Introduction to Nanophysics

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What is the size for a “nano” ?

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

厘米 10^{-3} m, **Macro**

微米 10^{-6} m, **Micro**

奈米 10^{-9} m, **Meso**

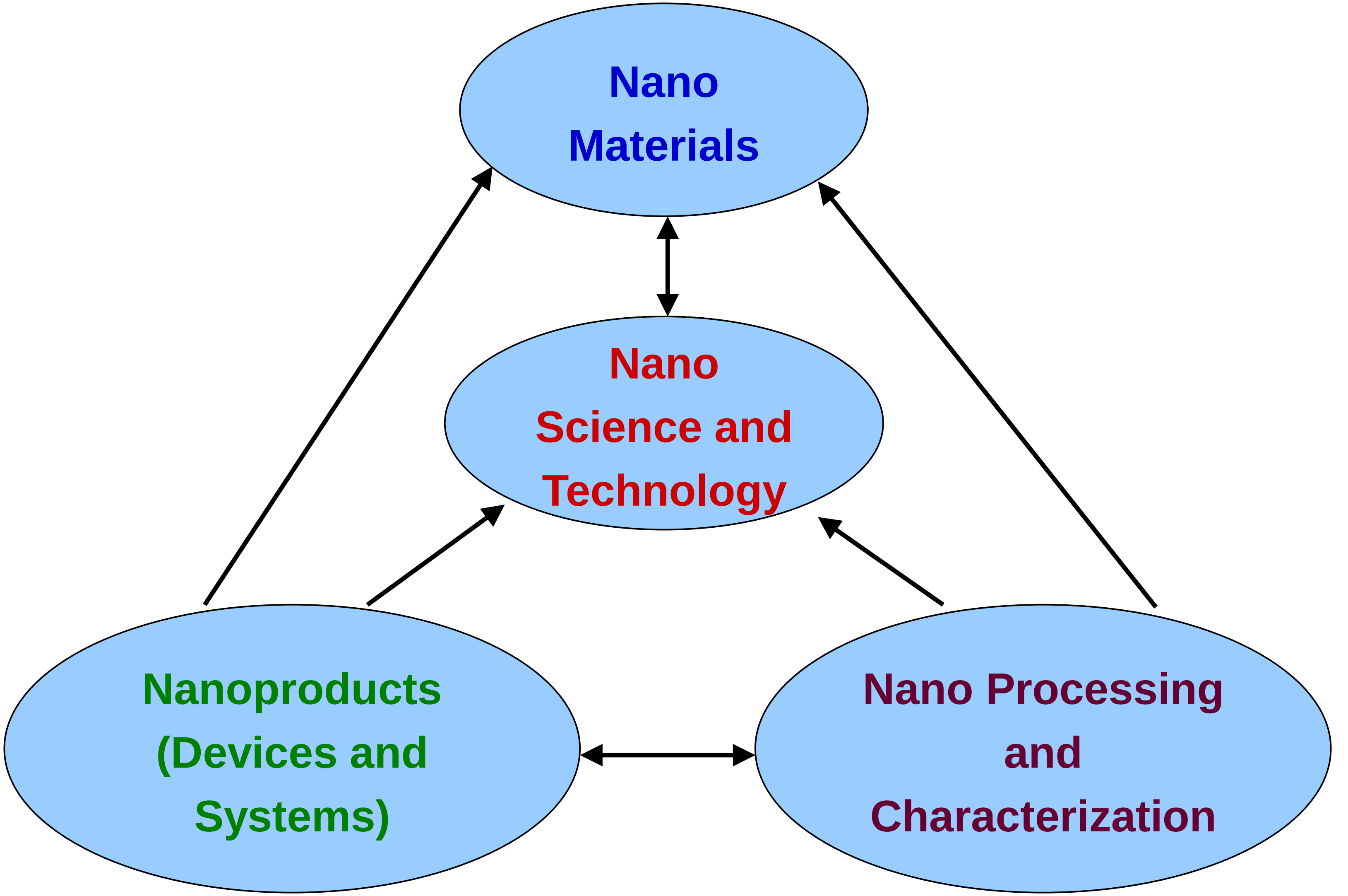
R. Feymann Already Knew about this !

“ 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 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 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

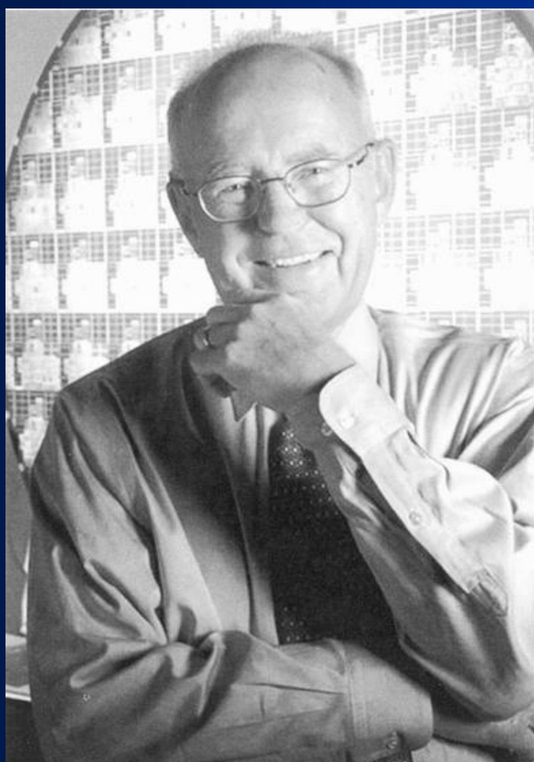
近來大力推動奈米科技的背景

來自微電子學可能遭遇瓶頸的考慮

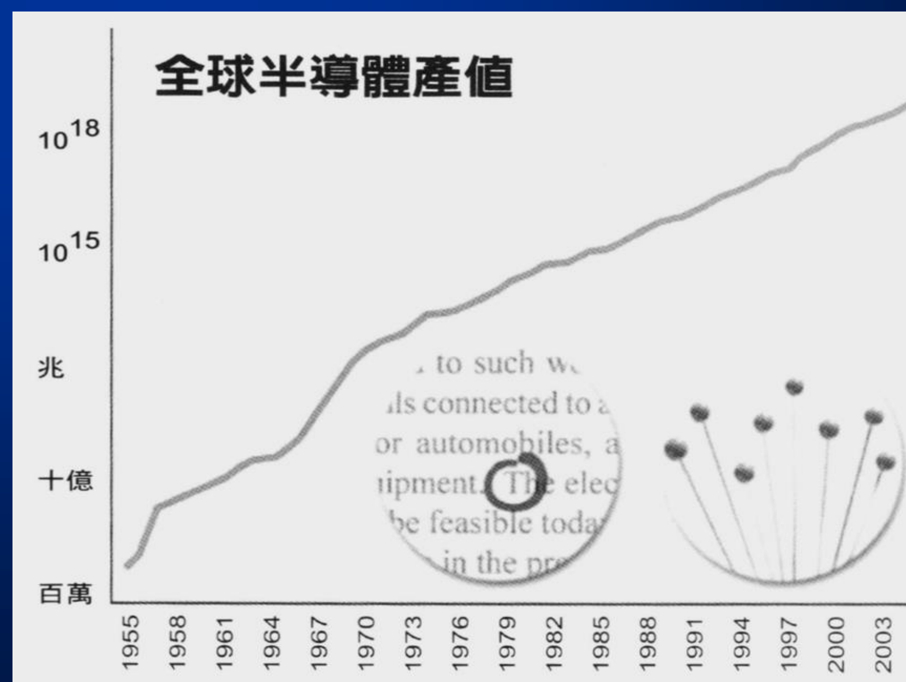
Moore's Law：摩爾定律

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



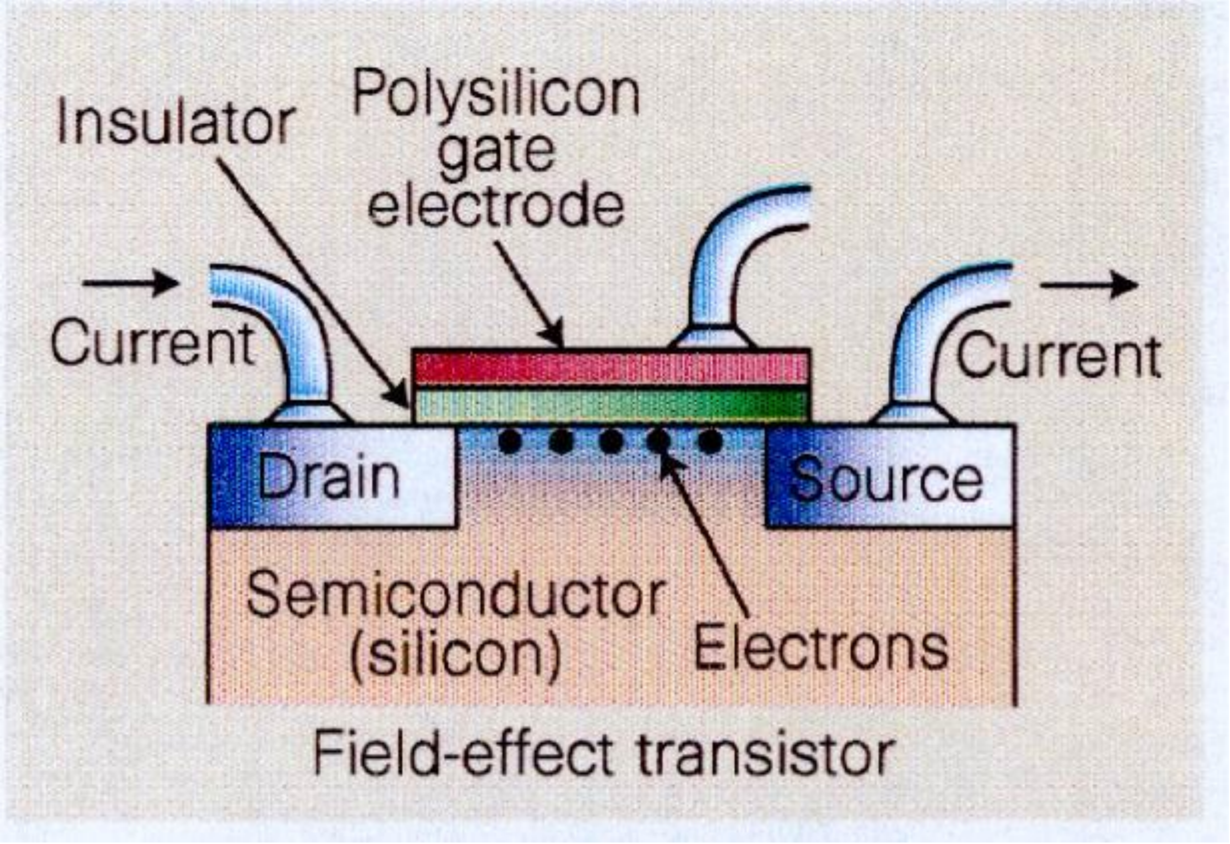
Gordon Moore



Two basic modern electronic technologies in condensed matter physics field

- MOSFET
- MRAM

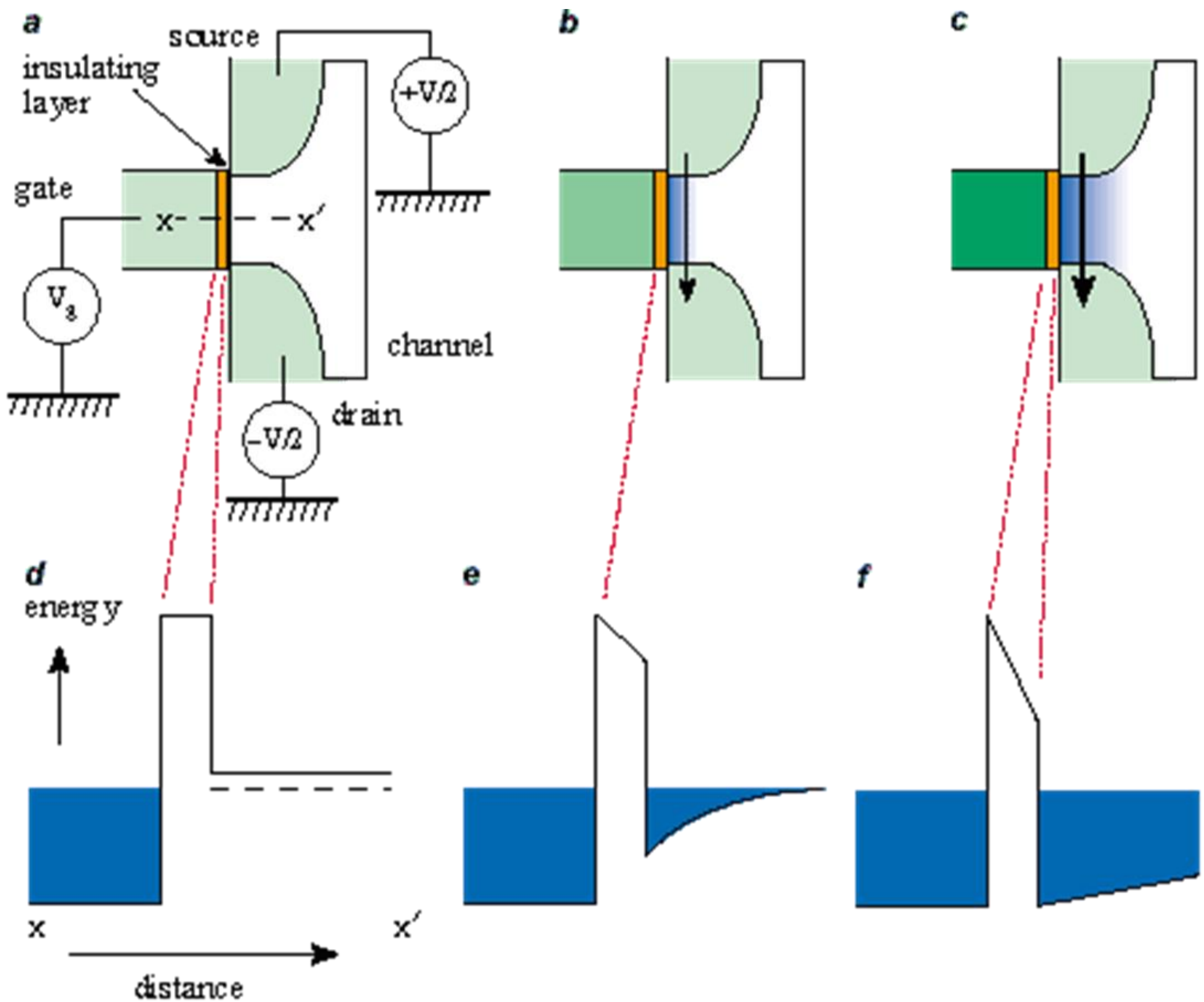
Metal-Oxide-Field Effect Transistor (MOSFET)



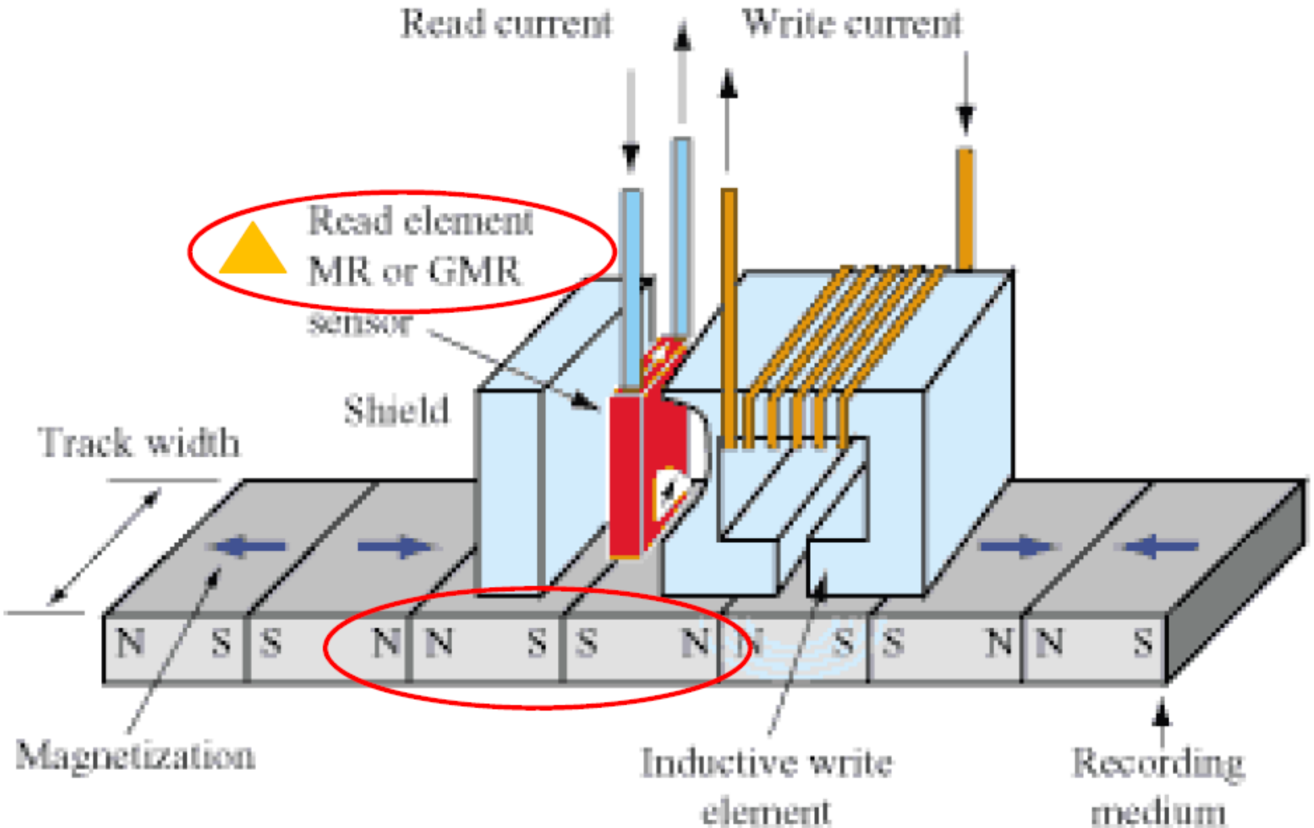
1960 Kahng and Atalla, First MOSFET

1970 First IC, 1 kbit, 750 khz microprocessor

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

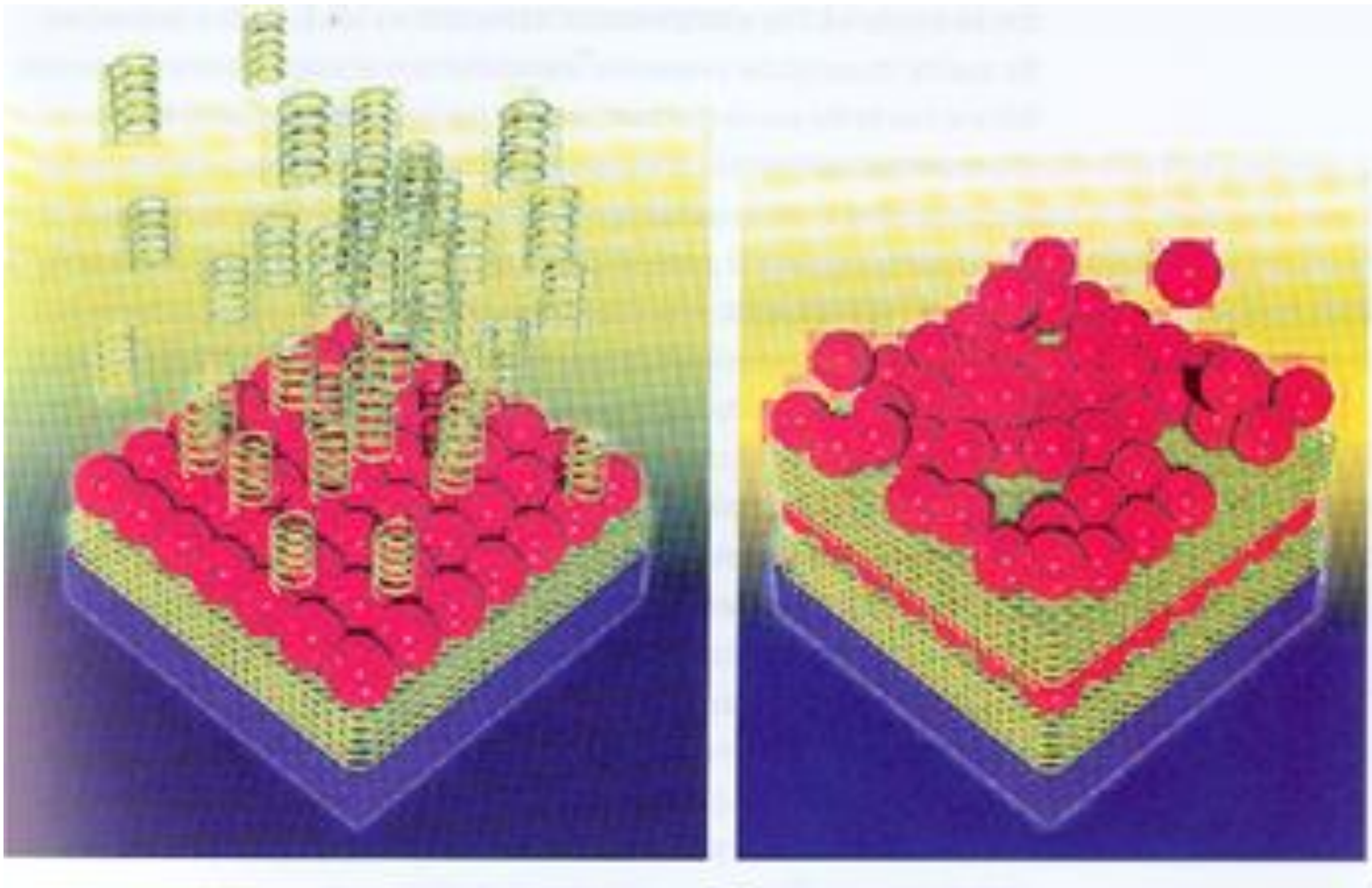


電子科技之基礎--磁記錄


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

Bottom-up Nano systems & Self-Assembly

enabling to design large molecules and nano materials



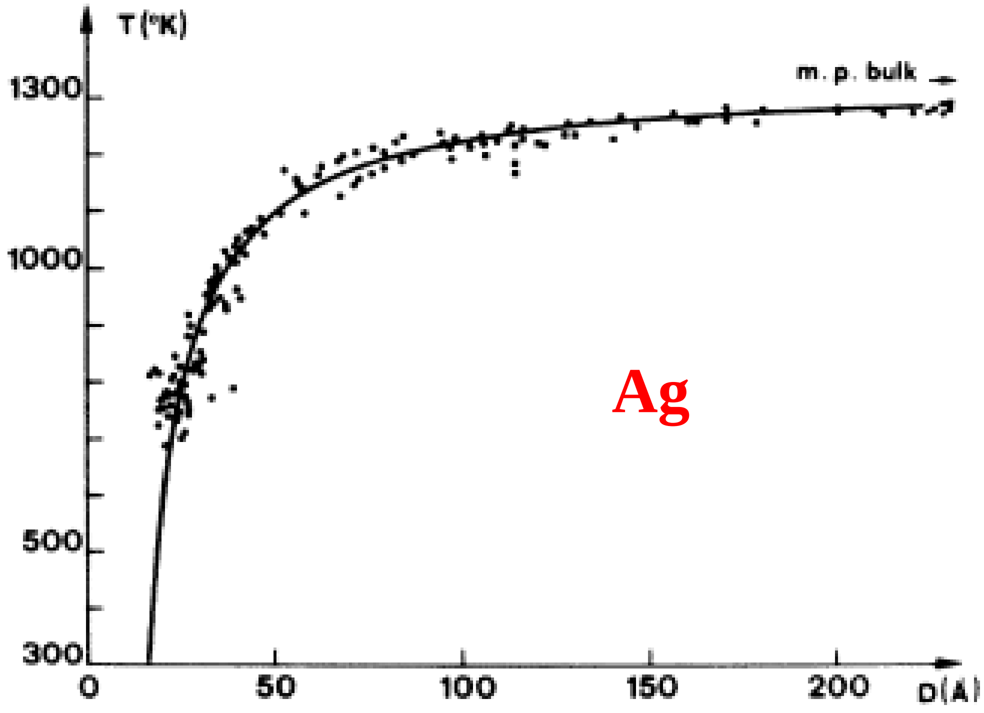
Five major lessons

that we learned

The First Lesson :

Bulk-to-nano Transition

Ex: size-dependence of melting temperature



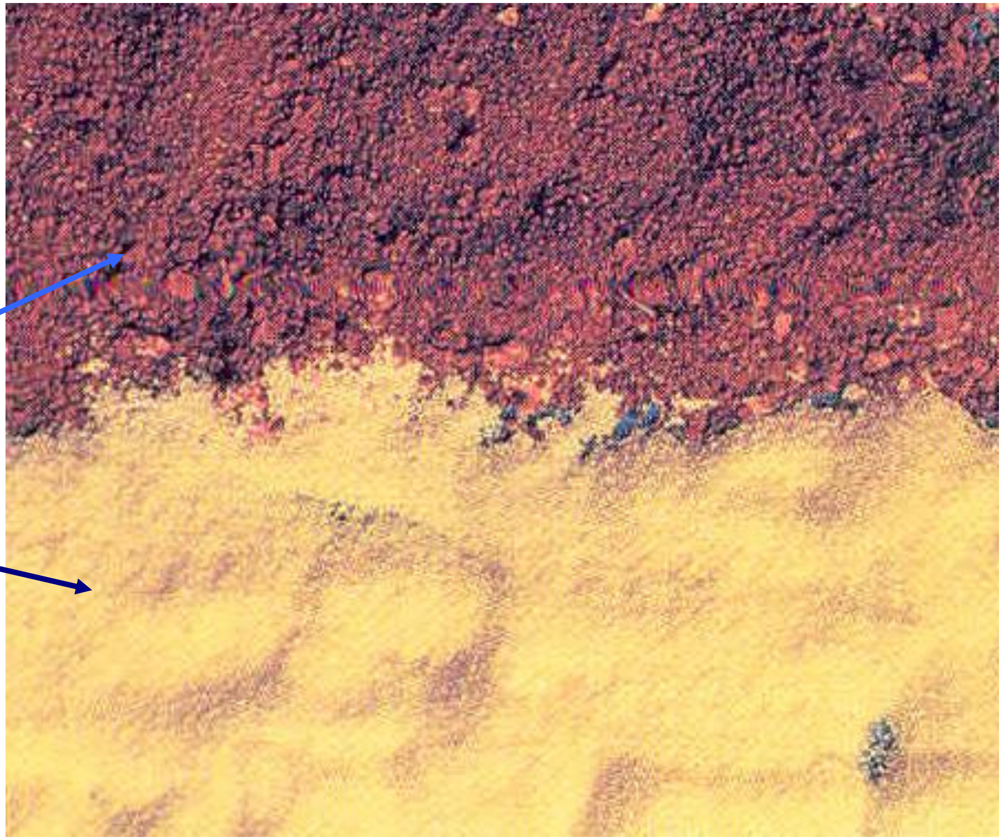
Ph. Buffat and J-P. Borel, Phys. Rev. A13, 2287 (1976)

Ex: size-dependence of color

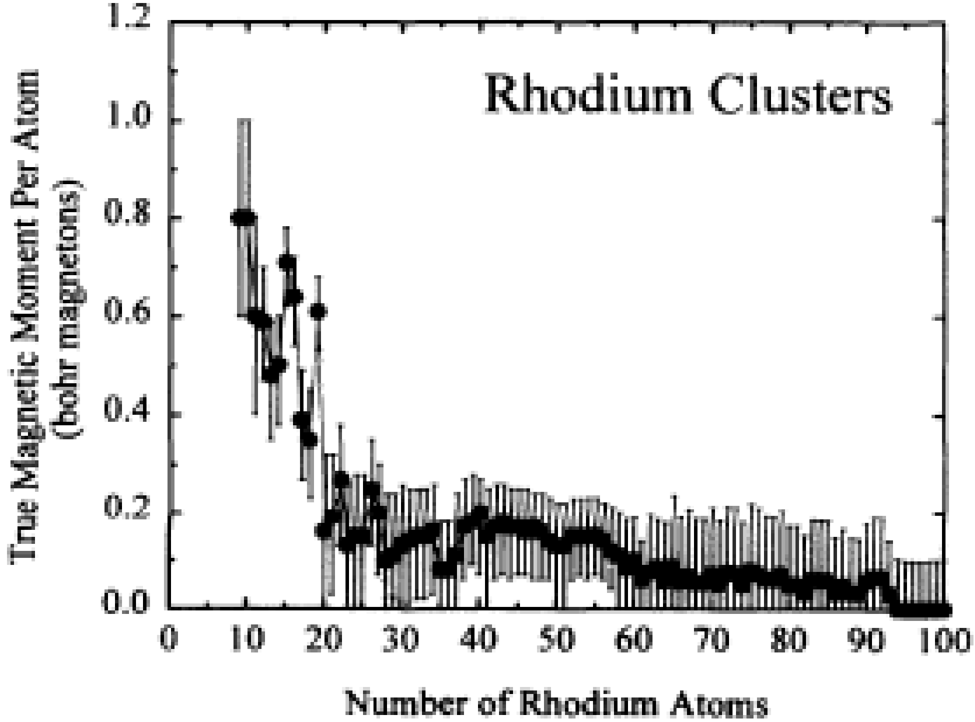
powered cadmium selenide (CdSe)

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 materials and structures on the nano scale***

- ***The ability of detecting and manipulating on the nano scale***

(I) Advance in thin film growth:

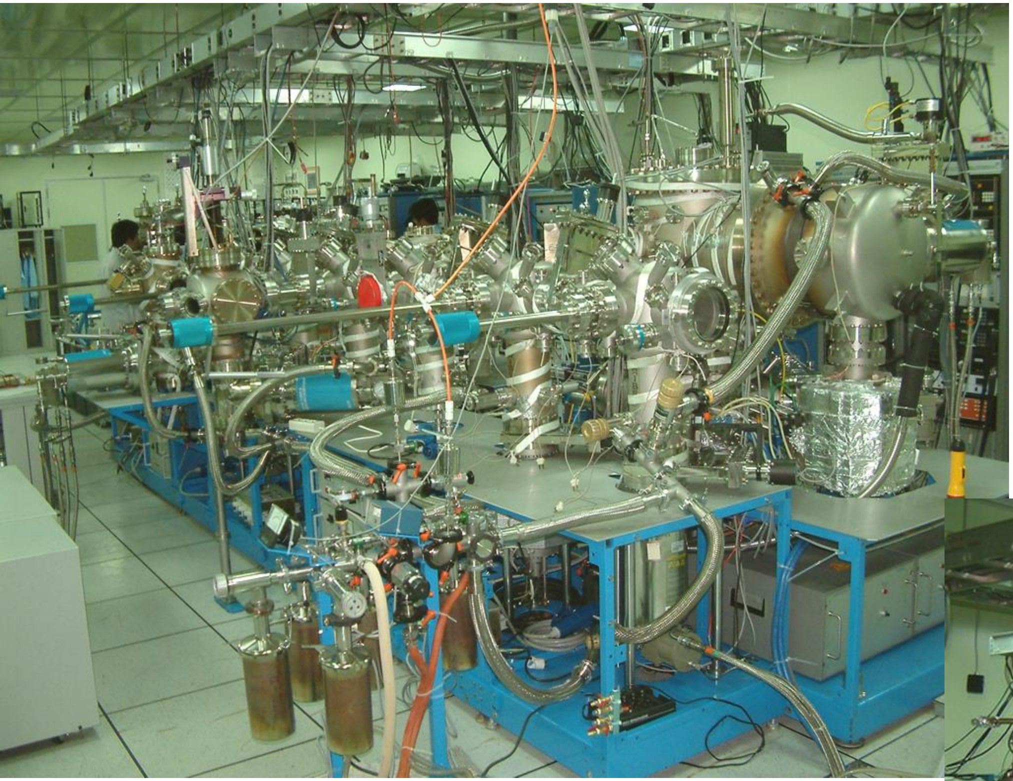
Molecular beam epitaxy (MBE), atomic layer deposition (ALD), laser MBE, etc…

- For nano electronics in metals, oxides, and semiconductors.

