Lecture 12: Review for Midterm Examination 1

Announcements

Laboratory Report 1/2:

- Details on the report are online now.
  - I.e. regulations, length, content, grading criteria, etc.
  - The report will be due on Wednesday May 8th at the start of the lecture (4pm). This is 2 weeks from today.
- This will be an individual report on the laboratory work you have carried out on MOS capacitors.
  - Report 2 will be a collaborative report (more details later).
- Report 1 will contribute 15% to the final grade of ECE418 / ECE518.
Announcements

Laboratory Report 1/2:

• Hand in the report at the start of the lecture on Wednesday May 8th.
  • Please do not hand it in late.
  • 10% will be deducted for every day late (e.g. 85% → 75%).
  • A day late is 6pm of the day it is due.
    • E.g. if you hand it in 7pm the day it is due you will be deducted 10%, 7pm the day after it is due 20%, etc.
    • (I normally go home at 6pm anyway).
  • The maximum it can be late is 5 days (~50%).
  • After this you will be awarded to 0%.

Last Time

• We covered the growth of silicon oxide.
Lecture 12

- Information on Midterm Examination.
- Units.
- Example (Quantitative) Questions
Midterm Exam Details

- Wednesday May 1st at 4:00pm in STAG 211
- Exam will last 90 minutes.
  - The exam will start exactly at 4:00pm!
- Closed book and closed notes.
  - You can, and are expected to, use a calculator.
- Choose 2 out of 3 questions.
  - If you answer 3 I will take best 2 scores.
- It will contribute 15% of overall grade for class.
- The exam will material covered in lectures 2-11 (inclusive).
- There will be 50 marks per question. 100 total.

Midterm Exam Details

- The format will be similar to homeworks.
  - Several sub-questions per question.
- The number of marks will be shown at the end of every sub-question. E.g. [5 marks].
- Read through all questions before deciding which 2 you wish to answer.
- There will be a mixture of descriptive and quantitative questions.
- I will not expect you to conduct any numerical methods (e.g. numerical differentiation / fitting).
- I would provide the results of such a method.
Front Page of Midterm

• This is the front page of the exam:

OREGON STATE UNIVERSITY
Midterm Examination I May 1st 2019
Semiconductor Processing

Answer 2 out of 3 questions. If more than 2 questions are answered, the 2 questions with the highest marks will be considered.

A maximum of 50 marks will be awarded for each question. The mark assigned to each part of the question is indicated by a number in square brackets at the end of the sub-question, e.g. [3 marks].

You have 90 minutes to complete this exam; please pace yourself accordingly.

No notes of any kind are allowed. You may use calculators for this exam.

Questions Start on page 6.

Equations

• All constants and relevant formulae will be provided.
• Parameters will be labeled as clearly as possible.

Useful Equations:
Electric Field due to an Applied Voltage between Two Plates:

\[ E = \frac{V}{d} \]

- \( E \) is the electric field strength.
- \( V \) is the voltage applied between the two plates.
- \( d \) is the separation distance between the plates.

Definition of Mobility:

\[ \mu = \frac{F}{E} \]

- \( \mu \) is mobility of a charge carrier.
- \( F \) is the force on the charge carrier.
- \( E \) is the applied electric field strength.

Charge Carrier Mobility under Multiple Trapping and Balance Model:

\[ 
\mu = \mu_0 \exp \left( -\frac{E_T}{kT} \right) 
\]

- \( \mu_0 \) is the charge carrier mobility.
- \( \mu_0 \) is the mobility parameter at band mobility.
- \( E_T \) is the activation energy.
- \( k \) is the Boltzmann constant.
- \( T \) is the temperature.

Conversion between Logarithms of Different Bases:

\[ \log_b(x) = \frac{\log_a(x)}{\log_a(b)} \]

- \( \log_b(x) \) is the logarithm to base \( b \) of \( x \).
- \( \log_a(x) \) is the natural logarithm of \( x \).
- \( \log_a(b) \) is a base.
Equations Not Provided

• You will be given most equations. However, simple relationships you would be expected to know.
• Examples:
  • Density:
    \[ n_{2D} = \frac{1}{A} \quad n_{3D} = \frac{1}{V} \]
  • Area:
    \[ A = \pi r^2 \]
  • Surface area of sphere:
    \[ A = 4\pi r^2 \]

