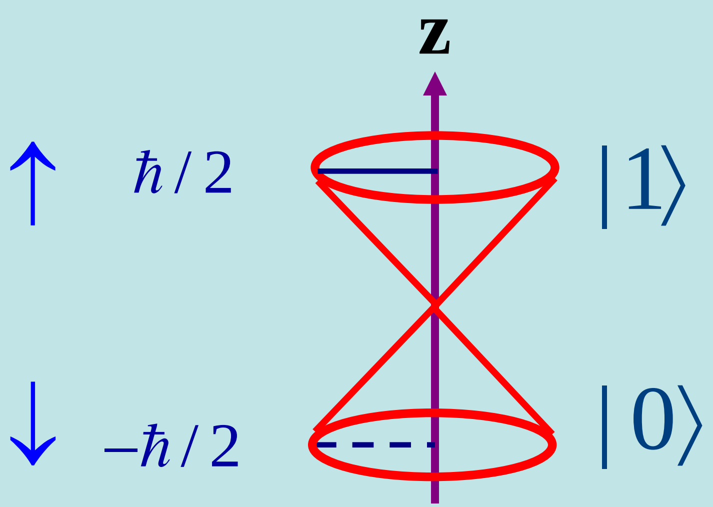
運算儲存一次完成



電源一開電腦就好！

磁鐵的量子行為

-以自旋為量子位元 (qubit)



$$qubit = \alpha|0\rangle + \beta|1\rangle$$

Due to superposition
More information!

Summary

奈米尺度的量子效應

- Interference
- Quantization
- Tunneling
- Quantum Spin

這些效應對人類生活的衝擊
正在發展進行中!