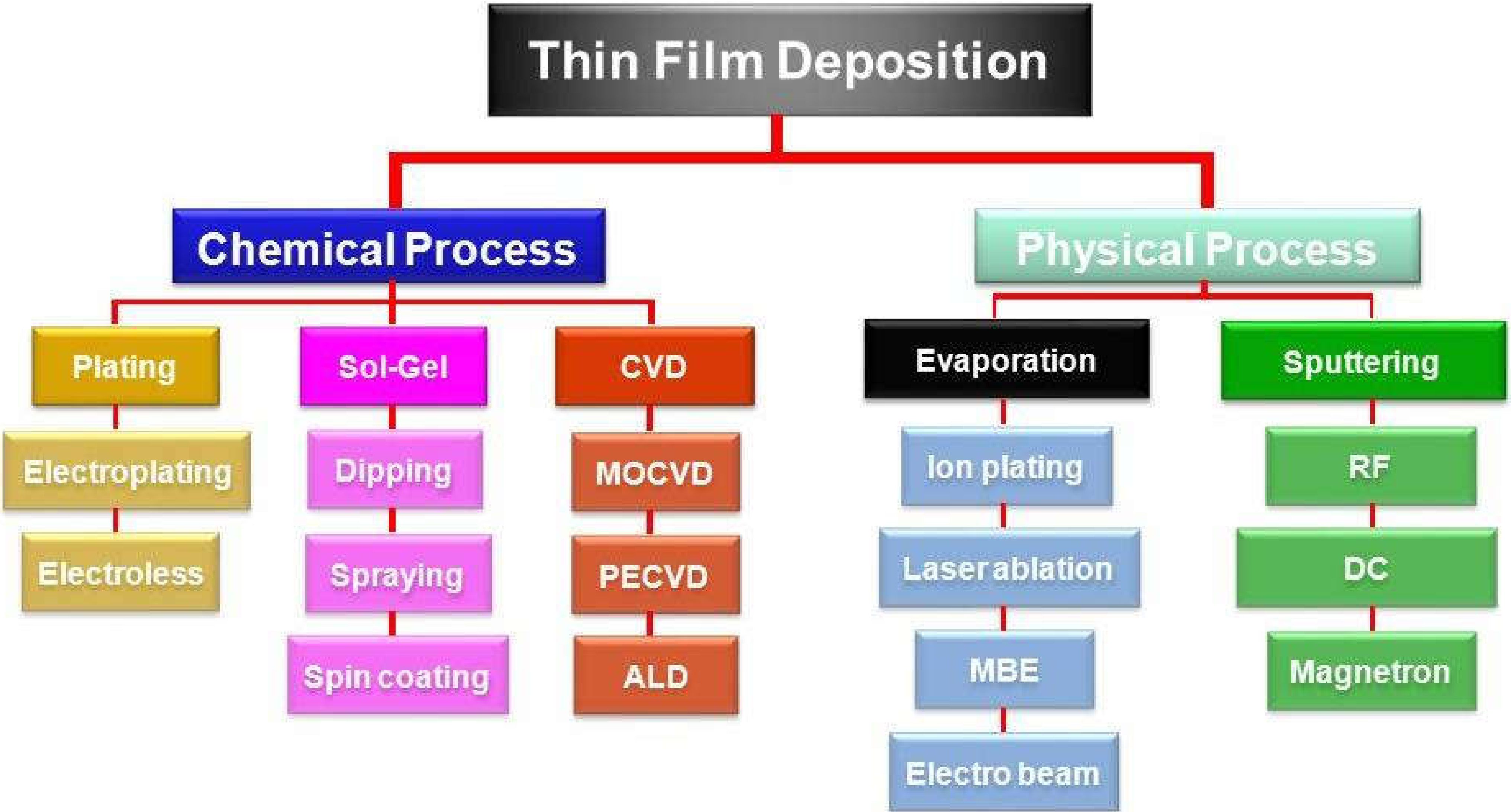
微纳光电子材料与器件工艺原理

Film Deposition
Part IV: PVD

Xing Sheng 盛兴

Department of Electronic Engineering
Tsinghua University
xingsheng@tsinghua.edu.cn

Film Deposition

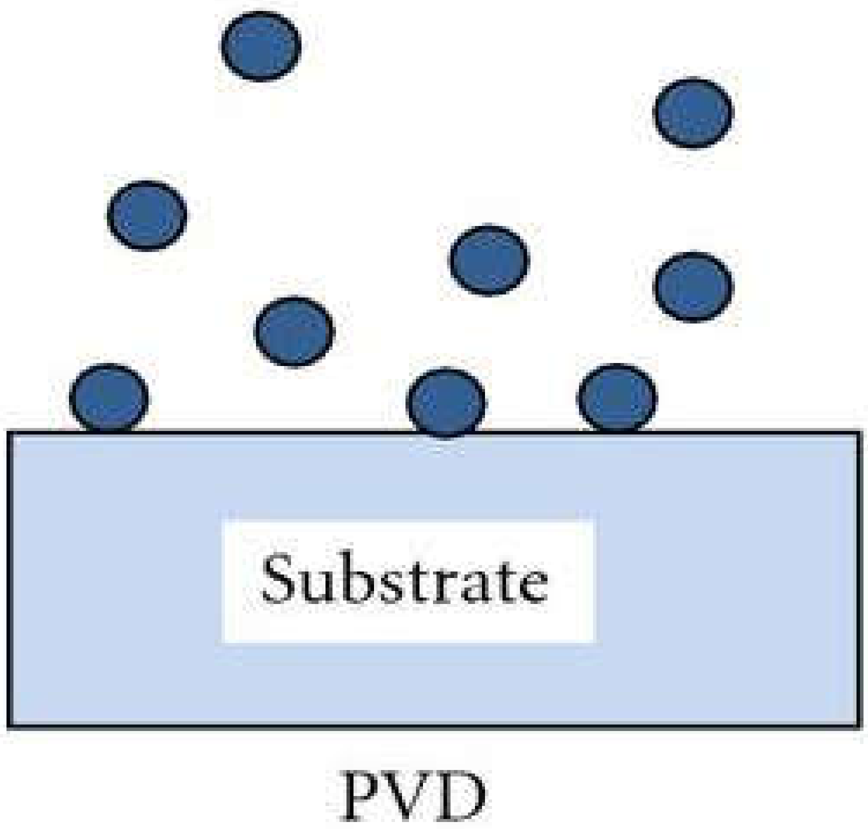


PVD: Physical Vapor Deposition

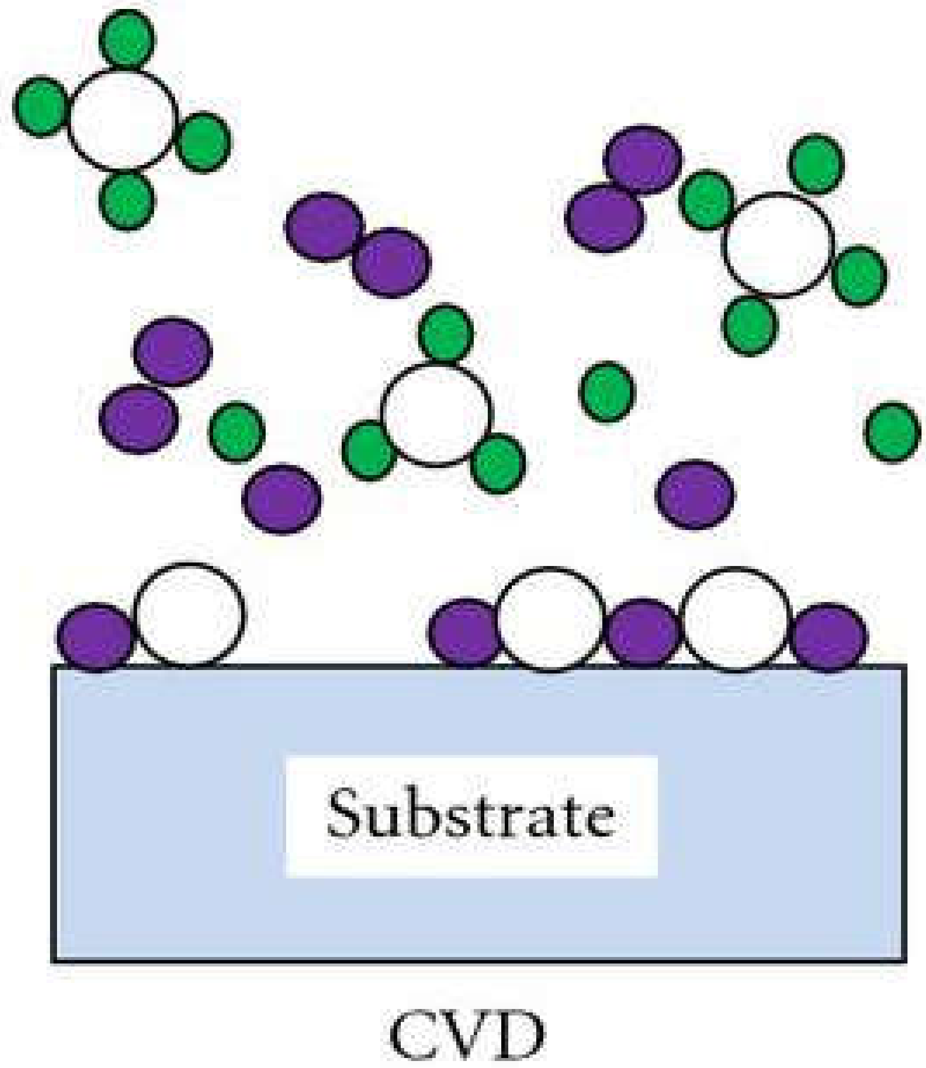
CVD: Chemical Vapor Deposition

PVD vs. CVD

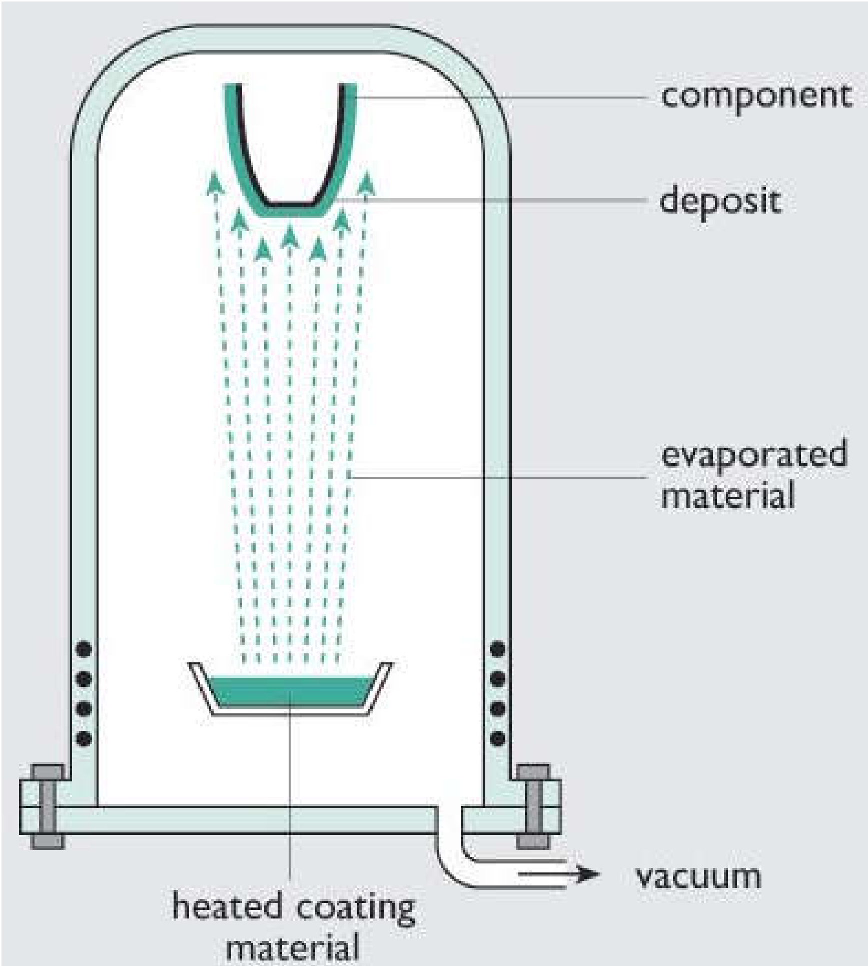
Physical process

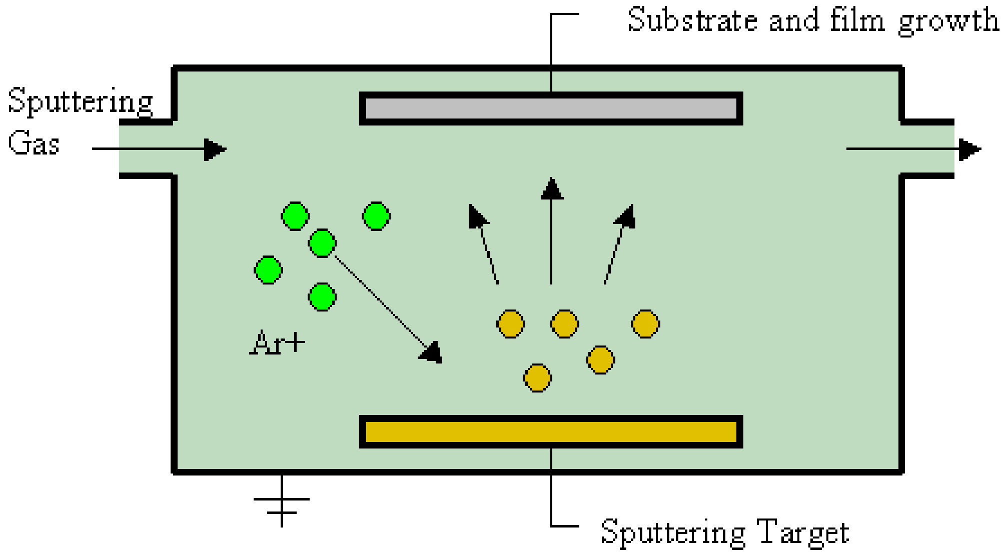


Chemical reactions



PVD





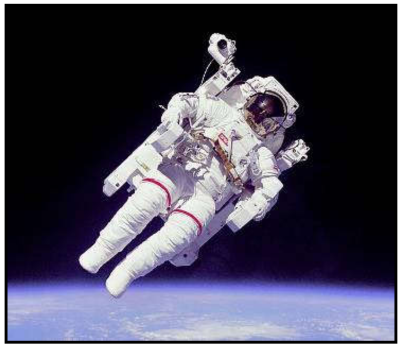
Evaporation (蒸发)

