电子与电气工程系
Department of Electrical and
Electronic Engineering

# Physical Vapor Deposition

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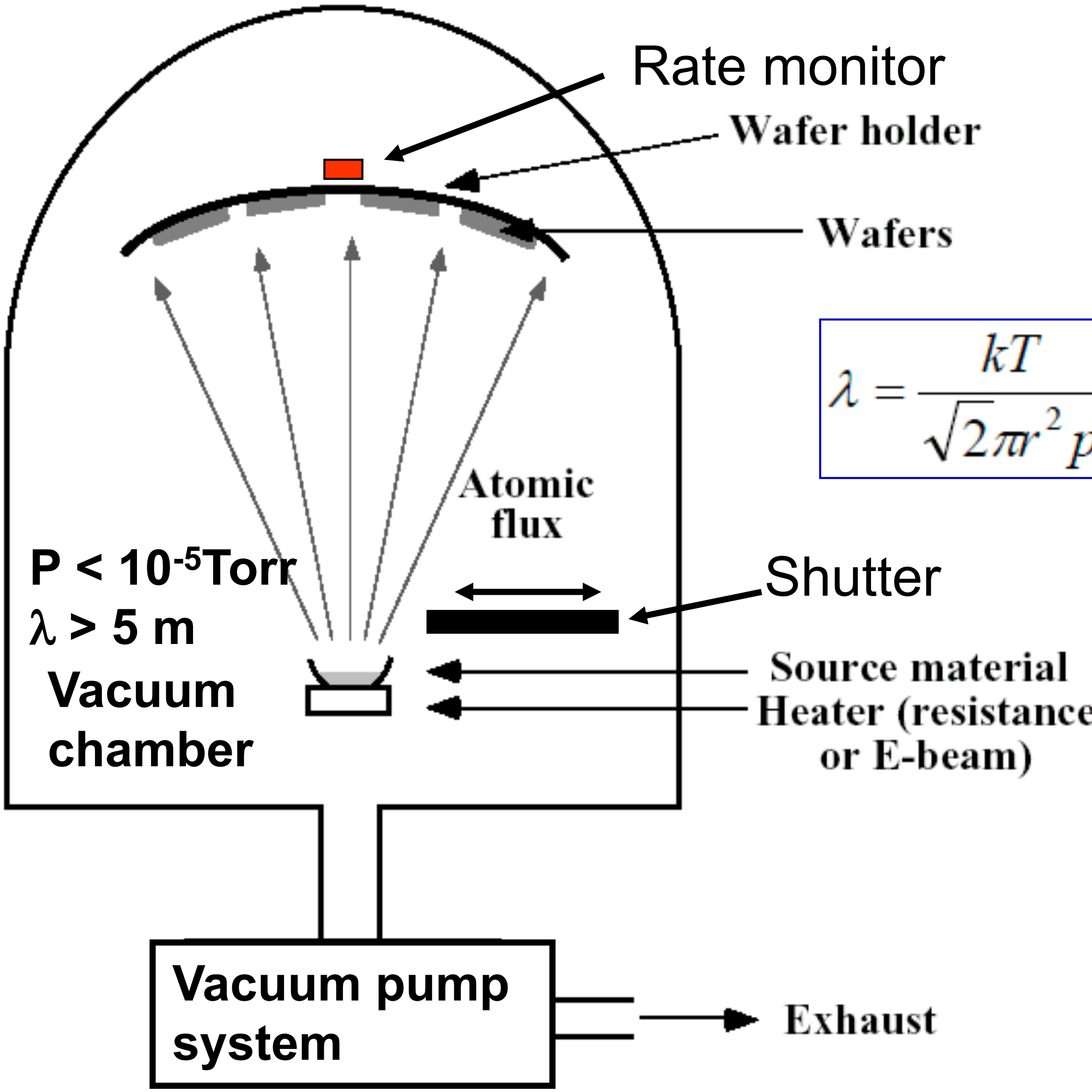
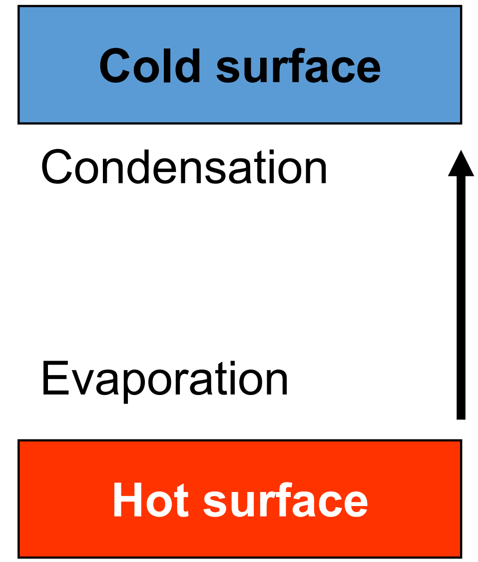
# Outline

- Applications
- Materials
  - Semiconductors
  - Insulators
  - Conductors
- Methods
  - CVD – Chemical Vapour Deposition
    - APCVD, LPCVD, PECVD, HDPCVD, VPE
  - PVD – Physical Vapour Deposition
    - Evaporation, Sputtering
  - Spin-on
  - Electrochemical Deposition

# PVD - Evaporation




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




**Basic principle**

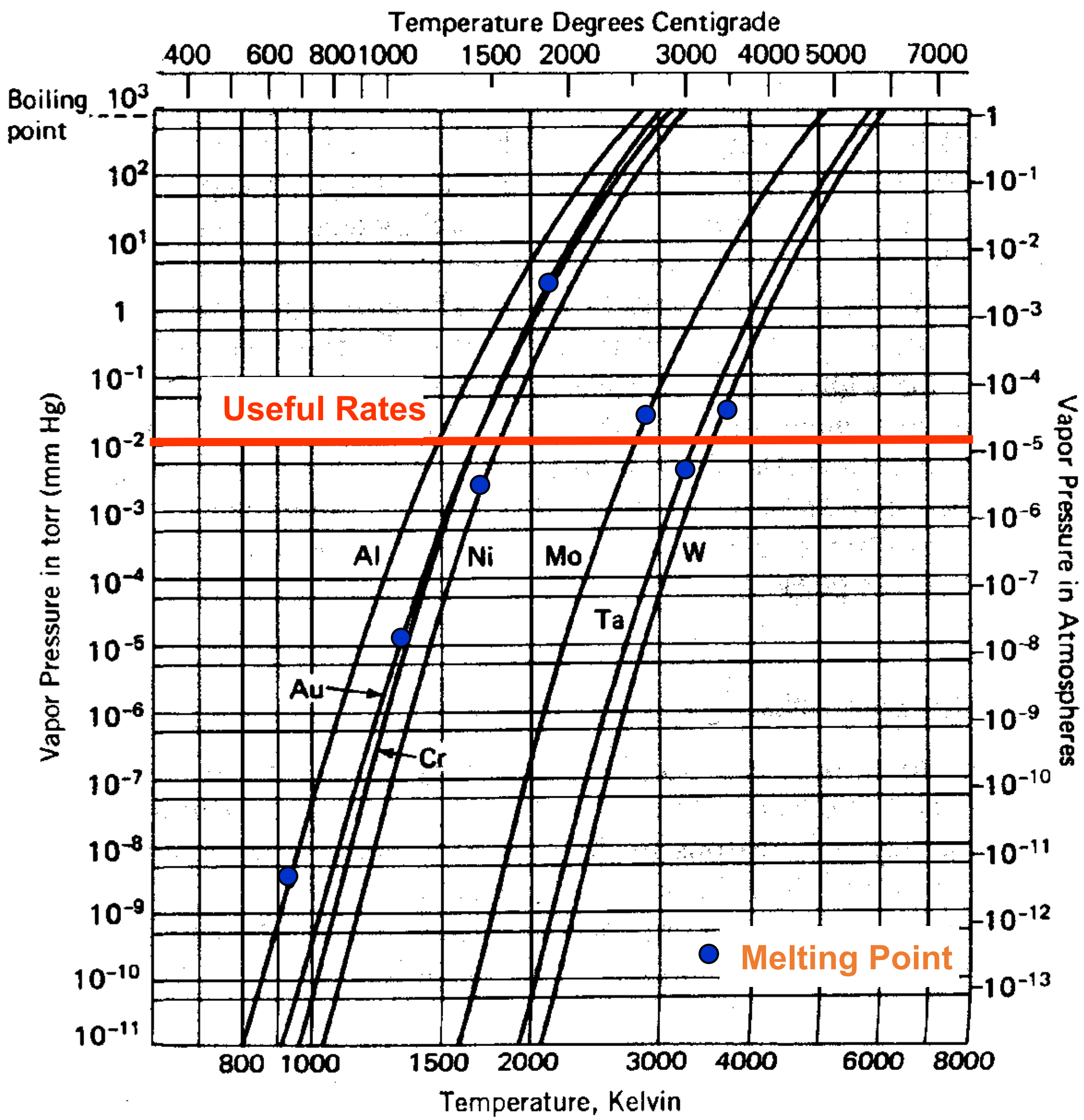
- **Very flexible tool**
- **Wide range of pure materials**
- **"No" gas-phase collisions**
- **Line-of-sight deposition**
- **High purity possible**
    - **UHV, P< $10^{-9}$ Torr**
    - **Pure source & e-beam**

# PVD - Evaporation

RTNN
RESEARCH TRIANGLE
NANOTECHNOLOGY NETWORK

暂停 (k)

# Vapour Pressure




**Evaporation:**

Melt→Gas

**Sublimation:**

Solid→Gas

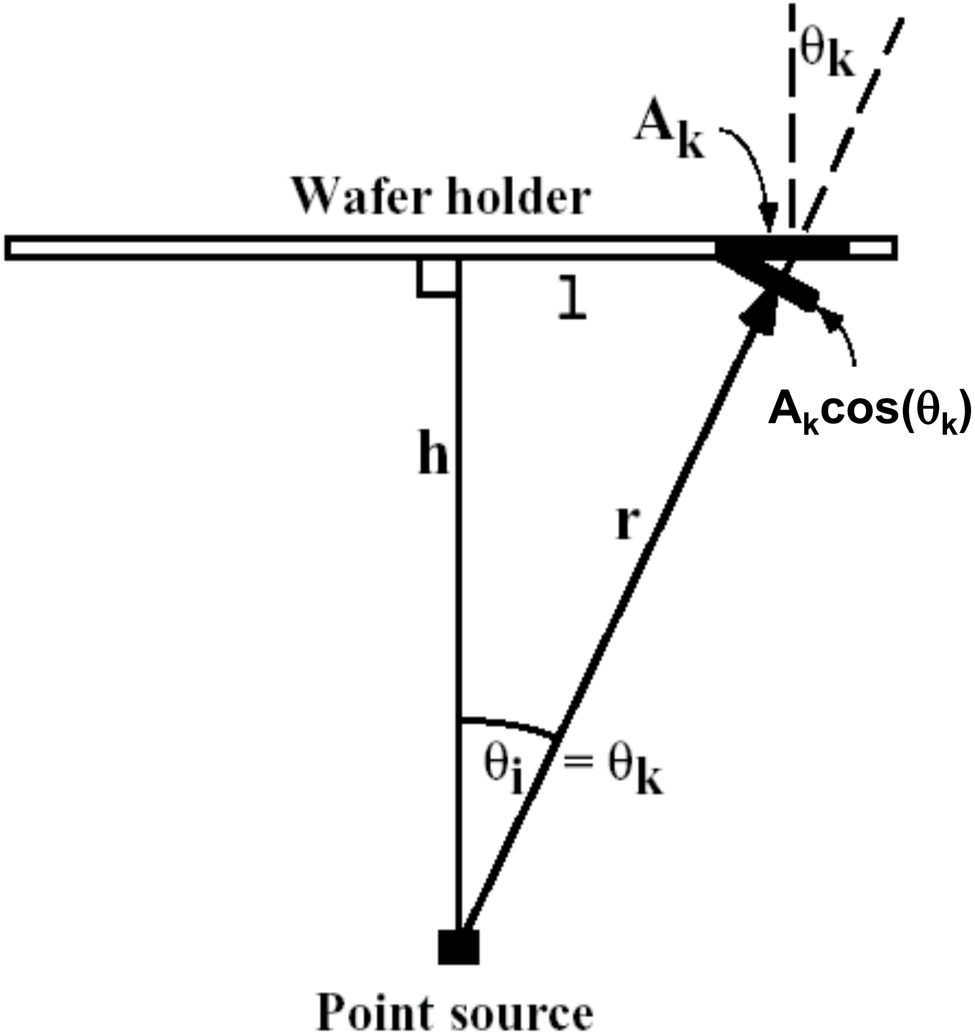
Useful rates:

P <10 mTorr ~ 1Pa

very often:

$P<10^{-5}$ Torr

# Point Source Evaporation




Receiving area inclination effect

**Isotropic point source emitter**

**Radial mass flux :** $F_r = \dfrac{R_{evap}}{\Omega r^2}$

**Full space emitter :** $F_r = \dfrac{R_{evap}}{4\pi r^2}$

**Half space emitter :** $F_r = \dfrac{R_{evap}}{2\pi r^2}$

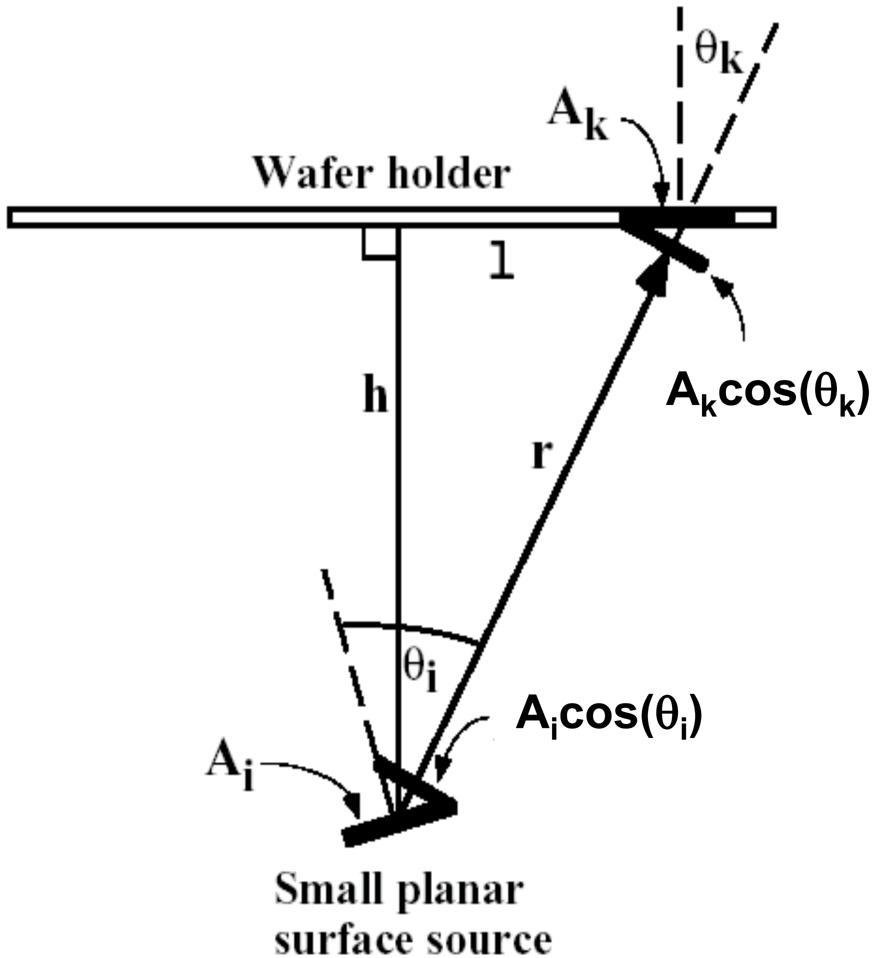
**Mass deposition flux :**

$$F_D = \frac{F_r\left(A_k \cos\theta_k\right)}{A_k} = F_r \cos\theta_k$$

$$F_D = F_r \cos\theta_k = \frac{R_{evap}}{\Omega r^2}\cos\theta_k$$

**Deposition rate :** $v = \dfrac{F_D}{\rho} = \dfrac{R_{evap}}{\rho\Omega r^2}\cos\theta_k$

# Plane Source Evaporation




Isotropic plane source emitter

Half space emitter: $F_r = \dfrac{R_{evap}}{2\pi r^2} 2\cos\theta_i$

Mass deposition flux:

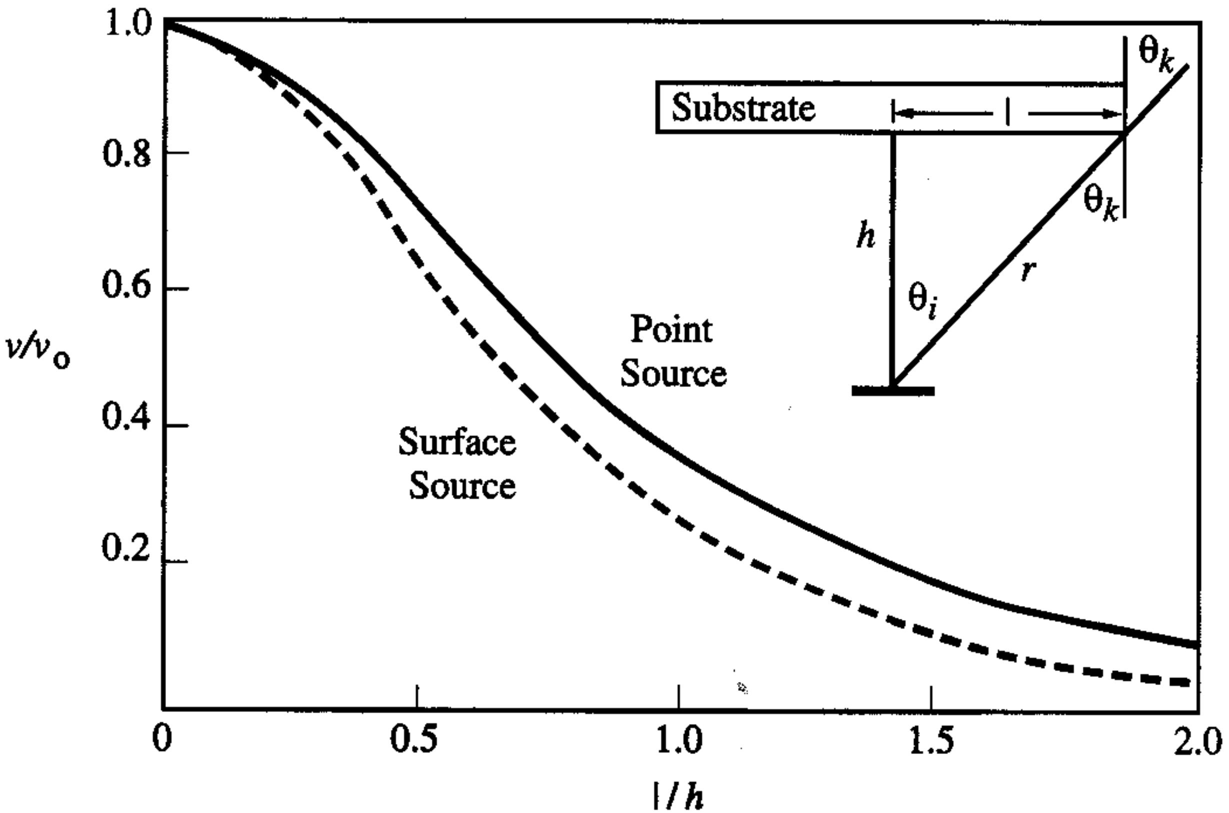
$$F_D = F_r \cos\theta_k = \frac{R_{evap}}{\pi r^2}\cos\theta_i \cos\theta_k$$

Deposition rate:

$$v = \frac{F_D}{\rho} = \frac{R_{evap}}{\rho \pi r^2}\cos\theta_i \cos\theta_k$$

Receiving area inclination effect
& Source area inclination effect

# Plane Receiving Surface




Deposition rate variation across a planar receiving surface for point and plane isotropic emitters.

**Plane receiving surface :**

$$\cos\theta_i = \cos\theta_k = \frac{h}{r}$$

$$\cos\theta = \frac{h}{\sqrt{h^2 + l^2}}$$

**Deposition rate :**

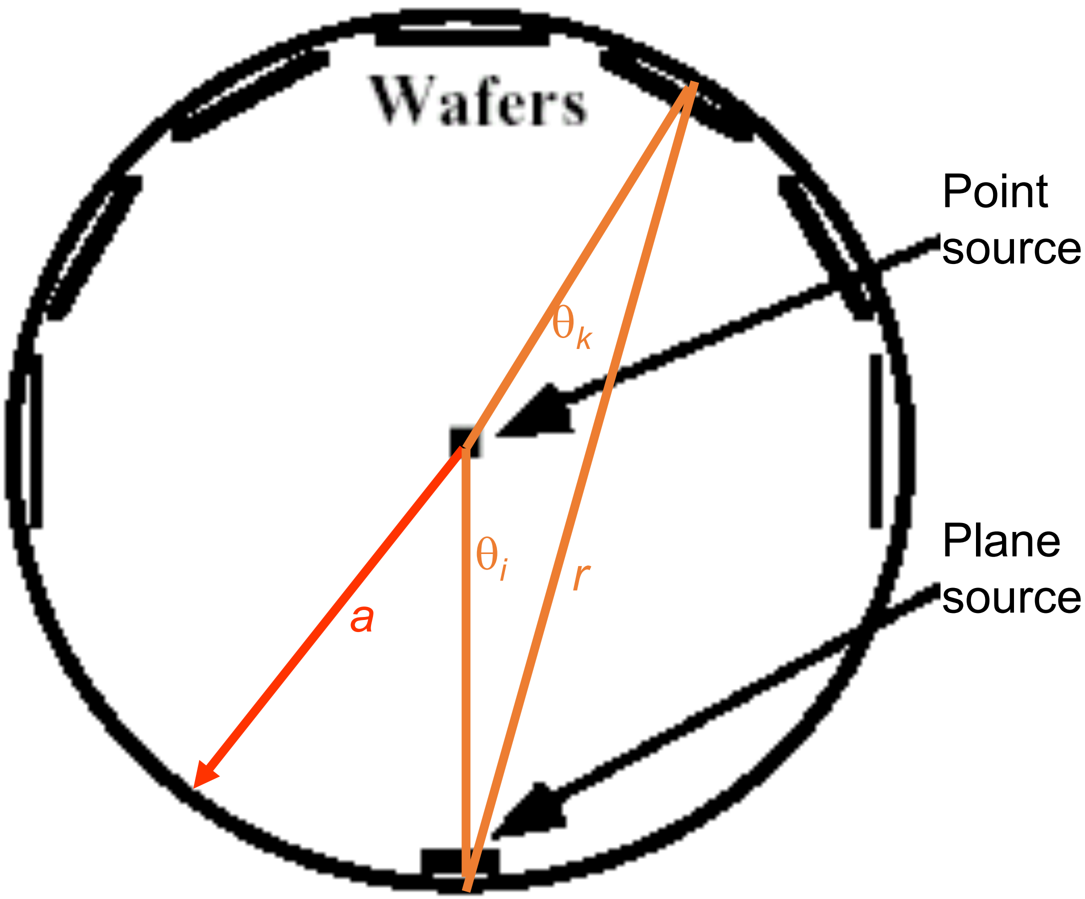
$$v_{\text{point}} = v_0 \cos\theta_k = \frac{v_0 h}{\sqrt{h^2 + l^2}}$$

$$v_{\text{plane}} = v_0 \cos\theta_i \cos\theta_k = \frac{v_0 h^2}{h^2 + l^2}$$

**Use a large source/sample distance** $h$

**Price : rate - reduction** $v_0 \propto \frac{1}{h^2}$

# Spherical Wafer Holder A Planet arium




Source/wafer arrangement for uniform deposition rate.

