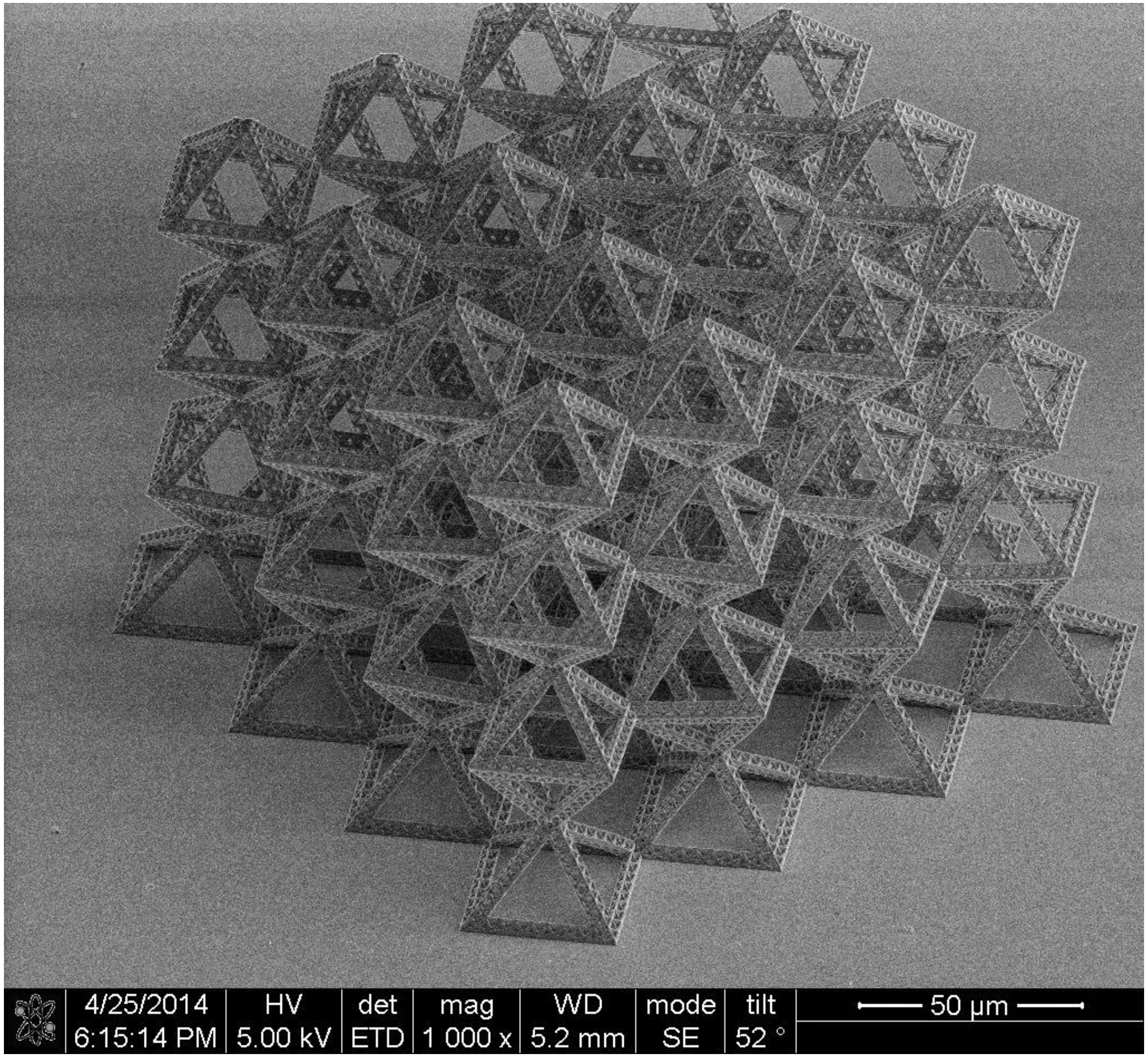
Current Microfabrication and Nanofabrication Technologies



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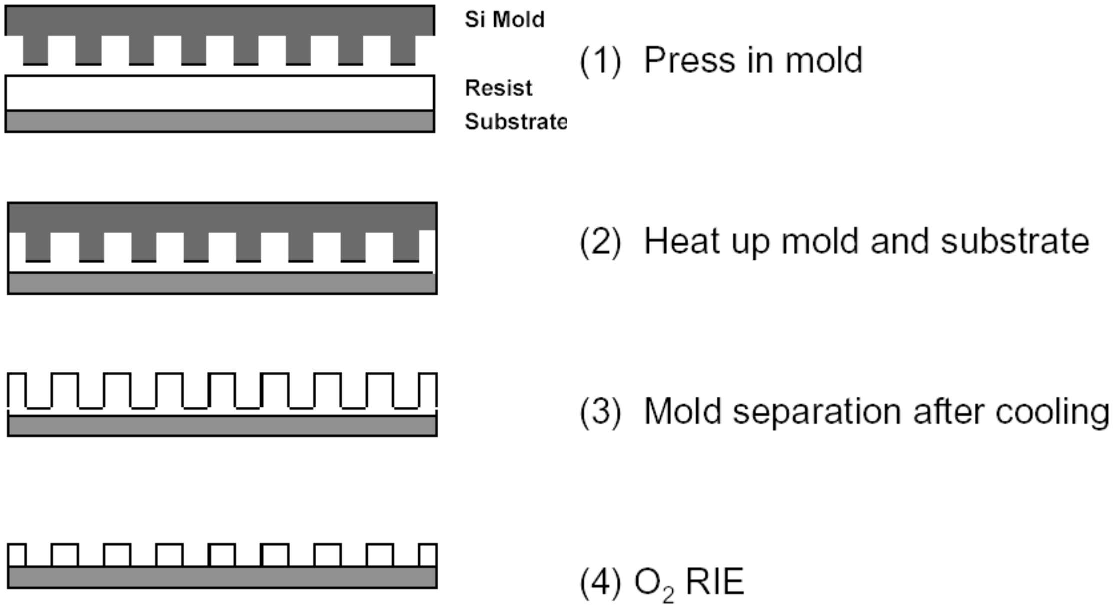
Nanoimprinting Lithogrpahy (NIL)

NIL Process



(1) Press in mold

(2) Heat up mold and substrate

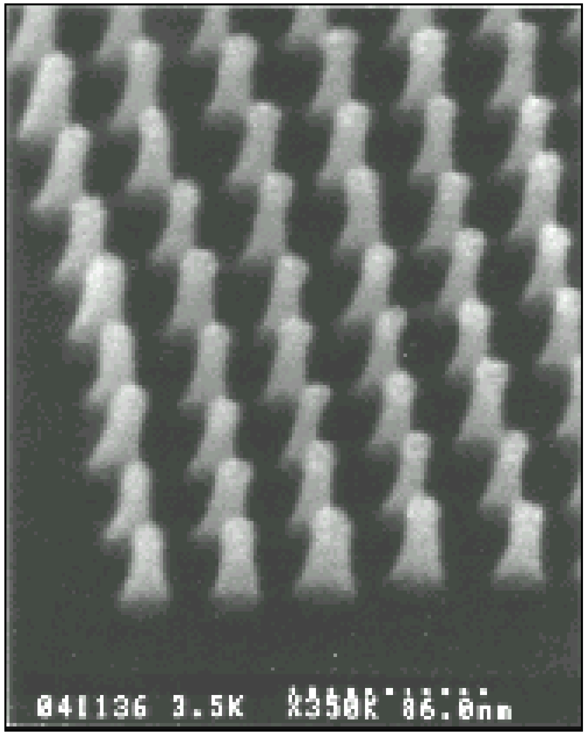
(3) Mold separation after cooling

(4) O_2 RIE

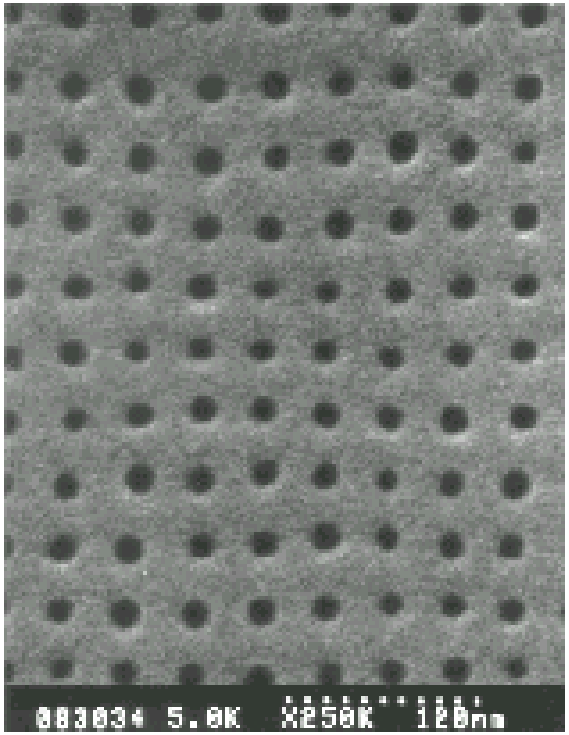
- Sub-10nm feature size
- Large area (4-8 in.)
- High throughput
- Low cost

Nanonex NX-2000 Nanoimprinter
Up to 4″ wafer
Sub-100 nm resolution
Up to 300°C, 600 psi, UV

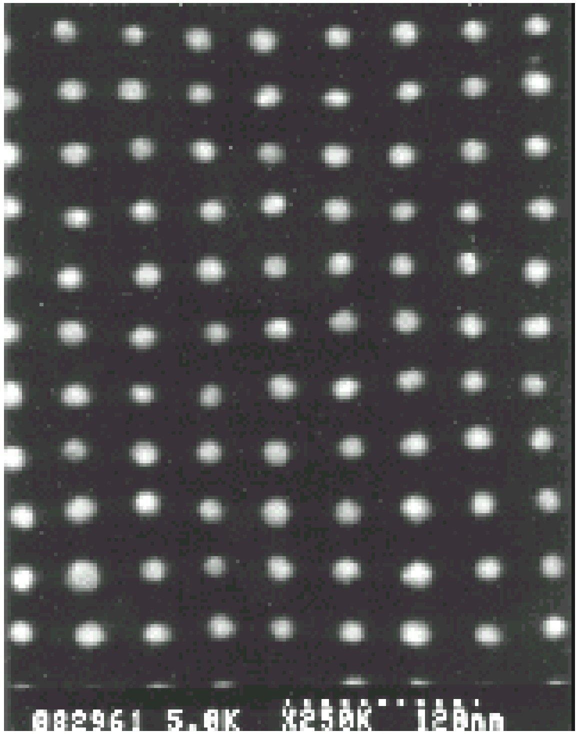
Sub-10 nm Resolution of NIL



Imprint mold with 10nm diameter pillars



10nm diameter holes imprinted in PMMA



10nm diameter metal dots fabricated by NIL

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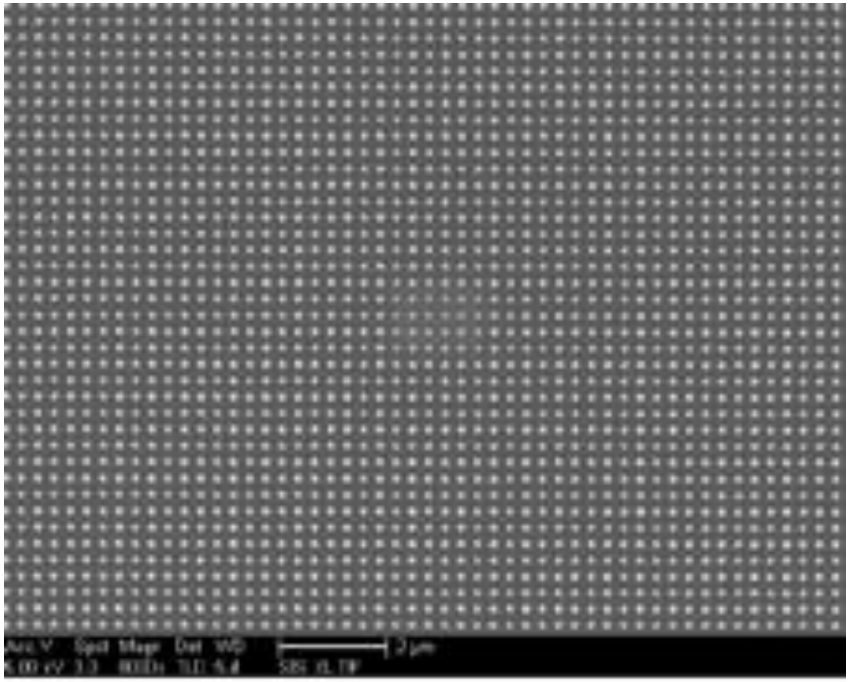
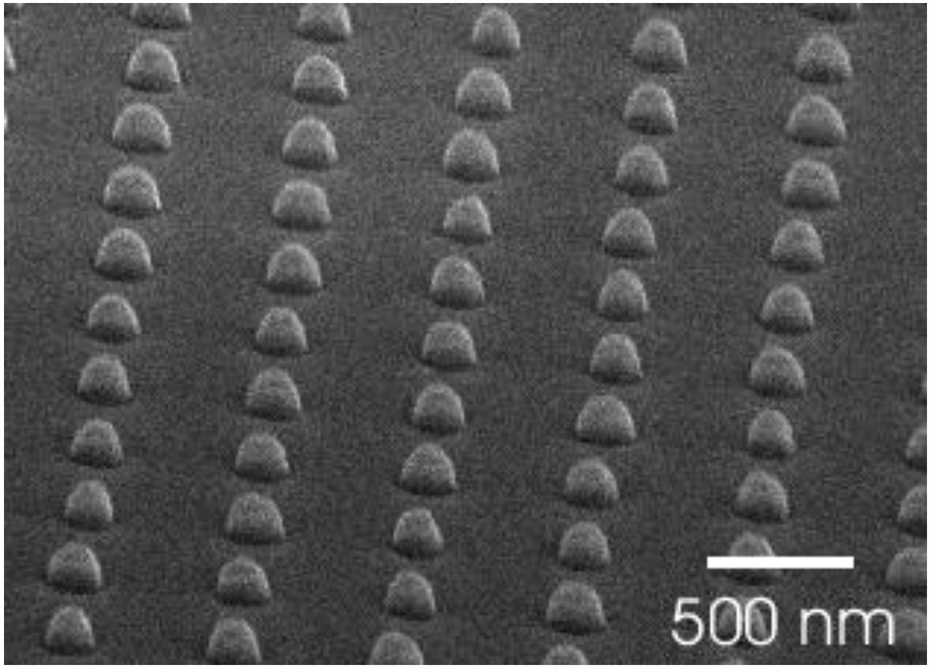
Metallic Nanodot Arrays

