5. *Calculating the weight of solid necessary* to achieve 99.8% conversion: Substituting into Equation (E11-3.4), we obtain

$$W = \frac{1 \times 10^{-6}\ \text{m}^3/\text{s}}{(0.0627)(4.42 \times 10^{-10}\ \text{m}^3/\text{m}^2\cdot\text{s})(530\ \text{m}^2/\text{g})} \ln \frac{1}{1-0.998}$$

$$= 423\ \text{g}$$

6. *The reactor length is*

$$L = \frac{W}{A_c\rho_b} = \frac{423\ \text{g}}{(2.03 \times 10^{-3}\ \text{m}^2)(1.4 \times 10^6\ \text{g/cm}^3)}$$

$$= 0.15\ \text{m}$$

11.7 The Determination of Limiting Situations from Reaction Data

For external mass transfer-limited reactions in packed beds, the rate of reaction at a point in the bed is

$$-r'_A = k_c a_c C_A \qquad (11\text{-}72)$$

Variation of
tion rate with
tem variables

The correlation for the mass transfer coefficient, Equation (10-66), shows that k_c is directly proportional to the square root of the velocity and inversely proportional to the square root of the particle diameter:

$$k_c \propto \frac{U^{1/2}}{d_p^{1/2}} \qquad (11\text{-}73)$$

We recall from Equation (11-55) that the variation of external surface area with catalyst particle size is

$$a_c \propto \frac{1}{d_p}$$

Consequently, for external mass transfer-limited reactions, the rate is inversely proportional to the particle diameter to the three-halves power:

$$-r'_A \propto \frac{1}{d_p^{3/2}} \qquad (11\text{-}74)$$

From Equation (10-85) we see that for gas-phase external mass transfer-limited reactions, the rate increases approximately linearly with temperature.

When internal diffusion limits the rate of reaction, we observe from Equation (11-35) that the rate of reaction varies inversely with particle diameter, is independent of velocity, and exhibits an exponential temperature dependence which is not as strong as that for surface-reaction-controlling reactions. For surface-reaction-limited reactions the rate is independent of particle size and is a strong function of temperature (exponential). Table 11-1 summarizes the dependence of the rate of reaction on the velocity

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If an industrial reaction is not mass transfer-limited, it is probably run incorrectly.

L. D. Schmidt, U. of Minn.

TABLE 11-1

Type of Limitation	Variation of Reaction Rate wit		
	Velocity	Particle Size	Ter
External diffusion	$U^{1/2}$	$(d_p)^{-3/2}$	≈
Internal diffusion	Independent	$(d_p)^{-1}$	Exp
Surface reaction	Independent	Independent	Exp

through the bed, particle diameter, and temperature for th limitations we have been discussing.

The exponential temperature dependence for interna tations is usually not as strong a function of temperature as is for surface reaction limitations. If we would calculate an a between 8 and 24 kJ/mol, chances are that the reaction is str limited. An activation energy of 200 kJ/mol, however, in reaction is reaction rate-limited.

11.8 Chemical Vapor Deposition (CVD) Reactors

As discussed in Section 6.6, CVD is a very important pro croelectronics industry. The fabrication of microelectronic d clude as few as 30 or as many as 200 individual steps to prod up to 10^6 transducers per chip. An abbreviated schematic o volved in producing a typical computer chip is shown in Fig

Starting from the upper left we see that single crystal sil grown in a Czochralski crystalizer, then sliced into wafers, a and physically polished. These polished wafers serve as a sta for a variety of microelectronic devices. A typical fabricatio shown for processing the wafer beginning with the formatic layer on top of the silicon. The SiO_2 layer may be formed eithe a silicon layer or by laying down a SiO_2 layer by Chemical Vap (CVD). Next the wafer is masked with a polymer photoresist (P with the pattern to be etched onto the SiO_2 layer is placed ov the wafer is exposed to ultraviolet irradiation. If the mask is a the light will cause scission in the polymer so that the expos dissolve when the wafer is placed in the developer. On the othe a negative PR mask is exposed to ultraviolet irradiation, cross polymer chains occurs and the *unexposed* areas dissolve in th The undeveloped portion of the PR (in either case) will protec areas from etching.

