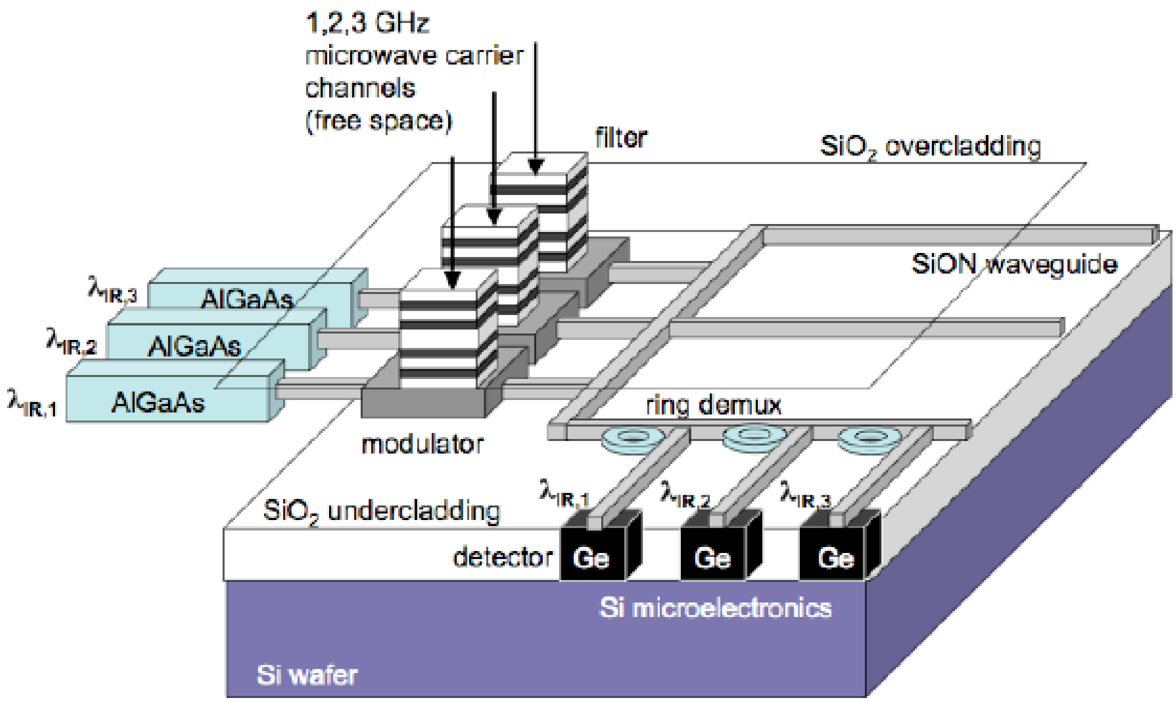
3.46 PHOTONIC MATERIALS AND DEVICES

Final Exam: "The UHF AM Satellite Radio"

Three hours are allotted for this quiz. It is to be answered closed book with no written aids. Calculators are allowed. Show all work that leads to the answer; answers should be brief and to the point. All equations and data needed to solve the questions are listed at the end of the exam. Extra credit will be given for answering the bonus question.

In Design Review 4, we began designing a transceiver for three UHF AM Satellite Radio channels. Your Final Exam, your mission today, is to finish the job!



Our receiver is an Opto-electronic Integrated Circuit (OEIC) that detects data that is amplitude modulation encoded (AM), on three microwave carrier frequencies (1, 2, 3 GHz). The encoding bandwidth on each carrier frequency, or channel, is 0.1 GHz. The 1, 2, 3 GHz carrier channels are de-multiplexed by transmission through three Bragg Filters (each with a different resonant cavity layer), designed to pass one channel to its own dedicated modulator. One of three off-chip constant power AlGaAs lasers with slightly different Infrared (IR) wavelengths ($\lambda_{IR,1}$ = 850 nm, $\lambda_{IR,2}$ = 855 nm, $\lambda_{IR,3}$ = 860 nm) couple to one of the modulators, respectively. The microwave signal modulates transmission through the modulator, thereby encoding the IR laser with the AM signal. We have now transferred our AM signal from the microwave carrier to the IR carrier. As a result, we can now work with integrated microphotonic devices. Our signals will be (multiplexed onto waveguides) routed to (our display and demultiplexed with each wavelength representing an entertainment/data channel). Each entertainment/data channel is read by integrated photodetectors that transduce the optical signals into an electrical signal for mpeg-4 compression format audio, video and graphics data.

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1. Bragg Filter for 1 GHz signal (15 points)
   Microwave wavelengths are very long, so we will want to use high refractive index materials in order to design a Bragg Filter that is of reasonable thickness (assume we have access to some rapid deposition process that can deposit ~cm/hour). For our Filter, we will use SiO_2 (n = 1.45) and stoichiometric Si_3N_4 (n = 2.0) to design our Bragg Mirrors and resonant defect/cavity layer.

