EE143 – Fall 2016
Microfabrication Technologies

Lecture 6: Thin Film Deposition
Reading: Jaeger Chapter 6

Prof. Ming C. Wu

wu@eecs.berkeley.edu

511 Sutardja Dai Hall (SDH)

Vacuum Basics

- **Units**
  - 1 atmosphere = 760 torr = $1.013x10^5$ Pa
  - 1 bar = 105 Pa = 750 torr
  - 1 torr = 1 mm Hg
  - 1 mtorr = 1 micron Hg
  - 1 Pa = 7.5 mtorr = 1 newton/m2
  - 1 torr = 133.3 Pa

- **Ideal Gas Law: PV = NkT**
  - k = 1.38E-23 Joules/K
    = 1.37E-22 atm cm^3/K
  - N = # of molecules (note the typo in your book)
  - T = absolute temperature in K

Dalton's Law of Partial Pressure

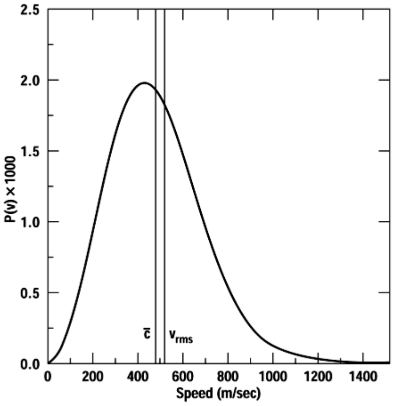
- For mixture of non-reactive gases in a common vessel, each gas exerts its pressure independent of others
- $P_{total} = P_1 + P_2 + \cdots . + P_N$
  - Total pressure = Sum of partial pressures
- $N_{total} = N_1 + N_2 + \cdots . + N_N$
  - Total number of molecules = sum of individual molecules
- Ideal gas law observed by each gas, as well as all gases
  - $P_1 \mathrm{V} = N_1 kT$
  - $P_2 \mathrm{V} = N_2 kT$
  - $P_N \mathrm{V} = N_N kT$

Average Molecular Velocity

- Assumes Maxwell-Boltzman Velocity Distribution

$$\bar{v} = \sqrt{\frac{8kT}{\pi m}}$$

- where m = molecular weight of gas molecule



Mean Free Path between collisions

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

- where
  - K = Boltzmann constant
  - T = temperature in Kelvin
  - d = molecular diameter
  - P = pressure
- For air at 300K

$$\lambda(in\, mm) = \frac{6.6}{P\ (in\ Pa)} = \frac{0.05}{P\ (in\ torr)}$$

Impingement Rate

- Φ = number of molecules striking a surface per unit area per unit time [1/cm^2-sec]

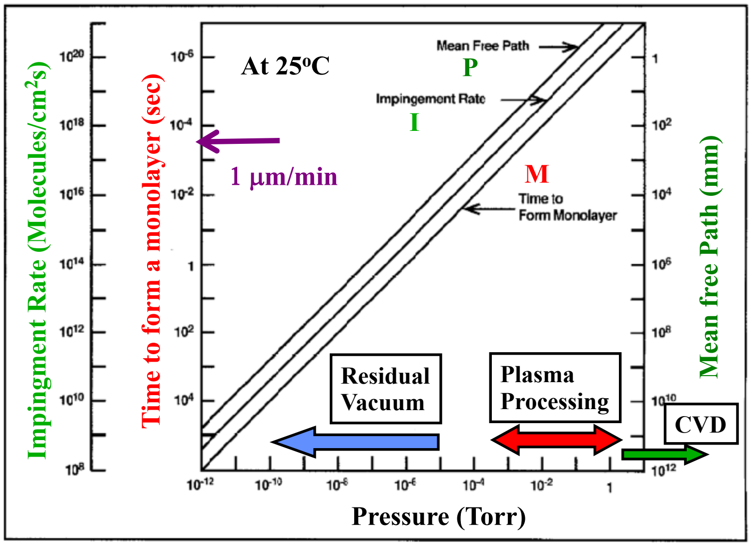
$$\Phi = 3.5\times10^{22}\frac{P}{\sqrt{MT}}$$

