ELEN E3106/4106 Lecture 13

Optoelectronics Part II: LEDs and Lasers

Outline

- Light-emitting diodes
- Lasers
- Semiconductor lasers

Assignments:

Reading: Streetman and Banerjee §8.2-8.4

Homework 5 due tomorrow Friday Oct. 1~~8~~7th by 5pm

Relationships between Optical Power, QE, Responsivity, and Photocurrent

- Recall, __g_{op}__: optical generation rate of EHPs ($cm^{-3}s^{-1}$)
- J_{op} or J_{ph}: Photocurrent density (A/cm^2) → I_{op} or I_{ph} (A)
- __P_0__: Incident optical power or power density (__W__ or W/cm^2)
- __R__: Responsivity, photocurrent generated per incident optical power (A/W)

$$R = \frac{J_{op}}{P_0} \quad \frac{(A/cm^2)}{(W/cm^2)}$$

- η_Q: External quantum efficiency (__%__) # of EHPs generated per photon

What is max η_Q if there is no gain mechanism (gain = 1)? 100% or 1

How many ~~photons~~ carriers per unit area per second? J_{op}/q

How many ~~carriers~~ photons per unit area per second do we collect? $P_{op}/(h\nu)$

Thus, we can write our QE: # carriers/# photons collected

$$\eta_Q = (J_{op}/q)/(P_{op}/h\nu)$$

Sources: Textbook

Vegard's Law for Alloys

- Resembles the law of mixtures
- Lattice parameter, band gap are approximately weighted means of the constituents in an alloy:

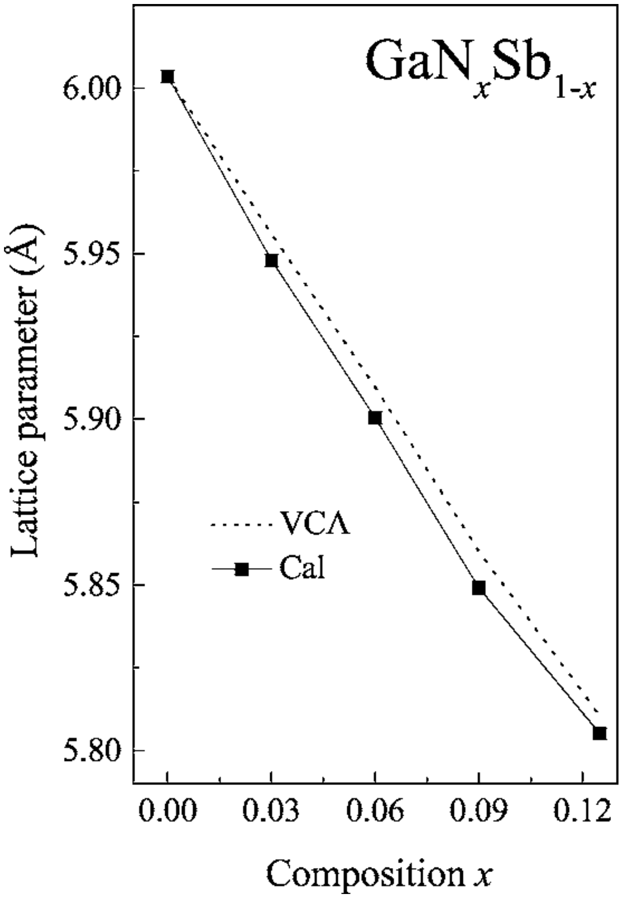
$$a_{A_{(1-x)}B_x} = (1-x)a_A + xa_B$$

- Where x is the molar fraction
- In many cases linear interpolation can be used to find the bandgap:

$$E_{g,E_{A_{(1-x)}}E_{B_x}} = (1-x)E_A + xE_B$$

$x=$ $(1-x)=$

- Ex. $E_{g,Al_{0.8}GaN} =$ 0.8 $E_{g,AlN} +$ 0.2 $E_{g,GaN}$



•Sources: DOI: 10.1063/1.2196049

Example: p-i-n photodiode design

Consider a p-i-n photodiode with "i" region made of $In_xGa_{1-x}As$. Design stoichiometry "x" and thickness of the "i" region (W_i) to enable response at 1.3 µm wavelength, up to 20 GHz signals. Assume fields are sufficiently high to reach $v_{sat} \approx 10^7$ cm/s in the "i" region. Name at least one design constraint on the "p" and "n" regions of this photodiode. You may assume the lattice constant and band gap of $In_xGa_{1-x}As$ vary linearly with composition "x".

intrinsic (Vegard's Law)

a) $\lambda = 1.3\ \mu m \rightarrow E_g = \frac{hc}{\lambda} = \frac{1.24}{\lambda(\mu m)} = \frac{1.24}{1.3} \approx \boxed{0.95\ eV}$

$0.95 = E_g(In_xGa_{1-x}As) = x\,E_g(InAs) + (1-x)\,E_g(GaAs)$

$= x(0.36) + (1-x)(1.43)$

$\rightarrow \boxed{x = 0.45}$ 45% molar fraction InAs

$\boxed{In_{0.45}GaAs}$

For p-i-n diodes, we assume nearly all depletion width is in "i"

