Lecture 17
Review for Final Exam
Announcements

Homework:

• Homework Number 4 is due today, please hand it in to me.
• Homework will be returned on the day of the final exam. Please pick up it up from me after the exam.
• Solutions will be posted later this afternoon.
Lecture 17

• Exam Details.
• Lecture 10: Thin-Film Growth
• Lecture 11: Diffusion.
• Lecture 12: Ion Implantation.
• Lecture 13: Basic Photolithography.
• Lecture 14: Advanced Photolithography.
• Lecture 15: Etching.
• Lecture 16: Chemical Mechanical Planarization.
• Other equations you will not be given in the exam.
Exam Details
Exam Details

- The exam will take place on Tuesday (5th December) at 2pm in Gleeson 100.
- You will have 110 minutes.
- Please arrive on-time, if you are late you will have less time to complete the exam.
- Closed book and no notes.
- Please bring calculator and pens.
- Spread yourself out in the room.
- You will be examined on material covered in lectures 10-17.
  - Some things from lectures 2-9 may also be covered.
Exam Format

- There will be **4 questions total**.
- You will answer **3** out of 4 questions.
  - If you answer >3 questions, I will take the marks from the top 3.
- 25 marks per question. 1 mark = 1 1/3 %.
- Maximum marks = 100%.
- Each question will be split into sub-questions: (a), (b), (c) etc...
- The mark breakdown will be indicated for each sub question.
- Each sub-question will be independently solvable.
  - E.g. to get full marks on 1(b) you did not have to complete 1(a).
Exam Format

- All relevant constants will be given.
- Even well-known constants (speed of light, charge on $e^-$).
- Most complex equations will be provided.
- Some simple equations you will be expected to know, and they will not be provided.
- You will use the paper provided.
- Please keep answers contained to the correct pages.
- There should be $>>$ paper than you need for each question.
- If you need more please put your hand up and I will provide you with more.
- Label extra pages with the question number, and make it clear the workflow.
Exam Format

• Questions will be a mixture of textual and mathematical problems.
• Equations will be given at the start of the exam, and could be used in any question(s).
  • Their order will not necessarily be relevant.
• Equations will be given by name only.
• The variables will be labeled.
• You will need to know their context.
• If you are asked to derive something, you will be given the starting equations and assumptions.
• Constants will be given on separate sheet (with units).
• You may be given a table with values in a specific question.
Sample Format
This Lecture

- I will not be telling you the exam questions.
- I will go through each lecture and remind you of the relevant topics.
- This lecture is designed to tell you what you need to know – don’t just use these notes to prepare!
- If I label an equation as “You will be given”, it could be used in a derivation, or you could be asked to derive it.
- If I label an equation as “You will not be given”, you may be expected to use it without it being given at the start of the exam.
- Equations not present in this lecture could come up in the exam, but they will be given.
Lecture 10: Thin Film Growth
Overview of Thin-Film Growth Process

Atom arrives:

Migration:

Collision and Combination:

Nucleation:

Coalescence:

Continuity:
Particle Flux

- From Lecture 3 (vacuum systems):

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

\[ P = nk_B T \]

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

- We can show:

\[ J_A = \frac{P}{\sqrt{2\pi mk_B T}} \]
# Pressure

- From Lecture 3 (vacuum systems):

<table>
<thead>
<tr>
<th>Unit</th>
<th>Pascals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Pascal</td>
<td>1</td>
</tr>
<tr>
<td>1 Torr</td>
<td>$\frac{101325}{760} \approx 133.3$</td>
</tr>
<tr>
<td>1 Bar</td>
<td>$1 \times 10^5$</td>
</tr>
<tr>
<td>1 atm</td>
<td>101325</td>
</tr>
</tbody>
</table>
Types of Adsorption

• Chemisorption.
  • A strong chemical bond is formed between the adsorbate atom or molecule. I.e. an ionic or covalent bond.

• Physisorption.
  • Physisorption is weaker, and is often considered as having no chemical interaction involved.
  • The attractive interaction, in this case, is largely due to the van der Waals force.
Fractional Coverage

- The fraction of surface covered is given by:

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

- Where:
  - \( \theta \) is fractional coverage of the substrate.
  - \( P \) is the partial pressure of the atoms in the vapor.
  - \( k_{ads} \) is the reaction rate of the adsorption process.
  - \( k_{des} \) is the reaction rate of the desorption process.

\[ K = \frac{k_{ads}}{k_{des}} \]
Example

Consider an adsorption process where:

- \( k_{ads} = 10^{-2} \text{ s}^{-1} \)
- \( k_{des} = 10^{-5} \text{ s}^{-1} \)

What percentage of the surface would be uncovered after 2 hours if the pressure of process gas was 0.1 Pa?

Just put in the numbers:

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

\[
K = \frac{k_{ads}}{k_{des}}
\]
Example

• First determine $K$ and $KP$:

$$K = \frac{10^{-2}}{10^{-5}} = 10^3$$

$$KP = 10^3 \times 0.1 = 100$$

• Now put in numbers:

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

$$\theta = \frac{100}{1 + 100} (1 - \exp[ -10^{-5} (1 + 100) \times 2 \times 3600 ])$$
Example

\[
\theta = \frac{100}{101} (1 - \exp[-10^{-5} \times 101 \times 7200])
\]

\[
\theta = 0.99(1 - \exp[-10^{-5} \times 101 \times 727200])
\]

\[
\theta = 0.99(1 - \exp[-734])
\]

\[
\theta = 0.99(1 - 0)
\]

\[
\theta = 0.99
\]

- Fractional coverage is 0.99, hence uncovered film is 1% of surface.
Diffusion

- The adatom can diffuse over the surface, with energy $E_d$ (migration barrier energy) and the corresponding frequency $\nu_d$ (order of $10^{14}$ s$^{-1}$).