**Point source:** $\cos\theta_k = 1$

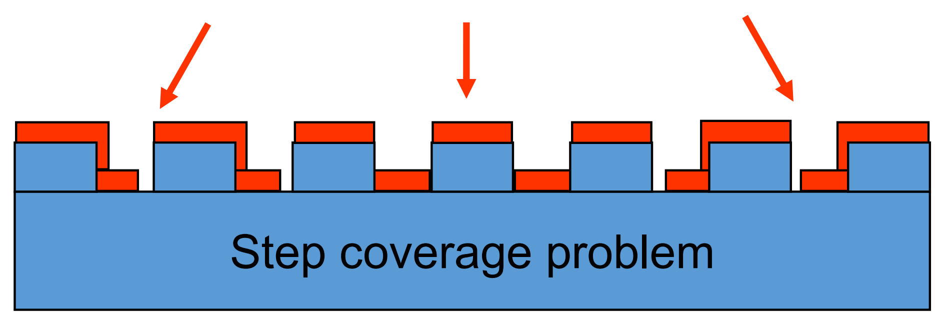
**Deposition rate:**

$$v_{\text{point}} = \frac{R_{evap}}{\rho\Omega r^2}\cos\theta_k = \frac{R_{evap}}{\rho\Omega a^2}$$

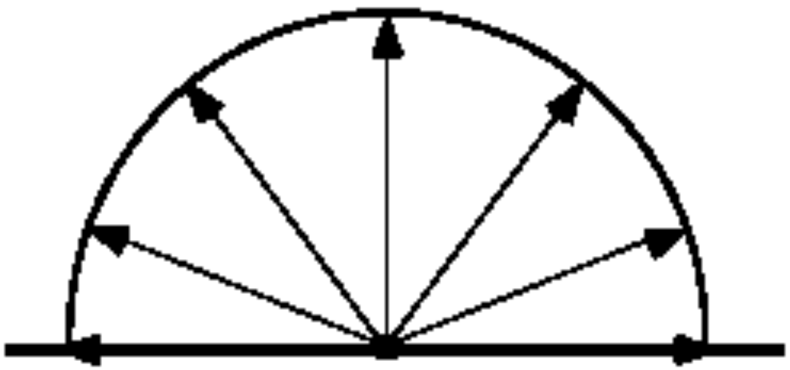
**Plane source:** $\cos\theta_i = \cos\theta_k = \dfrac{r}{2a}$

**Deposition rate:**

$$v_{\text{plane}} = \frac{R_{evap}}{\rho\pi r^2}\cos\theta_i\cos\theta_k = \frac{R_{evap}}{\rho 4\pi a^2}$$



# Ideal Radiation Patterns



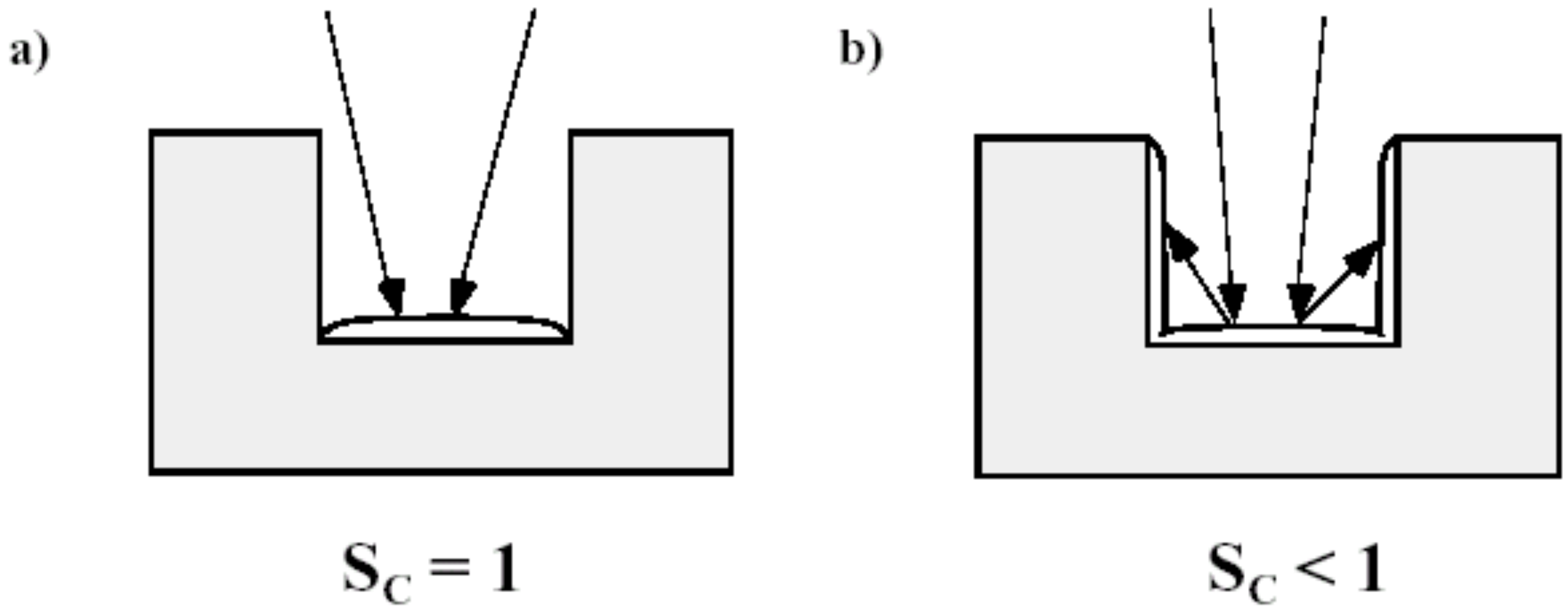
Ideal point source
Isotropic

Ideal plane source
$\cos\theta$

Directional source
$\cos^n\theta$

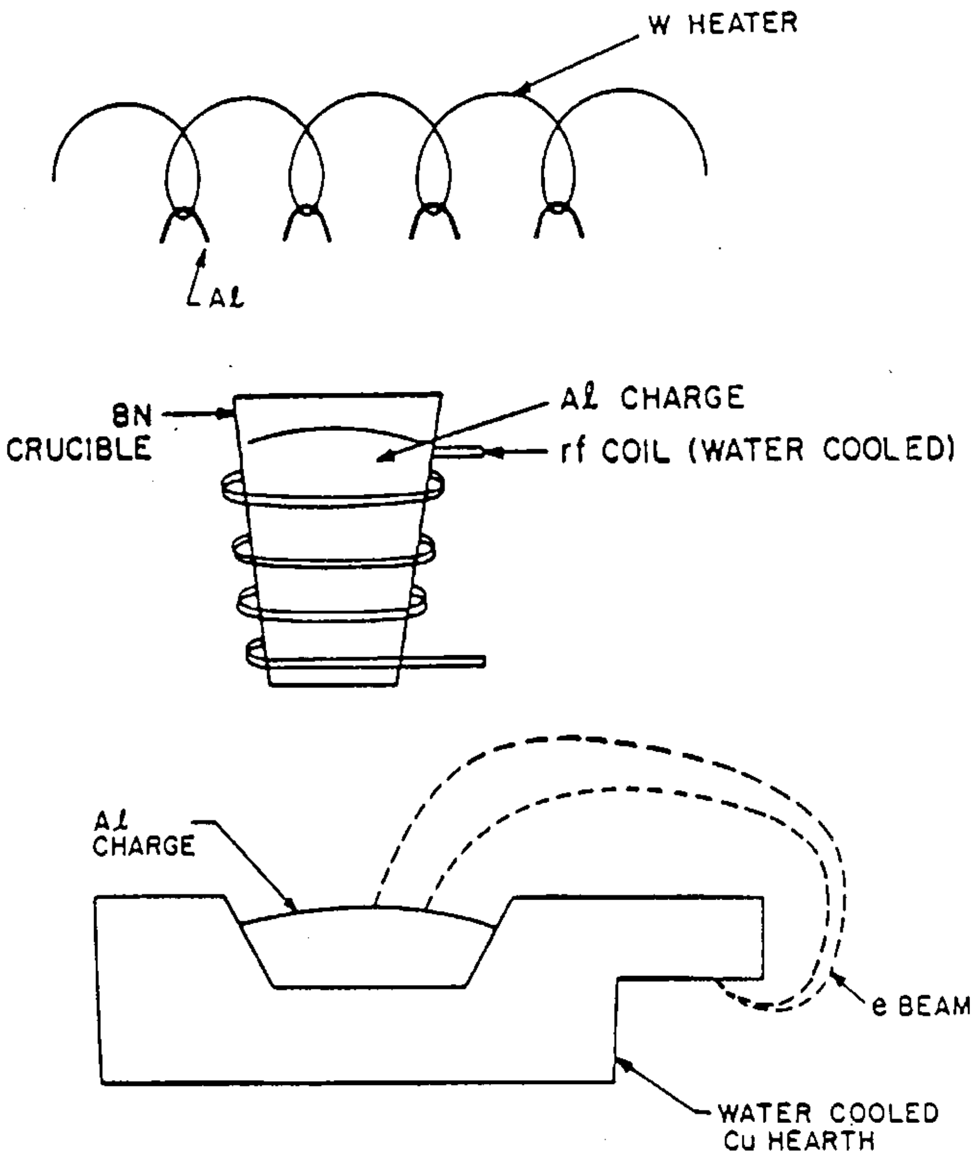
Real sources can have far more complicated radiation patterns!
But the ideal patterns are very useful in modelling.

# Trench Filling/Sidewall Coverage




In evaporation the sticking coefficient is very high, $S_C \approx 1$
Evaporated atoms arriving from a small space angle =>
Sidewalls are not covered, unless they directly see the source.