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

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

Integrated Multi-chamber MBE System



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

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

Scanning Tunneling Microscope (STM)

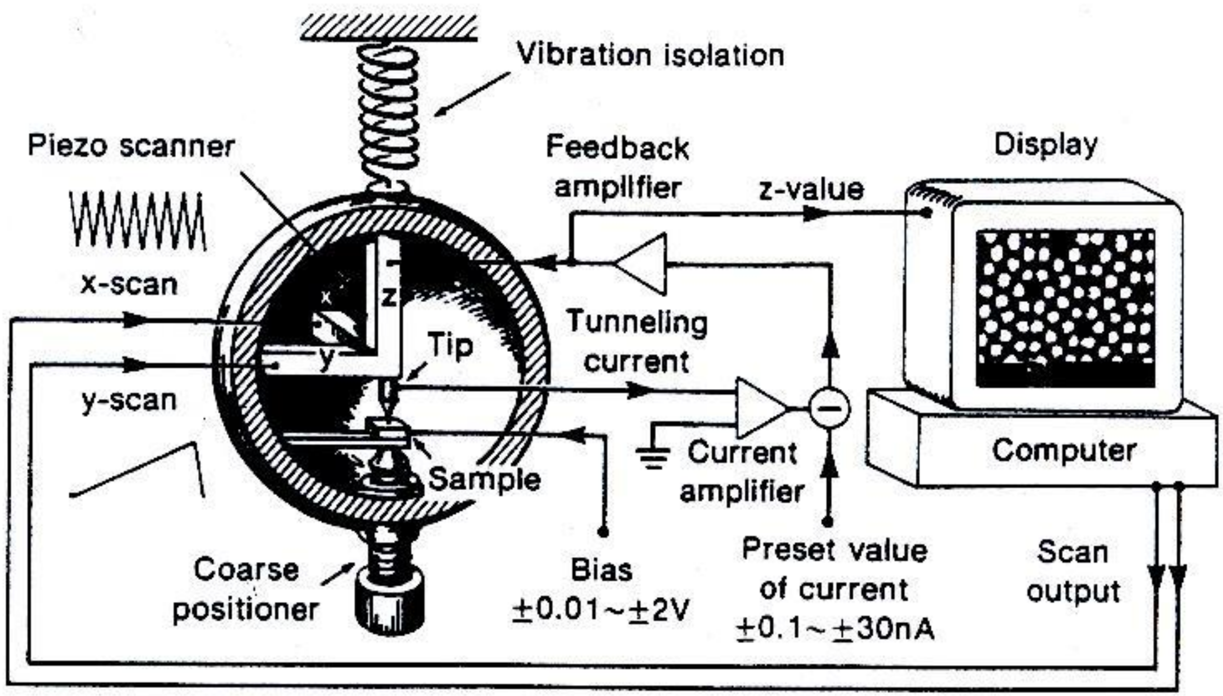
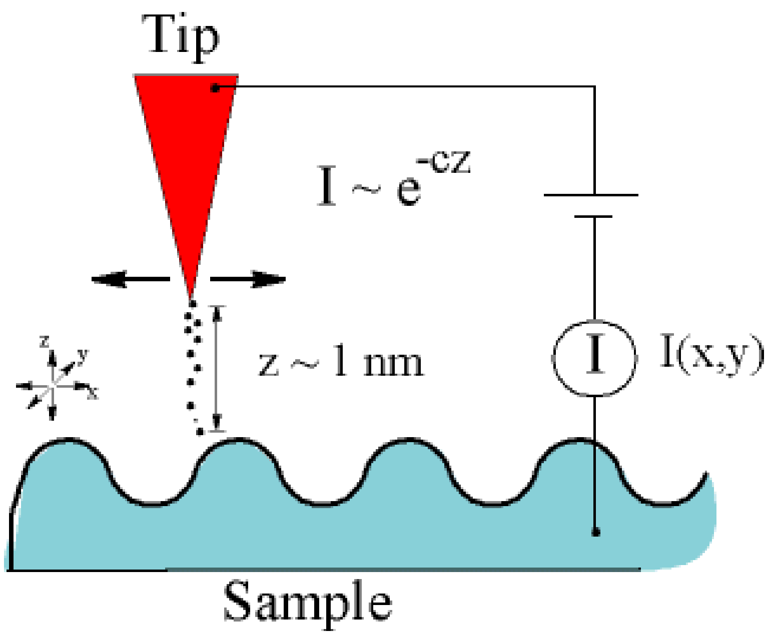
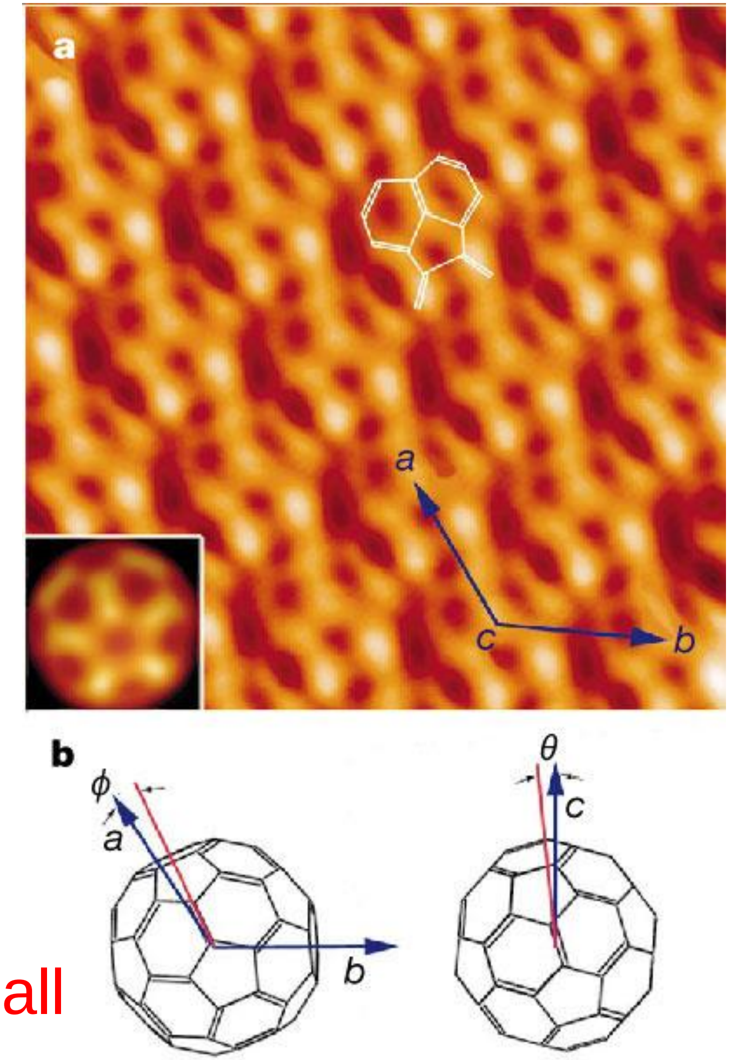


Figure 1.10 Scanning tunneling microscope. (From C. Julian Chen, *Introduction to Scanning Tunneling Microscopy*, Oxford: Oxford University Press, 1993.)

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



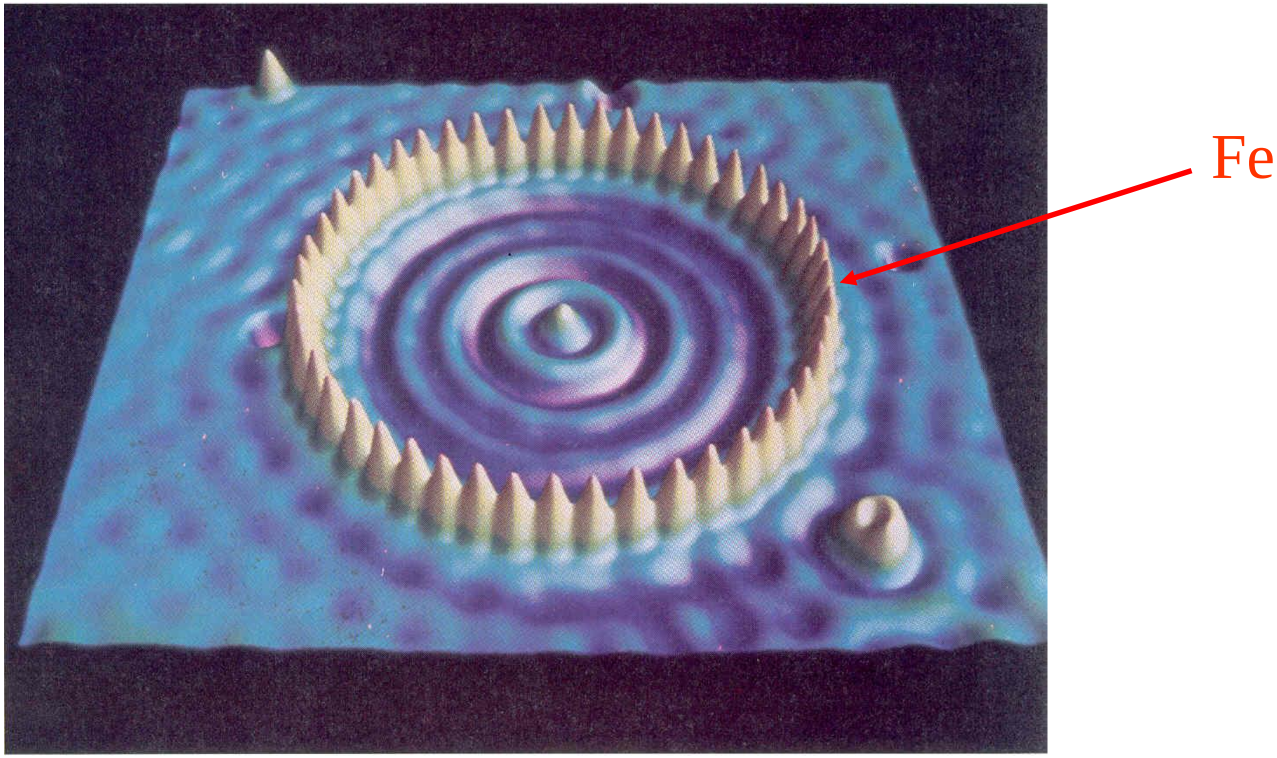
Nature 409, 304 (2001)



buckyball

Quantum Corral

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



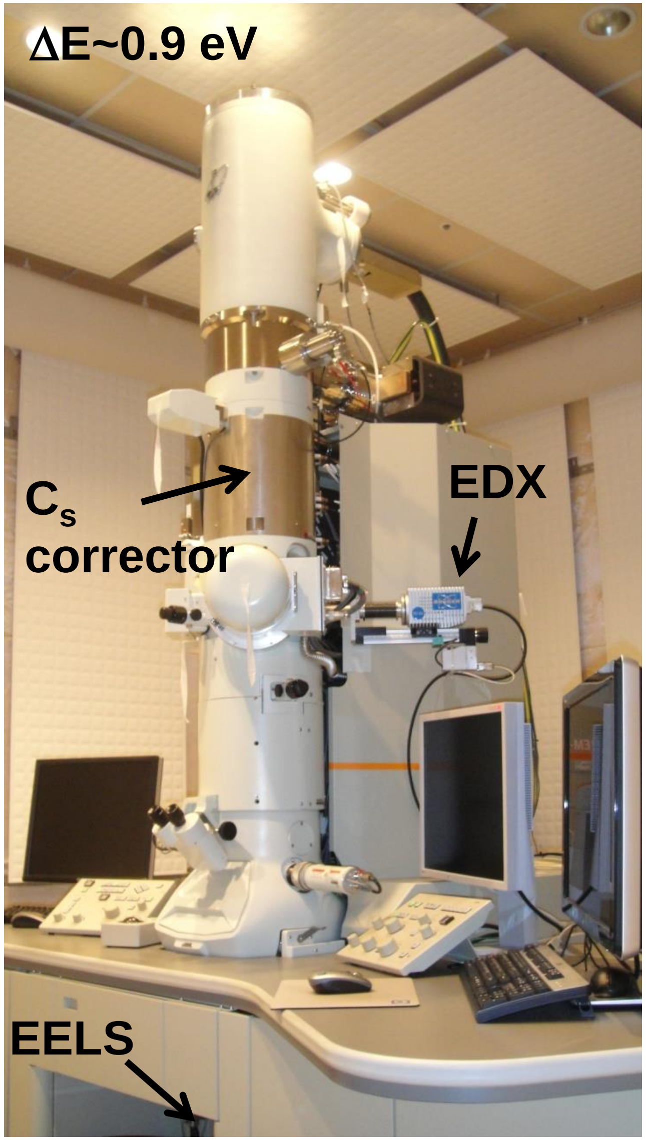
This STM image shows the direct observation of standing-wave patterns in the local density of states of the Cu(111) surface. These spatial oscillations are quantum mechanical interference patterns caused by scattering of the 2D electron gas off the Fe adatoms and point defects.

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

Scanning Transmission Electron Microscopy

2-Å STEM

1-Å STEM



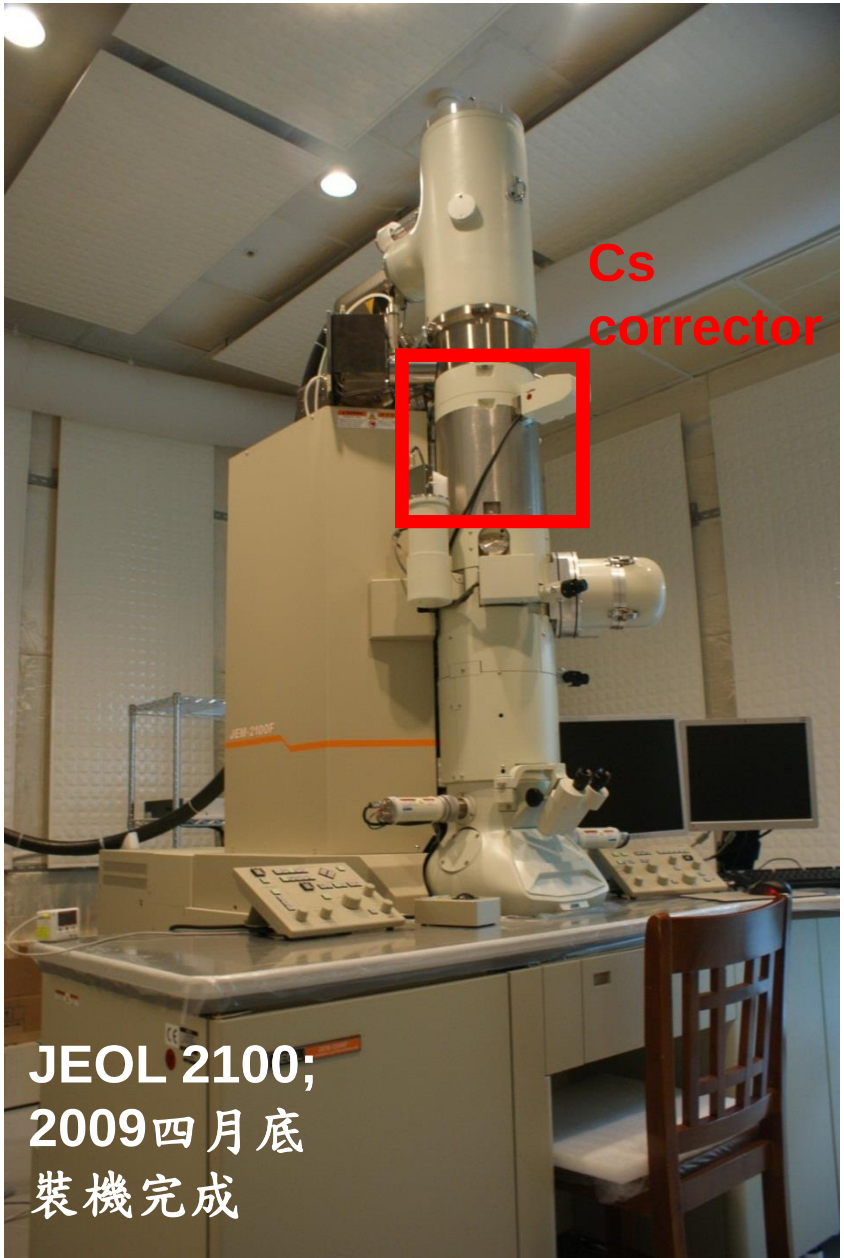
Prof. C. H. Chen and

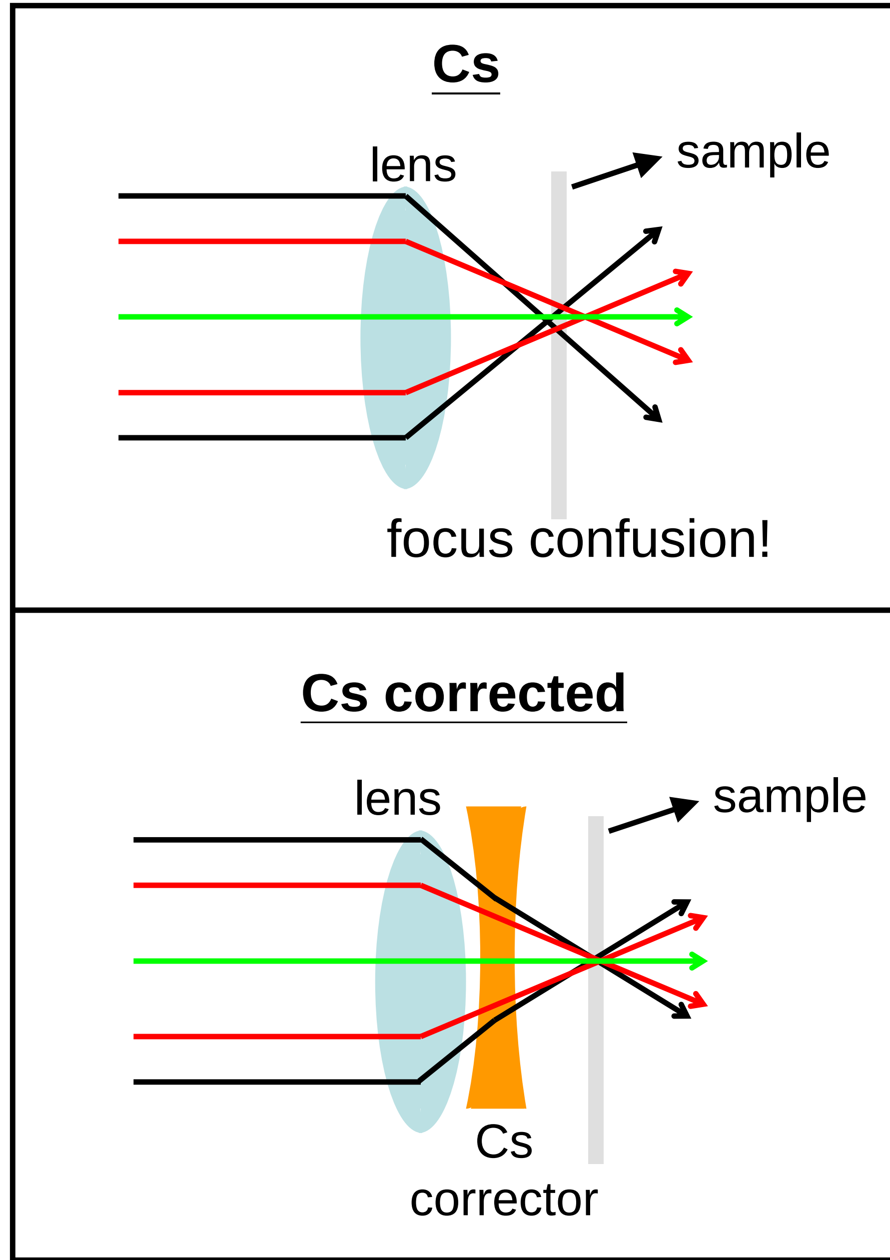
Dr. M.-W. Chu

in CCMS/NTU.

Spherical Aberration Corrected (球面相差)

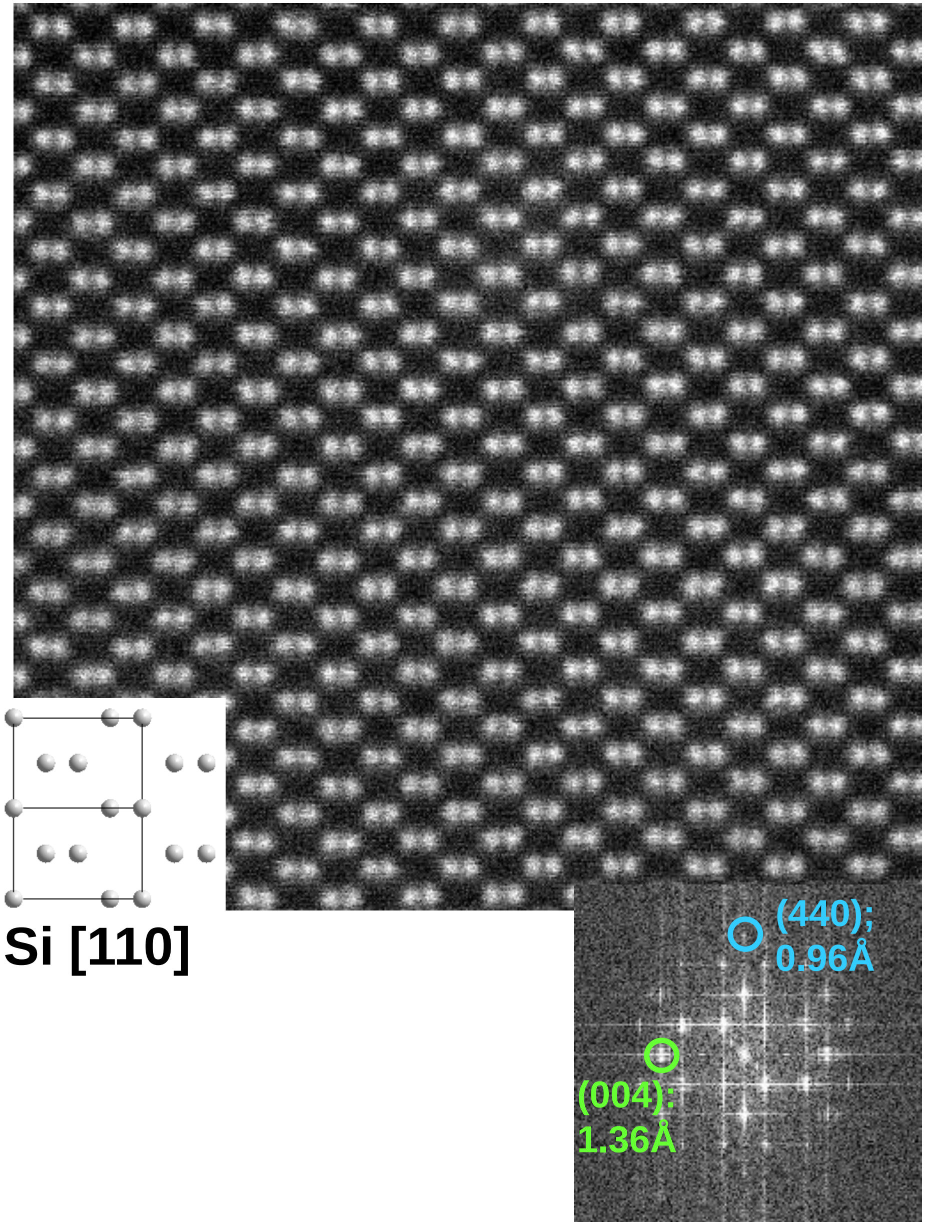
Cs-STEM by C. H. Chen at CCMS, NTU



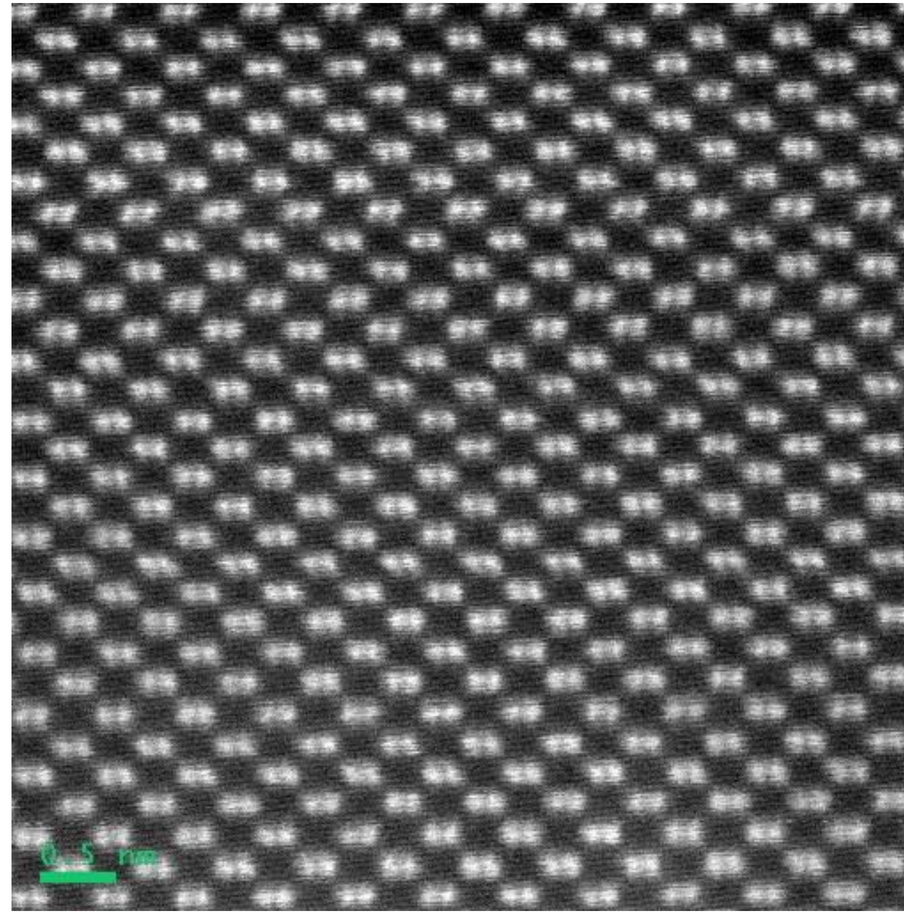


High-Angle ADF: Si dumbbell, 1.36 Å spacing

15s exposure

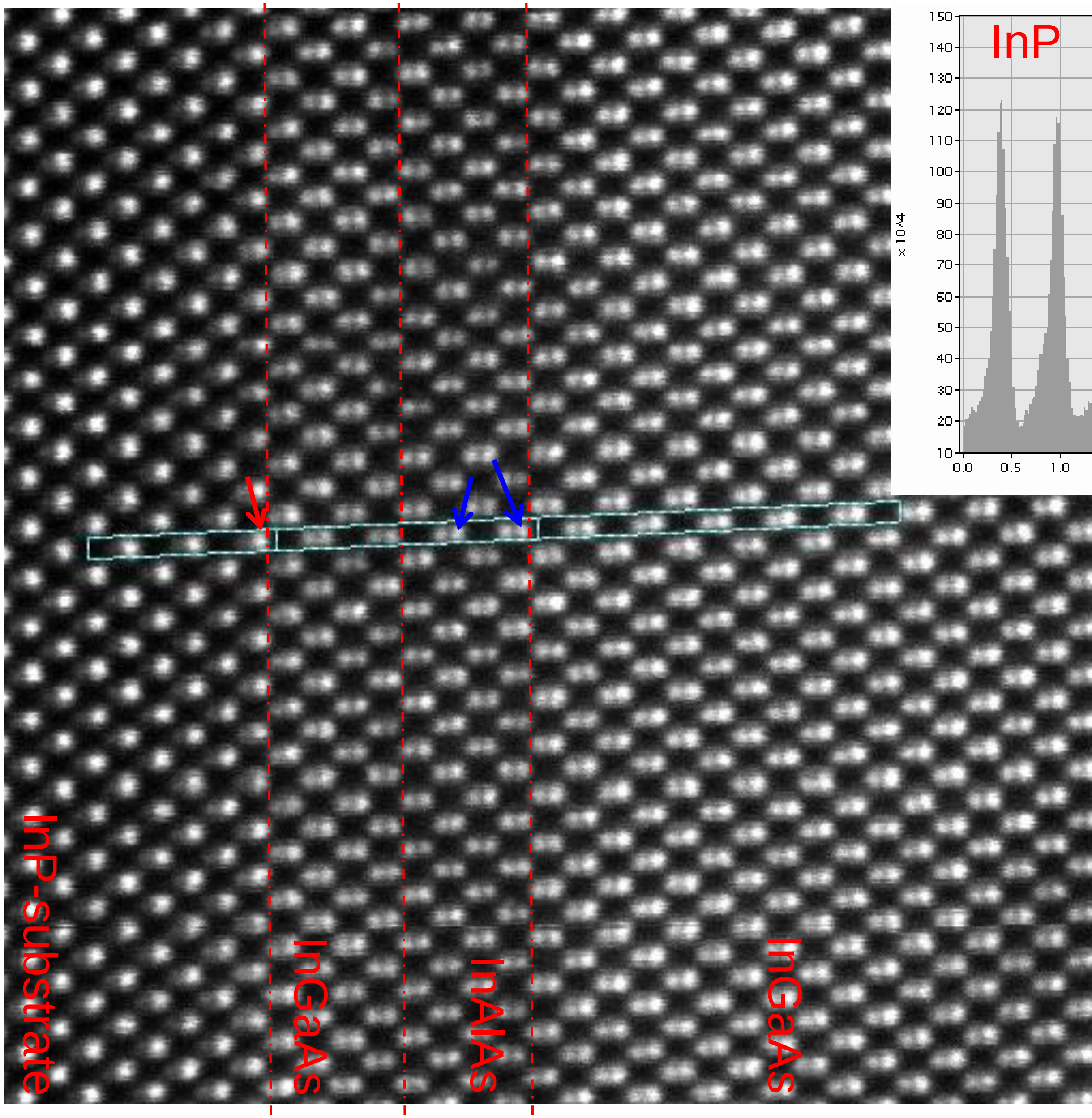


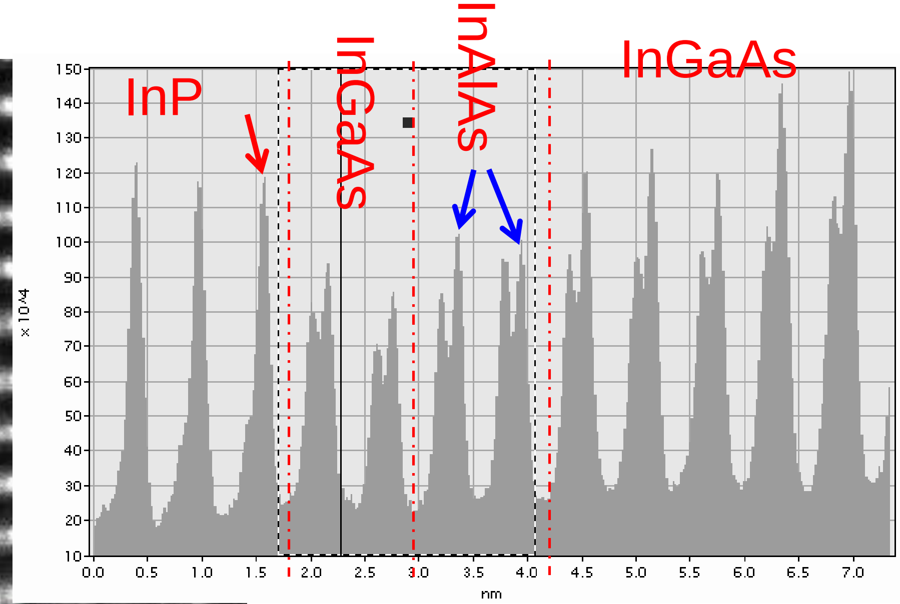
60s exposure



Drift ~1Å/min !!

