# ECE 416/516
# IC Technologies
## Lecture 13/14:
## Physical Vapor Deposition (PVD)

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Spring 2012

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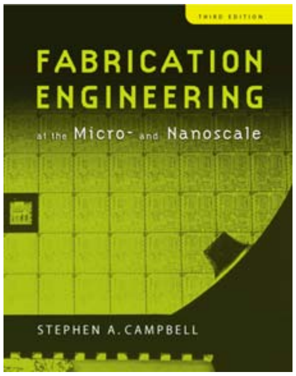
## Chapter 12

## Physical Deposition: Evaporation and Sputtering



# Lecture Topics

- Evaporation Sources
- Evaporation Rate
- Deposited Thicknesses
- Alloy composition & contamination
- Deposition thickness/rate monitors
- Homogeneous nucleation
- Heterogeneous nucleation
  - Capillary theory
    - Spherical cap nuclei
    - Shapes, charge, fields
    - Nucleation rate
  - Atomistic theory
  - Kinetic theory

- Sputtering systems
- Sputtering processes
- Sputtering yield
- Effects of bias, etc.
- Thornton diagram
- Contamination
- Stress

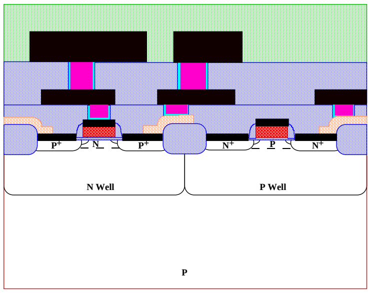
# Lecture Objectives

- Can calculate evaporation and deposition rates, thickness, variations, and contamination
- Have knowledge of standard PVD hardware and techniques
- Able to explain nucleation and growth concepts

- Distinguish homogeneous and heterogeneous nucleation
- Can calculate critical nucleus sizes and nucleation rates for capillary, atomistic and kinetic models.

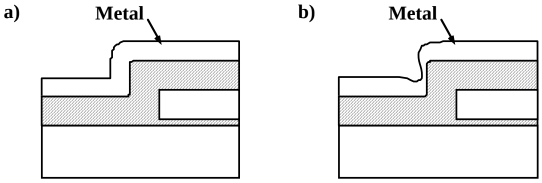
- Be able to explain physics of sputtering, yields, and various system configurations
- Anticipate the effects of bias, contamination and stress

## THIN FILM DEPOSITION: Introduction

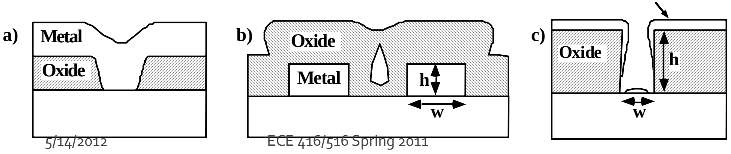


- Many films, made of many different materials, are deposited during a standard CMOS process.
- Requirements or desirable traits for deposition:

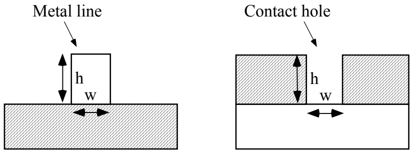
1. Desired composition, low contaminates, good electrical and mechanical properties.
2. Uniform thickness across wafer, and wafer-to-wafer.
3. Good step coverage ("conformal coverage").
4. Good filling of spaces.
5. Planarized films .



**Step Coverage Issues**



**Filling Issues**

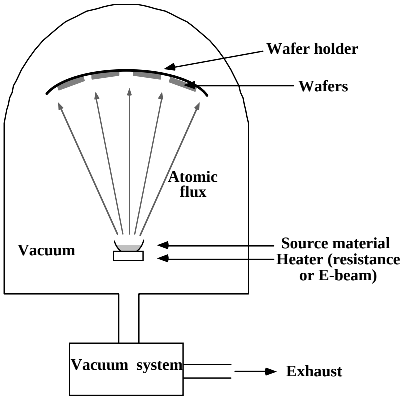


$$\text{Aspect ratio} = AR = \frac{h}{w}$$

| Year of Production | 1998 | 2000 | 2002 | 2004 | 2007 | 2010 | 2013 | 2016 | 2018 |
|---|---|---|---|---|---|---|---|---|---|
| Technology Node (half pitch) | 250 nm | 180 nm | 130 nm | 90 nm | 65 nm | 45 nm | 32 nm | 22 nm | 18 nm |
| MPU Printed Gate Length | | 100 nm | 70 nm | 53 nm | 35 nm | 25 nm | 18 nm | 13 nm | 10 nm |
| Min Metal 1 Pitch (nm) | | | | 214 | 152 | 108 | 76 | 54 | 42 |
| Wiring Levels - Logic | | | | 10 | 11 | 12 | 12 | 14 | 14 |
| Metal 1 Aspect Ratio (Cu) | | | | 1.7 | 1.7 | 1.8 | 1.9 | 2.0 | 2.0 |
| Contact Aspect Ratio (DRAM) | | | | 15 | 16 | >20 | >20 | >20 | >20 |
| STI Trench Aspect Ratio | | | | 4.8 | 5.9 | 7.9 | 10.3 | 14 | 16.4 |
| Metal Resistivity (µohm-cm) | 3.3, 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 |
| Interlevel Dielectric Constant | 3.9 | 3.7 | 3.7 | <2.7 | <2.4 | <2.1 | <1.9 | <1.7 | <1.7 |

- Note the aspect ratios and the need for new materials.
- Note also the number of metal layers requiring more deposition steps.

## Physical Vapor Deposition (PVD)



- PVD uses mainly physical processes to produce reactant species in the gas phase and to deposit films.
- In evaporation, source material is heated in high vacuum chamber. ($P < 10^{-5}$ torr).
- Mostly line-of-sight deposition since pressure is low.
- Deposition rate is determined by emitted flux and by geometry of the target and wafer holder.

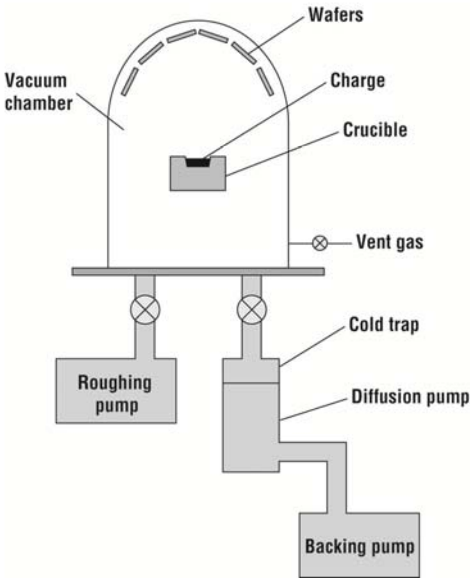
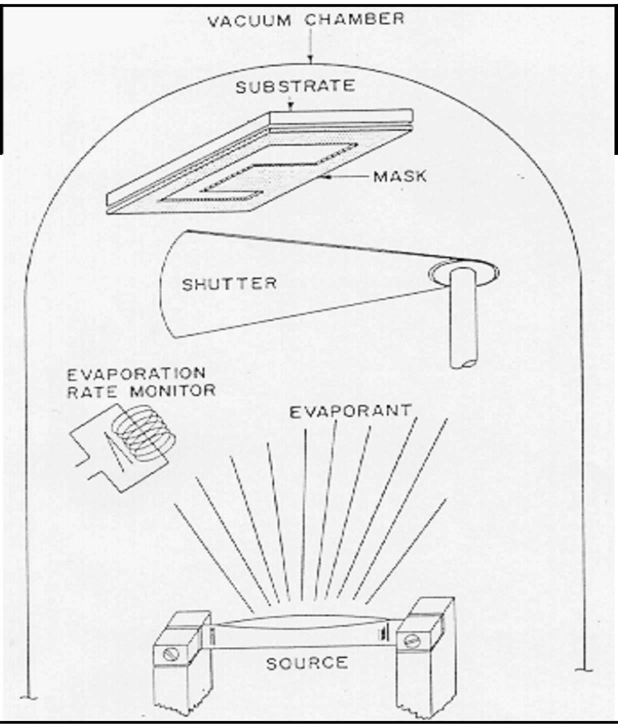


**Figure 12.1** A simple diffusion-pumped evaporator showing vacuum plumbing and the location of the charge-containing crucible and the wafers.

# Deposition System



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Equilibrium vapor pressure at the material surface

Sublimation from solid source
Evaporation from molten source

$$P_e = 3\text{x}10^{12}\sigma^{3/2}T^{-1/2}e^{\Delta H_v/NkT}$$

where $\sigma$ = surface tension
$\Delta H_v$ = enthalpy of evaporation
N = Avagadro's number

But equation gives large errors for small variations in ΔHv, so usually use experimental data

Deposition at VP~10mtorr
e.g. Ag, Au vs Ti, Mo, W, (Ta)
(refractory metals)
Also: Al

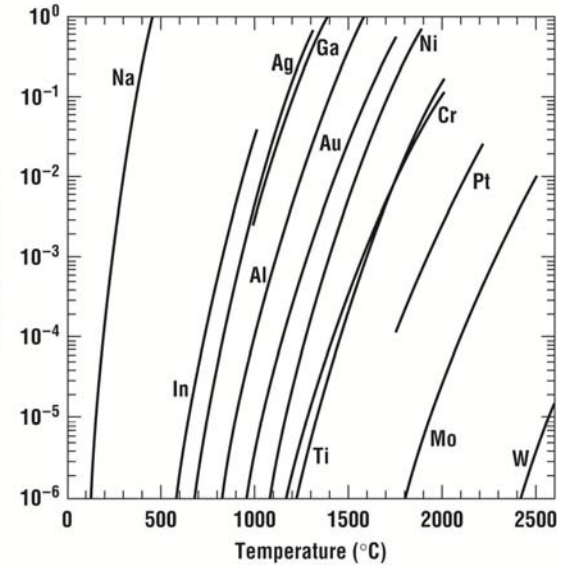
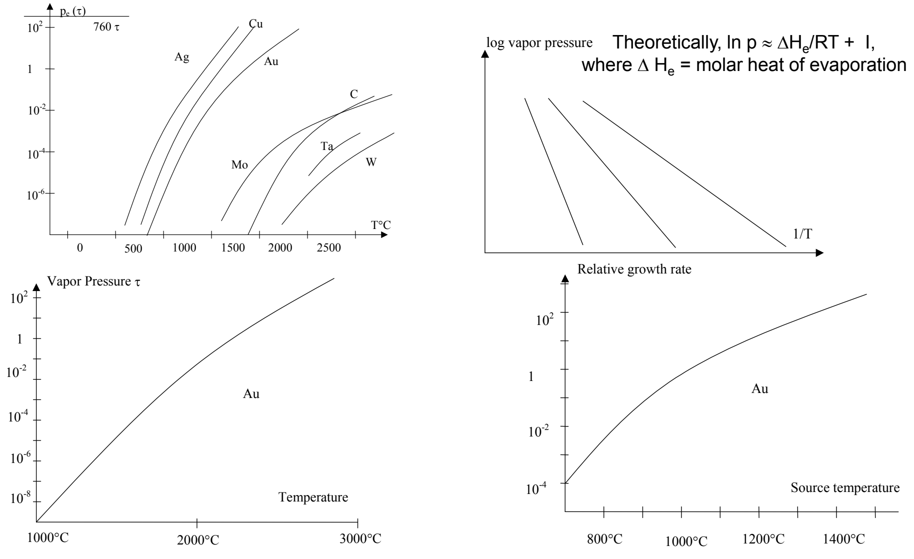


**Figure 12.2** Vapor pressure curves for some commonly evaporated materials *(data adapted from Alcock et al.).*

# Vapor Pressure & Growth Rate



Theoretically, $\ln p \approx \Delta H_e/RT + I$,
where $\Delta H_e$ = molar heat of evaporation

# Evaporation Rate

Molecular Impingement flux $J = p/(2\pi mkT)^{1/2}$
(see back)
p = partial pressure
m = molecular mass
J in molecules / unit area / unit time
J = evaporation rate at equilibrium

Non-equilibrium : $T_e >> T_{amb}$
$p_e >> p_n$ background
$J_e = \alpha_e [p_e(T_e) - p_n] / (2\pi mkT)^{1/2}$
$\alpha_e$ = evaporation coefficient

# Deposition rates

Number gas molecules crossing plane/unit area.unit time

$$J_n = \sqrt{\frac{P^2}{2\pi mkT}} \text{ gives mass evaporation rate } R_{ME} = \sqrt{\frac{m}{2\pi kT}} P_e$$

$$\text{so mass loss rate at crucible } R_{ML} = \int \sqrt{\frac{m}{2\pi kT}} P_e dA = \sqrt{\frac{m}{2\pi k}} \int \frac{P_e}{\sqrt{T}} dA$$

$$R_{ML} \approx \sqrt{\frac{m}{2\pi k}} \frac{P_e}{\sqrt{T}} A \text{, for T uniform and A constant}$$

# Example 12.1: Hemispherical water droplet, radius ro=1mm, in vacuum at 300K. How long to evaporate?

No of water molecules $N = \frac{1}{2}\frac{4}{3}\pi r^3 \rho \frac{1}{m}$

so $\frac{dN}{dt} = 2\pi r^2 \frac{dr}{dt}\frac{\rho}{m}$

and $J = \frac{1}{A}\frac{dN}{dt} = 2\pi r^2 \frac{dr}{dt}\frac{\rho}{m} \Big/ \frac{1}{2} 4\pi r^2 = \sqrt{\frac{P_e^2}{2\pi mkT}}$

so $\frac{dr}{dt} = \frac{P_e}{\rho}\sqrt{\frac{m}{2\pi kT}} = \text{constant with time}$

At 300K, $P_e$ is 27 torr = 3600 Pa, and

$$\mathrm{t} = \frac{\mathrm{r_0}}{\mathrm{dr/dt}} = \frac{r_0 \rho}{P_e}\sqrt{\frac{2\pi kT}{m}} = 35 m \sec$$

Note: Latent heat of evaporation would lower T with time, also reducing $P_e$.

# Point Source Deposition

Total mass evaporated = $M_e$

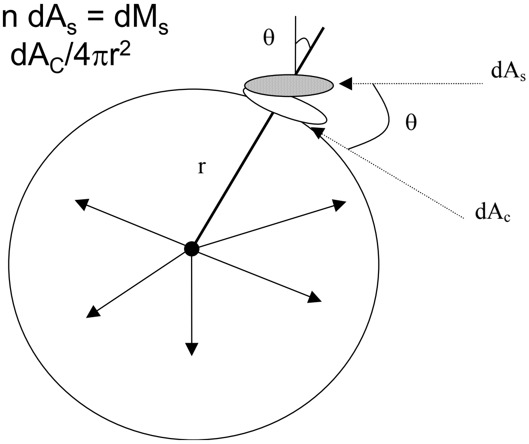
Mass deposited on $dA_s$ = $dM_s$

$dM_s/M_e = dA_C/4\pi r^2$

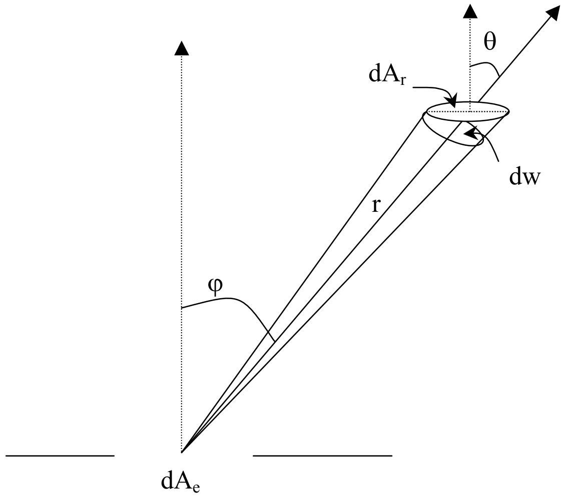
$dA_c$ is projection of $dA_s$,

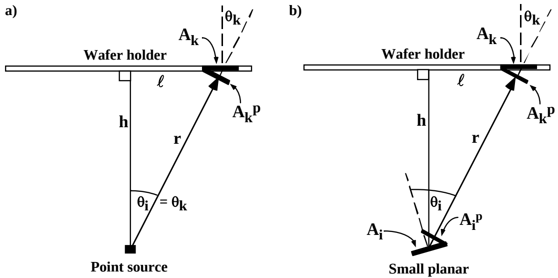
$dA_c = dA_s \cos\theta$

$\therefore dM_s/dA_s = M_e \cos\theta/4\pi r^2$



# Surface Source Deposition (Knudsen source-narrow aperture)



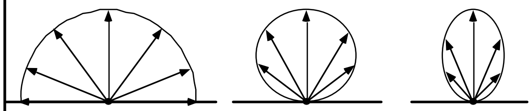


$$F_k^P = \frac{R_{evap}}{\Omega r^2}$$

$$v = \frac{R_{evap}}{\Omega N r^2}\cos\theta_k$$

$$F_k^P = \frac{R_{evap}}{\pi r^2}\cos^n\theta_i$$

$$v = \frac{R_{evap}}{\pi N r^2}\cos^n\theta_i \cdot \cos\theta_k$$



**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 Rates

- **The evaporation source can be considered either a point sourc or as a small area surface sourc (latter is more applicable to most evaporation systems).**
- **$\Omega$ is the solid angle over which the source emits (4π if all directions, 2π if only upwards); N is the density of the material being deposited.**
- **The outward flux $F_k^P$ from a point source, is independent of $\theta_i$ , while the outward flux from a small area surface source, varies as $\cos^n\theta_i$ .**

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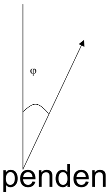
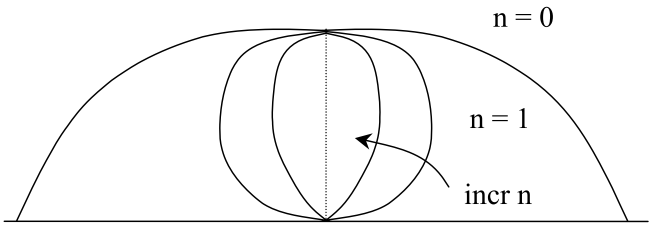
# Cosine Law in Practice



cos φ dependence: In practice $\cos^n \varphi$

$\therefore\ dM_r/dA_r = M_e\,(n+1)\cos^n\varphi\,\cos\theta\,/\,2\pi r^2$

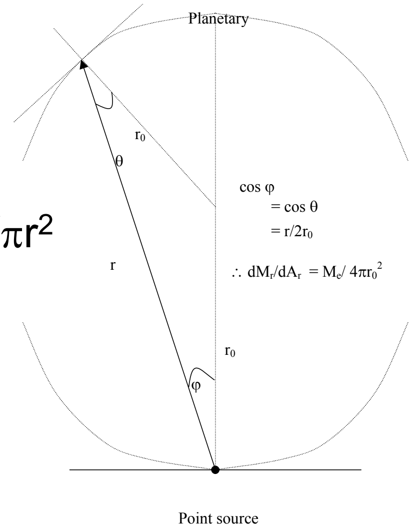
--> $M_e\cos\varphi\,\cos\theta\,/\,\pi\, r^2$ for n=1