Sputter (溅射)

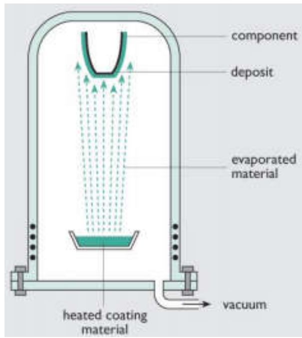
Vacuum Basics

- **Units**
  - **1 Pa = 1 N/m^2**
  - **1 atm = 760 torr = 760 mm Hg = 1.013*10^5 Pa**
  - **1 bar = 10^5 Pa = 750 torr**
  - **1 torr = 133.3 Pa**

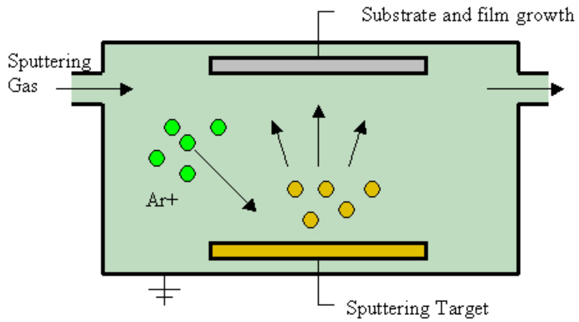
Pressure cooker
~ 1.5 atm



outer space
< 10^{-10} Pa

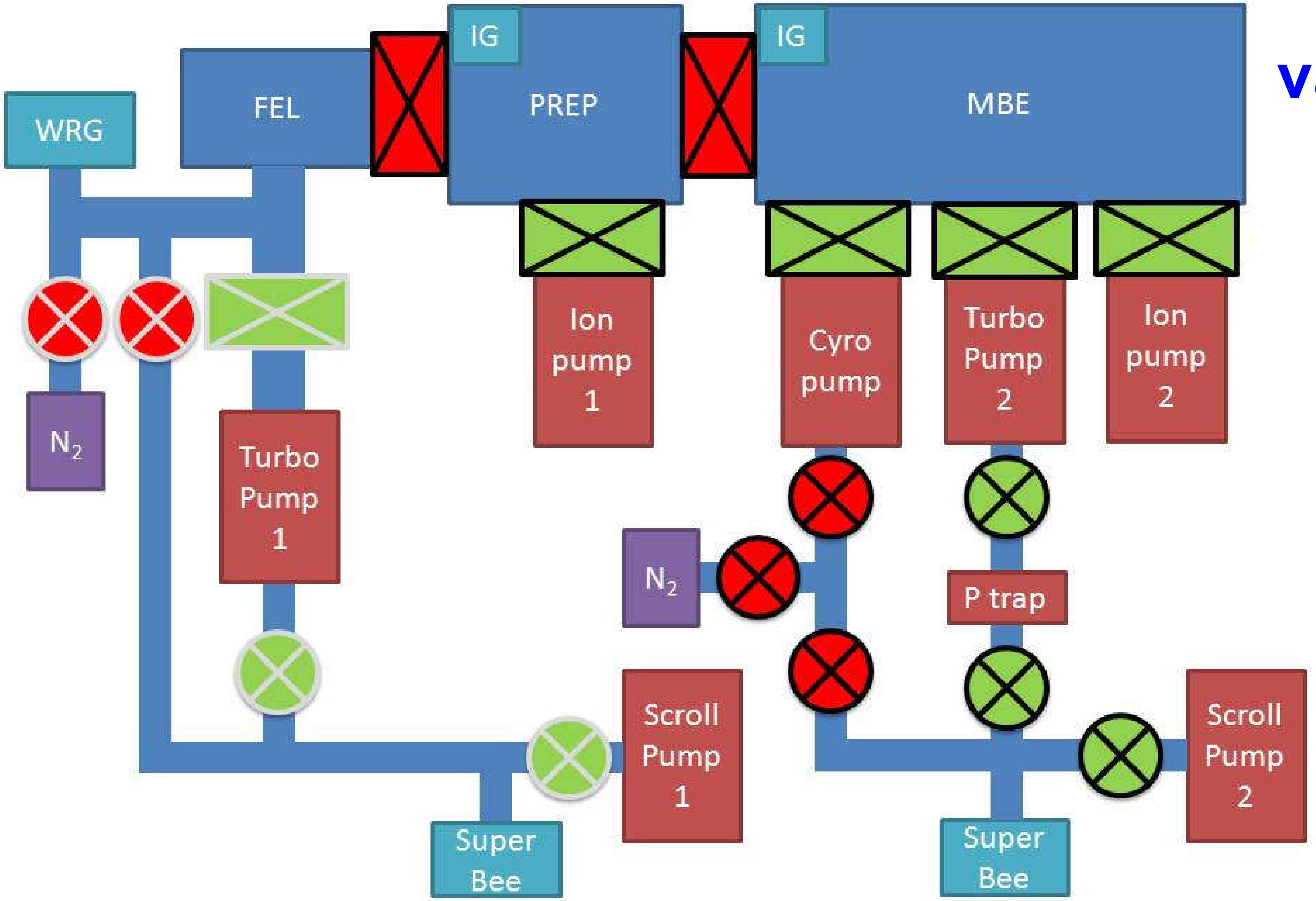


Evaporation
< 10^{-7} Pa

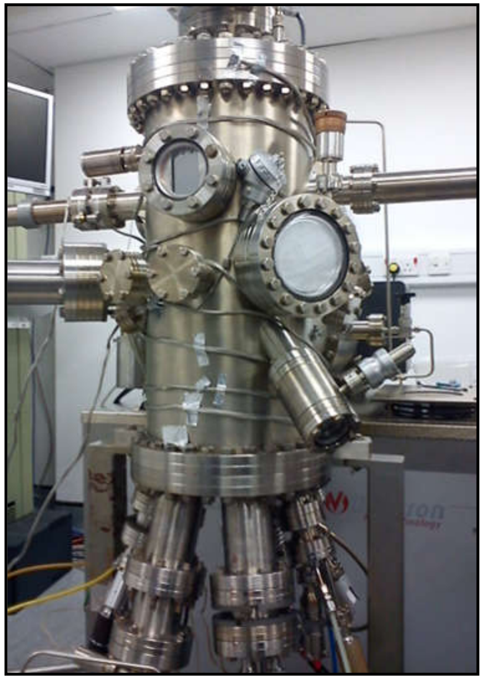


Sputter
~ 10^{-1} Pa

Vacuum Systems



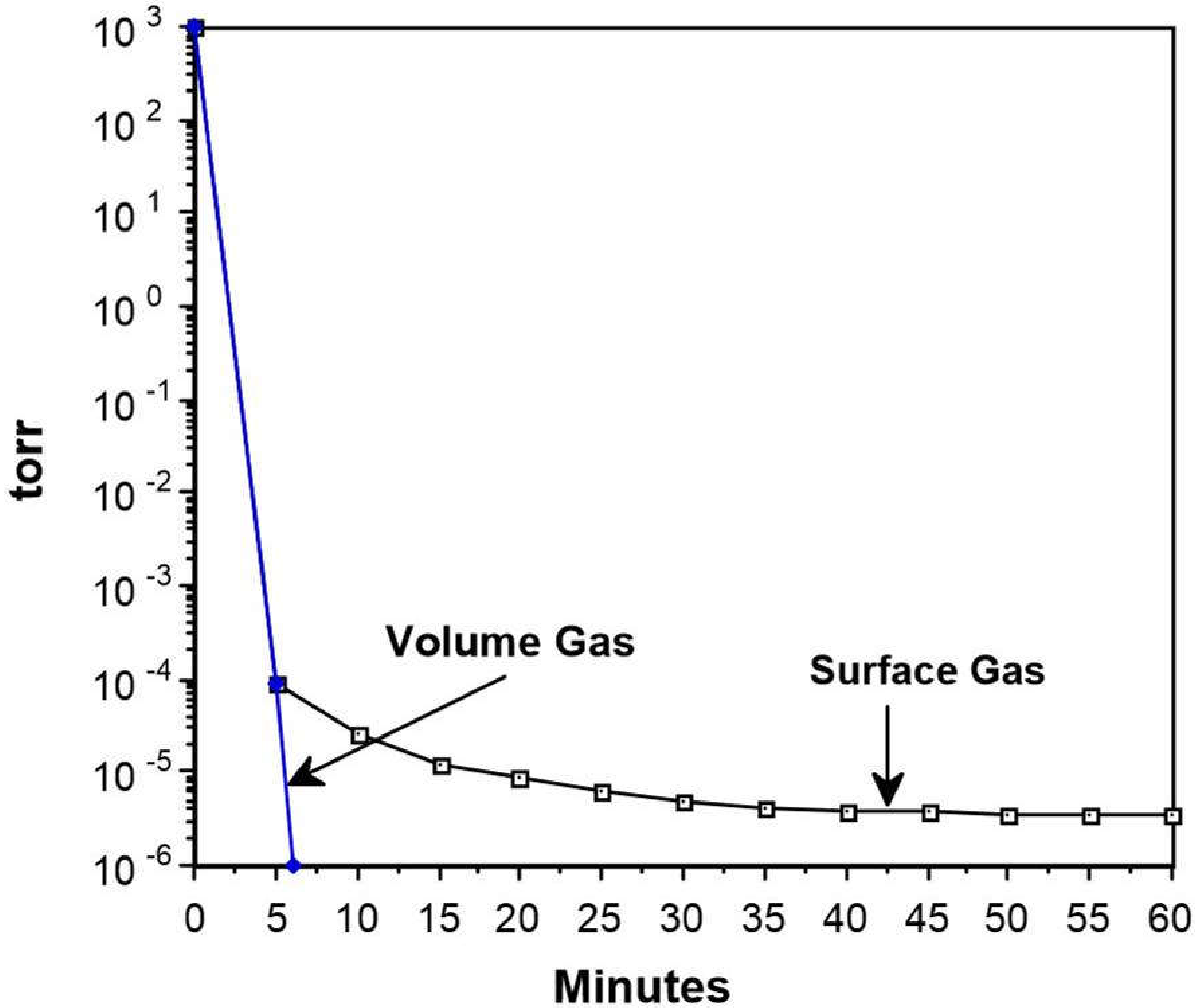
vacuum ~ 10^{-10} Pa



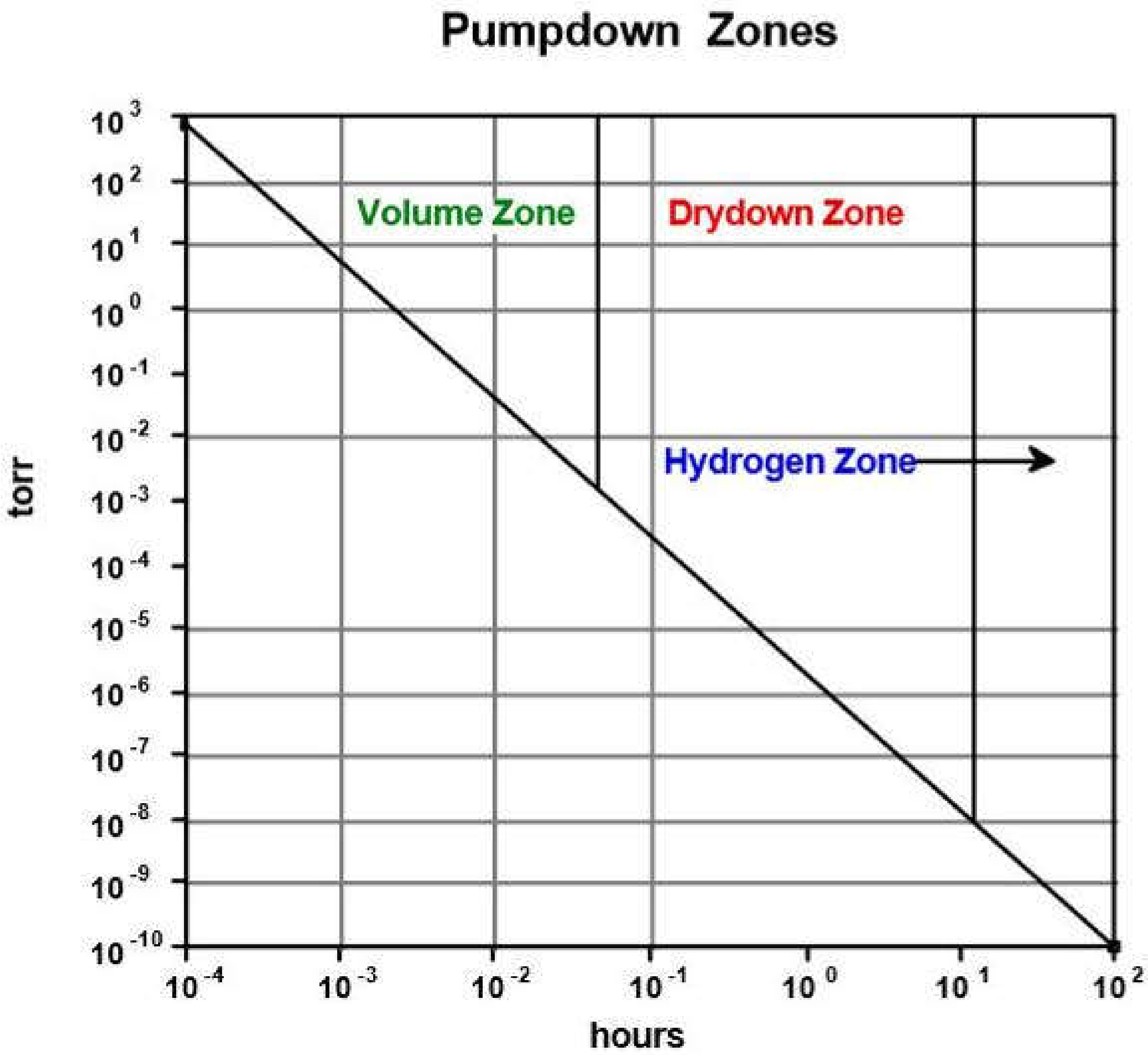
MBE: Molecular Beam Epitaxy

分子束外延

Vacuum Pumpdown

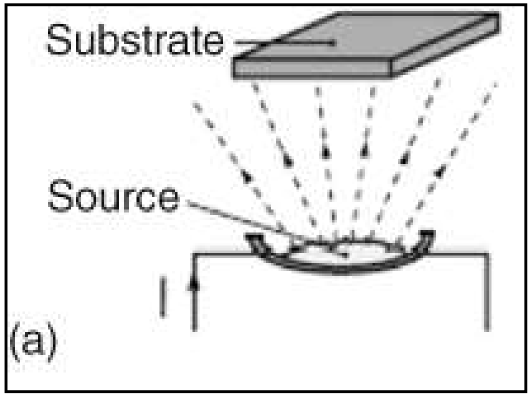