- Since $E_d \ll E_a$, surface diffusion is far more likely than desorption.
Diffusion

- The probability that during one second the adatom will have enough thermal energy to pass over the barrier is:

\[ P_d = \nu_d e^{-E_d/k_B T} \]

- The diffusion coefficient to jump a distance \( l \) can then be given by:

\[ D = l^2 P_d = \nu_d l^2 e^{-E_d/k_B T} \]

- We can quantify the probability of desorbing per unit time (or desorption rate) as:

\[ P_a = \nu_a e^{-E_a/k_B T} \]
Diffusion

• The characteristic time scale for desorption is then:

\[ \tau_a = \frac{1}{P_a} = v_a^{-1} e^{E_a/k_B T} \]

• The length scale of diffusion can then be described by:

\[ L = \sqrt{D \tau_a} \]

You will be given

Diffusion coefficient of adatoms on surface

Timescale for desorption

You will be given
Nucleation

- In the course of deposition, the atoms (monomer) arriving from the gas phase with a rate $F$ (units are atoms per surface unit cell, per second, MLs$^{-1}$).

- For simplicity, we assume the surface temperature is low enough so that only monomers diffuse on the surface and that dimers remain immobile.
Classification of Growth

Frank-van der Merwe Growth

Volmer-Weber Growth

Stranski-Krastanov Growth

• Layer-by-layer (2D) growth.

• Island (3D) Growth.

• Layer-plus-Island Growth.
Factors Affecting Growth:

- In thin-film growth there are three relevant surface energies:
  - $\gamma_s$: substrate free surface.
  - $\gamma_f$: film free surface.
  - $\gamma_i$: substrate/film interface.
Example

- Consider the growth of \{110\} GaAs on a \{110\} GaP substrate.
- Given the values of surface energy below, what type of growth would you expect?
  - $\gamma_{GaP} = 1.9 \text{ J/m}^2$.
  - $\gamma_{GaAs} = 0.86 \text{ J/m}^2$.
  - $\gamma_{GaP/GaAs} = 0.2 \text{ J/m}^2$. 
Example

- From Lecture 10, we know that layer-by-layer (Frank-van der Merwe) growth requires:
  \[ \gamma_i + \gamma_f < \gamma_s \]

- For our example:
  - \( \gamma_s = 1.9 \text{ J/m}^2 \).
  - \( \gamma_f = 0.86 \text{ J/m}^2 \).
  - \( \gamma_i = 0.2 \text{ J/m}^2 \).
  - \( 0.86 + 0.2 = 1.06 < 1.9 \)

- Therefore layer-by-layer growth will occur.
Crystallinity

- Amorphous films.
  - No long-range order.
- Polycrystalline films.
  - Randomly orientated grains of crystalline material, separated by boundaries.
- Single crystal.
  - Complete, long-range order.
Epitaxy

- Substrate and film the same material: homoepitaxy.
- Substrate and film different materials: heteroepitaxy.
Thickness Measurement

- Profilometer
- Four Point Probe
- Ellipsometer

![Diagram of thickness measurement methods]
Lecture 11: Diffusion
Diffusion

\[ D = 10^{-15} \text{ cm}^2 \text{s}^{-1} \]

- **t = 0s**
  - Concentration (cm\(^2\))
  - Position (nm)
  - Initial concentration distribution.

- **t = 10s**
  - Concentration (cm\(^2\))
  - Position (nm)
  - Concentration distribution after 10 seconds.

- **t = 1 hr**
  - Concentration (cm\(^2\))
  - Position (nm)
  - Concentration distribution after 1 hour.

- **t = 10m**
  - Concentration (cm\(^2\))
  - Position (nm)
  - Concentration distribution after 10 minutes.
Diffusion

$t = 0s$

$t = 10s$

$t = 1hr$

$t = 10m$
Diffusion

$t = 0s$

$D = 10^{-15} \text{ cm}^2 \text{s}^{-1}$

$t = 10s$

$D = 10^{-15} \text{ cm}^2 \text{s}^{-1}$

$t = 1m$

$D = 10^{-15} \text{ cm}^2 \text{s}^{-1}$

$t = 1hr$

$D = 10^{-15} \text{ cm}^2 \text{s}^{-1}$

$t = 10m$

$D = 10^{-15} \text{ cm}^2 \text{s}^{-1}$

$t = 5m$

$D = 10^{-15} \text{ cm}^2 \text{s}^{-1}$
What is Not Examinable

• You **will not** be required to know the general solution to Fick’s Law, or use it:

\[
C(z, t) = C_0 \left( 1 - \frac{z_0}{z_t} \right) - C_0 \sum_{n=1}^{\infty} \frac{2}{n\pi} \sin \left( \frac{n\pi z_0}{z_t} \right) \exp \left( -\frac{n^2\pi^2Dt}{z_t^2} \right) \cos \left( \frac{n\pi z}{z_t} \right)
\]

• You **will not** be expected to solve any differential equations (ordinary or partial).

• You **will not** be expected to use Fourier Transforms.

• The solutions to differential equations will be provided.

• Hence, the majority of what we covered in Lecture 11 is not examinable.
“Dose” of Impurity

- The initial impurity is described as a “dose” at a single position ($z = 0$).
- Mathematically it is described as a delta-function:

$$C(z, 0) = f(z) = Q \delta(z)$$

$$\int_{-\infty}^{\infty} C(z, 0) dz = Q$$

- This leads to the following:

$$C(z, t) = \frac{Q}{\sqrt{\pi Dt}} \exp \left[ -\frac{z^2}{4Dt} \right]$$

You will be given

You will be given
Example

- Consider a “dose” of $10^{10}$ cm$^{-2}$ phosphorus atoms, deposited on the surface of a silicon wafer.
- After applying this dose, we anneal the wafer for 1 hour at 1300K.
- If the diffusion coefficient of phosphorus in silicon at 1300K is: $D = 2.46 \times 10^{-14}$ cm$^2$/s, determine the concentration 50nm from the wafer surface after 1 hour?
Example

