

KEY

Name/SID: _____

CHEMICAL ENGINEERING 179

Exam 1

Friday, October 3, 2014

Closed Book with 3x5 Card

$k_B = 1.381 \times 10^{-23} \text{ J K}^{-1}$; $R = 8.314 \text{ J (mole K)}^{-1} = 1.987 \text{ cal (mole K)}^{-1}$; $N_A = 6.022 \times 10^{23} \text{ (mole)}^{-1}$;
 $e = 1.602 \times 10^{-19} \text{ C}$; $m_p = 1.673 \times 10^{-27} \text{ kg}$; 1 liter = 1000 cm³; STP = 273 K, 760 torr (1 atm); 1 atm =
 $1.013 \times 10^5 \text{ Pa}$; 1 Pa = 1 J/m³, mass density SiO₂ = 2.65 g/cm³. MW SiO₂ = 60.08 g/mole

Short Answer. 5 pts. each.

1. Fill in the associated SI units for the following quantities:

Electrical power	Joules
Electrical conductivity	Siemens/m
Electrical current density	A/m ²
Gas mass diffusivity	m ² /s
Gas viscosity	kg m/s; poise
Electric charge	Coulomb
Electrical capacitance	Farad; Coulomb/V
First-order (surface) reaction rate coef.	m/s
Number flux	m ⁻² s ⁻¹
Surface reaction rate	m ⁻² s ⁻¹ or moles m ⁻² s ⁻¹

2. What is the Boltzmann constant, k_B ? How is it related to the ideal gas constant R ?

Constant relating kinetic energy and gas temperature; $R = k_B \times (\text{Avagadro's number})$

3. For an activated process described by an Arrhenius rate coefficient (i.e. $k = k_0 \exp(-E_A/k_B T)$), what is the significance of E_A vs. $k_B T$?

The ratio of $E_A/k_B T$, or activation energy relative to thermal kinetic energy, determines the sensitivity of the rate coefficient k to temperature T .

4. In the context of the MOSFET gate dielectric capacitance, why does capacitance matter as a design parameter in the gate dielectric of a MOSFET?

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The capacitance of the gate dielectric determines the charges in the channel for a given gate voltage, thus strongly affecting the electrical properties of the device.

5. When molecules with a Maxwellian velocity distribution are described by a 'hard-sphere' elastic collision model, the mean free path can be estimated as a function of molecular diameter. In reality, gas molecules do not have a well-defined diameter and experience van der Waals attraction at longer separation distances and repulsion at shorter distances. What relationship can be used to model these interactions, and how can it be used to estimate the elastic collision cross section?

The model interatomic potential Lennard-Jones can be used: the point at which the potential is zero can be taken as an estimate of molecular radius; this is represented by one of the two parameters (r) characterizing the potential.

6. What are the major assumptions made in the derivation of the Deal-Grove Si oxidation model?

1. Film growth rate is slow compared to characteristic diffusion rate (i.e. pssa)
2. Reaction between mobile oxidizer and Si occurs at Si-SiO₂ interface only
3. Rate of reaction is first order in oxidant concentration

7. Briefly describe the types of semiconductor dopants used in devices and how they affect semiconductor conductivity.

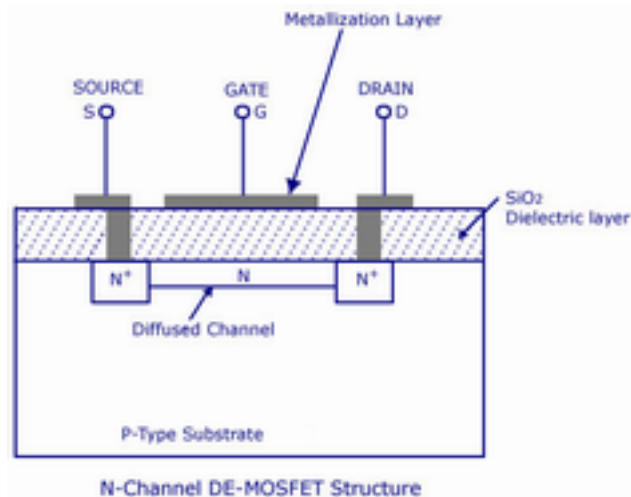
N-type dopants are electron donors; these increase electron concentration

P-type dopants are electron acceptors; these increase the hole concentration

Both types increase conductivity dramatically compared to intrinsic semiconductor levels.