After the exposed areas of SiO_2 are etched to form trench wet etching (see P5–11) or plasma etching), the remaining PR Next the wafer is placed in a furnace containing gas molecul

5. *Calculating the weight of solid necessary* to achieve 99.8% conversion: Substituting into Equation (E11-3.4), we obtain

$$W = \frac{1 \times 10^{-6}\ \text{m}^3/\text{s}}{(0.0627)(4.42 \times 10^{-10}\ \text{m}^3/\text{m}^2\cdot\text{s})(530\ \text{m}^2/\text{g})} \ln \frac{1}{1 - 0.998}$$

$$= 423\ \text{g}$$

6. *The reactor length is*

$$L = \frac{W}{A_c \rho_b} = \frac{423\ \text{g}}{(2.03 \times 10^{-3}\ \text{m}^2)(1.4 \times 10^6\ \text{g/cm}^3)}$$

$$= 0.15\ \text{m}$$

11.7 The Determination of Limiting Situations from Reaction Data

For external mass transfer-limited reactions in packed beds, the rate of reaction at a point in the bed is

$$-r'_A = k_c a_c C_A \tag{11-72}$$

Variation of reaction rate with system variables

The correlation for the mass transfer coefficient, Equation (10-66), shows that k_c is directly proportional to the square root of the velocity and inversely proportional to the square root of the particle diameter:

$$k_c \propto \frac{U^{1/2}}{d_p^{1/2}} \tag{11-73}$$

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---

If an industrial reaction is not mass transfer-limited, it is probably run incorrectly.

L. D. Schmidt, U. of Minn.

TABLE 11-1

Type of Limitation	Variation of Reaction	
	Velocity	Particle Size
External diffusion	$U^{1/2}$	$(d_p)^{-3/2}$
Internal diffusion	Independent	$(d_p)^{-1}$
Surface reaction	Independent	Independent

through the bed, particle diameter, and temperatu
limitations we have been discussing.

The exponential temperature dependence fo
tations is usually not as strong a function of tempera
for surface reaction limitations. If we would calcu
between 8 and 24 kJ/mol, chances are that the react
limited. An activation energy of 200 kJ/mol, how
reaction is reaction rate-limited.

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a silicon layer or by laying down a SiO_2 layer by Ch
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the wafer is exposed to ultraviolet irradiation. If t
the light will cause scission in the polymer so tha
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The undeveloped portion of the PR (in either case)
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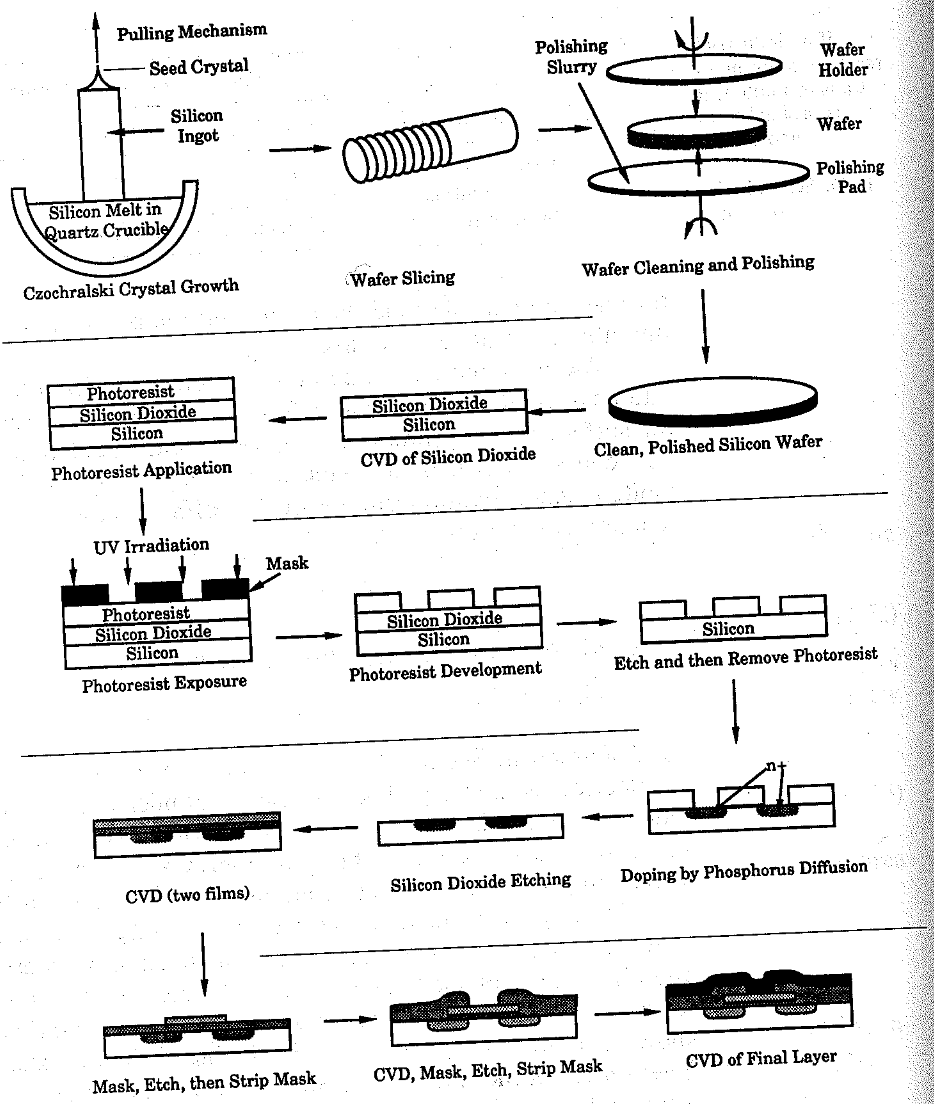

