Physical Vapor Deposition

Methods

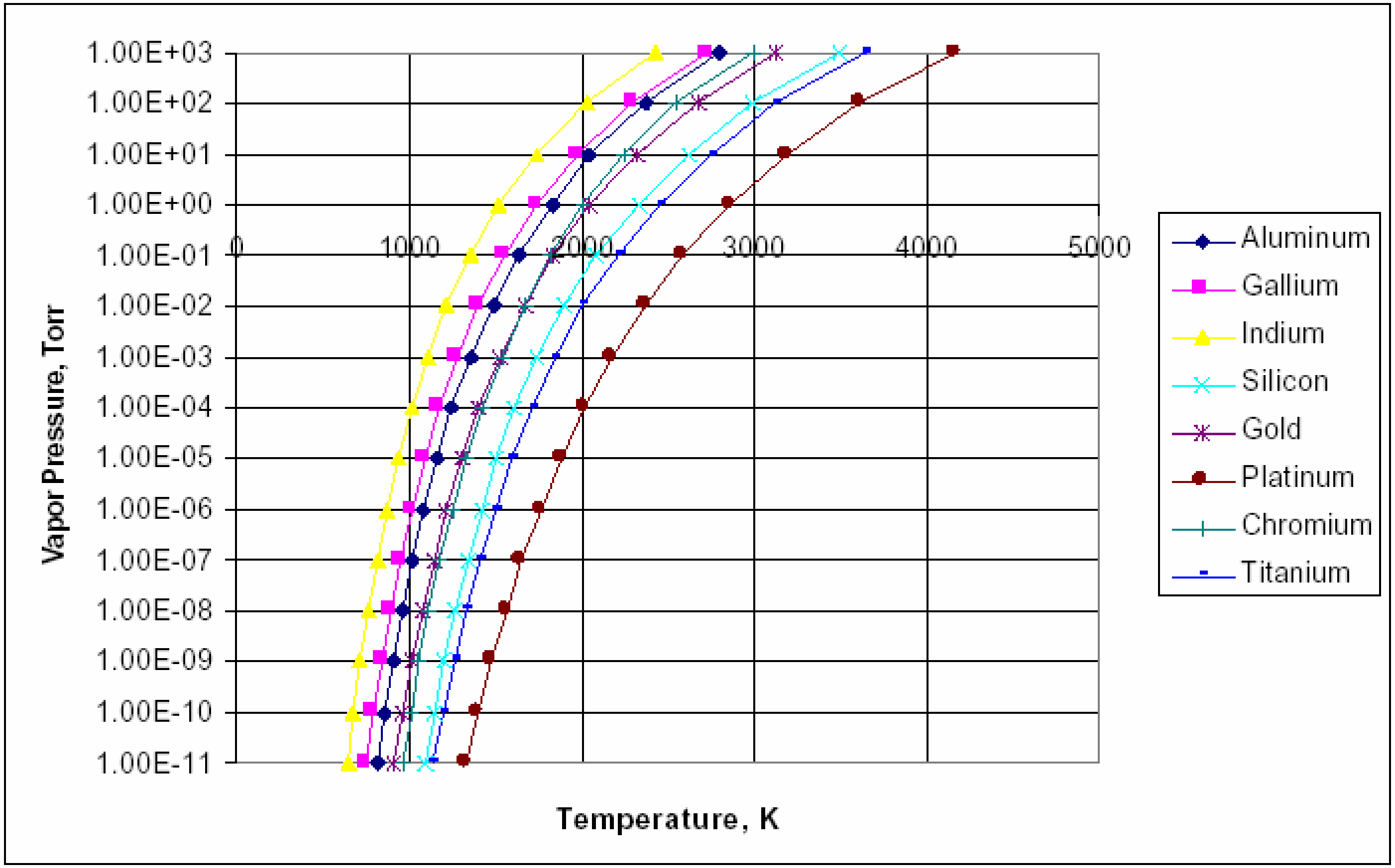
- Evaporation
- Sputtering
- E-Beam

Evaporation

- Evaporation (Metals)
  - Vacuum system
  - Material to be deposited heated in a crucible
  - Vapor travels hemi-spherically
- Phase Diagram
  - Equilibrium vapor pressure at every temperature
    - Sublimation: Phase change to vapor below Tmelt
    - Evaporation: Phase change to vapor above Tmelt

$$P_e = \frac{3x10^{12}\sigma^{1.5}\exp\left[\frac{\Delta H_v}{NkT}\right]}{\sqrt{T}}$$

Example of Equilibrium Pressure



More Evaporation

- P* - P ~ to evaporation rate (Heinrich Hertz)
- Additional heat will not increase evap rate (unless this increases the P*)
- Max evaporation rate is P → 0