$f_{max} \approx \frac{1}{\tau} = \frac{v_{sat}}{W_i} = 20 \times 10^9\ Hz$

Rearranging, $W_i = \frac{v_{sat}}{f} = \frac{10^7\ cm/s}{20 \times 10^9\ Hz} = \boxed{5\ \mu m}$

Sources: E. Pop ECE 340 Slides

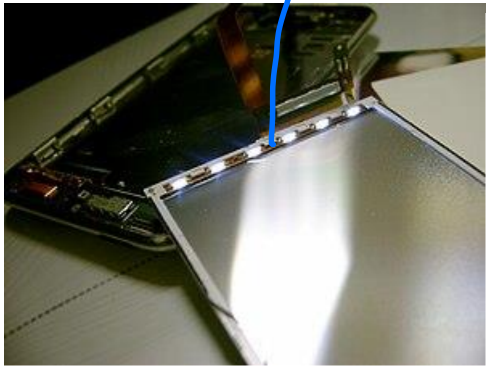
LED Basics Light emitting diode

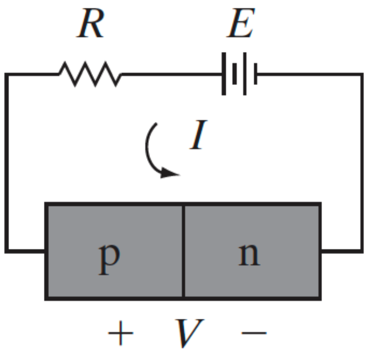
- Applications: displays, lighting, optical communications
- Convert electricity into light!
  - 1st quadrant
- Forward biased p-n junction
- What determines color of an LED?
  - Bandgap!
  - Governed by Planck relation
  - Practically, phosphors are also used to alter LED color

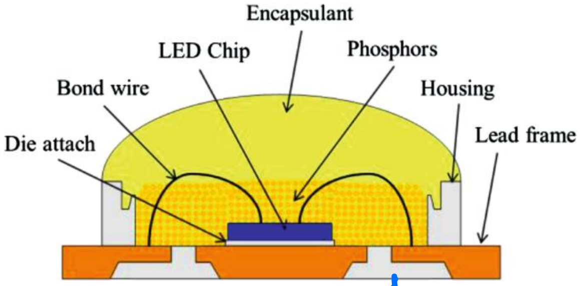
$$E_g\,(\text{eV}) = 1.24/\lambda\ (\mu\text{m})$$

- How does the dome shape of an LED help extract for photons?