Equations Not Provided

• You will be given most equations. However, simple relationships you would be expected to know.
• Examples:
  • Chain rule:
    \[ \frac{df}{dx} = \frac{df}{dg} \frac{dg}{dx} \]
  • Standard derivatives:
    \[ \frac{d}{dx} (ae^{bx}) = abe^{bx} \quad \frac{d}{dx} (\ln(ax)) = \frac{1}{x} \]
    \[ \frac{d}{dx} (\sin(ax + b)) = -a \cdot \cos(ax + b) \]
    \[ \frac{d}{dx} (\cos(ax + b)) = -a \cdot \sin(ax + b) \]
Equations Not Provided

- You will be given most equations. However, simple relationships you would be expected to know.
- Examples:
  - Velocity: \( v = \frac{x}{t} \)
  - Current from charge: \( I = \frac{Q}{t} \)
  - Ohm’s Law: \( V = IR \)
  - Kinetic Energy: \( E = \frac{1}{2}mv^2 \)
  - Momentum: \( p = mv \)
  - Mass density: \( \rho = \frac{m}{V} \)

Equations Not Provided

- You will be given most equations. However, simple relationships you would be expected to know.
- Examples:
  - Limits of exponentials:
    \[ e^0 = 1 \quad e^{-\infty} = 0 \]
    \[ e^{\pm 1/\infty} = e^0 = 1 \]
  - Unit conversions
    \[ 1\text{Å} = 10^{-10}\text{m} \]
    \[ 1\mu\text{m} = 10^{-6}\text{m} \]
    etc ...
Grading

• Hopefully I will not have to curve.
• But it depends on results.
• I may try to ~match grade distributions from previous years.
• Although if everyone does well the mean will be higher.
• I will return your examinations 2 weeks later (Wednesday 15th May).

Preparation

• Do not just use this lecture!
  • The examples today are just meant to give you a feel for the style of question to expect.
  • Go through the lectures and consider what questions you could be asked on the notes given.
  • Go back through the homework and solutions, and make sure you understand everything (not just memorize a procedure).
  • The textbook is another good resource – it explains things in more depth.
  • There are plenty of good problems to study.
  • I have purposely not used any of the problems in the textbook for homework, so they should all be new to you.
Units

Unit Conversions

- It is worth spending a few slides on units.
- In semiconductor characterization we tend to use often non-SI units as standard parameters.
- In particular, the use of $cm$ is common over $m$.
- For example:
  - Concentration, $n, p \sim cm^{-3}$ rather than $m^{-3}$.
  - Mobility, $\mu_e, \mu_h \sim cm^2/Vs$ rather than $m^2/Vs$.
- You are expected to know how to convert between units without notes / references.
- This is a useful skill generally.
Unit Conversions

- In one dimension it is straightforward:
  \[1 \text{ m} = 100 \text{ cm}\]
  \[1 \text{ cm} = 0.01 \text{ m}\]

- It can be easier to go from a unit to meters before going to cm:
  \[1 \mu \text{m} = 10^{-6} \text{ m}\]
  \[10^{-6} \text{ m} = 10^{-4} \text{ cm}\]
  \[1 \text{ km} = 10^3 \text{ m}\]
  \[10^3 \text{ m} = 10^5 \text{ cm}\]

Inverse Dimensions

- For inverse dimensions we go the other way:
  \[1 \text{ m} = 100 \text{ cm}\]
  \[1 \text{ m}^{-1} = 0.01 \text{ cm}^{-1}\]
  \[1 \text{ cm} = 0.01 \text{ m}\]
  \[1 \text{ cm}^{-1} = 100 \text{ m}^{-1}\]

- E.g. If you can have a line that is one meter long, it can accommodate 100 items in this meter. I.e. 100 m⁻¹. If you shorten the length to 1 cm, it can now only hold 1 item. I.e. 1 cm⁻¹.
Inverse Dimensions

• For inverse dimensions we go the other way:

\[ 1 \text{ m} = 100 \text{ cm} \quad \Rightarrow \quad 1 \text{ m}^{-1} = 0.01 \text{ cm}^{-1} \]
\[ 1 \text{ cm} = 0.01 \text{ m} \quad \Rightarrow \quad 1 \text{ cm}^{-1} = 100 \text{ m}^{-1} \]

