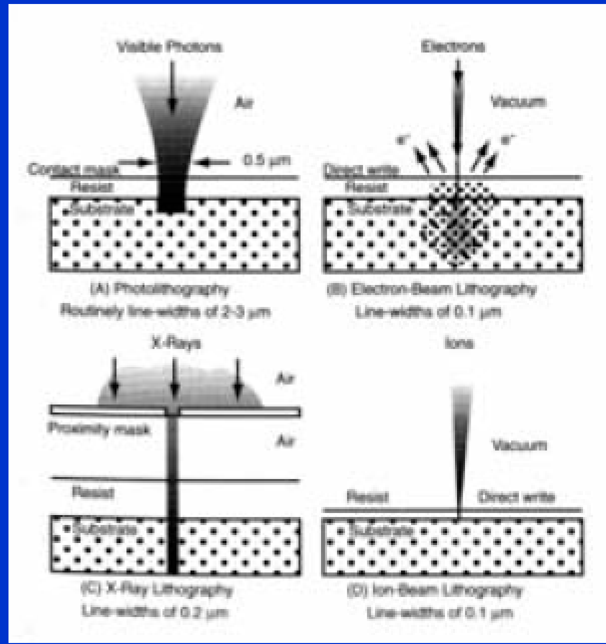
# NANOFABRICACION

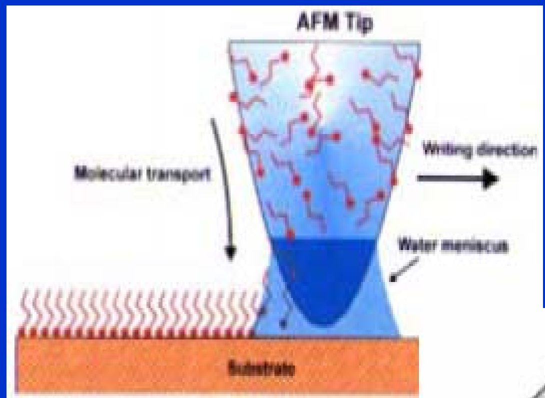
## TECNICAS TOP-DOW

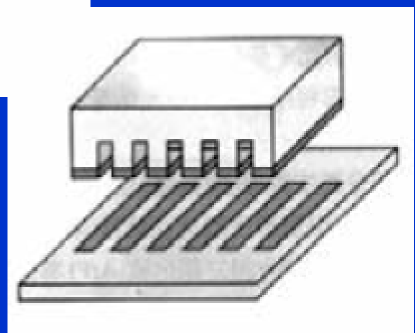
Litografía & Etching

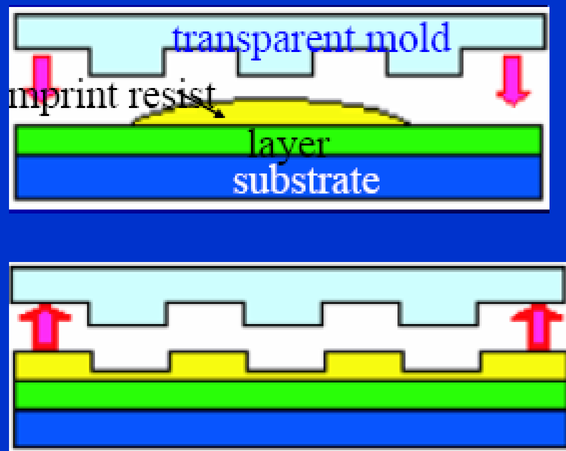
Escritura directa dip-pen

Nano impresión





# HERRAMIENTAS PARA CONSTRUIR NANO-ESTRUCTURAS

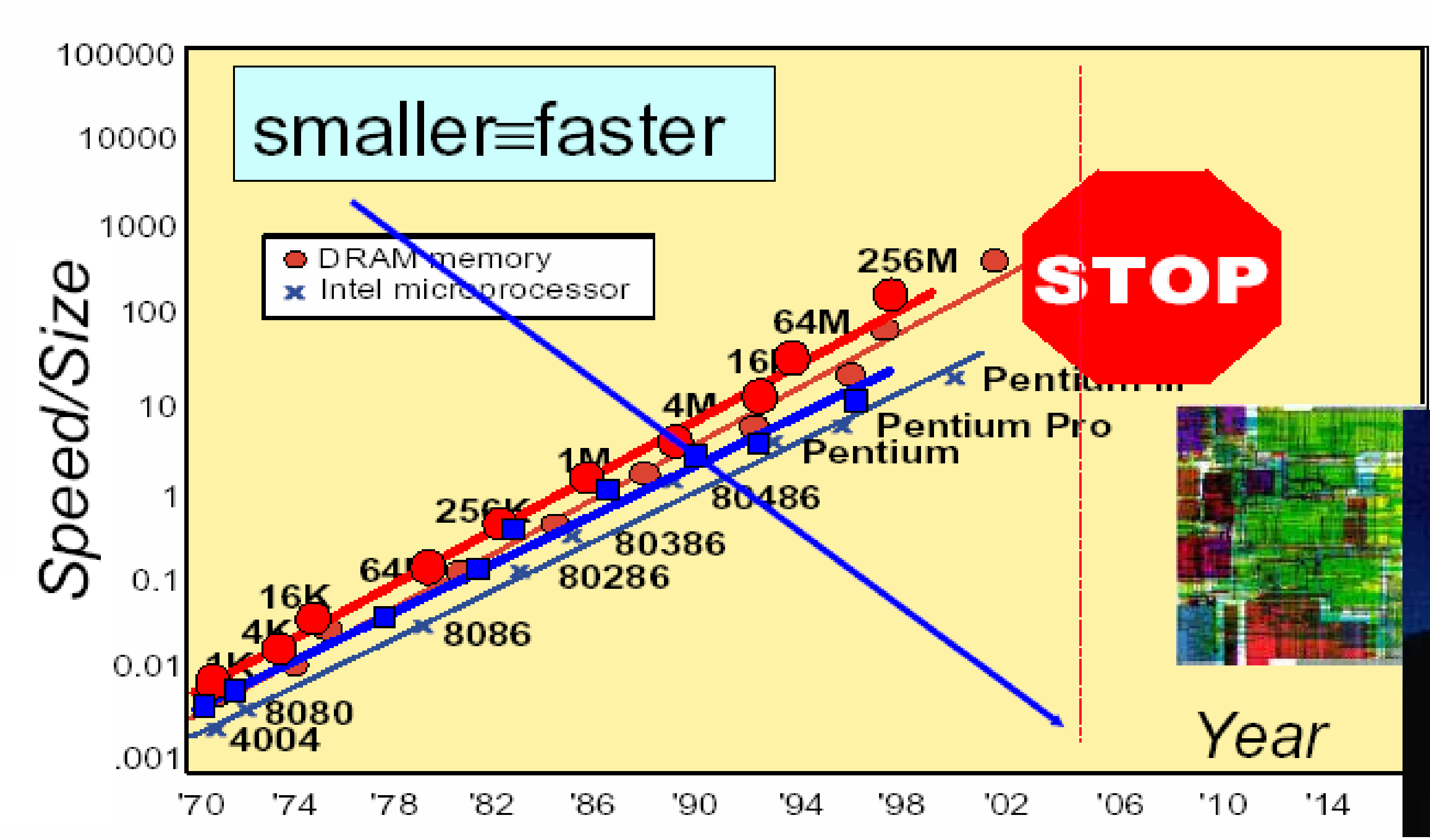
## APROXIMACION TOP-DOWN

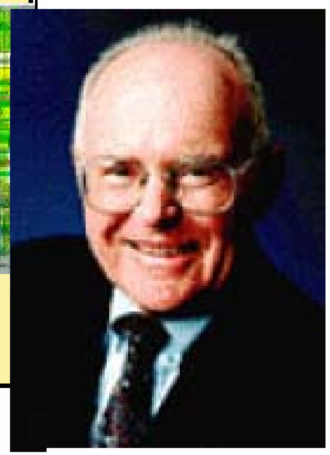
Litografía a nano-escala
Nano-impresión
Nano-manipulación (átomos o moléculas)

## APROXIMACIONES BOTTOM-UP

Auto-ensamblaje
Crecimiento cristalino a nano-escala
Síntesis molecular y biológica
Polimerización

# OTRO NANO-MUNDO: TECNOLOGIA DEL CHIP DE Si

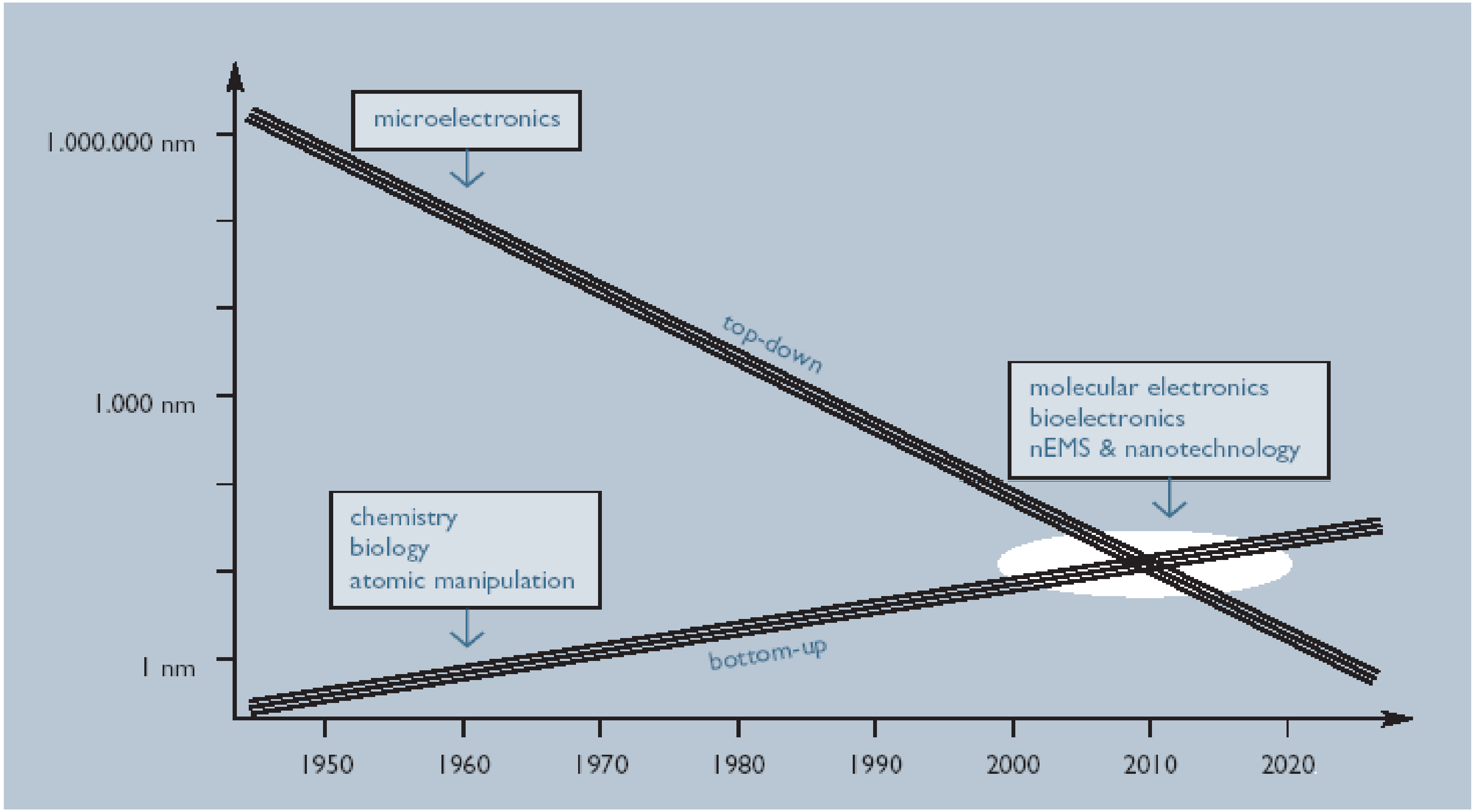


✓**La ley de Moore**: el numero de transistores encapsulados en un chip se duplica cada 18 meses

✓Transistores mucho mas pequeños, mas rápidos, de alta densidad, bajo consumo de energía

# Top-down and Bottom-Up Processing



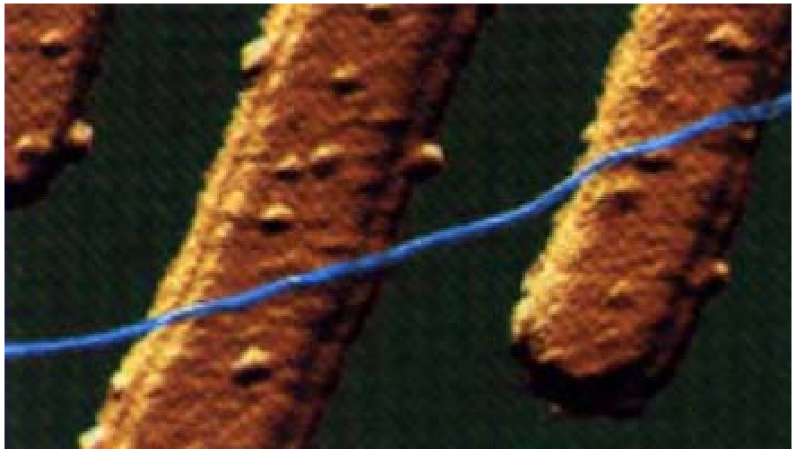

http://www.imec.be/wwwinter/business/nanotechnology.pdf

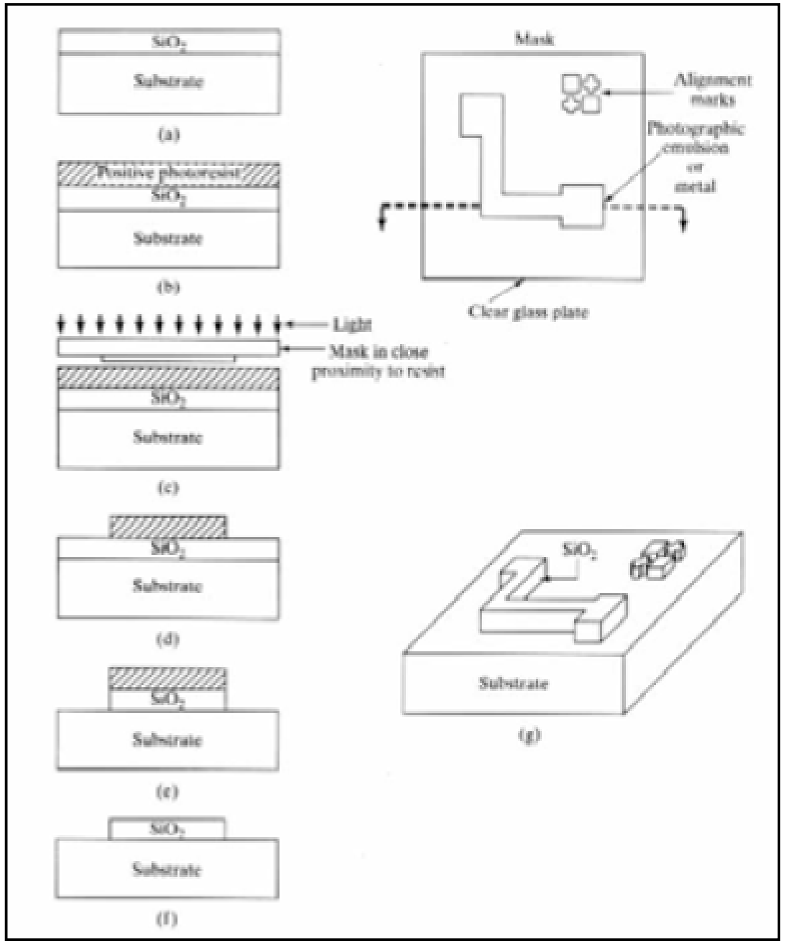
# TECNICAS DE FOTOLITOGRAFIA

Que es fotolitografía?

Transferencia Micro (nano) – patrones:

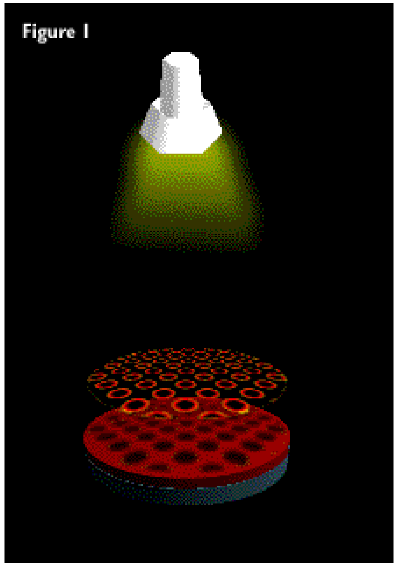
Impresión + etching

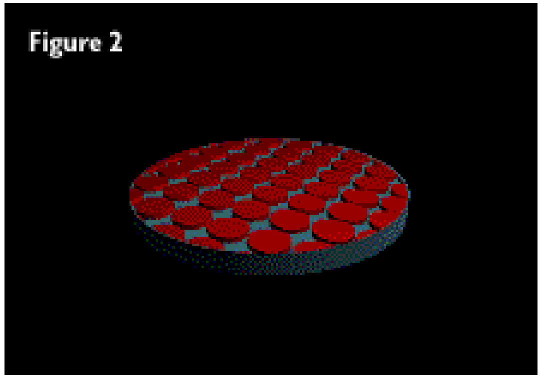




# Photolithography

- Light activated chemistry to define patterns
- Spin-coat a layer of polymers called photoresist
- Bake to drive off the solvent
- Exposure to UV light through a mask
- "Positive Tone"—exposure breaks down into shorter units that can be washed off
- "Negative Tone"---exposure promoted cross linking
- "Developing or Descumming" to get the final pattern
- Remove material by etching
- Add material by deposition

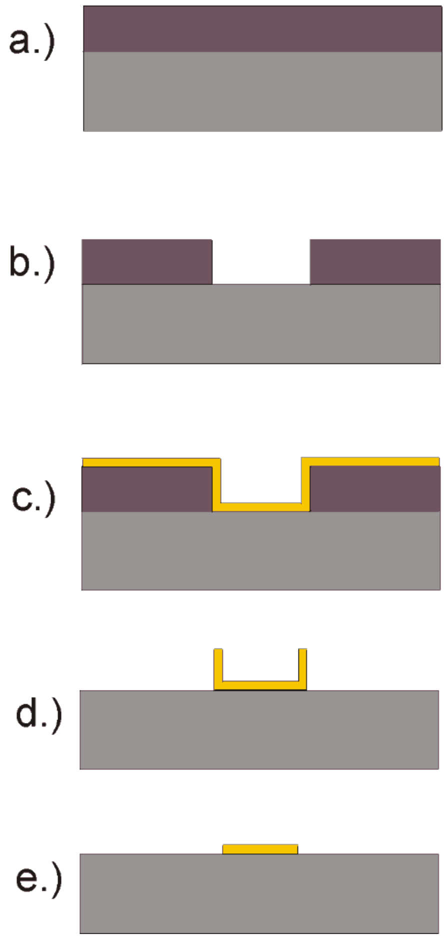


# Photolithography cont’

- Example: Lift-off Lithography
- Deposit through the resist mast
- Dissolve the resist layer

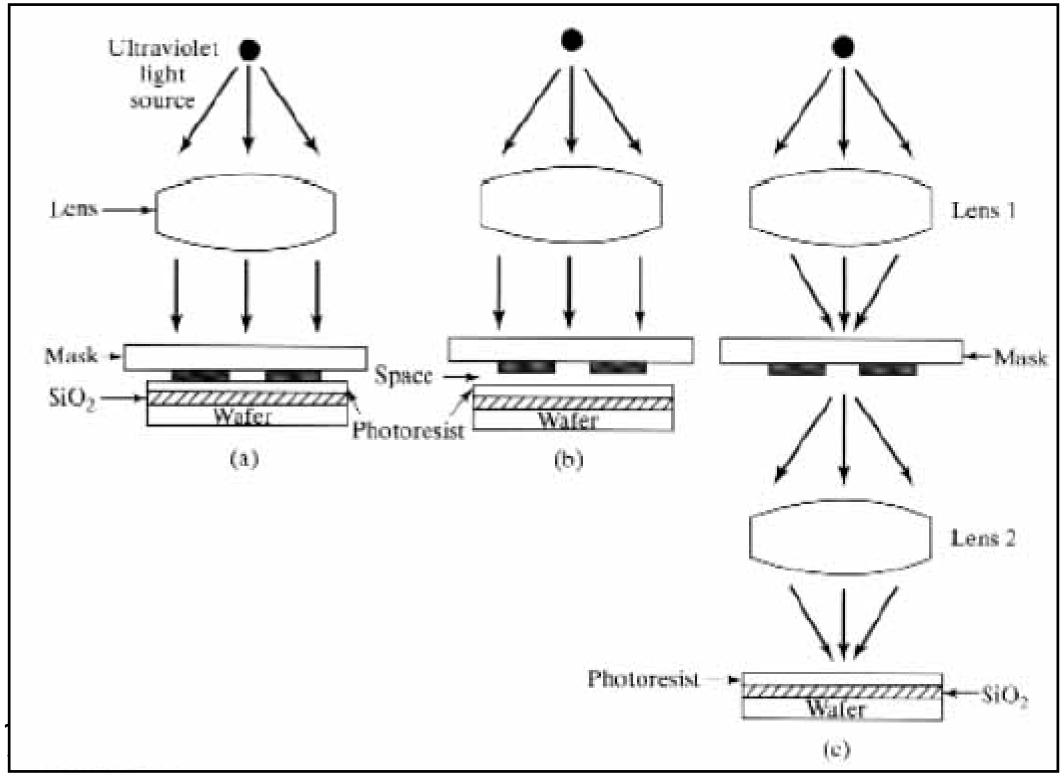
- **Current state-of-the art photolithography**
- UV light wavelength & the optics sets the smallest feature size
- Current state of art: 248nm




http://www.research.ibm.com/journal/rd/411/ausschnitt.html
http://www.research.ibm.com/journal/rd/455/bates.html

# TECNICAS DE FOTOLITOGRAFIA

## MODOS DE IMPRESIÓN LITOGRAFICA & LIMITACIONES DE RESOLUCION




**Contacto directo:**

$R \sim \lambda$

**Proximidad:**

$R \sim (\lambda d)^{1/2}$

**Proyección:**

$R=k(\lambda/NA)$

K=0.5-1

NA=sen$\alpha$ menor/igual

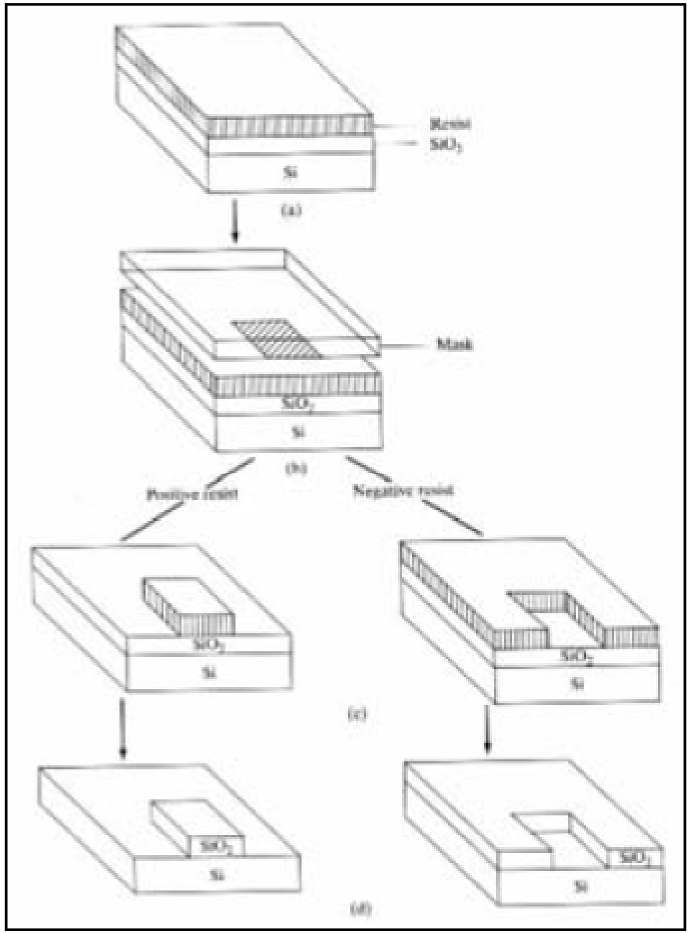
(apertura numerica)

# TECNICAS DE FOTOLITOGRAFIA

## FOTO LITOGRAFIA

**Componentes básicos:**

Fuente de luz, mascara (mask aligner, )
Fotoresist




Fuente de luz

Línea g: (Hg, Xe) : 436 nm

Línea i: (Hg-Xe): 365 nm

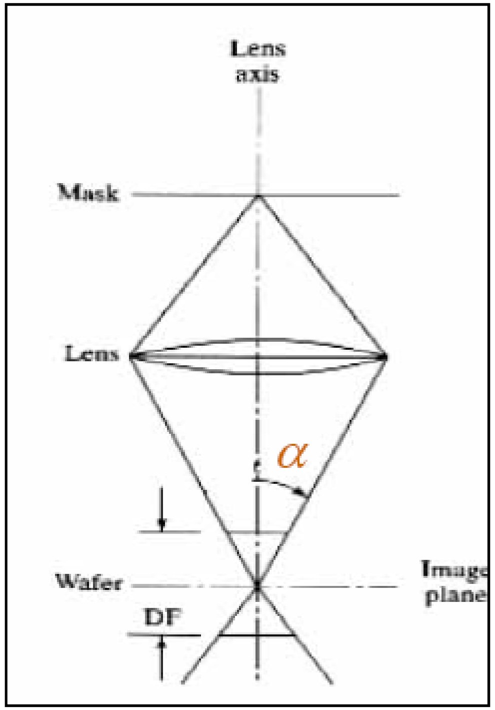
KrF: 248 nm

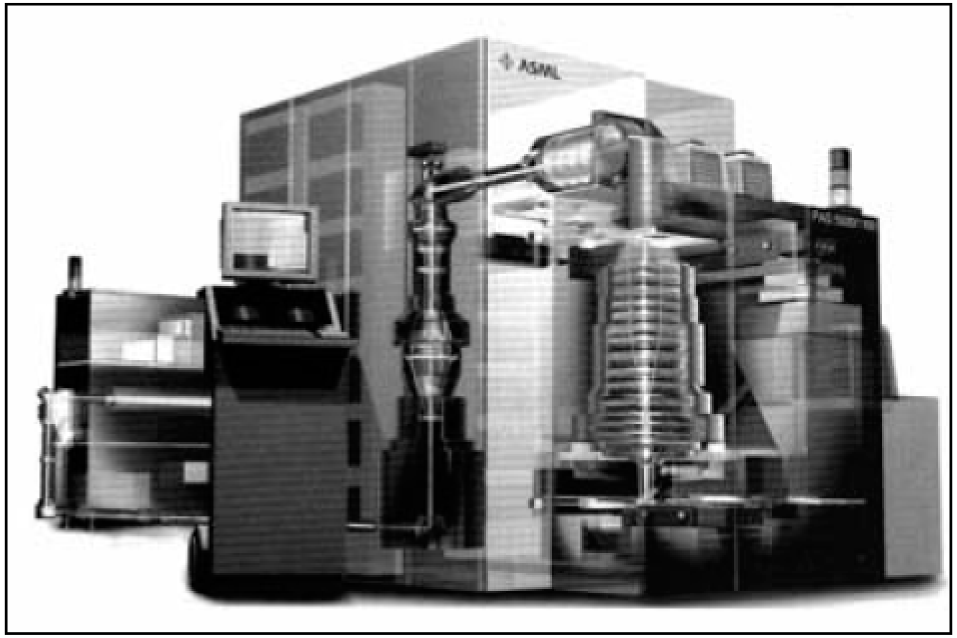
ArF: 193 nm

$F_2$: 157 nm

**Fotoresist: positiva o negativa**

# TECNICAS DE FOTOLITOGRAFIA



**Resolución:**

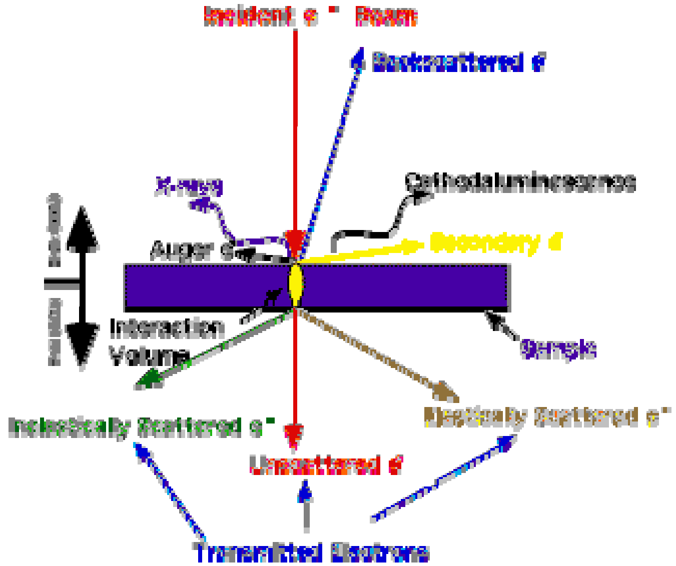
R=k(λ/NA), K=0.5-1

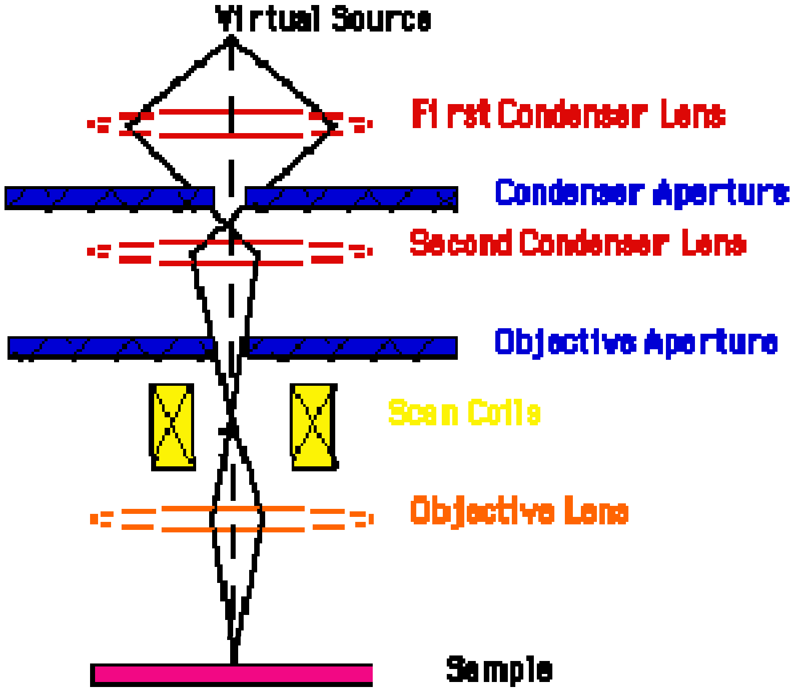
**Profundidad de foco:**

DF=C(λ/NA²), C=0.5-1

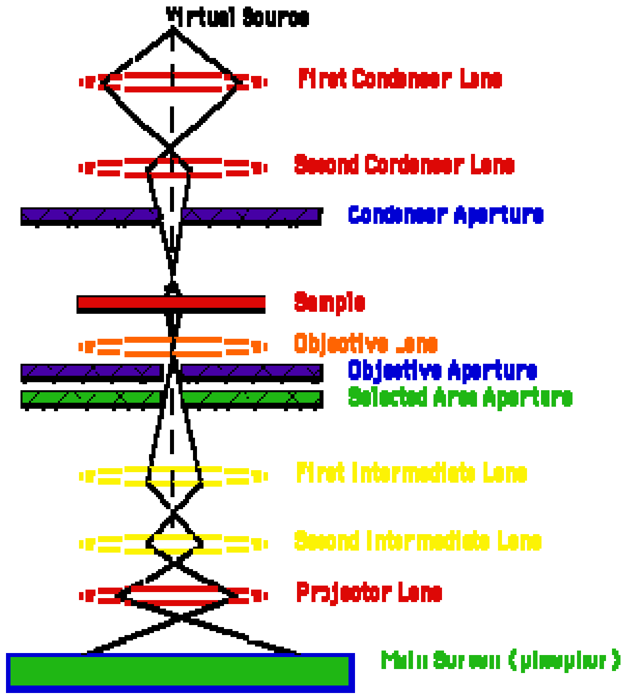
# Beyond light: Electrons

- Use electron waves to image down to the atomic scales
- Wavelength of electron: λ=h/p=h/mv (down to atomic scale)
- e-beam interacts with the sample (Z sensitivity)
- Detector picks up secondary electrons
- Scanning Electron Microscope (0.1-30 keV)
- Transition Electron Microscope (100-500keV)




SEM




TEM

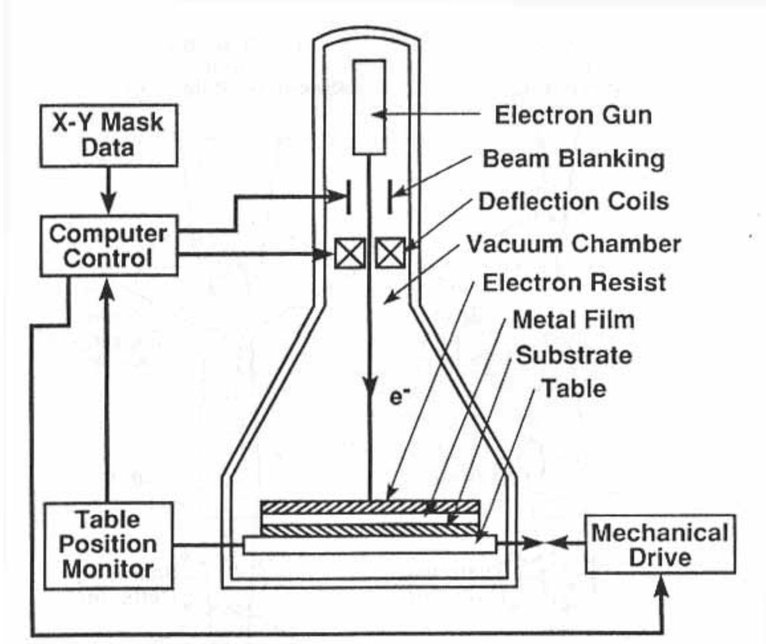
# Electron Beam Lithography I

• Sample is coated with a thin layer of a polymer chemical known as the resist. The most commonly used e-beam resist is polymethylmethacrylate (PMMA).