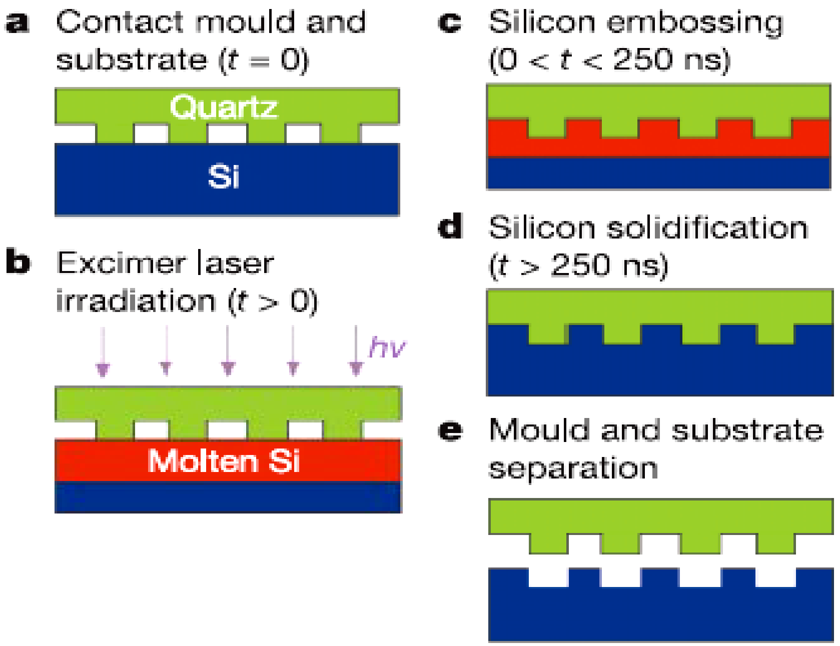


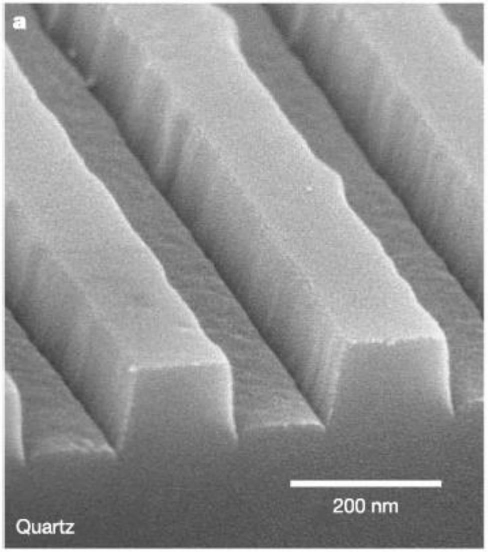


Nanodots localize magnetic or electrical fields at very small scales. Applications for nanodots could include high-density information storage devices.

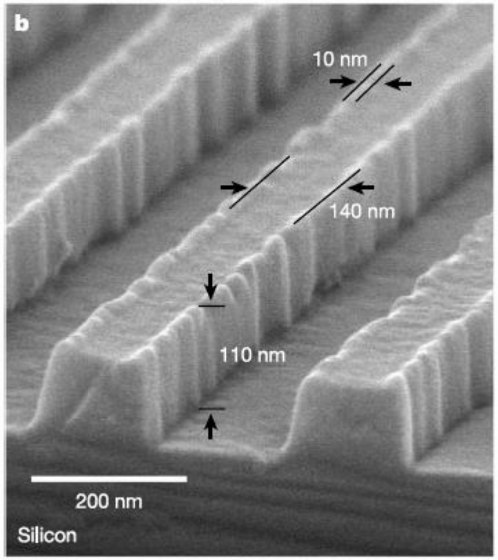
Laser-Assisted-Direct-Printing (LADI) in Silicon

LADI Process





Quartz mold

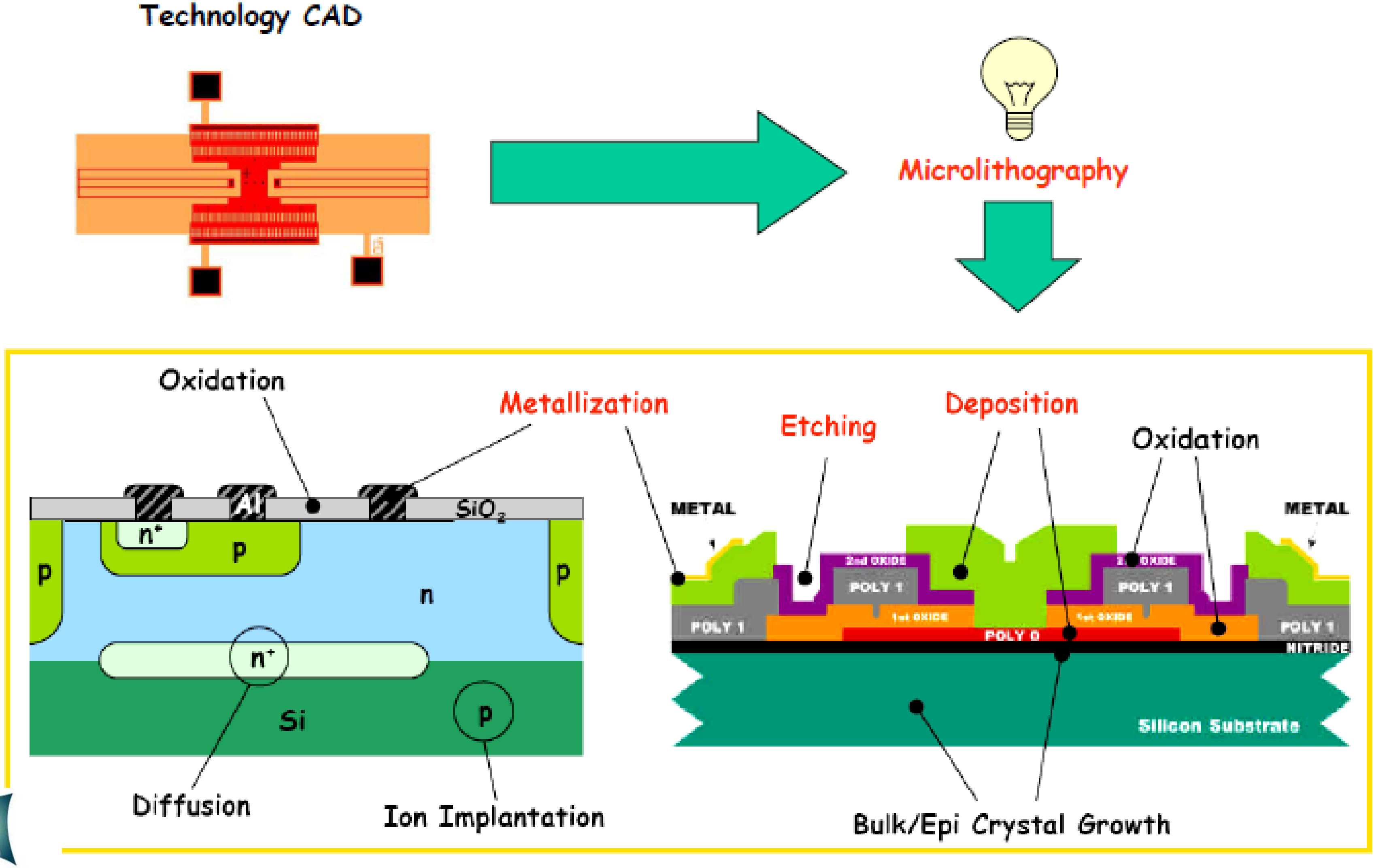


Imprinted Si

- Fast speed
- Direct patterning semiconductors
- Complex structures (e.g. lens) in Si
- With sub-10 nm resolution

Chou, S. et al., *Nature*, (2002)

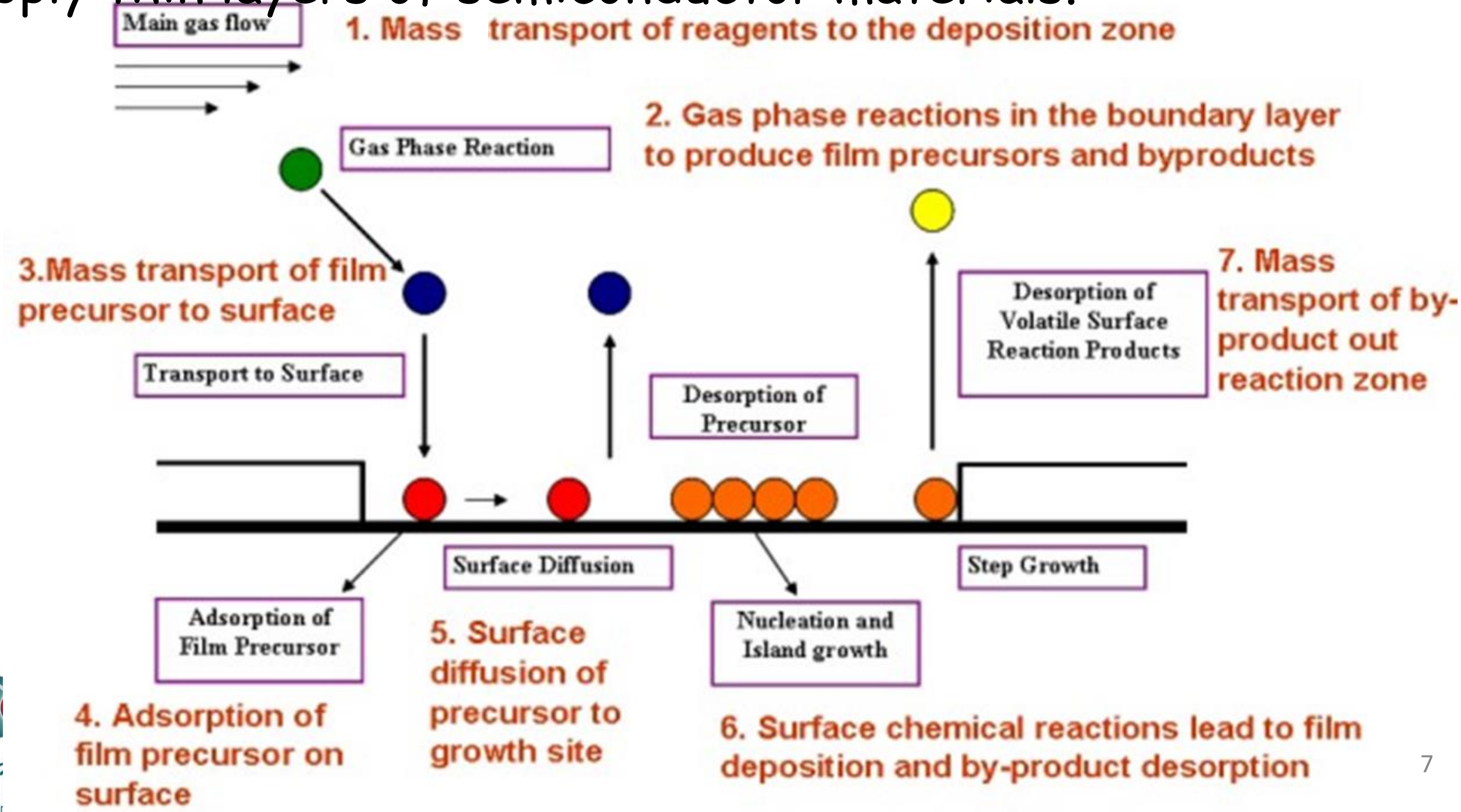
The Big Picture



Chemical Vapor Deposition Mechanism

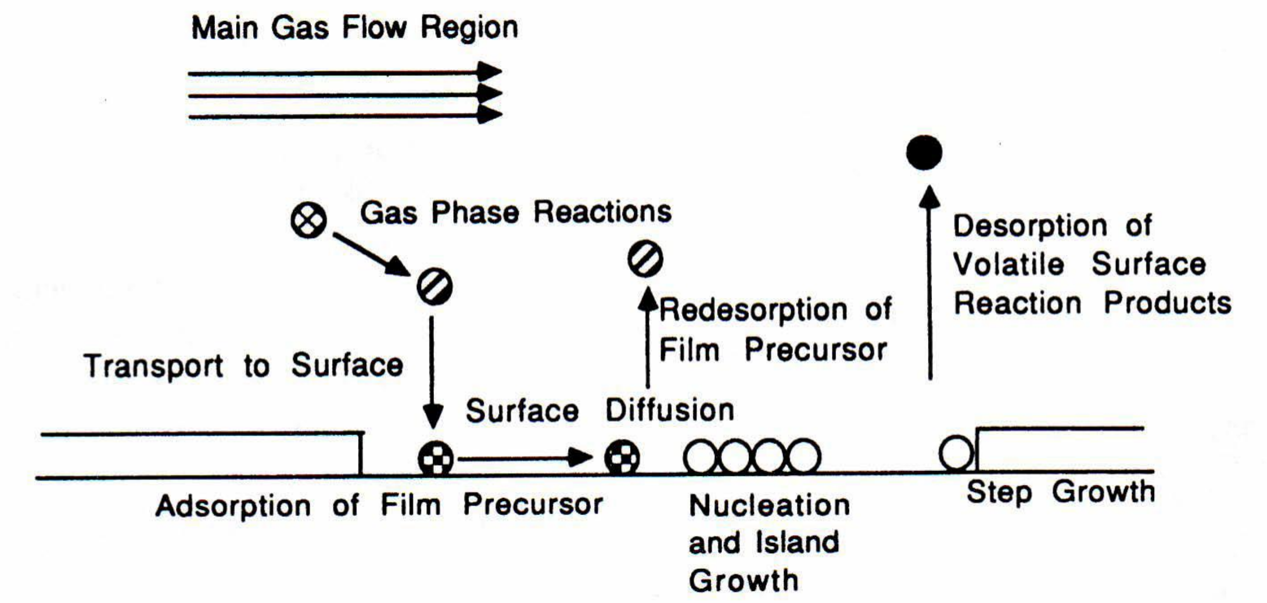
Chemical Vapor Deposition (CVD) :

Apply thin layers of semiconductor materials.



