University of California
College of Engineering
Department of Electrical Engineering
and Computer Sciences

EECS 239
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Tuesday May 12, 2009
9:30 AM-12:30 PM

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NAME ANSWERS

FINAL EXAM

Problem 1 __________

Problem 2 __________

Problem 3 __________

Problem 4 __________

TOTAL __________

There are four problems, each having equal weight.

Problem 1. Capacitive RF Discharge Equilibrium

Design a symmetric, parallel plate, capacitive rf discharge in argon gas at a pressure $p = 3$ mTorr with a plate separation $l = 10$ cm, having an ion flux at the plasma-sheath edge of $\Gamma_{+s} = 5 \times 10^{19}$ ions/m^2-s and an ion bombarding energy of $\varepsilon_i = 200$ V. To do this, choose an appropriate operating frequency f (Hz) and applied rf voltage amplitude V_{rf} (V) across the discharge electrodes. As in Example 1 of Chapter 11, the pressure is in the intermediate regime such that $l > \lambda_i > (T_i/T_e)l$, where λ_i is the ion-neutral mean free path. Assume that the sheath is collisionless, $s \ll \lambda_i$, and that stochastic heating dominates over ohmic heating. Also find the total power absorbed per unit area, S_{abs} (W/m^2), and find the sheath width s (m) for your design.

As in Ex. 1 of Cha. 11, choose $p = 3$ mTorr and $d = 8$ cm (with $s \ll d$). Then $\lambda_i = 1$ cm and $h_\ell = 0.325$. Then $n_g d_{\text{eff}} = 1.21 \times 10^{19}$ m^{-2} and Fig. 10.1 yields $T_e = 3.3$ V. Then $u_B = 2.8 \times 10^3$ m/s, and Fig. 3.17 gives $\mathcal{E}_c = 55$ V. Then $\mathcal{E}_c + \mathcal{E}_e' = 79$ V.

Using (11.2.36),

$$\cancel{2}\,\bar{S}_{\text{stoc}} = \cancel{2}\,e\,\Gamma_{+s}\,(\mathcal{E}_c + 2\mathcal{E}_e')$$

and with $\bar{S}_{\text{stoc}}$ given by (11.2.34) [see also (11.2.40)]

$$\bar{S}_{\text{stoc}} = 0.125\left(\frac{f_{\text{MHz}}}{13.56}\right)^2 \tilde{V}_1 = (1.6 \times 10^{-19})(5 \times 10^{19})(79)$$

Now $\tilde{V}_1 = 200/0.83 = 241$ V from (11.2.35). Hence solve for $f_{\text{MHz}} = 62.1$ MHz. Then $V_{\text{rf}} = 2\tilde{V}_1 = 482$ V. Now $S_{\text{abs}} = 2\Gamma_{+s}\,e(\mathcal{E}_c + \mathcal{E}_e' + \mathcal{E}_i)$. This yields $S_{\text{abs}} = 4460$ W/m^2. Use (11.2.15) to find s:

$$e\Gamma_{+s} = (0.82)\,\epsilon_0\left(\frac{2e}{M}\right)^{1/2}\frac{\bar{V}^{3/2}}{s^2}$$

with $\bar{V} = 200$ V, we find $s = 0.24 \times 10^{-2}$ m.

Note $s \ll \ell$.

Problem 2. Particle Balance in an N_2 Discharge

Consider a nitrogen (N_2) plasma chemistry in a steady state, low pressure rf inductive discharge. The discharge is a cylinder of radius R and length L. You may assume that the densities of all species (charged and neutral) are constant within the cylinder. Consider first the volume reactions with their second order rate coefficients [m^3/s]

$$e + N_2 \rightarrow N_2^+ + 2e \qquad \text{(rate coefficient } K_1\text{)}$$

$$e + N_2 \rightarrow 2N + e \qquad \text{(rate coefficient } K_2\text{)}$$

$$e + N \rightarrow N^+ + 2e \qquad \text{(rate coefficient } K_3\text{)}$$

In addition, the first order rate coefficients [s^{-1}] for loss of N_2^+, N^+, and N to the cylinder surfaces are K_{N2+}, K_{N+} and K_N, respectively.