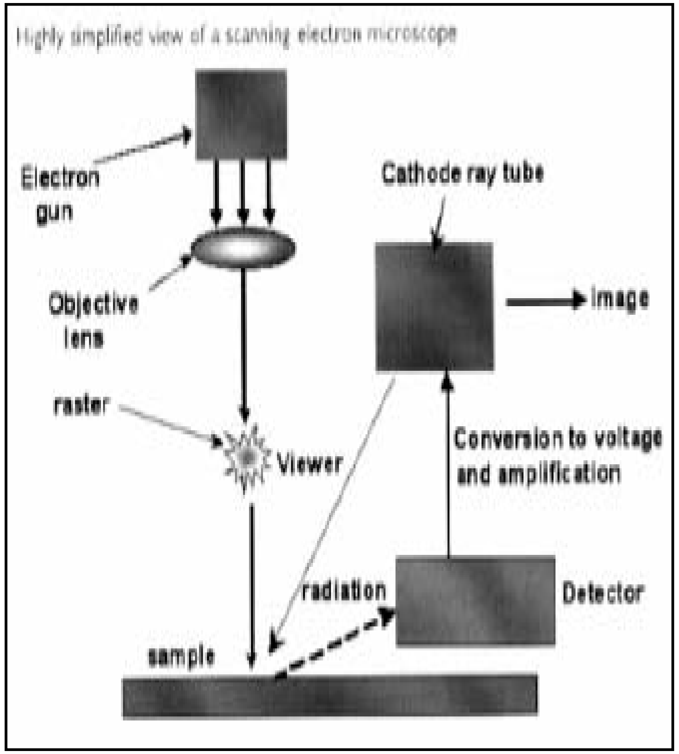
• With EBL, there must be a path to ground for the electrons. Thus, a small section of the PMMA must be scraped away on the edge of the sample so that conductive tape can be attached from the sample to the stage (ground). If the sample itself is an insulator, a very thin (10-20 Å) layer of gold must be deposited onto the PMMA.

• PMMA breaks down into smaller molecular weight monomers upon exposure to electrons. Afterwards, the exposed regions can be rinsed away (developed) using a chemical known as methyl-isobutyl-ketone.

• The rest is like optical lithography



**LITOGRAFIA DE HACES DE ELECTRONES**




Equipos disponibles: SEM

Longitudes de onda corta

- Alta resolucion

- $\lambda_e = h/(2m_eE)^{1/2}$, 1eV→12.3 A

- Escritura directa
(haz enfocado + scanning)

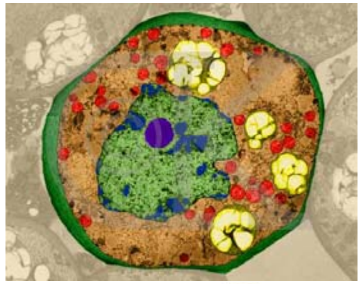
Dificultad para la producción en gran cantidad

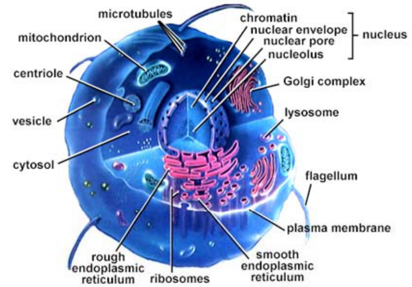
Limitación física: dispersión electrónica

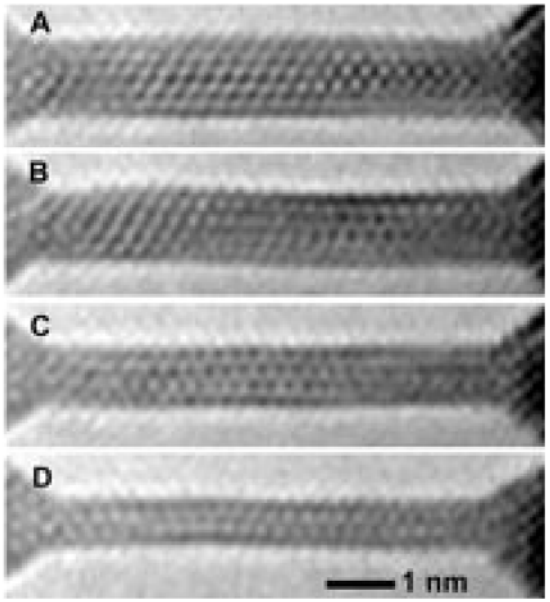
Substitución: litografía de ases iónicos enfocados (FIB)

# Electron Microscope Very Powerful tool!!

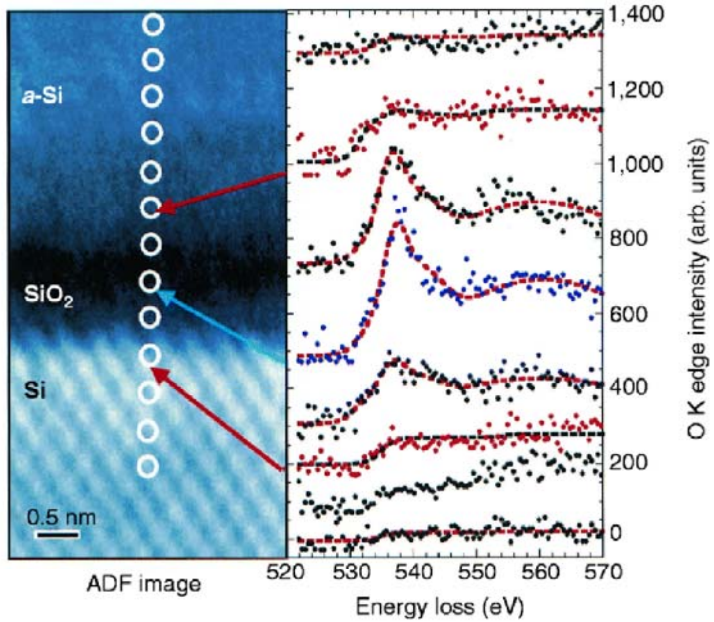
- Much of the knowledge about the structure of cells
- TEM down to the atomic scales
- An important for determining the structure of nanoscale objects





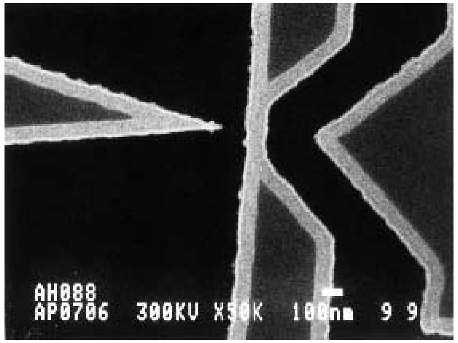

**TEM of in situ fabricated Au wires Kondo Science 2000**

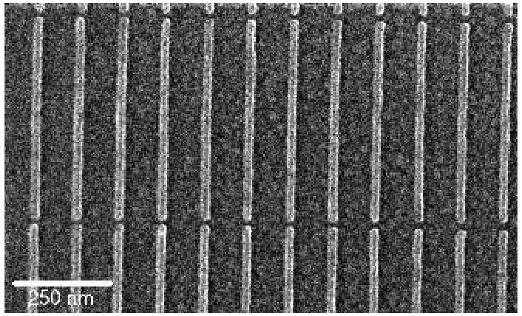


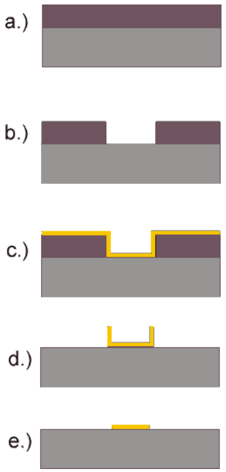

**TEM AND EELS spectra of thin oxide gates in FETs Muller et al. Nature 399, 758**

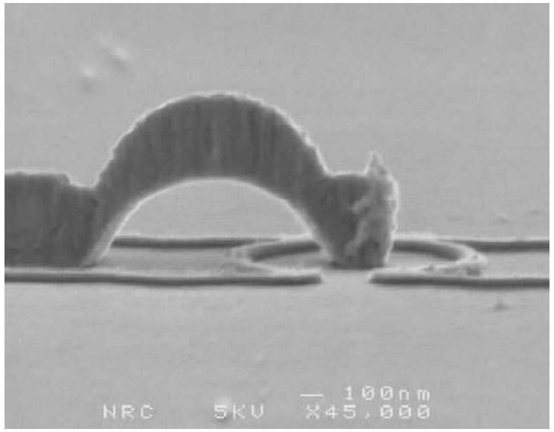
# Electron Beam Lithography II

- Similar techniques to optical lithography like lift-off
- Beam diameter 5nm
- Can achieve a resolution of about 15nm
- Limitation: secondary electrons…

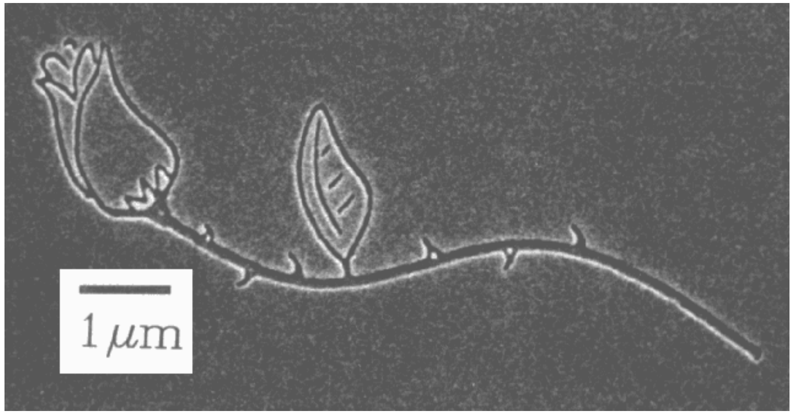



surface gated quantum dot device with submicron airbridge on GaAs/AlGaAs




Joe Nabity of Nabity Lithography Systems.

# LITOGRAFIA DE HACES DE ELECTRONES

# Focused Ion Beam

• A technique similar to EBL. Can achieve finer line widths (about 8 nm).

• Apparatus is similar to an SEM, but gallium ions are used instead of electrons.

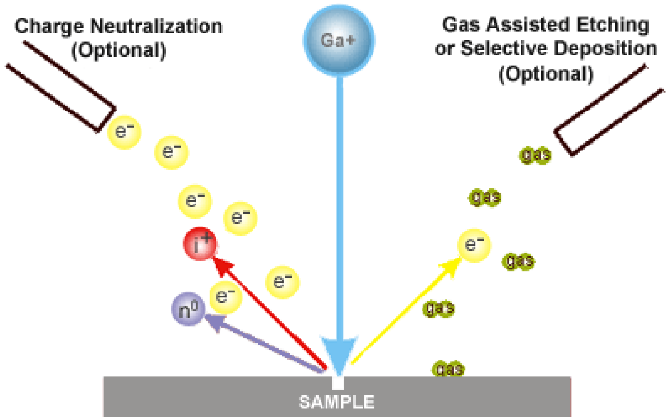
• The gallium ions are focused into a small beam just as in an SEM

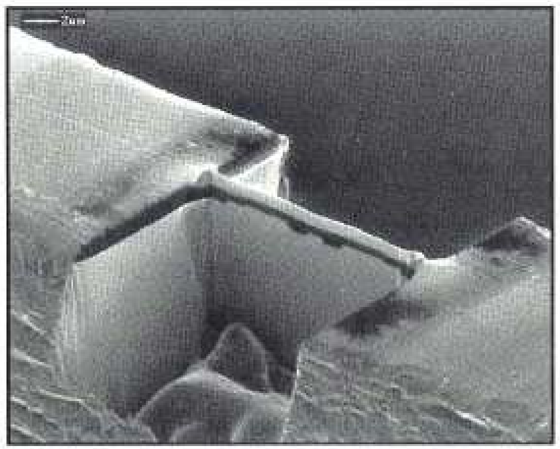
• At low currents—imaging (5nm resolution)

• The current from scattered ion or secondary electrons collected

• The beam itself since is powerful enough to etch away material. Thus no resist and developing is needed.

• Also useful for creating very deep holes or structures and for altering existing masks or patterns. Device-surgery!



SUB-0.1 MICRON THIN SECTION OF INTEGRATED CIRCUIT MILLED FOR LOCATION-SPECIFIC TRANSMISSION ELECTRON MICROSCOPE (TEM) ANALYSIS

# LITOGRAFIA DE RAYOS X

Longitudes de onda muy cortas (1-100 A)→ alta resolución
$\lambda_{fonon} = 1.24/E = 1.24/(h\nu)$

**Ventajas:**

Puede utilizar modos simples de impresión por proximidad
Para produccion en gran cantidad

Disponibilidad de mascaras y fotoresist

**Desventajas:**

- Fuentes de luz costosas. Ej: radiación de sincrotrón

- Dificultad de hacer mascaras de gran tamaño

# LITOGRAFIA DE RAYOS X

## FABRICACION DE LAS MASCARAS

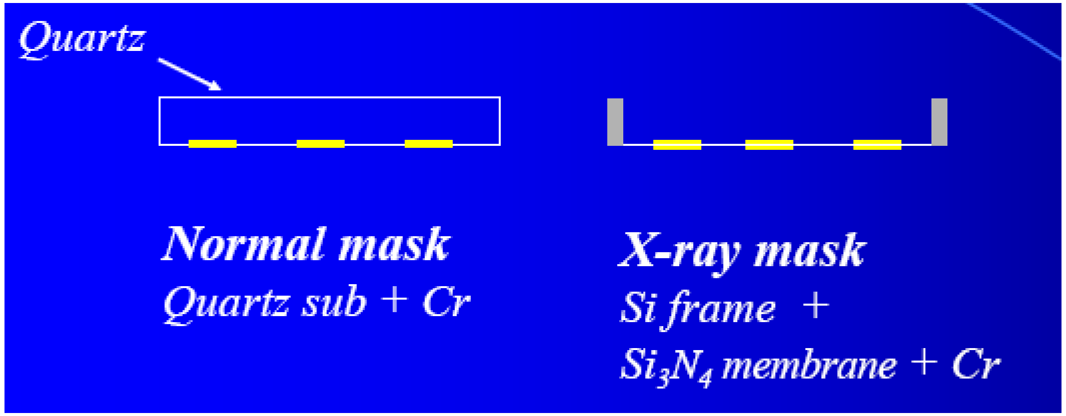
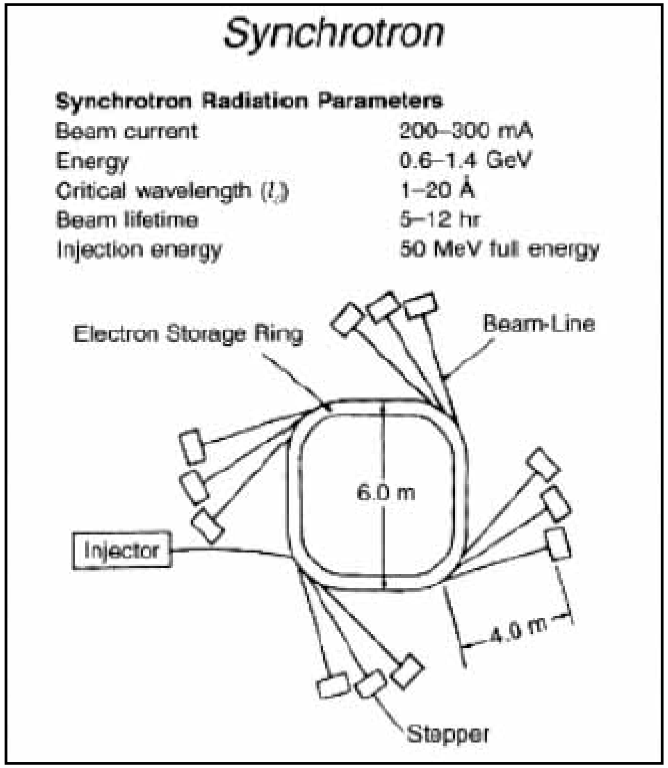



**TABLE 1.6** Optical vs. X-Ray Mask

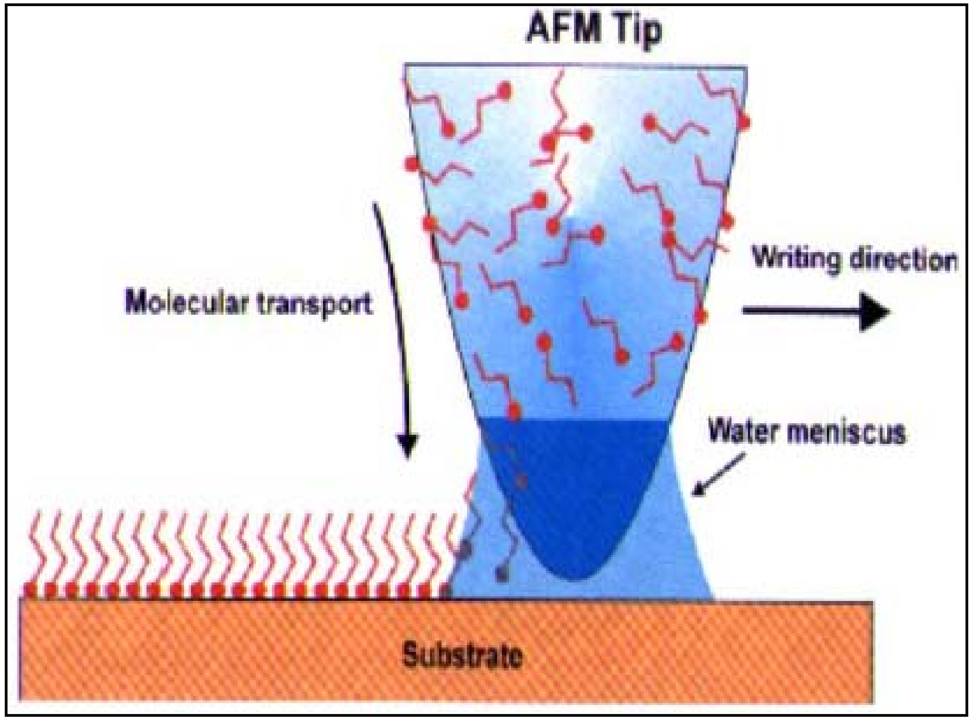
| Optical mask | X-ray mask |
|---|---|
| Mask design: CAD | Mask design: CAD |
| Substrate preparation: | Substrate preparation: |
| Quartz | Thin membrane substrate (Si, Be, Ti,) |
| Thin metal film deposition | Deposit plating base (50 Å Cr then 300 Å Au) |
| Pattern delineation: | Pattern delineation: |
| Coat substrate with resist | Coat with resist |
| Expose pattern (optical, e-beam) | Expose pattern (optical, e-beam) |
| Develop pattern etch Cr layer | Develop pattern |
| Strip resist | Absorber definition: |
| | Electroplate Au (~15 μm for hard x-rays) |
| | Strip resist |
| Cost: $1k–3k | Cost: $4k–$12k |
| Duration: 3 days | Duration: 10 days |

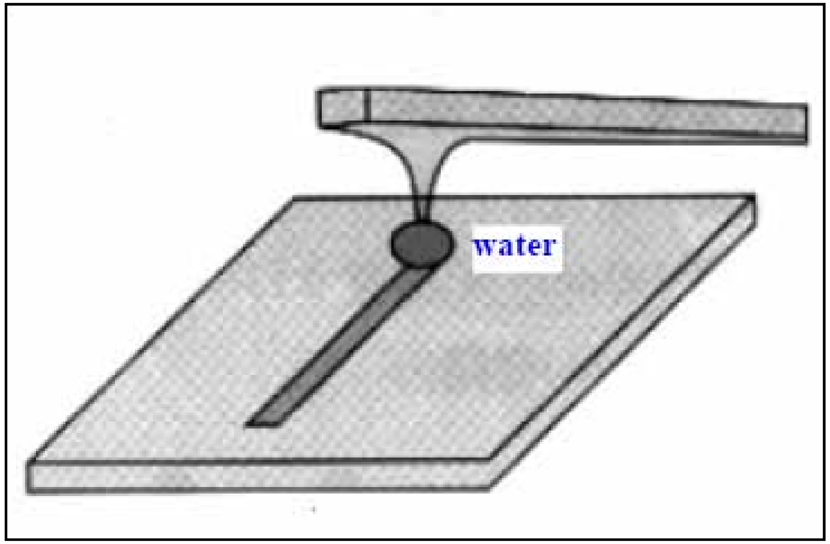



**Fuente sincrotrón de rayos X**

## NANO-LITOGRAFIA DIP PEN (BASADO EN AFM)

**Equipos disponibles :** AFM

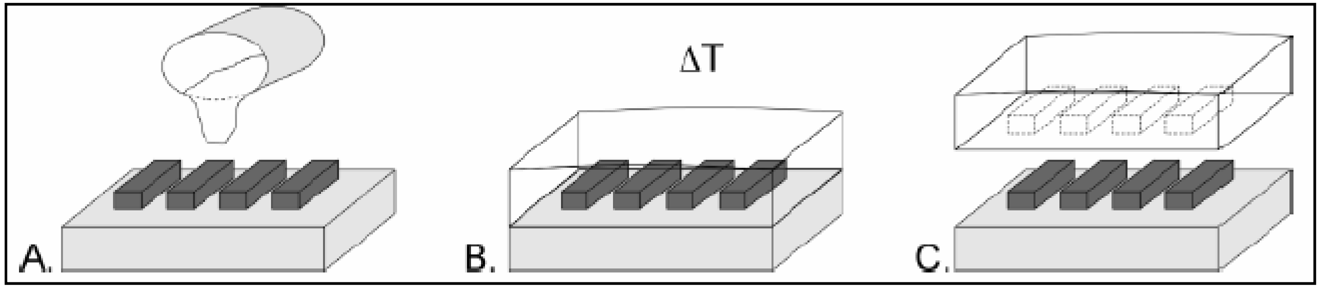


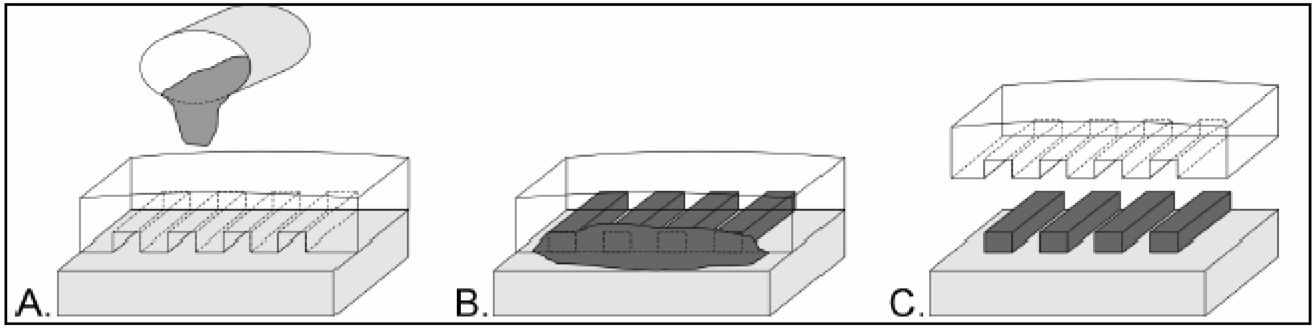

Las líneas son la “tinta” molecular

# LITOGRAFIA POR NANO-IMPRESION

## Pasos experimentales de un proceso de nano-impresión

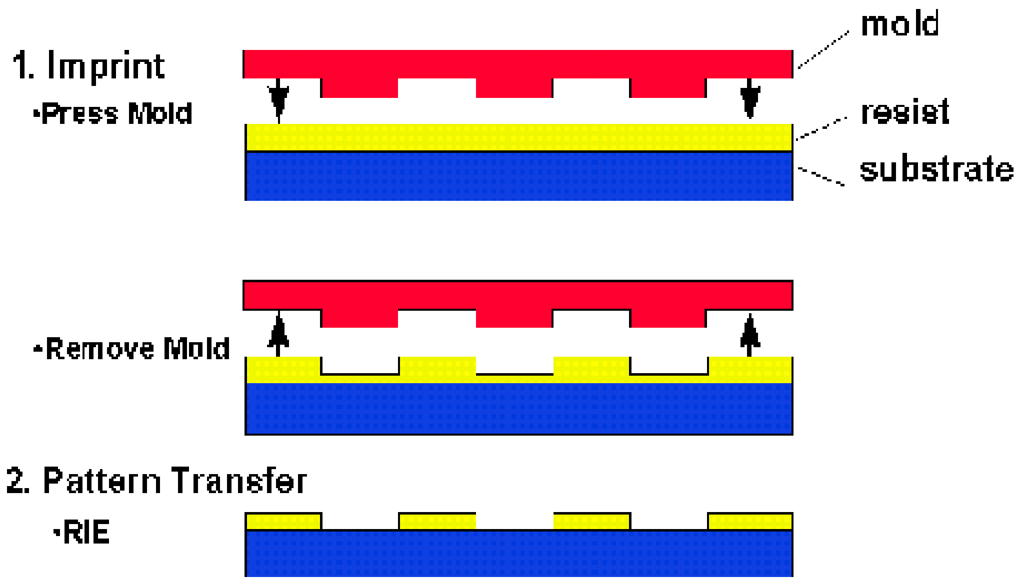



Preparación de la estampa

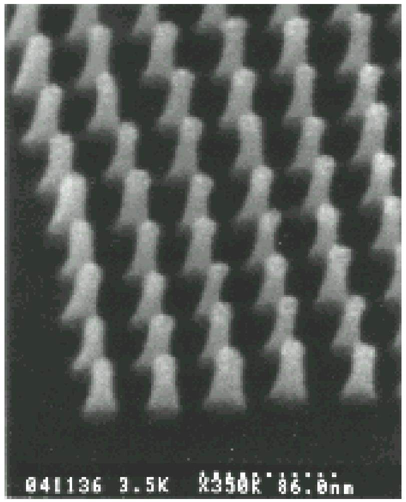



Impresión de patrones vía modo-estampa pre-diseñado

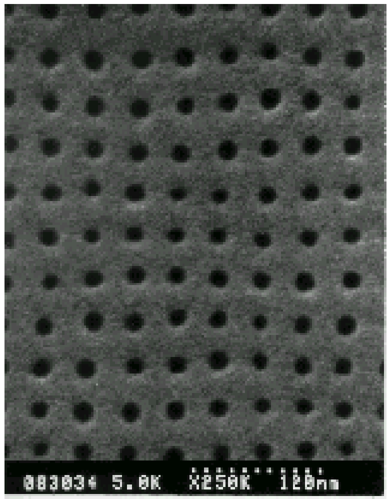
# Nano-printing technology



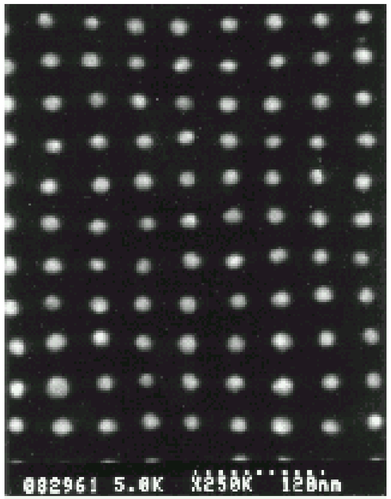

- Si Stamp by e-beam lithography
- Polydimethylsiloxan (PDMS) star
- OR add “ink” containing thiol mol
- print on Si/ Au demosnstrated
- Structured SAM on Si/ Au (50 nm
- Resolution depends on stamp and ink



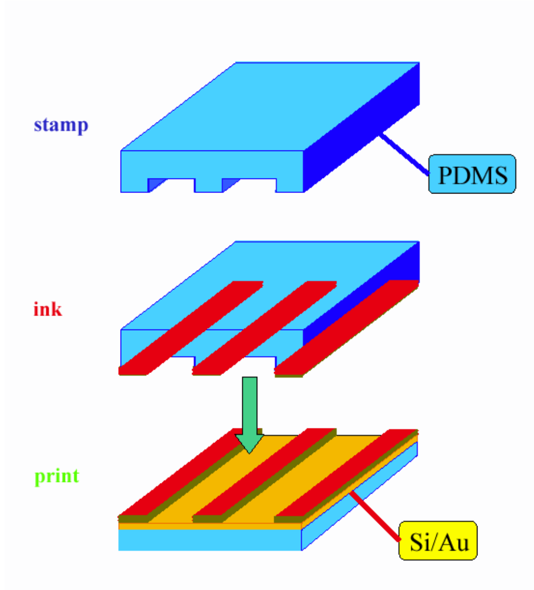
Imprint mold with 10nm diameter pillars



10nm diameter holes imprinted in PMMA



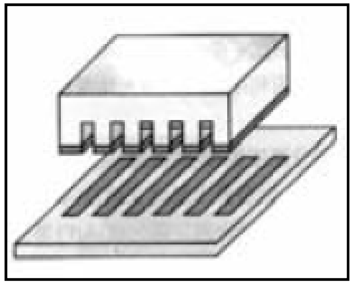
10nm diameter metal dots fabricated by NIL