- where
  - P = pressure in torr
  - M = molecular weight

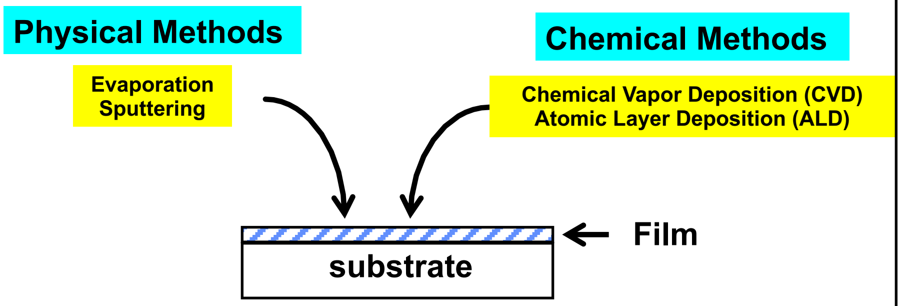
Question

- How long does it take to form a monolayer of gas on the surface of a substrate?

Vacuum Basics (Cont.)



Thin Film Deposition



Physical Methods

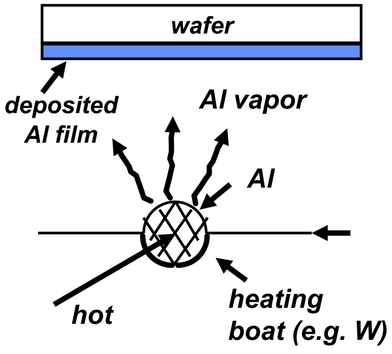
Evaporation
Sputtering

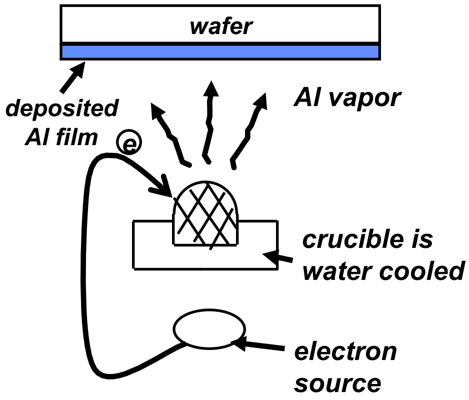
Chemical Methods

Chemical Vapor Deposition (CVD)
Atomic Layer Deposition (ALD)

- Applications
  - Metalization (e.g., Al, TiN, W, Silicide)
  - Polysilicon
  - Dielectric layers (SiO_2, Si_3N_4)

Evaporation

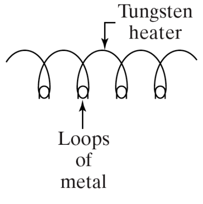




Thermal Evaporation   Electron Beam Evaporation

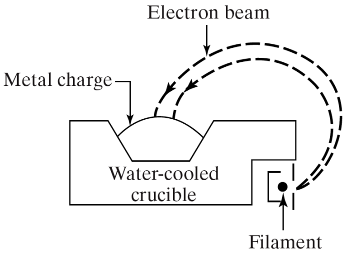
Gas Pressure: $< 10^{-5}$ Torr

Evaporation: Filament & Electron Beam



(a)

(a) Filament evaporation with loops of wire hanging from a heated filament

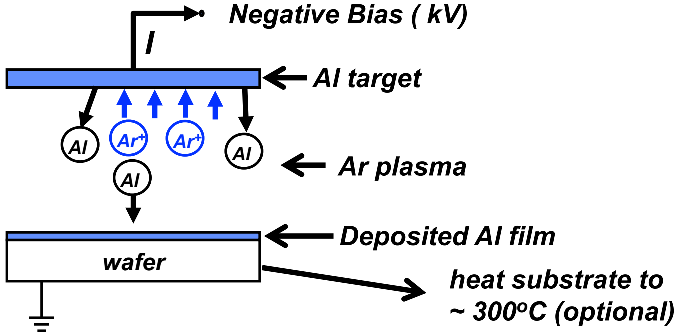


(b)

(b) Electron beam is focused on metal charge by a magnetic field

---

Sputtering



Negative Bias (kV)

