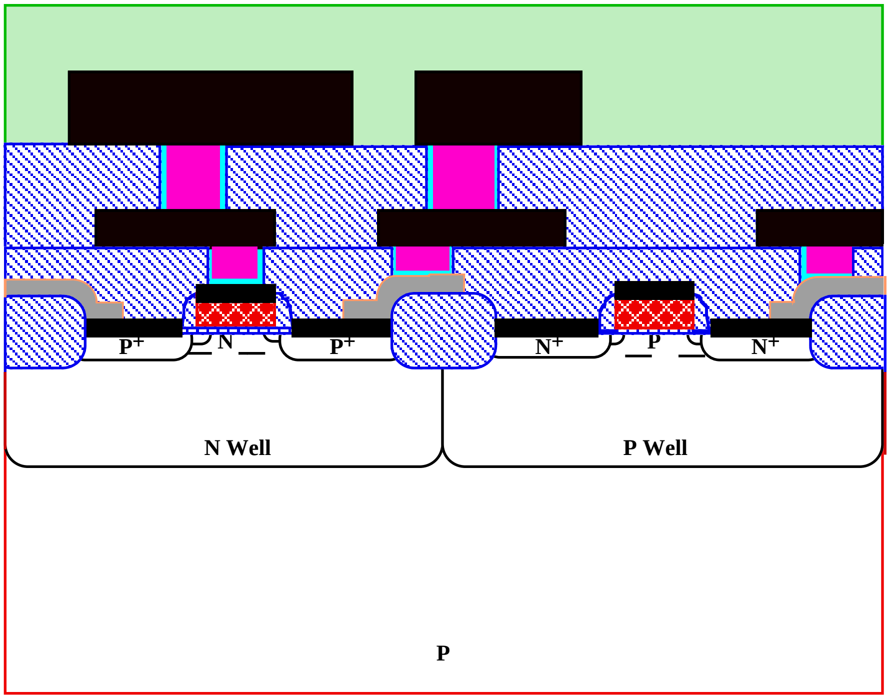
EE 212 FALL 1999-00

THIN FILM DEPOSITION - Chapter 9

Introduction



- **Many films, made of many different materials are deposited during a standard CMOS process.**

- **In this set of notes we describe the requirements, methods and equipment used to deposit these thin films.**

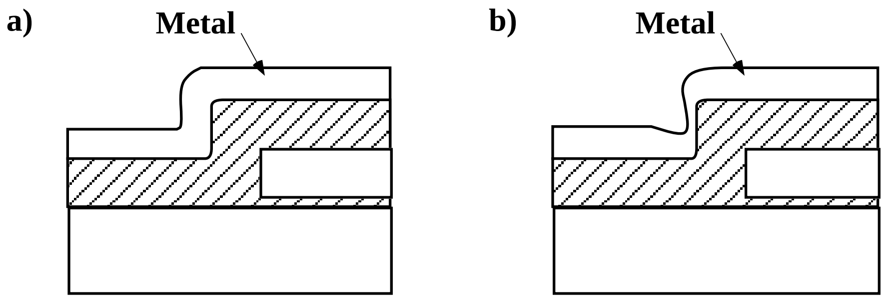
- **Simulation tools have become very important in recent years and will be used to illustrate some of the important concepts involved in deposition.**

Requirements or desirable traits for deposition:

1. **Desired composition, low contaminates, good electrical and mechanical properties.**

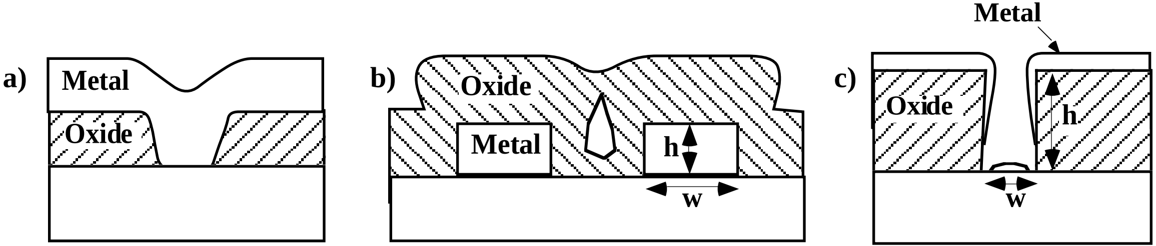
2. Uniform thickness across wafer, and wafer-to-wafer.
3. Good step coverage (“conformal coverage”).
4. Good filling of spaces.
5. Planarized films .

Step Coverage Issues:

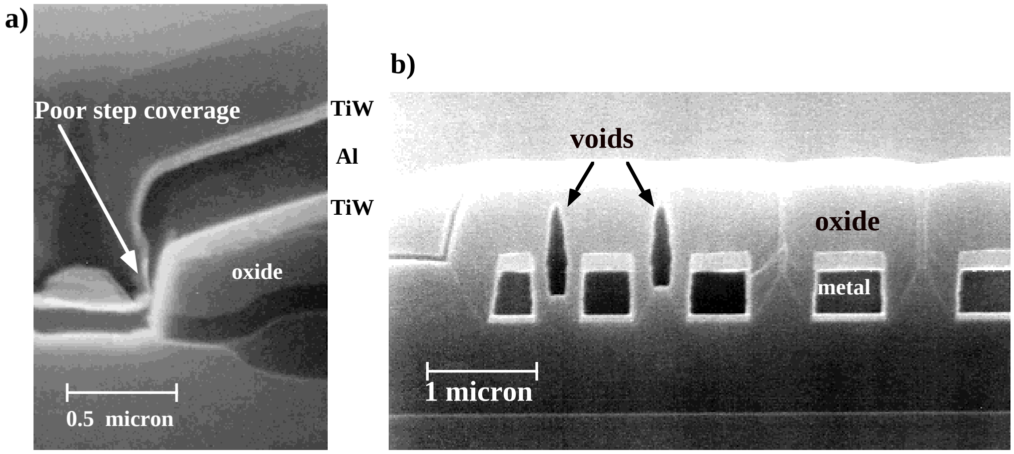


Uniform Poor coverage

Filling Issues:

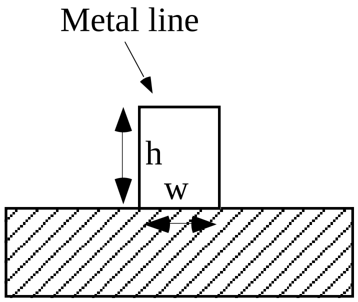


Good Void formation Poor bottom filling

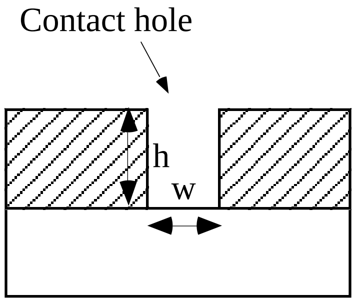


- Examples or problems in actual structures. a) step coverage in sputter deposition of Al. b). voids in CVD oxide

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



a



b

- **NTRS Roadmap for Interconnects:**

Year of 1st DRAM Shipment	1997	1999	2003	2006	2009	2012
Minimum Feature Size, F_{min} (nm)	250	180	130	100	70	50
DRAM Bits/Chip	256M	1G	4G	16G	64G	256G
DRAM Chip Size (mm^2)	280	400	560	790	1120	1580
MPU Chip Size (mm^2	300	360	430	520	620	750
Wiring Levels - Logic	**6**	**6-7**	**7**	**7-8**	**8-9**	**9**
Min metal CD (nm)	**250**	**180**	**130**	**100**	**70**	**50**
Min contact/via CD nm	**280/360**	**200/260**	**140/180**	**110/140**	**80/100**	**60/70**
Metal Aspect Ratio	**1.8**	**1.8**	**2.1**	**2.4**	**2.7**	**3.0**
Contact aspect ratio (DRAM)	**5.5**	**6.3**	**7.5**	**9**	**10.5**	**12**
Via aspect ratio (logic)	**2.2**	**2.2**	**2.5**	**2.7**	**2.9**	**3.2**
Metal resistivity (µohm-cm)	3.3	2.2	2.2	2.2	<1.8	<1.8
Interlevel metal dielectric constant	3.0-4.1	2.5-3.0	1.5-2.0	1.5-2.0	<1.5	<1.5

- **Note the aspect ratios and the need for new materials.**

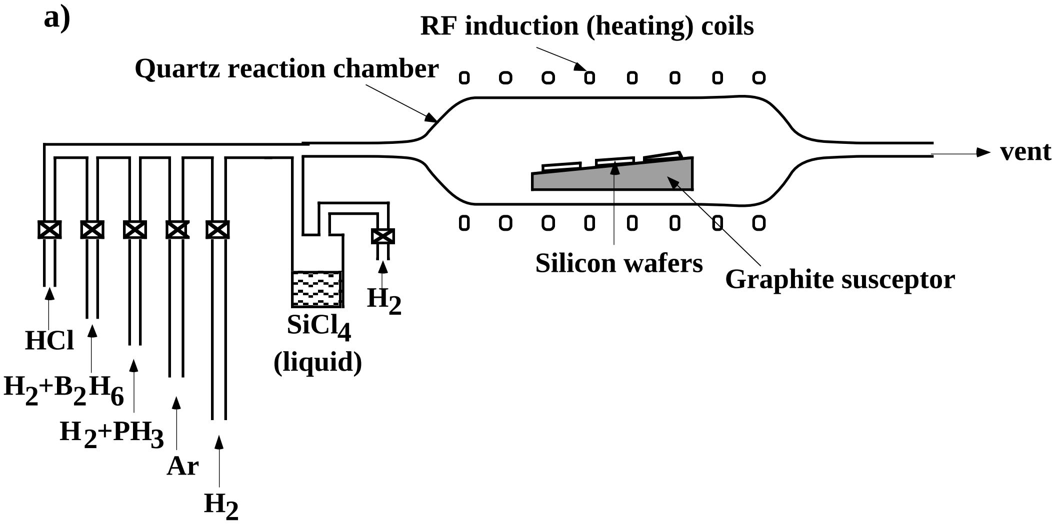
- **Note also the number of metal layers requiring more deposition steps.**

Historical Development and Basic Concepts

- **Two main types of deposition methods have been developed and are used in CMOS technology:**
  - **Chemical Vapor Deposition (CVD)**
    - **APCVD, LPCVD, PECVD, HDPCVD**
  - **Physical Vapor Deposition (PVD)**
    - **evaporation, sputter deposition**

Chemical Vapor Deposition (CVD)

a)



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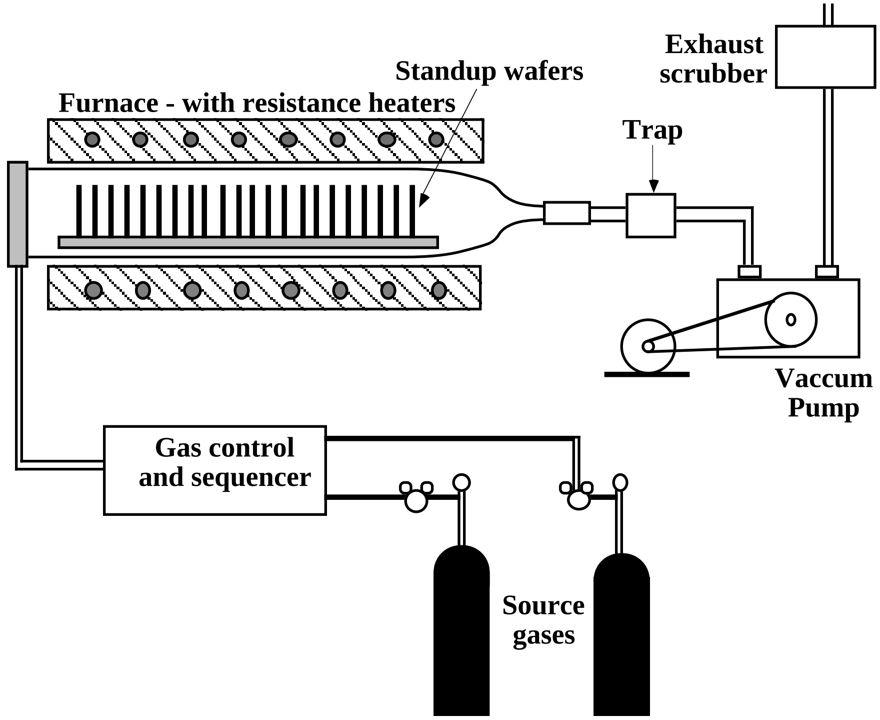