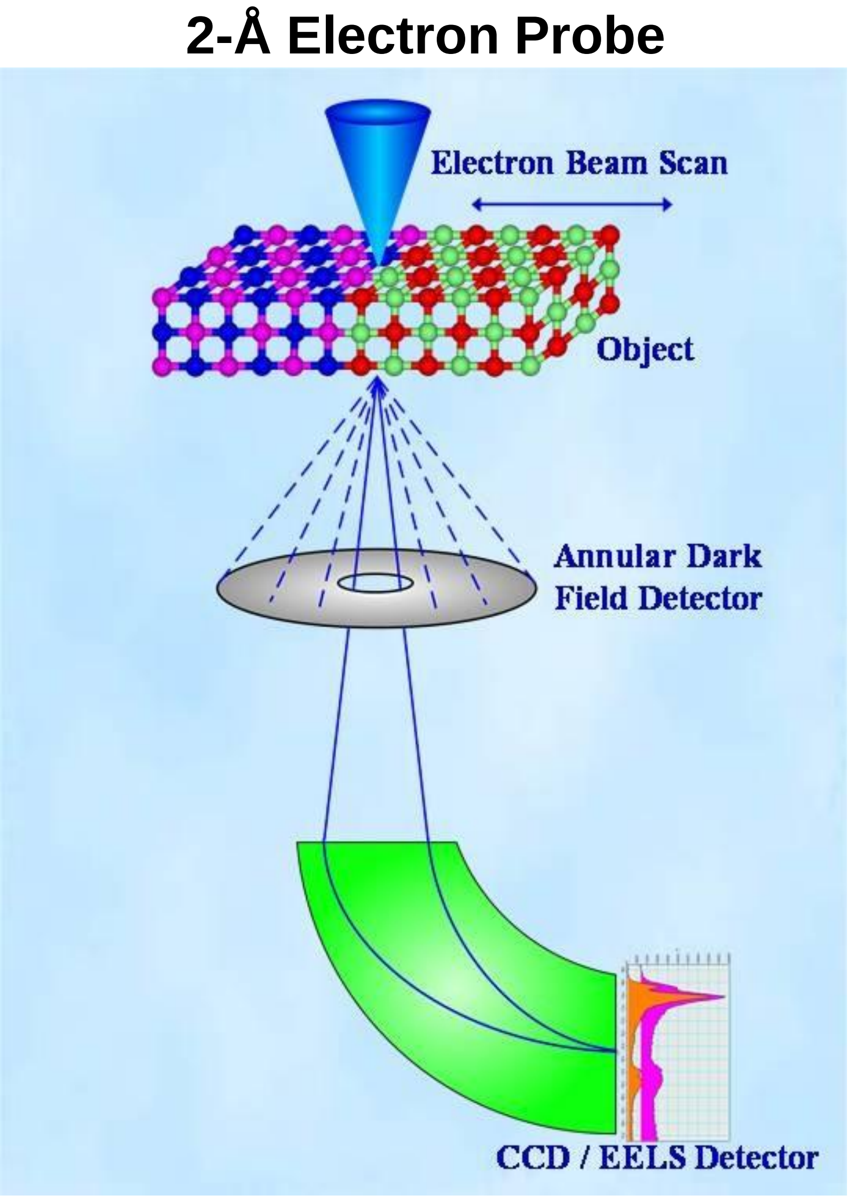
InGaAs/InAlAs superlattices on InP Substrate by MBE

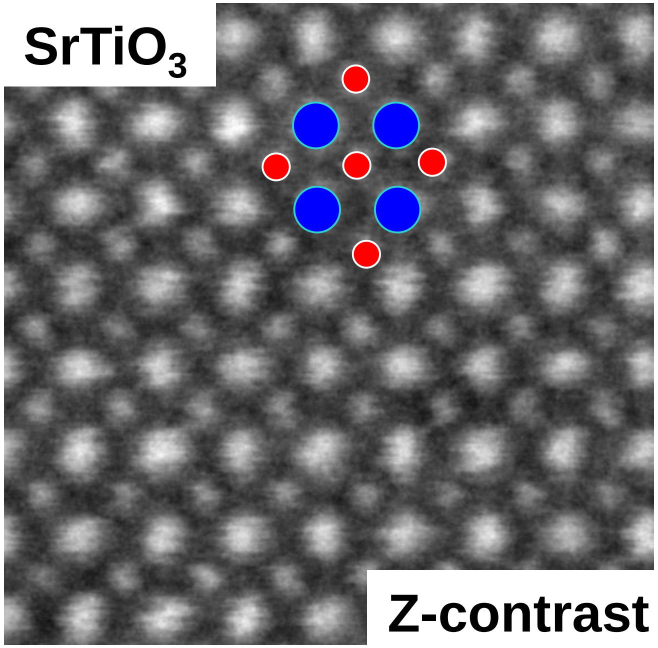


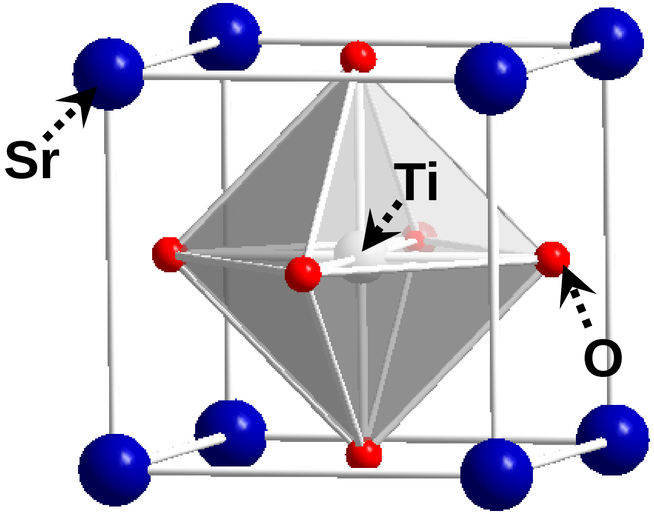


- Determining the interface location and sharpness is easy.
- The ***In***-distribution seems to be inhomogeneous in the InAlAs layer (blue arrows).
- Note that InP substrate is In-terminated (red arrow).

Atomic Resolution STEM Imaging: Z-contrast

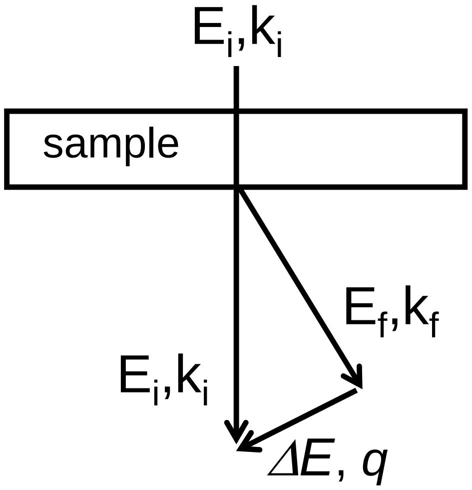






cubic; a = 3.905 Å

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 ρ_q the electron density operator

Inelastic Scattering (ΔE) Probability

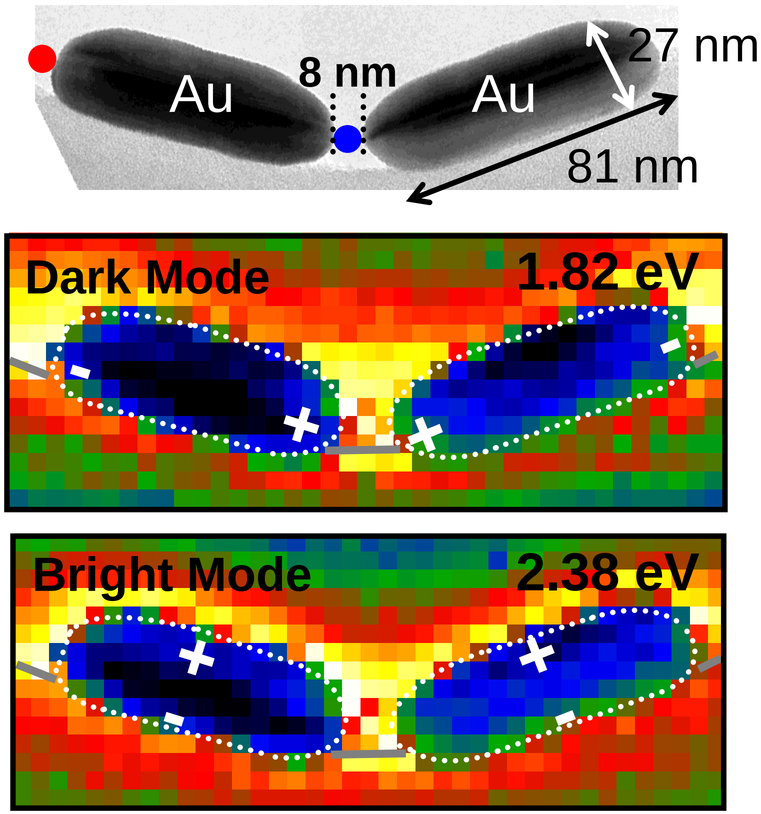
$$\frac{d^2\sigma}{d\Omega d_{\Delta} E} \sim \sum_f \left| \langle \psi_f | v(q) | \psi_i \rangle \right|^2 \delta(E_i - E_f - \Delta E)$$

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

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

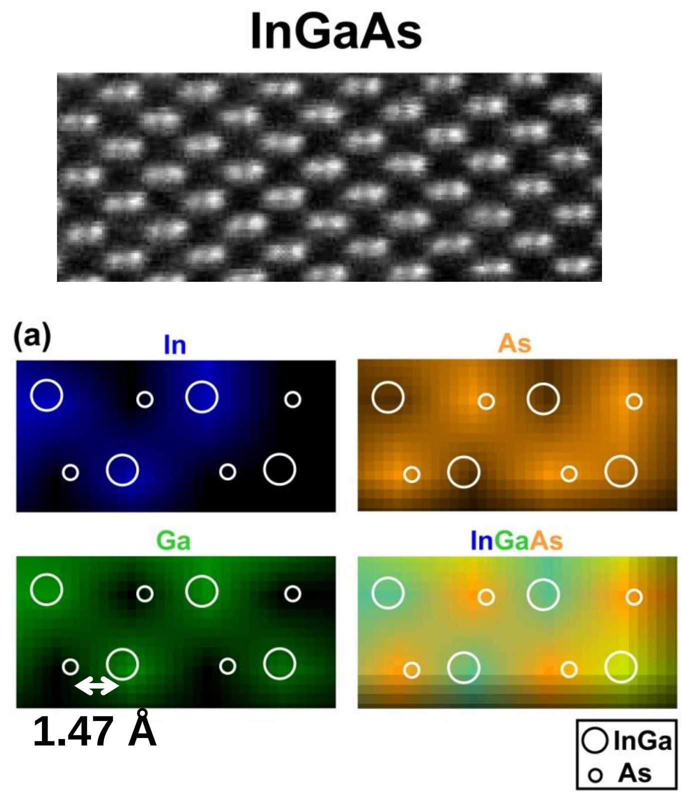
Spectral Imaging at Ultimate Spatial Resolution

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 perturbation

- Different scaling for different physical entity

Quantum Effect:

=> Most likely to have new breakthrough !

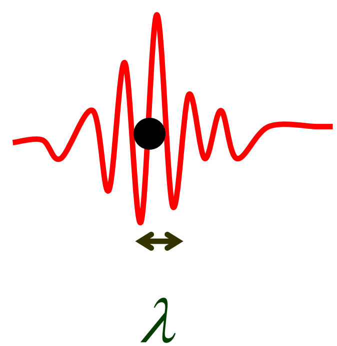
The connection of materials wave with mechanics

h = Planck constant

$(6.626\times10^{-34}$ joule-sec$)$

DeBroglie wave :

$\lambda = h/p$



Einstein:

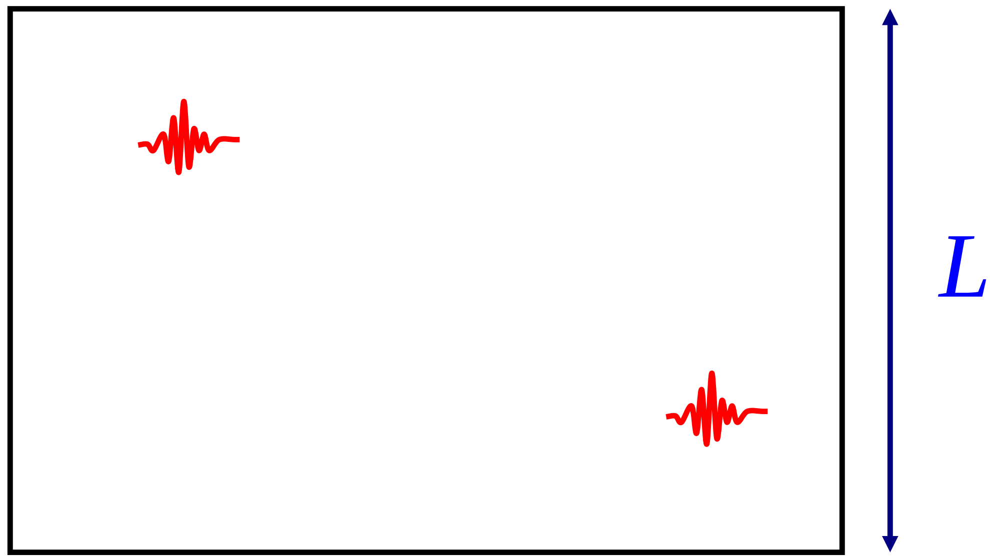
$E=h\nu=p^2/2m$

Wave length		
	Free electrons	自由電子: $\lambda_{th}(300K)=6.2nm$
	Semiconductors	(半導體中$10nm\leq\lambda\leq100nm$)
	Atoms	原子: $\lambda_{th}(300K)\leq0.2nm$

Bulk Limit ⟺ Nano Limit

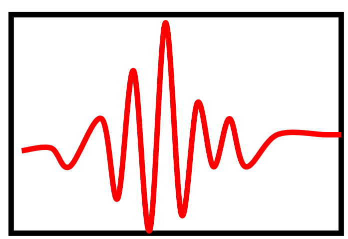
For bulk materials

λ << L



For nano materials

λ ~ L

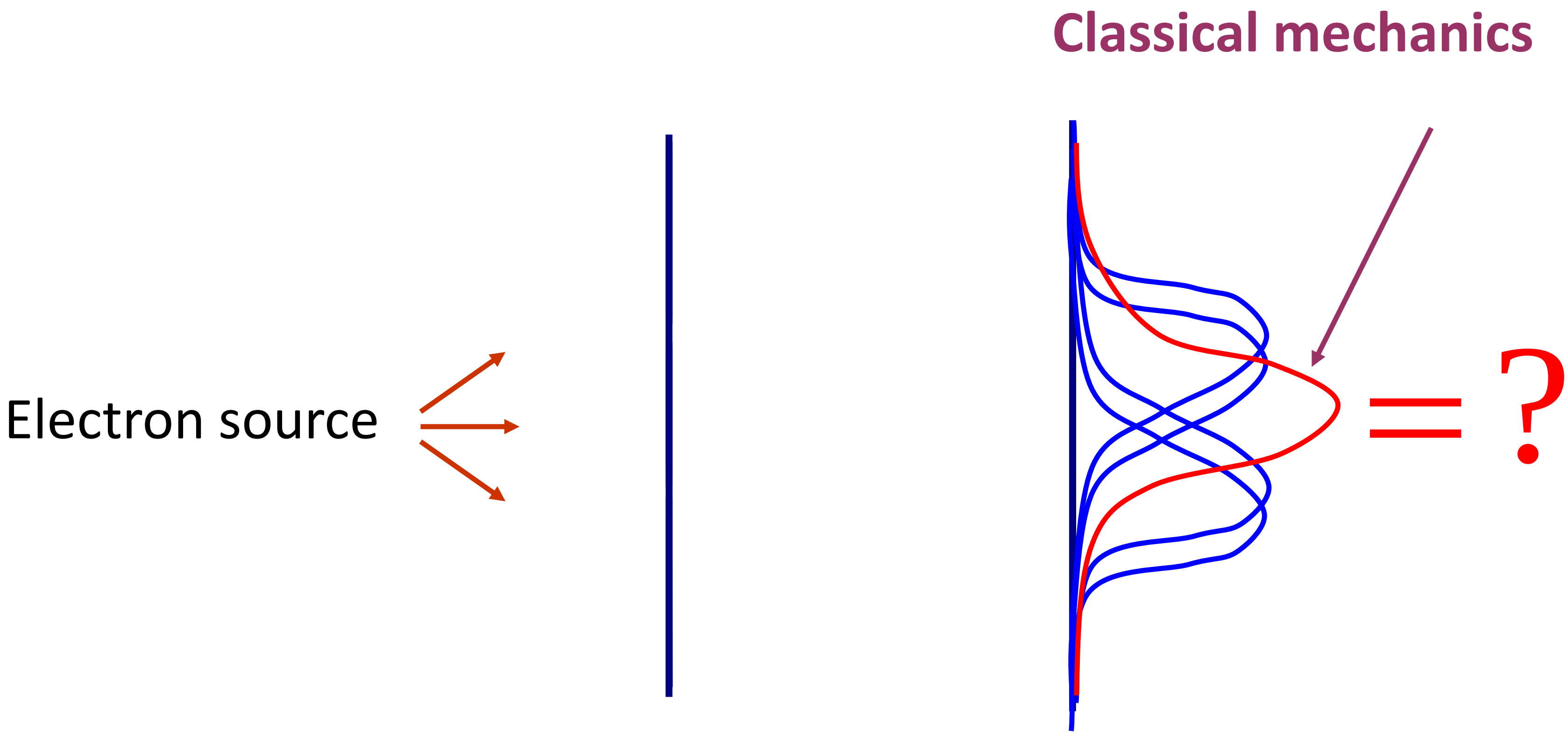


Major Quantum Effects at the Nano Scale

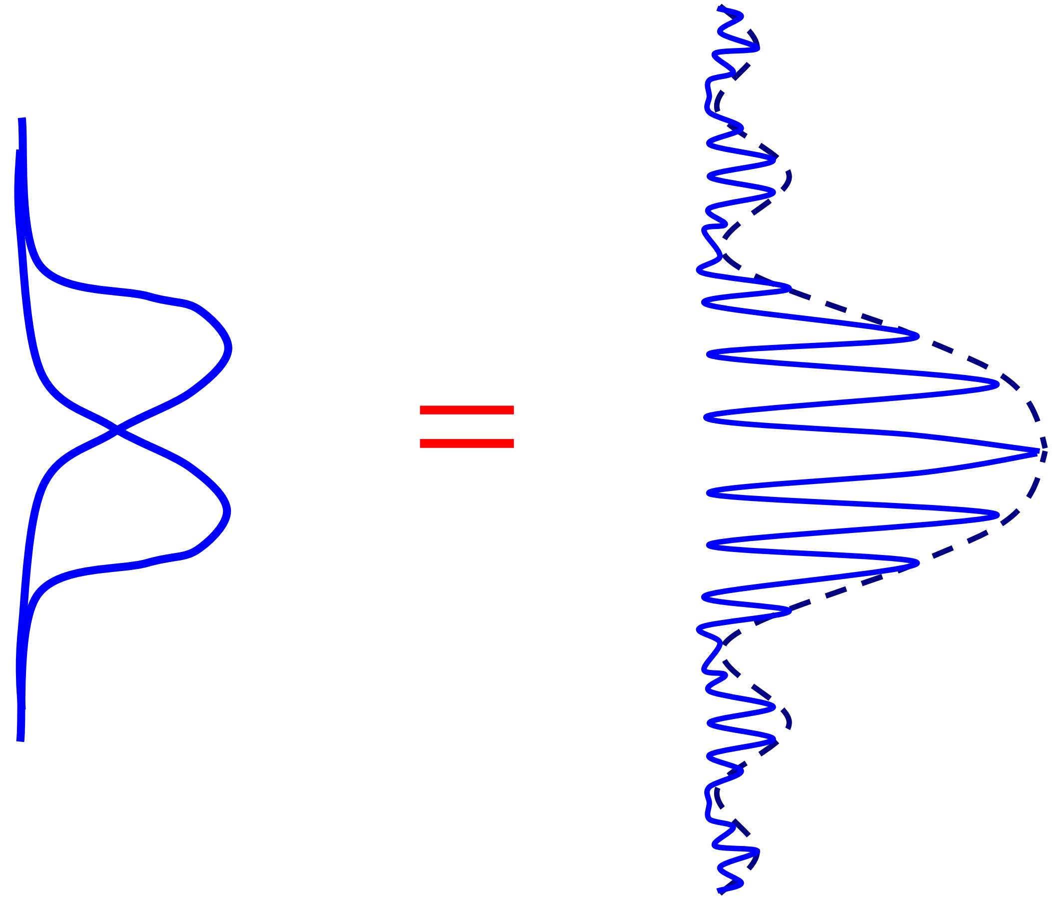
- Interference
- Quantization
- Tunneling
- Quantum spin