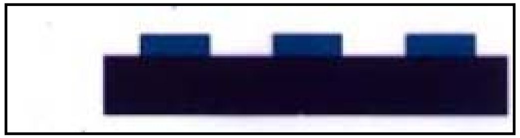

**Chou (Princeton)**

# IMPRESIÓN POR μ-CONTACTO (LITOGRAFIA SUAVE)

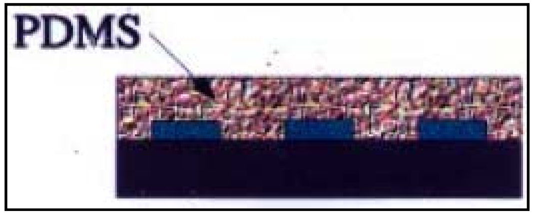
## Ejemplo: por transferencia molecular



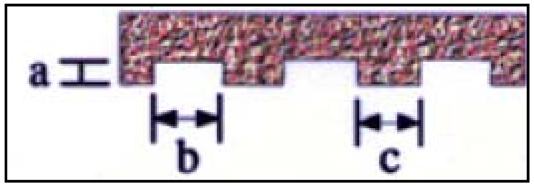
### Preparación de la estampa



Producción de patrones sobre
el substrato de Si

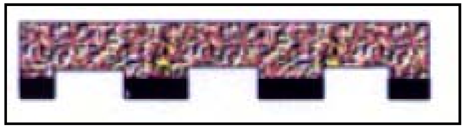



Llenado de PDMS sobre
Los patrones del substrato de Si

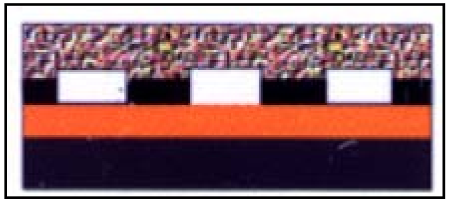



Polimerización, formación
de una estampa

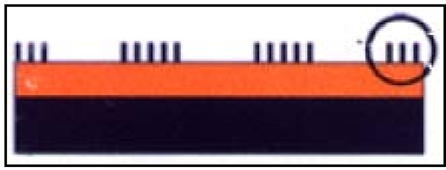
### Estampado molecular



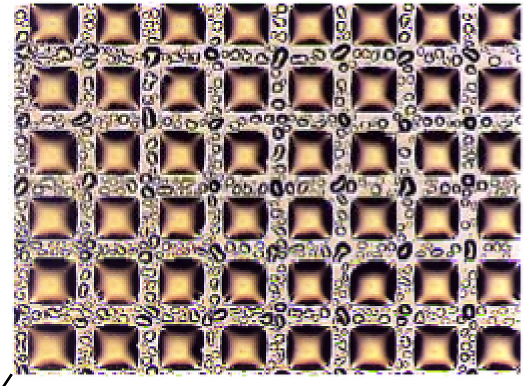
Moléculas incubadas sobre
La estampa



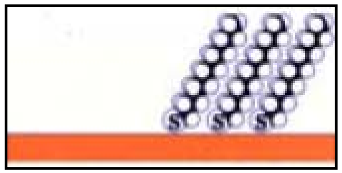
Moléculas estampadas
Sobre el substrato
Cubierto de Au



Las moléculas son
transferidas

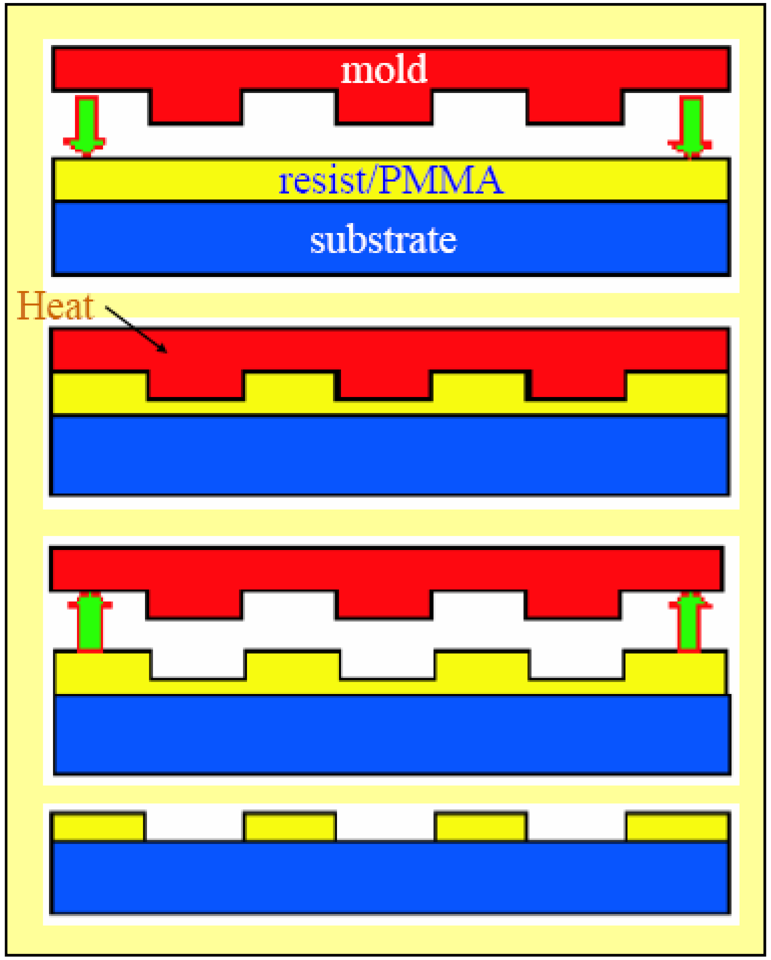


Patrones sobre la
superficie

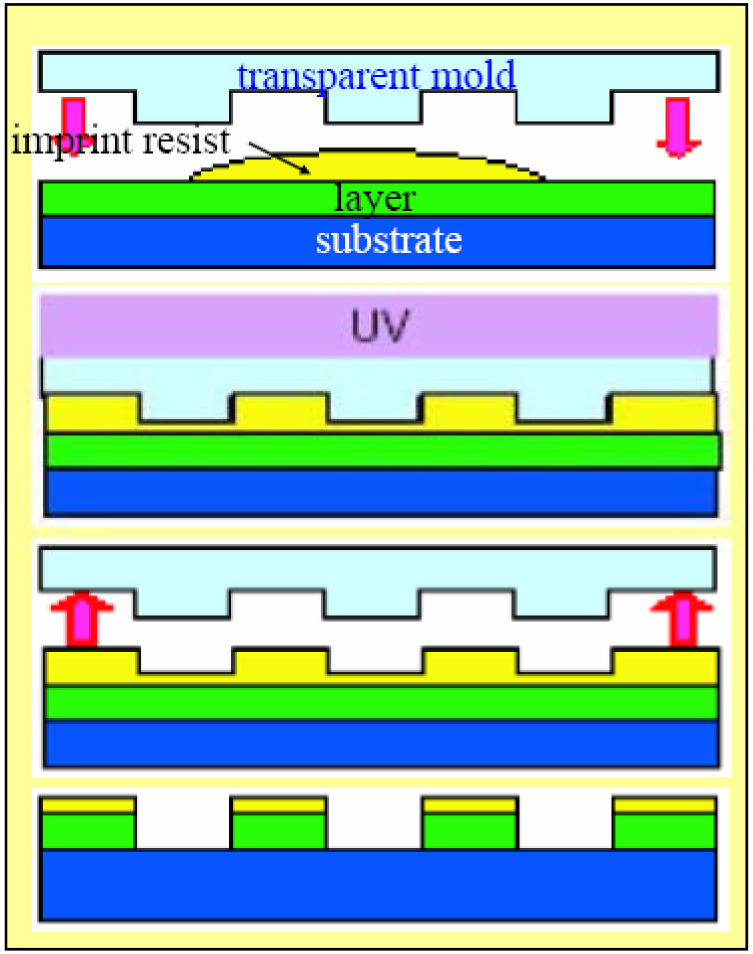


## NIL vs SFIL

### Nano-impresión (NIL)




### Impresión (Step and flash) (NIL)



## NANO-IMPRESOR

# HERRAMIENTAS AVANZADAS PARA NANO-IMPRESION

## Technical specifications:
**(for maskless lithography of nano-devices)**

- High resolution
Feature size produced was <6 nm by direct imprinting and < 10 nm by UV curling

- Precision overlay capability
Alignment (~ 10 nm, 3 $\sigma$)

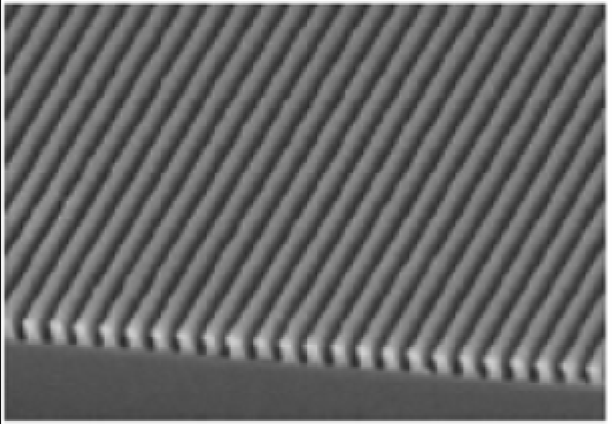
- Wafer handling capability
Up to 300 nm wafers

- Field size
26x32 mm active print area and step move

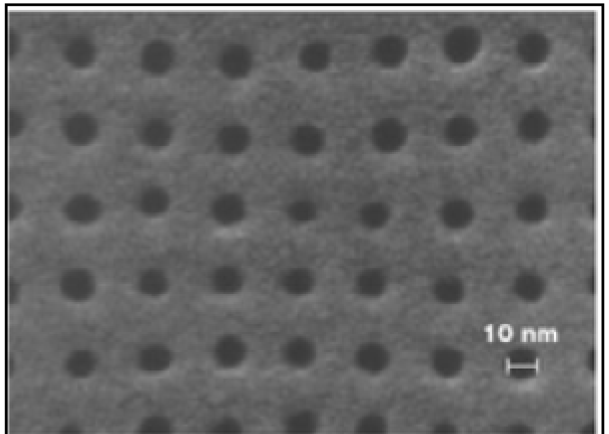
Nanoex/NIX 3000

Molecular imprint_Imprio 250

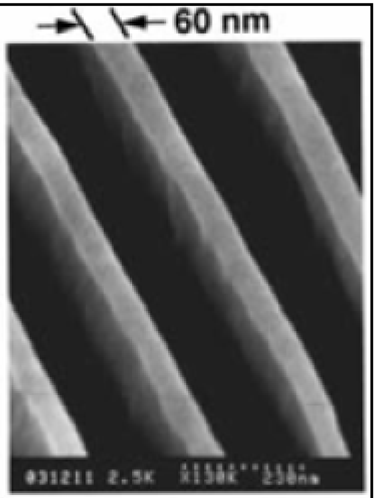
# LITOGRAFIA POR NANO-IMPRESIÓN (EJEMPLOS)



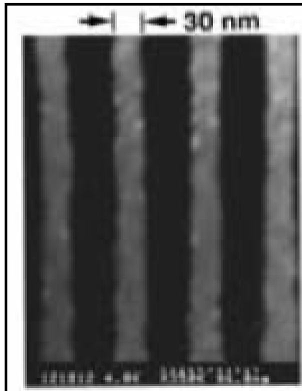
95 nm $SiO_2$ Grating



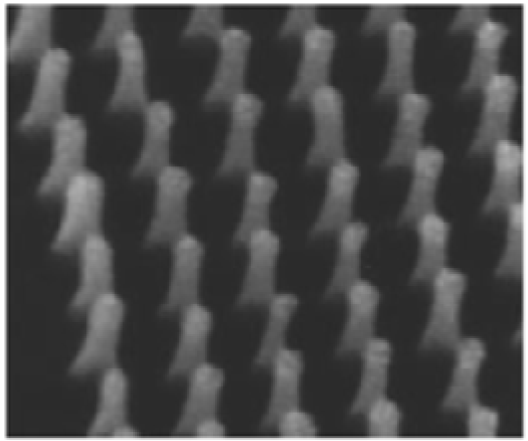

10 nm Hole of PMMA




60 nm PMMA Grating




30 nm Metal Wire



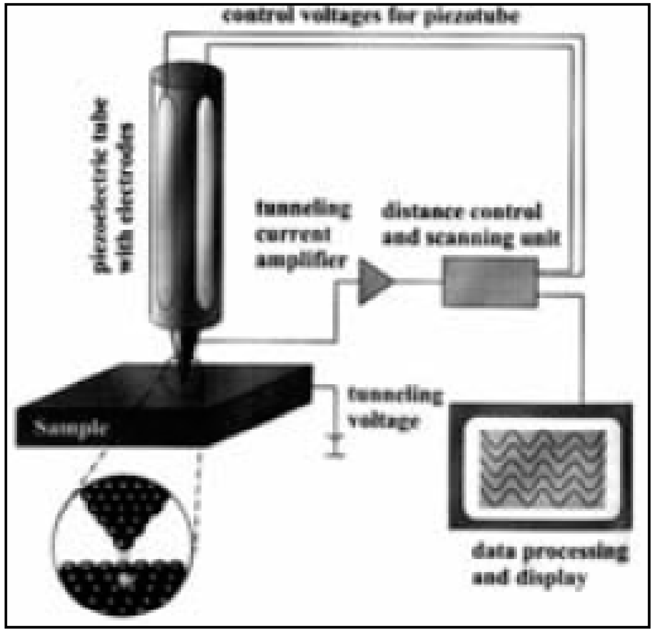
10 nm $SiO_2$ Stamp

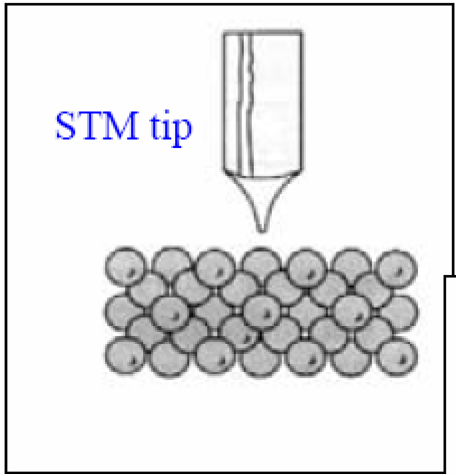
CLASIFICACION DE LAS TECNOLOGIAS DE NANO-IMPRESION

| Technology | Feature | Temperature | Pressure | Mold | Min. feature/pitch |
|---|---|---|---|---|---|
| **Micro(µ)-Contact Printing** | Soft-stamp | ~ RT | 0 ~ 15 psi | PDMS, others … | 60/200 nm |
| **Nano Imprint Lthography (NIL)** | Hot embossing (thermal) | 100 – 300 °C | 0-4 Mpa (0-600 psi) | Si, metal, others … | 6/40 nm |
| **Step-&-Flash Imprint Lithograpy (SFIL)** | UV expossure | ~ RT | 1 ~ 15 psi | Quartz, 7740 … | 10/50 nm |

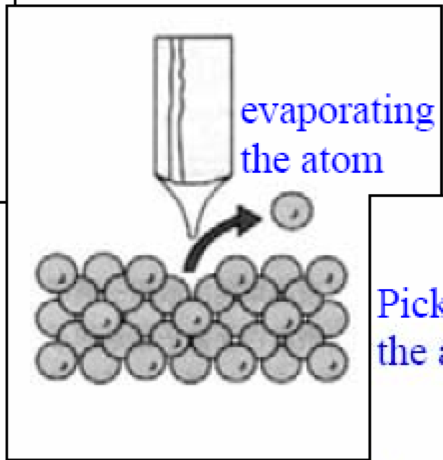
# NANO-MANIPULACION

# NANO-MANIPULACION USANDO STM/AFM

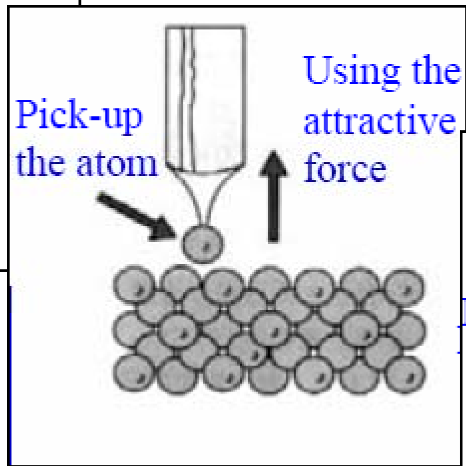



Gran campo E entre la punta y el substrato

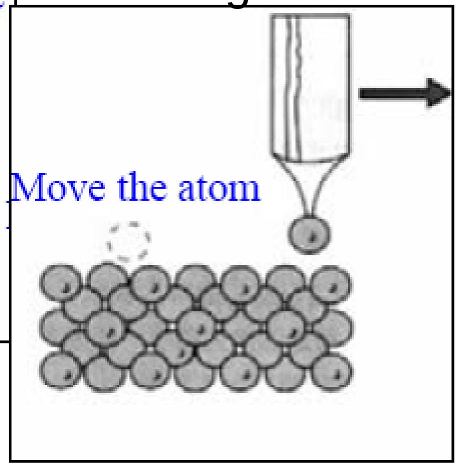



El campo E estimula la evaporación de la superficie atómica



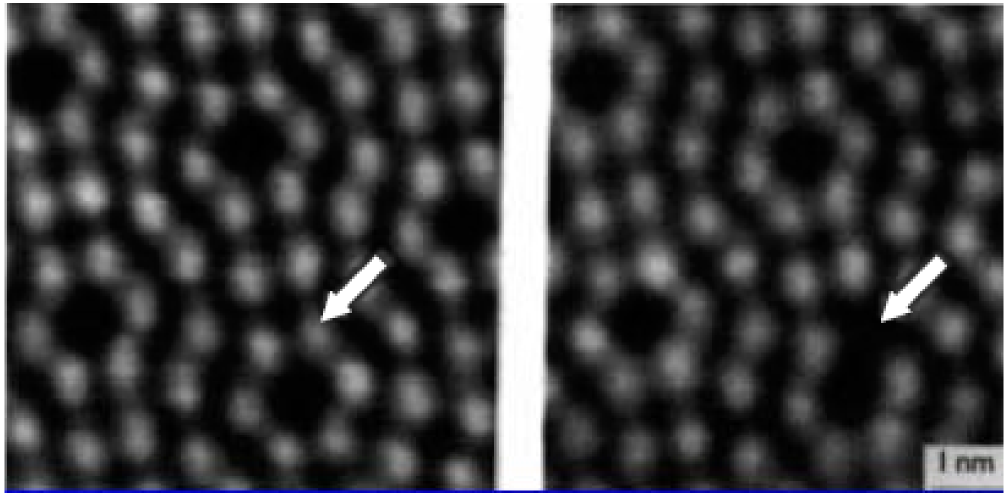

Captura de un Átomo usando la punta

Movimiento del átomo a otros lugares

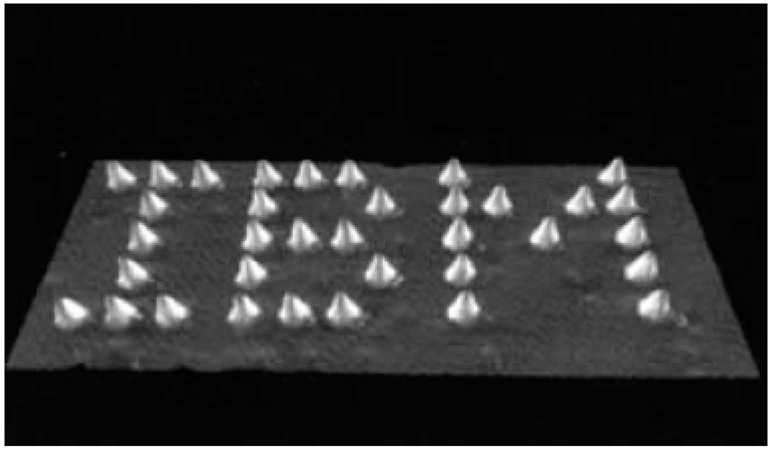


# NANO-MANIPULACION

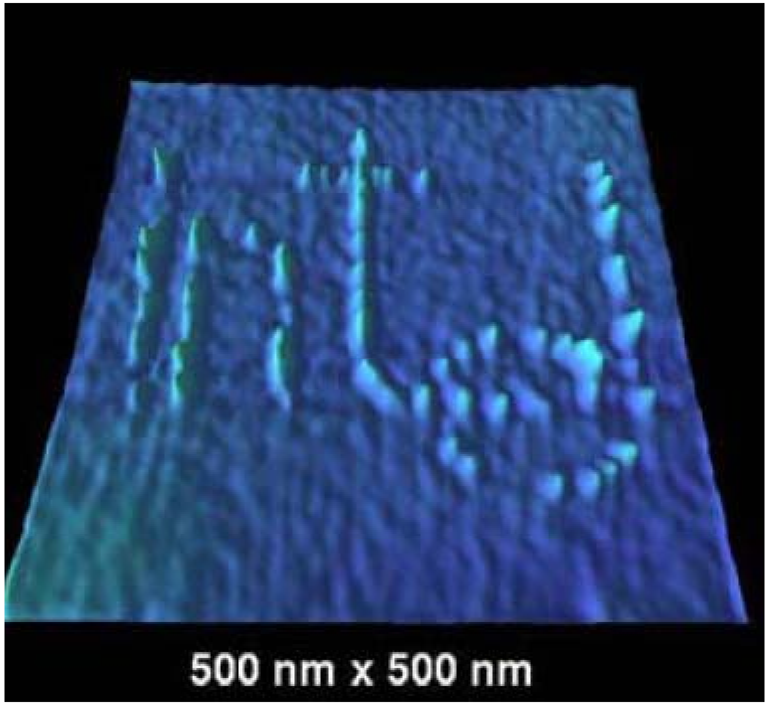
## Ejemplo: Manipulación de átomos usando STM/AFM




Remoción de un único átomo



Logotipo de IBM hecho por átomos de xenón



# Growth Techniques

**CRECIMIENTO CRSITALINO A NANO-ESCALA**

**TECNICAS DE CRECIMIENTO**

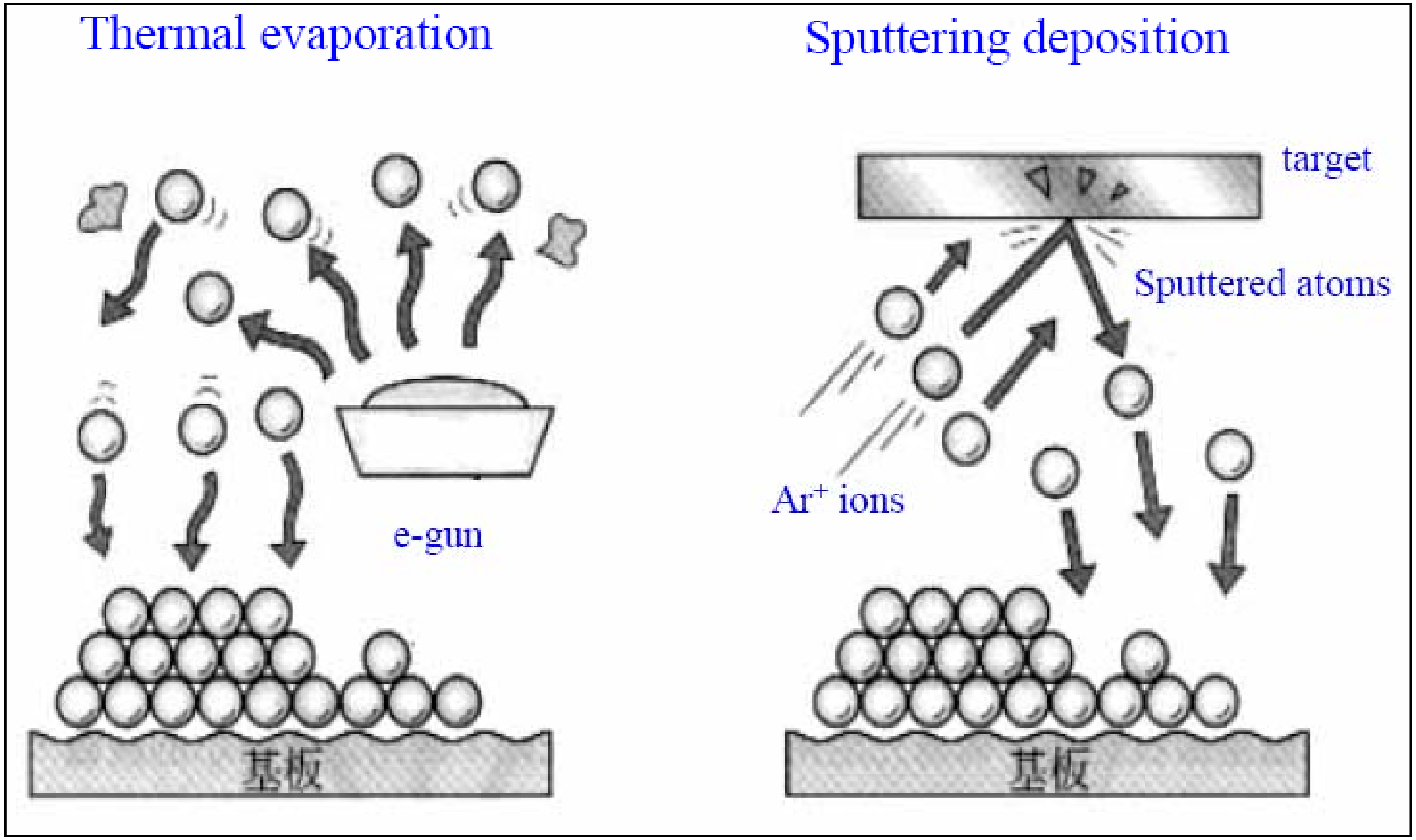
✓Physical Vapor Deposition (PVD)
✓ Molecular Beamn Epitaxy (MBE)