Transport and Reaction Processes of CVD

CVD of Si in a Si-Cl-H system

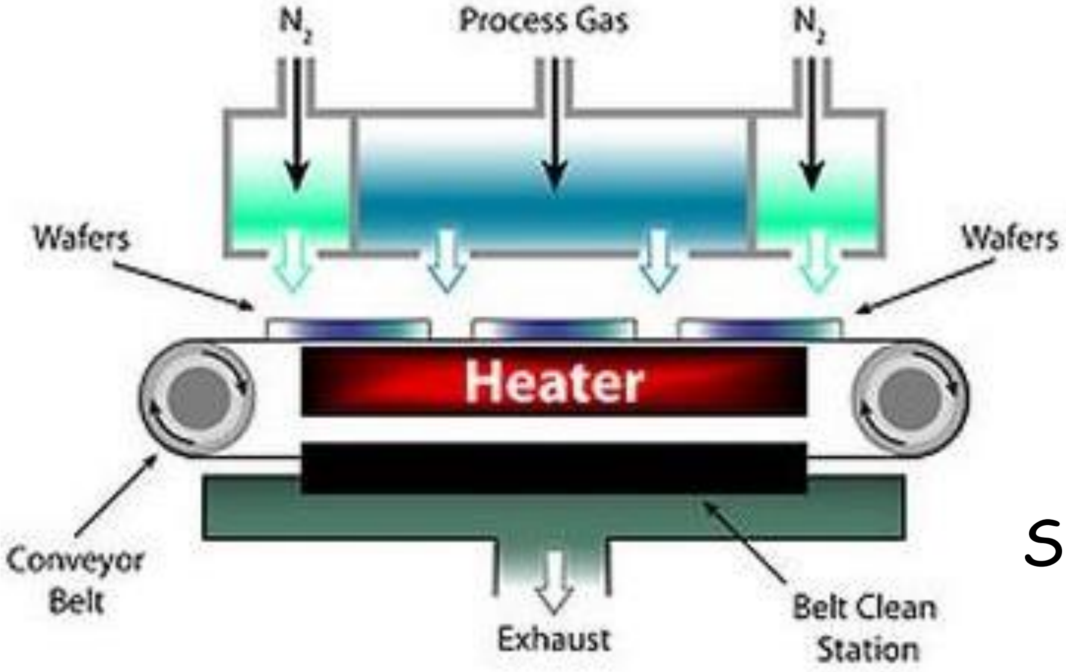


1. $SiCl_{4(g)} + 2H_{2(g)} \leftrightarrow Si_{(s)} + 4HCl_{(g)};$
2. $SiCl_3H_{(g)} + H_{2(g)} \leftrightarrow Si_{(s)} + 3HCl_{(g)};$
3. $SiCl_2H_{2(g)} \leftrightarrow Si_{(s)} + 2HCl_{(g)};$
4. $SiClH_{3(g)} \leftrightarrow Si_{(s)} + HCl_{(g)} + H_{2(g)};$
5. $SiCl_{2(g)} + H_{2(g)} \leftrightarrow Si_{(s)} + 2HCl_{(g)};$
6. $SiH_{4(g)} \leftrightarrow Si_{(s)} + 2H_{2(g)};$

Chemical Vapor Deposition Techniques 1

Atmospheric Pressure Chemical Vapor Deposition (APCVD)

- Dielectrics and metals
- Atmospheric pressure or partial pressure in N_2
- Low film purity
- Temperature of 600-1150°C

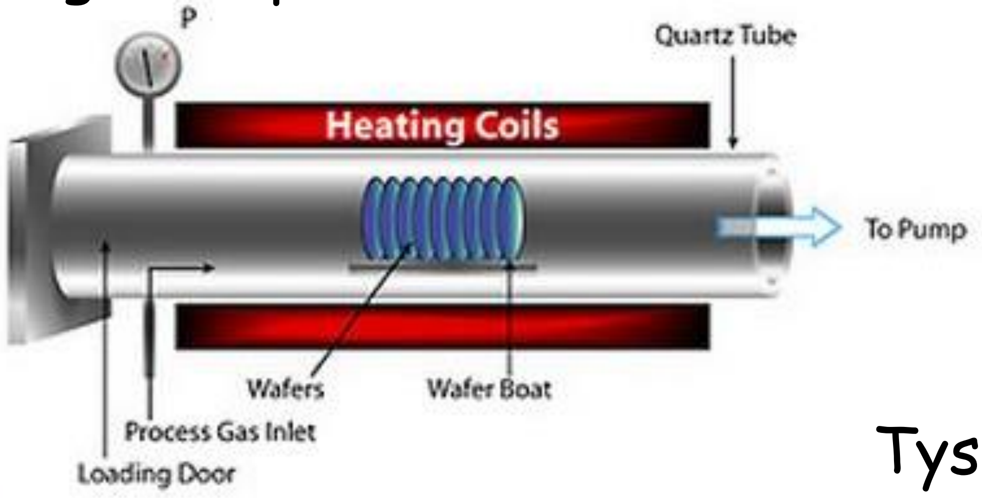


SierraTherm APCVD Furnaces

Chemical Vapor Deposition Techniques 2

Low-Pressure Chemical Vapor Deposition (LPCVD)

- Dielectrics and metals
- Performed at reduced pressure or "rough vacuum"
- 10^{-3} to 10^{-5} Torr (1 atm = 760 Torr)
- High purity
- High temperature

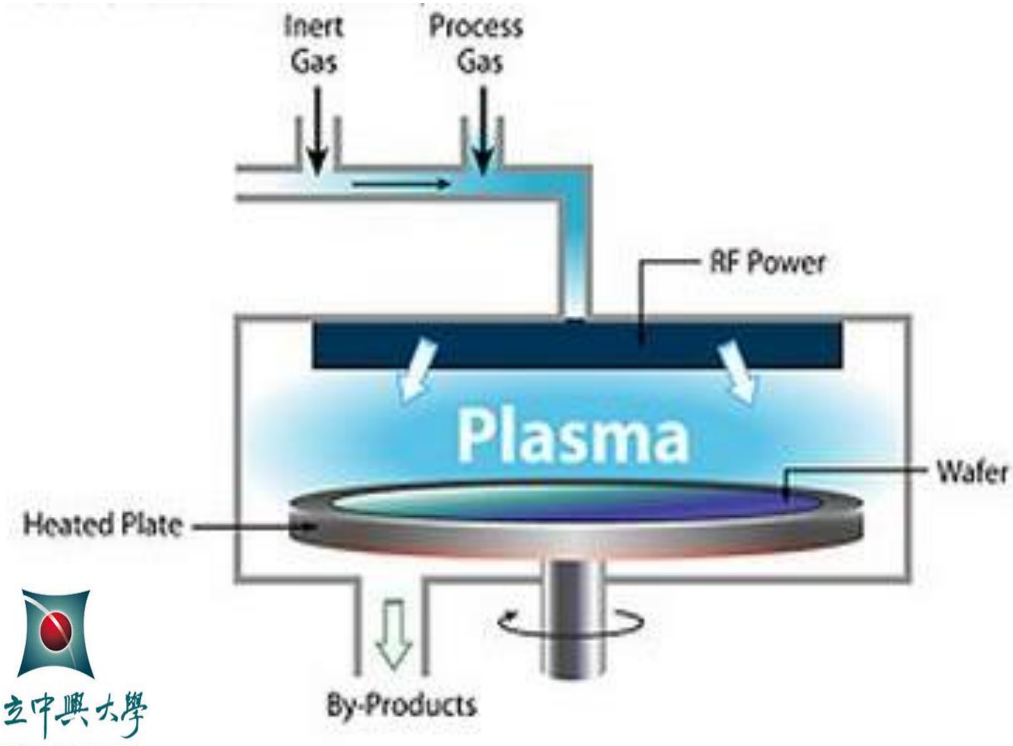


Tystar LPCVD Tube Furnaces

Chemical Vapor Deposition Techniques 3

Plasma Enhanced Chemical Vapor Deposition (PECVD)

- Dielectrics only
- 'High' vacuum (10^{-6} Torr)
- 300-400°C



Plasma-Therm 790 PECVD

Chemical Vapor Deposition Techniques

APCVD:

Advantages:

- Relatively low operating cost since no vacuum needed

Disadvantages:

- Uniformity of deposited layer compromised at higher temperatures and pressures
- Gas flow dynamics hard to control at high pressures

LPCVD:

Advantages:

- Lower reaction temperatures than APCVD reactors
- Good step coverage and uniformity
- Less dependence on gas flow dynamics

Disadvantages:

- More expensive than APCVD reactors
- Downstream depletion can occur in horizontal designs

PECVD:

Advantages:

- Combination of vacuum pressures and lower temperature produces better uniformity in the deposited layer.
- Reactor can be used in other microelectronic production process steps.

Disadvantages:

- More process variables to be controlled compared to other CVD reactors.
- Cost of operation is increased with increased number of components.

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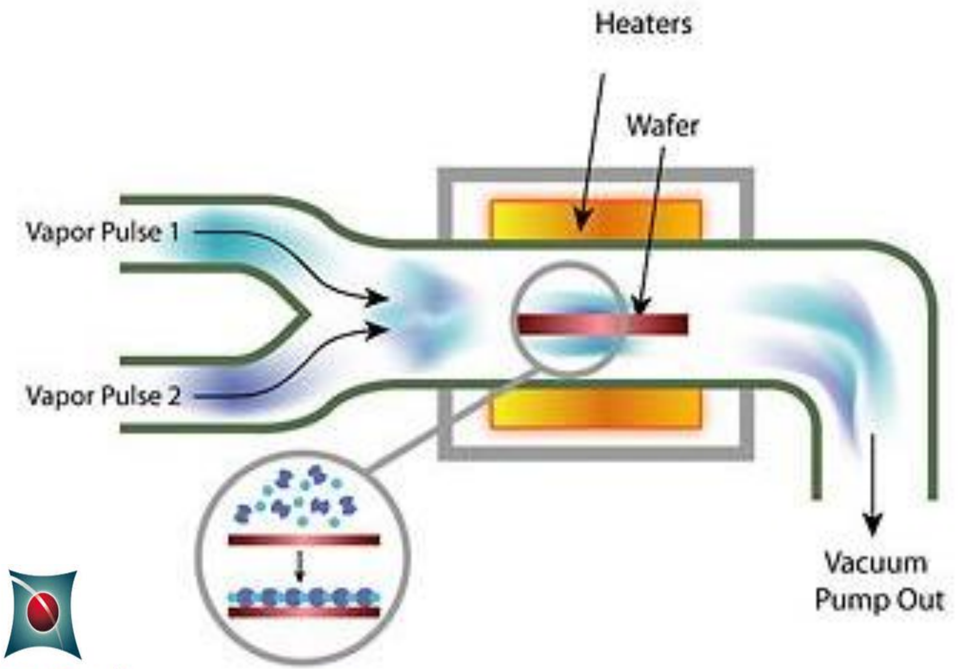
Chemical Vapor Deposition Techniques 4

Atomic Layer Deposition (ALD)

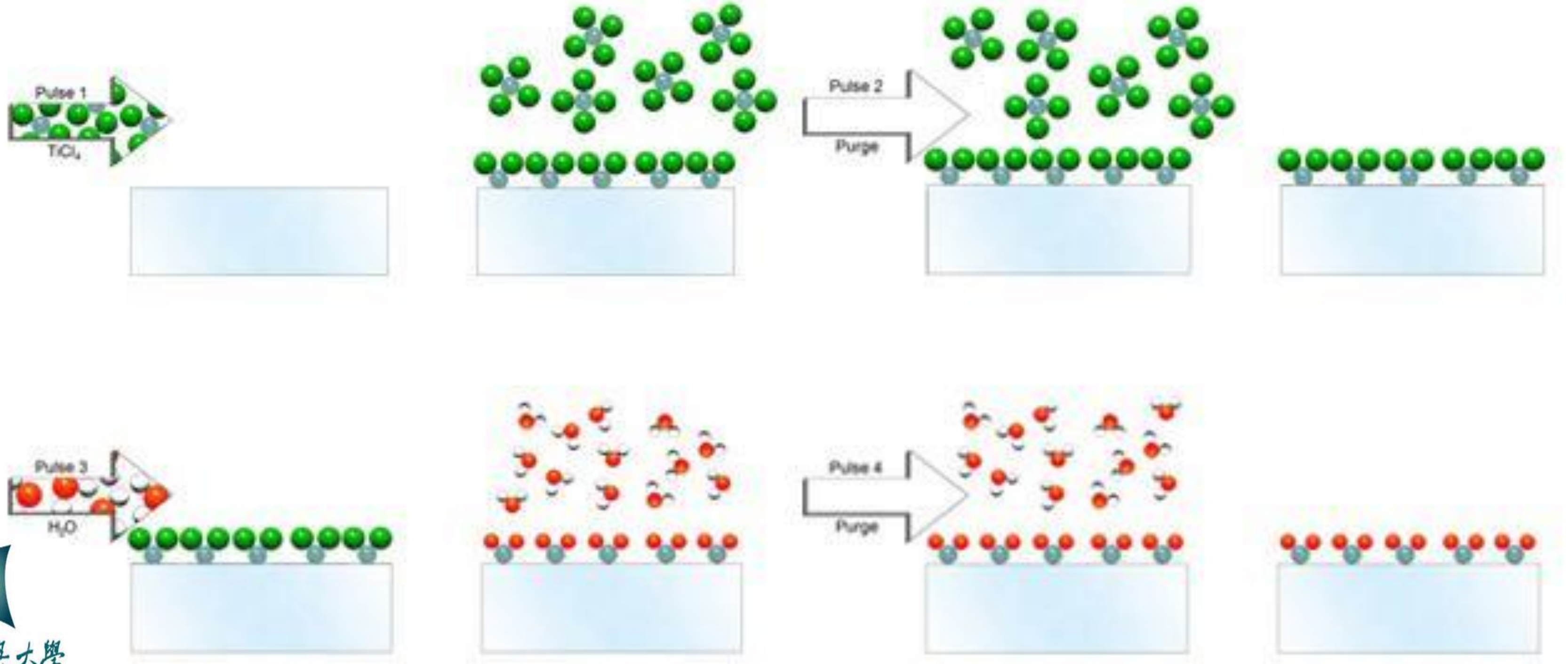
- Depositing one atomic layer at a time
- Highly uniform
- Process can be thermal or plasma-enhanced



NanoTech ALD

ALD Mechanism

1. Pulse of precursor is exposed to the surface.
2. Purge of excess unreacted precursor using inert gas.
3. Pulse of a second precursor followed by a surface reaction.
4. Purge of gaseous reaction by-products.



Physical (Vapor) Deposition Mechanism

Physical vapor deposition (PVD):

Deposit thin films by the condensation of a vaporized material onto substrate surface.