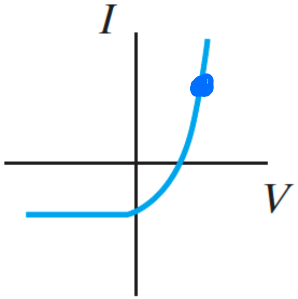
Minimizing total internal reflection





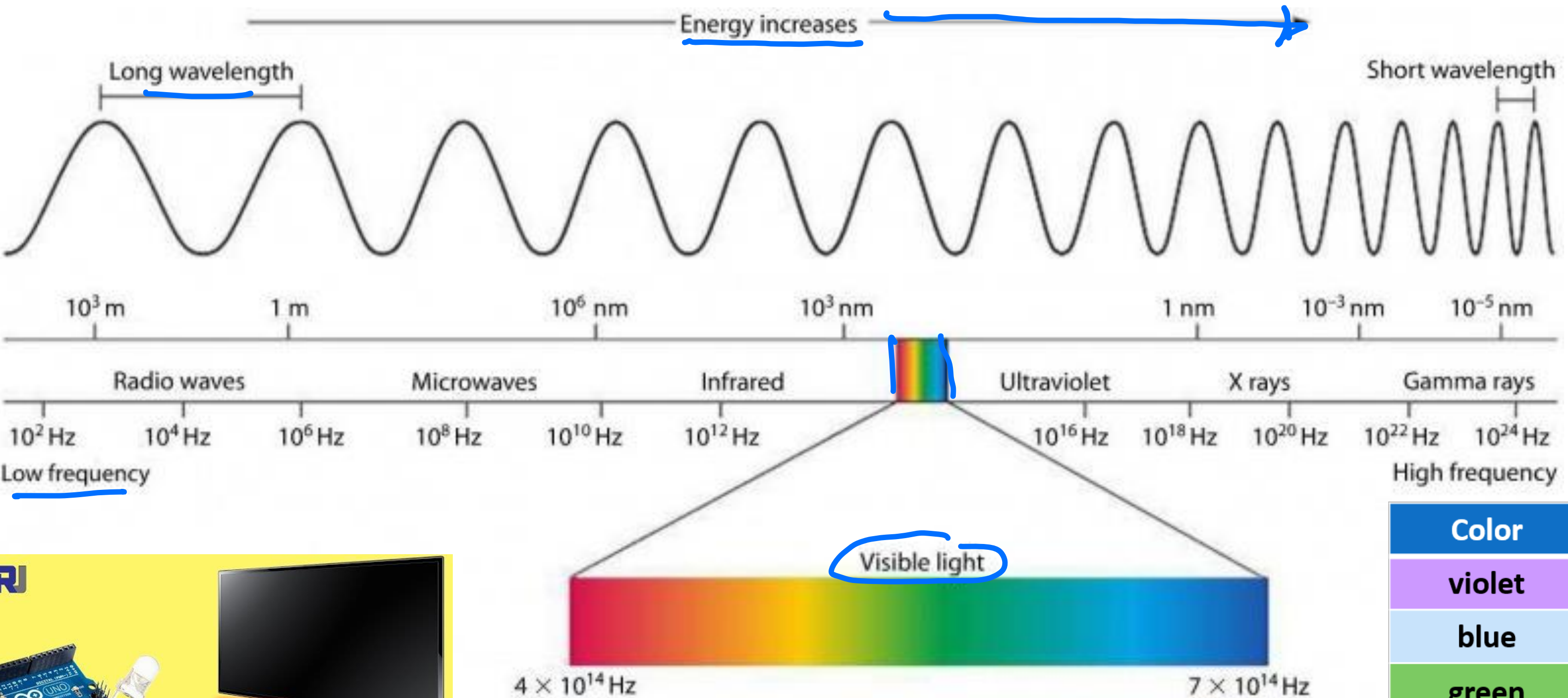


1st quadrant



Sources: Textbook, Wikipedia, https://doi.org/10.1007/978-3-030-81576-9_11

The Electromagnetic Spectrum



Color	Wavelength
violet	380–450 nm
blue	450–495 nm
green	495–570 nm
yellow	570–590 nm
orange	590–620 nm
red	620–750 nm

Sources: Principles of Structural Chemistry, Quora, Youtube

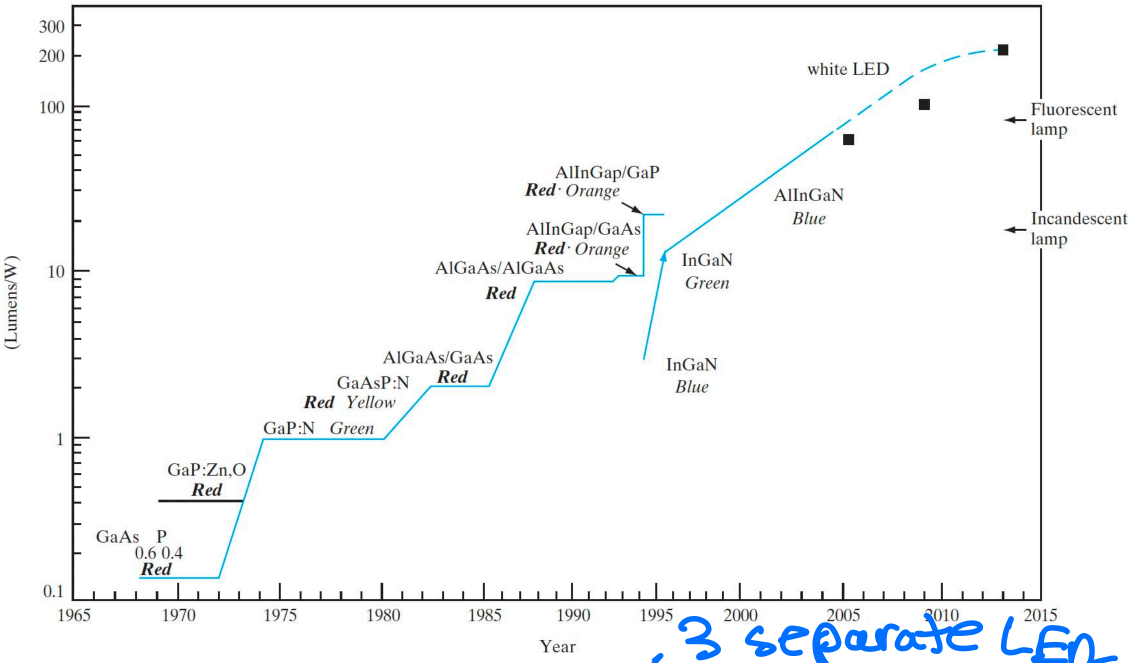
Improvement in luminous intensity of LEDs over time

Luminous intensity: quantity of visible light that is emitted in unit time per solid angle

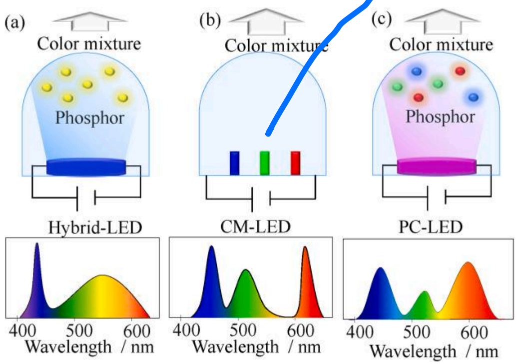
Why so much focus on developing green-blue LEDs?