- **Examples:**
  - **Deposition of epitaxial (single crystal) silicon in cold-walled, atmospheric pressure system (figure a above):**

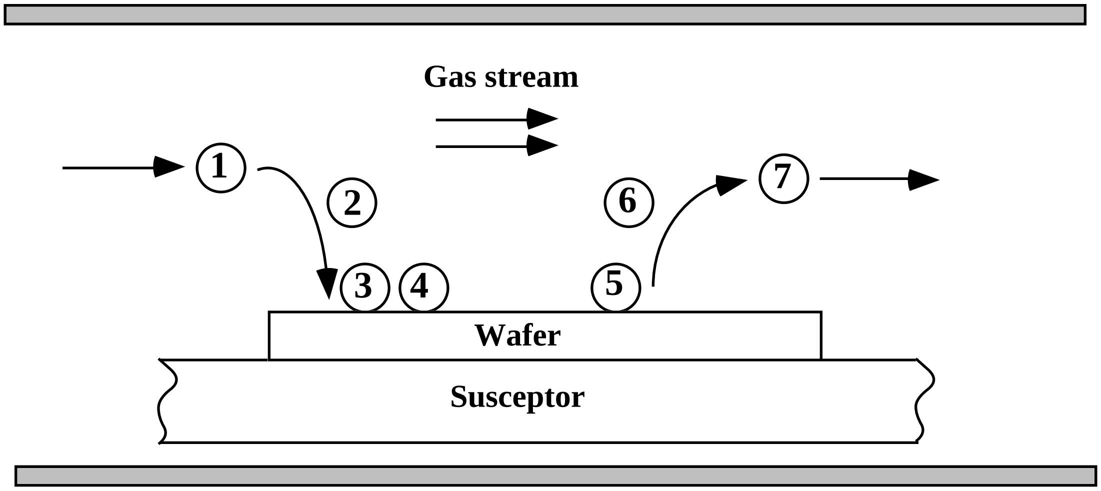
$$SiCl_4(g) + 2H_2(g) \Leftrightarrow Si(s) + 4HCl(g) \qquad (1)$$

$$SiH_4(g) \Leftrightarrow Si(s) + 2H_2(g) \qquad (2)$$

  - **Deposition of amorphous silicon dioxide in hot-walled, low pressure system (figure b above):**

$$SiH_4(g) + O_2(g) \Leftrightarrow SiO_2(s) + 2H_2(g) \qquad (3)$$

Atmospheric Pressure Chemical Vapor Deposition (APCVD)



- **Steps involved in a CVD process:**

1. Transport of reactants to the deposition region.

***2. Transport of reactants from the main gas stream through the boundary layer to the wafer surface.**

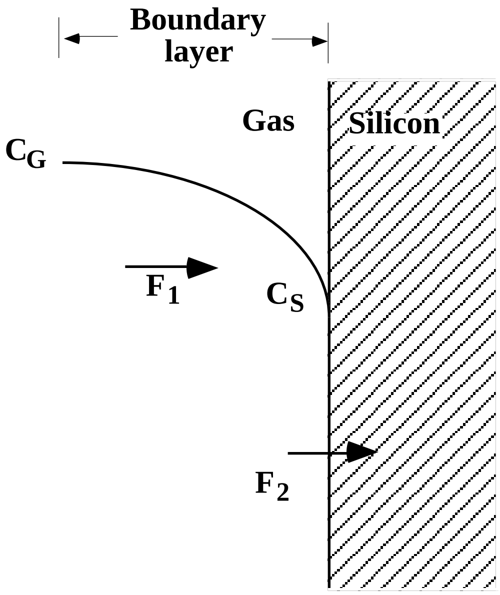
***3. Adsorption of reactants on the wafer surface.**

***4. Surface reactions, including: chemical decomposition or reaction, surface migration to attachment sites (kinks and ledges); site incorporation; and other surface reactions (emission and redeposition for example).**

***5. Desorption of by-products.**

6. Transport of by-products through the boundary layer.

7. Transport of by-products away from the deposition region.



F_1 = diffusion flux of reactant species to the wafer = mass transfer flux, step 2

F_2 = flux of reactant consumed by the surface reaction = surface reaction flux, steps 3-5

$$F_1 = h_G(C_G - C_S) \qquad (4)$$

where h_G is the mass transfer coefficient (in cm/sec).

$$F_2 = k_S C_S \qquad (5)$$

where k_S is the surface reaction rate (in cm/sec).

- In steady state:

$$F = F_1 = F_2 \qquad (6)$$

- Equating Equations (4) and (5) leads to

$$C_S = C_G \left(1 + \frac{k_S}{h_G} \right)^{-1} \qquad (7)$$

- The growth rate of the film is now given by

$$v = \frac{F}{N} = \frac{k_S h_G}{k_S + h_G} \frac{C_G}{N} = \frac{k_S h_G}{k_S + h_G} \frac{C_T}{N} Y \qquad (8)$$

where N is the number of atoms incorporated per unit volume in the film (5×10^{22} cm^{-3} for the case of epitaxial Si deposition) and Y is the mole fraction (partial pressure/total pressure) of the incorporating species.

- Note the similarity of this analysis to the Deal Grove oxidation model (Chapter 6).

- From this one sees that the deposition velocity is determined by the smaller of k_S or h_G, leading to two limiting cases:

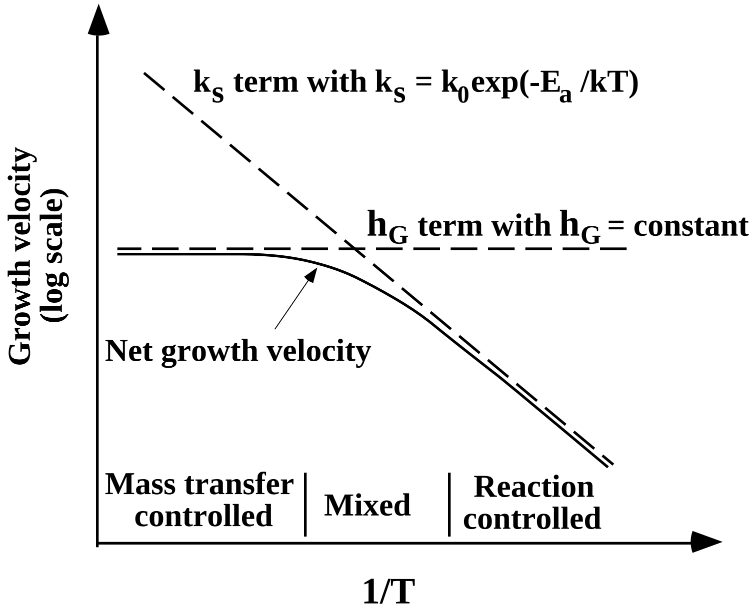
1. If $k_S << h_G$, then we have the surface reaction controlled case:

$$v \cong \frac{C_T}{N} k_S Y \qquad (9)$$

2. If $h_G << k_S$, then we have the mass transfer, or gas phase diffusion, controlled case:

$$v \cong \frac{C_T}{N} h_G Y \qquad (10)$$

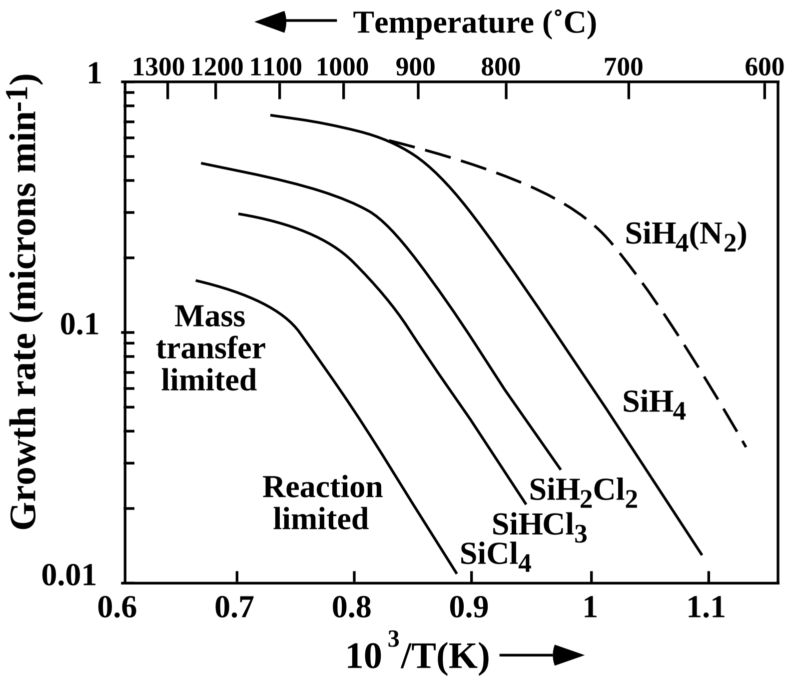
Experimentally, the rate constants are given by:



- The surface term is Arrhenius with E_A depending on the particular reaction (1.6 eV for single crystal silicon deposition).

- h_G is ≈ constant (diffusion through boundary layer).

- As an example, Si epitaxial deposition is shown below (at 1 atm. pressure). Note same E_A values and $h_G \approx$ constant. Rate is roughly proportional to (mol. wt.)$^{1/2}$.



- **Key points:**
  - **k_S limited deposition is VERY temp sensitive.**
  - **h_G limited deposition is VERY geometry (boundary layer) sensitive.**

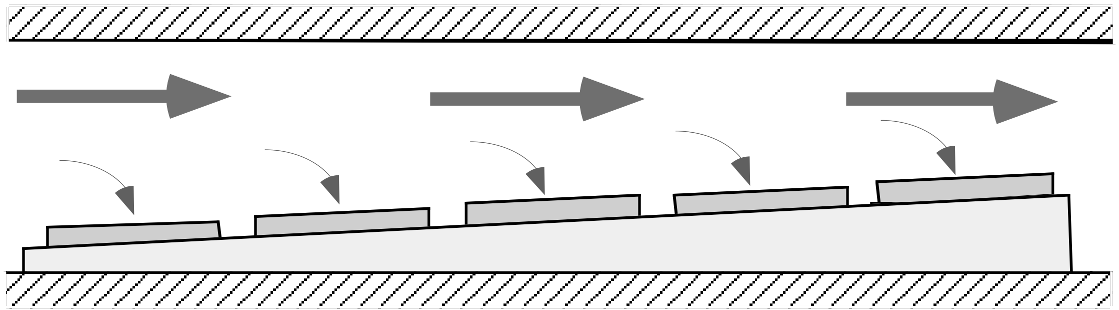
- **Si epi deposition often done at high T to get high quality single crystal growth. ∴ h_G controlled. ∴ horizontal reactor configuration.**

- **h_G corresponds to diffusion through a boundary layer of thickness δ_S.**

$$h_G = \frac{D_G}{\delta_S} \qquad (11)$$

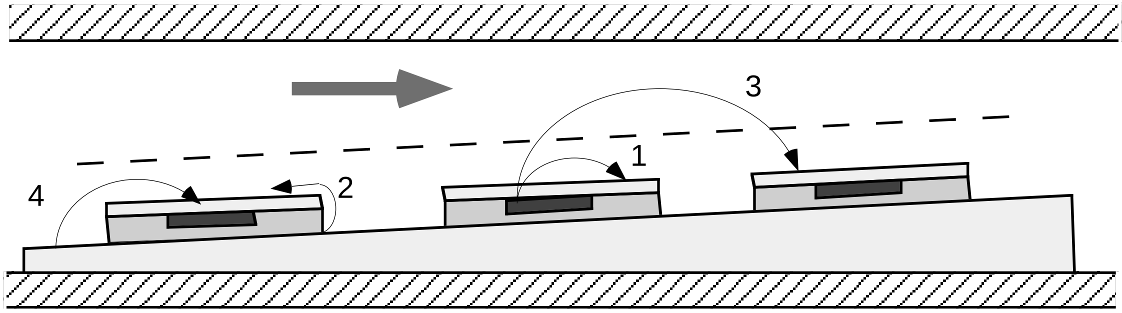
- **But δ_S typically is not constant as the gas flows along a surface.**

