Introduction to Nanotechnology

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Ph.D. 1989 Harvard University



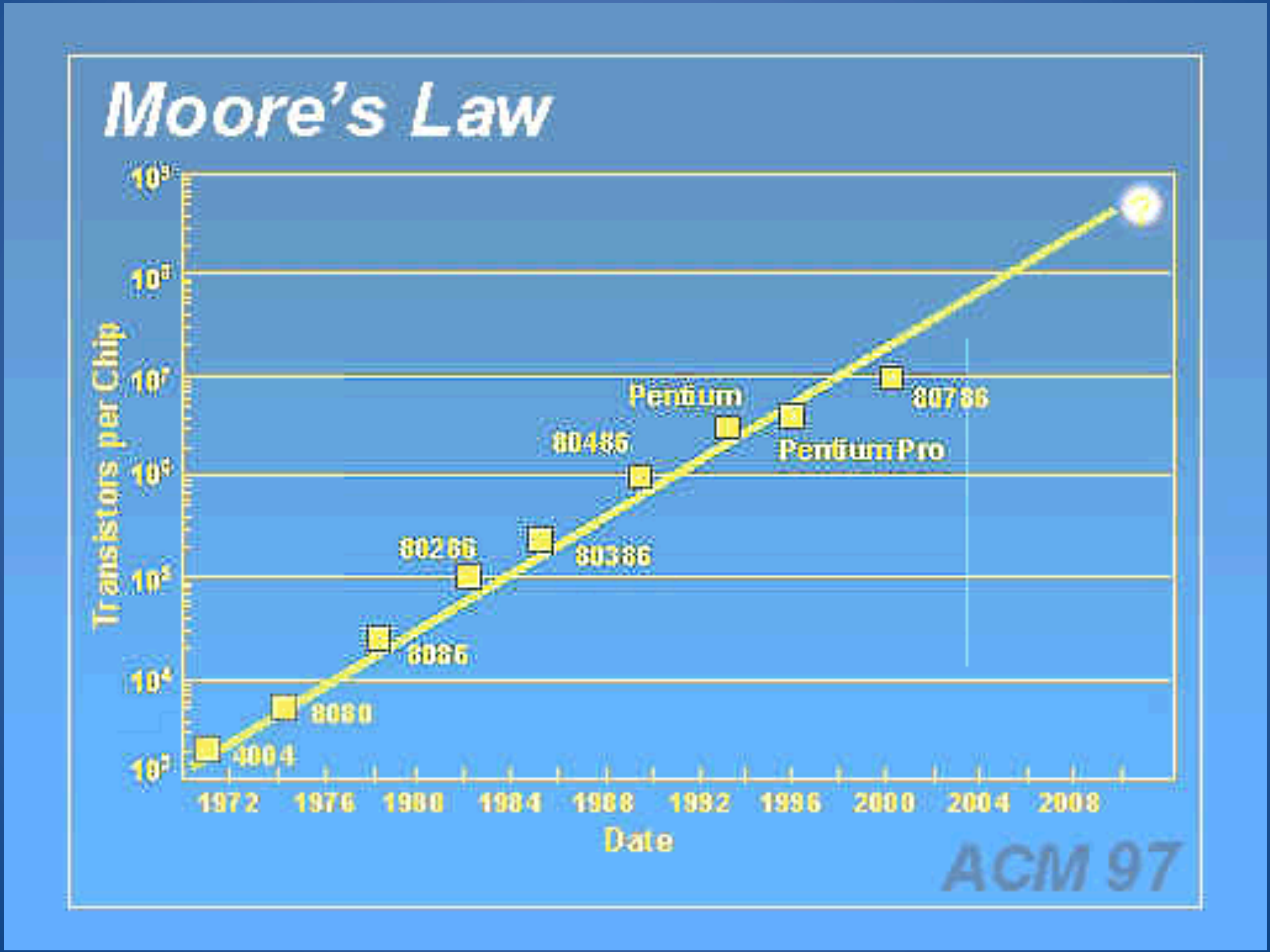
Introduction to Nanotechnology

9/20	Introduction (Prof. KH Chen)
9/27	Systematic of Making Things Smaller (Prof. Hossein)
10/4	What are limits to smallness (Prof. Hossein)
10/11	Self-Assembled Nano-Structure in Nature and Industry-1 (Prof. Hossein)
10/18	Self-Assembled Nano-Structure in Nature and Industry-2 (Prof. Hossein)
10/25	Quantum Nature of the Nano-world (Prof. CW Chen)
11/1	Optical Electronics of Low-D Materials (Prof. CW Chen)
11/8	Optical Properties of CNT & graphene (Prof. CW Chen)
11/15	Physical-based Experimental Approaches to Nanotechnology-1 (Prof. Hossein)
11/22	Midterm (Prof. Hossein)

Introduction to Nanotechnology

11/22	Midterm (Prof. Hossein)
11/29	Physical-based Experimental Approaches to Nanotechnology-2 (Prof. Hossein)
12/6	Silicon Nanoeletronic and Beyond (Prof. Hossein)
12/13	Nanomedicine-1 (Prof. Hossein)
12/20	Nanomedicine-2 (Prof. Hossein)
12/27	Nano Materials for Photovoltaic (Prof. LC Chen)
1/3	Nano Materials for Thermoelectric (Prof. LC Chen)
1/10	Looking into the Future (Prof. LC Chen)
1/17	Conclusion and Final Exam (Prof. KH Chen)

Moore's Law

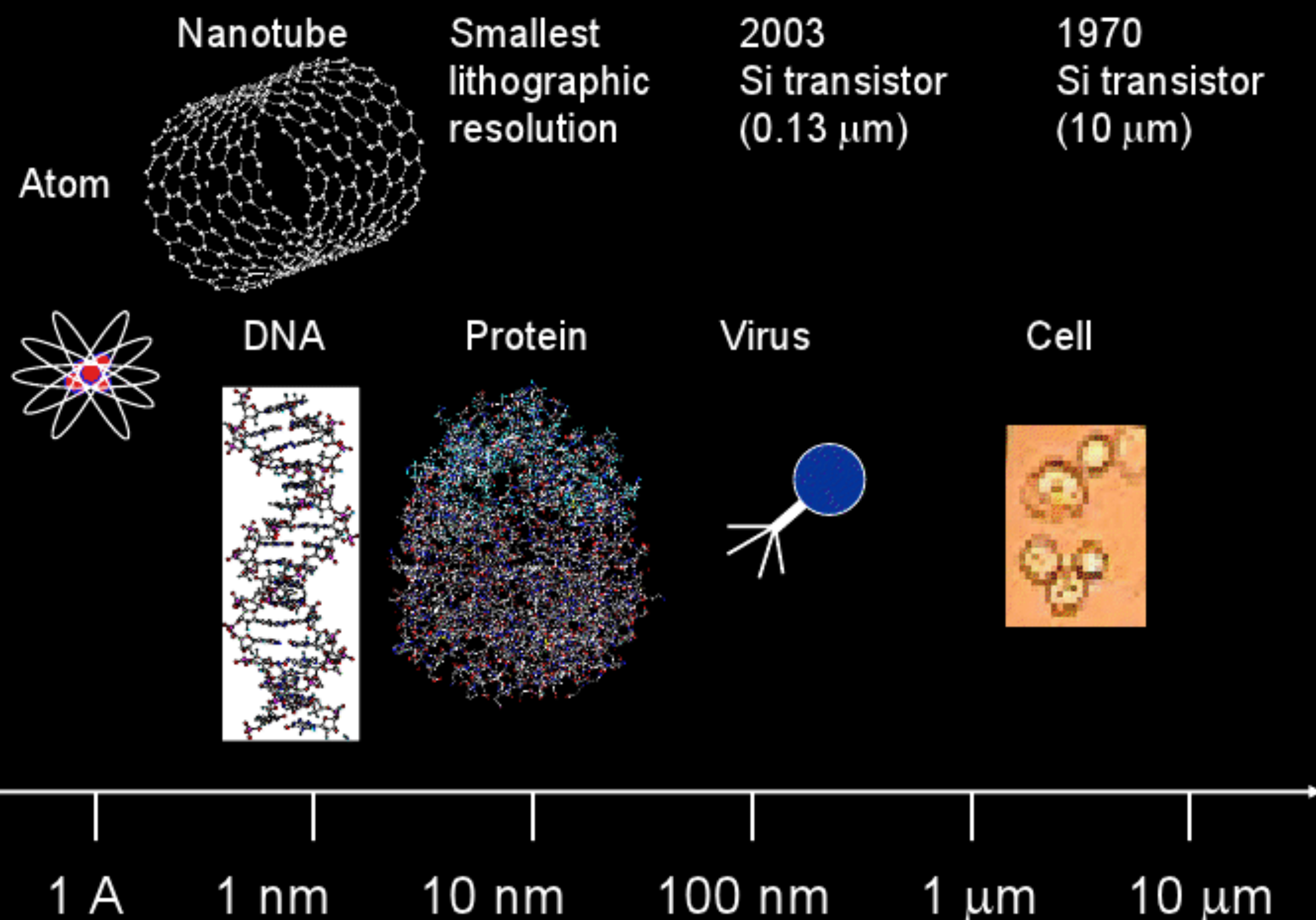


Moore's Law
Transistors per Chip
Date
4004
8080
8086
80286
80386
80486
Pentium
Pentium Pro
80786
1972
1976
1980
1984
1988
1992
1996
2000
2004
2008
ACM 97

Units

- Meter (m)
- Millimeter (mm) = 10^{-3} m
- Micrometer (μm) = 10^{-6} m
- Nanometer (nm) = 10^{-9} m
- Picometer (pm) = 10^{-12} m
- Femtometer (fm) = 10^{-15} m

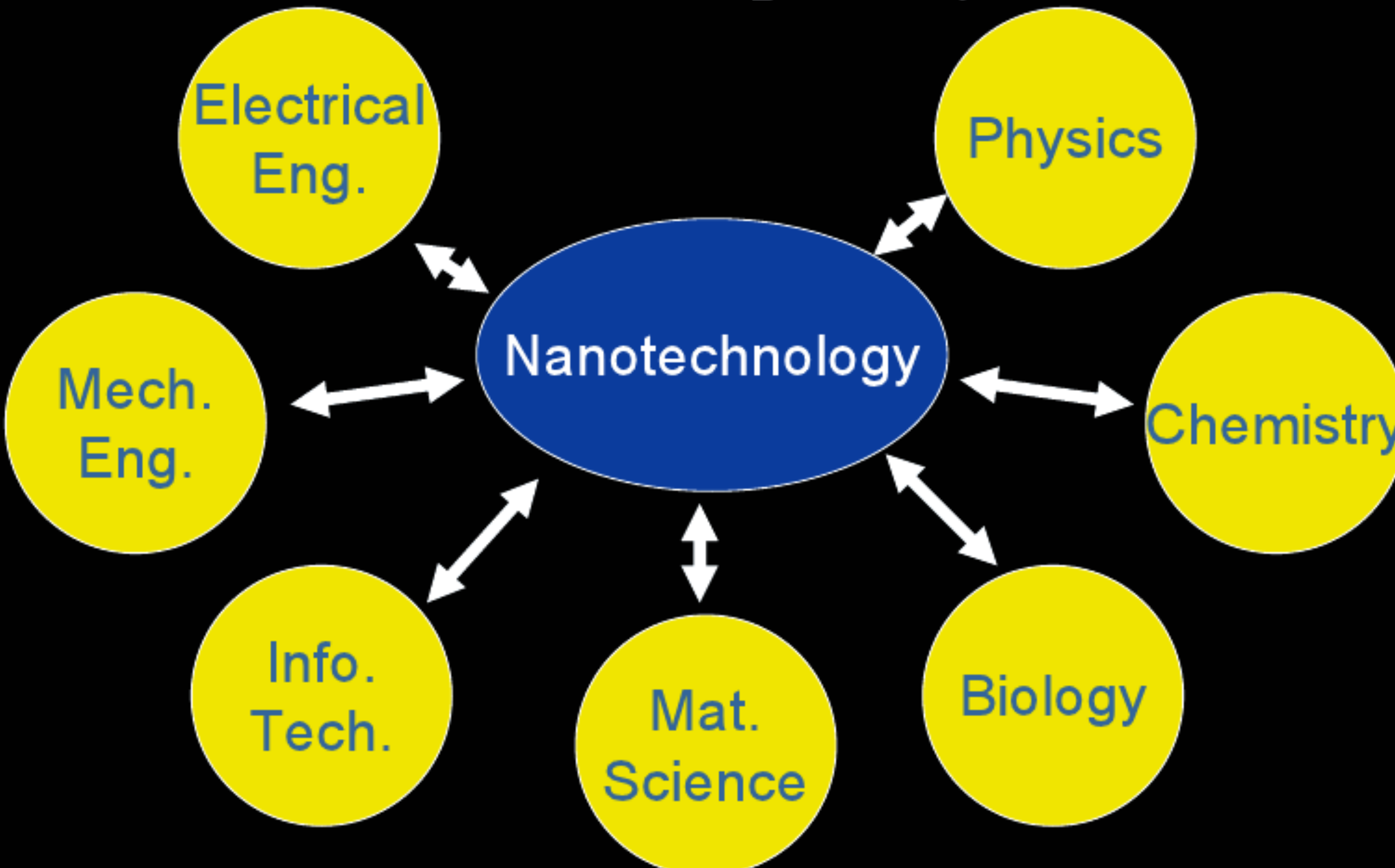
Length scales



What is nanotechnology?

- “Top down” approach
  - Micron scale lithography
    - optical, ultra-violet
    - Focused Ion Beam
  - 10-100 nm
    - Electron-beam lithography
- “Bottom up” approach
  - Chemical self-assembly
    - Man-made synthesis (e.g. carbon nanotubes)
    - Biological synthesis (DNA, proteins)
  - Manipulation of individual atoms
    - Atomic Force Microscopy
    - Scanning Tunneling microscopy

Nanotechnology is multidisciplinary:



A brief history of nanotechnology

- Democritus in ancient Greece: concept of atom
- Rutherford, 1900: discovery of atomic nucleus
- Feynman, 1960: speech at Caltech
- Drexler, 1986, 1992: *Engines of Creation*, *Nanosystems*
- Clinton, speech, Caltech, 2000
- *National Nanotechnology Initiative* since 2000

Nano-manufacturing

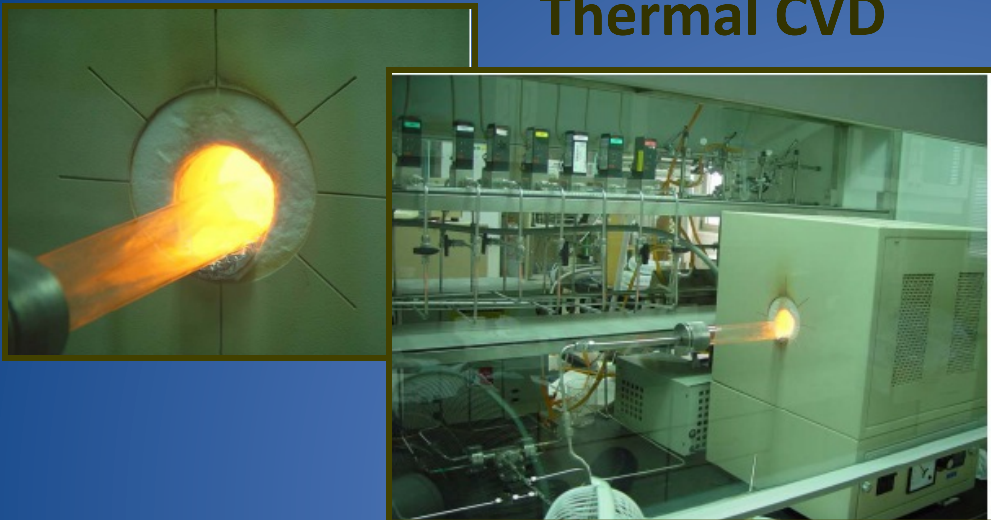
- Lithography can do 10 nm
- Tricks to 2 nm
- Biosystems can add 2 carbon atoms at a time
  - typical in lipid biosynthesis
  - enzymes are nano machines
- We do not know how to design enzymes, only copy them
- As such, nanotechnology does not yet exist according to Drexler's definition