RGB color mixing can be used to create efficient "white" LEDs

Pros of LED over other lamps: longer lifetimes, much higher efficiencies, less breakable, cool to the touch (safety)



3 separate LEDs



Sources: Textbook, https://doi.org/10.1016/j.jlumin.2021.118167

LED Design

- Besides dome shape, how else do we increase photon extraction?

  Texture / roughness to the surface → many mini lenses

- Challenge: Heat dissipation!
  - Heat decreases efficiency
  - Need proper packaging, like heat sinks

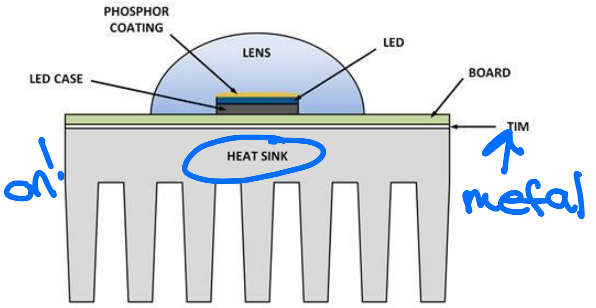
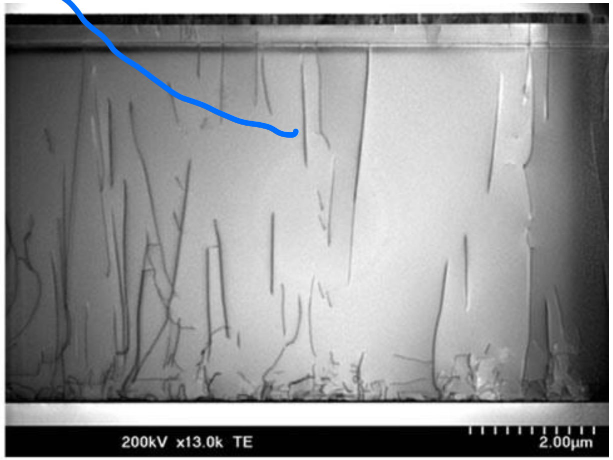


Figure 1 Diagram of the common elements of a LED light

dislocation!



- Important: Low dislocation density crystals
  - Defects can cause traps → non-radiative recombination centers, and decrease LED photon generation

Sources: Voltimum, EAG Laboratories

Semiconductor Laser Basics

- **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation

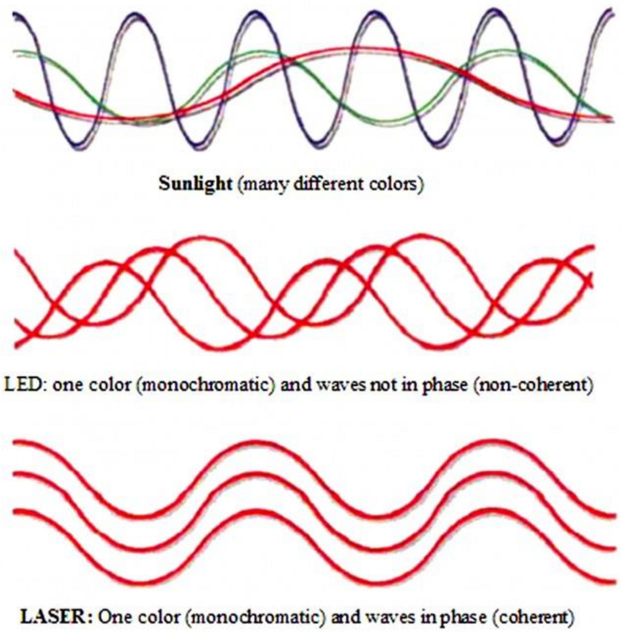
CO_2, ruby rod lasers

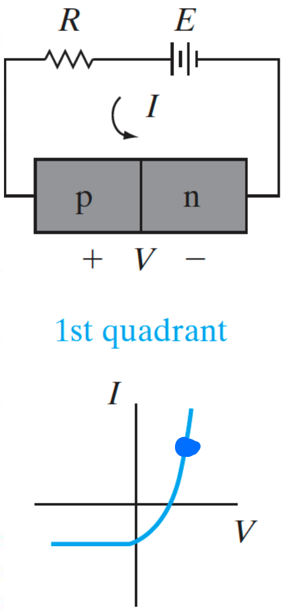
- Laser light is:
  - Highly directional (unlike LED)
  - Coherent (photons are phase)
  - Monochromatic (single λ)

- Pro of semiconductors over other laser types: small size, high efficiency, output easily modulated by junction current, low power)

- So far we have described spontaneous *emission* (excited carriers randomly fall to lower energy states)

- How do we stimulate emission?





