<u>EE 6313 Homework Assignments</u>

1. Homework I: Chapter 1: 1.2, 1.5, 1.7, 1.10, 1.12 [Lattice constant only] (Due Sept. 1, 2009).
2. Homework II: Chapter 1, 2: 1.17, 2.1 (a, c) ($k = \pi/a$ at zone edge), 2.3 (Do not comment on m^*_X), 2.4, 2.5 (b) (Due Sept. 8, 2009).
3. Homework III: Chapter 2: 2.7, 2.10 (Hint: Assume that $\xi - \xi_F >> k_B T$ and set derivative of $N(\xi)f(\xi) = 0$), 2.12a,b (Hint: Assume degeneracy factor = ½ in (a) and use Eqn 2.125 and use relation $np = n_i^2$ in (b)), 2.13a,b (Hint: Set flux to 0 in Eqn 2.139 in (a)), 2.20 (Due Sept. 15, 2009).
4. Homework IV: Chapter 3: 3.1 (Note 10^{20} $cm^{-3}s^{-1}$ is the recombination rate), 3.2 (Just determine the direct and indirect bandgaps by plotting up square or square root dependence of absorption on energy), 3.5, 3.7 (absorption is related to the field squared), 3.14 (Due Sept. 22, 2009).
5. Homework V: Chapter 3, 4: Supplemental Problem 1, 4.3 (Follow derivation on Page 167), 4.4 (Do resistive voltage drop across bulk using μ_e = 1450 cm^2/V-s and u_h = 500 cm^2/V-s), 4.6, 4.7 (Note that p = $n_i \exp\{(E_i-E_F)/kT\}$ and n = $n_i \exp\{(E_F-E_i)/kT\}$) (Due Oct. 1, 2009).
6. Homework VI: Chapter 5: 5.3 (Use Snell's Law $\sin(\theta_i)/\sin(\theta_t) = n_2/n_1$ where θ_i and θ_t are the incident angle and transmitted angle relative to the perpendicular to the surface and n_1 is the refractive index of the incident medium and n_2 the refractive index of the transmitting medium), 5.10 (Use Eqn 5.9, $n_{GaAs} = 3.6$, $n_{air} = 1.0$, $n_{external} = P_{opt}(transmitted)/P_{electrical}$), 5.13 ($\tau_{Si} = 10$ ns, $\tau_{GaAs} = 1$ ns), 5.15, Supplemental Problem 5 below (Due Oct. 22, 2009).
7. Homework VII: Chapter 6: 6.2 (Does increasing or decreasing the wavelength increase or decrease the relative ratio of stimulated emission?), 6.13 (Take $R_1 = R_2 = R_{GaAs} = 0.32$ for the original reflectivities), 6.14 (Take $R_1 = R_2 = R_{GaAs} = 0.32$ for both reflectivities), Supplemental Problem 4, Supplemental Problem 5 (Due Oct. 29, 2009).
8. Homework VIII: Chapter 7: 7.9, 7.10 (Assume $J >> J_{th}$), 7.11 (Note that φ will be small at threshold), Supplemental Problem 4, Supplemental Problem 5 (Due Nov. 5, 2009).
9. Homework IX: Chapter 7, 8: 7.15, 7.16 ($n_r = 3.66$), 8.7 (Name at least two possible materials: Use Table 7.1 to identify one of the potential materials), 8.8, 8.9 (Assume carriers travel at saturation velocity $v_{sat} = 10^7$ cm/s, neglect diffusion effects, cut-off frequency $f_c = 1/2\pi\tau$ for transit time and $f_c = 1/2\pi RC$ for RC delay, and use Eqn 4.42 and assume $V_{reverse} >> V_{bi}$), Supplemental Problem 1, Supplemental Problem 2, 8.10 (Assume I_B and I_D small), 8.14 (Assume $I_B = I_{PH} = 0$) (Due Dec. 3, 2009).