(a) Use the quarter wavelength and the lowest order resonant mode criteria to calculate the thickness of (i) the low refractive index layer, (ii) the high refractive index layer and (iii) the resonant cavity layer, for a Bragg Filter that transmits the 1 GHz channel. Specify which material and refractive index you're using for the cavity layer. (5/15 pts)

(b) Given the 0.1 GHz bandwidth of the 1 GHz carrier, what should be the channel width in units of frequency? (5/15 pts)

(c) (i) If your Bragg mirror is composed of two SiO_2/Si_3N_4 pairs, what will be its normal incidence reflectivity? (ii) If the Bragg Filter is composed of this mirror, both above and below the resonant cavity, what will be the external cavity loss coefficient α_e? (iii) What external cavity lifetime τ_e does this correspond to? (iv) Assuming there are no source of loss this filter, what will be the Quality Factor Q? (v) How does the frequency linewidth $\Delta\nu$ of this filter compare, with the channel frequency linewidth you calculated in part (b)? (vi) Will the AM signal successfully transmit into our transceiver? (5/15 pts)

2. The Light Source (15 points)

(a) How does the effective mass m^* influence the injection threshold current of a semiconductor laser? (5/15 pts)

(b) How does the average principal quantum number influence E_g and m^* for a compound semiconductor? (5/15 pts)

(c) Two light emitters are composed of a III-V compound and a II-VI compound, respectively, with each compound having the same average principal quantum number (see periodic table on the last page). Will the III-V compound laser have a lower threshold than the II-VI compound device? Explain. (5/15 pts)

3. The Light Source (15 points)
   Let's chose AlGaAs to be our materials system for making our three off-chip IR lasers. We'll work with low Al-doped compositions, i.e. very close to a pure GaAs material. The GaAs is deposited by a hydride CVD process that produces an As-rich nonstoichiometric layer, where the defect to accommodate this nonstoichiometry is the antisite defect, As_{Ga}^{++}.

(a) Write the chemical equation for ionization of As_{Ga} to As_{Ga}^{++}. (5/15 pts)

(b) The equilibrium constant for this reaction is given by K=Π[product]/ Π[reactant], where [product] is the concentration of a product constituent in the reaction equation. Give the expression for the equilibrium constant for your chemical equation in part (a)? (5/15 pts)

(c) The Law of Mass Action for free carriers is np = constant, where n is the concentration of electrons, and p is the concentration of holes. Sketch the behavior of the $[As_{Ga}^{++}]$ defect concentration versus the acceptor dopant concentration N_A. (5/15 pts)

4. The Light Source (12 points)

We've picked our lasing material, now let's pick an efficient laser device design.

(a) Sketch the conduction/valence band energies versus position perpendicular to the wafer plane for a double heterostructure (DH) laser. How does such a band profile improve device performance by reducing the laser threshold current? (3/12 pts)

(b) Sketch the conduction/valence band energies versus position perpendicular to the wafer plane for a Quantum Well in a DH laser. By what physical mechanism does this band profile enhance electron-hole recombination? (3/12 pts)

(c) Sketch the gain profile for a double heterostructure laser, at two different electrical injection levels. What is the difference between the two gain profiles (threshold and peak gain) and why? (Qualitative explanation.) (3/12 pts)

(d) Sketch the gain profile of a Quantum Well laser. How does it compare with the gain profiles in part (c) and why is there a difference? (Qualitative explanation.) (3/12 pts)

5. Couplers (10 points)

When plane wave light is incident on an interface between two media, the normal incidence reflection is $R = \left|\frac{n_f - n_i}{n_i + n_f}\right|^2$, where n_i is the refractive index of the incident medium and n_f is the refractive index of the destination, or final, medium. In a waveguide, light is deformed from a plane wave state to a confined mode profile (in two dimensions).

(a) Bearing these facts in mind, what are the two main criteria for optimizing coupling of light between an optical fiber and a strip waveguide? (5/10 pts)

(b) How does an Inverse-Taper waveguide coupler provide simultaneous solutions to these two criteria? (Note: assume that the waveguide core is made of Si_3N_4, and the cladding is made of SiO_2, and that the optical fiber is predominantly composed of SiO_2.) (5/10 pts)

6. Microwave modulator (10 points)

(a) A Mach-Zehnder interferometric modulator imparts a voltage dependent phase delay $\Delta\phi$ in one arm of a split waveguide and then combines the two arms into a single waveguide. The bias voltage V increases the refractive index of the electro-optic material in the biased arm. How does increasing the refractive index cause a phase delay, relative to the unbiased arm? As a result of this phase delay, what happens when the signals from the two arms are recombined at the output end? (5/10 pts)

(b) The phase delay is imparted by means of an electro-optic effect: applying an electric voltage V results in a phase delay. V_π is defined as the voltage value for which $\Delta\phi = \pi$. Sketch a plot of the output power as a function of applied voltage V, for values ranging from V = 0 to V = 2 V_π. (5/10 pts)

7. Strip/Channel waveguides (8 points)

We have chosen to work with SiON waveguides, which will be deposited by a PECVD process. In PECVD, the presence of a hydrogen precursor results in the formation of an N-H bond. The N-H bond acts as a damped simple harmonic oscillator, whose natural resonance frequency corresponds to a wavelength of λ = 1510 nm.