Figure 11-11 Microelectronic fabrication steps.

dopant, which then diffuse into the exposed silicon. After diffusion of dopant to the desired depth in the wafer it is removed and then covered with SiO_2 by CVD. The sequence of masking, etching, CVD, and metallization continues until the desired device is formed. A schematic of a final chip is shown in the lower right-hand corner of Figure 11-11.

One of the key steps in the chip making process is the deposition of different semiconductors and metals on the surface of the chip. This step can be achieved by CVD. CVD mechanisms were discussed in Chapter 6, consequently this section will focus on CVD reactors. A number of CVD

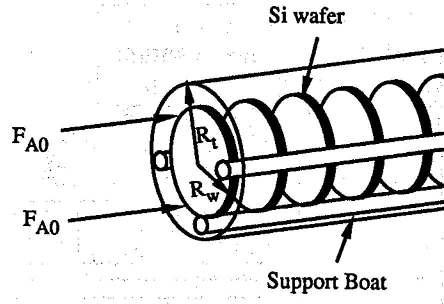

Figure 11-12 LPCVD boat reacto

horizontal and vertical reactors. A description of the
equations are given by Jensen.[6]

One of the more common CVD reactors is the
CVD (LPCVD) reactor. This reactor operates at pre
100 Pa. The main advantage of the LPCVD is its c
large number of wafers without detrimental effects t
to the large increases in the diffusion coefficient
Table 10-2) surface reactions are more likely to b
transfer. A schematic of a LPCVD reactor is show

To illustrate LPCVD modeling we shall use
example, the deposition of silicon from a gas strea
mechanism is

CVD Reaction Sequence in Silicon Deposition

$$SiH_2(g) + S \rightleftharpoons SiH_2{\cdot}S$$

$$SiH_2{\cdot}S \longrightarrow Si(s) + H_2$$

$$H_2{\cdot}S \rightleftharpoons S + H_2(g)$$

Here we have assumed that the equilibrium for
discussed in Problem 6-3 lies far to the right.

The corresponding rate law is

$$r''_{Si} = \frac{k_1 P_{SiH_2}}{1 + K_1 P_{H_2} + K_2 P_{SiH}}$$

Recalling that the adsorption constants K_1 and K_2
temperatures, an excellent approximation at high t