Some nanotechnology uses

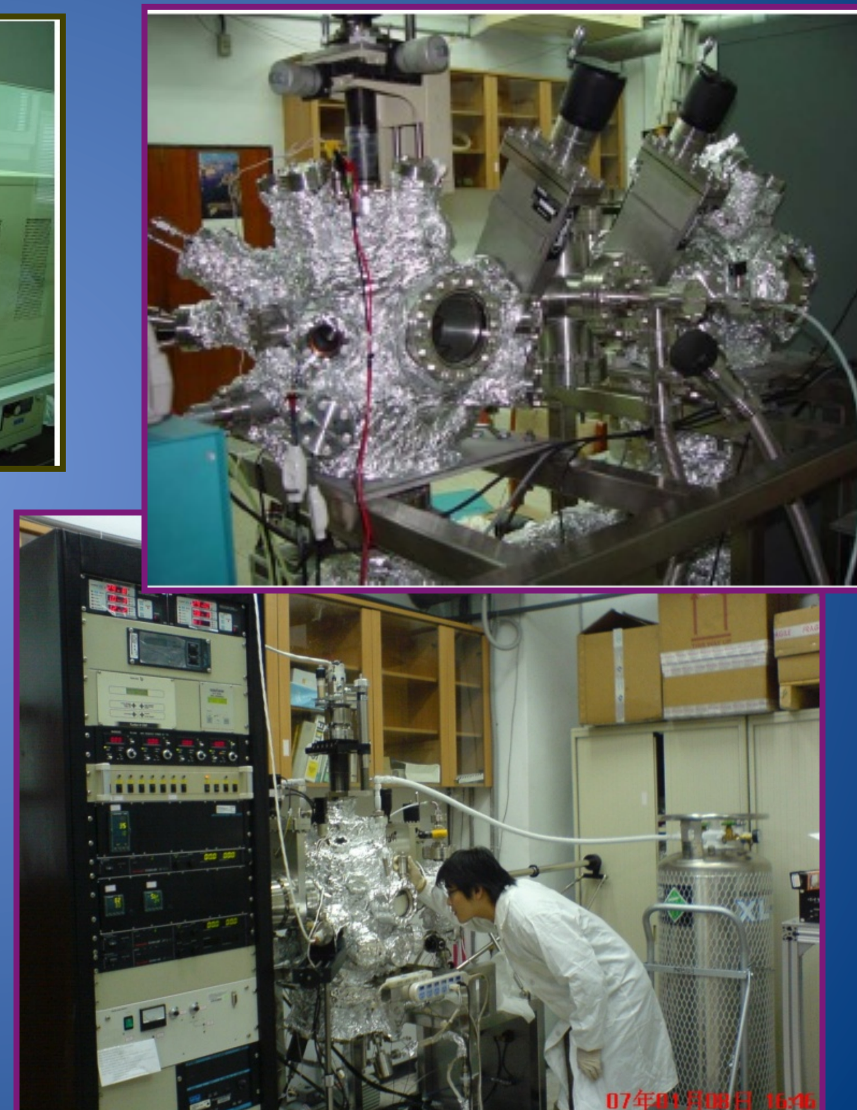
- Nanoparticles:
  - Catalysts for industrial chemical processing
- Nanocapsules
  - Possible organ specific drug delivery
- Nanomaterials
  - Improved strength and weight
  - E.g. carbon nanotube based materials could be stronger and lighter than steel
- Nanomechanical devices
  - RF signal processing
- Nanofluidic devices
  - Lab on a chip
- Nanoelectronic devices (focus of this course)
  - Computation
  - Communication
  - Nano-bio-electronic interfaces
    - Chemical and biological weapons detection
    - DNA sequencing
    - Point-of-care clinical diagnoses
    - Fundamental studies of molecular biology

Modern Alchemy (I)

Thermal CVD



Plasma-assisted MBE



MOCVD

Core Process Techniques at CCMS-AML

CVD

- Microwave plasma
- Electron-cyclotron-resonance plasma
- Thermal- and MO-CVD
- Inductively Coupled Plasma

Gas phase reaction, Gas-solid interaction
Formation kinetics

PVD

- Magnetron sputtering
- Ion beam sputtering
- Atom- and Ion-beam assisted PVD
- Molecular beam epitaxy

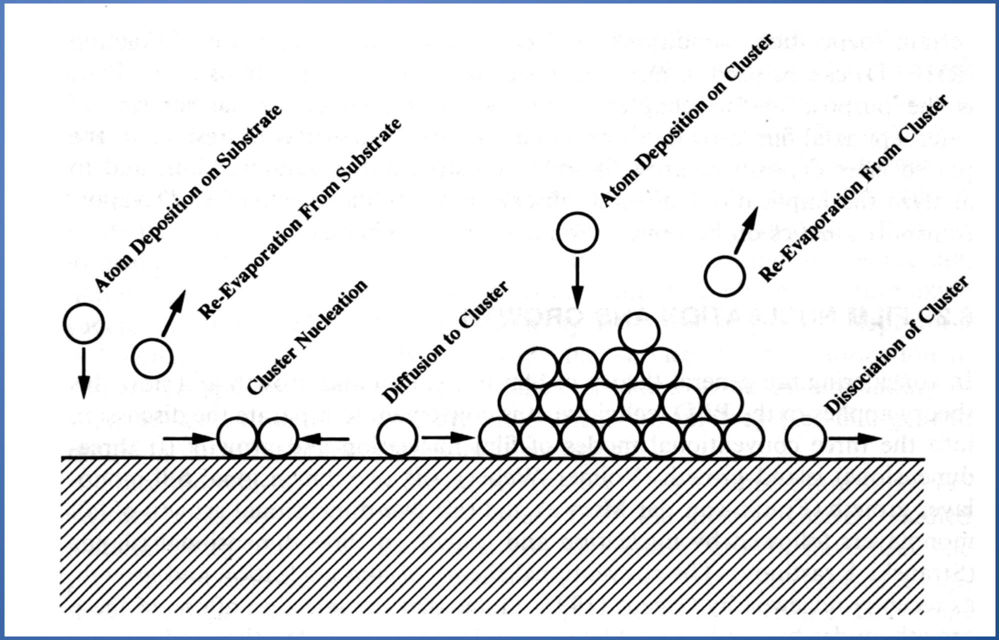
Hydrogen vs. H-free growth environments
Film formation via physical route (varying K.E.) vs. chemical route (reactive sputtering)

Highly energized vapor deposition/etching processes under situations far away from equilibrium

Gas Phase Syntheses

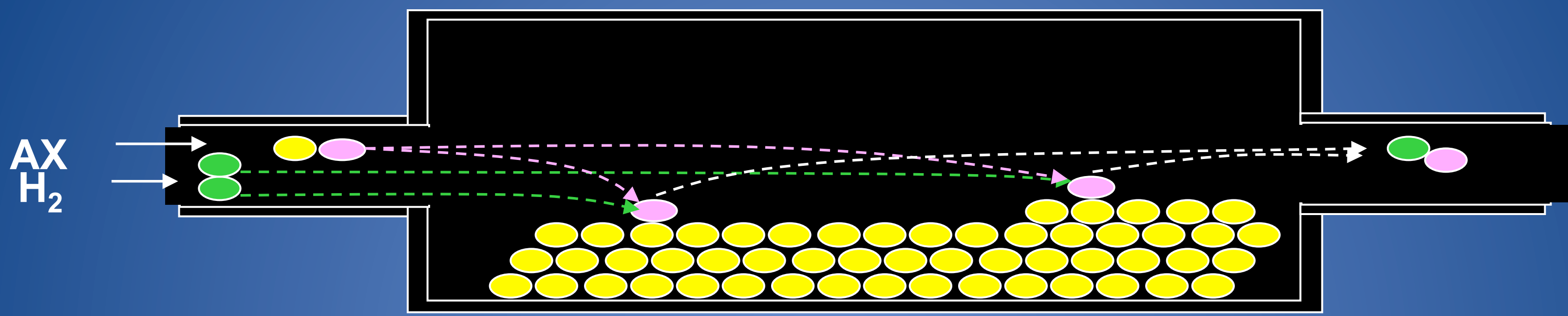
- Evaporation-Condensation (Earliest methods)
- Sputtering
- Laser Ablation
- Arc Discharge
- Aerosol Process
- Spray Pyrolysis
- Plasma Spray

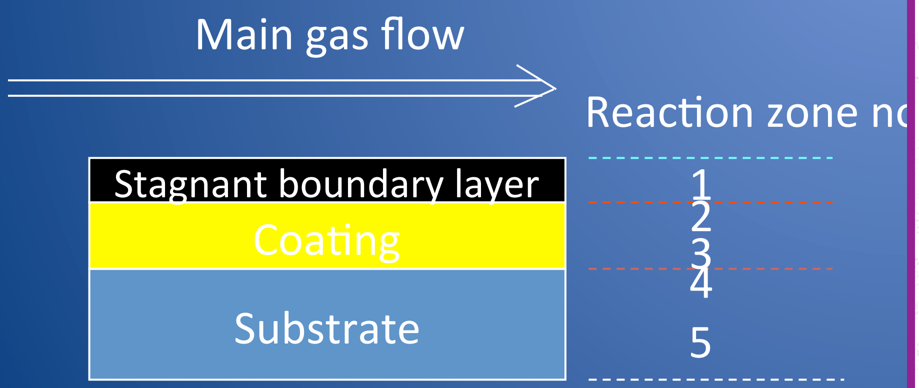
atomic process in the nucleation of three-dimensional clusters of deposited film atoms on a substrate



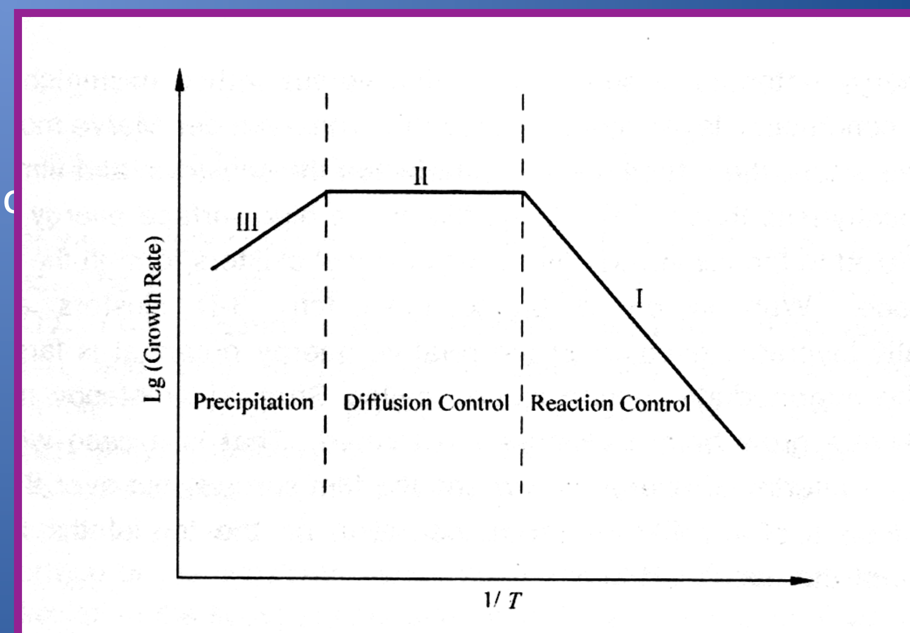
(J. S. Horowitz and J. A. Sprague, Chap. 8, Pulsed Laser Deposition of Thin Film, Eds., D. B. Chrisey and G. K. Hubler, Wiley Interscience)