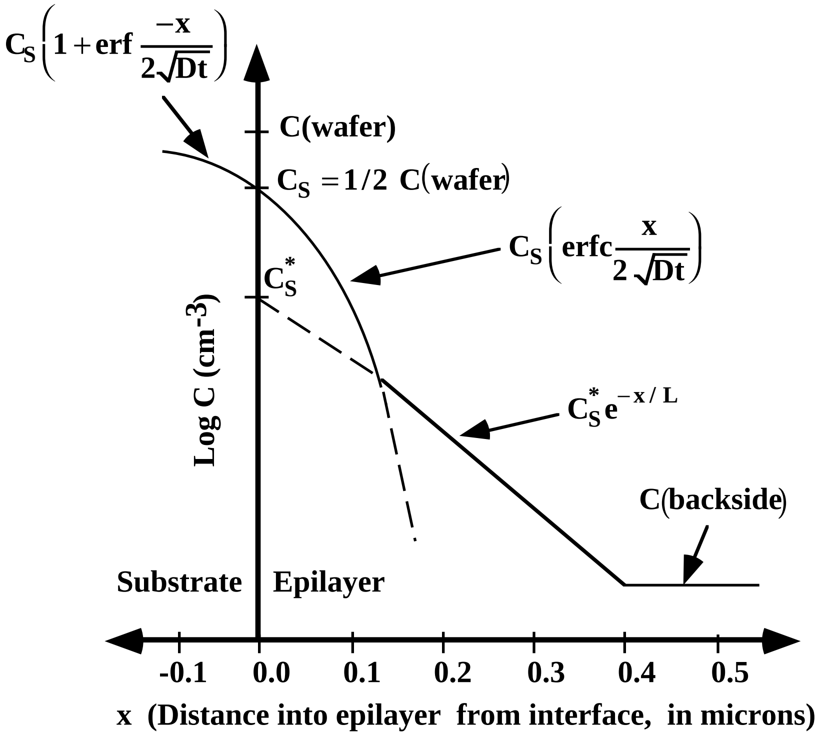
- **∴ a special reactor geometry is required to get uniform deposition.**



- **Tilting the susceptor increases the gas velocity which helps to keep δ_S constant.**

- **Autodoping is another problem with these kinds of systems:**





Low Pressure Chemical Vapor Deposition (LPCVD)

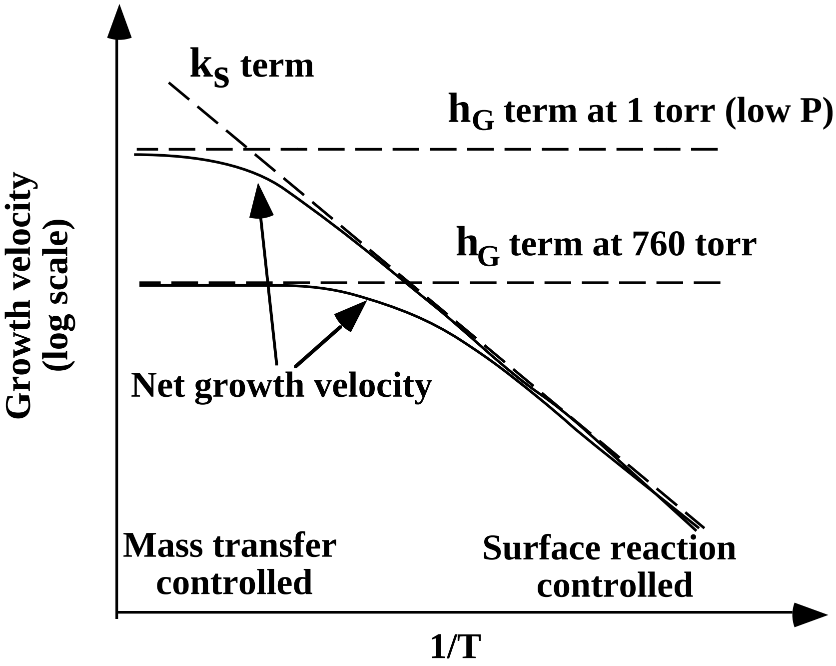
- **Atmospheric pressure systems have major drawbacks**
  - **If operated at high T, a horizontal configuration must be used (few wafers at a time).**
  - **If operated at low T, the deposition rate goes down and throughput is again low.**

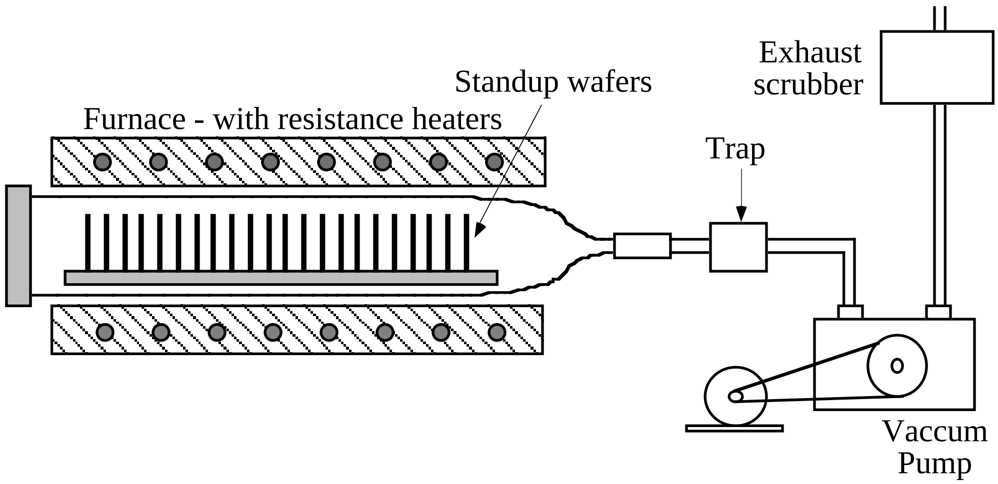
- **The solution is to operate at low pressure. In the mass transfer limited regime,**

$$h_G = \frac{D_G}{\delta_S} \quad \text{But} \quad D_G \propto \frac{1}{P_{total}} \qquad (12)$$

- **D_G will go up 760 times at 1 torr, while δ_S increases by about 7 times. Thus h_G will increase by about 100 times.**

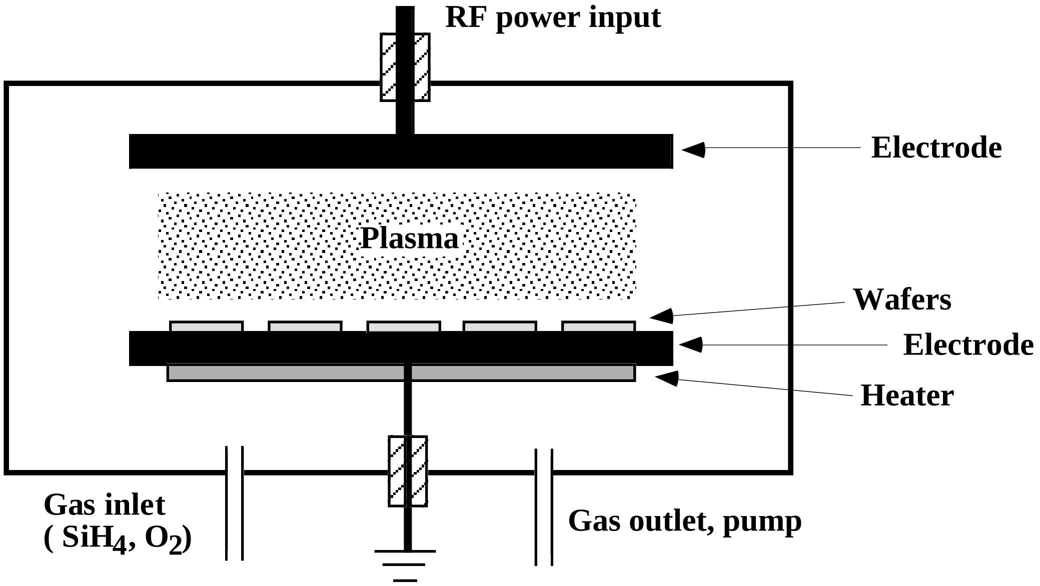
- **Transport of reactants from gas phase to surface through boundary layer is no longer rate limiting.**





- **Process is more T sensitive, but can use resistance heated, hot-walled system for good control of temperature and can stack wafers.**

Plasma Enhanced CVD (PECVD)



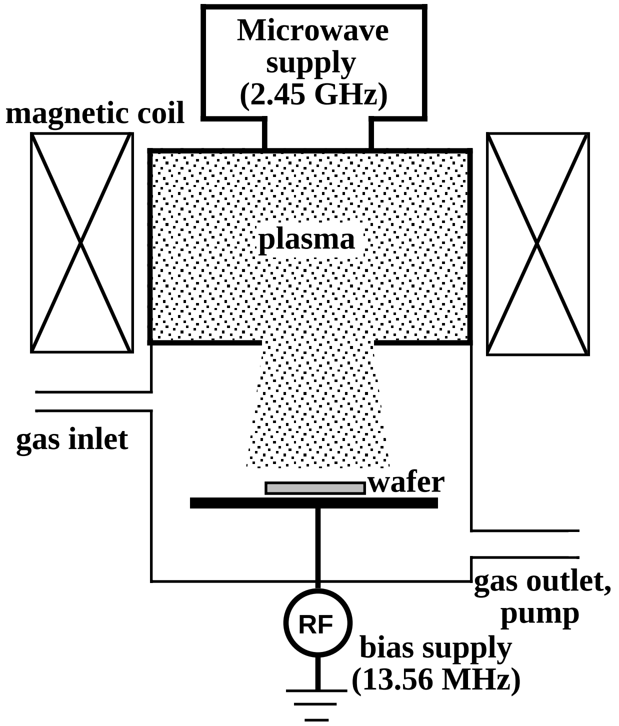
- **Non-thermal energy to enhance processes at lower temperatures.**

- **Plasma consists of electrons, ionized molecules, neutral molecules, neutral and ionized fragments of broken-up molecules, excited molecules and free radicals.**

- **Free radicals are electrically neutral species that have incomplete bonding and are extremely reactive. (e.g. SiO, SiH_3, F)**

- **The net result from the fragmentation, the free radicals, and the ion bombardment is that the surface processes and deposition occur at much lower temperatures than in non-plasma systems.**

High Density Plasma (HDP) CVD



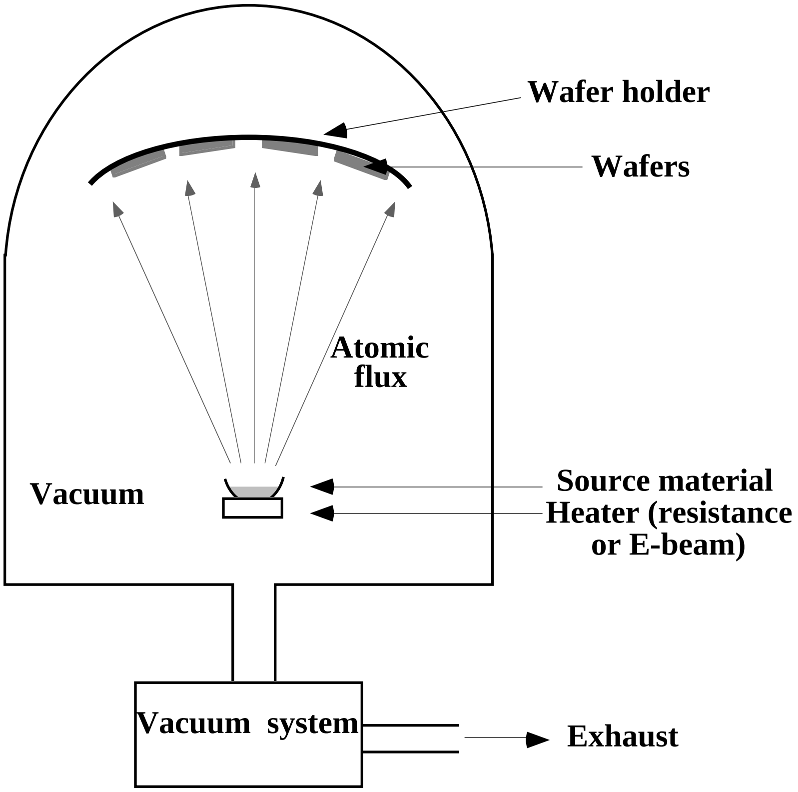
- **Remote high density plasma with independent RF substrate bias.**