• Use our solution to the diffusion equation for the application of a dose:

\[ C(z, t) = \frac{Q}{\sqrt{\pi Dt}} \exp \left[ -\frac{z^2}{4Dt} \right] \]

• We just need to put in numbers.
  • Remember to be consistent with units.
  • We will use cm for lengths, and seconds for time.
• 1hr = 3600s.
• 50nm = 5\times10^{-6}cm.
Example

• Put in numbers:

\[
C(z, t) = \frac{Q}{\sqrt{\pi Dt}} \exp \left[ -\frac{z^2}{4Dt} \right]
\]

\[
C(z, t) = \frac{10^{10}}{\sqrt{\pi \times 2.46 \times 10^{-14} \times 3600}} \exp \left[ -\frac{(5 \times 10^{-6})^2}{4 \times 2.46 \times 10^{-14} \times 3600} \right]
\]

\[
C(z, t) = \frac{10^{10}}{\sqrt{2.79 \times 10^{-10}}} \exp \left[ -\frac{2.5 \times 10^{-11}}{3.55 \times 10^{-10}} \right]
\]

\[
C(z, t) = 5.99 \times 10^{14} \times 0.932
\]

\[
C(z, t) = 5.58 \times 10^{14}
\]
Limitless Source of Dopant

• There is an infinite supply of impurity.

\[ C(z, t) = C_0 \text{erfc} \left( \frac{z}{2\sqrt{Dt}} \right) \]

Where:

\[ \text{erfc}(x) = 1 - \text{erf}(x) \]
\[ \text{erf}(x) = \frac{1}{\sqrt{\pi}} \int_{-x}^{x} e^{-\tilde{x}^2} d\tilde{x} \]
Error Function

- You will either be given a table, or an approximation.

### Complementary Error Function Table

<table>
<thead>
<tr>
<th>x</th>
<th>erfc(x)</th>
<th>x</th>
<th>erfc(x)</th>
<th>x</th>
<th>erfc(x)</th>
<th>x</th>
<th>erfc(x)</th>
<th>x</th>
<th>erfc(x)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.5887717</td>
<td>0.2</td>
<td>0.8470567</td>
<td>0.3</td>
<td>1.13190</td>
<td>0.4</td>
<td>1.47679</td>
<td>0.5</td>
<td>1.84159</td>
</tr>
<tr>
<td>0.2</td>
<td>0.9774350</td>
<td>0.3</td>
<td>0.1191011</td>
<td>0.4</td>
<td>0.14916</td>
<td>0.5</td>
<td>0.17875</td>
<td>0.6</td>
<td>0.20500</td>
</tr>
<tr>
<td>0.3</td>
<td>0.9615615</td>
<td>0.4</td>
<td>0.333361</td>
<td>0.5</td>
<td>0.45092</td>
<td>0.6</td>
<td>0.65624</td>
<td>0.7</td>
<td>0.86285</td>
</tr>
<tr>
<td>0.4</td>
<td>0.9481219</td>
<td>0.5</td>
<td>0.445261</td>
<td>0.6</td>
<td>0.54250</td>
<td>0.7</td>
<td>0.62846</td>
<td>0.8</td>
<td>0.70648</td>
</tr>
<tr>
<td>0.5</td>
<td>0.9336360</td>
<td>0.6</td>
<td>0.56578</td>
<td>0.7</td>
<td>0.68707</td>
<td>0.8</td>
<td>0.74679</td>
<td>0.9</td>
<td>0.79944</td>
</tr>
<tr>
<td>0.6</td>
<td>0.9233970</td>
<td>0.7</td>
<td>0.68384</td>
<td>0.8</td>
<td>0.78957</td>
<td>0.9</td>
<td>0.83711</td>
<td>1.0</td>
<td>0.88029</td>
</tr>
<tr>
<td>0.7</td>
<td>0.9114297</td>
<td>0.8</td>
<td>0.79581</td>
<td>0.9</td>
<td>0.89112</td>
<td>1.0</td>
<td>0.92228</td>
<td>1.1</td>
<td>0.94714</td>
</tr>
<tr>
<td>0.8</td>
<td>0.9002278</td>
<td>0.9</td>
<td>0.89750</td>
<td>1.0</td>
<td>0.97182</td>
<td>1.1</td>
<td>0.98968</td>
<td>1.2</td>
<td>0.99974</td>
</tr>
<tr>
<td>0.9</td>
<td>0.8987105</td>
<td>1.0</td>
<td>0.99075</td>
<td>1.1</td>
<td>1.00000</td>
<td>1.2</td>
<td>1.00000</td>
<td>1.3</td>
<td>1.00000</td>
</tr>
<tr>
<td>1.0</td>
<td>0.8965648</td>
<td>1.1</td>
<td>1.00000</td>
<td>1.2</td>
<td>1.00000</td>
<td>1.3</td>
<td>1.00000</td>
<td>1.4</td>
<td>1.00000</td>
</tr>
</tbody>
</table>

You will be given a table or an approximation for the complementary error function.
Example

• Consider an infinite supply of boron atoms $10^{18}$ cm$^{-3}$ on the surface of a silicon wafer.
• We then anneal the wafer for 1 hour at 1300K.
• If the diffusion coefficient of boron in silicon at 1300K is: $D = 1.41 \times 10^{-15}$ cm$^2$/s, determine the concentration 50nm from the wafer surface after 1 hour?
Example

• Use our equation for a limitless source of dopant:

\[ C(z, t) = C_0 \text{erfc} \left[ \frac{z}{2\sqrt{D t}} \right] \]

