1. **Quantum Wells**

   (a) Write the expression relating the quantized energy states of a 1D quantum well with well width.

   (b) Make a plot of the confined $E_n$ values versus quantum well layer thickness, $d$, for a GaAs/AlAs quantum well (refer to Fundamentals of Photonics pg. 550 for bandgap energy values). The range of your $d$ values should be from 5 nm to 100 nm.

2. **LEDs**

   Consider a GaAs Light-Emitting Diode. In a photoluminescence experiment, you measure the lifetime at temperature $T = 4.2$ K (the temperature of liquid helium) to be 100 ns. You assume that at this very low temperature, you have successfully damped phonons and all possible non-radiative sources of de-excitation; you assume $\tau_r = 100$ ns. You slowly raise the temperature of your cryostat sample holder back up to room temperature, and now measure a lifetime of 50 ns.

   At 300 K,

   (a) What is the non-radiative lifetime $\tau_{nr}$?

   (b) What is the internal quantum efficiency $\eta_i$?

   (c) For an LED design, assume an absorption coefficient of $\alpha = 10^4$ cm$^{-1}$, LED device top layer thickness of $t = 2 \mu$m, and the GaAs refractive index $n = 3.6$. What is the external quantum efficiency $\eta_{ext}$?

   (d) Sketch a schematic plot the output optical power $P_o$ versus input current $I$. Sketch a schematic plot of wall plug efficiency $\eta_{W}$ versus applied voltage $V$. (Note: a schematic plot means that no numbers need to be present on the two graph axes; the plot should show a qualitative trend.)