- **Allows simultaneous deposition and sputtering for better planarization and void-free films (later).**

- **Mostly used for SiO_2 deposition in backend processes.**

Physical Vapor Deposition (PVD)

- **PVD uses mainly physical processes to produce reactant species in the gas phase and to deposit films.**



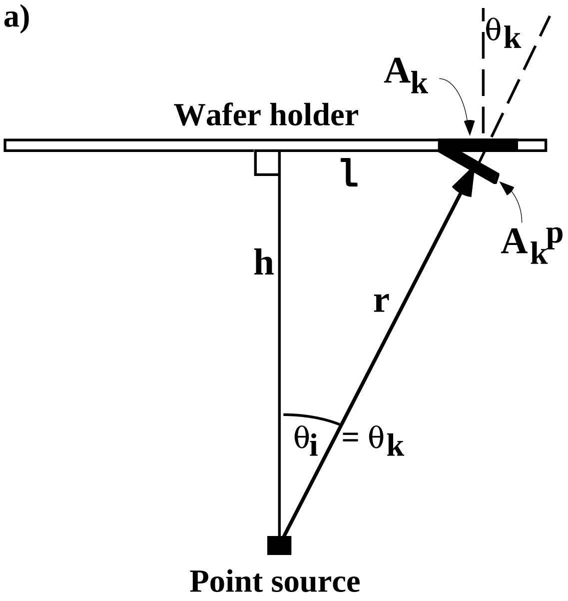
- **In evaporation, source material is heated in high vacuum chamber. ($P < 10^{-5}$ torr)**

- **Mostly line-of-sight deposition since pressure is low.**

- **Deposition rate is determined by emitted flux and by geometry of the target.**

- **The evaporation source can be considered either a point source or as a small area surface source (latter is more applicable to most evaporation systems).**

a)



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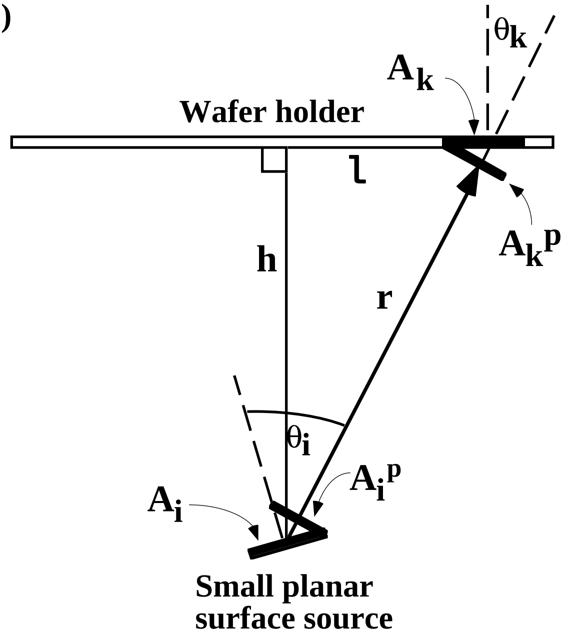


Point source

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

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

Small Planar Surface Source

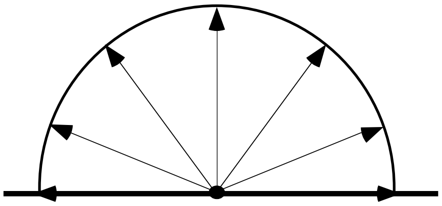
$$F_k^P = \frac{R_{evap}}{\pi r^2} \cos^n \theta_i$$

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

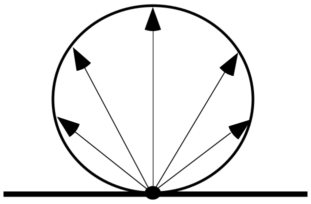
- **Ω is the solid angle over which the source emits (4π if all directions); N is the density of the material being deposited.**

- **The outward flux F_k^P from point source P, is independent of θ_i, while the outward flux from a small area surface source, varies as $\cos^n \theta_i$.**
  - **uniform, isotropic flux from a point source**

  - **ideal cosine emission for n = 1 from a surface**
  - **even more directed or anisotropic for n > 1**

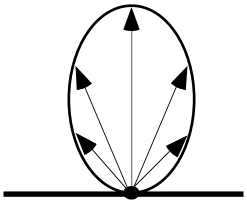


a. Uniform (isotropic) emission from a point source



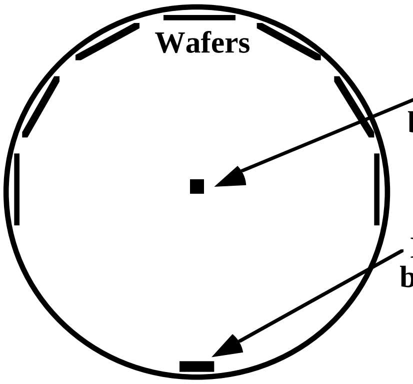
b. Ideal cosine emission from a small planar surface source.

(n = 1 in $\cos^n\theta$ distribution)



c. Non-ideal, more anisotropic emission from a small planar surface source.

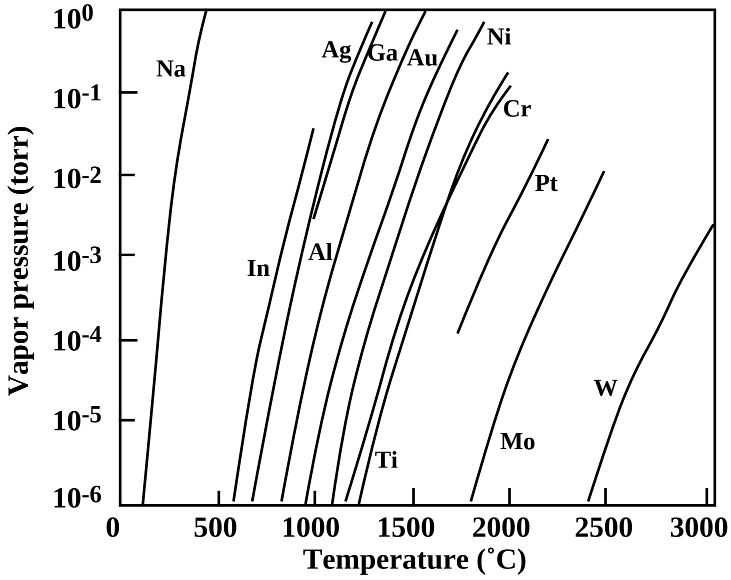
(n > 1 in $\cos^n\theta$ distribution)



Location of source which behaves like an ideal point source

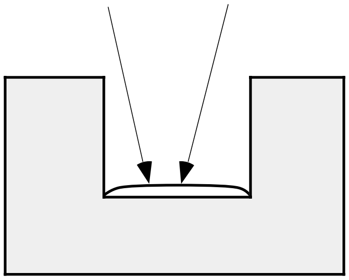
Location of source which behaves like an ideal small area surface source

- **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**
    - **Deposition rate of some elements very slow**
    - **Difficult to evaporate alloys and compounds**
    - **Step coverage is poor (line of sight and $S_c \approx 1$)**
    - **Rarely used today**

a)



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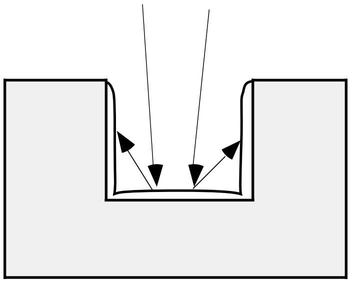
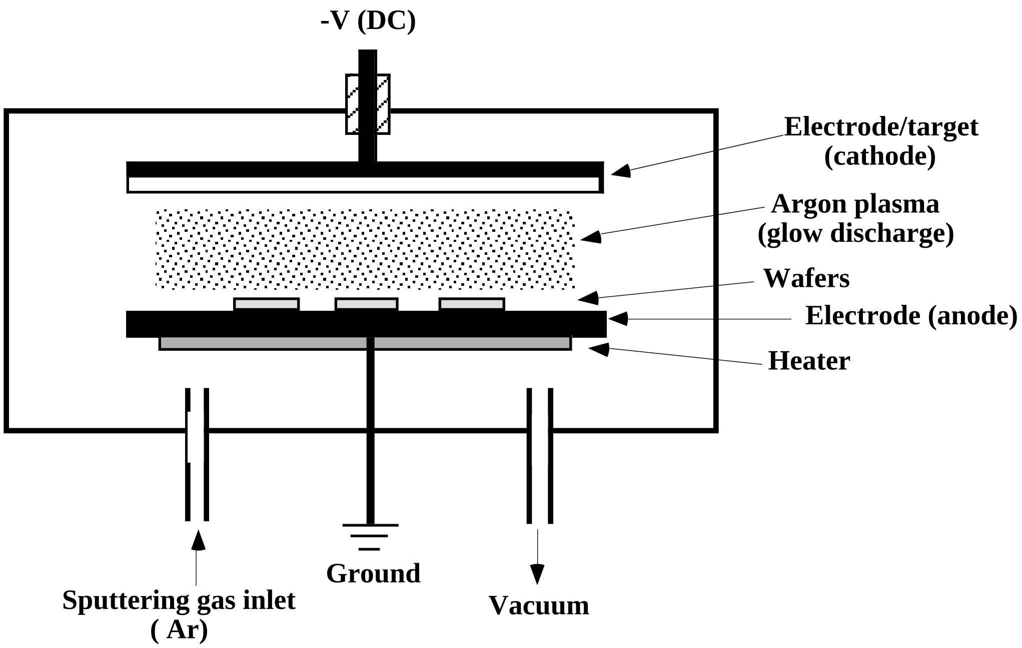
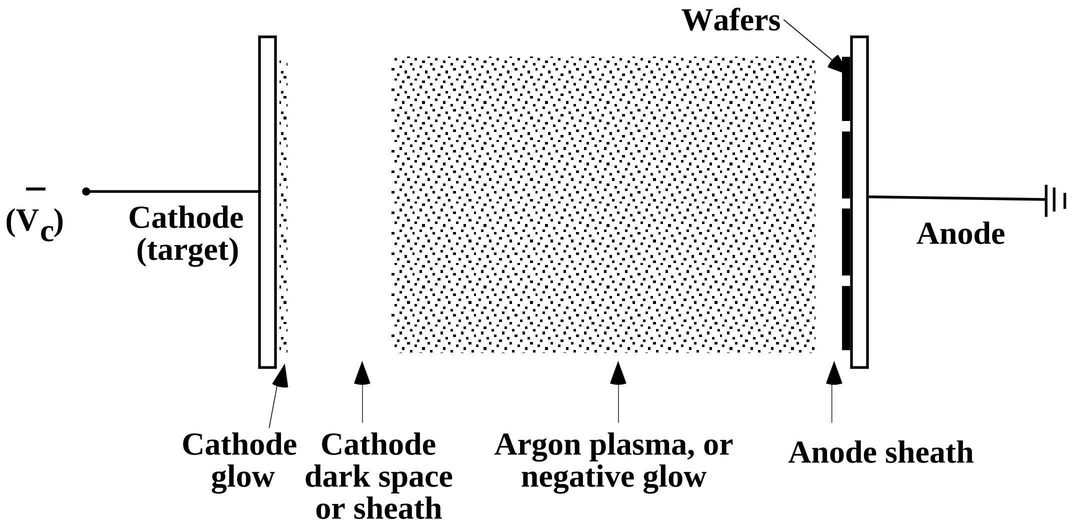


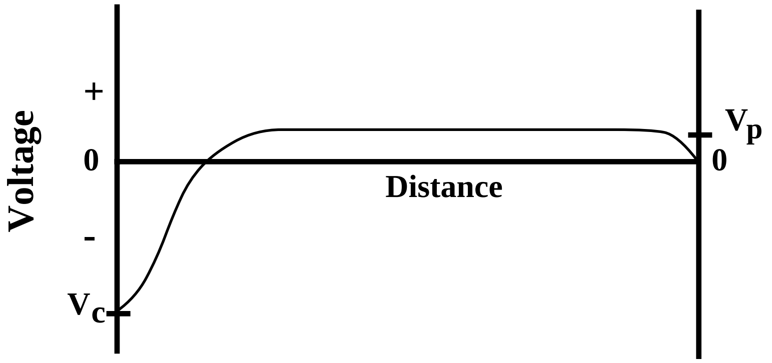
Sputter Deposition

- **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.**

DC Sputter Deposition







- **The plasma contains ~ equal numbers of positive argon ions and electrons as well as neutral argon atoms.**