- Assure low contamination
- Large mean free path at low pressures

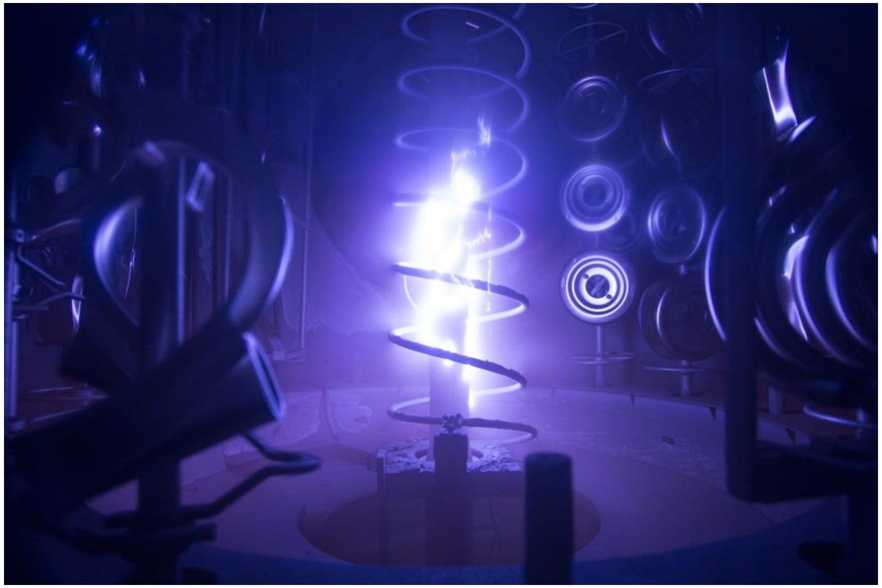
Source (Sloid/Liquid)

↓ Evaporation

Gas Phase

↓ Transport & Deposition

Solid Phase

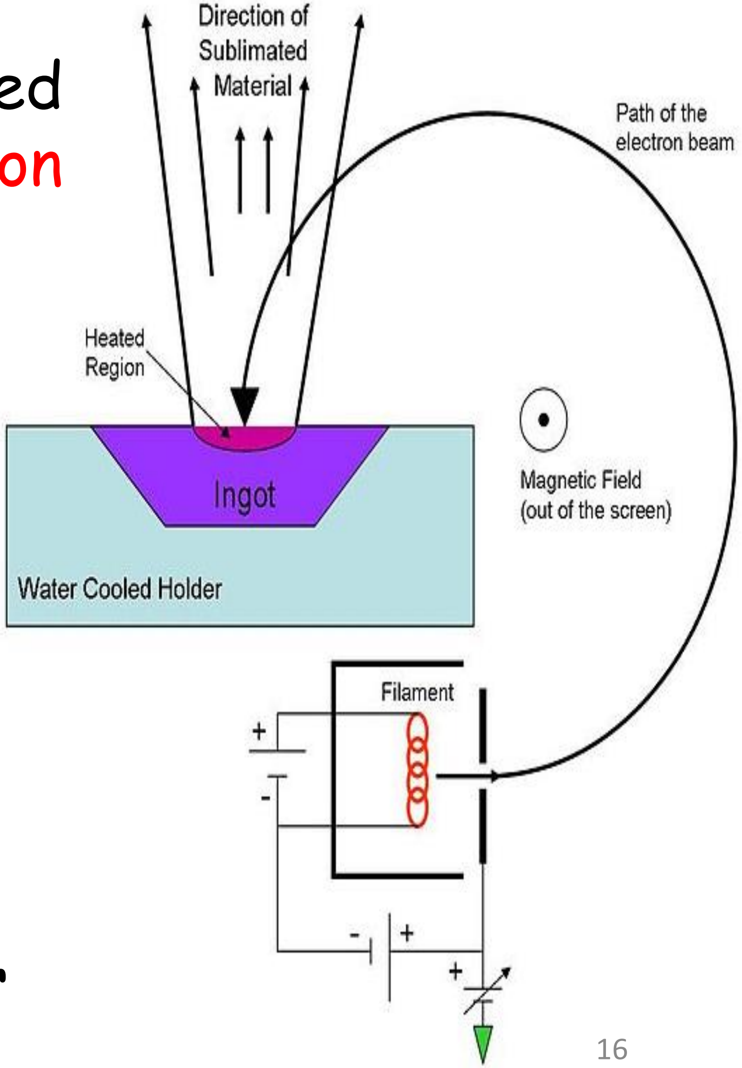


Physical Deposition Techniques 1

Evaporator Deposition:

The deposited materials are evaporated or sublimated, either by an electron beam or a heated source.

- Mainly metals
- High vacuum (10^{-6} Torr)



Edwards E306A thermal evaporator

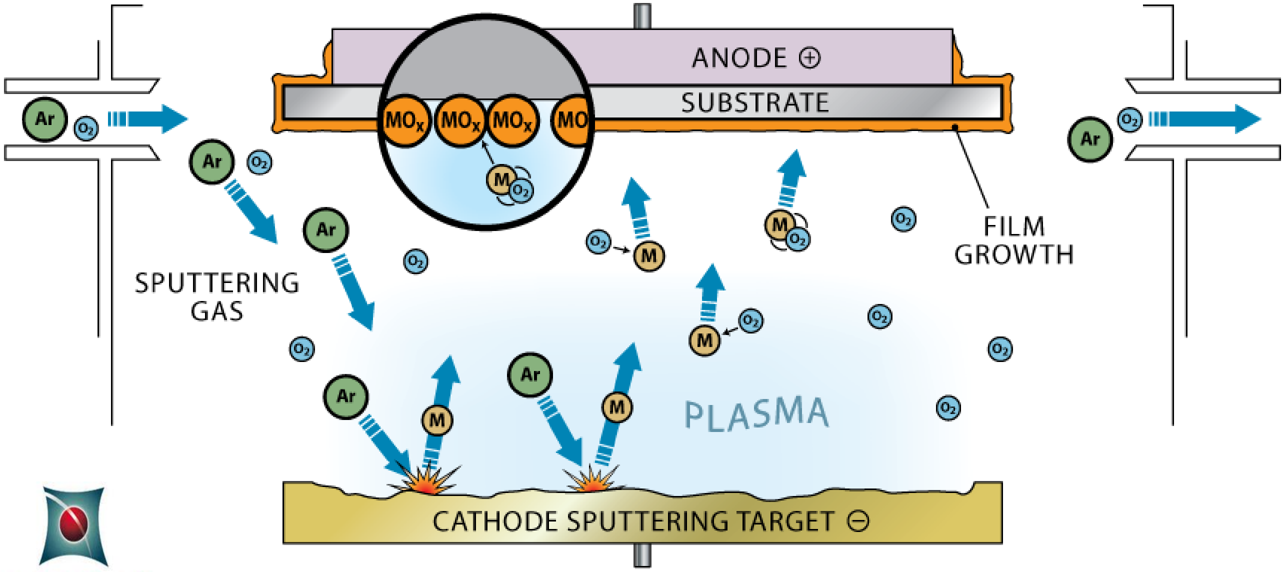
Denton DV-502A e-beam evaporator

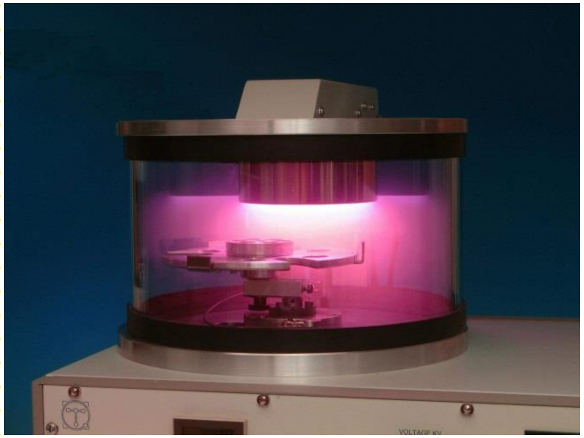
Physical Deposition Techniques 2

Sputter Deposition:

Sputtering involves the collisions of ions (Ar·) with target material, leading to the ejection of target atoms that are collected on a substrate.

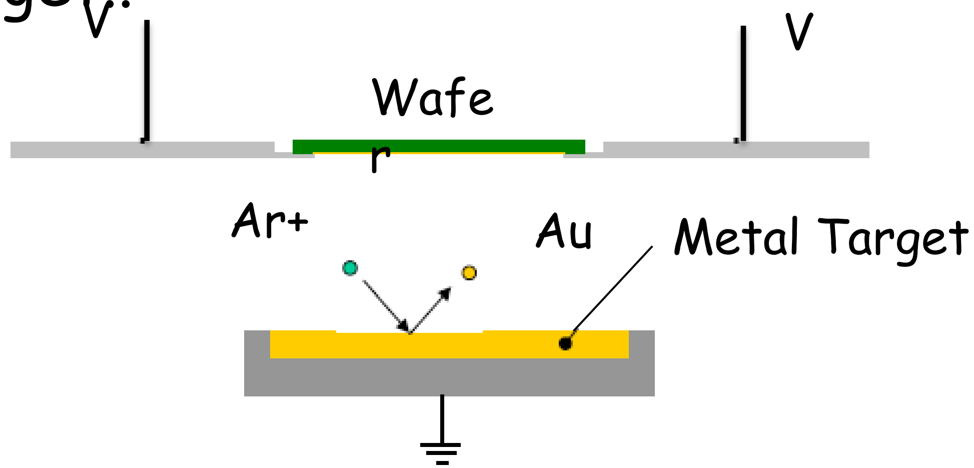
- Metals and dielectrics
- High vacuum (10^{-6} Torr)





Sputtering Process

A high electric field ionizes argon atoms and accelerates them into a metal target.



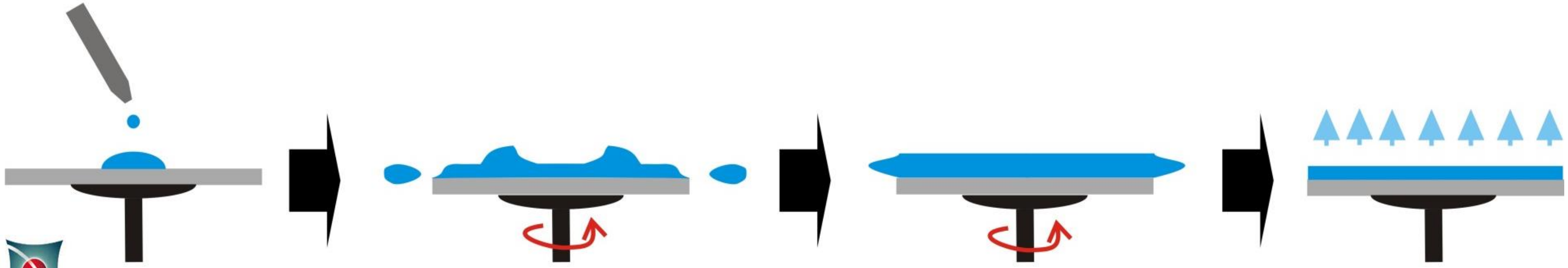
- Forms very uniform films
- Excellent step coverage (distributed angles of impact)
- Sputtering allows easy deposition of alloys (Al-Cu-Si)
- Wafer heating less than 300°C
- Sputtering of dielectrics uses both DC and RF fields

Physical Deposition Techniques 3

Spin-on Deposition:

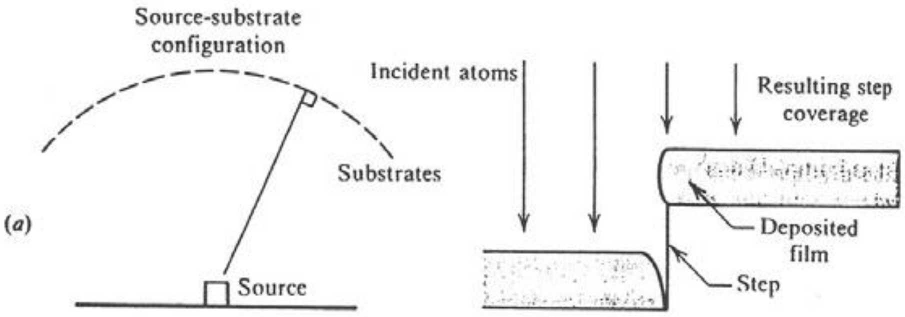
Coat the substrate with material which is originally in the liquid form. Liquid is dispensed onto the substrate surface and the substrate is rapidly rotated (during spinning, liquid is uniformly distributed on the surface by centrifugal forces), material is then solidified.

- Glass dielectrics
- Performed at atmosphere
- 100-1000°C

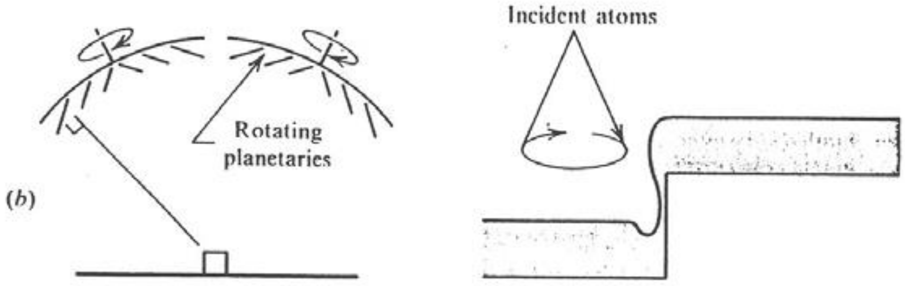


Step Coverage in PVD

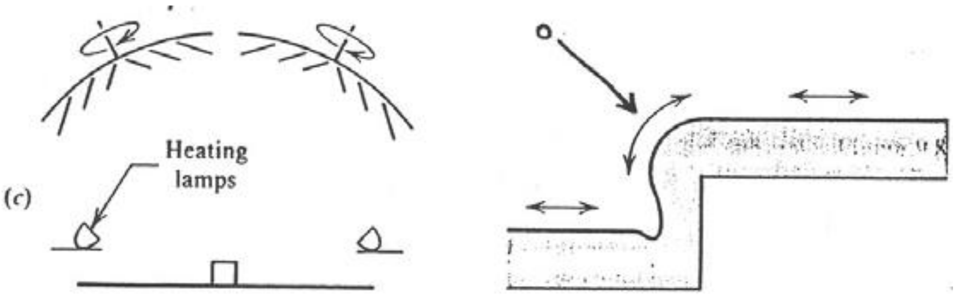
Factors governing step coverage in evaporation:



Perpendicular step on perpendicular substrate.
No coverage.