Schematic of Chemical Vapor Deposition





Important reaction zones in CVD

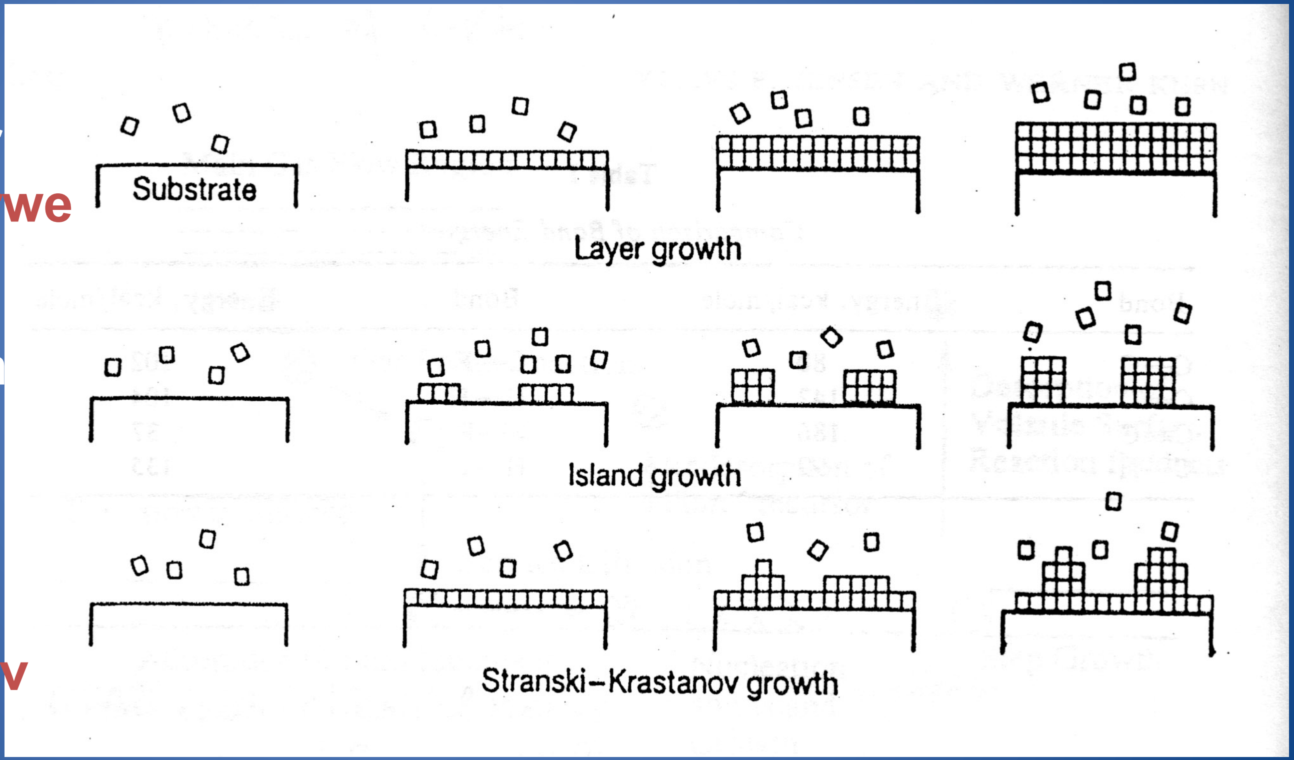


Nucleation and Growth of Films: The Three Conventional Modes

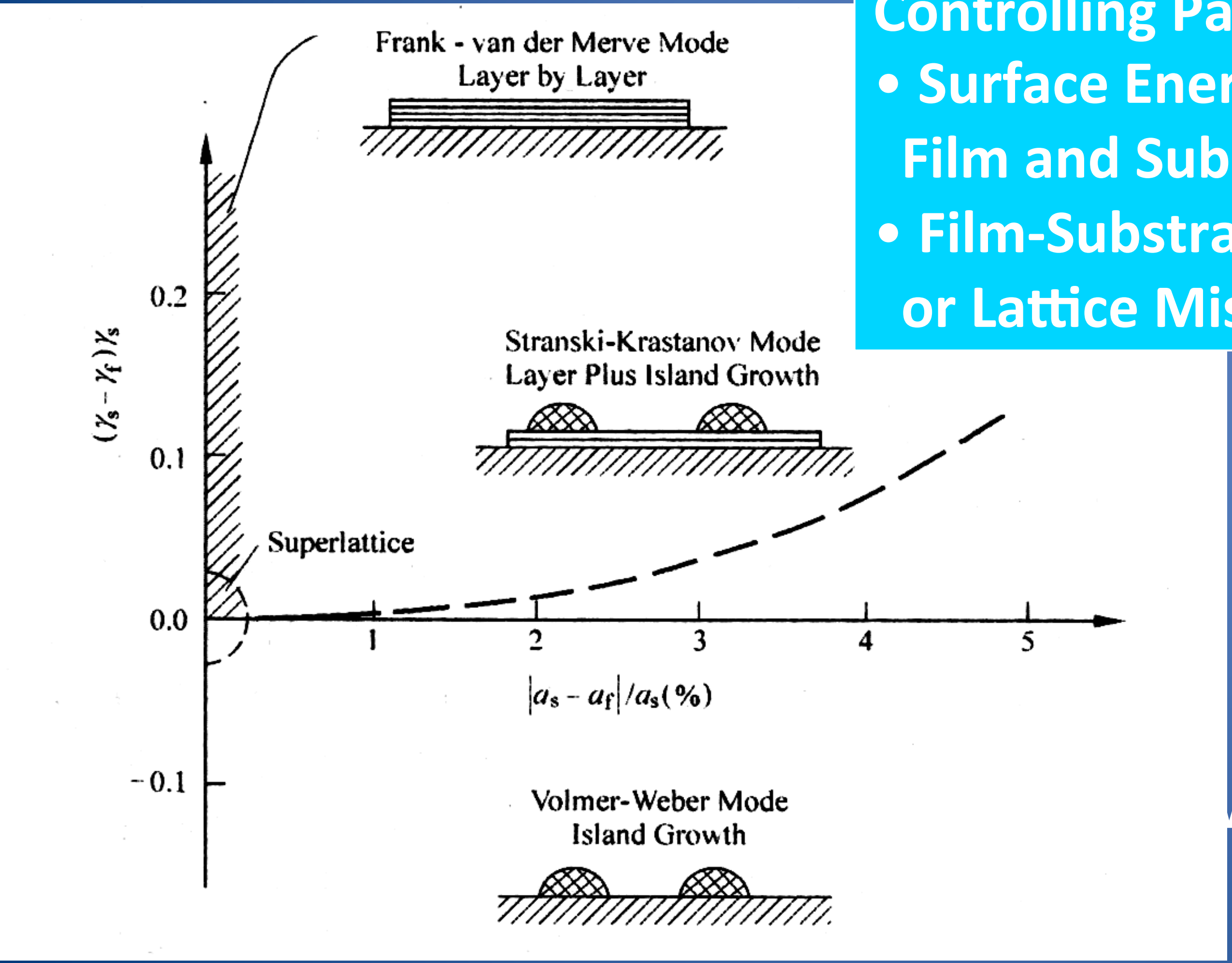
2-d full-monolayer
Frank-van der Merwe

3-d (or “0-d”) islan
Volmer-Weber

2-d and 3-d
Stranski-Krastinov



Selection of Growth Modes



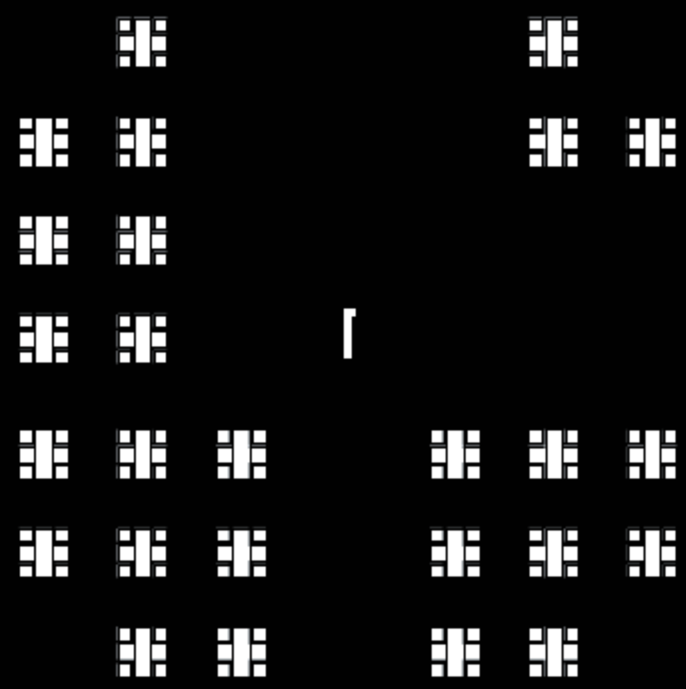
Controlling Parameters:

- **Surface Energies of both Film and Substrate**
- **Film-Substrate Interface Energy or Lattice Mismatch**

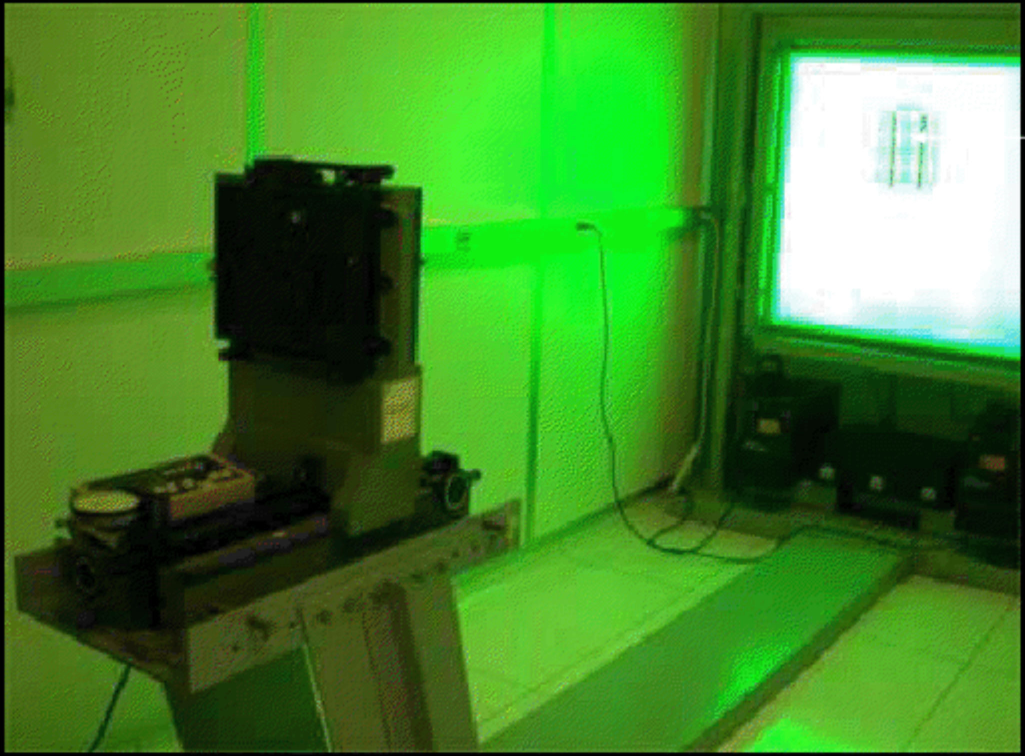
, et al, TMS, 1986.

Photomasks

Design geometry on computer.



Mask fabrication



transparency

After Exposure
Developer
Stop bath
Fixer

Dark room (1/20 reduction)

Spin on photoresist

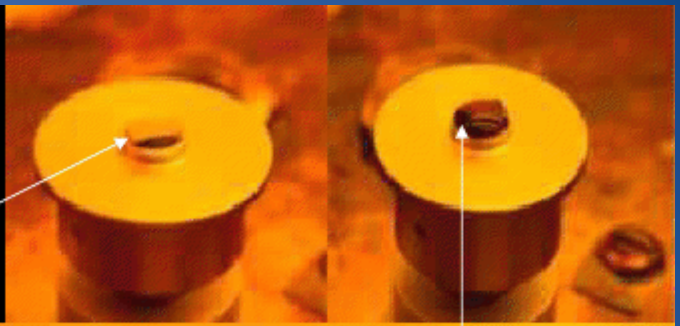
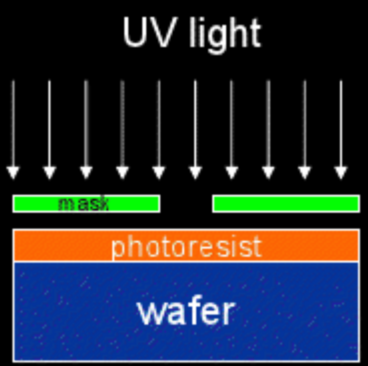


Photo resist spinner

Soft bake

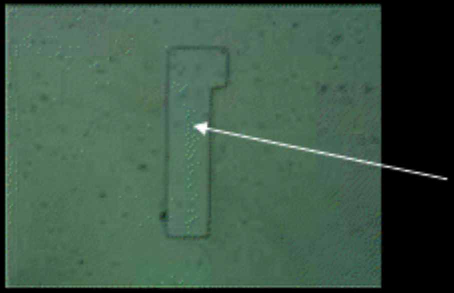
Oven for soft baking of photo resist (at 90C for 30 min)

Expose to UV light



Development
For Shipley 1827
Water : MF351 = 5.5 : 1

Mask Aligner

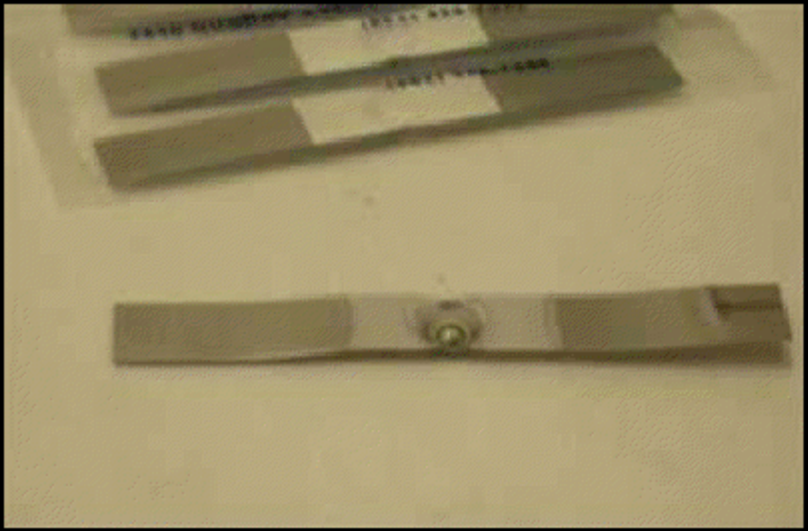


Exposed regions dissolved in developer leaving bare wafer

This is the step which limits the spatial resolution.

Thermal evaporation

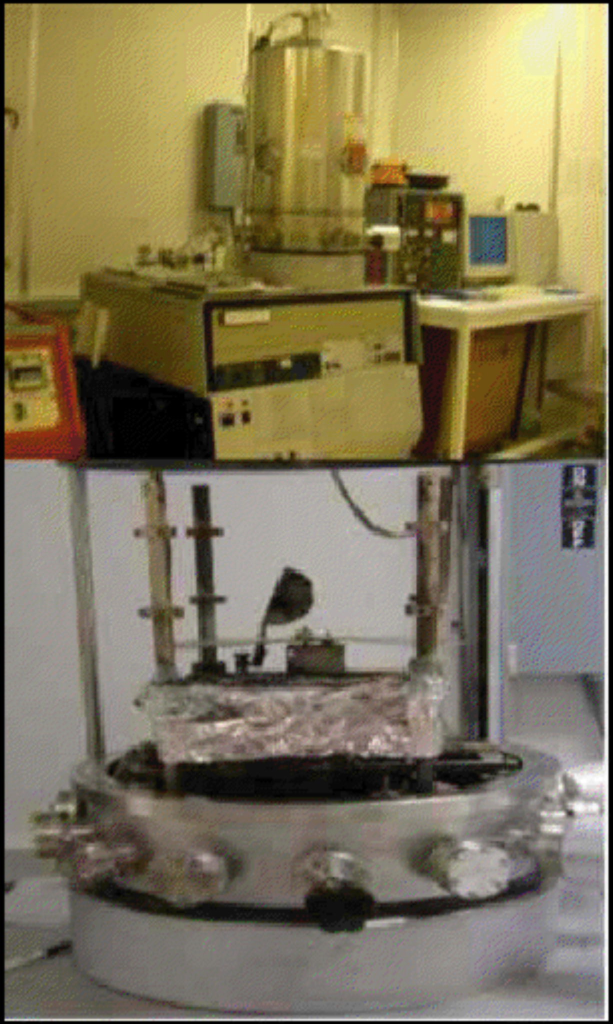
Thermo evaporator



Alumina coated W boat

Useful for e.g.
Al, Ni, Au, Cr, Ti, NiCr, Pb, Sn

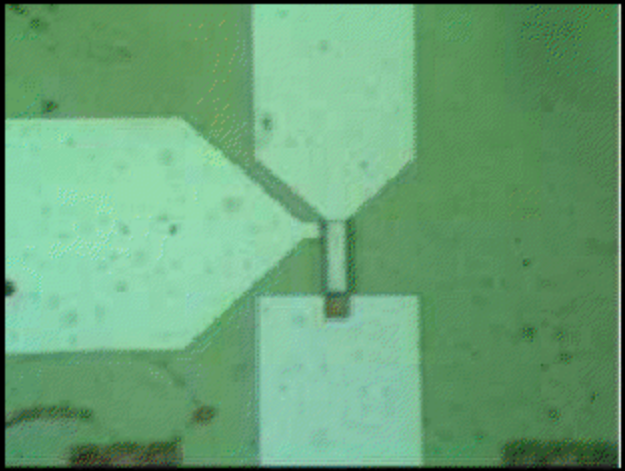
E-beam evaporation



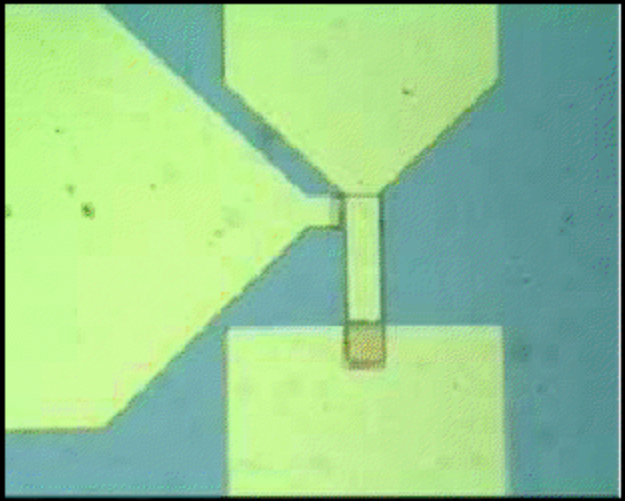
Electron beam evaporator

Au

Liftoff



Opening of photo resist
for Ti/Au gate



After deposition of Ti/Au,
then soaking in acetone

Resolution of optical lithography

$$R = \frac{3}{2}\sqrt{\frac{\lambda z}{2}}$$

Contact printing

z is resist thickness
(typically 0.1-1 μm)

$$R = 0.61\frac{\lambda}{NA}$$

Projection printing

NA is numerical aperture
(typically 0.5)

Light sources

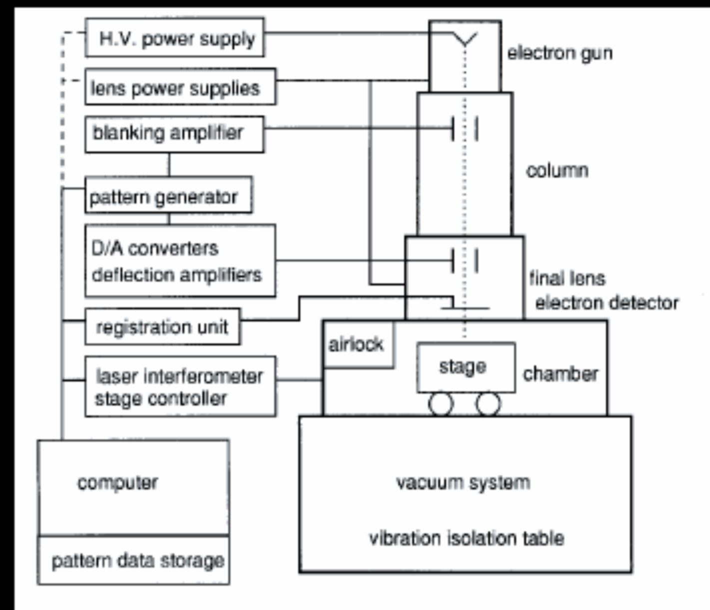
Source	λ	Resolution
• Hg lamp (g-line)	436 nm	400 nm
• Hg lamp (i-line)	365 nm	350 nm
• KrF	248 nm	150 nm
• ArF	193 nm	80 nm
• F_2	157 nm	research

increasing cost

Extreme UV, x-ray lithography research topics.
Difficulties lie in sources, and materials for optics and masks.