• Again we just need to put in numbers.
• First determine argument for erfc function:
• Let:

\[ x = \frac{z}{2\sqrt{D t}} \]
Example

\[ x = \frac{z}{2\sqrt{Dt}} \]

\[ x = \frac{5 \times 10^{-6}}{2\sqrt{1.41 \times 10^{-15} \times 3600}} \]

\[ x = \frac{5 \times 10^{-6}}{2\sqrt{5.08 \times 10^{-12}}} \]

\[ x = \frac{5 \times 10^{-6}}{2 \times 2.25 \times 10^{-6}} \]

\[ x = \frac{5 \times 10^{-6}}{4.51 \times 10^{-6}} \]

\[ x = 1.11 \]
Example

$x = 1.11$

\[ C(z, t) = C_0 \text{erfc} \left[ \frac{z}{2\sqrt{D}t} \right] \]

\[ C(z, t) = C_0 \text{erfc}[x] \]

\[ C(z, t) = C_0 \times 0.116467 \]

Use table:
Example

\[ C(z, t) = C_0 \times 0.116467 \]

- Now just put in concentration of limitless source of dopant:

\[ C(z, t) = 10^{18} \times 0.116467 \]

\[ C(z, t) = 1.165 \times 10^{17} \text{ cm}^{-3} \]
Early IC Fabrication (~1960s)

- Historically, diffusion was the process by which n-type (P, As) and p-type (B) dopants were introduced into Si.
- Wafer was exposed to gas containing the dopant (pre-deposition).
- Remove dopant source, anneal to allow dopant to diffuse deeper into the wafer (drive in).
Modern Fabrication

- Perform pre-deposition by ion implantation: high energy dopant ions are fired into the wafer.
- Perform anneal to repair damage to crystal, also causes dopant to diffuse.
- Many fabrication facilities still have “Diffusion” groups which can include a range of activities: from high $T$ processes (thermal CVD, oxidation and anneal) to ion implant.
Vacancy Diffusion

- Initial and final states have same energy:

\[ D = D_0 \exp \left( -\frac{E_A}{k_B T} \right) \]

You will be given
Direct Exchange

- Bonds are broken and re-formed.

- This has a higher energy barrier because more bonds are broken → even lower value of $D$.

- In Si, substitutional impurities are P, B, As, Al, Ga, Sb, Ge.
Interstitial Diffusion

- Very fast process with low activation energy.
- Common with small atoms.
- Examples in Si: H, Li, Na, O, Au, Fe, Ni, Cu, Zn, Mn.
- No vacancy needed.
Interstitalcy diffusion

- Combination of interstitial and vacancy.
- A dopant atom is “kicked out” by an interstitial Si.
- The dopant diffuses interstitially until it falls into a vacancy (Frank-Turnbull mechanism).
- Or until the dopant kicks out a Si atom.
- In Si, interstitial diffusion is important for P, B, Al, Ga.
T-Activated Diffusion

• Diffusion of defects in silicon are described as temperature-activated processes:

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

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

• Determine the diffusion coefficient of Arsenic in Silicon at 1500K.
  \[ D = D_0 \exp \left( - \frac{E_{VD}}{k_B T} \right) \]

• Put in numbers:
  • \( D_0 = 0.66 \text{ cm}^2/\text{s} \).
  • \( E_{VD} = 3.44 \text{ eV} \).

• Remember to convert energy to Joules:
  \[ D = 0.66 \times \exp \left[ - \frac{3.44 \times 1.602 \times 10^{-19}}{1.38 \times 10^{-23} \times 1500} \right] \]
Example

\[ D = 0.66 \times \exp \left[ - \frac{5.51 \times 10^{-19}}{2.07 \times 10^{-20}} \right] \]

\[ D = 0.66 \times \exp[-26.6] \]

\[ D = 0.66 \times 2.74 \times 10^{-12} \]

\[ D = 1.81 \times 10^{-12}\text{cm}^2/\text{s} \]
Lecture 12: Ion-Implantation
Ion Implantation

- An ion implanter is used to dope silicon.
- Doping is done by implanting ions of Phosphorus, Boron or Arsenic on the wafers.
- Ions implanted from the ion beam damage the lattice.
Anneal: Activation & Diffusion

- Annealing is a process where the wafer is heated to repair the damage to the lattice.

- The dopant ions become part of the crystal lattice (Activation)

- The ions also spread out during anneal (Diffusion)
Stopping Power in Substrate

- With each interaction, ion loses some energy. It travels through a vertical projected range $R_p$ before stopping.

- Ion loses energy by:
  - Vicious Drag
  - Electron excitation
  - Nuclear collisions

  More effective at larger $v_{ion}$
  More effective at smaller $v_{ion}$
Nuclear Stopping Power

- This process is due to Coulomb Scattering (assumed elastic).

- Incident ion \((E_1, M_1)\) interacts with nucleus of stationary ion \((M_2)\).

- \(b = \) impact parameter.

- Energy transferred by incoming ion:

\[
\Delta E = E_1 \left[1 - \frac{\sin^2 \phi}{\cos \theta \sin \phi + \cos \phi \sin \theta}\right]
\]

\[
\Delta E (b = 0, \phi = 0) = E_1 \frac{4M_1 M_2}{(M_1 + M_2)^2}
\]
Example

• Determine the change in energy of a 100 keV boron ion after colliding with a stationary silicon atom head on.

• For a head-on collision:
  • $b = 0$.
  • $\phi = 0$ (hence $\theta = 0$).

• We can hence use:

$$\Delta E = E_1 \frac{4M_1 M_2}{(M_1 + M_2)^2}$$
Example

• Just enter numbers:

\[ \Delta E = E_1 \frac{4 \times 10.8 \times 28.1}{(10.8 + 28.1)^2} \]

\[ \Delta E = E_1 \frac{1213}{(38.9)^2} \]

\[ \Delta E = 100 \times \frac{1213}{1513} \]

\[ \Delta E = 100 \times 0.80 \]

\[ \Delta E = 80 \text{ keV} \]
Electronic Stopping Power

- Ions interact with electrons as well, but we describe the interaction as inelastic.

- **Local:**
  - Passing ion causes internal electronic transitions or ionization:
    \[ E_1, M_1 + e^- \rightarrow E_1, M_1 e^- \]
  - Energy loss and momentum transfer.