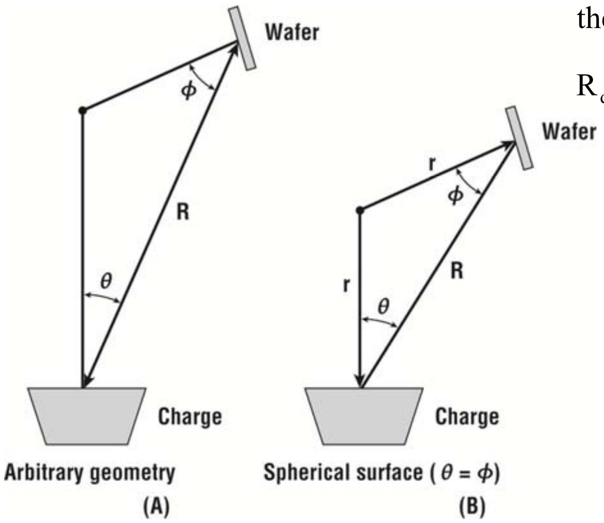


## Planetary Substrate Holder

$$\cos\vartheta = \cos\theta = (r/2)/r_0$$

$$\therefore dM_r/dA_r = M_e(r/2r_0)^2/\pi r^2 = M_e / 4\pi r_0^2$$





If $\cos\theta = \cos\phi = R/2r$

then deposition rate

$$R_d = \text{Evap rate x } \frac{\cos\theta.\cos\phi}{\pi\rho R^2}$$

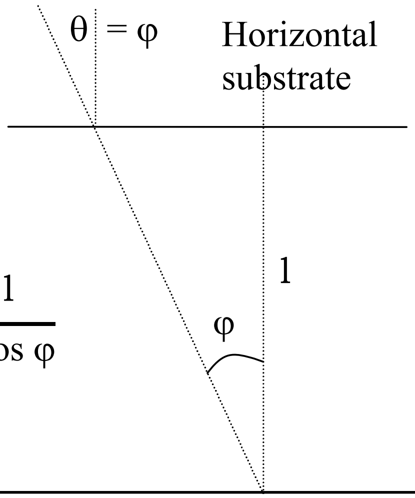
$$= \sqrt{\frac{m}{2\pi k}}\frac{P_e}{\sqrt{T}}A\frac{1}{\pi\rho R^2}\frac{R^2}{4r^2}$$

$$= \sqrt{\frac{m}{2\pi k}}\frac{P_e}{\rho\sqrt{T}}\frac{A}{4\pi r^2}$$

(Planetary deposition, independent of $\theta = \phi$)

**Figure 12.3** The geometry of deposition for a wafer (A) in an arbitrary position and (B) on the surface of a sphere.

# Horizontal Substrate Holder



$$r = \frac{l}{\cos \varphi}$$

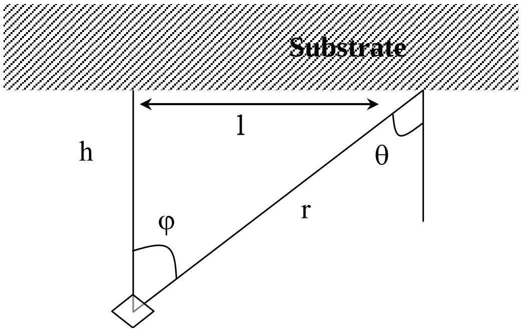
# Film Uniformity: Point Source

Film thickness $d = dM_r/\rho dA_s$

For point source $d = M_e \cos \theta / 4 \pi\rho r^2$

$= M_e h / 4 \pi \rho r^3$

$= M_e h / 4 \pi \rho (h^2 + l^2)^{3/2}$



& thickest point $d_0 = M_e h / 4 \pi \rho h^3$

$\therefore d/d_0 = h^3/(h^2 + l^2)^{3/2} = 1 / [1 + (l/h)^2]^{3/2}$

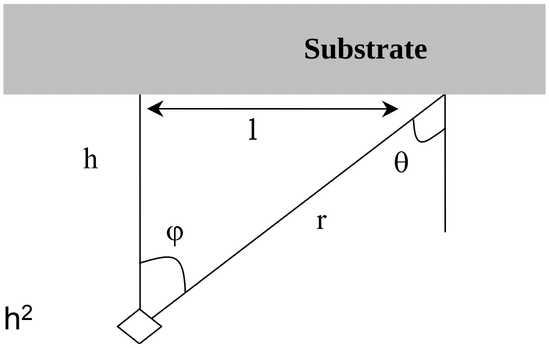
# Film Uniformity: Surface Source

Film thickness $d = M_e \cos\varphi \cos\theta / \pi \rho r^2$

$= (M_e / \pi \rho r^2)(h/r)(h/r)$

$= M_e h^2 / \pi \rho r^4$

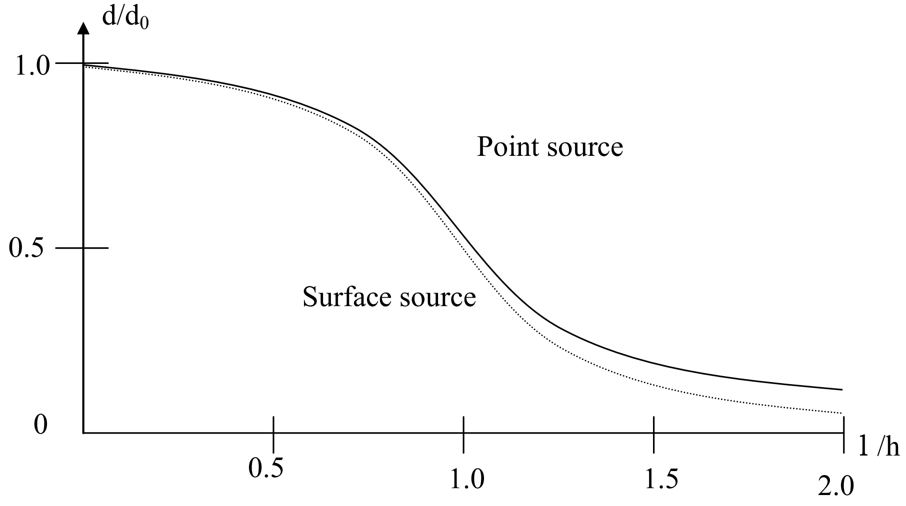
$= M_e h^2 / \pi \rho (h^2 + l^2)^2$



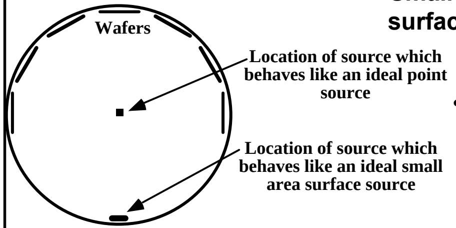
& for $d_0 = M_e / \pi \rho h^2$

$\therefore\ d/d_0 = h^4/(h^2 + l^2)^2 = 1 / [1 + (l/h)^2]^2$

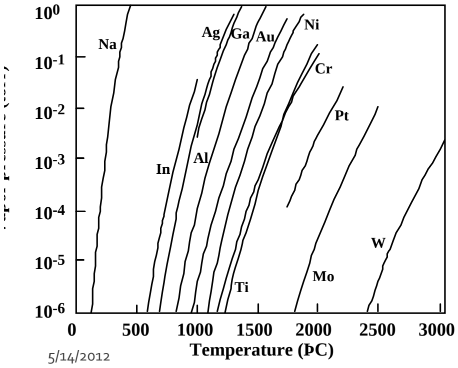
# Film Uniformity Comparison

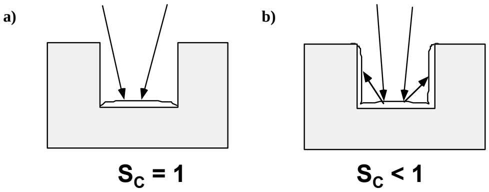


- Uniform thickness - use spherical wafer holder.
  - Point source: put source at center of sphere.
  - Small surface source: put source on inside surface of sphere (compensates for $\cos^n \theta_i$ ).



- With evaporation:
  - Can evaporate just about any element.
  - Difficult to evaporate alloys and compounds
  - Sticking coefficient $S_c=F_{reacted}/F_{incident}$
  - Step coverage is poor (line of sight and $S_c \approx 1$).
  - Rarely used today.





$R_{evap}=5.83\times10^{-2}A_s(m/T)^{1/2}P_e$ gm/sec

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**Figure 12.10** A commercial evaporator. Inset shows a planetary *(photographs courtesy of CHA Industries).*

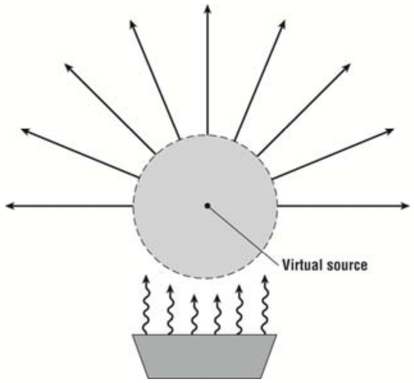
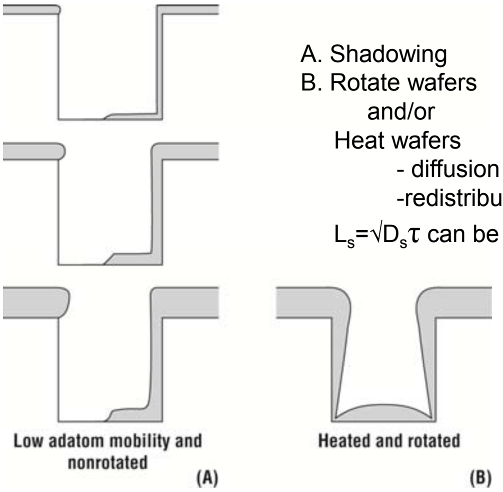


**Figure 12.4** At high deposition rates, the equilibrium vapor pressure of the charge puts the region just above the crucible into viscous flow, creating a virtual source up to 10 cm above the top of the crucible.

High rate depositions → high molecular density in the vapor
Hence vapor can condense into droplets
Hence deposit slowly → possible contamination

Step Coverage



A. Shadowing
B. Rotate wafers
and/or
Heat wafers
- diffusion
-redistribution

$L_s = \sqrt{D_s \tau}$ can be large

Aspect ratio
=step height/step diameter

**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.

Simulations

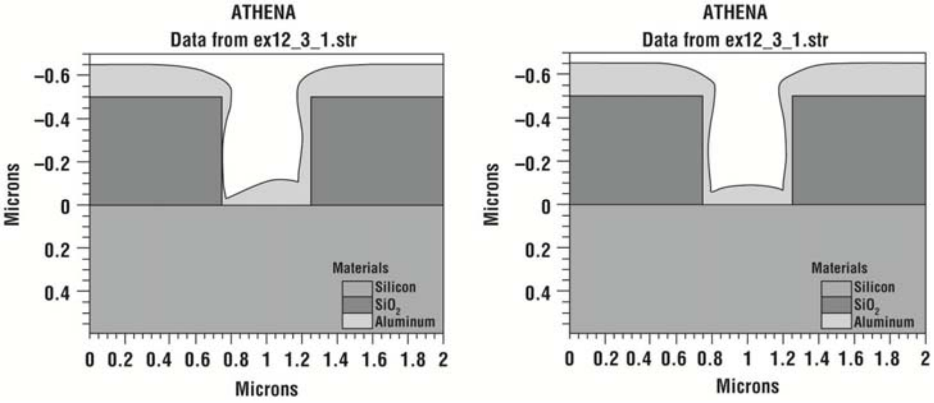


**Figure 12.6** Athena simulation of the evaporation of aluminum in a 1:1 aspect ratio contact deposition conditions that reasonably approximate: simple evaporation (left) and evaporation onto a sample mounted in a rotating planetary (right).

Evaporation Systems

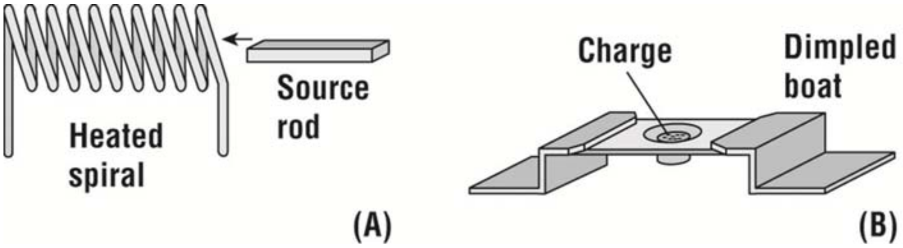
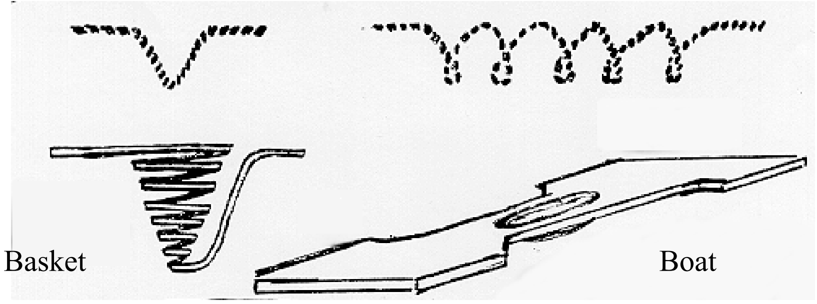
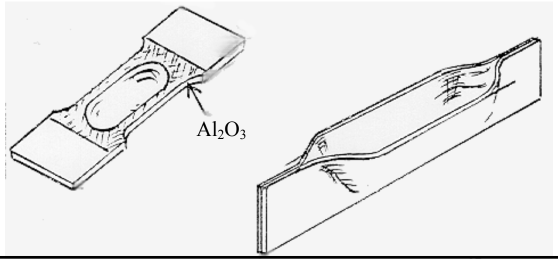


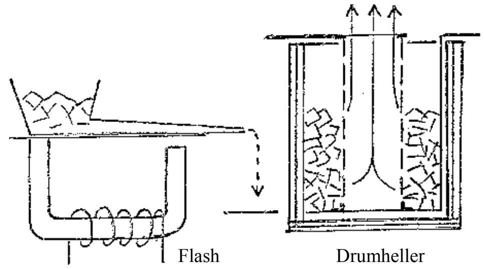
**Figure 12.7** Resistive evaporator sources. (A) Simple sources including heating the charge itself and using a coil of refractory metal heater coil and a charge rod. (B) More standard thermal sources including a dimpled boat in resistive media.

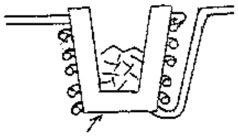
# Evaporation Sources #1



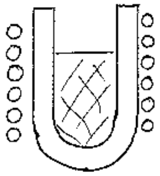


# Evaporation Sources #2





Crucible: $Al_2O_3$, C, BN, BeO, etc.



RF Coil Heating

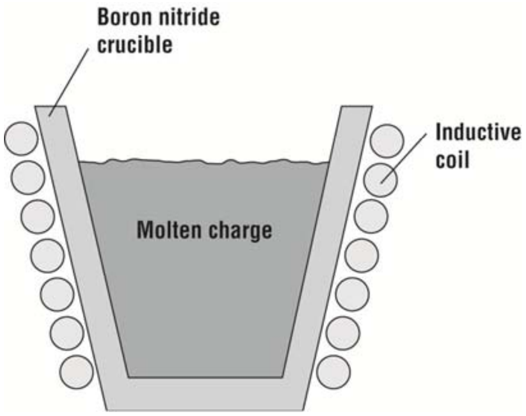


**Figure 12.8** Example of an inductively heated crucible used to create moderately charged temperatures.

Also baffled sources

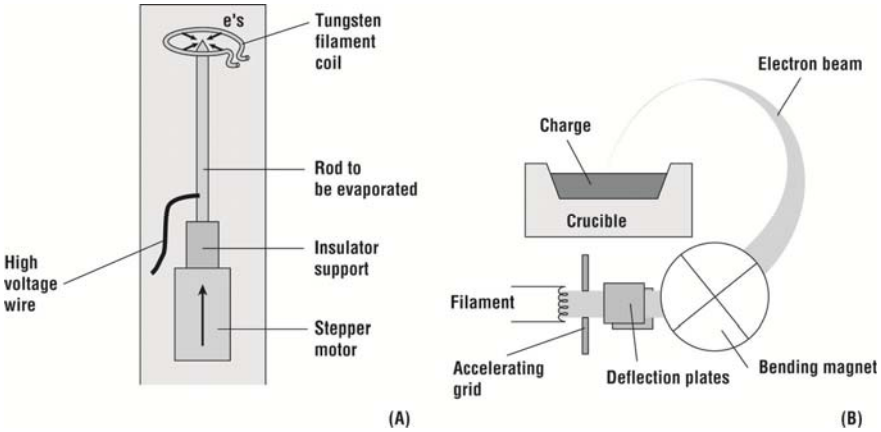
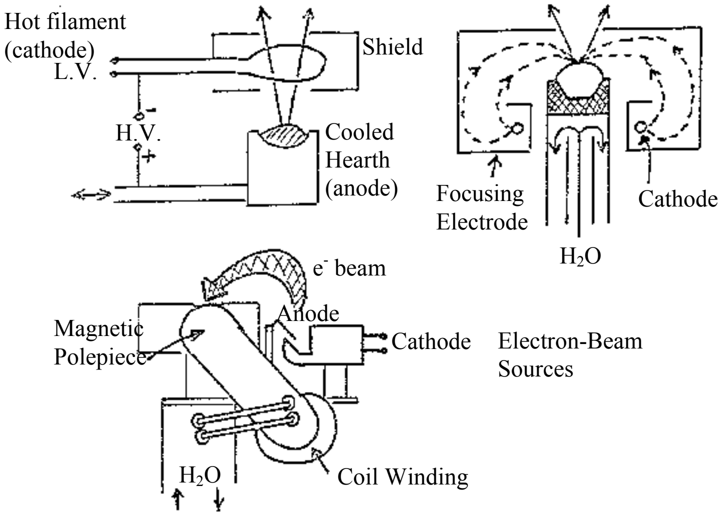


**Figure 12.9** Electron beam evaporative sources. (A) A simple low flux source using a hot wire electron source and a thin movable rod. (B) A popular source using a 2707 source arc in which the beam can be rastered across the surface of the charge. The magnet must be much larger than shown to achieve the full 270° of arc.

# Evaporation Sources #3



Electron-Beam
Sources

Alloy deposition

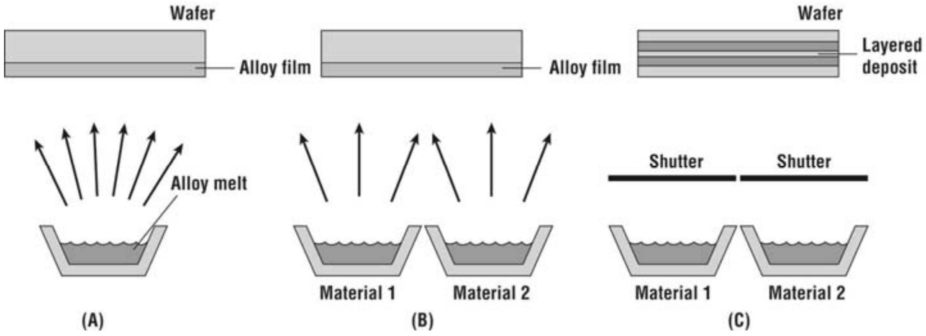
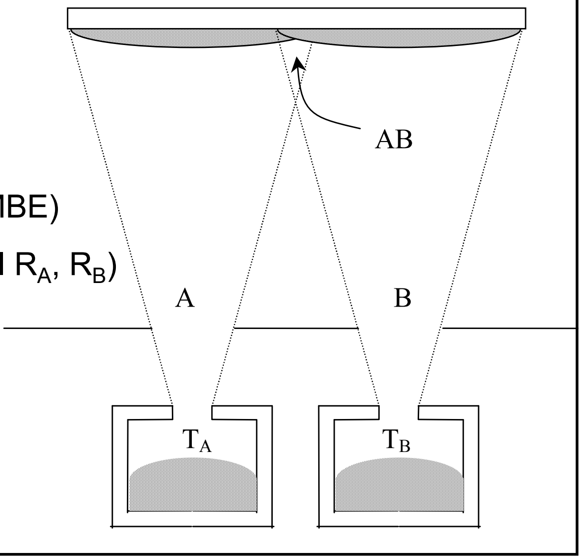


**Figure 12.11** Methods for evaporating multicomponent films include (A) single-source evaporation, (B) multisource simultaneous evaporation, and (C) multisource sequential evaporation.

