Vacuum Basics

1. Units

- 1 atmosphere = 760 torr = 1.013×10^5 Pa
- 1 bar = 10^5 Pa = 750 torr
- 1 torr = 1 mm Hg
- 1 mtorr = 1 micron Hg
- 1Pa = 7.5 mtorr = 1 newton/m^2
- 1 torr = 133.3 Pa

2. Ideal Gas Law: PV = NkT

- k = 1.38E-23 Joules/molecule –K
  = 1.37E-22 atm cm^3/K
- N = # of molecules
- T = absolute temperature in K
- [Note] At T = 300 K ; kT = 3.1E-20 torr-liter

3. Dalton's Law of Partial Pressure

For mixture of non-reactive gases in a common vessel, each gas exerts its pressure independent of others.

$P_{total} = P_1 + P_2 + \ldots + P_N$ (Total P = Sum of partial pressure)

$N_{total} = N_1 + N_2 + \ldots + N_N$

$P_1 V = N_1 kT$

$P_2 V = N_2 kT$

....

$P_N V = N_N kT$

4. Average Molecular Velocity

Assumes Maxwell-Boltzman Velocity Distribution

$$\overline{v} = (8kT/\pi m)^{1/2}$$

where m = molecular weight of gas molecule

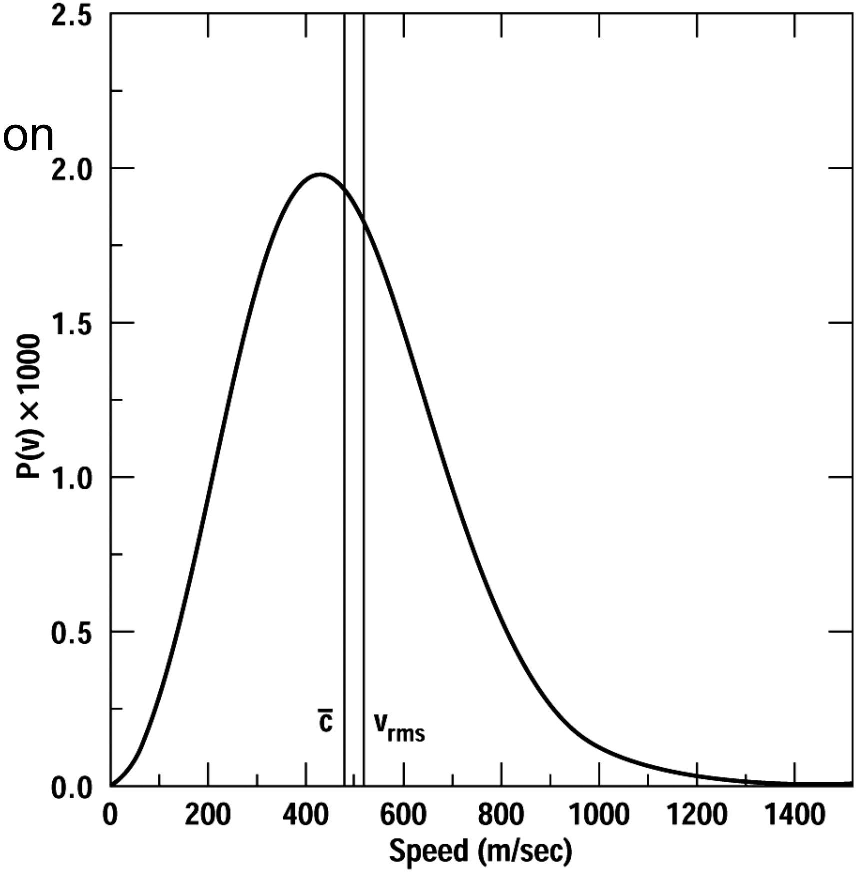


Figure 10.1 A Maxwellian speed distribution of particles. P(y) is the probability that a particular particle will have the magnitude of velocity.

5. Mean Free Path of molecular collision

$$\lambda = \frac{1}{\sqrt{2}\,\pi d_o^2 n}$$

where n = molecular density = N/V,

d_o = molecular diameter

[Note] For air at 300 °K, $\lambda = \frac{6.6}{P(\text{in Pa})} = \frac{0.05}{P(\text{in torr})}$

with λ in mm

6. Impingement Rate, Φ

$$\Phi = \frac{n\,\overline{v}}{4} = \#\ \text{of molecules striking unit surface /unit time.}$$

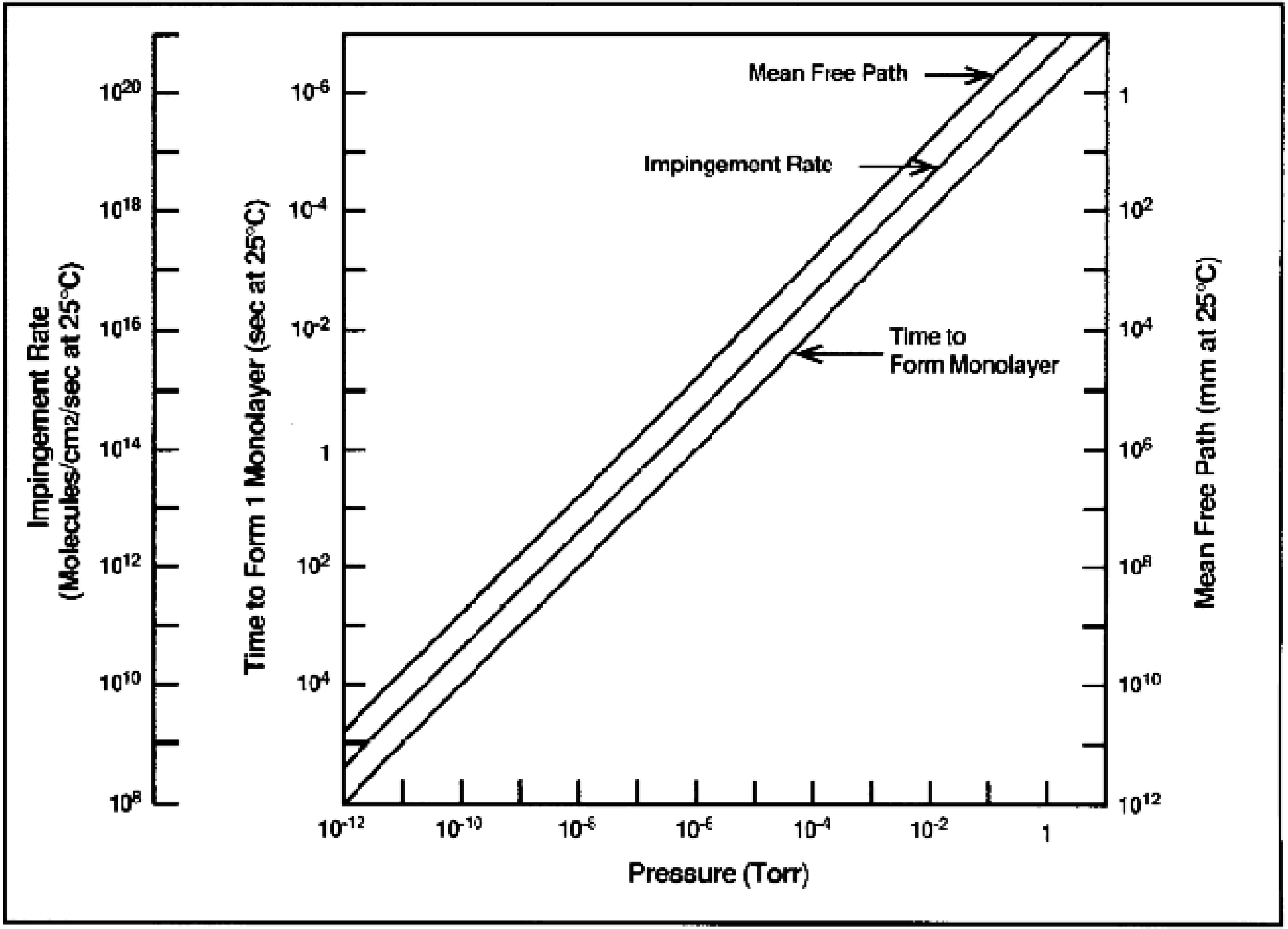
$$= 3.5\times10^{22}\times\frac{P}{\sqrt{mT}}$$

in #/cm^2-sec
with P in torr, m in amu

[Note] For air at 300 °K ; $\Phi(\text{in } \#/cm^2\text{-sec}) = 3.8\times10^{20}\cdot P$

Example Calculation : Contamination from Residual Vacuum

For a residual vacuum of 10^{-6} torr, $\Phi = 4 \times 10^{14}/cm^2$-sec
If each striking molecule sticks to the surface, the equivalent deposition rate of the residual gas is ~ 1/3 of a monolayer of solid per second.



Flux of gas molecules to a surface, time to form a monolayer of gas on a surface and the mean free path of a molecule in the gas as a function of gas pressure at room temperature.

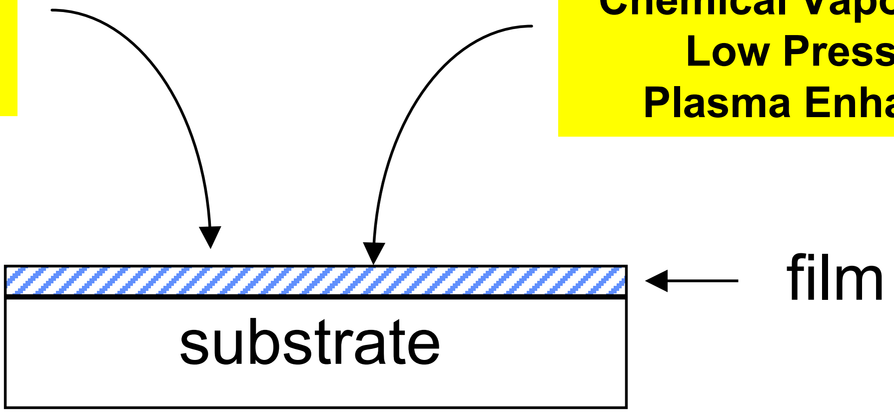
Thin Film Deposition

Physical Methods

Evaporation
Sputtering
Reactive Sputtering

Chemical Methods

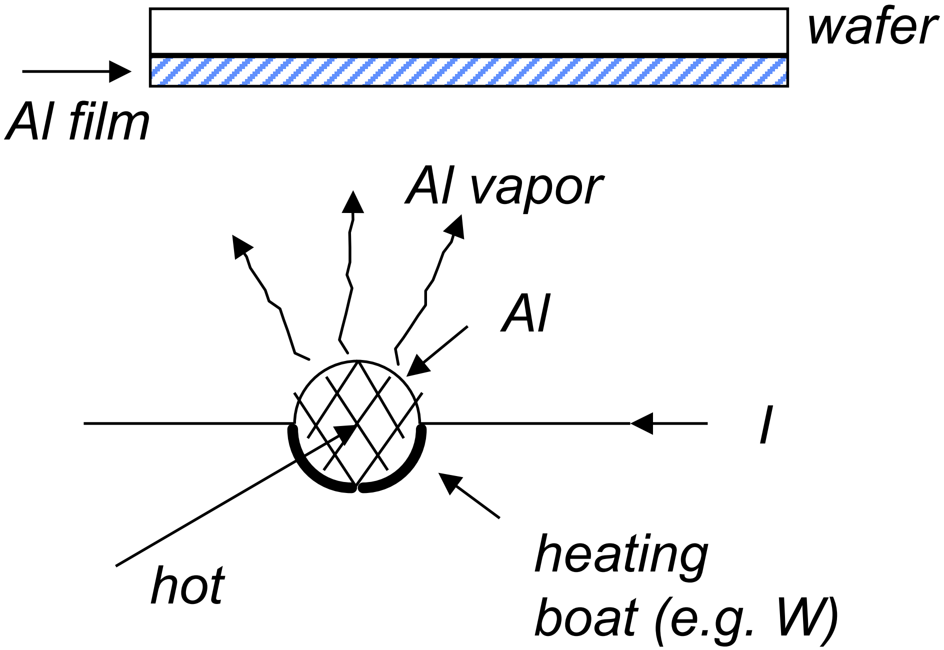
Chemical Vapor Deposition
Low Pressure CVD
Plasma Enhanced CVD