(a)

Sources: Textbook, Physics Stack Exchange

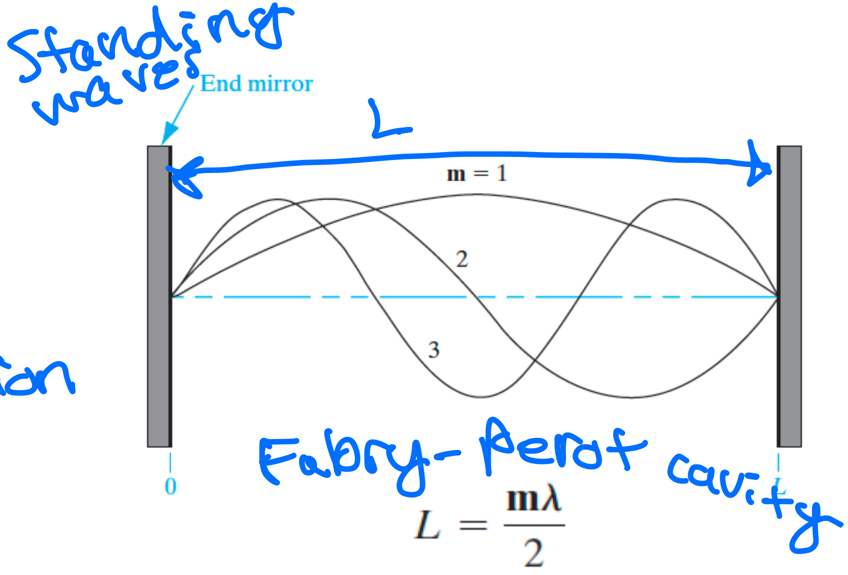
Optical Cavities

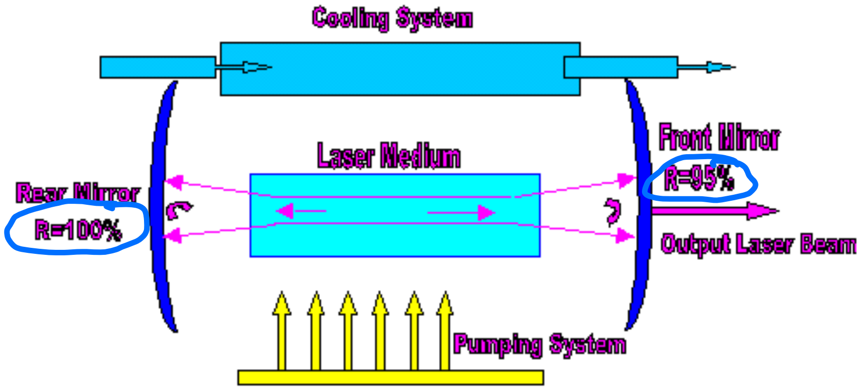
- Conditions for photon density due to stimulated emission to dominate over spontaneous emission and absorption:
  1. **Optical resonant cavity to encourage photon field to build up**
  2. A means of obtaining population inversion

- Stimulated emission at $\lambda = \frac{2L}{m}$ where m is an integer

- Parallel mirrors can provide multiple internal reflections

- Fraction of light that "leaks out" of the resonant system is the output of the laser





Sources: Textbook, http://www.aml.engineering.columbia.edu/ntm/level1/ch02/html/l1c02s04.html

Population Inversion

- We can degenerately *dope* semiconductors
  - N_a, N_d very very high!
  - Fermi levels can move into the bands
  - Recall: Fermi level is the energy with 50% probability of being occupied!

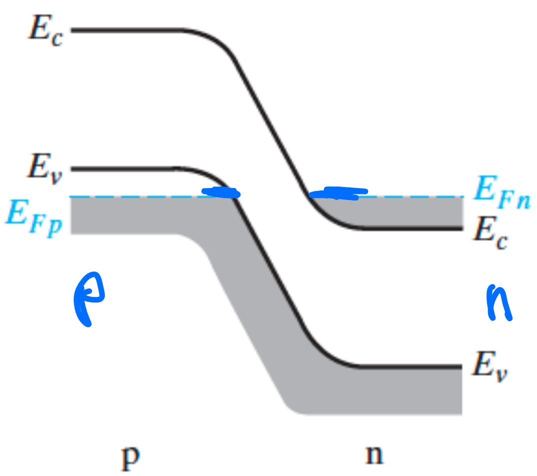
- At strong forward bias, barrier is lowered -> many e- and h+ are injected across junction

- Instead of depleting junction region, we have a large population of carriers around the junction

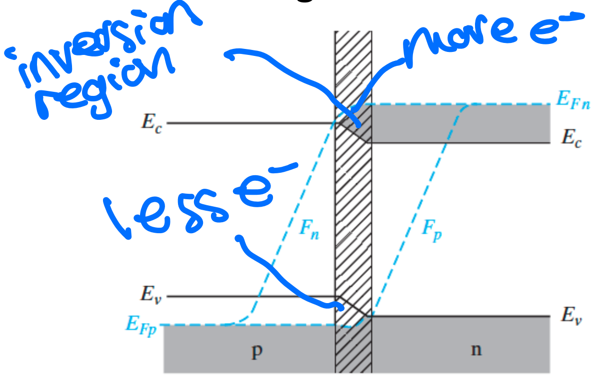
- AKA there are more e- in the conduction band than in the valence band!