$$1 \gg (K_1 P_{H_2} + K_2 P_{SiH_2})$$

consequently, the deposition rate can be modeled a

$$r''_{Si} \cong k_1 P_{SiH_2} \simeq kC_{SiH_2} \equiv kC$$

where $A \equiv SiH_2$

---

[6] K. F. Jensen, *Chemical Engineering Science, 42,* 923

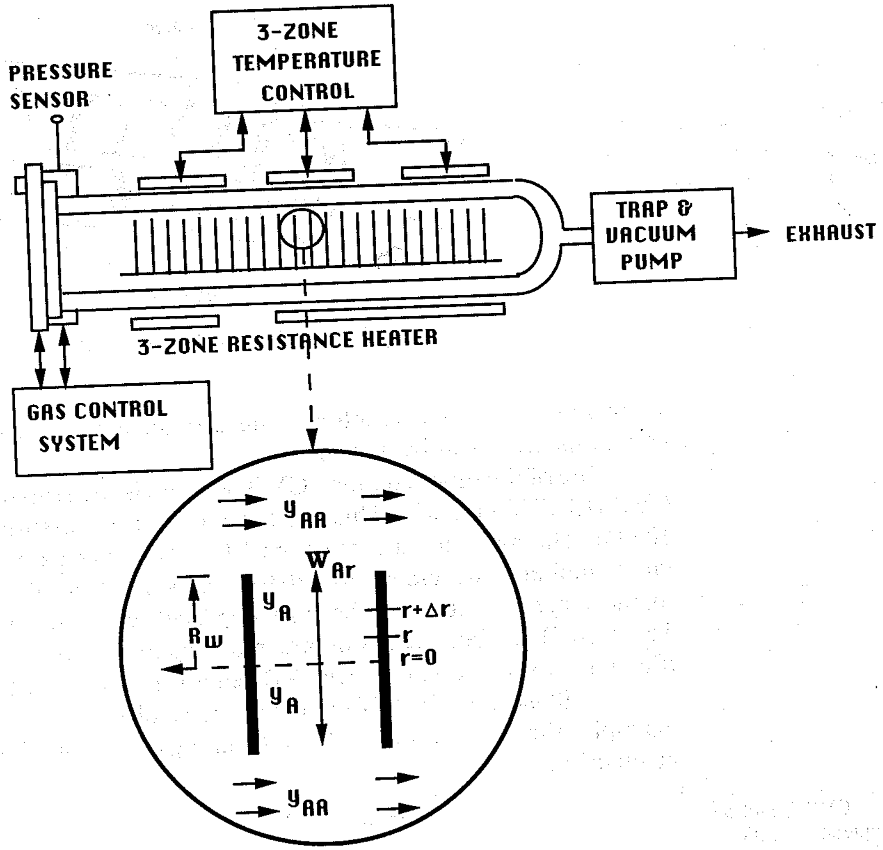

Figure 11-13 LPCVD boat reactor with peripherals.

Modeling Concepts We shall model the axial flow in the annular region as being laminar. This assumption is reasonable because a typical Reynolds number for flow in a LPCVD reactor is less than 1. As the reactant gases flow through the annulus, the reactants diffuse from the annulus radially inward between the wafers to coat them.[7]

The reacting gas flows through the annulus between the outer edges of the cylindrical wafers and the tube wall (see Figure 11-13). The corresponding cross-sectional area of the annulus is

Flow in the Annulus

$$A_c = \pi(R_t^2 - R_w^2)$$

where R_t and R_w are the radii of the tube and wafer, respectively. Because SiH_2 is being consumed by CVD, the mole fraction of SiH_2 (i.e., the reactant) in the annulus, y_{AA}, decreases as the reactant flows down the length of the annulus.

The reacting gases diffuse out of the annular
between the wafers where the mole fraction is repre
ecules diffuse radially *inward* some of them are adso
the wafer surface. The reaction products then diffus
the gas stream axially flowing in the annulus. This s
in a manner analogous to flow through a packed c
reaction gases diffuse into the catalyst pellets. In th
effectiveness factor to determine the overall rate of r
mass) of reactor bed. We can extend this idea to L
the reactants diffuse from the annular flow channel r
the wafers.

11.8.1 Effectiveness Factor for a LPCVD Re

Silicon will deposit on the wafers, the reactor
support. Deposition on the walls and support will ta
concentrations in the annulus. However, the conce
the wafers is less than the concentration in the annu
rate of deposition on the wafer will be less than the r
annulus. Fortunately these two concentrations can
tiveness factor. We can determine the effectivenes
centration profile in the region between the wafers i

$$\eta = \frac{\text{Actual rate of reaction}}{\text{Rate of reaction when entire wafer surface is e} \\ \text{the concentration in the annulus } C_{AA} \text{ (i.e.,}}$$

$$\eta = \frac{2\int_0^{R_w} 2\pi r(-r''_A(r))\,dr}{2\pi R_w^2(-r''_{AA})} = \frac{2\pi R_w \ell(-W_{Ar}|_{r=R_w})}{2\pi R_w^2(-r''_{AA})} =$$

where ℓ is the distance between wafers, and $-r''_{AA}$ i
ance of A at the concentration of A in the annular
use η to express the actual rate of reaction per uni
in terms of the rate of reaction at conditions in the

$$\text{Actual Rate} = -r''_{AA}\eta$$

Letting '*a*' be the wafer surface area per unit
rate of consumption of species A by the wafer per
is

Example 11-4 Diffusion Between Wafers

Derive an equation for the reactant gas concentration as a function of wafer radius and then determine the effectiveness factor.

