ECE 611 / CHE 611 - Electronic Material Processing
Fall 2019
Homework 4 - Solutions
Due at the beginning of class Tuesday November 26th

Question 1 [4 marks]:

a) In chemical vapor deposition (CVD) processes a process gas is passed through a chamber at a constant velocity \( u_0 \). Briefly explain (using either words and/or equations) why in the regime where \( u_0 \) is very high the CVD growth rate (velocity) is independent of \( u_0 \).[2 marks]

There are a couple of ways to answer this question. The simplest answer is simply that the growth rate in CVD processes is dependent on two main parameters: mass transport across the boundary layer and the reaction rate on the surface. The growth rate is limited by the slowest of these two processes. Hence if the reaction rate is very slow relative to mass transport then it doesn’t really matter how fast the mass transport is, the growth rate will be entirely dependent on the reaction rate. The mass transport rate depends on the flow rate of the material.

Equivalently we could start with our general equation for growth velocity (\( v \)):

\[
v = \frac{C_g h_g k_s}{N (k_s + h_g)}
\]

Where the symbol meanings are described in Lecture 11. \( h_g \) is the mass transport coefficient and \( k_s \) describes the reaction rate. In the regime when the reaction rate is much slower than mass transport we can say \( h_g \gg k_s \), leading to the approximation for growth rate:

\[
v = \frac{C_g k_s}{N}
\]

\( u_0 \) does not feature affect any of these variables, so we see in this regime that growth is independent of process gas velocity.

b) In the context of CVD deposition, briefly explain what an angled susceptor is used for.[2 marks]

If the process gas is passes over the surface of a wafer perpendicular to the plane of its surface, the boundary layer is known to vary as a function of position:

The thickness of the boundary layer affects the mass transfer coefficient (\( h_g \)) which in-turn affects the growth rate. This means that in this standard configuration the growth rate is likely not to be uniform over the surface of the wafer. Uniform growth is almost always desirable.
To solve this problem one can use what is called and angled susceptor. This is basically a way of holding the wafer / substrate at an angle to incoming gas flow. This results in a boundary layer which is more uniform as a function of position, hence leading to more uniform growth.

**Question 2 [5 marks]:**

a) Using the equation describing coverage ($\theta$) during the adsorption process, determine the adsorption rate required to form a film that has a stable coverage of $\theta = 0.99$, when the pressure of the deposited material is 0.01 Pa and the desorption rate is $10^{-5}$ s$^{-1}$. We define stable coverage as that which occurs after a very long time ($t \to \infty$).[3 marks]

The equation for coverage during the absorption process is:

$$\theta = \frac{KP}{1 + KP}(1 - \exp[-k_{des}(1 + KP)t])$$

Where:

$$K = \frac{k_{ads}}{k_{des}}$$

In the limit $t \to \infty$, the exponential term goes to zero: $e^{-\infty} \to 0$:

$$\theta = \frac{KP}{1 + KP}$$

Rearrange:

$$\theta(1 + KP) = KP$$

$$\theta + \theta KP = KP$$

$$\theta = KP - \theta KP$$

$$\theta = K(P - \theta P)$$

$$K = \frac{\theta}{P - \theta P}$$

Enter the values:

$$K = \frac{0.99}{0.01 - 0.99 \times 0.01} = 9900$$
\[ k_{ads} = K k_{des} \]
\[ k_{ads} = 9900 \times 10^{-5} = 0.099 \text{ Pa}^{-1}\text{s}^{-1} \]

b) The diffusion coefficient of Ge adatoms on a (111) Si surface is \( D = 8 \times 10^{-11} \text{ cm}^2/\text{s} \). If the diffusion length is 5nm, how long would we expect the atoms to reside on the surface before they desorb?\[2 \text{ marks}\]

The diffusion coefficient of adatoms on the surface is given by:
\[ L = \sqrt{D\tau_a} \]

Where:
- \( D \) is the Diffusion coefficient of adatoms on surface.
- \( \tau_a \) is the timescale for desorption.