✓Chemical Vapor Deposition (CVD)
✓ Atomic Layer Epitaxy

✓Crecimiento en la fase liquida

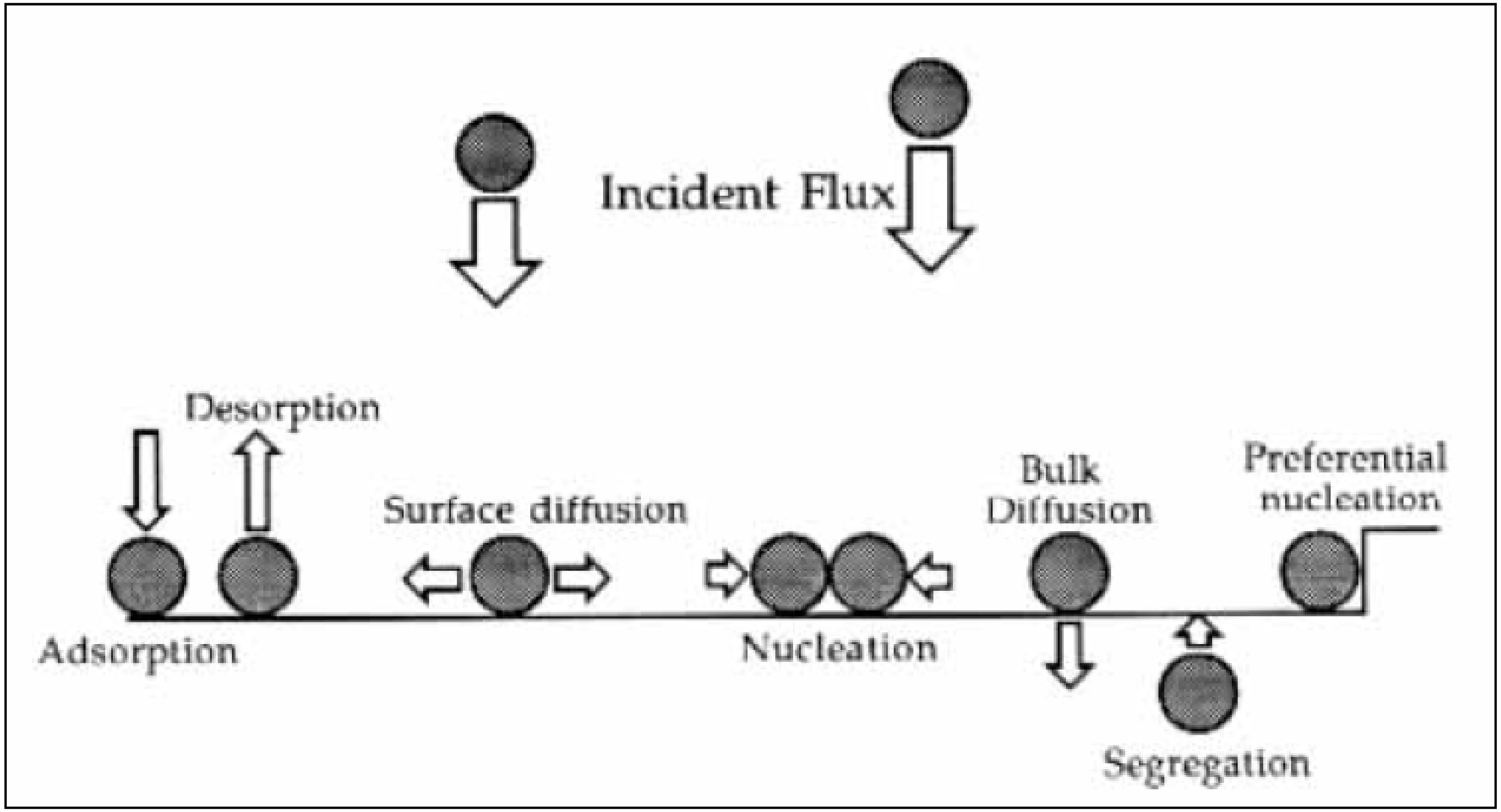
**PHYSICAL VAPOR DEPOSITION (PVD)**

**Generación de flujos atómico/molecular por procesos físicos**



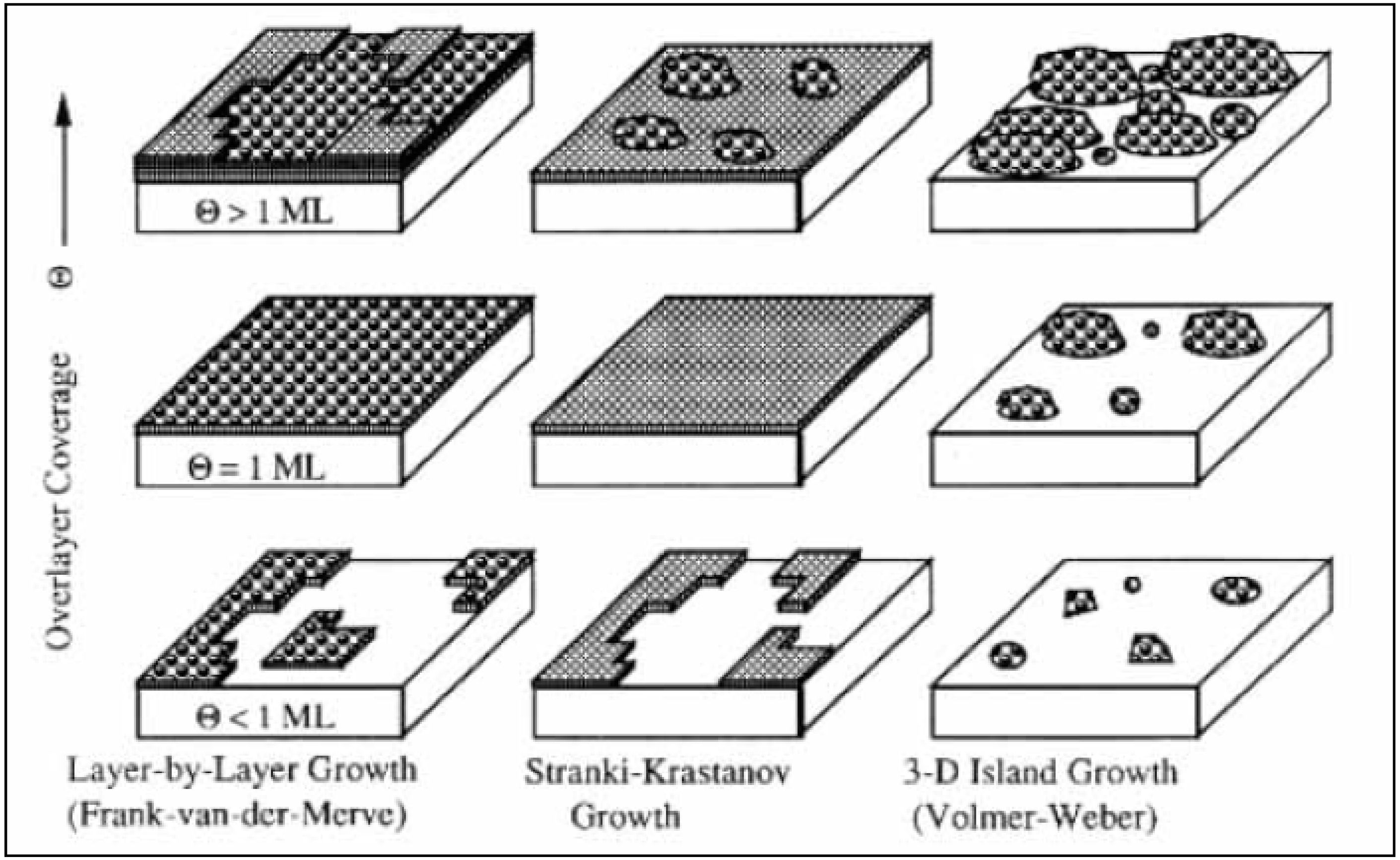
## PROCESOS SUPERFICIALES

## Cuando los átomos/moléculas arriban a la superficie

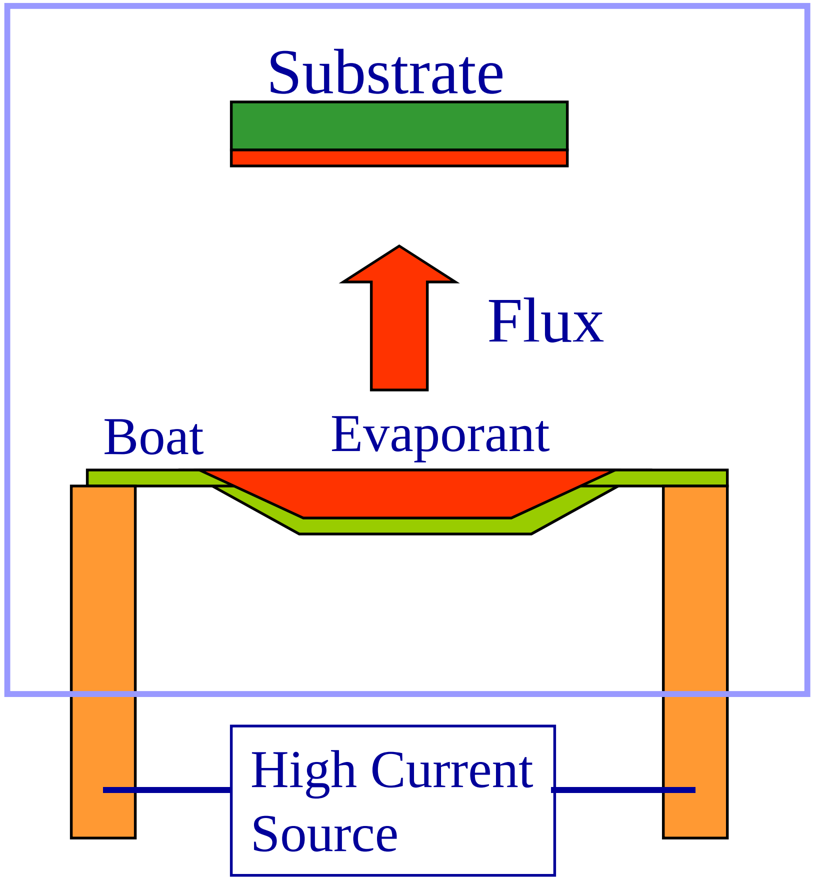


# MODOS DE CRECIMIENTO

## Tres caminos diferentes para poder crecer capas atomicas

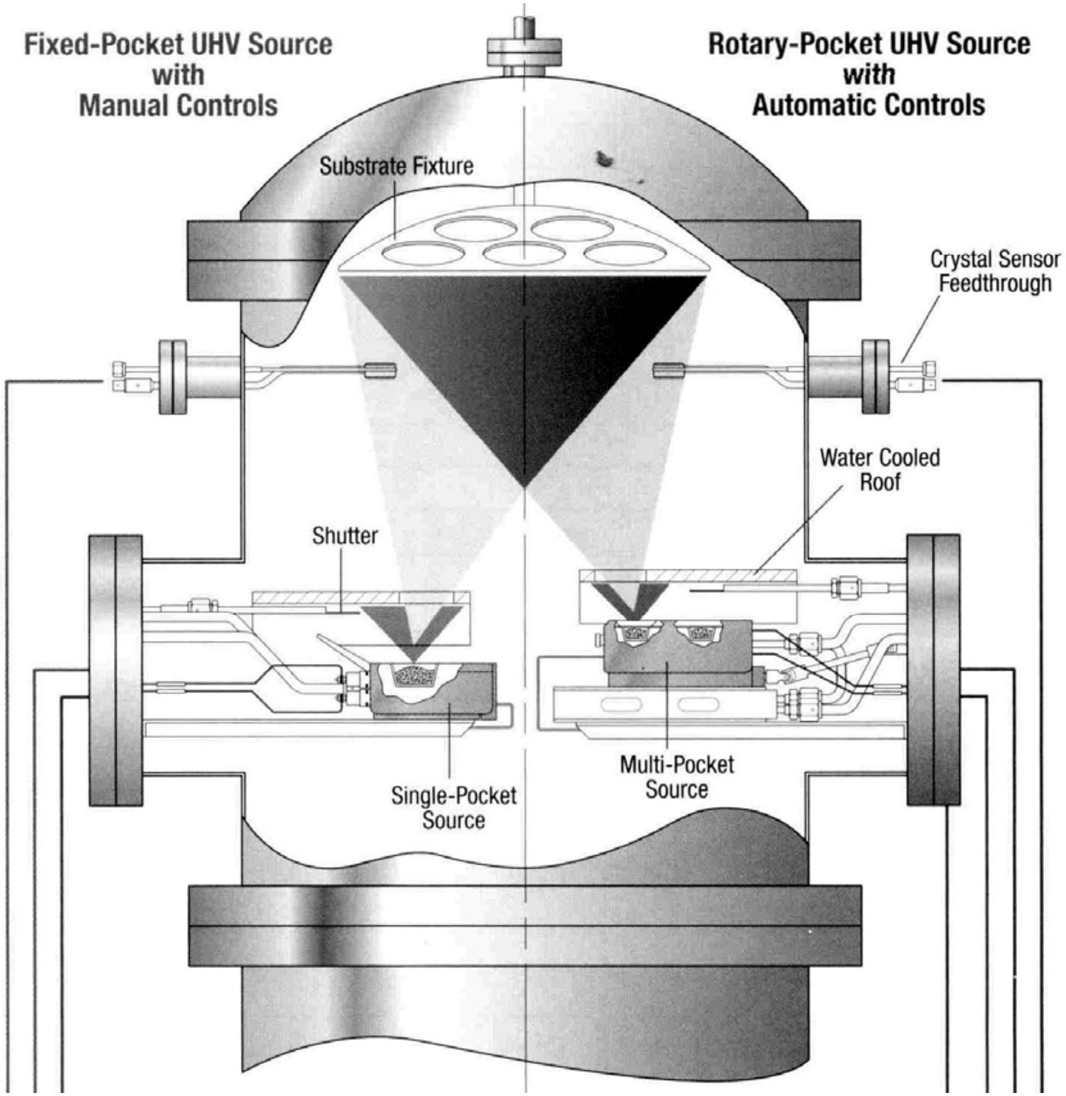


# Physical Evaporation

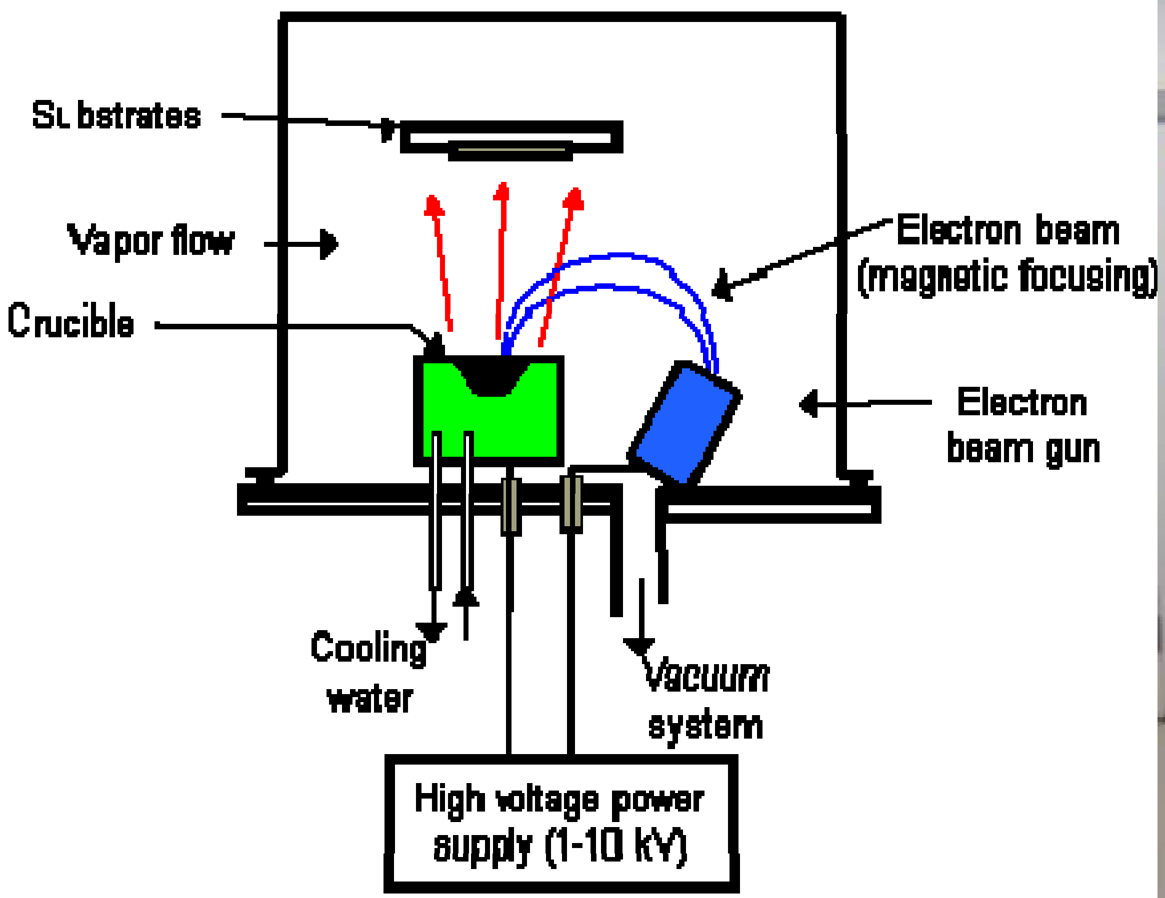



- A current, I, is passed through the boat to heat it.
- The heating power is $I^2R$, where R is the electrical resistance of the boat (typically a few ohms).
- For boats made of refractory metals (W, Mo, or Ta) temperatures exceeding 2000º C can be achieved.
- Materials which alloy with the boat material cannot be evaporated using this method.

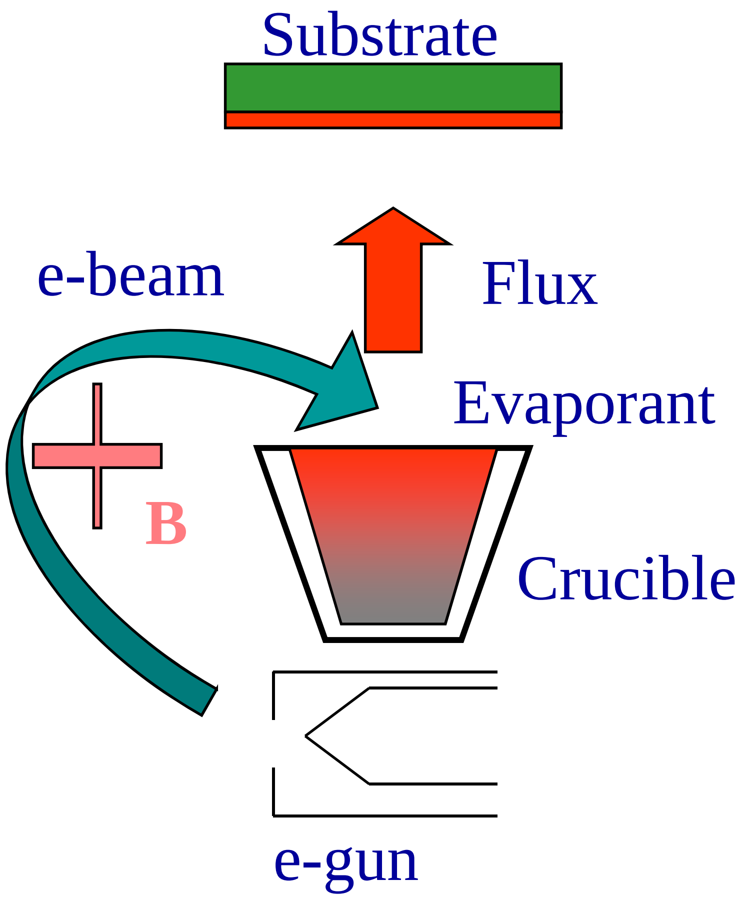
# E-beam Evaporation



# E-beam Evaporation of Thin films

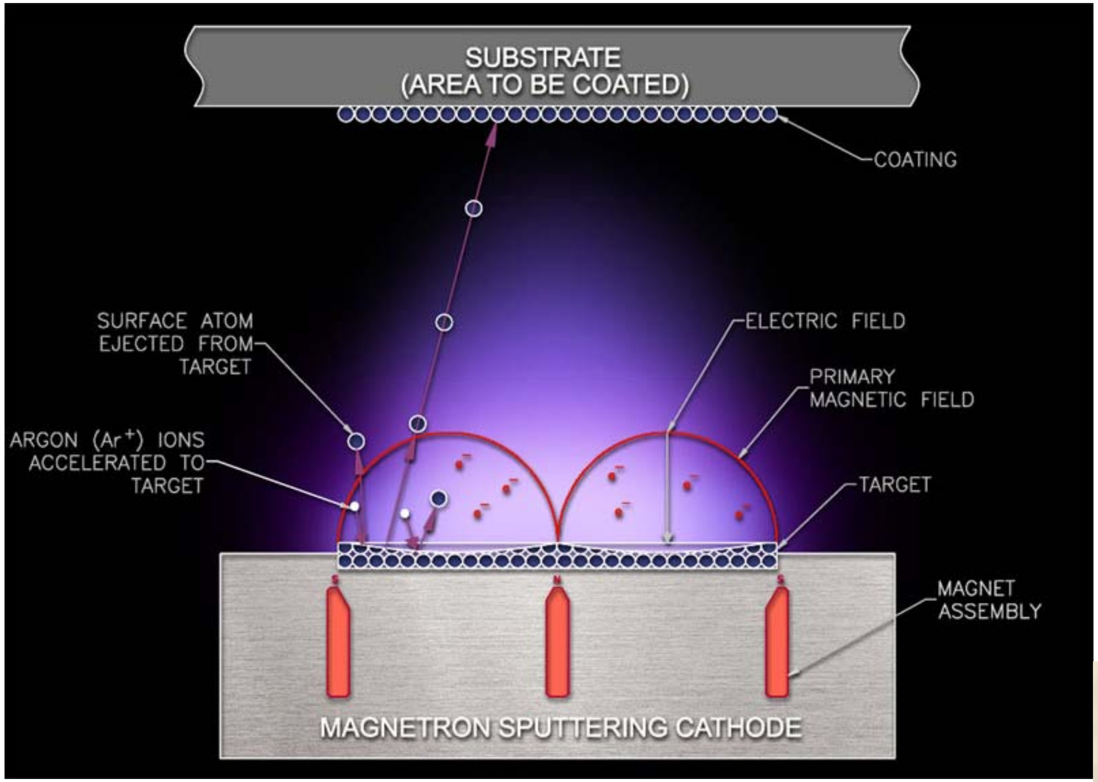



# Electron Beam Evaporator

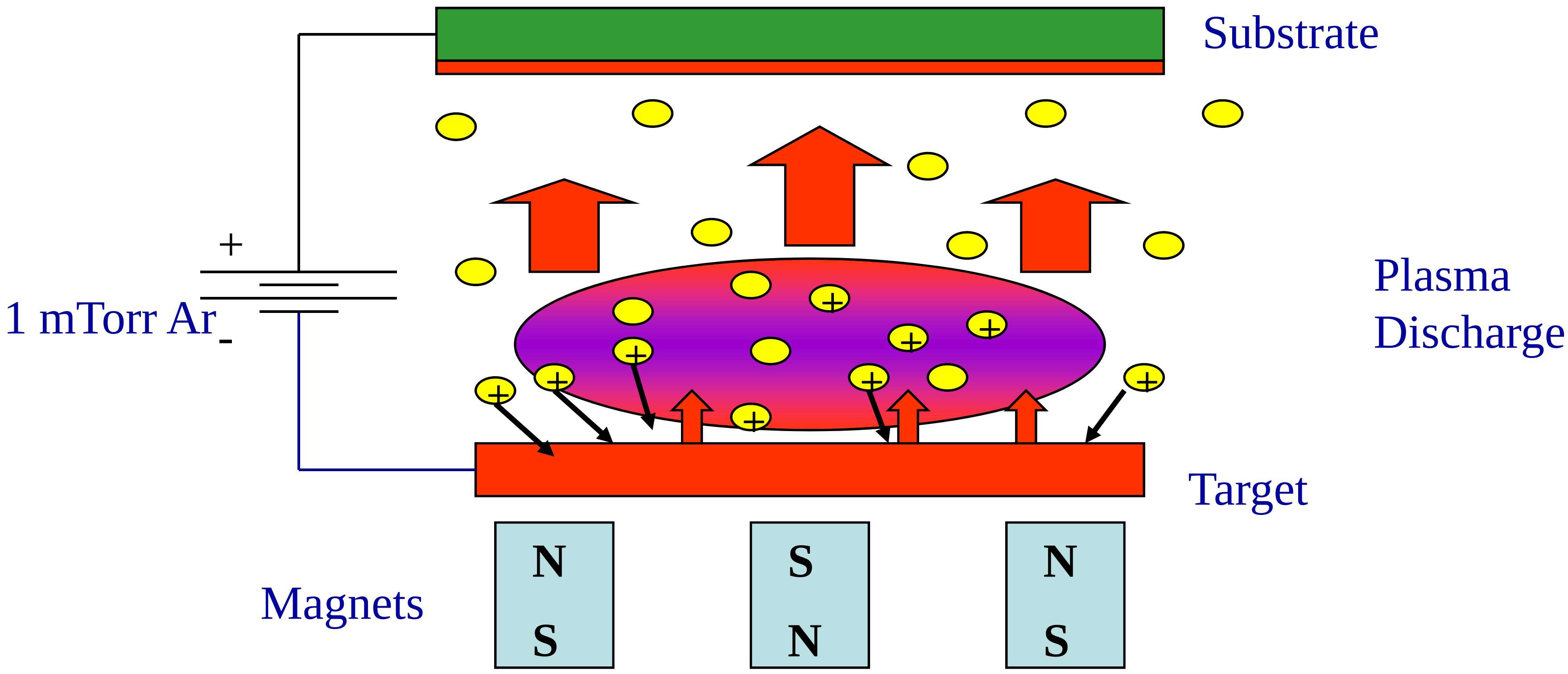



- The e-gun produces a beam of electrons with 15 keV kinetic energy and at a variable current of up to 100 mA.
- The electron beam is deflected 270$^o$ by a magnetic field, B.
- The heating power delivered to a small (~5mm) spot in the evaporant is 15 kV x 100 mA = 1.5 kW.
- The power is sufficient to heat most materials to over 1000 $^o$C.
- Heating power is adjusted by controlling the electron current.

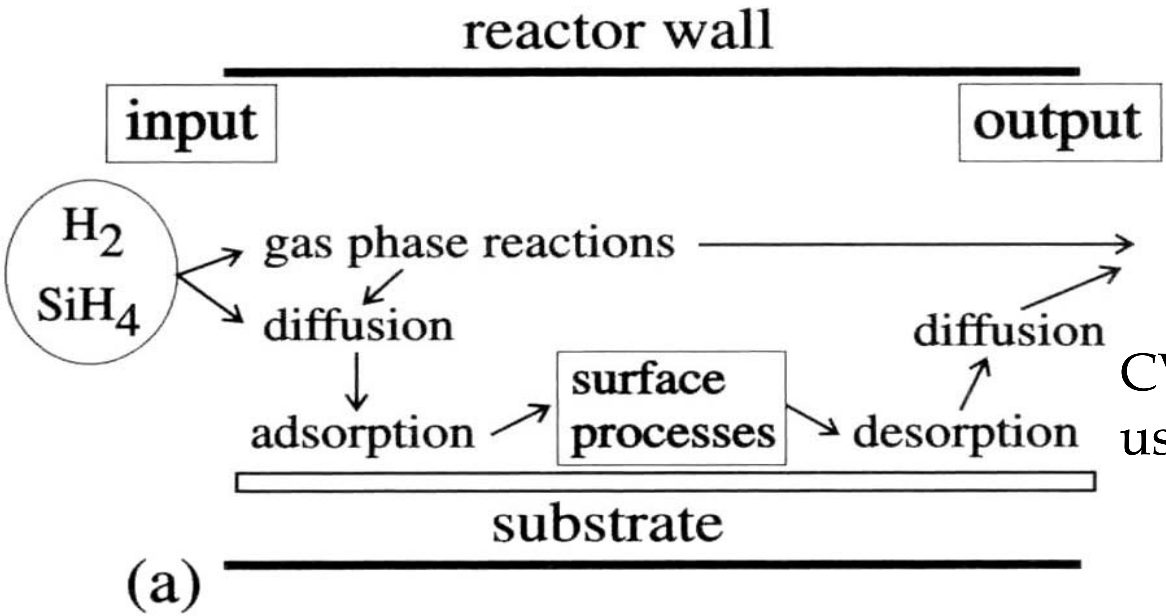
# Sputtering of Thin films




# The Sputtering Process

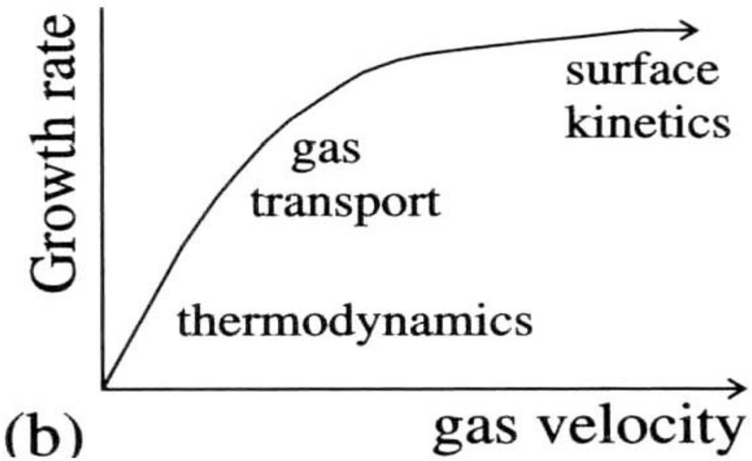


# CVD Reactor




**CVD = Chemical Vapor Deposition**

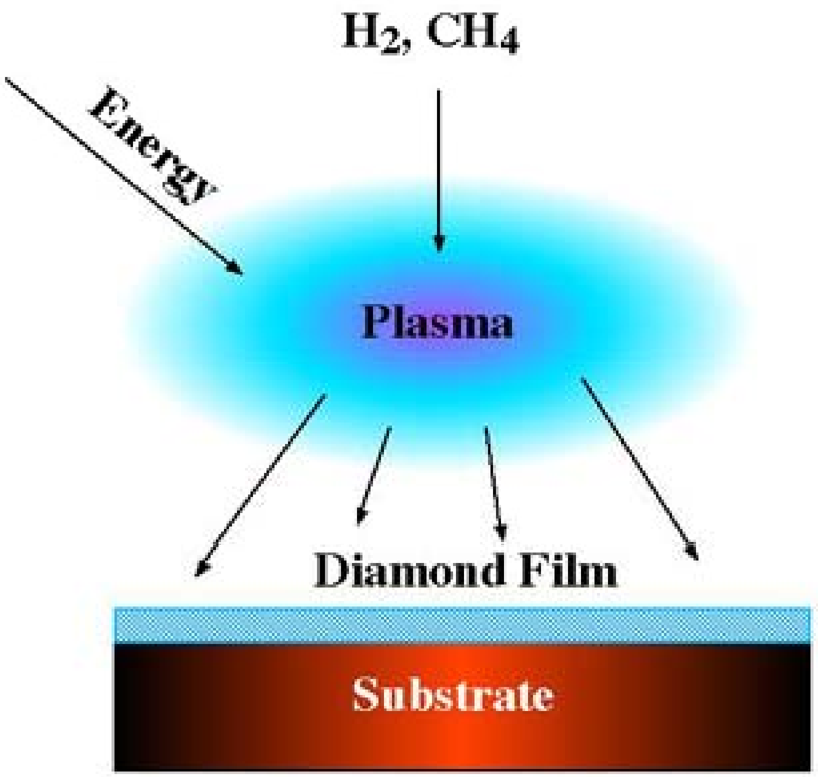
CVD reactions for Si growth using silane ($SiH_4$) and $H_2$.

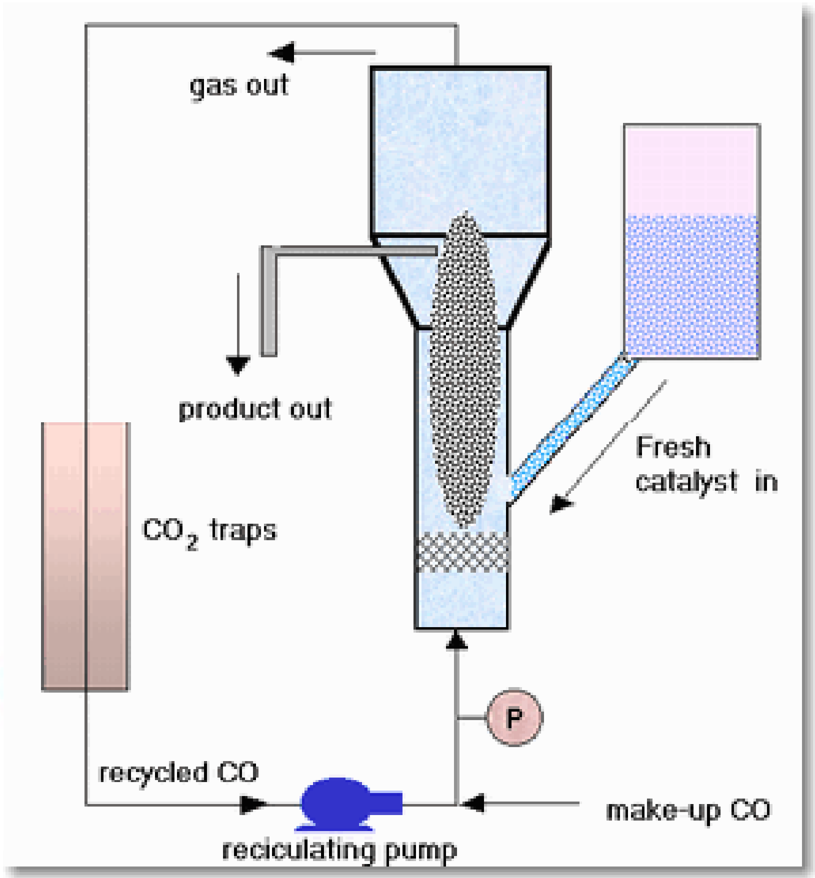



Growth rate vs. gas velocity with rate limiting steps given.

# Chemical Vapor Deposition (CVD) of Amorphous Thin Films

Chemical Vapor Deposition is chemical reactions which transform gaseous molecules , called precursor, into a solid material , in the form of thin film or powder, on the surface of a substrate
The process is widely used to fabricate semiconductor devices.



<u>EQUIPOS CVD</u>

DISTINTAS TECNICAS CVD

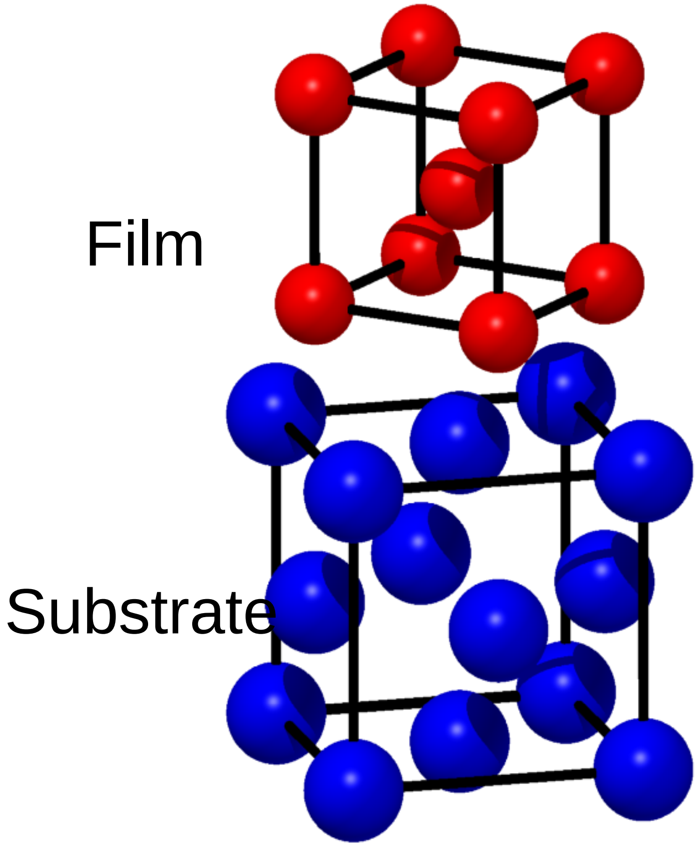
- CVD a presión atmosférica (APCVD)
- CVD a baja presión
- UHV-LPCVD
- Plasma Enhanced CVD (PECVD)
- Metal-Organic CVD (MOCVD)

Close view of wafer loading boat into the furnace

EMCORE D180 MOCVD system

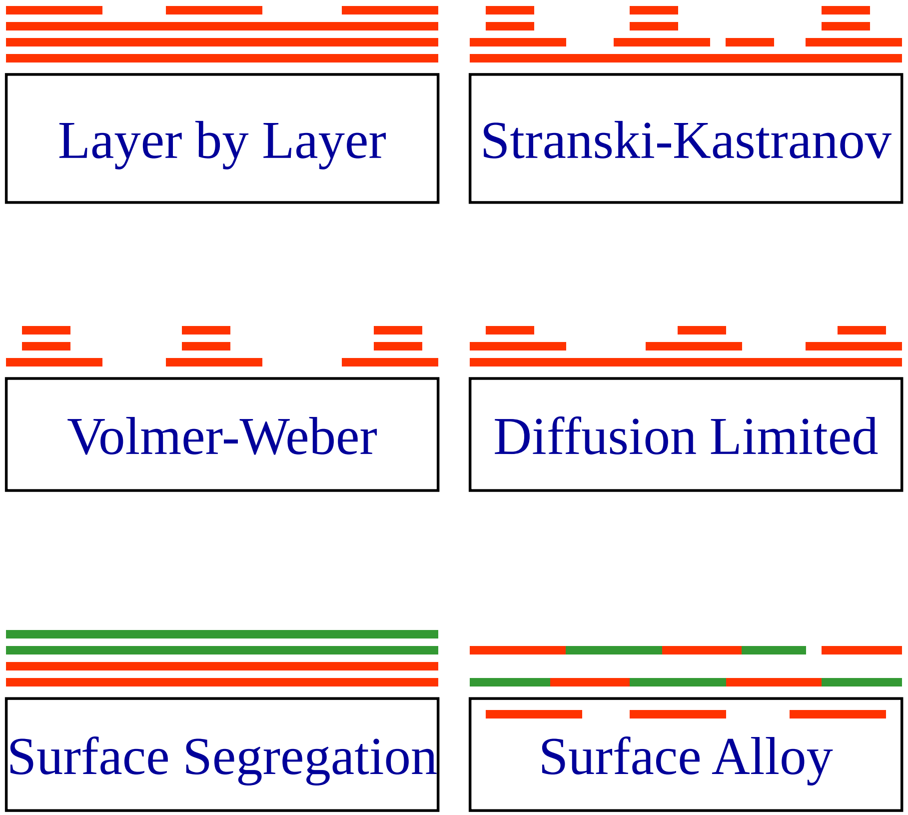
View of Reactor during the growth

# Epitaxial Growth




- Epi-Taxi (*greek)*
epi meaning “on”
taxi meaning “arrangement in relation to a source of stimulation”
- The crystal structure of the film has a direct relationship to that of the substrate

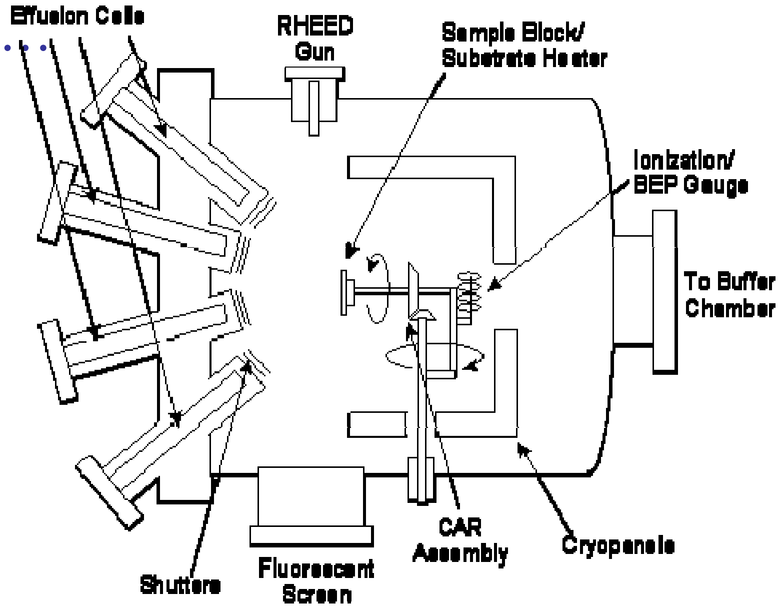
# Growth Modes for Ultrathin Films




- The growing film surface can exhibit different behaviors depending on substrate temperature, interfacial strain, and alloy miscibility.
- The growth modes must be characterized using a combination of chemical tools such as Auger electron spectroscopy and structural tools such as RHEED and atomic force microscopy.