$$SiH_2(g) \longrightarrow Si(s) + H_2(g)$$

In terms of the diffusing gas phase components, we can write this reaction as:

$$A(g) \longrightarrow B(g)$$

Solution

ffusion between the wafers

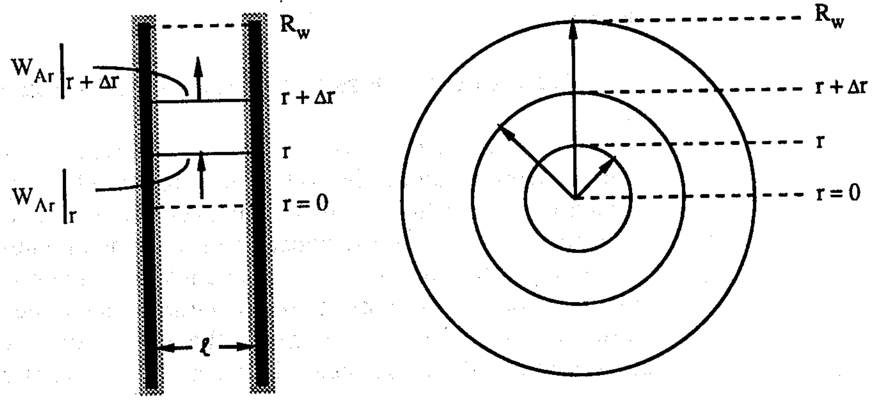

Figure E11-4.1

The shell balance on the reactant diffusing between two wafers separated by a distance ℓ shown in Figure E11-4.1 gives

$$\text{In} \quad - \quad \text{Out} \quad + \quad \text{Generation} \; = 0$$

$$W_{Ar} 2\pi r \ell \,|_r - W_{Ar} 2\pi r \ell \,|_{r+\Delta r} + 2(2\pi r \Delta r \, r''_{Aw}) = 0$$

where r''_{Aw} = rate of generation of species A per unit wafer surface area. The factor of 2 appears in the generation term because there are two wafer surfaces exposed in each differential volume element. Dividing by $2\pi r \Delta r \ell$, taking the limit as Δr approaches zero, and then rearranging gives

$$\frac{1}{r}\frac{d(W_{Ar}r)}{dr} = \frac{2r''_{Aw}}{\ell} \qquad \text{(E11-4.1)}$$

Recalling the constitutive equation for the molar flux W_{Ar} in radial coordinates

$$W_{Ar} = -cD_{AB}\frac{dy_A}{dr} + y_A(W_{Ar} + W_{Br}) \qquad \text{(E11-4.2)}$$

For every one molecule of SiH_2 (i.e., species A) that diffuses *IN* one molecule of H_2 (i.e., species B) diffuses *OUT*.

$$W_{Br} = -W_{Ar}$$

Then

For a first-order reaction

$$-r''_{Aw} = kC_A$$

Diffusion with reaction between wafers

Substituting equations (11-76) and (E11-4.3) into Equatio

$$\frac{1}{r}\frac{d}{dr}\left(\frac{r\,dC_A}{dr}\right) - \frac{2k}{D_{AB}}\frac{C_A}{\ell} = 0$$

The corresponding boundary conditions are

$$\text{At } r = R_w \qquad C_A = C_{AA}$$

$$\text{At } r = 0 \qquad \frac{dC_A}{dr} = 0 \text{ and } C_A \text{ is fini}$$

Let $\lambda = r/R_w$ and $\Psi = C_A/C_{AA}$

then

$$\boxed{\frac{1}{\lambda}\frac{d}{d\lambda}\left(\lambda\frac{d\Psi}{d\lambda}\right) - \phi_1^2\Psi = 0}$$

where $\phi_1^2 = \dfrac{2kR_w^2}{D_{AB}\ell}$

The boundary conditions are

$$\text{at } \lambda = 0: \quad \frac{d\Psi}{d\lambda} = 0 \text{ and } \Psi \text{ is finite}$$

$$\text{at } \lambda = 1 \quad \Psi = 1.0$$

Equation (E11-4.7) is a form of Bessel's Equation.

The general form of the solution to Bessel's equat

$$\Psi = AI_o(\phi_1\lambda) + BK_o(\phi_1\lambda)$$

Where I_o is a modified Bessel function of the first k
K_o is a modified Bessel function of the second kin
second boundary condition requires Ψ to be finite
B must be zero because $K_o(0) = \infty$. Using the firs
we get $1 = AI_o(\phi_1)$, then $A = 1/I_o(\phi_1)$. The concer
space between the wafers is

$$\boxed{\Psi = \frac{C_A}{C_{AA}} = \frac{I_o(\phi_1\lambda)}{I_o(\phi_1)}}$$

$$\eta = \frac{-W_{Ar}|_{r=R_w}(2\pi R_w \ell)}{2\pi R_w^2(-r''_{AA})}$$

---

[8] Mickley, H. S., T. K. Sherwood, and C. E. Reed, *Applie*

$$\eta = \frac{-\left(-D_{AB}\left.\frac{dC_A}{dr}\right|_{r=R_w}\right)(2\pi R_w \ell)}{2kC_{AA}\pi R_w^2} = 2\,\frac{\left.\frac{d\Psi}{d\lambda}\right|_{\lambda=1}}{\frac{2kR_w^2}{D_{AB}\ell}} \qquad \text{(E11-4.11)}$$

$$\eta = 2\,\frac{\left.\frac{d\Psi}{d\lambda}\right|_{\lambda=1}}{\phi_1^2}$$

$$\boxed{\eta = \frac{2I_1(\phi_1)}{\phi_1 I_o(\phi_1)}} \qquad \text{(E11-4.12)}$$

The concentration profile along the radius of the wafer disk as well as the wafer shape is shown in Figure E11-4.2 for different values of the Thiele modulus.

