Semiconductor Optical Communication Components and Devices

Questions and Problems

Review Questions Lec 4:

1. Take a one dimensional periodic structure of a=5nm, b=20nm, and a V_o=100meV. Take an effective mass of the electron to be $m_e^*=0.07m_o$. m_o is the free electron mass. Write a computer program to find the Energy at k=0 and $k=\pi/(a+b)$ to an accuracy of 0.1meV. This is the first quantization energy.

2. (i) Increase 'b' till you reach where the two energies are same to the accuracy that you are working with. This is the energy for a single quantum well.
(ii) Now increase V_o in steps till you reach a few eV. Compare this result with that of an infinite potential well $E_n=n^2h^2/(8m_e^*a^2)$ for n=1.

Review Questions Lec 5:

1. Take a=5nm and b=4nm with $m_e^*=0.07m_o$. Check for the k=0 and $k=\pi/(a+b)$ energy difference again. This would be the first mini-band of a superlattice. What is your comment with respect to that found in P2 above.

Review Questions Lec 6:

1. Find the composition of InGaAsP alloy lattice matched to InP for which the band gap is 0.85eV.

2. Check the band shape of an indirect semiconductor and that of a direct band gap semiconductor. Justify whose electron effective mass would be larger.

3. Look at the shapes of the conduction band and the valence band of a direct band gap semiconductor. For electrons in the conduction band and holes in the valence band, which should have a larger effective mass?

4. Take $m_e^*=0.07m_o$ and $m_h^*=0.7m_o$ and plot the density of states for both. How similar are they?

5. Note that there are two valence bands at the Γ-point (k=0). Their curvatures are very different. Which should be called Heavy Hole (hh) and which should be called Light Hole (lh)?

6. Do a similar exercise as that in the previous lecture and find the quantization energies for a=5nm, b=200nm, $m_e^*=0.07m_o$, and $m_h^*=0.7m_o$

Review Questions Lec 7:

1. Of the two different kind of Phonons studied which would probably most interact with an inter-band transition in an indirect semiconductor? Justify your answer.

2. Write a mathematical expression of the temperature dependence of the electron distribution in a conduction band.

3. Out of the three different transitions, absorption of a photon, spontaneous emission of a photon, and stimulated emission of a photon, which are resonant processes ?

4. What happens when an electron in the conduction band is accelerated to an energy above the bottom of the conduction band which is larger than the separation in energy between the bottom of the direct conduction band and the bottom of the indirect conduction band in a direct band gap semiconductor?

5. Why is it less probable to have an optical transition in an indirect semiconductor as compared to that of a direct semiconductor?

Review Questions Lec 8:

1. Which system should one use for the growth of $In_xGa_{(1-x)}As_yP_{(1-y)}$? What are the disadvantages of this growth system?

2. Why is VPE system not popular for the growth of $In_xGa_{(1-x)}As_yP_{(1-y)}$ communication device applications?

3. Which growth system is suitable for obtaining highest quality material ? What are the disadvantages of this system?

4. How should one select the growth temperature for a particular semiconductor?

5. Between MBE and MOCVD, which is more suitable in obtaining better electronic devices (Should have less non-compensated unintentional doping)

6. Which growth system should one choose if both optical

Review Questions Lec 9:

1. A graded $Al_{0.36}Ga_{0.64}As$ is to be grown on GaAs for a thickness of 1μm at a growth rate of 1μm/hr. in an MOCVD system using TMG, TEG, and AsH_3. Find the flow rates of TMG, TEG, and AsH_3 with time if growth is done at 750 ^oC. The carrier gas (H_2) flow rate is 10 SLM (Standard Litres per minute).

2. An $In_xGa_{(1-x)}As_yP_{(1-y)}$ is to be grown lattice matched to InP at a band gap of 0.8eV. Find the flow rates of TMG, TMI, AsH_3, and PH_3, if growth is to be done at 700 ^oC. The carrier gas (H_2) flow rate is 15 SLM.

Review Questions Lec 10:

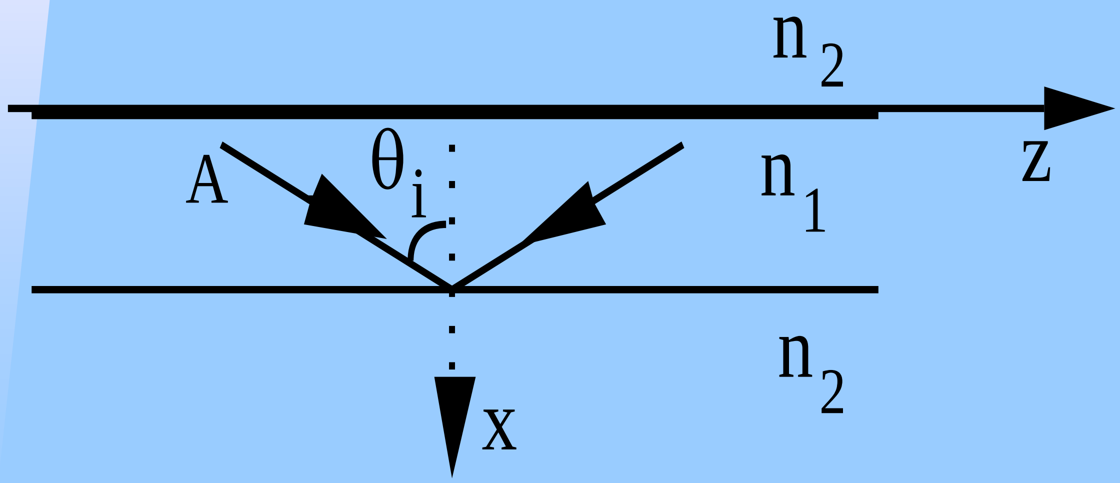
1. A graded $Al_{0.36}Ga_{0.64}As$ is to be grown on GaAs for a thickness of 1μm at a growth rate of 1μm/hr. in an MOCVD system using TMG, TEG, and AsH_3. Find the flow rates of TMG, TEG, and AsH_3 with time if growth is done at 750 ^{o}C. The carrier gas (H_2) flow rate is 10 SLM (Standard Litres per minute).

2. An $In_xGa_{(1-x)}As_yP_{(1-y)}$ is to be grown lattice matched to InP at a band gap of 0.8eV. Find the flow rates of TMG, TMI, AsH_3, and PH_3, if growth is to be done at 700 ^{o}C. The carrier gas (H_2) flow rate is 15 SLM.

Review Problems Lec 12:

1. **For a TM wave incident from the medium n_1 to the interface of n_1 and n_2 where $n_1 > n_2$, derive the phase change due to reflection for $\pi/2 > \theta_i > \theta_c$.**

2. **A plane wave 'A' is incident in a planar waveguide as shown in the figure above, where $n_1 > n_2$. Show that for $\theta_i > \theta_c$ the propagation in the x-direction in the medium n_2 is exponentially decaying whereas in the z-direction in the same medium the propagation is identical to that of medium n_1.**



Review Problems Lec 13:

1. For a planar GaAs waveguide of thickness 0.5μm and refractive indices n_f = 3.5, n_s = 3.45, and n_c= n_o =1.0, find a value of the thickness t_g for which there would be propagation of only the lowest order mode for a wavelength of 1.5μm but with the maximum propagation constant possible. Calculate this propagation constant. Find the cutoff wavelength for the lowest order mode in this waveguide.

2. A five layer slab waveguide structure composed of layers n_o=1.000, t_{go}= semi-infinite; n_1=3.498, t_{g1}=1.5mm; n_f =3.500, t_{gf}=2.5mm; n_2 = 3.495, t_{g2}=1.5mm; and n_s = 3.5, t_{gs}=semi-infinite is supposed to guide TE light at a wavelength 'λ'. Find the range of wavelengths for which there would be single mode propagation. [Hint: Write the wave equation, i.e. the field expressions in the five layers for the field components E_z and H_z. Match the boundary conditions at the four interfaces. Then use Matlab or any other suitable software to solve the equations and find the relationship of b vs V. Define b and V with respect to n_f and t_{gf}. Get your answer from the plot.]

Review Problems Lec 14:

1. A rib waveguide is formed with n_c=1.0, n_f=1.55, and n_s=1.63. If the width of the stripe for the rib is 4 μm and the thickness of the film is 1.0μm and the rib height is 0.2μm. Find the propagation constant of the guided mode for a wavelength of 1.55μm in air.

2. For a planar waveguide of thickness '2d' and refractive indices n_f=1.501, n_s=1.500, and n_c=1.0 find the thickness of the guide for which there would be propagation of only the lowest order mode for a wavelength of 1.65μm but with the maximum propagation constant. If a rib waveguide is to be made from this slab waveguide, given that the rib height 'h' needs to be only 5%-20% of the slab waveguide thickness, choose a slab waveguide thickness and plot the maximum rib width 'a' as a function of 'h' for a single transverse mode of propagation in the rib waveguide.