Vacuum Pumpdown

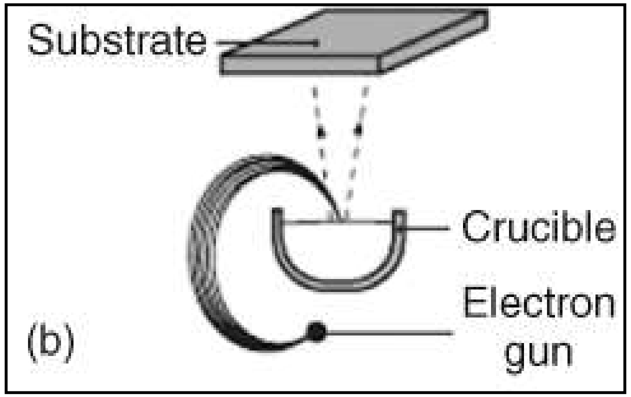


1. air
2. water
3. hydrogen

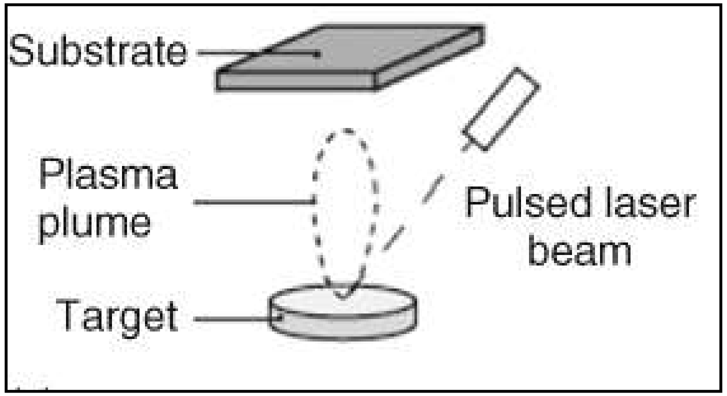
Evaporation



Thermal



Electron Beam (Ebeam)

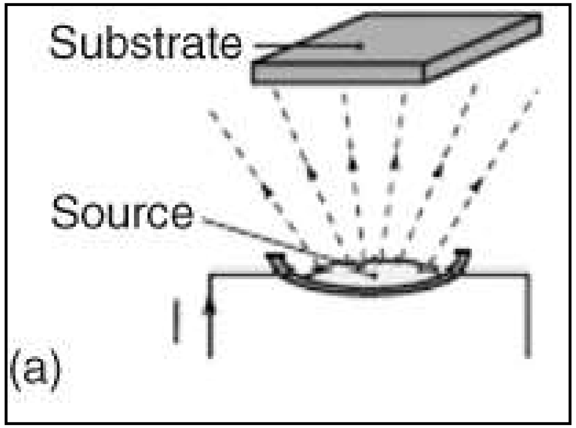


Pulsed Laser Deposition (PLD)

Q: Why do we need the vacuum?

Evaporation

- Reduce the impurities (N_2, O_2, H_2O, ...)
- Prevent oxidation
  - e.g. $Cu + O_2 \rightarrow CuO$
- Ballistic transport
  - molecular mean free path λ



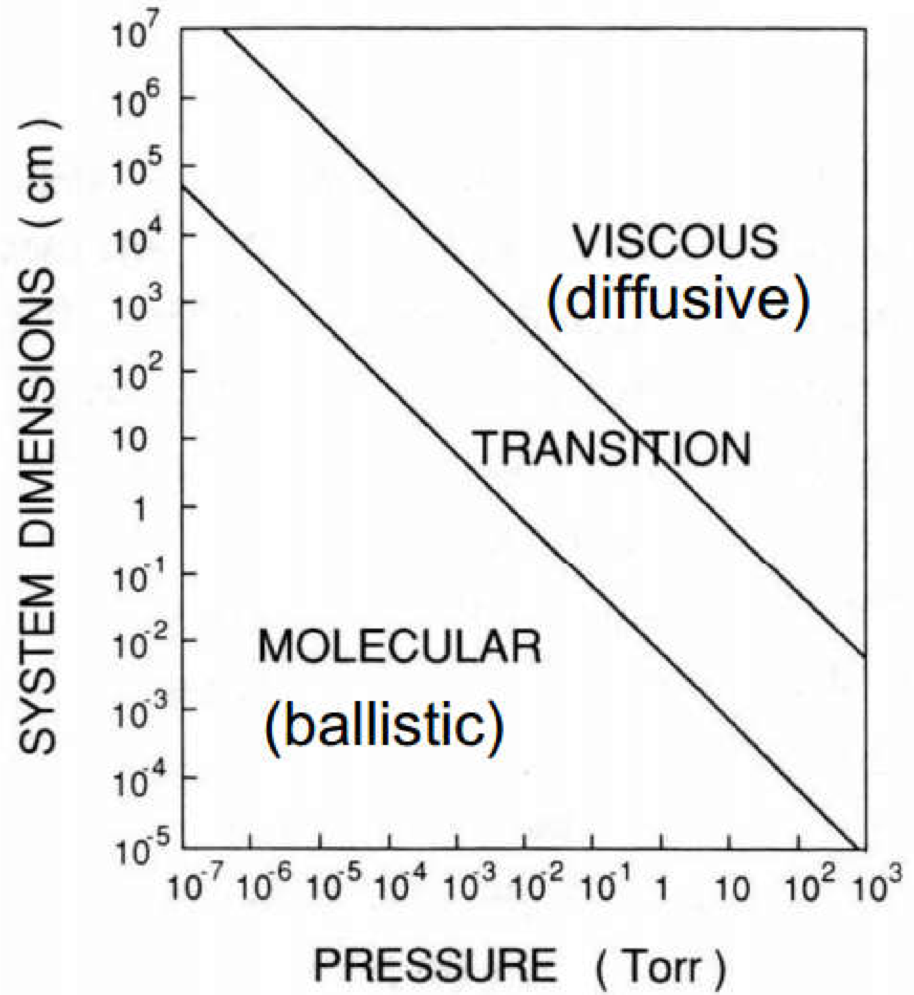
$$\lambda = \frac{kT}{\sqrt{2}\pi r^2 p}$$

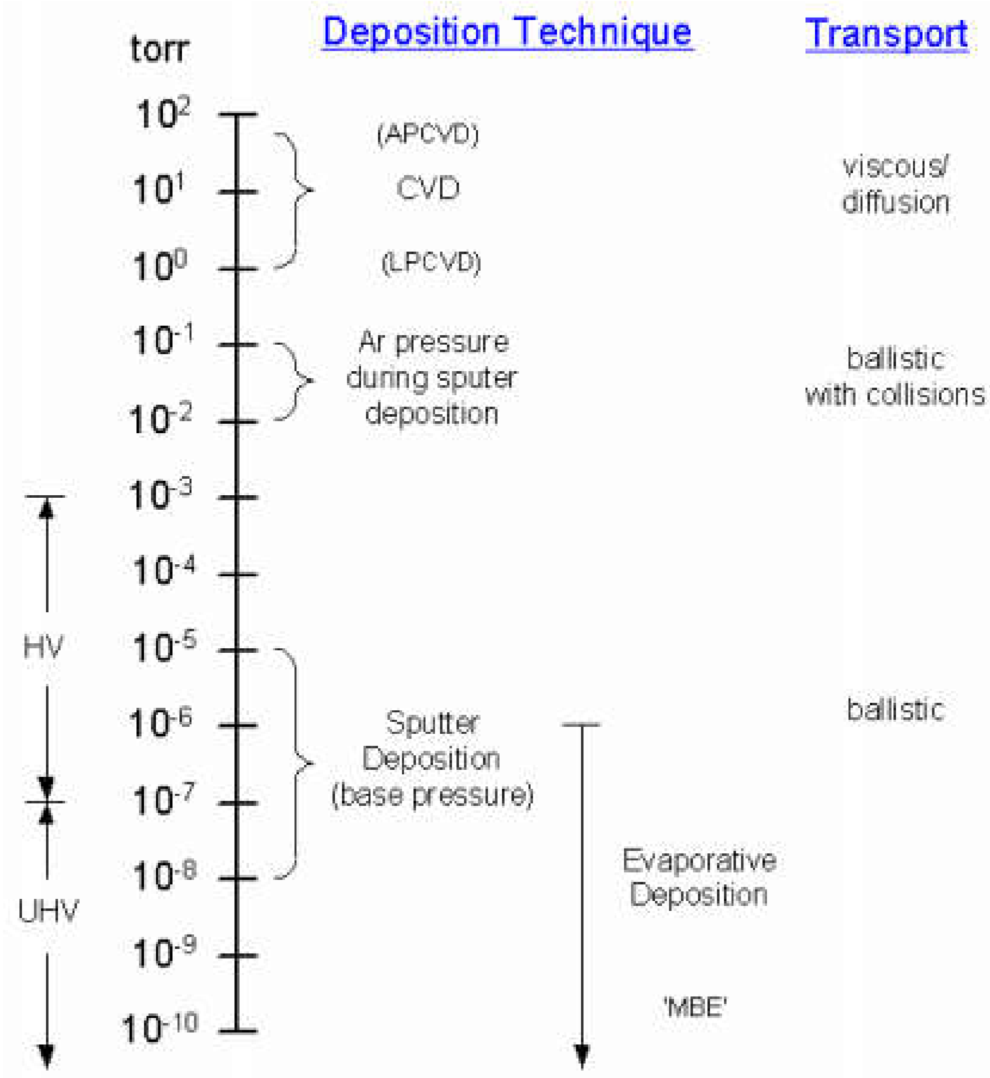
$$\lambda\,(\mathrm{cm}) \approx \frac{0.5}{pressure\,(\mathrm{Pa})}$$

Q: Required pressure?