# Alloy Deposition Control



Composition control:

(a) Source temperature (MBE)

(b) Twin monitors (Control $R_A$, $R_B$)

(c) Master-Slave monitors
(Control $R_B=kR_A$)

# Alloy Deposition

Single Source e.g. NiCr

- Vapor pressure difference
- Equilibrium
- Film composition function of source temp, time

Flash Evaporation

- Intermetallics (GaAs, PbTe, InSb, etc.)
- Cermets

Sputter

## Impurity Contamination

Relate to deposited evaporant flux

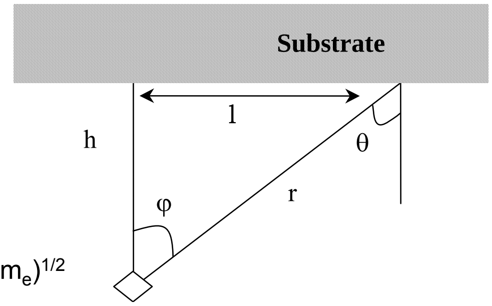
$J_e = p_e/(2\pi m_e kT_e)^{1/2}$

& at horizontal substrate (surface source)

$J' = J_e A_e \cos^4 \varphi / \pi h^2$

(valid only for small $A_e$)

$= J_e A_e (h^2/\pi l^2)$



Contaminant in source

$J_c = p_c / (2\pi m_c kT_e)^{1/2}$

i.e. contamination $(p_c/p_e)/(m_c/m_e)^{1/2}$

Background contamination

$J = p_p / (2\pi mkT)^{1/2}$,

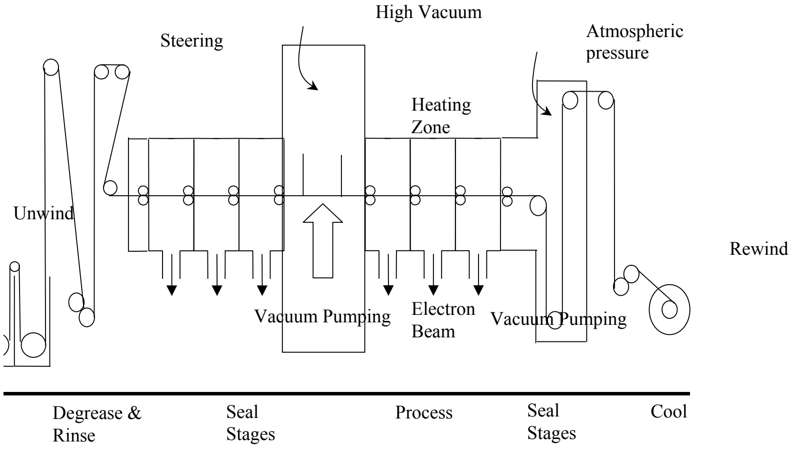
$p_p$ partial pressure of contaminant,

molecular mass m,

ambient temperature T.

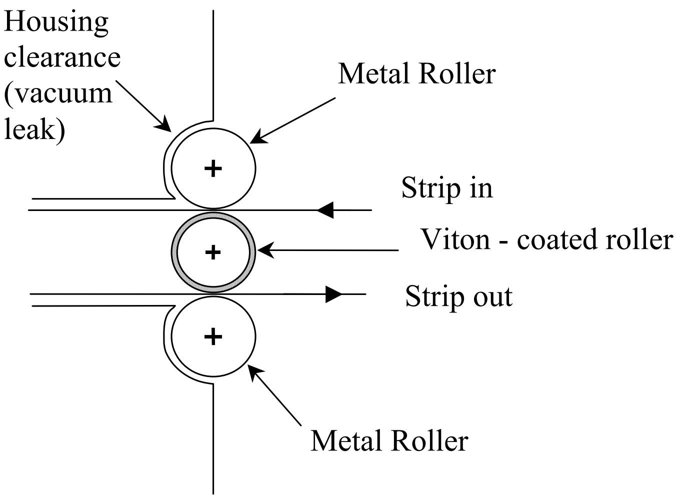
Uniform across substrate.

## Roll Coater #1



Differential Pumping

# Roll Coater #2



Housing clearance (vacuum leak)

Metal Roller

Strip in

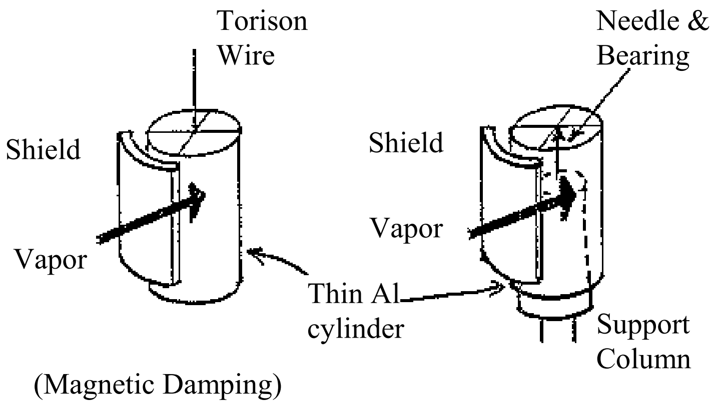
Viton - coated roller

Strip out

Metal Roller

# Deposition Rate Monitors 31

## Particle impingement



Torison Wire

Needle & Bearing

Shield

Shield

Vapor

Vapor

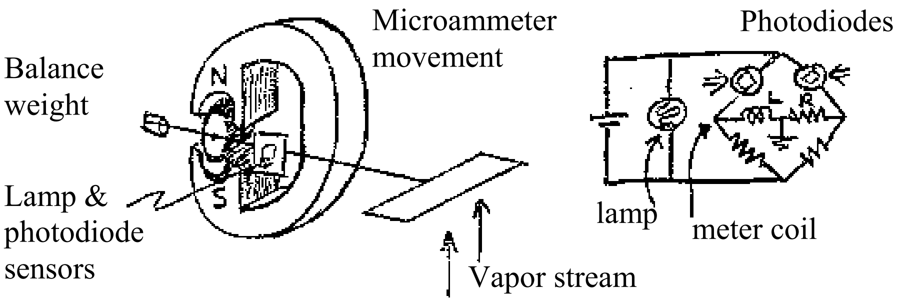
Thin Al cylinder

Support Column

(Magnetic Damping)

# Deposition Rate Monitors #2

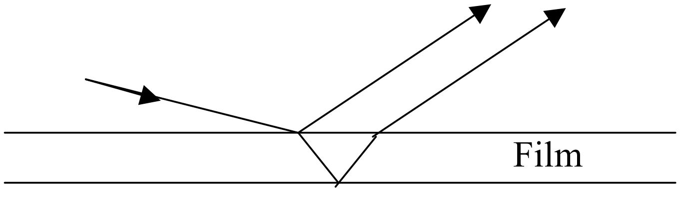
Mechanical Microbalance measures deposited mass.



(see also Quartz crystal)

# Deposition Rate Monitors #3

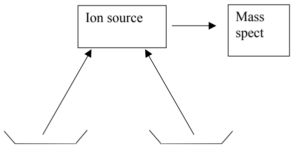
Optical Monitors
- (a) Reflectance
- (b) Transmittance
- (c) Absorption
- (d) Interference (oscillatory with thickness)



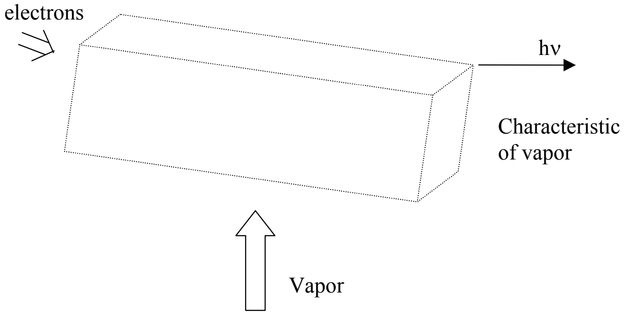
Resistance

# Deposition Rate Monitors #4

Ionization gauge monitors



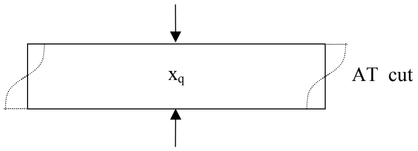
Mass spectrometry (especially for alloy deposition)



EIES: electron induced emission spectroscopy

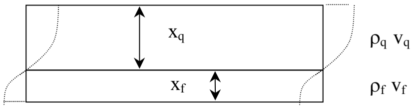
Detector for each species, no build up

# Quartz Crystal Monitor



Thickness shear oscillation mode:

$x_q = \lambda/2 = v_q/2f_q = ½v_q\tau_q$



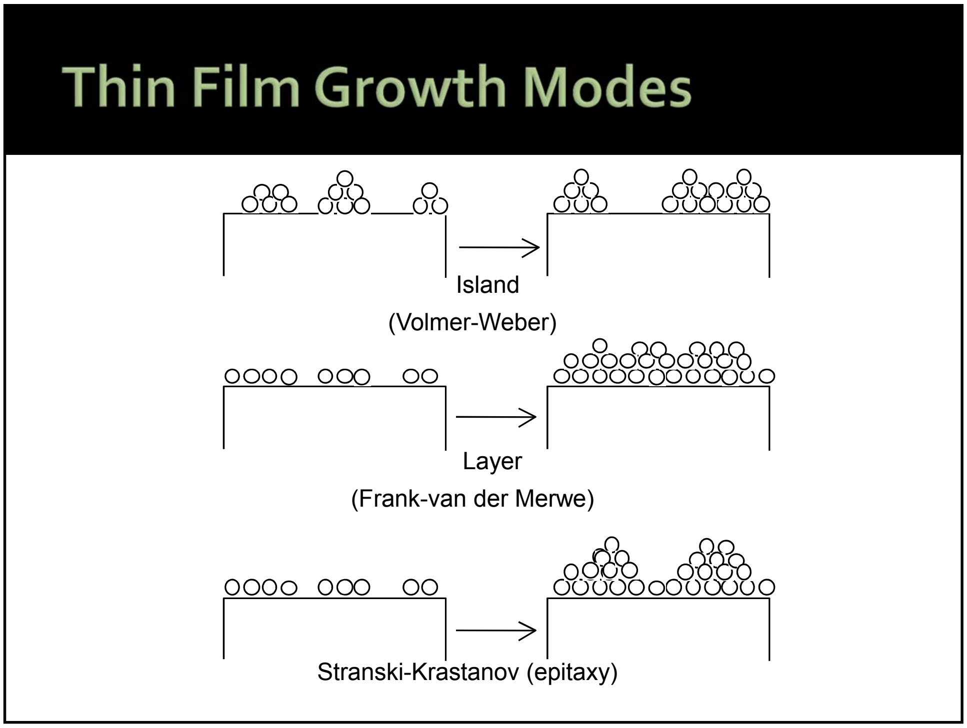
$\Delta f_q/f_q \approx -\Delta m_q/m_q$ --> $\Delta f \approx -(m_f/m_q)\,f_q$
for $m_f/m_q \leq 0.01$

Write $\Delta f \Rightarrow -m_f * f_q/(\rho_q x_q) = -m_f * 2f_q^2/(\rho_q v_q)$
Only time AT $f_q$ (single frequency)

write $dm_f = -(\rho_q v_q/2f_c^2)\,df_c$
& integrate ${}_0\int^{mf} dm_f = -\rho_q v_q/2\ {}_{fq}\int^{fc} df_c/f_c^2$

$m_f = \rho_q v_q/2\,(1/f_c - 1/f_q)$

$\therefore\ x_f = (v_g\,\rho_g/2\,\rho_f)(\tau_c - \tau_q)$



# Thin Film Growth Modes

Island

(Volmer-Weber)

Layer

(Frank-van der Merwe)

Stranski-Krastanov (epitaxy)

# Homogeneous Nucleation: Vapor Pressure

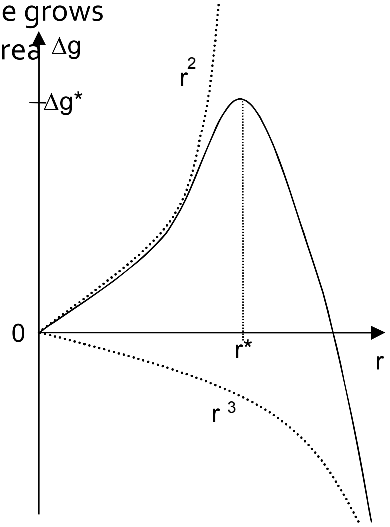
- Spontaneous nucleation in gas phase
  -no surface, dust, charge, etc.
  -undesirable in practice -> polycrystals
- If solid has vapor pressure $P_\infty$ & pressure of vapor above solid is P
  - if $P = P_\infty$ , vapor does not condense, solid does not evaporate
  - vapor condenses if $P > P_\infty$

# Homogeneous Nucleation: Gibbs Free Energy

- PV = (NR)T =(nk)T
  - -N = number moles, R = gas constant
  - -n = number molecules, k = Boltzmann constant
- When vapor condenses:
  - Energy change when P -> $P_\infty$ = $\int VdP$
  - $= nkT \int_P^{P_\infty} dP/P$
  - $= -nkT \ln P/P_\infty = \Delta G_v$
  - $\Delta G_v$ =Gibbs Free Energy of Formation
- As atoms add to nucleus,
  - nucleus grows with release of free energy
- Note: $\Delta G_v$ negative

# Homogeneous Nucleation: Critical Nucleus

- As nucleus grows, solid-vapor interface grows
  - ∴ increase in free energy σ/unit area
- Total increase in energy:
- $\Delta G_{homo} = (4/3)\pi r^3 \Delta Gv + (4\pi r^2)\sigma$
  - Max at $r^* = -2\sigma/\Delta G_v$
- $\Delta G^* = (16\pi/3)(\sigma^3/\Delta G_v^2)$



# Homogeneous Nucleation: Growth

For nucleus $r < r^*$, $\Delta G$ decreases by breaking up.

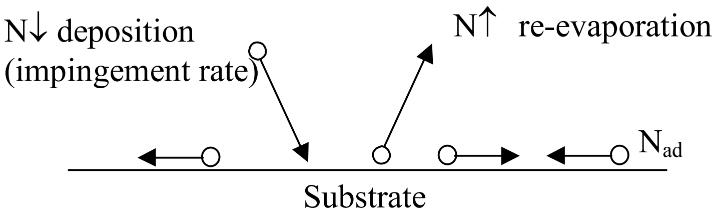
For nucleus $r > r^*$, $\Delta G$ decreases by growth.

If $P/P_\infty$ large, i.e. high supersaturation,
$|\Delta G_v|$ incr. --> $r^*$ decr.

Note:This is classical bulk thermodynamic approach. As $r^*$ -> $r_{atomic}$, cannot use bulk values of $\sigma$, surface concept, etc.

# Heterogeneous Nucleation

- Introduce substrate, dust, etc. into vapor
- Consider adatoms on substrate, $N_{ad}$/unit area



## Heterogeneous Nucleation: Residence Time

- Re-evaporation probability: $W = \nu \exp Q_{ad}/ kT$
  where $Q_{ad}$ = binding energy to substrate (negative)
- Re-evaporation rate $N\uparrow = N_{ad}\, \nu \exp (Q_{ad}/ kT)$
- Steady State: $N\uparrow = N\downarrow$ gives $N_{ad} = (N\downarrow/\nu) \exp(-Q_{ad}/kT)$
- Residence time $\tau = W^{-1} = \nu^{-1} \exp(Q_{des}/kT)$
  where $Q_{des}$ = desorption energy (positive)
  and $Q_{ad} = -Q_{des}$
  & $W$ = Re-evaporation probability
  $= \tau^{-1} = \nu \exp-(Q_{des}/ T)$

## Heterogeneous Nucleation: Adsorption Rate

Note: Assumes only adatom population with no further interaction. If $N\downarrow$ -->0 (deposition stopped),
$N_{ad}$ -->0, i.e. all eventually re-evaporate.

Adsorption Rate: $dN_{ad}/dt = N\downarrow - N\uparrow = N\downarrow - N_{ad} / \tau$

Solve: $dN_{ad} / (N\downarrow \tau - N_{ad}) = dt / \tau$ for $N_{ad} = 0$ at $t = 0$,

gives: $N_{ad}(t) = N\downarrow \tau (1\text{-}\exp\text{-}t/ \tau)$

--->$N\downarrow \tau$ for $\tau \ll t$

i.e. independent of time for weak physical adsorption.
(compare steady state result previous slide)

--->$N\downarrow t$ for $\tau \gg t$

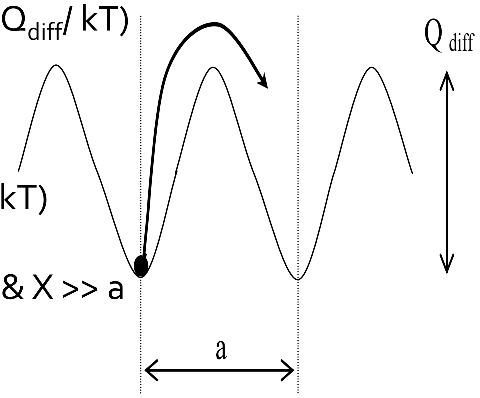
i.e. defines "complete condensation" for strong adsorption or initial transient.

## Heterogeneous Nucleation: Surface Diffusion

Surface diffusion of adatom --->moves X from pt. of impact $X = (2D\tau)^{1/2} = (2D)^{1/2}\,\nu^{-1/2}\ \exp(-Q_{ad}/2kT)$

where D = surface diffusivity

$= a^2\,\nu \exp - (Q_{diff}/kT)$



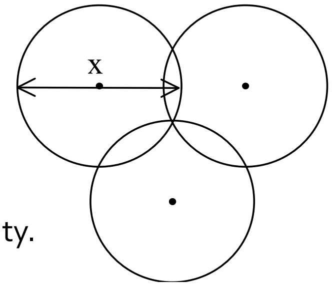
$X = 2^{1/2}\,a \exp -((Q_{diff} + Q_{ad})/2kT)$

$|Q_{ad}| > Q_{diff}$ always

$|Q_{ad}| - Q_{diff} >> kT$ typically & $X >> a$

## Heterogeneous Nucleation: Capture Distance

When adjacent nuclei separation < X, no further nuclei created - all atoms join existing nuclei.

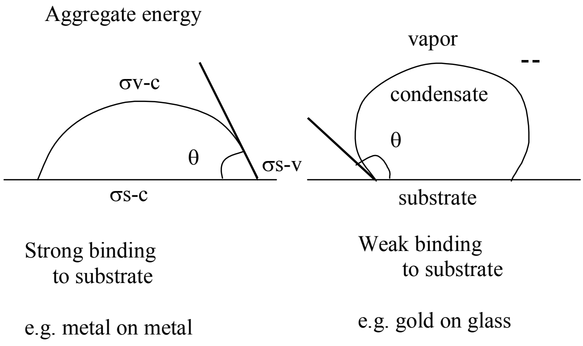


∴ Can find a saturation nucleation density.