Review Problems Lec 15:

1. Photons of wavelength λ=813 nm are absorbed in InP at room temperature (E_g=1.344eV, m_e^*=0.08m_o, m_h^*=0.60m_o) and excites electron-hole pairs (EHP). Calculate the average kinetic energy of the electrons and holes before they relax to the bottom of the bands. [Hint: they will not be the same]
2. Find the peak emission wavelength (λ_o) for an $Al_{0.2}Ga_{0.8}As$ LED operating at 400^{o}K, given the band gaps $AlAs_\Gamma$=3.03eV, $AlAs_X$=2.15eV, $AlAs_L$=2.36eV, $GaAs_\Gamma$=1.43eV, $GaAs_X$=1.73eV, and $GaAs_L$=1.89eV. (assume linear interpolation to be valid)
3. Derive the fraction of radiation escaping from an LED (point source) imbedded in a medium of refractive index n_1 into the upper medium of refractive index n_2, assuming there is no absorption in the medium. Also assume the transmission coefficient is that of normal incidence at the interface.
4. An LED at room temperature under 0.8V forward bias conducts a current of I =12mA and emits light at a peak wavelength of 1.0µm. The radiative and the non-radiative time constants are 0.1ns and 1ns, respectively. Assuming that the unity extraction efficiency and the injection efficiency is 0.9, calculate the power conversion efficiency of the diode. Is this calculated efficiency greater than or less than unity? Does it surprise you, explain. What is the new conversion efficiency, if for the same set of conditions, the emission wavelength is now 1.3µm ?

Review Questions Lec 16:

1. How does a double - heterostructure LED help in increasing the efficiency ?

2. Why is it necessary to take precautions that in an SLD standing modes do not develop? How is the facet handled for that purpose?

3. Qualitatively compare the same for the SLED and SLD when the junction temperature rises to 200^{o}C above room temperature.

4. Explain why the modulation bandwidth of an SLD is larger than that of a SLED.

Review Questions Lec 17:

1. A InGaAs LED with minority carrier lifetimes (for both electrons and holes) of τ = 1ns is excited by a modulating current of I=[10+Cos(2πft+θ)] mA. If the steady state optical output is Po=5mW, derive expressions for P(t) for modulating frequencies of (a) f=1.0MHz and (b)f = 10GHz.

2. An edge-emitting LED has stripe width of 10 μm. The active layer thickness is 0.5 μm and has a refractive index of 3.5. The length of the LED is 0.5 mm and the radiative recombination lifetime of the carriers is 0.1 ns. The optical output is taken out from one end of the diode only. When the bias current is switched off, find the time required for the output intensity to decrease from the steady state value to 1% of the steady state intensity.

3. A GaAs LED fabricated from fairly lightly doped materials has an effective recombination region of width 0.1 μm. If it is operated at a current density of 2 x 107 A/m^2, estimate the modulation bandwidth that can be expected. Assume the recombination constant B(recomb)=7x10^{-16} m^{-3}. [Hint: Get relation between recombination time constant with B(recomb)]

4. Explain why the edge emitting LED (ELED) has a narrower spectral width than the surface emitting LED, (SLED). How does it differ from the Superluminescent diode (SLD) ?

Review Questions Lec 18:

1. Which of the semiconductors Si, Ge, GaAs, and GaP are suitable for the fabrication of diode lasers? Justify your conclusion.

2. An $In_{0.53}Ga_{0.47}As$ semiconductor at 300K has parabolic conduction and valence bands [$E_{c,v} \alpha k^2$]. The effective masses of the electrons and holes in this material are $m_e^*=0.06m_o$ and $m_{hh}^*=0.15m_o$, respectively. If the electron concentration peak is $0.5k_BT$ above the bottom of the conduction band, then find the hole energy (eV) below the top of the valence band for efficient photon emission, assuming the density of states for the conduction and the valence bands to be the same.

3. What are the different varieties of Fabry-Perrot cavity diode lasers?

4. What are the configurations for which one would be able to get narrow linewidths for diode lasers?

5. Why is it essential that the diode laser output is emitted normal to the surface of the semiconductor substrate? What are the disadvantages associated with it?

Review Questions Lec 19:

1. **How should the direction of the optical waveguide oriented with respect to the crystal axes for the formation of cleaved cavity mirrors for the diode lasers?**

2. **What is the effect of the introduction of Dopuble Heterostructure in the active region on the performance of the Laser diode? Calculate the optimum thickness of a GaAs/$Al_{0.3}Ga_{0.7}As$ DH structure from a consideration of the optical mode – carrier overlap.**

3. **What is the advantage of introducing QWs in the DH active region? How does the number of QWs determine the speed of operation of the device?**

4. **How does compressive strain in the active region improve the efficiency of a diode laser?**

Review Questions Lec 20:

1. Explain how grading of a DH-SQW active region of a diode laser help in high speed modulation of a diode laser.

2. Design a GaAs/AlGaAs GRIN-SCH-SQW laser for maximum stability of the threshold current with temperature.

3. What are the considerations of choosing the number of QWs in the active region of a Diode Laser?

4. How does cladding layer thickness determine the Far Field FWHM width of a GRIN-SCH diode laser?

Review Questions Lec 21:

1. Consider a bump δL on one of the mirrors of a Fabry-Perot cavity, calculate the mode positions δq for a change of δL in the cavity thickness. Introduce this value in the expression for Finesse, and show that for a Finesse '*F*', the mirrors must be flat to λ/N. Determine 'N'.
2. Show that the longitudinal mode spacing of a semiconductor laser resonator cavity of length 'L' (considering the presence of dispersion at the semiconductor band edge) is given by: $|dl| = l2.[2n_r L\{1- (l/n_r)(dn_r/dl)\}]^{-1}$
3. Show that $\Delta E_F > E_{ph} > E_g$ is the condition for gain in a laser. Where ΔE_F is $(E_{F_n} - E_{F_p})$. What is the condition identified as population inversion in semiconductors. Derive your answer.
4. A DH diode laser gain profile has g_{max}=2000m^{-1} and attenuation α_s=600m^{-1}
   (a) If $R_1 = R_2 = 0.35$, what is the minimum value of the length of the cavity for which lasing action can be obtained ?
   (b) If the length is 400 μm, and $R_1 = R_2 = R$, what is the minimum value for R?
   (c) How would the laser threshold change if the value of R is increased from this value by applying reflective coatings to the end facets ?
5. An uncoated Gallium Arsenide (GaAs) injection diode laser with a cavity length of 500 μm has a loss coefficient of 20cm^{-1}. The measured differential external quantum efficiency of the device is 45%. Calculate the internal quantum efficiency of the laser. Assume the refractive index of GaAs is 3.6.

Review Questions Lec 22:

1. The threshold current density for a stripe-geometry AlGaAs laser is 3kA.cm^{-2} at a temperature of 15^{o}C. Estimate the required threshold current at a temperature of 60^{o}C when T_o for the device is 180^{o}K, and the contact stripe is 20 x 100 (mm)^2.
   [Hint: G. H. B. Thompson, IEE proceedings (optoelectronics), 1981, Vol.128, pp37-43]

2. Explain why in steady state the carrier concentration in the injection laser active region remains constant even when the current is increased above threshold.

3. The output power of a junction laser above threshold is proportional to R_b/τ_{ph} as $R_{bias} = [G\tau_{ph}/qw](J_{bias} - J_{th})$.
   Where τ_{ph} is the photon lifetime in the cavity. Show that, above threshold, the output power still depends on τ_{ph} and is proportional to $\{J-(qw/\tau_{tot})[N_T + (g_1 G\tau_{ph})^{-1}]\}$. Where g_1 is the constant of Stimulated emission, N_T is the carrier concentration for which transparency is obtained, and G is the fraction of injected carrier distribution and mode overlap.

Review Questions Lec 23:

1. A diode laser is operated at a current $I_o=2I_{th}$. If the Carrier and Photon Lifetimes are 1ns and 10ps, respectively, then estimate the modulation bandwidth of the laser. Given that the transparency carrier concentration is 1.0×10^{18} cm^{-3} and $g_1=5x10^{-7} cm^3 s^{-1}$.

2. A 800nm thick DH laser is biased at $0.5I_{th}$ and a pulse current step of $1.0I_{th}$ is applied to the laser at t=0. If the Carrier and Photon Lifetimes are 1ns and 10ps, respectively, find the delay time after which the output power reaches the steady state value. Calculate the time after which the output power reaches steady sate.

3. Where would you bias a semiconductor laser for high speed direct modulation? What is the penalty paid for this state of operation?

Review Questions – I (Lec 24)

1. At what frequencies should a diode laser be directly modulated to encounter chirping? What is the origin of chirping and how does it affect the bit rate of optical communication?

2. Does a negative chirp affect the maximum bit rate of transmission through a dispersive optical fiber in the same way as a positive chirp? Explain your answer.