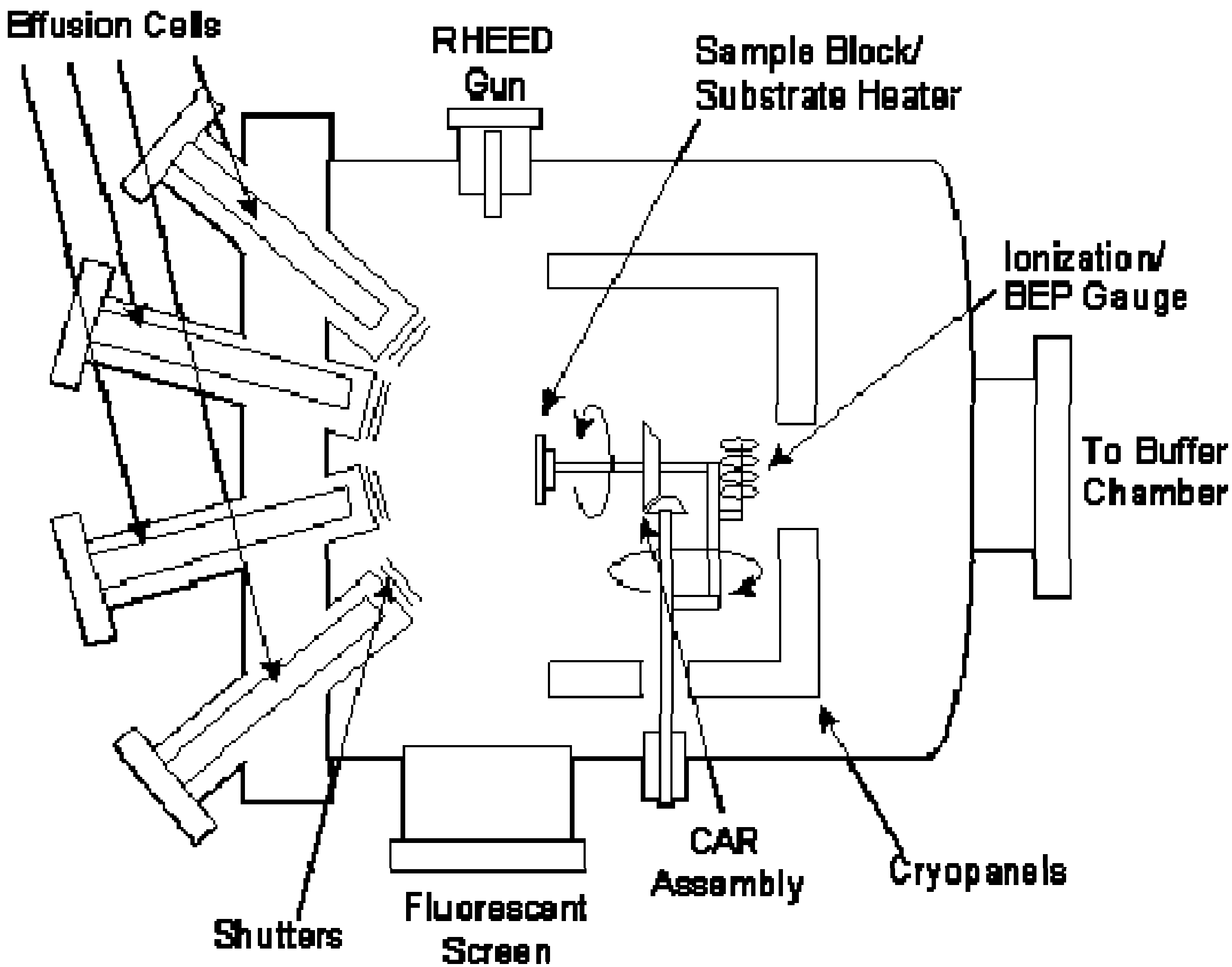
# Molecular Beam Epitaxy-1

- Molecular beam:  how to get atoms to surface: sources are heated
- Epitaxy:  follow crystal pattern in next layers….
- "Single crystal films"
- Real time feedback from REED
- Reflection high-Energy Electron Diffraction
- UHV chambers ($10^{-10}$ Torr)
- Semiconductors: Si, GaAs, …
- Metals: Nb, …
- Complex oxides: YBaCuO….
- Lattice matching to a single crystal substrate the most important aspect



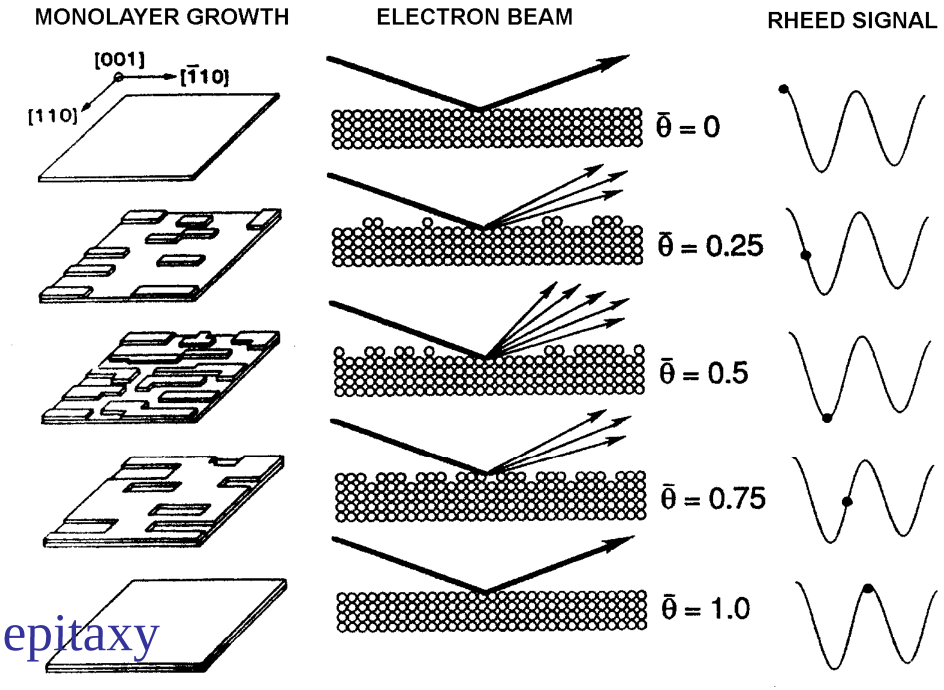

http://www.ece.utexas.edu/projects/ece/mrc/groups/street_mbe/mbechapter.html

# Molecular Beam Epitaxy-2

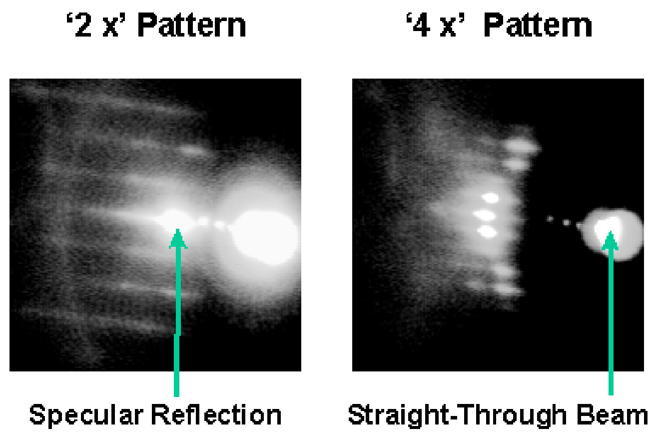


# Molecular Beam Epitaxy II

- Real time feedback from REED
- Reflection high-Energy Electron Diffraction
- REED oscillation
- Layer-by-layer interference
- Also in-plane interference if there is epitaxy
- Quantity & thickness monitored

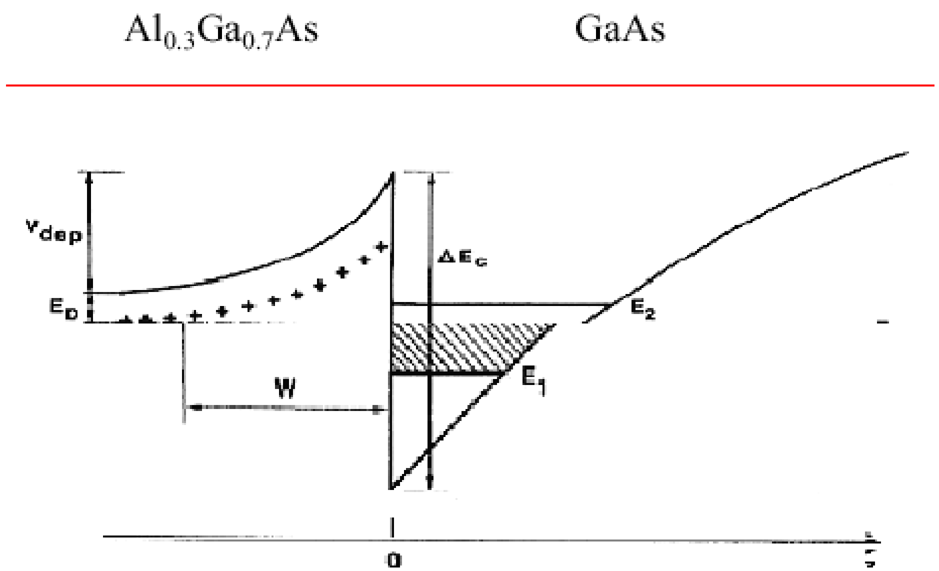


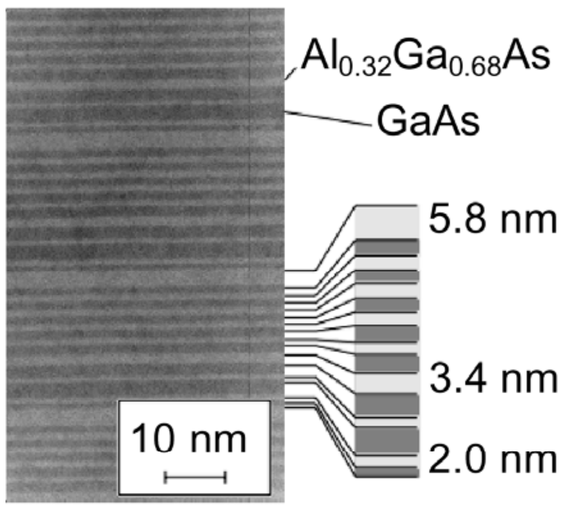

- Images on the RHEED screen with the electron beam pointed along the [011] (2 x) and [ ] (4 x) directions on an As-terminated GaAs surface at 600°C



# Molecular Beam Epitaxy-3

- MBE growth of GaAs/AlGaAs hetrostructures
- Interfaces between semiconductors create two-dimensional electron states
- Modulated doping: dopant put far away from the interface
- Very high mobility two-dimensional electron gas---discuss in detail later



# MOLECULAR BEAM EPITAXY (MBE)

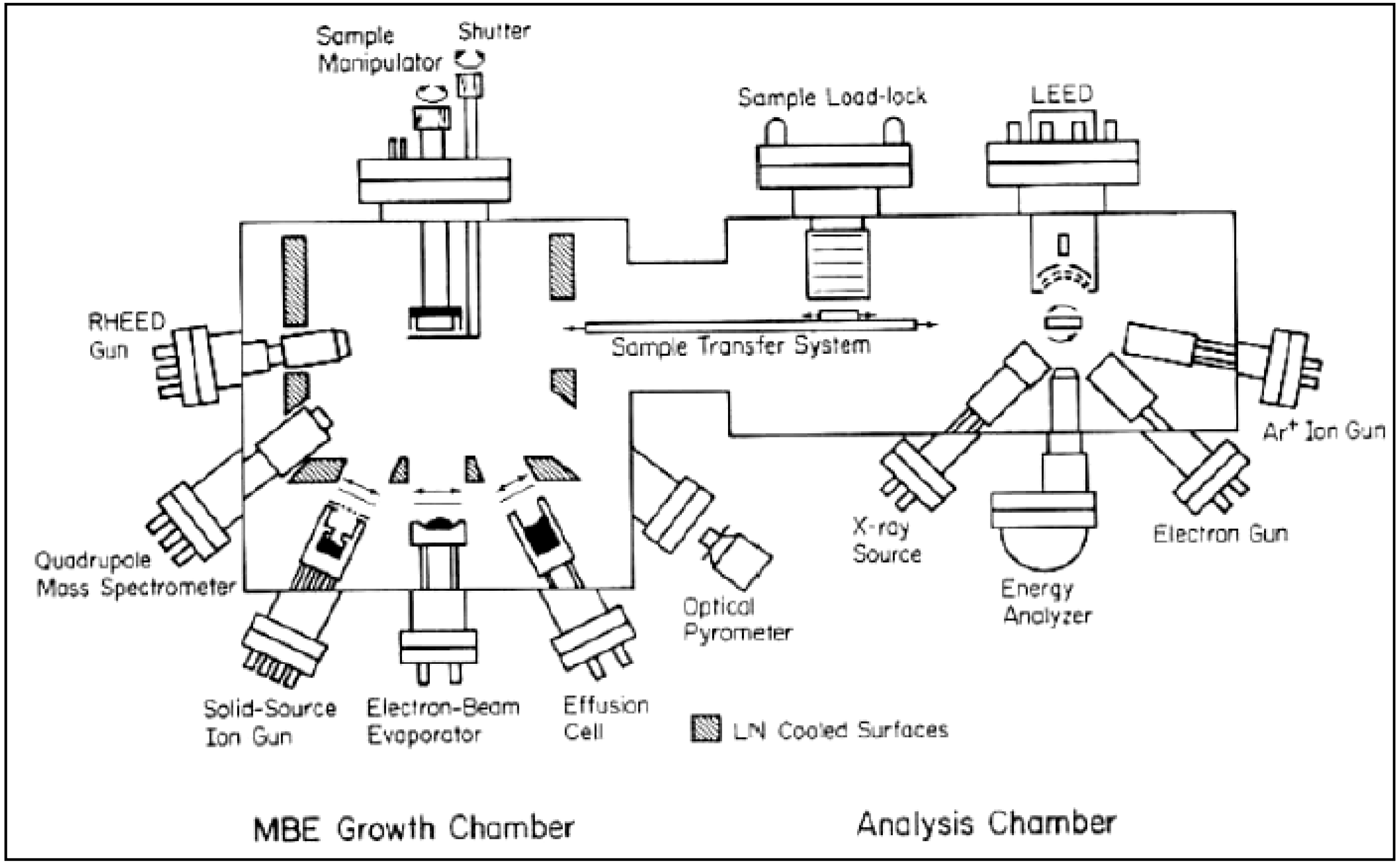
## EQUIPO MBE

VGV-80

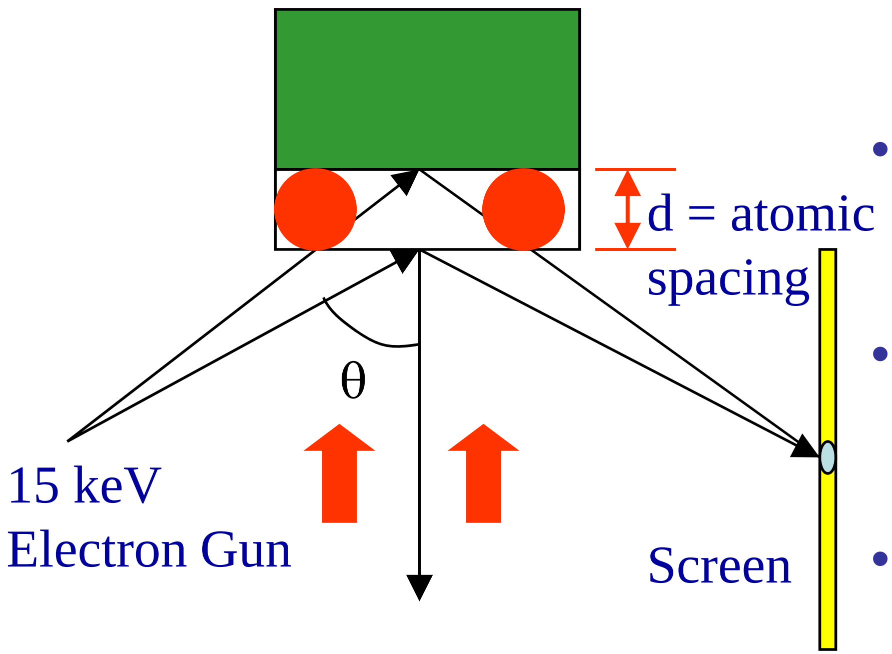
BALZERS UMS-630

# MOLECULAR BEAM EPITAXY (MBE)

## Esquema de un equipo de MBE  DE UN EQUIPO MBE



# Reflection High-Energy Electron Diffraction

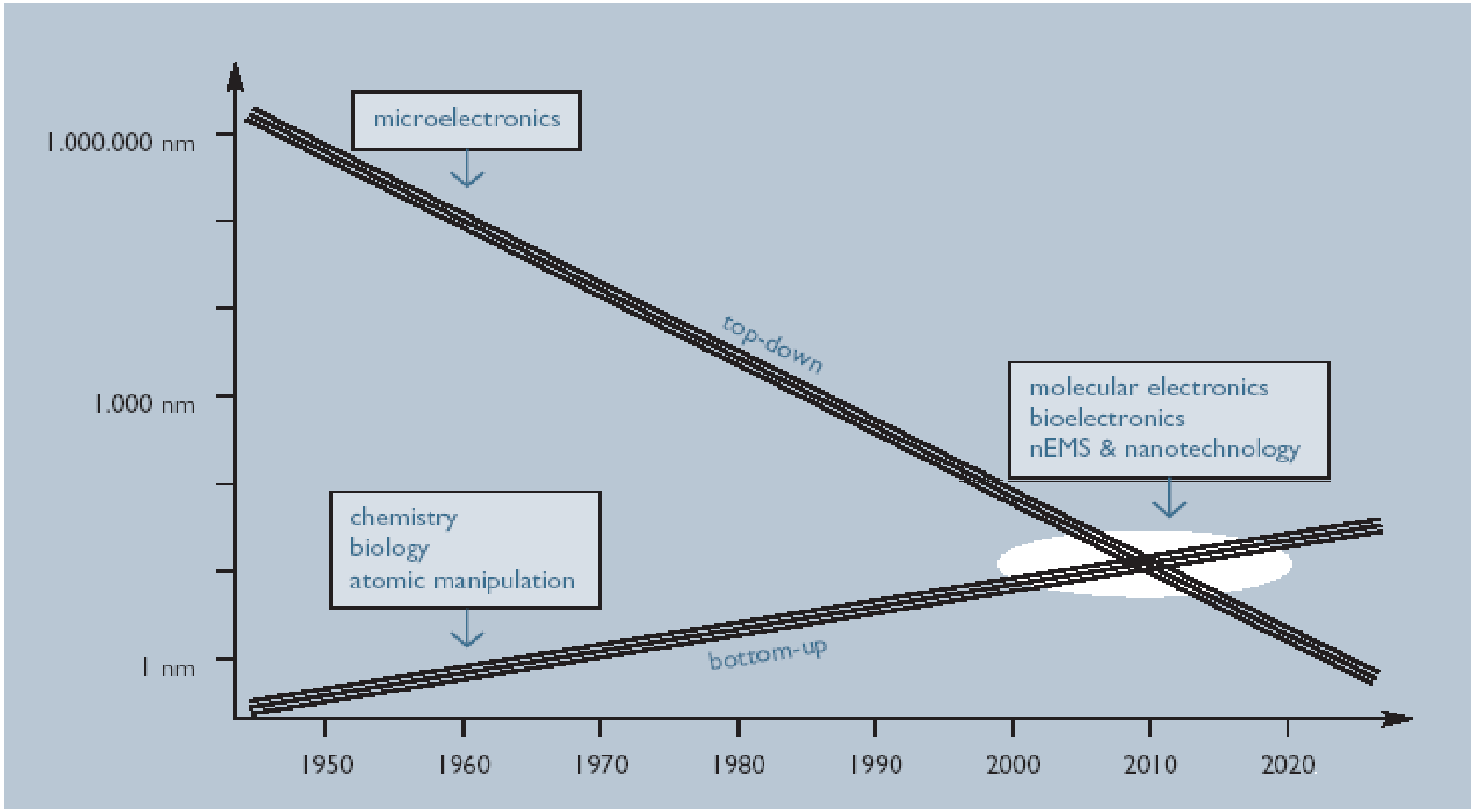



Path difference = $2d\sin\Theta = (n+1/2)\,\lambda$

$\lambda = [150 / E(eV)]^{1/2}$

- 15 keV electrons reflect from the surface and are displayed as a spot on a phosphor screen.
- The angle is adjusted such that electrons reflecting from adjacent layers interfere destructively.
- When only one layer is exposed, the spot is bright.
- When the top layer covers half of the surface, the spot is extinguished.
- The time between two maxima in the intensity plot is the monolayer time.

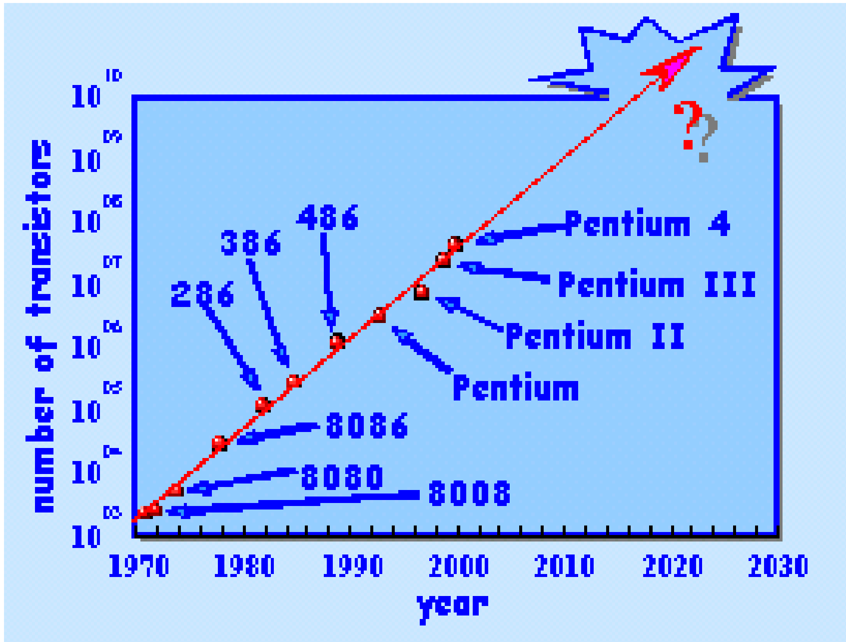
# Future of Top-down and Bottom-Up Processing




http://www.imec.be/wwwinter/business/nanotechnology.pdf

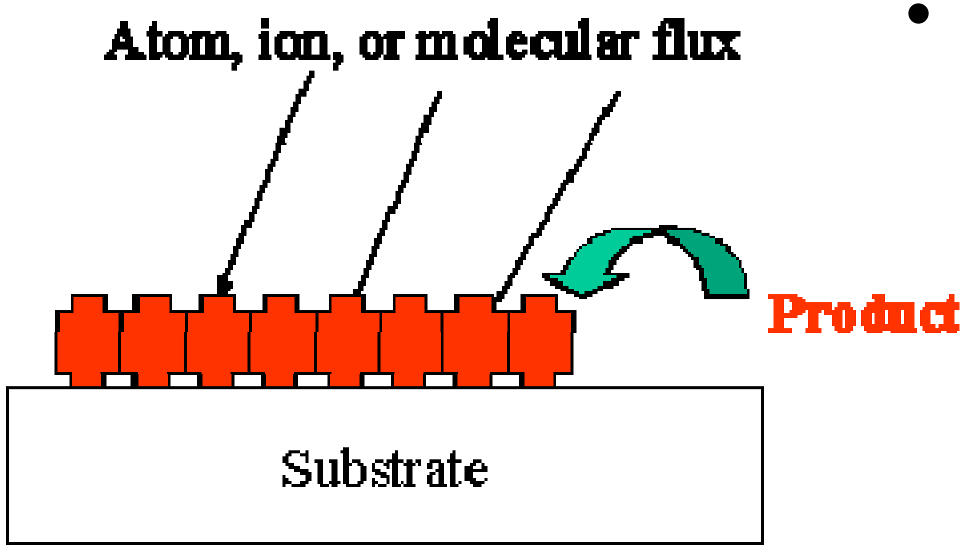
# Problems with the Top-down Process

- Cost of new machines and clean room environments grows exponentially with newer technologies.
- Physical limits of photolithography are becoming a problem.
- With smaller geometries and conventional materials, heat dissipation is a problem.




http://www.cit.gu.edu.au/~s55086/qucomp/gifs/intro.moore1.gif

# Bottom-Up Approach

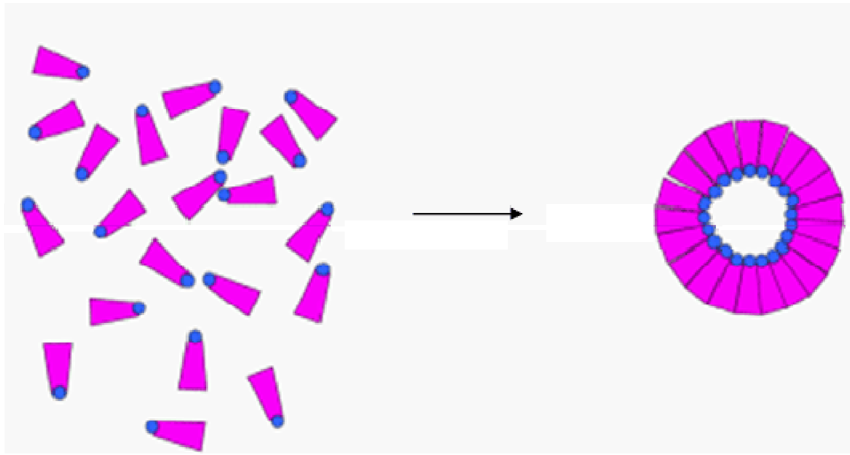



- The opposite of the top-down approach.
- Instead of taking material away to make structures, the bottom-up approach selectively adds atoms to create structures.

http://idol.union.edu/~malekis/ESC24/KoskywebModules/sa_topd.htm

# The Ideas Behind the Bottom-up Approach

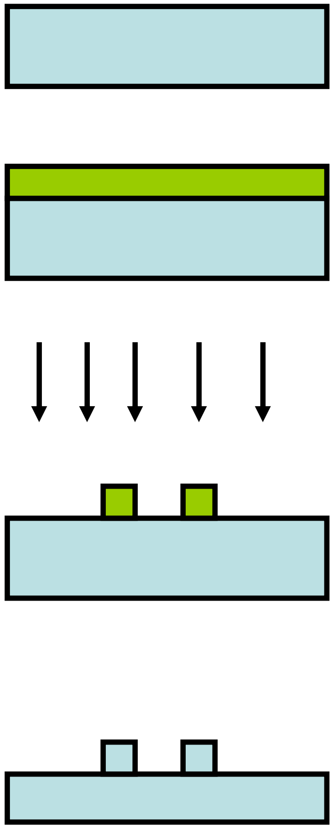
- Nature uses the bottom up approach.
  - Cells
  - Crystals
  - Humans
- Chemistry and biology can help to assemble and control growth.



http://www.csacs.mcgill.ca/selfassembly.htm

# Top-down Versus Bottom-up

## Top Down Process



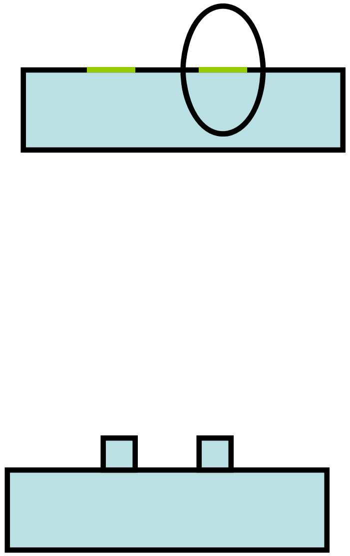
Start with bulk wafer

Apply layer of photoresist

Expose wafer with UV light through mask and etch wafer

Etched wafer with desired pattern

## Bottom Up Process



Start with bulk wafer

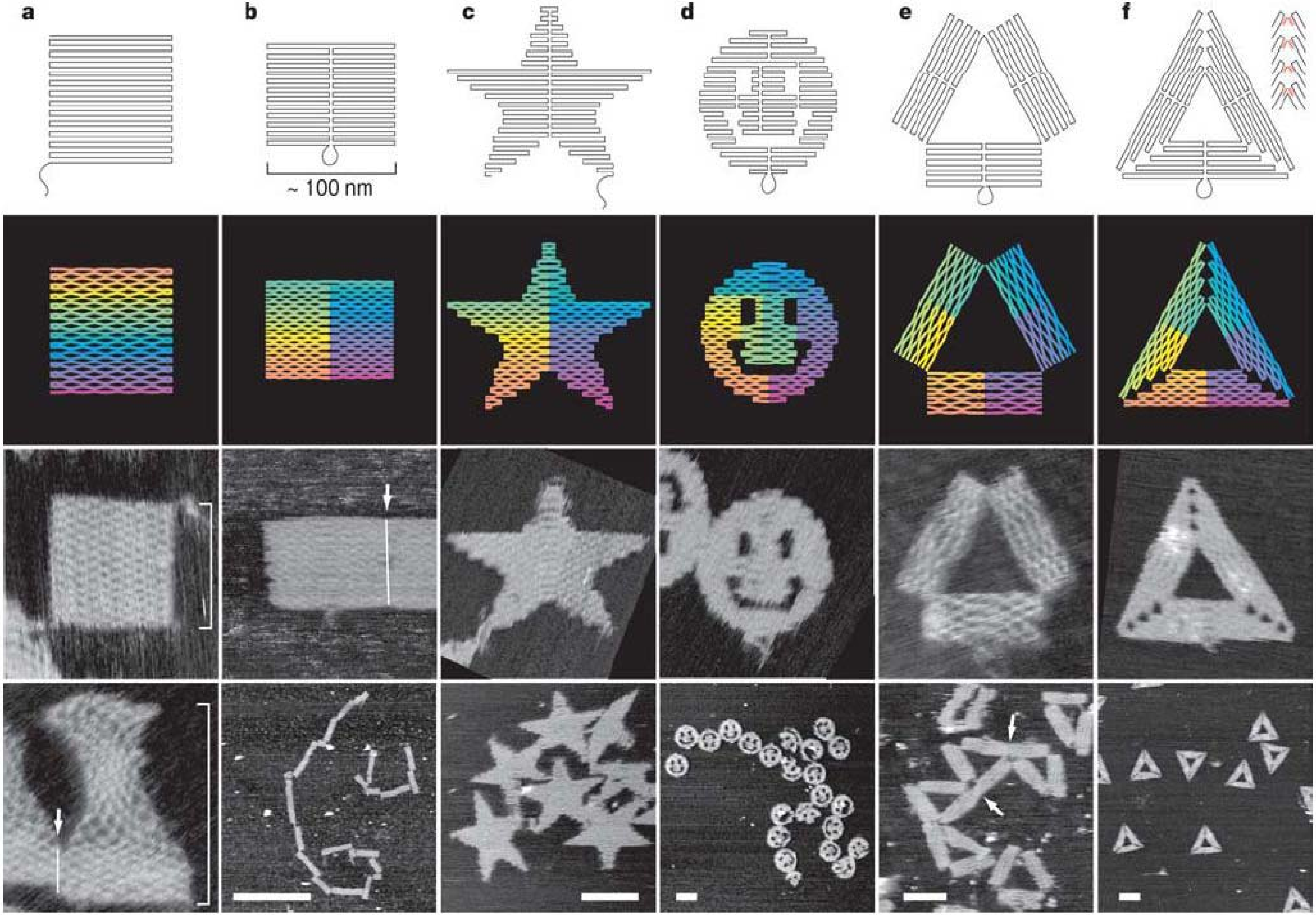
Alter area of wafer where structure is to be created by adding polymer or seed crystals or other techniques.

