1. Review questions

a) List three recombination-generation mechanisms. (2 points)

- Band-to-band recombination
- Trap-assisted recombination
- Auger recombination

b) Describe the continuity equation in words. (2 points)

The rate of change of the carrier density equals the net influx of carriers due to the current minus the net recombination of particles.

c) How do the diffusion equations (2.9.9) and (2.9.10) differ from the continuity equations? (2 points)

The diffusion equations are obtained from the continuity equations (2.9.5) and (2.9.6) by assuming that the electric field is either zero or is so close to zero that it can be ignored and by assuming that the minority carrier density is much smaller than the majority carrier density, so that the simple recombination model can be used.

2. A piece of p-type silicon \( (p = 10^{16} \text{ cm}^{-3}) \) contains no electrons. The minority carrier lifetime is 10 \( \mu \text{s} \).

a) Calculate the net generation rate of holes under these conditions. List any assumptions you make. (4 points)

\[
U_n = \frac{n_p - n_{p0}}{\tau_n} = 0 - \frac{10^4}{10^{-5}} = -10^9 \text{ cm}^{-3} \text{s}^{-1}
\]

where the minority carrier density in thermal equilibrium, \( n_{p0} \), was calculated using the mass action law: \( n_{p0} = n_i^2/p = 10^{20}/10^{16} = 10^4 \text{ cm}^{-3} \)

Assumptions: simple recombination model, non-degenerate semiconductor

b) Is this piece of semiconductor in thermal equilibrium? Why? (2 points)

The semiconductor is not in thermal equilibrium since the electron density does not equal the thermal equilibrium electron density.

3. Consider two pieces of silicon, one n-type, doped with donors only, and the other p-type, doped with acceptors only. The acceptor density in the p-type material equals the donor density in the n-type material and the electron mobility in the n-type
material is twice the hole mobility in the p-type material. Calculate the acceptor density in the p-type material. (6 points) Also calculate the corresponding conductivity of the n-type material. (2 points)

<table>
<thead>
<tr>
<th></th>
<th>Arsenic</th>
<th>Phosphorous</th>
<th>Boron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{\text{min}}$ (cm$^2$/V-s)</td>
<td>52.2</td>
<td>68.5</td>
<td>44.9</td>
</tr>
<tr>
<td>$\mu_{\text{max}}$ (cm$^2$/V-s)</td>
<td>1417</td>
<td>1414</td>
<td>470.5</td>
</tr>
<tr>
<td>$N_r$ (cm$^{-3}$)</td>
<td>9.68 x 10$^{16}$</td>
<td>9.2 x 10$^{16}$</td>
<td>2.23 x 10$^{17}$</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.68</td>
<td>0.711</td>
<td>0.719</td>
</tr>
</tbody>
</table>

Since the electron mobility in the n-type material equals twice the hole mobility in the p-type material, one has to solve the following equation:

$$\mu_n = 55.2 + \frac{1417 - 55.2}{1 + \left(\frac{N_a}{9.68 \times 10^{16}}\right)^{0.68}} = 2\mu_p = 2 \times \left[44.9 + \frac{470.5 - 44.9}{1 + \left(\frac{N_a}{2.23 \times 10^{17}}\right)^{0.719}}\right]$$

Where arsenic was assumed to be the n-type dopant.

The resulting solution – obtained through iteration - for the acceptor (boron) density is $N_a = 4.16 \times 10^{17}$ cm$^{-3}$ and the corresponding conductivity of the n-type material equals:

$$\sigma_n = q\mu_n N_a = 1.6 \times 10^{-19} \times 422 \times 4.16 \times 10^{17} = 28.1 \text{ Siemens/cm}$$

where the donor density was set equal to the acceptor density and the electron mobility was calculated from:

$$\mu_n = 55.2 + \frac{1417 - 55.2}{1 + \left(\frac{4.16 \times 10^{17}}{9.68 \times 10^{16}}\right)^{0.68}} = 422 \text{ cm}^2/\text{V-s}$$