# Practical Evaporation Sources

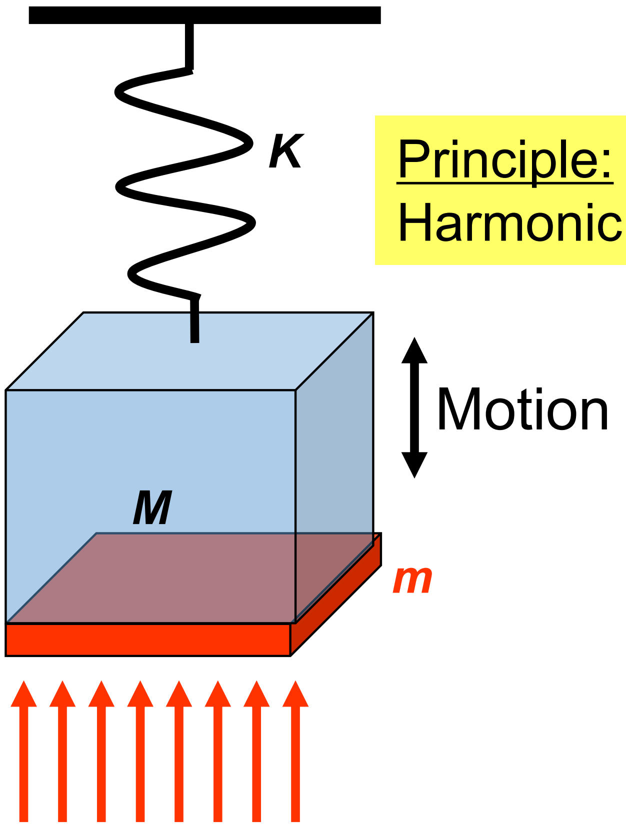



<u>**Resistance heating – Filament**</u>:
Easy & cheap
Melt/Heater contact:
 Contamination problem
 Materials compatibility problem

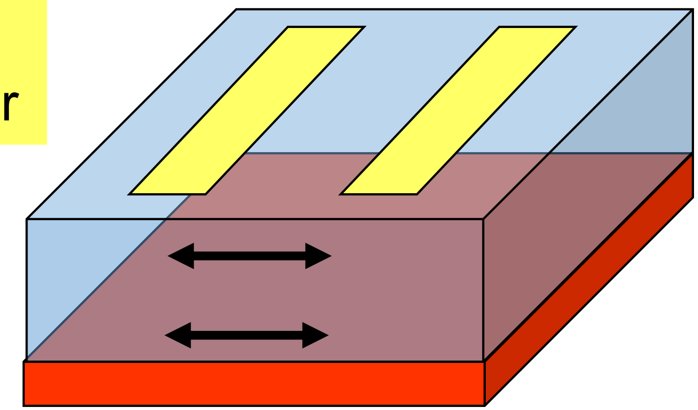
<u>**RF-Heating:**</u>
Reduced contamination

<u>**E-Beam Heating:**</u>
Water cooling: Partly molten source
No Melt/Crucible contact
Contamination eliminated
No materials compatibility problem
5-10keV electrons:
 Radiation (X-Ray) problem

# Deposition Rate Monitor




<u>Principle:</u>
Harmonic mechanical oscillator



**Resonant frequency :**

$$\omega = \sqrt{\frac{K}{M+m}} = \omega_0 \sqrt{\frac{1}{1+\frac{m}{M}}} \approx \omega_0 \left(1 - \frac{m}{2M}\right)$$

<u>Real rate monitor:</u>
Piezo-electric crystal (Quartz) in a shear-vibration mode. Electronic feedback circuit sustains and detects vibration.

Rate monitors needed due to the strongly temperature dependent vapour pressure & rate.

# PVD - Evaporation

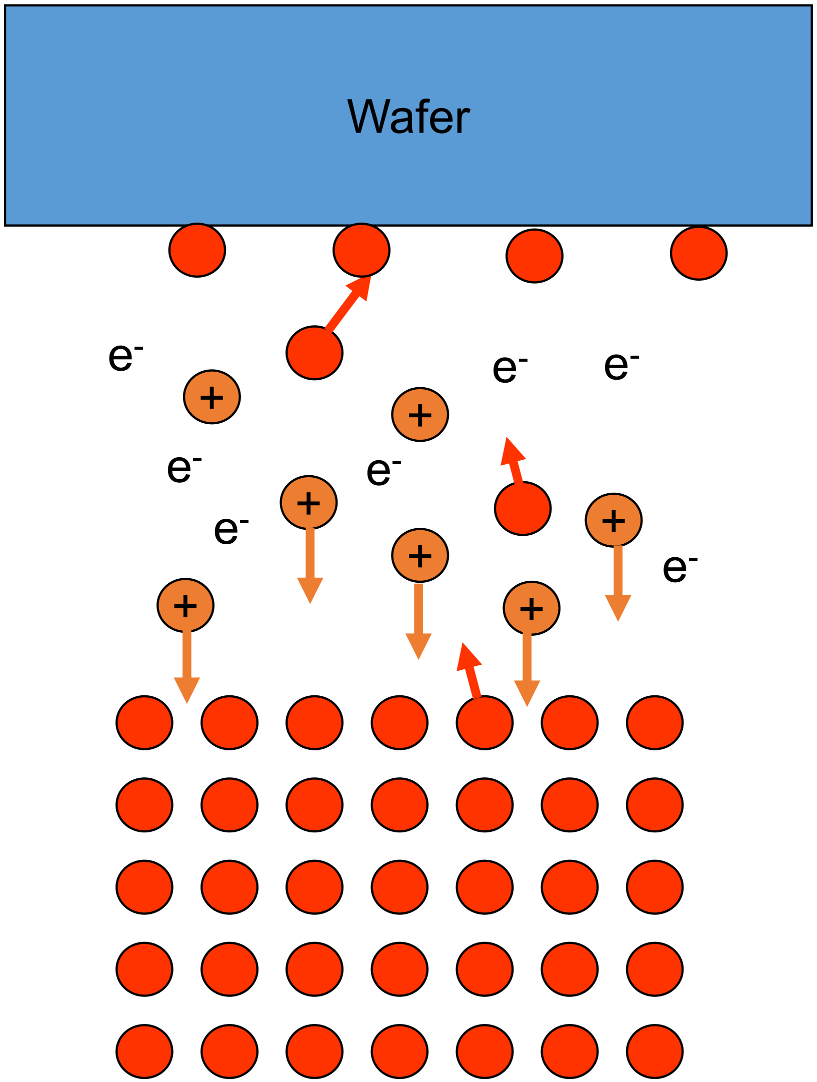
<u>Advantages</u>

- Flexible, many pure materials in one system
- In-situ multilayer materials
- No step coverage
  - Lift-off
- Rate & substrate temperature independent
- Real time rate measurements easy
- Single sided deposition

<u>Disadvantages</u>

- Alloy composition difficult to control
  - Also in co-evaporation
- No step coverage
  - Move wafer to cover steps
- Rates difficult to control
  - Affects morphology
- Single sided deposition
- Pump-down time long
  - Use a load-lock: reduce pump-down time & contamination

# PVD – Sputtering: Basic Principle




Target: source material

Energetic ions, usually $Ar^+$, knock out source atoms.
These atoms travel and deposit on the wafer/substrate.
Gas phase collisions occur before deposition, *P*~10-100mTorr, $\lambda$<5mm.

**Result**

•Deposited atoms arrive from a wide space angle.

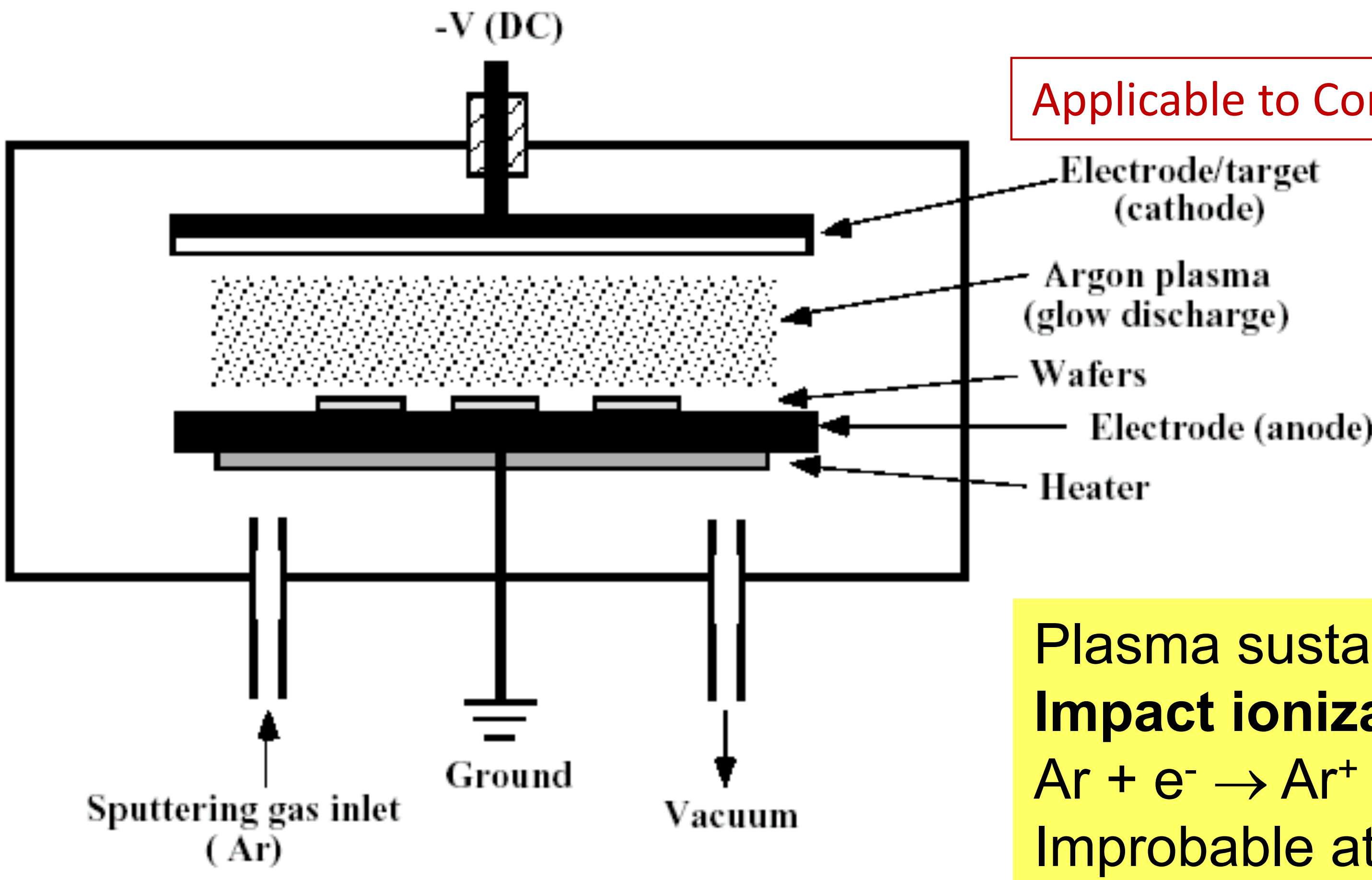
•Improved step coverage.

**Sputter yields** (atoms/ion) rather insensitive to material:

•0.1 to 3, determined by the DC bias and inject angle

•Controlled alloy deposition possible

# DC - Sputtering

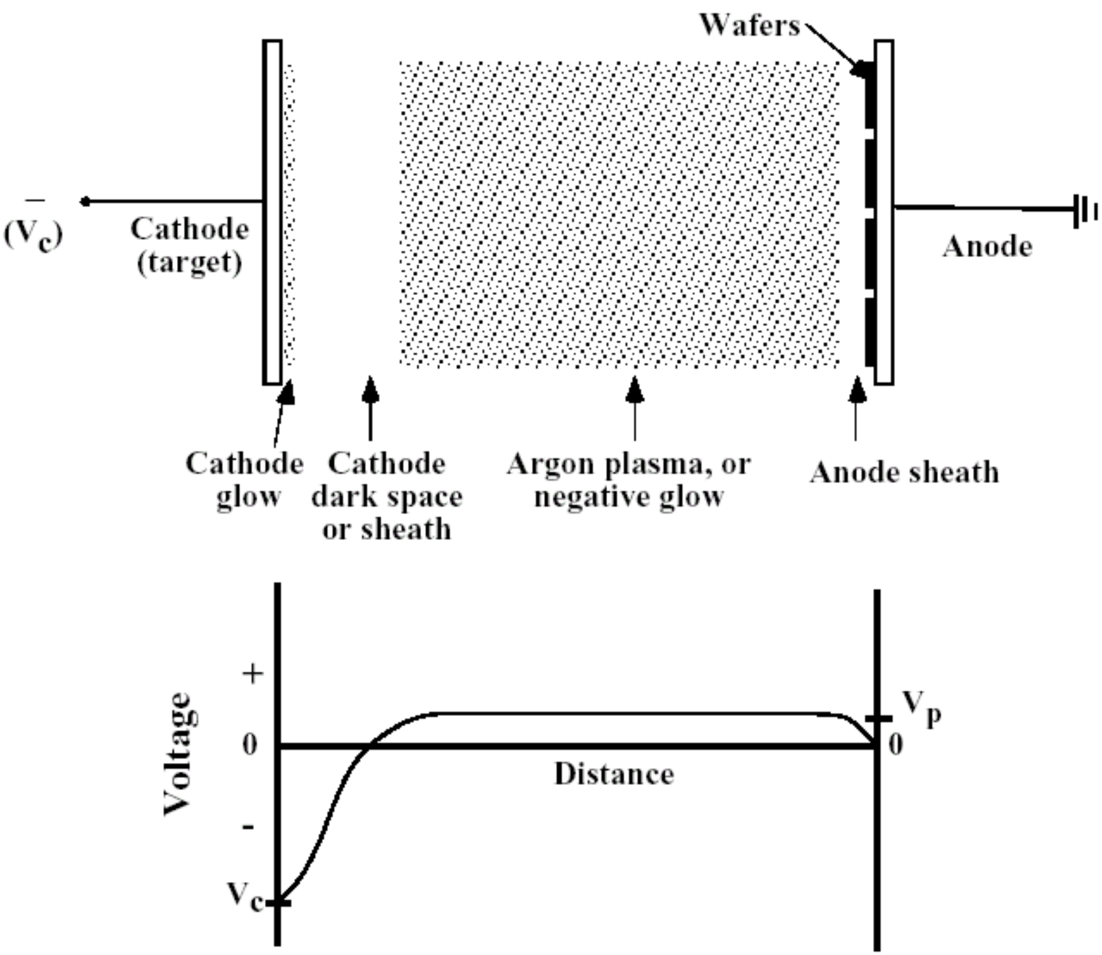



Applicable to Conductive target

Basic two-electrode DC sputter system
p~10-100mTorr, $V_{DC}$~0.5-5kV.

