

Evaporation

- Resistive evaporation
 - Uses resistive heating to evaporate a metallic filament
 - Drawbacks
 - Limited to low melting point metals
 - Small filament size limits deposit thickness
- Electron-beam evaporation
 - Uses a stream of high energy electrons (5-30 keV) to evaporate source material
 - Can evaporate any material
 - Electron-beam guns with power up to 1200 kw
 - Drawbacks
 - At >10kv incident electrons can produce x-rays
 - Redeposition of metal droplets blown of source by vapor
- Ion beam evaporation
- Inductive heating evaporation

September 21, 2001

Microsystems Principles

Evaporation

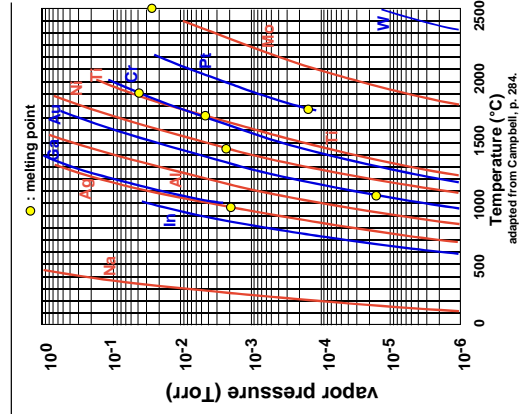
- Material is heated to attain gaseous state
- Carried out under high-vacuum conditions ($\sim 5 \times 10^{-7}$ torr)
- Advantages
 - Films can be deposited at high rates (e.g., $0.5 \mu\text{m}/\text{min}$)
 - Low energy atoms ($\sim 0.1 \text{ eV}$) leave little surface damage
 - Little residual gas and impurity incorporation due to high-vacuum conditions
 - No substrate heating

September 21, 2001

Microsystems Principles

Physical vapor deposition: thermal evaporation

- high vacuum to avoid contamination
 - “line-of-sight” deposition, poor step coverage
- heating of source material
 - potential problem: thermal decomposition
- rates ~ 0.1 - few nm/sec
 - typically $P_{\text{vapor}} \sim 10^{-4}$ Torr immediately above source
 - “pressure” at sample surface is much lower
 - few monolayers per sec $\rightarrow P_{\text{equiv}} \sim 10^{-6}$ Torr



September 21, 2001

Microsystems Principles

Evaporation

- Limitations
 - Accurately controlled alloy compounds are difficult to achieve
 - No in situ substrate cleaning
 - Poor step coverage
 - Variation of deposit thickness for large/multiple substrates
 - X-ray damage

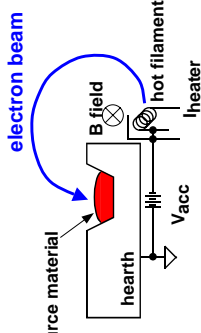
Evaporation Support Materials

- Refractory metals:
 - Tungsten (W); MP = 3380°C, $P^* = 10^{-2}$ torr at 3230°C
 - Tantalum (Ta); MP = 3000°C, $P^* = 10^{-2}$ torr at 3060°C
 - Molybdenum (Mo); MP = 2620°C, $P^* = 10^{-2}$ torr at 2530°C
- Refractory ceramics:
 - Graphitic Carbon (C); MP = 3700°C, $P^* = 10^{-2}$ torr at 2600°C
 - Alumina (Al_2O_3); MP = 2030°C, $P^* = 10^{-2}$ torr at 1900°C
 - Boron nitride (BN); MP = 2500°C, $P^* = 10^{-2}$ torr at 1600°C
- Engineering considerations:
 - Thermal conductivity
 - Thermal expansion
 - Electrical conductivity
 - Wettability and reactivity

R. B. Darling / EE-527

Thermal evaporation

- main heating mechanisms
 - resistively heat “boat” containing material
- tungsten (mp 3410°C), tantalum (mp 2996°C), molybdenum (mp 2617°C) very common “heater” materials
- reaction with boat potential problem
- electron beam evaporator
 - source material “directly” heated by electron bombardment
 - can generate x-rays, can damage substrate/devices
 - $I_{beam} \sim 100 \text{ mA}$, $V_{acc} \sim \text{kV} \rightarrow P \sim \text{kWatts}$