Grow or assemble the structure on the area determined by the seed crystals or polymer. (self assembly)

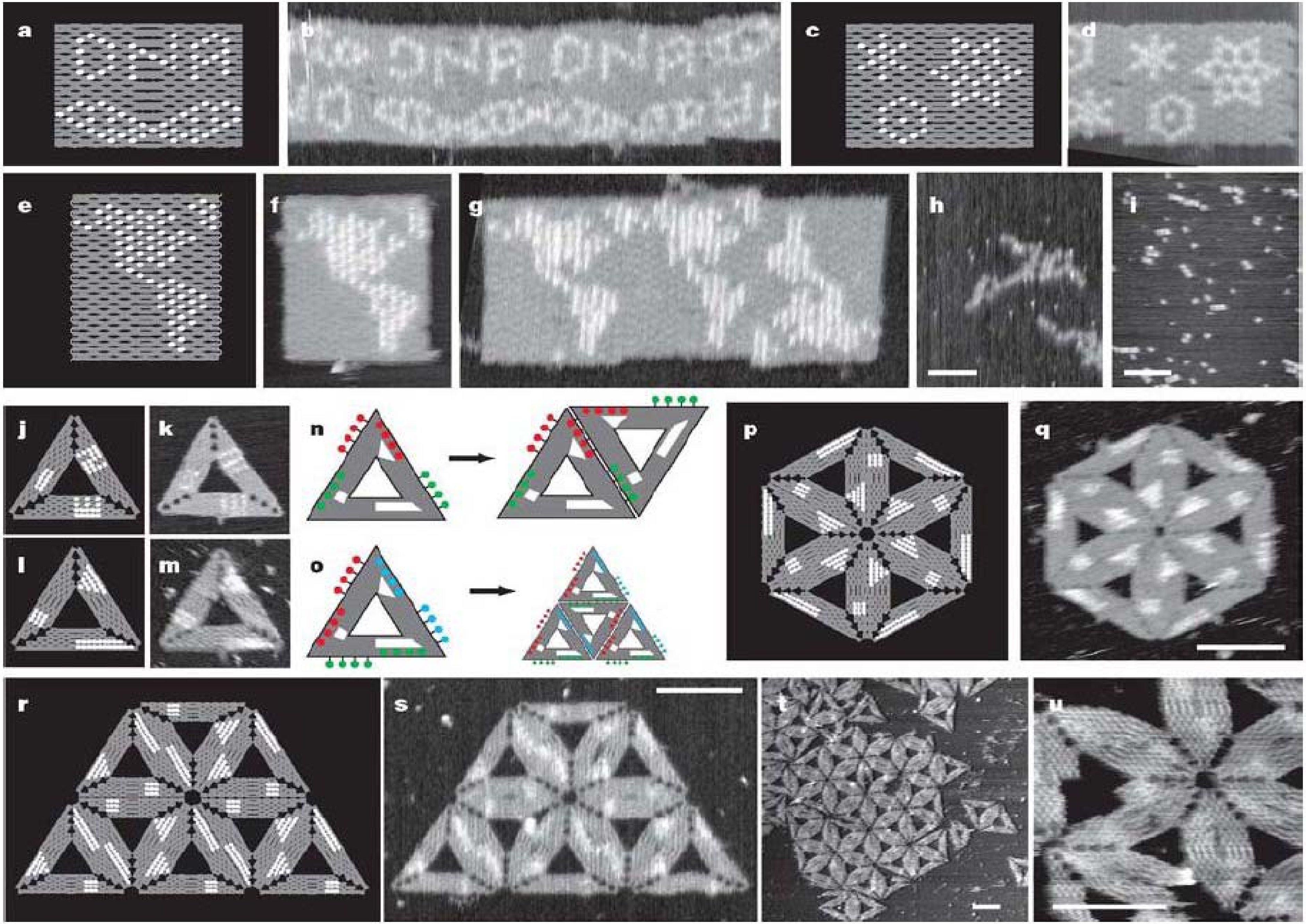
Similar results can be obtained through bottom-up and top-down processes

# Self Assembly

- ✓The principle behind bottom-up processing.
- ✓Self assembly is the coordinated action of independent entities to produce larger, ordered structures or achieve a desired shape.
- ✓Found in nature.
- ✓Start on the atomic scale.




Rothemund PWK, **“Folding DNA to create nanoscale shapes and patterns”, Nature 2006**




Rothemund PWK, **"Folding DNA to create nanoscale shapes and patterns", Nature 2006**

# Self assembly

Understand and control the intramolecular quantum behavior of specifically designed and synthesized molecules

Using a surface to localize and stabilize them

To interconnect, assemble and test nano-devices and nano-machines starting from atomic or molecular parts

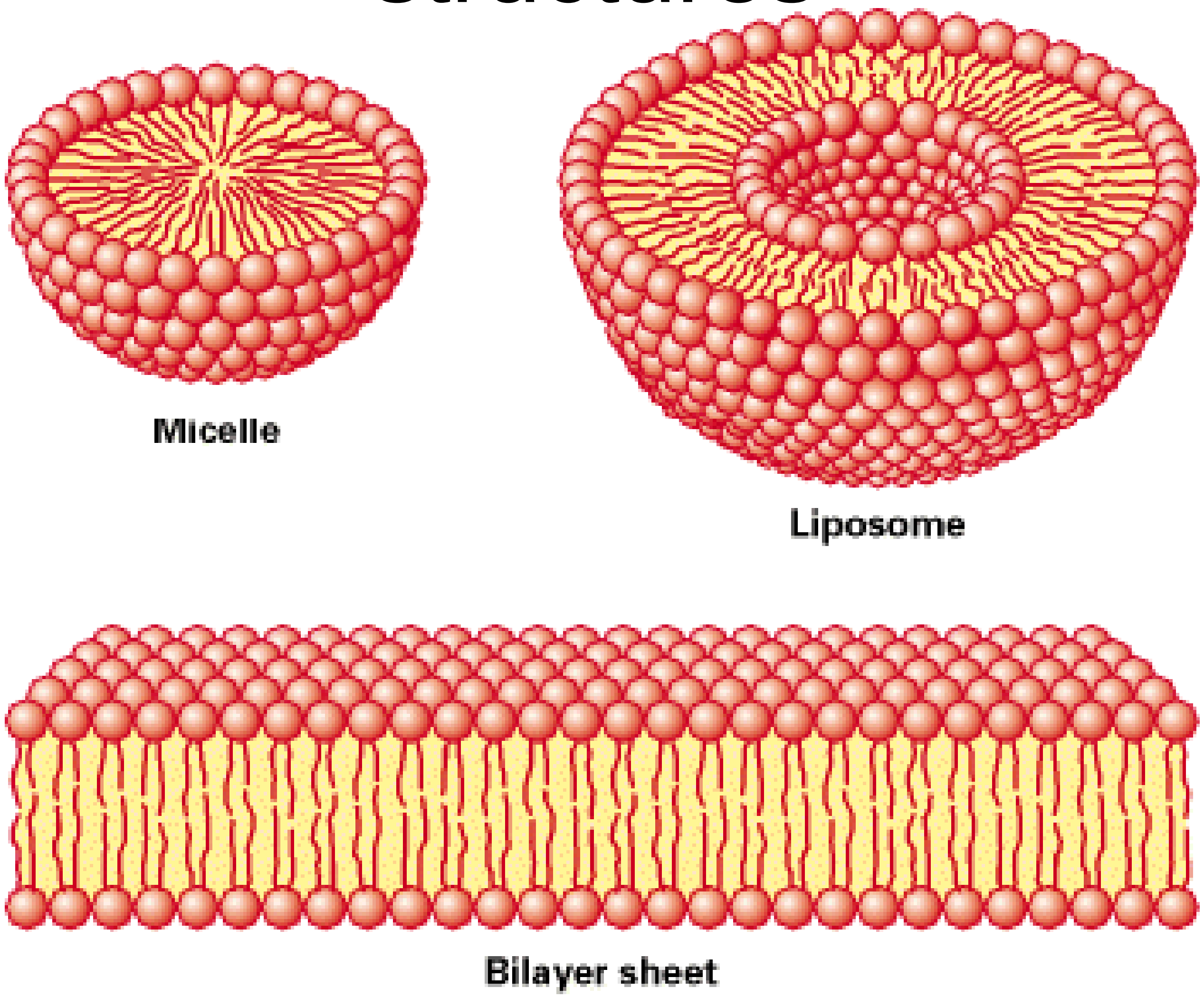
# Self Assembly: intrinsic, autonomous

Self assembly mechanisms are inherent within the structures

Self assembly occurs without any external forces or controls

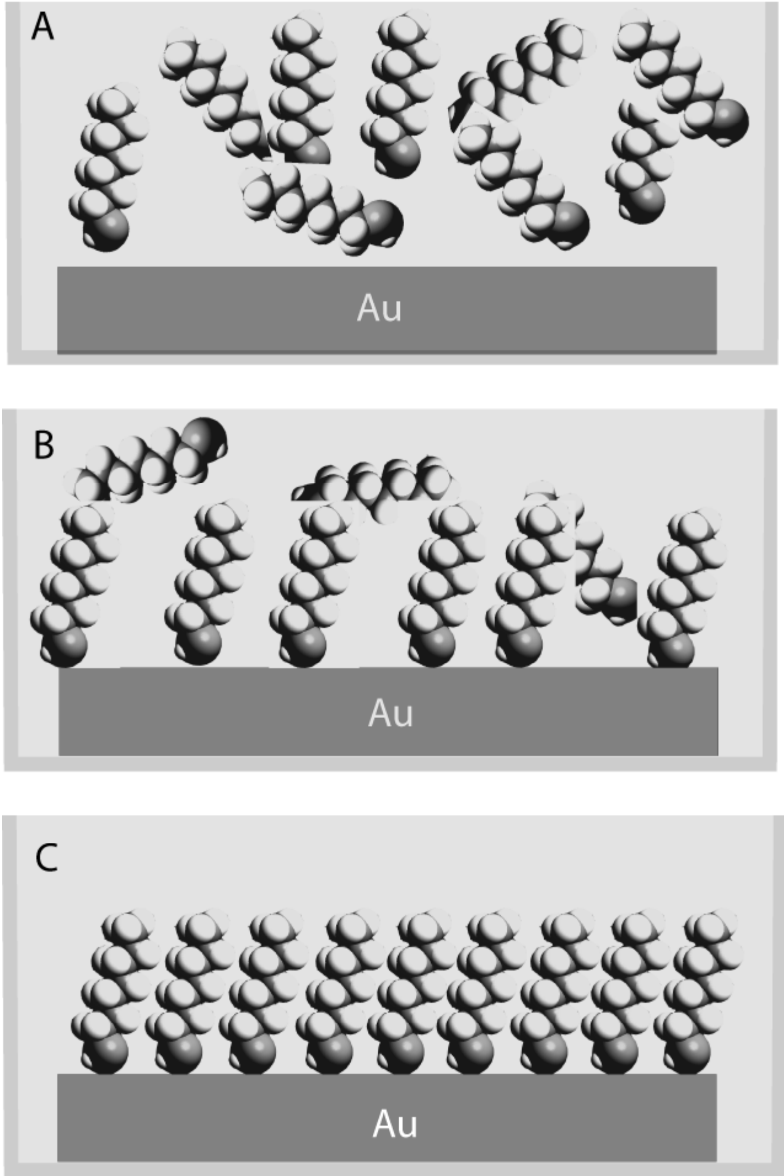
i.e. crystals

# Self-assembled amphiphilic structures

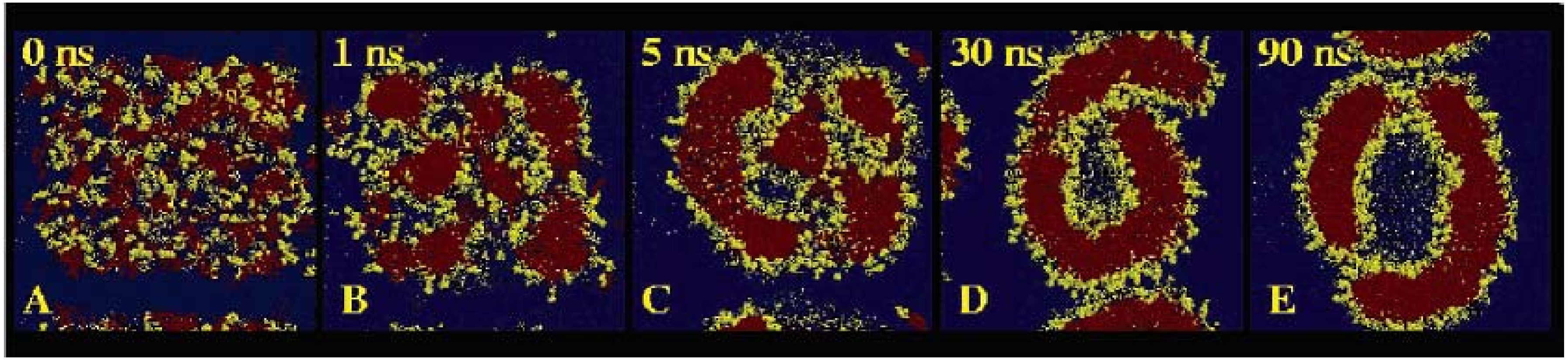



(From Molecular Cell Biology, 4th ed. By H. Lodish, A. Berk, S.L. Zipursky, P. Matsudara, D. Baltimore, J. Darnell. © 2000, W.H. Freeman and Company. Used with permission)

# Self-assembled monolayers



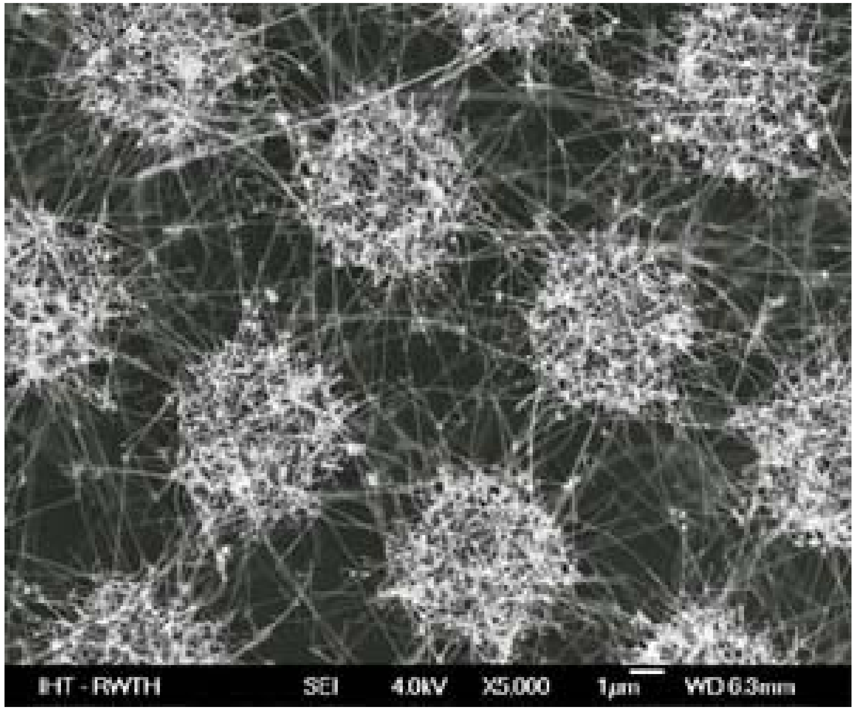
# MD Simulation of vesicle formation




(Reprinted with permission from Molecular dynamics simulation of the spontaneous formation of a small DPPC vesicle in water in atomistic detail, A.H de Vries et al., A.E. Mark, and S.J. Marrink, J. Am. Chem. Soc. 2004 **126**: 4488. Published 2006 by American Chemical Society)

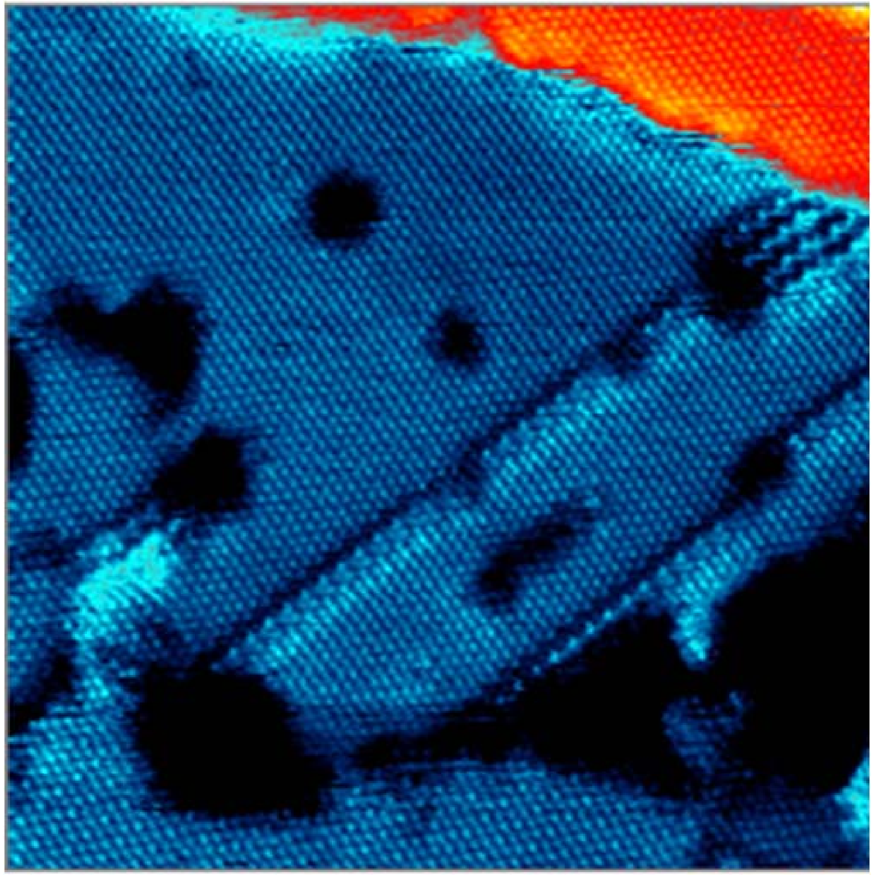
# Applications of self assembly Processes

- ✓ Self-organizing deposition of silicon nanodots.
- ✓ Formation of Nanowires.
- ✓ Nanotube transistor.
- ✓ Self-assembled monolayers.
- ✓ Carbon nanotube interconnects.

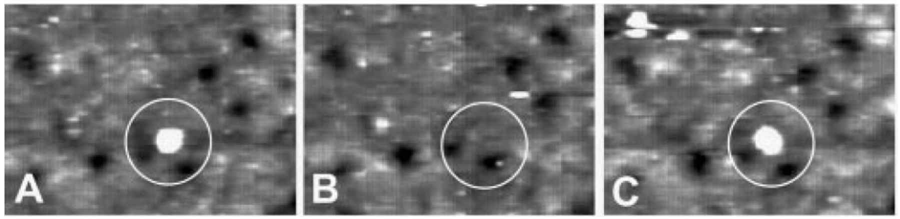



http://web.ics.purdue.edu/~mmaschma/bias_image_gallery1.htm

# Self-assembled monolayers



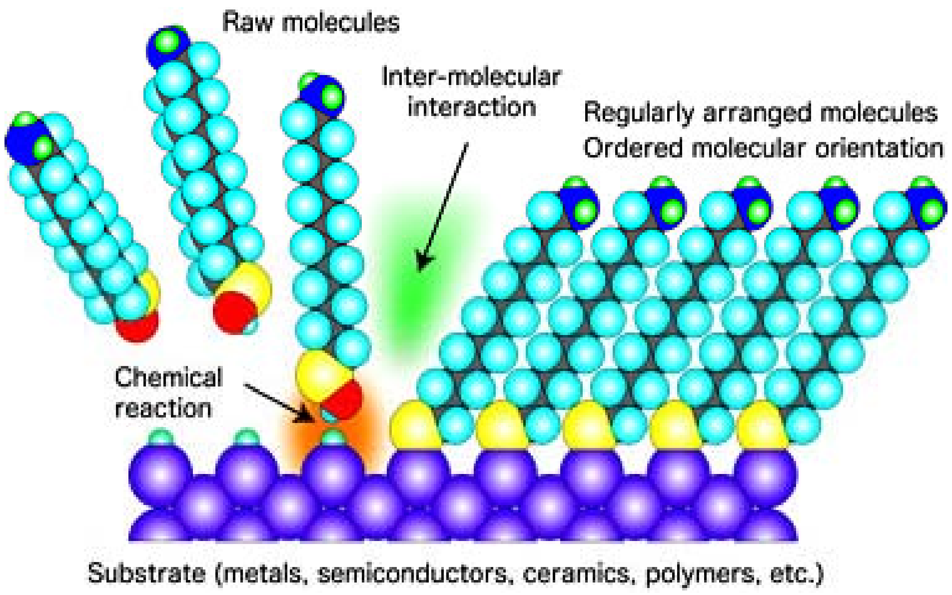
(Reproduced with permission from Functional molecules and assemblies in controlled environments, Weiss, P.S. published by Accounts of Chemical Research, 2008, courtesy of Professor Paul Weiss.)




Bond fluctuations

(From A  bond-fluctuation mechanism for stochastic switching in wired molecules, G.K. Ramachandran, T.J. Hopson, A.M. Rawlett, L.A. Nagahara, A. Primak and S.M. Lindsay,  Science 2003, 300, 3413. Reprinted with permission AAAS. Readers may view, browse and/or download material for temporary copying purposes only, provided that these uses are for noncommercial personal purposes.  Except as provided by law, this material may not be  further reproduced, distributed, transmitted, modified, adapted, performed, displayed, published or sold in whole or part without prior written permission from the publisher.)

# Self-assembled Monolayers (SAMS)




- ✓ Molecules are deposited molecule-by-molecule to form a self-assembled monolayer.
- ✓ Creates a high quality layer of material.
- ✓ Layers are deposited one layer at a time.

http://www.mtl.kyoto-u.ac.jp/english/laboratory/nanoscopic/nanoscopic.htm

# Monolayer Deposition

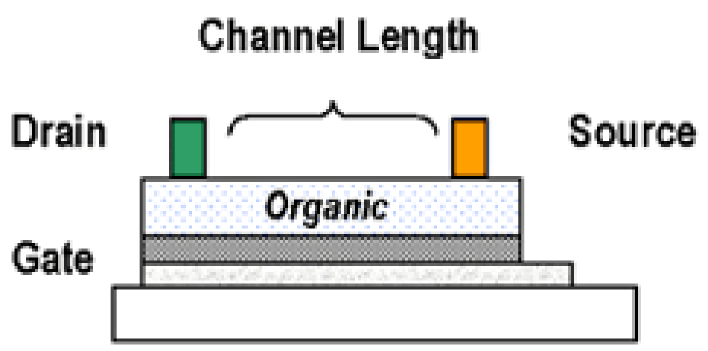
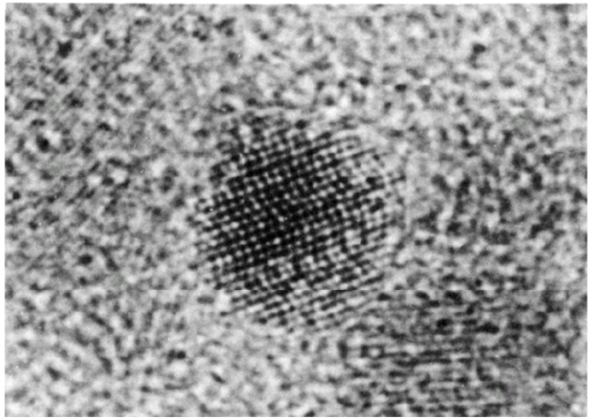


Figure 1 - Traditional OFET

- Organic molecules can't be deposited using extreme conditions because it would damage the organic molecules.
- SAMS technique does not damage organic molecules.
- SAMS films are nearly defect free.
- Used to deposit organic semiconductors.

http://www.orfid.com/images/img-vofet1.gif

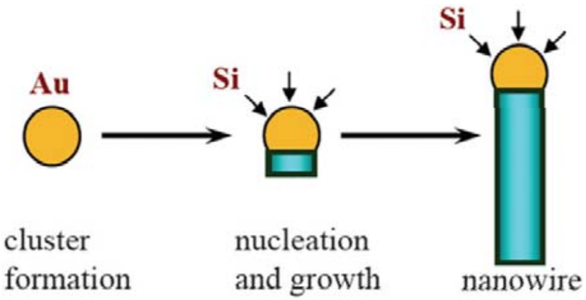
# Nanoparticles kinetically trapped



(ACS)

Quantum dots from 2 phase synthesis with Ostwald ripening

(Reprinted with permission from Synthesis and characterization of nearly monodisperse CdE (E=S,Se,Te) semiconductor nanocrystallites, C.B. Murray, D.J. Noms and M.G. Bawendi, J. Am. Chem. Soc. 115 8706 Published 1993 by American Chemical Society).

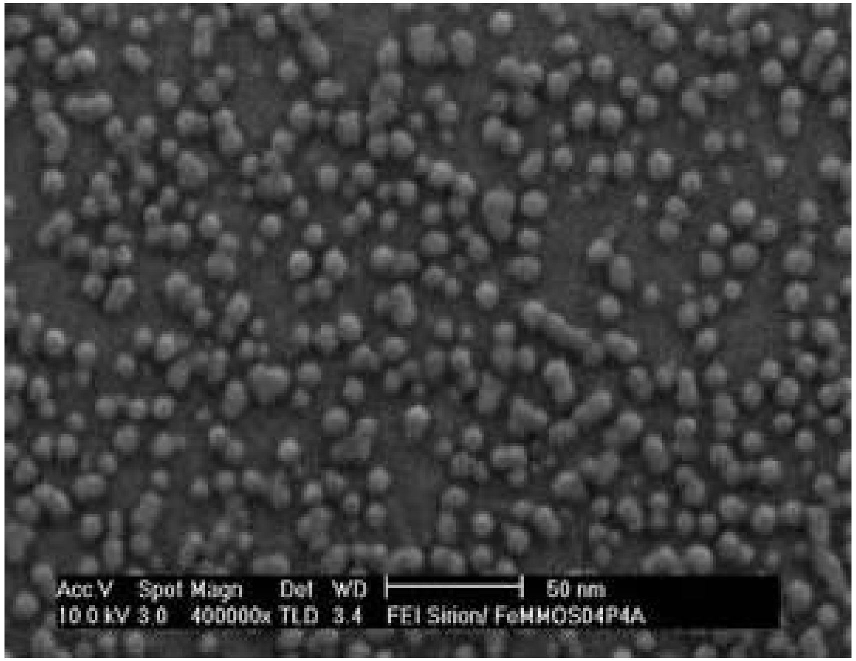



(IOP)

Si Nanowires from Au/Si eutectic seeded on Au NP

(Reproduced with permission from Semiconductor nanowires, W. Lu and C.M. Lieber J. Phys. D: Applied Physics 2006 with permission from IOP publishing and courtesy Wei Lu.)

# Self-organizing Deposition of Silicon Nanodots.




- ✓ Most common applications are in optical devices and memory.
- ✓ Silicon nanodots are deposited onto silicon dioxide with no need for lithographic patterning.

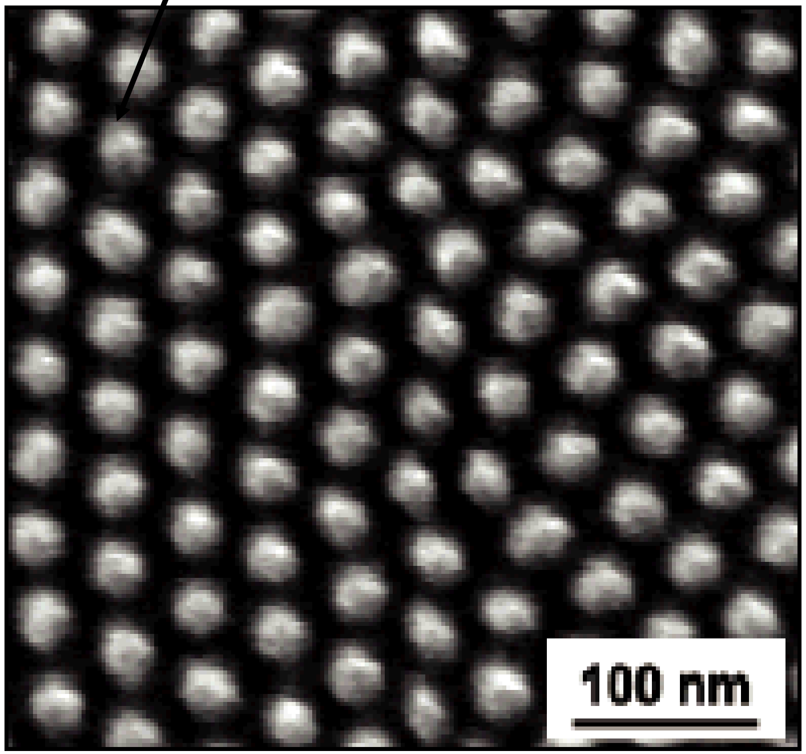
http://www.iht.rwth-aachen.de/en/Forschung/nano/bottomup/deposition.php

# Making Nanodots

Process for making nanodots

1. Apply layer of self-assembled polymer film.
2. Grow layer of desired material to create nanodot.

Polymer template for nanodot

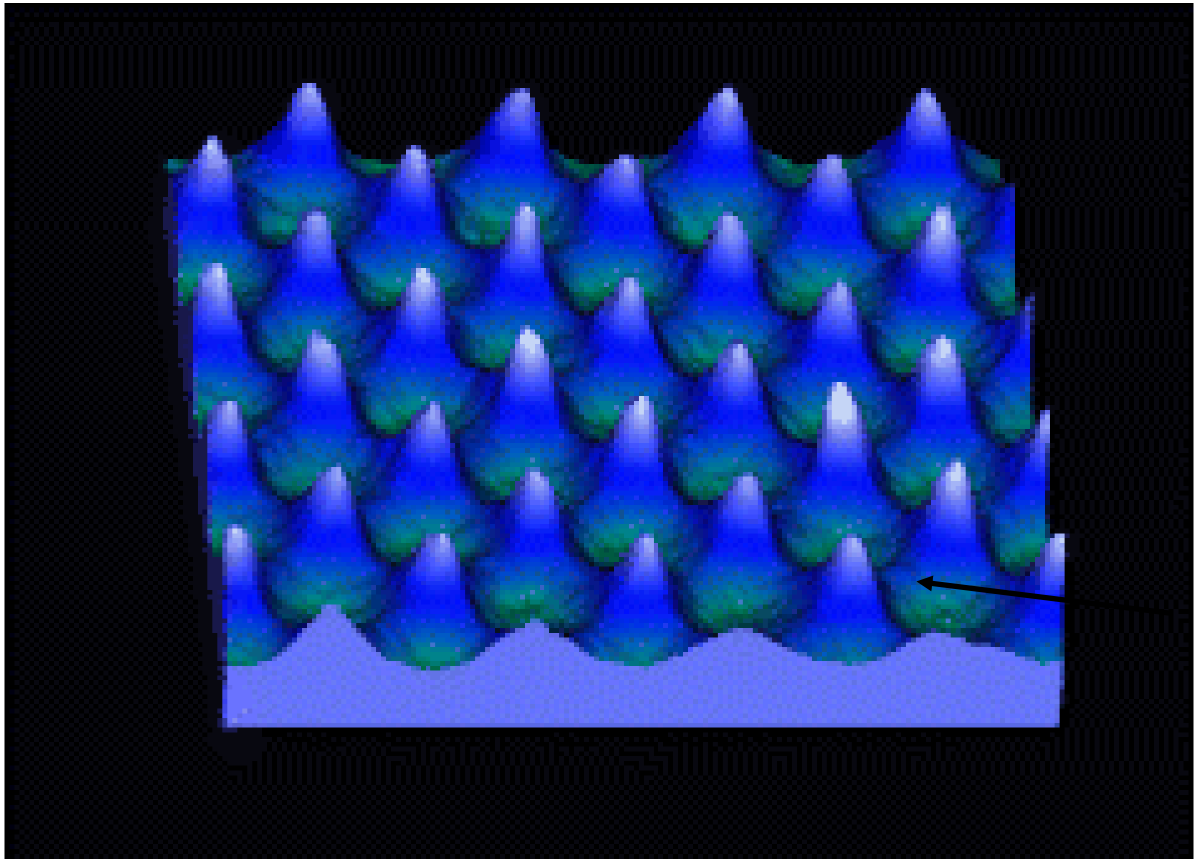



65 billion nanodots per square cm

http://news.bbc.co.uk/1/hi/sci/tech/33010241.stm

# Nanodots

Each nanodot can hold one bit of information.