The timescale for desorption is then:
\[ \tau_a = DL^2 \]

Work in cm:
\[ L = 5\text{ nm} \]
\[ L = 5 \times 10^{-7} \text{ cm} \]
\[ \tau_a = 8 \times 10^{-11} \times (5 \times 10^{-7})^2 \]
\[ \tau_a = 3.13 \text{ ms} \]

**Question 3 [8 marks]:**

a) We are exposing a wafer to 365nm light through a 200 nm aperture, at a distance of 10µm from the wafer surface. What approximation for diffraction is most appropriate in this case: Fresnel or Fraunhofer?\[2 \text{ marks}\]

To answer this question we need to evaluate the Fresnel number \( (F) \):
\[ F = \frac{W^2}{L\lambda} \]

Where:
- \( W \) is the size of the aperture.
- \( L \) is the distance of the wafer from the aperture.
- \( \lambda \) is the wavelength of the incident light.

For \( F \ll 1 \) the diffraction is described by Fraunhofer diffraction. For \( F \gg 1 \) the diffraction is described by Fresnel diffraction.

Evaluating \( F \) (in nm):

\[ F = \frac{200^2}{10^4 \times 365} = 0.011 \]

Hence this situation is best described by Fraunhofer diffraction.

b) A photoresist that is deposited via spin-coating at a speed of 1,000 rpm has a thickness of 400nm. What would its thickness be if the speed was 4,000 rpm. [2 marks]

This is a simple problem, and can be solved intuitively. Here is a long answer for completeness.

We know that the film thickness (\( t \)) is related to the angular velocity via this proportionality constant:

\[ t \propto \frac{1}{\sqrt{\omega}} \]

We can change this into a proportionality relationship into an equation by introducing an constant \( A \):

\[ t = \frac{A}{\sqrt{\omega}} \]

\[ t\sqrt{\omega} = A \]

We are told for a certain speed (\( \omega_1 = 1,000 \text{ rpm} \)) we obtain a certain thickness (\( t_1 = 400 \text{ nm} \)). Hence we can say that the proportionality constant is:

\[ A = 400\sqrt{1000} \]

Then to determine the thickness (\( t_2 \)) for a different speed (\( \omega_2 = 4,000 \text{ rpm} \)) we can use this constant:

\[ t_2 = \frac{A}{\sqrt{\omega_2}} \]

\[ t_2 = \frac{400\sqrt{1000}}{\sqrt{4000}} \]

\[ t_2 = 200 \text{ nm} \]

c) A positive photoresist with a contrast of \( \gamma = 3 \) is exposed to illumination, then developed to remove it from the wafer surface. If the incident optical power density is 200 mW/cm\(^2\), this photoresist will remain unaltered by the development process up until an exposure of 120 seconds. How long must this photoresist be exposed to ensure that all the resist is removed during development?[4 marks]

To solve this problem we use the equation for contrast:
\[ \gamma = \frac{1}{\log_{10} \left( \frac{Q_f}{Q_0} \right)} \]

We are given the contrast: \( \gamma = 3 \), and we need to determine the amount of time we need to expose the photoresist for, to ensure that all of the resist is removed during development.

\( Q_0 \) here is the dose of optical radiation required to begin the exposure effect. What this means is that if we apply any dose \( < Q_0 \), then develop the film, 100% of the photoresist will remain. It is not until we reach this critical dose \( Q_0 \), that anything happens to the film upon development. From the text in this question we are told that “this photoresist will remain unaltered by the development process up until an exposure of 120 seconds” and we are also told that the optical power density is 200 mW/cm\(^2\). Therefore we can determine the onset dose for exposure as:

\[ Q_0 = 200 \text{ mW/cm}^2 \times 120 \text{ s} = 24,000 \text{ mJ/cm}^2 \]

The parameter \( Q_f \) is the dose at which exposure is complete. What this means is, that upon applying any dose of radiation of \( Q_f \) or above, then developing the photoresist, 100% of the photoresist will be removed. From the question, we seek the amount of time required for all photoresist to be removed upon development, i.e. we seek the time that gives rise to the dose \( Q_f \).