(I) Interference

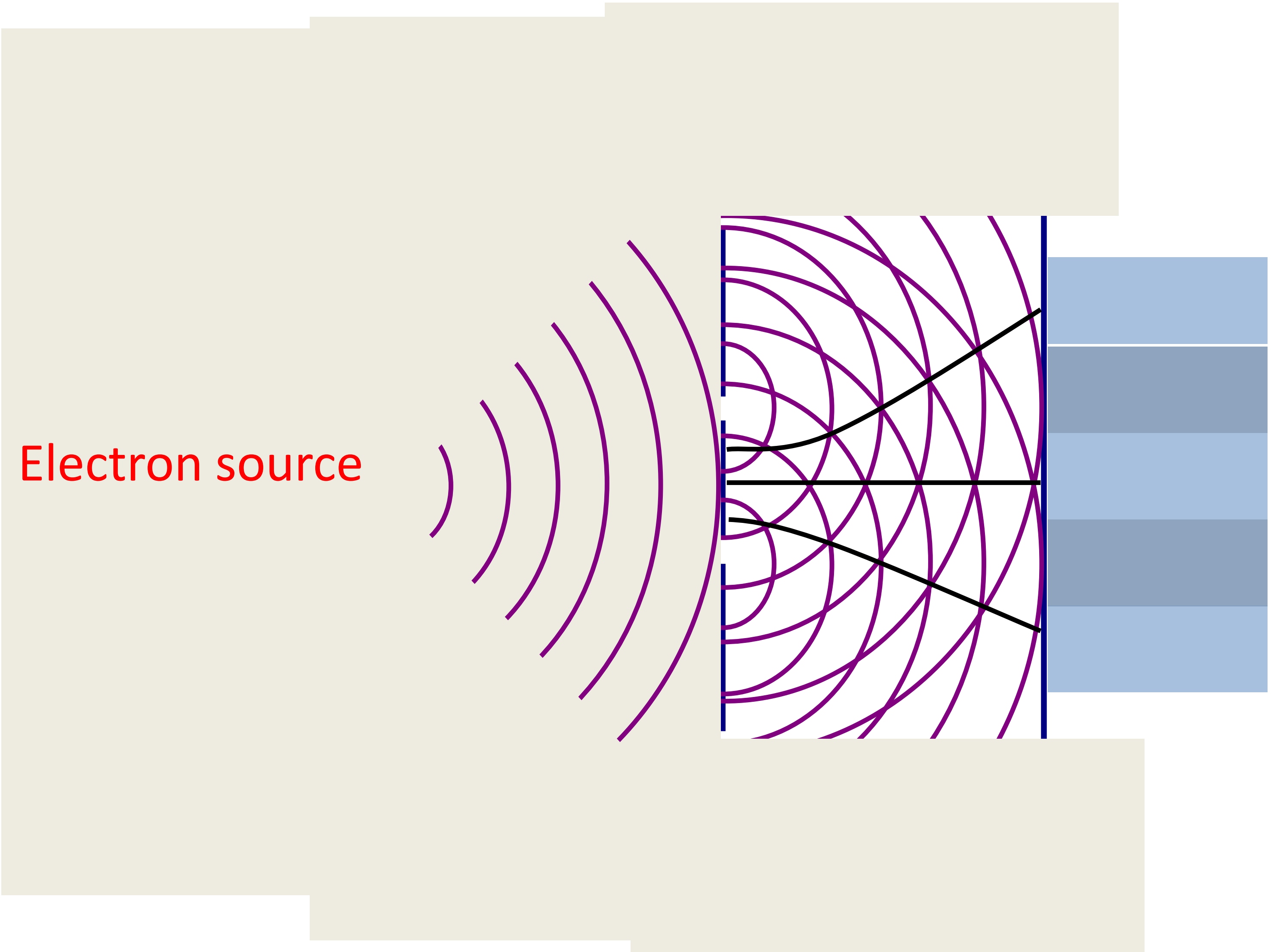
The wonder of electron in waves

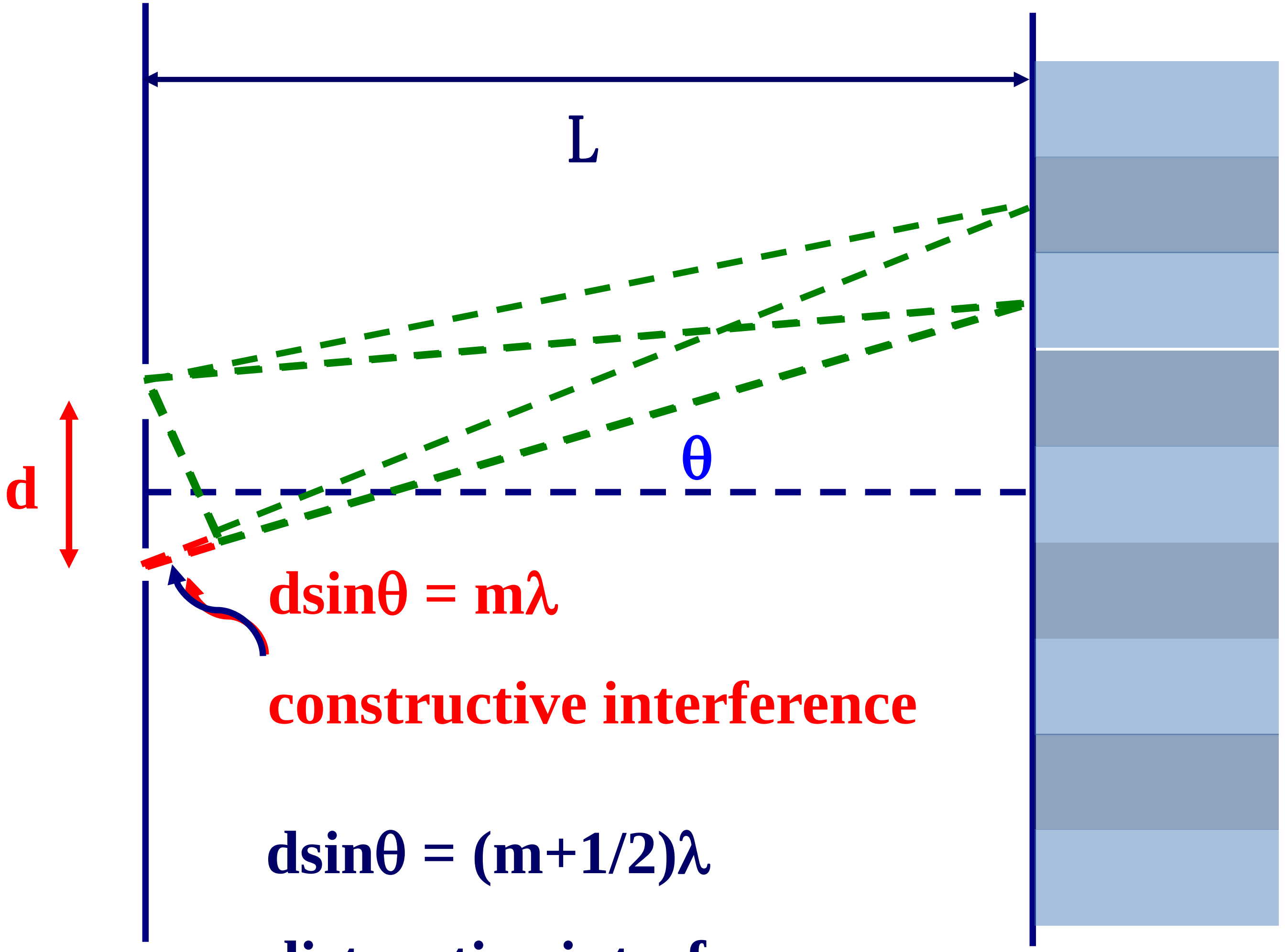


The wave property of electrons



Double Slit Interference of Electrons





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

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

$d\sin\theta = m\lambda$

constructive interference

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

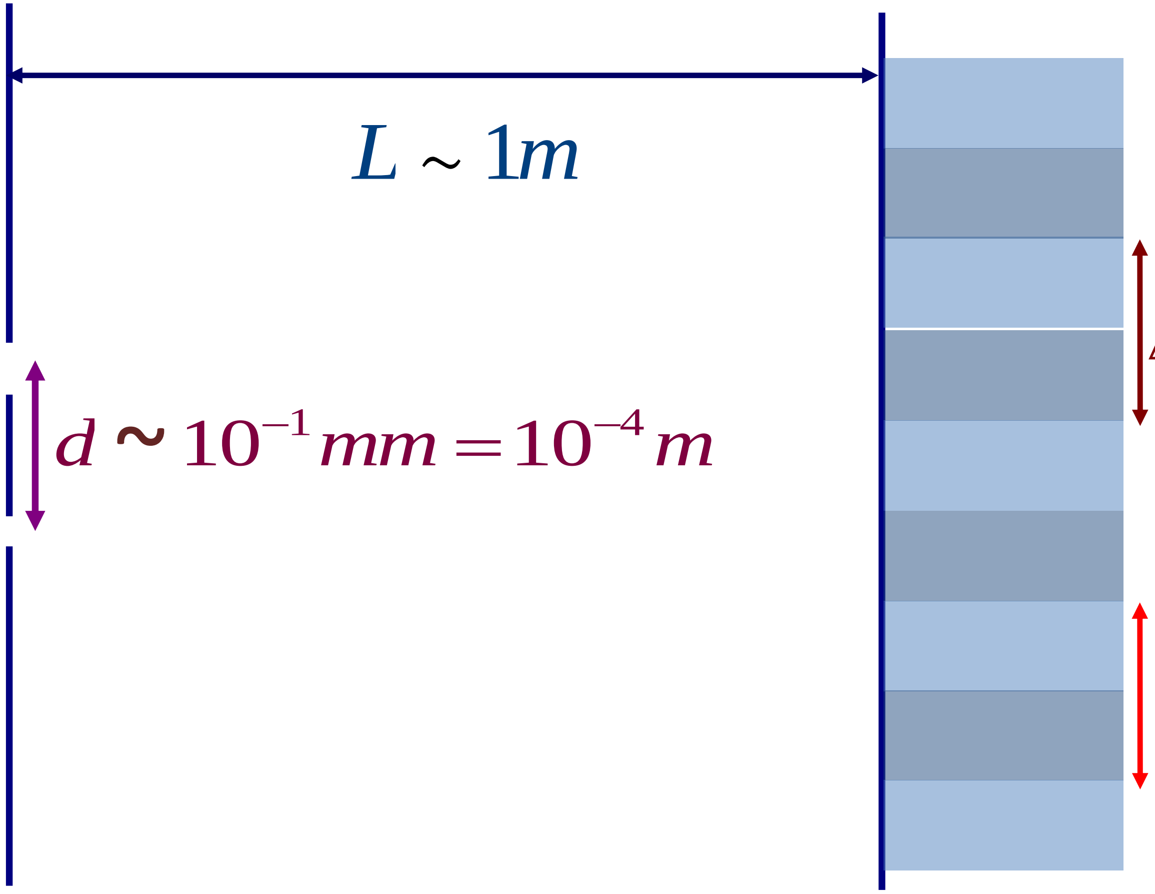
distructive interference

For light

$\lambda \sim 700nm$

For electrons

λ ~ 0.17nm



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

$$= 7mm$$

$$\Delta y = 1.7 \mu m$$

(II) Quantization

Confinement of the materials wave

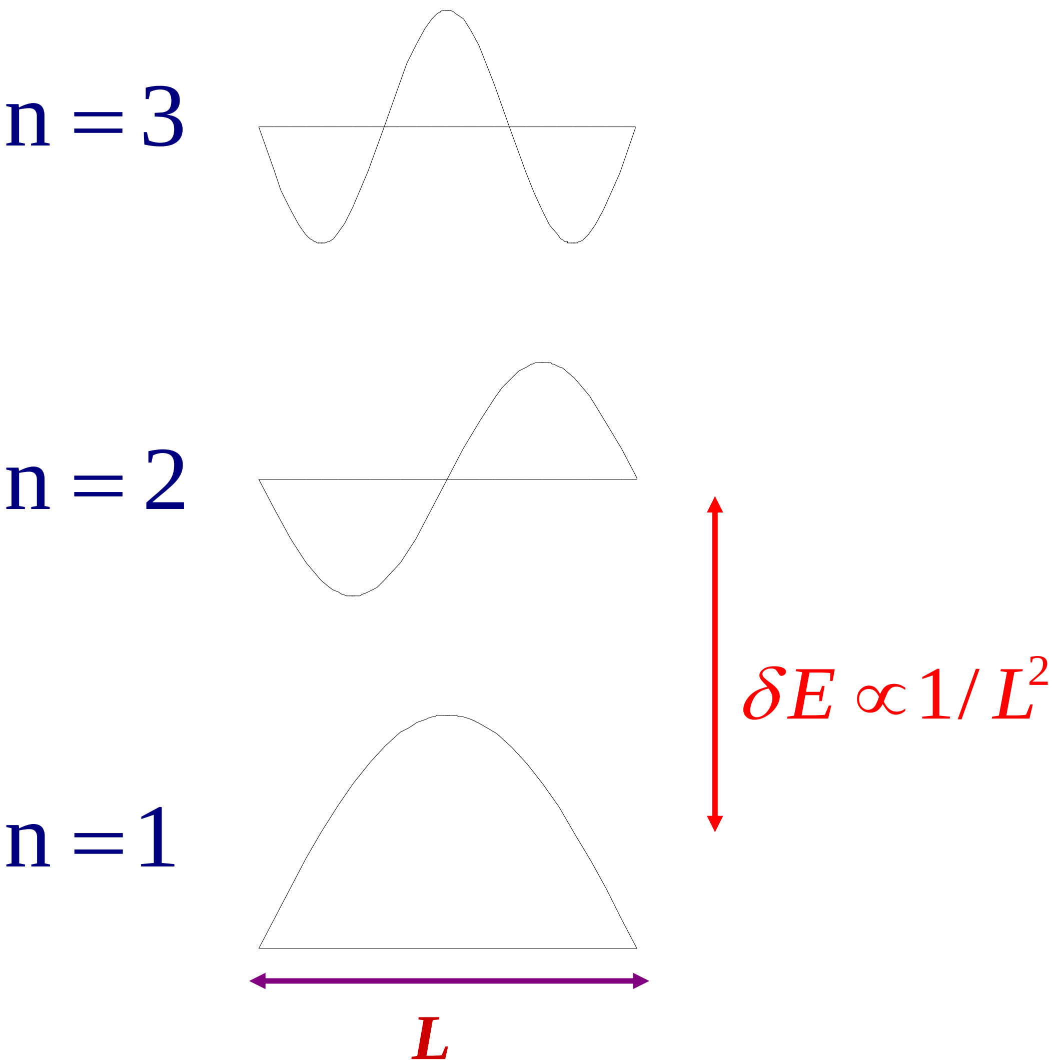
↓

Standing Wave

↓

Quantizations

The Qauntization of Energy



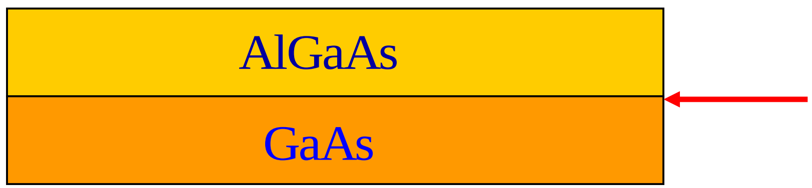
$$L = \frac{n}{2}\lambda$$

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

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

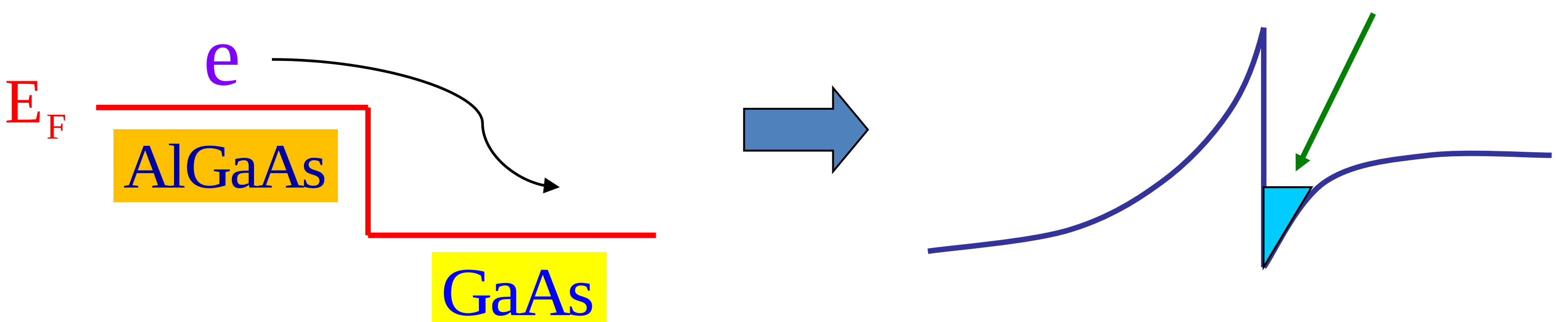
Quantum well: 1D confinement

MOSFET:

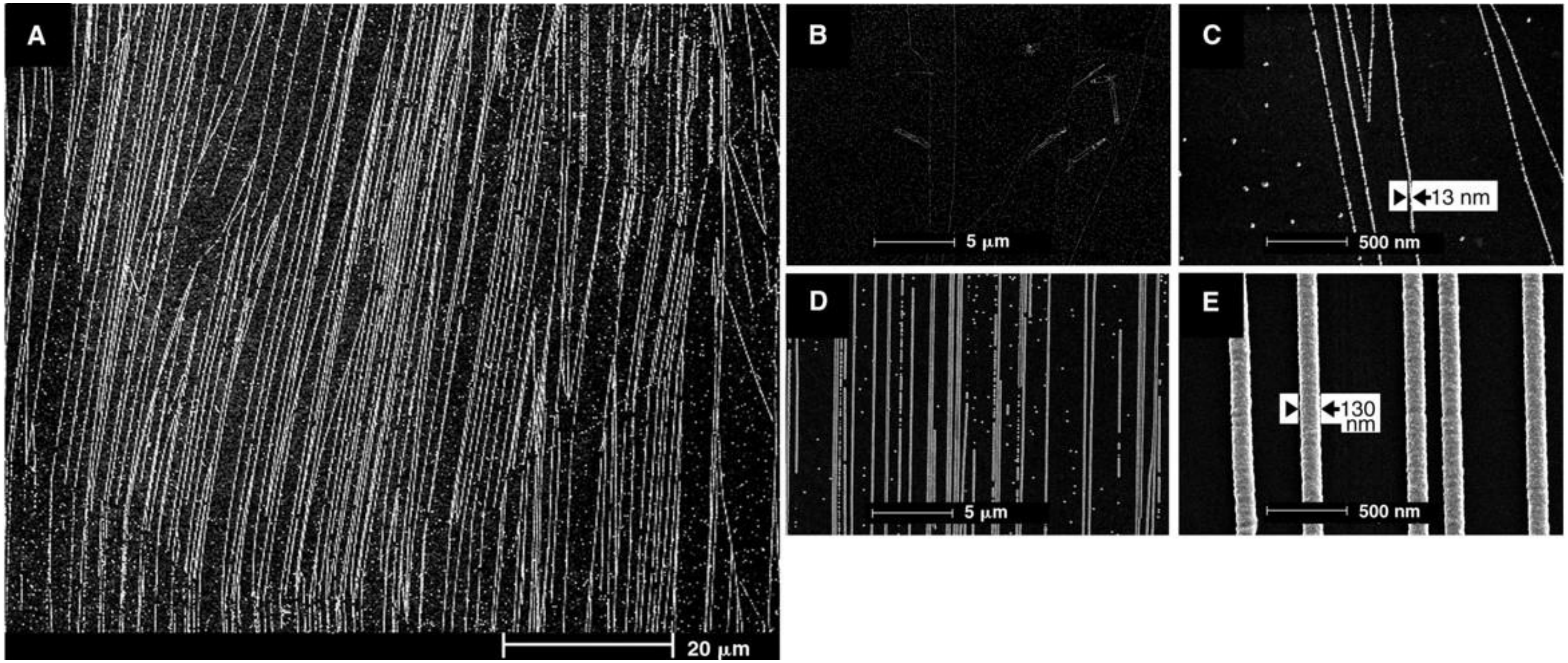


2D electron Gas

二維電子氣



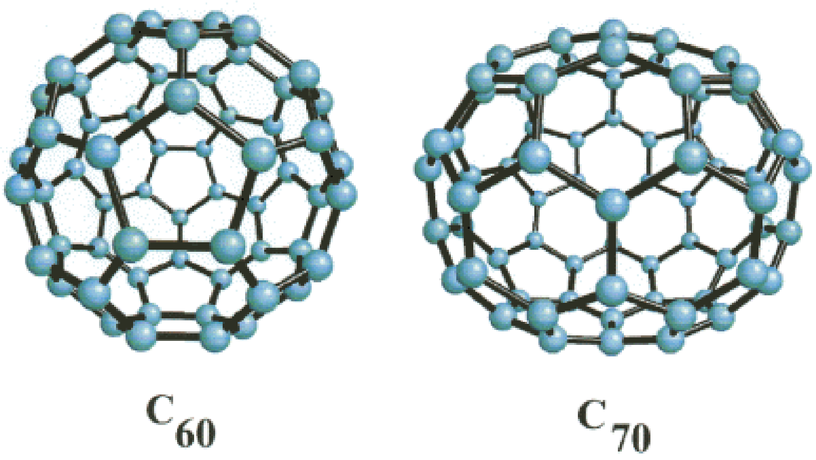
Quantum wire: 2 D-Confinement



SEM images of MoO_x nanowires on graphite surfaces

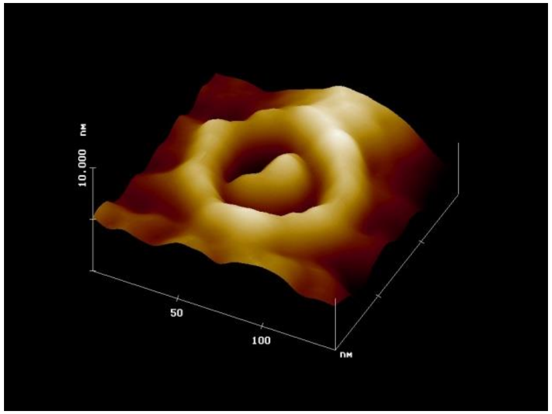
Science **290**, 2120-2123, (2000).

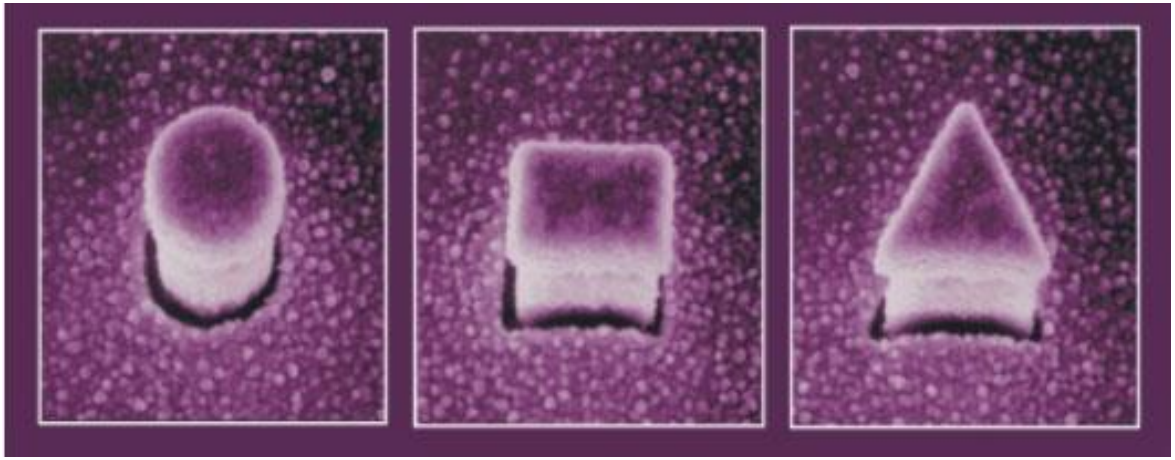
Quantum dot: 3D - Confinement



Smalley et al, Rice Univ, (1985)

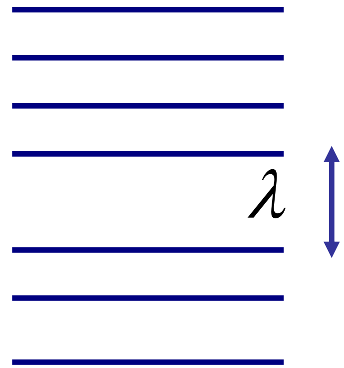
Quantum Dots of various shape





Absorption in scattering from red to yellow

larger λ_0

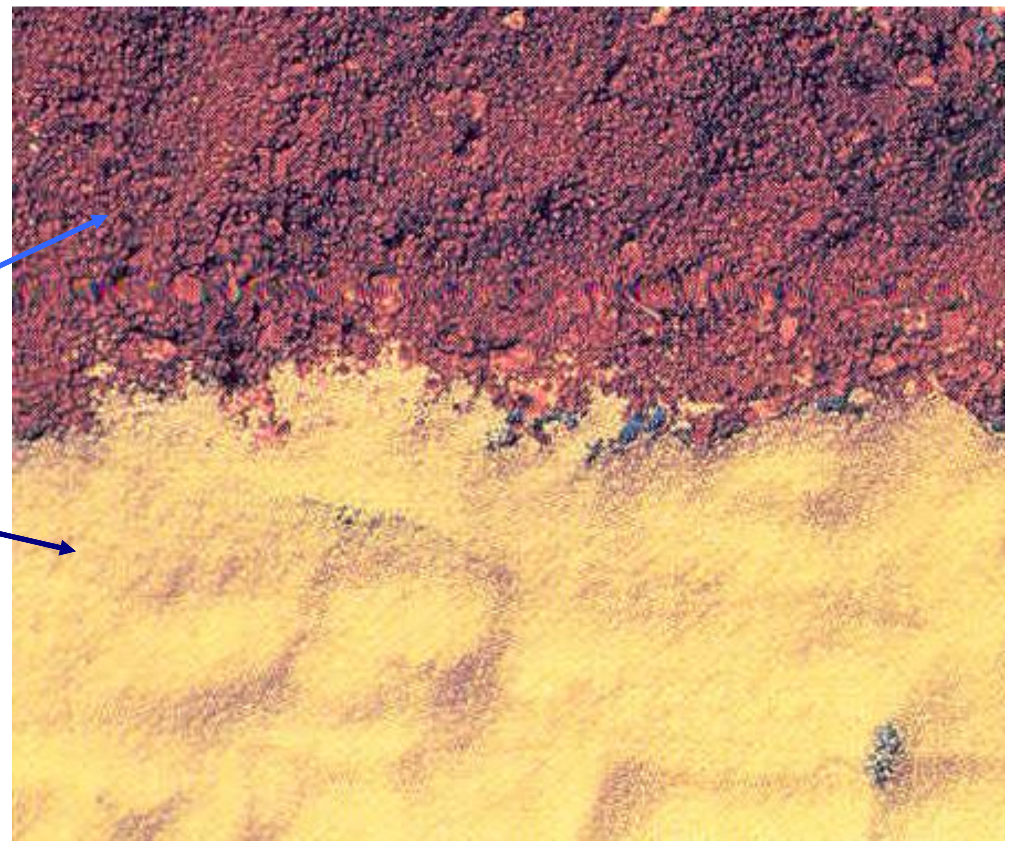


$$E = hc/\lambda \propto 1/L^2$$

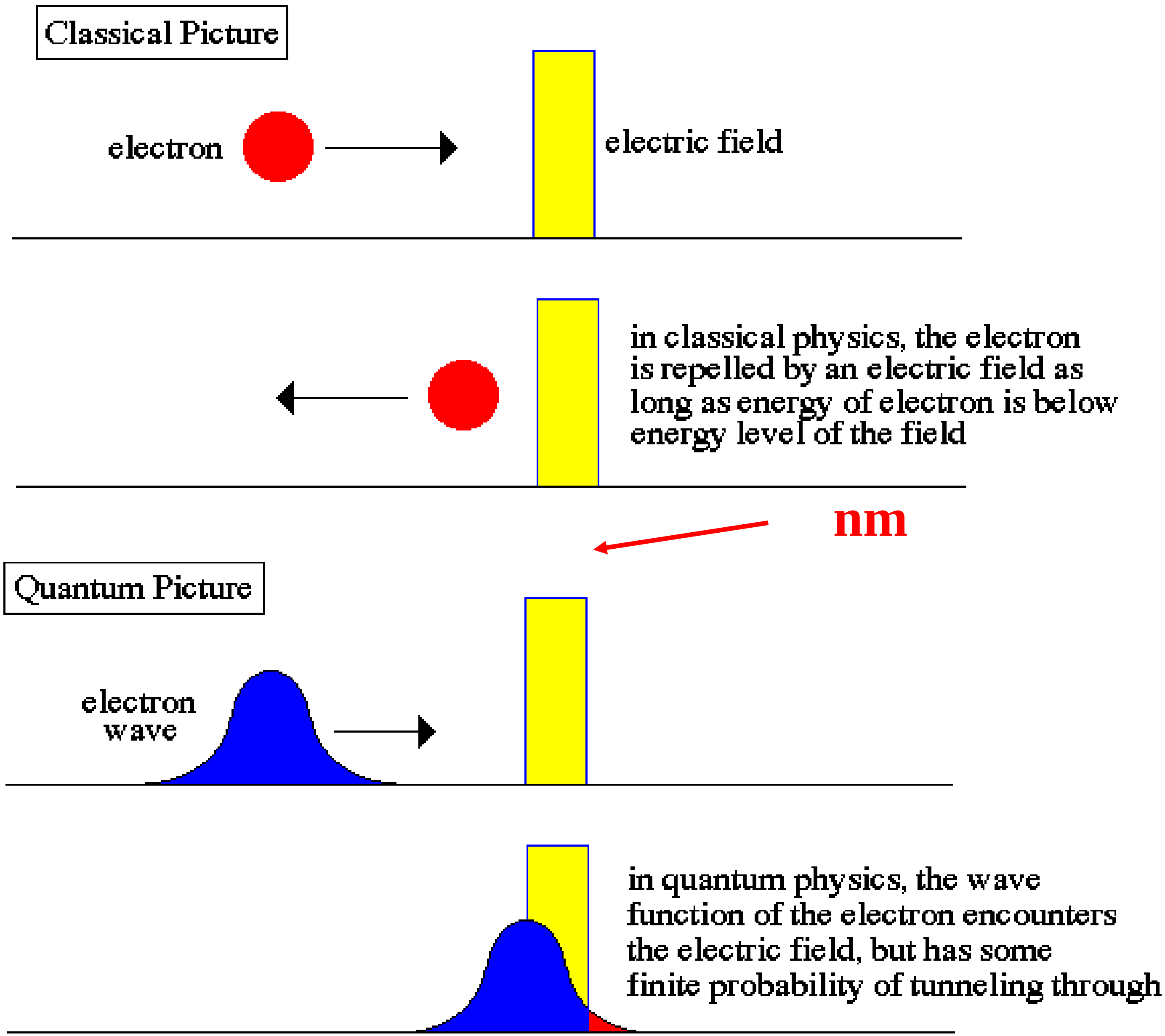
powdered CdSe (Cadium Selenide)