Plasma sustaining reaction:
**Impact ionization**
$Ar + e^- \rightarrow Ar^+ + 2e^-$
Improbable at low pressure, since $\lambda \geq L$,
Improbable at high pressure, since $E \sim \lambda V/L < E_{ionization}$

# Glow Discharges



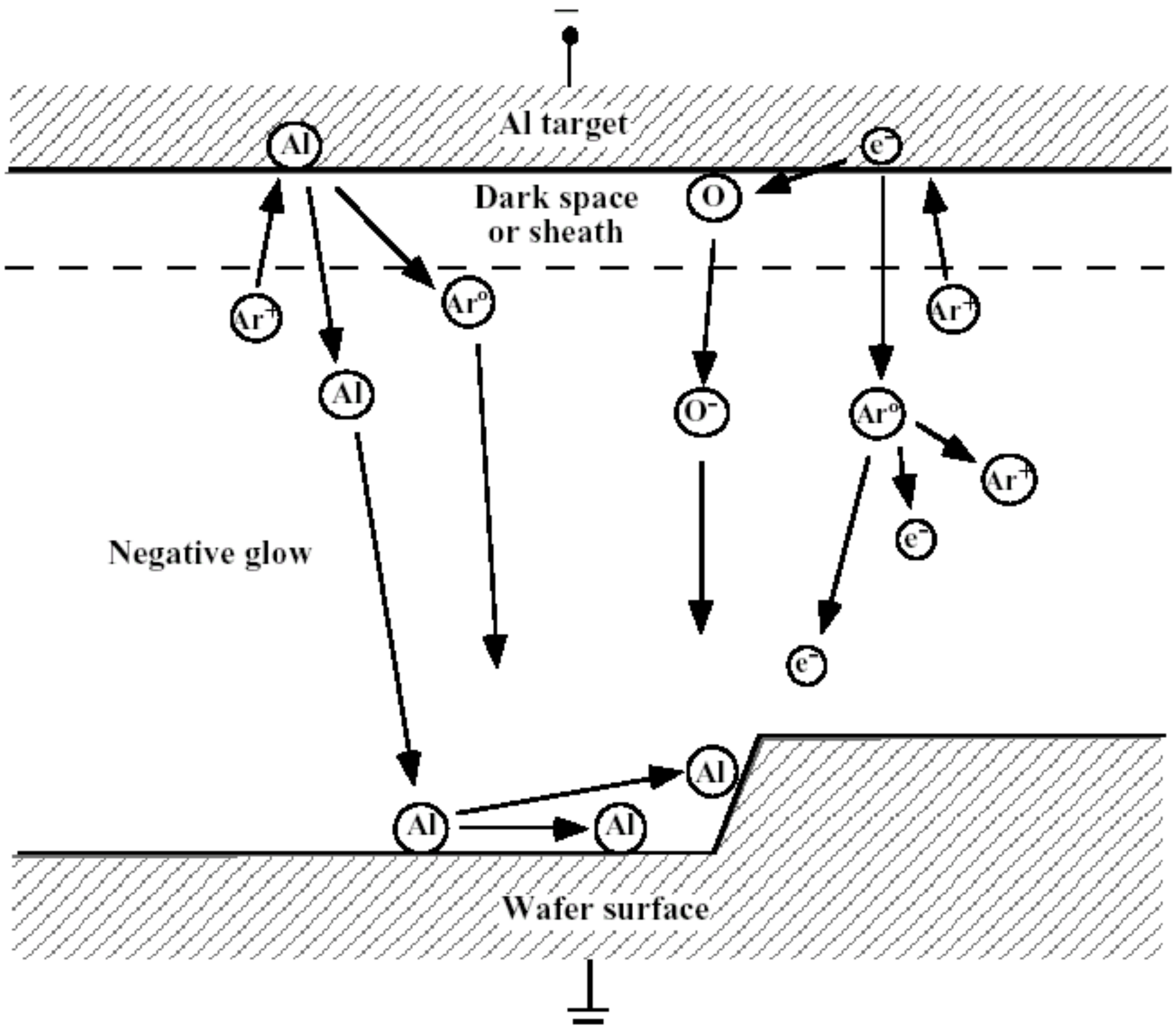

The plasma region is
- Almost charge neutral $Ar^+$ & $e^-$.
- At the positive plasma potential $V_p$ ~1-10V, $E_{electron}$~1-10eV.

The applied voltage is dropped across the cathode dark space.
The cathode dark space is:
- A space charge region, $Ar^+$.
- 0.1-10mm thick, d.

Current space-charge limited
Langmuir-Child: $I \sim V^{1.5}/d^2$

Why the plasma potential is possitive with respect to the anode?

# Sputtering – Important Processes




Ionization in gas-phase:

- $Ar + e^- \rightarrow Ar^+ + 2e^-$

Sputtering of Al & neutralisation of $Ar^+$

- $Al + Ar^+ + e^- \rightarrow Al_{gas} + Ar$

Secondary electron emission

- $Ar^+ + 2e^- \rightarrow Ar + e^-$

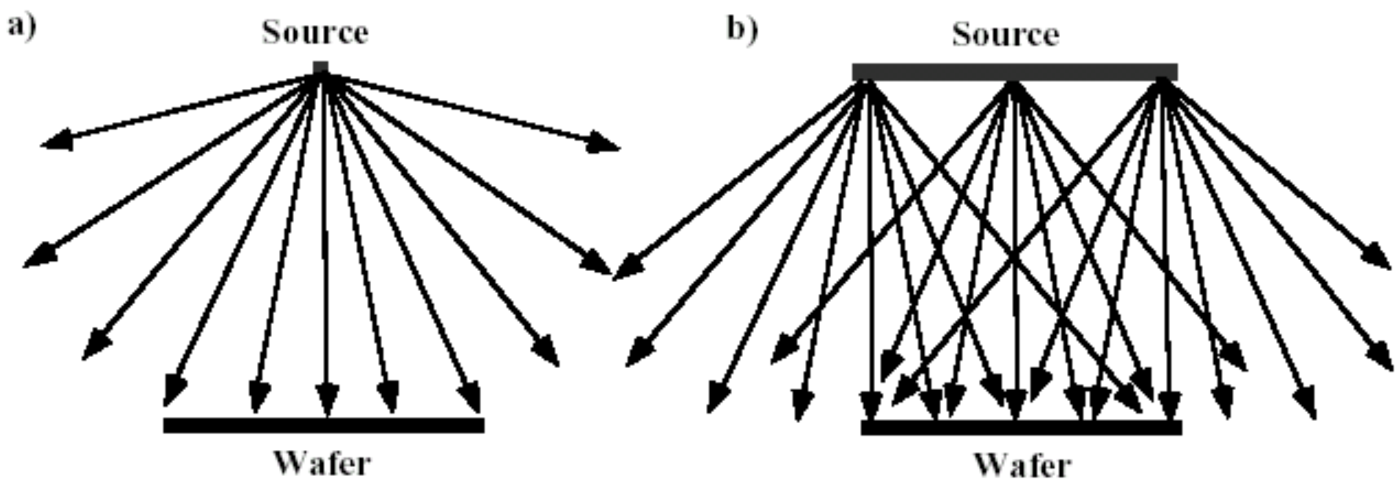
Ionization of background gas

- $O_2 + e^- + Solid \rightarrow O_2^-$

Gains energy in darkspace →
High energy ions hit substrate
Electrons ~10eV hit substrate
+ a few ~1keV electrons
+ high energy photons ~100eV

# PVD – Sputtering

# Sputtering - Uniformity



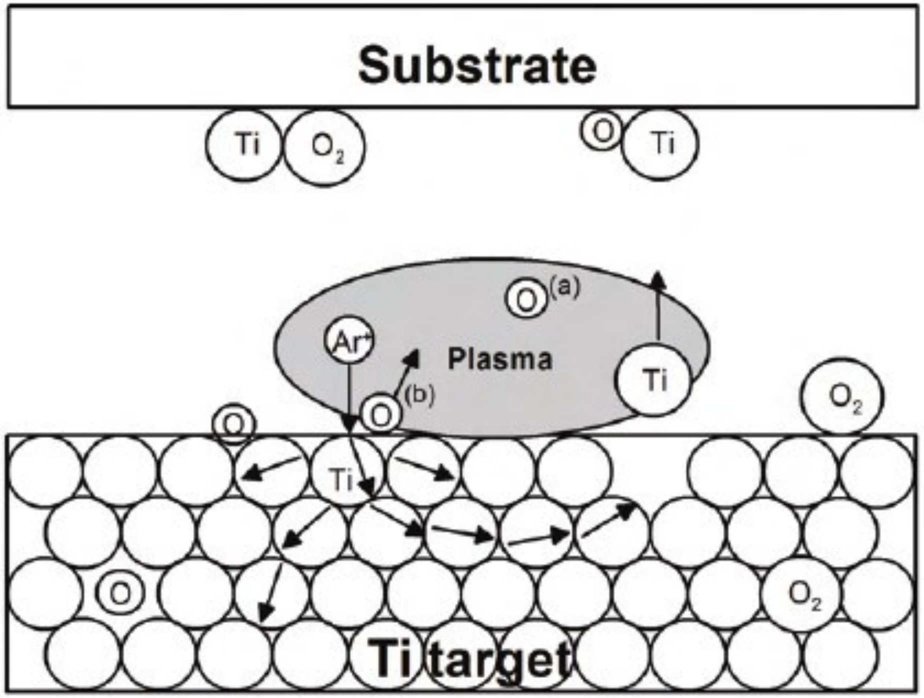

Target usually much larger than the wafer =>
Very good uniformity across a wafer, but still worse than CVD

Well controlled sputter parameters (Power, pressure etc.) =>
Very good uniformity from run to run

Rate monitors not necessary!
Composition of deposits reproducible!