Evaporation Deposition Rates

- Based upon Fickian diffusion
  - Vapor travels randomly from the molten source
  - Line of sight deposition

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

Evaporation

- Very simple
- Easy to maintain
- Poor step coverage
- Slow
  – To avoid contamination
- High vacuum required to avoid condensation

E-Beam Evaporation

- Higher T (3000C)
- More complex
- Crucible evaporation (Cu)
- Emission voltage ~10kV
- Substrate subjected to 2^{nd}ary electron radiation (possible x-ray exposure)
- 10-100Å/s
- Able to evaporate oxides of Al, Si, Zr, Ti

Sputtering

- Improved step coverage
- Requires a plasma
- Less radiation damage than e-beam evaporation
- Superior films
  - Alloys
  - Layered films

Sputtering Mechanism

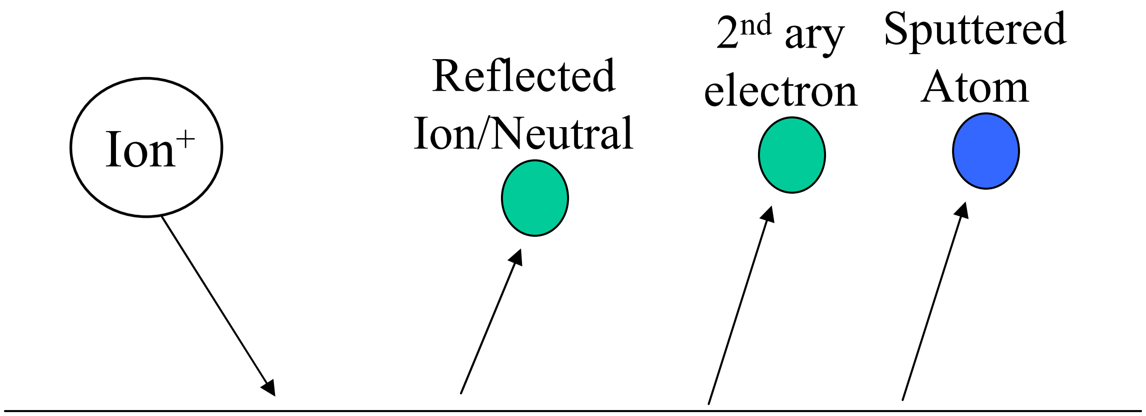
- Requires a plasma
  - Typically and inert gas (Ar)
- Target material is bombarded by ions
  - Target material placed in area of largest ion density
- Spacing between electrodes typically 5-10λ
- Ion collides with target material
  - Material is ejected from surface and deposits on wafer (everywhere)

Energy of Collisions

- Depends upon KE of impinging particle
  - <5eV reflection, physisorption of material
  - 5-10eV , Exceeding binding energy of target
    - Surface migration
    - Surface damage
  - >10keV Implantation
  - Between 10ev to 10keV sputtering

Results of Collision

- Depending upon KE different type of products will result from collisions



More Collisions

- Mechanism of sputtering not well understood
  - Incident angle of ions
  - Material
    - Binding energy
    - Lattice structure
  - Kinetic Energy
  - Plasma gas
  - Temperature

Types of Sputtering

- DC
  - Will it work for dielectrics?
- RF
  - Can sputter etch
  - Low yield→low dep rate
- Magnetron
  - Magnetic field used to capture electrons around target

Sputter Yield

- Ion Flux
- Probability of sputtered collision
- Sputtered atom makes it way to target.

$$J_{ion} \propto \sqrt{\frac{1}{m_{ion}}} \frac{V^{1.5}}{d^2}$$

- V=voltage difference electrode to wafer
- D=thickness of darkspace
- m_{ion} = ion mass

Sputter Yield

- Minimum Threshold Energy for Sputtering
  - 5-10eV
  - Yield increases as the square of energy up to 100eV
  - Linear increase up to 800eV

$$E_{threshold} = \frac{U_o}{\gamma(1 - \gamma)}, \quad \gamma = \text{xfer energy parameter} = \frac{4M_1M_2}{(M_1 + M_2)^2}$$

Sputter Deposition

- Species that strike the wafer
  - Sputtered atoms
  - Fast neutral sputter gas atoms
    - High energy gas neutrals
    - Could implant into wafer
  - Negative ions
    - Due to gas impurities (O and N)
  - High energy e
    - Results in heating of wafer
  - Contaminants

PVD Methods

- Thermal (~20Å/sec)
  - Au, Ag, Al, Sn, Cr, Sb, Ge, In, Mg, Ga
  - CdS, PbS, CdSe, NaCl, KCl, AgCl, MgF_2, CaF_2, $PbCl_2$
- E-Beam (everything thermally +) (100Å/s)
  - Ni, Pt, Ir, Rh, Ti, V, Zr, W, Ta, Mo
  - Al_2O_3, SiO, SiO_2, SnO_2, TiO_2, ZrO_2
- Sputtering (100Å/s)
  - Al, Cu, Si, AlSi, AlCu, TiW, TiN, Ta, TaN

Why Does it Stick?