Electron Beam Lithography

- Advantages
  - Resolution
    - electron wavelength small
    - beamsize 1 nm
    - resolution from scattering typically 10 nm
  - Flexibility
    - All patterns under computer control
- Disadvantages
  - Cost
    - Need high vacuum
    - Need precision electron focusing magnets
  - Throughput
    - Only one pixel exposed at a time
    - Not commercially viable except for a few applications

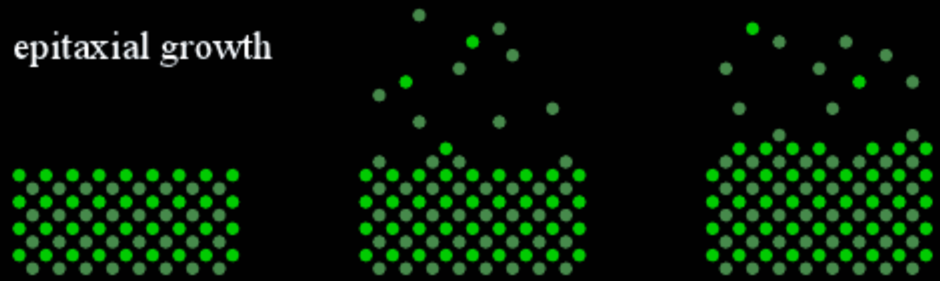


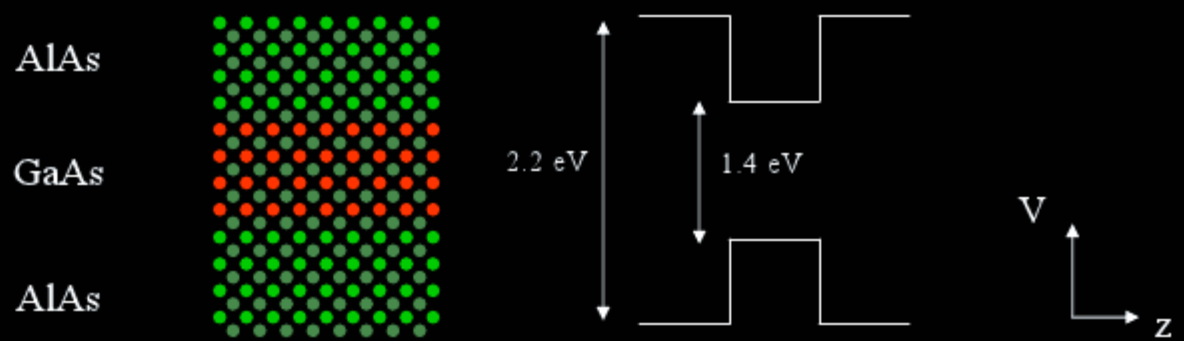
Reference: SPIE Handbook of Microlithography, Micromachining, and Microfabrication available at http://www.cnf.cornell.edu/spiebook/toc.htm

In spite of its disadvantages,
e-beam lithography is the main tool for nanotechnology research.

MBE

epitaxial growth



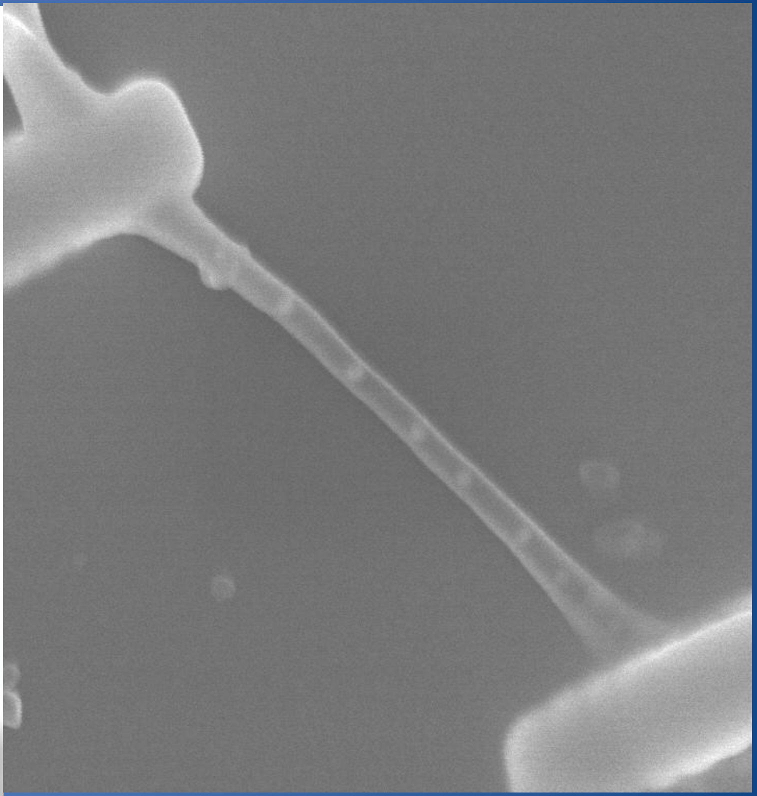


Also InP, InGaAs, InAlAs, InGaAsP …

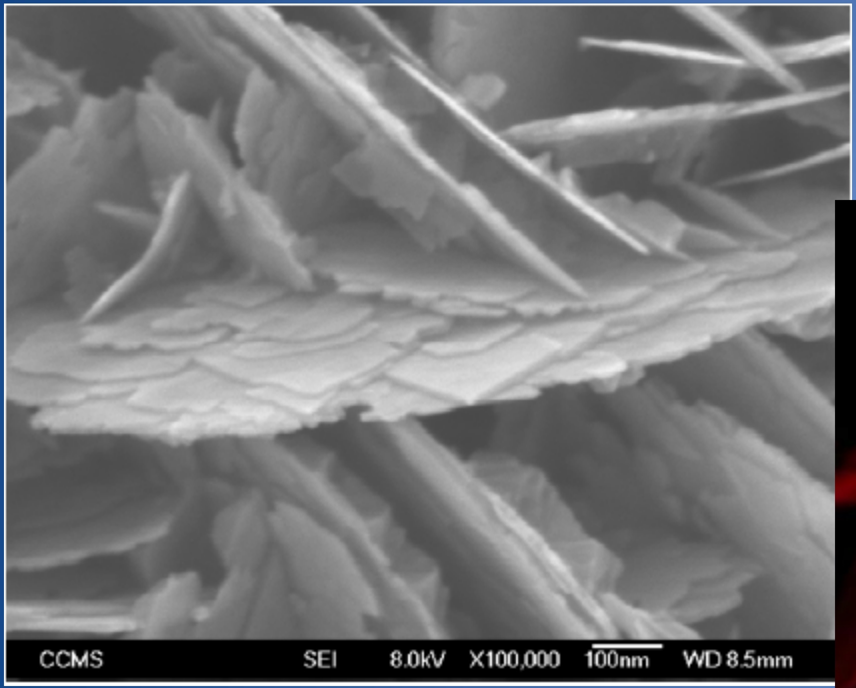
Characterization

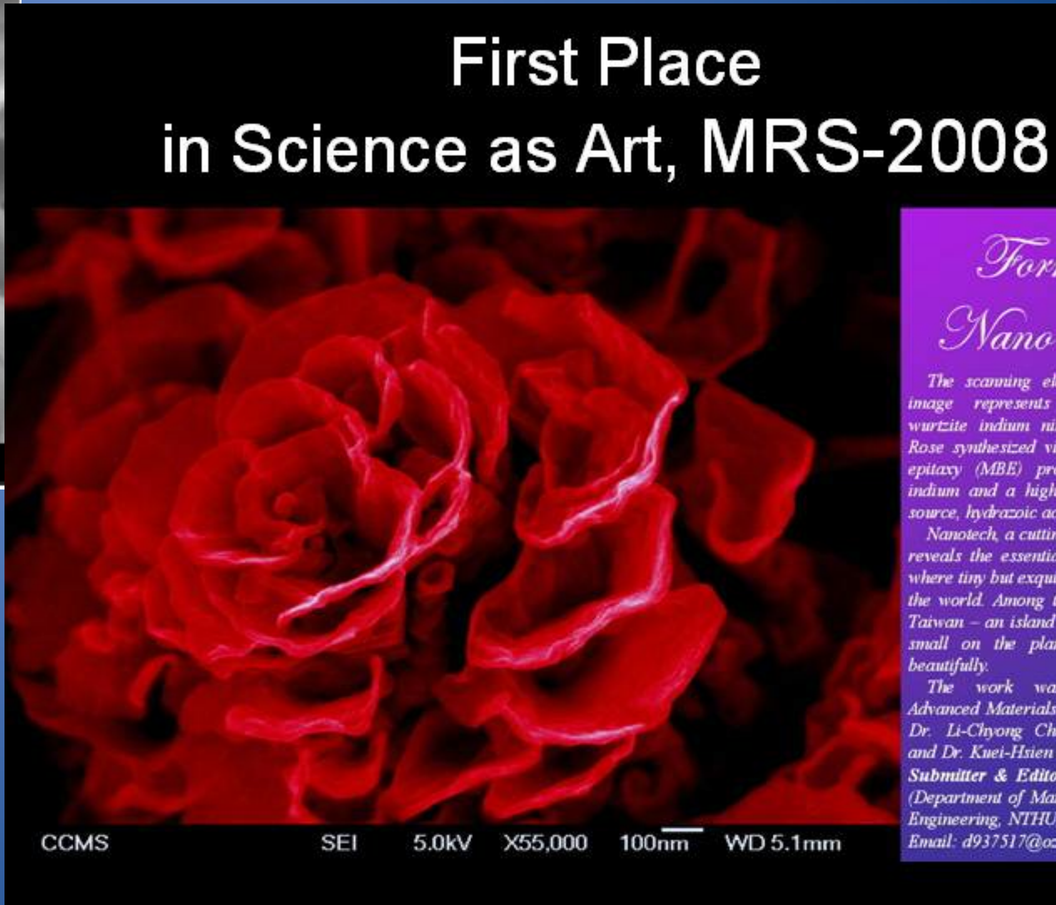
- Optical microscopy cannot see better than wavelength of light, ~ 1 μm
- Scanning electron microscope (SEM)
- Transmission electron microscope (TEM)
- Scanning probe microscopy (SPM)
- Atomic force microscope (AFM)

