SOLID STATE DEVICES

SSD-1. Basic physics of semiconductors and pn junctions

a) A Silicon sample at 300 K is doped with Phosphorus at a donor concentration of $N_D = 10^{15}$ cm$^{-3}$. Calculate the equilibrium concentration of electrons ($n_0$) and holes ($p_0$). (20 points).

For the below parts, assume that the Silicon sample in part (a) is uniformly illuminated, resulting in an optical electron-hole pair generation rate $G_L = 10^{12}$ cm$^{-3}$ s$^{-1}$. Use electron and hole minority carrier recombination lifetimes of $\tau_n = \tau_p = 10^{-7}$ s.

b) Find the electron concentration $n$ under steady state conditions. (20 points).

c) Find the hole concentration $p$ under steady state conditions. (20 points).

d) Is the low-level injection condition satisfied? Why or why not? Explain in a sentence or two. (20 points).

e) Consider that the light is suddenly turned off at $t = 0$. Find the hole concentration $p$ at $t = 1$ s. (20 points).

Properties of Silicon:
$E_g = 1.11$ eV
$\alpha = 11.8$
$n_i$ (at $T=300$ K) = $1.5 \times 10^{10}$ cm$^{-3}$

Continuity equations under low-level injection conditions:

For electrons:
$$\frac{\partial n}{\partial t} = -\frac{1}{q} \frac{\partial J_n}{\partial x} + G_L - \frac{(n - n_0)}{\tau_n}$$

For holes:
$$\frac{\partial p}{\partial t} = -\frac{1}{q} \frac{\partial J_p}{\partial x} + G_L - \frac{(p - p_0)}{\tau_p}$$

Transport equations:

For electrons:
$$J_n = q\mu_n n E + qD_n \frac{\partial n}{\partial x}$$

For holes:
$$J_p = q\mu_p p E - qD_p \frac{\partial p}{\partial x}$$
SOLID STATE DEVICES

SSD-2. Quantum Mechanics

Consider the 1D “particle in a box” problem, where the potential \( V(x) \) is zero for \( -a < x < a \), and infinite elsewhere. The solutions are given by

\[
\psi_n(x) = \frac{1}{\sqrt{a}} \cos\left(\frac{n\pi x}{2a}\right), \quad n = 1, 3, 5...(\text{odd}), \quad -a < x < a
\]

\[
\psi_n(x) = \frac{1}{\sqrt{a}} \sin\left(\frac{n\pi x}{2a}\right), \quad n = 2, 4, 6...(\text{even}), \quad -a < x < a
\]

\[
E_n = \frac{\hbar^2 \pi^2 n^2}{8ma^2}, \quad n = 1, 2, 3...
\]

For the below parts, consider a particle in the \( n = 4 \) state of this 1D “particle in a box” problem, namely \( \psi_4(x) \).

a) Write down explicitly the expression for the wavefunction of the particle at any time \( t \), namely \( \Psi_4(x, t) \). (20 points).

b) Calculate the probability of finding the particle in the region \( \frac{a}{2} \leq x \leq a \). (20 points).

c) Calculate the probability current density \( j(x, t) \) for this particle. (20 points).

d) Sketch the probability density \( P(x) \) for this particle as a function of \( x \), clearly labeling the values on the \( x \)- and \( y \)-axes. (20 points).

e) Calculate the expectation value of the energy of this particle \( \langle E \rangle \). (20 points).