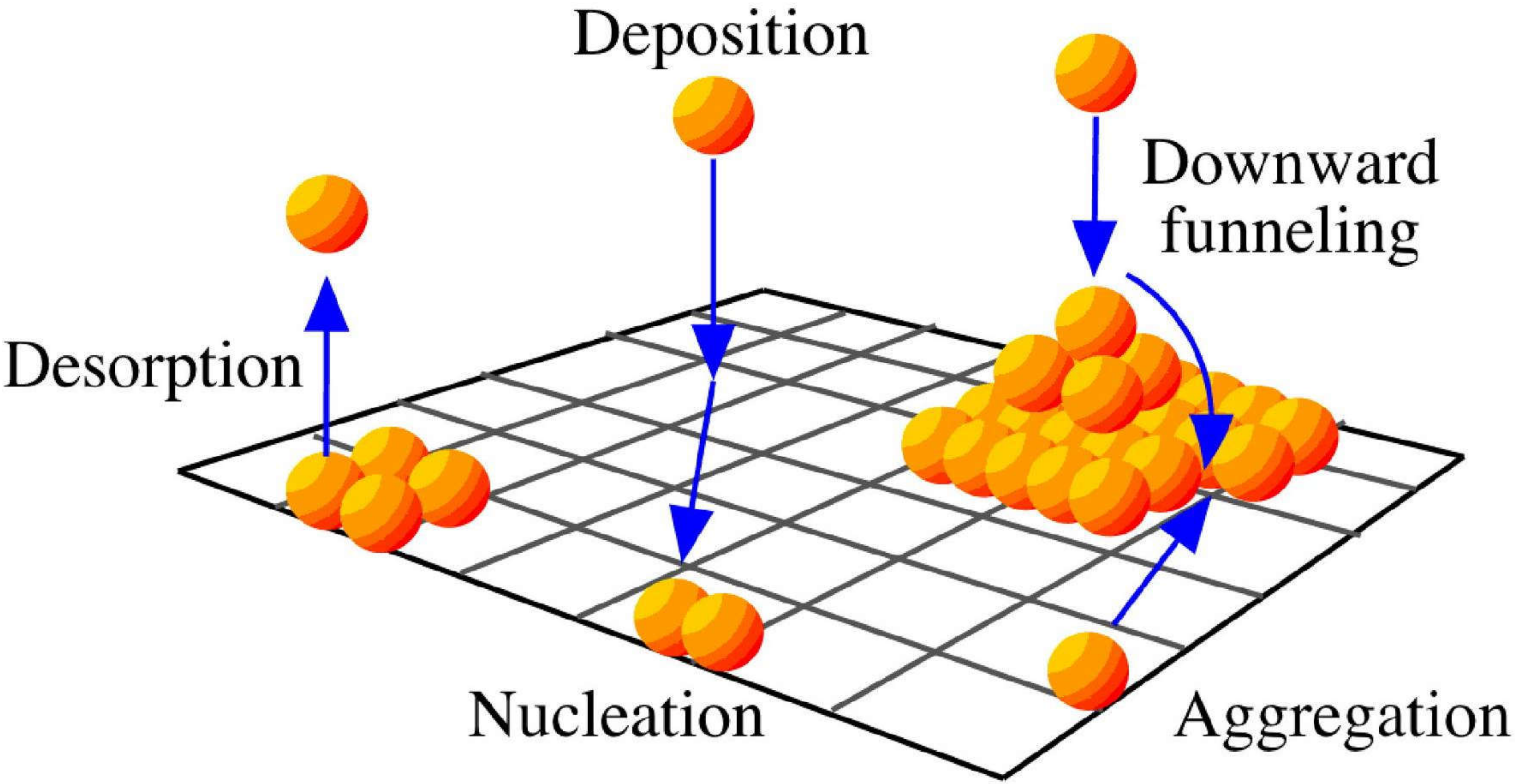
Mass Transport

$$\lambda\,(\mathrm{cm}) \approx \frac{0.5}{pressure\,(\mathrm{Pa})}$$





Mass Transport



absorption - movement - desorption

Evaporation Rate

Langmuir-Knudsen Theory

$$R_{evap} = 5.83\times10^{-2} A_s \sqrt{\frac{m}{T}} P_e$$

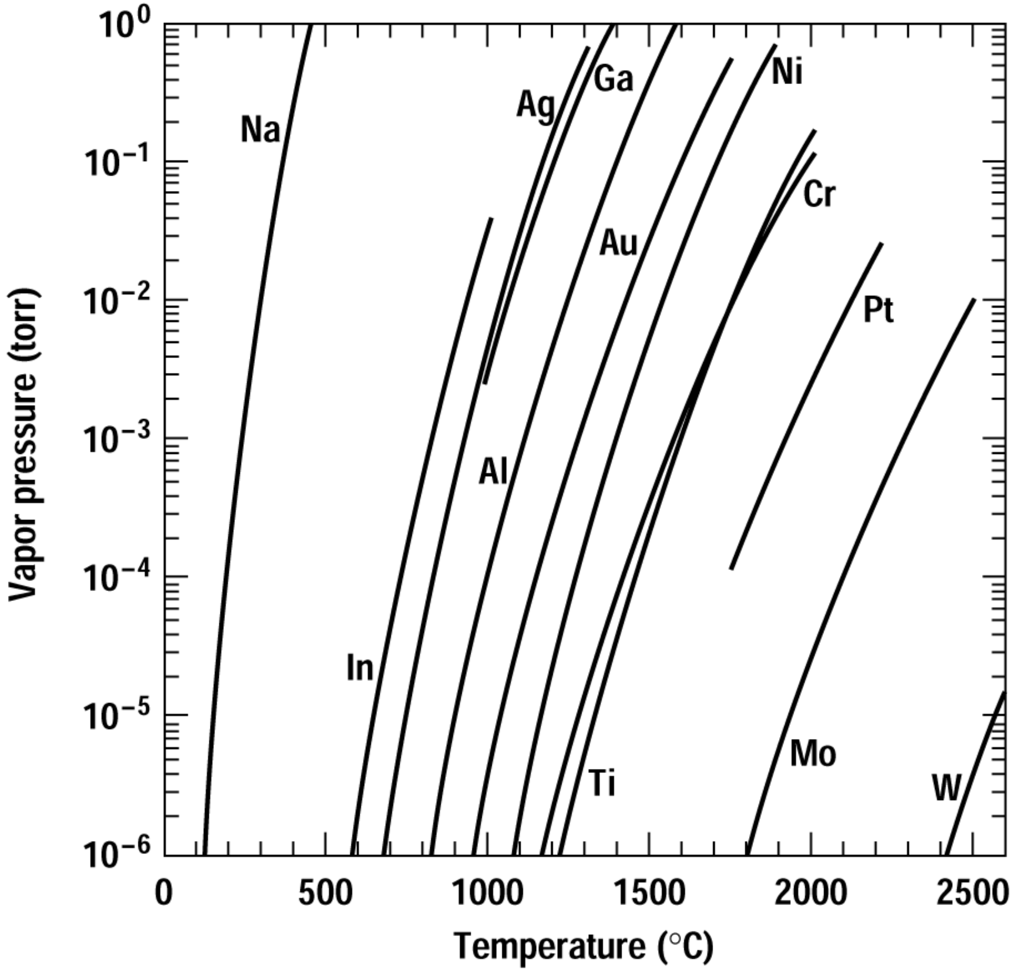
R_{evap}: Evaporation rate (g/s)

A_s: area of sources (cm^2)

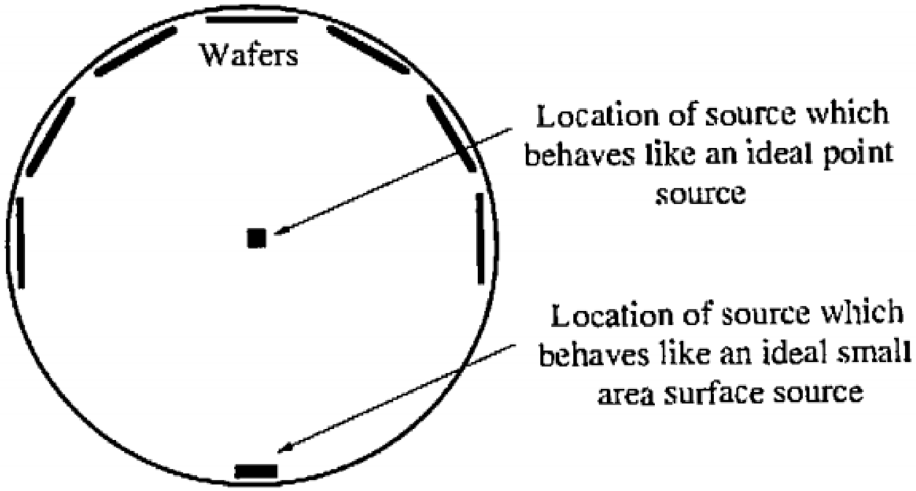
m: molecular weight (g/mol)

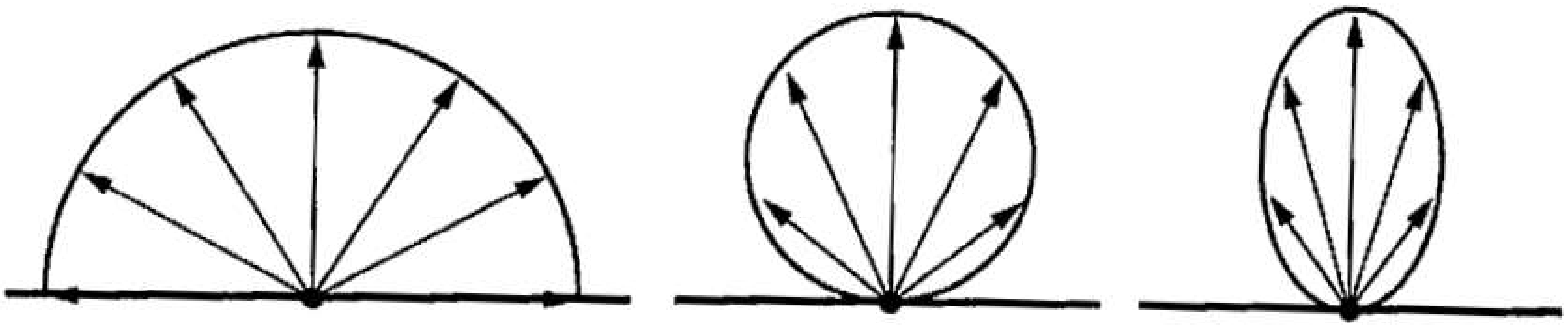
T: temperature (K)

P_e: vapor pressure of sources (Torr) (*not* chamber pressure)



Evaporation Sources





(a) Uniform (isotropic) emission from a point source

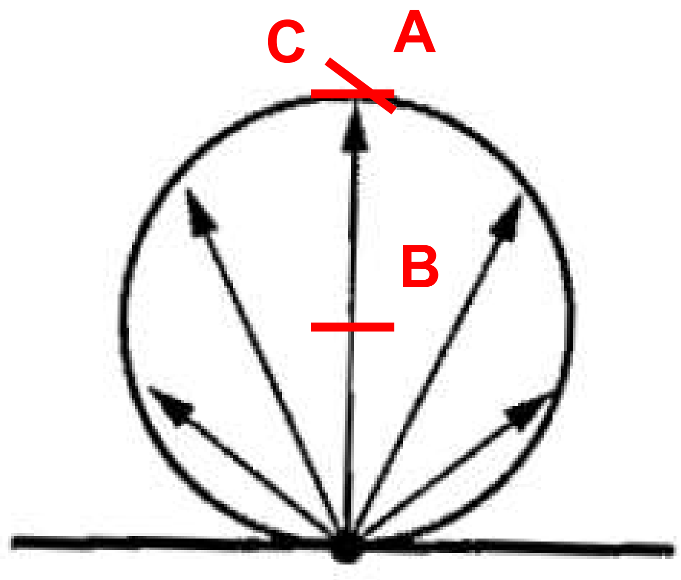
(b) Ideal cosine emission from a small planar surface source. ($n = 1$ in $\cos^n\theta$ distribution)

(c) Non-ideal, more anisotropic emission from a small planar surface source. ($n > 1$ in $\cos^n\theta$ distribution)

Deposition rate

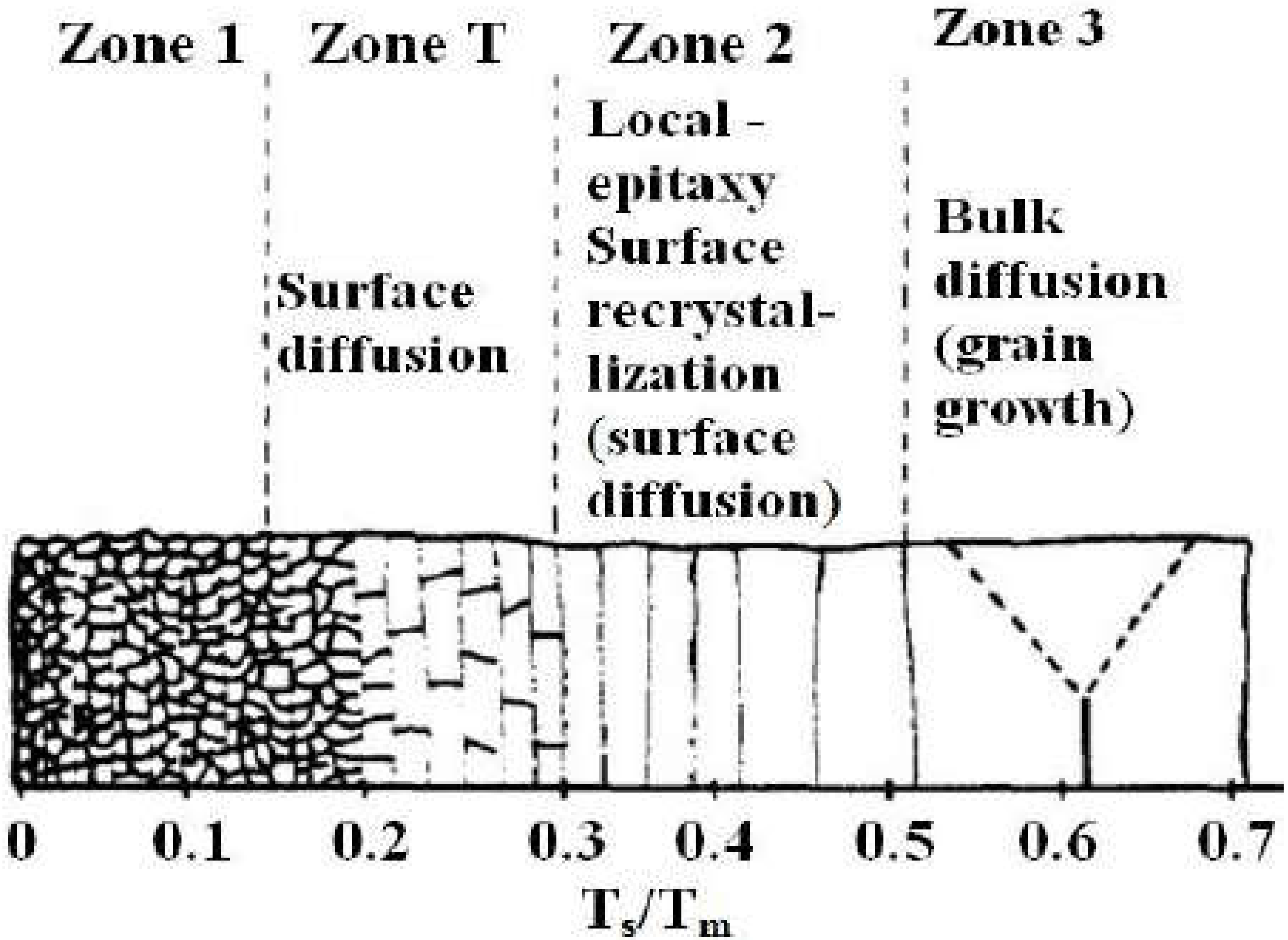
Question:

1. $R_A : R_B = ?$
2. $R_A : R_C = ?$



Ideal cosine emission from a small planar surface source.