10. Homework X: Chapter 8, 11: 8.11 (Note avalanche gain is equivalent to multiplication factor M), Supplemental Problem 1, 11.7. 11.8 (Please complete by Dec. 7, 2009 and will post answers online).

Homework V

Problem 1:

A 100 μm long by 0.50 μm wide by 0.25 μm high nanophotonic InP waveguide is forward injected with an electron-hole plasma with a concentration of 5.0 x 10^{17} cm^{-3} electron-hole pairs/cm^{-3}. This plasma will cause a refractive index shift of -0.004 which can be used to modulate an extremely compact 100 μm long Mach-Zehnder interferometer. Calculate the recombination rate across this waveguide using the equation given for recombination at the end of the Chapter 3 Lecture assuming that

$\Delta n = \Delta p = 5 \times 10^{17}$ cm^{-3}
$\tau_h = 20$ ns
$\tau_e = 1$ ns
Surface recombination only occurs across the top and bottom of the 0.25 μm-thick device
$v_h = v_e = 5.0 \times 10^3$ cm/s
$B = 2.5 \times 10^{-10}$ cm^3/s
$C = 1.0 \times 10^{-30}$ cm^6/s

and assuming that the equilibrium carrier concentrations n_i and p_i and the trap densities n_l and p_l are all small and can safely be ignored. Also, assume high level injection so $\Delta n = \Delta p$ is much larger than the equilibrium concentration.

Calculate the recombination rate due to Shockley-Read-Hall trap assisted recombination, the recombination rate due to surface recombination, the recombination rate due to radiative recombination, the recombination rate due to Auger recombination, and the total recombination rate. Report the data in terms of recombinations $cm^{-3}s^{-1}$. Compare these rates.

Also assume that these carriers are injected across both sides of this 100 μm long by 0.25 μm high device. Using the recombination rate and the volume of the waveguide and this area, calculate the current density in Amps/cm^2. Current density is often limited to around 10^5 Amps/cm^2 because of heat and reliability reasons. How does this current density compare to this limit.

Homework VI

Problem 5:

(a) Determine the radiative recombination efficiency η_r for a GaAs p-n junction LED assuming that the light emission primarily results from electron injection and its recombination in the p-region where $N_A = N_D = 10^{18}\ cm^{-3}$ and assuming that $B_r = 7.2 \times 10^{-10}\ cm^3s^{-1}$ and that the electron nonradiative recombination lifetime is $5 \times 10^{-9}\ sec$ (Use Eqns in Section 3.1.1 with Eqn 5.3).
(b) Calculate the electron injection efficiency η_i if $D_e = 120\ cm^2/s$ and $D_h = 1.2\ cm^2/s$ assuming that the hole lifetime is equal to the electron lifetime (Use Eqns in Section 5.4.1).

(c) Determine the extraction efficiency η_e if the overall device efficiency η_o is one percent.

Homework VII

Problem 4:

A single mode GaAs laser is to be fabricated with GaAs-$Al_xGa_{1-x}As$ heterojunctions. Determine the range of the thicknesses over which this device can be designed and still give single mode operation given that the refractive index for GaAs is 3.66 and that x = 0.40 for the composition of the $Al_xGa_{1-x}As$ alloy with the larger refractive index in an asymmetric waveguide and also given the relation for the refractive index for $Al_xGa_{1-x}As$, $n_{AlxGa1-xAs} = 3.66 - 0.71x + 0.09x^2$. Note that single mode operation occurs between m = 0 and m = 1 for an asymmetric waveguide.

Problem 5:

Derive the expression for A_{21}/B_{21} in Equation 6.24 given that $B_{21} = B_{12}$ and using Planck's black body radiation law given in Equation A6.10 in Appendix 6 and also using Equation 6.17 using $g_{D1} = g_{D2} = 1$.