Al target

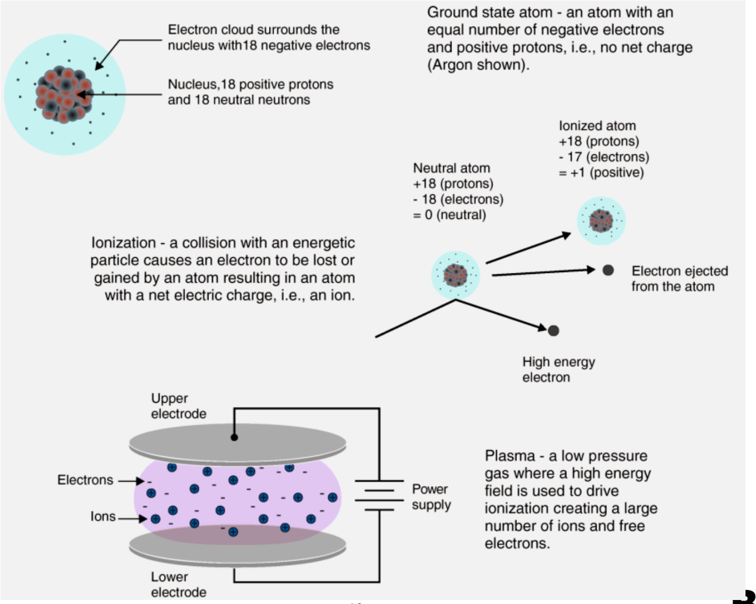
Ar plasma

Deposited Al film

heat substrate to ~ 300°C (optional)

- Gas pressure ~ 1 to 10 mTorr
- Deposition rate = constant × I × S
  - Where I = ion current
  - S = sputtering yield

Plasma Basics



Ground state atom - an atom with an equal number of negative electrons and positive protons, i.e., no net charge (Argon shown).

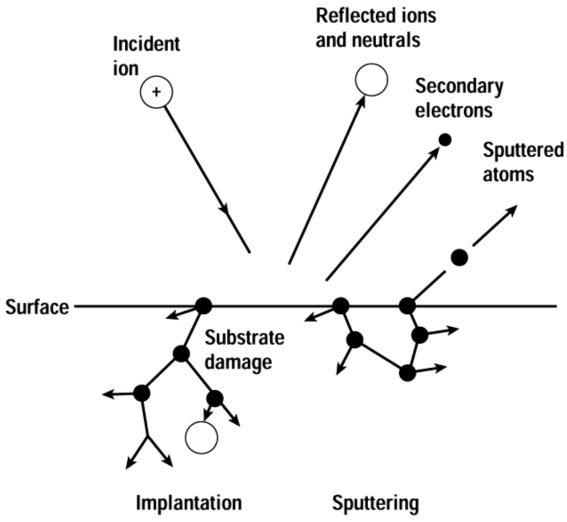
Ionization - a collision with an energetic particle causes an electron to be lost or gained by an atom resulting in an atom with a net electric charge, i.e., an ion.

Plasma - a low pressure gas where a high energy field is used to drive ionization creating a large number of ions and free electrons.