(a) Give the three rate equations for dn_α/dt, where $\alpha = N_2^+$, N^+ and N, in terms of the rate coefficients and the concentrations n_e, n_{N2} and n_α.

$$\frac{dn_{N_2^+}}{dt} = K_1 n_e n_{N_2} - K_{N_2^+} n_{N_2^+}$$

$$\frac{dn_{N+}}{dt} = K_3 n_e n_N - K_{N+} n_{N+}$$

$$\frac{dn_N}{dt} = 2K_2 n_e n_{N_2} - K_3 n_e n_N - K_N n_N$$

(b) In the steady state, find n_N, n_{N+}, and n_{N2+} in terms of n_e, n_{N2}, and the rate coefficients.

$$n_{N_2+} = \frac{K_1 n_e n_{N_2}}{K_{N_2+}} \quad //$$

$$n_N = \frac{2 K_2 n_e n_{N_2}}{K_3 n_e + K_N} \quad //$$

$$n_{N+} = \frac{K_3 n_e n_N}{K_{N+}}$$

$$n_{N+} = \frac{2 K_2 K_3 n_e^2 n_{N_2}}{K_{N+} (K_3 n_e + K_N)} \quad //$$

(c) Assume that all volume second order rate coefficients have an Arrhenius form $K_\alpha = K_{\alpha 0}\exp(-\mathcal{E}_\alpha/T_e)$. Find the equation that determines the electron temperature T_e of the discharge, for a given n_e, n_{N2}, and set of rate coefficients. **Do not try to solve for T_e.**

Use $n_e = n_{N^+} + n_{N_2^+}$ (quasi-neutrality)

$$1 = \frac{2K_2 K_3 n_e n_{N_2}}{K_{N^+}(K_3 n_e + K_N)} + \frac{K_1 n_{N_2}}{K_{N_2^+}}$$

$\Rightarrow T_e$

Problem 3. High Pressure Singlet Molecular Oxygen Source

The metastable species singlet molecular oxygen (SMO) can be used to clean surfaces such as silicon wafers, printed circuit boards, and clothes. SMO is an excited molecular metastable state ($^1\Delta_g$) of O_2 (see Table 8.1 of text) with an intrinsic lifetime of 4400 seconds. SMO can be made in a plane parallel O_2 discharge operating at atmospheric pressure (760 Torr) and room temperature (300 K). No vacuum pump is used.

To estimate the generation and loss of SMO, consider a one-dimensional model with parallel plates located at $x = -l/2$ and $x = l/2$, where $l = 0.1$ cm. Assume that SMO is created in the volume by reaction 15 (Table 8.2), $e + O_2 \rightarrow O_2^* + e$, with rate coefficient $K_{15} = 1.37 \times 10^{-10} e^{-2.14/T_e}$ cm^3/s and is lost from the volume by reaction 18 (Table 8.2), $O_2^* + O_2 \rightarrow 2O_2$, with rate coefficient $K_{18} = 2.2 \times 10^{-18}$ cm^3/s. Because the discharge is highly electronegative, the electron density within the plates is uniform, $n_e(x) = n_{e0} = 10^8$ cm^{-3}, and $T_e \approx 2.14$ V. Neglect the volume loss of SMO due to its decay at its natural lifetime of 4400 s.

(a) Assuming that all SMO molecules incident on the surfaces (plates) are reflected back into the discharge volume (zero sticking coefficient), find a numerical value for the SMO density n^* (cm^{-3}).

$$n_g = 2{,}5 \times 10^{19} \text{ cm}^{-3}$$

$$\frac{dn^*}{dt} = K_{15} n_e n_g - K_{18} n_g n^* = 0$$

$$n^* = \frac{K_{15}}{K_{18}} n_e = 2.3 \times 10^{16} \text{ cm}^{-3} \quad //$$

(b) Give a numerical estimate for the actual lifetime (in seconds) of an SMO molecule in this discharge. Give a numerical estimate for the flux of SMO molecules (cm^{-2}-s^{-1}) incident on a surface.

$$\tau = \frac{1}{K_{18} n_g} \approx \frac{1}{60} \text{ s} \quad //$$

$$\Gamma^* = \frac{1}{4} n^* \bar{v}^*$$

$$\bar{v}^* = \left(\frac{8 e T_g}{\pi M}\right)^{1/2} \approx 4.4 \times 10^4 \text{ cm/s}$$

$$\Gamma^* = 2.5 \times 10^{20} \text{ cm}^{-2}\text{-s}^{-1} \quad //$$

(c) Assume now that a fraction $\gamma = 0.2$ of all SMO molecules incident on the surfaces react at these surfaces and are lost from the system. Hence there is an additional diffusive loss of SMO molecules from the system. Give the diffusion equation that determines $n^*(x)$ and give an estimate for the diffusion coefficient D for diffusion of SMO molecules through the background (O_2) gas. Give a numerical estimate for D (cm^2/s). Finally, give the boundary conditions on n^* that are needed in order to solve the diffusion equation to determine $n^*(x)$. **Do not solve for $n^*(x)$.**