SEM

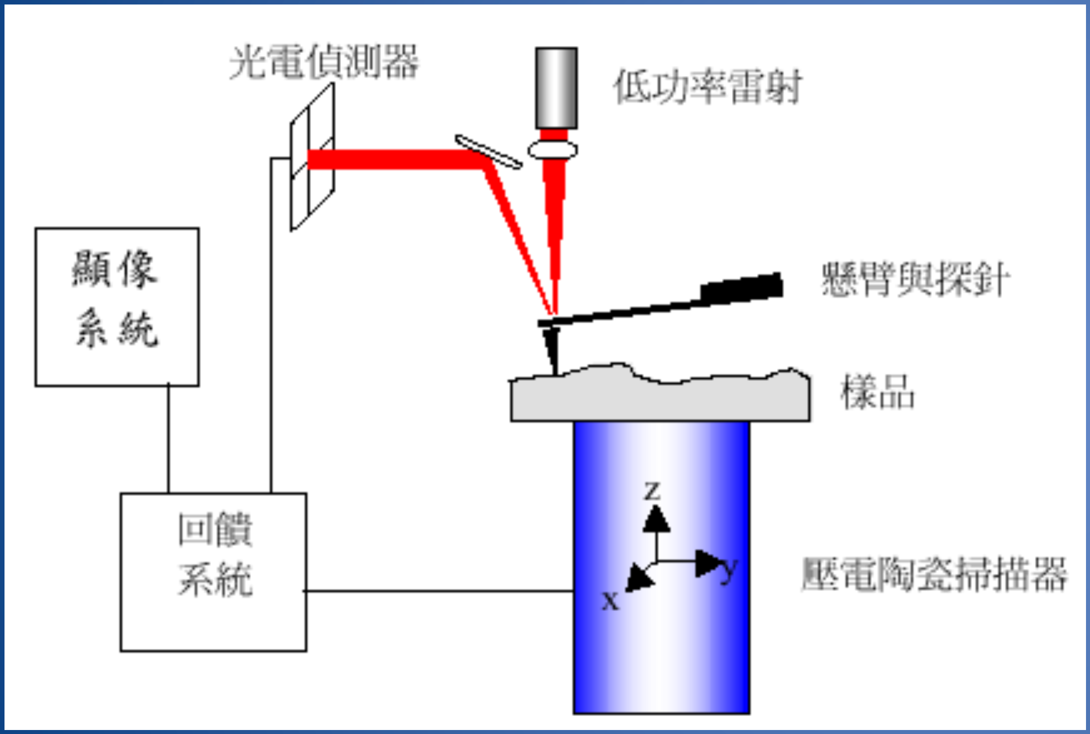


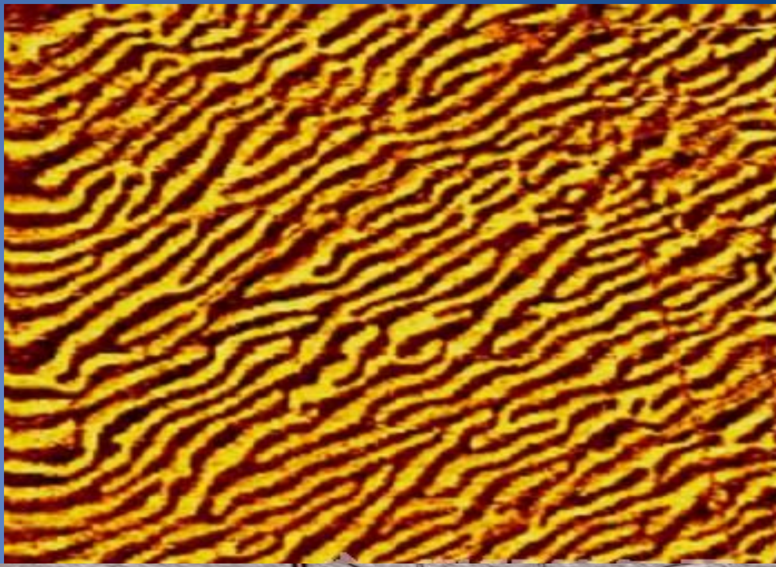
SEM


CCMS
SEI
8.0kV
X100,000
100nm
WD 8.5mm


First Place
in Science as Art, MRS-2008
CCMS
SEI
5.0kV
X55,000
100nm
WD 5.1mm

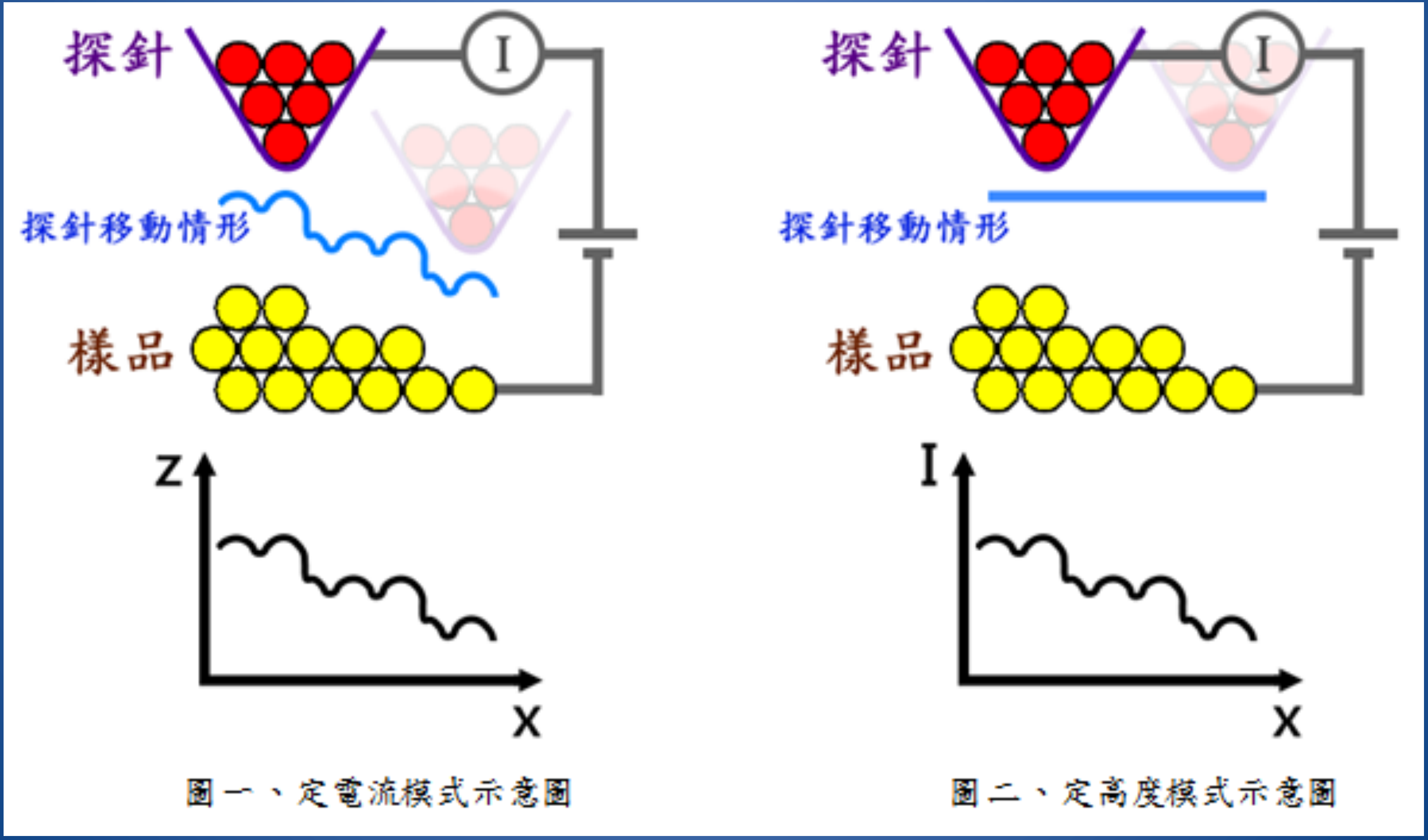
AFM


光電偵測器
低功率雷射
顯像
系統
懸臂與探針
樣品
z
y
x
回饋
系統
壓電陶瓷掃描器

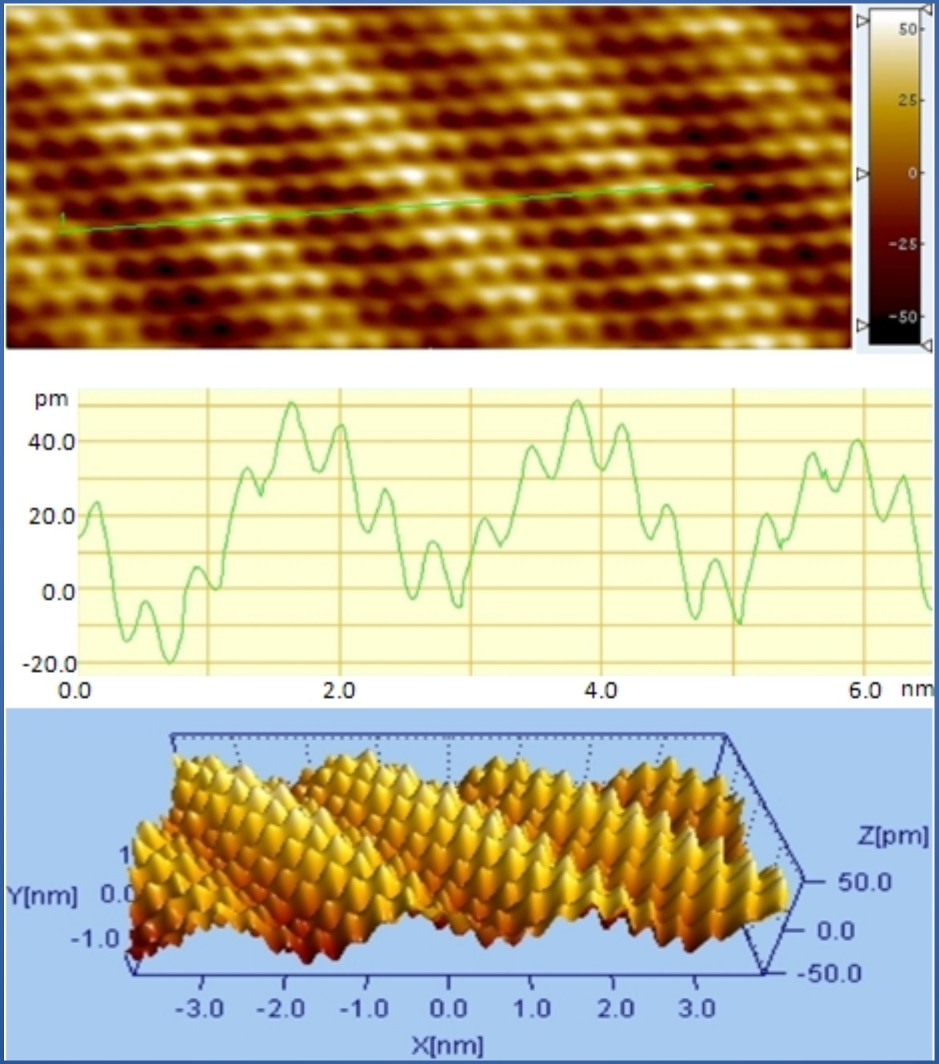



discover.163.com
SPMAGE07

STM

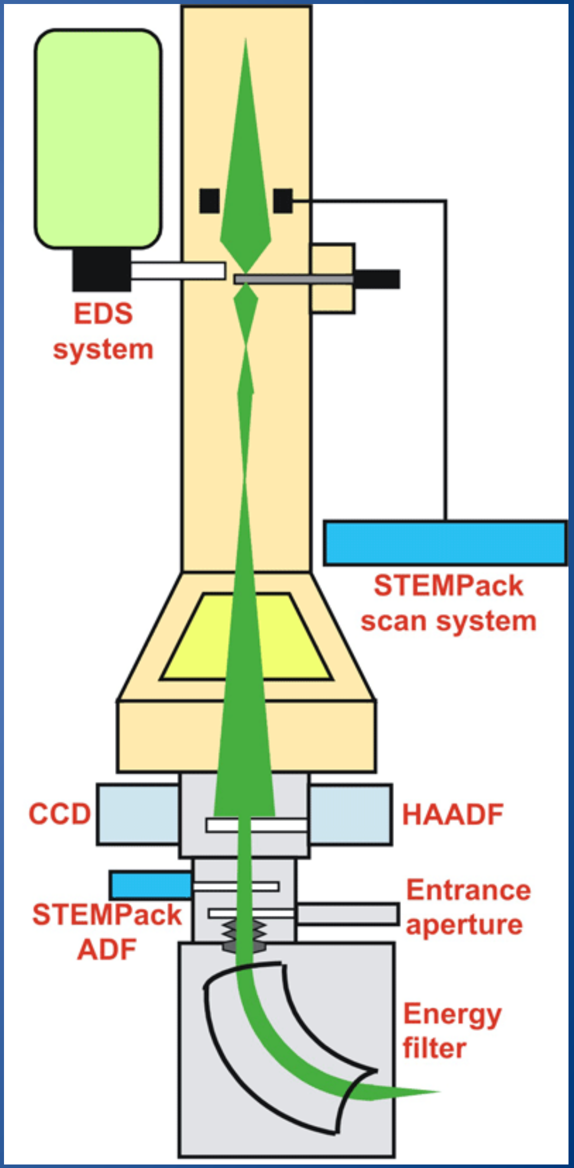


STM

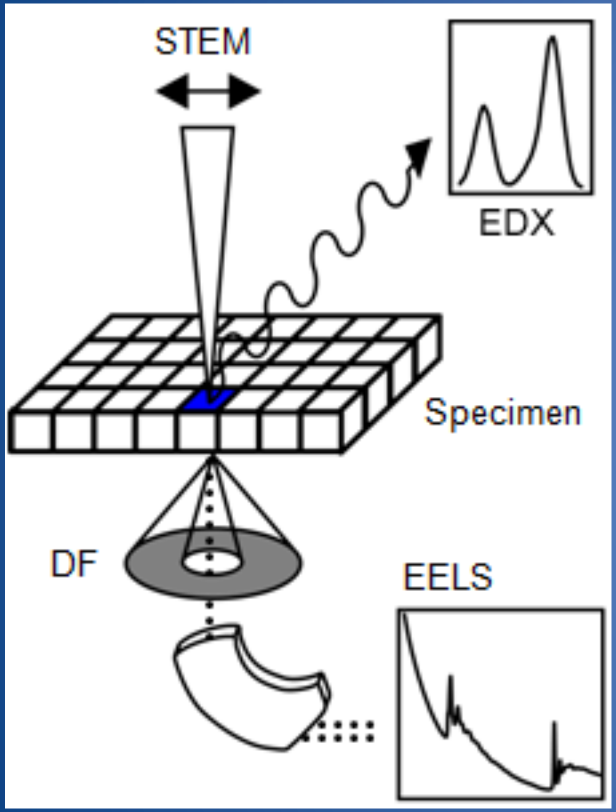

50
25
0
-25
-50
pm
40.0
20.0
0.0
-20.0
0.0
2.0
4.0
6.0
nm
Z[pm]
50.0
0.0
-50.0
Y[nm]
-1.0
-3.0
-2.0
-1.0
0.0
1.0
2.0
3.0
X[nm]

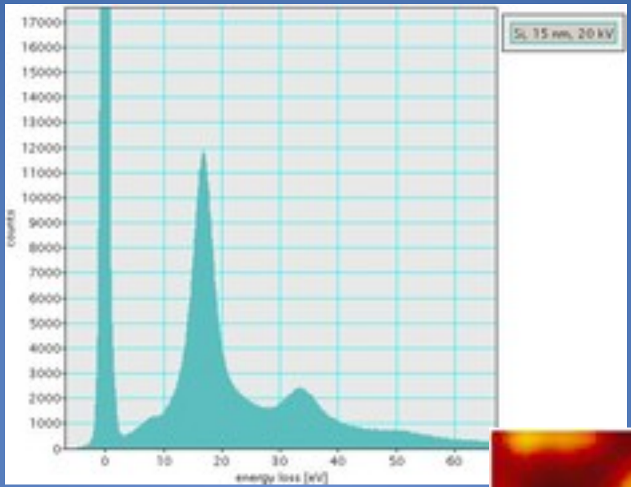
TEM

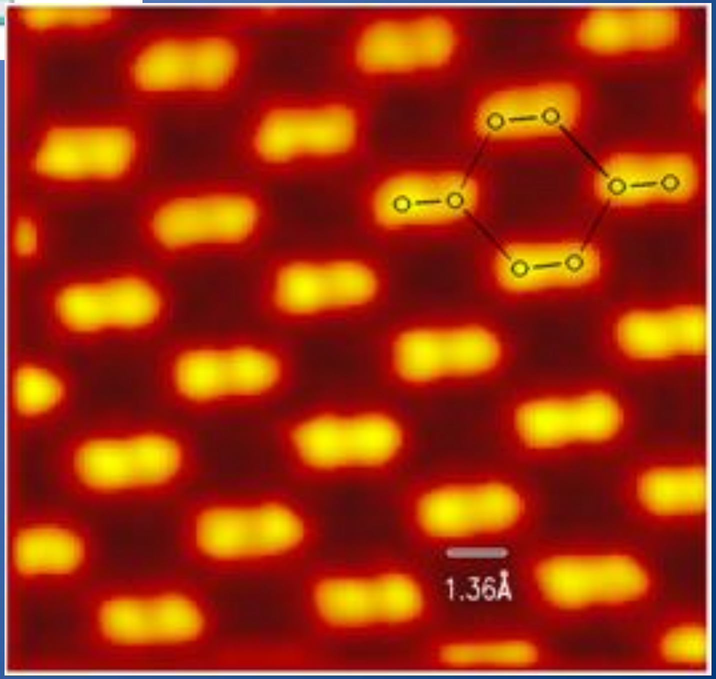

TECNAI
www.cam.zjut.edu.cn


EDS
system
STEMPack
scan system
CCD
HAADF
STEMPack
ADF
Entrance
aperture
Energy
filter

TEM (EELS)


STEM
EDX
Specimen
DF
EELS


17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
0
10
20
30
40
50
60


1.36Å

Composition Analysis

1. EL（元素分析儀）
2. EDS (X射線能量散佈分析儀)
3. AES (歐傑電子光譜)
4. NMR（核磁共振波譜分析）
5. ICP MASS (電子耦合電漿質譜）
6. MALDI（Matrix-assisted laser desorption/ionization）

NMR, MRI

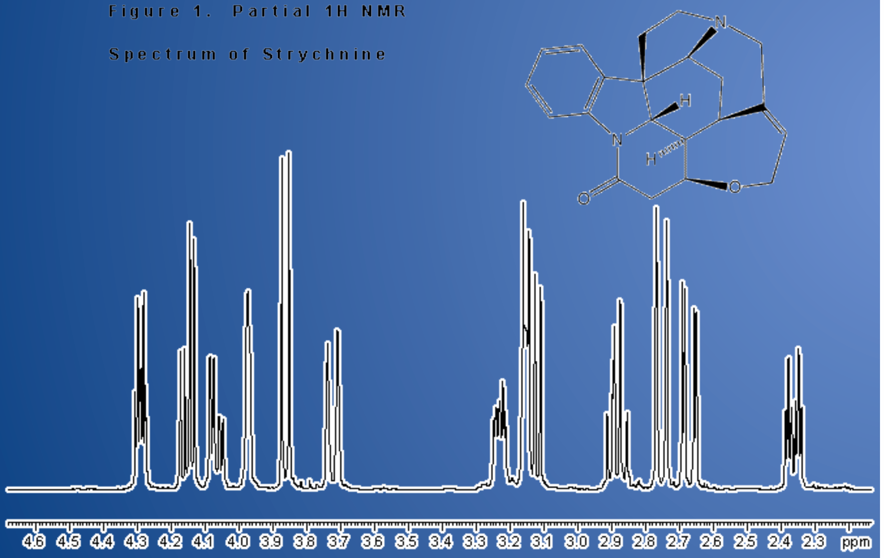
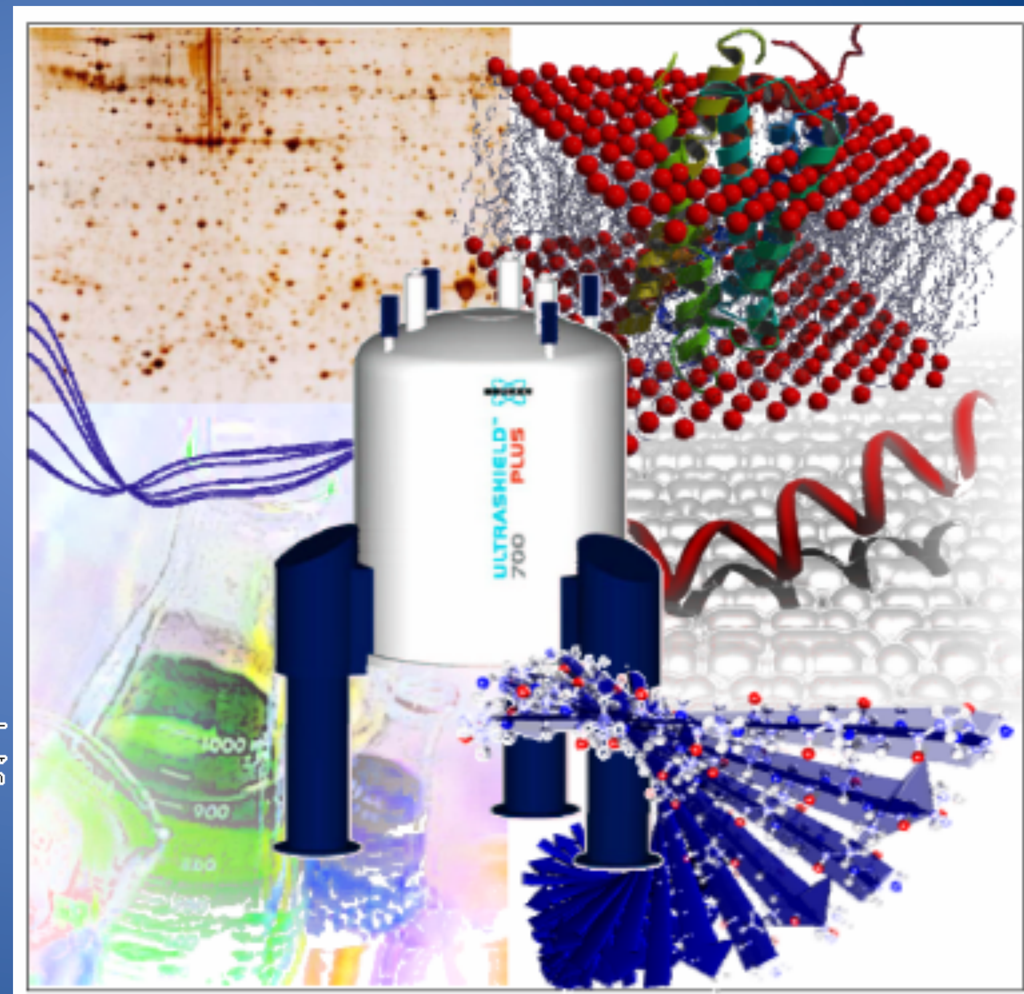
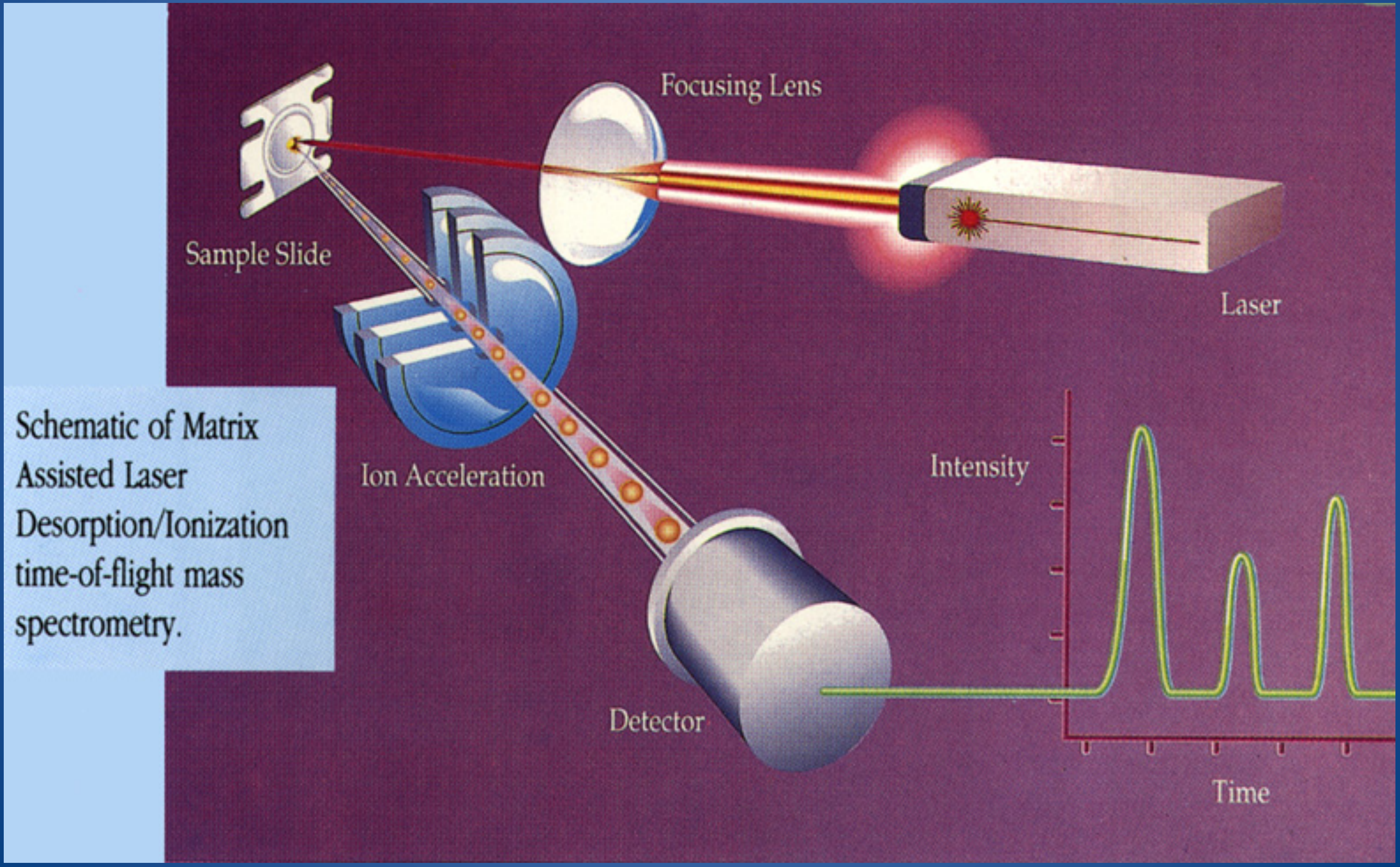