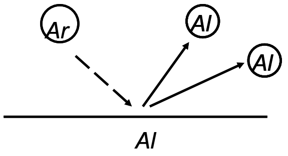
Basic Properties of Plasma

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

Outcomes of Plasma bombardment



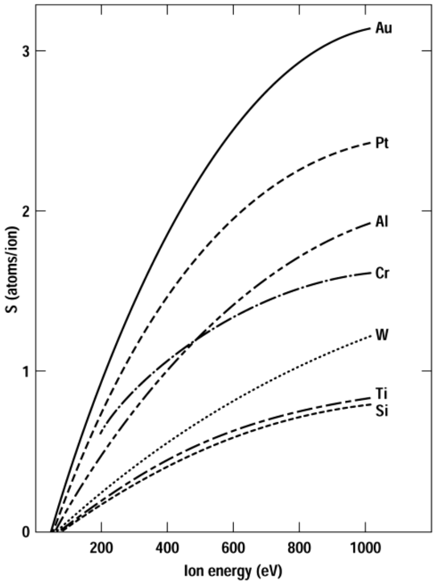
Sputtering Yield



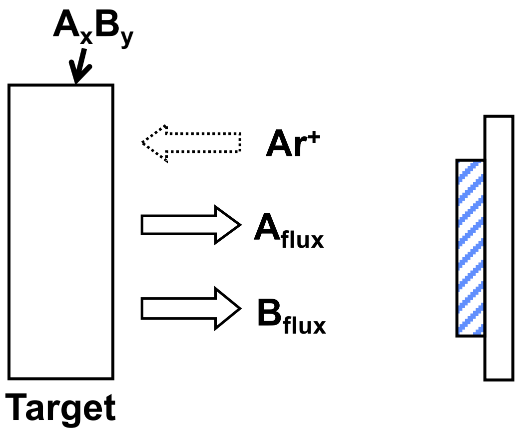
Sputtering Yield S

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

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



Sputtering of Compound Targets



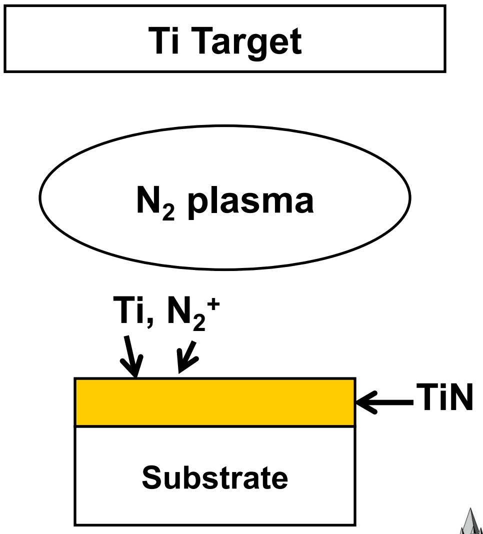
Because $S_A \neq S_B$, target surface will acquire a composition $A_{x'}B_{y'}$ at steady state.

Reactive Sputtering

Sputtering deposition while introducing a reactive gas into the plasma.

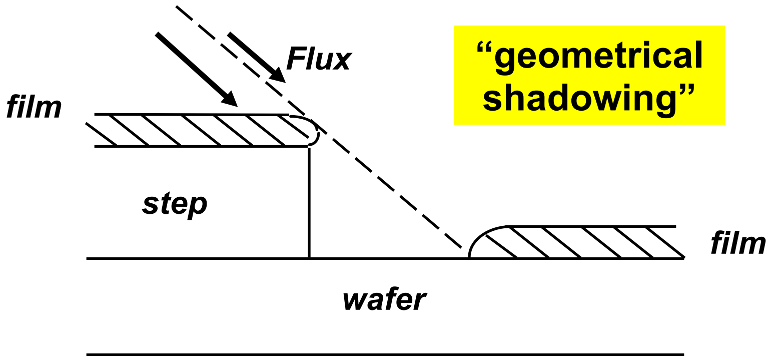
Example:

- **Formation of TiN**
  - **Sputter a Ti target with a nitrogen plasma**



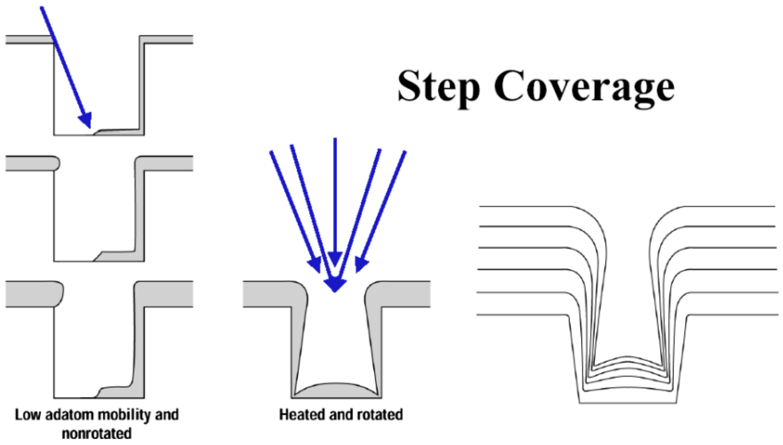
Step Coverage Problem with PVD

- Both evaporation and sputtering have directional fluxes



“geometrical shadowing”

