14. Physical Vapor Deposition

A. Evaporation

from M.B. distribution:

$$\Phi = \left(P^2 / 2\pi kTM \right)^{1/2}$$

flux of molecules hitting surface.

also describes flux of atoms leaving evaporation source at temperature T with vapor pressure P.

mass evaporation rate is thus

$$R_{ME} = \sqrt{\frac{M}{2\pi kT}}\, P_e$$

R_{ME} = is mass evaporative rate

M = mass of each molecule

P_e = equilibrium vapor pressure.

Can skip straight to here

Rate Mass loss from heated crucible is thus:

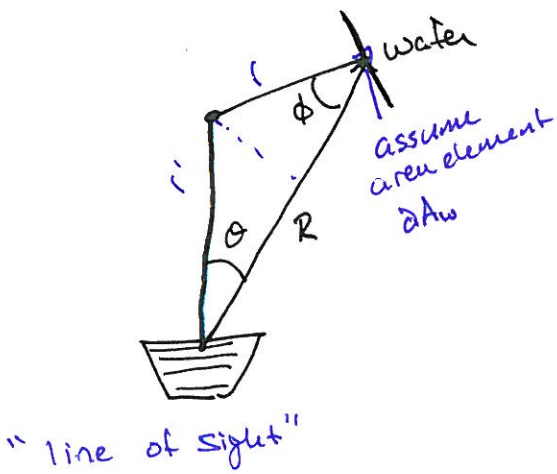
$$R_{ML} = \int \sqrt{\frac{M}{2\pi kT}}\, P_e \, dA = \underline{\sqrt{\frac{M}{2\pi k}} \int \frac{P_e}{\sqrt{T}}\, dA}$$

assume that we have constant T and hence constant P_e

$$\boxed{= \sqrt{\frac{M}{2\pi k}} \frac{P_e}{\sqrt{T}} A}$$

to find deposition rate, determine fraction of material leaving crucible that hits the wafer.

HV conditions → λ large ⇒ evaporation is line of sight.



Constant of proportionality is given by so-called "view factor"

$$V.F. = \frac{\cos\theta \cos\phi}{\pi R^2} \cdot \partial A_w$$

~~consider $\theta = 20°$, $\phi = 30°$~~

to simplify → place wafers on ~~the~~ spherical surface: $r = r'$

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

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

$$VF = \frac{1}{4\pi r^2} \cdot \partial A_w$$ → ratio of sphere at same distance to the size of the surface-area element.

Deposition rate is mass arrival rate per unit area divided by density of the film:

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

← vapor pressure of source

← area of crucible

The vapor pressure of the source is usually determined ~~theoretically~~ experimentally.

~~By theory~~: But is related to ΔH_v

$$\boxed{P_e = 3\times10^{12}\,\sigma^{3/2}\,T^{-1/2}\exp\left(\Delta H_v / NkT\right)}$$

σ is the surface tension of the metal

N is Avogadro's number

ΔH_v is the enthalpy of vaporization

for reasonable deposition rates $P_e \sim 10\,m\,torr$

planetary w/ radius of 40 cm

example: Al at 1200°C, $P_e \sim 5\,m\,torr$, $A_{crucible} = 20\,cm^2$

$M_{Al} = 27\,g/mol$, $\rho = 2.7\,gm/cm^3$

$$Rate = \left(\frac{27\,g/mol}{N_A} \Big/ \left(2\pi \times 1.38\times10^{-23}\,J/K \cdot \left(2700\,\frac{kg}{m^3}\right)\right)\right)^{1/2} \cdot \frac{(.5\,Pa)}{\sqrt{1473}} \cdot \frac{2\times10^{-5}\,m^2}{(.4)^2\cdot 4\pi}$$

$$= 3.45\times10^{-9}\,\frac{m}{s} \quad \boxed{3.5\,nm/s}$$

fairly slow growth rate: even for fairly hot easy to evaporate material...