# Reactive Sputter Deposition

**Compounds deposition**




Reactive gas is added ($O_2/N_2$)

- $Ar + e^- \rightarrow Ar^+ + 2e^-$
- $O_2 + e^- \rightarrow O_2^-$
- $N_2 + e^- \rightarrow N_2^-$

Reacte with Ti on the wafer surface or on the target

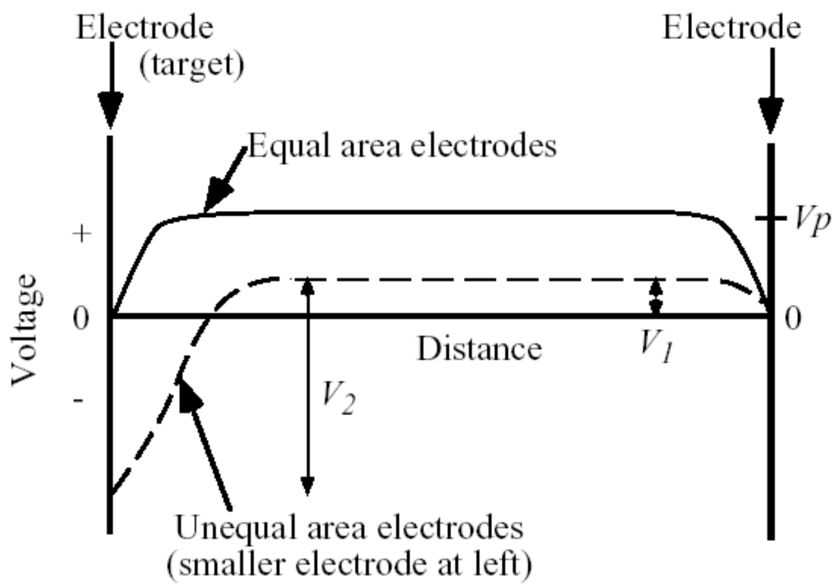
- $2Ti + N_2 \rightarrow 2TiN$
- $Ti + O_2 \rightarrow TiO_2$

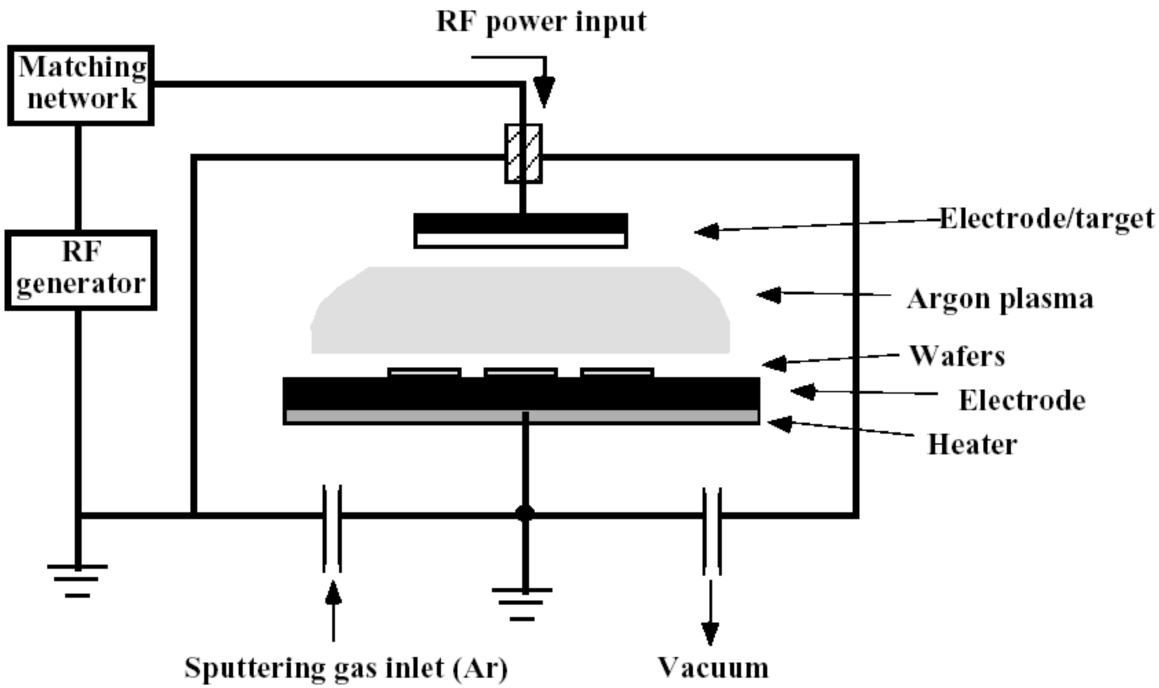
Diffcult to control the ratio

Used to improve the preperties of a film

- Oxygen or nitrogen doped TiW

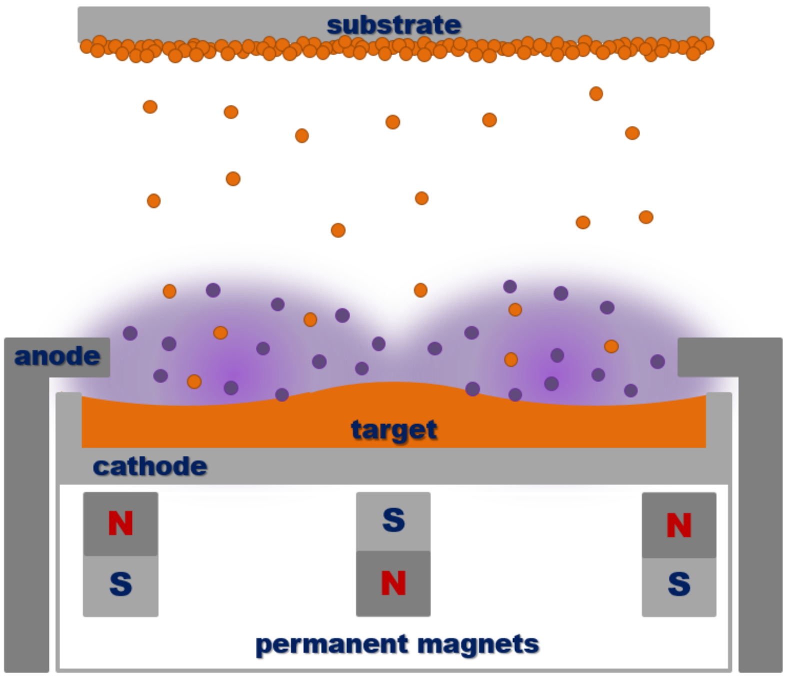
# RF - Sputtering




- RF sputtering allows nonconducting materials to be sputtered & deposition on dielectrics.
- Substrates on the larger electrode
- Allows more intense plasmas – higher ion-density by RF-exceted electrons → The ionization rate is still quite low

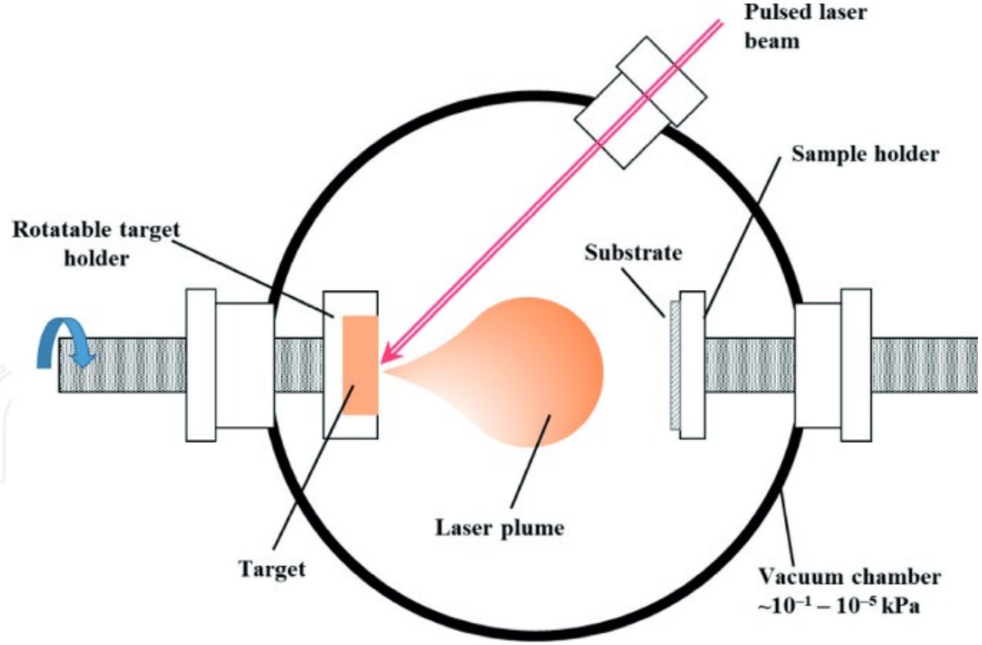
# Magnetron Sputtering




A magnetic field makes the electrons take a longer spiralling path

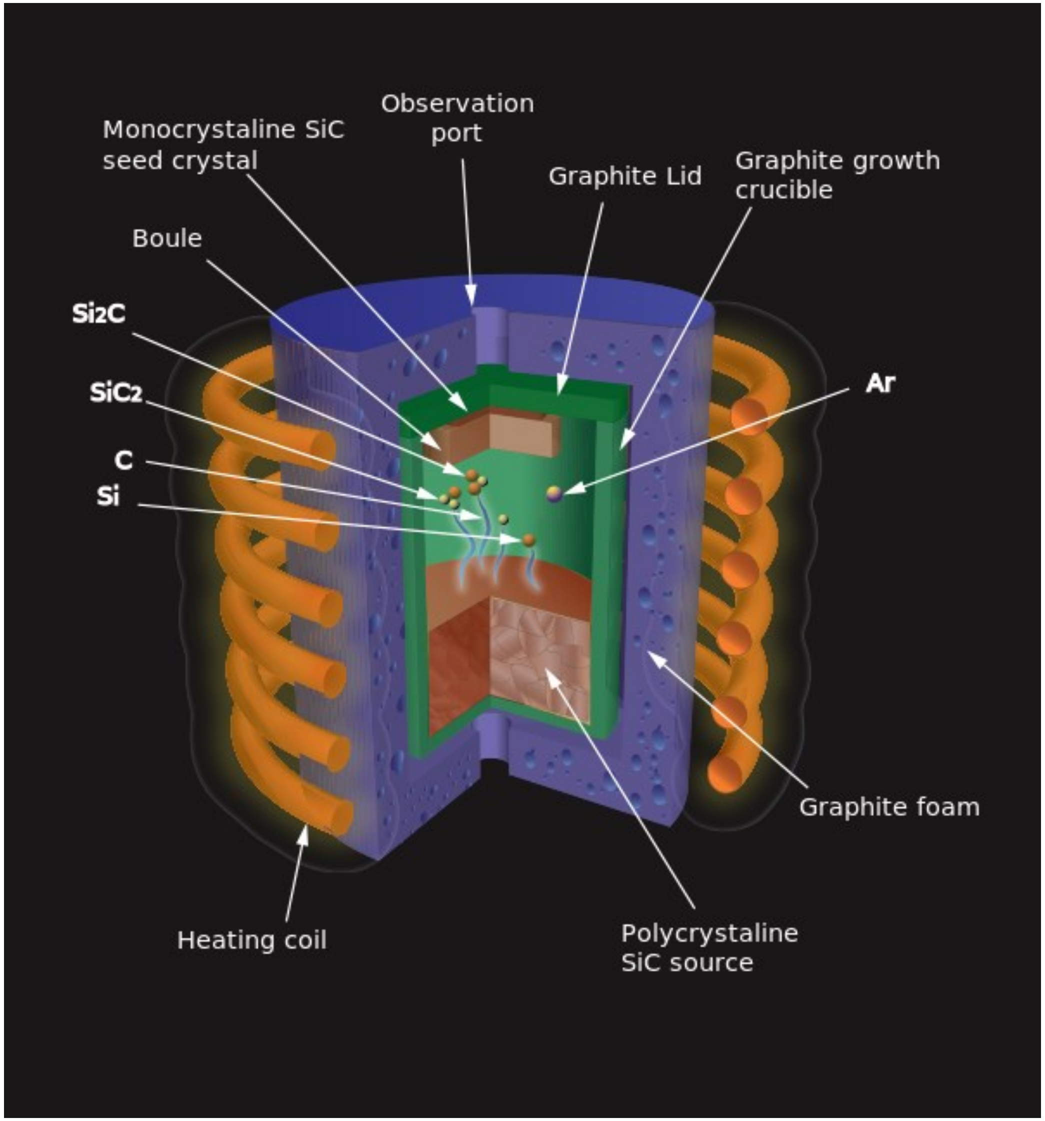
- More intense plasmas by confined electrons
- More confined plasmas → reduced Si sputter
- Higher deposition rates
- Lower Ar pressure → improved film quality