Step Coverage concerns in contacts

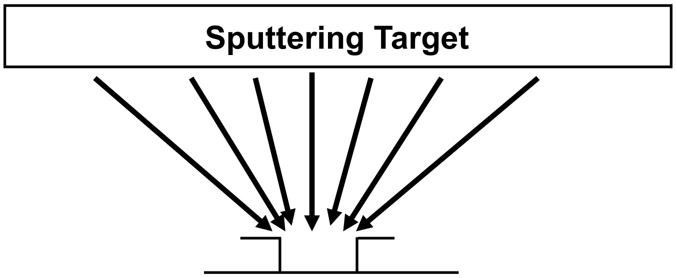


Low adatom mobility and nonrotated

Heated and rotated

Methods to Minimize Step Coverage Problems

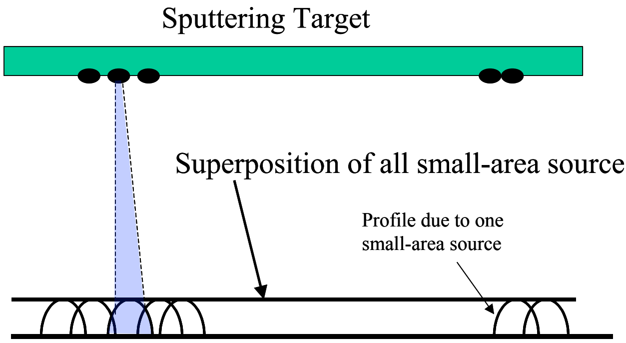
- Rotate + Tilt substrate during deposition
- Elevate substrate temperature (why?)
- Use large-area deposition source



Sputtering Target

Advantages of Sputtering over Evaporation

- For multi-component thin films, sputtering gives better composition control using compound targets.
  - Evaporation depends on vapor pressure of various vapor components and is difficult to control.
- Better lateral thickness uniformity
  - Superposition of multiple point sources

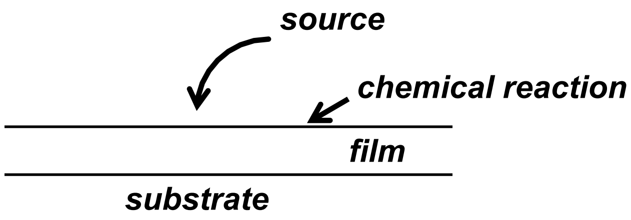


Sputtering Target

Superposition of all small-area sources

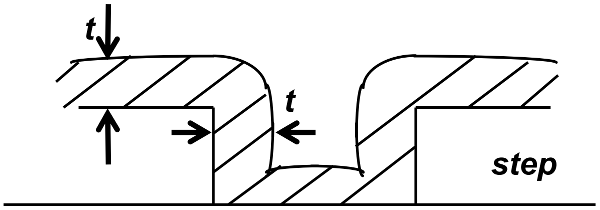
Profile due to one small-area source

Chemical Vapor Deposition (CVD)



More conformal deposition than PVD

Shown here is 100% conformal deposition



LPCVD Examples

- SiO_2

$$SiH_4 + O_2 \xrightarrow{350\sim500^{\circ}\mathrm{C}} SiO_2 + 2H_2 \uparrow$$

- PSG (phosphosilicate glass): doped glass
  - ($\sim 5\%\ P_2O_5 + 95\%\ SiO_2$)
  - The film "reflows" at 900℃

$$4PH_3 + 5O_2 \xrightarrow{350\sim500^{\circ}\mathrm{C}} 2P_2O_5 + 6H_2 \uparrow$$
$$SiH_4 + O_2 \xrightarrow{350\sim500^{\circ}\mathrm{C}} SiO_2 + 2H_2 \uparrow$$

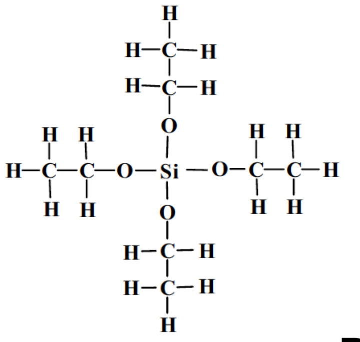
LPCVD Examples

- TEOS (Tetraethylorthosilicate) $Si(OC_2H_5)_4$

$$\boldsymbol{Si(OC_2H_5)_4 \rightarrow SiO_2 + C_XH_YO_Z \uparrow}$$

  - The liquid chemical TEOS is a safer alternative to gases silane or dichlorosilane