larger

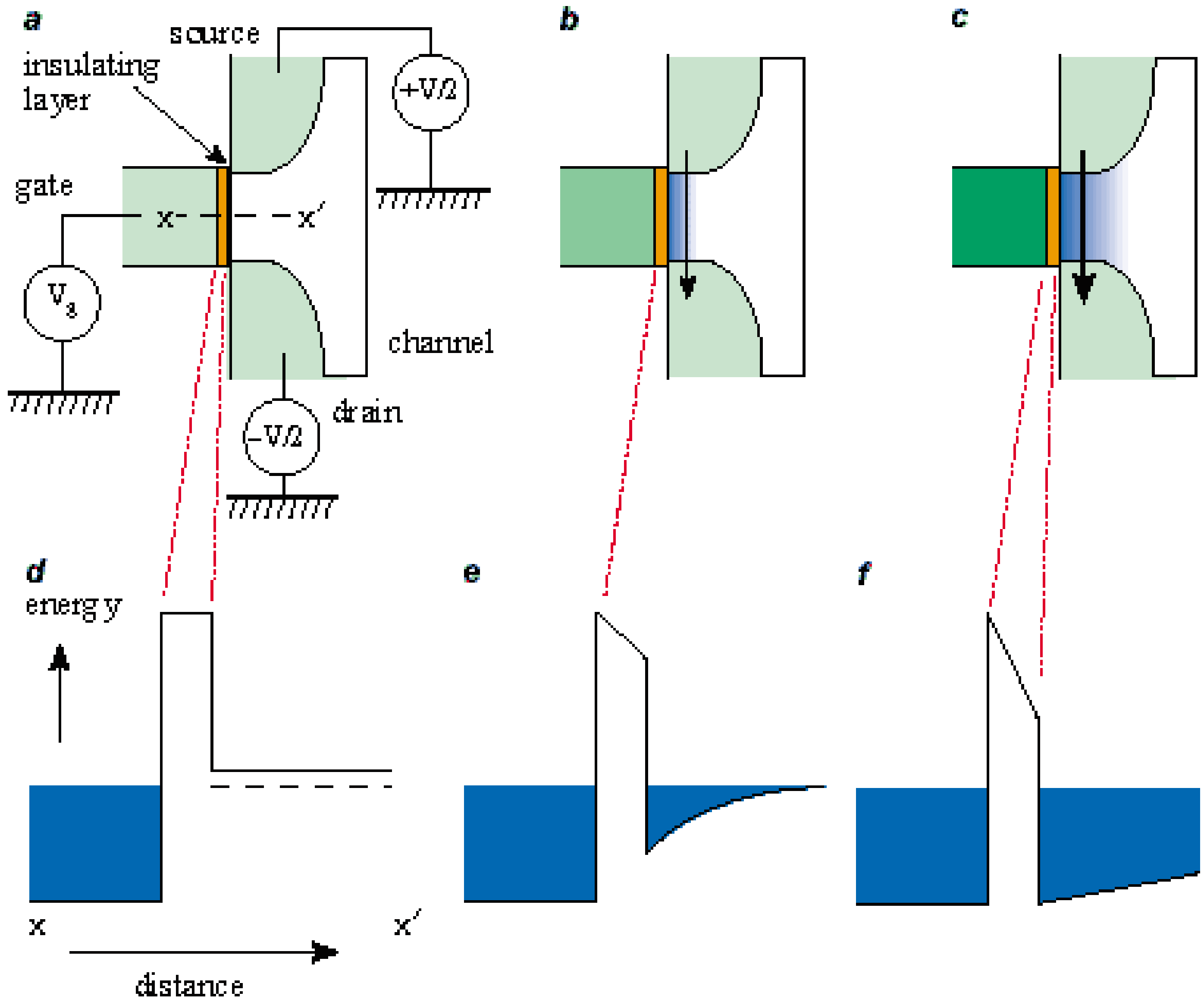
smaller



(III) Tunneling and Nano-electronics


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

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



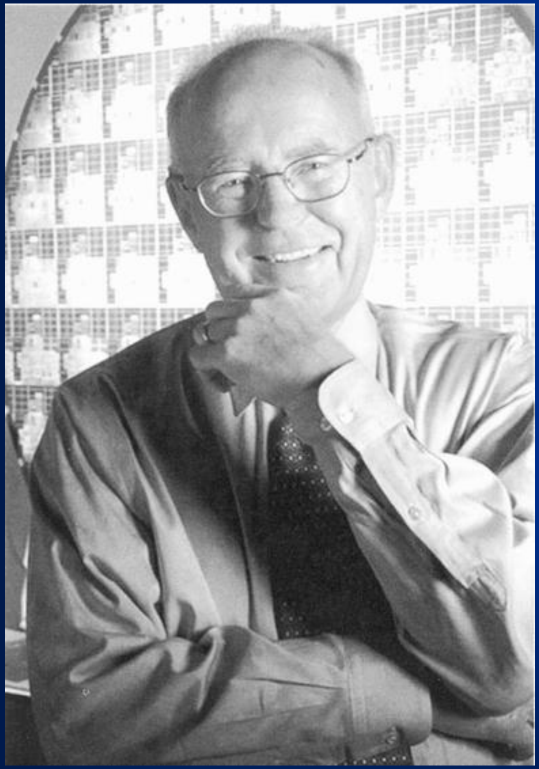
近來大力推動奈米科技的背景

來自微電子學可能遭遇瓶頸的考慮

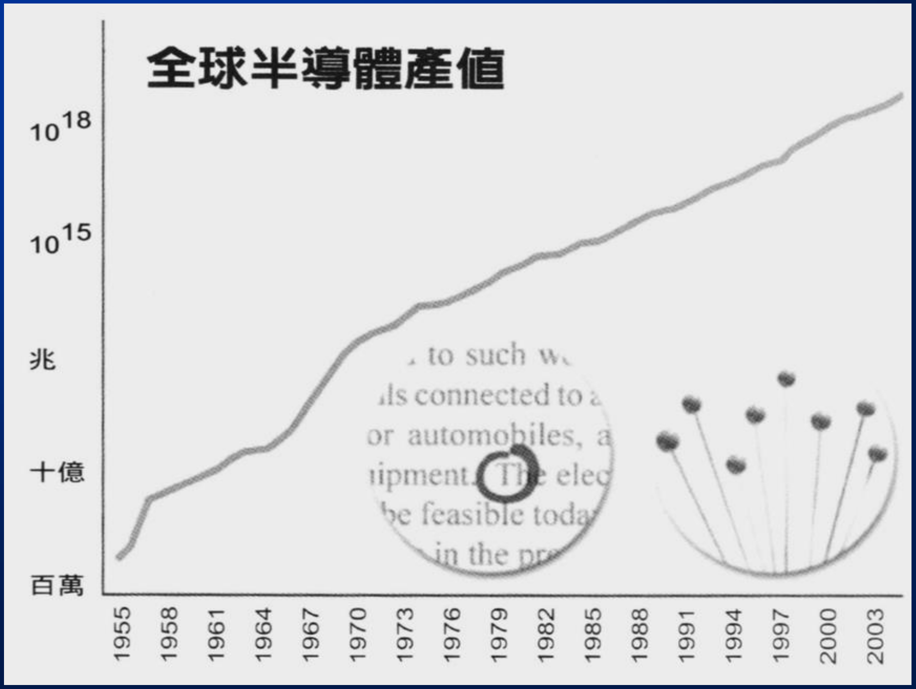
Moore's Law：摩爾定律

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

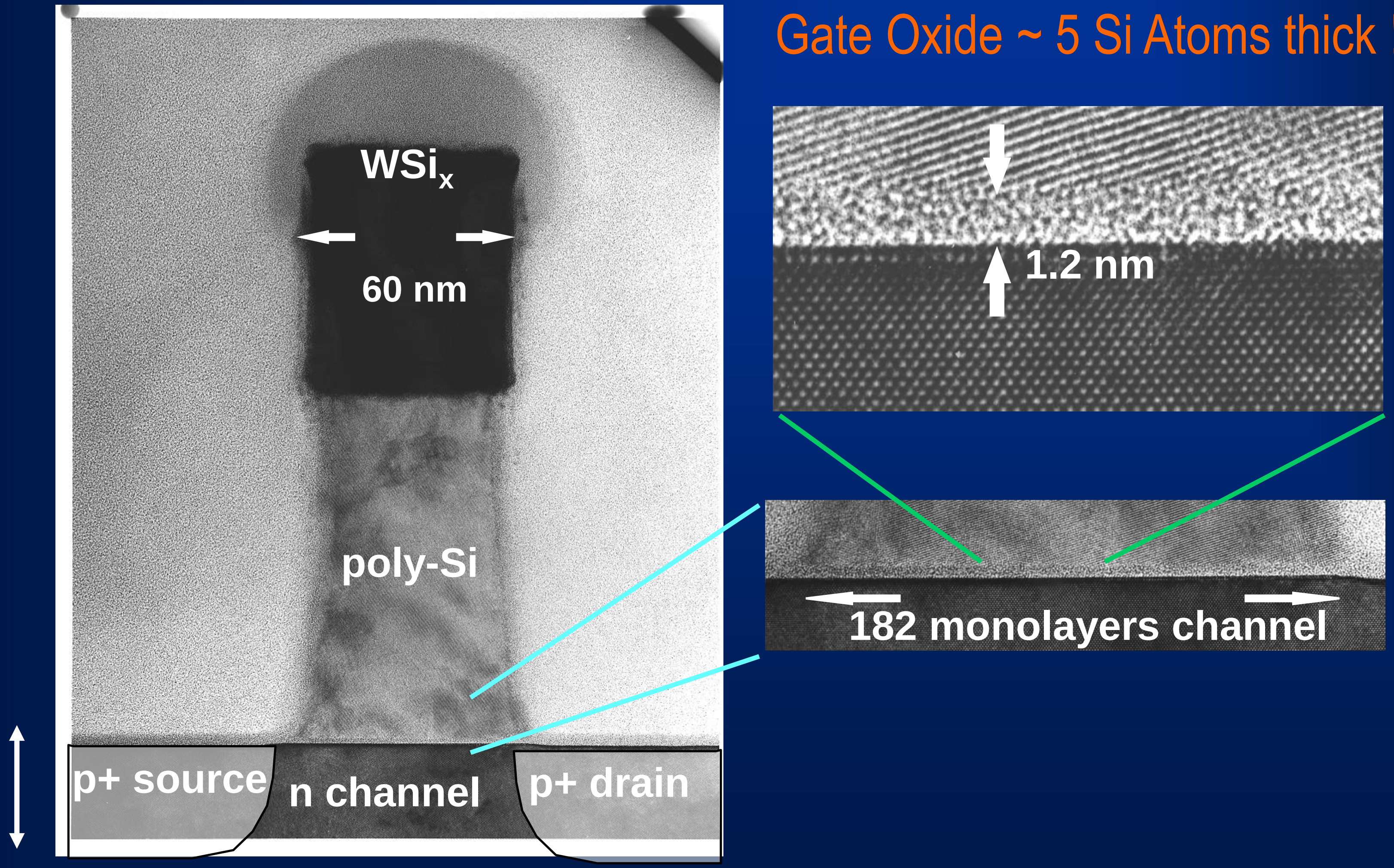
矽晶上電子原件數每1年半會增加一倍



Gordon Moore



Scaling Limits to CMOS Technology



Shrinking the junction depth ⇨ 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 $1 A/cm^2$ leakage

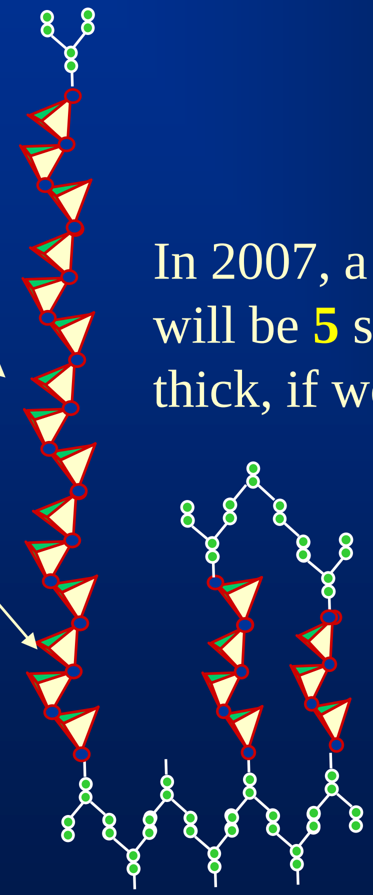
I_{on}/I_{off} >> 1 at 12 Å

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?

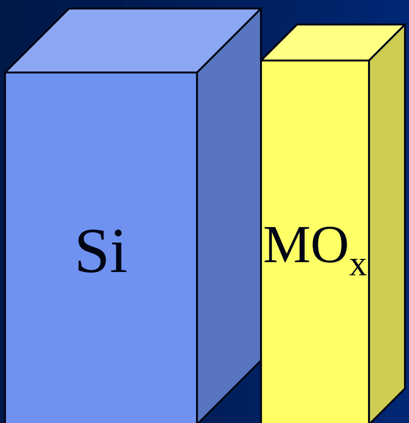
In 1997, a gate oxide was 25 silicon atoms thick.



In 2007, a gate oxide will be **5** silicon atoms thick, if we still use SiO_2

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

Fundamental Materials Selection Guidelines



$Si + MO_x \longrightarrow M + SiO_2$

$Si + MO_x \longrightarrow MSi_2 + SiO_2$

$Si + MO_x \longrightarrow MSiO_x + SiO_2$

- 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_2 at $t_{eq} < 1.5$ nm
- Low interfacial state density $D_{it} < 10^{11}\ eV^{-1}cm^{-2}$
- Low oxygen diffusivity
- Crystallization temperature >1000°C

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

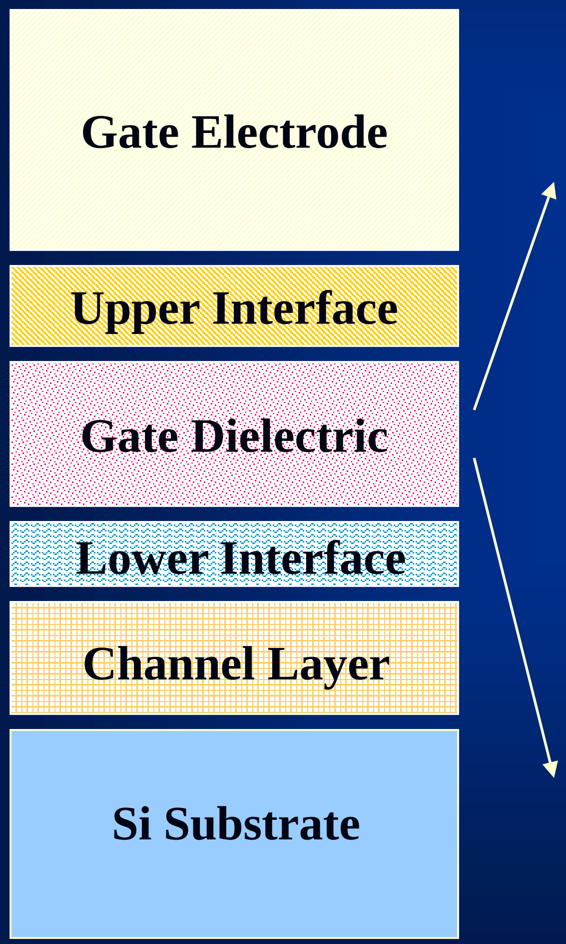
$t_{eq} = t_{ox}\ \kappa_{SiO2} / \kappa_{ox}$

Basic Characteristics of Binary Oxide Dielectrics

Dielectrics	SiO_2	Al_2O_3	Y_2O_3	HfO_2	Ta_2O_5	ZrO_2	La_2O_3	TiO_2
Dielectric constant	3.9	9.0	18	**20**	25	27	30	80
Band gap (eV) Band offset (eV)	9.0 3.2	8.8 2.5	5.5 2.3	**5.7** **1.5**	4.5 1.0	7.8 1.4	4.3 2.3	3.0 1.2
Free energy of formation $MO_x + Si_2 \longrightarrow M + SiO_2$ @727C, Kcal/mole of MO_x	-	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^2/sec)	2×10^{-14}	5×10^{-25}	?	**?**	?	10^{-12}	?	10^{-13}

Integration Issues for High κ Gate Stack

FET Gate Stack



Critical Integration Issues

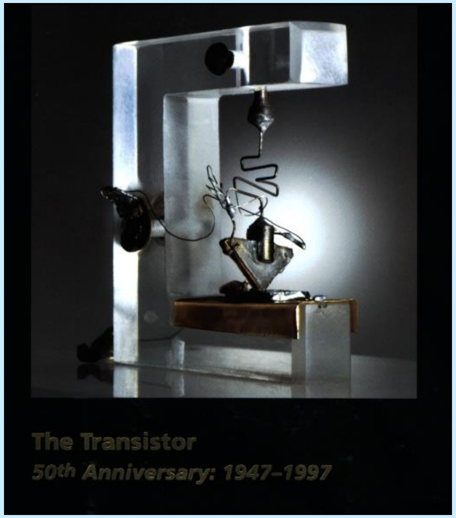
- Morphology dependence of leakage
  Amorphous vs crystalline films?
- Interfacial structures
- Thermal stability
- Gate electrode compatibility
- Reliability

Fundamental Limitations

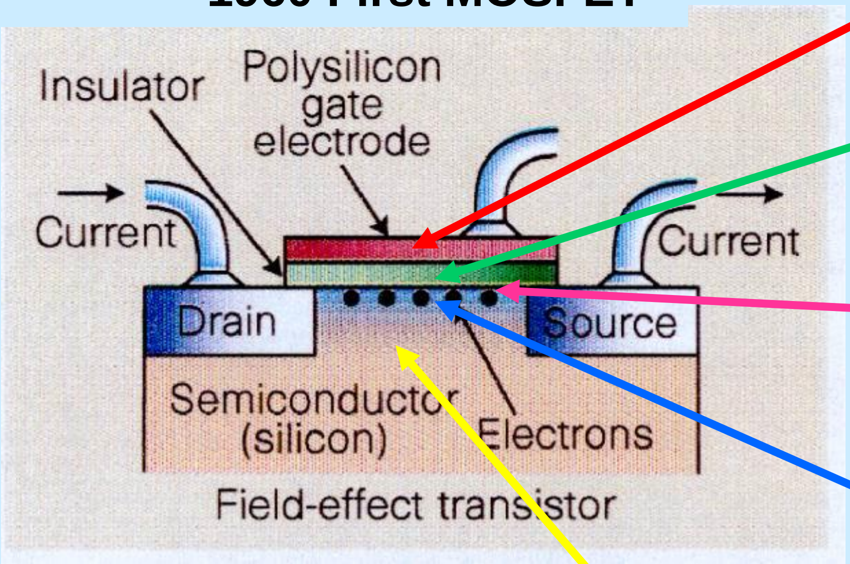
- Fixed charge
- Dopant depletion in poly-Si gate
- Dopant diffusion
- Increasing field in the channel region

Si CMOS Device Scaling – Beyond 22 nm node
High κ, Metal gates, and High mobility channel

1947 First Transistor



1960 First MOSFET



Metal Gate

High κ gate dielectrics

Oxide/semiconductor interface

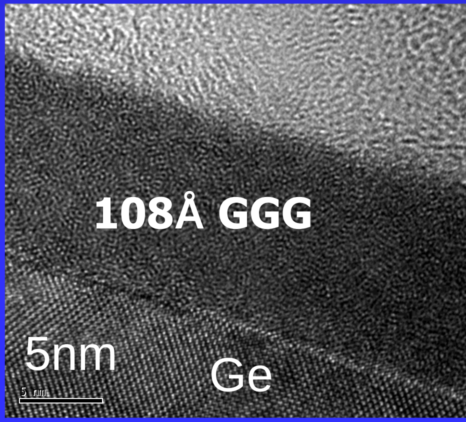
High mobility channel

Integration of Ge, III-V with Si

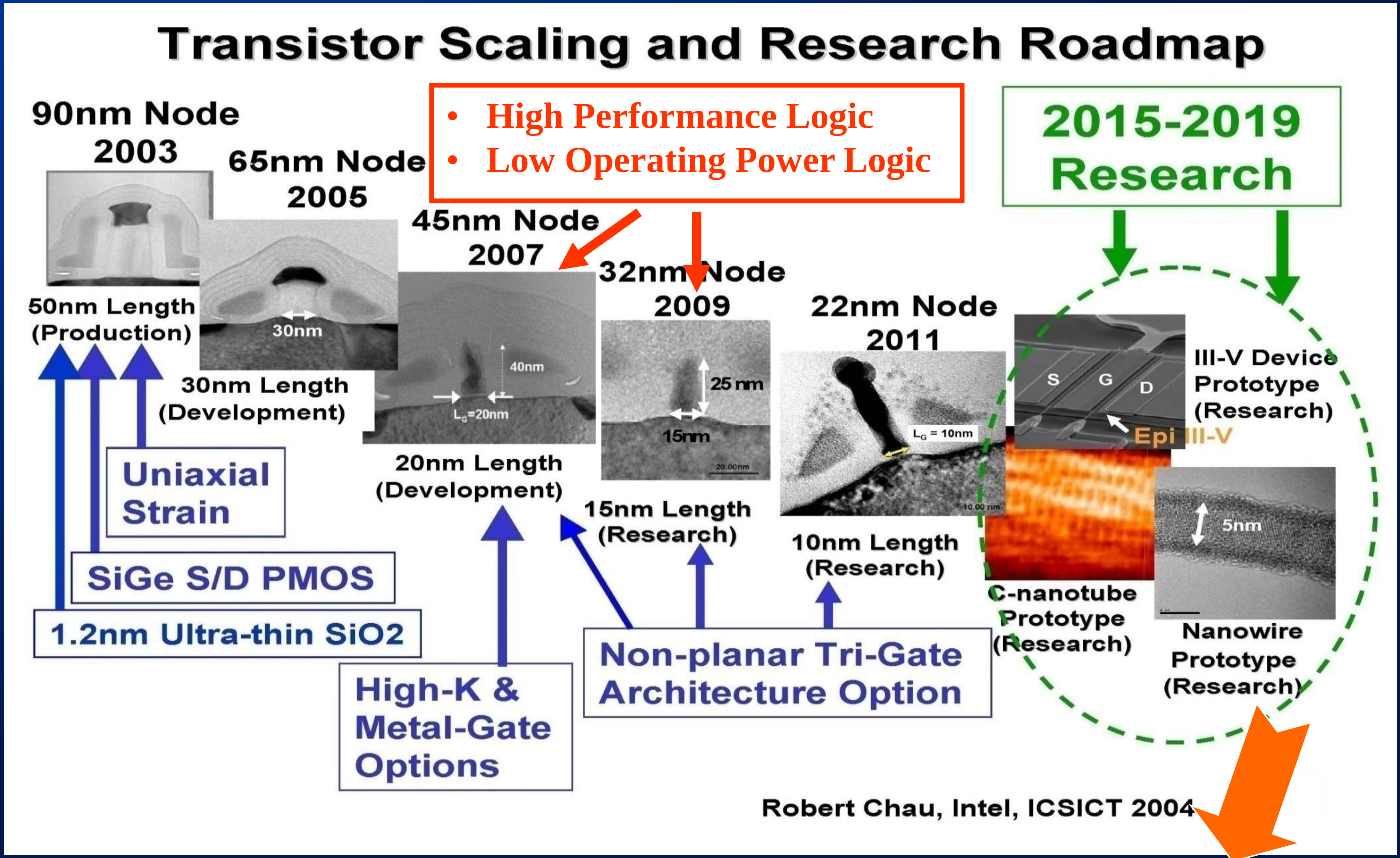
Moore's Law: The number of transistors per square inch doubles every 18 months

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

Driving force :
High speed
Low power consumption
High package density



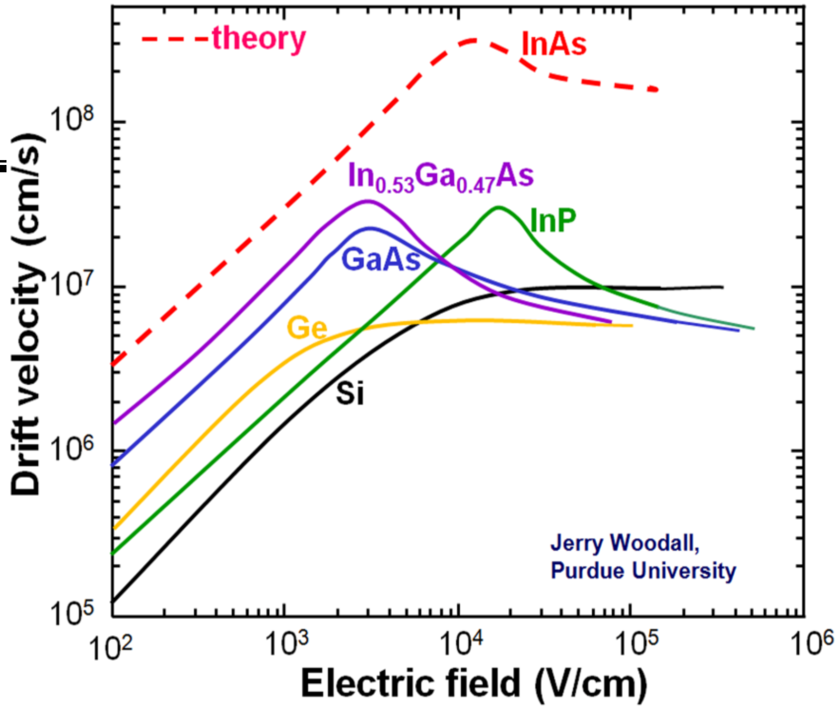
Intel Transistor Scaling and Research Roadmap



More non-silicon elements introduced

Intel
R&D PIPELINE
2011
2013
2015+
22 nm
14 nm
10 nm
7 nm
5 nm
IN PRODUCTION
IN DEVELOPMENT
IN RESEARCH
Lithography • Materials • Interconnect
... and more
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-κ / III-V MOSFETs

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

	IV		III-V				
	Si	Ge	GaAs	$In_{0.53}Ga_{0.47}As$	InAs	GaSb	InSb
Electron Mobility ($cm^2/V\cdot s$)	1,400	3,900	8,500	12,000	40,000	3000	77,000
Hole mobility ($cm^2/V\cdot s$)	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

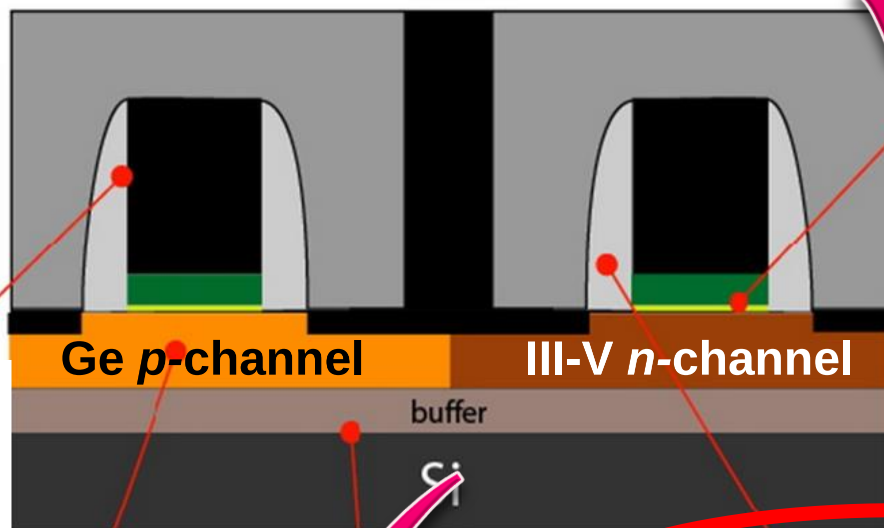
III-V/Ge CMOS

J. A. del Alamo
IEDM 2007 Short Course: Emerging Nanotechnology and Nanoelectronics

high-κ dielectric gate insulator

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

non-planar device architecture



Ge *p*-channel MOSFETs

scalable, self-aligned, E-mode device architectures

III-V epitaxy on large-area Si wafers

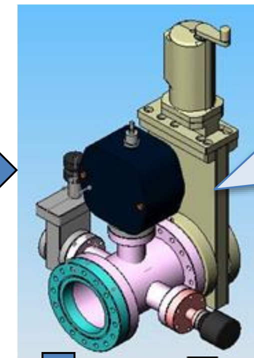
Science and Technology of Ultimate CMOS

The Ultimate CMOS – End of road map

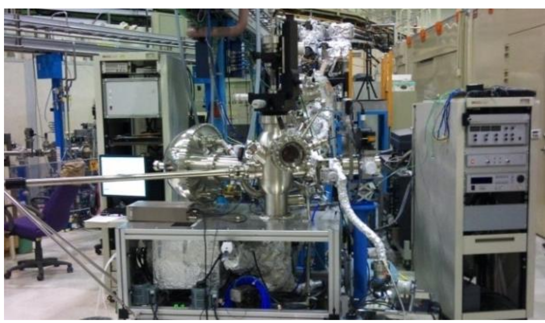
To achieve higher speed and lower power consumption

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



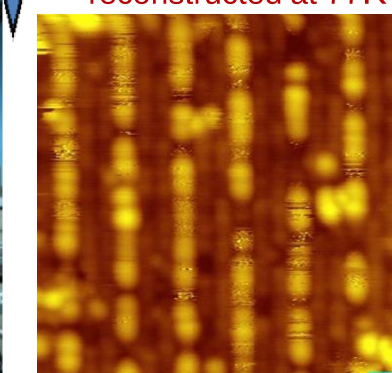
Portable UHV chamber for transfer 2”wafers in 3×10^{-10} torr for ARPES, PES and STM analysis



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

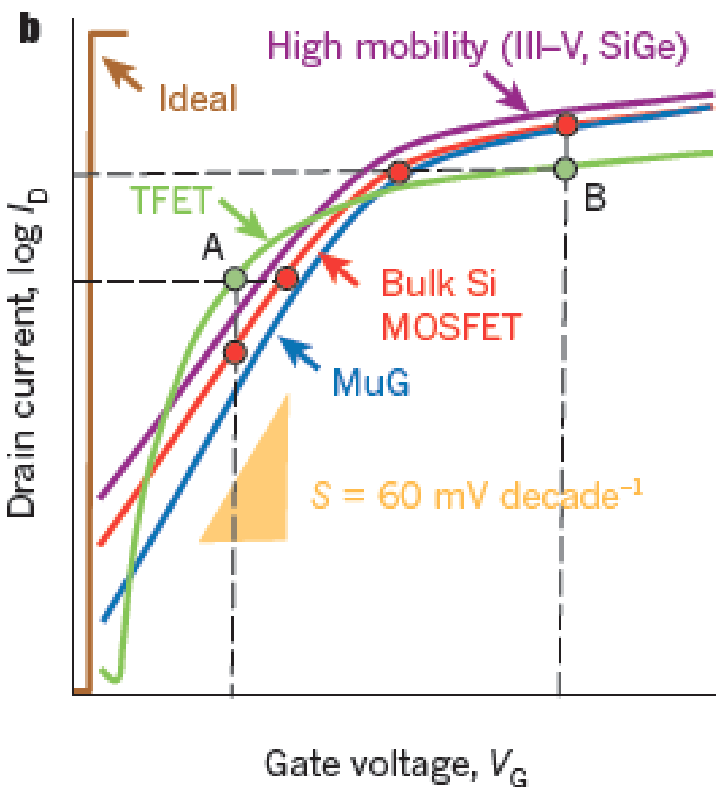


Tunneling-FETs offer sharper turn-on devices compared to MOSFETs

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

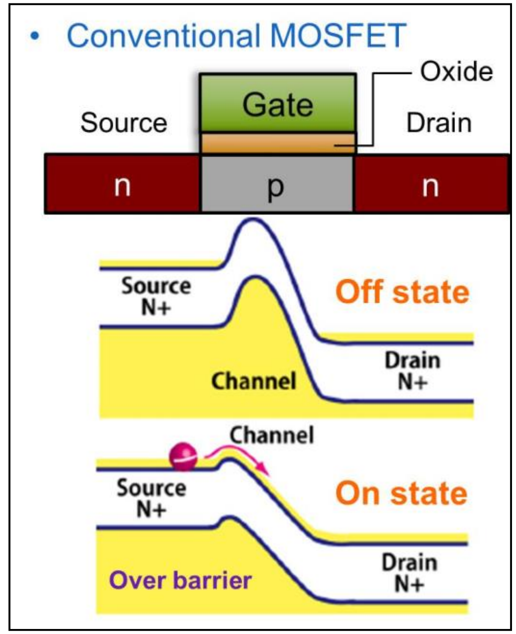
Better performance for ultra low-power applications

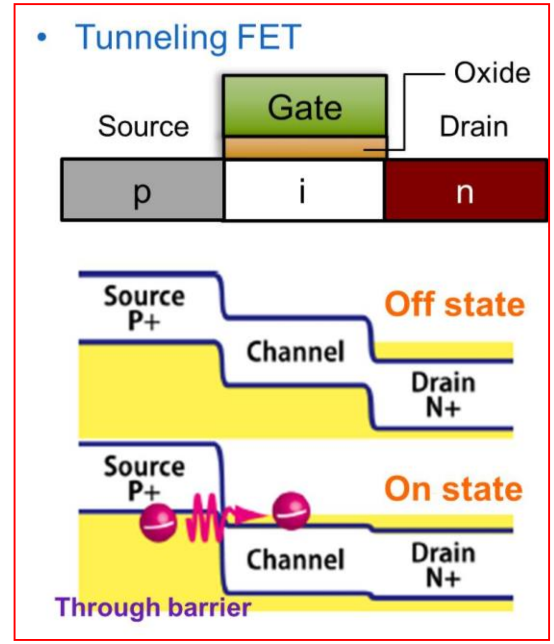
Atomic Model Prediction



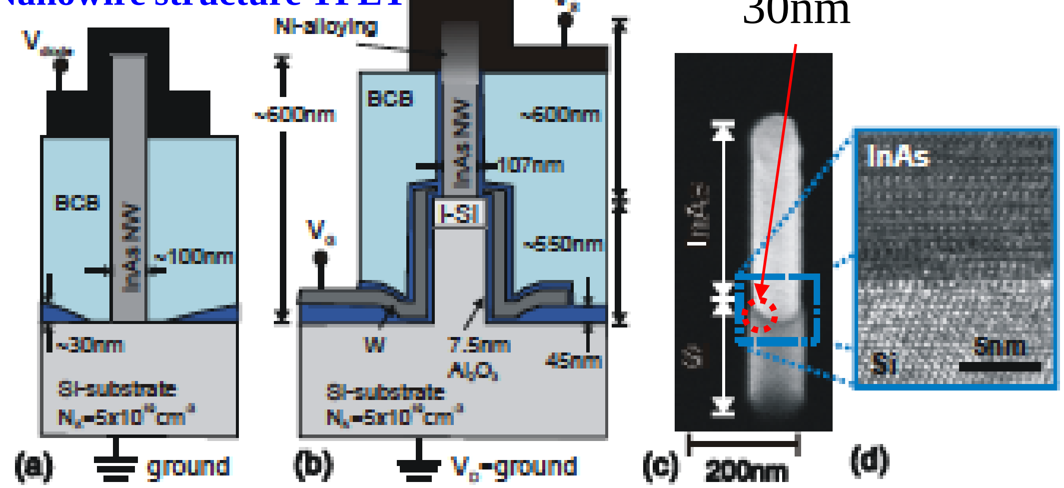
Much smaller subthreshold swing !