Rotating planetaries with substrate inclination.
Improved coverage.



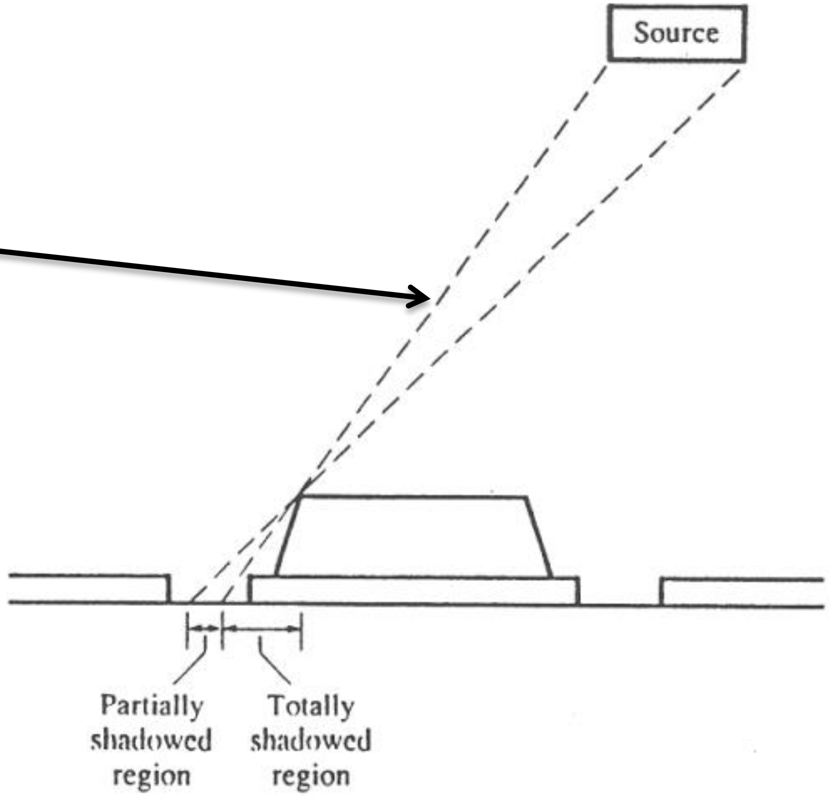
Same as (b) with substrate heating.
Further improved coverage.
(Heat raises the surface mobility of atoms and improves step coverage)

Reduced slope of step, plus rotation and heating.
No thinning over step.

Shadowed Deposition

Material deposition is highly dependent on the orientation angle of the samples due to the large mean free path of the depositing atoms.

Large mean free path (λ) allows a direct path from source to substrate.



Great for lift-off process

Film Etching

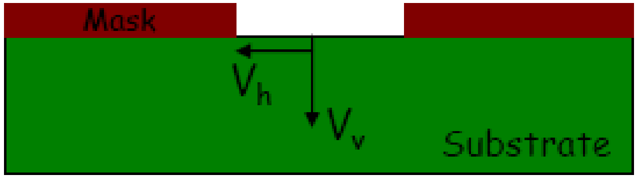
Materials of interest:

- Conductors: Al, Cu, Au, Cr
- Dielectrics: SiO_2, Si_3N_4, Polyimide
- Semiconductors: Si, GaAs

Etches are characterized by the verticality and anisotropy.

- If Vh is the horizontal etch rate and Vv is the vertical etch rate, the anisotropy can be given by:

$$A = 1 - \frac{V_h}{V_v}$$



- A=1 for fully anisotropic etches (Vh =0)
- A=0 for fully isotropic etches (Vv =0)

Etches can be performed using chemical solutions (wet) or plasmas (dry).

Isotropic Wet Etching

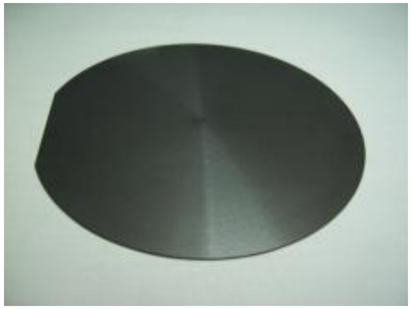
Wet etching of amorphous (polycrystalline) materials is usually isotropic, meaning no direction is favored.

- SiO_2: buffered hydrofluoric acid (HF)
- Si_3N_4: hot phosphoric acid (65-70 °C)
- Al: nitric/phosphoric/acetic acid (can't use if on GaAs!) or hydrochloric acid (HCl; OK on GaAs)
- PolySi: HF and nitric acid
- Cr: potassium permanganate
- Au: potassium iodide and iodine (KI/I_2)

Anisotropic Wet Etching

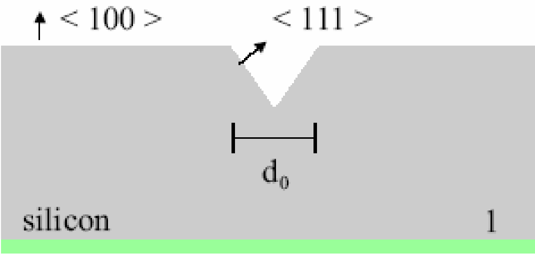
Wet etching of crystalline (single-crystal) materials is usually anisotropic, meaning some crystallographic directions are favored than others.

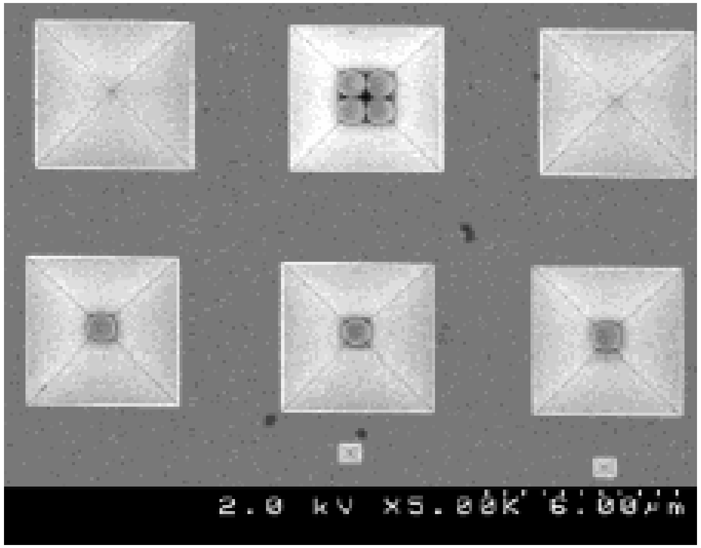
- Silicon – anisotropic etch: basis of silicon micromechanics.
- GaAs – anisotropic etch: bromine and methanol (highly exothermic!!) or hydrogen peroxide/sulfuric acid.



Single-crystal

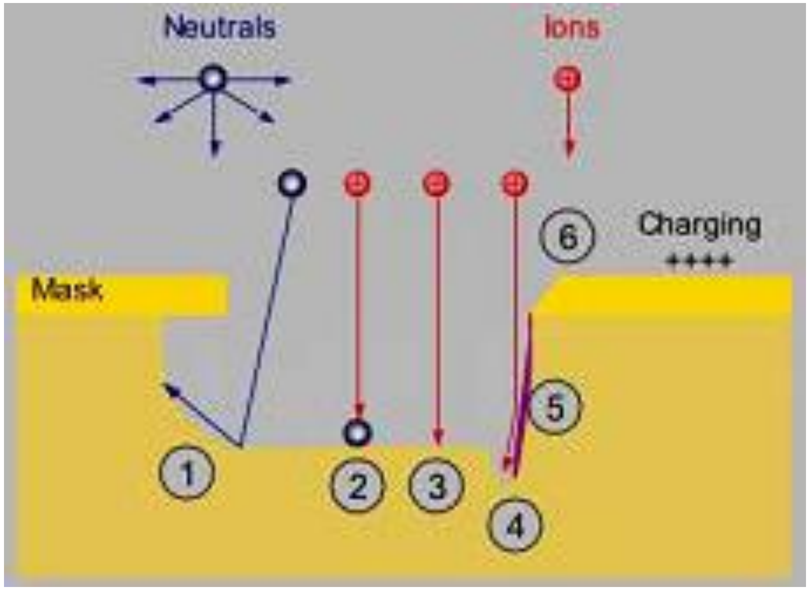
Multi-crystal





Pyramid shaped pits in Si (100)

Overview of Plasma Etch Mechanisms



1. **Chemical etching**:
   Spontaneous, isotropic, very selective.
2. **Ion enhanced etching**:
   Neutrals and ions involved, ion energy needed to stimulate chemical reaction or to remove reaction products. Anisotropic and selective.
3. **Physical etching**:
   Anisotropic and non-selective.
4. **Trenching**:
   Caused by ion deflection from sidewalls.
5. **Sidewall passivation**:
   Deposition of non-violate materials: Etch byproducts, surface reactions with gas or mask materials.
6. **Mask erosion**:
   Caused by ion bombardment/sputtering.

Electron-Impact Dissociation:

$e^- + O_2 \longrightarrow O + O + e^-$

$e^- + SF_6 \longrightarrow SF_5 + F + e^-$

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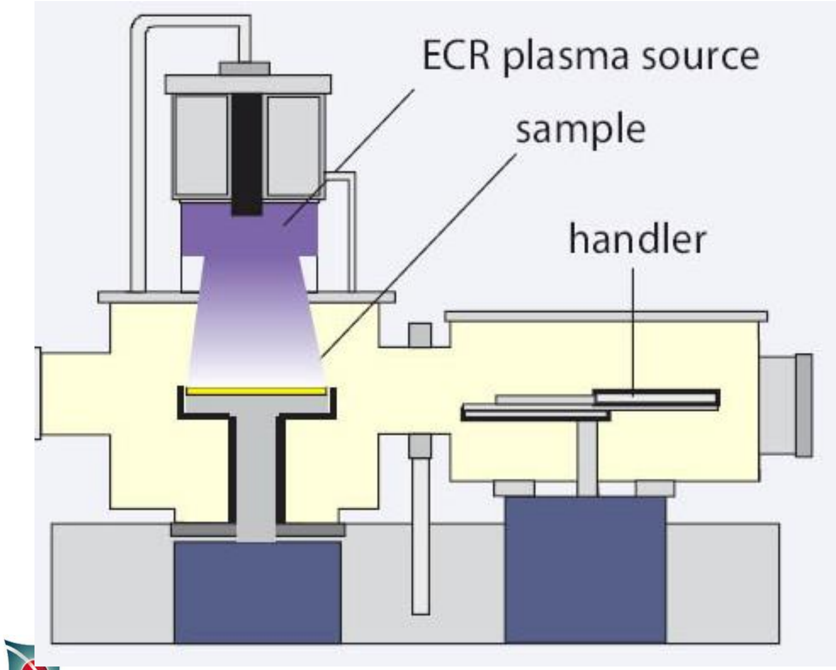
Dry Etching Techniques 1

Reactive ion etching (RIE)

- Isotropic: barrel configuration (or high gas pressure)
- Anisotropic: parallel plate configuration



Nanotech reactive ion etcher

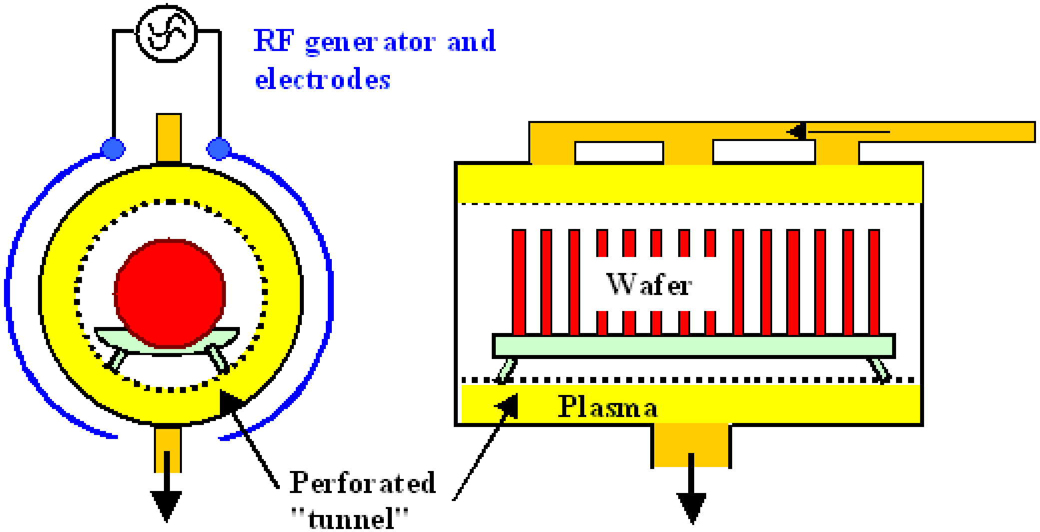
Dry Etching Techniques 2 & 3

Barrel etcher

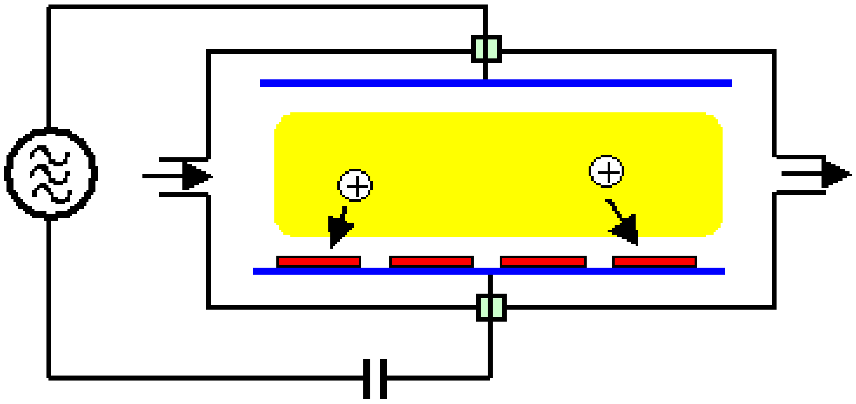
- Uniform stripping of films (e.g. resist)

Parallel plate etcher

- High anisotropy



Barrel etcher



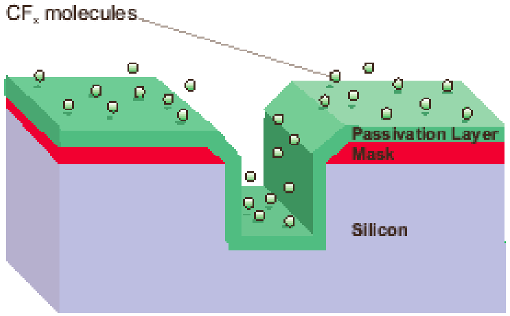
Parallel plate etcher

Dry Etching Techniques 4

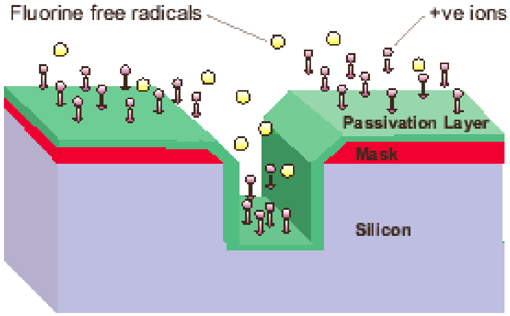
Deep Reactive Ion Etch (DRIE)

Anisotropy arises from material processes as redeposition / passivation. Anisotropy enhanced by:

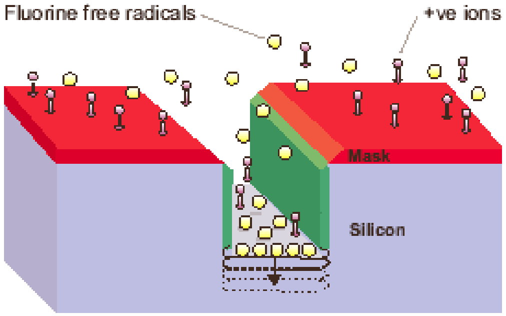
- Sputtering – physical removal of atoms
- Chemical reaction and heating due to bombardment
- Protective sidewall residue enhances vertical etch rate



Passivation Step: At the beginning of each cycle a C_4F_8 based plasma is used to conformally deposit a few monolayers of PTFE-like fluorocarbon polymer across all surfaces exposed to the plasma.