Figure 1. Partial 1H NMR Spectrum of Strychnine



MALDI （Matrix-assisted laser desorption/ionization)

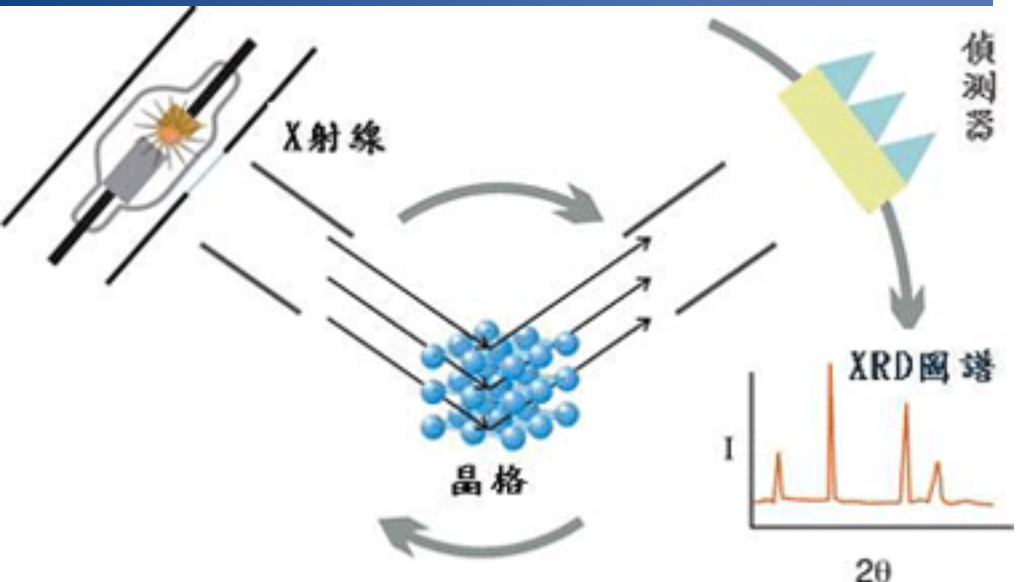


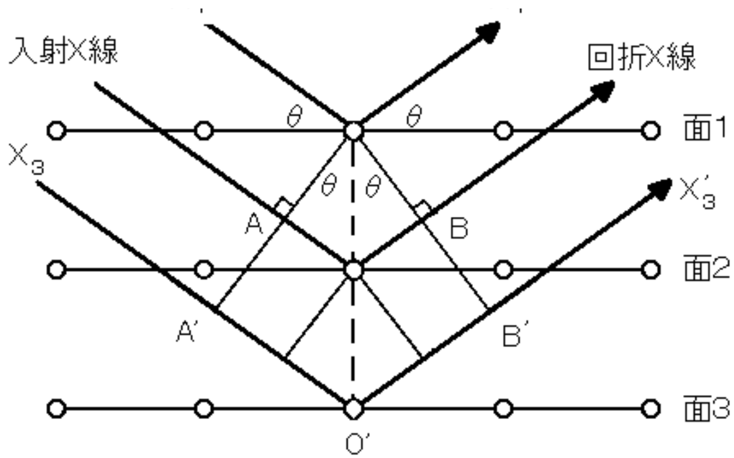
Schematic of Matrix Assisted Laser Desorption/Ionization time-of-flight mass spectrometry.

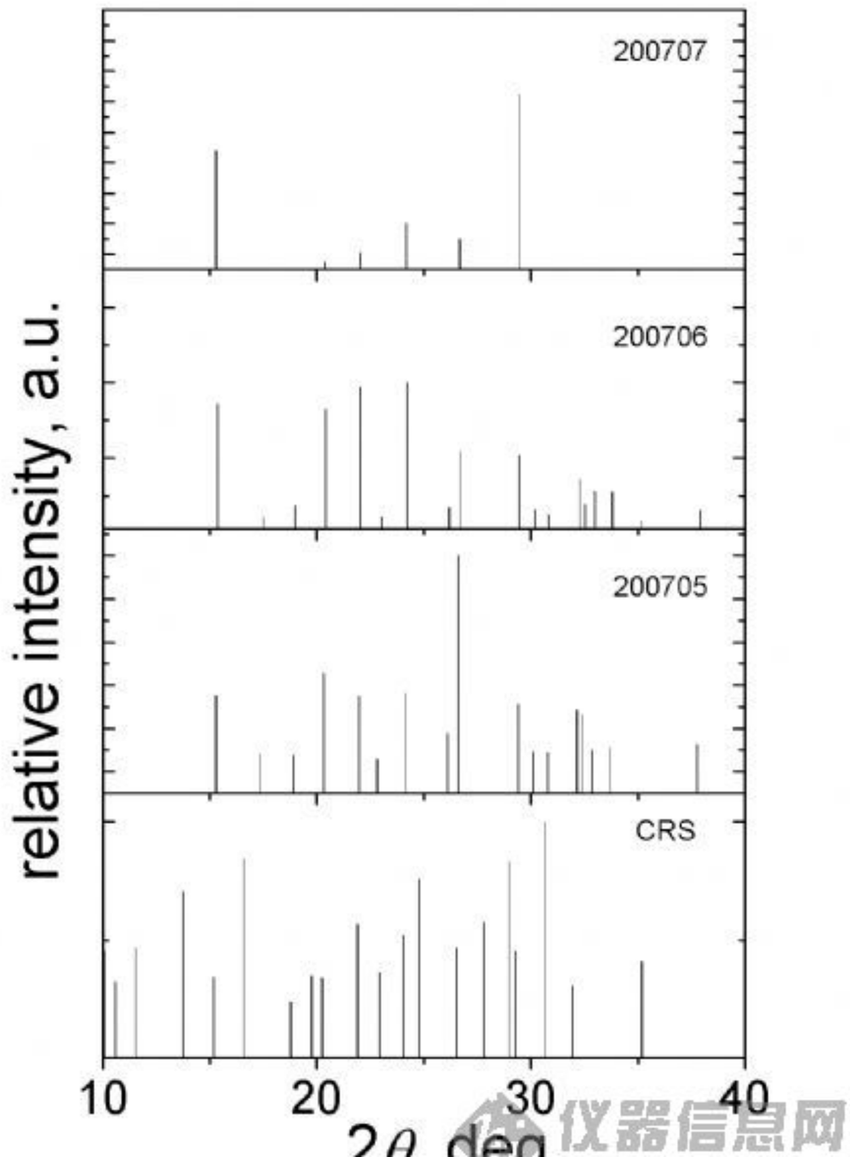
Structure Analysis

1. XRD (X光繞射)
2. TEM (穿透式電子顯微鏡)
3. FTIR (紅外光譜）
4. Raman （拉曼光譜）

XRD (X光繞射)


X射線
偵測器
晶格
XRD圖譜
I
2θ


入射X線
回折X線
θ
面1
面2
面3
X_3
X'_3
A
B
A′
B′
O′

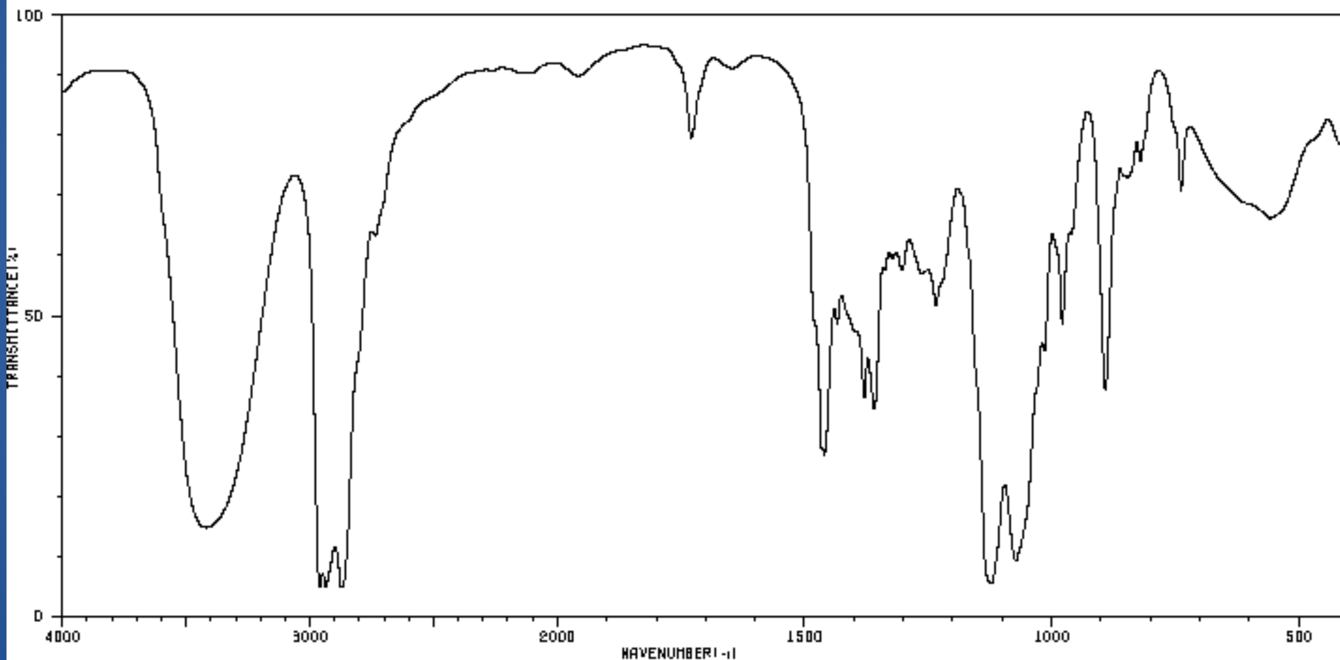

200707
200706
200705
CRS
relative intensity, a.u.
10
20
30
40
2θ, deg

FTIR (紅外光譜)(鍵結）

HIT-NO=1110	SCORE= ( )	SDBS-NO=662	IR-NIDA-05124 : LIQUID FILM

ETHYLENE GLYCOL MONOBUTYL ETHER

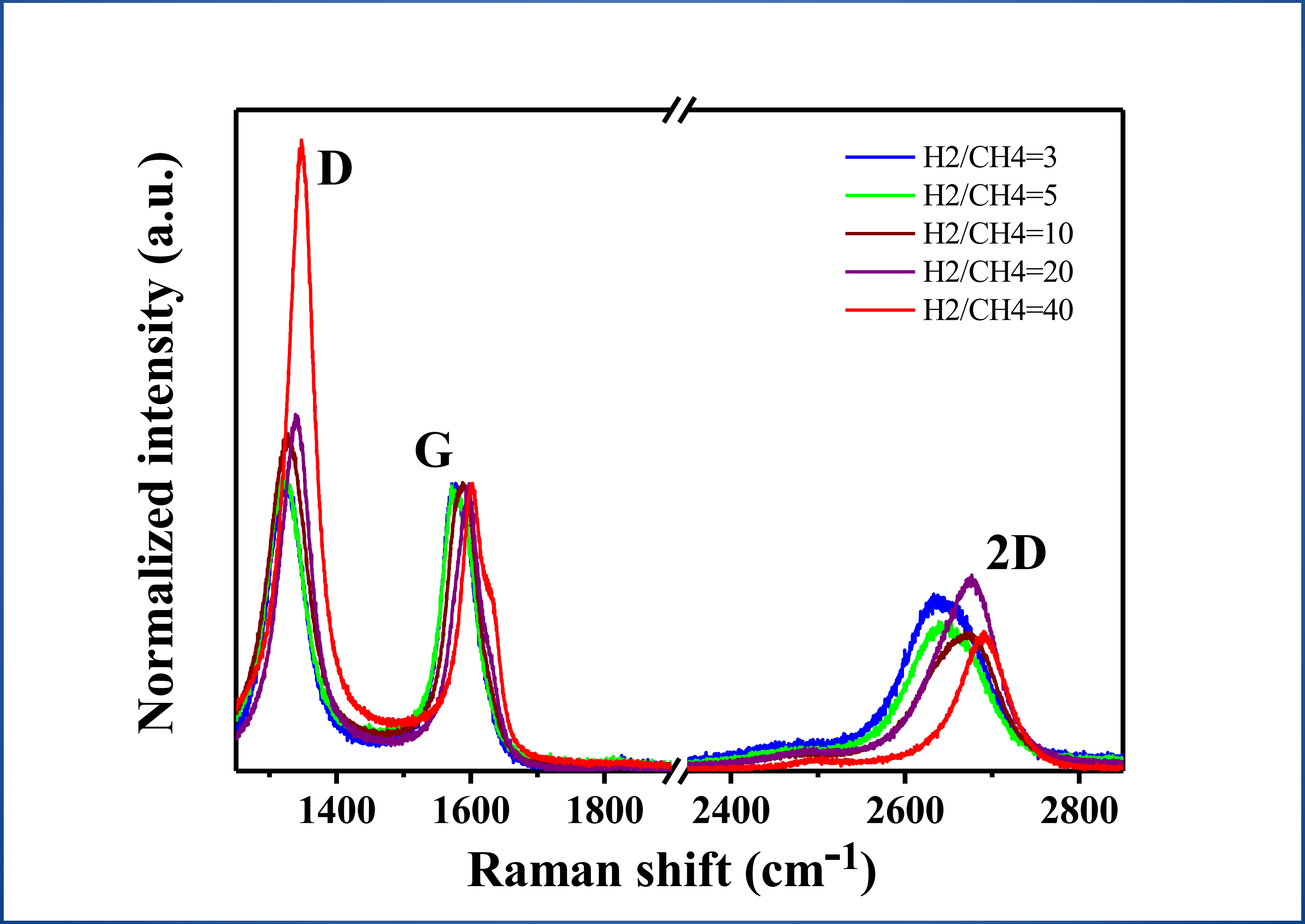
$C_6H_{14}O_2$



3416	14	1466	26	1236	60	820	72
2959	4	1460	26	1123	5	738	68
2935	4	1434	47	1073	9	556	64
2871	4	1379	36	1014	43		
1961	86	1360	33	979	47		
1956	86	1322	57	891	36		
1729	77	1303	66	848	70		