Molecular structure of TEOS



LPCVD Examples

- Si_3N_4

$$\boldsymbol{3SiH_4 + 4NH_3 \rightarrow Si_3N_4 + 12H_2 \uparrow}$$

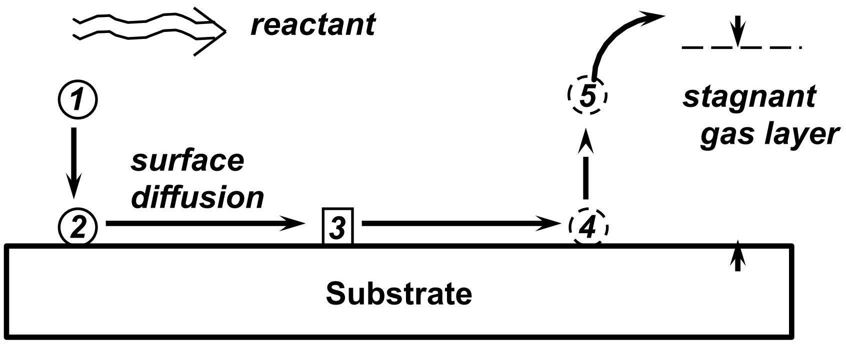
- Polysilicon

$$\boldsymbol{SiH_4 \xrightarrow{600°C} Si + 2H_2 \uparrow}$$

- Tungsten

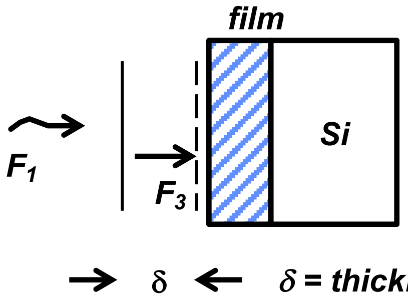
$$\boldsymbol{WF_6 + 3H_2 \rightarrow W + 6HF \uparrow}$$

CVD Mechanisms



1 = Diffusion of reactant to surface
2 = Absorption of reactant to surface
3 = Chemical reaction
4 = Desorption of gas by-products
5 = Out-diffusion of by-product gas

CVD Deposition Rate [Grove Model]



$$\frac{D}{\delta} = h_G$$

$$k_S = k_0 e^{-\frac{\Delta E}{kT}}$$

δ = *thickness of stagnant layer*

$$F_1 = D\frac{C_G - C_S}{\delta}$$

$$F_3 = k_S C_S$$

At steady state, $F_1 = F_3$

Grove model of CVD (cont'd)

$$F_1 = D\frac{C_G - C_S}{\delta} = h_G(C_G - C_S) = k_S C_S = F_3$$

$$C_S = \frac{h_G}{k_S + h_G} C_G$$

$$F_3 = \frac{k_S h_G}{k_S + h_G} C_G = \frac{1}{\frac{1}{h_G} + \frac{1}{k_S}} C_G$$

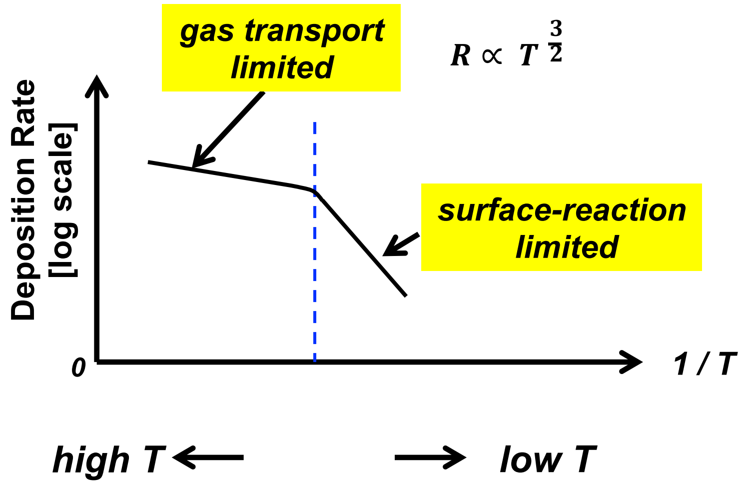
Film growth rate is constant with time:

$$\frac{dx}{dt} = \frac{F_3}{N}$$

where N = atomic density of deposited film

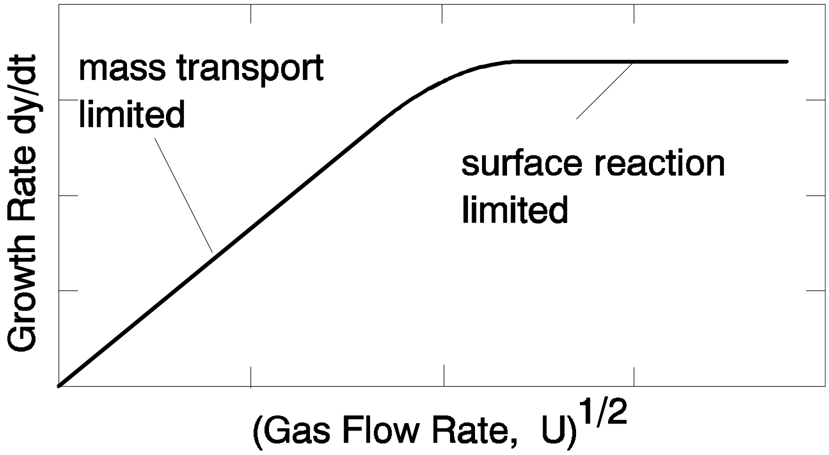
Note: This result is exactly the same as the Deal-Grove model for thermal oxidation with oxide thickness = 0