13 nm high

80 nm wide

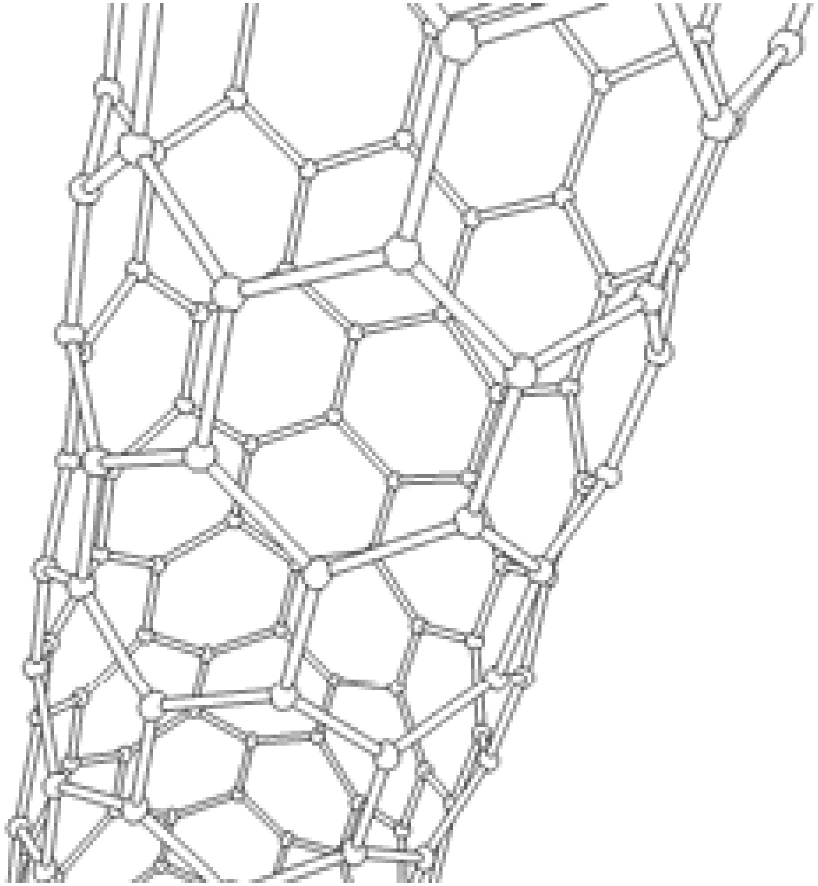
10 Trillion dots per square inch.

Self Assembled Nanodots

http://physics.nist.gov/Divisions/Div841/Gp3/Projects/Atom/atom_dots_proj.html

# Self Assembly of Carbon Nanotubes

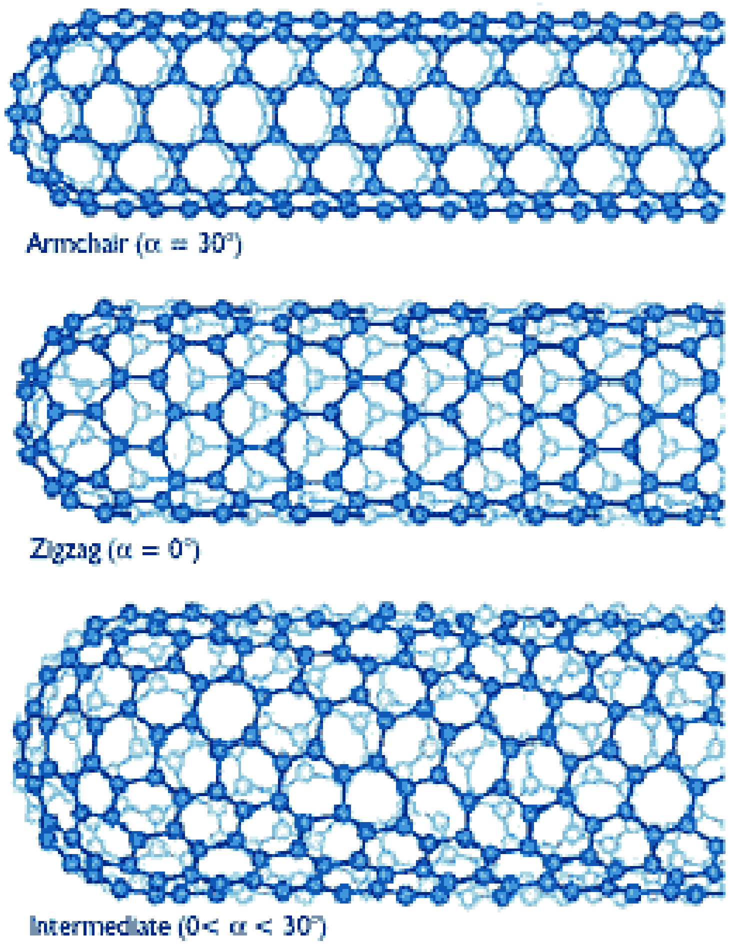
- ✓ Stronger than steel
- ✓ Multiple tubes slide inside of each other with minimal effects of friction.
- ✓ Electrical current density 1000 times greater than silver or copper.
- ✓ Can range from having metallic properties to semiconductor properties based on it's configuration.



http://en.wikipedia.org/wiki/Nanotubes

# Types of Carbon Nanotubes

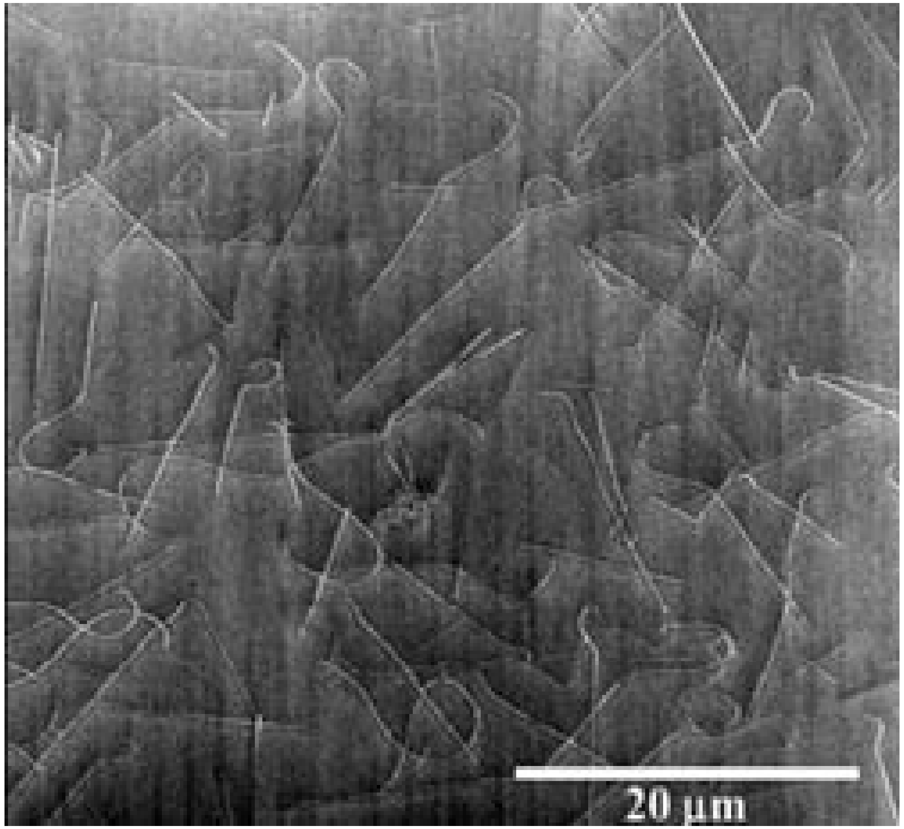
metallic




Semimetallic and semiconducting

http://www.tipmagazine.com/tip/INPHFA/vol-10/iss-1/p24.html

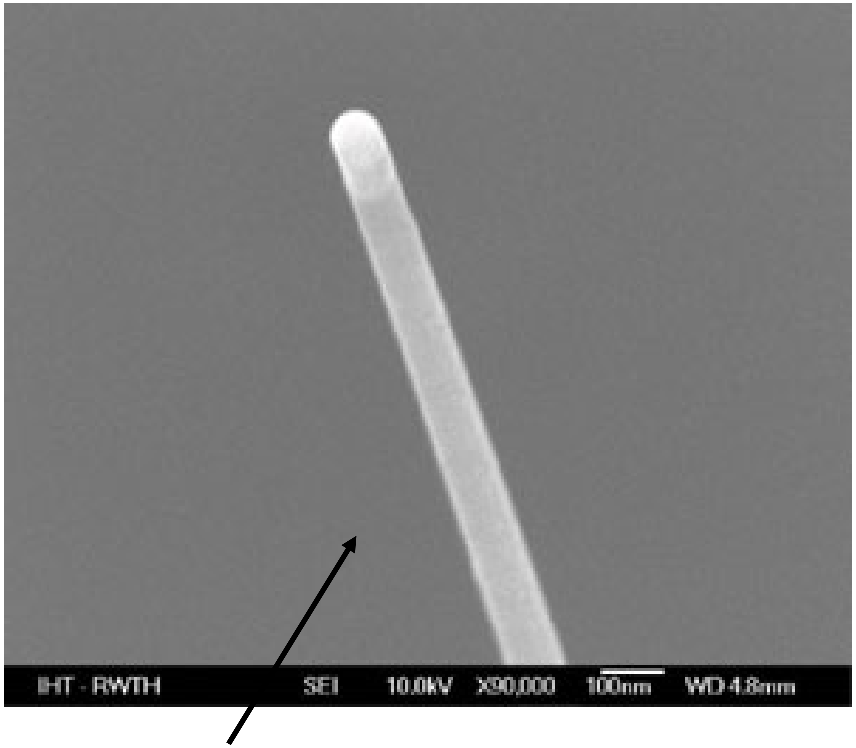
# Growing Carbon Nanotubes




- Deposit few particles of Iron (most common) to act as catalyst.
- Apply a hot environment of carbon containing gas (typically $CH_4$)
- The particle catalyzes the decomposition of the gas and carbon dissolves in the particle.
- When the particle is supersaturated with carbon, it extrudes the excess carbon in the form of a tube.

http://www.phys.hawaii.edu/~sattler/Archives/archives91-94Apr7-2.htm

# Carbon Nanowire Interconnects

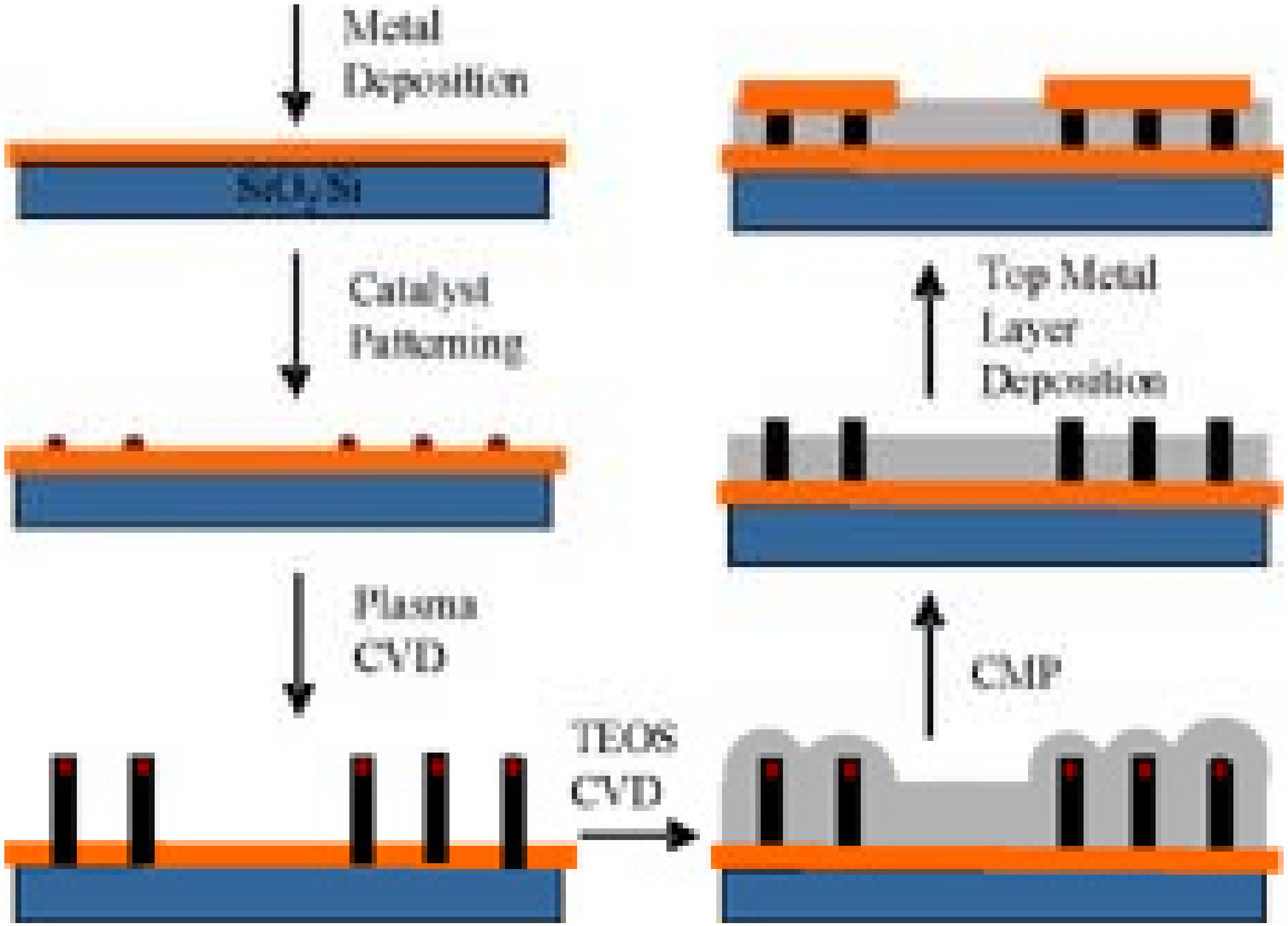



Silicon Nanowire Diameter <1nm

- ✓ Metal contact acts as a catalyst to promote one-dimensional crystal growth.
- ✓ Can one day be implemented as interconnects.

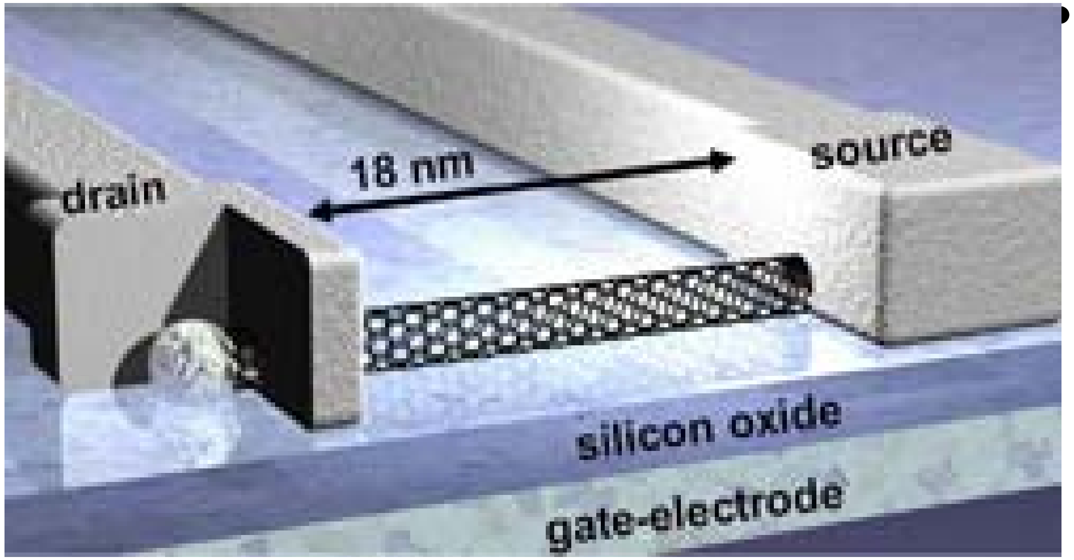
http://www.iht.rwth-aachen.de/en/Forschung/nano/bottomup/nanowires.php

# Nanotube Interconnect Process




http://www.nasa.gov/centers/ames/research/technology-onepagers/carbon_nanotubes_vertical.html

# Nanotube Transistor



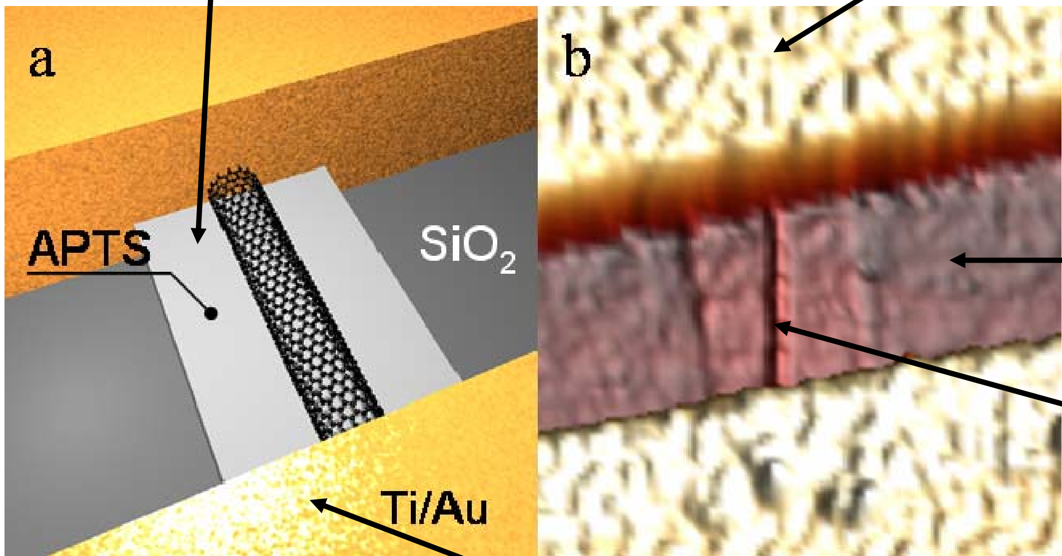

- Basic diagram for a nanotube transistor
- Benefits of transistor over conventional designs:
  - Smaller
  - Faster
  - Less material used
  - Many of the problems associated with conventional devices are solved

www.nanotech-now.com/ news.cgi?story_id=06788

# Nanotube Transistor-self Assembled

Amine silane

Ti/Au Contact




AFM Image

$SiO_2$

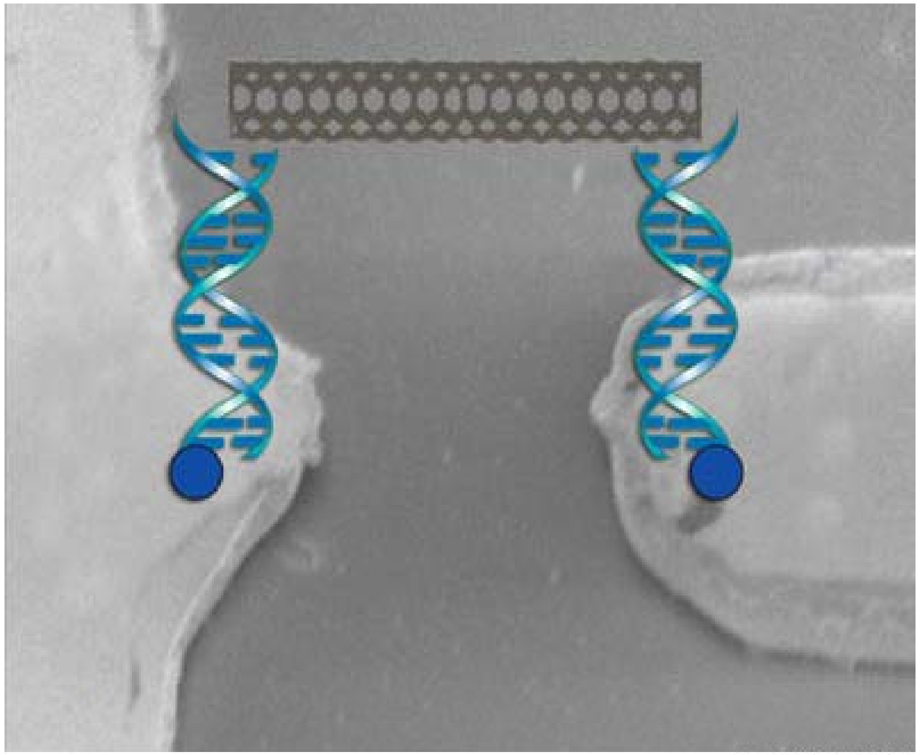
Carbon Nanotube

Diagram of Nanotube transistor

www-drecam.cea.fr/.../ LEMautoassemblage.html

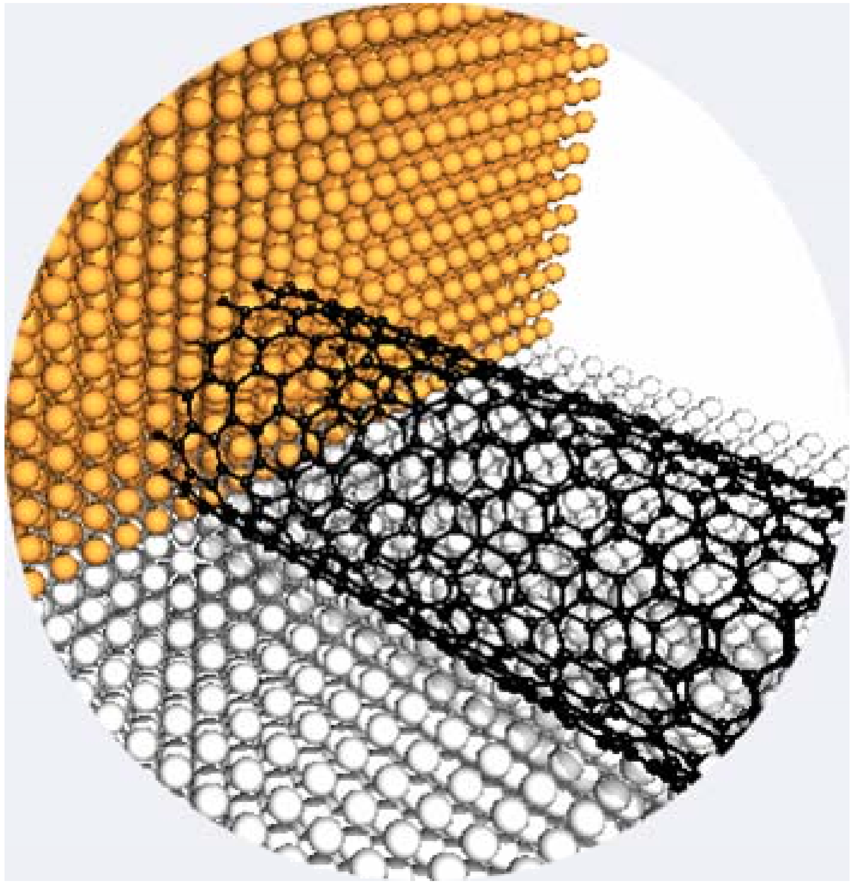
# Nanotube Transistor Construction by DNA

- ✓ DNA strands connect to gold electrodes on top of silicon.
- ✓ DNA strands connect to ends of carbon nanotube.
- ✓ Silicon and nanotubes are mixed and the DNA makes the connections to form nanotube transistors.




http://www.trnmag.com/Photos/2004/121504/DNA%20makes%20nanotube%20transistors%20Image.html

# Problem With Carbon Nanotube Transistors



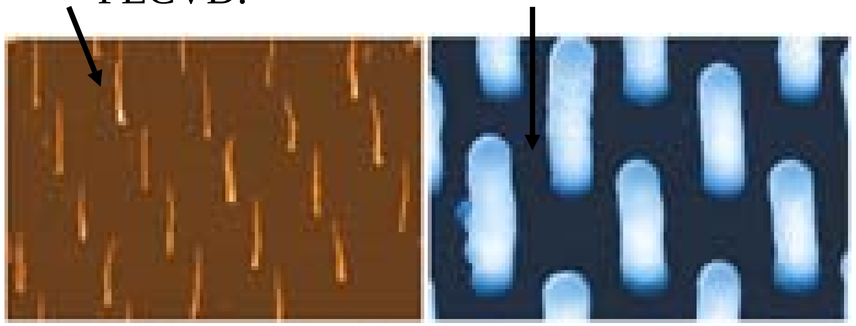
http://www.thomas-swan.co.uk/pages/nano_images.html

- ✓ Interface between metal electrodes and carbon nanotube is very sensitive.
- ✓ Changing just one atom can significantly affect transistor performance.
- ✓ Self-assembling nanotubes is not efficient.
- ✓ Growing nanotubes in place has had little success.

# Benefits and Challenges of Nanotube Interconnects

Carbon nanotubes grown on a metal contact through PECVD.

Carbon nanotubes after layer of silicon dioxide added.

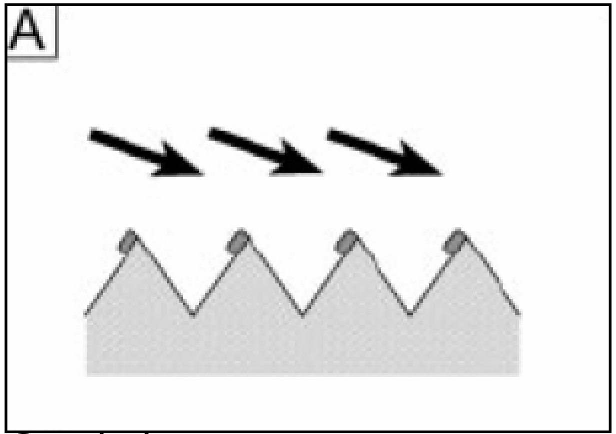


- ✓ Can have a much greater conductivity than copper.
- ✓ Is more heat resistant than copper.
- ✓ Carries a much larger current than copper.
- ✓ Orientation of carbon nanotubes remains a problem.
- ✓ Technology is not reliable enough to be used in device manufacturing.