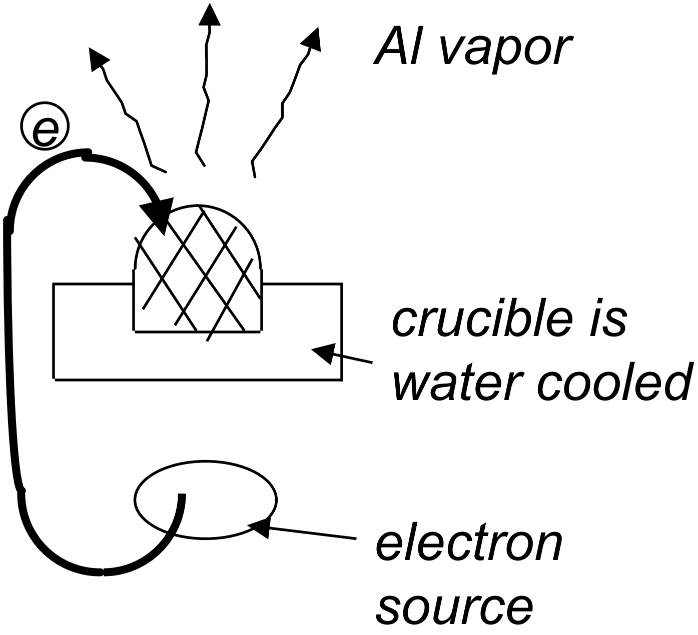
Applications:

Metalization (e.g. Al, TiN, W, silicide)
Poly-Si
dielectric layers; surface passivation.

(1) Evaporation Deposition



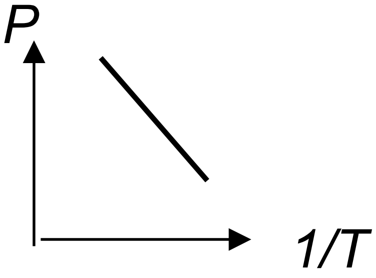
$\text{Vacuum} < \sim 10^{-5}\,\text{Torr}$



Vapor Pressure $P = P_0 e^{-\Delta H / kT}$

Evaporation Rate (max)= $\dfrac{P}{\sqrt{2\pi mkT}}$

m=molecular weight of vapor



Vapor Pressure versus Temperature

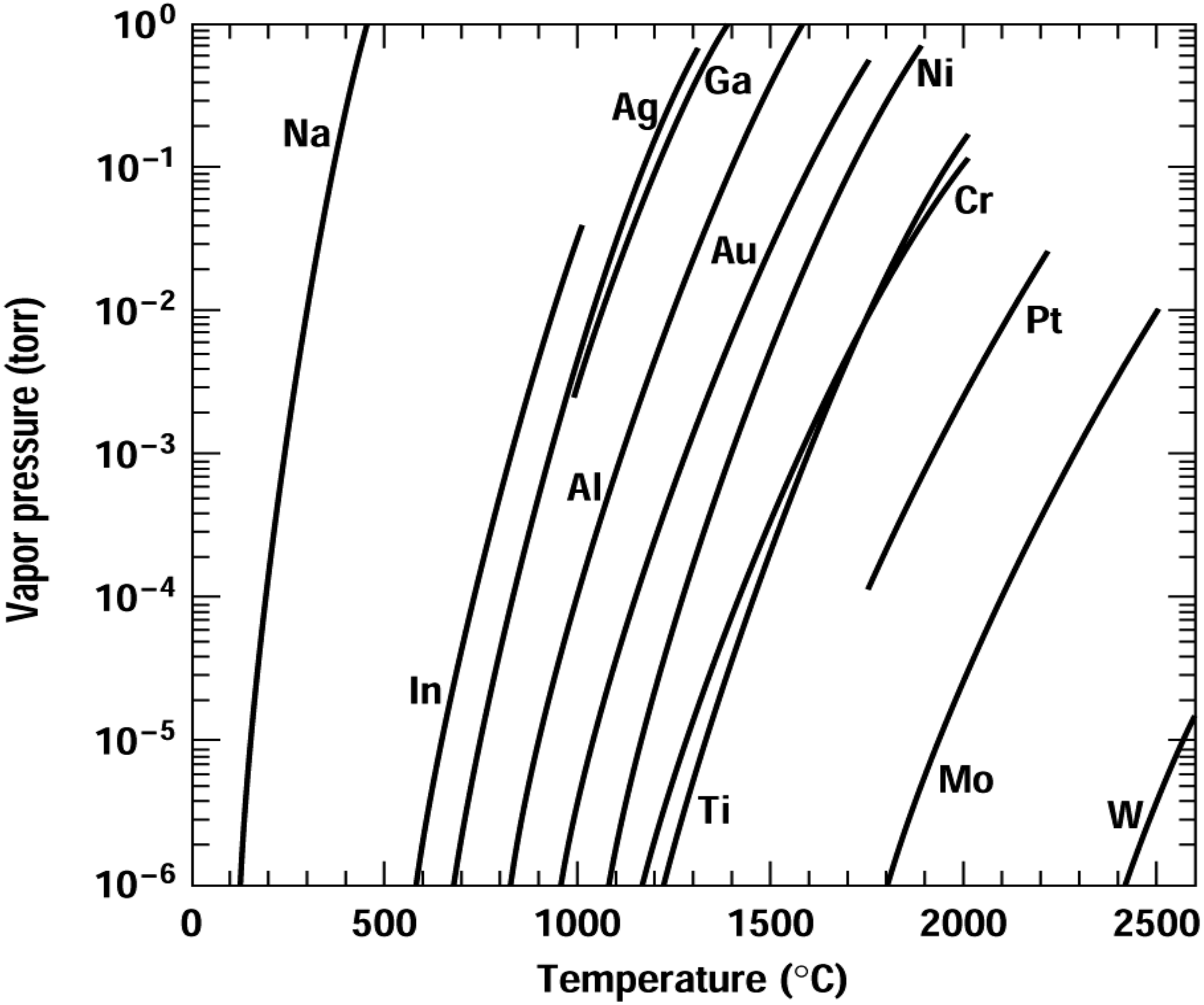
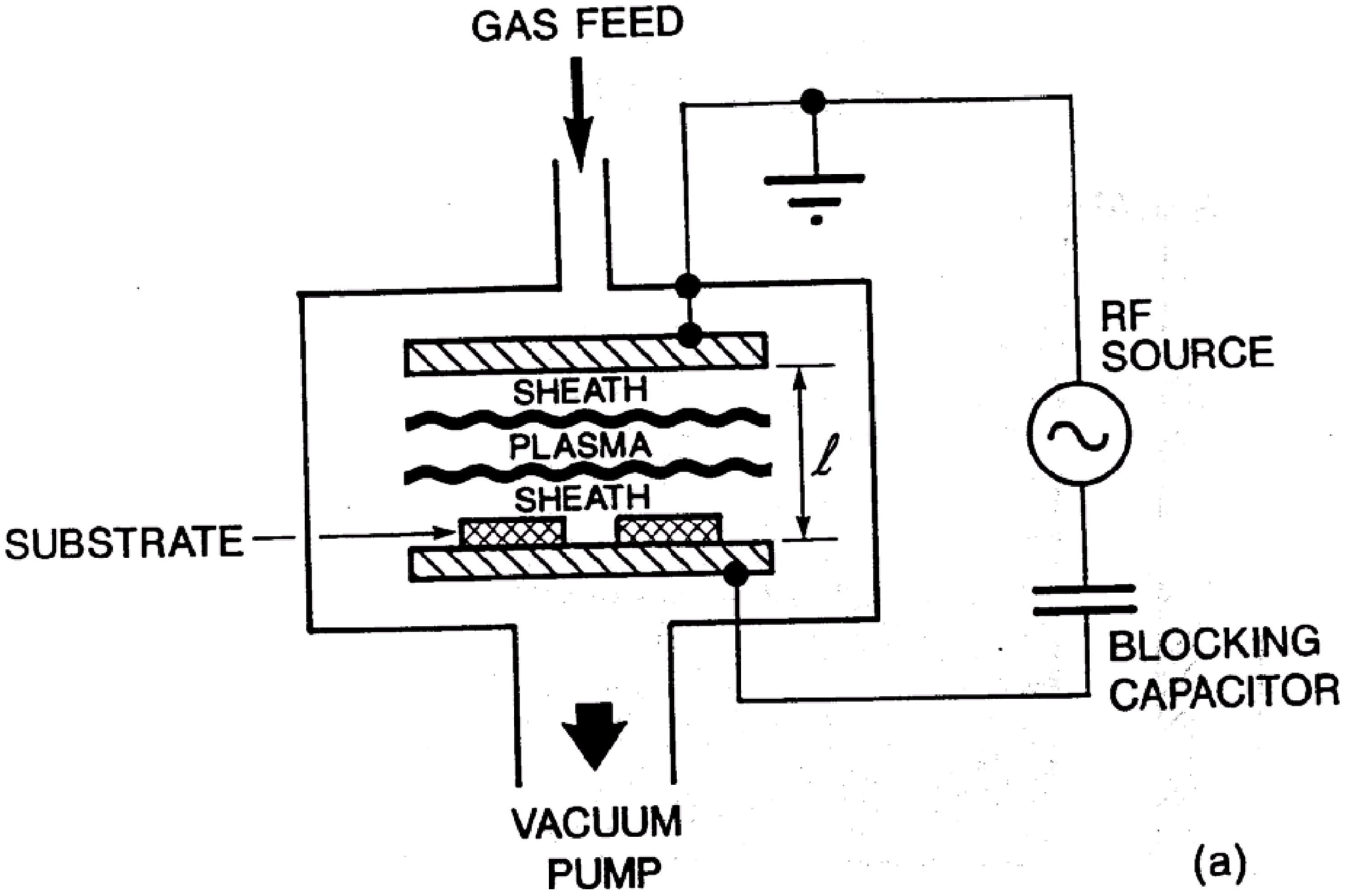