# Capillary Model

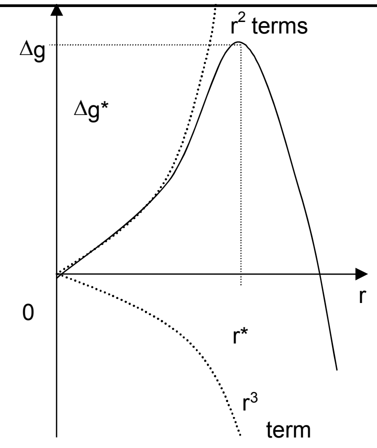
For island clusters with $|Q_{ad}|>> kT$ (cold substrate/metal on metal)

$N\uparrow$ small & $N_{ad}$ large
Interatomic collisions
>clustering.



$\Delta G= a_3 r^3 \Delta G_v + a_1 r^2 \sigma_{v\text{-}c} + a_2 r^2 \sigma_{s\text{-}c} - a_2 r^2 \sigma_{s\text{-}v}$
where $\Delta G_v$ = Free energy of condensation (negative)
$= (kT/V) \ln N\downarrow / N\uparrow$ (V= molecular volume)

# Critical Cap Size

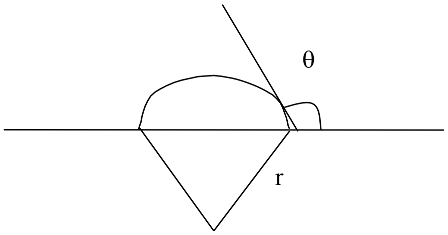


Differentiate ∂

$\Delta G/\partial r = 3a_3 r^2 \Delta G_v + 2a_1 r \sigma_{v\text{-}c} + 2a_2 r(\sigma_{s\text{-}c} - \sigma_{s\text{-}v})$
=>0 at r* = critical radius

gives $\Delta G^* = [4(a_1 \sigma_{v\text{-}c} + a_2 \sigma_{s\text{-}c} - a_2 \sigma_{s\text{-}v})]/(27 a_3^2 \Delta G_v^2)$
at $r^* = [-2(a_1 \sigma_{v\text{-}c} + a_2 \sigma_{s\text{-}c} - a_2 \sigma_{s\text{-}v})]/3a_3 \Delta G_v$

# Spherical Cap



Also: For spherical cap nucleus, contact angle θ
[θ determined by σ's, Δ $G_v$ for min tot Δ G
i.e. $\theta = f^{\underline{n}}(\sigma_{v-c}, \sigma_{s-c} - \sigma_{s-v}, \Delta G_v)$]
gives: $\Delta G^* = [(4\pi\, \sigma_{v-c}{}^3)/3\Delta G_v{}^2](2+\cos\theta)(1-\cos\theta)^2$
at $r^* = -2\, \sigma_{v-c} / \Delta G_v$
No. of monomers in critical cluster $i^* = (a_3 r^{*3}/V)$

# Data:Surface Energies

| | | | |
|---|---|---|---|
| Ag at | 1173k | σ c-v=1140 erg/cm² | $\partial\sigma_1/\partial T$ =-0.47 erg/cm²k |
| Au | 1276k | 1450 | =-0.43 |
| Cu | 1323k | 1550 | =-0.46 |
| Sn | 488k | 685 | |
| (from creep rates at melting point) | | | |
| Al | | 1157 | |
| Cd | | 743 | |
| Fe | | 1520 | |
| Pb | | 528 | |
| Mg | | 643 | |
| Zn | | 932 | |
| (from liquid surface tensions at melting point) | | | |
| glass | | 250-360 | |
| Polymers(non-polar) | | <100 | |
| Polymers(polar) | | <300 | |
| γ $Al_2O_3$ | | 560 | |
| CdO | | 500 | |
| CuO | | <760 | |
| MgO | | 1400 | |
| $Mg(Oh)_2$cryst | | 330 | |
| $Sn_2O_3$ | | 140 | |

**"Total" energy (all above are "free" energy).**

## Data:Adsorption Energy

| | | | $Q_{ad}$ | $Q_D$ |
|---|---|---|---|---|
| Na | on | W | -2.73eV | |
| Rb | | W | -2.60 | |
| Cs | | W | -2.80 | 0.61eV |
| Ba | | W | -3.80 | 0.65 |
| W | | W | -5.83 | 1.31 |
| Hg | | Ag | -0.11 | |
| Cd | | Ag | -1.61 | |
| Al | | NaCl | -0.60 | |
| Cu | | glass | -0.14 | |
| Hg | | Hg | | 0.048 |

## Capillary Example: #1

Ag on glass at 300k at 1A/sec.

$\sigma_{c\text{-}v}$=1140 - 0.47(300-1173) at 1173k (temp correction)

= 1550 ergs/cm$^2$

$\sigma_{s\text{-}c} = \sigma_{c\text{-}v} + \Delta G_{ad}$ <---- (-ve) Free energy of absorption

$Q_{ad} \sim 0.12\text{eV} \times 1.6\text{x}10^{-19}\text{J/eV} \times 10^7\text{ergs/J} / \pi(1.5\text{x}10^{-8}\text{cm})^2$

= 300 ergs/cm$^2$

i.e. $\sigma_{sc} \sim 1550\text{-}300 = 1250$ ergs/cm$^2$

$\sigma_{s\text{-}v} = 300$ ergs/cm$^2$ (250 to 360)

$\Delta G_v = -1.9 \times 10^{11}$ ergs/cm$^3$

## Capillary Example: #2

Ag on glass at 300k at 1A/sec. (continued)

$\Delta G_v = -1.9 \times 10^{11}$ ergs/cm$^3$

$N\uparrow$ ~$10^{-40}$ $\tau$ from vapor pressure data

& $N\downarrow \sim 10^{-6}$ $\tau$

from $p(\tau) = (MT)^{1/2}/[3.5 \times 10^{22} A]$ (dN/dt) / s.cm$^2$

Assuming hemispherical cap i.e. $\theta = 90°$ ,

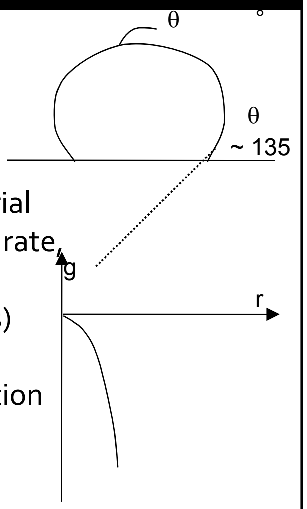
r* ~`0.22nm for Ag on glass

Similarly for W on glass, r* even less

r* ≤ atomic radius

Can't use macroscopic concepts like surfaces

## Spherical Cap:General Trends



a) Weak substrate binding, θ large
e.g. Au on glass

b) High supersaturation ratio
$N\downarrow / N\uparrow$ --> small r*
e.g. low v.p. material
(e.g. W, etc), cold substrate, high deposition rate, strong substrate adhesion
Continuity reached early (many small islands)

c) $\Delta G_v$ large, r* --> 0,
No nucleation barrier, monolayer formation
(or $\sigma_{s\text{-}v}$ high, so $\sigma_{c\text{-}v} + \sigma_{c\text{-}s} \sim \sigma_{s\text{-}v}$)

d) $(\partial r^*/\partial T)_{N\downarrow} > 0$
$(\partial r^*/\partial N\downarrow)_T < 0$
but large $\Delta N\downarrow$ required for significant $\Delta r^*$.

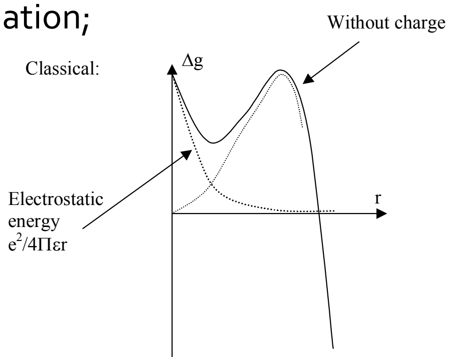
# Charge Effects on Nucleation

N.B. <u>NO</u> initial barrier to nucleation;
only barrier to growth.

<u>Experimental:</u>

Substrate positively charged:
- No effect
- (random nucleation at low deposition rates)

Substrate negatively charged:
- Nucleation density ≈ charge density

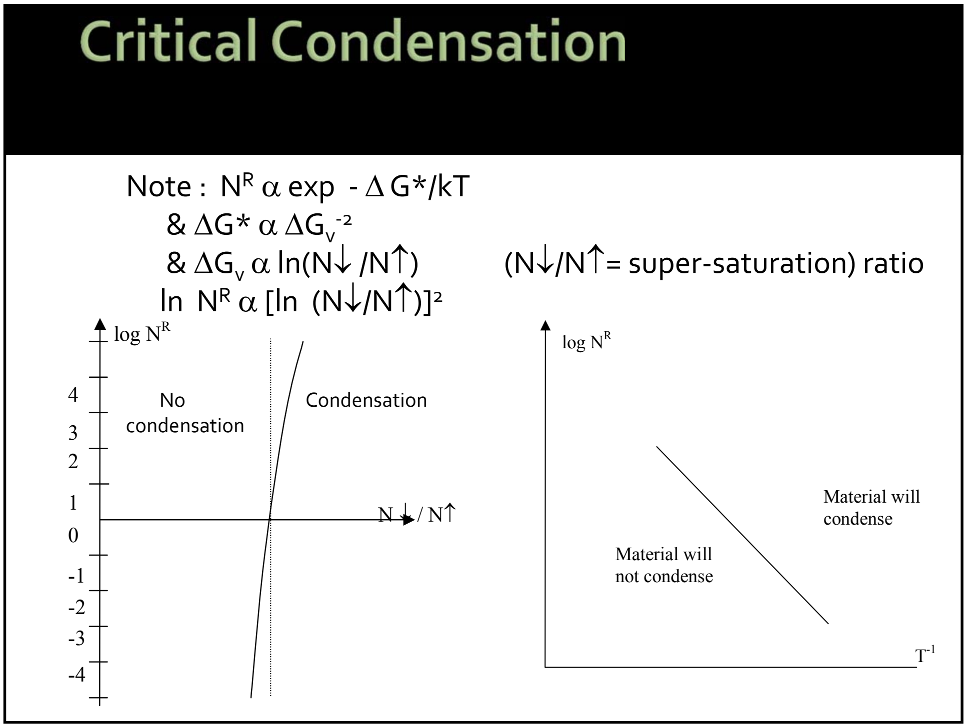


i.e. charge sites are nucleation (binding) sites.

# Nucleation Rate

Adatom residence time $\tau = \nu^{-1} \exp -Q_{des}/kT$
where $N\downarrow = N_A P/(2\pi MRT)$
$N_{ad} = N\downarrow \tau$
Nucleation rate $N^R = N^* A^* \omega$
where $N^* = n_s \exp - \Delta G^*/kT$
$n_s$ = nucleation site density
$A^* = 2\pi r^* a_o \sin\theta$
(area of circumferential belt of adjacent atoms)
Impingement rate onto area A*, $\omega = \tau N\downarrow D$, and
$N^R=2\pi r^* a_o \sin\theta \, PN_A/(2\pi MRT)^{1/2} n_s \exp(E_{des}-E_{diff}-\Delta G^*)/kT$
=Rate of creation super critical nucleus

## Critical Condensation



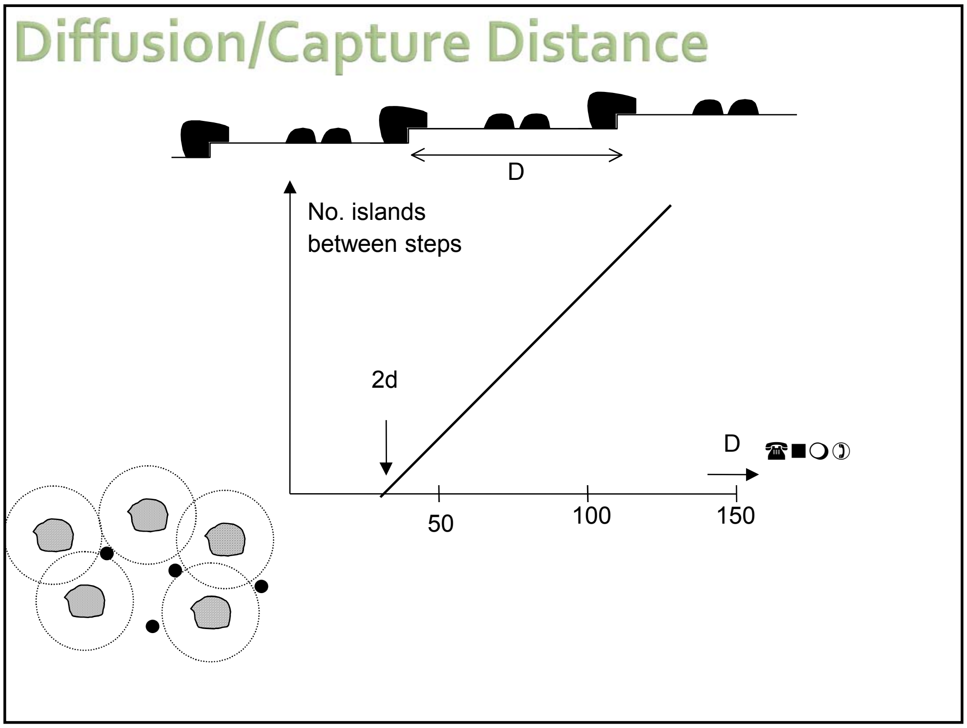
Note : $N^R \alpha \exp -\Delta G^*/kT$

& $\Delta G^* \alpha \Delta G_v^{-2}$

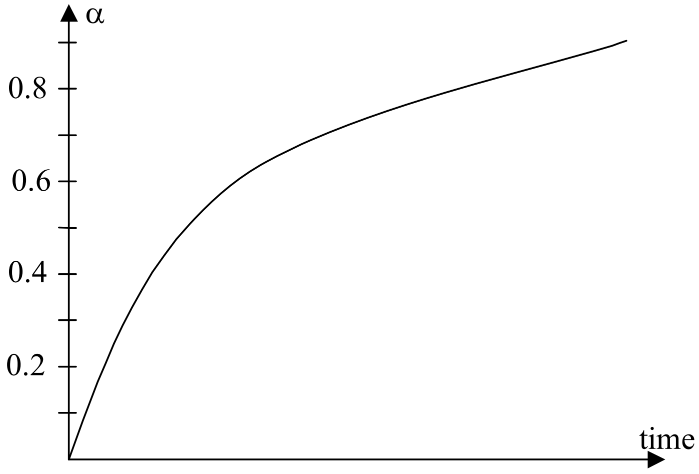
& $\Delta G_v \alpha \ln(N\downarrow/N\uparrow)$ (N↓/N↑= super-saturation) ratio

$\ln N^R \alpha [\ln (N\downarrow/N\uparrow)]^2$

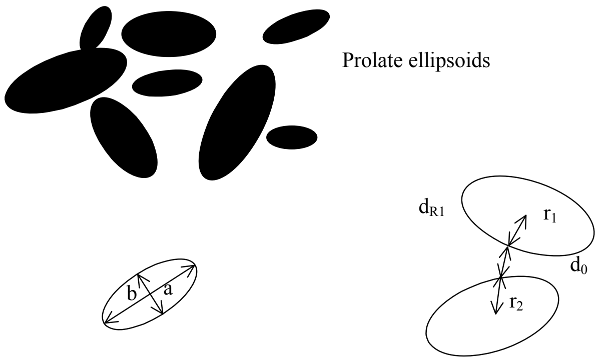
## Diffusion/Capture Distance



# Condensation Coefficient



# Island Shapes



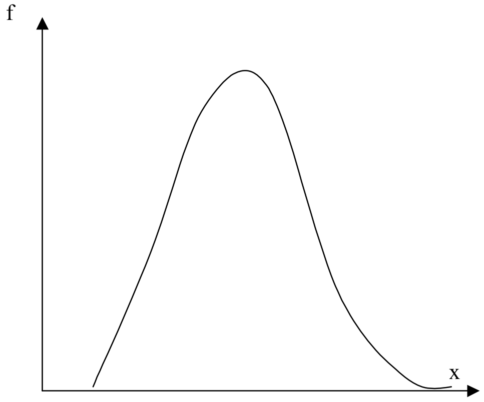
$e^2 = 1 - (b/a)^2$

$\underset{CTC}{R_1} = r_1 + r_2 + \underset{ETE}{d}$

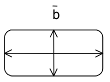
# Island Shape distributions

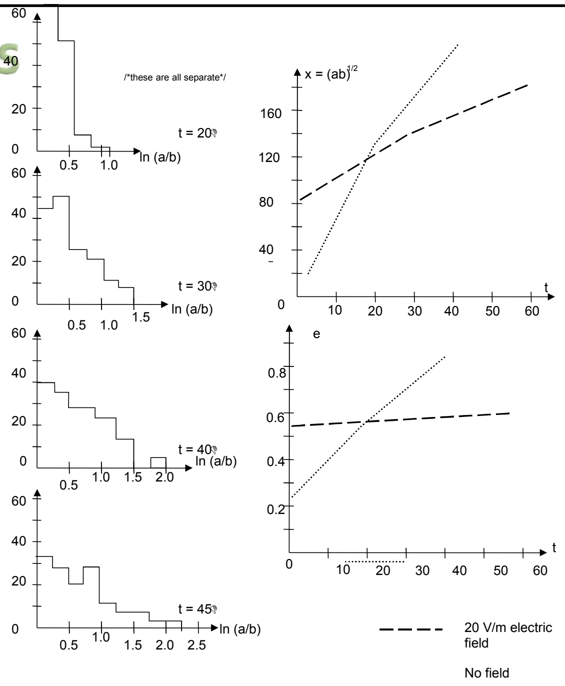
Log-normal:-

$f_{LN}(x)=((2\pi)^{1/2}\ln\sigma)^{-1}\exp-½[(\ln(x/x_m))/(\ln\sigma)]^2$

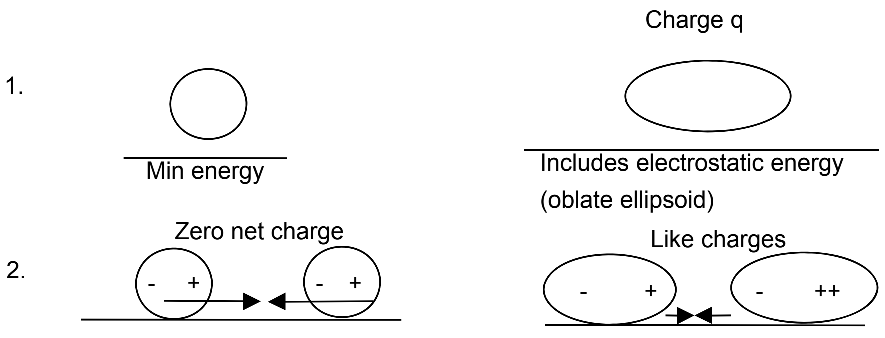


# Eccentricities

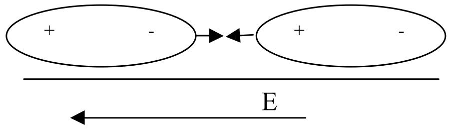




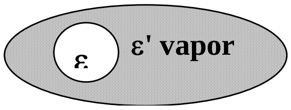
# Charge Effects



# Field Effects



1. Field enhanced coalescence



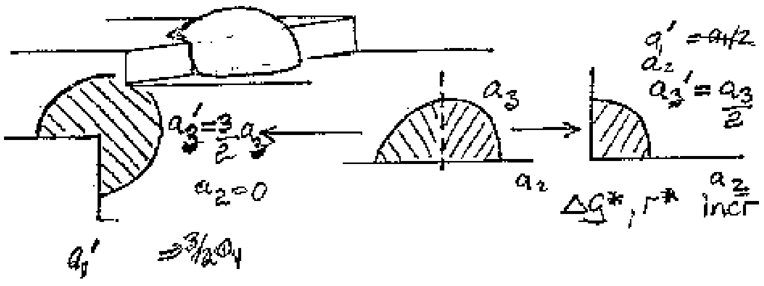
2.Nucleation

Field inhibited $\varepsilon > \varepsilon`$

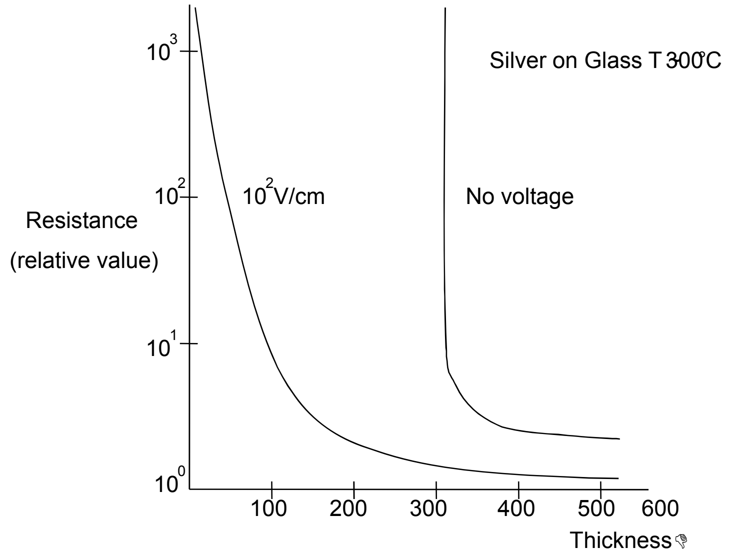
Field enhanced $\varepsilon < \varepsilon`$

$$\Delta = r^3E^2 [((\varepsilon` - \varepsilon)\, \varepsilon`)/(2\, \varepsilon` + \varepsilon)]$$