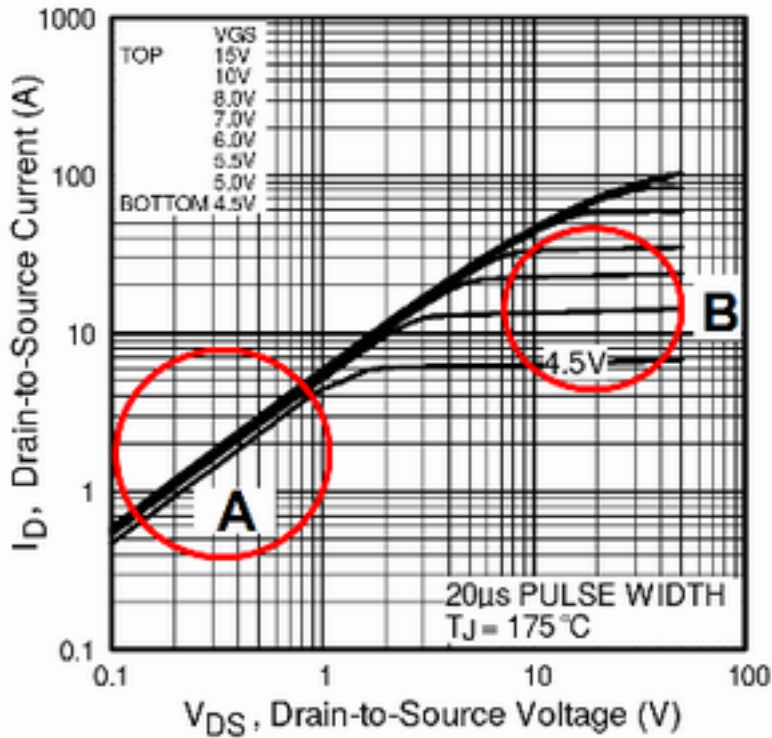
8. MOSFETs we have discussed in class are "enhancement-mode" devices—they are normally 'off', and are turned 'on' by applying a voltage to the gate and enhancing the concentration of majority charge carriers in the channel. It is also possible to configure the MOSFET as a "depletion-mode" device—they are normally 'on', and are turned 'off' by applying a voltage to the gate and depleting the concentration of majority charge carriers in the channel.

Draw an N-channel depletion-mode MOSFET and label the component parts with names and compositions



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9. In the device with the following current-voltage characteristic, in what region (A or B) would you operate the MOSFET as an amplifier? Why?



In a MOSFET amplifier, a constant voltage is applied across the source and drain; the input is the gate voltage (V_{GS}) and the output is current flow (I_D). In A, changes in V_{GS} have no effect on I_D ; in B, changes in V_{GS} are reflected as predictable changes in I_D .

10. True or False

- F intrinsic charge carrier concentration is a function of temperature
- F ideal gas viscosity decreases with temperature
- F the electrical conductivity of semiconductor is a function of temperature
- F ideal gas pressure is proportional to molecular diameter
- F ideal gas viscosity increases with pressure

KEY

Problems.

(20 points)

1. The rate coefficient for the silicon oxidation reaction and the diffusion coefficient are both temperature-dependent with activation energies (E_R) and (E_D), respectively. Given that the film thickness 'L' at which the system transitions from linear to parabolic film growth decreases with increasing temperature, what conclusions can be drawn about these activation energies? Justify your answer using physical arguments and/or expressions.

$$k = k_0 \exp(-E_R/kT)$$

$$D = D_0 \exp(-E_D/kT)$$

kx/D : dimensionless group describing the relative timescales of reaction and diffusion

For a given oxide growth configuration (e.g. oxidant concentration, silicon type, geometry, &etc) the growth of oxide can be said to transition from reaction-limited to diffusion-limited when kx/D reaches a certain value. In the problem statement, this transition is said to occur at lower values for x when temperature is increased; this indicates that the quantity k/D is increasing with increasing temperature:

$$k/D = (k_0 \exp(-E_R/kT)) / (D_0 \exp(-E_D/kT))$$

$$k/D = (k_0/D_0) * (\exp(E_D/kT) * \exp(-E_R/kT))$$

$$k/D = (k_0/D_0) * \exp((E_D - E_R)/kT)$$

if k/D is increasing with increasing T , then the quantity $(E_D - E_R)$ must be negative: $E_D < E_R$