- If concentrations around junction are large enough, the condition of population inversion is met -> called inversion region

Equilibrium



Strong forward bias



Sources: Textbook

Population Inversion Continued

- Our carrier concentrations can still be found as a function of quasi-Fermi levels

$$n = N_c e^{-(E_c - F_n)/kT} = n_i e^{(F_n - E_i)/kT}$$

$$p = N_v e^{-(F_p - E_v)/kT} = n_i e^{(E_i - F_p)/kT}$$

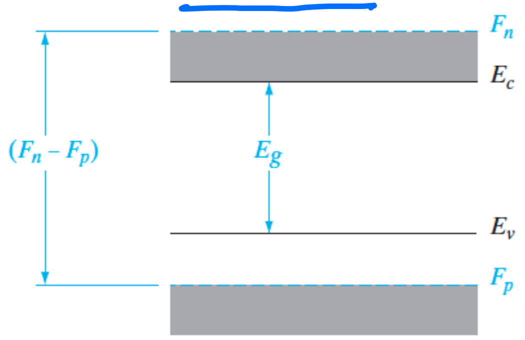
- Where the minimum carrier concentration that allows for population inverse occurs when $F_n - F_p = E_g$
- Normally a range of transition energies, from

$$E_g < h\nu < (F_n - F_p)$$

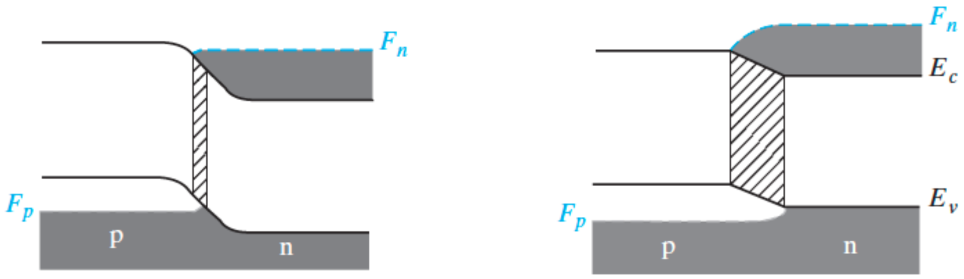
- What does this mean for the emission spectra?

Condition for population inversion:

$$(F_n - F_p) > E_g$$



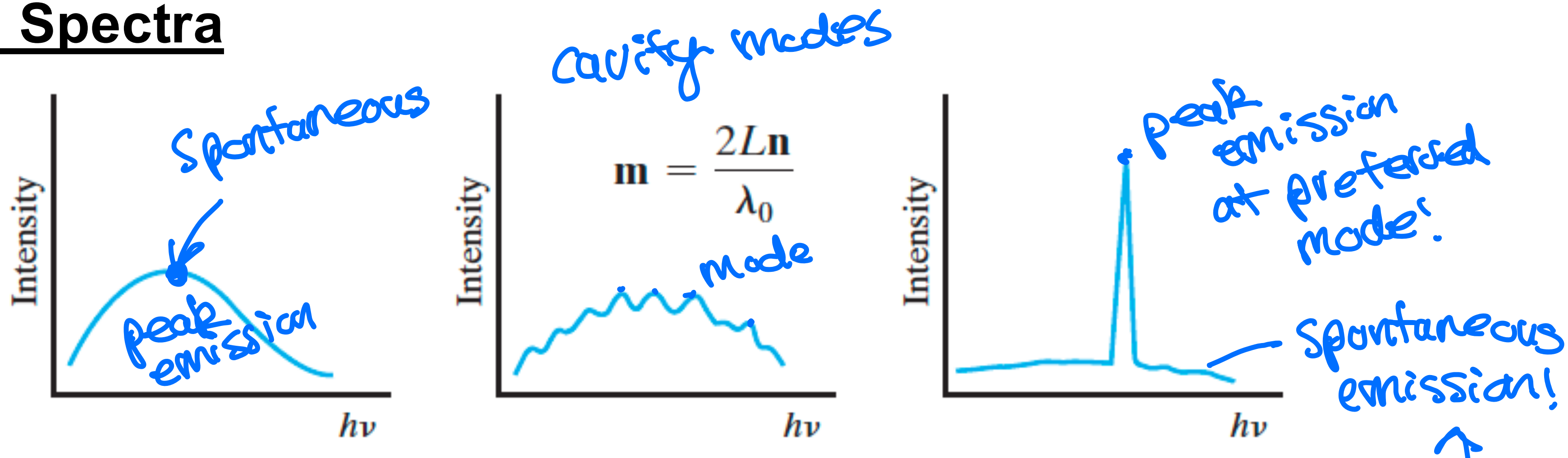
Variation of inversion-region width with forward bias V(a) < V(b):



(a) (b)

Sources: Textbook

Emission Spectra



(a)

Low forward bias: spontaneous emission between

$$E_g < h\nu < (F_n - F_p)$$

(b)

Increased forward bias: Significant pop. inversion. Stimulated emission occurs at cavity modes.