# Substrate Defects

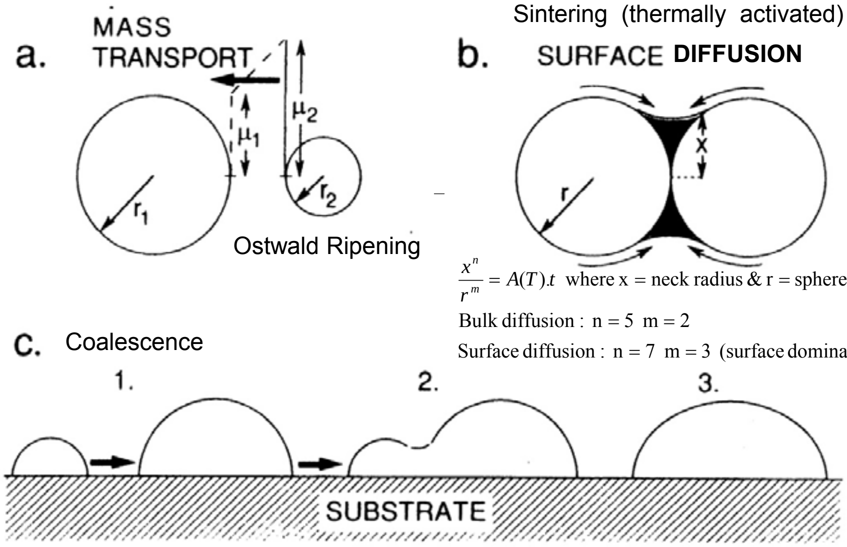


ΔG*, r* increase, but less atoms/critical nucleus



# Experimental Field Effect

# Coalescence (Ohring (2002))



Sintering (thermally activated)

DIFFUSION

Ostwald Ripening

Coalescence

$$\frac{x^n}{r^m} = A(T).t \text{ where x = neck radius \& r = sphere radius}$$

Bulk diffusion : n = 5 m = 2

Surface diffusion : n = 7 m = 3 (surface dominant)

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Sputter Deposition

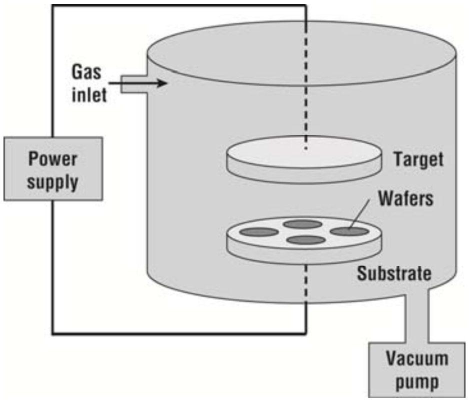
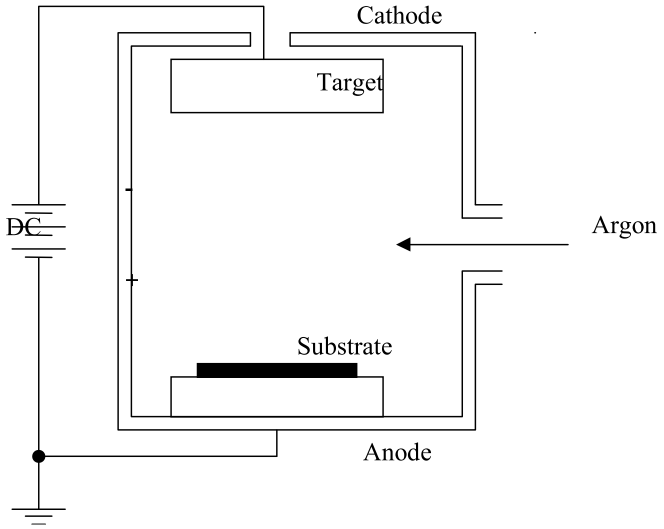
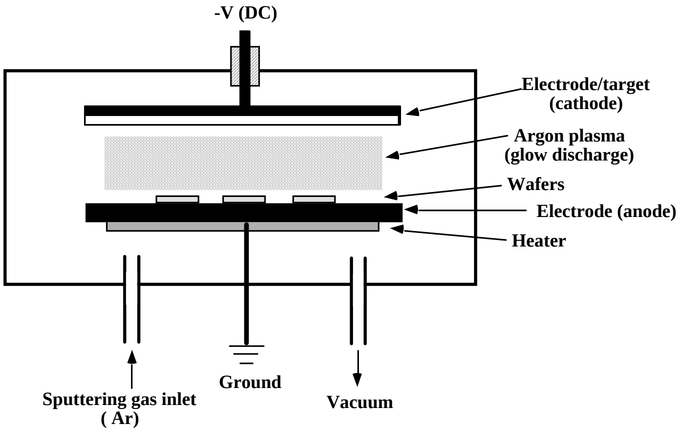


**Figure 12.12** Chamber for a simple parallel-plate sputtering system.

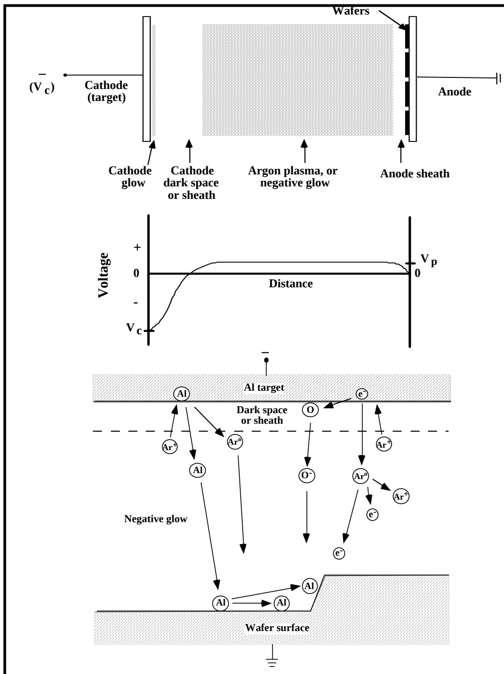
# DC Sputter Deposition



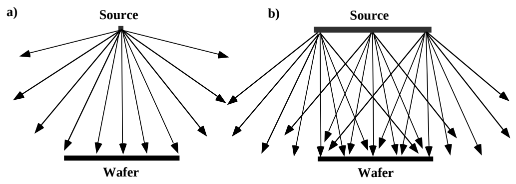
## DC Sputter Deposition



- Uses plasma to sputter target, dislodging atoms which then deposit on wafers to form film.
- Higher pressures than evaporation - 1-100 mtorr.
- Better at depositing alloys and compounds than evaporation.
- The plasma contains ≈ equal numbers of positive argon ions and electrons as well as neutral argon atoms.



- Most of voltage drop of the system (due to applied DC voltage, $V_c$) occurs over cathode sheath.
- $Ar^+$ ions are accelerated across cathode sheath to the negatively charged cathode, striking that electrode (the "target") and sputtering off atoms (e.g. Al). These travel through plasma and deposit on wafers sitting on anode.
- Rate of sputtering depends on the sputtering yield, Y, defined as the number of atoms or molecules ejected from the target per incident ion.
- Y is a function of the energy and mass of ions, and the target material. It is also a function of incident angle.



$$mfp\ \lambda = kT/\sqrt{2}\pi d^2 P$$

$$\text{where } k = 1.36x10^{-22}\,cc.atmos/K$$

$$d = collision\ \ c/s \text{ in cm} \sim 4x10^{-8}cm$$

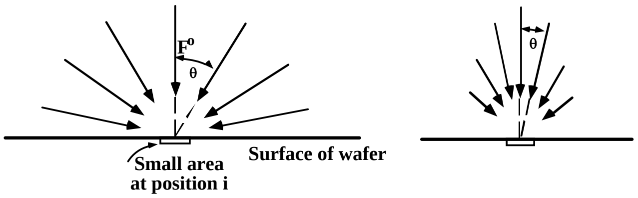
$$P = pressure\,(atmos)$$

$$P \sim 5mtorr \rightarrow mfp\ \lambda \sim 1cm$$

- Sputtering targets are generally large and provide a wide range of arrival angles in contrast to a point source.

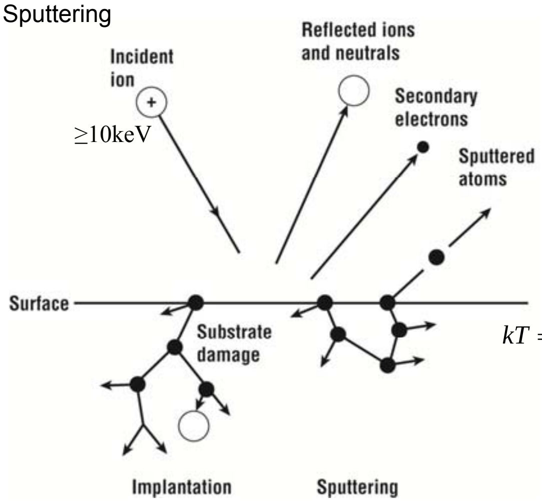
**a)** Isotropic flux arrival
n = 1 in $\cos^n\theta$ arrival angle distribution

**b)** Anisotropic flux arrival
n > 1 in $\cos^n\theta$ arrival angle distribution



- Arrival angle distribution generally described by a $\cos^n\theta$ distribution (the normal component of flux striking the surface determines the deposition or growth rate).
- Size and type of source, system geometry and collisions in gas phase important in arrival angle distribution.

Sputtering



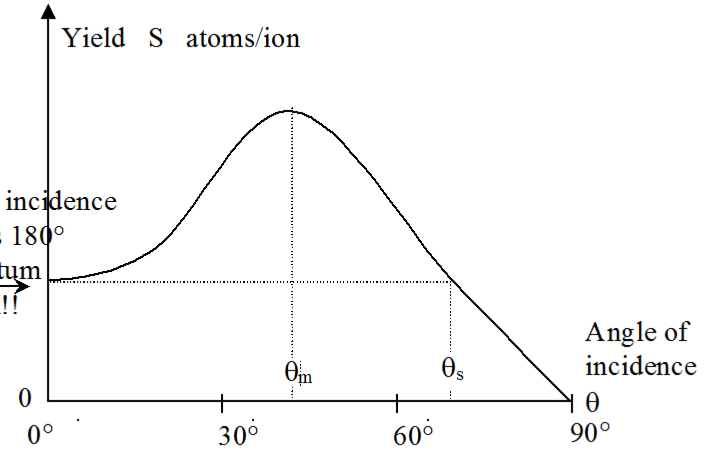
10-50eV
(High surface mobility for step coverage)
Compare evaporation :
kT~ 0.1-0.2eV

$$kT = \frac{1.38x10^{-23} J/K}{1.6x10^{-19} J/eV}(1500-2000K)eV$$

**Figure 12.13** Possible outcomes for an ion incident on the surface of a wafer.

Breakdown voltage to initiate plasma: $V_{bd}$ α P.L/(log P.L + b)
P pressure, L electrode separation, b constant (Paschen's Law)
Ar, $O_2$, $N_2$: 1st ionization potentials 13-16 eV

## Sputtering Yield:Geometry



Normal incidence requires 180° momentum reversal!!

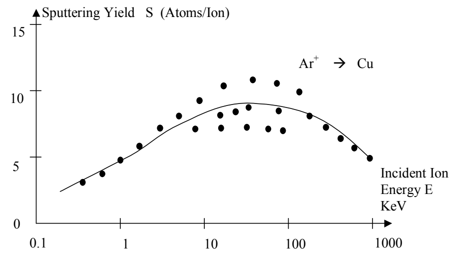
## Sputtering Yield: Energy

**E< 1 keV : $S = 3\alpha/4\pi^2 * 4m_i m_t/(m_i + m_t)^2 * E/U_o$**

$U_o$ Surface binding energy of target

**$\alpha = f(m_t/m_i)$ $\mapsto$ 0.17, $m_t = m_i/10$**

**$\mapsto$ 1.40, $m_t = 10m_i$**

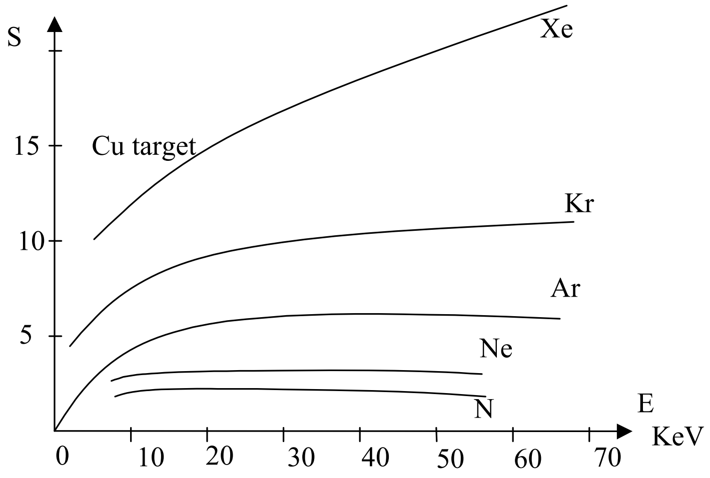


**E>1 keV:**

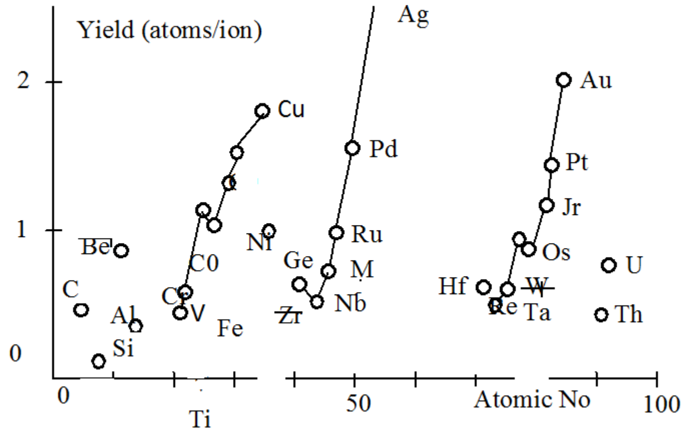
**$S = 3.56\alpha[Z_1 Z_t/(Z_1^{2/3} + Z_t^{2/3})][m_i/(m_i + m_t)]S_n(E)/U_o$**

where $S_n(E)$ is reduced stopping power

## Sputtering Yield: Gas



# Sputtering Yield:Target



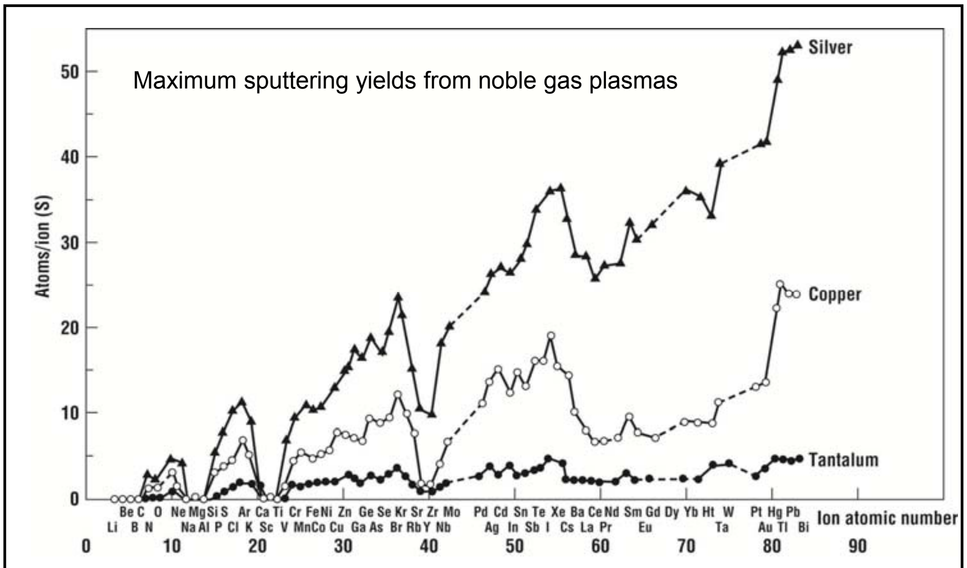
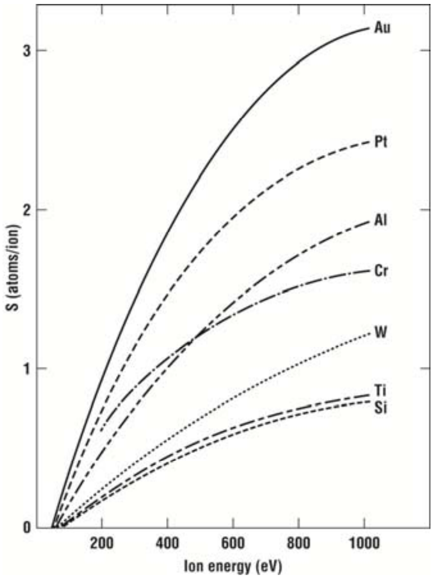


**Figure 12.15** Sputter yield as a function of the bombarding ion atomic number for 45-keV ions incident on silver, copper, and tantalum targets *(after Wehner, reprinted by permission, AIP).*



Ion flux at target ~ $J_{ion} \alpha m_{ion}^{-1/2}V^{3/2}/d^2$
(Langmuir-Child Law)
d = dark space width

Note threshold ~10-30eV
(different materials)

**Figure 12.14** Sputter yields as a function of ion energy for normal incidence argon ions for a variety of materials *(after Anderson and Bay, reprinted by permission).*