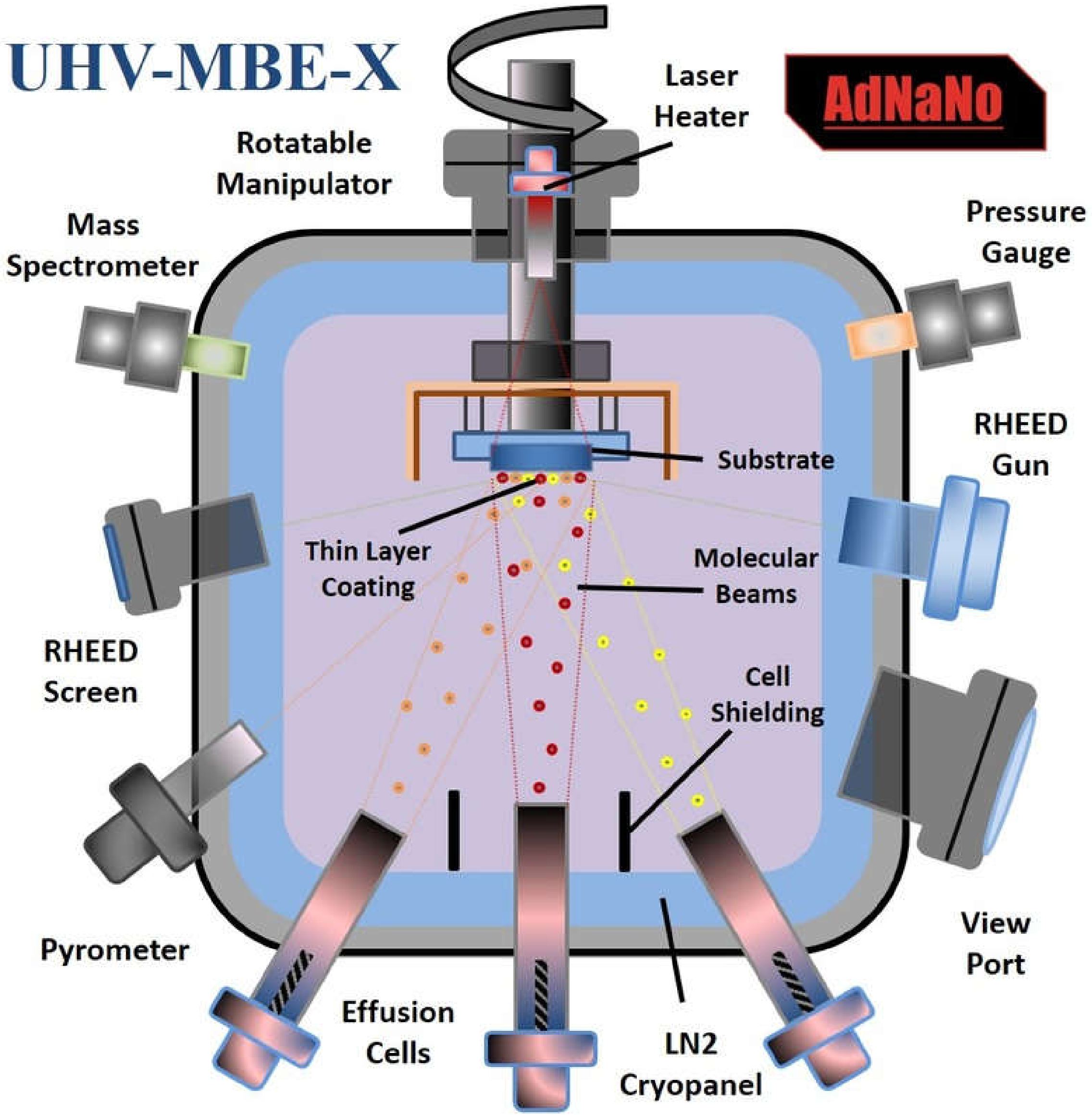
Effects of Substrate Temperature



Zone Model

Higher Temperature
-> Larger Atom Mobility
-> Larger Grain Size

MBE: Molecular Beam Epitaxy

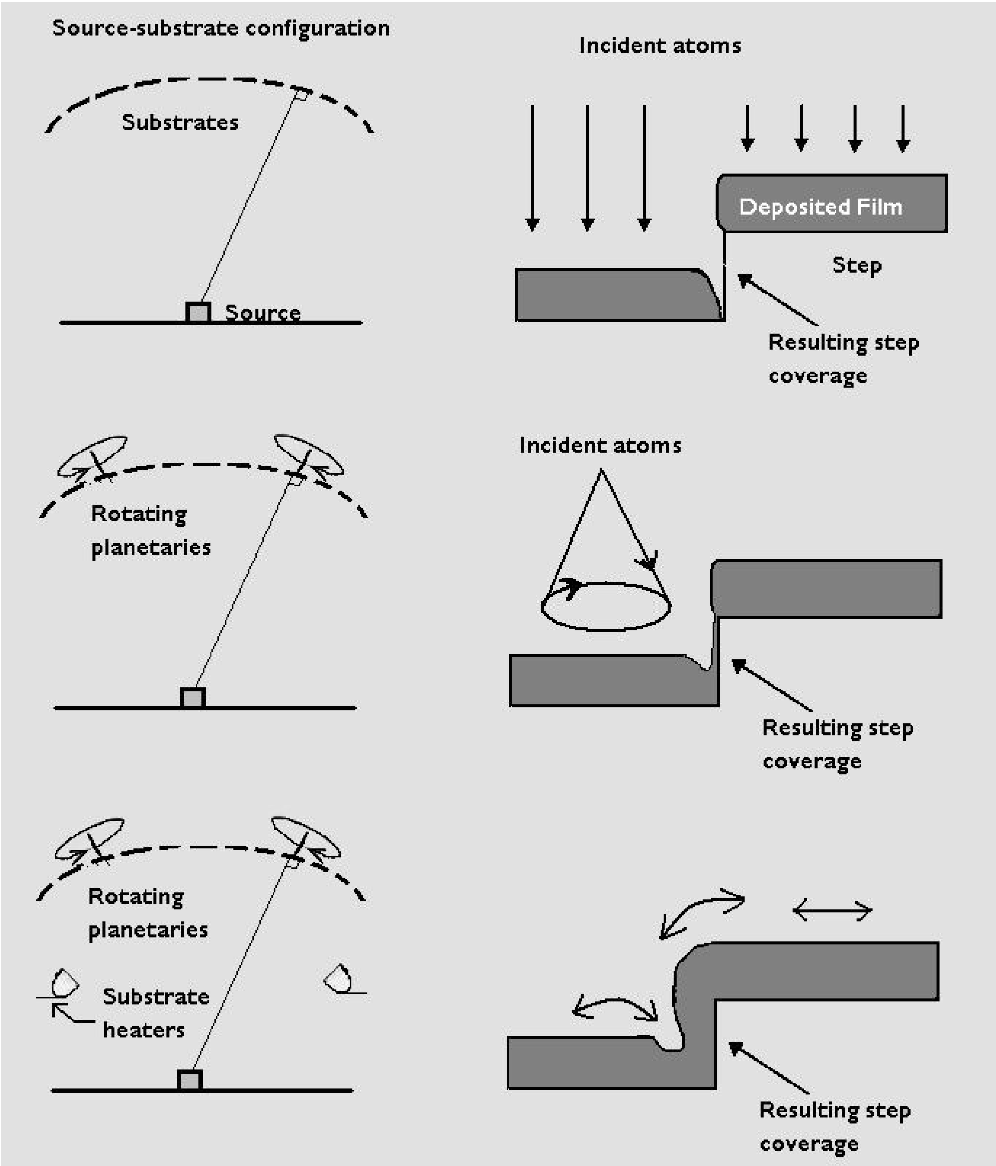


Ultrahigh Vacuum
High Substrate Temperature
Lattice Matched Substrate

↓

High Quality,
Single Crystal Films

Step Coverage



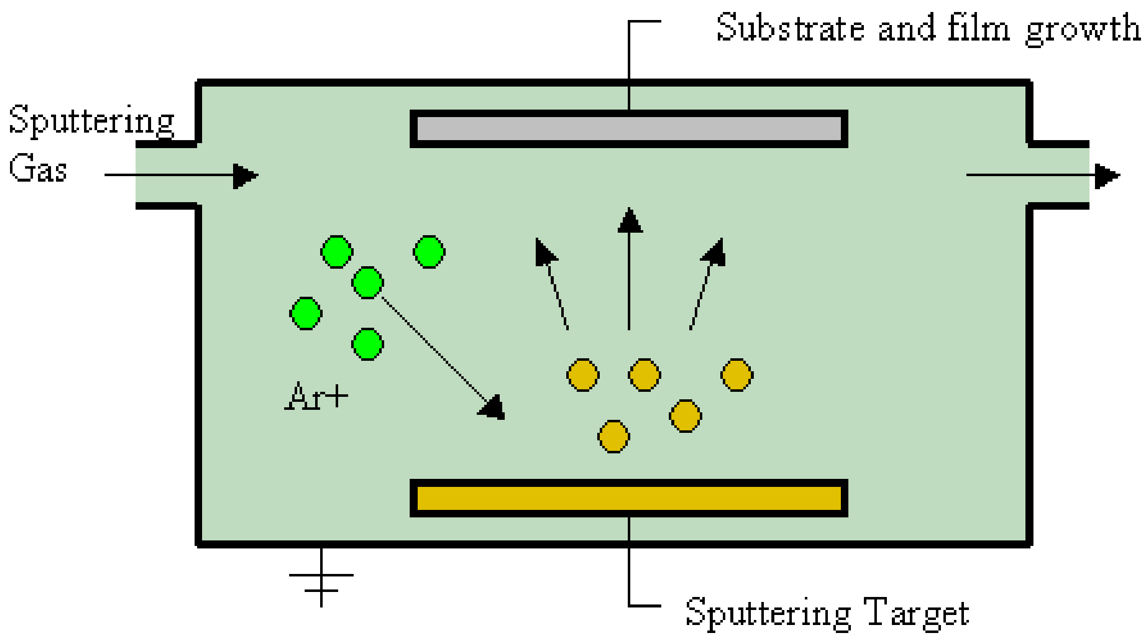
Substrate rotation and heating improve step coverage

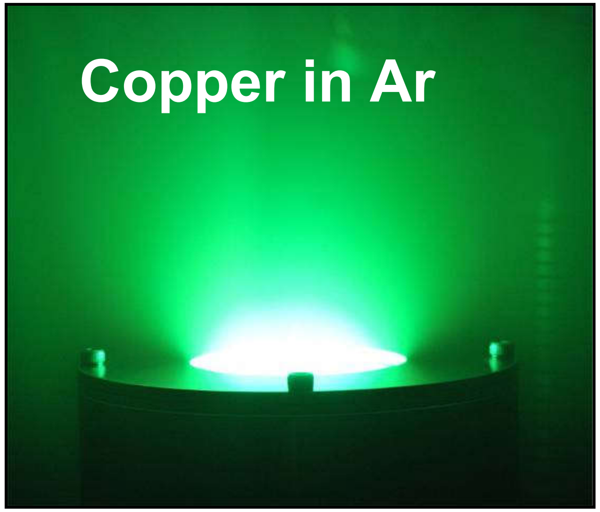
Challenges of Evaporation

- Materials with high melting points / low vapor pressure
  - W, Mo, SiO_2, ...
- Compounds and alloys (non-stoichiometry)
  - FeCoB alloy
  - TiO_2 -> TiO_x
- Radiation damage generated by Ebeam
  - electron beam and X-ray radiation
- Poor step coverage
  - via filling

Sputter (溅射)