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





Nanowire structure TFET

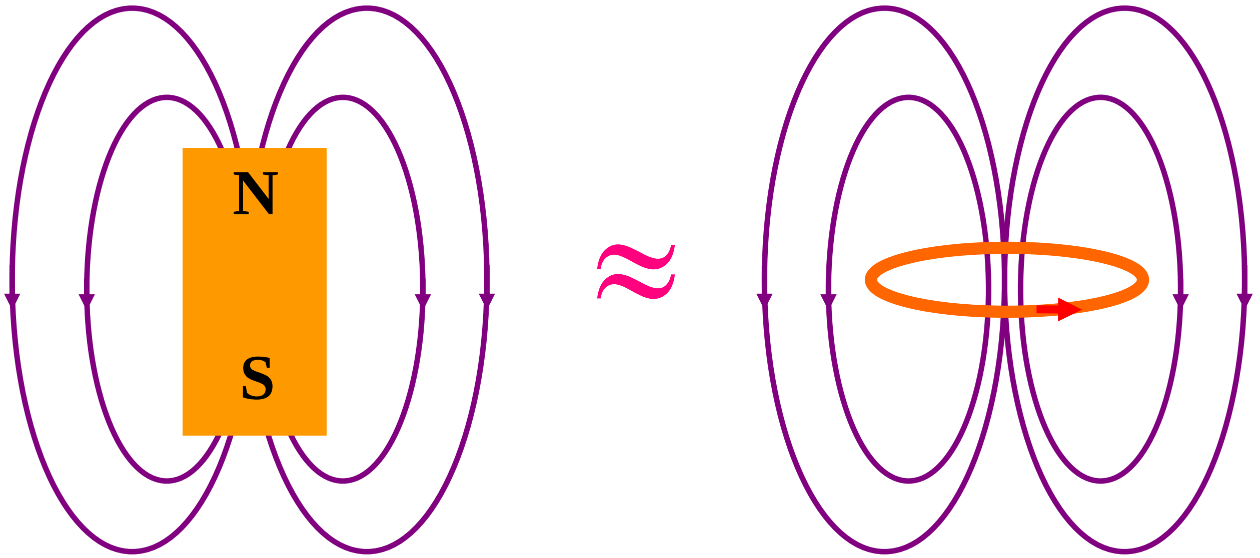


H. Riel et al., *IEDM* 391 (2012).

(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 ⇔ Electronics

New generation of computer

Computation and storage in one shot

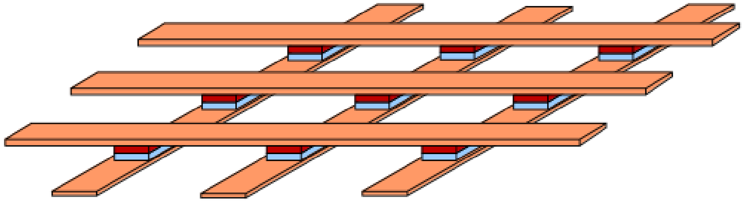
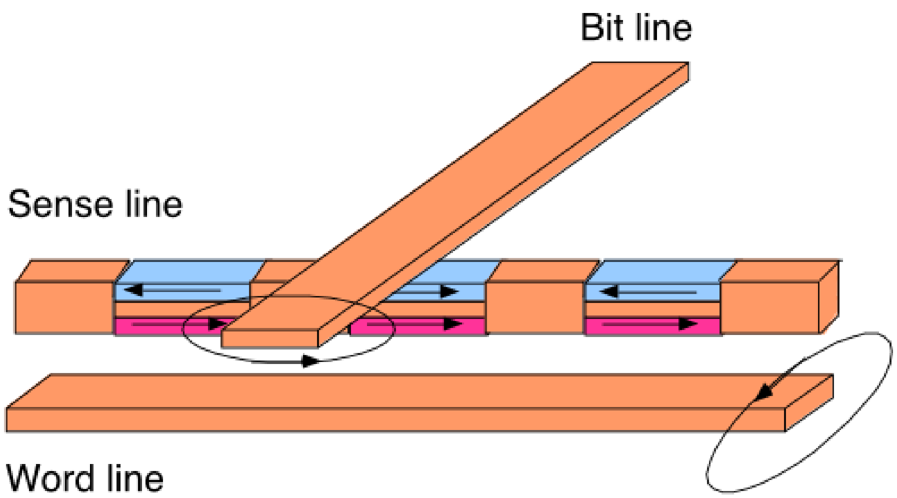


Fig. 7. A schematic representation of RAM that is constructed of magnetic tunnel junctions connected together in a point contact array. The conducting wires provide current to the junctions and permit voltage measurements to be made. They also enable the manipulation of the magnetization of the elements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

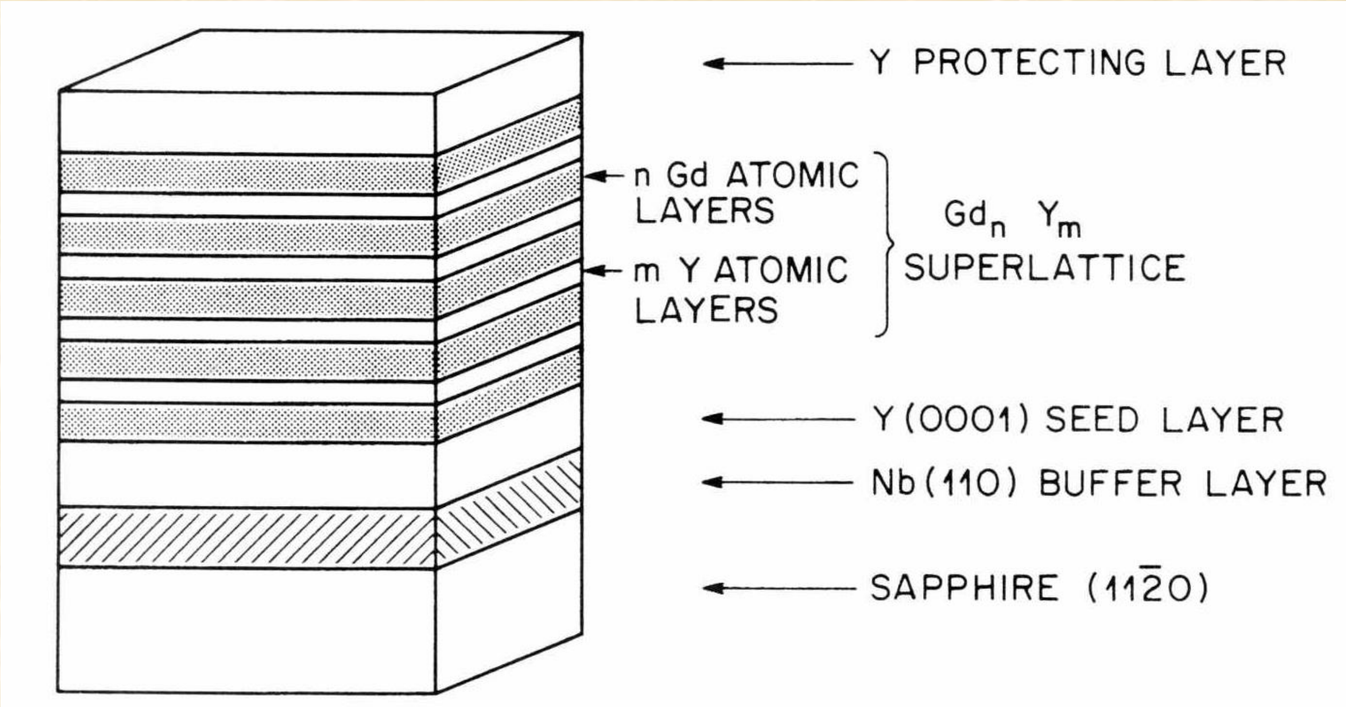


When turn-on, it is ready!

Artificial Superlattice

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

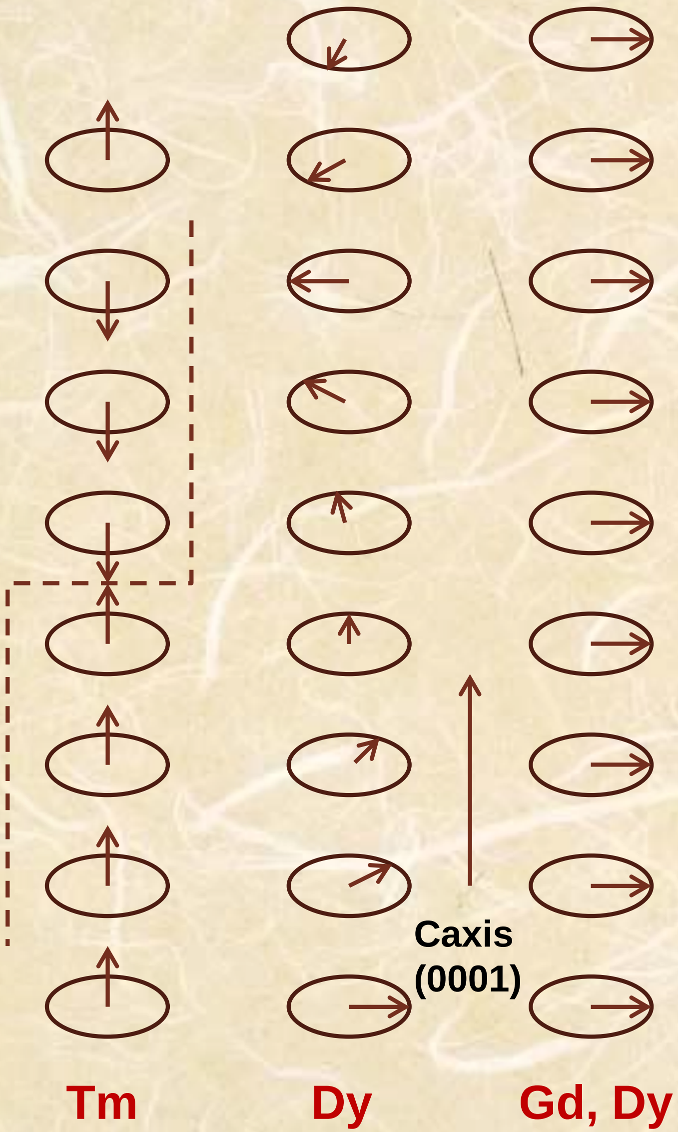
-- **Modulation of physical properties**



Invention of metal molecular beam epitaxy in 1981

-- Single crystal epitaxial superlattices with atomically abrupt interfaces

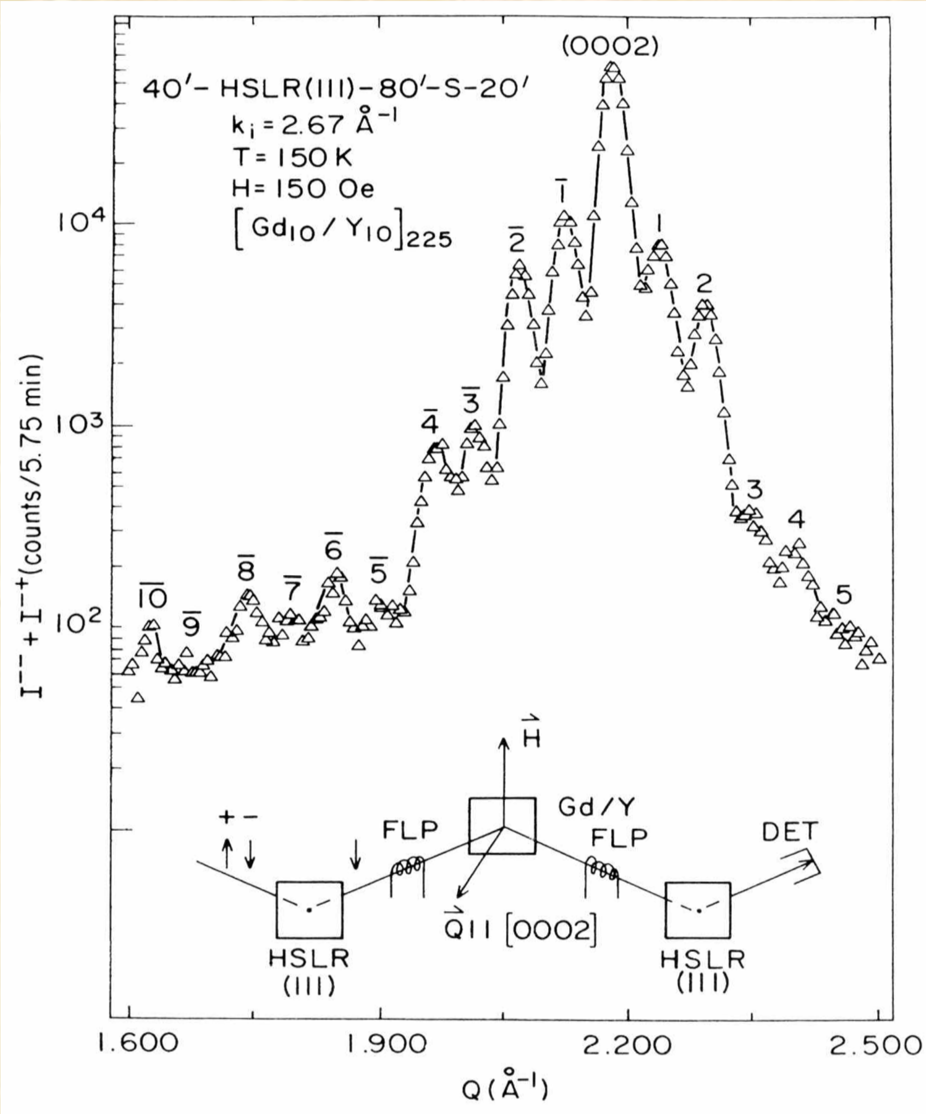
HCP crystal structure

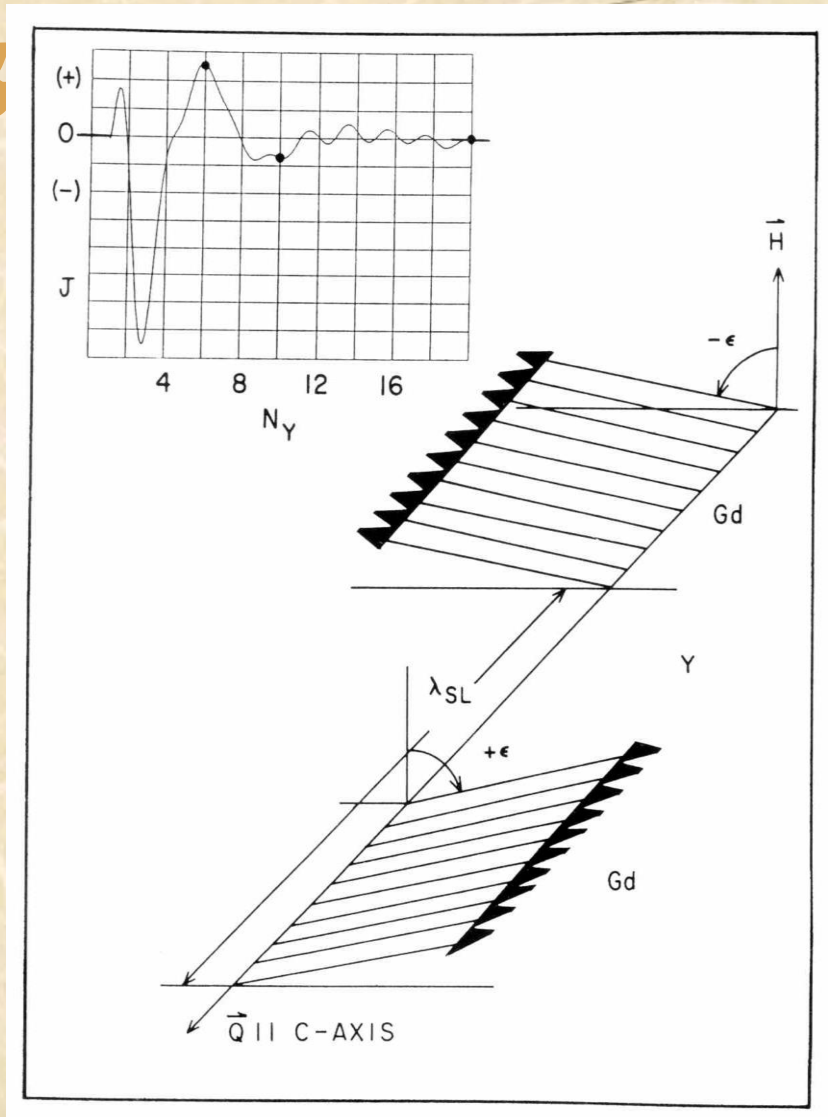


Spin structures of heavy rare - earths

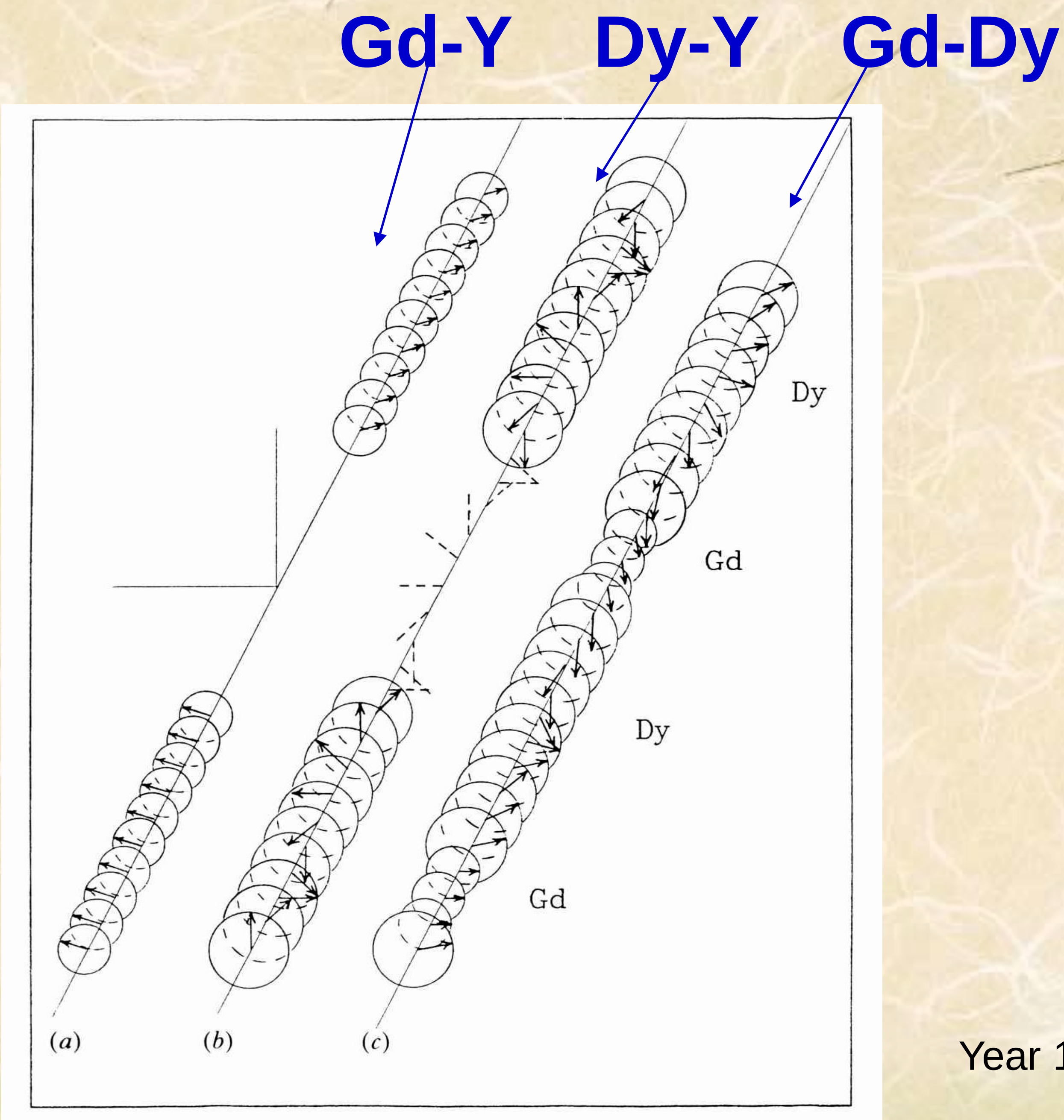
- Similar crystal- chemical nature of rare earths form coherent superlattices
- Metallic superlattice effect
  - Long range nature of the indirect exchange interaction
  - Magnetic coupling of magnetic rare earth through non – magnetic Y, Lu
  - Modulation of magnetic properties of Gd - Y Superlattices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

Neutron Diffraction Studies of the Gd_{10}-Y_{10} Magnetic Superlattice Antiferromagnetically coupled below 200K





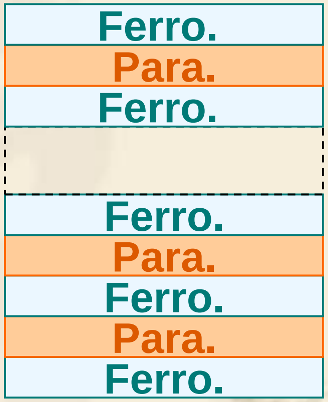
Spin Structure Tailoring in artificial Superlattices



Year 1984-1989

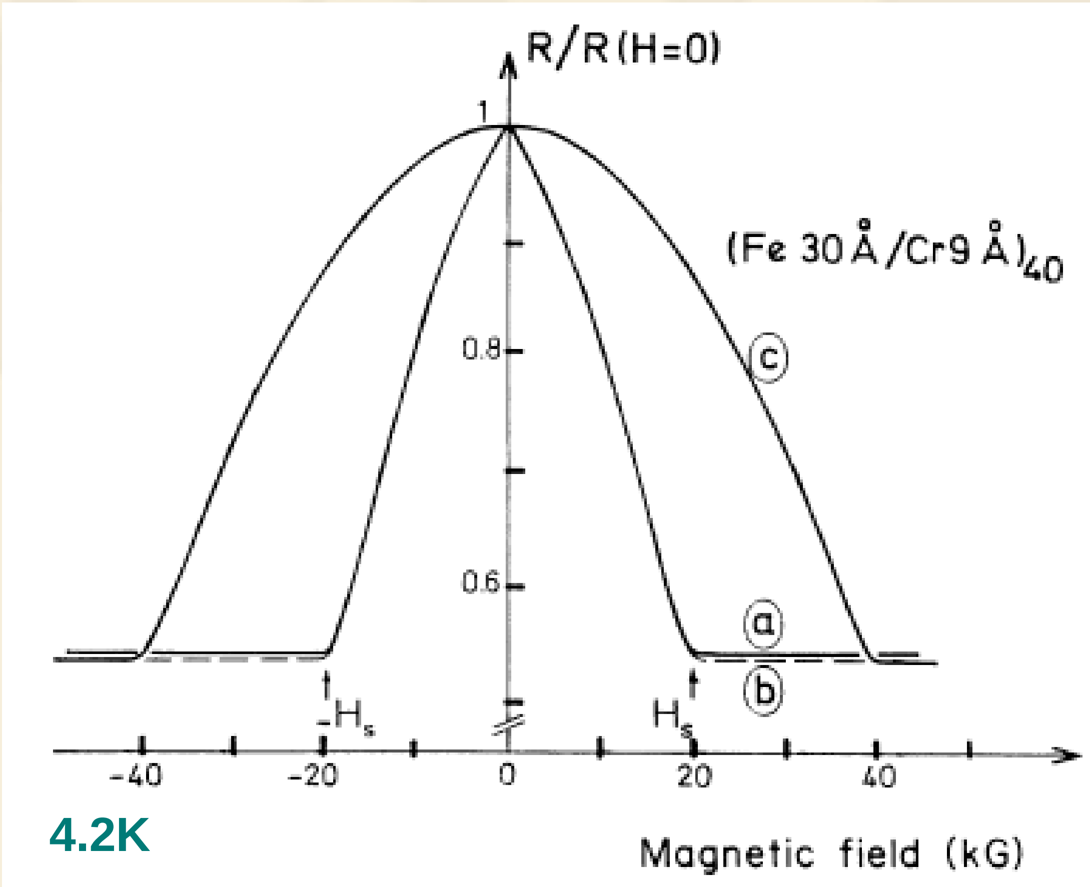
Giant Magnetoresistance (GMR)

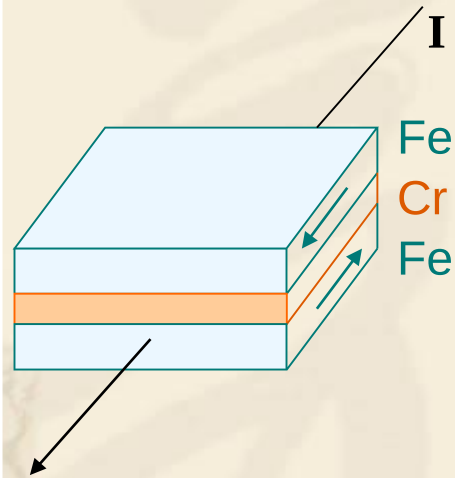
- **What is GMR?**
  - **GMR is a very large change in electrical resistance that is observed in a ferromagnet/paramagnet multilayer structure.**
  - **Resistance change occurs when the relative orientations of the magnetic moments in alternate ferromagnetic layers change as a function of applied field.**
  - **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.**



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

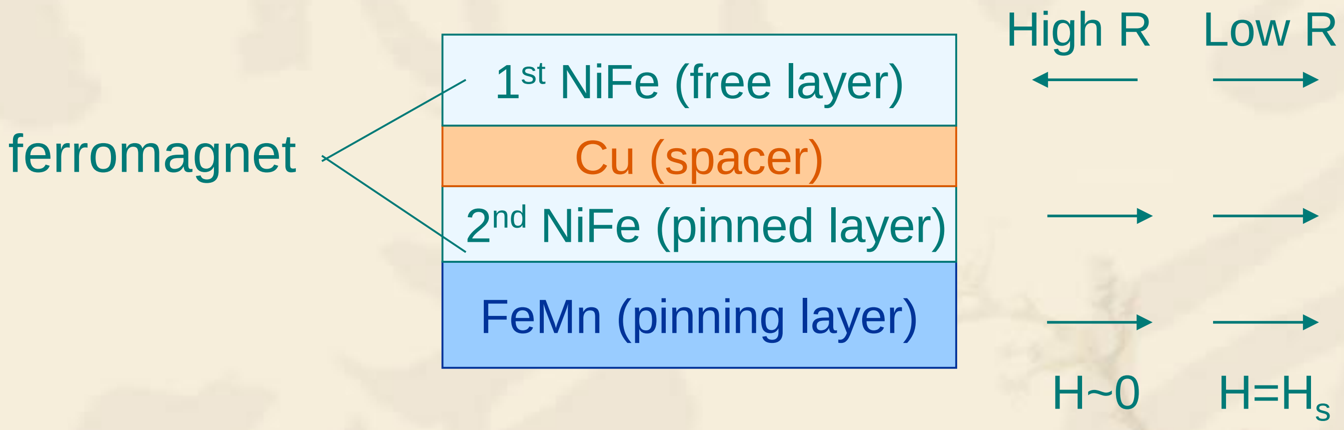




***H_s* corresponds to the field at which all layer magnetizations point along the field direction.**

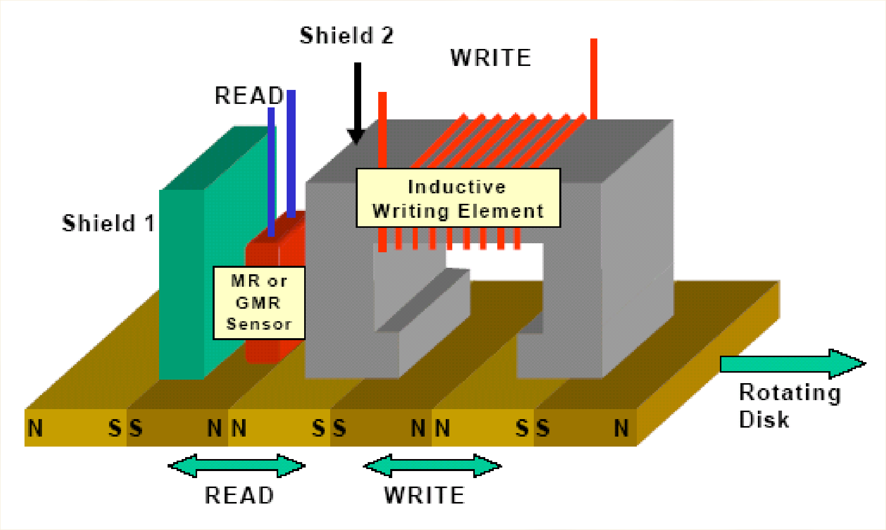
Spin-Valve GMR

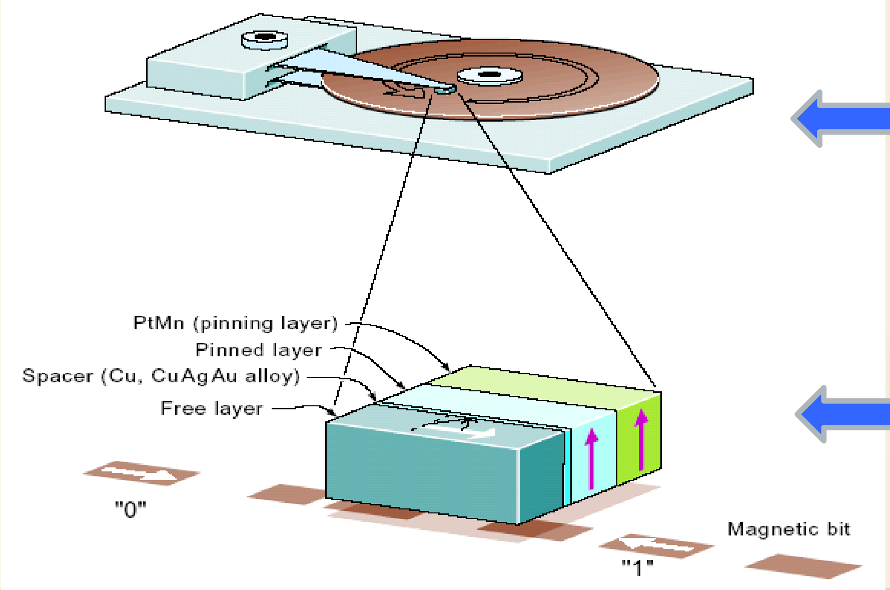
- **The simple structure of Spin-Valve GMR :**



- **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





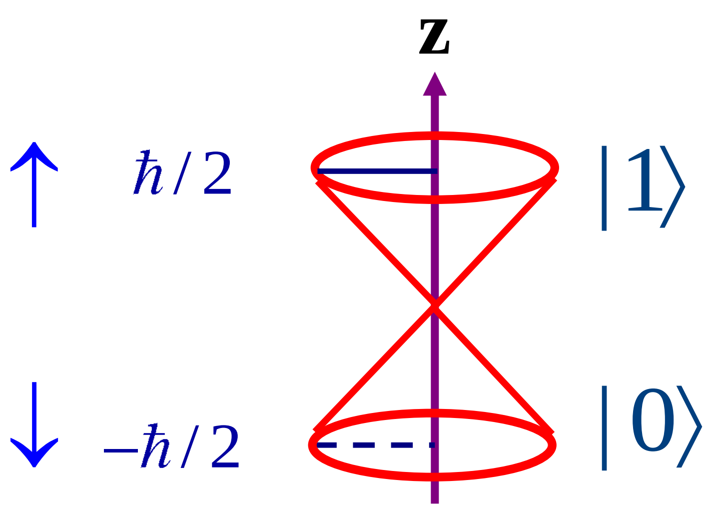
- Magnetization is stored as a "0" in one direction, and as a "1" in the other. This is the magnetic field sensed by the GMR head.