So, re-arranging the equation for contrast in terms of \( Q_f \):

\[ \gamma = \frac{1}{\log_{10} \left( \frac{Q_f}{Q_0} \right)} \]

\[ \log_{10} \left( \frac{Q_f}{Q_0} \right) = \frac{1}{\gamma} \]

\[ \frac{Q_f}{Q_0} = 10^{\frac{1}{\gamma}} \]

\[ Q_f = Q_0 10^{\frac{1}{\gamma}} \]

Putting in the numbers gives:

\[ Q_f = 24,000 \times 10^{\frac{1}{3}} \]

\[ Q_f = 5.17 \times 10^4 \text{ mJ/cm}^2 \]

Now we just need to determine the amount of time required to provide this dose, from the incident optical power density (200 mW/cm\(^2\)).

\[ t = \frac{Q_f}{I} = \frac{5.17 \times 10^4}{200} = 258 \text{ s} \]

**Question 4 [8 marks]:**
a) If we have a projection lithography system that in air, gives rise to a feature size of 400nm, what feature size would an equivalent immersion lithography system achieve that uses decalin as the immersion fluid and a LuAg lens? Assume that the experimental parameter \( k_1 \), the maximum half angle, \( \alpha \), and the incident wavelength \( \lambda \), are the same in air as in the immersion fluid. Use the table of refractive indices below:[2 marks]

<table>
<thead>
<tr>
<th>Substance</th>
<th>Refractive Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
</tr>
<tr>
<td>Decalin</td>
<td>1.64</td>
</tr>
<tr>
<td>LuAg</td>
<td>2.1</td>
</tr>
<tr>
<td>Resist</td>
<td>1.8</td>
</tr>
</tbody>
</table>

When talking about projection lithography and immersion lithography, we use the same equation for resolution \( R \), just with a different refractive index \( n \):

\[
R = \frac{k_1 \lambda}{n \sin \alpha}
\]

We are told that \( k_1, \lambda, \) and \( \alpha \) are the same for the projection system and the immersion system. So although we can’t determine them individually, we can say that:

\[
\frac{k_1 \lambda}{\sin \alpha} = Rn = 400\text{nm} \times 1 = 400\text{nm}
\]

For the immersion lithography system we can then say:

\[
R = \frac{k_1 \lambda}{n \sin \alpha} = \frac{400\text{nm}}{n}
\]

We then just determine the minimum refractive index from the table above (\( n = 1.64 \)):

\[
R = \frac{400\text{nm}}{1.64} = 244\text{nm}
\]

b) Describe 3 difficulties associated with extreme UV becoming widespread in VLSI processing, and what can be done to overcome them.[6 marks]

There are a number of difficulties when it comes to implementing extreme UV lithography (EUVL). Some answers are given below, but other reasonable answers will also be accepted.

- A high vacuum must be employed for EUVL, rather than cleanroom conditions for standard PL. This due to the fact that air will absorb heavily at the low wavelengths of EUVL (~10nm), meaning that the radiation cannot be transmitted to the wafer.
- Traditional organic photoresists are not suitable for EUVL. Many organic photoresists absorb strongly at the low wavelengths of EUVL (~10nm). The absorption is normally atomic and these photoresists will not convert predictably in the same way as in conventional lithography. Similarly, the opaque nature of these resists to low-wavelength radiation will mean that light will not penetrate all the way through the resist, and complete conversion will not occur. Additionally, organic photoresists are generally not stable in the high-vacuums of EUVL chambers – they will often swell or


degas. Finally, organic photoresists will also collapse if the aspect ratio is too high (for very small features).

- Most known optical lenses (such as CaF₂) will not transmit the low wavelengths of EUVL (~10nm). This means that light cannot be transmitted through such lenses. The approach taken in EUVL is to use specially-designed mirrors (e.g. bilayer Mo/Si mirrors) to focus and direct light. The surface roughness of these mirrors also needs to be very low, as the wavelength and feature sizes are decreased to ~10nm.

- Finding an economically-viable source of radiation at approximately 10nm is also not trivial. The source need to have sufficient power (30-60W) while maintaining low implementation and operation/maintenance costs. The leading contender at present is laser-produced plasma radiation.