Etch Step 1: The plasma gas is then switched to SF_6 to create a plasma chemistry that isotropically etches silicon. Through the application of a d.c. bias to the platen, ions from the plasma bombard the surface of the wafer, removing the polymer. Increased ion energy in the vertical direction results in a much higher rate of removal of fluorocarbon polymer from surfaces parallel to the wafer surface.



Etch Step 2: Following selective polymer removal, the silicon surface at the base of the trench is exposed to reactive fluorine-based species that isotropically etch the unprotected silicon. The remaining fluorocarbon polymer protects the vertical walls of the trench from etching.

Common Plasma Etchants

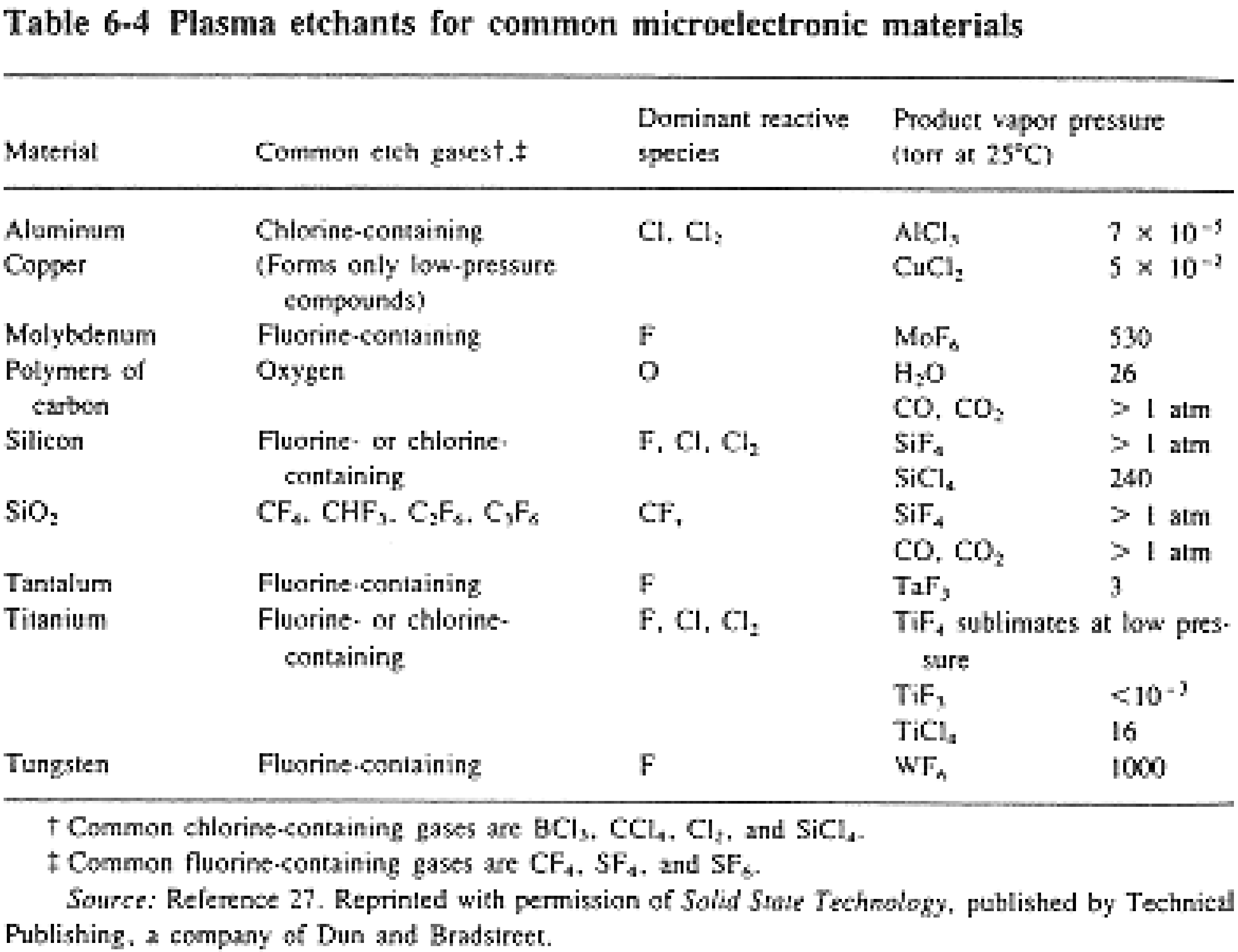


Table 6-4 Plasma etchants for common microelectronic materials

Material	Common etch gases†,‡	Dominant reactive species	Product vapor pressure (torr at 25°C)	
Aluminum	Chlorine-containing	Cl, Cl_2	$AlCl_3$	7×10^{-3}
Copper	(Forms only low-pressure compounds)		$CuCl_2$	5×10^{-2}
Molybdenum	Fluorine-containing	F	MoF_6	530
Polymers of carbon	Oxygen	O	H_2O	26
			CO, CO_2	> 1 atm
Silicon	Fluorine- or chlorine-containing	F, Cl, Cl_2	SiF_4	> 1 atm
			$SiCl_4$	240
SiO_2	CF_4, CHF_3, C_2F_6, C_3F_8	CF_x	SiF_4	> 1 atm
			CO, CO_2	> 1 atm
Tantalum	Fluorine-containing	F	TaF_5	3
Titanium	Fluorine- or chlorine-containing	F, Cl, Cl_2	TiF_4 sublimates at low pressure	
			TiF_3	$<10^{-2}$
			$TiCl_4$	16
Tungsten	Fluorine-containing	F	WF_6	1000

† Common chlorine-containing gases are BCl_3, CCl_4, Cl_2, and $SiCl_4$.

‡ Common fluorine-containing gases are CF_4, SF_4, and SF_6.

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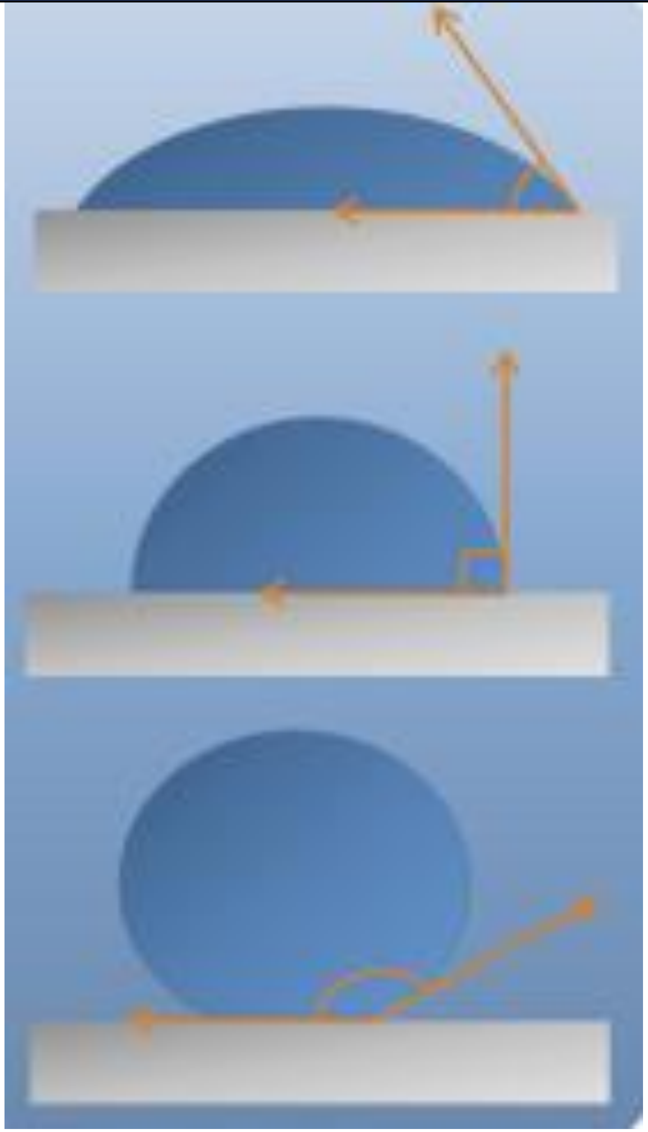
Superhydrophobic/Self-Cleaning Coatings

Hydrophilic

Hydrophobic

What does "Superhydrophobicity" mean?



Hydrophilic Surface:

Water Contact Angle $< 90^o$

Hydrophobic Surface:

Water Contact Angle $> 90^o$

Superhydrophobic Surface:

Water Contact Angle $> 150^o$

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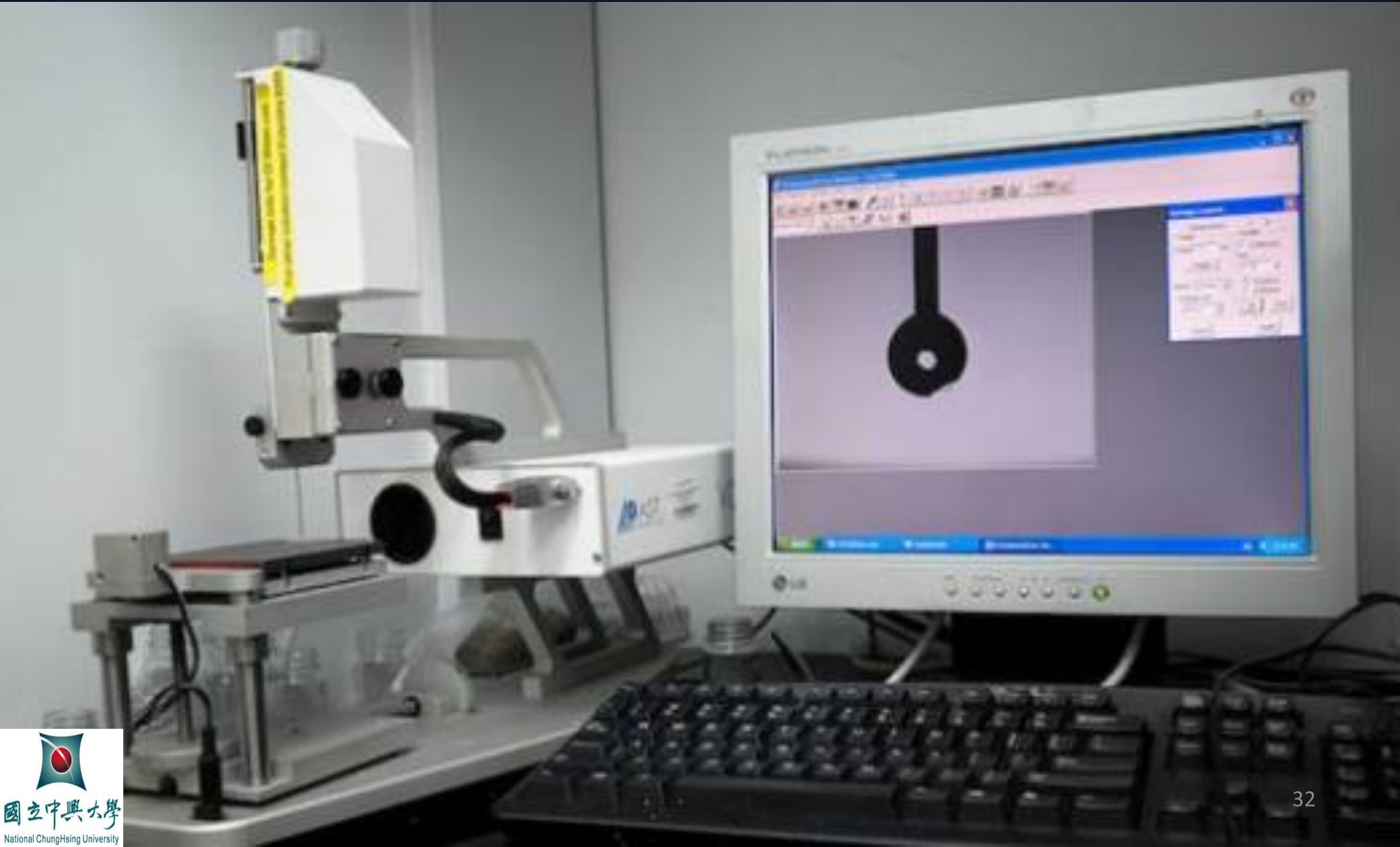
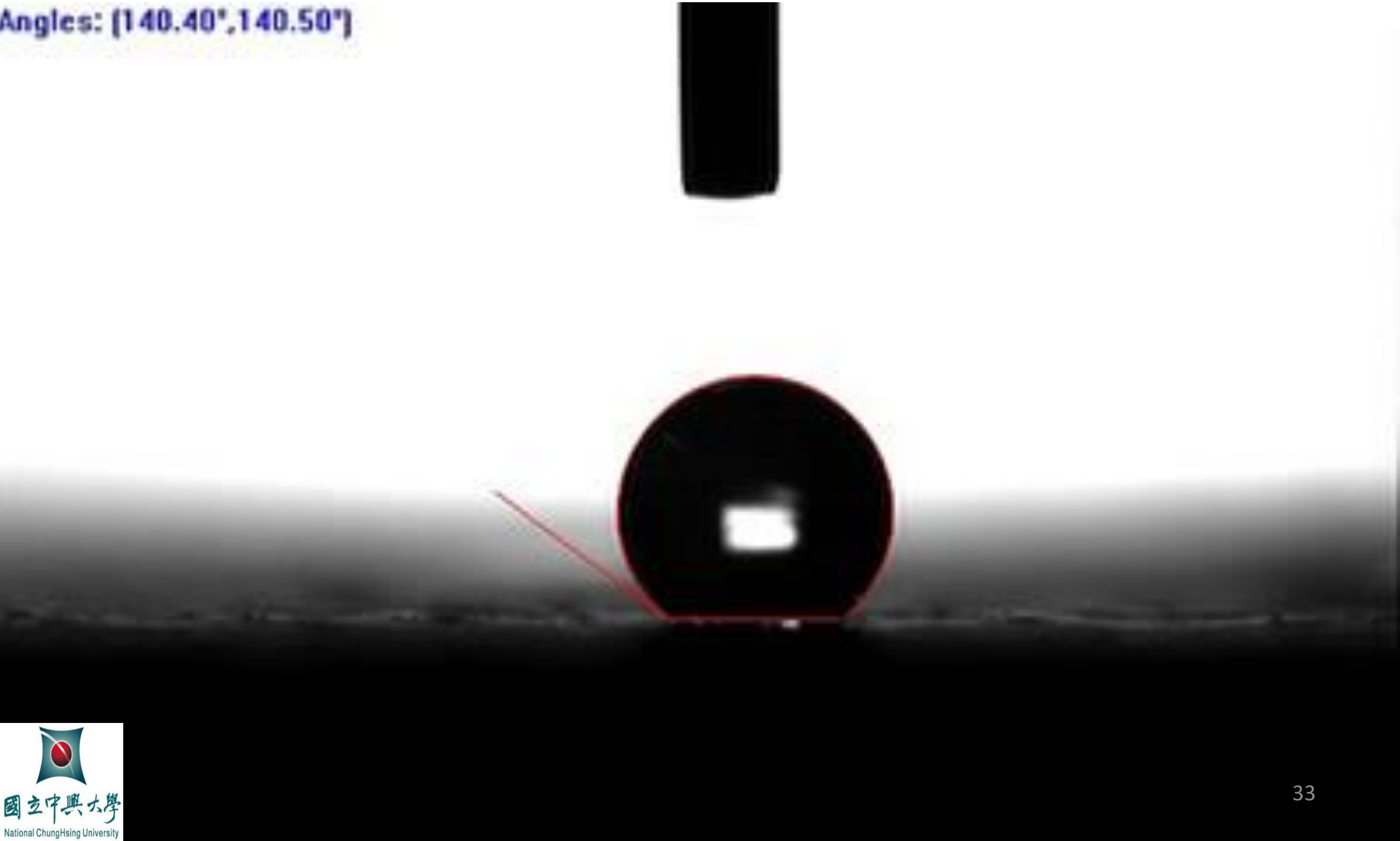
Water Contact Angle Measurement