- inductively heat material (direct for metals)
- essentially eddy current losses

Dean P. Heibak © 2003. Last update February 2, 2001

22

Dept. of ECE, Univ. of Texas at Austin

Resistance Heated Evaporation

- Simple, robust, and in widespread use.
- Can only achieve temperatures of about 1800°C.
- Use W, Ta, or Mo filaments to heat evaporation source.
- Typical filament currents are 200-300 Amperes.
- Exposes substrates to visible and IR radiation.
- Typical deposition rates are 1-20 Angstroms/second.
- Common evaporant materials:
 - Au, Ag, Al, Sn, Cr, Sb, Ge, In, Mg, Ga
 - CdS, PbS, CdSe, NaCl, KCl, AgCl, MgF_2 , CaF_2 , $PbCl_2$

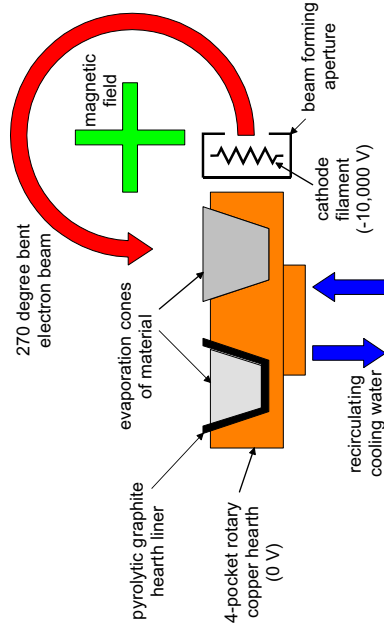
R. B. Darling / EE-527

Evaporation System Requirements

- Vacuum:
 - Need 10^{-6} torr for medium quality films.
 - Can be accomplished in UHV down to 10^9 torr.
- Cooling water:
 - Hearth
 - Thickness monitor
 - Bell jar
- Mechanical shutter:
 - Evaporation rate is set by temperature of source, but this cannot be turned on and off rapidly. A mechanical shutter allows evaporant flux to be rapidly modulated.
- Electrical power:
 - Either high current or high voltage, typically 1-10 kW

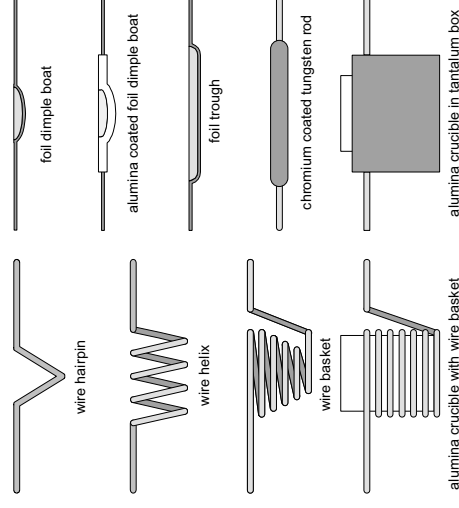
R. B. Darling / EE-527

Electron Beam Heated Evaporation Source



R. B. Darling / EE-527

Resistance Heated Evaporation Sources



R. B. Darling / EE-527

Electron Beam Heated Evaporation - 2

- 270° bent beam electron gun is most preferred:
 - Filament is out of direct exposure from evaporant flux.
 - Magnetic field can be used for beam focusing.
 - Magnetic field can be used for beam positioning.
 - Additional lateral magnetic field can be used produce X-Y sweep.
- Sweeping or rastering of the evaporant source is useful for:
 - Allows a larger evaporant surface area for higher deposition rates.
 - Allows initial charge to be “soaked” or preheated.
 - Allows evaporant source to be more fully utilized.
- Multiple pocket rotary hearth is also preferred:
 - Allows sequential deposition of layers with a single pump-down.
 - Allows larger evaporation sources to be used.