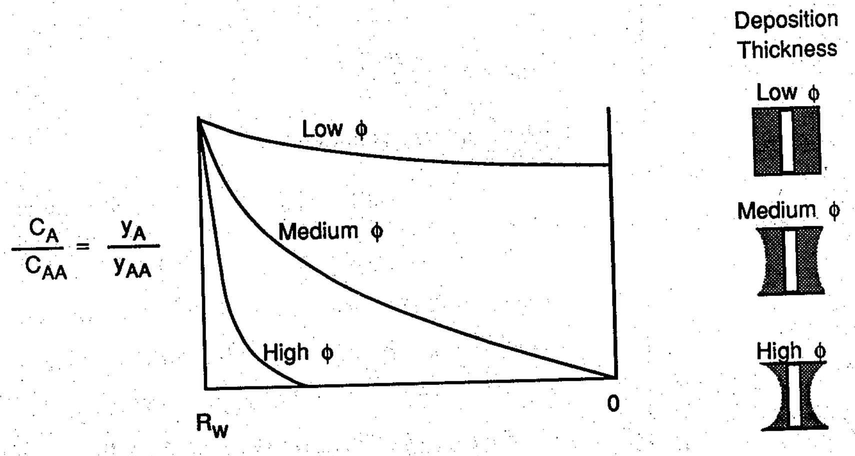

Figure E11-4.2 Radial concentration profile.

Accounting for Si deposition on the walls and support

Deposition on the Peripherals Silicon will deposit on the walls of a reactor and on the boat support in addition to the wafers. This rate of deposition on the walls and support is

$$-r''_{\text{Si},p} = -r''_{AA} = (1 + \alpha)kC_{AA}$$

$$\alpha = \frac{\text{surface area of boat support}}{\text{surface area of tube}}$$

Owing to high temperature and low pressure, radiation is the dominant heat transfer mechanism, therefore small temperature differences exist between the wafer and reactor wall. Consequently, there is no need to couple the

Example 11-5 CVD Boat Reactor

Silicon is to be deposited on wafers in a LPCVD reactor.
an analytical solution for the silicon deposition rate and reac
profile for the simplified version of the LPCVD reactor ju
lytical solutions of this type are important in that an engine
an understanding of the important parameters and their se
making a number of *'runs'* on the computer. The reaction t
is

$$SiH_2(g) \rightleftharpoons Si(s) + H_2(g)$$

Sections of the reactor are shown in Figures E11-5.1 and E

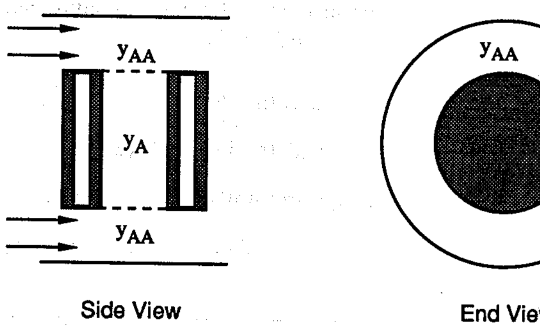

Figure E11-5.1

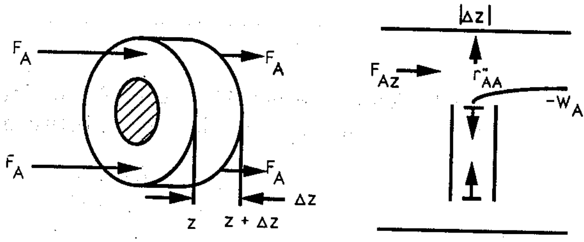

Figure E11-5.2

1. **Balances:** In forming our shell balance on the annul
assume there are no radial gradients in the annulu
outer tube walls and the boat which consume som
by deposition on the walls in the balance. In additio
any dispersion or diffusion in the axial direction.