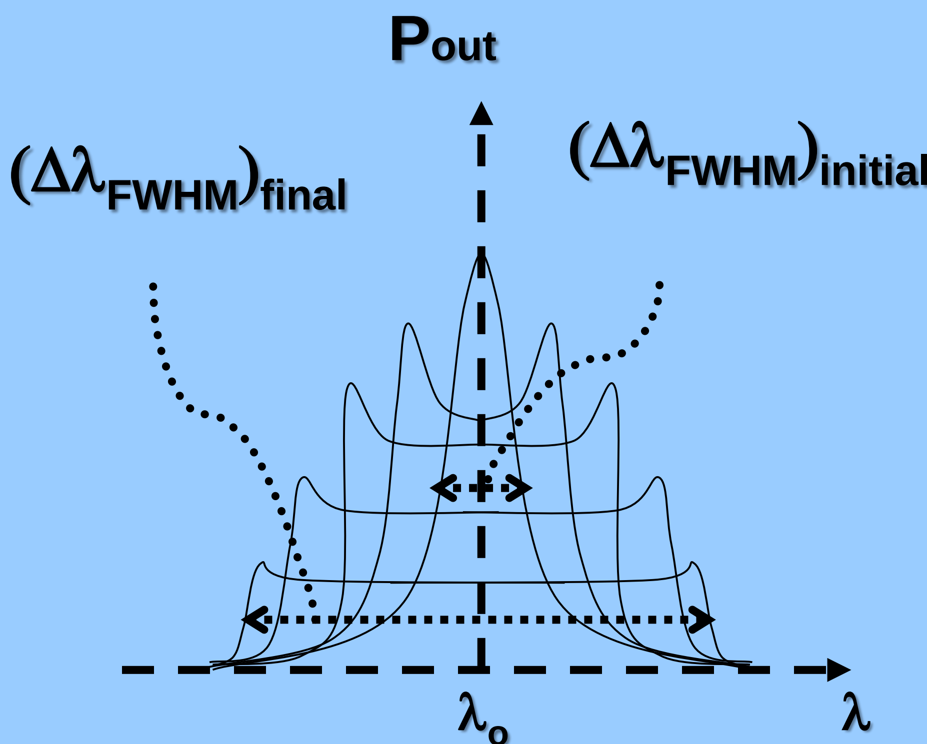
3. An InGaAsP/InP DH single mode laser is operating at a power P_o in the steady state with a FWHM linewidth of 0.5nm. Estimate the average linewidth of the laser due to chirp when it is modulated at a frequency $1.5\omega_o$ modulated to a power level of $2P_o$. ω_o= 5GHz and the Henry factor is α_H=3.5.

4. Does one expect the same α_H for all modes of a multimode semiconductor laser? Explain you amswer.

5. Guess how the linewidth would be affected for a large signal modulated diode laser.

Review Questions – II (Lec 24)

5. A direct detection optical fiber PCM communication system, operating at a wavelength of λ_o=1610nm, is to operate over a distance of 50Km without any repeaters. The link is formed with a dispersion shifted (zero dispersion at 1550nm) silica fiber of 0.2dB/Km loss at the operational wavelength of λ_o=1610nm and a residual dispersion of 50 $ps.Km^{-1}.nm^{-1}$. The laser output is 200mW at a line-width of $(\Delta\lambda_{FWHM})_{initial}$=0.2nm, as shown in the adjacent figure.



The chirp in the laser, on modulation, is given as:

$$(\Delta\lambda_{FWHM})_{final}=[8.633\times10^{-21}].Exp(0.4.f_m)\ nm,$$

where f_m is the modulation frequency in GHz. The modulation delay (exponential) for the laser, t_d=12.0ps. The detector Noise equivalent power (NEP) is 12.6 pW/√Hz and has a transit time limited 3dB bandwidth of 45GHz. (assume the pulses to be Gaussian in nature). <u>What is the MAXIMUM POSSIBLE BIT RATE of the communication link</u>? Show calculations to justify your conclusion. (May need iterative solution)

Review Questions Lec 25:

1. What is the main source of Diode-Laser noise? Enumerate other sources of this noise.

2. Find the relative intensity noise at λ=1.5μm for a laser operating at 100mW, with a small signal bandwidth of 30GHz. Given that the active volume is 250x4x0.01μm^3, τ_{ph}= 2.5ps, τ_c= 0.5ns, τ_{nr}= 1.0ns, N=$10^{19}cm^{-3}$, $|H(\omega)|=\omega_r^4/[(\omega_r^2-\omega^2)+(\omega\gamma)^2]$, γ= $(2+0.3\omega_r^2)x10^{-9}$, and f_r=25GHz.

3. If the resonance frequency of a diode laser is 15GHz and the small signal f_{3dB}=30GHz, what should be the range of the upper limit of the relative intensity noise given that at low frequency modulation the relative intensity noise at unit bandwidth is –100dB/Hz and τ_c= 1.0ns.

4. How is the noise affected by the size of the cavity? Explain your conclusions.

Review Questions Lec 26:

1. Should one use an undoped or heavily doped substrate for the fabrication of diode lasers? Explain your conclusion.

2. What is the necessity of an insulating layer before the final top contact metallization?

3. If a DH Diode Laser is grown on an n+ substrate, why is it advantageous to package the laser with its anode connected to the heat-sink? What precautions need to be taken during die bonding of this laser?

