Question 1 [6 marks]:
   a) How many charge carriers (electrons or holes) are associated with Shockley-Read-Hall recombination?[1 mark]
   b) How many charge carriers (electrons or holes) are associated with radiative recombination?[1 mark]
   c) How many charge carriers (electrons or holes) are associated with Auger recombination?[1 mark]
   d) Various notations are used for recombination coefficients. Equation (1) is a simplified differential equation use to describe the rate of change of total carrier concentration in a solar cell. In this context, we conventionally use cm as the length dimension (for example carrier concentration, \( n \), is expressed in cm\(^{-3} \)) and seconds as the time dimension. Using Equation (1), determine the standard units for the Auger recombination rate (\( k_3 \)).[3 marks]

   \[
   \frac{dn}{dt} = k_1 n + k_2 n^2 + k_3 n^3
   \]  

In this context:
   • \( n \) is total carrier concentration (holes and electrons).
   • \( t \) is time.
   • \( k_1 \) is the Shockley-Read-Hall (mono-molecular) recombination rate.
   • \( k_2 \) is the radiative (bi-molecular) recombination rate.
   • \( k_3 \) is the Auger (tri-molecular) recombination rate.

Question 2 [6 marks]:
   The net capture rate for electrons (\( U_n \)) and holes (\( U_p \)) are given by the equations (2) and (3) below:

   \[
   U_n = \sigma_n v_{th} N_T [n(1 - f_T) - n_1 f_T] \tag{2}
   \]

   \[
   U_p = \sigma_p v_{th} N_T [p f_T - p_1 (1 - f_T)] \tag{3}
   \]

Where:
   • \( \sigma_n, \sigma_p \) are the capture cross-sections of the trap for electrons and holes, respectively.
   • \( v_{th} \) is the thermal velocity of electrons and holes (assumed to be equal).
   • \( n, p \) are the delocalized electron and hole densities, receptively.
   • \( N_T \) is the density of trap states.
   • \( n_1, p_1 \) are the concentration of electrons in the conduction band or holes in the valence band, respectively, when the Fermi level is located at the trap energy level.

   a) By considering the steady state situation where the net rate of electron and hole capture are identical, derive the steady-state trap occupancy factor (\( f_T \)) given by equation (4).[3 marks]
b) Using the equation for \( f_T \) given in Equation (4) above, show that the Shockley-Read-Hall capture rate \((U_{SRH})\) can be given by the following expression. [3 marks]

\[
U_{SRH} = \frac{\sigma_n \sigma_p v_{th} N_T(pn - n_i^2)}{\sigma_n(n + n_i) + \sigma_p(p + p_i)}
\]

You will need to use the relationship: \(n_i p_i = n_i^2\), and the definition of the Shockley-Read-Hall capture rate \((U_{SRH})\) as the steady-state situation in which the net rates of electron and hole capture are equal:

\[
U_n = U_p = U_{SRH}
\]

Question 3 [3 marks]:

a) Photoconductance decay (PCD) is often used to determine recombination lifetime. The following table shows the measured effective lifetime data \((\tau_{eff})\) vs wafer thickness \((d)\) for a set of samples. If we assume that the surface recombination velocity \((s_r)\) is very small, use this data to determine the bulk recombination lifetime \(\tau_B\).

<table>
<thead>
<tr>
<th>Wafer Thickness (μm)</th>
<th>Effective Lifetime (μs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>250</td>
</tr>
<tr>
<td>125</td>
<td>278</td>
</tr>
<tr>
<td>200</td>
<td>333</td>
</tr>
<tr>
<td>250</td>
<td>357</td>
</tr>
<tr>
<td>500</td>
<td>417</td>
</tr>
</tbody>
</table>

Question 4 [10 marks]:

a) A DC Hall measurement is carried out on a thick sample, as shown in the figure below:

The sample has dimensions of \(L = 5\text{mm}\), \(W = 500\text{μm}\), and \(d = 200\text{μm}\). When a voltage of \(V_p = 1\text{V}\) is applied along the length of the sample, a current of \(I = 4\text{mA}\) is measured. If a \(B\) field of magnitude \(0.7\text{T}\) is applied in the \(z\) direction, a Hall voltage of \(V_H = -8.74\text{ mV}\) is measured. The sample is assumed to be completely n-type (i.e. number density of holes, \(p = 0\)) and to have
a Hall factor of $r = 1$. What is the carrier concentration ($n$) and Hall mobility ($\mu_H$) in this sample? Give your answers in cm$^3$ and cm$^3$/Vs respectively. [4 marks]

You will need:
- The fundamental unit of charge is $q = 1.602 \times 10^{-19}$ C.

b) We are attempting to measure a low mobility sample, using the AC Hall technique. The sample has a thickness of $d = 100$ μm. We apply an AC magnetic field in the $z$ direction of the form given by Equation 6.

\[ B(t) = B_0 \sin(\omega t) \]  

(6)

Where, the applied magnetic field strength prefactor is $B_0 = 0.25$ T. The measured voltage ($V_m$) is shown in Figure below (a). After filtering the high-frequency noise, the measured voltage ($V_{m_0}$) is given in the Figure below (b). If we measure a current of $I = 250$ μA when carrying out the resistivity measurement, determine the Hall coefficient ($R_H$) from this data. Give your answer in m$^3$C$^{-1}$. [3 marks]

c) Give a reason why choosing a frequency ($f = \omega / 2\pi$) of 60 Hz is not a good idea when conducting AC Hall mobility measurements. [1 mark]

d) Briefly describe basic concept of the Time-of-Flight Drift Mobility technique. [2 marks]