Balance on reactant A

IN	−	OUT	+	GENER-ATION	+	GENER-ATION	+
By Convection		By Convection		By reaction on wafer surface		By reaction on tube walls	

$$F_{Az}\big|_z \;-\; F_{Az}\big|_{z+\Delta z} \;+\; r''_{AA}\eta a\pi R_t^2\Delta z \;+\; r''_{AA}2\pi R_t\Delta z \;+\; r''$$

Dividing through by Δz and taking the limit as $\Delta z \longrightarrow 0$

Mole balance on the reacting gas

$$-\frac{dF_{\text{A}z}}{dz} + \overbrace{r''_{\text{AA}}[(1+\alpha)2\pi R_t + \eta a\pi R_t^2]}^{R''_{\text{AA}}} = 0 \qquad \text{(E11-5.2)}$$

2. **Rate laws:** The rate of silicon deposition, r''_{Si}, (mol/dm²·s) is equal to the rate of depletion of SiH_2.

$$r''_{\text{Si}} = -r''_{\text{A}} = kC_{\text{A}} \qquad \text{(11-76)}$$

where the units of C_{A} and k are (mol/dm³) and (dm/s), respectively. Deposition takes place on the reactor walls, the support, and on the wafer surfaces. The corresponding depletion of reactant gas on each of these surfaces is

Wafer (mol/s): $kC_{\text{AA}}\eta a\pi R_t^{\,2}\Delta z$

Reactor wall (mol/s): $kC_{\text{AA}}2\pi R_t\Delta z$

Boat support (mol/s): $kC_{\text{AA}}\alpha 2\pi R_t\Delta z$

Total: $-R''_{\text{AA}}\Delta z = -r''_{\text{AA}}(2\pi R_t + \alpha 2\pi R_t + \eta a\pi R_t^2)\Delta z$

$$\boxed{-R''_{\text{AA}} = kC_{\text{AA}}(2\pi R_t + \alpha 2\pi R_t + \eta a\pi R_t^2)} \qquad \text{(E11-5.3)}$$

Radial concentration profile

3. **Concentration profile and effectiveness factor:** From Example 11-4 we derived the radial concentration profile between the wafers as

$$\frac{C_{\text{A}}}{C_{\text{AA}}} = \frac{I_o(\phi_1\lambda)}{I_o(\phi_1)} \qquad \text{(E11-4.9)}$$

the corresponding effectiveness factor was

$$\eta = \frac{2I_1(\phi_1)}{\phi_1 I_o(\phi_1)} \qquad \text{(E11-4.12)}$$

4. **Concentration profile in the annular region:** Combining equations (E11-5.2) and (E11-5.3) yields

$$-\frac{dF_{\text{A}z}}{dz} = kC_{\text{AA}}[(1+\alpha)2\pi R_t + \eta a\pi R_t^2] \qquad \text{(E11-5.4)}$$

Writing $F_{\text{A}z}$ and C_{AA} in terms of conversion we have

Axial concentration profile

$$F_{\text{A}z} = F_{\text{A0}}(1 - X)$$

$$C_{\text{AA}} = \frac{C_{\text{A0}}(1 - X)}{(1 + \epsilon X)} \qquad \text{(E11-5.5)}$$

refer to the reactant concentration and molar flow

Combining equations (E11-5.4) and (E11-5

$$F_{\text{A0}}\frac{dX}{dz} = kC_{\text{A0}}[(1+\alpha)2\pi R_t + \eta a\pi R_t^2]$$

$$\epsilon = y_{\text{A0}}\delta = 1\cdot(1 - 1 - 0) =$$

Collecting terms we can obtain an expression invol number, Da.

$$\boxed{\frac{dX}{dz} = \frac{\text{Da}}{L}(1 - X)}$$

where

$$\text{Da} = \frac{\text{Rate of consumption of A by react}}{\text{Rate of transport of A by convecti}}$$

and

$$\text{Da} = \frac{kC_{\text{A0}}[(1+\alpha)2\pi R_t + \eta a\pi R_t^2]L}{F_{\text{A0}}}$$

Solving for conversion as a function of distance al reactor yields

$$X = 1 - \exp[(-\text{Da}z/L)]$$

or, in terms of concentration

$$C_{\text{AA}}/C_{\text{A0}} = \exp[-\text{Da}(z/L)]$$

The deposition rate as a function of r and z can follows. The deposition rate at a location r and z is

$$-r''_{\text{A}w}(r, z) = kC_{\text{A}}(r, z)$$

First, using Equation (E11-4.9) to relate $C_{\text{A}}(r, z)$ and C_{A}

$$-r''_{\text{A}w}(r, z) = kC_{\text{A}}(r, z) = kC_{\text{AA}}(z)\frac{I_o(\phi_1 r/}{I_o(\phi_1}$$