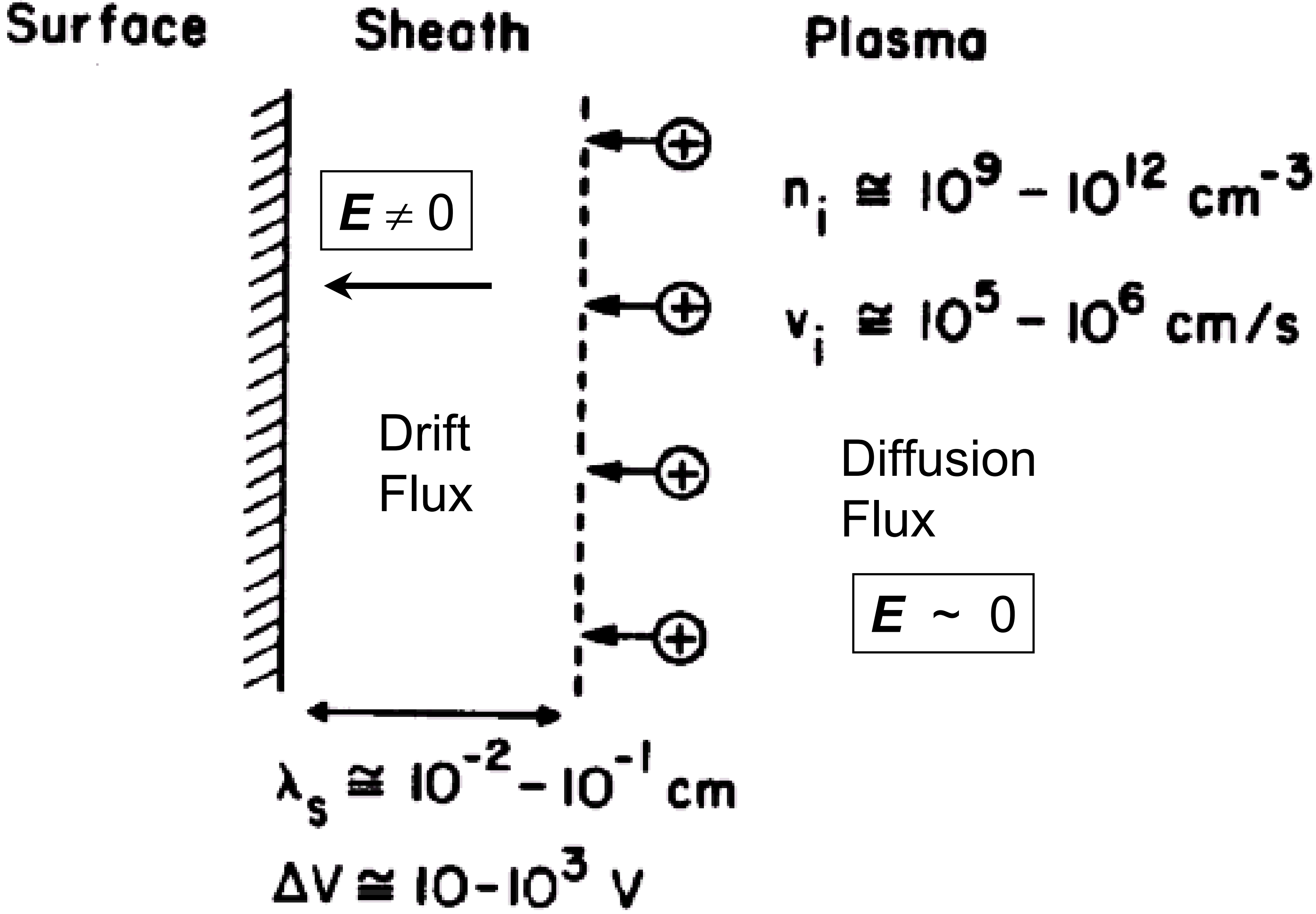
Figure 12.2 Vapor pressure curves for some commonly evaporated materials *(data adapted from Alcock et al.).*

Parallel Plate Reactor for Plasma Generation



Basic Properties of Plasma

- The bulk of plasma contains equal concentrations of ions and electrons.
- Electric potential is ≈ constant inside bulk of plasma. The voltage drop is mostly across the sheath regions.
- Plasma used in IC processing is a “weak” plasma, containing mostly neutral atoms/molecules. Degree of ionization is ≈ 10^{-3} to 10^{-6}.



$E \neq 0$

Drift Flux

$n_i \cong 10^9 - 10^{12}\ \text{cm}^{-3}$

$v_i \cong 10^5 - 10^6\ \text{cm/s}$

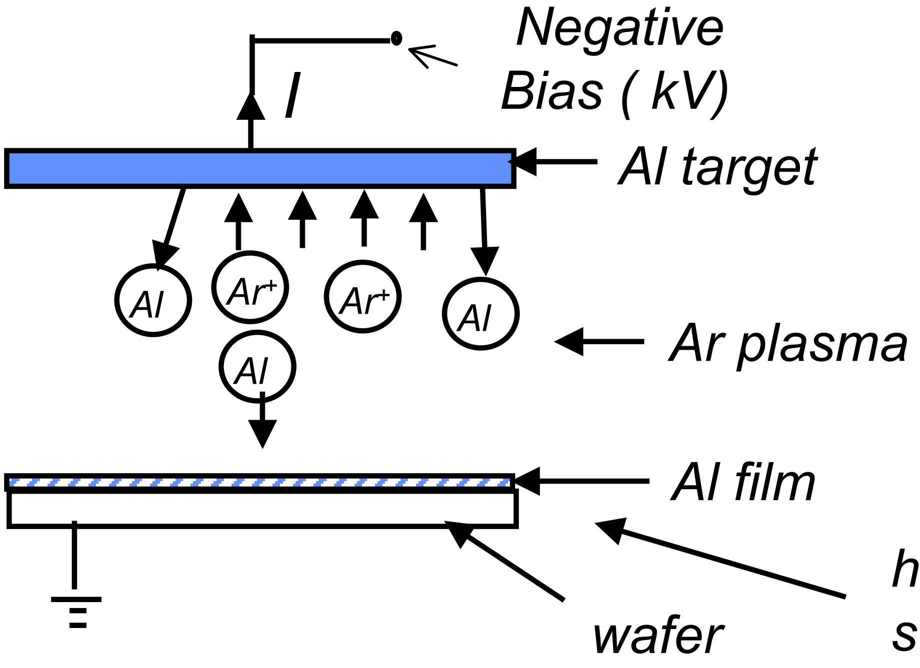
Diffusion Flux

$E \sim 0$

$\lambda_s \cong 10^{-2} - 10^{-1}\ \text{cm}$

$\Delta V \cong 10 - 10^3\ \text{V}$

(2) Sputtering Deposition



Negative Bias (kV)

Al target

Ar plasma

Al film

wafer

heat substrate to ~ 300^{o}C (optional)

Example: DC plasma

Gas Pressure ≅1-10 m Torr

Deposition rate = $constant \bullet I \bullet S$ ← *sputtering yield*

↑ *ion current* (I)

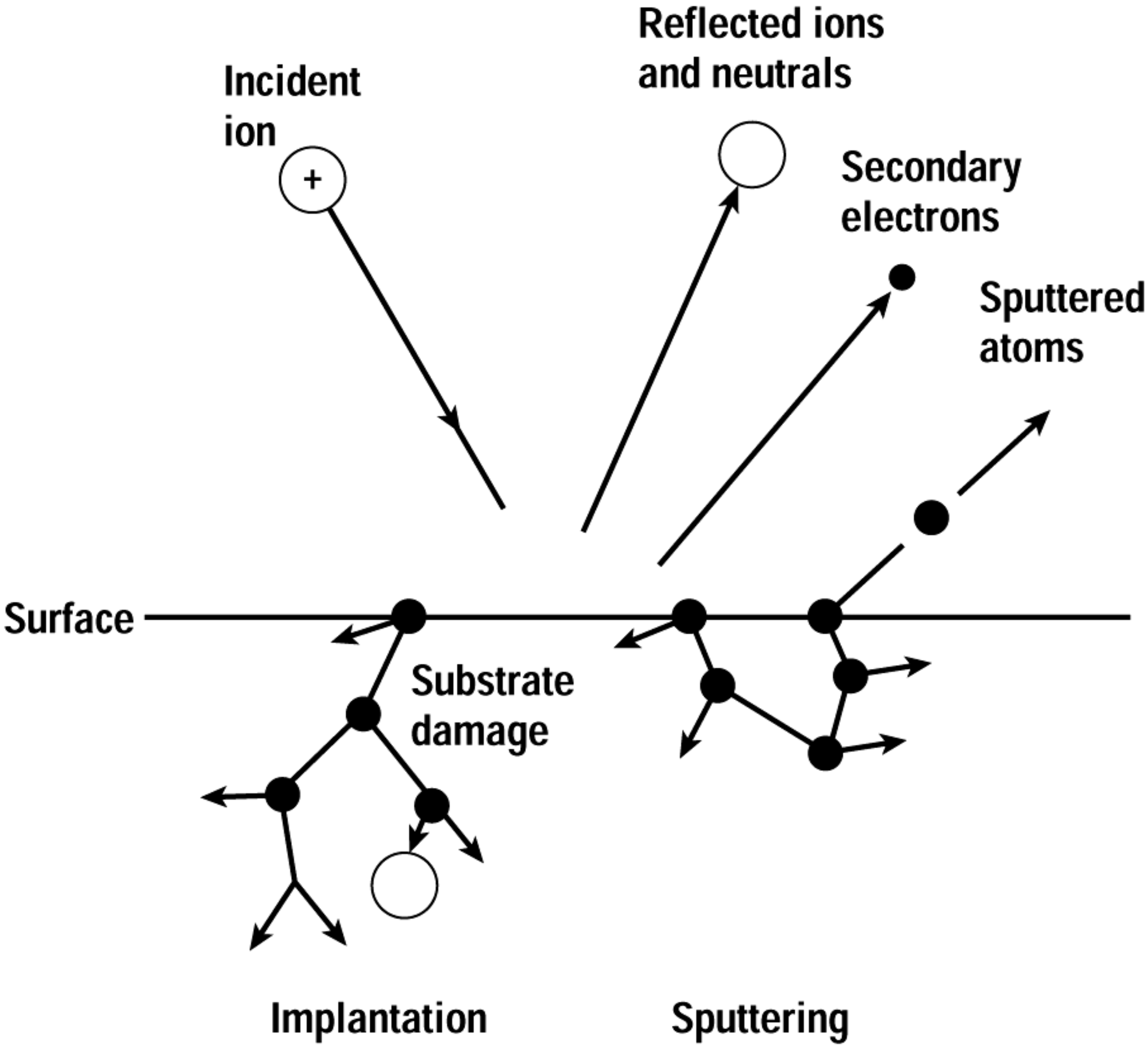
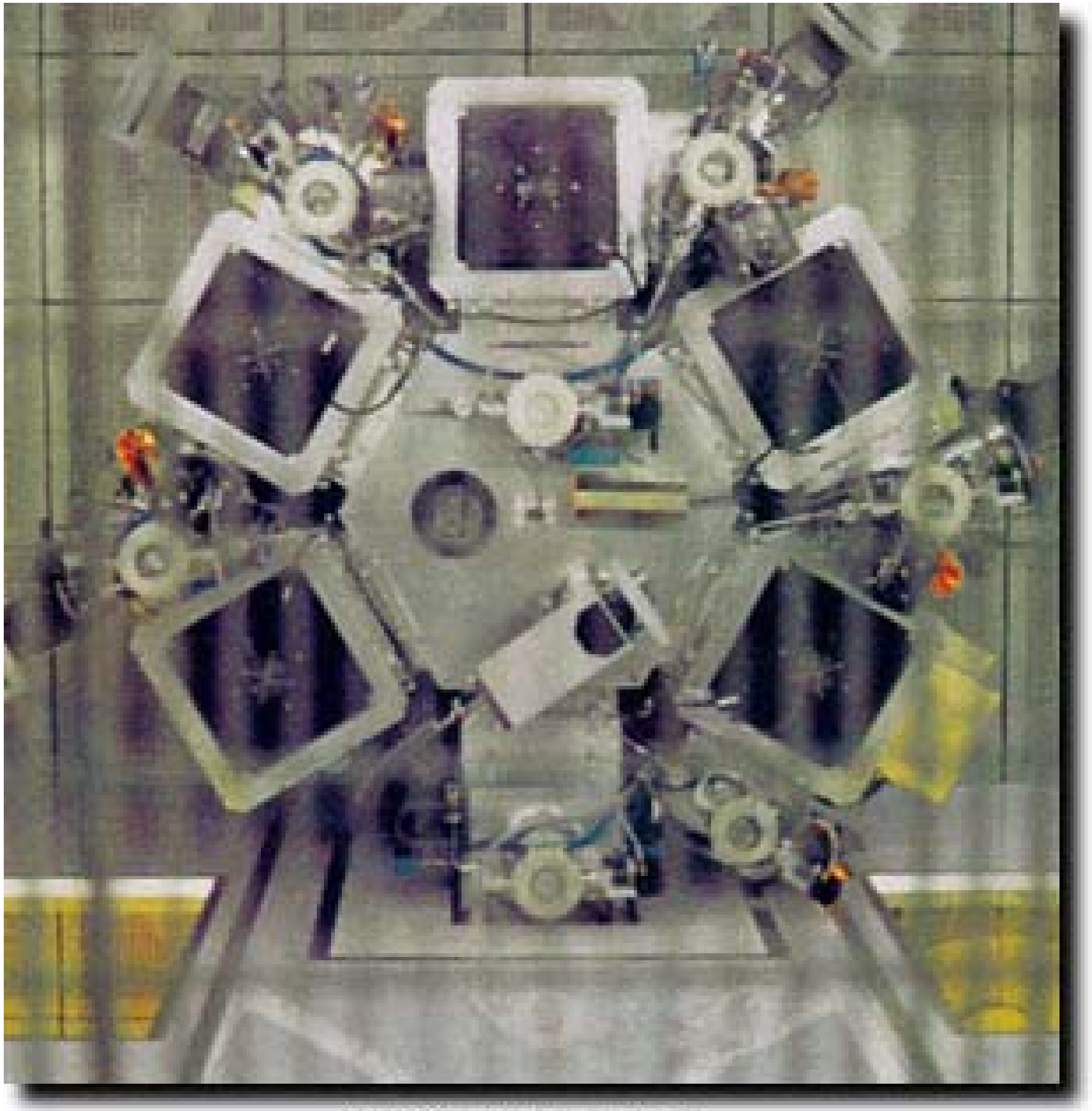
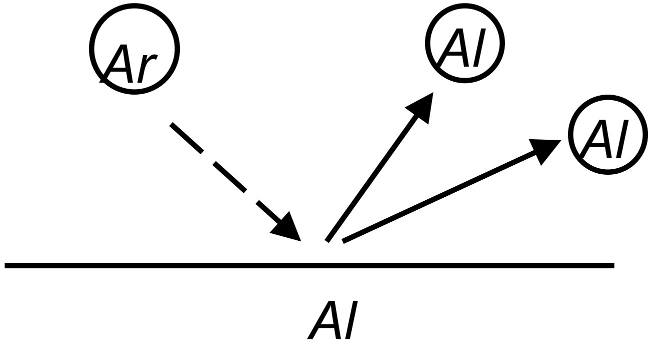