- 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

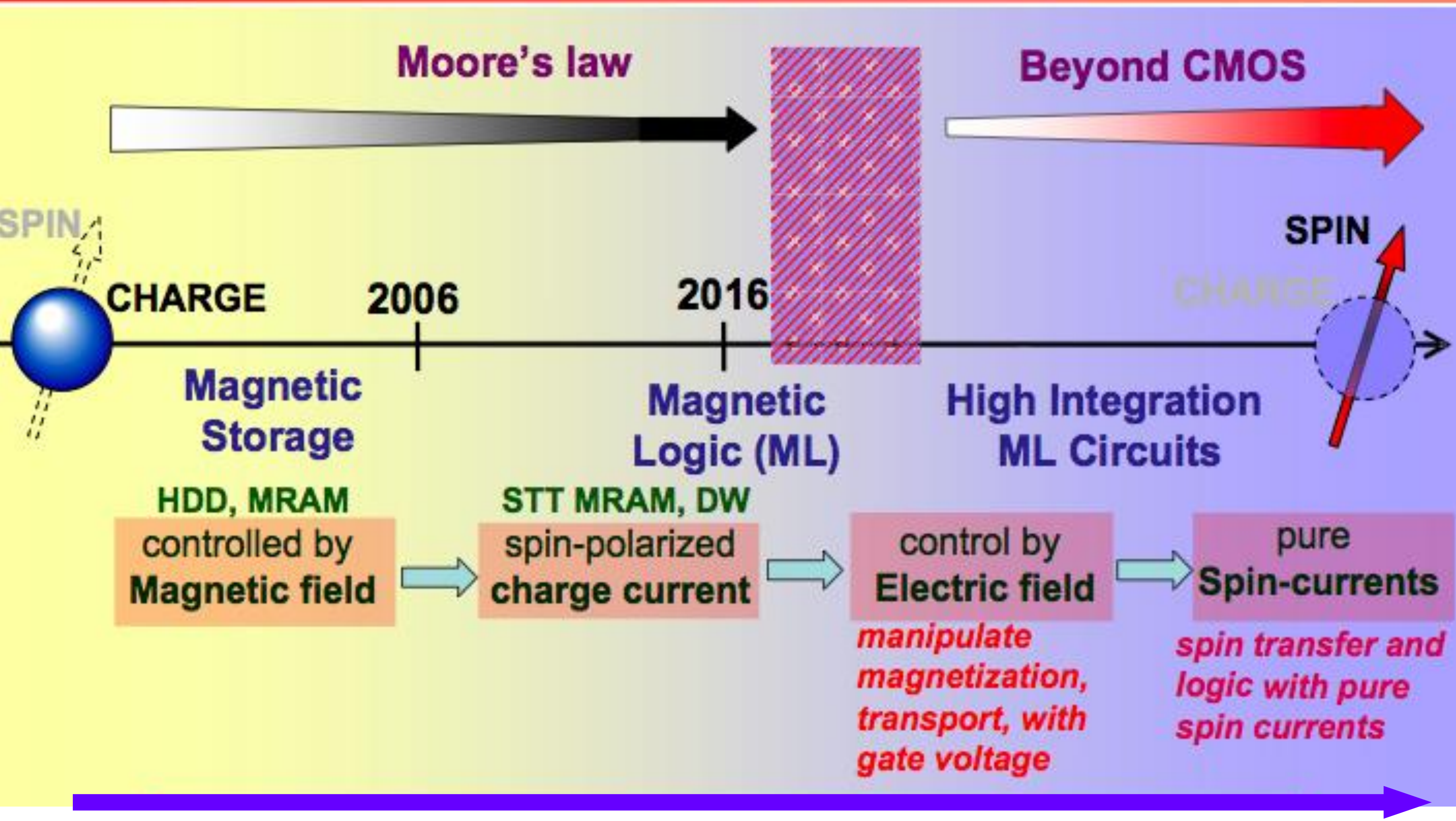
-Spin as a quantum qubit



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

Due to superposition
More information!

Tentative roadmap



Can we take the "charge" out of Spintronics ?

To generate pure spin current !

Courtesy Claude Chappert, Université Paris Su, INTERMAG 2008, Madrid, Spain

Reciprocal conversion between spin and charge currents

Spin Hall effect (2004)

Charge Current

↓

Transverse

Spin Imbalance

Inverse Spin Hall effect (2006)

Spin Current

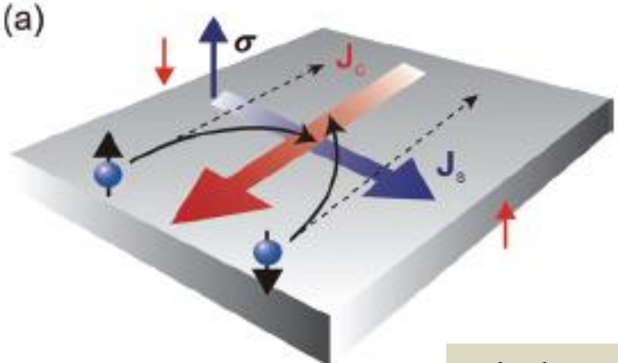
↓

Transverse

Charge Imbalance

Spin-Orbit Interaction
without magnetic field

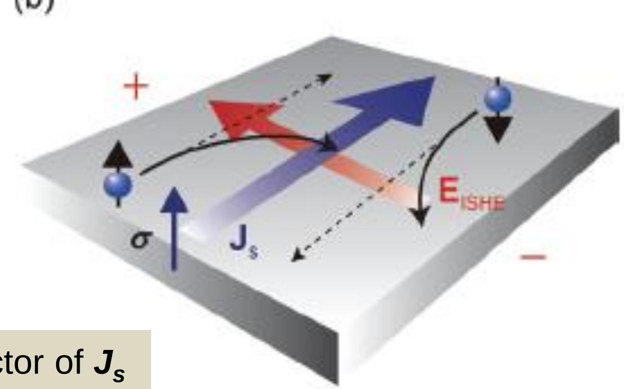
(a)



$$J_s = \theta_H \hat{\boldsymbol{\sigma}} \times J_c$$

Generate the spin current

(b)



$$J_c = \theta_H \hat{\boldsymbol{\sigma}} \times J_s$$

Detect the spin current

$\boldsymbol{\sigma}$ is the spin-polarization vector of $\boldsymbol{J}_s$

Y. K. Kato, R. C. Myers, A. C. Gossard, and D. D. Awschalom, Science, 306, 1910 (2004). ; J. Wunderlich, B. Kaestner, J. Sinova, and T. Jungwirth, Phys. Rev. Lett. 94, 047204 (2005). ; E. Saitoh, M. Ueda, H. Miyajima, and G. Tatara, Appl. Phys. Lett, 88, 182509, (2006).

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.

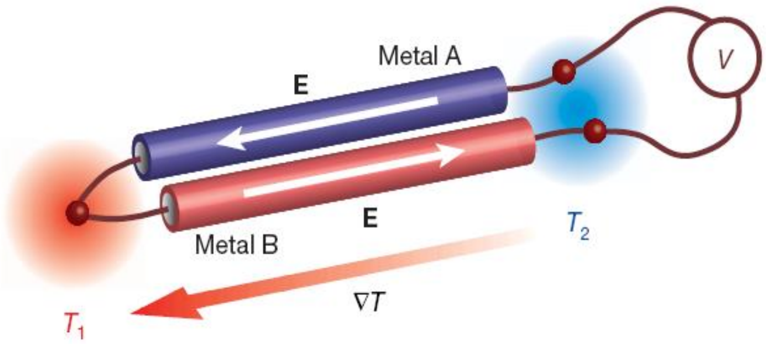
Reliable generation of pure spin currents !

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

Thermoelectric effect

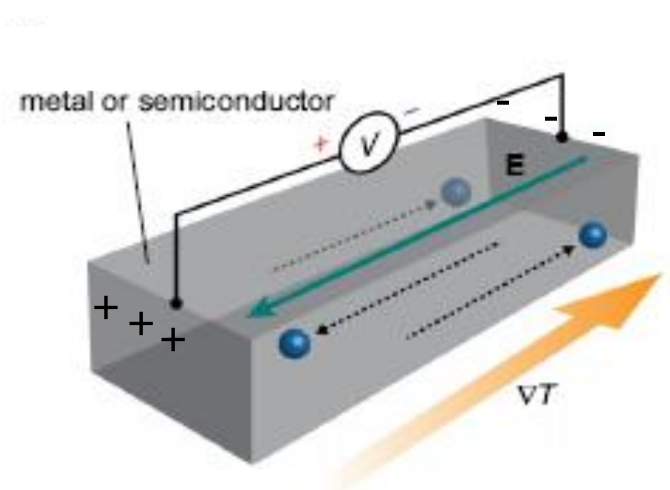
- The interplay between charge currents and heat
- To convert temperature differences ΔT to electric voltage ΔV

1. Thermocuple



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

2. Seebeck effect (1821)

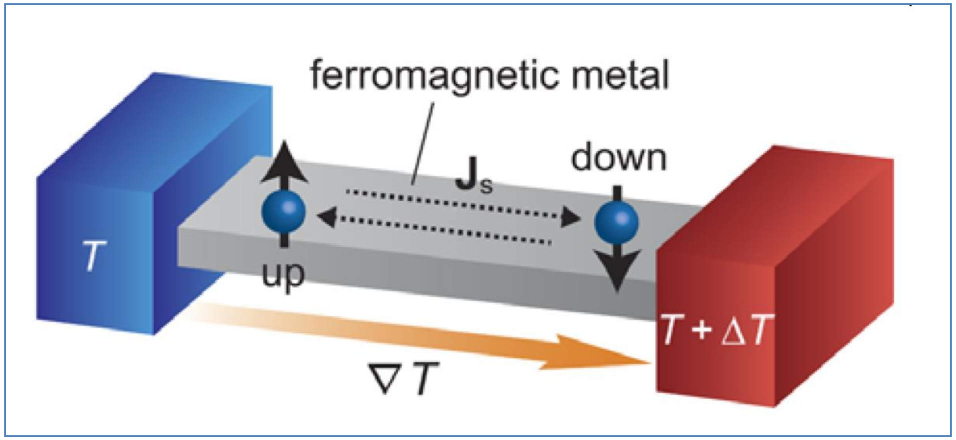


$\Delta T \rightarrow V$

$S = \Delta V / \Delta T$

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

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

∇T ⇨ **a spin imbalance**

- **The up- spin** and **down-spin conduction electrons** of a FM metal have **different chemical potential μ, 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 ∇T, and lead to a net J_s

$$\boldsymbol{j}_s = \boldsymbol{j}_\uparrow - \boldsymbol{j}_\downarrow = (\boldsymbol{\sigma}_\uparrow \boldsymbol{S}_\uparrow - \boldsymbol{\sigma}_\downarrow \boldsymbol{S}_\downarrow)(-\nabla \boldsymbol{T})$$

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

Use heat to generate the spin current ➞ Spin Caloritronics !

K. Uchida et al., Nature, **455**, 778, (2008).

K. Uchida, JAP 111, 103903 (2012)

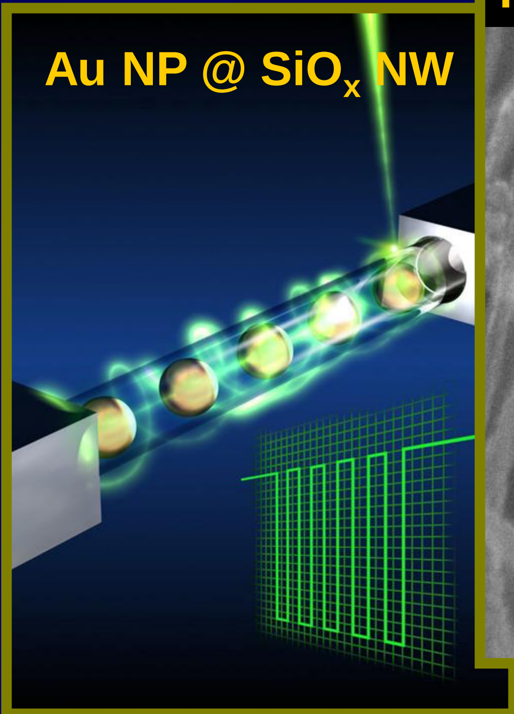
Major Quantum Effect at the Nano Scale

- Interference
- Quantization
- Tunneling
- Quantum spin

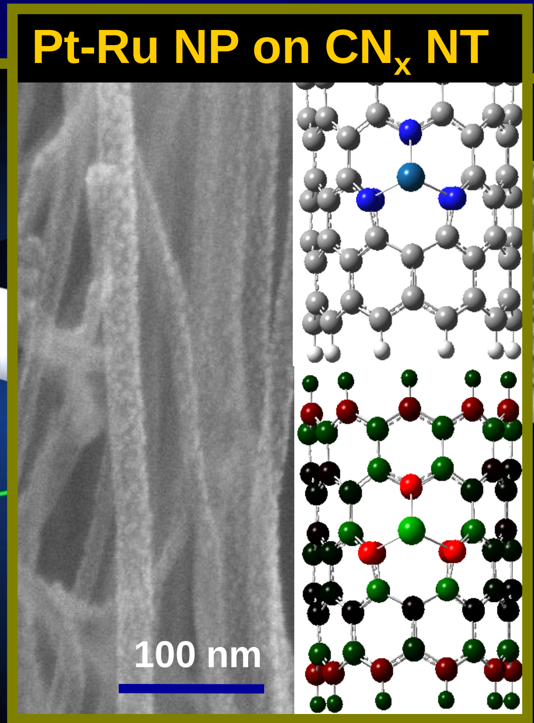
The Fourth Lesson:

Innovations of
nano structures and
nano materials
for various applications

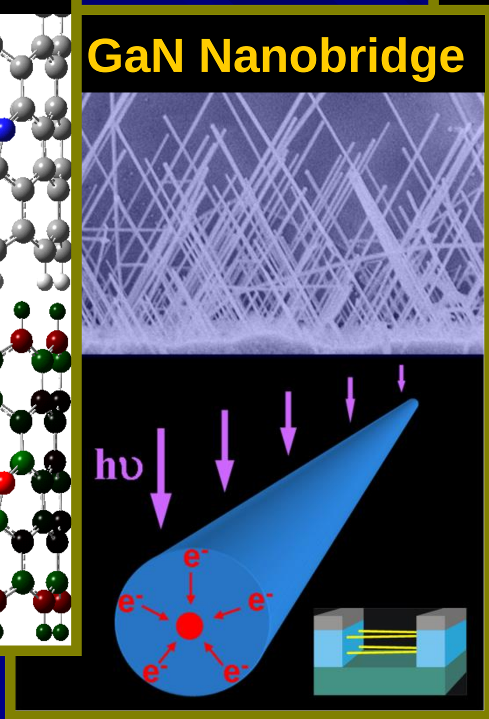
Overview of Advanced Materials Laboratory



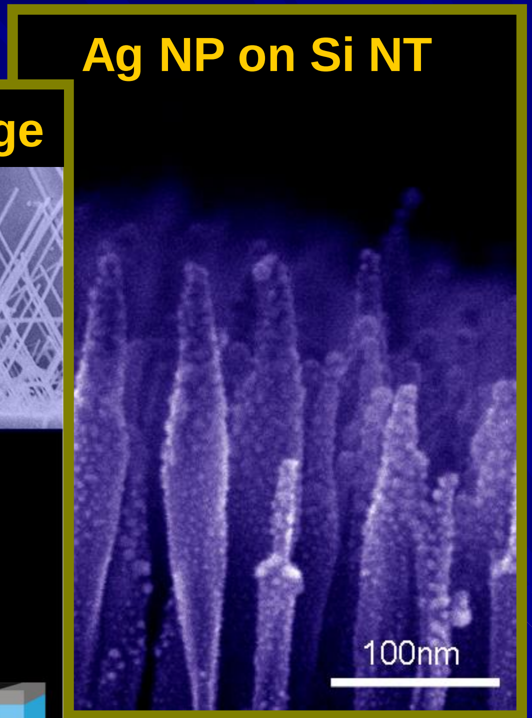
Color-selective Optical Switch, SPR-enhanced Sensor



Fuel Cells, Supercapacitors



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



SERS: Molecule/Bio-sensing

Li-Chyong Chen

Center for Condensed Matter Sciences

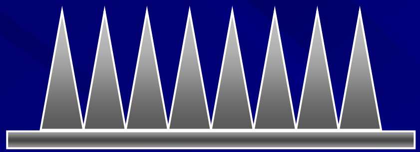
National Taiwan University

The Nano-world at CCMS-AML:

a Fruitful Research Field with Technology Implications

Wire/Rod

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)



Nanotip

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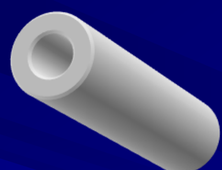
APL 89, 143105 (2006)
Nature Nanotech. 2, 170 (2007)
Nano Lett. 9, 1839 (2009)

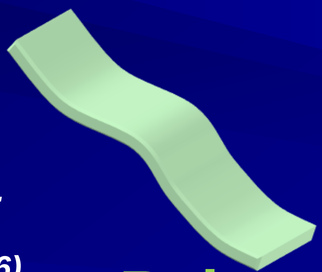


Tube

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)

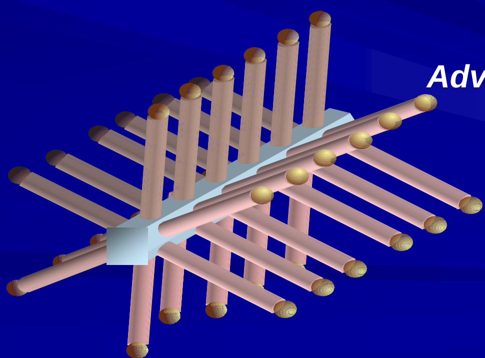
Core-shell

APL 81, 1312 (2002)
Nano. Lett. 3, 537 (2003)



Belt

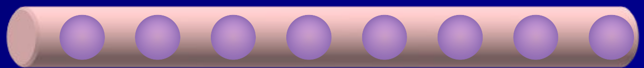
Chapter 9, pp. 259-309,
Nanowires and nanobelts, Z.L.
Wang Ed., Kluwer (2004)
Adv. Func. Mater. 16, 537 (2006)
APL 90, 123109 (2007)
Adv. Mater. 19, 4524 (2007)



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)



Peapod

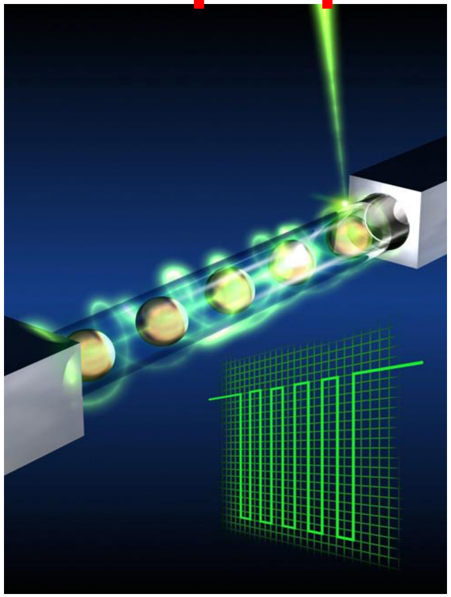
Adv. Mater. 14, 1847 (2002)
Nature Mater. 5, 102 (2006)

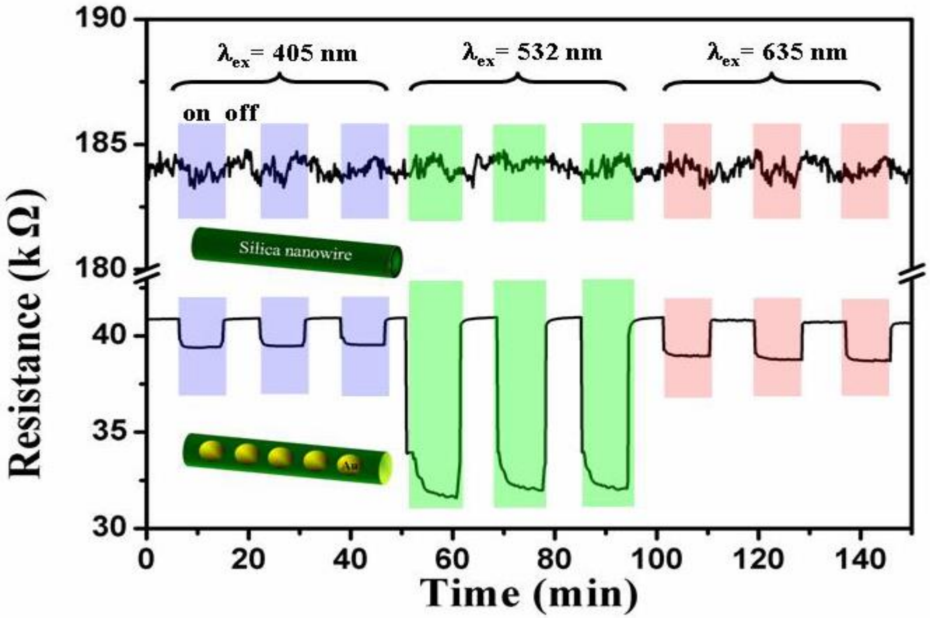
A Color-selective Nanoswitch

Photosensitive Gold Nanoparticle-embedded Dielectric Nanowires

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

nanopeapod





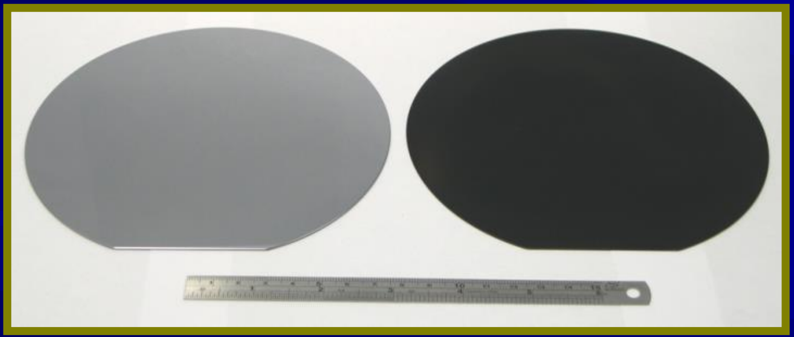
In ancient Arabian story of “Ali Baba and the Forty Thieves”, the treasure is in a cave, of which the mouth is sealed by magic. It opens on the words "Open Sesame" and seals itself on the words "Close Sesame".

