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

EECS 239
Spring 2007
Wednesday, May 16, 2007
8:00 AM-11:00 AM

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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. Diffusion of F Atoms in a CF_4 Discharge

A one-dimensional parallel plate discharge operating in CF_4 gas at a known uniform gas density n_{CF_4} has the left hand wall located at $x = 0$ and the right hand wall located at $x = l$. The electron density n_e within the plates is everywhere uniform, $n_e = n_{e0}$. Room temperature ($T = 300$ K) fluorine atoms, having density $n_F(x)$, are created in the volume by dissociation of the feedstock gas according to the reaction

$$e + CF_4 \rightarrow CF_3 + F + e \qquad \text{(rate constant } K_2\text{)}$$

where K_2 [m^3/s] is the second order rate coefficient for generation of F atoms by electron impact with CF_4 molecules. F atoms diffuse in the CF_4 gas with a constant diffusion coefficient D_F [m^2/s]. F atoms *are not lost* to the left hand wall (the recombination coefficient $\gamma_{rec} \approx 0$ at this wall.) F atoms *are lost* to the right hand wall, on which a wafer is placed, with a reaction coefficient $\gamma_{reac} = 0.2$.

(a) Give the diffusion equation and the boundary conditions at the two walls required to determine $n_F(x)$.

$$-D_F \frac{d^2 n_F}{dx^2} = K_2 n_{CF_4} n_{e0} \qquad (1)$$

$$\text{At } x = 0, \quad \Gamma_F = D_F \frac{dn_F}{dx} = 0 \qquad (2)$$

$$\text{At } x = l, \quad \Gamma_F = -D_F \frac{dn_F}{dx} = \underbrace{\frac{\gamma_{reac}}{2(2-\gamma_{reac})}}_{\frac{1}{4}\gamma_{reac} \text{ ok}} n_F \bar{v}_F \qquad (3)$$

$$\bar{v}_F = \left(\frac{8kT}{\pi M_F}\right)^{1/2}$$

(b) Solve the equation in (a) to determine $n_F(x)$ and the flux Γ_F [m^{-2}-s^{-1}] of F atoms incident on the right hand wall.

$$n_F = -\frac{K_2 n_{CF_4} n_{eo}}{2 D_F} x^2 + C$$

satisfies (1) and (2)

$$\frac{dn_F}{dx} = -\frac{K_2 n_{CF_4} n_{eo}}{D_F} x$$

At $x = \ell$:

$$K_2 n_{CF_4} n_{eo} \ell = \frac{\gamma_{rec} \bar{v}_F}{2(2-\gamma_{rec})} \left[-\frac{K_2 n_{CF_4} n_{eo}}{2 D_F} \ell^2 + C \right]$$

$$\frac{K_2 n_{CF_4} n_{eo} \ell}{\bar{v}_F} \frac{2(2-\gamma)}{\gamma} + \frac{K_2 n_{CF_4} n_{eo} \ell \ell}{2 D_F} = C$$

$$\frac{K_2 n_{CF_4} n_{eo}}{2 D_F} \left[\frac{2 D_F \ell}{\bar{v}_F} \frac{2(2-\gamma)}{\gamma} + \ell^2 \right] = C$$

$$\boxed{n_F(x) = \frac{K_2 n_{CF_4} n_{eo}}{2 D_F} \left[\ell^2 - x^2 + \frac{2 D_F \ell}{\bar{v}_F} \frac{2(2-\gamma)}{\gamma} \right]}$$

$$\boxed{\Gamma_F = K_2 n_{CF_4} n_{eo} \ell}$$

Problem 2. RF Inductive Discharge Design

A cylindrical discharge ($R = 7$ cm, $l = 30$ cm) operating at a pressure of 10 mTorr in argon gas has an ion flux at the plasma-sheath edge at each endwall of $\Gamma_{+s} = 2 \times 10^{20}$ ions/m^2-s. Assume that there are low voltage sheaths at all discharge surfaces and that the discharge operates in the intermediate pressure regime, $R > \lambda_i > (\mathrm{T}_i/\mathrm{T}_e)l$, where λ_i is the ion-neutral mean free path, and T_i and T_e are the ion and electron temperatures in volts.

(a) Find *numerical values* for the electron temperature T_e [V], the ion bombarding energy ε_i [V], and the power supplied to (and absorbed by) the discharge, P_{abs} [W].