R. B. Darling / EE-527

Electron Beam Heated Evaporation - 1

- More complex, but extremely versatile.
- Can achieve temperatures in excess of 3000°C.
- Use evaporation cones or crucibles in a copper hearth.
- Typical emission voltage is 8-10 kV.
- Exposes substrates to secondary electron radiation.
 - X-rays can also be generated by high voltage electron beam.
- Typical deposition rates are 10-100 Angstroms/second.
- Common evaporant materials:
 - Everything a resistance heated evaporator will accommodate, plus:
 - Ni, Pt, Ir, Rh, Ti, V, Zr, W, Ta, Mo
 - Al₂O₃, SiO, SiO₂, SnO₂, TiO₂, ZrO₂

R. B. Darling / EE-527

Condensation of Evaporant - 1

- Condensation of a vapor to a solid or liquid occurs when the partial pressure of the vapor exceeds the equilibrium vapor pressure of the condensed phase at this temperature.
- The vapor is “supersaturated” under these conditions.
- This is only true if condensation takes place onto material which is of the same composition as the vapor.
- When a material is first deposited onto a substrate of a different composition, a third adsorbed phase must be included to describe the process.

R. B. Darling / EE-527

High Throughput Evaporation Techniques

- Box coaters are used for evaporating large substrate materials, often up to several meters in size.
- Large amounts of source material are required, but cannot be all heated at once because of realistic power limitations.
- Two popular techniques:
 - Powder trickler source
 - Wire feed source
- Both can be adapted for either resistance heated or electron beam heated evaporation systems.

R. B. Darling / EE-527

Condensation of Evaporant - 2

- Molecules impinging upon a surface may:
 - Adsorb and permanently stick where they land (rare!).
 - Adsorb and permanently stick after diffusing around on the surface to find an appropriate site.
 - This can lead to physisorption or chemisorption.
 - Adsorb and then desorb after some residence time τ_r .
 - Immediately reflect off of the surface.
- Incident vapor molecules normally have a kinetic energy much higher than $k_B T$ of the substrate surface.
- Whether an atom or molecule will stick depends upon how well it can equilibrate with the substrate surface, decreasing its energy to the point where it will not subsequently desorb.

R. B. Darling / EE-527

Adsorption

- Adsorption is the sticking of a particle to a surface.
- Physisorption:
 - The impinging molecule loses kinetic (thermal) energy within some residence time, and the lower energy of the molecule does not allow it to overcome the threshold that is needed to escape.
- Chemisorption:
 - The impinging molecule loses its kinetic energy to a chemical reaction which forms a chemical bond between it and other substrate atoms.

R. B. Darling / EE-527

Condensation of Evaporant - 5

- If the impingement rate stops, then the adsorbed molecules will all eventually desorb.
- Condensation of a permanent deposit will not occur, even for low substrate temperatures, unless the molecules interact.
- Within the mean residence time, surface migration occurs and clusters form.
- Clusters have smaller surface-to-volume ratios, and therefore desorb at a reduced rate.
- Nucleation of a permanent deposit is therefore dependent upon clustering of the adsorbed molecules.

R. B. Darling / EE-527

Condensation of Evaporant - 3

- Thermal accommodation coefficient:

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

- E_v, T_v = energy, temperature of impinging vapor molecules.
- E_r, T_r = energy, temperature of resident vapor molecules;
 - (Those which have adsorbed, but have not permanently found a site.)
- E_s, T_s = energy, temperature of substrate surface.
- If $\alpha_T < 1$, ($E_r > E_s$), then some fraction of the impinging molecules will desorb from the surface.

R. B. Darling / EE-527

Observed Growth of a Deposited Film

- Adsorbed monomers
- Subcritical embryos of various sizes
- Formation of critically sized nuclei
- Growth of nuclei to supercritical size and depletion of monomers within their capture zones
- Nucleation of critical clusters within non-depleted areas
- Clusters touch and coalesce into new islands, exposing fresh substrate areas
- Adsorption of monomers onto fresh areas
- Larger islands grow together leaving holes and channels
- Channels and holes fill to form a continuous film

R. B. Darling / EE-527

Condensation of Evaporant - 4

- Mean residence time for an adsorbed molecule:

$$\tau_a = \frac{1}{\nu_0} \exp\left(\frac{\Delta G_{\text{des}}}{k_B T}\right)$$