Deposition Rate vs. Temperature



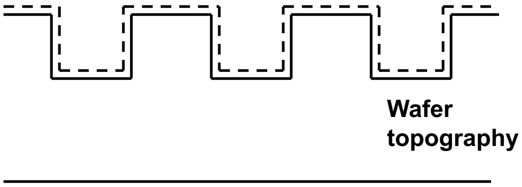
$$R \propto T^{\frac{3}{2}}$$

Growth Rate Dependence on Flow Velocity



CVD Features

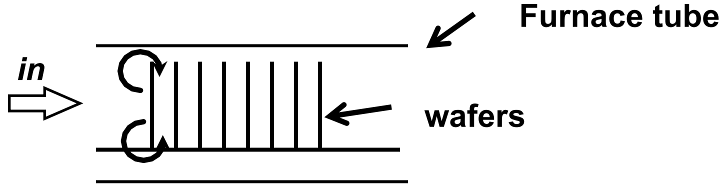
1. More conformal deposition if T is uniform



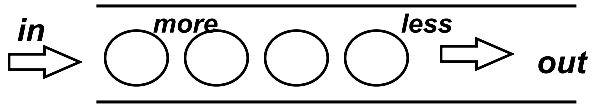
2. Inter-wafer and intra-wafer thickness uniformity less sensitive to gas flow patterns. (i.e. wafer placement).