Particle balance:

$\lambda_i = 3 \times 10^{-3}$ m

$h_\ell = 0.12$, $h_R = 0.15$

$d_{eff} = 0.19$ m

$n_g d_{eff} = 6.3 \times 10^{19}$ m^{-2}

Fig 10.1 $\Rightarrow$ $T_e = 2.5$ V

$\mathcal{E}_i = 5.2\, T_e \doteq 13$ V

Power balance:

Fig 3.17 $\Rightarrow$ $\mathcal{E}_c = 81$ V

$\mathcal{E}_T = 99$ V

$A_{eff} = 2.4 \times 10^{-2}$ m^2

$u_B = 2.5 \times 10^3$ m/s

$n_{s\ell} = \Gamma_{+s} / u_B = 8.1 \times 10^{16}$ m^{-3}

$n_0 = n_\ell / h_\ell = 6.9 \times 10^{17}$ m^{-3}

$P_{abs} = e\,\mathcal{E}_T \cdot n_0 u_B \cdot A_{eff}$

$= 640$ W

(b) Assuming that this discharge is inductively driven at 27.12 MHz by a 5-turn circumferential coil having a radius b = 8 cm, find *numerical values* for the rf current I_{rf} [A] flowing in the coil, and for the voltage V_{rf} [V] across the coil terminals.

HINT: Assume that stochastic heating is small compared to ohmic heating.

Fig 3.16 $\Rightarrow$ $\nu_m = 2.1 \times 10^7 \ s^{-1}$

$n_{sR} = n_0 h_R = 1.1 \times 10^{17} \ m^{-3}$

$\omega_{pe} = 1.8 \times 10^{10}$ rad/s

$\delta_p = c/\omega_{pe} = 1.6 \times 10^{-2}$ m

$\sigma_m = 108$ S/m

$$R_s = N^2 \frac{\pi R}{\sigma_m l \delta_p} = 9.1 \ \Omega$$

$L_s = 4.9 \times 10^{-7}$ H

$I_{rf} = 11.8$ A

$V_{rf} = 1000$ V

Problem 3. Etchant/Unsaturate Ratio in a CF_4 Discharge With O_2 Addition.

Consider a CF_4/O_2 plasma chemistry in a steady state, low pressure discharge. You may assume that the densities of all species (charged and neutral) are constant within the discharge. Consider first the reactions in the discharge volume with their second order rate coefficients [m^3/s]

$$e + CF_4 \rightarrow CF_3 + F + e \qquad \text{(rate coefficient } K_1\text{)}$$

$$e + O_2 \rightarrow 2O + e \qquad \text{(rate coefficient } K_2\text{)}$$

$$CF_3 + O \rightarrow COF_2 + F \qquad \text{(rate coefficient } K_3\text{)}$$

$$e + CF_3 \rightarrow CF_2 + F + e \qquad \text{(rate coefficient } K_4\text{)}$$

In addition, assume that the first order rate coefficients [s^{-1}] for loss of F atoms, COF_2 molecules, and CF_2 molecules to all discharge wall surfaces are K_F, K_{COF_2}, and K_{CF_2}, respectively, and that *there are no losses of* CF_3 *molecules and* O *atoms to the walls.*

(a) Give the three rate equations for dn_α/dt, where α = CF_3, O and F, in terms of the rate coefficients, the known concentrations n_e, n_{CF_4}, n_{O_2}, and the n_α's.

$$\frac{dn_{CF_3}}{dt} = K_1 n_e n_{CF_4} - K_3 n_{CF_3} n_O - K_4 n_e n_{CF_3} = 0 \qquad (1)$$

$$\frac{dn_O}{dt} = 2K_2 n_e n_{O_2} - K_3 n_{CF_3} n_O = 0 \qquad (2)$$

$$\frac{dn_F}{dt} = K_1 n_e n_{CF_4} + K_3 n_{CF_3} n_O + K_4 n_{CF_3} n_e - K_F n_F = 0 \qquad (3)$$

(b) In the steady state, solve these equations to determine n_{CF_3}, n_O, and n_F, as functions of the rate coefficients and the assumed known concentrations n_e, n_{CF_4}, and n_{O_2}. Hence, show that the ratio of n_F/n_{CF_3} increases with (small) O_2 addition to a CF_4 discharge.

$$(1)-(2) \Rightarrow n_{CF_3} = \frac{K_1 n_{CF_4} - 2K_2 n_{O_2}}{K_4} \quad (4)$$

$$(2)+(4) \Rightarrow n_O = \frac{K_4}{K_3} \frac{2K_2 n_e n_{O_2}}{(K_1 n_{CF_4} - 2K_2 n_{O_2})} \quad (5)$$

$$(1)+(3) \Rightarrow n_F = \frac{2K_1 n_e n_{CF_4}}{K_F} \quad (6)$$

Hence

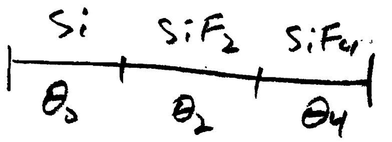
$$\frac{n_F}{n_{CF_3}} = \frac{K_4}{K_F} \frac{2K_1 n_e n_{CF_4}}{K_1 n_{CF_4} - 2K_2 n_{O_2}}$$