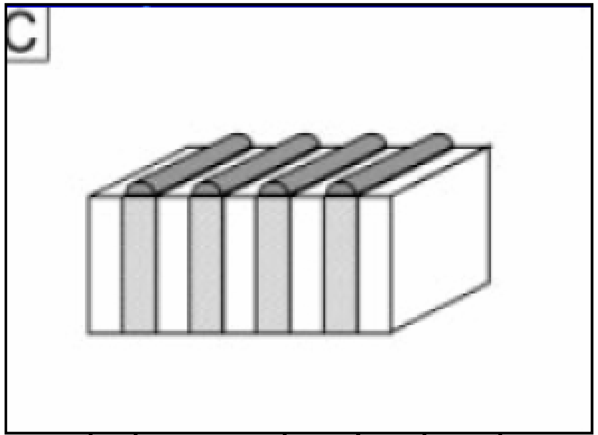
http://www.nasa.gov/centers/ames/research/technology-onepagers/carbon_nanotubes_vertical.html

# CRECIMIENTO EN 1-D DE NANO-ALAMBRES SOBRE UN SUBSTRATO

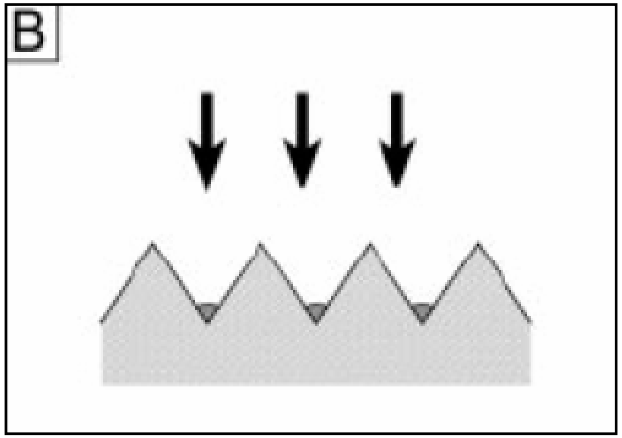
## Crecimiento auto-ordenado de los patrones sobre el substrato



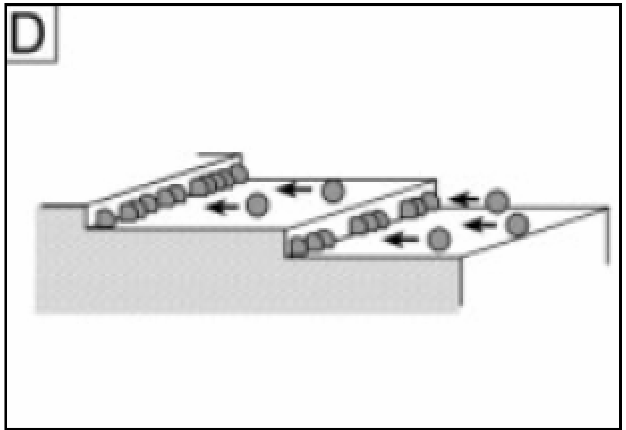

Crecimiento aparente
(crecimiento en forma de sombra)




Crecimiento sobre los bordes
De una muestra en forma de
multicapa



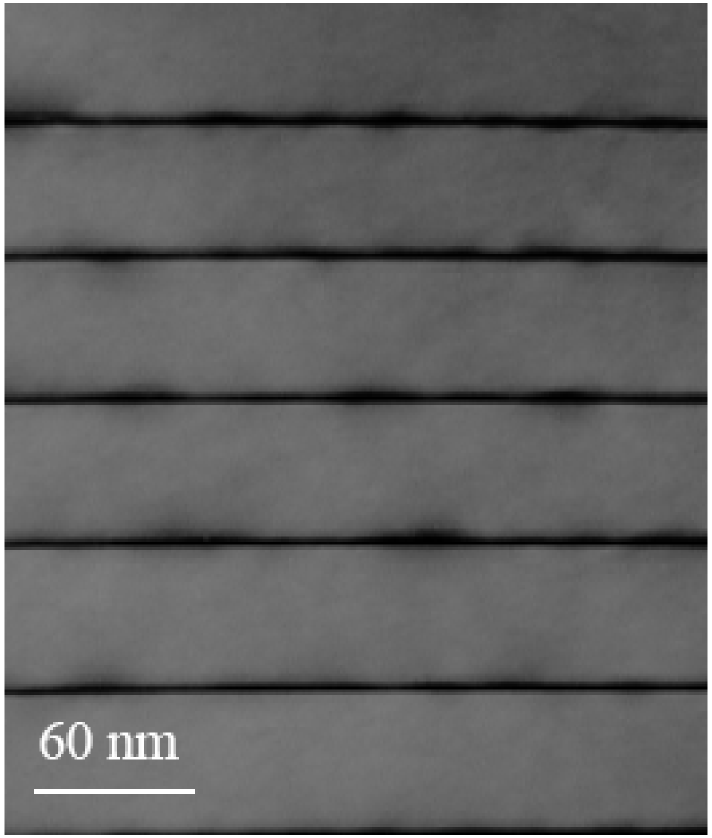

Crecimiento en canales V




Ubicación de las moléculas en los
bordes de patrones en forma de
escalón

**CRECIMIENTO AUTO ENSAMBLADOS Y ORDENADO DE PUNTOS CUANTICOS 0-D**

**Influencia del espesor y del espaciado de las capas**



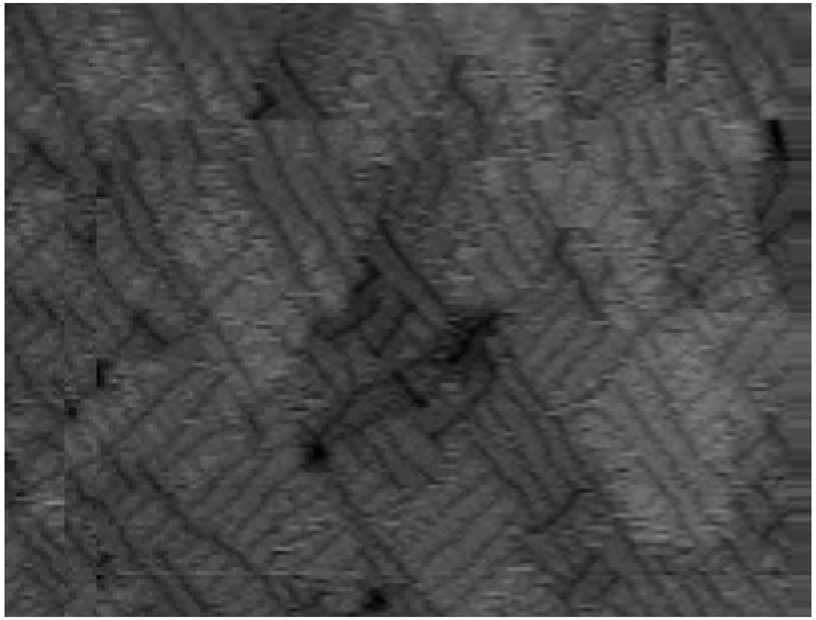


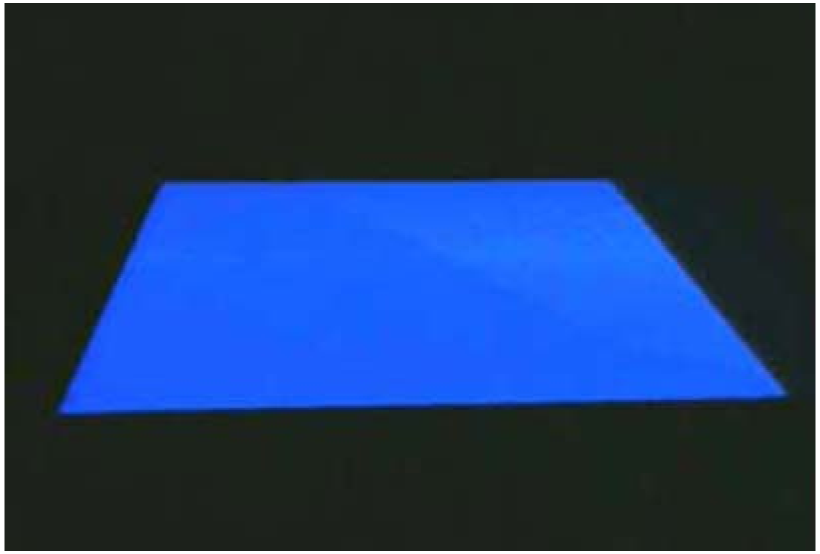
Alineamiento vertical perfecto
Obtenido cuando se reduce el
Espaciado de Si de 60 a 17nm

## CRECIMIENTO AUTO ENSAMBLADOS Y ORDENADO DE PUNTOS CUANTICOS 0-D

### Influencia del crecimiento con la temperatura

**Clouster "tipo choza" (430ºC)**

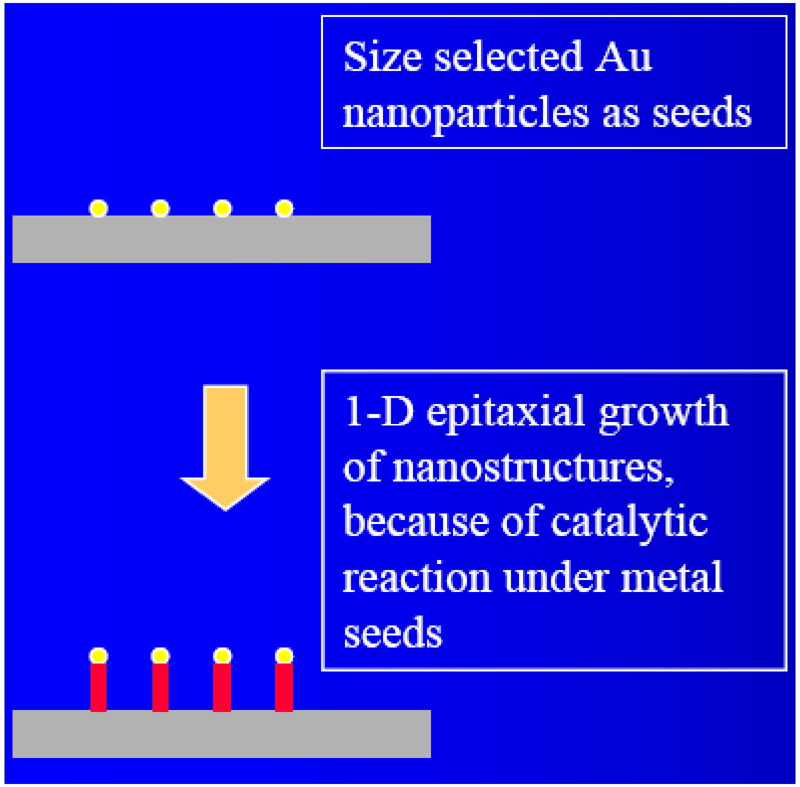


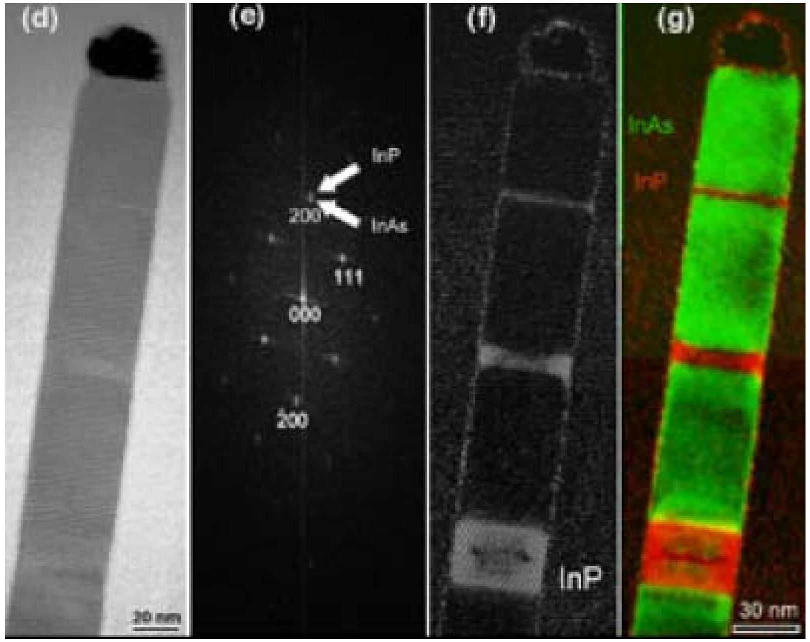


**Clouster "tipo domo" (700ºC)**

# CRECIMIENTO DE "NANO-WHISKERS" SEMICONDUCTORES

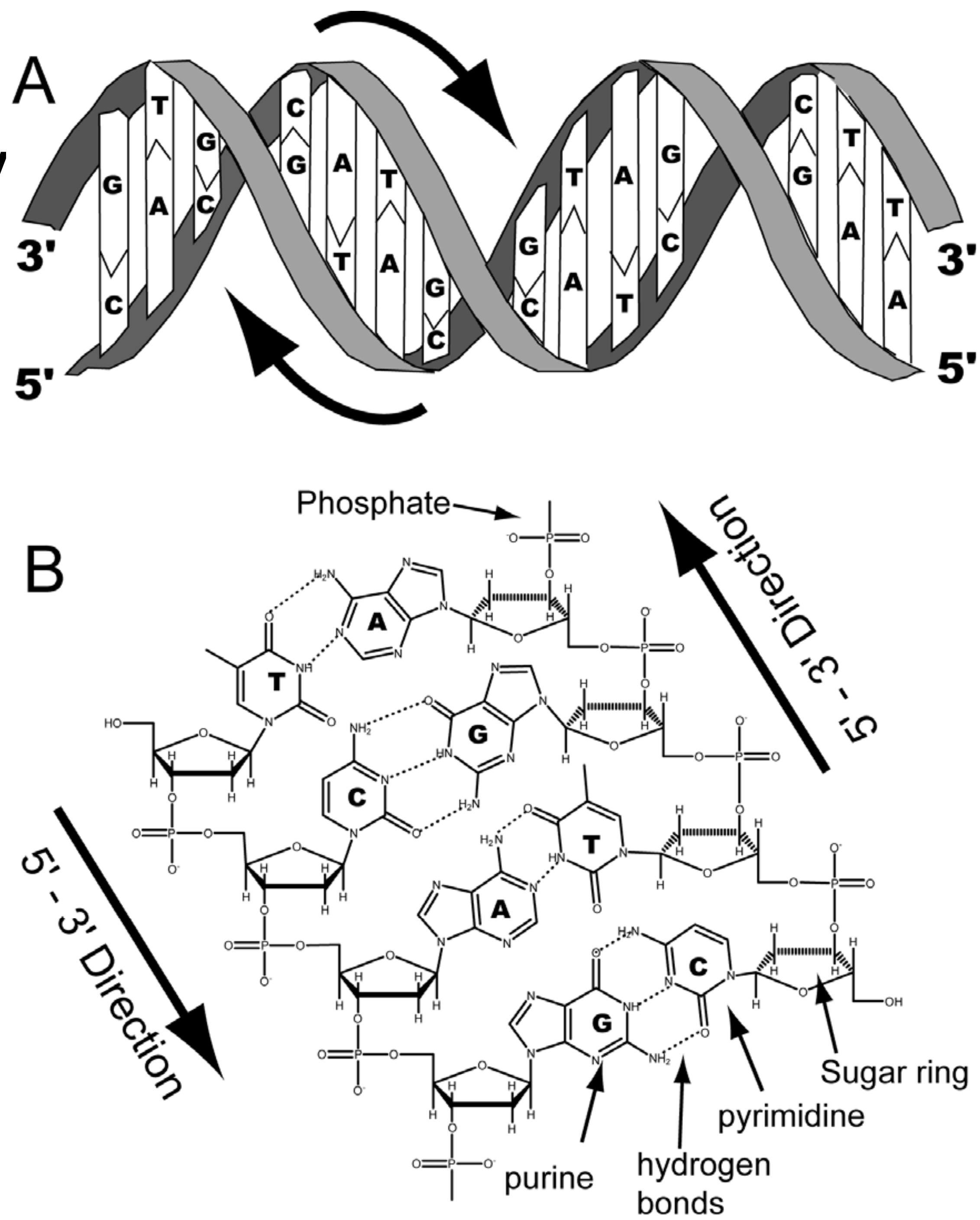
Crecimiento mediado con Au (para combinar semiconductores dis-similares de partículas de 0-D a estructuras 1-D



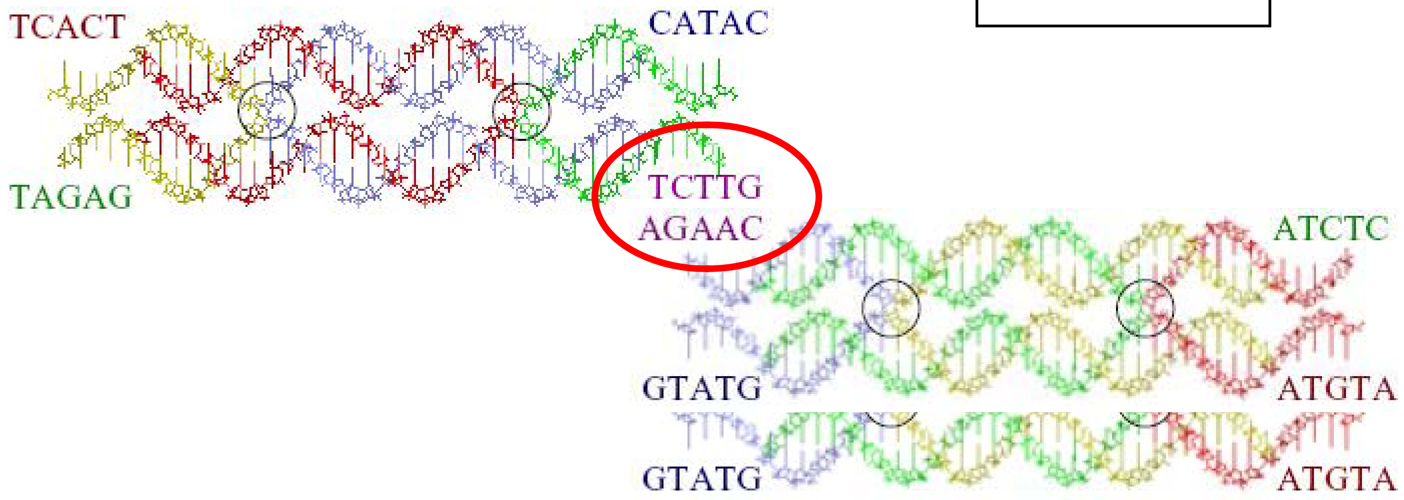

**$\phi$= 80-100nm**

# DNA Nanotechnology



# From theory to practice (biology)

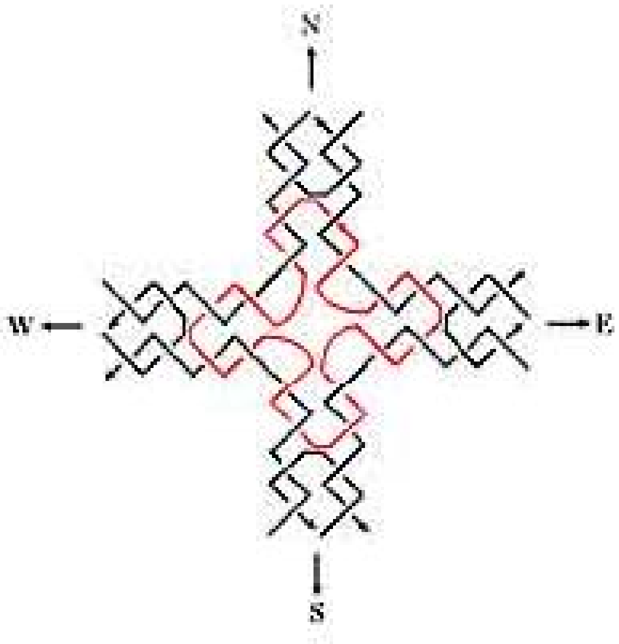
- Tiles are “do-able” in practice
- *DNA Nano-technology*

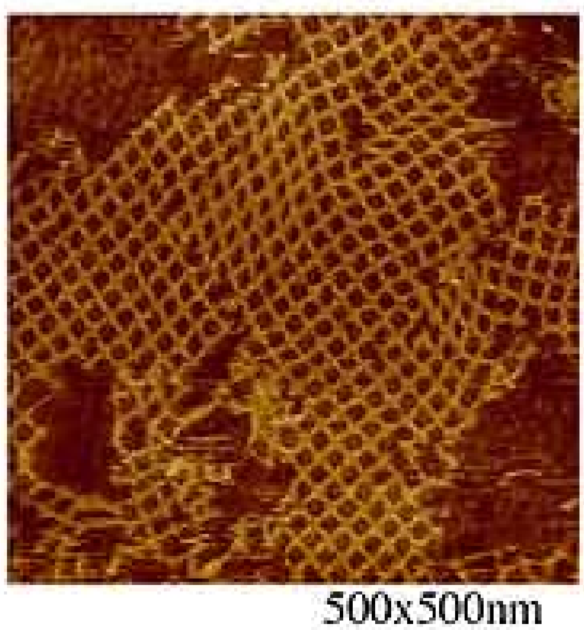



Winfree, E. et at. Design and self-assembly of two dimensional. DNA crystals. 1998.

# More on the *technology*

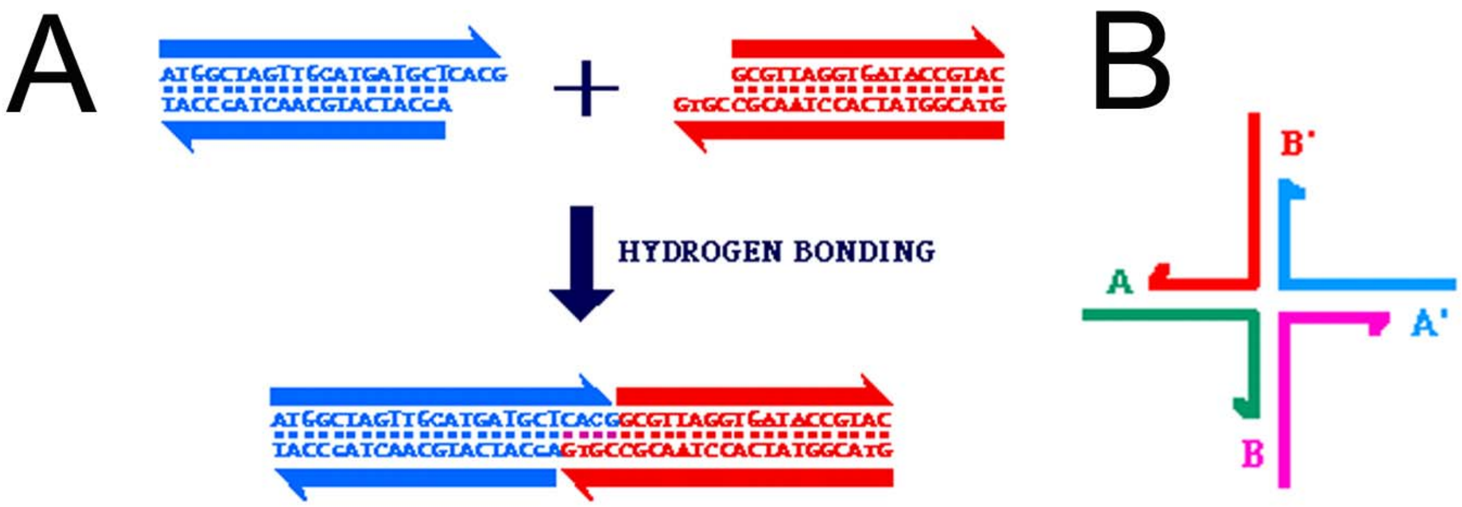
- More tiles from DNA



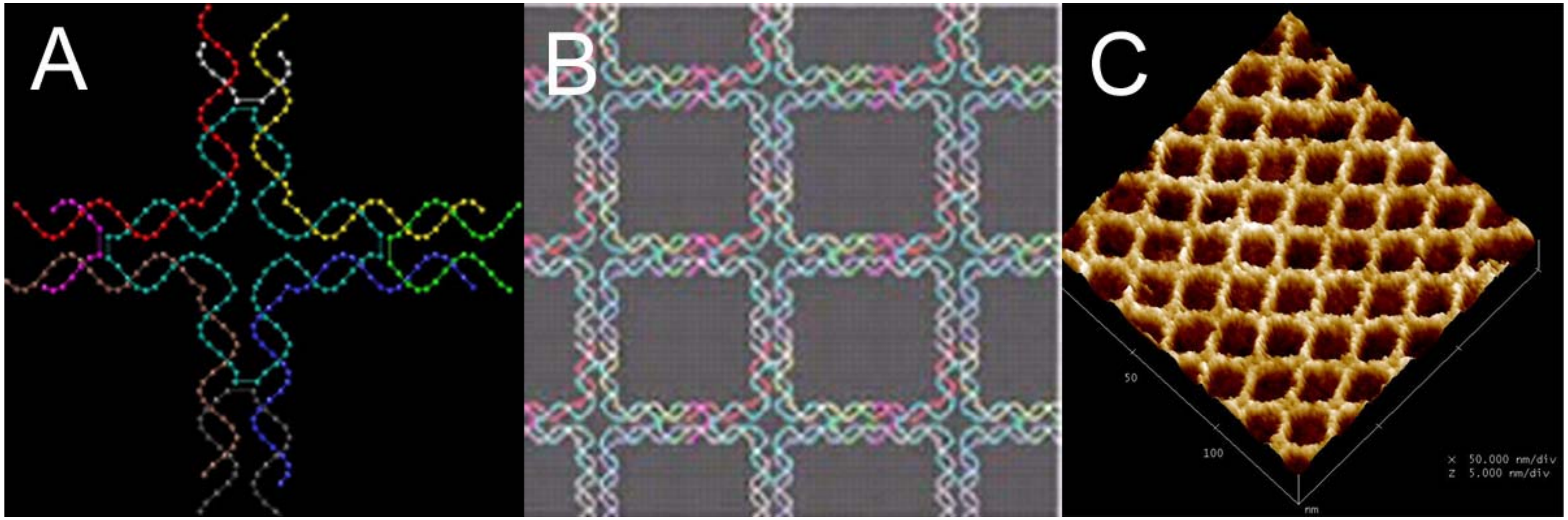

Hao Yan et al. *"4x4 DNA Tile and Lattices: Characterization, Self-Assembly and Metallization of a Novel DNA Nanostructure Motif"* 2003.

# DNA Nanotechnology



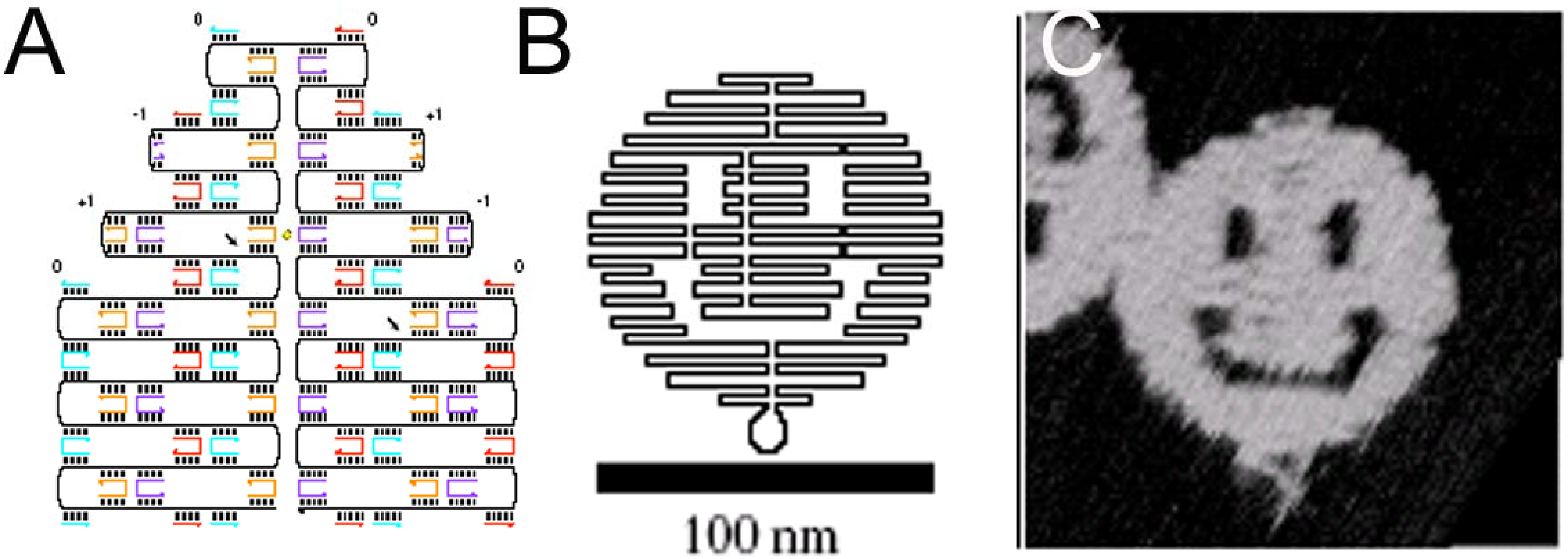

(Courtesy of Professor Hao Yan, Arizona State University)

# DNA Nanotechnology



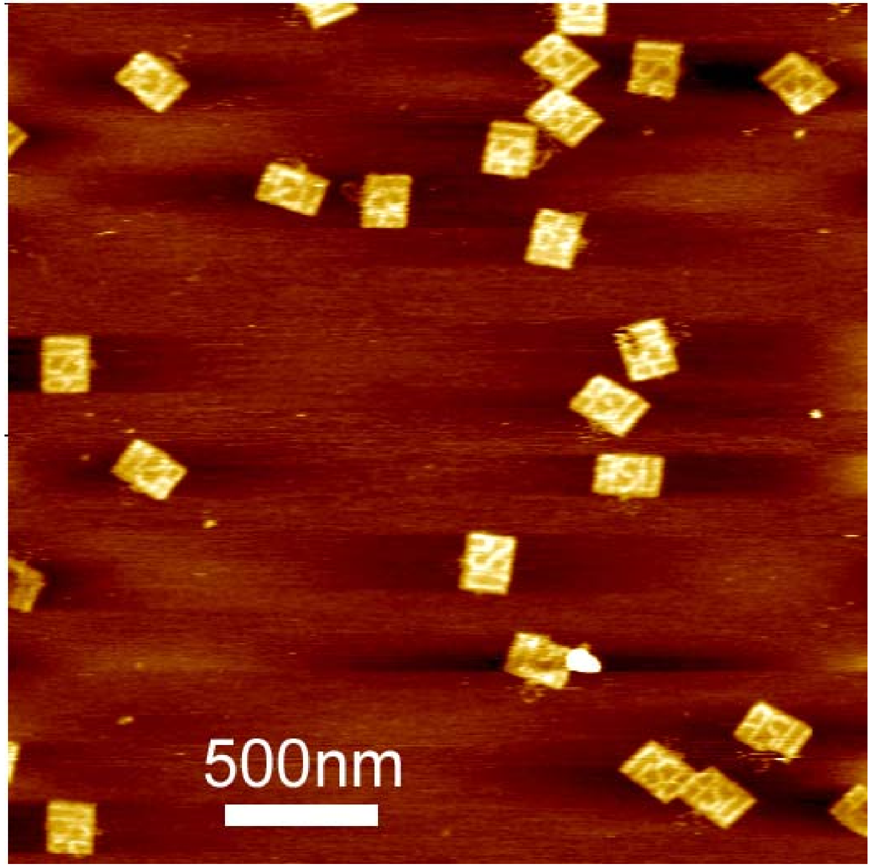

(Courtesy of Professor Hao Yan, Arizona State University)

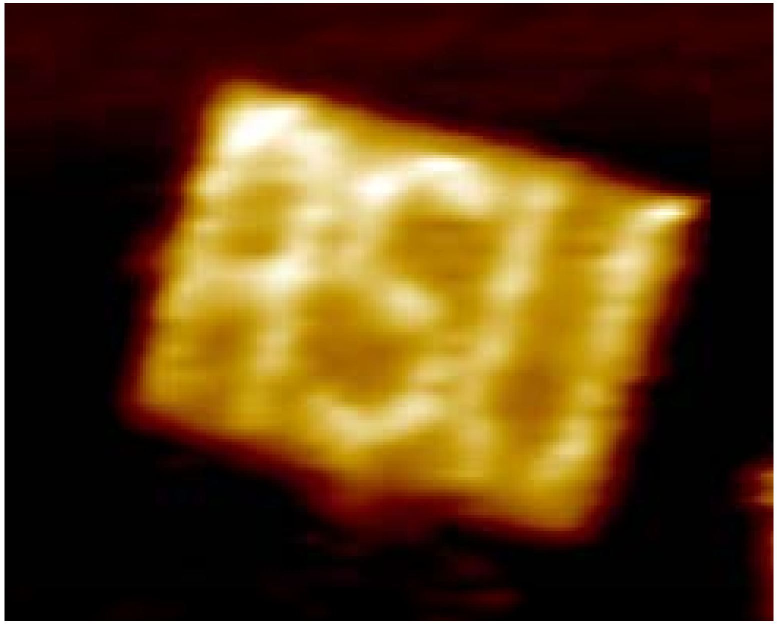
# DNA Nanotechnology




(Reprinted by permission from McMillan Publishers Ltd.: Nature Publishing Group, Folding DNA to create nanoscale shapes and patterns, P. Rothmunde, Nature 2006, **440**, 297.)

# DNA Nanotechnology

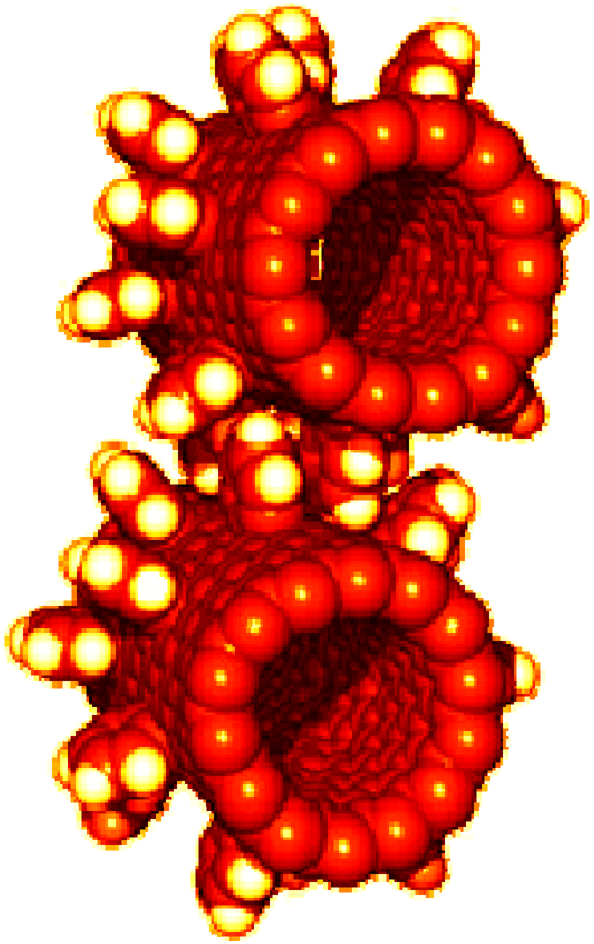


(Courtesy of Professor Hao Yan, Arizona State University)

# Advancements Made so Far Using self assembly

- Carbon nanotube transistor (Stanford U.)
- Organic monolayers for organic transistor (Yale U.)
- Nanotube based circuit constructed (IBM)
- Nanomotors and gears created (NASA)



http://snf.stanford.edu/Education/Nanotechnology.SNF.ppt