- Because electrons can respond to fields up to optical frequencies electronic losses are more significant at higher ion velocities.
Electronic Stopping Power

- **Local:**

  \[ E_1, M_1 \]

- **Non-Local:**

  \[ E_1, M_1 \]
Composition Profile for Ions

- If the depth is \( z \), the impurity concentration \( c(z) \) is (approximated by a Gaussian).

\[
c(z) = c_p \exp\left(-\frac{(z - R_p)^2}{2\Delta R_p^2}\right)
\]
200 keV Implants in Si

- Concentration distribution for implantation of various ions at 200 keV.

Greater tendency of lighter ions to backscatter

\[ m_B < m_P < m_{AS} < m_{Sb} \]

- Greater velocity $\rightarrow$ longer $R_p$.
- Less loss / collision $\rightarrow$ larger $\Delta R_p$.

You will be given
Energy-Dependence of Profiles

• Concentration distribution for implantation of boron at various energies:

![Graph showing concentration distribution for implantation of boron at various energies: Gaussian profile.](image)
Ion Implanter

- The major sub-units of an ion implanter are shown below.
Ion Implanter Parameters

Input Parameters:
- Time
- Current
- Energy
- Implant Angle
- Implant Species

Output Parameters:
- Dose
- Uniformity
- Dose Depth
Issues with Implantation

Wafer Charging

Metallic contaminants

Cross Contaminants

Knocked off metal atom

Ion

Boron

Phosphorous

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Safety Issues with Ion Implantation

• The safety issues with ion implantation, covered at the end of lecture 12, are not examinable.
Lecture 13: Basic Photolithography
The Photolithography Process

- Apply photoresist.
- Expose photoresist through a patterned mask or reticle.
- Develop PR by immersing it in a solvent which preferentially dissolves the PR of higher solubility.
- Process the exposed part of the wafer.
- Strip away the remaining photoresist.
- Inspect pattern.
HMDS: Adhesion Promoter

- Adhesion can be improved with application of HMDS.
- Cleaning or oxygen plasma can be used.
- HMDS is applied in vapor phase:

\[
\text{H} \quad \begin{array}{c}
\text{Si} \\
\text{N} \\
\text{Si}
\end{array}
\]
Photoresist Deposition

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

Film thickness \( t \) and angular velocity \( \omega \) are related by the equation above. You will be given the desired film thickness and the spin speed, and you need to calculate the angular velocity.
Exposure Techniques

- Three approaches are typically taken to exposure:

  - **Contact Printing**
    - Defects
    - Bowing of mask
  
  - **Proximity Printing**
    - 2 - 4 μm resolution
  
  - **Projection Printing**
    - 2 - 5 X reduction

<table>
<thead>
<tr>
<th>Printing System</th>
<th>Magn.</th>
<th>Resolution (μm)</th>
<th>Use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact</td>
<td>1 ×</td>
<td>0.1 – 1</td>
<td>Research</td>
</tr>
<tr>
<td>Proximity</td>
<td>1 ×</td>
<td>2 – 4</td>
<td>Low Cost</td>
</tr>
<tr>
<td>Projection</td>
<td>2-5 ×</td>
<td>0.1 - 1</td>
<td>Mainstream VLSI</td>
</tr>
</tbody>
</table>
Fresnel Diffraction

- Fresnel (near field) occurs in proximity printing.

Minimum resolvable feature size is:

\[ W_{min} = \sqrt{kL\lambda} \]

- Where:
  - \( k \) is an experimental parameter associated with the process conditions.
Fraunhofer Diffraction

Not resolved

Rayleigh

Clearly resolved

c1) c2) c3)

d1) d2) d3)
Fraunhofer Diffraction

- The resolution in Fraunhofer diffraction is quantified by the Rayleigh Criterion ($R$):
  
  \[
  R = k_1 \lambda \frac{f}{d}
  \]

  - $f = \text{Focal length}$
  - $d = \text{Lens diameter}$

- $k_1$ is an experimental parameter associated with the system and resist ($0.6 < k_1 < 0.8$).

- The parameter $d/f$ is sometimes called $NA$ (numerical aperture):
  
  \[
  NA = \frac{d}{f} = n \sin \alpha
  \]

  - $n = \text{index of refraction (1 in air)}$
  - $\alpha = \text{maximum half angle of incident light}$

  \[
  R = \frac{k_1 \lambda}{NA}
  \]
Modulation Transfer Function

- The modulation transfer function (MTF) quantifies how much modulation of light we achieve on the wafer:

\[ MTF = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]

Divergent light source

Collimating lens

Mask

Focusing lens

Photoresist on wafer

Intensity at Mask

Intensity on wafer

Position

Position

\( I_{\text{Max}} \)

\( I_{\text{Min}} \)
Example

• The figure below shows the optical power density on a wafer as a function of position.

• Determine the MTF for this system.
Example

- Simply enter values:

\[ MTF = \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}} \]

\[
MTF = \frac{0.75 - 0.25}{0.75 + 0.25} = 0.5
\]

\[
MTF = \frac{0.5}{1} = 0.5
\]
Depth Focus: \( \delta \)

- Depth of focus defines distance along straight optical path that wafer can be moved but keep the image in focus

\[
\delta = \frac{k_2 \lambda}{(NA)^2} = k_2 \lambda \left(\frac{f}{d}\right)^2
\]

- \( k_2 \) is experimental parameter associated with the system and resist \((k_2 \sim 0.5)\).
Development

- We now wish to dissolve the regions of the photoresist which have higher solubility.
  - Exposed regions (positive photoresist).
  - Masked regions (negative photoresist).