So as $n_{O_2} \uparrow$, $n_F/n_{CF_3} \downarrow$

Problem 4. Etching of a Silicon Substrate in a Fluorine Gas Discharge

Consider the following model of F_2 molecule chemical etching of a silicon substrate having volume density n_{Si} [m^{-3}] and surface site density n'_0 [m^{-2}]. Let θ_0 be the fraction of the surface sites that are bare silicon, θ_2 be the fraction covered with SiF_2, and θ_4 be the fraction covered with SiF_4 ($\theta_0 + \theta_2 + \theta_4 = 1$). Let F_2 molecules with gas phase density n_{F_2} [m^{-3}] near the substrate adsorb on θ_0 to form SiF_2 and on θ_2 to form SiF_4, with the same rate coefficient K_{ads}. Let SiF_4 molecules thermally desorb from θ_4 with rate coefficient K_{desor}. There is no adsorption of F_2 molecules on θ_4 and no thermal desorption of SiF_2 (or Si).

(a) Find the surface coverages θ_0, θ_2, and θ_4, and find the chemical (horizontal) etch rate E_h [m/s].



$$\frac{d\theta_4}{dt} = K_{ads} n_{F2} \theta_2 - K_{desor} \theta_4 = 0$$

$$\frac{d\theta_2}{dt} = \cancel{K_{ads} n_{F2}} (1-\theta_2-\theta_4) - \cancel{K_{ads} n_{F2}} \theta_2 = 0$$

$$\Rightarrow \quad 1 - 2\theta_2 - \theta_4 = 0 \quad \text{and} \quad \theta_4 = \frac{K_{ads} n_{F2}}{K_{desor}} \theta_2$$

Solving,

$$\theta_2 = \frac{K_{desor}}{2K_{desor} + K_{ads} n_{F2}} \; ; \quad \theta_4 = \frac{K_{ads} n_{F2}}{2K_{desor} + K_{ads} n_{F2}}$$

$$\theta_0 = \frac{K_{desor}}{2K_{desor} + K_{ads} n_{F2}}$$

$$E_h = \frac{n_0'}{n_{Si}} K_{desor} \theta_4 = \frac{n_0'}{n_{Si}} K_{ads} n_{F2} \theta_2 \quad //$$

(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 SiF_2 and SiF_4, having a yield Y_i of desorbed molecules per incident ion, which is the same for SiF_2 and SiF_4. In addition, there is thermal desorption of SiF_4 as in part (a). Find the ion enhanced (vertical) etch rate E_v of the silicon substrate, and find the ratio $\Gamma_{SiF_2}/\Gamma_{SiF_4}$ of the fluxes of the etch products.

Let $K_i = u_B / n_0'$

$$\frac{d\theta_4}{dt} = K_{ads}\, n_{F2}\, \theta_2 - K_{desor}\, \theta_4 - Y_i K_i n_{is}\, \theta_4 = 0$$

$$\frac{d\theta_2}{dt} = K_{ads}\, n_{F_2}(1-\theta_2-\theta_4) - K_{ads}\, n_{F2}\theta_2 - Y_i K_i n_{is}\, \theta_2 = 0$$

$$\Rightarrow \theta_4 = \frac{K_{ads}\, n_{F2}}{K_{desor} + Y_i K_i n_{is}}\, \theta_2 \text{ ; substitute into 2nd eq:}$$

$$1-\theta_2 - \frac{K_{ads}\, n_{F2}}{K_{desor} + Y_i K_i n_{is}}\,\theta_2 - \theta_2 - \frac{Y_i K_i n_{is}}{K_{ads}\, n_{F2}}\,\theta_2 = 0$$

$$\theta_2 = \frac{1}{2 + \dfrac{K_{ads}\, n_{F2}}{K_{desor} + Y_i K_i n_{is}} + \dfrac{Y_i K_i n_{is}}{K_{ads}\, n_{F2}}}$$

$$E_V = \frac{n_0'}{n_{Si}}\left[\left(K_{desor} + Y_i K_i n_{is}\right)\theta_4 + Y_i K_i n_{is}\,\theta_2\right]$$

$$= \frac{n_0'}{n_{Si}}\left(K_{ads}\, n_{F2} + Y_i K_i n_{is}\right)\theta_2$$

$$\frac{\Gamma_{SiF_2}}{\Gamma_{SiF_4}} = \frac{Y_i K_i n_{is}\,\theta_2}{\left(K_{desor} + Y_i K_i n_{is}\right)\theta_4} = \frac{Y_i K_i n_{is}}{K_{ads}\, n_{F2}}$$