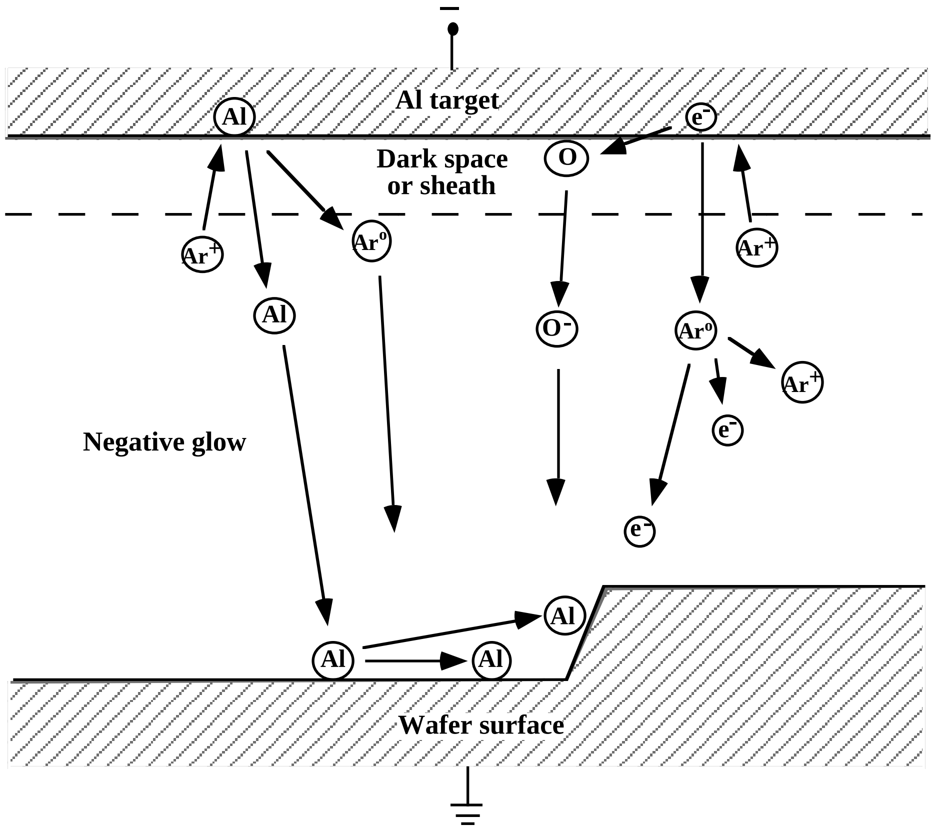
- **Most of voltage drop of the system (due to applied DC voltage, V_c) occurs over cathode sheath.**

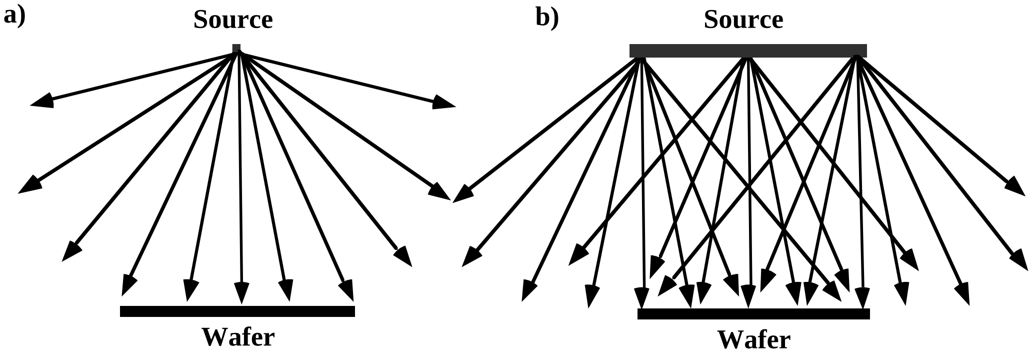
- **Ar^+ ions are accelerated across cathode sheath to the negatively charged cathode, striking that electrode (the “target”) and sputtering off atoms (e.g. Al). These travel through plasma and deposit on wafers sitting on anode.**

- **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.**

- **Y does not vary between target materials as much as the vapor pressure does. Controlling composition of alloys is easier with sputtering than with evaporation.**

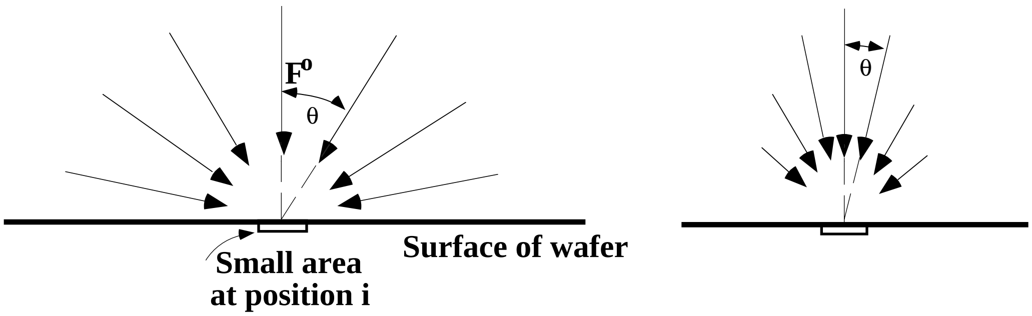




- **Sputtering targets are generally large and provide a wide range of arrival angles in contrast to a point source.**

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



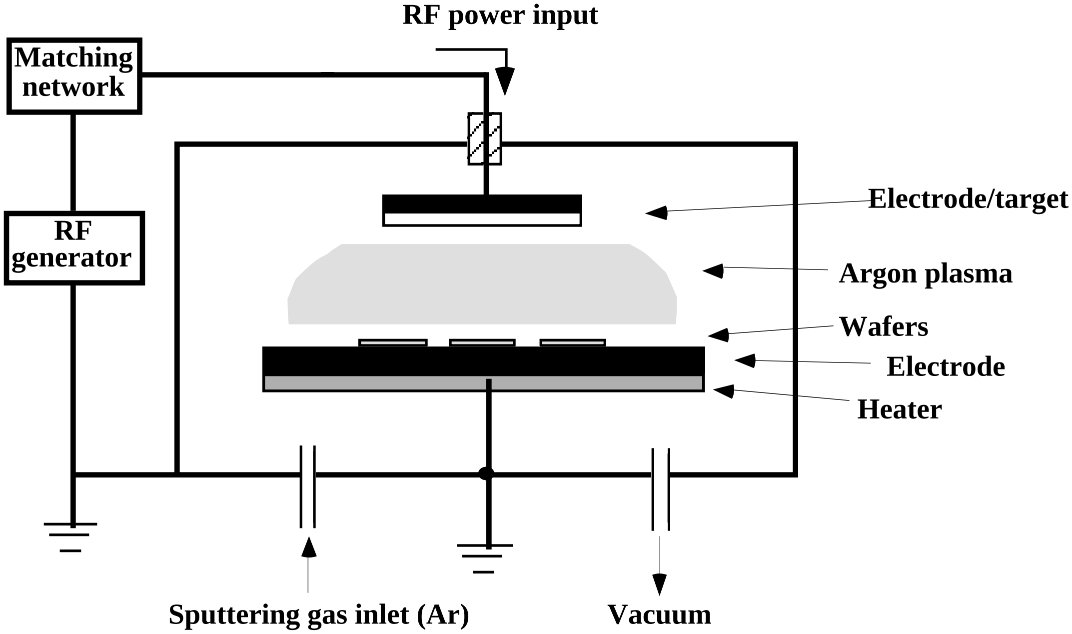
- **Arrival angle distribution generally described by $\cos^n\theta$ distribution (the normal component of flux striking the surface detrmines the deposition or growth rate).**

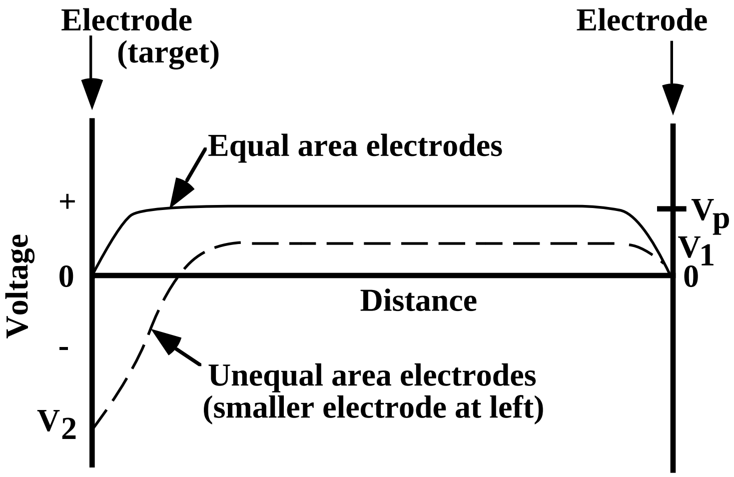
- **Size and type of source, system geometry and collisions in gas phase important in arrival angle distribution.**

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 must be zero.) ∴ continuous sputtering.**

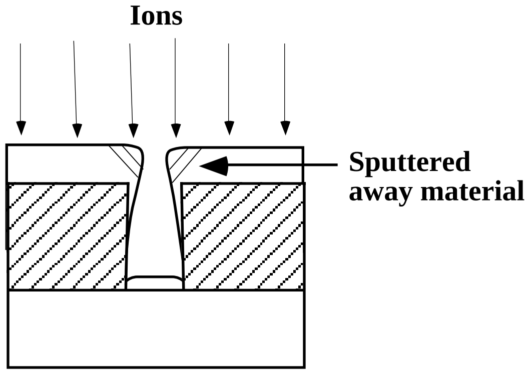
- **When the electrode areas are not equal, the field must be higher at the smaller electrode (higher current density), to maintain overall current continuity**

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

- **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_1/V_2.**

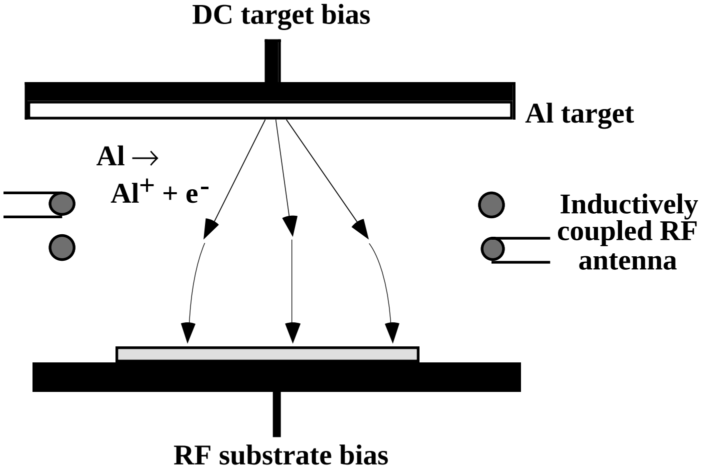
- **The wafer electrode can be separately biased (RF), which allows cleaning or controlled sputtering of the wafer with Ar^+ ions (bias-sputter deposition).**

- **This can allow more conformal deposition because the ions are highly directional and sputter selectively.**