• Again, it is often easier to convert to meters first.

\[ 1 \text{ nm}^{-1} = 10^9 \text{ m}^{-1} \quad \Rightarrow \quad 10^9 \text{ m}^{-1} = 10^7 \text{ cm}^{-1} \]
\[ 1 \text{ km}^{-1} = 10^{-3} \text{ m}^{-1} \quad \Rightarrow \quad 10^{-3} \text{ m}^{-1} = 10^{-5} \text{ cm}^{-1} \]

Inverse Volume

• For inverse volume you apply the conversion in reverse 3 times

\[ 1 \text{ m} = 100 \text{ cm} \quad \Rightarrow \quad 1 \text{ m}^{-2} = 10^{-4} \text{ cm}^{-2} \quad \Rightarrow \quad 1 \text{ m}^{-3} = 10^{-6} \text{ cm}^{-3} \]
\[ 1 \text{ cm} = 0.01 \text{ m} \quad \Rightarrow \quad 1 \text{ cm}^{-2} = 10^4 \text{ m}^{-2} \quad \Rightarrow \quad 1 \text{ cm}^{-3} = 10^6 \text{ m}^{-3} \]

• Again it is often easier to convert to meters first.

\[ 1 \text{ nm}^{-3} = 10^{27} \text{ m}^{-3} \quad \Rightarrow \quad 10^{27} \text{ m}^{-3} = 10^{21} \text{ cm}^{-3} \]
\[ 1 \text{ km}^{-3} = 10^{-9} \text{ m}^{-3} \quad \Rightarrow \quad 10^{-9} \text{ m}^{-3} = 10^{-15} \text{ cm}^{-3} \]
Non-SI Units in Equations

• If all parameters in an equation are in SI units you are guaranteed to get the correct answer.
  • You may have to convert input parameters to SI, depending on how they are provided.
  • You also may have to convert the final answer from SI, if the question asks for a non-SI final unit.
• However sometimes it is more convenient to just use the non SI unit.
• For example if input parameters are in cm, and final answer is in $\Omega \text{ cm}$.

For example, the resistivity in terms of resistance and dimensions:

$$\rho = \frac{RA}{L}$$

• If we are told:
  • $R = 1\Omega$.
  • $A = 1\text{cm}^2$.
• $L = 1\text{cm}$.
  • We want answer in $\Omega \text{ cm}$

• So we can just use cm directly.
Non-SI Units in Equations

• However consider this example of photon energy:

\[ E = \frac{hc}{\lambda} \]

• If for example we are told:
  • \( \lambda = 1\mu m \).
  • We want the energy in J.

\[ E = \frac{hc}{\lambda} \quad \text{J} \]

Unit mismatch

\[ 3.0 \times 10^8 \text{ m/s} \]

\[ 3.0 \times 10^{14} \text{ J/m}^2 \text{s} \]
Example (Quantitative) Questions

Example 1

• **Question:** What is the nearest neighbor distance in silicon?

• Give your answer in Å.

• You would be told the lattice spacing is $a = |a| = 5.43$ Å.
Example 1

• The nearest neighbor distance is the **shortest distance** between two silicon atoms.
• Identify the shortest distance as \( \frac{1}{4} \) of the unit cell diagonal:

![Top-down view of a crystal lattice with labels for nearest neighbor distances](image)

Top-down view

Number represents height in cell

\[ \text{Number represents height in cell} \]

\[ \begin{align*}
0 & \quad 1/2 & \quad 0 & \quad 1/2 \\
3/4 & \quad 1/4 & \quad 3/4 & \quad 0 \\
1/2 & \quad 0 & \quad 1/2 & \quad 0 \\
0 & \quad 1/2 & \quad 0 & \quad 1/2 \\
\end{align*} \]

• So we can just determine the length of the diagonal across the unit cell.
• First determine the length of the diagonal in the \( xy \) plane.
• Define this length as \( d \). Use Pythagoras’ Theorem:

\[
\begin{align*}
d &= \sqrt{a^2 + a^2} \\
d &= \sqrt{2a^2} \\
d &= \sqrt{2}a
\end{align*}
\]
Example 1

- We find the diagonal across the unit cell \((r)\) by using Pythagoras’ Theorem again.