→ can go faster ~ but go to viscous flow rate

→ material aggregates in the gas phase! above water where $P_e \to 1$ smoth

14.3

B. Sputtering → mechanism by which atoms ejected from a material when struck by energetic particles

- dominant technology for the deposition of metallic films (also used for the fabrication of thin film solar cells) absorbers, TCO's (transparent oxides)

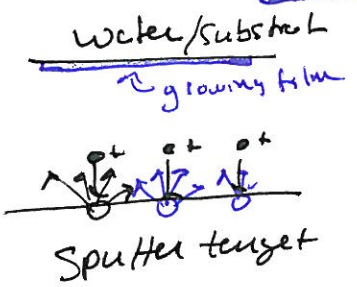
(1) large targets → uniform films

(2) alloy composition controlled easily

(3) no device damage due to x-rays from e-beam

(4) very fast : up to 1 μm/min.

Basic Idea



(1) large Voltage is applied between two electrodes in inert gas until they ionize

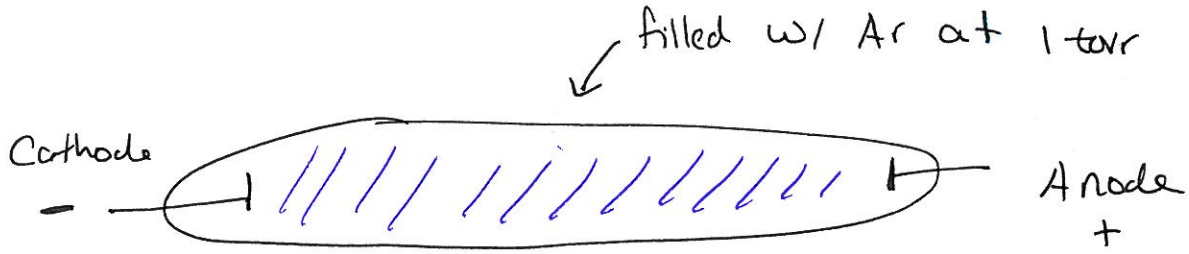
(2) (a) ions strike target and (b) dislodge atoms of material (c) Some land on substrate to (d) make a film.

energetic particles → glow discharges

→ self sustaining plasma

Spend a few minutes discussing plasmas!

I. Glow discharges



i. → 15 cm length, apply 1.5 kV potential

ii → initially, <u>no current</u>

iii $\boxed{\vec{E} = \frac{V}{d} = 1.5\,kV / 15\,cm = 100\,V/cm}$

iv. if free electron enters the tube (Ar + Cosmic Ray) accelerated toward anode (gain energy 100eV/cm)

v. moves λ, before hitting Ar (1 torr, $\lambda = 0.12$ mm)

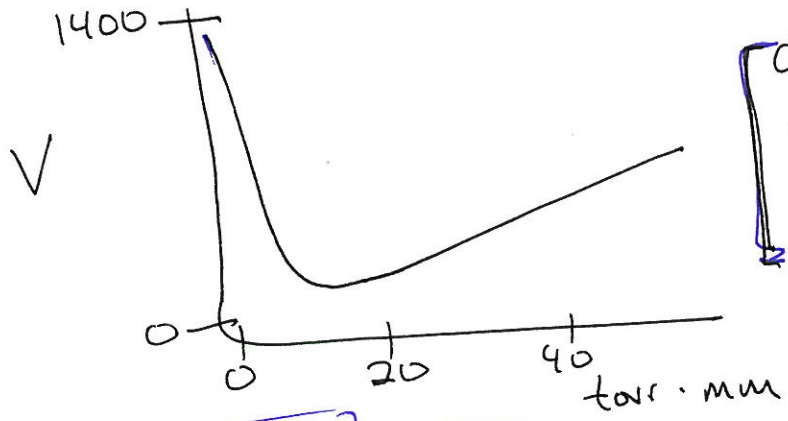
vi most collisions <u>elastic</u>, <u>1</u> in <u>10</u> inelastic →
(mass of electron is small relative to the atomic mass)

vii. if $\boxed{E_{transferred} < 15.7\,eV}$ electron in <u>Ar excited</u> and decays in 10 ns (gives <u>blue-purple</u> glow of plasma)

viii if $E_{trans} > 15.7\,eV$, second e^- and Ar^+ is created

$\Rightarrow$ $\boxed{\text{cascade of ions and electrons}}$ (breakdown ie. <u>Lightning!</u>)