Figure 12.12 Possible outcomes for an ion incident on the surface of a wafer.



PVD Sputtering Tool
(Sputtered Films Corporation)



Sputtering Yield S

$$S \equiv \frac{\text{\# of ejected target atoms}}{\text{incoming ion.}}$$

$$\boxed{0.1 < S < 30}$$

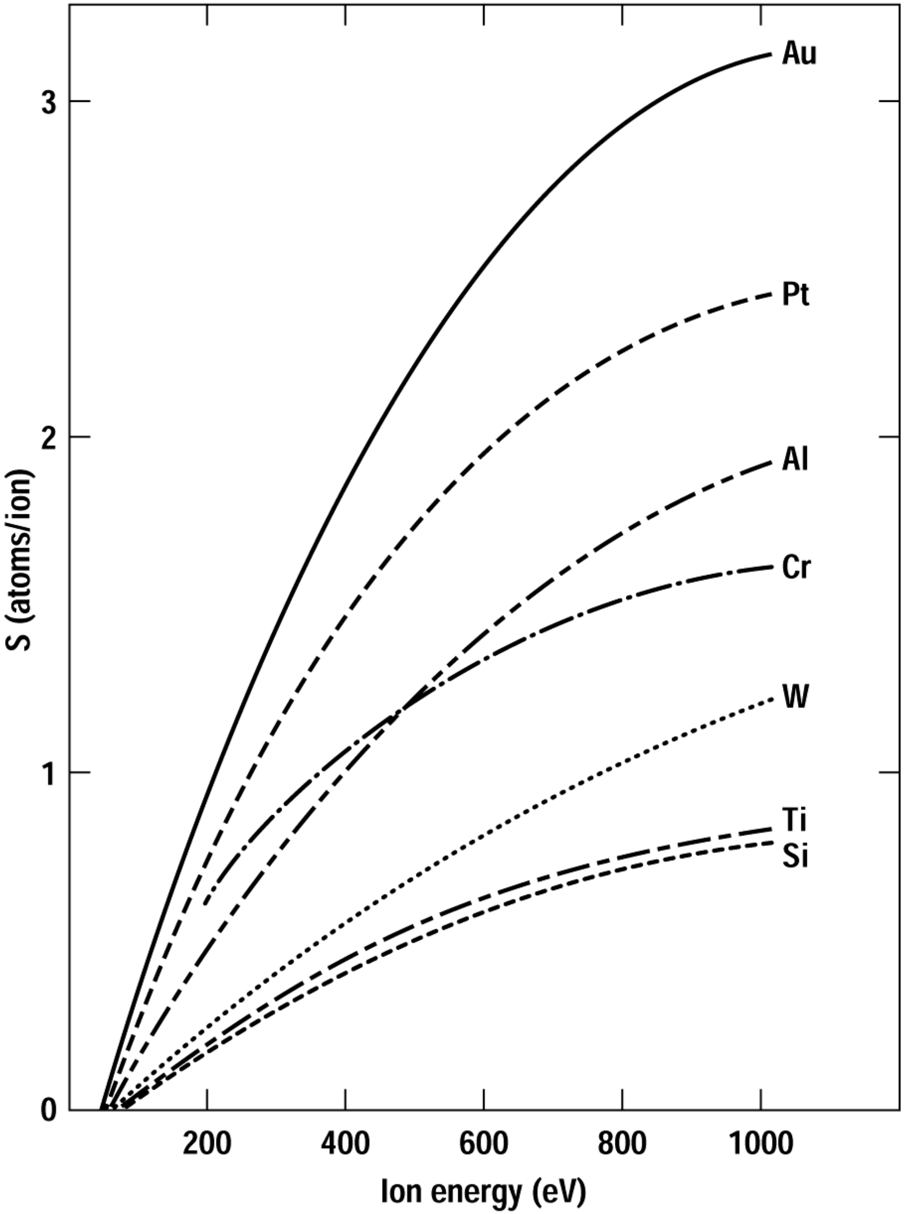
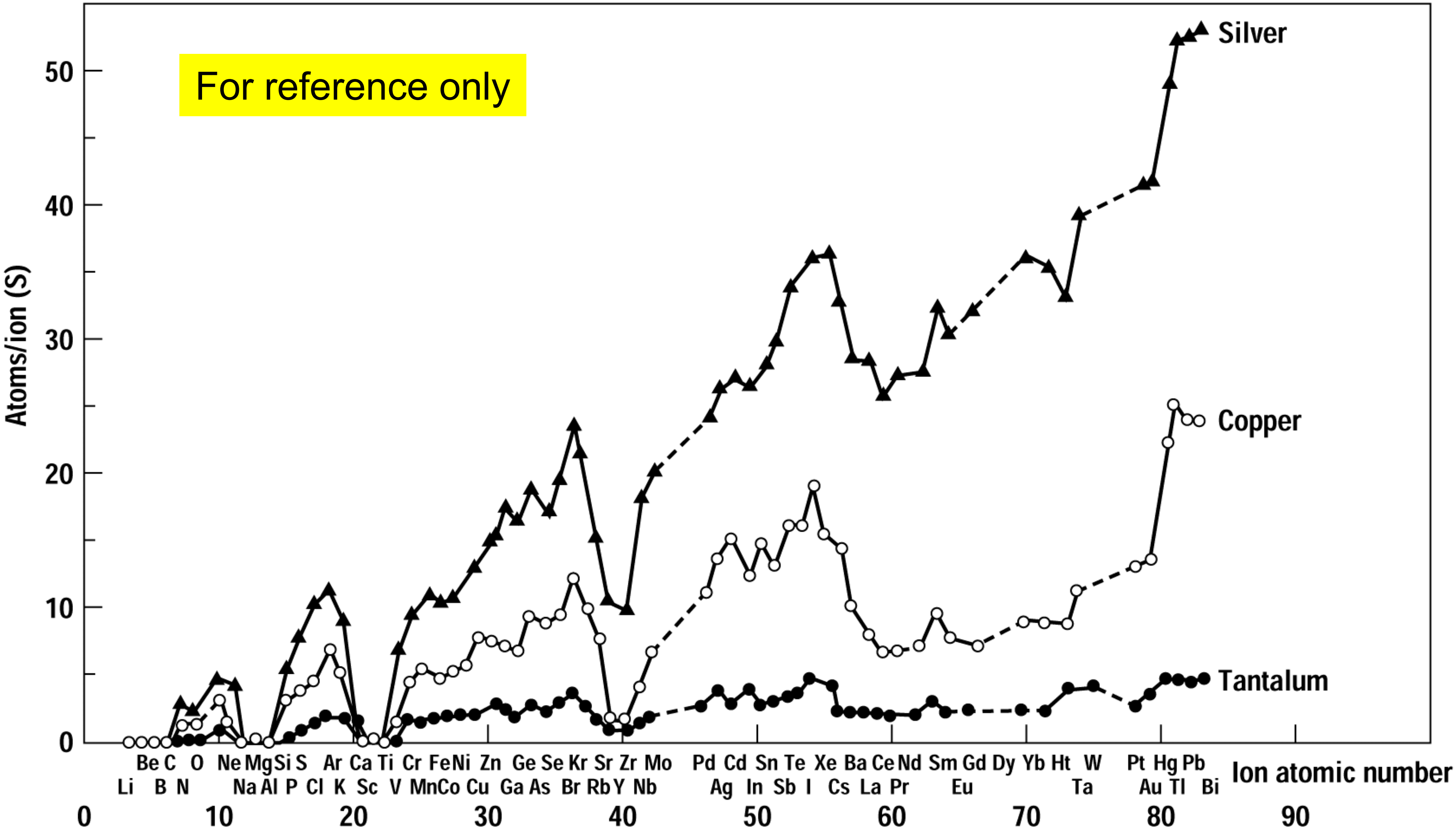


Figure 12.13 Sputter yield as a function of ion energy for normal incidence argon ions for a variety of materials (*after Anderson and Bay, reprinted by permission*).

