Question 1 [5 marks]:
Gallium arsenide (GaAs) adopts the Zinc blende crystal structure (see Figure 1). The zinc blende structure is cubic, and similar to the diamond crystal structure, but the two interpenetrating face-centered-cubic structures consist of different atoms.

Figure 1: Crystal structure of gallium arsenide.

a) What is the nearest neighbor distance between gallium and arsenic atoms (in Å)? [2 marks]
b) What is the atomic density of gallium arsenide (in atoms/cm$^3$)? [2 marks]
c) What is the mass density of gallium arsenide (in g/cm$^3$)? [1 mark]

You will need:
- Lattice constant of GaAs = 5.65 Å.
- Mass of gallium atom = 69.72 amu.
- Mass of arsenic atom = 74.92 amu.
- 1 atomic mass unit = 1.66 × 10$^{-27}$ kg.

Question 2 [2 marks]:
Determine the Miller indices for the two crystal planes shown in Figure 2. The crystals are cubic and the tick marks on the axes are even spaced. Quote the miller indices in standard form: with the lowest possible, integer values. For example, the plane (600) should be quoted as (100).
Question 3 [7 marks]:

a) The charge carrier mobility in silicon depends on doping concentration. There is an empirical relationship that has been reported[1] to relate doping concentration and carrier mobility:

\[ \mu = \mu_{\text{min}} + \frac{\mu_{\text{max}} - \mu_{\text{min}}}{1 + \left( \frac{n}{n_r} \right)^\alpha} \]

Where: \( \mu \) is the carrier mobility in the wafer, \( n \) is the dopant concentration, and the remaining parameters: \( \mu_{\text{max}}, \mu_{\text{min}}, n_r \) and \( \alpha \), are all fitting parameters of the empirical relationship.

Phosphorus is an electron (n-type) dopant in silicon. We wish to grow a silicon ingot, doped with phosphorus, that has an electron mobility of 1000 cm²/Vs halfway through the growth process. Using the normal freezing relation, determine the concentration (in atoms / cm³) required in the starting material (melt), to grow a wafer with this mobility halfway through the ingot. [4 marks]

b) Using the normal freezing relationship, determine the average phosphorus concentration (in atoms / cm³) throughout the top half of an ingot pulled from a melt containing an impurity concentration of \( 1 \times 10^{16} \text{ cm}^{-3} \). Remember, X in the normal freezing relation is the fraction of the melt solidified. So if X = 0.25 for example, 25% of the melt has been solidified and 75% remains as liquid. [3 marks]

You will need the following information:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu_{\text{max}} )</td>
<td>68.5 cm²/Vs</td>
</tr>
<tr>
<td>( \mu_{\text{min}} )</td>
<td>1414 cm²/Vs</td>
</tr>
<tr>
<td>n_r</td>
<td>$9.20 \times 10^{16}$ cm$^{-3}$</td>
</tr>
<tr>
<td>-----</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.711</td>
</tr>
<tr>
<td>$k_a$</td>
<td>0.35</td>
</tr>
</tbody>
</table>

**Question 4 [3 marks]:**
Consider a cubic chamber filled with nitrogen gas ($N_2$). The dimensions of the chamber are $L \times L \times L$, where $L = 50$ cm. The temperature in the chamber is 300K. Determine the pressure at which the flow in the chamber makes the transition from viscous to molecular. Give your answer in Torr.

You will need to know:
- The molecular diameter of $N_2$ is 3.16 Å.
- The Boltzmann constant $= 1.38 \times 10^{-23}$ m$^2$kgs$^{-2}$K$^{-1}$.

**Question 5 [6 marks]:**

a) In a vacuum chamber filled with $O_2$ at a pressure of $2.5 \times 10^{-4}$ Torr, what is the impingement rate onto a surface when the chamber is at 300K. Give your answer in cm$^2$/s.[2 marks]

b) A (111) terminated silicon wafer is placed in a chamber containing $O_2$, held at 300K for 5 minutes. What type of pump (high vacuum or low vacuum) would be sufficient to ensure a complete monolayer is not formed on the wafer? Approximate $O_2$ molecules as spheres that form a monolayer in a 2D square array, as shown below:

![Diagram of O2 molecules forming a monolayer](image)

You will need to know:
- The molecular diameter of $O_2$ is 2.96 Å.
- The mass of an O atom is 15.999 amu.
- The sticking coefficient of $O_2$ on (111) Si is 0.15.
- The Boltzmann constant $= 1.38 \times 10^{-23}$ m$^2$kgs$^{-2}$K$^{-1}$.
- 1 atomic mass unit $= 1.66 \times 10^{-27}$ kg.

(Just guessing the answer will give you zero even if you get it right!)

**Question 6 [2 marks]:**
Explain why cryocondensation of hydrogen and helium is not effective in most cryogenic pumps.

**References:**