$CH_3—(CH_2)_3—O—(CH_2)_2—OH$

Raman （拉曼光譜)

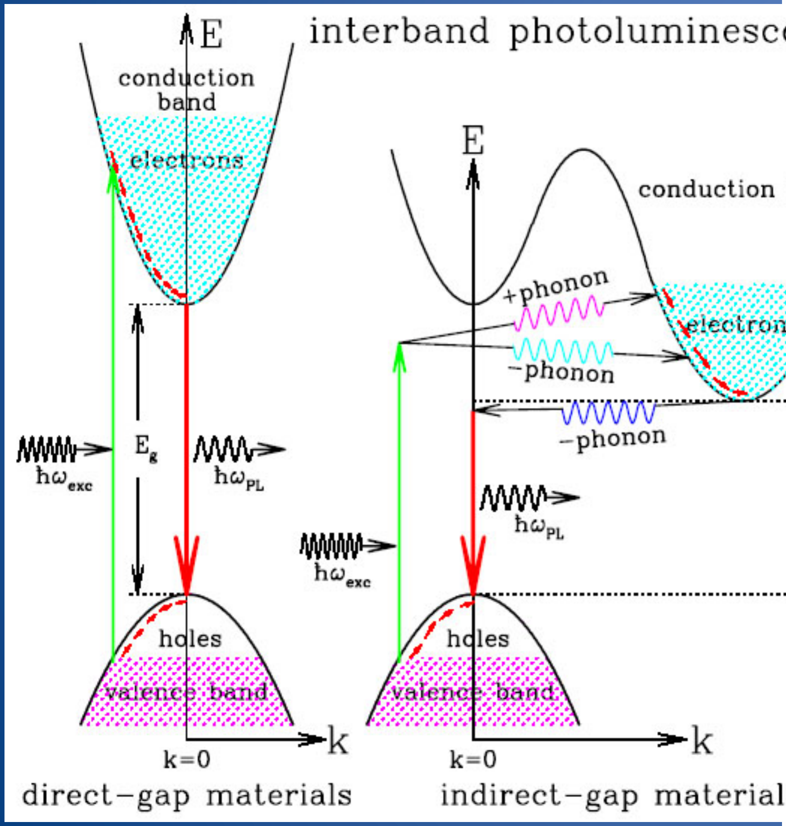


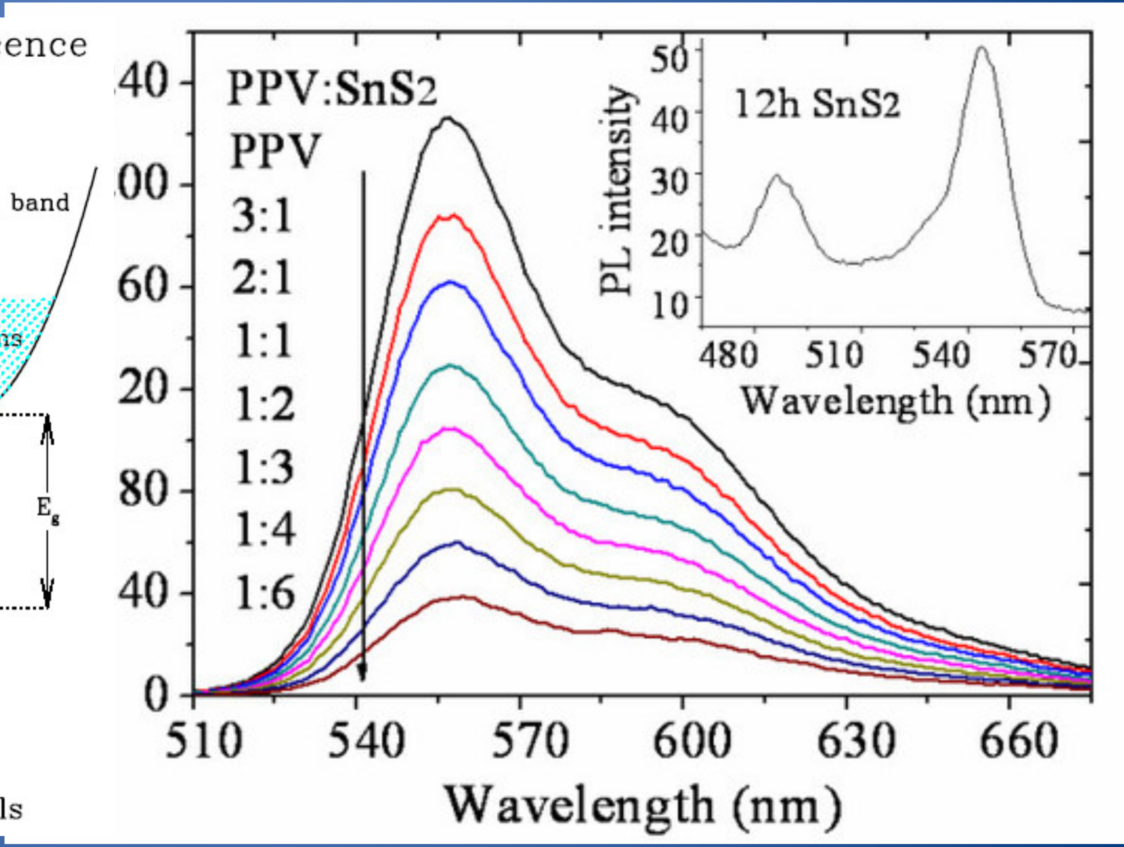
D
G
2D
H2/CH4=3
H2/CH4=5
H2/CH4=10
H2/CH4=20
H2/CH4=40
Normalized intensity (a.u.)
1400
1600
1800
2400
2600
2800
Raman shift (cm-1)

Electronic properties

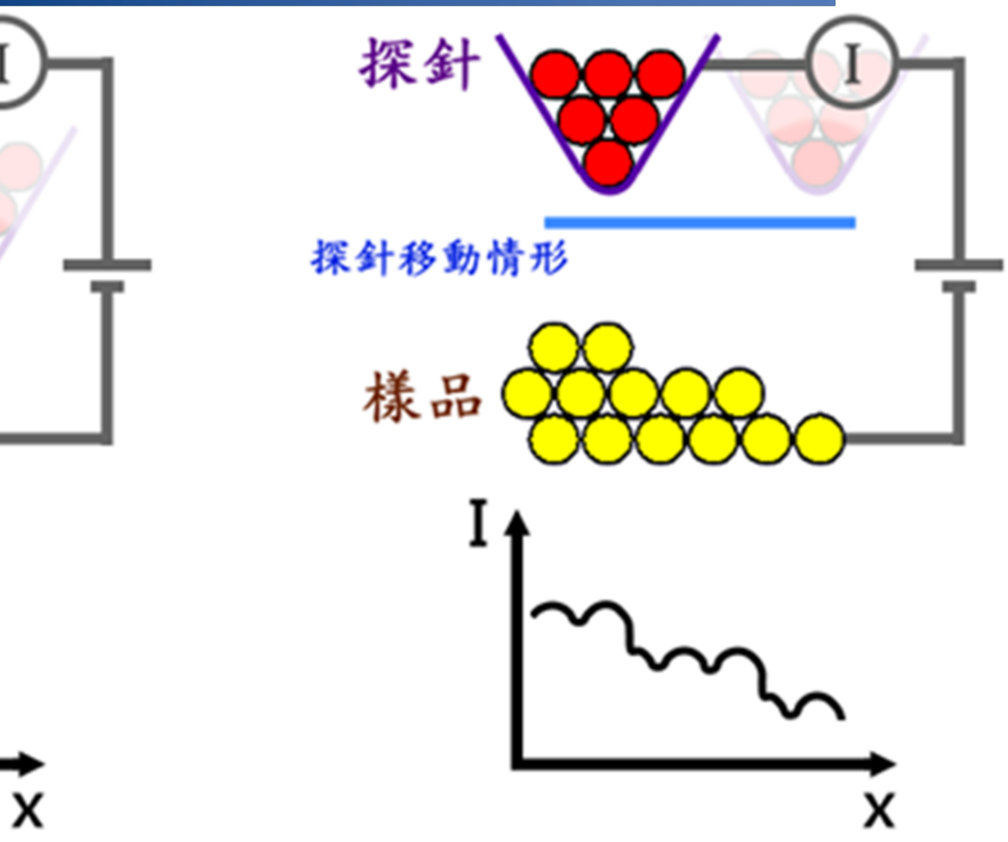
1. Optical Absorption (吸收光譜)
2. Photoluminescence (螢光光譜)
3. STS (掃描穿隧顯微術)
4. XPS (X光電子光譜)
5. 同步輻射測量(SRRC)

Photoluminescence (PL & CL)

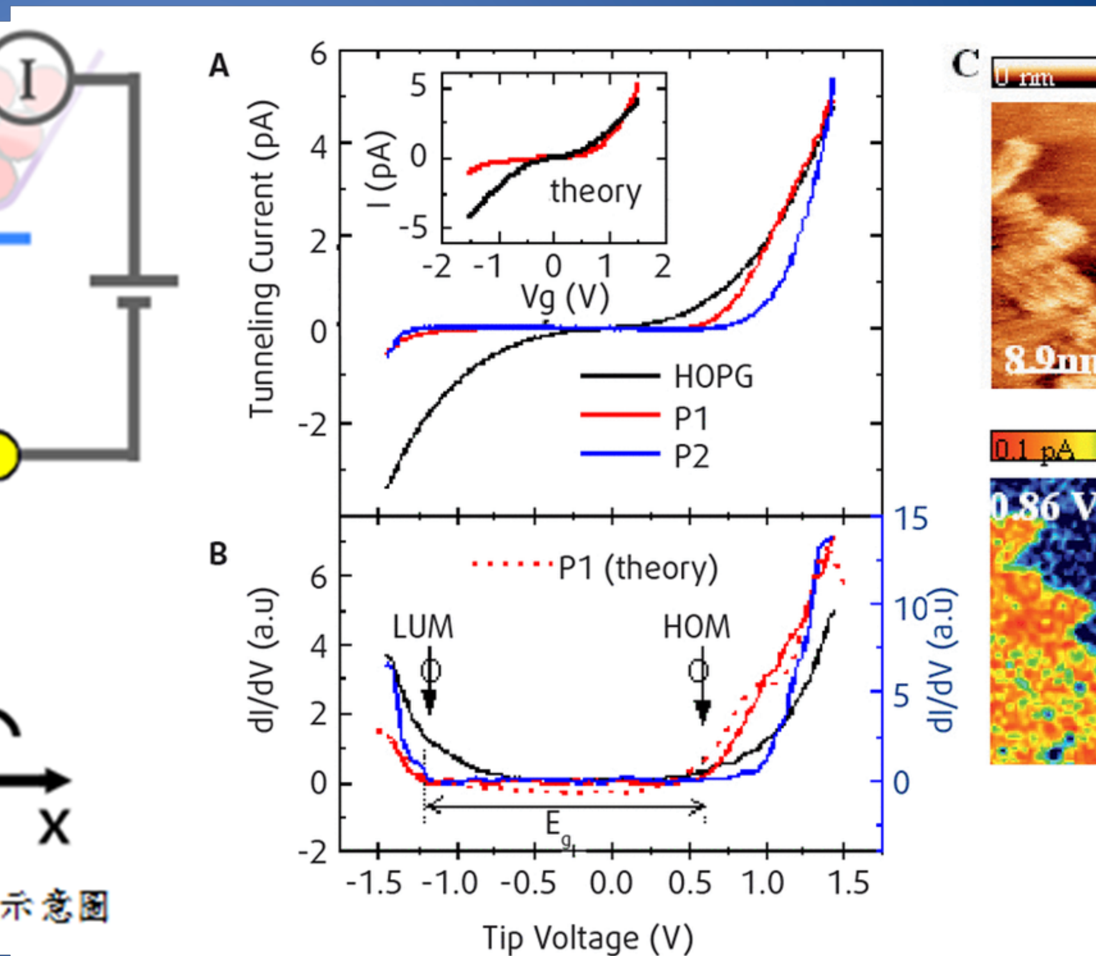




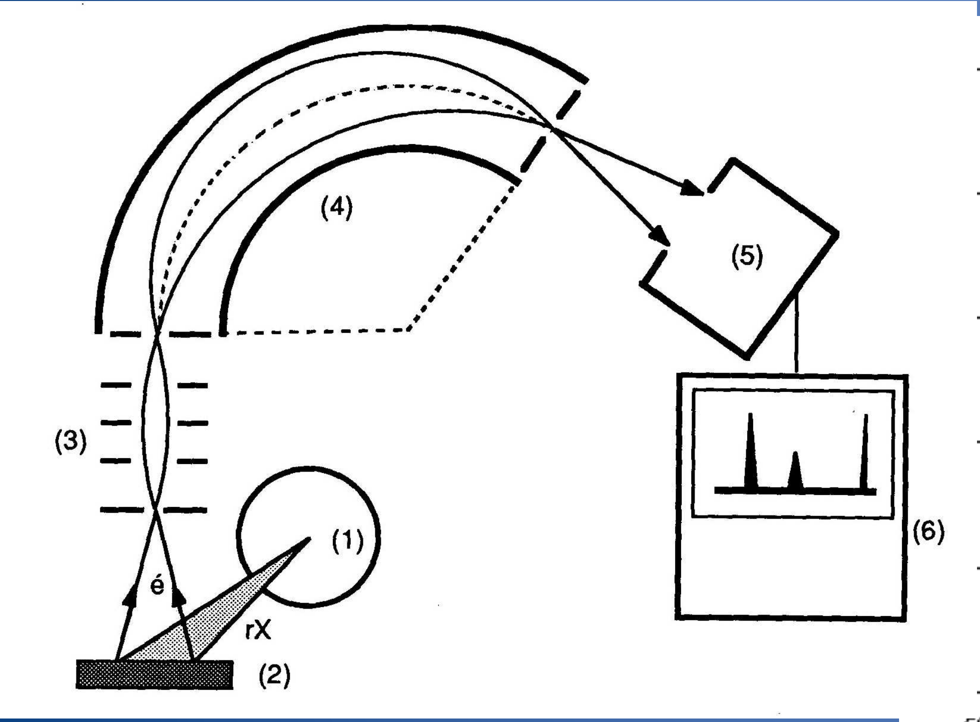
STS (掃描穿隧顯微術)