\[ r = \sqrt{a^2 + d^2} \]

\[ d = \sqrt{2a^2} \]

\[ r = \sqrt{a^2 + 2a^2} = \sqrt{3a^2} = \sqrt{3}a \]

- We are told the unit cell is \(a = 5.43\ \text{Å} \).
- Recall, this is the unit cell length. The nearest neighbor distance is \(a/4\).

\[ \frac{\sqrt{3}}{4} a = \frac{\sqrt{3}}{4} \times 5.43\text{Å} = 2.35\text{Å} \]

Example 2

- Using the normal freezing relationship, determine the average phosphorus concentration (in atoms / cm\(^3\)) throughout the top half of a silicon ingot pulled from a melt containing an impurity concentration of \(1 \times 10^{16} \text{ cm}^{-3}\).
- We would be told the segregation coefficient of phosphorus in silicon \(k_0 = 0.35\).
- It is important to identify here that we are interested in the average concentration throughout the top half of the ingot. I.e. not just the concentration at the halfway point.
Example 2

- We would be given the equation for the normal freezing relationship, and associated parameters:
  \[ C_s = k_0 C_0 (1 - X)^{k_0 - 1} \]

- Where:
  - \( X \) is the fraction of the melt solidified.
  - \( C_0 \) is the initial melt impurity concentration.
  - \( C_s \) is the solid impurity concentration.
  - \( k_0 \) is the segregation coefficient.
  - So, remember that \( X \) is the fraction of the melt solidified. We treat it such that \( X = 0 \) when the ingot has just began to be pulled out and \( X = 1 \), when the ingot is completely out.

Example 2

- Recall, we are looking for the average concentration over the first half of the ingot. I.e. between \( X = 0 \) and \( X = 0.5 \).
- To quantify this, we take the integral over this part of the ingot:
  \[ \bar{C}_s = \frac{1}{0.5} \int_0^{0.5} C_s(X) dX \]

- Where \( C_s(X) \) is the solid impurity concentration at \( X \).
- We use the bar in \( \bar{C}_s \) denotes this is an average.
- Putting in the normal freezing relation:
  \[ \bar{C}_s = \frac{1}{0.5} \int_0^{0.5} k_0 C_0 (1 - X)^{k_0 - 1} dX \]
Example 2

\[ \bar{C}_s = \frac{1}{0.5} \int_0^{0.5} k_0 C_0 (1 - X)^{k_0-1} dX \]

- The rest of this question is just the evaluation of the integral.
- Start by pulling out the constants:
  \[ \bar{C}_s = \frac{k_0 C_0}{0.5} \int_0^{0.5} (1 - X)^{k_0-1} dX \]
- The easiest way to solve this integral is to use a change of variables:
  \[ Y = 1 - X \]

\[ \frac{dY}{dX} = -1 \]
\[ dX = -dY \]

Example 2

\[ \bar{C}_s = \frac{k_0 C_0}{0.5} \int_0^{0.5} (1 - X)^{k_0-1} dX \]

- Before we integrate, we also need to change out limits to \( Y \) rather than \( X \) using \( Y = 1 - X \):

\[ \bar{C}_s = -\frac{k_0 C_0}{0.5} \int_{X=0}^{X=0.5} Y^{k_0-1} dY \]

- Now integrate:

\[ \bar{C}_s = -\frac{k_0 C_0}{0.5} \left[ \frac{Y^{k_0}}{k_0} \right]_1^{0.5} \]

\[ \bar{C}_s = -\frac{C_0}{0.5} \left[ Y^{k_0} \right]_1^{0.5} \]
Example 2

\[ \bar{C}_s = -\frac{C_0}{0.5} [Y^{k_0}]^{0.5} \]

- Now we can just evaluate the answer:

\[ \bar{C}_s = -\frac{C_0}{0.5} (0.5^{k_0} - 1^{k_0}) = -\frac{C_0}{0.5} (0.5^{k_0} - 1) = \frac{C_0}{0.5} (1 - 0.5^{k_0}) \]

- Enter the values (\(k_0 = 0.35\) and \(C_0 = 1\times10^{16}\) cm\(^{-3}\)):

\[ \bar{C}_s = \frac{1 \times 10^{16}}{0.5} (1 - 0.5^{0.35}) \]

\[ \bar{C}_s = 4.3 \times 10^{15} \text{ cm}^{-3} \]

Example 3

- Consider the following circuit:

- If we measure the peak-to-peak output voltage (\(V_{out}\)) as a function of input voltage, we see a plot like the following:

- If we are told that the corner frequency is:

\[ f_c = 318.3 \text{ Hz} \]

- What is the capacitance of our capacitor?
Example 3

- You would be given:
  \[ \tau = \frac{1}{2\pi f_c} = RC \]
- So:
  \[ C = \frac{1}{2\pi f_c R} \]
- We just put in the numbers:
  \[ C = \frac{1}{2\pi \times 318.3 \times 5000} \]
  \[ C = 100 \text{ nF} \]

Example 4

- Consider a vacuum-deposition chamber pumped down to a pressure of \(10^{-6}\) Torr at 300K. Before pumping down, the chamber was filled with \(N_2\) gas.
- If we place a sample inside the chamber, what particle flux will it experience?
- Give your answer in \#/cm\(^2\)/s.
- You would be given the following equations:
  - Pressure:
    \[ P = nk_BT \]
  - Mean particle velocity:
    \[ \bar{c} = \sqrt{\frac{8k_BT}{\pi m}} \]
  - Flux:
    \[ J_A = \frac{1}{4} n \bar{c} \]
Example 4

- You would be given all the variables as well:

\[ P = nk_BT \quad J_A = \frac{1}{4} n\bar{c} \quad \bar{c} = \sqrt[\frac{8k_BT}{\pi m}} \]

- Where:
  - \( P \) is pressure.
  - \( n \) is the 3-dimensional particle number density.
  - \( k_B \) is Boltzmann Constant.
  - \( T \) is Temperature.
  - \( J_A \) is the Impingement Rate or Flux.
  - \( \bar{c} \) is the average (mean) velocity.
  - \( m \) is the particle mass.

Example 4

- We are told \( P = 10^{-6} \) Torr. The first thing we have to do when given a non-SI pressure is convert it to SI units (Pascals).
- You would be told that 760 Torr = 101,325 Pascal.

\[ P = 10^{-6} \times \frac{101325}{760} = 1.33 \times 10^{-6} \text{ Pa} \]

- We seek the flux:

\[ J_A = \frac{1}{4} n\bar{c} \]

- So we need both the particle number density (\( n \)) and mean velocity (\( \bar{c} \)). We have neither at present.
Example 4

\[ P = nk_B T \]
\[ n = \frac{P}{k_B T} \]

1.38 \times 10^{-23} \text{ JK}^{-1}

\[ n = \frac{P}{k_B T} \]

\[ n = 3.21 \times 10^{16} \text{ m}^{-3} \]

- We will stick to SI units.
- We also need the average particle velocity: \( \bar{c} \):

\[ \bar{c} = \sqrt{\frac{8k_B T}{\pi m}} \]

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Example 4

\[ \bar{c} = \sqrt{\frac{8k_B T}{\pi m}} \]

- We are told the temperature is 300K, and would either be told the mass of a nitrogen atom, or given the periodic table.
- The mass of a single N atom is 14.007 but we are talking about gaseous nitrogen (N\(_2\)) formed of two nitrogen atoms.

\[ m = 14.007 \times 2 = 28.014 \text{ amu} \]

- You would be given the conversion: 1 amu = 1.66 \times 10^{-27} \text{ kg}.
- Hence:

\[ \bar{c} = \sqrt{\frac{8 \times 1.38 \times 10^{-23} \times 300}{3.14 \times 28.014 \times 1.66 \times 10^{-27}}} = 476 \text{ m/s} \]
Example 4

• Finally, we can work out the flux:

\[ J_A = \frac{1}{4} n \bar{c} \]

\[ J_A = \frac{1}{4} \times 3.21 \times 10^{16} \times 476 \]

\[ J_A = 3.82 \times 10^{18} \text{ m}^{-2}\text{s}^{-1} \]

• We were asked to give the answer in \#/cm\(^2\)/s (\(\equiv\) cm\(^{-2}\)s\(^{-1}\)).

1m = 100cm
1m\(^2\) = 100cm \times 100cm = 10\(^4\) cm\(^2\)
1m\(^2\) = 10\(^{-4}\) cm\(^{-2}\)

\[ J_A = 3.82 \times 10^{14} \text{ cm}^{-2}\text{s}^{-1} \]

Example 5

• Say we deposit a photoresist via spin-coating with an angular velocity of 2000 rpm and measure the thickness to be 1μm.