- Three strategies:
  - **Immersion Developing**
  - **Spray Developing**
  - **Puddle Technique**

  - pH and # of lots processed are monitored
  - Fresh developer with each batch
  - Fixed amount of developer dispensed and rinsed
Resist Contrast

- Resist Contrast quantifies the ability of the resist to distinguish light/dark in the aerial image.
- To evaluate it we plot the developed thickness (i.e. thickness remaining after development) as a function of dose ($Q$).

\[
Q = It
\]

Dose (mJcm\(^{-2}\)) = Intensity (mW/cm\(^{-2}\)) \times \text{time (s)}

\[
\gamma = \frac{1}{\log_{10} \left( \frac{Q_f}{Q_0} \right)}
\]
Lecture 14: Advanced Photolithography
Optical Proximity Correction

- Optical Proximity Correction (OPC): Clever mask engineering based on software algorithms can compensate some of this error.

- This requires sophisticated computer modeling.
Phase Shift Masks

- Masks can be manufactured (albeit expensively) to shift the phase of the light:

![Mask Diagram]

- Amplitude At Wafer
- Intensity
- 180° phase shift
Multilayer Resist Processing

Conventional photoresist

Exposed regions become transparent to UV light

Contrast enhancement layer

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Multilayer Resist Processing

Resist is patterned on silicon or other materials.

Silicon dioxide film is deposited.

Film is removed, leaving sidewalls.

Silicon dioxide is removed, leaving double pattern.

Silicon is removed from spaces.

Resist is removed.

Reactive ion etch
Immersion Lithography

Refractive index of air

Refractive index of resist

Refractive index of lens

Refractive index of fluid

$n_0$

$n_g$

$n_f$

$n_r$
Immersion Lithography

Resolution:

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

Depth of Field:

\[ \delta = \frac{k_2 \lambda}{(n \sin \alpha)^2} \]

Where:

- \( k_1 \) is the resolution constant
- \( k_2 \) is the depth of field constant
- \( \lambda \) is the wavelength
- \( n \) is the refractive index
- \( \sin \alpha \) is the sine of the angle of incidence
- \( n_g \) is the refractive index of the lens
- \( n_f \) is the refractive index of the fluid
- \( n_r \) is the refractive index of the resist

\[ n = \text{Min}(n_g, n_f, n_r) \]

You will be given:

- The values of \( k_1 \), \( k_2 \), \( \lambda \), and \( \sin \alpha \)

You will be given:

- The values of \( n_g \), \( n_f \), and \( n_r \)

Material | Use | Refractive Index |
--- | --- | --- |
SiO_2 | Oxide (to etch) | 1.56 |
CaF_2 | Lens (for UV) | 1.51 |
Water | Immersion Fluid | 1.435 |
Various Resists | Resist | ~1.70 |

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Extreme UV Lithography (EUV)

- The approach of EUV is to reduce wavelength.

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

- \( f \) = Focal length
- \( d \) = Lens diameter
- Numerical aperture
Next-Gen Resists Photoresists

- Organic resist can collapse at small linewidths:

- Inorganic resists are candidates to replace organic resists:
Electron Beam Lithography

3-5 nm
Electron Beam Lithography

- Wavelength of electrons is given by de Broglie Equation:

\[ \lambda = \frac{h}{\sqrt{2m_0eV}} \]

- At high energies a relativistic correction must be applied:

\[ \lambda = \frac{h}{\sqrt{2m_0eV}} \sqrt{1 + \frac{eV}{2m_0c^2}} \]

- Where:
  - \( \lambda \) = Electron wavelength
  - \( h \) = Planck Constant
  - \( m_0 \) = Rest mass of electron.
  - \( V \) = Accelerating voltage
  - \( e \) = Charge on electron
  - \( c \) = Speed of light in vacuum.

You will be given

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Nano-Imprint Lithography

1. Imprint
   • Press Mold

2. Pattern Transfer
   • RIE

- 70 nm
- 10 nm
- 60 nm
- 60 nm
Lecture 15: Etching
Wet Etch vs Dry Etch

• Wet Etch:

• Dry Etch:
Selectivity

- There are two types of selectivity:
  
  **Film-mask selectivity**
  \[ S_{fm} = \frac{R_f}{R_m} \]

  **Film-substrate selectivity**
  \[ S_{fs} = \frac{R_f}{R_s} \]

- Where:
  
  - \( R_f \) = Vertical etch rate in film.
  - \( R_f \) = Vertical etch rate in mask (photoresist).
  - \( R_s \) = Vertical etch rate in substrate.
Bias

- Bias is a way of quantifying etch anisotropy.

\[ B = d_f - d_m \]

Bias

Largest length etched

Target etch length

Smallest length of film remaining

Target etch length

You will be given
Anisotropy Parameter

- A dimensionless variable used to quantify how anisotropic an etch is:

\[ A = 1 - \frac{R_l}{R_v} \]

\[ 0 \leq A \leq 1 \]

Completely anisotropic (ions)

You will be given

You will be given

Lateral etch rate

Vertical etch rate

Film

Photoresist

Substrate
Mask Erosion

- A parameter with units of length.
- \( \Delta m \), is eroded from the mask on either side of the feature.
Etching Features With a Slope

- For the lateral etch, we have two contributions.

  - There is the contribution from the lateral etch rate:
    \[ x_1 = R_l t \]

  - The contribution from the vertical etch rate is:
    \[ x_2 = \frac{R_v t}{\tan \theta} = R_v t \cot \theta \]

- The total etched distance in time \( t \) is then:
  \[ x = (R_v \cot \theta + R_l) t \]
Uniformity

- The etch rate is not always uniform across the wafer.
- This is quantified with the uniformity parameter:
  \[ U = \frac{R_{\text{max}} - R_{\text{min}}}{R_{\text{max}} + R_{\text{min}}} \]

- If \( R_{\text{max}} = R_{\text{min}} \), i.e. the etch is completely uniform:
  \[ U = 0 \]

- If we have a high film-substrate selectivity \( (S_{fs}) \), then \( U > 0 \) isn’t necessarily a problem.