4. What should be the special properties of the carrier material of a fiber which is used for fiber coupling of a diode laser?

5. Why is it essential to mount both the fiber carrier as well as the diode-laser on the same base plate when thermoelectric cooling is used?

6. Why are diode laser packages for high speed modulation different from those of a TO3, TO5, or TO8 packages? Which ones should be used for this purpose? Explain how these packages are suitable for high frequency operation.

Review Questions Lec 27:

1. Why are DFB lasers essentially single mode? How are the modes determined?

2. What is the need for $\pi/4$ phase slip in a DFB Laser?

3. What is the order of linewidth of a DFB laser? Which factors does it depend on?

4. List the fabrication steps that would be required for the fabrication of a MQW-DFB laser.

5. A DH DBR laser has a cavity n_{eff} =3.4 of length L=100μm and is supposed to work at λ_o=1.55μm. The end facets are AR coated with R=0.5 coupled to two gratings of length L_{DBR} =150μm. Assuming a coupling coefficient of κL_{DBR}=4, for a 1st order grating find the grating period 'Λ' and the end-loss of the end facet F-P modes about the selected mode.

6. Why is chirp expected to be much less than that of a Fabry-Perrot Laser

Review Questions Lec 28:

1. What determines the linewidth of a semiconductor diode laser?
2. Show that for $G \approx G_{th}$, $\Delta\omega = \hbar\omega(1+\alpha_H^2)/[\tau_{ph}^2.2P_{out}]$ and hence the cavity quality factor $Q = \Delta f/f = \omega\tau_{ph}$.
3. A F-P cavity of length L=250μm has an effective refractive index n_{eff}=3.7 and α_H=2. The F-P cavity has bare end facets at one end and is coated to R=1 at the other end. Assume cavity losses α_S to be negligible. If the laser is operating at an output power of 10mW at a wavelength λ_o=1.24μm, find the cavity linewidth and compare it with the intrinsic laser linewidth.
4. Compare "thermal" and "electronic" tuning mechanisms of DFB lasers.
5. What are the advantages of multi-slot tuning and what are the constraints of this technique?
6. Check QCSE tuning of diode laser principles: B. Cai, A. J. Seeds, and J. S. Roberts, IEEE Photon. Technol. Lett. , vol. 6(4), 496 (1994).

Review Questions Lec 29:

1. What are the usages of VCSEL lasers?
2. What are the reasons for narrow linewidth and low threshold for VCESLs?
3. If $R_{Top}.R_{Bot}$= 0.95 and α_1= 1000cm^{-1}, α_2= 10cm^{-1}, and α_{diff}= 20cm^{-1}, find the threshold gain required for d=0.25μm and L=1μm. Compare this with that of a typical F-P diode laser of length 250μm.
4. Why is oxide aperture very useful in the fabrication of VCSEL arrays? Which other technique is used?
5. What are the usages of tunable VCSELs? What method is used for this tuning?
6. Which techniques are used for controlling the polarization of VCSELs? Compare the efficiency of these techniques and the complexities of fabrication of each of these techniques.

Review Questions Lec 30:

1. A diode laser had been working fine for 200 hrs. at the rated power, but suddenly failed to produce any power except that expected from an LED. Can you suggest a reason for the failure? What would be the possible solutions to avoid this kind of failure?
2. A similar diode as above, which has been working for 5000 hrs. is found to produce less output power at the same bias current over a period of a month. Suggest a reason for this kind of failure. Can this failed laser be restored?
3. What precautions can be taken to avoid soldering and fiber-couple degredation?
4. If the optical output power of a diode laser is linearly dependent on the drive current, then why does the failure rate be dependent exclusively on the m^{th} power of current and n^{th} power of the output optical power?.

Review Questions Lec 31:

1. Upon the sudden removal of the external generation stimulus (rate=G_{ext}) in an n-type semiconductor ($n_o >> p_o$) at time t = 0, where the excess carrier concentration is $\Delta n(0) >> n_o$, calculate the time dependence of the excess electron density $\Delta n(t)$, where n_o and p_o are the equilibrium carrier concentrations. Assume that direct band-to-band transitions are the only recombination mechanisms. [Let B be the recombination constant].

2. Is the absorption process a resonant process or a random process? Justify your answer.

3. Why would one use a direct band gap semiconductor for the fabrication of a photodiode?

4. For high speed operation in communications, would one choose to operate the photodiode in the photovoltaic mode or photoconductive mode? Justify your answer.