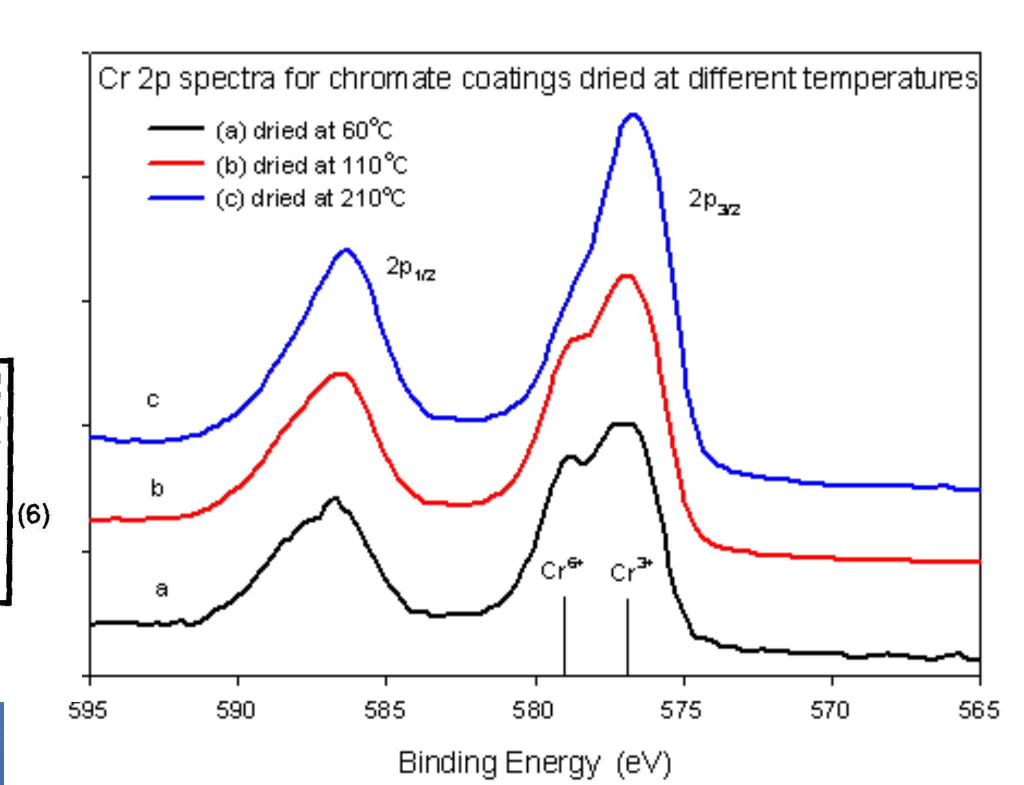
意圖 圖二、定高度模式示意圖



XPS (X光電子光譜)

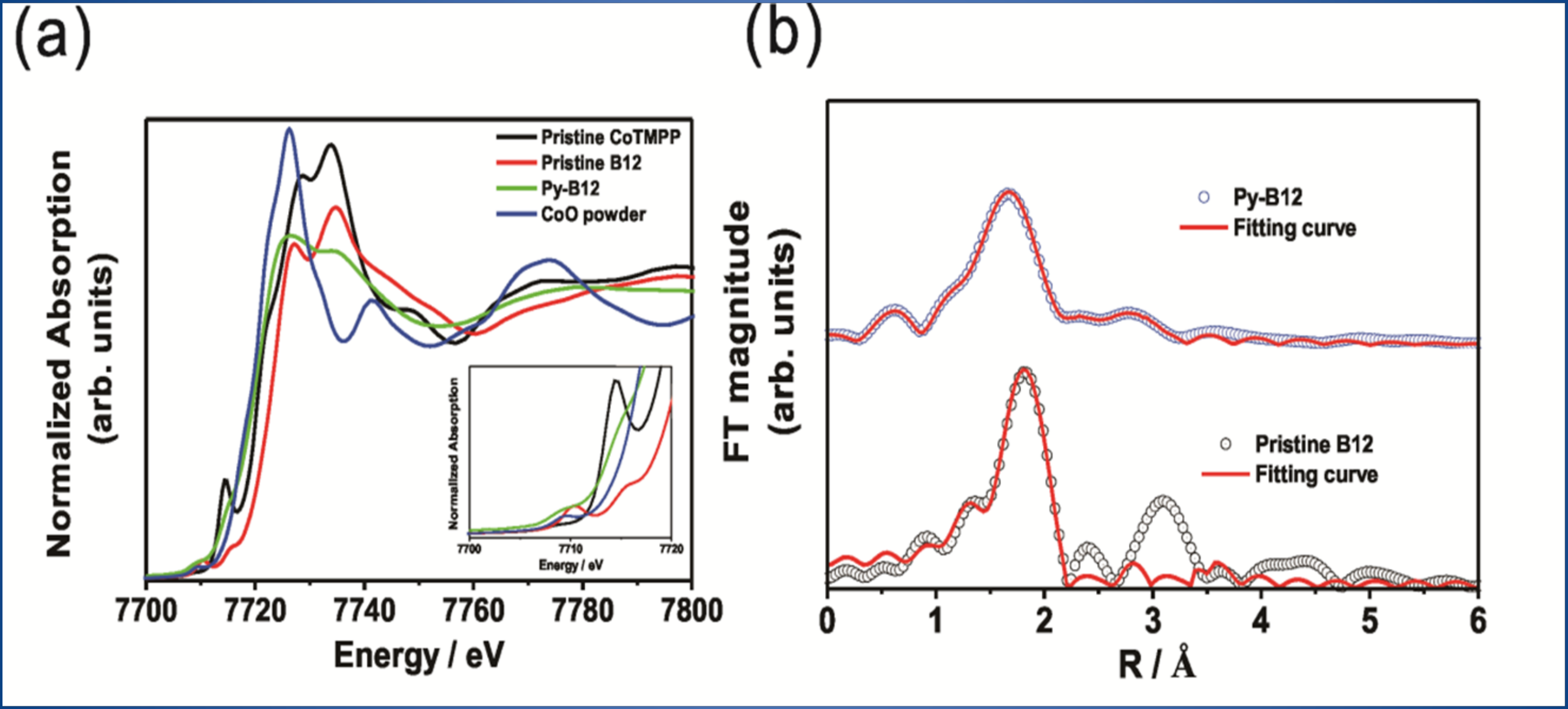


(1)
(2)
(3)
(4)
(5)
(6)
é
rX



Cr 2p spectra for chromate coatings dried at different temperatures
(a) dried at 60°C
(b) dried at 110°C
(c) dried at 210°C
2p1/2
2p3/2
c
b
a
Cr6+
Cr3+
595
590
585
580
575
570
565
Binding Energy (eV)

同步輻射測量(SRRC)

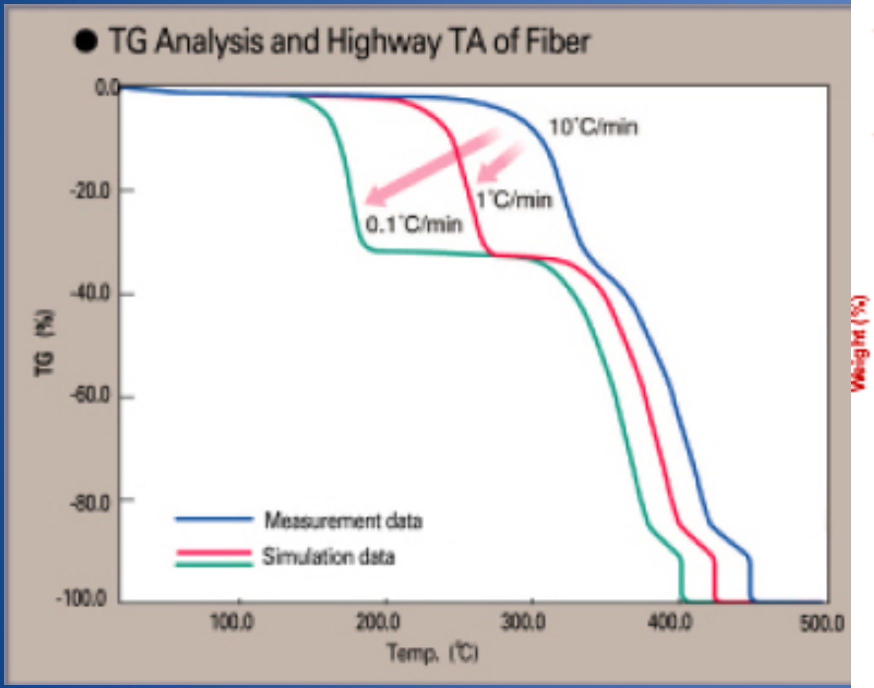


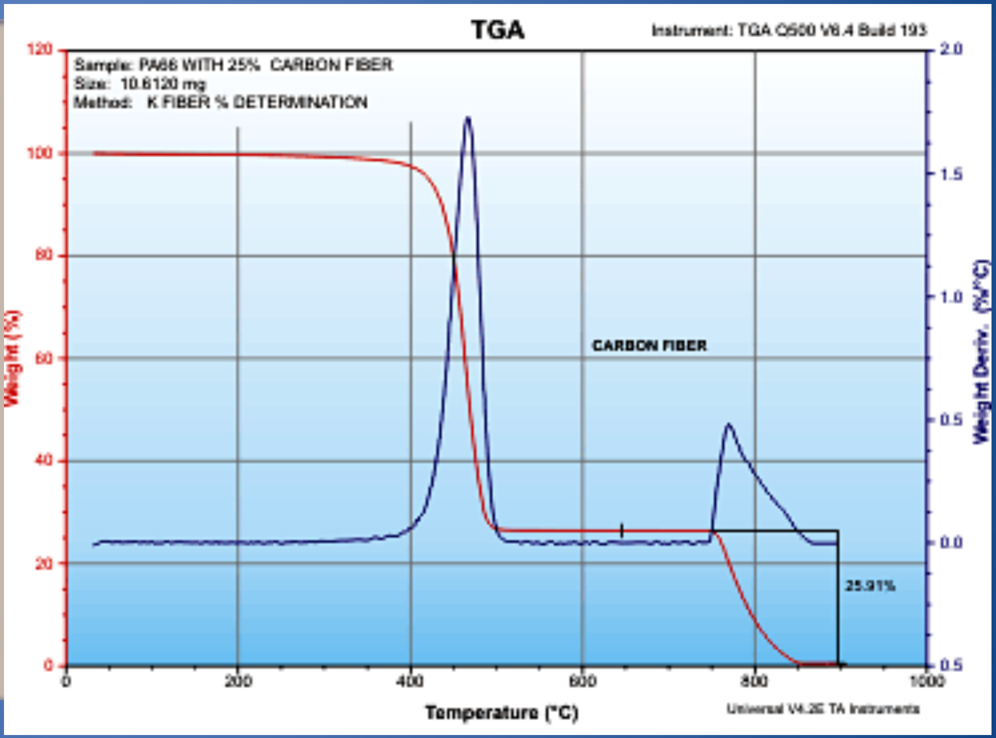
(XANES & EXAFS)

Other Thermal and Magnetic Measurements

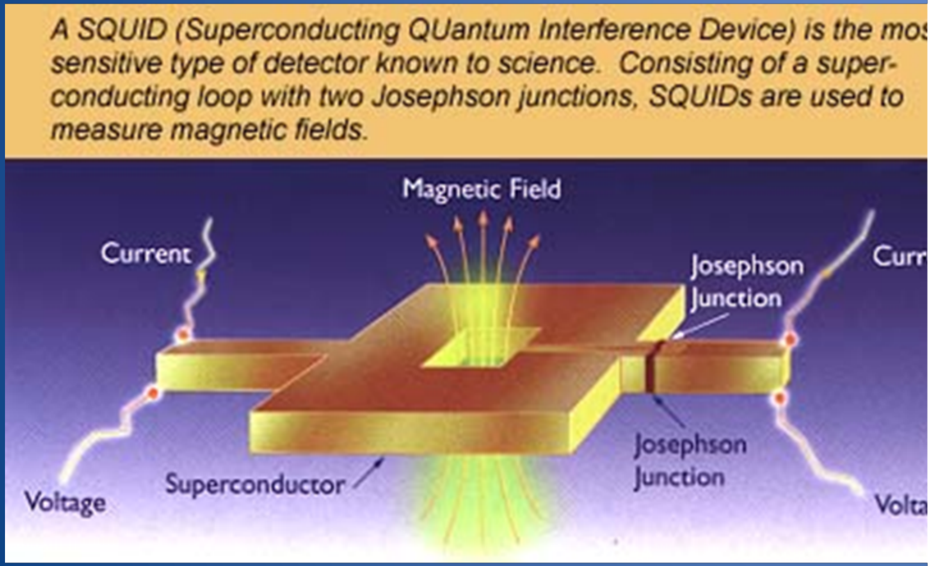
1. 熱傳導係數測量(Thermal conductivity)
2. 熱重分析(TGA)
3. 熱分析儀 (DSC)
4. SQUID (Superconducting Quantum Interference Device)

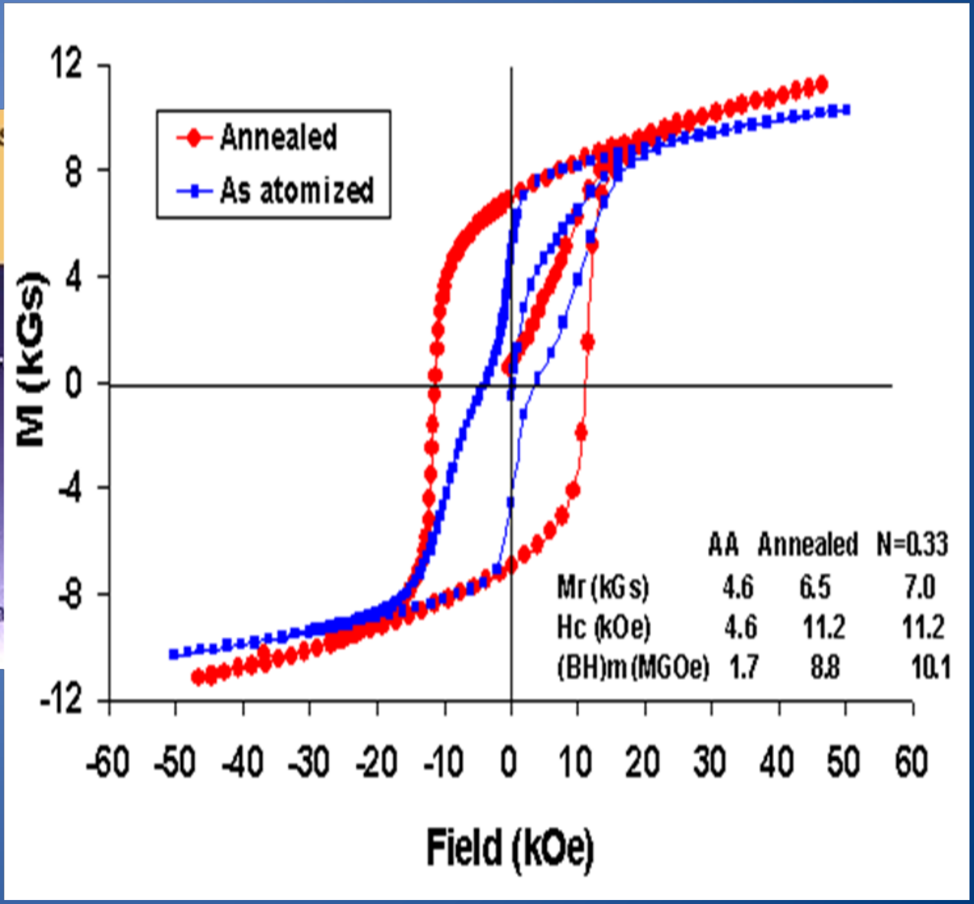
TGA & DSC


TG Analysis and Highway TA of Fiber
10˚C/min
1˚C/min
0.1˚C/min
TG (%)
0.0
-20.0
-40.0
-60.0
-80.0
-100.0
100.0
200.0
300.0
400.0
500.0
Temp. (℃)
Measurement data
Simulation data


TGA
Instrument: TGA Q500 V6.4 Build 193
Sample: PA66 WITH 25% CARBON FIBER
Size: 10.6120 mg
Method: K FIBER % DETERMINATION
CARBON FIBER
25.91%
Weight (%)
Weight Deriv. (%/°C)
Temperature (°C)
Universal V4.2E TA Instruments

SQUID (Superconducting Quantum Interference Device)





Length scales

- Atoms
  - ~ angstrom 10^{-10} m
- Light
  - wavelength ~ μm
- Electrons
  - De Broglie wavelength = h/p (quantum mechanics)
  - = sqrt (150/V) in angstroms (V is energy in volts)
  - ~0.1-10 nm
  - If a nanoelectronic circuit element is about the size of an electron wavelength, wave nature will be *crucial*
  - Conductance quantized at these small scales in units of e^2/h
- Mean free path (MFP)
  - 10^{-10} m in metals at room temperature
  - 10^{-4} m in ultra high quality semiconductors at low temperatures

Energies

- Electronic transistion energies
  - ~ 1-10 eV
- Fermi energy
  - 1-10 eV in metals
  - 1-10 meV in semiconductors
- kT
  - 30 meV at room temperature