Breakdown Voltage



depends on pressure and electrode spacing

→ note: hard to start plasma for very small pressures

$$V_{bd} \propto \frac{P \cdot L}{(\log P \cdot L + b)}$$ Paschen's Law

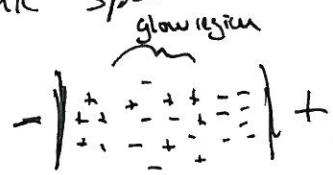
→ insight into operation of penning or "cold-cathode" gauge.

→ Lightning = discharge

→ want <u>self-sustained</u> <u>continuous</u> discharge.

Structure of Self-Sustaining Plasma

→ dark spaces near the electrodes



ions polarize, higher field at electrodes, electrons spend less time there, collisions are high E, lead to ionization rather than excitation and emission.

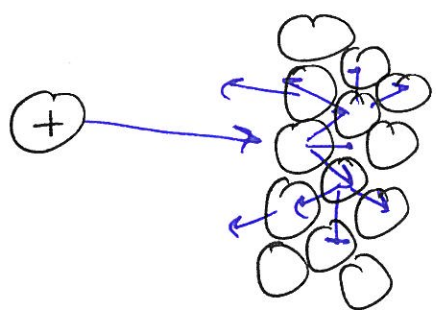
electrons are ejected by <u>cathode</u> when positive ions collide with it.

→ DC system lowest pressure 10 – 40 mtorr before system no longer "self-sustaining"

14.7 The Physics of Sputtering

→ Bombardment of cathode w/ positive (Ar^+) ion stream gives rise to sputter action.

Wehner → Billiard ball model of sputtering



hard sphere collisions

Sputter yield → $\frac{\text{number of atoms}}{\text{ion}}$

depends on ion mass, energy, and material

minimum ion energy needed to eject atom

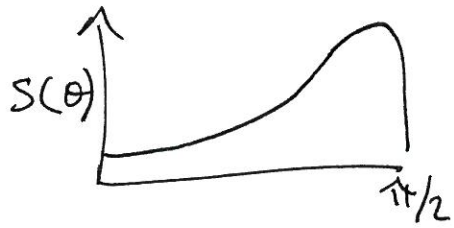
$$E_{threshold} = \frac{U_0}{\gamma(1-\gamma)}$$

U_0 = heat of sublimation (energy needed to break all the bonds)

$$\gamma = \frac{4 M_1 M_2}{(M_1 + M_2)}$$

→ energy transfer parameter

Sputter yield depends on angle of incidence:



$S \propto \frac{1}{\cos\theta}$

* oblique angles of incidence give rise to higher sputter yields

---

Growth of Films

→ ejected ions 10-40eV, 3-6 $\times 10^5$ cm/s velocity

→ want all atoms to hit substrate

- best target and wafer substrate close, typically 5-10 cm
- $\lambda < 5$cm (e.g. λ at 5mtorr $\hat{=}$ 1cm)
- multiple scattering events (would go to lower P, but difficult to sustain plasma... more later.)
- Thermalization, Back scattering, etc (see figure)

(other)
→ Species that strike the wafer
1) neutral gas atoms (O, N) 2) negative ions, high E electrons

impurities (if $P_{O_2} = 10^{-6}$ Torr ~ 10^{15} O/s ~ 1 monolayer/s

Radio Frequency (RF) Sputtering

→ DC sputtering doesn't work for insulators!