• If we instead deposit the photoresist at 8000rpm (keeping all other parameters the same), what would you expect the thickness to be?

• You would be told that:

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

• If we define \( A \) as some constant we could say:

\[ t = \frac{A}{\sqrt{\omega}} \]
Example 5

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

- We are told that if \( \omega = 2,000 \text{ rpm} \) then \( t = 1 \mu m \). Work in \( \mu m \).
  
  \[ A = t\sqrt{\omega} \quad \rightarrow \quad A = 1 \times \sqrt{2000} \quad \rightarrow \quad A = 4.47 \]

- So if we increase the speed to 8,000 rpm then:
  
  \[ t = \frac{4.47}{\sqrt{8000}} \]
  
  \[ t = 0.5 \mu m \]

Example 6

- Consider a Si wafer with a native film of SiO\(_2\).
- The SiO\(_2\) film has a mean thickness of \( h_f = 5 \text{nm} \) and a thickness variation parameters of \( \delta = 0.05 \).
- We need to remove all of the native SiO\(_2\) before we can proceed with our processing, but cannot tolerate more than 1nm of Si being removed anywhere on our wafer.
- If we use an etchant with a film-substrate selectivity of \( S_{fs} = 10 \) for such an etch, what is the highest acceptable etch
Example 6

- Notice we are not given a etch rate here, just the selectivity and thicknesses.
- We would be given the equation for maximum \( (h_f^{(max)}) \) and minimum \( (h_f^{(min)}) \) film thickness, for a film with a uniformity parameter of \( \delta \) and a mean thickness of \( h_f \):
  \[
  h_f^{(max)} = h_f (1 + \delta)
  \]
  \[
  h_f^{(min)} = h_f (1 - \delta)
  \]
- We can show:
  \[
  h_f^{(max)} = 5(1 + 0.05) = 5.25 \text{ nm}
  \]
  \[
  h_f^{(min)} = 5(1 - 0.05) = 4.75 \text{ nm}
  \]

Example 6

- For an unknown etch rate of \( R_f \) in the film (SiO\(_2\)), lets say would hence take \( t_f^{(max)} \) time to remove 5.25nm of SiO\(_2\) and \( t_f^{(min)} \) time to remove 4.75nm of SiO\(_2\).
- I.e., if we work in nm we can say:
  \[
  t_f^{(max)} = \frac{h_f^{(max)}}{R_f} = \frac{5.25 \text{ nm}}{R_f}
  \]
  \[
  t_f^{(min)} = \frac{h_f^{(min)}}{R_f} = \frac{4.75 \text{ nm}}{R_f}
  \]
Example 6

\[ t_f^{(\text{min})} = \frac{4.75 \text{ nm}}{R_f} , \quad t_f^{(\text{max})} = \frac{5.25 \text{ nm}}{R_f} \]

- This means that some parts of the silicon wafer will be exposed to the etchant for:

\[ t_s = t_f^{(\text{max})} - t_f^{(\text{min})} = \frac{5.25 \text{ nm}}{R_f} - \frac{4.75 \text{ nm}}{R_f} = \frac{0.5 \text{ nm}}{R_f} \]

- We are told the film-substrate selectivity is \( S_{fs} = 10 \). Hence:

\[ S_{fs} = \frac{R_f}{R_s} \quad \Rightarrow \quad R_f = 10 \times R_s \quad \Rightarrow \quad t_s = \frac{0.5 \text{ nm}}{10 \times R_s} = \frac{0.05 \text{ nm}}{R_s} \]

- The etchant is ok.

Example 6

- We are told the amount of Si removed from the wafer cannot be more than 1 nm.

- For a certain amount of time \( t_s \) and a certain silicon etch rate \( (R_s) \) we would hence say we require the exposure time to be:

\[ t_s \leq \frac{h_s}{R_s} \leq \frac{1 \text{ nm}}{R_s} \]

- Since 0.05 nm < 1 nm, this satisfies the inequality. The etchant is ok.
Example 7

• At a temperature of $T = 1200$ K, would you expect interstitial oxygen defects or substitutional phosphorus defects to be more mobile in a silicon wafer?