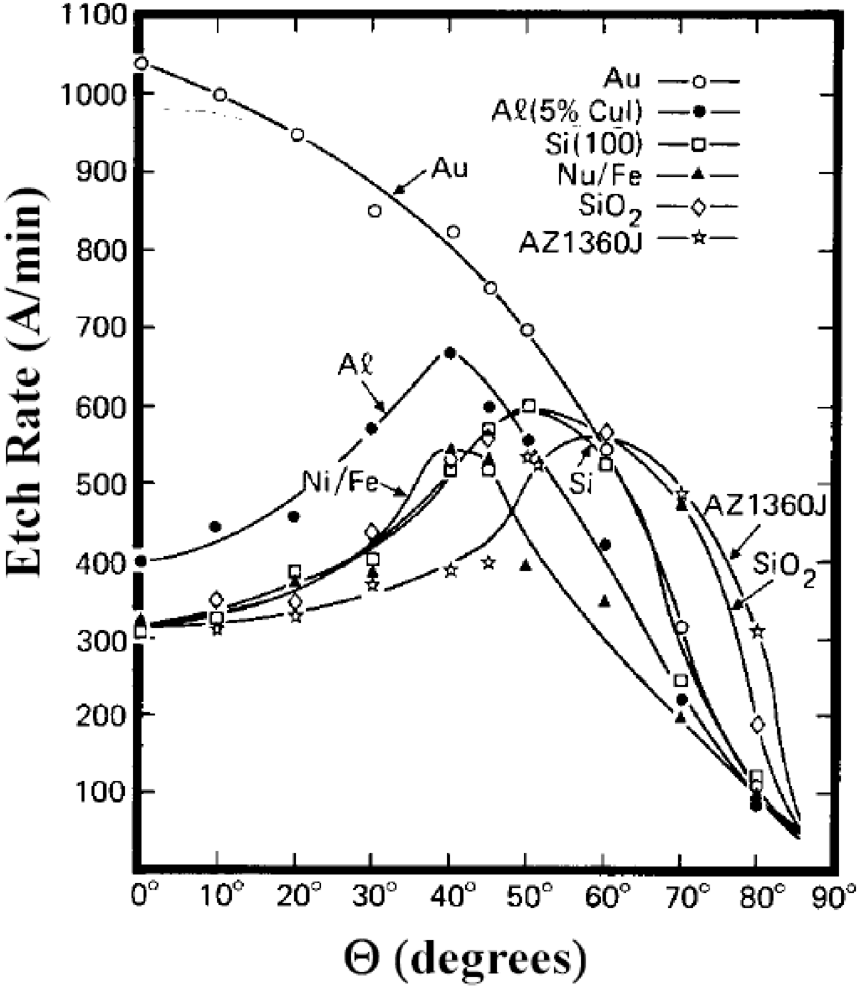
Sputtering Yield of bombarding ion atomic number



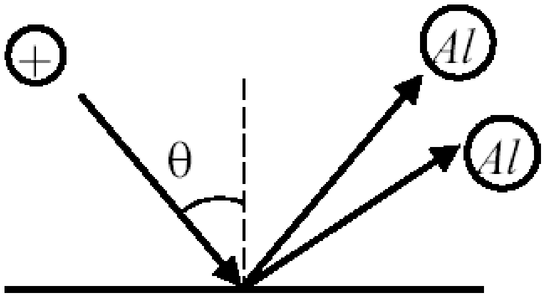
For reference only

Figure 12.14 Sputter yield as a function of the bombarding ion atomic number for 45-keV ions incident on silver, copper, and tantalum targets *(after Wehner, reprinted by permission, AIP).*

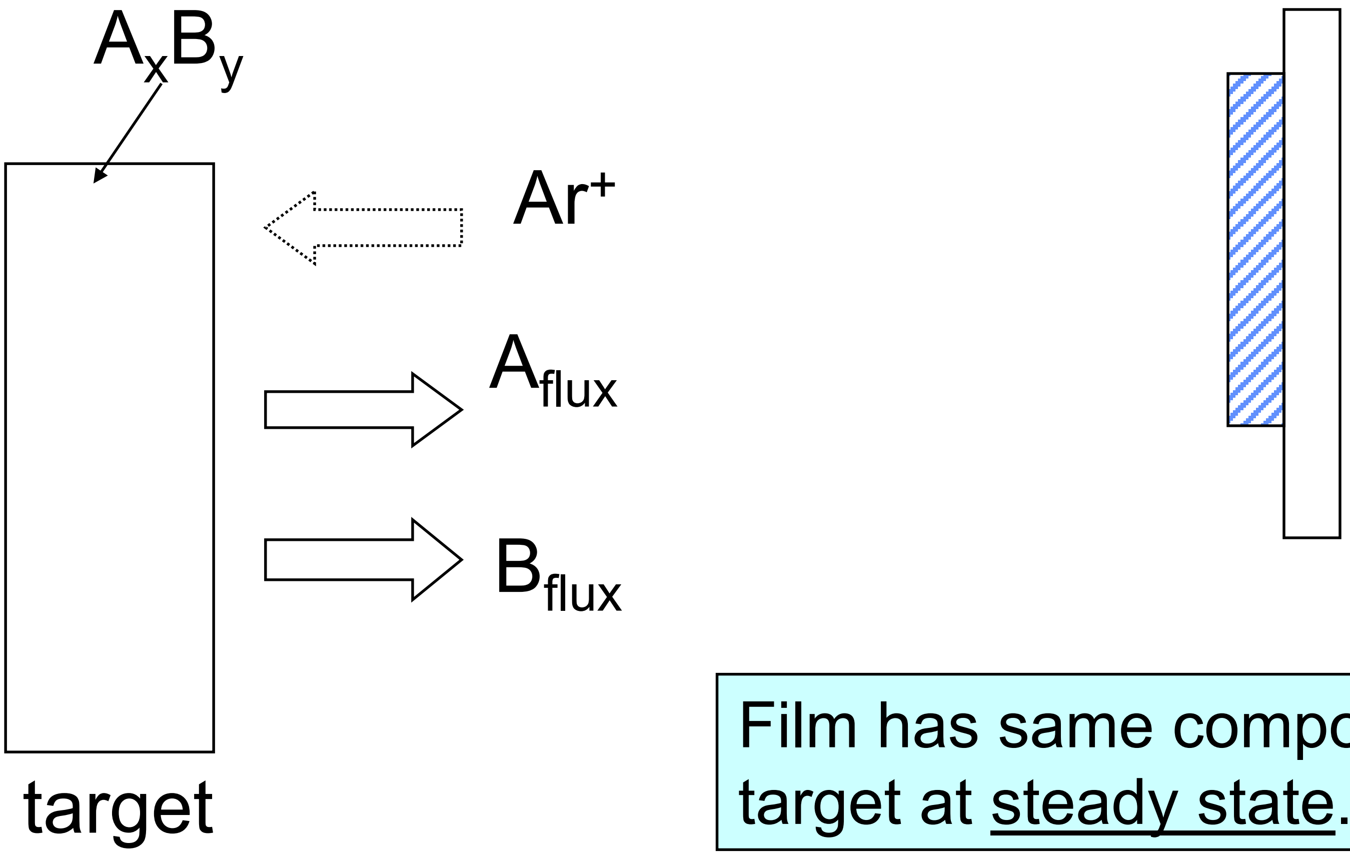
The Sputtering Yield with incidence angle



The Sputtering Yield S depends on ion, substrate, energy, and incidence angle



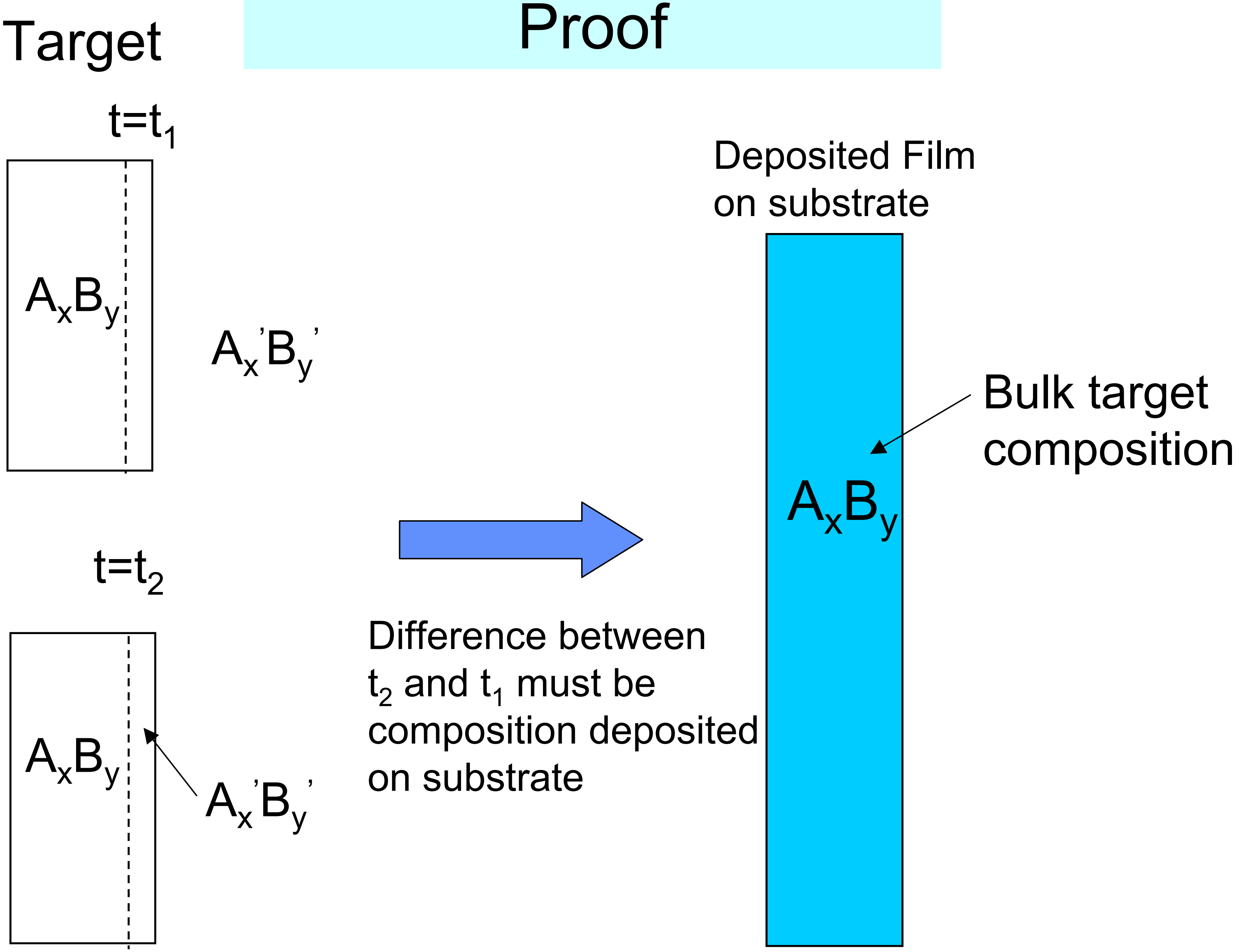
Sputtering of Compound Targets



Film has same composition of target at <u>steady state</u>.

Because $S_A \neq S_B$, Target surface will acquire a composition Ax'By' at steady state.