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

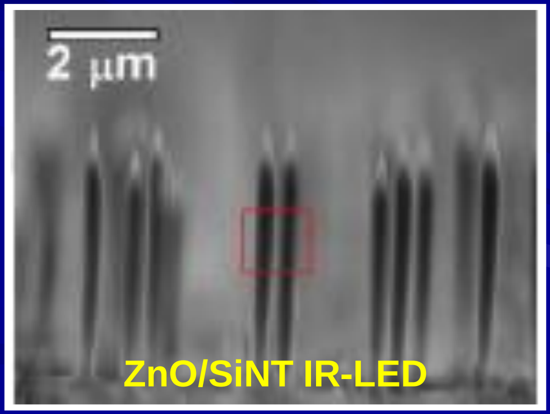
Si Nanotips-Array and their Hetero-junctions: On-chip, IC-compatible

* Antireflection:
  Broadband (UV-terahertz), Omnidirectional (>70°)

* Electroluminescence in ZnO/SiNTs:
  IR emission, x10 higher; turn-on ~3V, x2 lower than film



Nature-Nanotechnology 2 (2007) 770

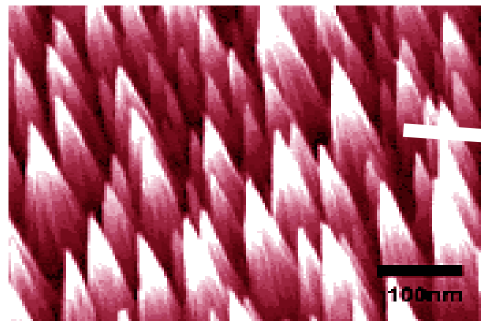


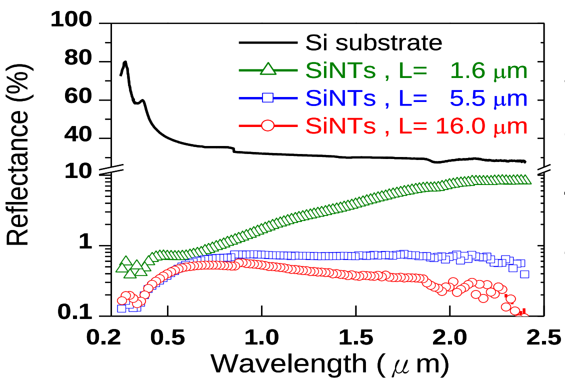
Nano Letters 9 (2009) 1839

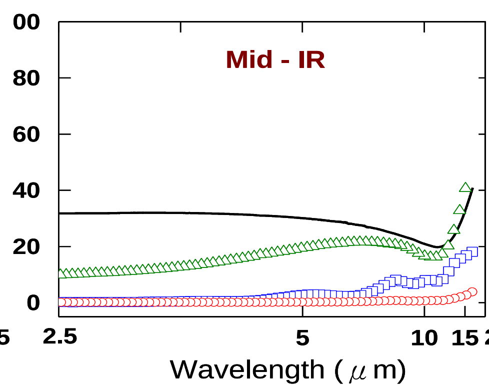
A Man-made Moth Eye

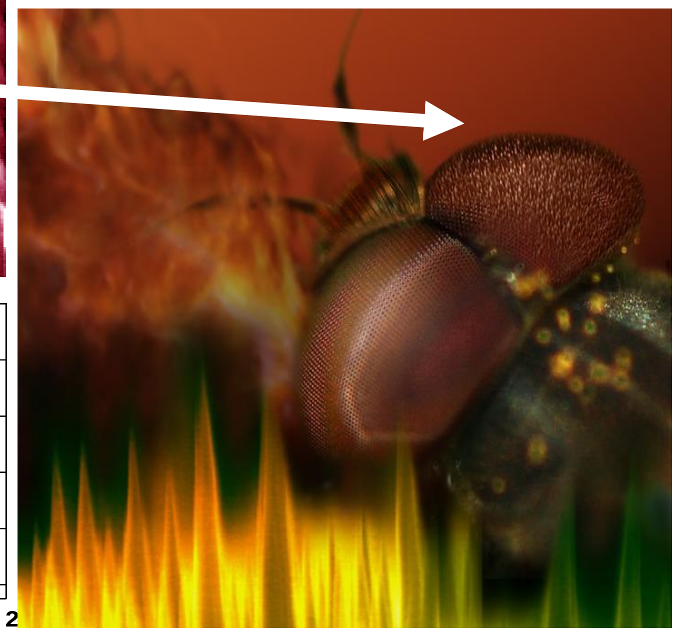
Broadband and quasi-omni-directional, anti-reflection properties with biomimetic Silicon nanostructure

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









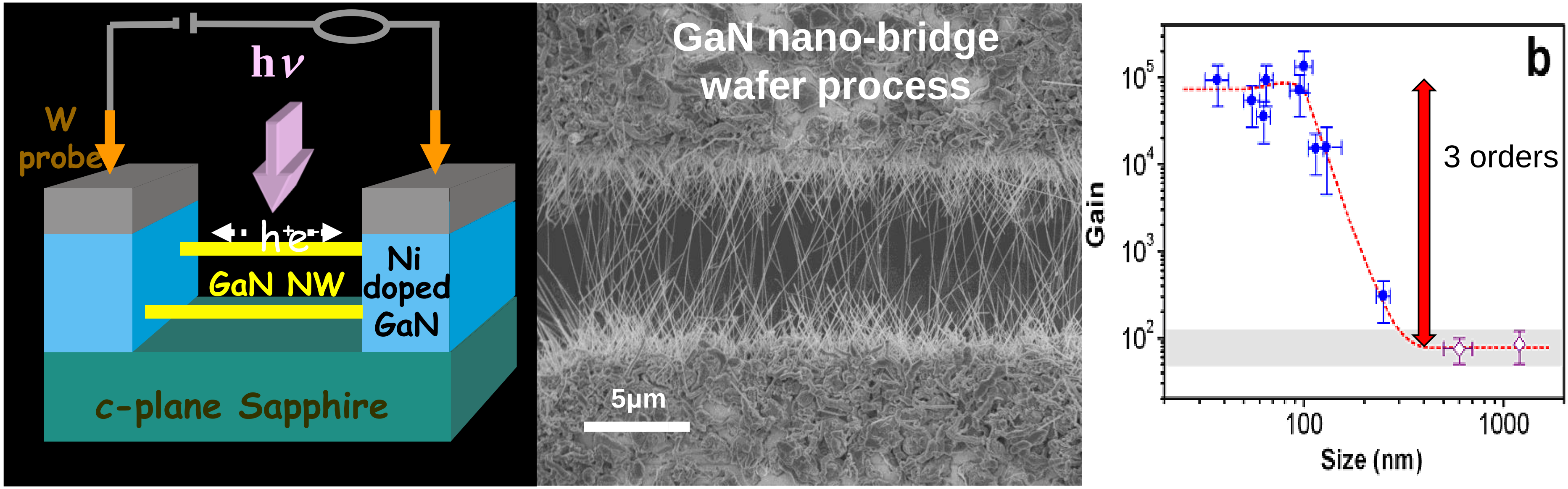
Many plants and animals have tiny surface structures that absorb certain wavelengths of light. These naturally formed nanostructures provide the colors in butterfly wings, camouflage for cicadas and enable moths to capture as much light as possible when flying at night.

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

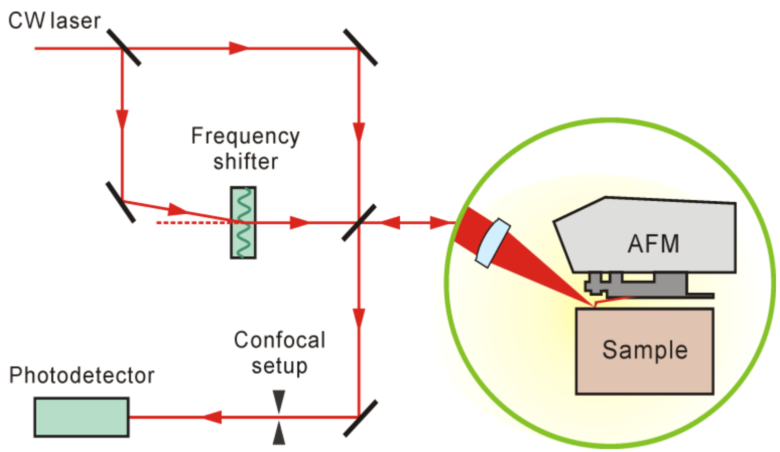
and

Bio-applications

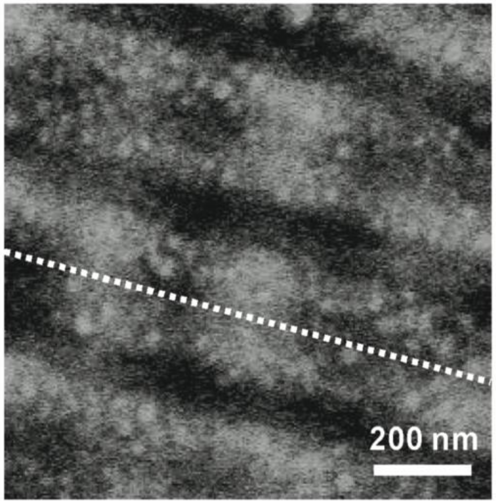
Nano-photonics and Plasmonics
Near-field examination of blue-ray discs

Dr. Juen-Kai Wang, CCMS, NTU

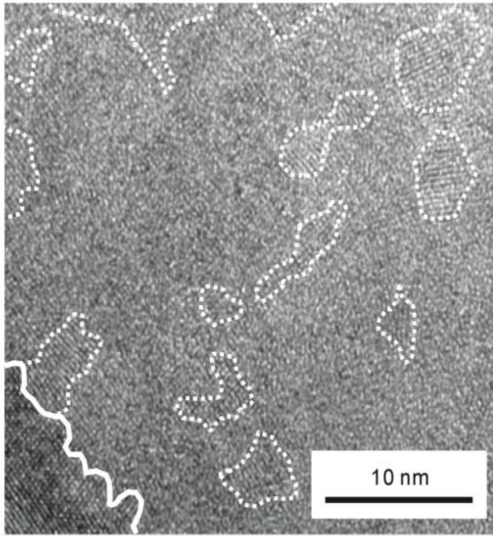
S-SNOM setup



Near-field image of recorded disc



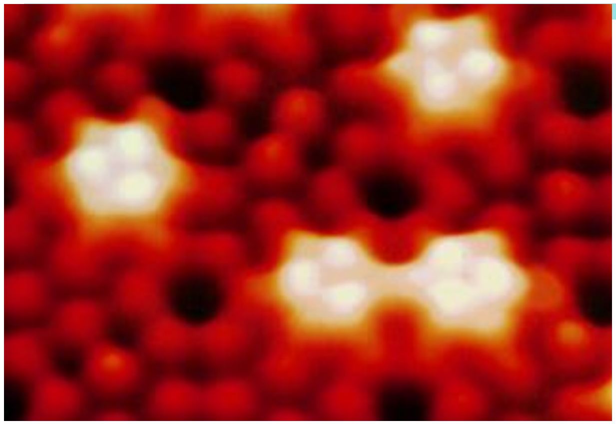
TEM image of recorded mark

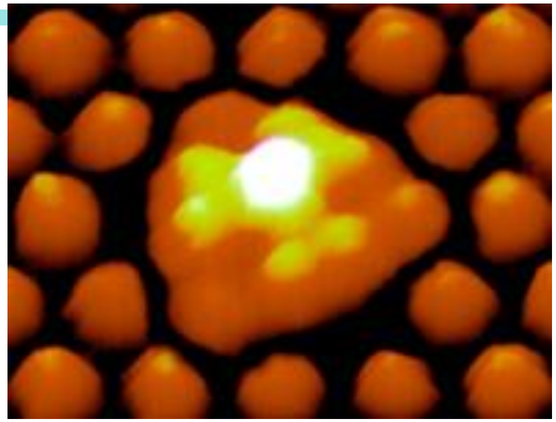


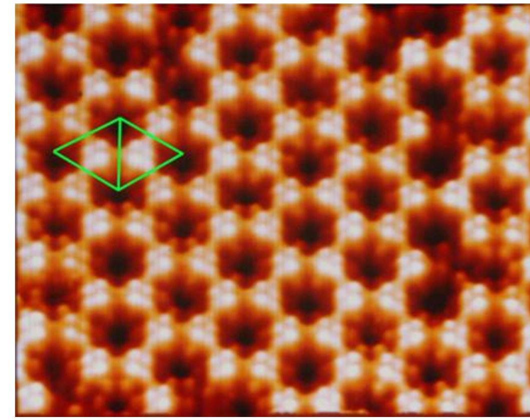
- **Scattering-type SNOM reveals sub-10 nm optical signature.**
- The optical contrasts of the dark and the bright regions in near-field image of phase-change layer correspond to amorphous and polycrystalline AgInSbTe, respectively.
- Small bright spots with a size of ~30 nm emerge within the dark region, 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.**

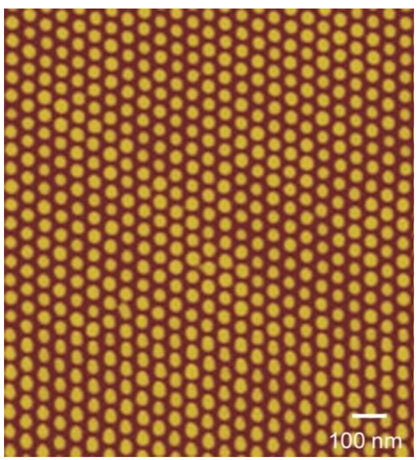
J. Y. Chu et al., Appl. Phys. Lett. 95, 103105 (2009).

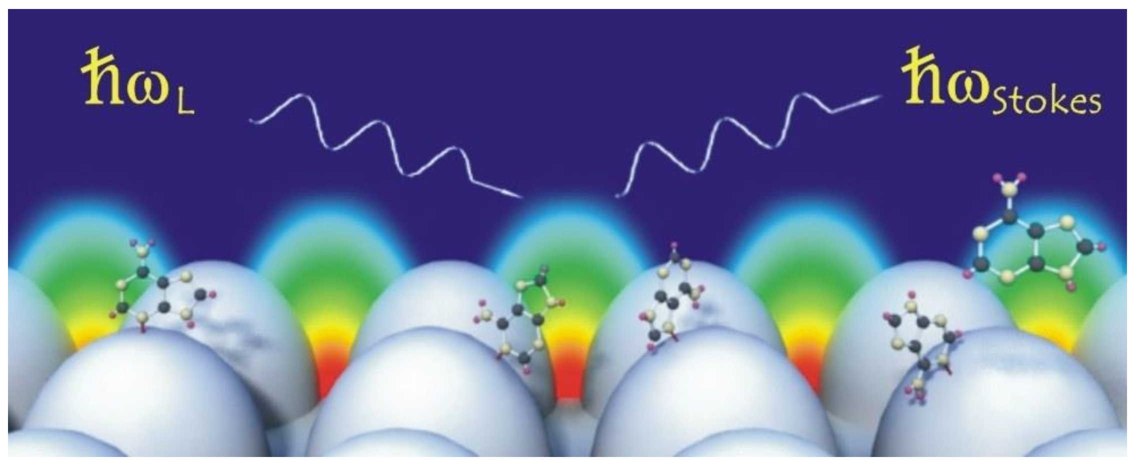
Creating Monodispersed Ordered Arrays of Surface-Magic-Clusters and Anodic Alumia Nanochannels by Constrained Self-organization







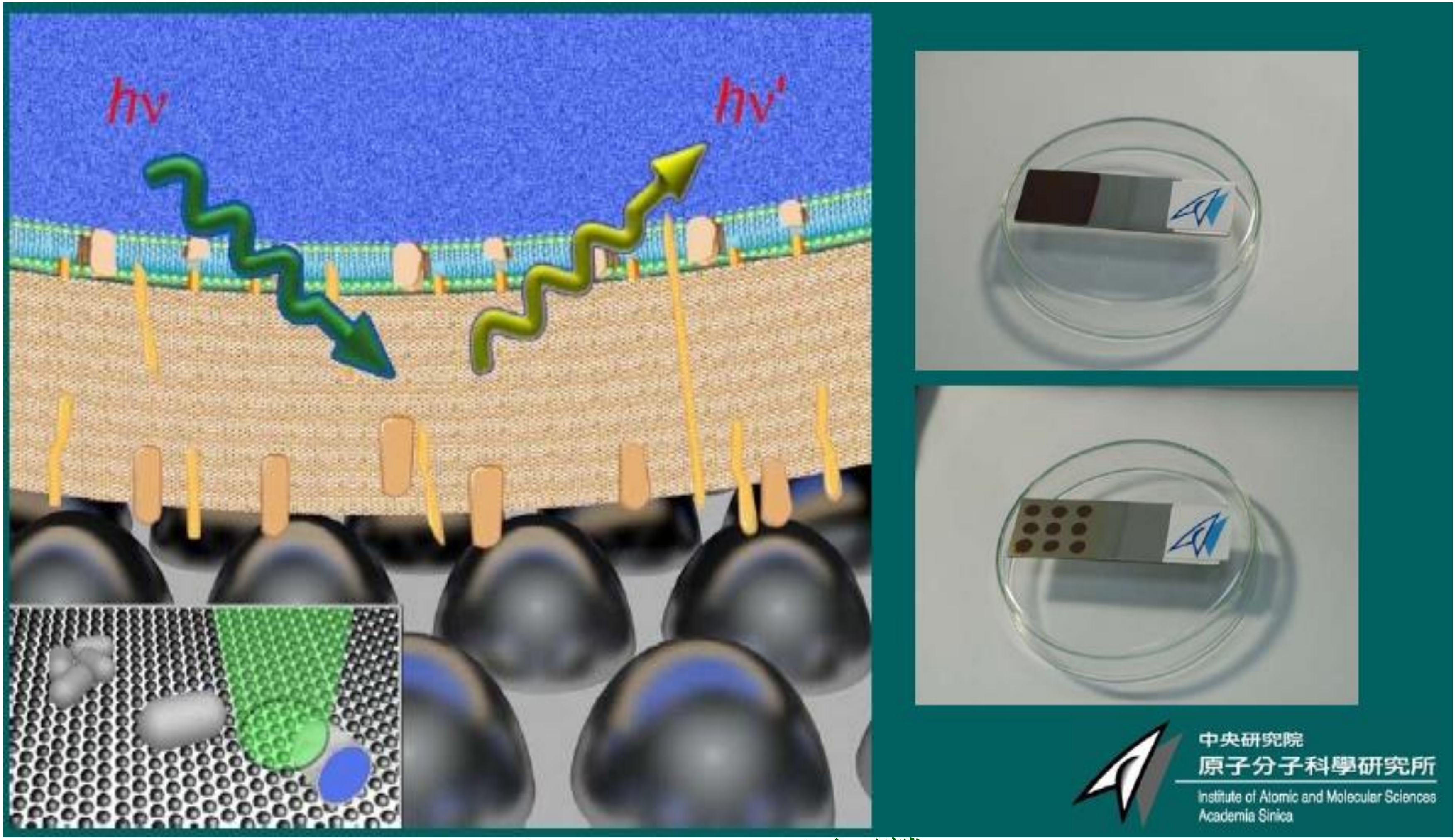




Prof. Yuh-Lin Wang 王玉麟
IAMS Academia Sinica, Taiwan

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

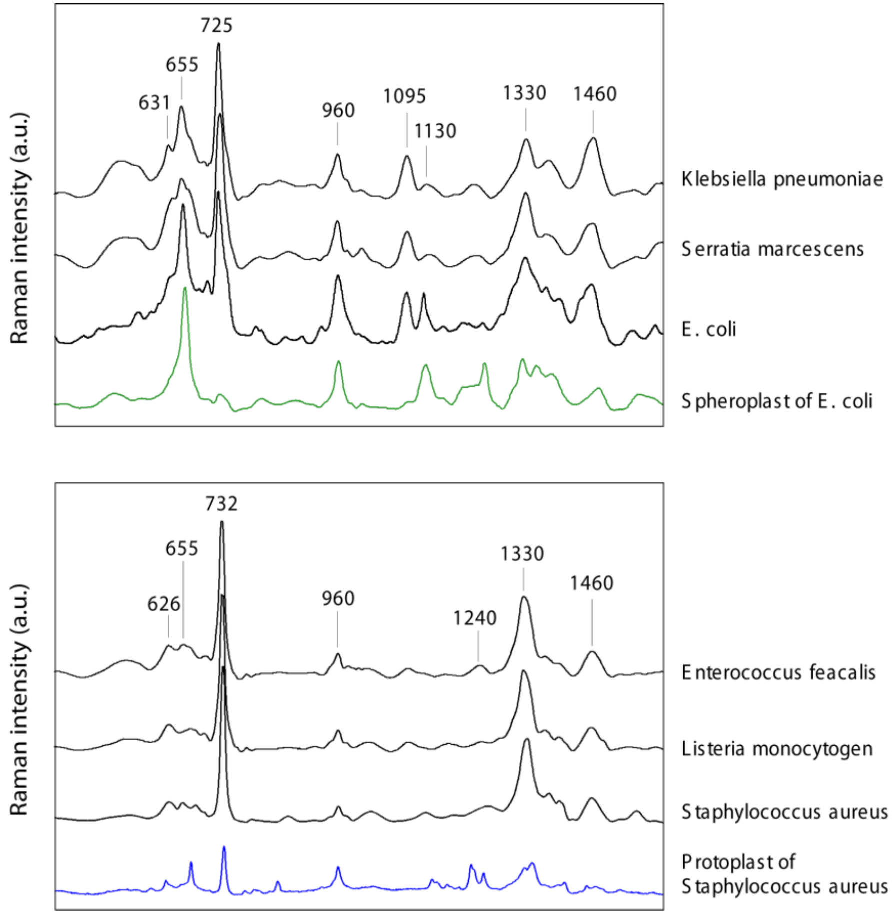
Dr. Juen-Kai Wang, CCMS, NTU

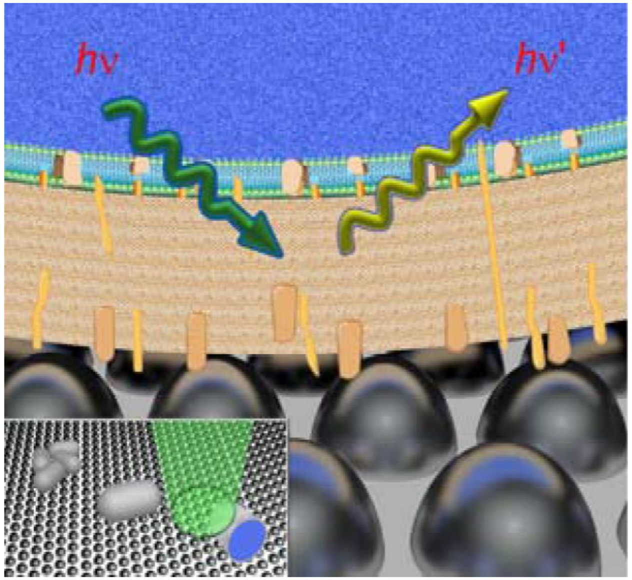


Prof. Yuh-Lin Wang 王玉麟
IAMS Academia Sinica, Taiwan

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.

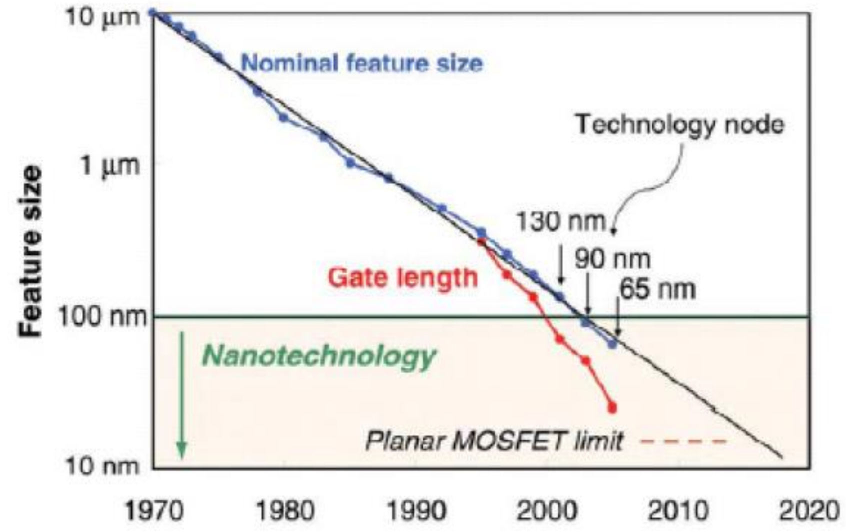
H.-H. Wang et al., Adv. Mater. 18, 491 (2006); T.-T. Liu et al., PLoS ONE 4, e5470 (2009).

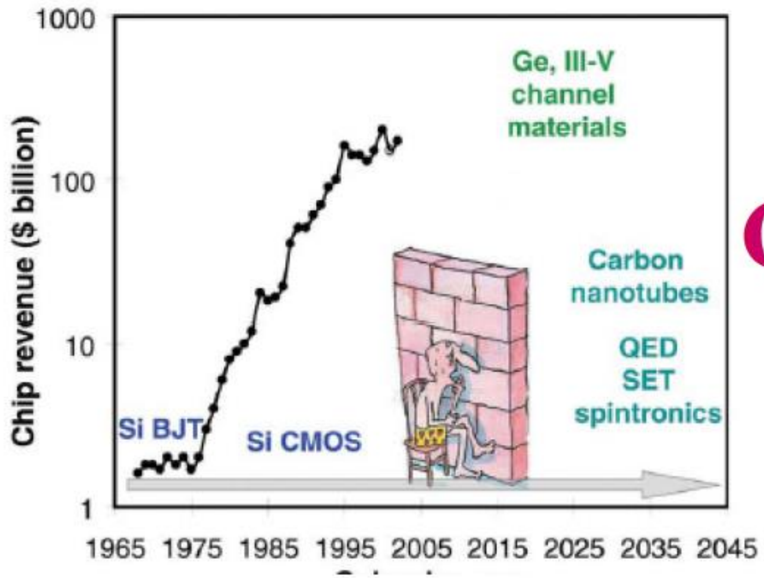
The Advent of Carbon Era ?

The Physics of Graphene:
- Possibility of relativistic electronics and spintronics

Background for search new platform

Scaling limit of Si MOSFET
& superparamagnetism





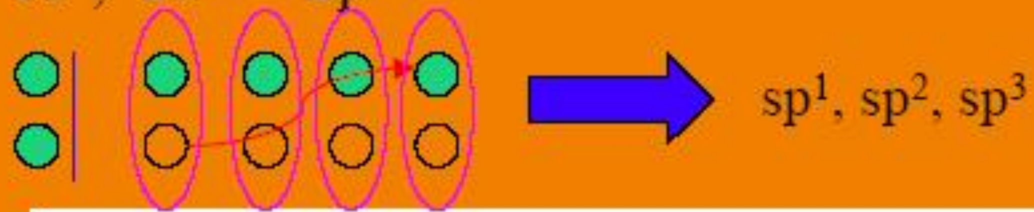
Carbon era?

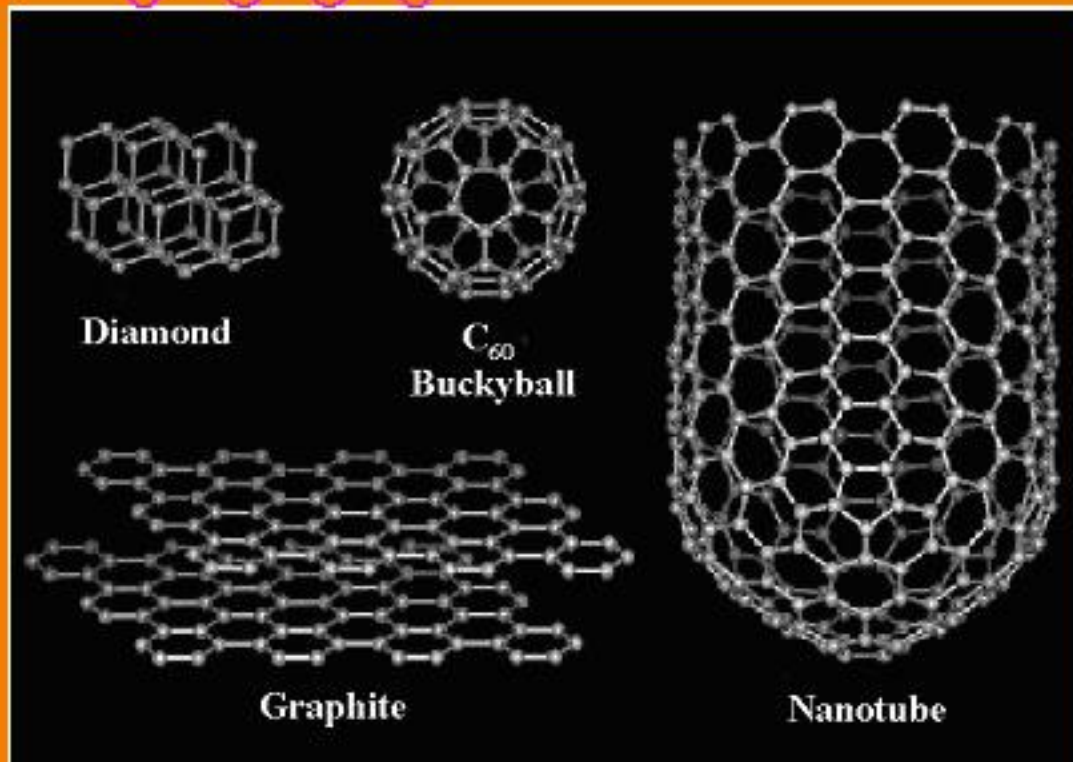
Thompson and Parthasarathy, Materialstoday 9, 20, 2006

Carbon Nanotube

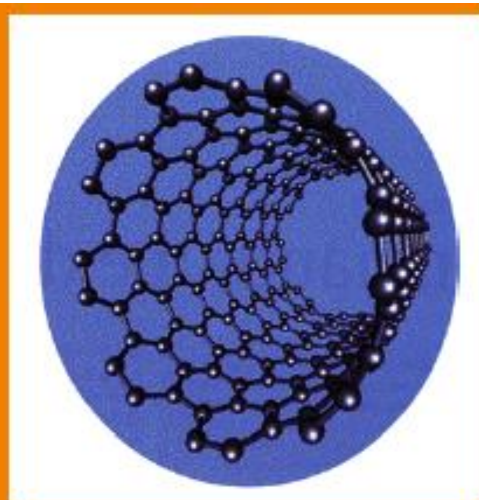
- Structure of carbon nonatubes

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



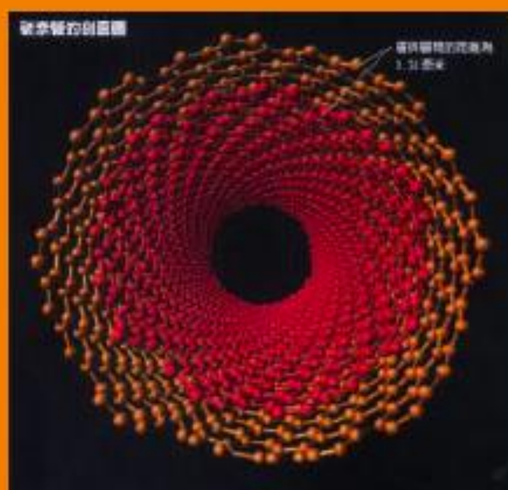


Carbon Nanotube



Sumio Iijma

Single-walled carbon nanotube, SWCNT



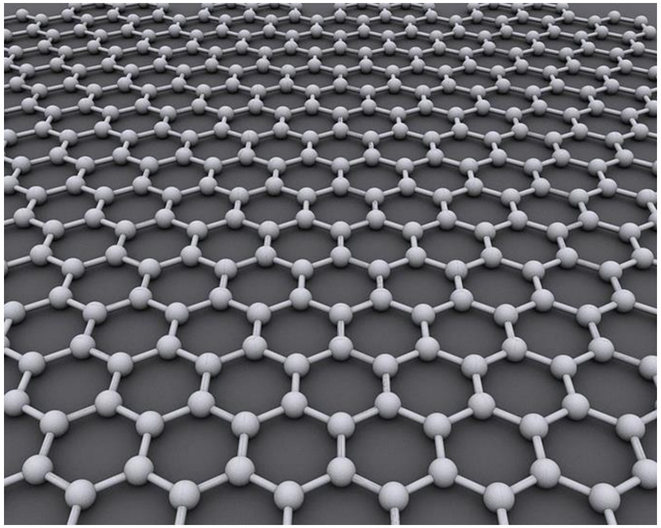
Multi-walled carbon nanotube, MWCNT

Carbon Nanotube based Transistors / Electronics

Unexpected realization of graphene sheet

(

mechanically exfoliated graphene sheets



AFM image of single-layer graphene on SiO_2
K.S. Novoselove et al., Science 306, 666 (2004)

Twisted (bilayer) Graphene

- ❑ $\theta = 1.1^{o}$
- ❑ 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 Gd_2O_3 and Y_2O_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 Gd_2O_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).