# Pulsed Laser Deposition

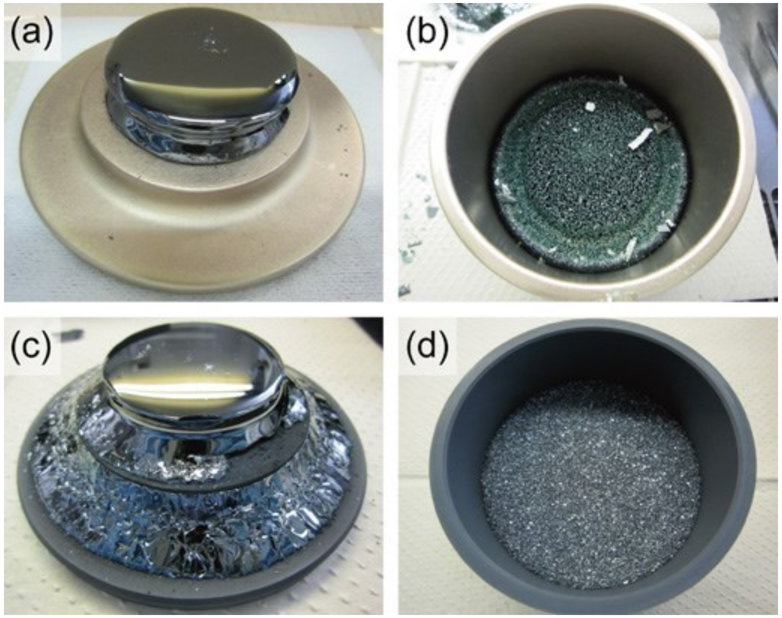



- A high-power pulsed laser beam is focused to strike a target that is to be deposited in ultra high vacuum or in the presence of a background gas.
- Rapid adoption in the 1990s with the development of short-pulse lasers.
- Good choice to grow thin films of complex composition and structure
    - metastable phases
    - laser source is external to the reaction chamber→"clean" reactor
    - No charge effects appear
    - No "memory" reactor
    - cost-effective: one laser can serve many vacuum systems.

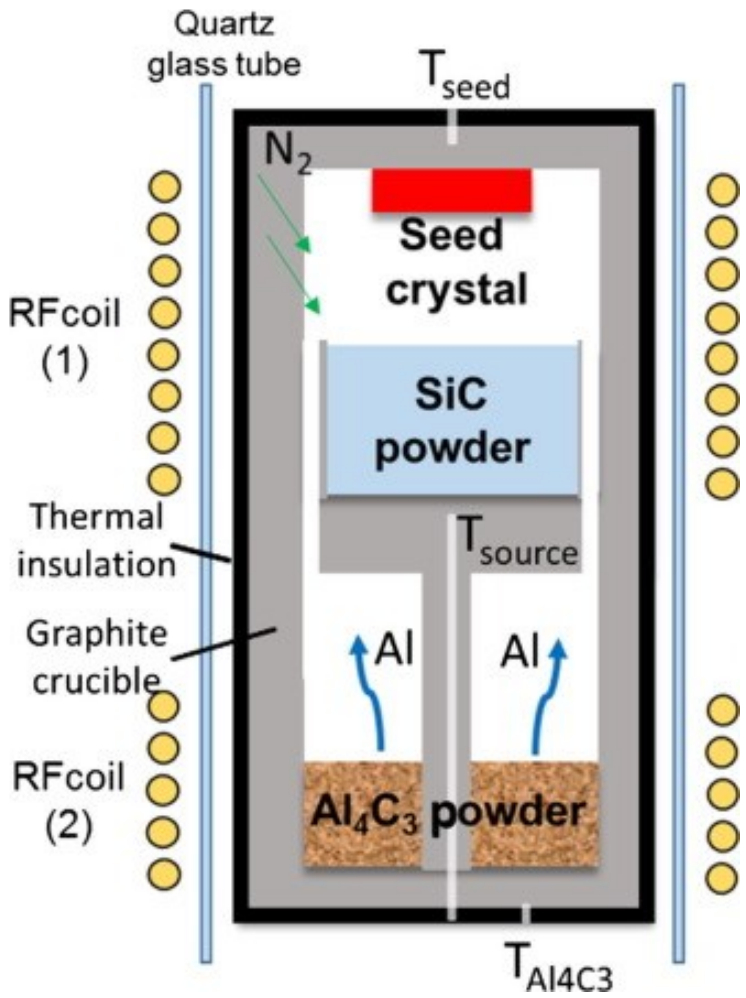
# Lely method

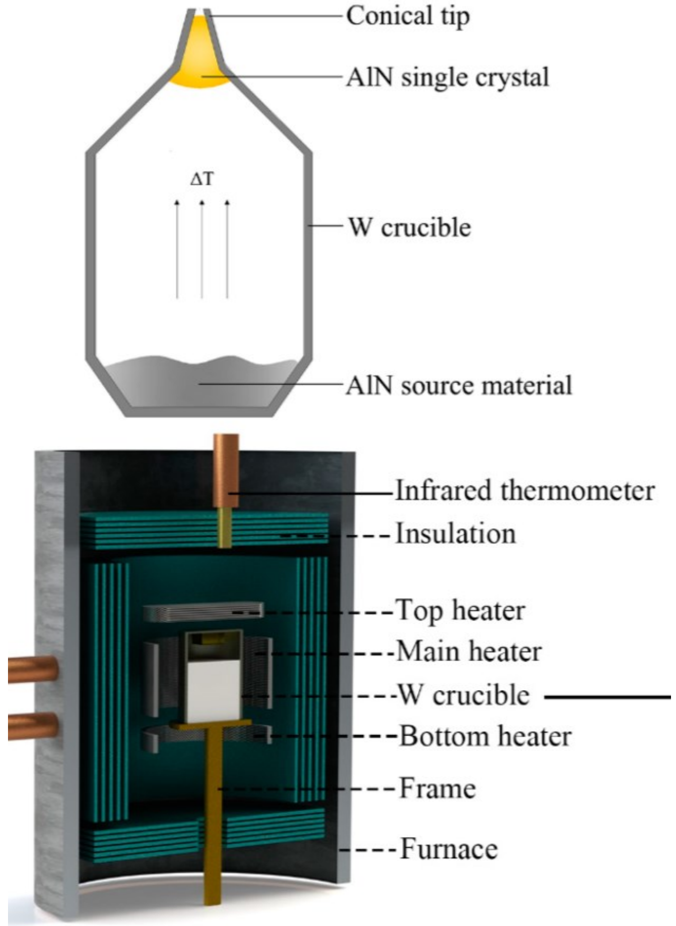



- A crystal growth technology used for producing silicon carbide crystals.
- Produce bulk SiC crystals through the process of sublimation.
- Silicon carbide powder is loaded into a graphite crucible, which is purged with argon gas and heated to 2500 °C