$\lambda_{AB} = \dfrac{1}{n_g \sigma_{AB}}$. From Table 9.3,

$$\sigma_{AB} \approx 4.9 \times 10^{-15}\ \text{cm}^2 \Rightarrow \lambda_{AB} \approx 8.2 \times 10^{-4}\ \text{cm}$$

$$\bar{v}_{AB} \approx \sqrt{2}\,\bar{v}^* \approx 6.2 \times 10^{4}\ \text{cm/s}$$

$$D \approx \frac{\pi}{8} \lambda_{AB} \bar{v}_{AB} \approx 20\ \text{cm}^2/\text{s} \quad //$$

The diffusion equation is

$$-D \frac{d^2 n^*}{dx^2} = K_{15} n_{e0} n_g - K_{18} n_g n^*$$

$$-\frac{\ell}{2} < x < \frac{\ell}{2}$$

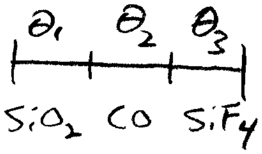
At $x = \ell/2$, $\left. -D \dfrac{dn^*}{dx} \right|_{\ell/2} = \gamma \dfrac{1}{4} n^*(\ell/2)\, \bar{v}^*$

Also, $n^*(x)$ is a symmetric function of x

Problem 4. Etching of SiO_2 by CF_2 Radicals

Consider the following simple model of CF_2 chemical etching of an SiO_2 substrate having volume density n_{SiO_2} (m^{-3}) and surface density n'_0 (m^{-2}). Let θ_1 be the fraction of the surface sites that are bare SiO_2, θ_2 be the fraction covered with CO, and θ_3 be the fraction covered with SiF_4 ($\theta_1 + \theta_2 + \theta_3 = 1$). Let CF_2 radicals with gas phase density n_S (m^{-3}) near the substrate adsorb on θ_1 to form CO + $\frac{1}{2}$ SiF_4, with the rate coefficient K_a (m^3/s). Let CO molecules thermally desorb from θ_2 with rate coefficient K_{d2} (s^{-1}) and SiF_4 molecules thermally desorb from θ_3 with rate coefficient K_{d3} (s^{-1}).

(a) Find the surface coverages θ_1, θ_2, and θ_3, and find the chemical (horizontal) etch rate E_h (m/s).



$$2CF_2 + SiO_2 \rightarrow 2CO + SiF_4$$

$$\frac{d\theta_2}{dt} = K_a n_s \theta_1 - K_{d2}\theta_2 = 0 \qquad \text{(C-atom balance)}$$

$$\frac{d\theta_3}{dt} = \frac{1}{2} K_a n_s \theta_1 - K_{d3}\theta_3 = 0 \qquad \text{(F-atom balance)}$$

$$\Rightarrow \theta_2 = \frac{K_a n_s}{K_{d2}}\theta_1 \ ; \quad \theta_3 = \frac{K_a n_s}{2K_{d3}}\theta_1 \qquad //$$

$$\theta_1\left(1 + \frac{K_a n_s}{K_{d2}} + \frac{K_a n_s}{2K_{d3}}\right) = 1$$

$$\theta_1 = \frac{1}{1 + K_a n_s\left(\frac{1}{K_{d2}} + \frac{1}{2K_{d3}}\right)} \qquad //$$

$$E_h = \frac{n'_0}{n_{SiO_2}} K_{d3}\theta_3 = \frac{n'_0}{n_{SiO_2}} \frac{K_a n_s}{2} \frac{1}{1 + K_a n_s\left(\frac{1}{K_{d2}} + \frac{1}{2K_{d3}}\right)}$$

//

(b) Now assume that a flux $\Gamma_i = n_{is}u_B$ of ions is incident on the substrate surface, where u_B is the Bohm velocity. This flux produces an ion enhanced desorption of CO and SiF_4, having a yield Y_2 of desorbed CO molecules and Y_3 SiF_4 molecules per incident ion. In addition, there is thermal desorption of CO and SiF_4 as in part (a). Find the ion enhanced (vertical) etch rate E_v.

Same as before, except add the terms yielding ion-enhanced desorption:

$$\theta_2 = \frac{K_a n_s}{K_{d2} + Y_2 K_i n_{is}} \theta_1 \qquad //$$

$$\theta_3 = \frac{K_a n_s}{2(K_{d3} + Y_3 K_i n_{is})} \theta_1 \qquad //$$

$$\theta_1 = \frac{1}{1 + \frac{K_a n_s}{K_{d2} + Y_2 K_i n_{is}} + \frac{K_a n_s}{2(K_{d3} + Y_2 K_i n_{is})}} \qquad //$$

$$E_v = \frac{n_0'}{n_{SiO_2}} \frac{K_a n_s}{2} \theta_1 \qquad //$$