Comments about CVD

(1) Sensitivity to gas flow pattern

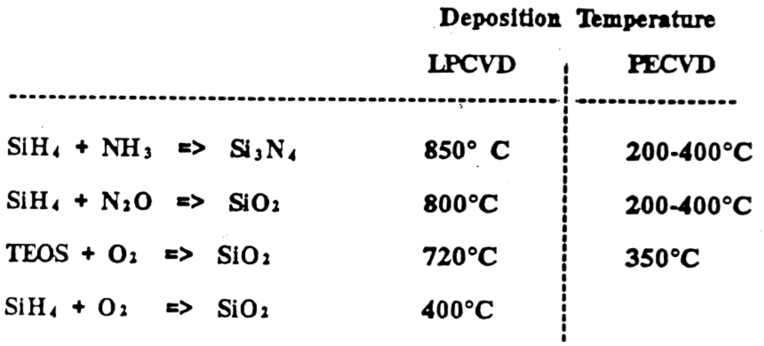


(2) Mass depletion problem

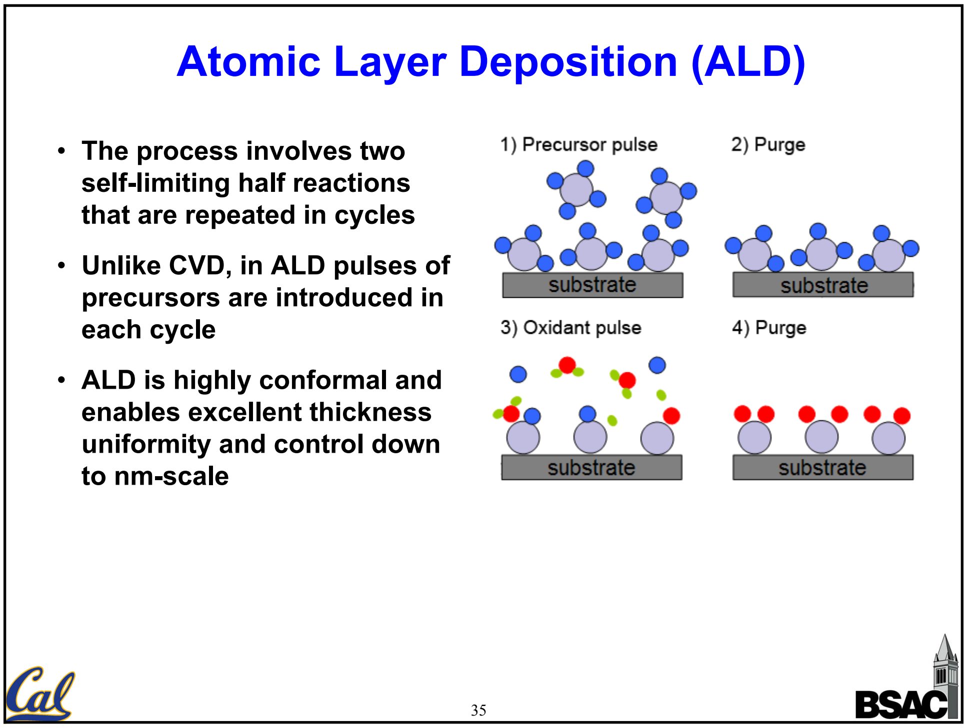


Plasma Enhanced CVD (PECVD)

- Ionized chemical species allows a lower process temperature to be used
  - Plasma helps dissociate the precursor molecules at lower temperatures).
- Film properties (e.g. mechanical stress) can be tailored by controlling ion bombardment with substrate bias voltage.



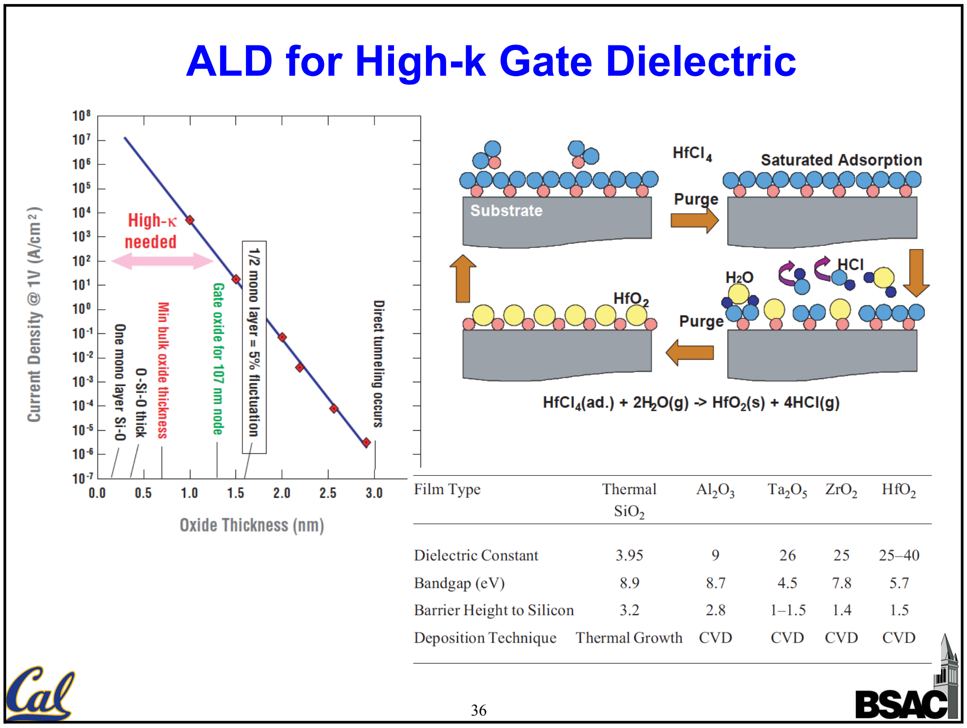
	Deposition Temperature	
	LPCVD	PECVD
$SiH_4 + NH_3$ => Si_3N_4	850° C	200-400°C
$SiH_4 + N_2O$ => SiO_2	800°C	200-400°C
TEOS + O_2 => SiO_2	720°C	350°C
$SiH_4 + O_2$ => SiO_2	400°C	



Atomic Layer Deposition (ALD)

- The process involves two self-limiting half reactions that are repeated in cycles
- Unlike CVD, in ALD pulses of precursors are introduced in each cycle
- ALD is highly conformal and enables excellent thickness uniformity and control down to nm-scale

---



ALD for High-k Gate Dielectric

$HfCl_4$(ad.) + $2H_2O$(g) -> HfO_2(s) + 4HCl(g)

Film Type	Thermal SiO_2	Al_2O_3	Ta_2O_5	ZrO_2	HfO_2
Dielectric Constant	3.95	9	26	25	25–40
Bandgap (eV)	8.9	8.7	4.5	7.8	5.7
Barrier Height to Silicon	3.2	2.8	1–1.5	1.4	1.5
Deposition Technique	Thermal Growth	CVD	CVD	CVD	CVD