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if k/D is increasing with increasing T , then the quantity $(E_D - E_R)$ must be negative: $E_D < E_R$

$$\frac{d}{dT} \left(\frac{k}{D} \right) > 0$$

$$\frac{d}{dT} \left(\frac{k_0 e^{(-E_R/kT)}}{D_0 e^{(-E_D/kT)}} \right) > 0$$

$$\left(\frac{k_0}{D_0} \right) \frac{d}{dT} \left(\frac{e^{-E_R/kT}}{e^{-E_D/kT}} \right) > 0$$

$$\frac{d}{dT} \left(e^{(E_D/kT - E_R/kT)} \right) > 0$$

$$\frac{d}{dT} \left(\exp\left(\frac{E_D - E_R}{kT}\right) \right) > 0$$

$$\frac{-\frac{(E_D - E_R)}{kT^2} \exp\left(\frac{E_D - E_R}{kT}\right)}{T^2} > 0$$

$$(E_R - E_D) \exp\left(\frac{E_D - E_R}{kT}\right) > 0$$

if $E_R > E_D$: $(+) \exp(-) = (+)(+) = (+)$

if $E_R < E_D$: $(-) \exp(+)$ = $(-)(+) = (-)$

$$\therefore E_R > E_D$$

less than zero!

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(30 points)

2. Consider a gas with the molecular mass of N_2 (28 amu). This gas reacts and sticks permanently at the walls of a cylindrical chamber 10 cm in diameter and 10 cm high with a reaction probability that has an activation energy of 0.1 eV. If the gas initially has a pressure of 1 torr, how long would it take for the gas pressure (300K) to reach 1 millitorr? The gas and walls remain at 300K for the entire process.

The time it takes to reduce pressure from 1 torr to 1 millitorr follows from a transient mass balance on gas molecules:

$$V \frac{dn}{dt} = -rA_s = \frac{1}{4} n \bar{v} \gamma A_s$$

$$\gamma = \exp\left(\frac{-E}{kT}\right) = \exp\left(\frac{-0.1}{0.03}\right) = 3.6 \times 10^{-2}$$

$$\bar{v} \cong 4 \times 10^4 \frac{\text{cm}}{\text{s}}$$

$$\frac{A_s}{V} = \frac{2(r+h)}{rh} = 0.6$$

$$\frac{dn}{n} = \frac{1}{4} n \bar{v} \gamma \frac{A_s}{V} dt$$

$$\ln \frac{n}{n_0} = -6.9$$

$$t \cong 0.05 \text{ s}$$

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$$\gamma = e^{\left(\frac{-E}{k_B T}\right)}$$

$$\gamma = 0.0209 \text{ to } 0.0360$$

$$E = 0.1 \text{ eV}$$

$$k_B = 8.617 \times 10^{-5} \text{ eV/K}$$

$$T = 300 \text{ K}$$

$$m = \left(\frac{28 \text{ g}}{\text{mol}}\right) \left(\frac{\text{mol}}{6.022 \times 10^{23}}\right) \left(\frac{1 \text{ kg}}{1000 \text{ g}}\right)$$

$$= 4.65 \times 10^{-26} \text{ kg}$$

$$\bar{v} = \sqrt{\frac{8k_B T}{\pi m}} = 476 \text{ m/s}$$

$$V = \pi \left(\frac{d}{2}\right)^2 L = \pi (0.05 \text{ m})^2 (0.10 \text{ m})$$

$$= 250 \pi \text{ cm}^3$$

$$= 0.000785 \text{ m}^3$$

$$A_s = \pi d L + 2 \pi \left(\frac{d}{2}\right)^2$$

$$= 150 \pi \text{ cm}^2$$

$$= 0.0471 \text{ m}^2$$

$$\frac{A_s}{V} = 0.60 \text{ cm}^{-1}$$

$$= 60 \text{ m}^{-1}$$

$$V \frac{dn}{dt} = -rA_s = \frac{1}{4} n \bar{v} \gamma A_s$$

$$\frac{dn}{dt} = \frac{1}{4} n \bar{v} \gamma \left(\frac{A_s}{V}\right)$$

$$\frac{dn}{n} = 0.69 dt$$

$$\int_{n_0}^{n_f} \frac{dn}{n} = \ln \left(\frac{n_f}{n_0}\right) = \ln \left(\frac{P_f}{P_0}\right) = \ln \left(\frac{1}{1000}\right) = -6.9$$

$$t = \frac{6.9}{\gamma \bar{v} \left(\frac{A_s}{V}\right)}$$

$$= 0.0467 \text{ s}$$