(c)

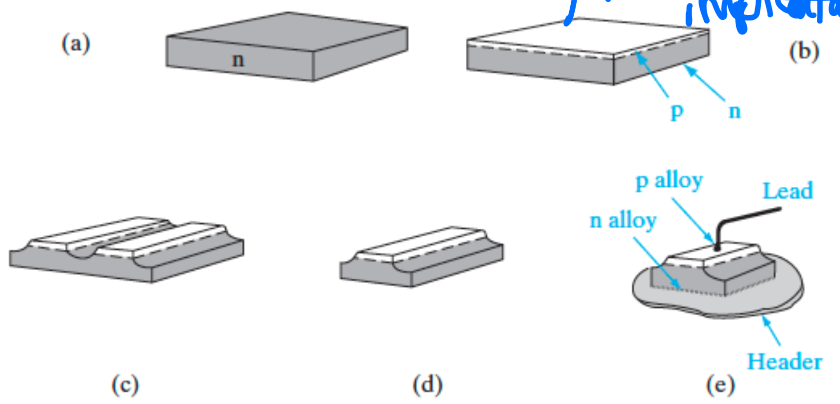
Higher forward bias: Preferred mode will dominate and is the main laser output. Nearly monochromatic.

- Question: what's the weak background "noise" in c?

Sources: Textbook

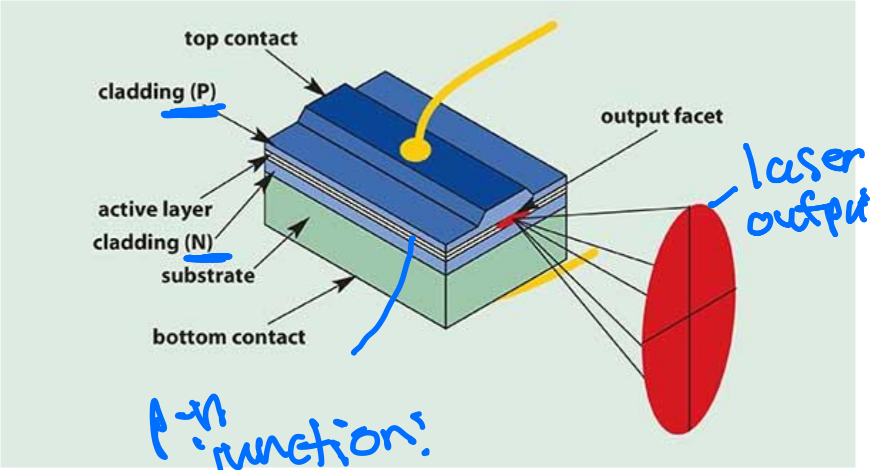
Semiconductor Laser Design and Fab

1. Form a highly doped (degenerate) p-n junction, usually from a direct semi like GaAs
2. Construct cavity with proper geometry (depends on junction)
3. Make contact
4. Design to allow for efficient heat transfer



- Important: front and back faces must be flat and parallel (resonant cavity)