- Plasma (e.g. Ar) assisted transport
  - high energy
  - high deposition rate

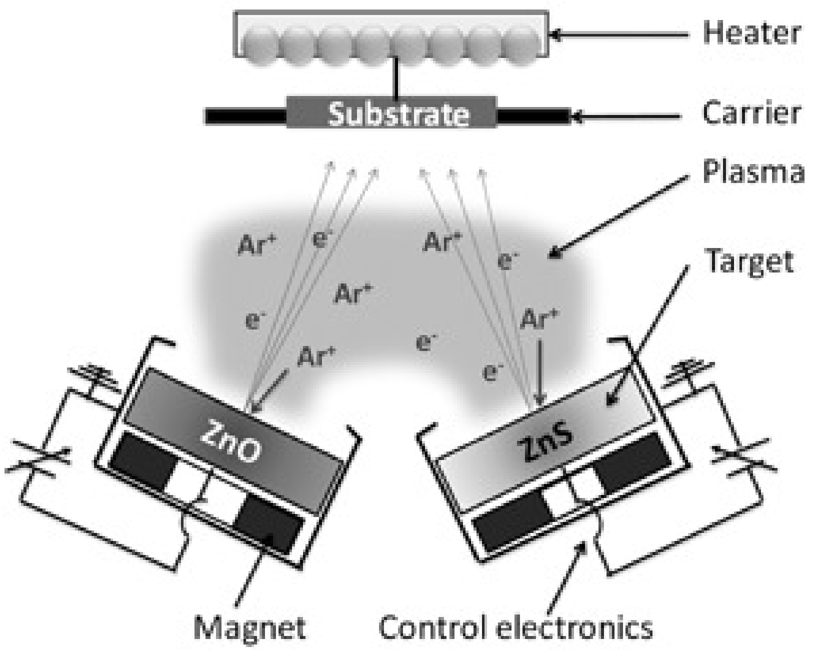


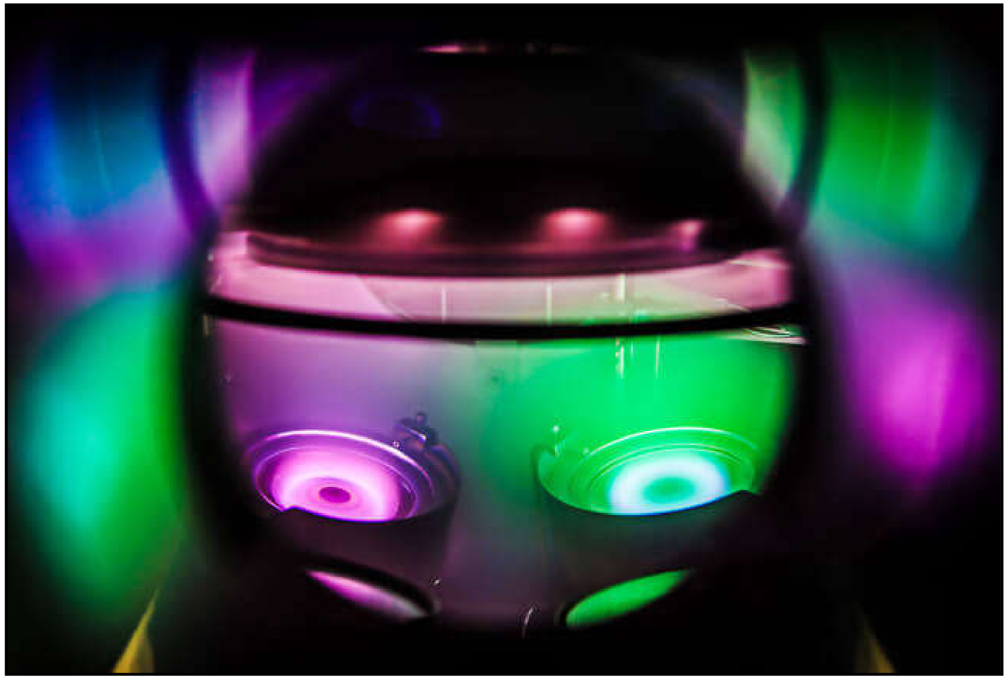


Plasma

Co-Sputter

- **Deposit more than one material**
  - **composition control**





Sputter: Pros. & Cons.

- **Advantages**
  - Higher pressure than evaporation
  - Higher deposition rate
  - Better uniformity and step coverage
  - Better stoichiometry control
  - Work for most materials

- **Disadvantages**
  - Plasma induced damages (etching)
  - More impurities and defects
  - Not good for single crystal epitaxy
  - Mostly polycrystalline and amorphous films

Sputter

- **Process Parameters**
  - Type: DC, RF/AC, Magnetron, ...
  - Substrate temperature
  - Gas type (Ar, O_2, N_2, ...)
  - Chamber pressure
  - Sputter power
  - ...

- **Control Parameters**
  - Deposition rate
  - Crystallinity
  - Film quality (defects, ...)
  - ...

Sputter

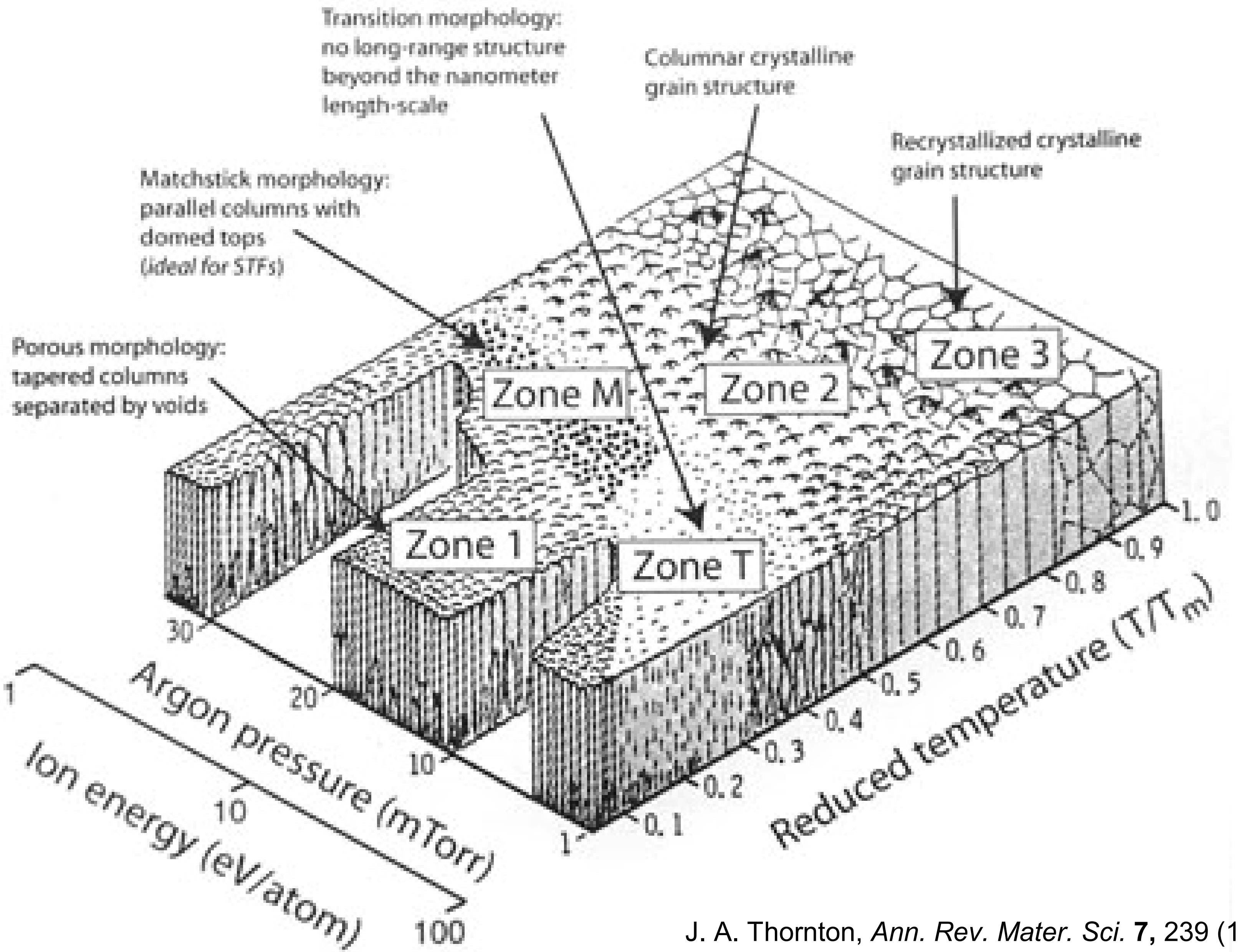
Sputtering Process Trend for typical metals and films

	Base Pressure	Sputtering Pressure	Power	Substrate RF Bias
Deposition Rate	↔	⇧ | ⇩ Below~3mT Above~8mT	↑	⇩
Stress (+ tensile, - compressive)	↔	↑	↓	↓
Step Coverage/ Sidewall coverage	↔	⇧	2nd order effect depending on geometry	⇧ Can cause re-dep onto sidewalls thru collisions
Resistivity	↑	⇧	2nd order effect with substrate or target heating on some films	2nd order effect with some films by changing density or stress

Legend

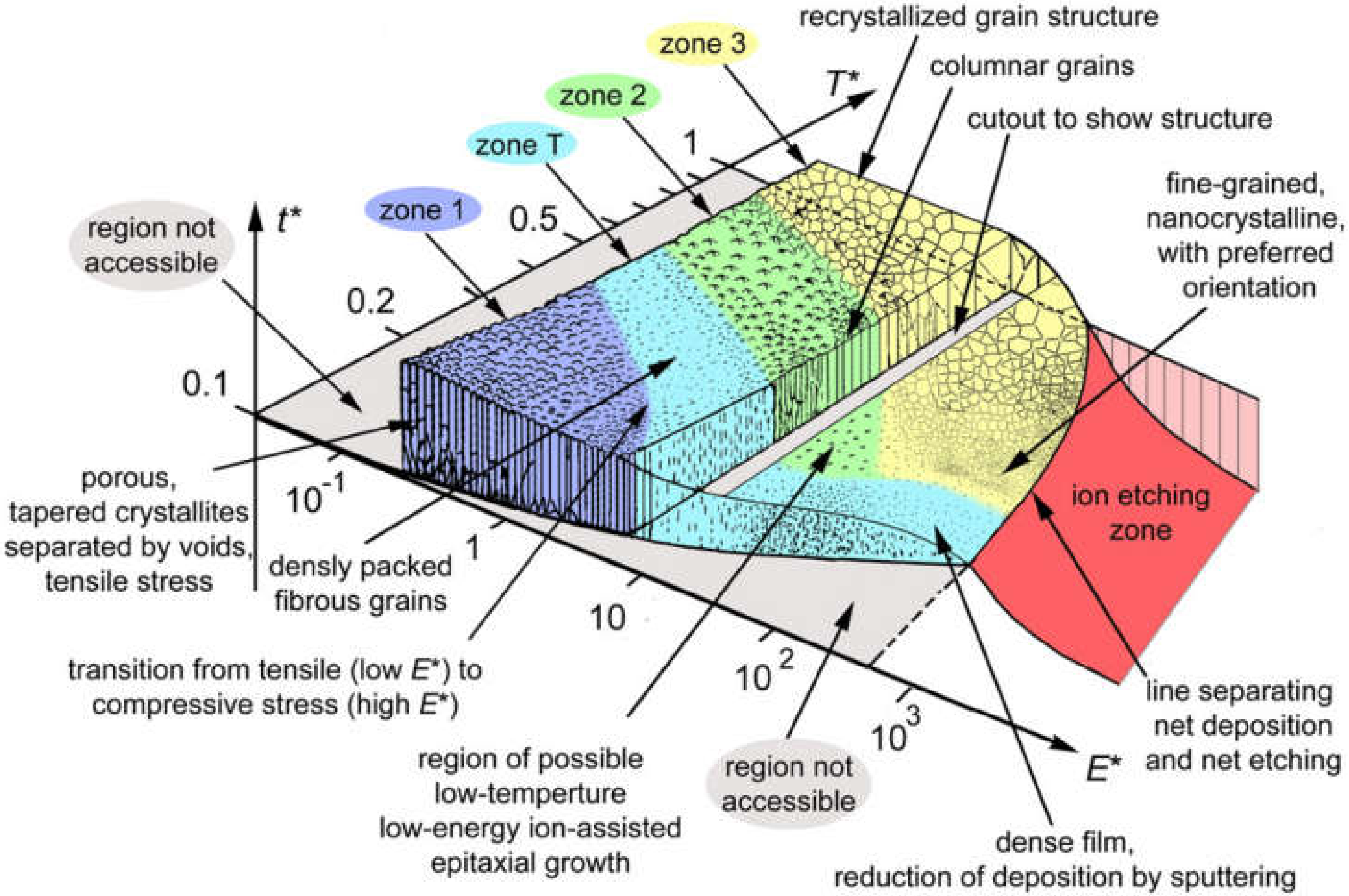
↑	Strong increase in response	⇧	Slight increase in response	↔	Typically no response
↓	Strong decrease in response	⇩	Slight decrease in response		

Thornton's Zone Model



J. A. Thornton, *Ann. Rev. Mater. Sci.* **7,** 239 (1977)

Refined Zone Model



A. Anders, *Thin Solid Films* **518,** 4087 (2010)

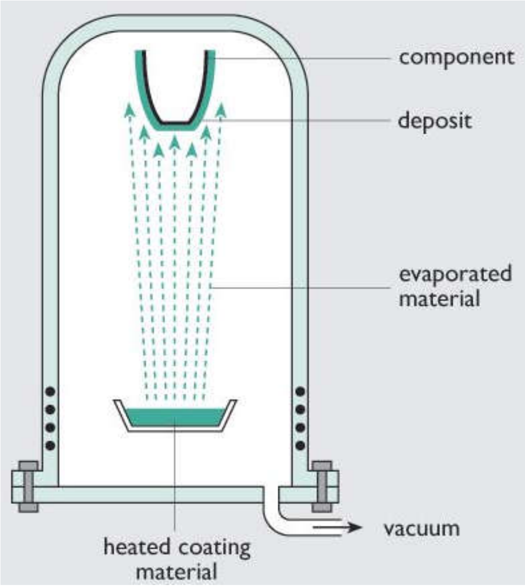
Evaporation vs. Sputter

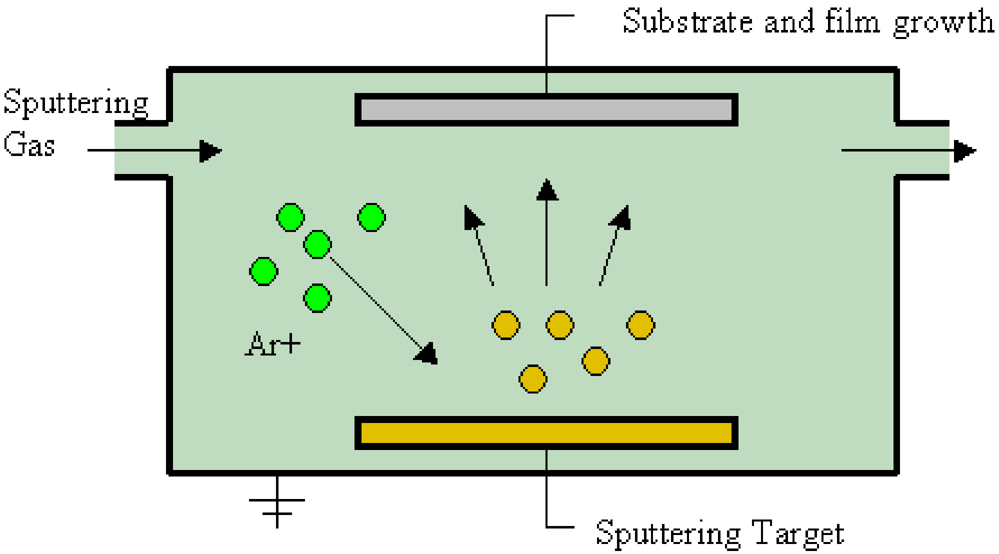
Evaporation:

- **higher temperature**
- **radiation (Ebeam)**
- **lower pressure**
- **poor step coverage**

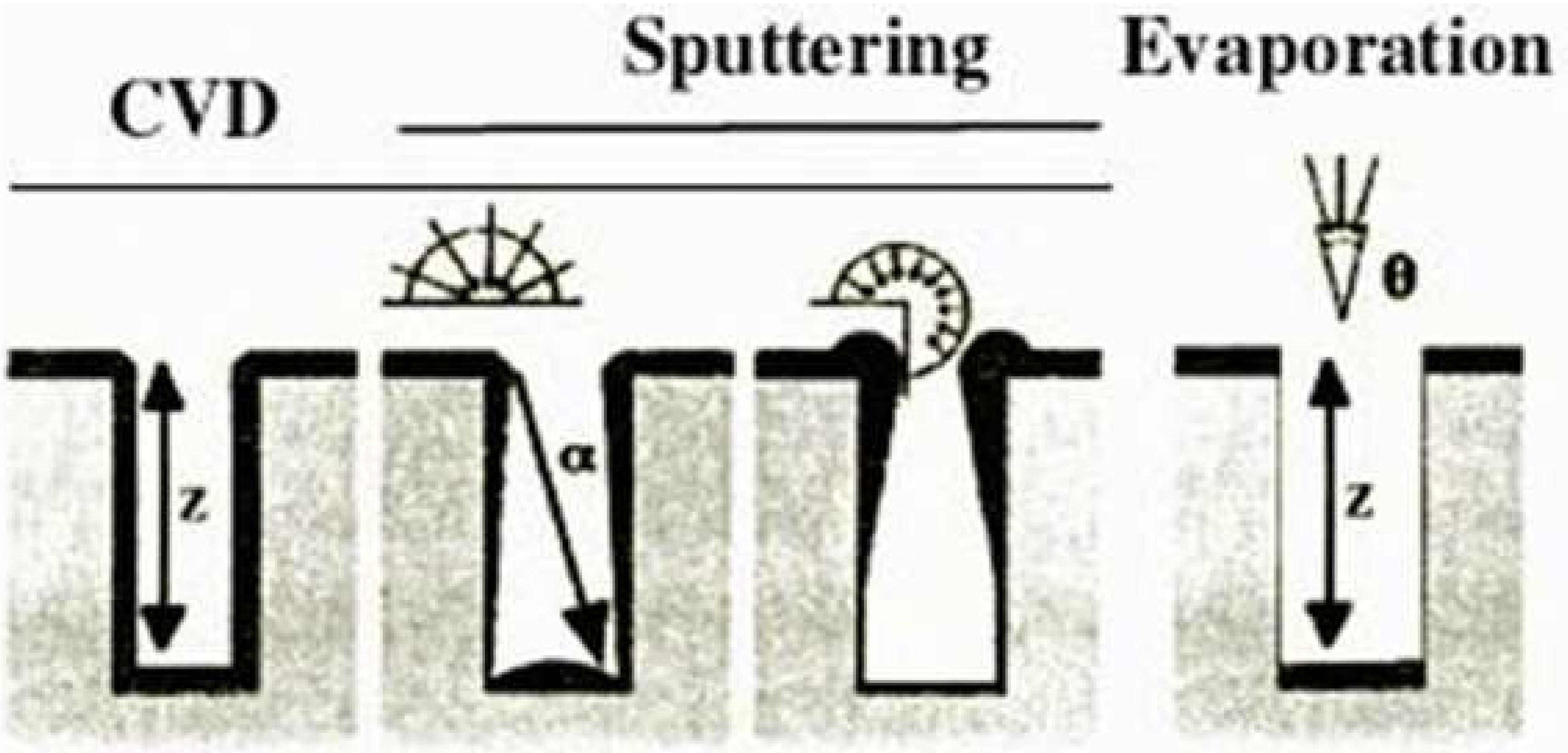
Sputter:

- **lower temperature**
- **plasma damage**
- **higher pressure**
- **better step coverage**





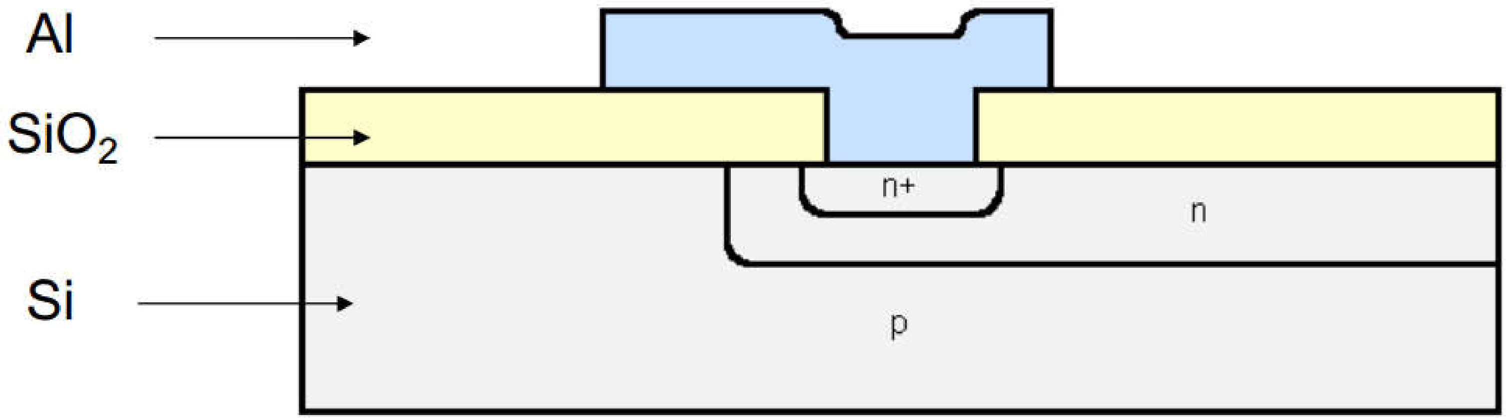
Step Coverage



surface reaction → ***ballistic transport***

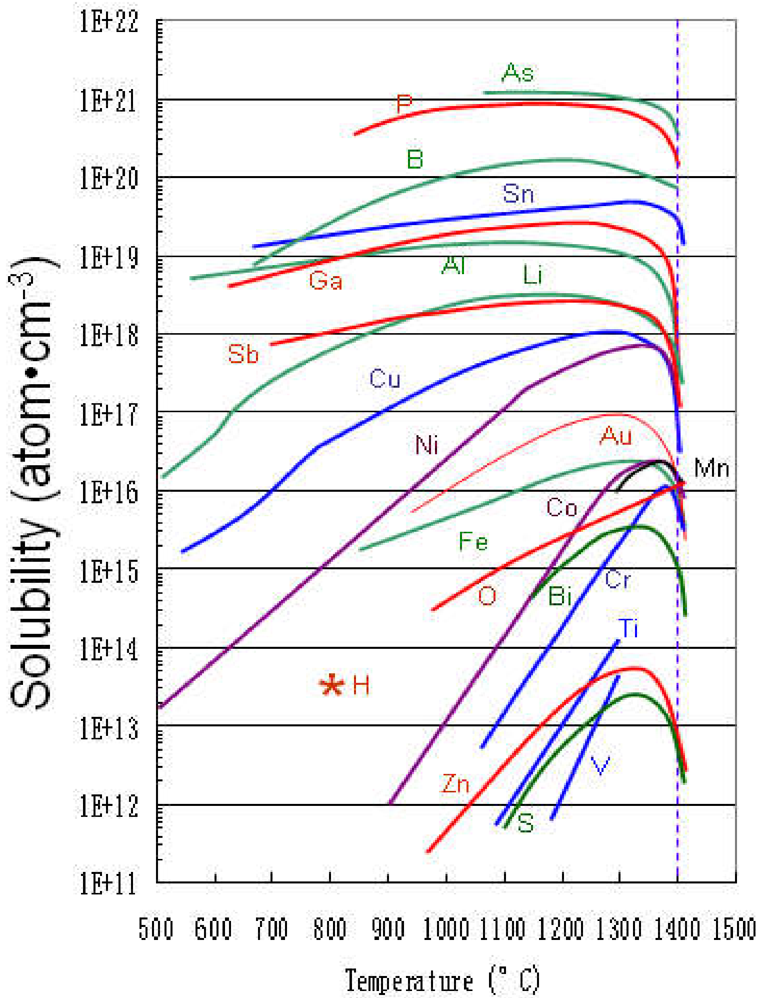
Film Adhesion

- **Al has good adhesion on Si and SiO_2**
  - **Al has high solubility in Si**
  - **$Al + SiO_2 = Al_2O_3 + Si$**



Q: How about Cu and Au?