Proof



Target

$t=t_1$

A_xB_y

$A_x'B_y'$

$t=t_2$

A_xB_y

$A_x'B_y'$

Deposited Film on substrate

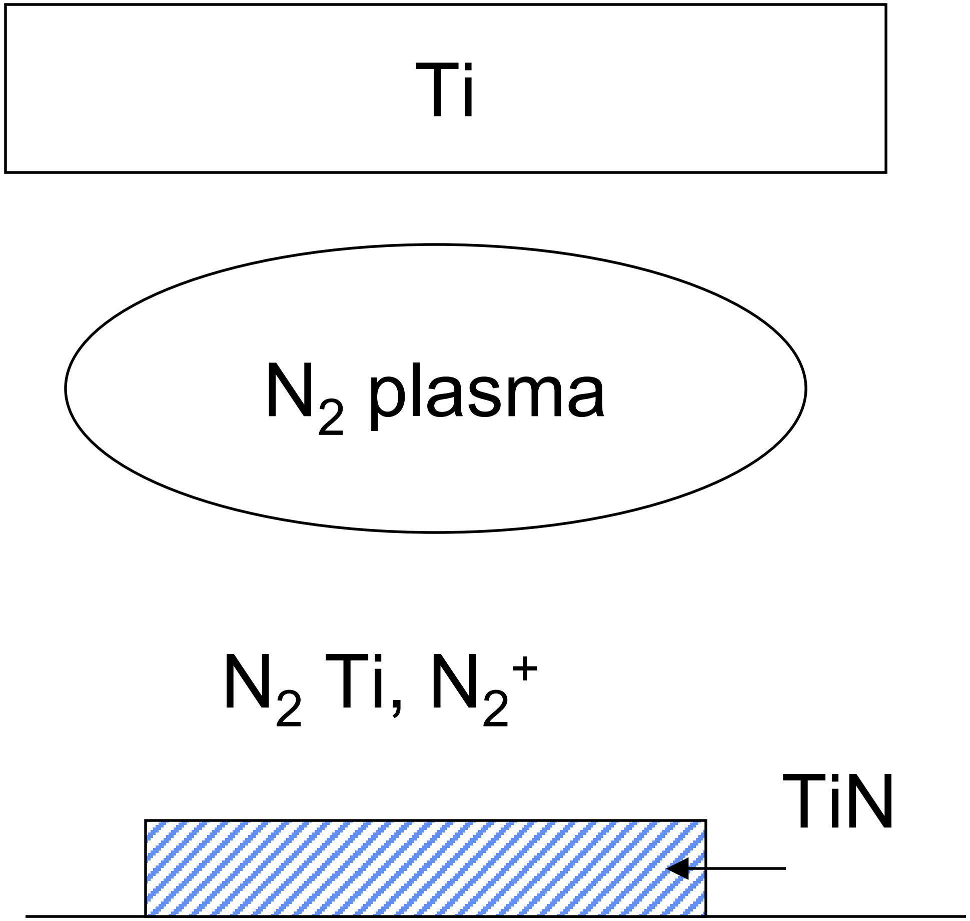
Bulk target composition

A_xB_y

Difference between t_2 and t_1 must be composition deposited on substrate

Reactive Sputtering

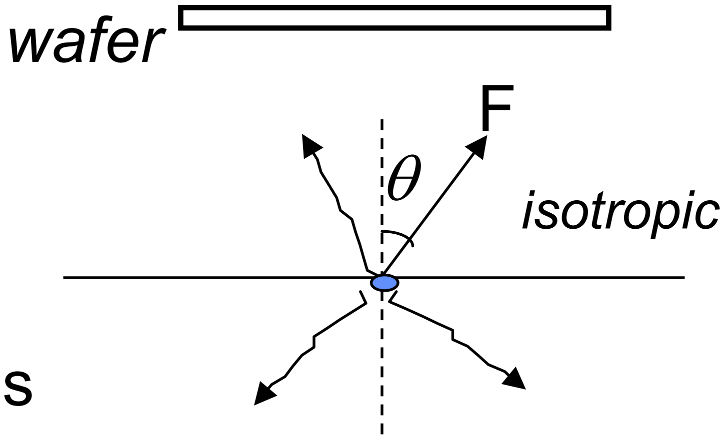
Example: Formation of TiN



- A mixture of inert +reactive gases used for sputtering (e.g. Ar-N_2, Ar-O_2).

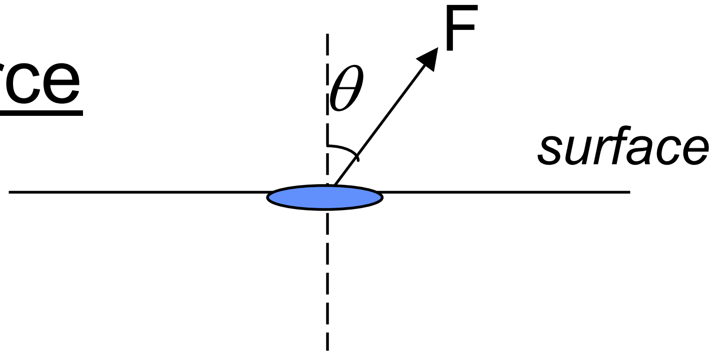
Thickness Uniformity with various PVD sources

(i) Point-like Source



- Ideal situation
- Flux F leaving source surface is independent of θ (isotropic source)

(ii) Plane-like small-area Source



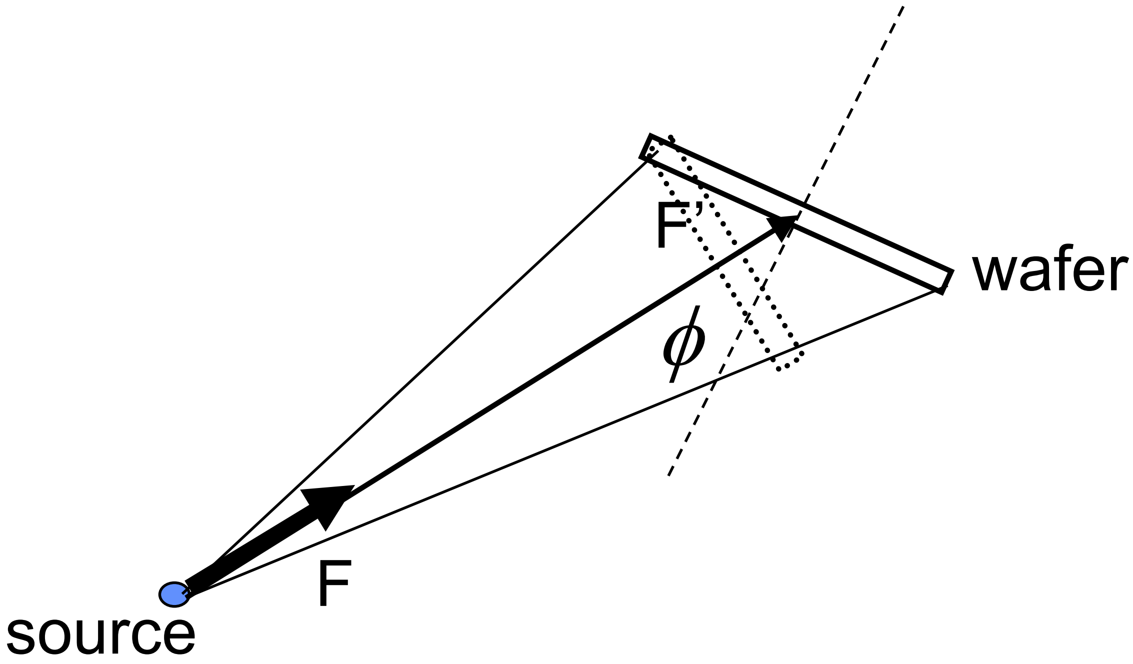
- Flux F leaving surface $\propto$ cos θ

Example: E-beam evaporation

Film Thickness Deposition on Wafer

$$\text{Thickness deposited} \propto \frac{F \cdot \cos\phi}{r^2} = F' \cos\phi$$

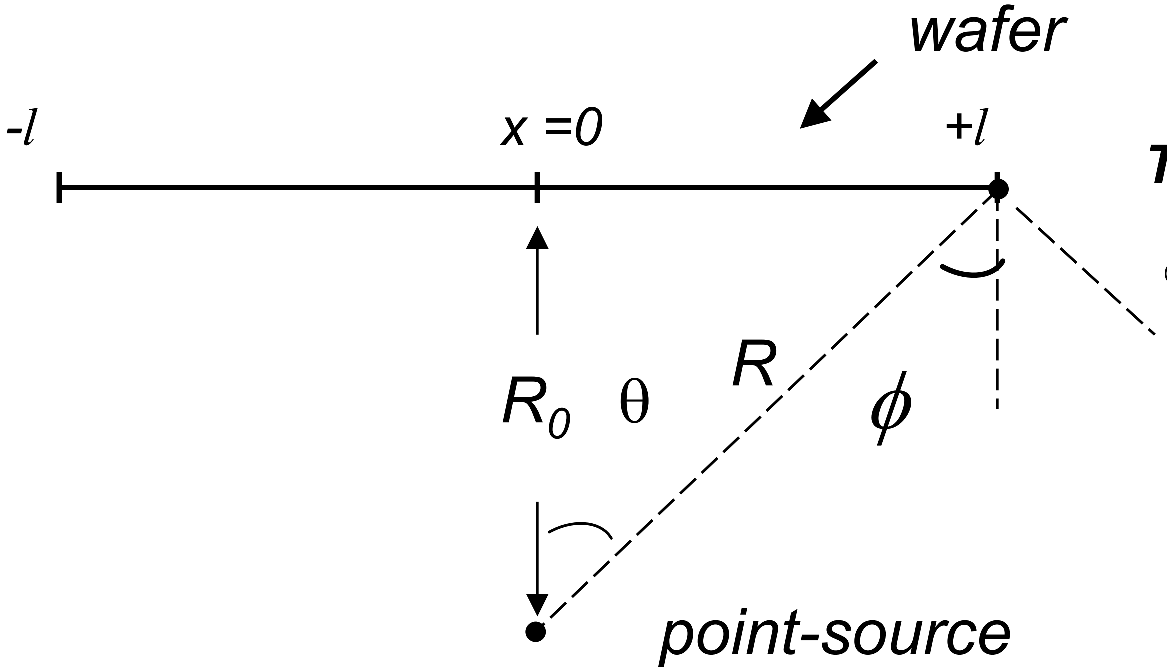
($F' = F/r^2$ is the flux at distance r from source)



Flat Wafer directly on top of Point Source

Example

For this geometry,
$\theta = \phi$



Thickness t at x=0

$\propto \cos\phi / R_o^2$

$= 1 / R_o^2$

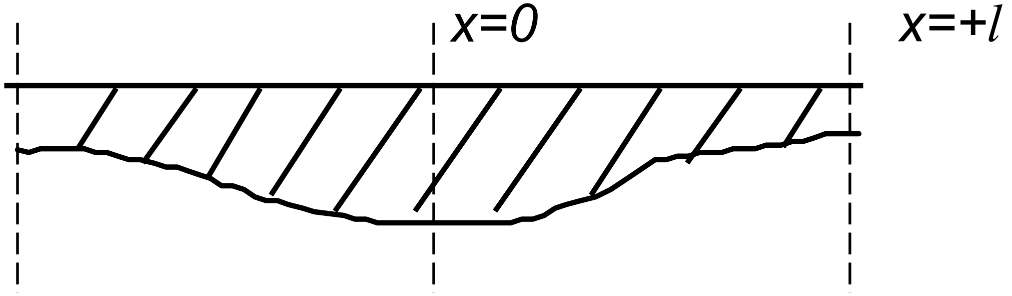
because $\phi = 0$ at x=0

Thickness t at x= +l $\propto \cos\phi / R^2$

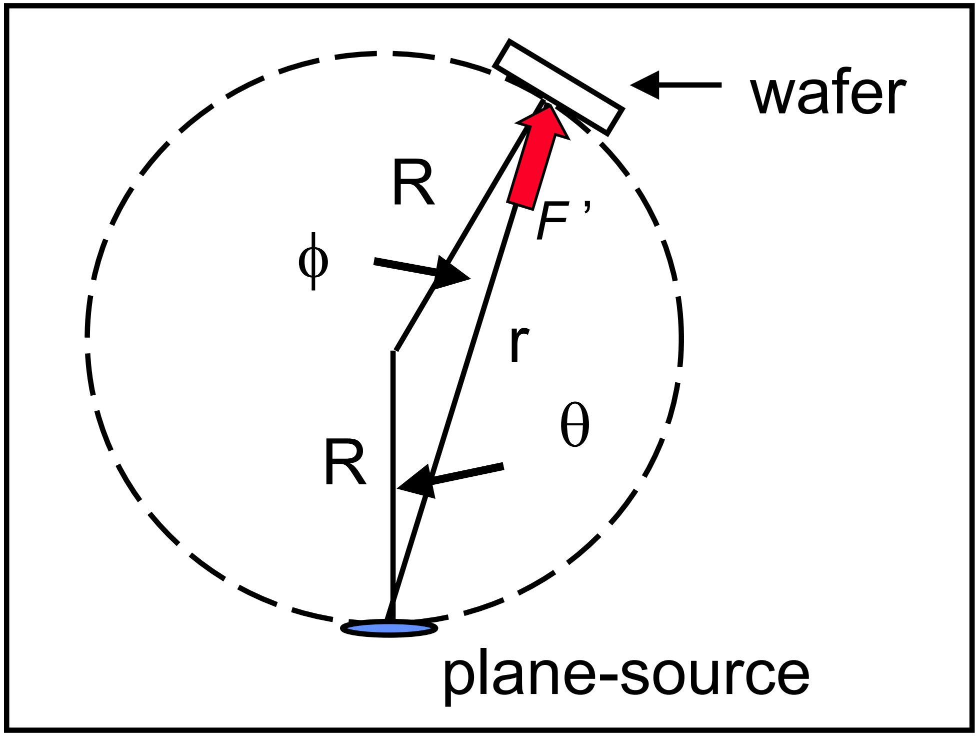
$$= \frac{\cos\phi}{\left(R_0^{\,2} + l^2\right)} = \frac{\cos\theta}{\left(R_0^{\,2} + l^2\right)}$$

$$= \frac{R_0}{R^3}$$

$$\frac{t(x = +l)}{t(x = 0)} = \left(\frac{R_0}{\sqrt{R_0^{\,2} + l_2}}\right)^3 = \left[1 + \left(\frac{l}{R_0}\right)^2\right]^{-3/2}$$



