Name: Solution Key

CHE323/384 Chemical Engineering for Micro- and Nanofabrication
Fall, 2014, Chris A. Mack

Final Exam - Practice

closed book, closed notes, three formula sheets, calculators allowed

Definitions: Please provide short (one to two sentence) definitions of the following terms. DO NOT use any equations. Make all definitions in words. (1 pt each)

1) Shot noise

Uncertainty that occurs when the finite number of particles is sufficiently small so that uncertainties due to the Poisson distribution, which describes the occurrence of independent random events, are of significance.

2) Cpk

A process capability metric that judges how the actual distribution of a process parameter compares to the specification of that parameter, including mean shift.

3) Pellicle

A thin transparent film placed over a photomask to prevent particles from reaching the mask, positioned so that particles on the pellicle are sufficiently out of focus as to be unimportant.

4) Bottom-up patterning

A self-assembly approach where the inherent characteristics of the material naturally result in the building up of the desired structures (as opposed to top-down patterning such as lithography + etch). Note that subtractive patterning and additive patterning are both examples of top-down patterning.

Questions: Please provide short (one to two sentence) answers to the following questions. (3 pts each)

1) How can the natural period of directed self-assembly be reduced?

$$L_0 \approx a\chi^{1/6}N^{2/3}$$

1) Reduce the size of the monomer unit a
2) Reduce the length of the polymer (the number of monomers in the chain, N)
3) Reduce the block interaction parameter χ

However, we must keep Nχ sufficiently high to get microphase separation. Thus, we generally decrease N and increase χ to keep Nχ sufficiently high.

2) Explain the main advantages and disadvantages of electron-beam lithography.

Electron-beam lithography has many advantages:
Maskless (R&D, prototyping, mask making)
High resolution (20 nm easily, 5 nm with much work)
Very flexible
E-beam lithography has many disadvantages:
Very slow: hours per wafer, not wafers per hour
Current is limited by Coulomb-Coulomb interactions
Projection printing with large fields is very hard

Problems: Show all work. State all assumptions clearly.
1. (10 pts) Given a (100) silicon wafer with an existing 200-nm thick oxide film, you wish to grown an additional 150 nm of SiO_2 (for a total oxide thickness of 350 nm). Design a wet, atmospheric pressure oxidation process at 950˚C to do this job.

For an atmospheric wet oxidation at 950 ˚C and (111) wafers, use Figures 4.2 and 4.3 in the book. Alternately, interpolate 1/T vs. log(A or B) from the table, then correct A for pressure by multiplying by 760/640.

B = 0.28 μm^2/hr
B/A = 0.75 μm/hr, giving A = 0.37 μm.

Correcting for (100) wafer, we multiply A by 1.68 to give A = 0.62 μm.

Calculating $\tau = \frac{t_o^{\,2} + At_o}{B} = \frac{0.2^2 + (0.62)(0.2)}{0.28} = 0.59\ hr$.

$$t_{ox}^{\,2} + At_{ox} = B(t+\tau),\quad t = \frac{t_{ox}^{\,2} + At_{ox}}{B} - \tau = \frac{0.35^2 + (0.62)(0.35)}{0.28} - 0.59 = 0.62\ hr$$

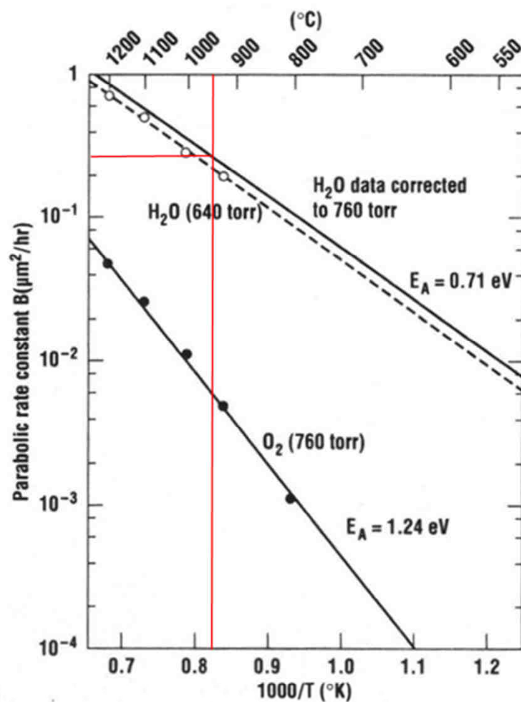


Figure 4.2 Arrhenius plot of the *B* oxidation coefficient. The wet parameters depend on the H_2O concentration and therefore on the gas flows and pyrolysis conditions *(after Deal and Grove)*.