Film Adhesion

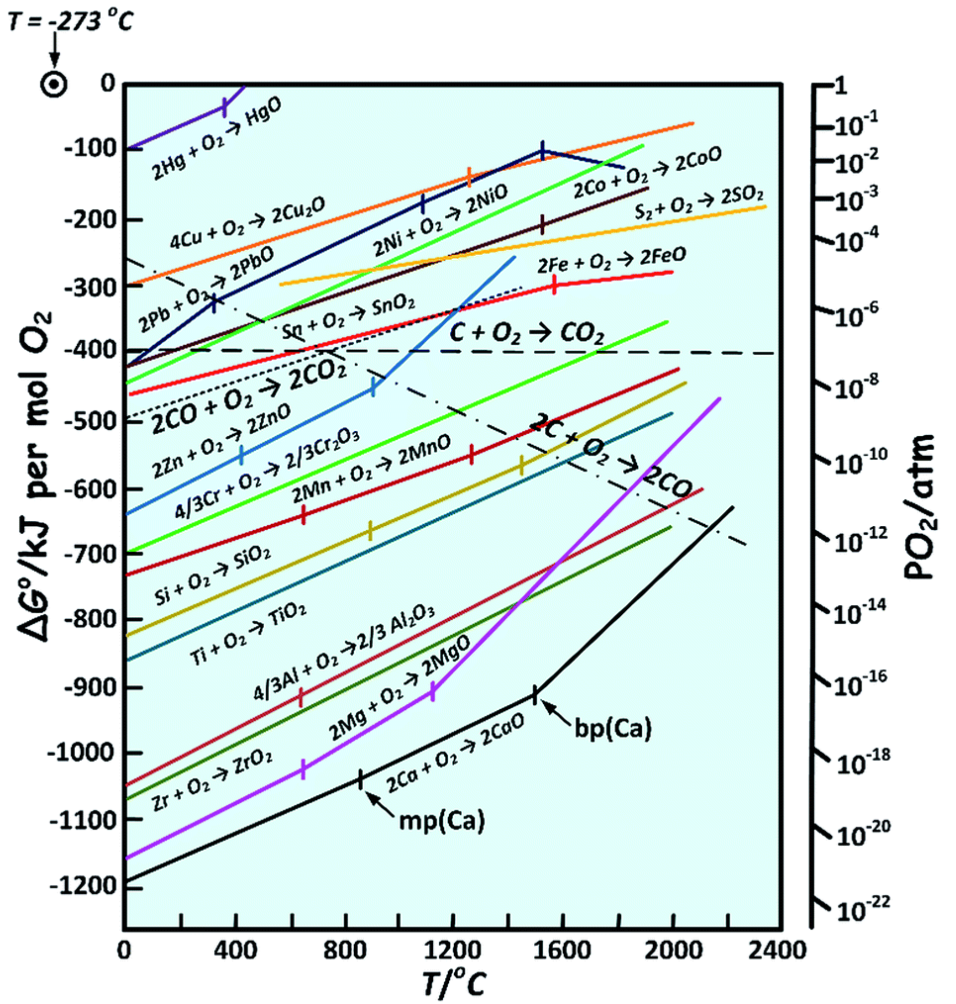


solubility of metals in Si

Film Adhesion

Ellingham diagram

Formation of metal oxides

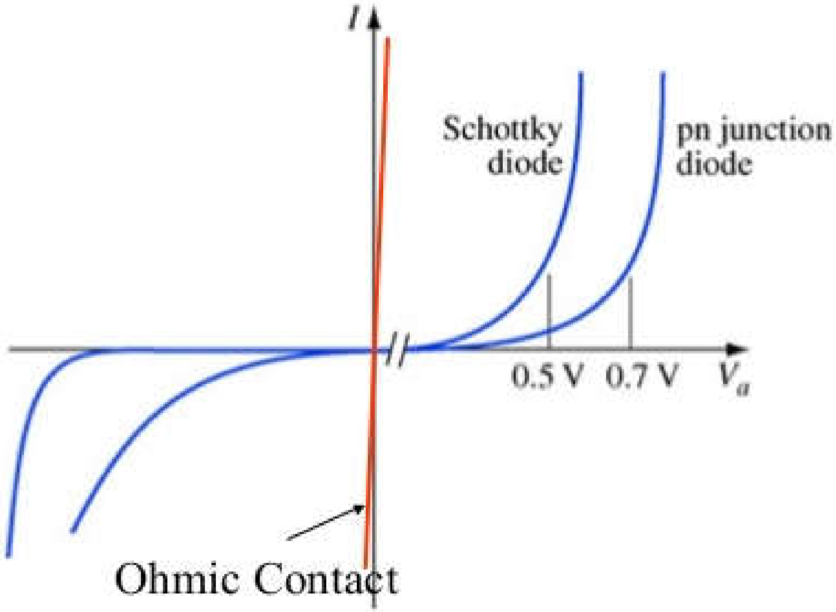


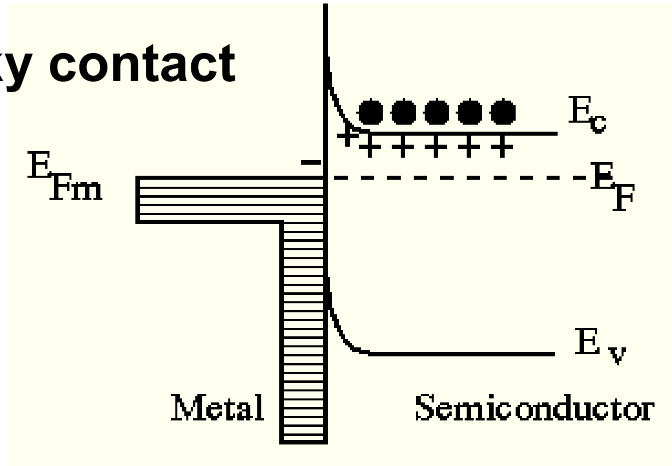
Film Adhesion

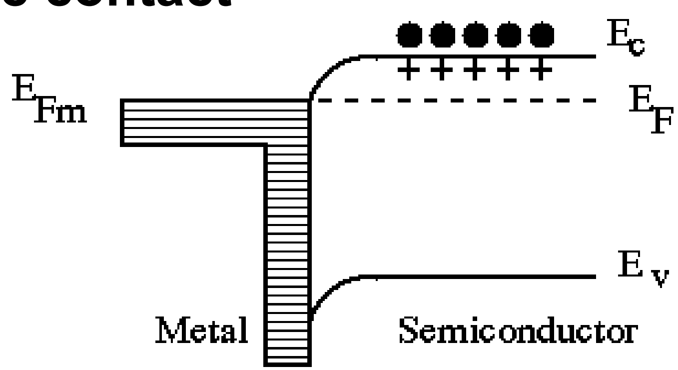
- Metals like Ag and Au tend to have poor adhesion on Si and SiO_2
- Substrate clean
- Deposit a thin (~5 nm) Ti or Cr layer for adhesion
- Plasma treatment
- Monolayer bonding
- ...

Typical Ohmic Contacts for III-V

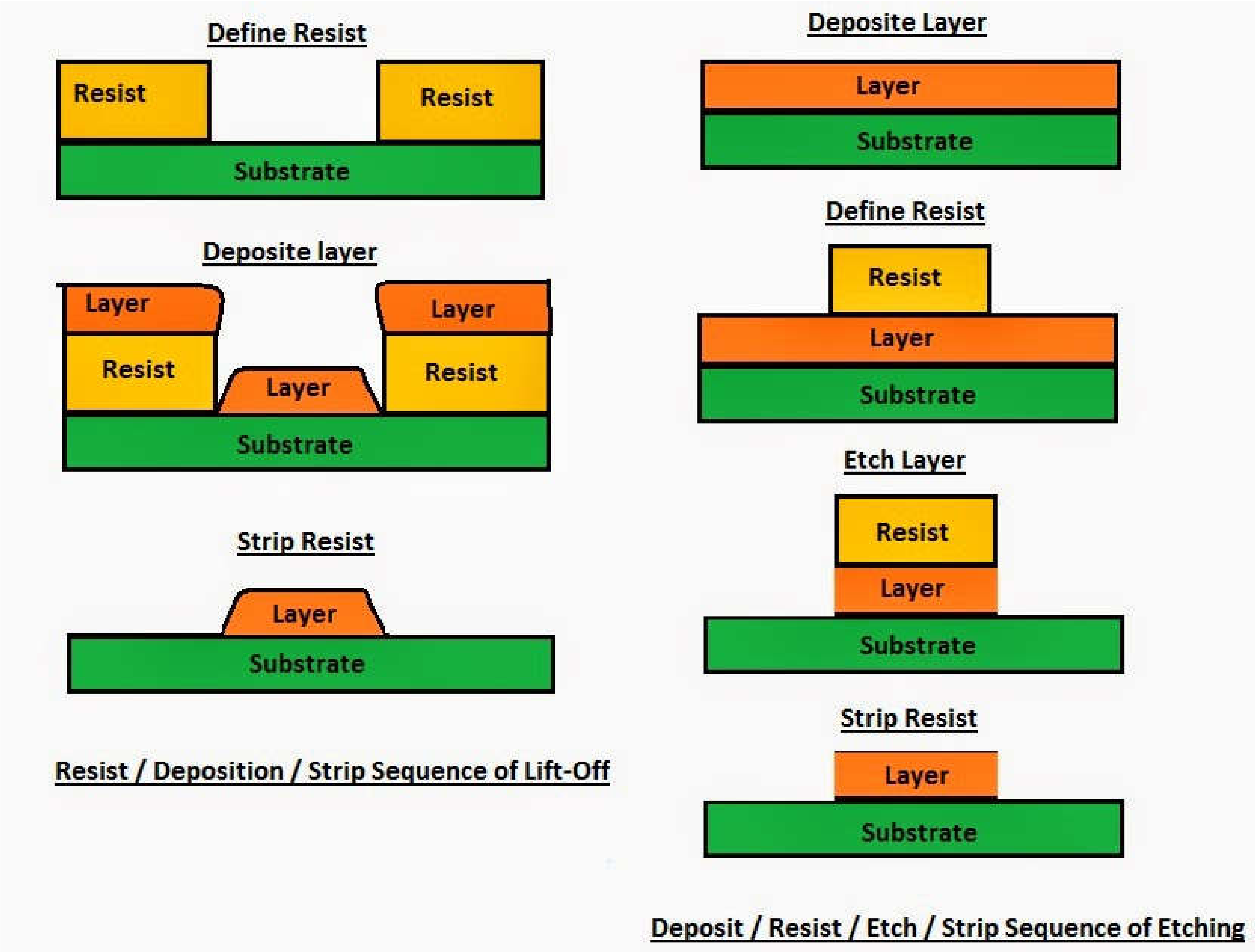
- **GaAs**
  - p-GaAs Be/Au, Ti/Pt/Au, ...
  - n-GaAs Ge/Ni/Au, Pd/Ge, ...
- **GaN**
  - p-GaN Ni/Au
  - n-GaN Ti/Al/Au





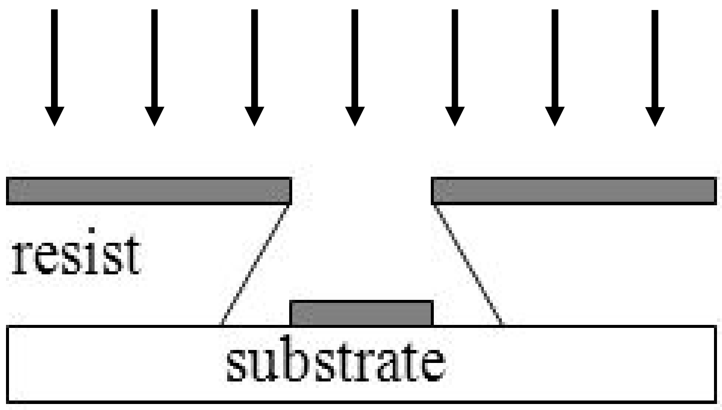


Thin Film Patterning

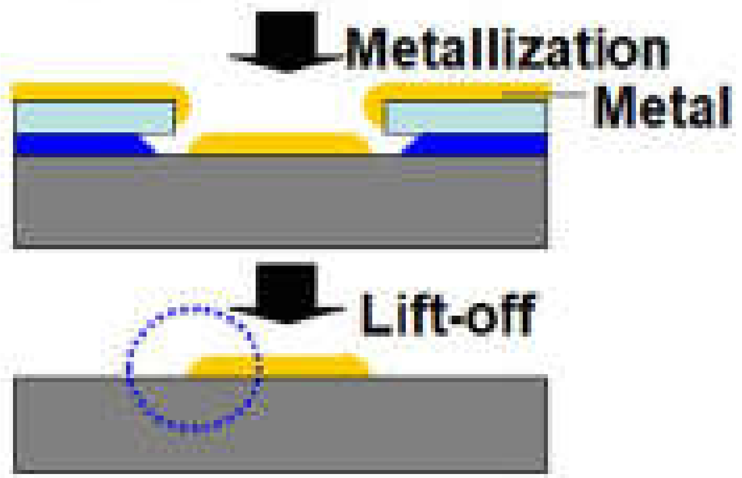


Requirements for Liftoff

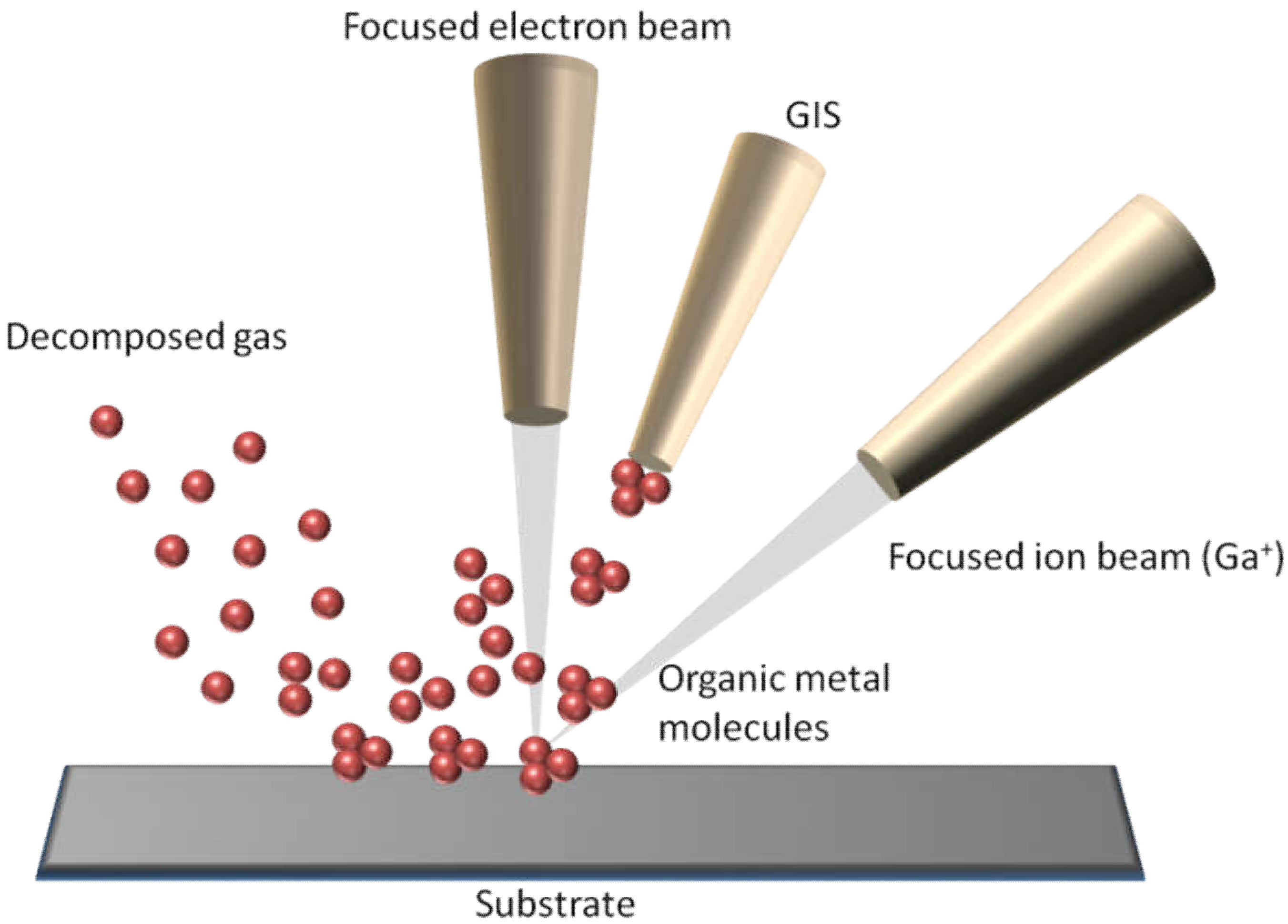
- Avoid Step Coverage

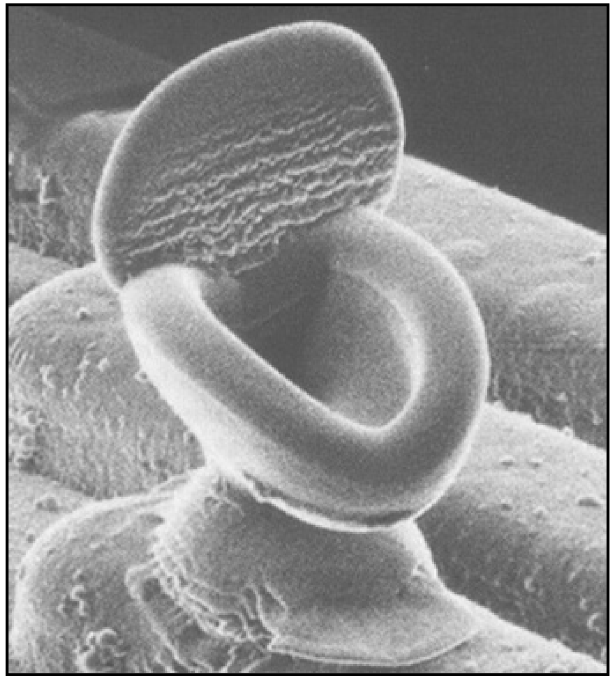


- PVD instead of CVD
  - avoid high temperature
- Photoresist (PR) process
  - negative PR preferred (*Why?*)
  - increase PR thickness
  - multilayer PR



Focused Ion Beam (FIB) Deposition





world's smallest toilet

Etch: Ga
Deposition: Pt

Thank you for your attention