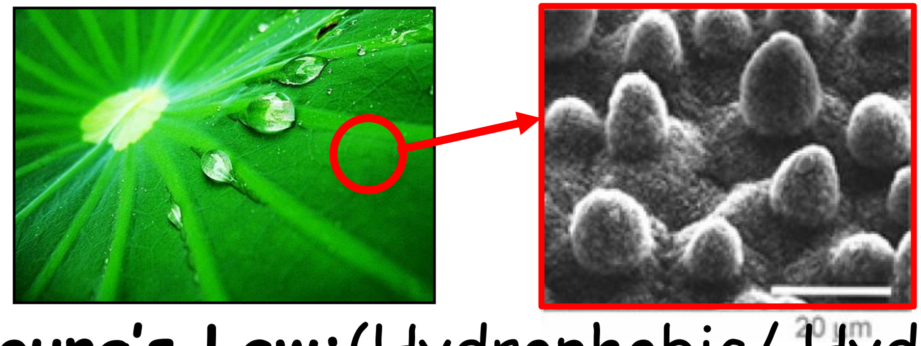


Measure Water Contact Angle



Superhydrophobic Surface

Lotus Effect: Water Contact Angle > 150°

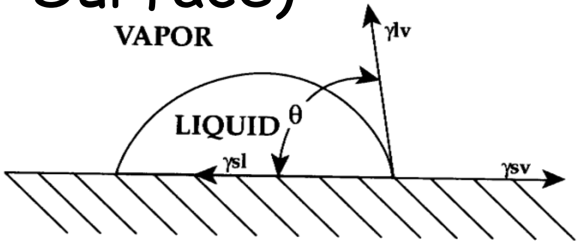


Factors affect lotus effect:

- Hydrophobic surface
- High surface roughness

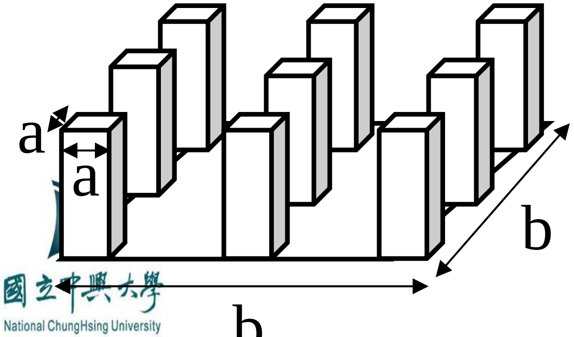
Young's Law:(Hydrophobic/ Hydrophilic Flat Surface)

$$\cos\theta_Y = \frac{\gamma_{SV}-\gamma_{SL}}{\gamma_{LV}}$$



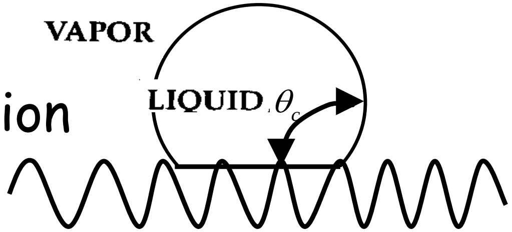
Cassie's Lew:(Hydrophobic Rough Surface)

$$\cos\theta_c = f\cdot(\cos\theta_Y+1)-1$$



f : Solid Projected Area Fraction

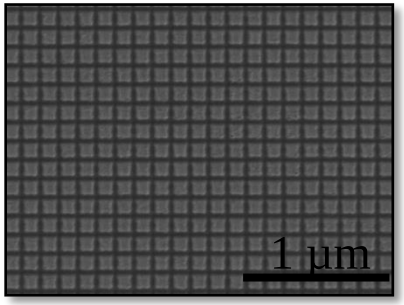
$$f=\frac{9a^2}{b^2}$$



Superhydrophobic Coating Technologies

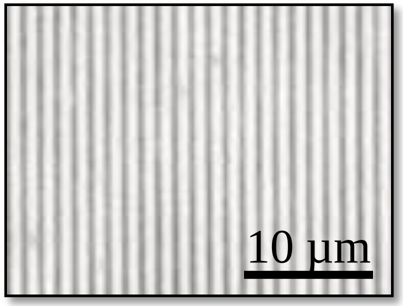
Top-Down Method

Focus Ion Beam Etching



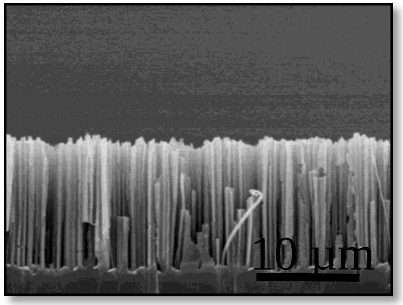
Principe, E L. et al, *Microscopy & Microanalysis* (2005)

Lithographic Patterning



Mazur, E.et.al, *Langmuir* (2006)

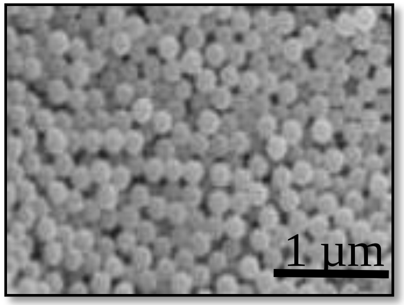
Reactive Ion Etching



Yang, H. et al, Submitted (2014)

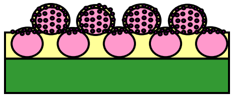
Bottom-Up Method

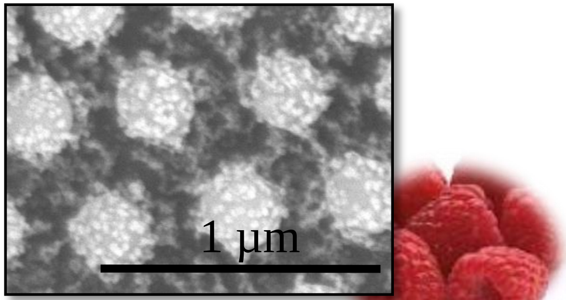
Multilayer Deposition Method



Yang, H. et al, *J. Colloid Inter. Sci.* (2008)

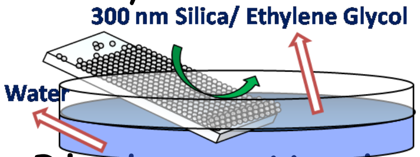
Spin-coating Tech.

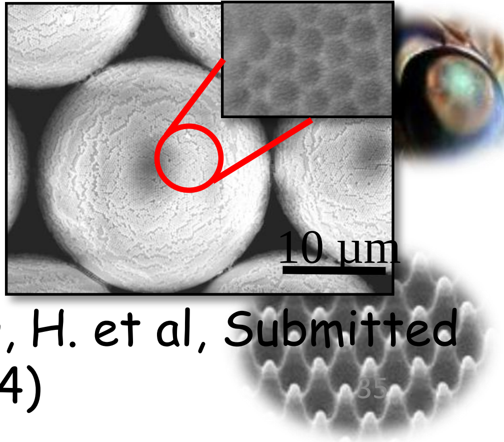




Yang, H. et al, *J. Colloid Inter. Sci.* (2010)

Langmuir-Blodgett Method



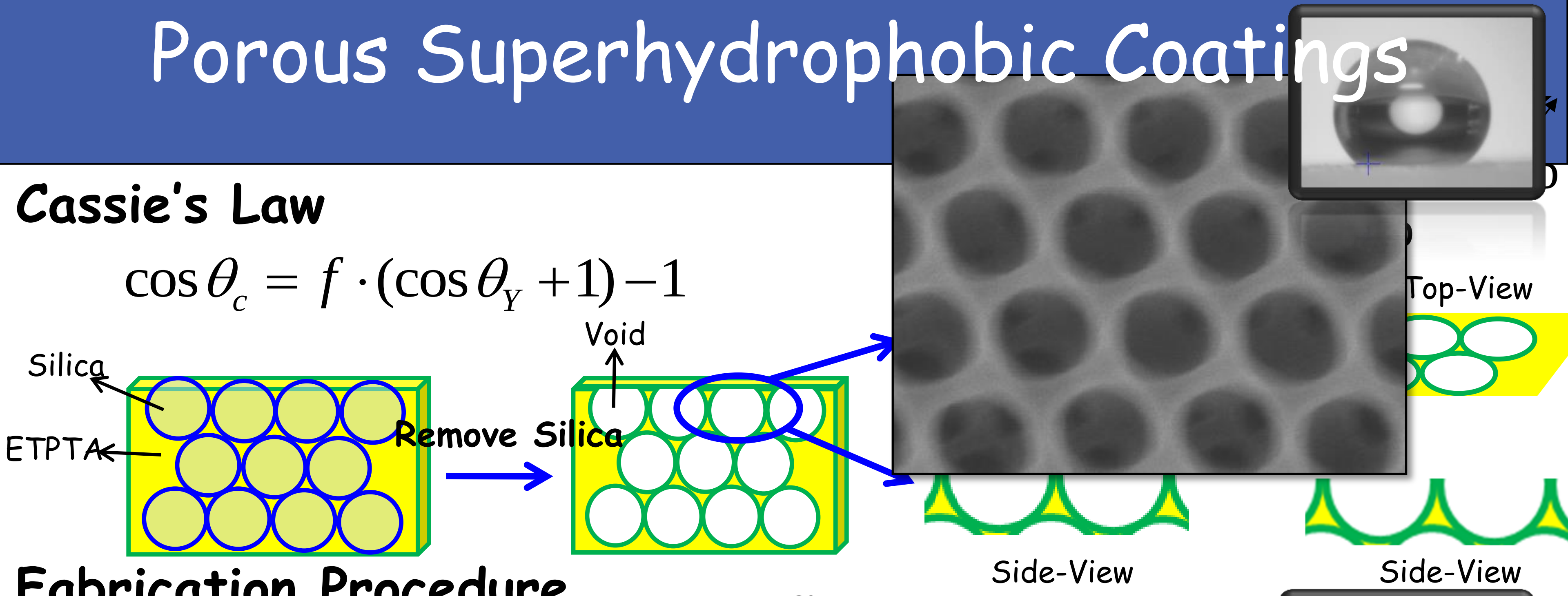


Yang, H. et al, Submitted (2014)