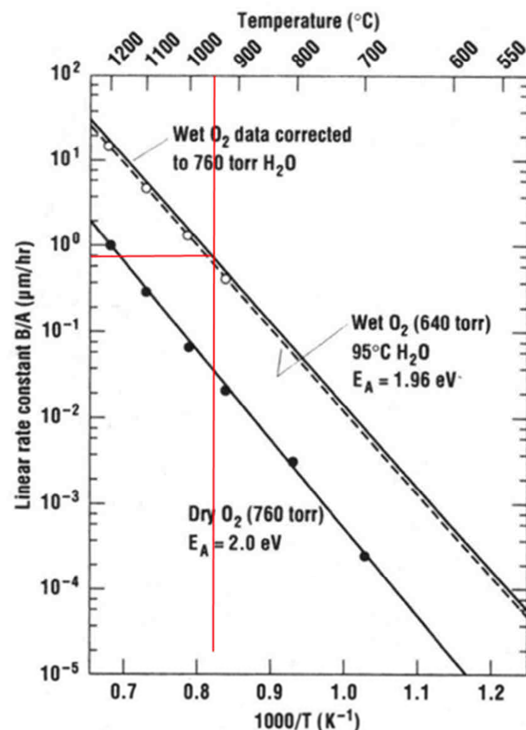


Figure 4.3 Arrhenius plot of the ratio *(B/A)* of the oxidation parameters *(after Deal and Grove)*.

2. (10 points) Consider a resistor made of p-type silicon with a cross-sectional area of 0.3 μm^2, and a length of 15 μm. The doping level in the resistor is 3×10^{17} cm^{-3}. What is the room temperature resistance?

For p-type silicon, the electron concentration can be ignored and the conductivity will be

$\sigma = qp\mu_p = qN_A\mu_p$ (since $p \approx N_A$). Thus,

$$\sigma = (1.602 \times 10^{-19}C)\left(450\frac{cm^2}{Vs}\right)(3 \times 10^{17}cm^{-3}) = 21.6\ (\Omega cm)^{-1}$$

$$R = \rho\frac{L}{A} = \frac{L}{\sigma A} = \left(\frac{\Omega cm}{21.6}\right)\frac{15\mu m}{0.3\mu m^2}\left(\frac{10{,}000\mu m}{1cm}\right) = 23\ k\Omega$$

3. (10 points) Determine the film deposition rate for an LPCVD system in which the mass transport coefficient h_G = 700 cm/s, the surface reaction rate constant k_s = 65 cm/s, the partial pressure of the reacting species is 0.2 torr, the total pressure in the chamber is 4 torr, the total concentration of all atoms/molecules in the gas is 4 X 10^{16} cm^{-3}, and the final atom density in the deposited film is 5 X 10^{22} cm^{-3}. Is this system reaction-controlled or diffusion-controlled?

$$C_G = C_T \frac{P_G}{P_T} = 4\text{x}10^{16}\,cm^{-3}\,\frac{0.2torr}{4torr} = 2\text{x}10^{15}\,cm^{-3}$$

$$k_T = \frac{k_S h_G}{k_S + h_G} = \frac{1}{\left(\frac{1}{h_G} + \frac{1}{k_S}\right)} = \frac{1}{\left(\frac{1}{700} + \frac{1}{65}\right)} = 59.5\,cm/s$$

$$v = k_T \frac{C_G}{N} = 59.5\,cm/s\,\frac{2\text{x}10^{15}\,cm^{-3}}{5\text{x}10^{22}\,cm^{-3}} = 2.38\,\text{x}\,10^{-6}\,cm\sec^{-1} = 0.024\mu m/s$$

Since $h_G >> k_S$, we are in the reaction-controlled regime.

4. (10 pts) A silicon diode is doped such that the *n*-side has $N_D = 2 \times 10^{18}$ cm^{-3} and on the *p*-side $N_A = 5 \times 10^{16}$ cm^{-3}. What is the room temperature built-in voltage for the resulting p-n junction? At zero bias, what is the depletion region width?

$$V_0 = \frac{kT}{q}\ln\left(\frac{N_A N_D}{n_i^2}\right) = 0.0259V\ln\left(\frac{(5\times10^{16})(2\times10^{18})}{(1.5\times10^{10})^2}\right) \;=\; 0.87\text{ V (built-in voltage)}$$

$$W = \sqrt{\frac{2\varepsilon_{Si}V_0}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)} = \sqrt{\frac{(2)(11.7)(8.8542\times10^{-14})(0.87)}{1.602\times10^{-19}}\left(\frac{1}{5\times10^{16}}+\frac{1}{2\times10^{18}}\right)} = 1.5 \times 10^{-5}\text{ cm}$$

= 150 nm

5. (20 pts) We wish to design a dual-well CMOS such that the two wells have the same depth at the substrate concentration of $3\times10^{15}\ cm^{-3}$, with arsenic used for the n-well and boron used for the p-well. Very shallow implants are used with a dose of $2\times10^{14}\ cm^{-2}$ for both. Since arsenic diffuses more slowly, it is introduced first and then driven-in partially. Then the boron is introduced and the rest of the anneal (drive-in diffusion) is performed until both junctions reach 1.2 microns. For a 1100 ºC process what drive-in times will be needed? Assume that the diffusivities are constant at their intrinsic silicon values.