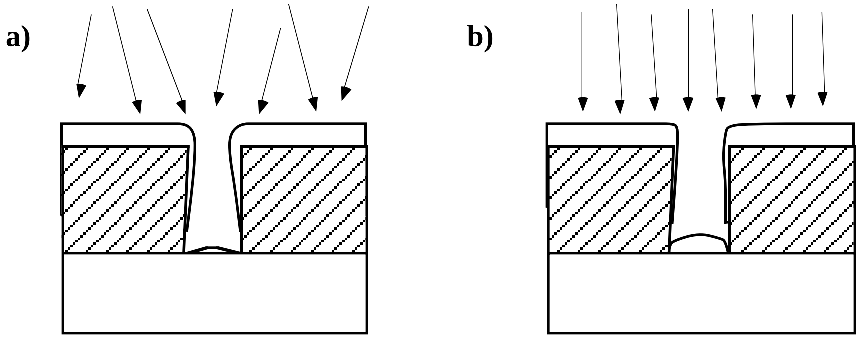


Ionized Sputter Deposition or HDP Sputtering

- **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.**



Manufacturing Methods

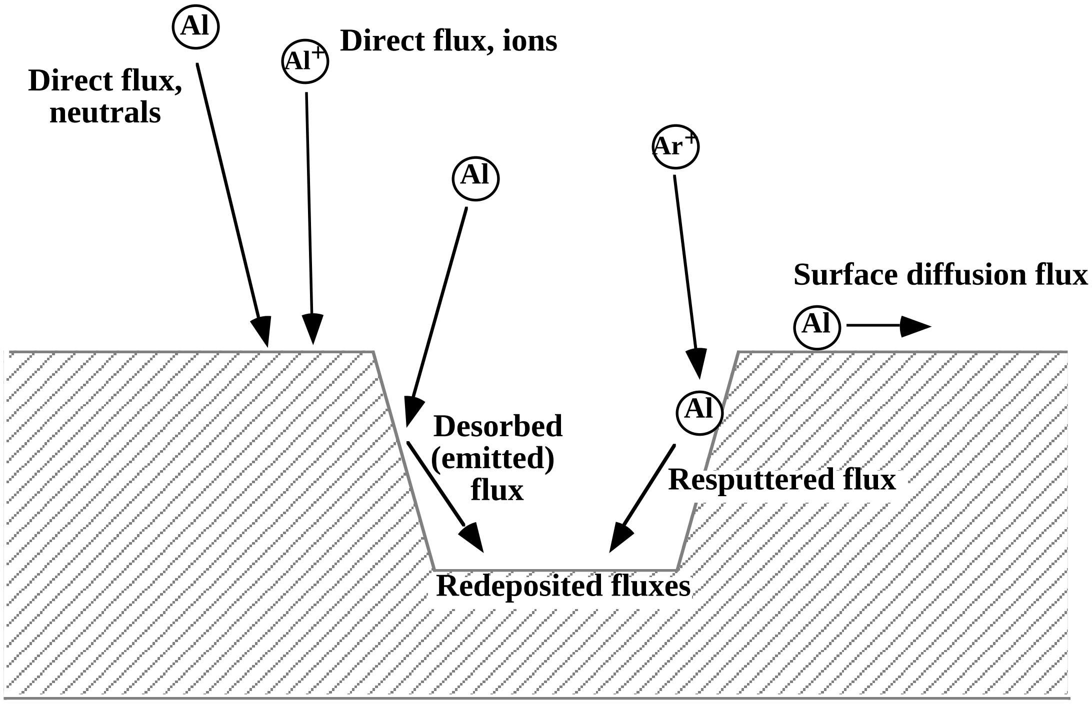
Thin film	Equipment	Typical Reactions	Comments
Epitaxial silicon	APCVD, LPCVD	$SiH_4 \rightarrow Si + 2H_2$ $SiCl_4 + 2H_2 \rightarrow Si + 4HCl$ Also $SiHCl_3$, SiH_2Cl_2	1000-1250˚C Reduce pressure for lower temperature deposition.
Polysilicon	LPCVD	Same as epitaxial Si	575-650˚C Grain structure depends on deposition conditions and doping.
Si_3N_4	LPCVD, PECVD	$3SiH_4 + NH_4 \rightarrow Si_3N_4 + 12H_2$	650-800˚C for oxidation mask. 200-400˚C (PECVD) for passivation.
SiO_2	LPCVD, PECVD, HDPCVD	$SiH_4 + O_2 \rightarrow SiO_2 + 2H_2$ $Si(OC_2H_5)_4\ (+O_3) \rightarrow SiO_2 + \text{byproducts}$	200-800˚C 200-500˚C (LTO) - may require high T anneal. 25-400˚C (TEOS-ozone, PECVD, HDPCVD)
Al	Magnetron sputter deposition		25-300˚C (standard deposition) 440-550˚C (hot Al for in-situ reflow) CVD difficult for alloys (Al-Cu-Si)
Ti and Ti-W	Magnetron sputter deposition (standard, ionized or collimated)		CVD difficult Nitrogen can be added to Ti-W to stuff grain boundaries.
W	LPCVD	$2WF_6 + 3SiH_4 \rightarrow 2W + 3SiF_4 + 6H_2$ $WF_6 + 3H_2 \rightarrow W + 6HF$	250-500˚C Blanket deposition with two step process using both reactions is common.
$TiSi_2$	Sputter and surface reaction Co-sputtering or CVD	$Ti(\text{sputtered}) + Si(\text{exposed}) \rightarrow TiSi_2$	Sputter/reaction give self-aligned silicide Two step anneal process required (600/800˚C)
TiN	Reactive sputter deposition	$Ti + N_2(\text{in plasma}) \rightarrow TiN$	Organometallic source possible for MOCVD deposition

	CVD	$6TiCl_4 + 8NH_3 \rightarrow$ $6TiN + 24HCl + N_2$	TiN can also be formed in $TiSi_2$ process
Cu	Electroplating, electroless, sputtering, CVD	$Cu^{2+} + 2e^- \rightarrow Cu$	Electroplating is most common method today.

- **See the text for a more complete discussion of manufacturing practice for specific deposited films.**

Models and Simulation

- **Within the past decade, a number of simulation tools have been developed for topography simulation.**



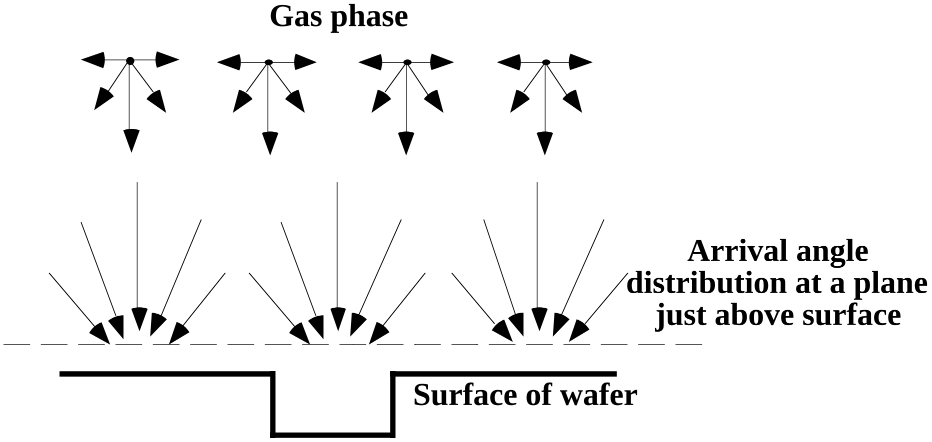
- **Generalized picture of fluxes involved in deposition. (No gas phase boundary layer is included, so this picture doesn't fully model APCVD.)**

- **Essentially the same picture will be used for etching simulation.**

- **To simulate these processes, we need mathematical descriptions of the various fluxes.**

$$\mathbf{F^i_{net} = F^i_{direct(neutrals)} + F^i_{direct(ions)} + F^i_{redep} + F^i_{diff.in} - F^i_{emitted} - F^i_{sputtered} - F^i_{diff.out}} \quad \mathbf{(14)}$$

- **Modeling specific systems involves figuring out which of these fluxes needs to be included.**



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

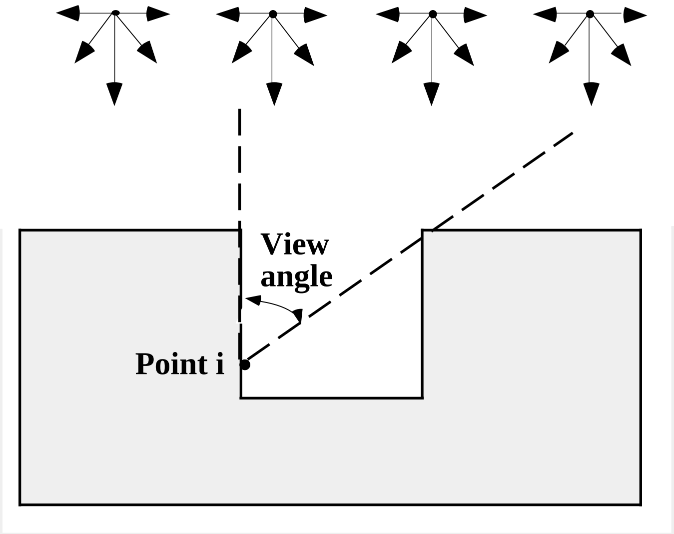
$$\mathbf{F_{direct}(\theta) = F^o \cos^n \theta} \quad \mathbf{(15)}$$

- **$\mathbf{F_{direct}(\theta)}$ is thus the normal component of the incoming flux which is what determines the growth rate.**

- **Examples:**
  - **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 all 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, γ_s is the surface energy, K is the curvature and Ω and υ are constants.

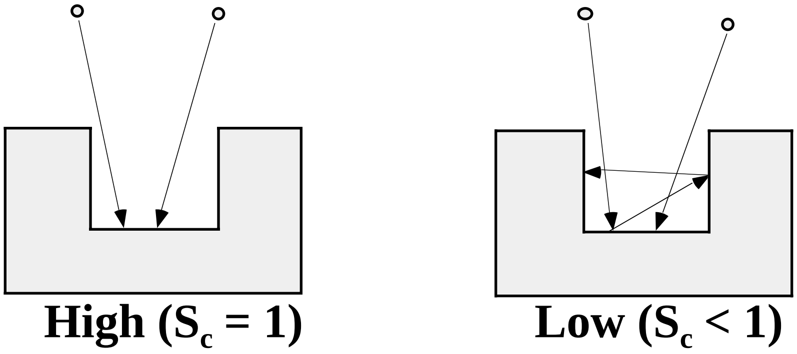
- **Surface diffusion helps to fill in corners, and produces more conformal depositions because molecules can diffuse to "smooth out" the topography.**

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

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

where S_C is the sticking coefficient.

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



- **S_C depends on the deposition system, T, chemistry etc.**

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

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

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

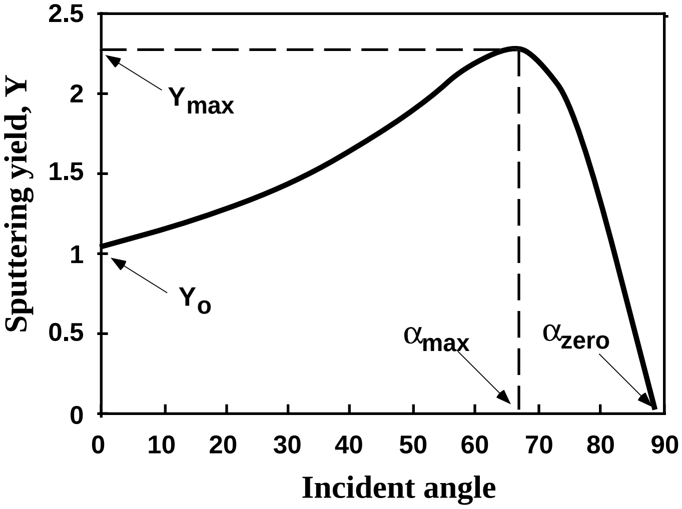
- The redeposited flux at point i due to an emitted flux at point k can then be summed over all i and k. g^{ik} accounts for the geometry between i and k.

- Thus a low $S_C < 1$ can produce more conformal coverage because of redeposition (usually more important than surface diffusion).

- The sputtered flux $F^i_{sputtered}$ is caused primarily by energetic incoming ions.

$$F^i_{sputtered} = Y * \left(F^i_{argon} + F^i_{direct(ions)}\right) = Y * F^i_{ions} \qquad (20)$$

where Y is the sputtering yield.



- Y is angle sensitive which can be used to achieve more planar surfaces during deposition (example later).

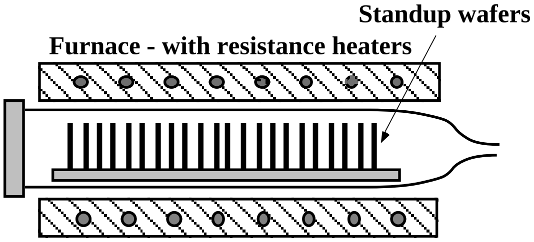
- The sputtered molecules can be redeposited. This is modeled as in Eqn. (19), i.e.