Example: Plane-like Source & Spherical Receiving Surface



$$\theta = \phi$$

$$flux\ F' \propto \frac{1}{r^2} \cdot \cos\theta$$

$$thickness\ \propto F' \cdot \cos\phi$$

$$\propto \frac{1}{r^2} \cos\theta \cos\phi$$

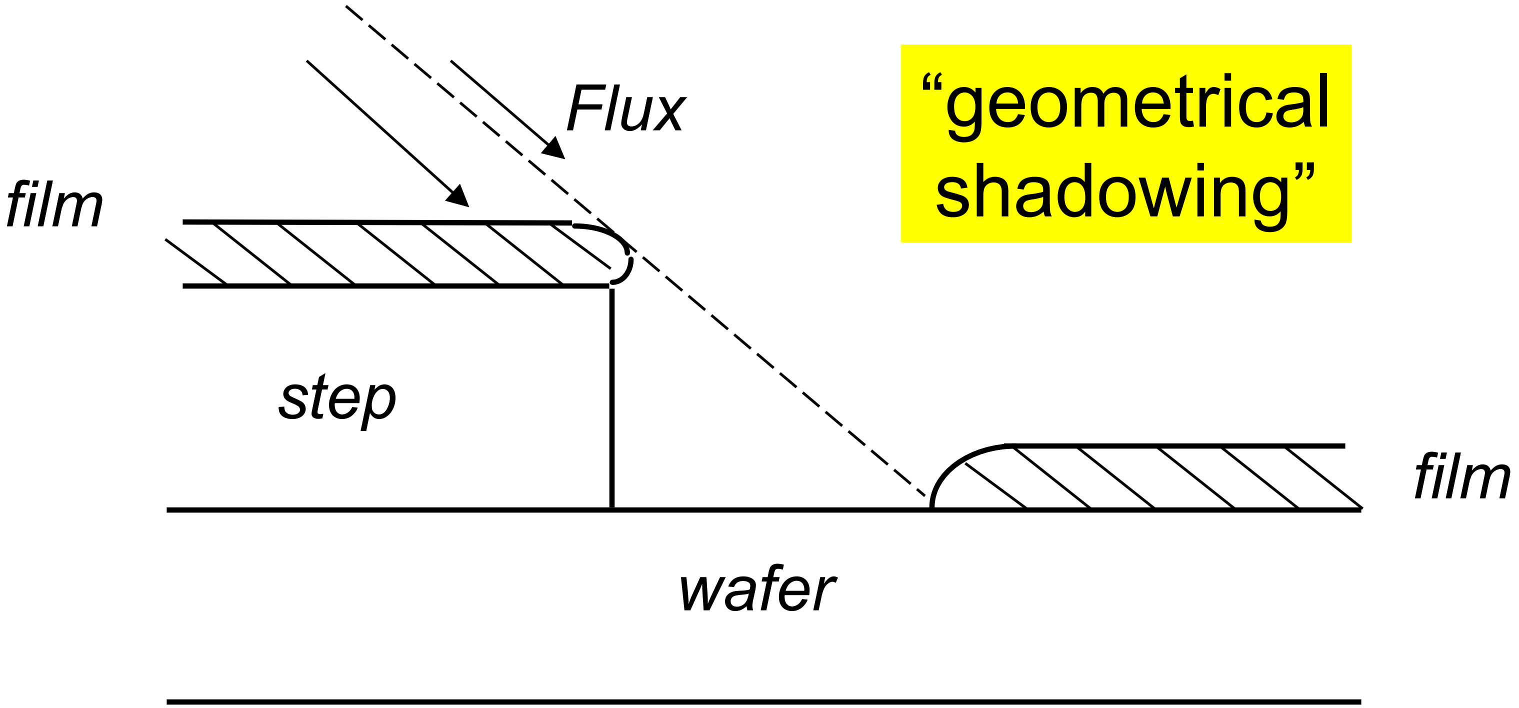
$$\propto \frac{1}{r^2} \cos^2\theta$$

Since $\cos\theta = (r/2)/R$

$\therefore$ *Thickness* $\propto (1/r^2)\,(r^2/4R^2) =$ *constant*

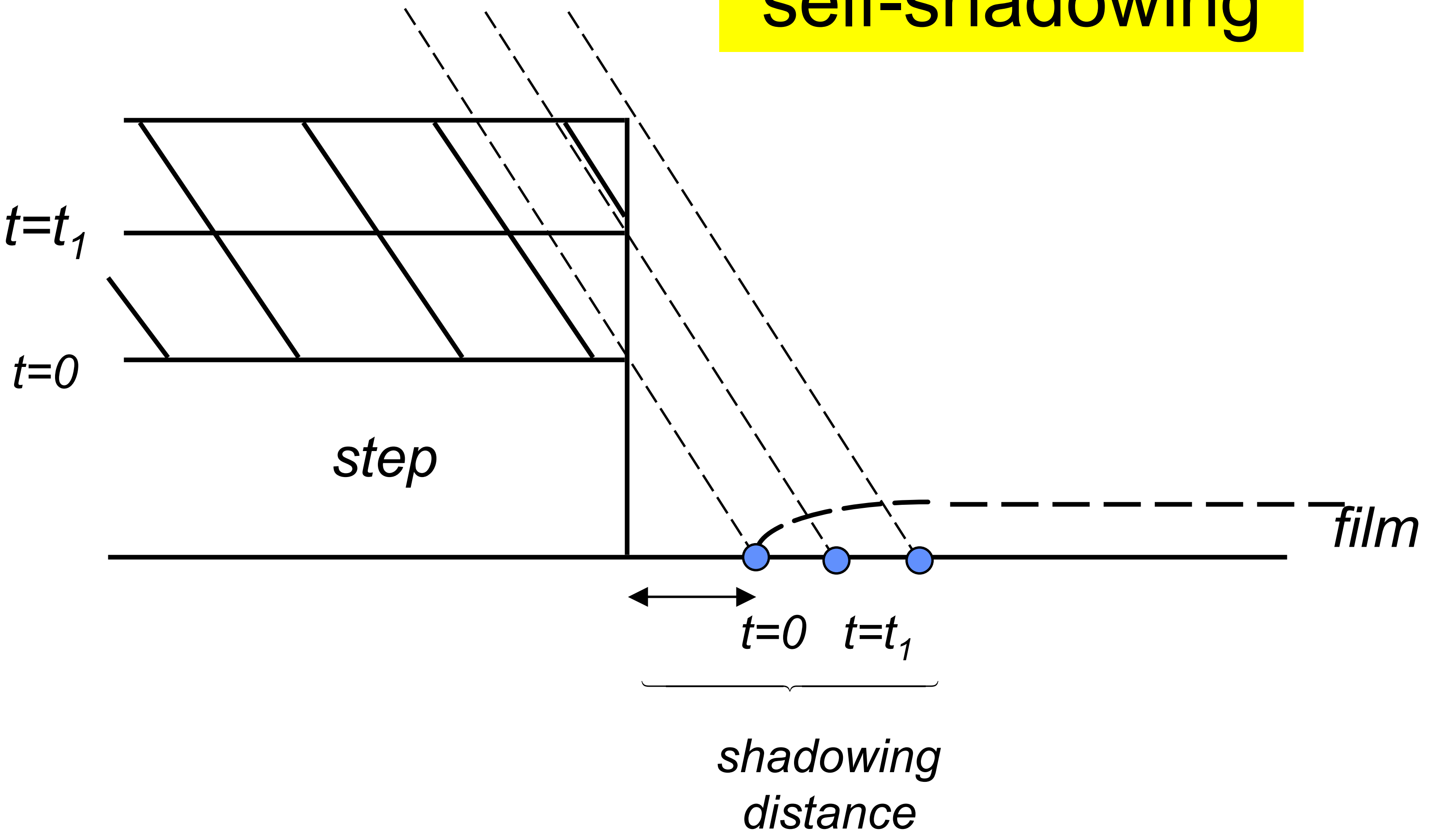
Step Coverage Problem with PVD

- Both evaporation and sputtering have directional fluxes.

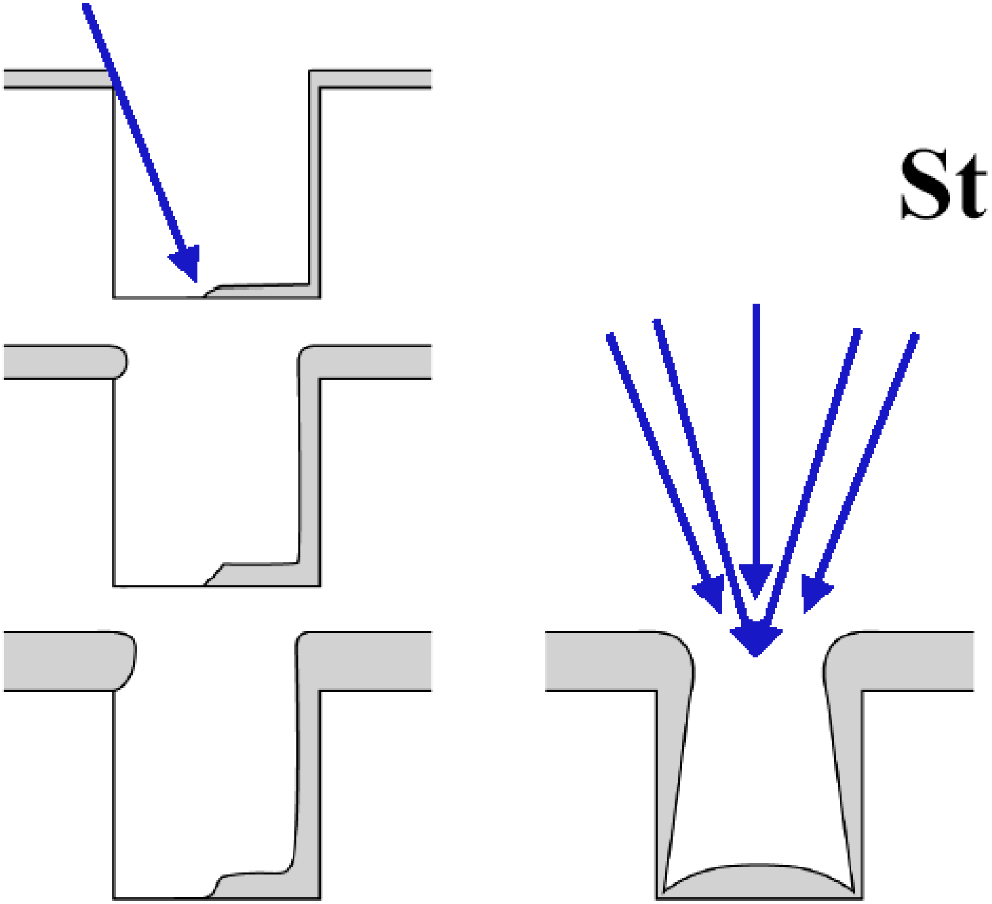


"geometrical shadowing"

"self-shadowing"



Step Coverage



Low adatom mobility and nonrotated

(A)

Heated and rotated

(B)

Figure 12.5 (A) Time evolution of the evaporative coating of a feature with aspect ratio of 1.0, with little surface atom mobility (i.e., low substrate temperature) and no rotation. (B) Final profile of deposition on rotated and heated substrates.