To reach the same depth, the diffusion lengths must be the same. If t_1 and t_2 are the first and second drive-in times, and D_B and D_{As} are the boron and arsenic diffusivities, then $D_B t_2 = D_{As}(t_1 + t_2)$. First, let's calculate the two diffusivities. Using Table 3.2, at 1100˚C and for the junction ($n = p = n_i$)

$$D_B^{1100C} = (0.037 + 0.41)\exp\left(-\frac{3.46}{kT}\right) = 8.93\times10^{-14}\,cm^2 s^{-1}$$

$$D_{As}^{1100C} = 12.0\exp\left(-\frac{4.05}{kT}\right) + 0.066\exp\left(-\frac{3.44}{kT}\right) = 3.20\times10^{-14}\,cm^2 s^{-1}$$

Both dopants were implanted near the surface and are diffusing from a finite source, giving a one-sided Gaussian:

$$C(x,t) = \frac{Q_T}{\sqrt{\pi Dt}}\exp\left(-\frac{x^2}{4Dt}\right)$$

For boron, set x equal to the junction depth and t equal to t_2,

$$3\times10^{15} = \frac{2\times10^{14}}{\sqrt{\pi D_B t_2}}\exp\left(-\frac{\left(1.2\times10^{-4}\right)^2}{4D_B t_2}\right)$$

Iterating gives two solutions, but we need the smaller solution since the smaller time will create the junction first (the larger solution just smears out the dopants to near infinity).

$$D_B t_2 = 4.84\times10^{-10}\,cm^2$$

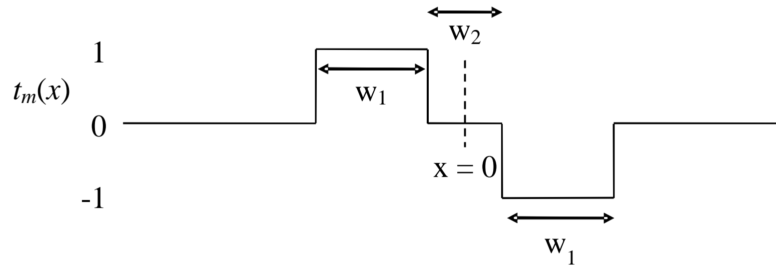
Thus, the second drive-in time is $t_2 = \frac{4.84\times10^{-10}}{8.93\times10^{-14}} = 5{,}420\,s = 1.50\,hours$

$$D_{As}(t_1 + t_2) = D_B t_2 = 4.84\times10^{-10}\,cm^2$$

$$t_1 + t_2 = \frac{4.84\times10^{-10}}{3.2\times10^{-14}} = 15{,}120\,s = 4.20\,hours$$

$$t_1 = 4.2 - 1.5 = 2.7\ hours$$

6. (20 pts) Derive the diffraction pattern of a phase-shifted double space pattern that does not repeat:



We can solve this directly using the Fourier Transform formula, or more easily by using the superposition of two spatially shifted spaces.

For a centered space of width w_1, $T_m(f_x) = \frac{\sin(\pi f_x w_1)}{\pi f_x}$

Use the shift theorem to shift that space to $-(w_1+w_2)/2$:

$$T_m(f_x) = \frac{\sin(\pi f_x w_1)}{\pi f_x} e^{+i\pi f_x (w_1+w_2)}$$

Use superposition to subtract the second phase-shifted space that is spatially shifted by $(w_1+w_2)/2$:

$$T_m(f_x) = \frac{\sin(\pi f_x w_1)}{\pi f_x} e^{+i\pi f_x (w_1+w_2)} - \frac{\sin(\pi f_x w_1)}{\pi f_x} e^{-i\pi f_x (w_1+w_2)} = 2i \sin(\pi f_x (w_1 + w_2)) \frac{\sin(\pi f_x w_1)}{\pi f_x}$$

7. (10 pts) Assume a typical chemically amplified positive resist with an exposure rate constant C = 0.030 cm^2/mJ, and a PEB time of 60 s at 115 °C. If the resist shows no deblocking until a dose of 8.0 mJ/cm^2, what is the relative quencher loading for the resist?

$$q_0 = h = 1 - e^{-CIt} = 1 - \exp[(-0.03)(8)] = 0.213$$