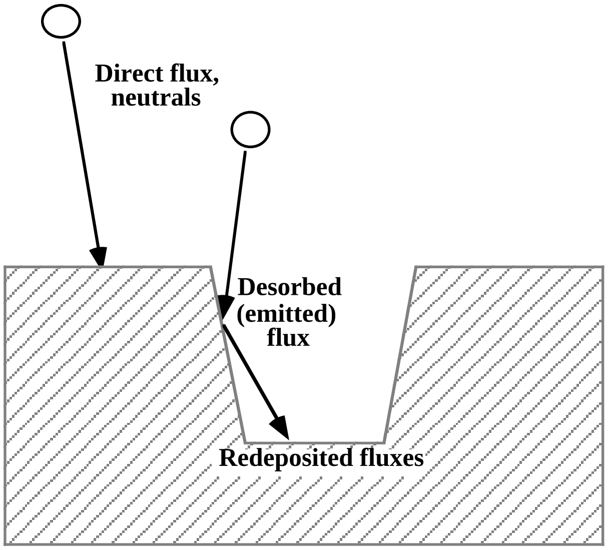
$$F^{ik}_{redep(sput)} = g^{ik} * F^k_{sputtered} = g^{ik} * Y * F^k_{ions} \qquad (21)$$

- **Finally, ions striking the surface can sometime enhance the deposition rate (by supplying the energy to drive chemical reactions for example), so that**

$$\mathbf{F^{i}_{ion-induced} = K_i * F^{i}_{ions}} \qquad \mathbf{(22)}$$

LPCVD Deposition Systems





$\mathbf{F^{i}_{direct(neutrals)}}$	**Yes**
$\mathbf{F^{i}_{direct(ions)}}$	**No**
$\mathbf{F^{i}_{diff(net)} = F^{i}_{diff(in)} - F^{i}_{diff(out)}}$	**No**
$\mathbf{F^{i}_{emitted}}$	**Yes**
$\mathbf{F^{i}_{redep(emitted)}}$	**Yes**
$\mathbf{F^{i}_{sputtered}}$	**No**
$\mathbf{F^{i}_{redep(sputtered)}}$	**No**
$\mathbf{F^{i}_{ion-induced}}$	**No**

- **In these systems there are no ions involved and hence no sputtering. Surface diffusion also is usually not important. Thus at each point on the surface,**

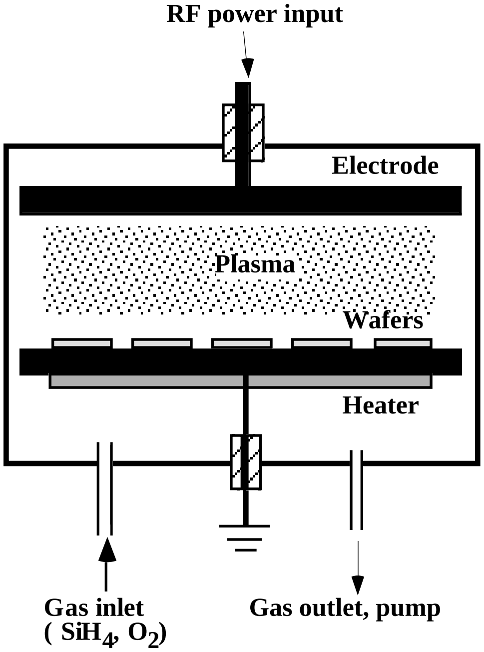
$$\begin{aligned} F^i_{net} &= F^i_{direct(neutrals)} + F^i_{redep} - (1 - S_c)\left(F^i_{direct(neutrals)} + F^i_{redep}\right) \\ &= S_c * \left(F^i_{direct(neutrals)} + F^i_{redep}\right) \\ &= S_c * \left(F^i_{direct(neutrals)} + g^{ik} * (1 - S_c) * F^k\right) \end{aligned} \quad (23)$$

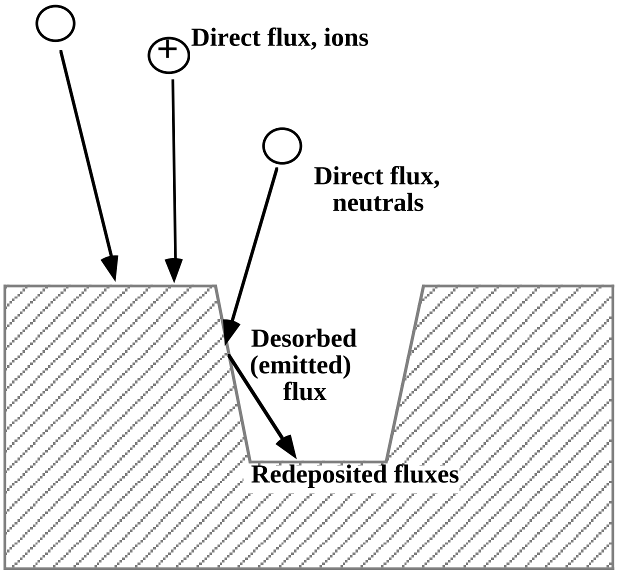
- **We define $\left(F^i_{direct(neutrals)} + F^i_{redep}\right) = F_d$ the deposition flux at each point, so the deposition rate is simply**

$\text{Rate} = S_C F_d / N$ where N is the film density. (24)

- **$\cos^n \theta$ distribution is used for the incoming molecules.**

PECVD Deposition Systems





- **In these systems an ion flux can enhance the deposition rate by changing the surface reactions. Sputtering is usually not significant because the ion energy is low.**

$F^{i}_{direct(neutrals)}$	**Yes**
$F^{i}_{direct(ions)}$	**No**
$F^{i}_{diff(net)} = F^{i}_{diff(in)} - F^{i}_{diff(out)}$	**No**
$F^{i}_{emitted}$	**Yes**
$F^{i}_{redep(emitted)}$	**Yes**
$F^{i}_{sputtered}$	**No**
$F^{i}_{redep(sputtered)}$	**No**
$F^{i}_{ion-induced}$	**Yes**

- **Thus**

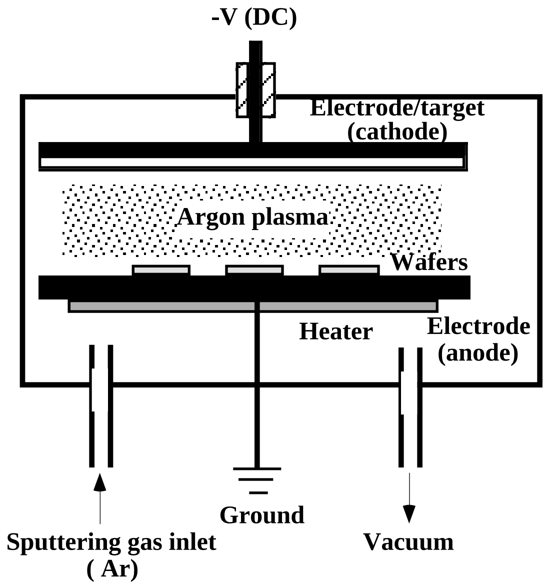
$$\text{rate} = \frac{\left(S_c K_d F_d\right) + \left(K_i F_i\right)}{N} \qquad (25)$$

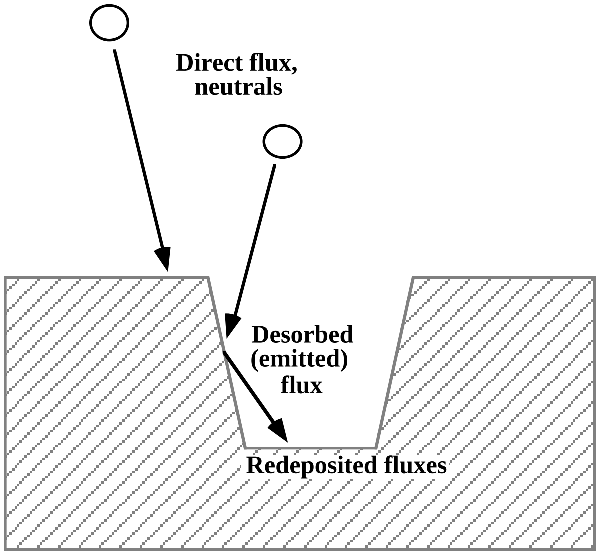
where K_d and K_I are relative rate constants for the neutral and ion-enhanced components respectively.

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 $\cos^n \theta$ would be different for LPCVD and PVD systems however.

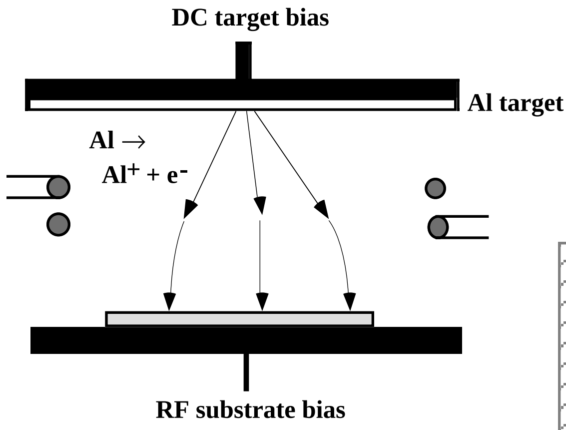
- Sometimes these systems are operated at high temperatures, so a surface diffusion term must be added.

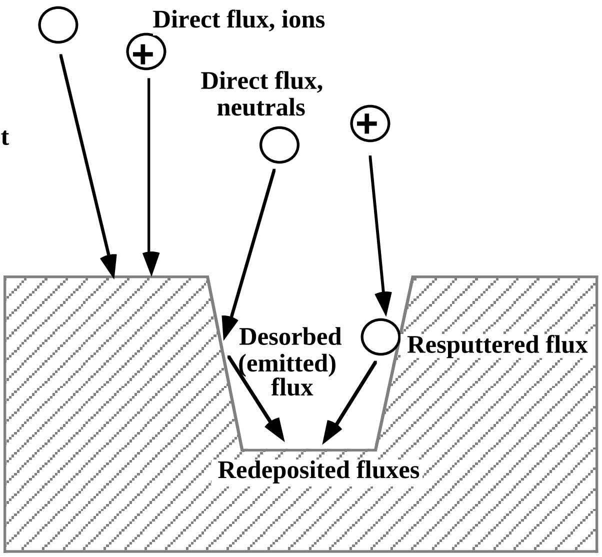
$$\text{rate} = \frac{S_c F_d + \frac{D_s}{kT} \gamma_s \Omega \upsilon \frac{\partial^2 K}{\partial s^2}}{N} \qquad (27)$$

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.





$F^{i}_{direct(neutrals)}$	Yes
$F^{i}_{direct(ions)}$	Yes
$F^{i}_{diff(net)} = F^{i}_{diff(in)} - F^{i}_{diff(out)}$	No
$F^{i}_{emitted}$	Yes
$F^{i}_{redep(emitted)}$	Yes
$F^{i}_{sputtered}$	Yes
$F^{i}_{redep(sputtered)}$	Yes
$F^{i}_{ion-induced}$	Yes

- Thus almost all the possible terms are included and

$$\text{rate} = \frac{\left(S_c F_d\right) + F_i - \left(K_{sp} Y F_i\right) + \left(K_{rd} F_{rd}\right)}{N} \quad (28)$$

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

Parameter Values for Specific Systems

	n (exponent in cosine arrival angle distribution)	S_C (sticking coefficient)
Sputter deposition		
-standard	~ 1 - 4	1
-ionized or collimated	8 - 80	1
Evaporation	3 - 80	1
LPCVD silicon dioxide		
- silane	1	0.2 - 0.4
-TEOS	1	0.05 - 0.1
LPCVD tungsten	1	0.01 or less
LPCVD polysilicon	1	0.001 or less

- PVD systems - much more vertical arrival angle distribution (low pressure line of sight or $\mathcal{E}$ field driven ions). $\therefore$ $n > 1$ typically.

- CVD systems provide isotropic arrival angle distributions (higher pressure, gas phase collisions, mostly neutral molecules). $\therefore$ $n \approx 1$ typically.