You will be given
Uniformity

\[ h_f^{(\text{max})} = h_f (1 + \delta) \]

\[ R_f^{(\text{min})} = R_f (1 - \phi) \]

\[ 0 \leq \delta \leq 1 \]

\[ 0 \leq \phi \leq 1 \]

You will be given
Variations in Etch Time

• Worst case scenario:
  • The maximum time it takes, to etch everything for a given $\delta$ and $\phi$.

\[
t_{\text{max}} = \frac{h_f^{(\text{max})}}{R_f^{(\text{min})}} = \frac{h_f (1 + \delta)}{R_f (1 - \phi)}
\]

You will be given

• Best case scenario:
  • The minimum time it takes to etch through the film (at the lowest point with highest etch rate).

\[
t_{\text{min}} = \frac{h_f^{(\text{min})}}{R_f^{(\text{max})}} = \frac{h_f (1 - \delta)}{R_f (1 + \phi)}
\]

You will be given
Example

- Way we are carrying out the following etch of SiO$_2$ on Si:
  - The etch rate of SiO$_2$ is 100 nm/min.
  - The thickness of the oxide is $h_f = 200$ nm.
  - The etch rate variation parameter is $\phi = 0.05$.
  - The thickness variation parameter is $\delta = 0.01$.
- Determine the amount of time to first reach the Si and the amount of time to remove all the SiO$_2$. 
Example

- First determine time to first reach the Si. This requires best-case conditions:

\[
t_{\text{min}} = \frac{h_f^{(\text{min})}}{R_f^{(\text{max})}} = \frac{h_f (1 - \delta)}{R_f (1 + \phi)}
\]

- Put in numbers:

\[
t_{\text{min}} = \frac{200(1 - 0.01)}{100(1 + 0.05)}
\]

\[
t_{\text{min}} = \frac{198}{105} = 1.89 \text{ min}
\]
Example

- Now determine time to remove all the SiO$_2$. This requires the worst-case scenario:

\[
 t_{\text{max}} = \frac{h_f^{(\text{max})}}{R_f^{(\text{min})}} = \frac{h_f (1 + \delta)}{R_f (1 - \phi)}
\]

- Again, just put in numbers:

\[
 t_{\text{max}} = \frac{200(1 + 0.01)}{100(1 - 0.05)}
\]

\[
 t_{\text{max}} = \frac{202}{95} = 2.12 \text{ min}
\]
Wet Etching

- The rate of etch depends on the relative concentration of acids:
  - The lines indicate etch rates for a given composition.
  - The percentages refer to the concentration of the acids in water.
  - HF(50%) = HF:H₂O (1:1 volume %)
  - HNO₃(70%) = HNO₃:H₂O (7:3 volume %)

You will be given
Wet Etching of Photoresist

- Photoresist are generally formed of organic polymers (C,H-containing molecules).
- Piranha solution is typically used:
  - H$_2$SO$_4$ and H$_2$O$_2$.
- H$_2$SO$_4$ dissolves the polymer.
- H$_2$O$_2$ oxidized the polymer:

\[
CH \text{ polymer}(S) + H_2O_2(L) \rightarrow CO_2(G) + H_2O(L)
\]
# Common Wet Etches

<table>
<thead>
<tr>
<th>Material</th>
<th>Etchant</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>HF (49% in water) “straight HF” NH$_4$F:HF (6:1) “Buffered HF” or “BOE”</td>
<td>Selective over Si (i.e., will etch Si very slowly in comparison). Etch rate depends on film density, doping. About $1/20$ th the etch rate of straight HF. Etch rate depends on film density, doping. Will not lift up photoresist like straight HF.</td>
</tr>
<tr>
<td>Si$_3$N$_4$</td>
<td>HF (49%) H$_3$PO$_4$:H$_2$O (boiling @ 130–150°C)</td>
<td>Etch rate depends strongly on film density, O, H in film. Selective over SiO$_2$. Requires oxide mask.</td>
</tr>
<tr>
<td>Al</td>
<td>H$_3$PO$_4$:H$_2$O:HNO$_3$:CH$_3$COOH (16:2:1:1)</td>
<td>Selective over Si, SiO$_2$, and photoresist.</td>
</tr>
<tr>
<td>Polysilicon</td>
<td>HNO$_3$:H$_2$O:HF (+ CH$_3$COOH) (50:20:1)</td>
<td>Etch rate depends on etchant composition.</td>
</tr>
<tr>
<td>Single crystal Si</td>
<td>HNO$_3$:H$_2$O:HF (+ CH$_3$COOH) (50:20:1) KOH:H$_2$O:IPA (23 wt. % KOH, 13 wt. % IPA)</td>
<td>Etch rate depends on etchant composition. Crystallographically selective; relative etch rates: (100): 100 (111): 1</td>
</tr>
<tr>
<td>Ti</td>
<td>NH$_3$:OH:H$_2$O:H$_2$O (1:1:5)</td>
<td>Selective over TiSi$_2$.</td>
</tr>
<tr>
<td>TiN</td>
<td>NH$_3$:OH:H$_2$O:H$_2$O (1:1:5)</td>
<td>Selective over TiSi$_2$.</td>
</tr>
<tr>
<td>TiSi$_2$</td>
<td>NH$_4$:F:HF (6:1)</td>
<td></td>
</tr>
<tr>
<td>Photoresist</td>
<td>H$_2$SO$_4$:H$_2$O$_2$ (125°C) Organic stripers</td>
<td>For wafers without metal. For wafers with metal.</td>
</tr>
</tbody>
</table>
Dry Etching

- Free radicals:

\[ e^- + CF_4 \rightarrow CF_2 + F + F + e^- \]
Dry Etching

- Ions:

  \[ \text{High Speed Electron} \quad e^- + \text{CF}_4 \rightarrow \text{CF}_4^+ + e^- + e^- \]

  - Neutral Molecule (CF$_4$)
  - Ion (CF$_4^+$)
End Point Detection

• At the end of an etch the underlying film or substrate becomes exposed.

• This is known as the end point.