Review Questions Lec 32:

1. A photon of λ=1.55μm is absorbed by a lattice matched InGaAs/InP PIN photodiode at room temperature. If the kinetic energy of the generated hole is $0.5k_BT$, then find the kinetic energy of the generated electron. Given that the electron and hole effective masses are $0.042m_o$ and $0.5m_o$, respectively.
2. An optical signal P_{in}=[1.0mW]{1+0.1Cosωt} of λ=1.5μm is normally incident on a DH InGaAs/InP PIN photodiode. The two semiconductors having band gaps E_g(InP)=1.5 eV and E_g(InGaAs)=0.75eV. The absorption coefficients at λ=1.55mm are α(InP)=$1.0\text{x}10^2 m^{-1}$ and α(InGaAs)=$1.0\text{x}10^6 m^{-1}$. Assuming internal quantum efficiency to be 0.8, calculate the total external quantum efficiency of the detector for W_{InGaAs}=0.5μm, $n_{r(InP)}$=3.4, $n_{r(InGaAs)}$=4.2.
3. An incoherent detection system operates with a PIN photodiode R=0.45A/W at λ=1.55mm at 300^{o}K with a dark current i_D=1.0nA and when connected to a load resistance of 50Ω the operational bandwidth is B=6.0MHz. The incident power is $P_i=P_o+P_m Cos(\omega_m t)$ and that the background radiation is neglected. Assuming $P_o=P_m$, plot the SNR for 1mW > P_o > 1nW.
4. A load resistance R_L=100Ω is connected to a PIN detector of responsivity 0.4A/W at a λ=1.0μm and dark current of 1.0nA. Assuming the equivalent load resistance (including the diode resistance and the input resistance of the amplifier) ≈ R_L, calculate the NEP of the detector. What is the minimum detectable power if the operational bandwidth of the photodiode is 250MHz?

Review Questions Lec 33:

1. Consider the detector of prob. 2, lec. 32. If the photons are incident from the P+ side and the detector is operated under saturated velocity of the electrons (v_e=2.5x10^5 m/s) and holes (v_h=5x10^3 m/s), <u>estimate</u> the response time of the detector if the junction-area of the diode is very small.

2. What composition of InGaAsP should be used for the detection of λ=1.3μm from speed considerations.

3. How should the a PIN Photodiode be biased for maximum speed of operation.

Review Questions Lec 34:

1. In prob. 1 of lec. 34 if the width of the absorption region is increased to 2.0μm, how is the above estimate in variance with the actual value. Determine the same by writing a small program.

2. What are the techniques for the speed measurement of fast photodiodes? If one measures the impulse response by a fs laser, how does one find the 3dB bandwidth of the photodiode from the measured response? How does one do a photodiode speed measurement when neither a laser can be modulated at the highest speed that the photodiode responds nor can an oscilloscope be found to respond to the speed of the detector? Do some research on it.

3. A communication link is driven by a λ_o=1.5μm single mode laser of linewidth 10nm, which has a 3dB modulation bandwidth of 31.8GHz and negligible chirping. The channel is a single mode dispersion shifted fiber with a dispersion of 0.5 ps/(Km.nm) at λ_o. The front end of the receiver is a PIN photodiode whose response time is transit time limited to 10ps. What is the maximum length of the fiber for which 10 Gbits/s operation is possible ?

Review Questions Lec 35:

1. Why does one expect to have enhanced responsivity in a RCE-PD even though the absorption region could be quite thin for high speed operation?

2. How is the transit time limitation overcome without compromising on the absorption length in a RFPD? What are the disadvantages of this detector?

3. What are the limitations of a waveguide photodiode, although speed may be enhanced substantially?

4. Why is it essential to match the velocity of the RF generated from the photo-response with the optical velocity in the waveguide?