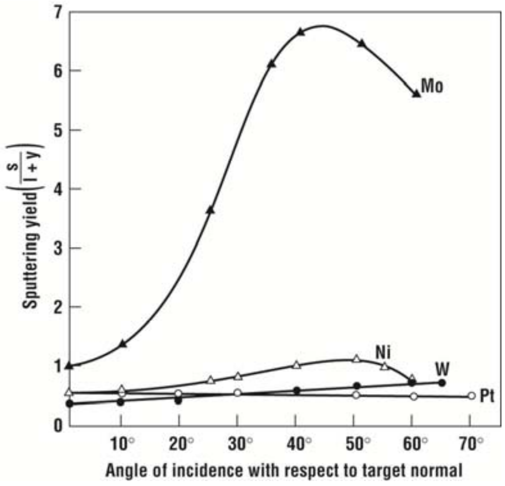
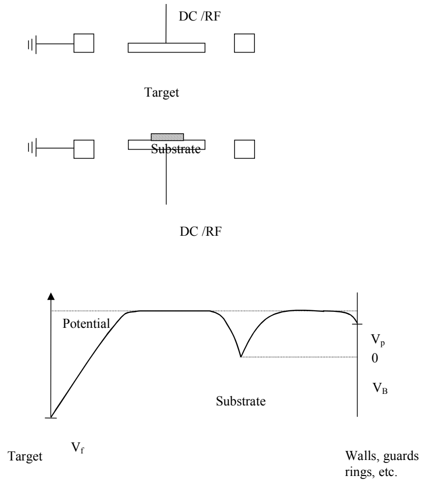


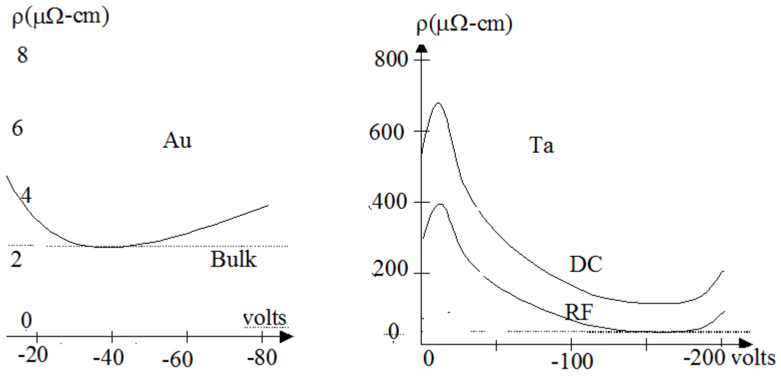
**Figure 12.16** Typical angular dependence of the sputter yield for several different materials. The sputter profiles follow a cosine distribution *(after Wehner, reprinted by permission, AIP)*.

$$\text{At high energies E, } S \propto \frac{M_{gas}}{M_{target}}\frac{\ln(E)}{E}\frac{1}{\cos\theta}$$

# Substrate Bias

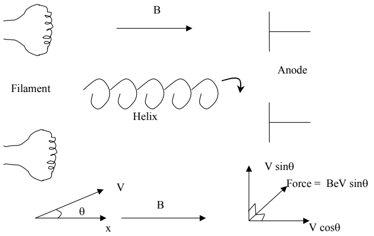


# Effect of Substrate Bias



# Magnetic Confinement

Uses axial field



$m_e(V\sin\theta)^2 / r = BeV\sin\theta \mapsto r = m_e V\sin\theta / Be$

Negligible effect on ions

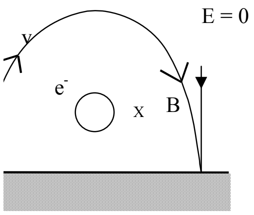
Confine electrons to minimize loss to walls, etc.

Results in increased ionization efficiency ($n_i = n_e$)

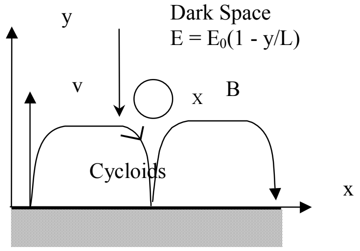
Increases ion current/sputtering rate

Can lead to non-uniform erosion

# Magnetron



Secondary electrons returned to target

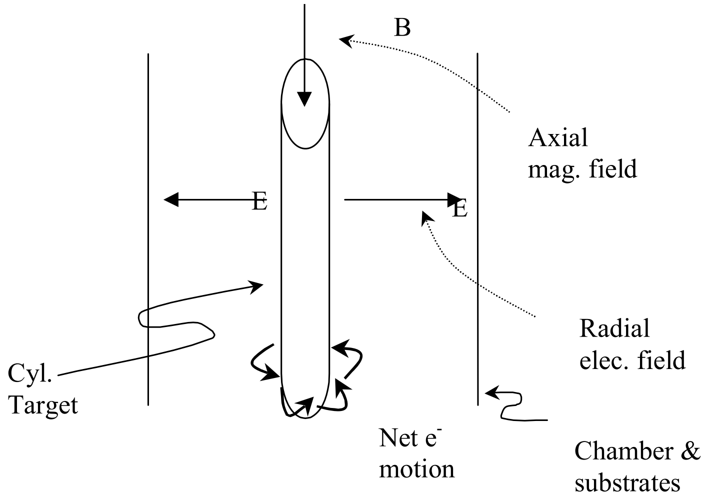


Max excursion from target

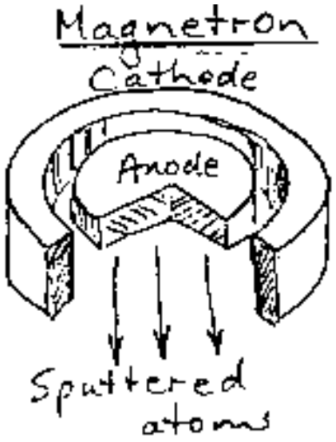
$Y_{max}=\sqrt{(2m/e)}(v-v_T)/B$

at $Y_{max}$↑ ↑at target

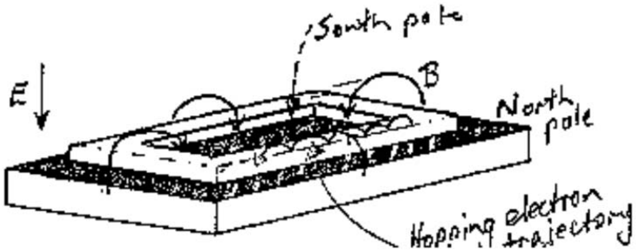
# Cylindrical Magnetron



# Circular Magnetron



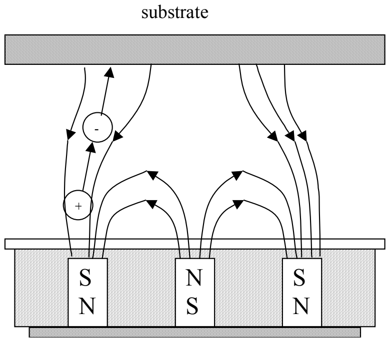
# Planar Magnetron



Magnetically confined plasma defines area of erosion

# Unbalanced Magnetron

Central magnet weakened
↦field lines to substrate
Electrons channeled to substrate
↦ions by ambipolar diffusion



(High density) Magnetron sputtering

r = mv/qB

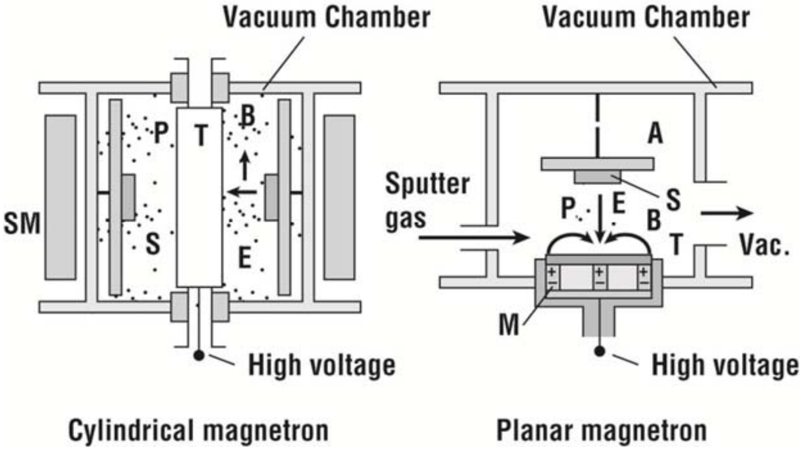
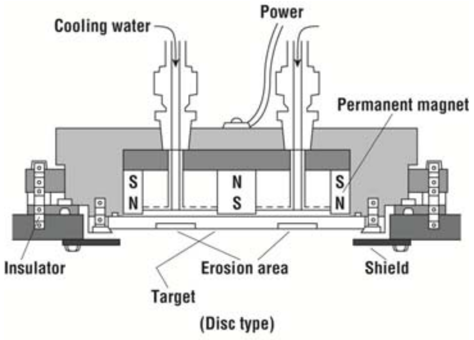


**Figure 12.17** Planar and cylindrical magnetron sputtering systems T: target; P: plasma; SM: solenoid; M: magnet; E: electric field; B: magnetic field *(after Wasa and Hayakawa, reprinted by permission, Noyes Publications).*



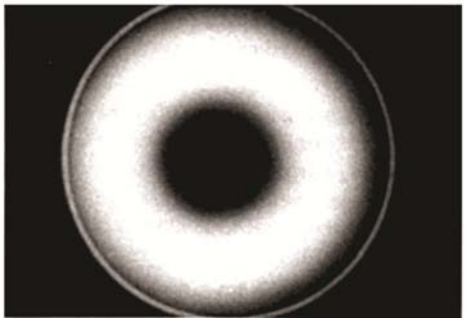


**Figure 12.18** Detailed cross section of a rectangular planar magnetron target using permanent magnets to supply the field *(after Wasa and Hayakawa, reprinted by permission, Noyes Publications).*

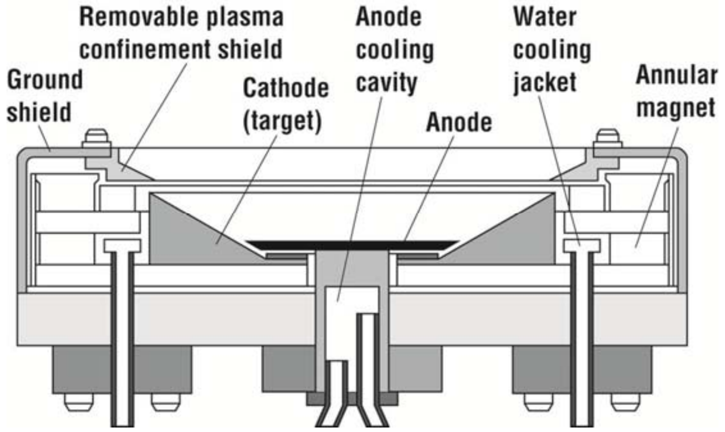


**Figure 12.19** Cross-sectional diagram of an S-Gun® sputtering source *(courtesy Varian Associates).*

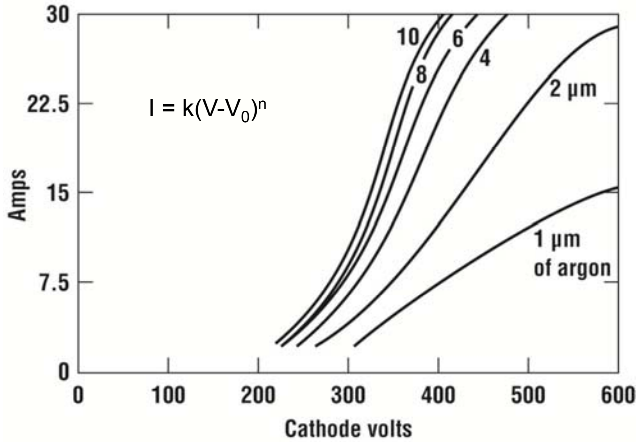
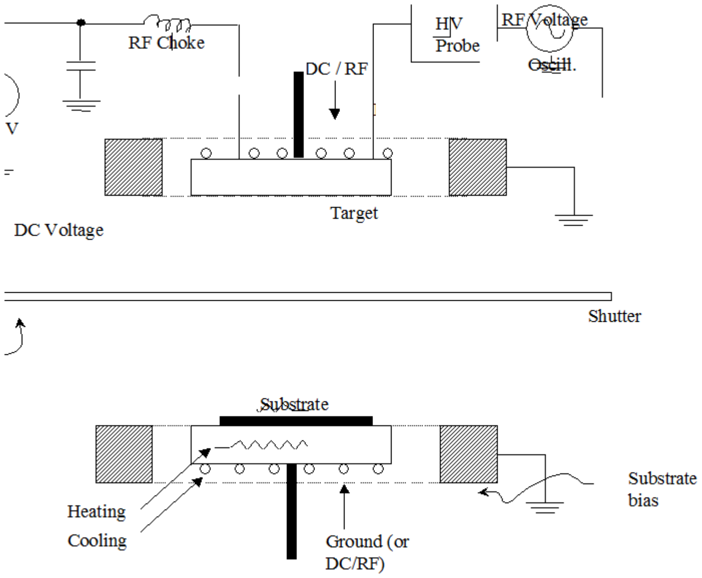


**Figure 12.20** Current–voltage characteristics of a magnetron system with chamber pressure as a parameter. The lines are for 1, 2, 4, 6, 8, and 10 μm of Ar *(after Van Vorous, reprinted by permission, Solid State Technology).*

# RF Sputter Deposition



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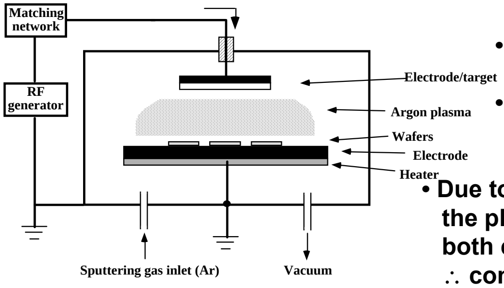
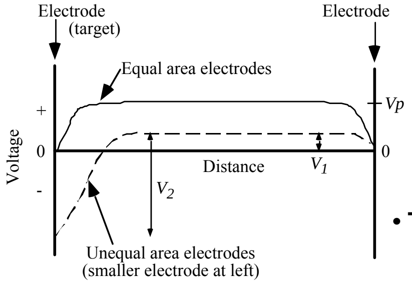
## RF Sputter Deposition



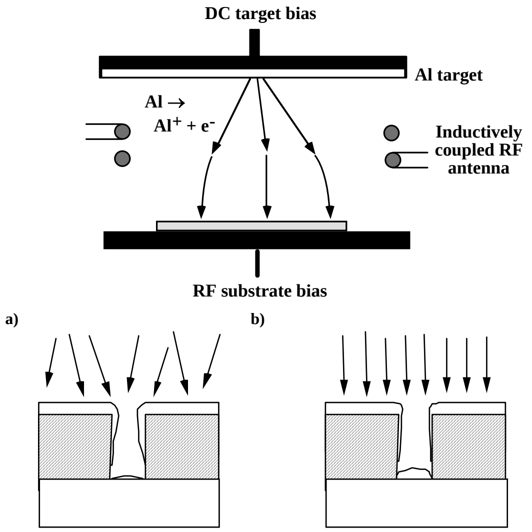


- **For DC sputtering, target electrode is conducting.**
- **To sputter dielectric materials use RF power source.**
- **Due to slower mobility of ions vs. electrons, the plasma biases positively with respect to both electrodes. (DC current = zero.) ∴ continuous sputtering.**
- **When the electrode areas are not equal, the field must be higher at the smaller electrode (higher current density), to maintain overall current continuity**

$$\frac{V_1}{V_2} = \left(\frac{A_2}{A_1}\right)^m \quad \text{(m = 1-2 experimentally) (13)}$$

- **Thus by making the target electrode smaller, sputtering occurs "only" on the target. Wafer electrode can also be connected to chamber walls, further increasing $V_2/V_1$.**

## Ionized Sputter Deposition or HDP Sputtering



- In some systems the depositing atoms themselves are ionized. An RF coil around the plasma induces collisions in the plasma creating the ions.

- This provides a narrow distribution of arrival angles which may be useful when filling or coating the bottom of deep contact hole.

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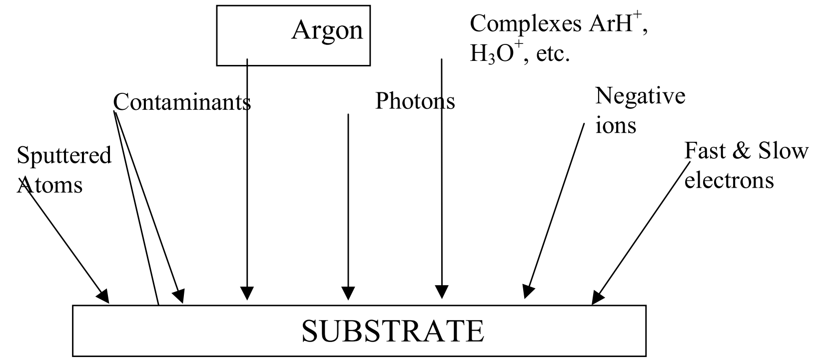
## Sputtering Contamination #1



Argon

Complexes $ArH^+$, $H_3O^+$, etc.

Contaminants

Photons

Negative ions

Sputtered Atoms

Fast & Slow electrons

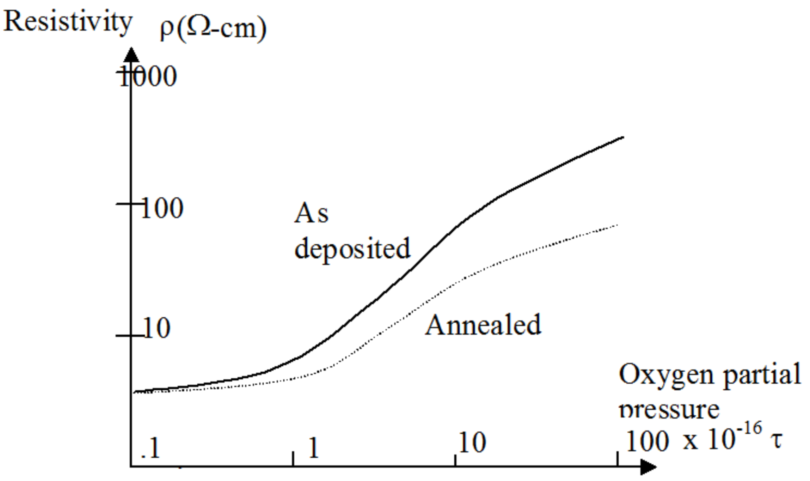
SUBSTRATE

Argon:

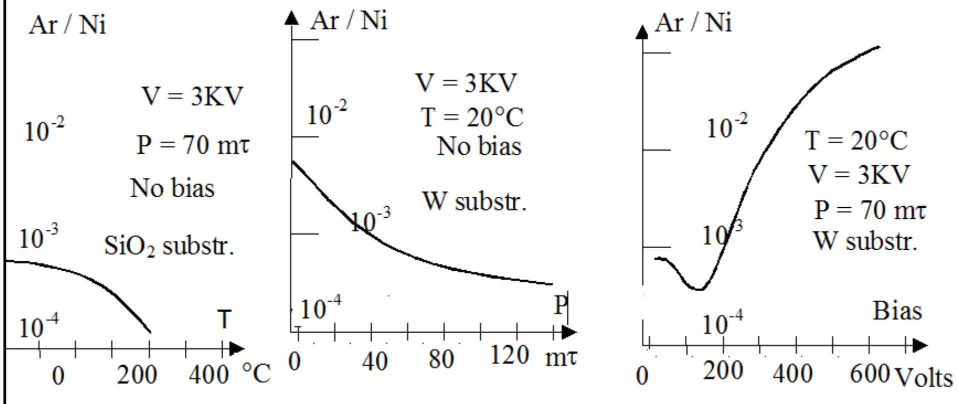
Thermal neutrals
Metastables
$Ar^{2+}$ / $Ar^+$ / $Ar_2^+$
etc.