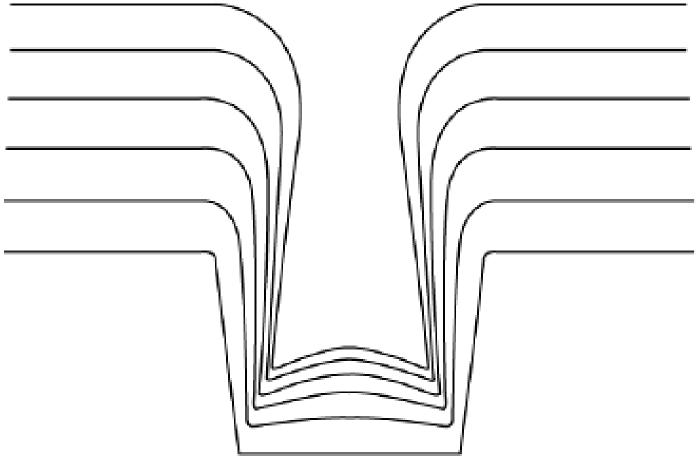
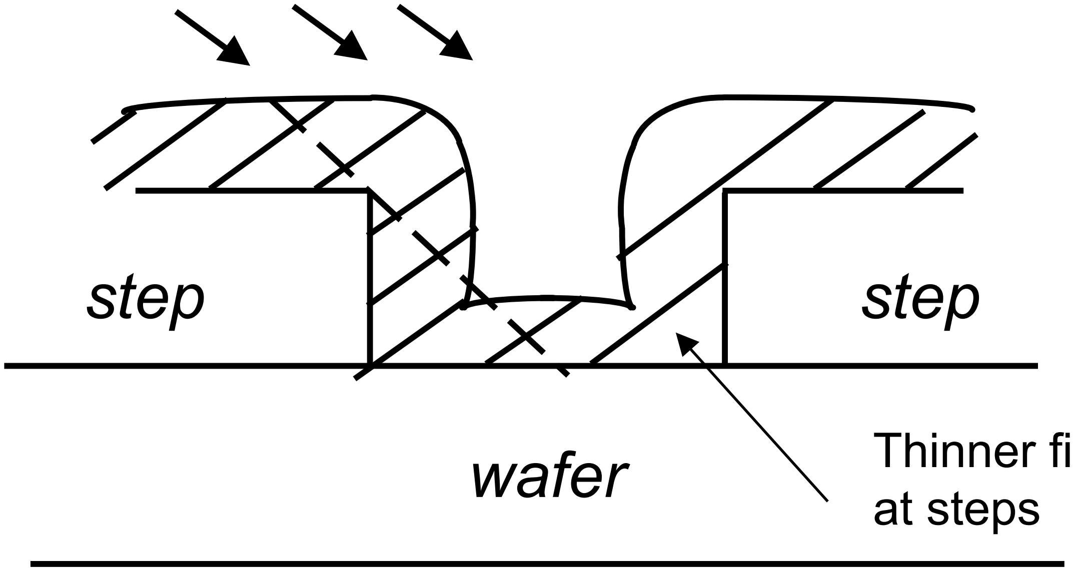


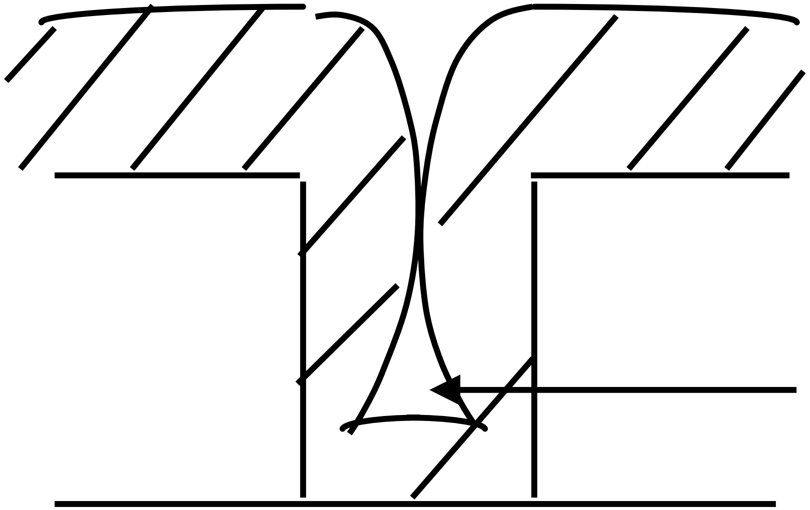
Figure 12.21 Cross section of the time evolution of the typical step coverage for unheated sputter deposition in a high aspect ratio contact.

Film Thinning at steps



Thinner film deposition at steps

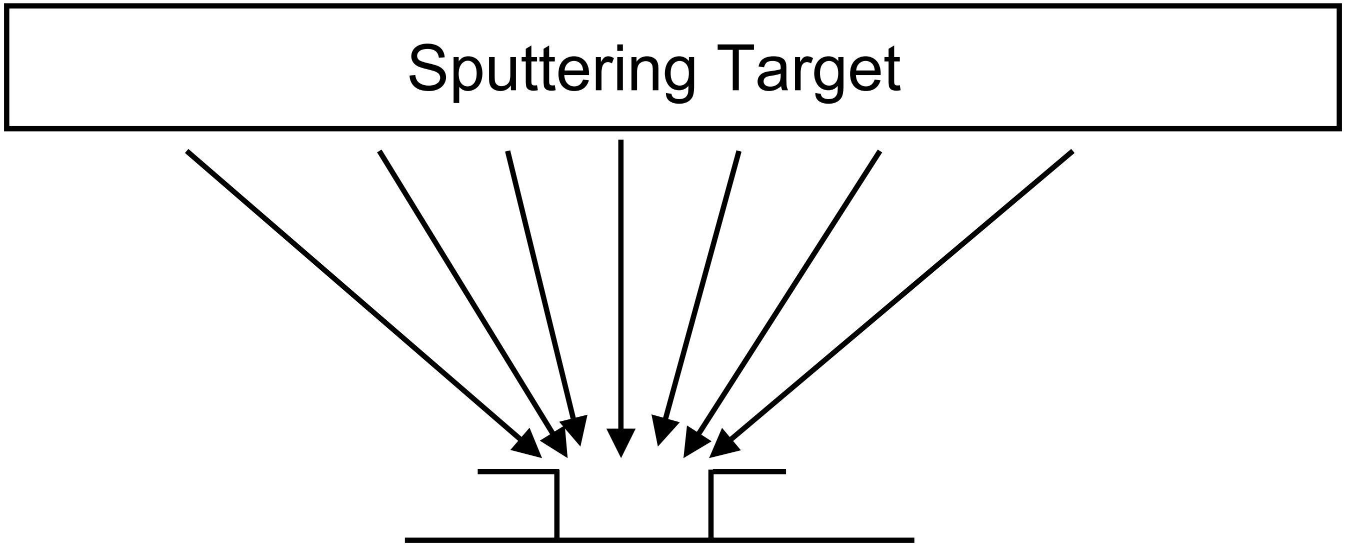
Key Hole Formation



“key hole”

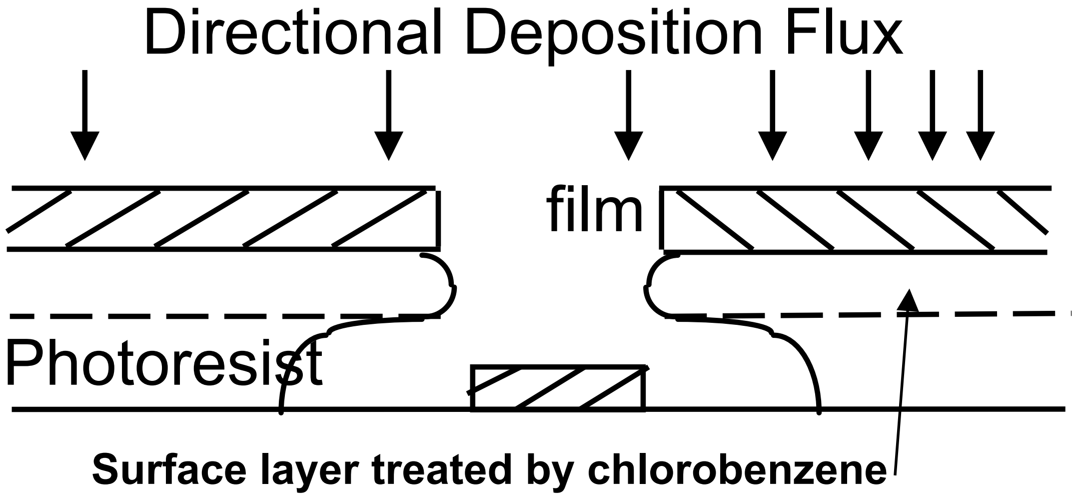
Methods to *Minimize* Step Coverage Problems

- Rotate + Tilt substrate during deposition
- Elevate substrate temperature (enhance surface diffusion)
- Use large-area deposition source



Lift-off Technique

Patterning of deposited layer using directional deposition.

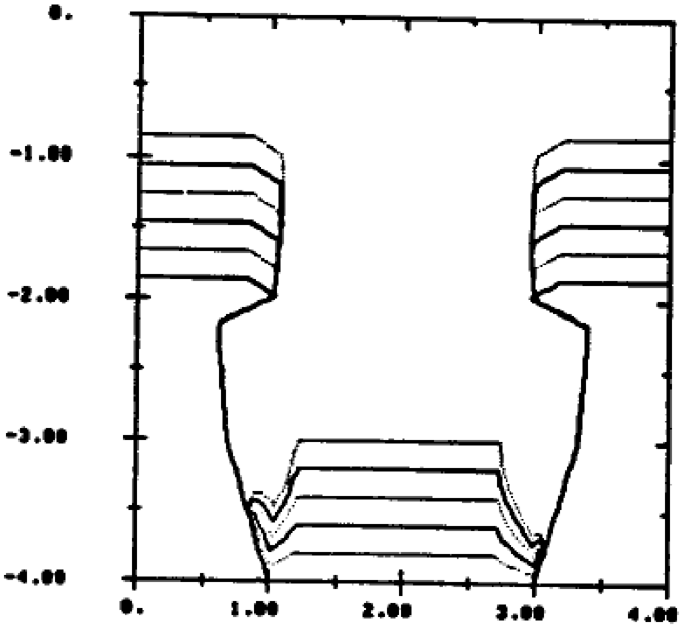


Directional Deposition Flux

film

Photoresist

Surface layer treated by chlorobenzene



Dip Photoresist in Chlorobenzene to slow down developing rate of surface layer .

Advantages of Sputtering over Evaporation

- For multi-component thin films, sputtering gives **better composition control** using compound targets. Evaporation depends on vapor pressure of various vapor components and is difficult to control.

- **Better lateral thickness uniformity**

Area of sputtering target can be made much larger than that of an evaporating source.
A larger area can be considered as a superposition of many small-area sources.
By adding the flux from all the sources, a large area source will provide better lateral film deposition uniformity on wafer.