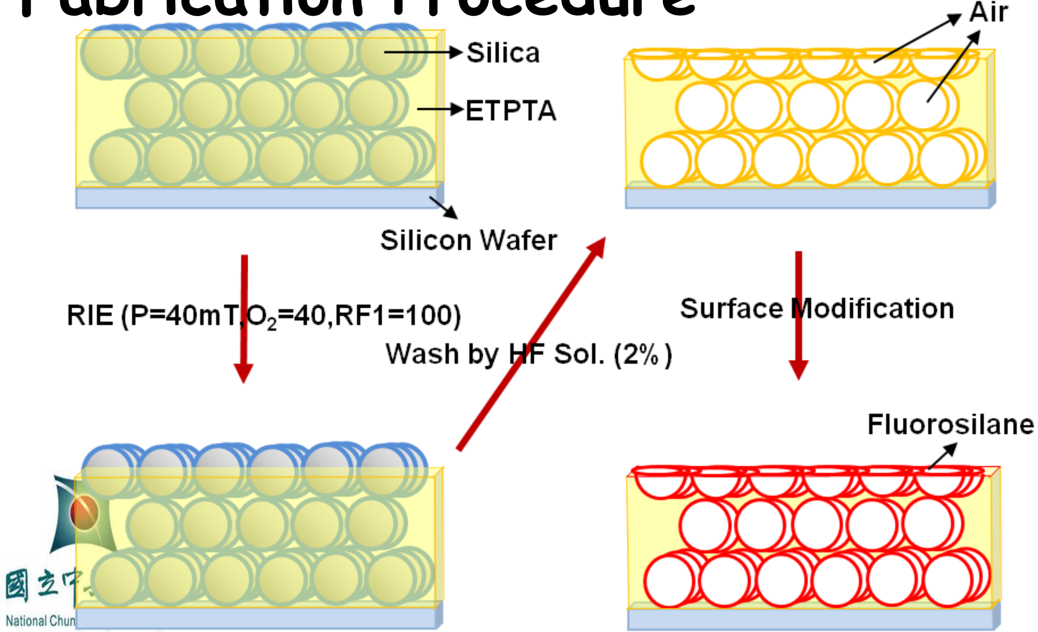
Porous Superhydrophobic Coatings

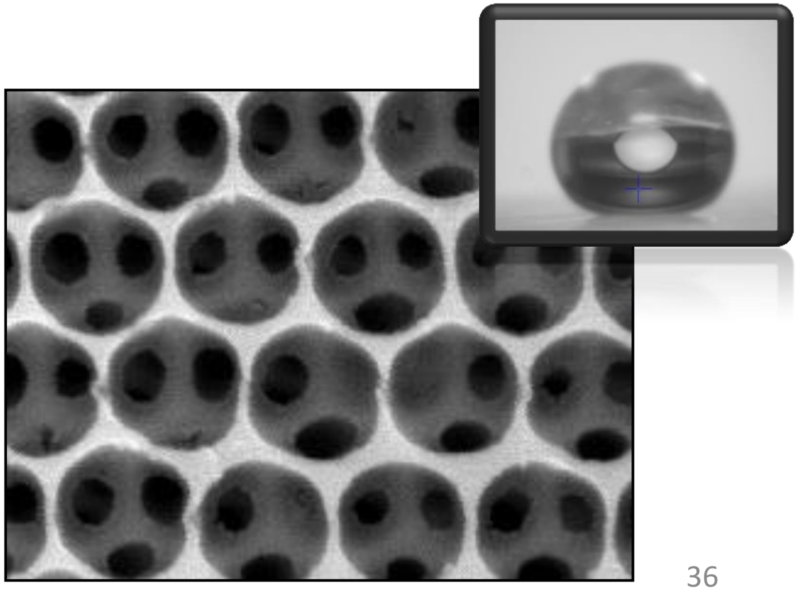
Cassie's Law

$$\cos\theta_c = f\cdot(\cos\theta_Y + 1) - 1$$



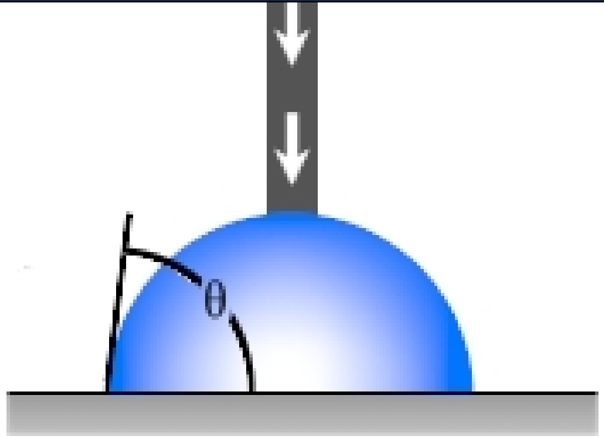
Fabrication Procedure



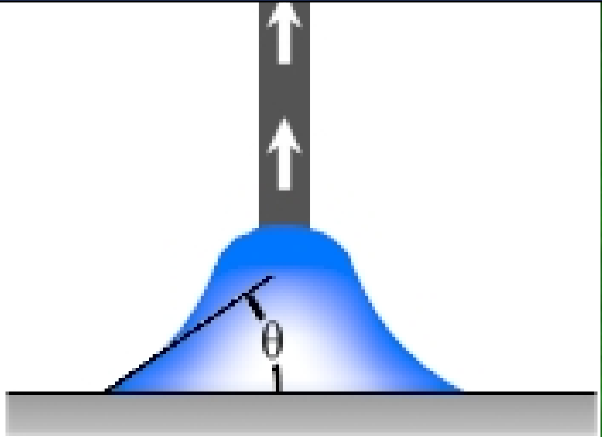


Yang, H. et al, *Langmuir* (2010)

What does “Self-Cleaning” mean?

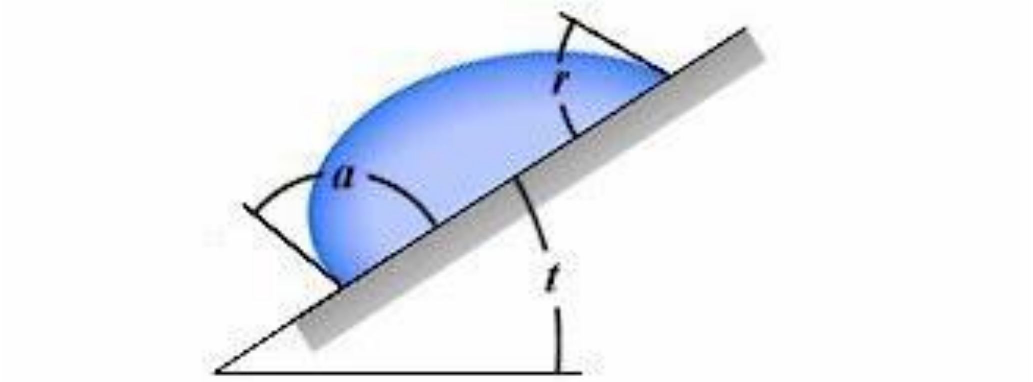


Advancing Angle

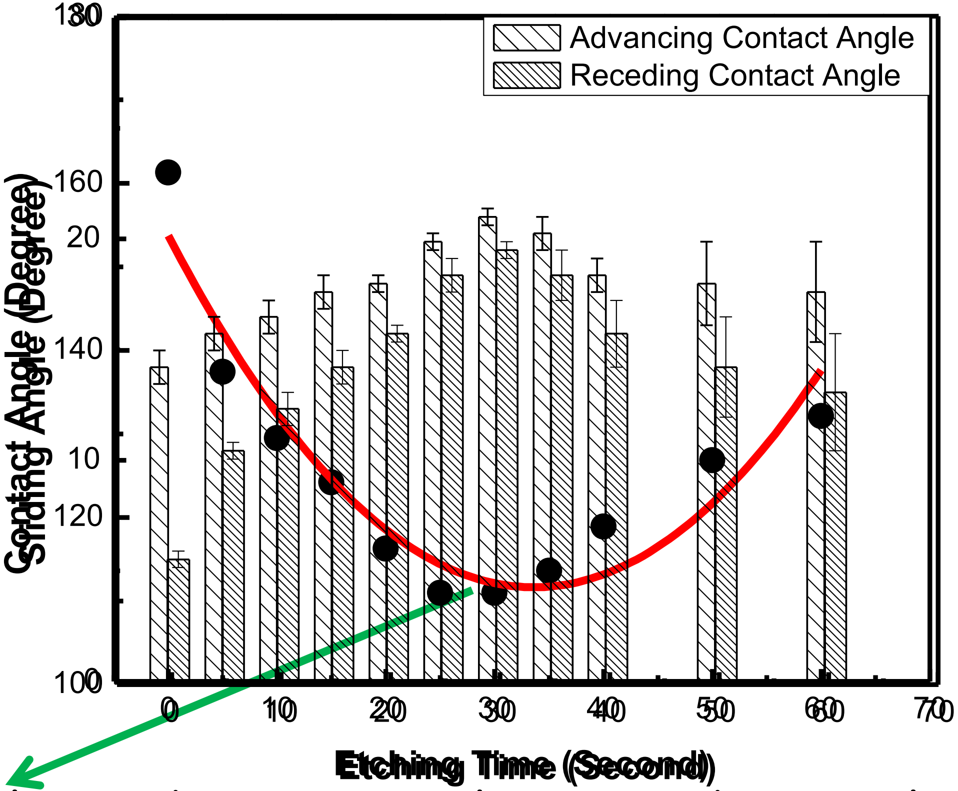


Receding Angle

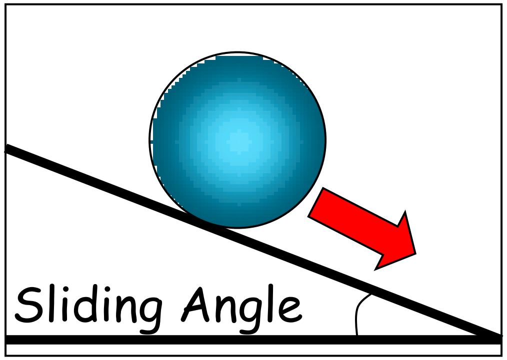
Sliding Angle
= Advancing Angle – Receding Angle

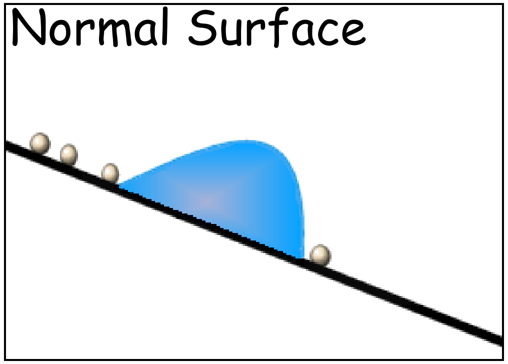


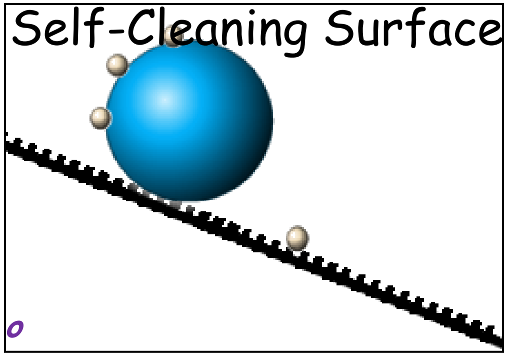
Self-Cleaning Surface

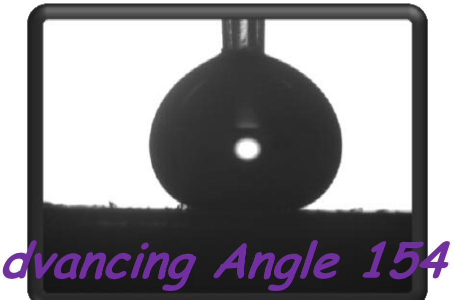


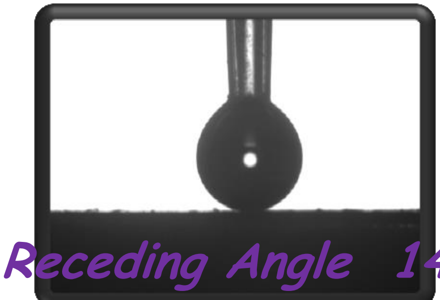
Sliding Angle = Advancing Angle – Receding Angle











Advancing Angle 154° *Receding Angle 149°*

Self-Cleaning Property

🟩 Flat ETPTA

🟦 Surface-Modified Flat ETPTA

🟥 Surface-Modified Macroporous ETPTA (0 Sec RIE)

🟨 Surface-Modified Macroporous ETPTA (30 Sec RIE)

Spray Escherichia coli-ampicillin Solution

↓

Offer an Inclining Angle of 5°

↓

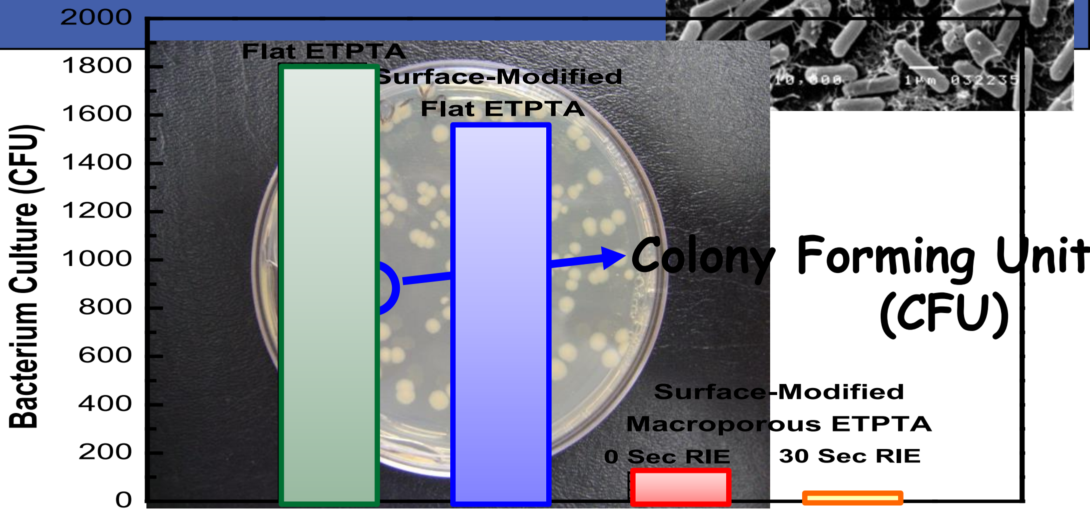
Submerge in LB Broth Medium Respectively

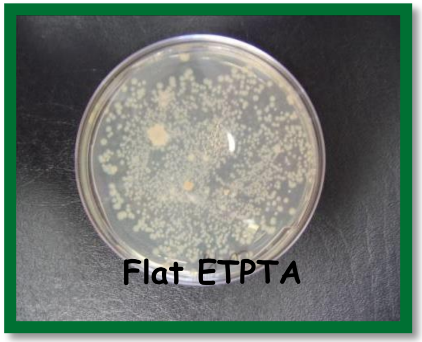
↓

Culture at 37°C for 24 Hours Respectively

↓

Account the CFU of E-coli in the LB Broth Agar Medium Respectively





Flat ETPTA

Surface-Modified Flat ETPTA

Surface-Modified Macroporous ETPTA (0 Sec RIE)

Surface-Modified Macroporous ETPTA (30 Sec RIE)

Applications of Self-Cleaning Surface