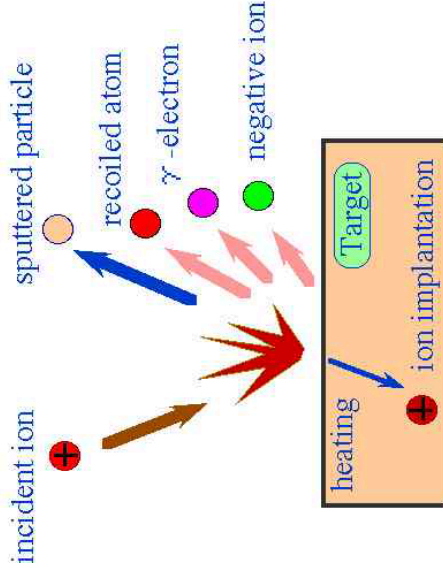
- $\nu_0 = k_B T/h$ = vibrational frequency of adsorbed molecule ($\sim 10^{14}$ Hz)
- This is the frequency at which the molecule “attempts” to desorb.
- ΔG_{des} = free activation energy for desorption.
- Under a constant impinging vapor flux of R , the surface density of the deposit is then:

$$n_s = R \tau_a = \frac{R}{\nu_0} \exp\left(\frac{\Delta G_{\text{des}}}{k_B T}\right)$$

- R = deposition rate in molecules/cm²-sec.
- n_s = surface density of deposited molecules in cm².

R. B. Darling / EE-527

What is sputtering?



Condensation Control

- Control of condensation of the evaporant is achieved through the control of substrate temperature T_s .
- Higher substrate temperatures:
 - Increase thermal energy of adsorbed molecules.
 - (Shortens the residence time.)
 - Increase surface diffusivity of adsorbed molecules.
 - Performs annealing of deposited film.
- Substrate heaters:
 - Quartz IR lamps from frontside
 - Ta, W, or Mo foil heaters from backside
 - Graphite impregnated cloth heaters from backside
- Too much heat will desorb the deposited film, evaporating it away! (But this can be used for cleaning...) (R. B. Darling / EE-527)

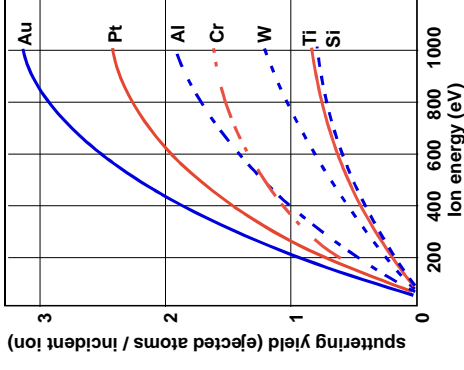
Sputtering

- Limitations
 - Deposition rate of some materials quite low
 - Some materials (e.g., organics) degrade due to ionic bombardment
 - Incorporation of impurities due to low-medium vacuum

Sputtering

- Uses high energy particles (plasma) to dislodge atoms from source surface
- Carried out under low-medium vacuum (~10 mtorr)
- Advantages
 - Can use large area targets for uniform thickness over large substrates
 - Easy film thickness control via time
 - Ease of alloy deposition
 - Substrate surface can be sputter cleaned (etched)
 - Step coverage
 - Sufficient material for many depositions
 - No x-ray damage

Sputtering

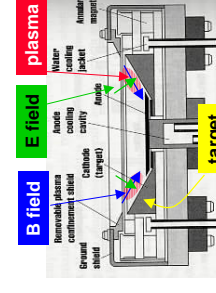
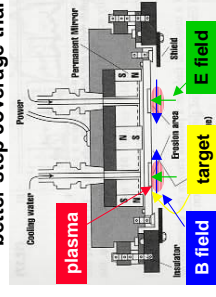


adapted from: Campbell, p. 295

- use moderate energy ion bombardment to eject atoms from target
- “purely” physical process
 - can deposit almost anything

Sputtering

- plasma generates high density, energetic incident particles
 - magnetic field used to confine plasma, electric field (“bias”) to accelerate
 - dc plasma: metals
 - rates up to $\sim 1 \mu\text{m} / \text{minute}$
 - rf plasma: dielectrics
- typically inert (noble) gas used to form incident ions
 - ion energies \sim few hundred eV ; ejected atoms \sim tens eV
 - $\sim 10^{-2}$ Torr, $\lambda, \sim 5 \text{ mm}$
 - better step coverage than evaporation



planar magnetron
S-gun conical magnetron
adapted from: Campbell, p. 298