- Sputtered or Evaporated atoms migrate toward the wafer surface.
- How does the vaporized material become a solid?
- What driving forces make the atoms adhere?

Adsorption Phenomena

- Physisorption
  - Impinging molecule loses kinetic (thermal) energy within some residence time
  - Lower energy of the molecule cannot escape surface
- Chemisorption
  - The impinging molecule loses its kinetic energy to a chemical reaction which forms a chemical bond between it and other substrate atoms.

Condensation

- Condensation of a vapor to a solid or liquid
  - P* > Pe at a specific temperture
- When P* > Pe then vapor is "supersaturated"
- Condensation of material on a dissimilar substrate
  - Adsorb on impact
  - Adsorb, move along surface (diffusion) then stick
  - Adsorb and then desorb
  - Reflect off
- Incident vapor higher KE than surface energy of substrate (kT)
- Sticking dependent on target material equilibrating with substrate.
  - Energy of target must decrease enough so it won't desorb

Condensation

- Thermal accommodation coefficient
  - T_v = impinging vapor temp
  - T_s = substrate temp
  - T_r = resident vapor molecule temp (have not permanently adhered)
- $\alpha_T < 1$ fraction of impinging molecules will desorb

$$\alpha_T = \frac{E_v - E_r}{E_v - E_s} = \frac{T_v - T_r}{T_v - T_s}$$

Condensation Mechanism

- Adsorbed molecule diffuses along surface for τ_a.
- Constant flux of vapor had more molecules adsorbing on surface
- Clusters form during surface migration
  - Clusters have smaller S/V than individual molecules (ΔG is getting smaller)

$$\tau_a = \frac{1}{\upsilon_o} \exp\left[\frac{\Delta G_{des}}{k_B T(K)}\right] \qquad n_s = R\tau_a$$

Growth of Films

- Adsorb monomers on exposed surface
- Monomers diffuse along surface until critical size nuclei achieved (Gibbs free energy is reduced)
  - Size of nuclei reach supercritical
  - Monomers in local region depleted bare surface re-exposed
- Nucleation of clusters
- Individual clusters contact each other (island)
  - Joining clusters expose more surface
- Additional monomers adsorb on exposed surface
- Islands grow together to form channels and holes
- Channels and holes fill to form continuous film

Film Growth

- Atom clustering
  - Molecular clusters reach critical size where Gibbs free energy is decreasing
    - Nuclei form
- Island Stage
  - Nuclei grow in 3D
- Coalescence
  - Nuclei contact each other
    - Form new/larger shapes
- Channel Stage
  - Island grow creating channels of exposed substrate
    - Channels filled by 2nd ary nucleation
- Continuous Film Stage

Models of Film Growth

- Island Growth
- Layered growth (ideal epitaxy)
- Mixture of the Island and Layered

Controlling Parameters

- Substrate Temperature (T_s)
- Increase T_s
  - Thermal energy of adsorbed molecules higher
    - Shorter τ_a
  - Surface diffusion greater
- Need to be cautious of too much heat
  - Desorb film (Cleaning technique?)

Sputtered Aluminum

- Al/Si alloys replacing Al
  - Better ohmic contact
    - 0.5 – 2 atomic %
- Al/Cu
  - Reduced hillock formation
    - 0.5 – 2 atomic %
    - Pass higher current w/o e-migration or stress induced voiding

Sputtered Material

- DC magnetron systems
- Stoichiometry control
  - Film deposited is “close” to target composition
  - Composition controlled by transport properties
    - Low P higher Cu concentration in film
      - Ar thermalizes lighter Al – Selective Thermalization
  - Better control of stoichiometry is by multiple targets
- Gas contamination will effect film resisitivity
  - Function of pressure
- Film Reflectance
  - Large grain size-hazy film
  - Litho difficult

Advances

- May be replaced by electrodeposition of CVD
- Still may be critical for metals
- Used for seed layers
  - Cu
- Barrier layers
  - Ta, TaN,Ti, N
- Used for silicides (refractory metal compounds)
  - Thermally stable, low Ω,@ Si/refractory metal
  - Ti, Co metals with Si
  - Reduce contact resistances over SD&G
- Need to address defect densities and contamination