• End Point Detection:
  • Products from the reaction of free radicals and the etched film (SiO\textsubscript{2}) give color to the plasma.
  • Products from the reaction of free radicals and the underlying film (Si) give a different color to the plasma.

• This color change indicates the end point.
End Point: Overetch

• When the end point is reached, the etch process is often continued for a set time.
  • This is called overetch.
• Overetch makes sure that the etch is complete at every feature and no residue is left.

\[
\text{Si} \quad \text{SiO}_2 \quad \text{PR}
\]

RIE lag: Variation in depth with feature size

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Lecture 16: Chemical Mechanical Planarization
https://www.youtube.com/watch?v=AMgQ1-HdELM
CMP

Pressure = 5 – 10 psi

Wafer rotation, $\omega_w = 60$ rpm

Pad rotation, $\omega_p = 30$ rpm
Slurry Solution

- In reality the slurry consist of many components:
  - Water.
  - Abrasive nanoparticles.
  - Acids and bases.
  - Anti-coagulating agents.
  - Corrosion inhibitors.
  - Surfactants.
  - Oxidizers.
  - Buffers.
  - Bactericides and fungicides.

  For mechanical abrasion
  For controlling pH
  To ensure high dispersion
  To stop corrosion pits in metals
  To neutralize charged surfaces
  Metals are often oxidized before being polished
  To control reaction rate
  To stop solution spoiling
Mechanism of Metal CMP
Quantifying Planarity

• Planarity is quantified via step properties:

<table>
<thead>
<tr>
<th>Step</th>
<th>R</th>
<th>φ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global Planarization</td>
<td>≥100 μm</td>
<td>≤0.5°</td>
</tr>
<tr>
<td>Local Planarization</td>
<td>2 -100 μm</td>
<td>0.5° - 30°</td>
</tr>
<tr>
<td>Surface Smoothing</td>
<td>0.1 - 2 μm</td>
<td>≥ 30°</td>
</tr>
</tbody>
</table>

• Degree of planarization:

  \[ DP = 1 - \frac{SH_{post\text{CMP}}}{SH_{pre\text{CMP}}} \]
Example

- Consider the following planarization process:

\[ DP = 1 - \frac{SH_{postCMP}}{SH_{preCMP}} \]

- What is the degree of planarization for this process?

\[ DP = 1 - \frac{10}{100} = 0.9 \]
## Issues With CMP

<table>
<thead>
<tr>
<th>Defect mode</th>
<th>Potential causes</th>
<th>Impact to device</th>
<th>Potential solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles</td>
<td>Slurry/pad residue</td>
<td>Shorting/opens</td>
<td>Cleaner tooling</td>
</tr>
<tr>
<td></td>
<td>Polish byproducts</td>
<td>Pattern distortion</td>
<td>Clean Chemistries</td>
</tr>
<tr>
<td>Macro scratches</td>
<td>Large/hard foreign particles on polish pad</td>
<td>Pattern removal over multiple die</td>
<td>Pad conditioning</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pad cleaning Environment</td>
</tr>
<tr>
<td>Micro scratches</td>
<td>Slurry agglomeration</td>
<td>Shorting/opens</td>
<td>Slurry filters</td>
</tr>
<tr>
<td></td>
<td>Pad asperities</td>
<td></td>
<td>Pad/pad conditioning</td>
</tr>
<tr>
<td>Corrosion (metal CMP)</td>
<td>Slurry chemistry</td>
<td>Opens, Reliability</td>
<td>Passivating films, Chemistry optimization</td>
</tr>
<tr>
<td></td>
<td>Clean chemistry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Film delamination</td>
<td>Weak adhesion</td>
<td>Shorting/Opens</td>
<td>Improve adhesion</td>
</tr>
<tr>
<td></td>
<td>CMP shear force</td>
<td>Device parametrics</td>
<td>Low pressure CMP</td>
</tr>
<tr>
<td>Organic residue</td>
<td>Inadequate cleaning, residual slurry components</td>
<td>Shorting/opens Disturbed patterning of next layer</td>
<td>Cleaner tooling, Slurry optimization, Clean Chemistries</td>
</tr>
</tbody>
</table>
Other equations you will not be given in the exam
Simple Geometrical Equations

• Density:

\[ n_{2D} = \frac{1}{A} \quad n_{3D} = \frac{1}{V} \]

• Area:

\[ A = \pi r^2 \]

• Surface area of sphere:

\[ A = 4\pi r^2 \]

• Volume:

\[ V = \frac{4}{3}\pi r^3 \]
Other Simple Equations

- **Velocity:**
  \[ v = \frac{x}{t} \]

- **Current from charge:**
  \[ I = \frac{Q}{t} \]

- **Reaction rate:**
  \[ R = \frac{N}{t} \]

- **Energy from wavelength:**
  \[ E = \frac{hc}{\lambda} \]

- **Kinetic Energy:**
  \[ E = \frac{1}{2}mv^2 \]

- **Momentum:**
  \[ p = mv \]

- **Mass density:**
  \[ \rho = \frac{m}{V} \]

- **Ohm’s Law:**
  \[ V = IR \]
Calculus

• Chain rule:

\[
\frac{df}{dx} = \frac{df}{dg} \frac{dg}{dx}
\]

• Standard derivatives:

\[
\frac{d}{dx} (ae^{bx}) = abe^{bx}
\]

\[
\frac{d}{dx} (\ln(ax)) = \frac{1}{x}
\]

\[
\frac{d}{dx} (\sin(ax + b)) = -a \cdot \cos(ax + b)
\]

\[
\frac{d}{dx} (\cos(ax + b)) = -a \cdot \sin(ax + b)
\]
Other Relationships

- Limits of exponentials:
  \[ e^0 = 1 \]
  \[ e^{-\infty} = 0 \]
  \[ e^{\pm 1/\infty} = e^0 = 1 \]

- Unit conversions
  \[ 1\text{Å} = 10^{-10}\text{m} \]
  \[ 1\mu\text{m} = 10^{-6}\text{m} \]
  etc ...