(a) What is the expected loss performance of the waveguide at λ = 1510 nm? (4/8 pts)

(b) For our carrier wavelengths, λ_{IR} ~ 850 nm, what is the expected loss performance of the waveguide? Will our carrier frequencies induce a dipole oscillation of the N-H bond? Why or why not? (4/8 pts)

8. Photodetectors (15 points)

(a) Give an expression for the Figure-of-Merit of a p-i-n photodetector in terms of its materials properties. (5/15 pts)

(b) Which factor in this expression represents the influence of defects? How do defects influence photocurrent and Bit Error Rate? (5/15 pts)

(c) In order to make the fastest p-i-n photodetector, what is the appropriate inequality relating the value of the device RC time constant τ_{RC} with the carrier transit time

$\tau_{transit}$? If we want to make a photodetector for 850 nm light with a short transit time, should we make it out of Ge or Si? Why? (5/15 pts)

9. <u>(Bonus) Thin film deposition of SiON</u> (10 points)

In-situ measurements of PECVD deposition rates can be done using the plasma emission as a 450 nm monochromatic light source. A detector can be fitted inside the PECVD chamber that measures the reflection of this 450 nm wavelength light, from the deposited SiON film. Plot the reflected light intensity as a function of time, at angles $\theta = 0°$ and $\theta = 45°$ (θ is the angle with respect to substrate normal incidence). Assume a deposition rate of 300 nm/min for SiON on a thick SiO_2 layer. The index of refraction at 450 nm is n = 1.8 for the SiON composition of interest, and n = 1.45 for SiO_2. Absorption should be neglected.

Explain how your plot of reflected light intensity versus time allows one to determine the deposition rate of SiON thin films. Of the two angles θ that you considered, which angle will give us a higher resolution for measuring deposition rate (film thickness/time)? Why?

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Equations

$$\lambda\nu = c$$
$$c = 3\times10^{8}\,\mathrm{m/s}$$

$$Q = \frac{\omega\tau}{2} = \frac{\lambda}{\Delta\lambda} = \frac{\nu}{\Delta\nu}, Q_e = \frac{\omega\tau_e}{2}$$
$$\omega = 2\pi\nu$$
$$\frac{1}{Q} = \frac{1}{Q_e} + \frac{1}{Q_{loss}}$$

Q_e, τ_e: external Quality Factor, resonant cavity lifetime

$$R = \left|\frac{\left(\frac{n_L}{n_H}\right)^{2m} - n_H^{\,2}}{\left(\frac{n_L}{n_H}\right)^{2m} + n_H^{\,2}}\right|^2$$

n_L: lower refractive index

n_H: higher refractive index

m: # of n_L, n_H pairs in Bragg Mirror

$$\alpha_e = \frac{1}{d}\ln\left(\frac{1}{R}\right)$$

d: defect layer thickness

$$\frac{1}{\tau_e} = \alpha_e v_g$$

v_g: group velocity (approximate as c/n)

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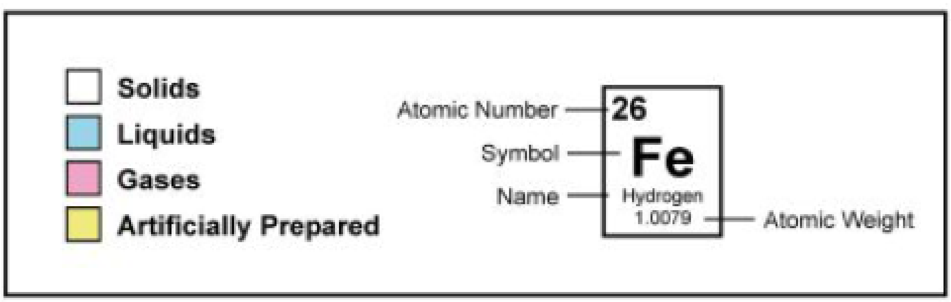
Selected columns from the Periodic Table

	IIIB	IVB	VB	VIB
4 Be Beryllium 9.01218	5 B Boron 10.811	6 C Carbon 12.0107	7 N Nitrogen 14.00674	8 O Oxygen 15.9994
12 Mg Magnesium 24.3050	13 Al Aluminum 26.98154	14 Si Silicon 28.0855	15 P Phosphorus 30.97376	16 S Sulfur 32.066
20 Ca Calcium 40.078	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.92160	34 Se Selenium 78.96
38 Sr Strontium 87.62	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.60
56 Ba Barium 137.327	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98038	84 Po Polonium (209)



Note: “principal quantum number” = ”atomic number”