- Heterojunctions, vertical cavity surface-emitting lasers (VCSELs) also popular

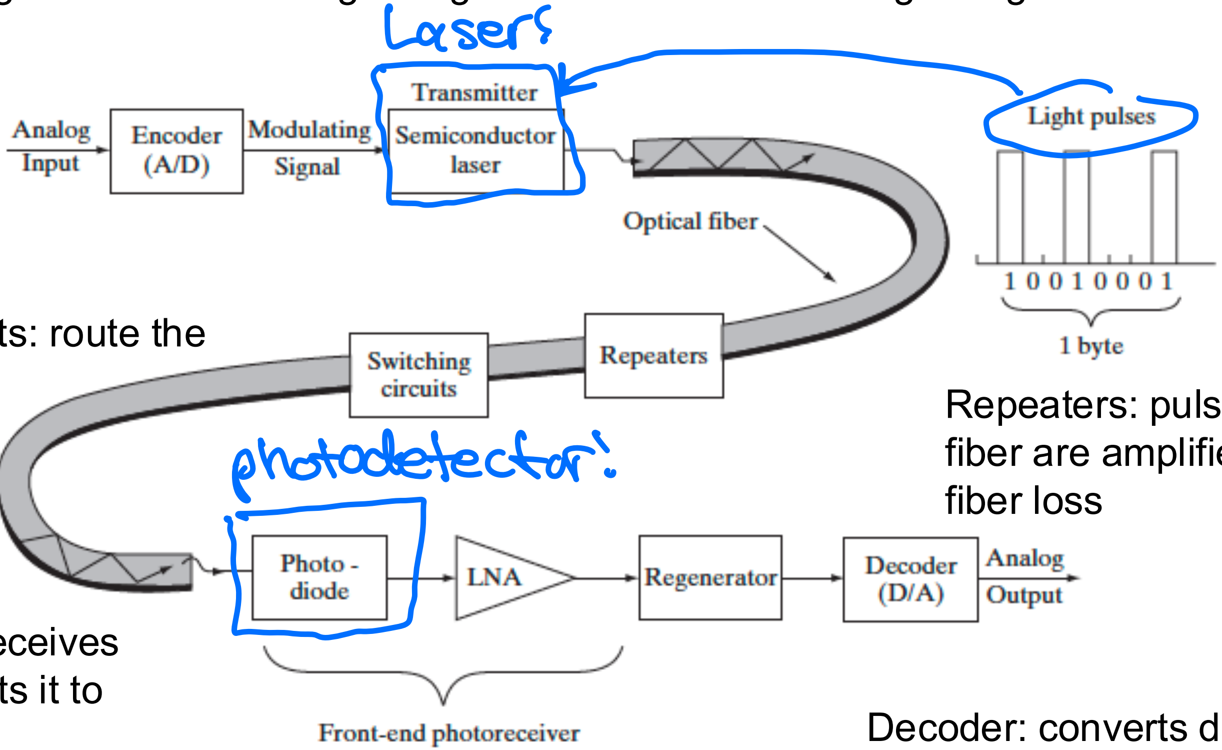


Sources: Textbook, Photonics.com

Optoelectronics in Fiber Optics Communication

Encoder: Analog signal converted to digital signal

Transmitter: Digital signal modulates laser light as pulses



Switching circuits: route the signal

Repeaters: pulses sent down optical fiber are amplified to compensate for fiber loss

Photodiode + LNA: receives optical signal, converts it to electrical output

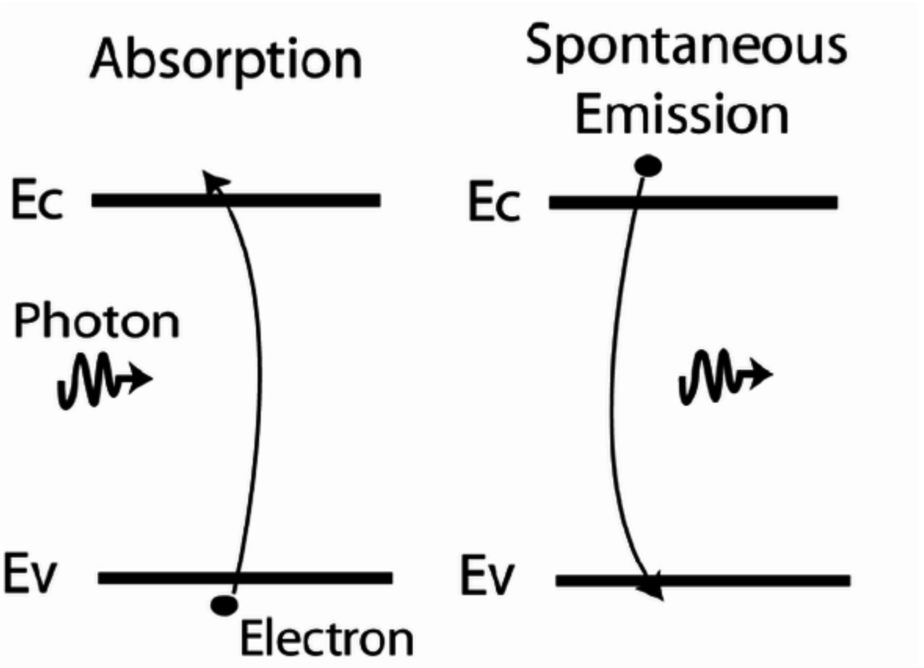
Decoder: converts digital signal back to analog

Regenerator: Corrects propagation distortion

Sources: Textbook

Summary: Interaction of Light with Semiconductors

- Absorption: High probability that light (photons) with energy $E > E_g$ are absorbed by the atoms. e- are excited from E_v to E_c
- Spontaneous emission: If ~~atoms~~ carriers are in an excited state, spontaneous decay events cause e- to "fall" from E_c to E_v, and emit a photon with E $= E_g$



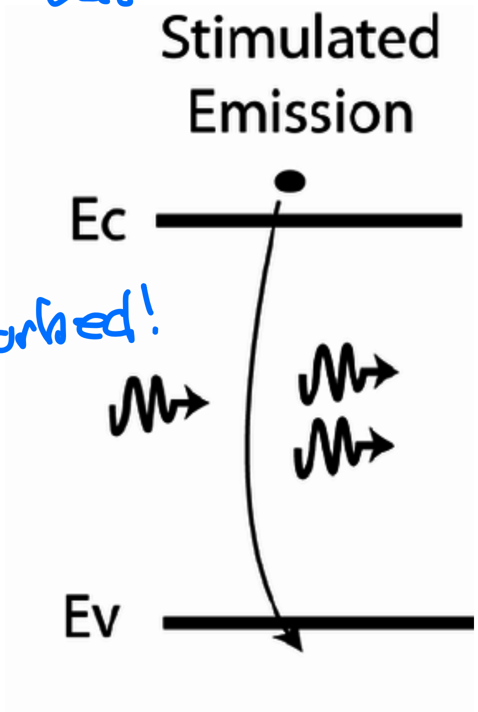
Photodiodes, LEDs!

Sources: Textbook, Photonics.com

Summary: Interaction of Light with Semiconductors

Lasers

- e- already in the excited state can be agitated by the passage of a photon that has E ≥Eg. The excited e- relaxes to the ground state, e- "falls" from Ec to Ev, and produces a **second photon** with energy E=Eg
  - What happens to the original photon? It is not absorbed!
  - Results: 2 photons of the same frequency are emitted (amplification)
  - Population inversion is necessary condition, because it ensures that there are more e- in an excited state than in the ground state, allows for a chain reaction of photon emission



Sources: Textbook, Photonics.com