Homework VIII

Problem 4:

(a) Determine the relative change in the output wavelength caused by a small refractive index change in the laser cavity. Derive this relationship by using Equation 6.78 in order to determine the change in the wavelength of the longitudinal mode caused by the refractive index change.
(b) An increase in temperature can cause a significant change in the wavelength of a WDM channel. Calculate the shift in wavelength that a 10 ºC rise would have on an InGaAsP-based laser centered at 1550 nm given that these alloys have a thermo-optic coefficient of approximately 2.0 x 10^{-4} ºC^{-1} and a refractive index of approximately 3.4.
(c) Given that the WDM channel spacing is 0.8 nm at 1550 nm, will this size of change cause a problem?

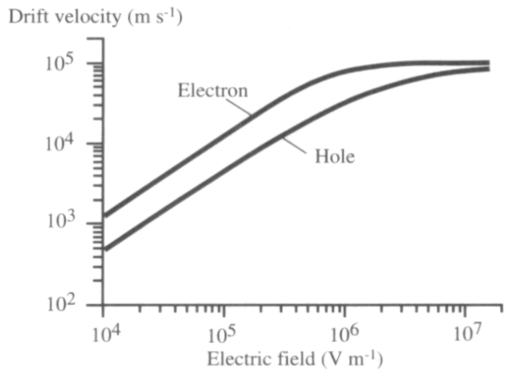
Problem 5:

Consider a DFB laser operating at 1550 nm. Suppose that the refractive index $n = 3.4$ (InGaAsP). What should be the corrugation period Λ for a first order grating $m = 1$. What is Λ for a second order grating $m = 2$. How many corrugations are needed for a first order grating if the cavity length is $20\ \mu m$? How many corrugations are there for $m = 2$? Which grating would be easier to fabricate?

Homework IX

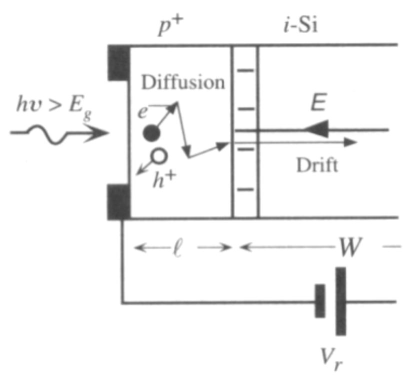
Problem 1:

A Si PIN photodiode has an i-Si layer of width 20 μm. The p^+ layer on the illumination side is very thin (0.1 μm). The PIN is reverse biased by a voltage of 100 V and then illuminated with a very short optical pulse of wavelength 900 nm. What is the duration of the photocurrent if absorption occurs over the whole i-Si layer? Use the drift velocity data for electrons and holes in silicon given below.



Problem 2:

A reverse biased PIN photodiode is illuminated with a short wavelength photon that is absorbed very near the surface as shown below. The photogenerated electrons have to diffuse to the depletion region where they are swept into the i-layer and drifted across. What is the speed of response of this photodiode if the i-Si layer is 20 μm and the p^+ layer is 1 μm and the applied voltage is 120 V? The diffusion coefficient of electrons (D_e) in the heavily doped p^+ region is approximately 3×10^{-4} m^2/s. Assume that the root mean square distance l the electrons will travel in the p^+ region is given by the relation $l = (2D_e t)^{1/2}$ where t is the time.



Diffusion occurring in reverse biased PIN photodiode at the surface.

Homework X

Problem 1:

40 mW of optical power of frequency 4.7×10^{14} Hz is incident on an avalanche photodiode which has a multiplication region width of 1 μm. The internal quantum efficiency is 90% and the electron impact ionization coefficient α_e is 9.5×10^3 cm^{-1}. Assume all incident photons are absorbed and that $\alpha_e = \alpha_h$ (the hole impact ionization coefficient). Calculate the generation rate of electron-hole pairs in units of s^{-1}, the multiplication factor M, and the photocurrent generated from the multiplication process.