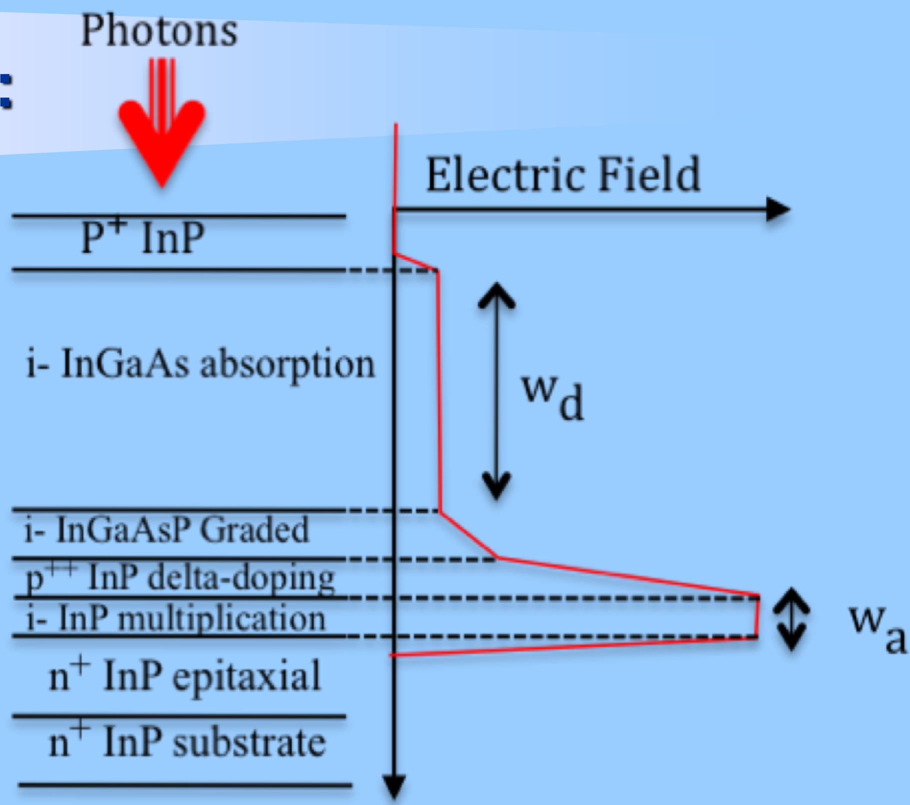
5. How does waveguide photodiodes enable on-chip integration and for that matter also makes it possible to have a periodic photodiode structure? (Check last lecture on integration)

Review Questions Lec 36:

Check review questions on APDs (Lec. 38).

Review Questions Lec 37:

An intensity modulated optical signal, $P_S=P_o[1+0.5.Sin(\omega_m t)]$ is incident on an InGaAs (λ_g=1.65mm)/InP SAM-APD from the p+ end at 300K, as shown in the figure. The ionization coefficients of the carriers in the avalanche region are $\alpha_e=100\beta_h$. Avalanche width is 'w_a', $\alpha_e w_a=1.5$, and w_d=0.7μm. Neglect all capacitances and inductances. The APD is connected to an equivalent load of R_L=1.0kW.



1. Show that $M_e \simeq e^{\alpha_e w_a}$ and $M_h \simeq 1$.
2. If the responsivity $\mathcal{R}$=0.6 A/W at λ=1.64μm when this diode is operated as a PIN-photodiode, write an expression for the RMS signal power of the APD as a function of P_o.
3. Find the Noise-Equivalent-Power (NEP) of the APD for a shot and thermal noise limited operation neglecting any dark current.
4. The electron and hole velocities are $v_{sat_e}=2\times10^7 cm.s^{-1}$ & $v_{sat_h}=7\times10^6 cm.s^{-1}$. Neglecting any delay due to the avalanche process, estimate the bandwidth of the APD for λ=1.64mm.

Review Questions Lec 38:

1. An avalanche Photodiode has η_{ext}= 0.62 at λ=1μm, a dark current of 10pA at 100V bias, α/β = 0.85, multiplication M = 30 and a noise equivalent bandwidth of 10 GHz. If a signal of 1.0mW is incident on the detector, calculate the current SNR. If the bias is changed to 250V the dark current, the α/β, and the multiplication factor changes to 100pA, 0.02, and 250 respectively. What is the change in the SNR ?

2. A PIN photodiode operating at room temperature, generating a photocurrent I_{ph}=50μA is connected to a HEMT pre-amplifier through a photodiode load of 50Ω. The HEMT operates at I_D=1mA, I_G=20nA, and g_m=10mS to provide an overall bandwidth (B)=20GHz. What is the r.m.s noise at the input of the pre-amplifier?

3. An APD has responsivity $\mathcal{R}$=0.5, k=0.1, and operated at M=15 receives an optical signal of 100nW which is intensity modulated with a signal of f(t)=Cos[2πf_mt] at a modulation index of m=0.4. The photodiode sees a total load of R_L=1.0kΩ in parallel with C=300fF when connected to a transimpedance pre-amplifier having a feedback resistance of R_F=0.5kΩ to provide an overall bandwidth (B)=1GHz. Assume the photodiode and the amplifier to work at 300K and f_m << B. Also assume $\{i_a^2\}$=0 and $\{v_a^2\}$=2x10^{-18} V^2Hz^{-1}.
   Find the SNR at the pre-amplifier output.

Review Questions Lec 39:

1. What are the disadvantages of direct modulation of diode lasers?
2. What are the main phenomena on which an external modulator works?
3. Which devices are suitable for digital and which for analog external modulation of a laser?
4. What limits the operation frequency of external modulators?
5. What are the advantages and disadvantages of resonant ring modulators?
6. Why are embeded ring modulators becoming important? What are its limitations?