Next, we use Equation (E11-5.9) to determine the rate as a down the reactor.

$$\boxed{-r''_{\text{A}w}(r, z) = kC_{\text{A0}}\frac{I_o(\phi_1 r/R_w)}{I_o(\phi_1)}\exp[-\text{Da}(z/L)]}$$

The thickness, T, of the deposit is obtained by integrating with respect to time, i.e.,

$$\frac{dT}{\ } = \frac{2(-r''_{\text{A}w})}{\ }$$

where ρ = molar density of the material deposited, gmole/cm³. The *two* accounts for deposition on both sides of the wafer. Integrating, we obtain

$$\boxed{T(r, z) = \frac{-r''_{Aw}(r, z)}{\rho} 2t} \qquad \text{(E11-5.12)}$$

The reactant concentration profile and deposition thickness along the length of the reactor is shown schematically below in Figure E11-5.3 for the case of small values of the Thiele modulus ($\eta \simeq 1$).

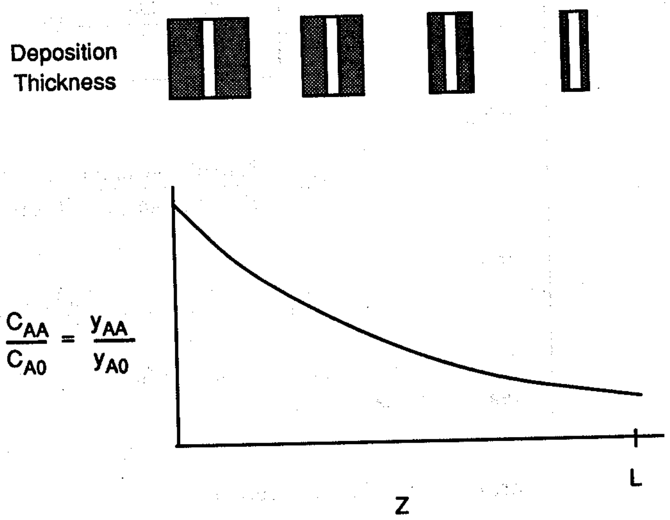

Figure E11-5.3 Axial concentration profile.

SUMMARY

1. The concentration profile for a first-order reaction occurring in a spherical catalyst pellet is

$$\frac{C_A}{C_{As}} = \frac{R}{r}\left[\frac{\sinh(\phi_1 r/R)}{\sinh \phi_1}\right] \qquad \text{(S11-1)}$$

where ϕ_1 is the Thiele modulus. For a first-order reaction

$$\phi_1^2 = \frac{k\rho_p S_a}{D_e} R^2 \qquad \text{(S11-2)}$$

2. The effectiveness factors are

$$\begin{array}{c}\text{internal}\\ \text{effectiveness}\\ \text{factor}\end{array} = \eta = \frac{\text{actual rate of reaction}}{\text{reaction rate if entire interior}}$$

$$\begin{array}{c}\text{overall}\\ \text{effectiveness}\\ \text{factor}\end{array} = \Omega = \frac{\text{actual rate of re}}{\text{reaction rate if entire}\\ \text{exposed to bulk con}}$$

3. For large values of the Thiele modulus,

$$\eta = \left(\frac{2}{n+1}\right)^{1/2} \frac{3}{\phi_n}$$

4. For internal diffusion control, the true re the measured reaction order by

$$n_{\text{true}} = 2n_{\text{apparent}} - 1$$

The true and apparent activation energies

$$E_{\text{true}} = 2E_{\text{app}}$$

5. The Weisz–Prater parameter is

$$C_{WP} = \frac{-r'_A(\text{observed})}{D_e C_{As}}$$

The Weisz–Prater criterion dictates that

If $C_{WP} \ll 1$ no internal diffusion lin

If $C_{WP} \gg 1$ internal diffusion limita

6. The deposition thickness on wafers in a bo z down the reactor and at a wafer radius r

$$T = \frac{kC_{A0}I_o(\phi_1 \cdot r/R_w)}{\rho I_o(\phi_1)}(\exp[-$$

QUESTIONS AND PROBL

P11-1$_C$ Make up an original problem using the conce _____ (your instructor will specify the section). if you obtain and use real data from the literatu

P11-2$_C$ Review the example problems in this chapter. use a software package such as POLYMATH sensitivity analysis. Perhaps reconsider the LP Example 11-4. What are the effects of wafer spa deposition support area, α, and gas velocity i shape of the wafer? If there were a significant length of the reactor, how would the wafer sha the effects of increasing or decreasing the temp