• You would be given the following information:

<table>
<thead>
<tr>
<th></th>
<th>Substitutional</th>
<th>Interstitial</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D_0$ (cm$^2$/s)</td>
<td>$E_{VD}$ (eV)</td>
</tr>
<tr>
<td>P</td>
<td>3.85</td>
<td>3.66</td>
</tr>
<tr>
<td>B</td>
<td>0.037</td>
<td>3.46</td>
</tr>
<tr>
<td>As</td>
<td>0.066</td>
<td>3.44</td>
</tr>
<tr>
<td>Sb</td>
<td>0.214</td>
<td>3.65</td>
</tr>
</tbody>
</table>

$D = D_0 \exp\left[-\frac{E_{VD}}{k_B T}\right]$

Example 7

• The key to this question is to understand that diffusivity quantifies how mobile impurities are.

• After identifying this, the question is simply about evaluating the diffusivities at 1200 K.

• Start with phosphorus (you would be given $e = 1.60 \times 10^{-19}$ J):

$$E_{VD}^P = 3.66 \text{ eV} = 3.66 \times 1.6 \times 10^{-19} = 5.86 \times 10^{-19} \text{ J}$$

• You would also be given $k_B = 1.38 \times 10^{-23}$ J/K:

$$D^P = D_0^P \exp\left[-\frac{E_{VD}^P}{k_B T}\right] = 3.85 \times \exp\left[-\frac{5.86 \times 10^{-19}}{1.38 \times 10^{-19} \times 1200}\right]$$

$$D^P = 1.69 \times 10^{-15} \text{ cm}^2/\text{s}$$
Example 7

- Follow the same procedure for oxygen:

\[ E_{VD}^O = 2.44 \text{ eV} = 2.44 \times 1.6 \times 10^{-19} = 3.90 \times 10^{-19} \text{ J} \]

\[ D^O = D_0^O \exp \left[- \frac{E_{VD}^O}{k_B T} \right] = 0.21 \times \exp \left[- \frac{3.90 \times 10^{-19}}{1.38 \times 10^{-19} \times 1200} \right] \]

\[ D^O = 1.21 \times 10^{-11} \text{ cm}^2/\text{s} \]

- We hence see that:

\[ D^O \gg D^P \]

- So we can say that at 1200K interstitial oxygen defects are more mobile than substitutional phosphorus defects.

Example 8

- We wish to grow a 200nm film of SiO\(_2\) on Si using a dry oxidation process at a temperature of 1000°C. Use the parameters in the below table to determine how long the oxidation process will take. Give your answer in hours.

- You would be given:

\[ X_0(t) = 0.5A \left[ 1 + \frac{4B}{A^2} (t + \tau) \right]^{1/2} - 1 \]
Example 8

- This is essentially an exercise in entering numbers. We are given the target thickness and need to determine the oxidation time. We hence need to re-arrange the below:

\[
X_0(t) = 0.5A \left[ 1 + \frac{4B}{A^2} (t + \tau) \right]^{1/2} - 1
\]

\[
\frac{2X_0}{A} = \sqrt{1 + \frac{4B}{A^2} (t + \tau) - 1}
\]

\[
\frac{2X_0}{A} + 1 = \sqrt{1 + \frac{4B}{A^2} (t + \tau)}
\]

\[
\frac{2X_0}{A} + 1 = 1 + \frac{4B}{A^2} (t + \tau)
\]

\[
t + \tau = \frac{A^2}{4B} \left( \frac{2X_0}{A} + 1 \right)^2 - 1
\]

\[
t = \frac{A^2}{4B} \left( \frac{2X_0}{A} + 1 \right)^2 - 1 - \tau
\]

- Now we just need to enter the parameters for a dry growth at \( T = 1000^\circ C \).

Example 8

- We are told the target thickness is 200nm. Work in \( \mu m \) and hr:

\[
t = \frac{A^2}{4B} \left( \left[ \frac{2X_0}{A} + 1 \right]^2 - 1 \right) - \tau
\]

\[
t = \frac{0.165^2}{4 \times 0.0117} \left( \left[ \frac{2 \times 0.2}{0.165} + 1 \right]^2 - 1 \right) - 0.37 = 5.87 \text{ hr}
\]

\[
= 5 \text{ hr} 52 \text{ min}
\]
Next Time...

• After the midterm we will start to cover transistors.

Good Luck!