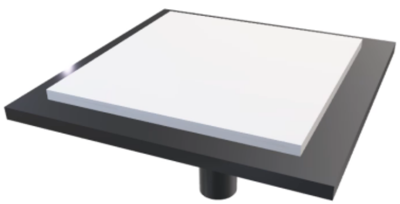
# Physical Vapor Transport



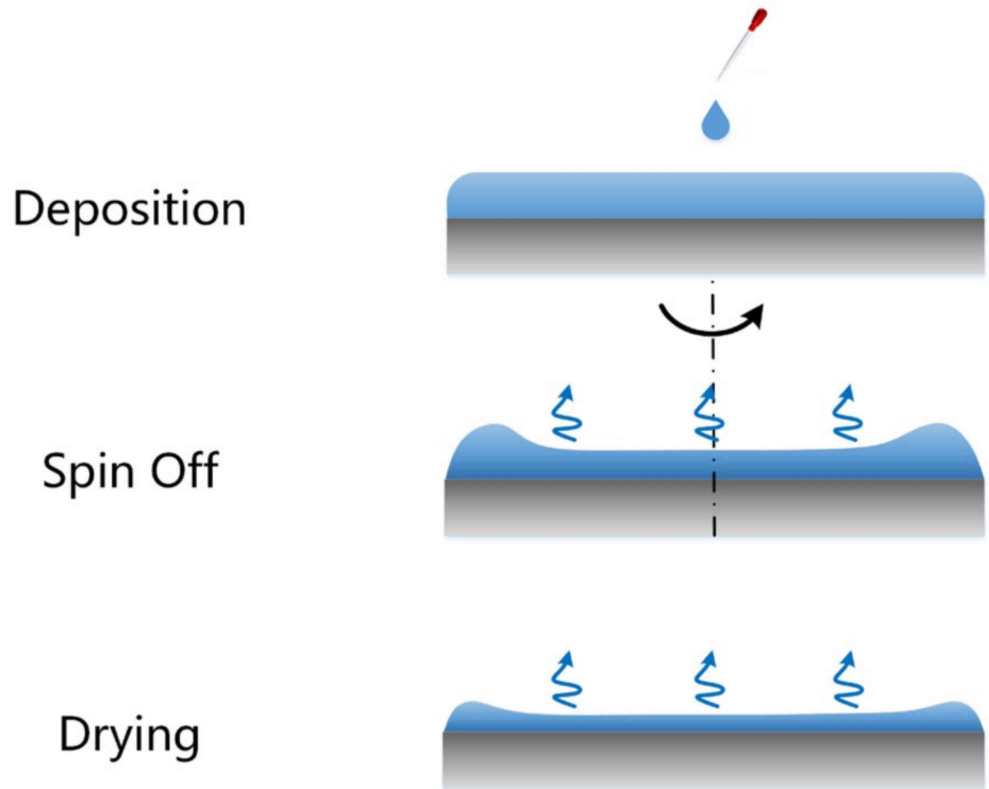




- ➢ Gradient temperature
- ➢ AlN growth

# Spin Coating

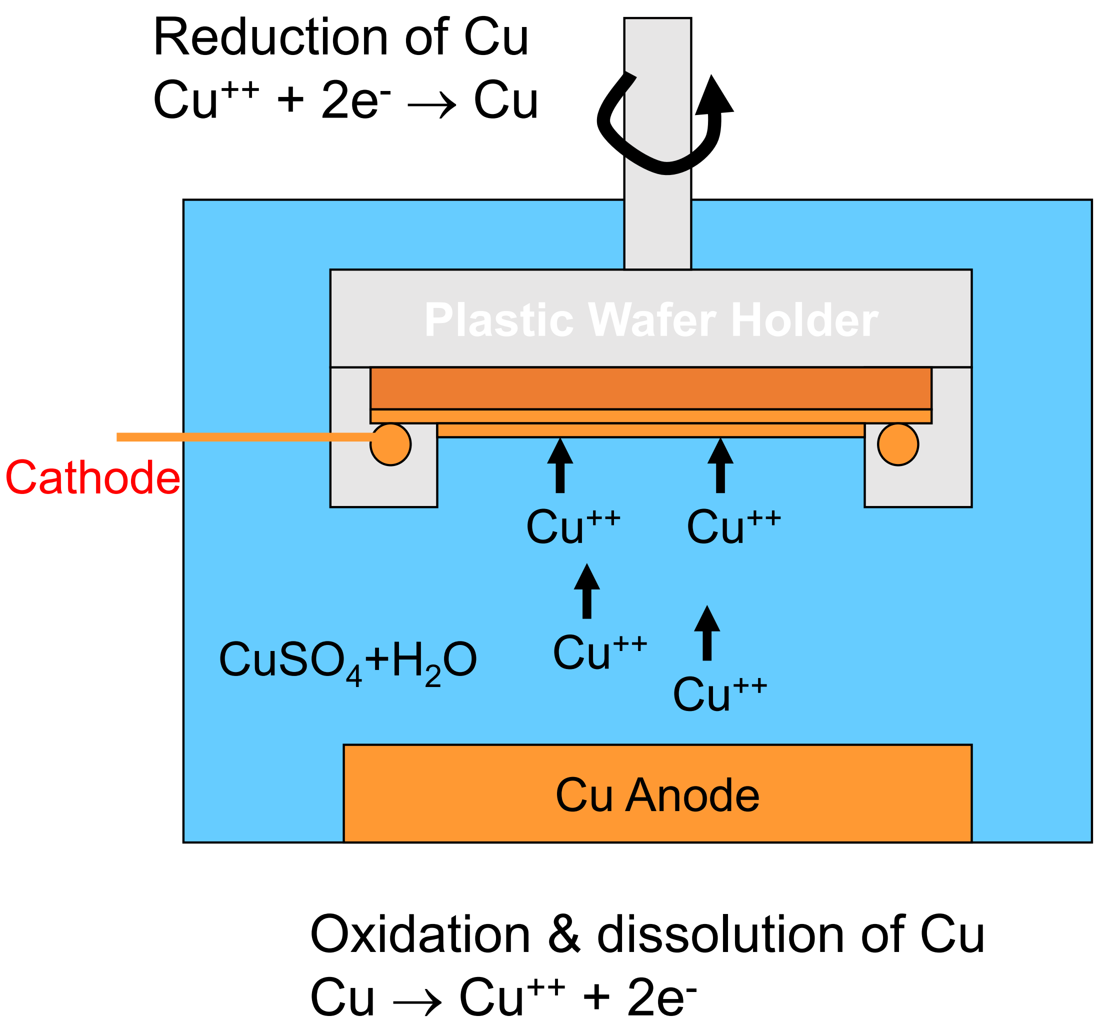


$$h_f = \left(\frac{3\eta_0 E}{2(1-C_0)\rho\omega^2}\right)^{\frac{1}{3}}$$




- Spin coating is a procedure used to deposit uniform thin films onto flat substrates.
- Industrial uses of spin coating: Photoresist for patterning wafer, insulating layers such as polymers, flat screen display coatings such as antireflection coatings and conductive oxides, television tube antireflection coatings, DVD and CD ROM

# Electroplating




**Low cost technology**
**Easily scaled to industrial scale**

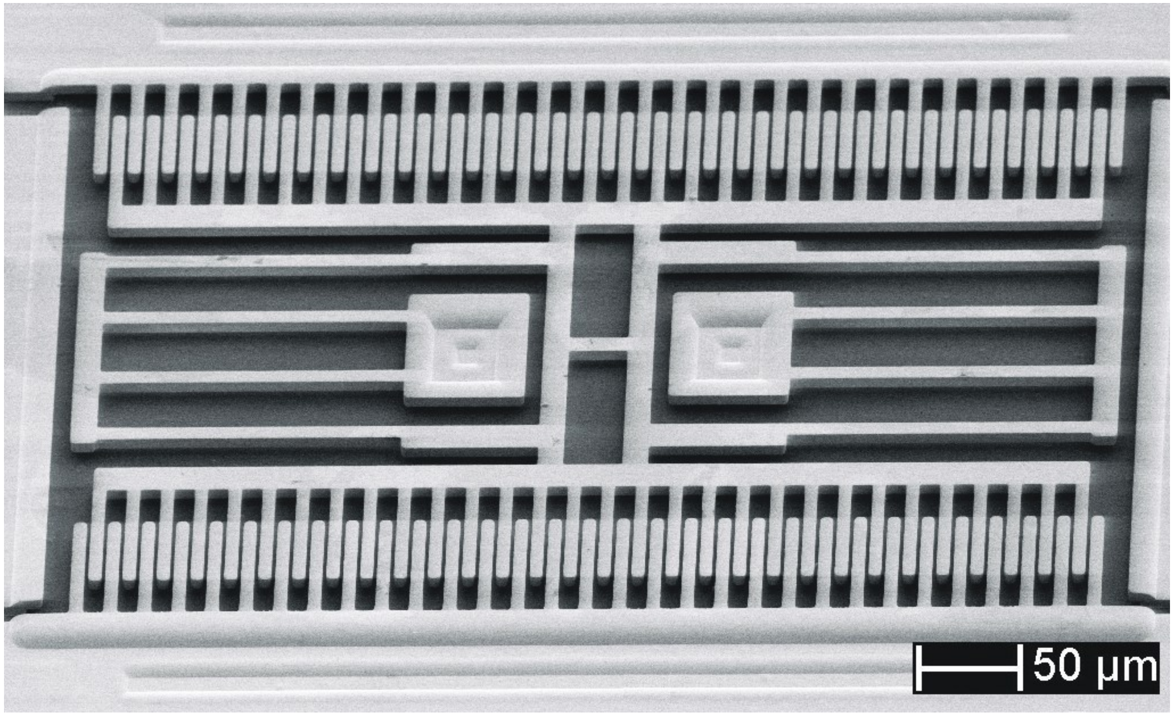
Current density ~1-5A/$dm^2$
Temperature 20-70$^{o}$C

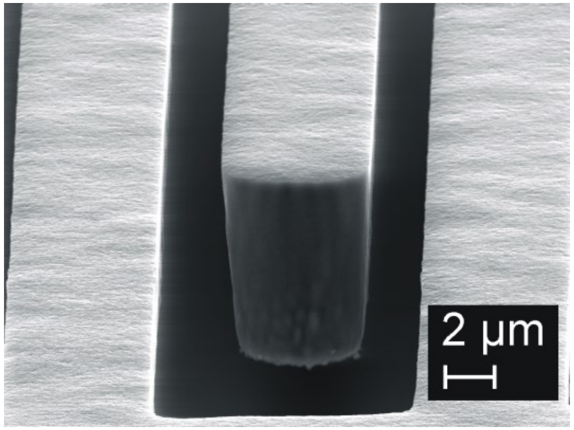
Stress & morphology affected by
- Current density
- Temperature
- Bath composition
- Bath additives

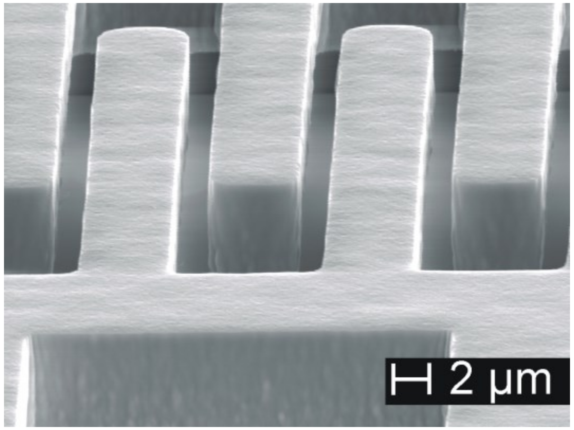
Materials:
Cu, Ni, Au, NiFe, CoNiFe, Sn

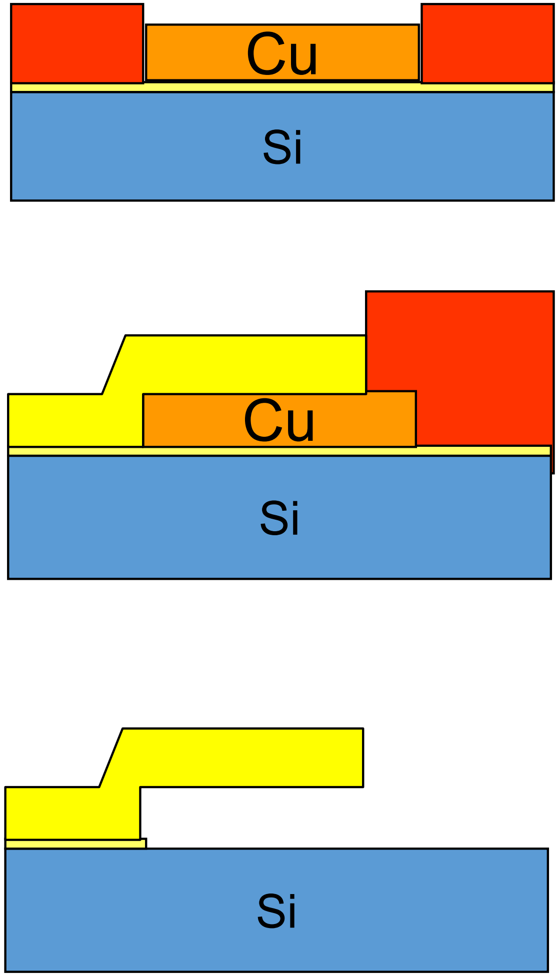
Problems: Purity, uniformity, composition & stress control

# Electroplated Ni Structures



# Summary of thin film deposition

| Thin film | Equipment | Typical Reactions | Comments |
|---|---|---|---|
| Epitaxial silicon | APCVD, LPCVD | $SiH_4 \rightarrow Si + 2H_2$<br>$SiCl_4 + 2H_2 \rightarrow Si + 4HCl$<br>Also $SiHCl_3$, $SiH_2Cl_2$ | 1000-1250˚C<br>Reduce pressure for lower temperature deposition. |
| Polysilicon | LPCVD | Same as epitaxial Si | 575-650˚C<br>Grain structure depends on deposition conditions and doping. |
| $Si_3N_4$ | LPCVD, PECVD | $3SiH_4 + NH_4 \rightarrow$<br>$Si_3N_4 + 12H_2$ | 650-800˚C for oxidation mask.<br>200-400˚C (PECVD) for passivation. |
| $SiO_2$ | LPCVD, PECVD, HDPCVD | $SiH_4 + O_2 \rightarrow SiO_2 + 2H_2$<br>$Si(OC_2H_5)_4\ (+O_3)$<br>$\rightarrow SiO_2 +$ byproducts | 200-800˚C<br>200-500˚C (LTO) - may require high T anneal.<br>25-400˚C (TEOS-ozone, PECVD, HDPCVD) |

# continued

| | | | |
|---|---|---|---|
| Al | Magnetron sputter deposition | | 25-300°C (standard deposition)<br>440-550°C (hot Al for in-situ reflow)<br>CVD difficult for alloys (Al-Cu-Si) |
| Ti and<br>Ti-W | Magnetron sputter deposition (standard, ionized or collimated) | | CVD difficult<br>Nitrogen can be added to Ti-W to stuff grain boundaries. |
| W | LPCVD | $2WF_6 + 3SiH_4 \rightarrow$<br>$2W + 3SiF_4 + 6H_2$<br>$WF_6 + 3H_2 \rightarrow$<br>$W + 6HF$ | 250-500°C<br>Blanket deposition with two step process using both reactions is common. |
| $TiSi_2$ | Sputter and surface reaction<br>Co-sputtering or CVD | Ti(sputtered) +<br>Si(exposed) $\rightarrow$ $TiSi_2$ | Sputter/reaction give self-aligned silicide<br>Two step anneal process required (600/800°C) |
| TiN | Reactive sputter deposition | $Ti + N_2$(in plasma) $\rightarrow$ TiN | Organometallic source possible for MOCVD deposition |

# CVD versus PVD (coarse comparison)

| | CVD | PVD |
|---|---|---|
| Flexibility | Poor | Good |
| Deposition temperature | High | Low |
| Deposition pressure | High | Low |
| Step coverage (conformality) | Good | Poor |
| Thickness uniformity | Good | Good |
| Composition control | Good | Poor |
| Film purity | High | Low |
| Dielectric | Preferred | - |
| Metal | - | Preferred |