- glow discharge cannot be maintained
- electrons discharged from cathode can't be replaced!

→ But we want to sputter oxides and other insulators.

→ Solution: use AC Voltage to drive the sputtering

Complications

1. must sustain glow discharge
2. must still maintain strong $\bar{E}$ field to bombard target
3. must supress sputtering substrate!
4. must efficiently couple RF power into chamber
5. e^- taken off must be replaced.

RF Sputtering

→ usually 13.56 MHz

→ fast enough so that electronic charge does not build up (1-10 μs)

→ chose due to regulations (ie FCC etc.)

→ RF plasmas remain sustained w/o electron discharge from cathode

- not well understood.

→ can also use lower pressure.

Prevent Sputtering of Substrate:

- ground substrate / non sputtering electrode
- use entire chamber as second electrode
- blocking capacitor
- sheath voltage

= no sputtering of sample!

Magnetron Sputtering

① to get ion current (and hence sputter rate) high enough for deposition. →
must use high pressure (20-200 mtorr) for sputtering. (in DC)

② leads to poor transport away from substrate (collisions w/ gas molecules and scattering, etc.)

Simple DC diodes rarely used!

→ Magnetron sputtering 10-100 fold higher current density and sputterrate

→ P as low as 1mtorr possible ⇒ $\lambda = 6.6$ cm
~ no collisions!

Dominant Technology!

Motion of charged Particle in $\bar{B}$ field

charged particle, q = charge
m = mass
$\bar{v}$ = velocity

surface

$$\bar{F} = q\,(\bar{v} \times \bar{B})$$

cross product

Lorentz Force

Particle moves in circular path

$$\boxed{r_g = \frac{m|\bar{v}|}{q|\bar{B}|}}$$

r_g = radius

$$r_g\,(\text{electron}) = 3.37 \times \left(\frac{E^{1/2}\,(eV)}{B\,(\text{gauss})} \right)$$

$$r_g\,(Ar^+) = 911 \times 10^2 \left(\frac{E^{1/2}\,(eV)}{B\,(\text{gauss})} \right)$$

→ $\boxed{Ar^+ \text{ radii} >>> e^- \text{ radii}}$

300x!

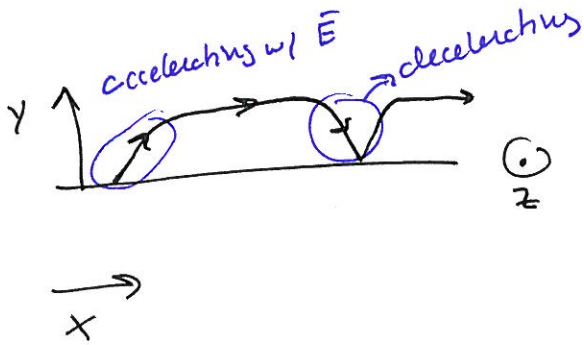
- electron motion strongly influenced
- Ar+ motion <u>not</u> ☆

Now consider case where $\bar{E}$ and $\bar{B}$

L is dimension of dark space or ... the space charge region.

$$\bar{E} = E_0 (1 - y/L)\,\hat{y} \quad \text{along } y \text{ direction.}$$

$$\bar{B} = B\,\hat{z} \quad \text{(parallel to the surface)}$$



$$y_{max} = \frac{1}{B} \left(\frac{2m}{q} (V - V_T) \right)^{1/2}$$

V_T is target voltage

V is voltage at edge of dark space (space-charge zone)

Many more ions (Ar^+) generated in the vicinity of target electrode than before! Better sputtering.

Magnetron Sputtering

Disadvantages

→ slow discharge of max intensity forms a ring

→ target wears unevenly

cross-section

→ poor utilization (can be recycled)

→ also causes ~~less~~ non uniform deposition!

→ trade off between substrate thickness uniformity and deposition rate