Fast (target)
Fast (charge-exchange)

# Sputtering Contamination #2



# Sputtering Contamination #3



Morphology

1. Low T, low E, high P → amorphous
   T: Decr P, incr T → small grains (often optimum for thin film purpose)
2. Incr T &/or E → grain incr (tall narrow grains)
3. Incr T &/or E → large 3D grains (single crystal, epitaxy?)
   Note: 2 & 3 → rough surfaces

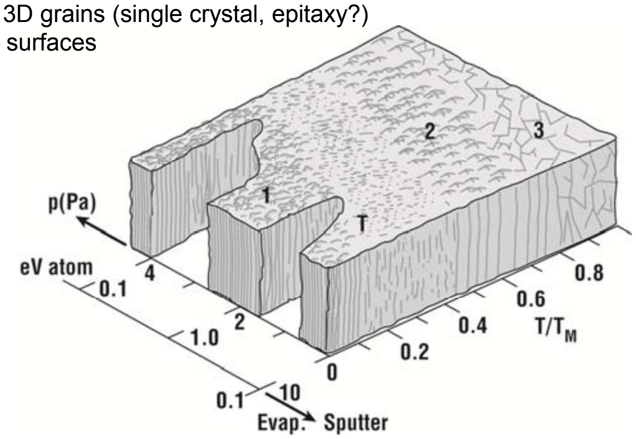
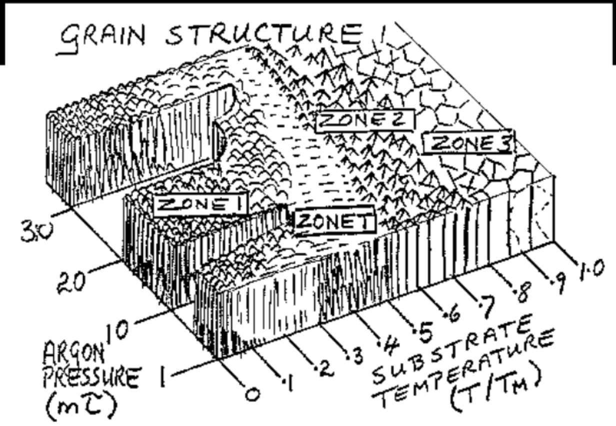


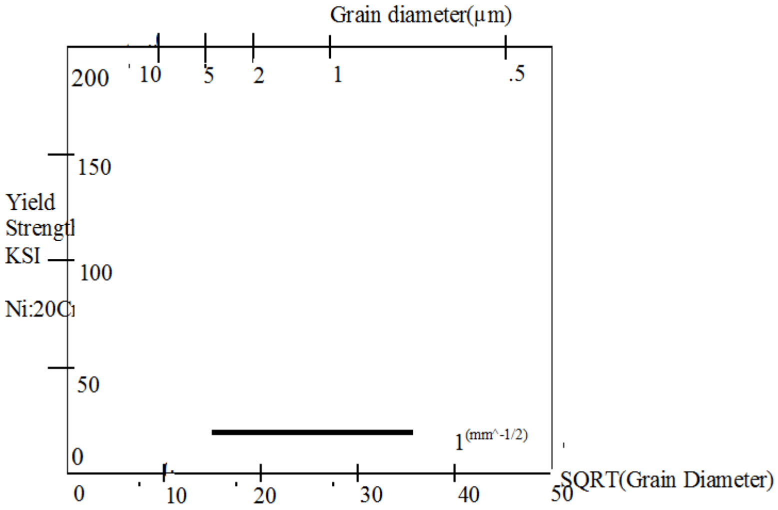
**Figure 12.21** The three-zone model of film deposition as proposed by Movchan and Demchishin *(after Thornton, reprinted by permission, AIP)*.

## Grain Structure



Zone 1: Porous structure, tapered crystallites sep'd by voids
Zone 2:Columnar grains; Zone 3:Recrystallized grain structure
Zone T:Transition structure:-Densely packed fibrous grains

# Grain Size Significance



## Step coverage

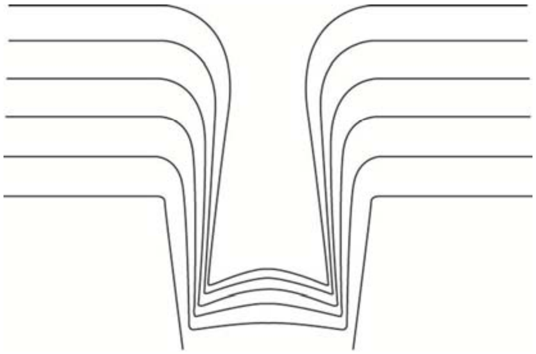
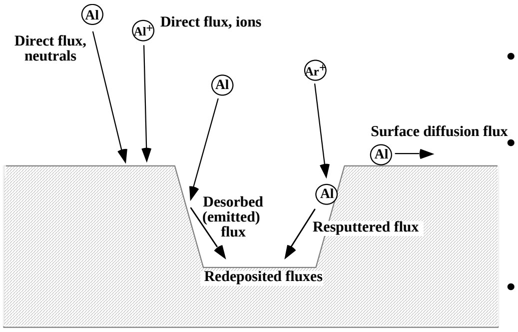


**Figure 12.22** Cross section of the time evolution of the typical step coverage for unheated sputter deposition in a high aspect ratio contact.

## Models and Simulation



- Within the past decade, a number of simulation tools have been developed for topography simulation.
- Generalized picture of fluxes involved in deposition. (No gas phase boundary layer is included, so this picture doesn't fully model APCVD.)
- Essentially the same picture can be used for etching simulation

$$F^{i}_{net} = F^{i}_{direct\,(neutrals)} + F^{i}_{direct\,(ions)} + F^{i}_{redep} + F^{i}_{diff.in} - F^{i}_{emitted} - F^{i}_{sputtered} - F^{i}_{diff.out} \qquad (14)$$

- To simulate these processes, we need mathematical descriptions of the various fluxes.
- Modeling specific systems involves figuring out which of these fluxes needs to be included.

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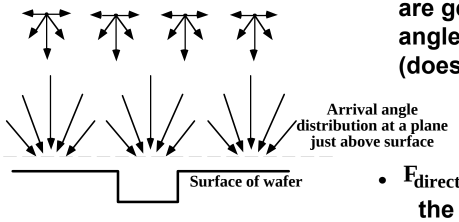
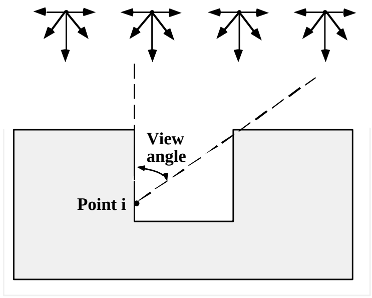


- Direct fluxes ( $F^{i}_{direct\,(neutrals)} + F^{i}_{direct\,(ions)}$ ) are generally modeled with an arrival angle distribution just above the wafer (doesn't model equipment).

$$F_{direct}(\theta) = F^{o} \cos^{n}\theta \qquad (15)$$

- $F_{direct}(\theta)$ is the normal component of the incoming flux (which is what is needed in determining the growth rate).
  - Higher pressure systems ⇒ more gas phase collisions, shorter mean free path ⇒ n = 1 (isotropic arrival).
  - Lower pressure systems ⇒ fewer gas phase collisions, longer mean free path ⇒ n > 1 (anisotropic arrival).
  - Ionic species in biased systems ⇒ directed arrival ⇒ n > 1 (anisotropic arrival).
- Once the direct fluxes are known, surface topography must be considered.
- Surface orientation, viewing angle and shadowing are important. Gas phase collisions are neglected near the wafer surface.

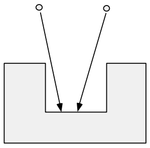


- The indirect fluxes are associated with processes on the wafer surface.
- Surface diffusion is driven by the local curvature of the surface (to minimize the surface free energy) and is given by

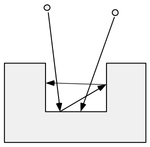
$$F_{diff.in} - F_{diff.out} = F_{diff.net} = \frac{D_s}{kT}\gamma_s \Omega \upsilon \frac{\partial^2 K}{\partial s^2} \qquad (16)$$

where $D_S$ is the surface diffusivity, $\gamma_s$ is the surface energy, K is the curvature and $\Omega$ and $\upsilon$ are constants.

- Surface diffusion helps to fill in holes, and produces more planar depositions because molecules can diffuse to "smooth out" the topography.



High ($S_c = 1$)



Low ($S_c < 1$)

- $F^i_{emitted}$ arises because not all molecules "stick" when they arrive at the surface.

$$F^i_{emitted} = (1 - S_c)F^i_{incident} \qquad (17)$$

where $S_C$ is the sticking coefficient.

$$S_c = \frac{F_{reacted}}{F_{incident}} \qquad (18)$$

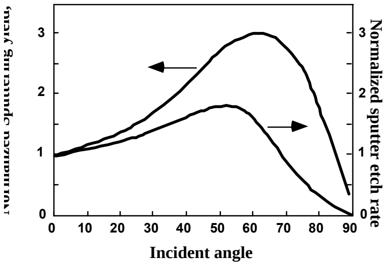
- Generally ions are assumed to stick ($S_C = 1$), neutrals have $S_C < 1$ and are assumed to be emitted with a $\cos\theta$ angle distribution (no memory of arrival angle).

---

- $F^i_{redep\,(emitted)}$ arises because the emitted flux $F^i_{emitted}$ can land elsewhere on the surface. Thus

$$F^{ik}_{redep\,(emitted)} = g^{ik} * F^k_{emitted} = g^{ik} * (1 - S_c) * F^k \qquad (19)$$

- The redeposited flux at point i due to an emitted flux at point k can then be summed over all i and k. $g^{ik}$ accounts for the geometry between i and k.
- Thus a low $S_C < 1$ can produce more conformal coverage because of emission/redeposition (usually more important than surface diffusion in CVD).



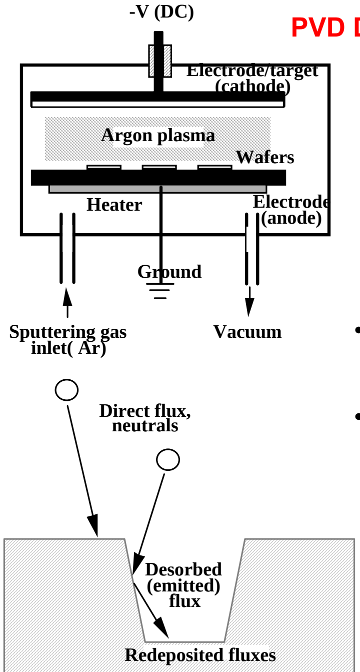
- The sputtered flux is caused primarily by energetic incoming ions.

$$F^i_{sputtered} = Y * \left(F^i_{argon} + F^i_{direct\,(ions)}\right) = Y * F^i_{ions}$$

where Y is the sputtering yield. (20)

- Y is angle sensitive which can be used to achieve more planar surfaces during deposition (example later).
- The sputtered molecules can be redeposited. This is modeled as in Eqn. (19), i.e.

$$F^{ik}_{redep\,(sput)} = g^{ik} * F^k_{sputtered} = g^{ik} * Y * F^k_{ions} \qquad (21)$$



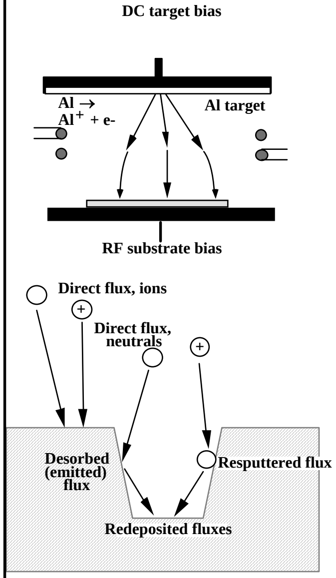
## PVD Deposition Systems

- Standard PVD systems might include DC and RF sputtering systems and evaporation systems.
- Ions generally do not play a significant role in these systems, so modeling is similar to LPCVD systems.

Thus
$$\text{rate} = \frac{S_c F_d}{N} \qquad (26)$$

- The values for $S_c$ and  would be different for LPCVD and PVD systems however.
- Sometimes these systems are operated at high temperatures, so a surface diffusion term must be added.

$$\text{rate} = \frac{S_c F_d + \frac{D_s}{kT}\gamma_s \Omega \upsilon \frac{\partial^2 K}{\partial s^2}}{N} \qquad (27)$$



## Ionized PVD Deposition Systems

- These systems are complex to model because both ions and neutrals play a role.
- They are often used for metal deposition so that $Ar^+$ ions in addition to $Al^+$ or $Ti^+$ ions may be present.
- Thus almost all the possible terms are included

| | |
|---|---|
| $F^i_{\text{direct (neutrals)}}$ | Yes |
| $F^i_{\text{direct (ions)}}$ | Yes |
| $F^i_{\text{diff (net)}} = F^i_{\text{diff (in)}} - F^i_{\text{diff (out)}}$ | No |
| $F^i_{\text{emitted}}$ | Yes |
| $F^i_{\text{redep (emitted)}}$ | Yes |
| $F^i_{\text{sputtered}}$ | Yes |
| $F^i_{\text{redep (sputtered)}}$ | Yes |
| $F^i_{\text{ion - induced}}$ | Yes |

$$\text{rate} = \frac{(S_c F_d) + F_i - (K_{sp} Y F_i) + (K_{rd} F_{rd})}{N}$$

where $F_d$ includes the direct and redeposited (emitted) neutral fluxes, $F_i$ includes the direct and ion-induced fluxes associated with the ions, and $F_{rd}$ models redeposition due to sputtering.

Wafer heating

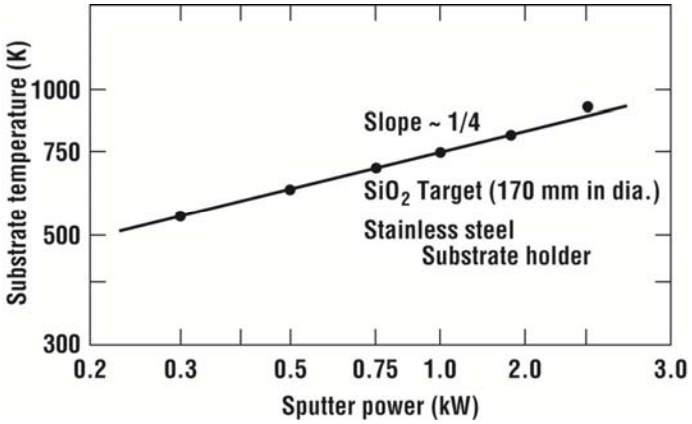


**Figure 12.23** The temperature rise of substrates as a function of the plasma power for an argon RF plasma with an $SiO_2$ target *(after Wasa and Hayakawa, reprinted by permission, Noyes Publications).*

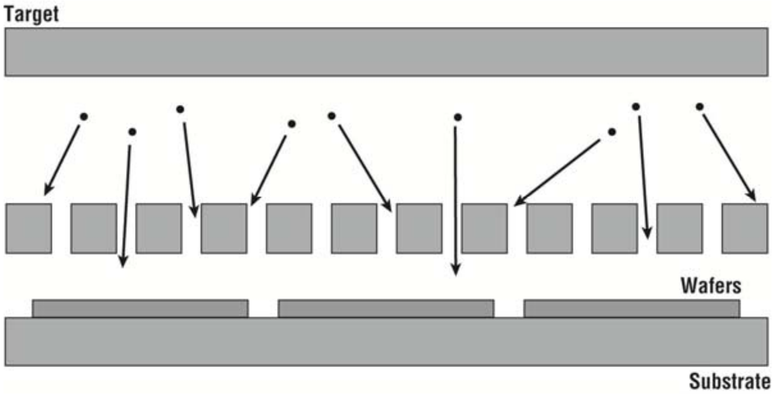


**Figure 12.24** In collimated sputtering a disposable collimator is placed close to the wafers to increase directionality.

Ions ~ perpendicular to surface

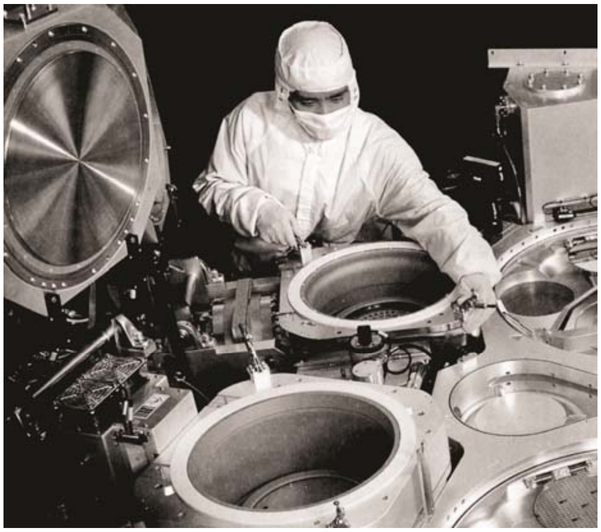


**Figure 12.25** The Endura system by Applied Materials uses a number of PVD or CVD chambers fed by a central robot. For conventional and IMP (ionized metal plasma) sputtering, targets are hinged to open upward. Two open chambers are shown, along with the load lock *(from Applied Materials).*

(Negative) Bias sputtering

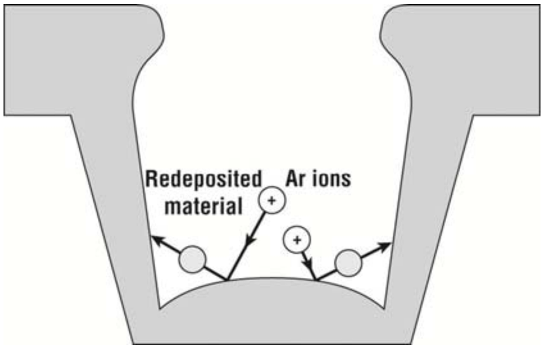


**Figure 12.26** In bias sputtering, the ions incident on the surface of the wafer redistribute the deposited film to improve step coverage.