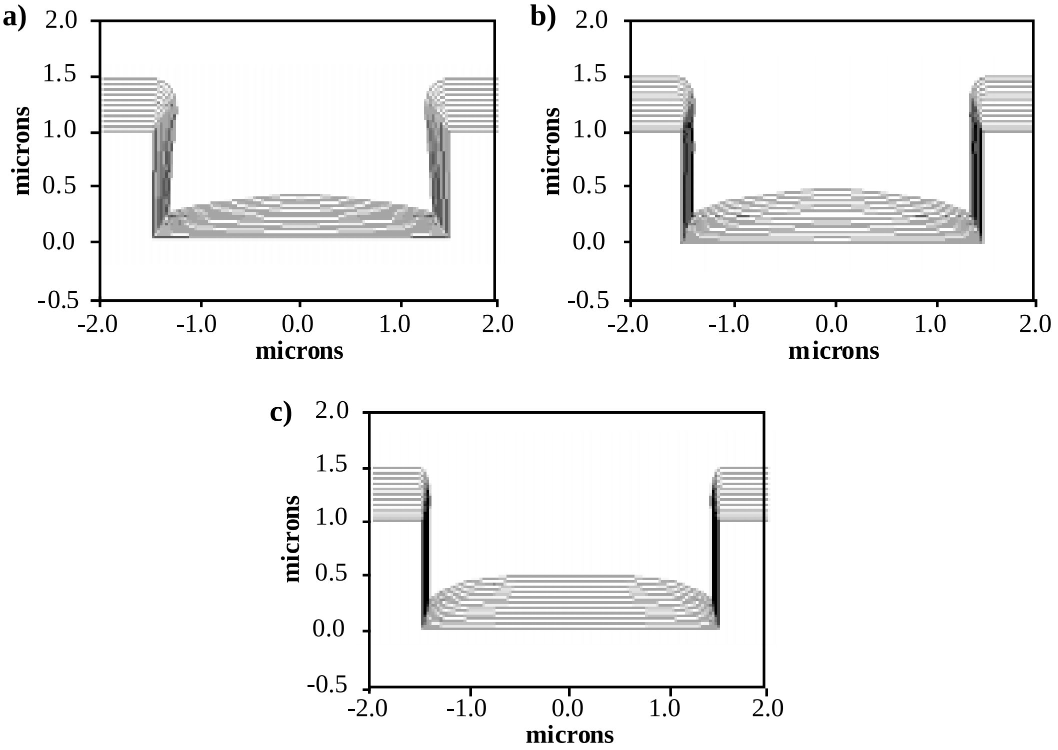
- PVD systems usually provide S_c of 1. Little surface chemistry involved. Atoms arrive and stick.

- CVD systems involve surface chemistry and S_c <<1. Molecules often evaporate before reacting.

$\therefore$ CVD systems provide more conformal deposition.

(This may or may not be what is desired!)

Topography Simulation (Using SPEEDIE)

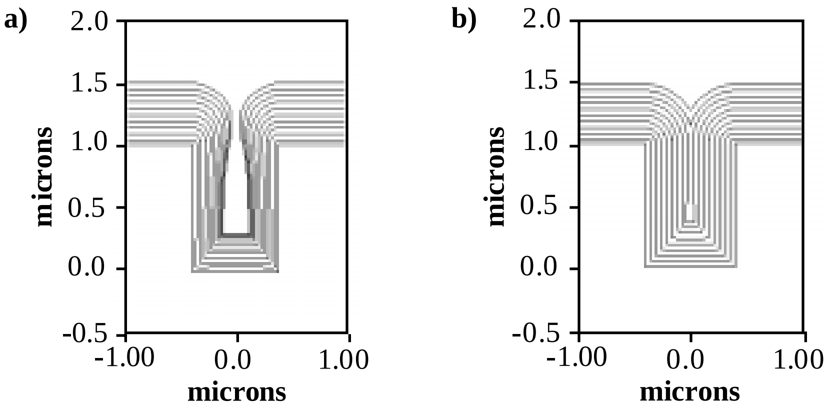


- **SPEEDIE simulations for LPCVD deposition of SiO_2 with $S_c = 1$ (which is more typical of PVD than LPCVD) and varying values of n, the arrival angle distribution factor: (a) n=1; (b) n=3; (c) n=10.**

- **Worse step coverage results as n increases (the arrival angle distribution narrows).**

- **Even for n = 1, conformal coverage is not achieved.**

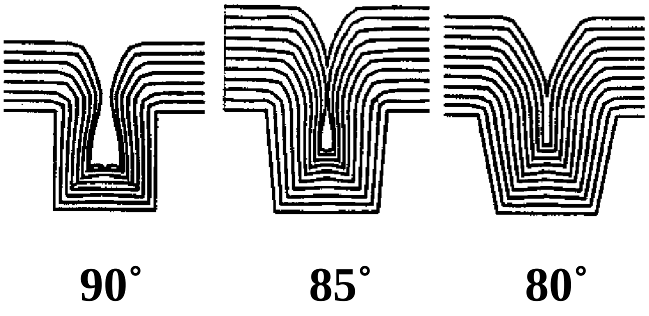
- **i.e. with $S_c = 1$, geometry and line of sight issues are VERY important.**



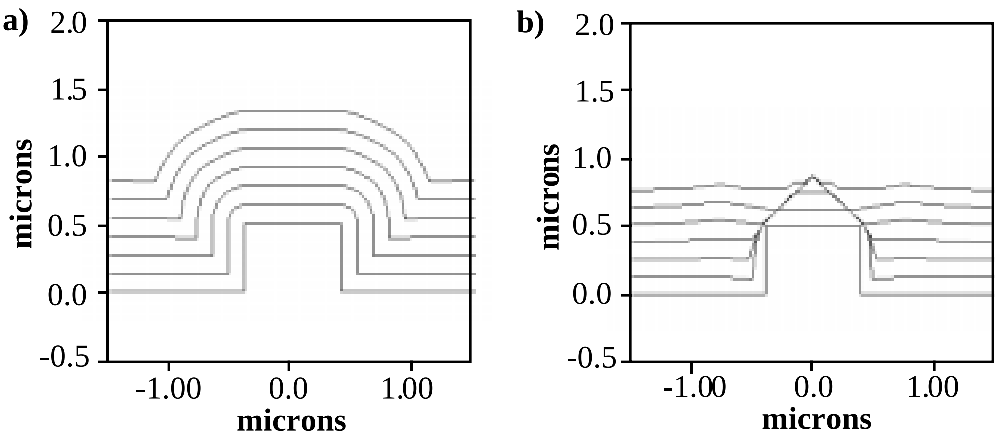
- SPEEDIE simulations for LPCVD deposition of SiO_2 in a narrow trench with the same isotropic arrival angle distribution (n=1) but with different values of the sticking coefficient: (a) $S_c = 0.1$; and (b) $S_c = 0.01$.

- Lowering the sticking coefficient below 1 results in much more conformal coverage. (a) has model parameters typical of CVD SiO_2 depositions, while (b) is typical of CVD W depositions.

- Reducing S_c is much more effective than changing n (previous page) if conformal deposition is desired.

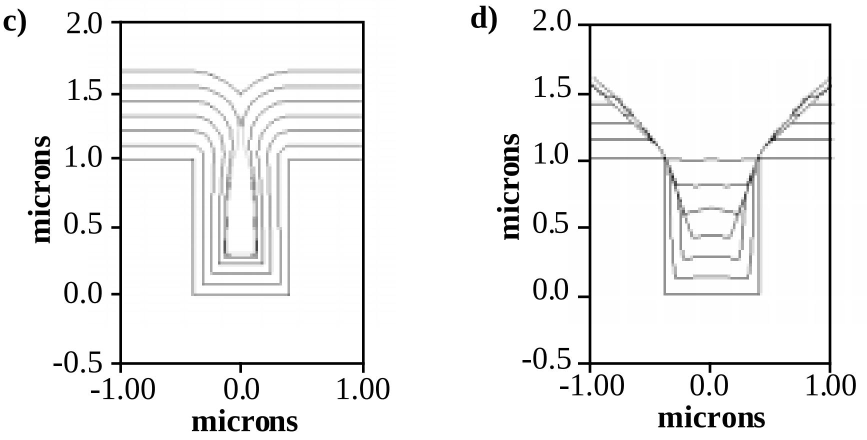


- Results of SPEEDIE LPCVD simulations in which the sidewall angle is changed. $S_c = 0.2$ and n = 1. Decreasing the angle from 90 to 80˚ greatly improves the trench filling.



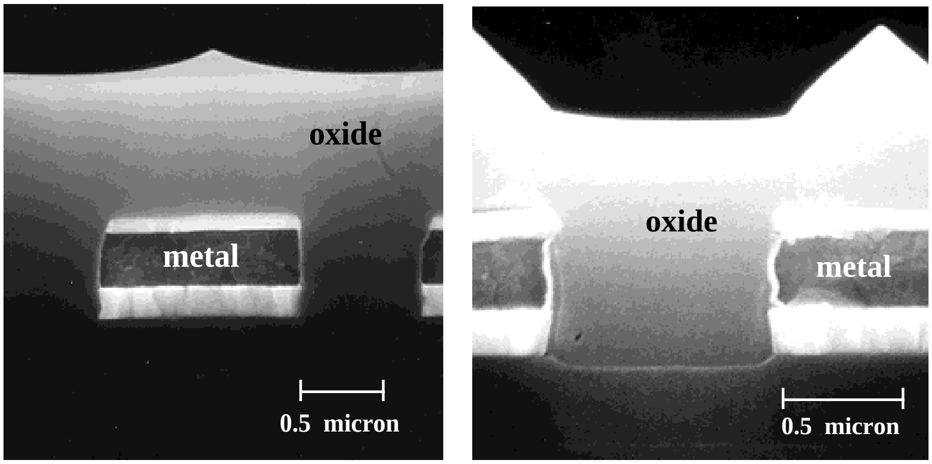
- **SPEEDIE simulations comparing LPCVD and HDPCVD depositions. (a) LPCVD deposition of SiO_2 over rectangular line. S_c = 0.1 and n = 1. (b) HDPCVD deposition, with directed ionic flux and angle-dependent sputtering, over rectangular line showing much more planar topography.**

- **CMP might still be required in the HDPCVD case to fully planarize the surface.**

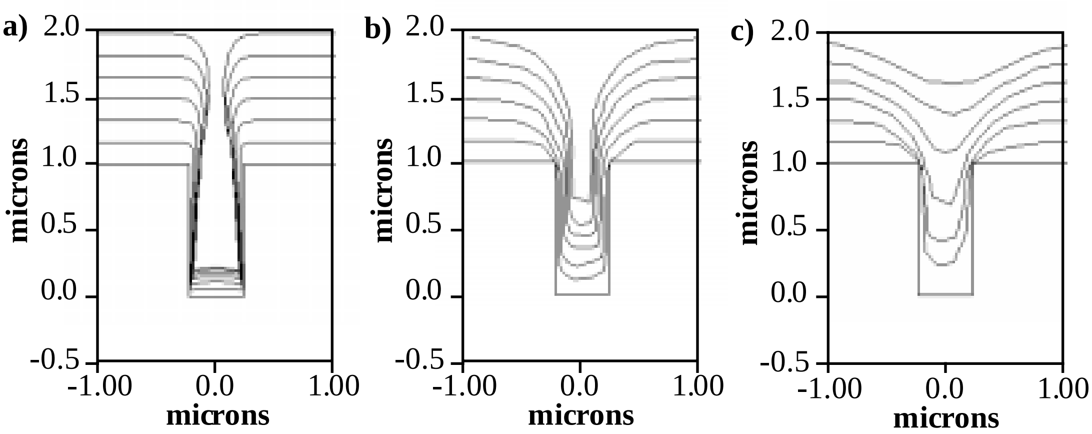


- **SPEEDIE simulations comparing LPCVD and HDPCVD depositions. (c) LPCVD deposition in trench, showing void formation. S_c = 0.2 and n = 1. (d) HDPCVD deposition in trench, showing much better filling.**

- **HDPCVD has a strong directed ion component and any overhangs that form are sputtered away.**



- **Actual SEM images of HDP oxide deposition.**



- **SPEEDIE simulations for high temperature PVD (HTPVD). (a) Standard PVD deposition with $S_C = 1$, n = 4, for comparison, showing poor filling. (b) HTPVD with surface diffusion at a deposition temperature of 400˚C. Better filling is seen with the HTPVD. (c) HTPVD again but at a higher deposition temperature of 550˚C, showing even more reflow during deposition than in (b), and even better filling and a smoother topography.**