Ion Plating

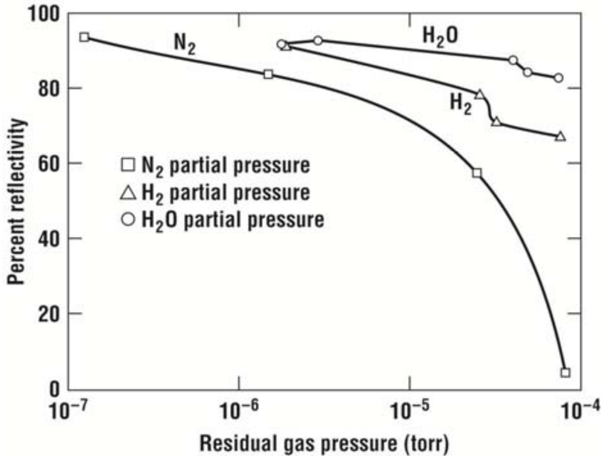


**Figure 12.27** Reflectance of Al–Si layers at 400 nm as a function of the partial pressures of $N_2$,$H_2$, and $H_2O$ *(after McLeod and Hartsough, reprinted by permission, AIP).*

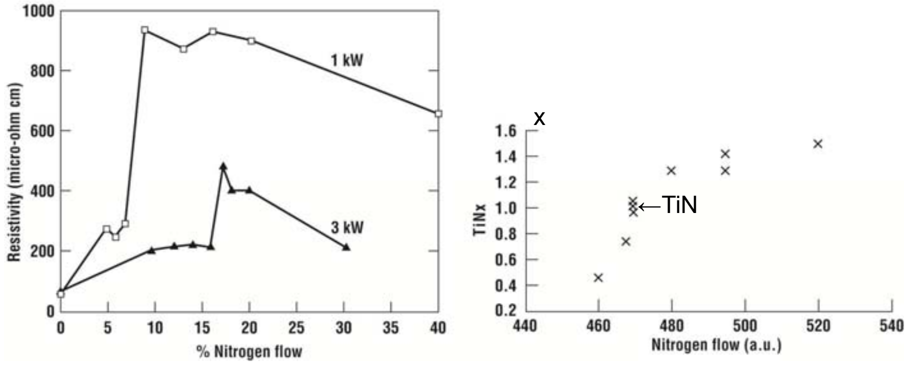
$$R \propto e^{-4\pi\sigma/\lambda^2}$$

$\lambda =$ light wavelength

$\sigma =$ rms surface roughness

---

TiN: Low resistance diffusion barrier for ohmic contacts
(also very hard)



x

←TiN

↑ max conductivity

**Figure 12.28** Resistivity and composition of reactively sputtered TiN as a function of the $N_2$ flow in the sputtering chamber *(after Tsai, Fair, and Hodul, reprinted by permission, The Electrochemical Society, and Molarius and Orpana, reprinted by permission, Kluwer Academic Publishing).*

High aspect ratio step coverage

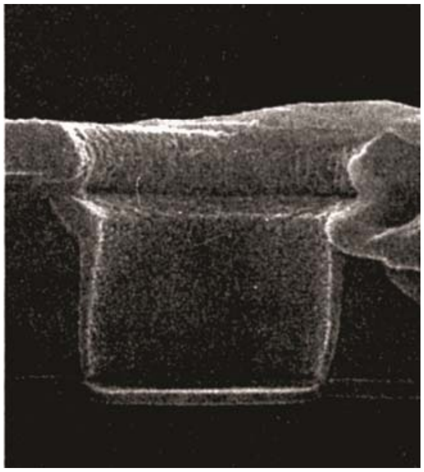


**Figure 12.29** Cross section electron micrograph of a moderately high aspect ratio contact that has been sputter-deposited with TiN *(after Kohlhase, Mändl, and Pamler, reprinted by permission, AIP).*

Thin film stress

Thermal stress (thermomechanical stress) due to deposition at $T>T_{amb}$

$$\sigma_{th} = \frac{E_{film}}{1-\nu_{film}} \int_{T_0}^{T_{dep}} \left(\alpha_{film} - \alpha_{sub}\right) dT, \text{ where E = Young's modulus, } \nu = \text{Poisson's ratio}$$

$$\sigma = \frac{\delta}{t} \cdot \frac{E}{1-\nu} \cdot \frac{T^2}{3R^2}$$

T = wafer thickness

t = film thickness

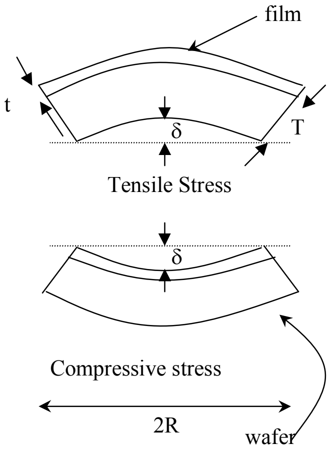
R = wafer radius

**Figure 12.30** The change in wafer deflection may be used to measure the stress in a deposited layer. This is typically measured using a reflected laser beam.

$\sigma = \sigma_{th} + \sigma_i$

Intrinsic stress: Grain growth after deposition
Also, stress due to incorporated impurities (Ar)

## Thin Film Stress #1



Stress $\sigma = (\delta/t)(T^2/3R^2)\ E_f/(1-\nu_f)$

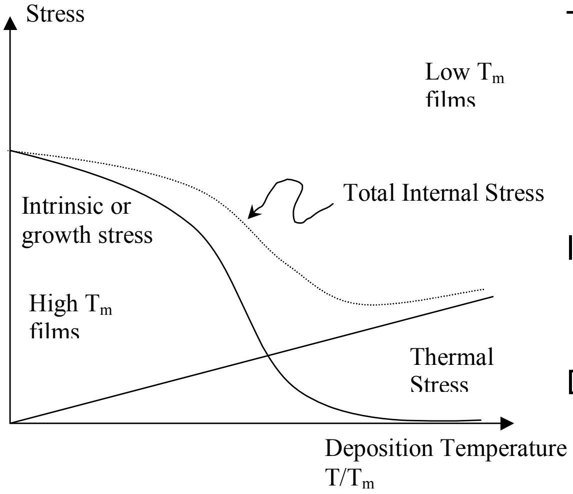
$E_f$ = Young's modulus for film

$\nu_f$ = Poisson's ratio for film

$$\sigma = \sigma_{thermal} + \sigma_{intrinsic}$$

$$\sigma_{thermal} = [E_f/(1-\nu_f)] \int_{To}^{Tdep} (\alpha_{film} - \alpha_{sub})\, dT$$

## Internal Stress

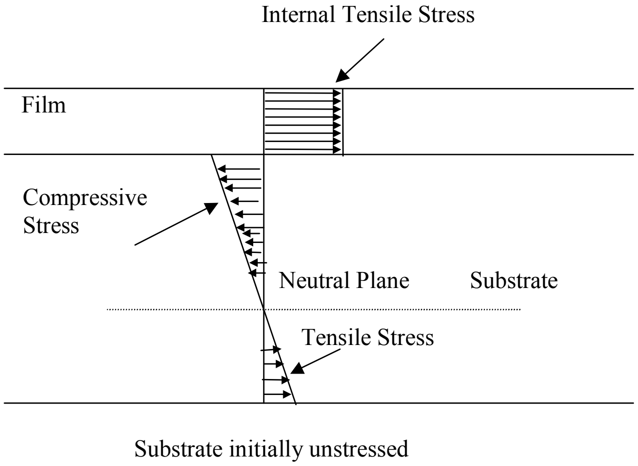


Thermal Stress:- mismatch of thermal coefficients of expansion of substrate & film.

Intrinsic Stress:- due to growth of film, distortion of lattice.

Determine by measuring total stress & subtract thermal.

# Stress Distribution



Internal Tensile Stress

Film

Compressive
Stress

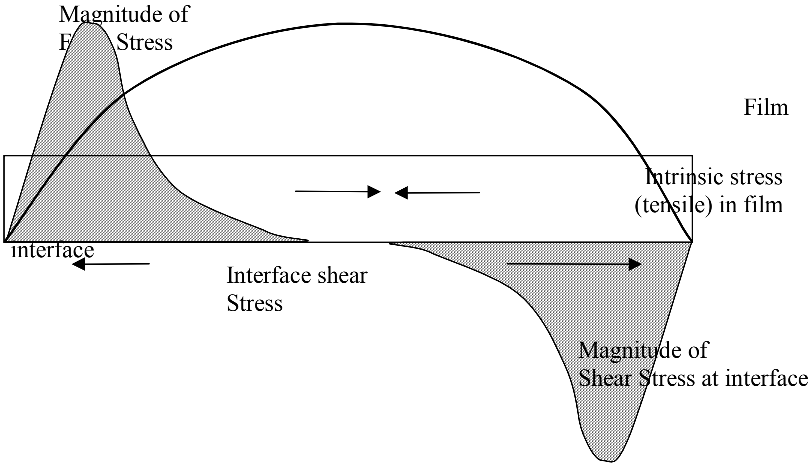
Neutral Plane

Substrate

Tensile Stress

Substrate initially unstressed

# Interface Shear Forces



Magnitude of
F Stress

Film

Intrinsic stress
(tensile) in film

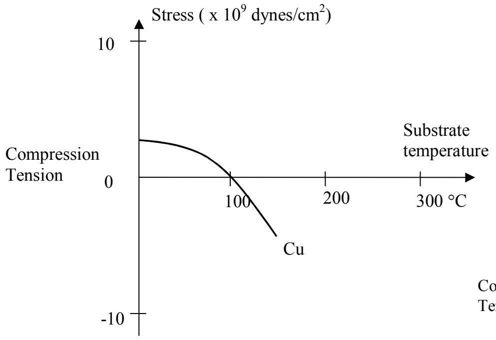
interface

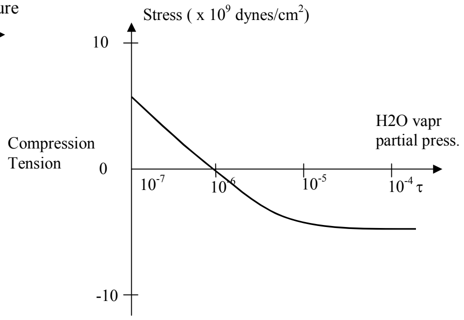
Interface shear
Stress

Magnitude of
Shear Stress at interface

# Stress: Evaporated Films #1

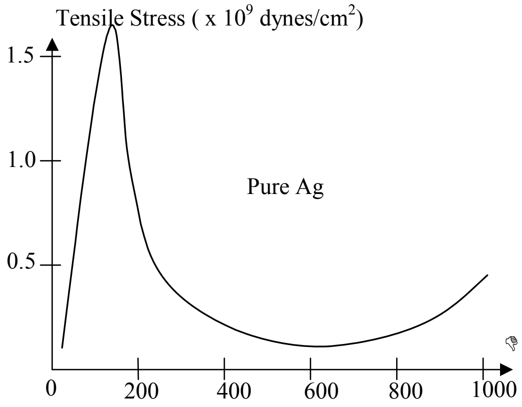
After removal of thermal stress effects





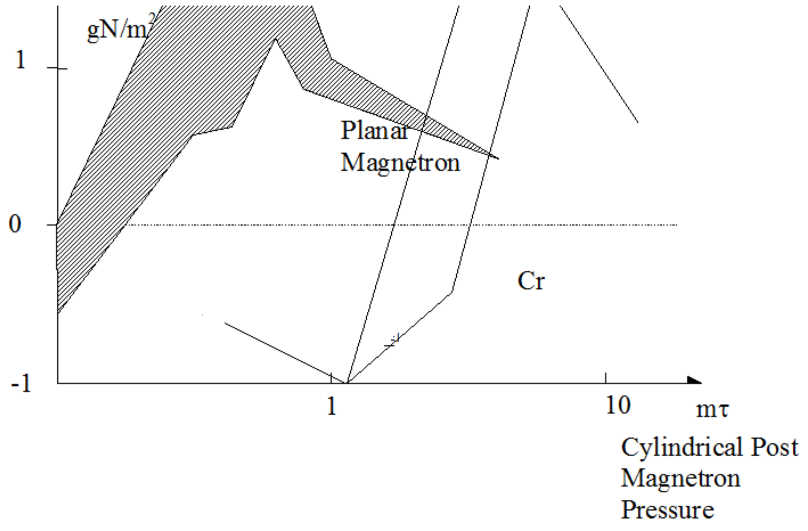
Compressive stress commonly due to contaminants

# Stress:Evaporated Films

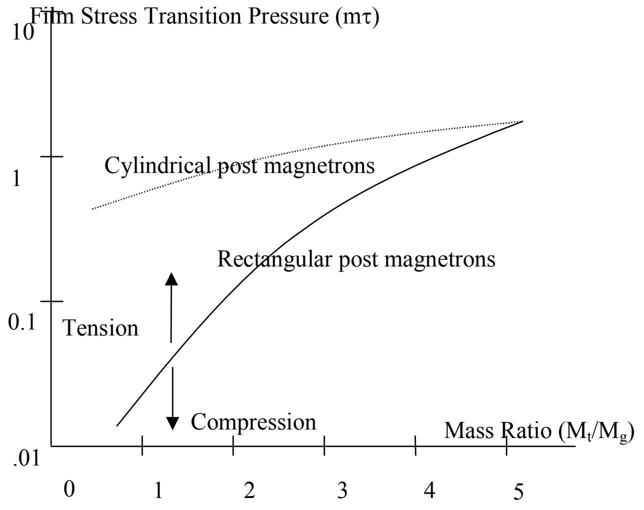


Max stress as last voids fill as film becomes fully continuous.

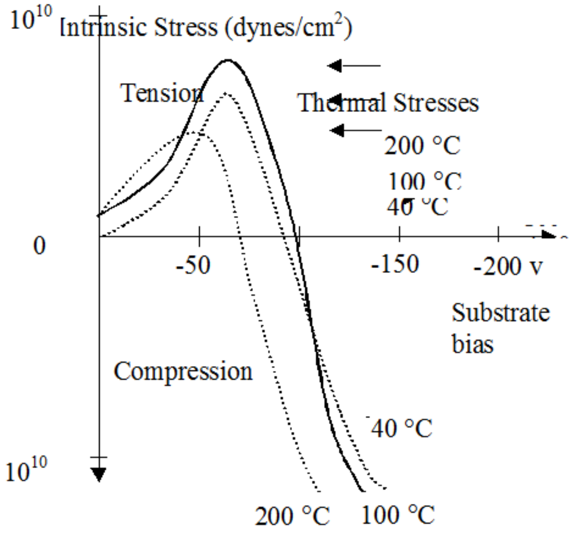
## Stress:Sputtered Films #1



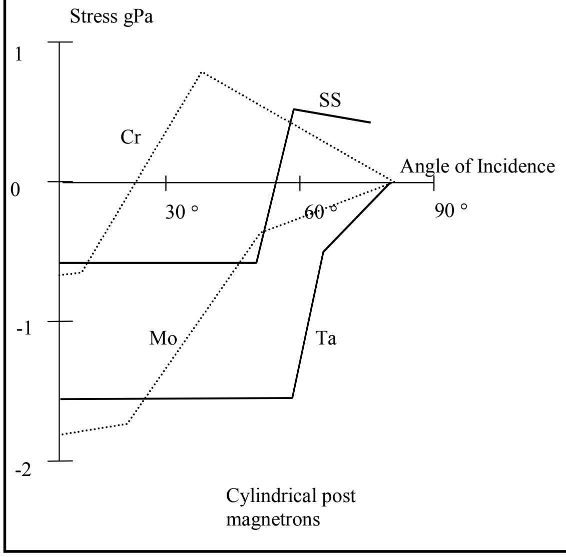
## Stress:Sputtered Films #2



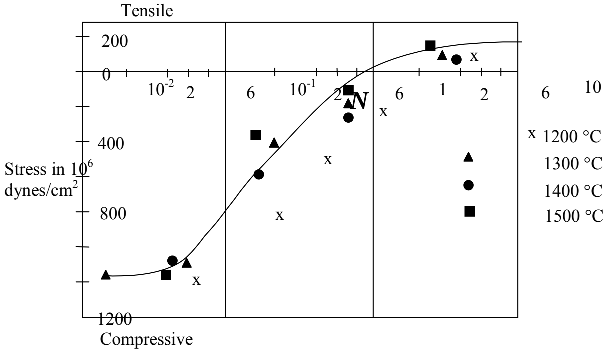
# Stress:Sputtered Films #3



# Stress:Sputtered Films #4

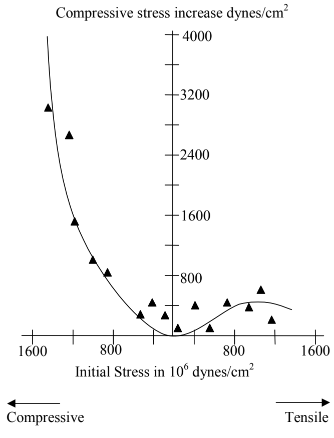


# Stress:Sputtered Films #5



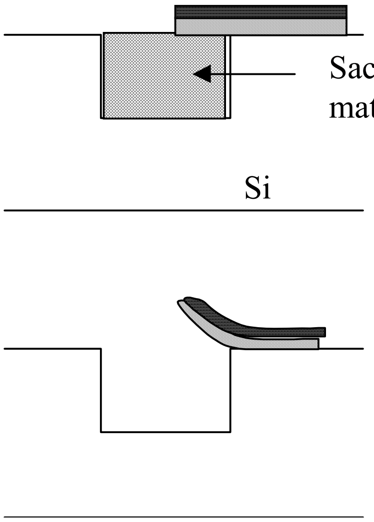
Stress of Silicon oxide films deposited in residual $O_2$ as a function of log N. (N = number of silicon monoxide molecules/number of residual gas molecules impinging on the substrate per unit area and time.)

# Stress:Sputtered Films #6

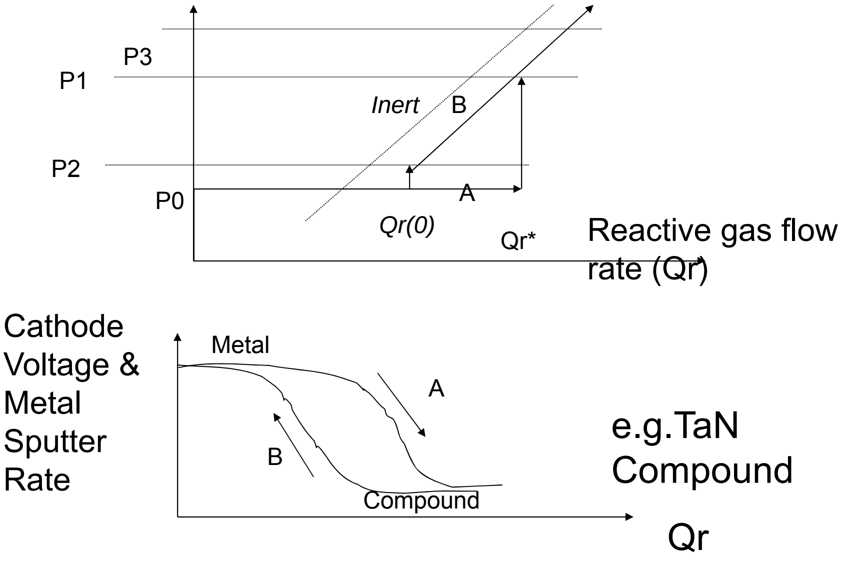


Increase in compressive stress observed on evaporated SiO films after exposure to air

# Stress:A Practical Use



# Sputter Rate Hysteresis



## Summary of Key Ideas

- Thin film deposition is a key technology in modern IC fabrication.
- Topography coverage issues and filling issues are very important, especially as geometries continue to decrease.
- CVD and PVD are the two principal deposition techniques.
- In PVD systems arrival angle distribution is very important in determining surface coverage. Shadowing can be very important.
- A wide variety of systems are used in manufacturing for depositing specific thin films, e.g. magnetron sputtering.
- Advanced simulation tools are becoming available, which are very useful in predicting topographic issues.
- Generally these simulators are based on physical models of mass transport and surface reactions and utilize parameters like arrival angle and sticking coefficients from direct and indirect fluxes to model local deposition rates.
- Thin film stress can be due to differential CTEs, impurities, and grain growth.

## Summary

- Various evaporation sources
- Evaporation rate from vapor pressure
- Deposition geometrics
- Alloy composition and contamination
- Rate & thickness monitors
- Nucleation theory
  - Capillary model
    - $\Rightarrow$ critical nucleus
    - $\Rightarrow$ nucleation rate
- Physics of sputtering
- RF and Magnetron Sputtering
- Film Contamination
- Film Stress
- (Thornton diagram)

# Assignment #6

- 11.2
- 11.5

- 12.1
- 12.3
- 12.6
- 12.10