COLUMBIA | ENGINEERING
The Fu Foundation School of Engineering and Applied Science

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. 18th by 5pm

Relationships between Optical Power, QE, Responsivity, and Photocurrent

- Recall, ______: optical generation rate of EHPs ($cm^{-3}s^{-1}$)
- $J_{op}\ or\ J_{ph}$: Photocurrent density (A/cm^2)
- _____: Incident optical power or power density (___ or W/cm^2)
- _____: Responsivity, photocurrent generated per incident optical power (A/W)

$$R = \frac{J_{op}}{P_0}$$

- η_Q: External quantum efficiency (___)

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

How many photons per unit area per second?

How many carriers per unit area per second do we collect?

Thus, we can write our QE: $\eta_Q = (J_{op}/q)/(P_{op}/hv)$

Sources: Textbook

Vegard's Law for Alloys

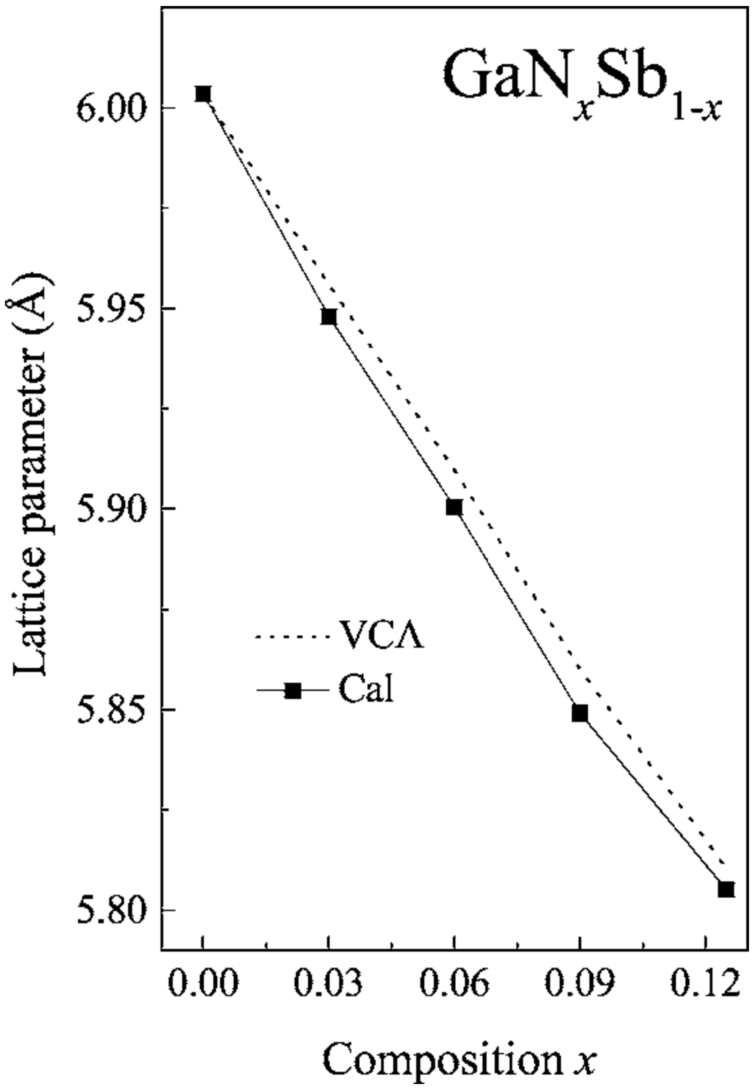
- Resembles the law of mixtures
- Lattice parameter, band gap are approximately weighted means of the constituents in an alloy:

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

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

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

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



•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".

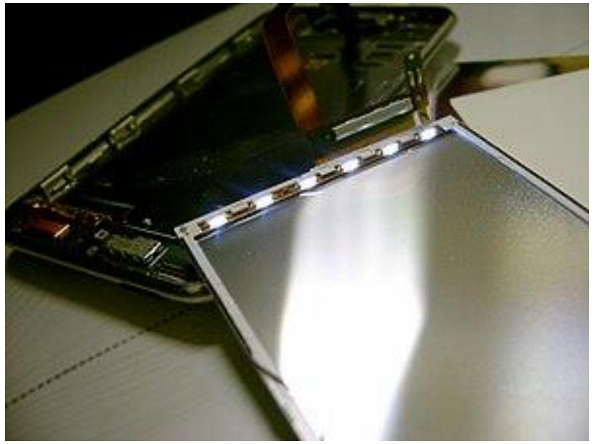
Sources: E. Pop ECE 340 Slides

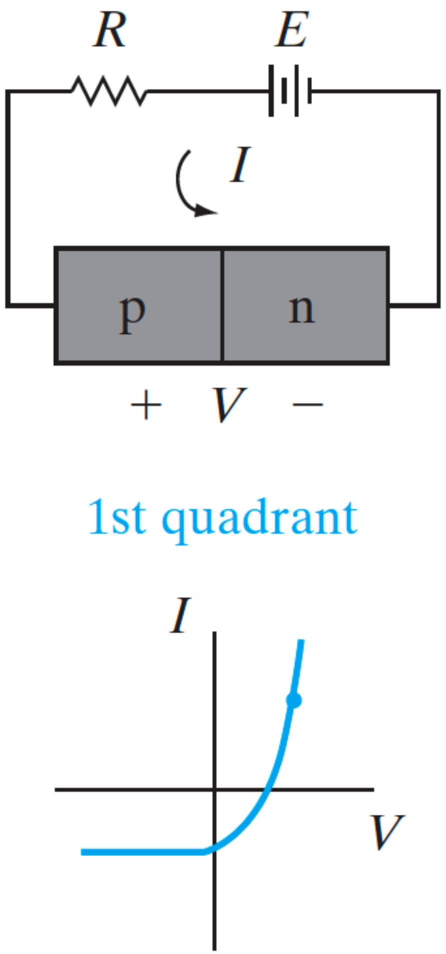
LED Basics

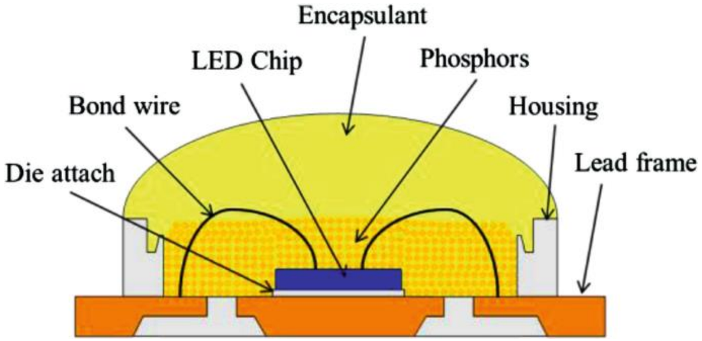
- Applications: displays, lighting, optical communications
- Convert electricity into ________
  - ____ quadrant
- _______ p-n junction
- What determines color of an LED?
  - __________!
  - Governed by Planck relation
  - Practically, phosphors are also used to alter LED color

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

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

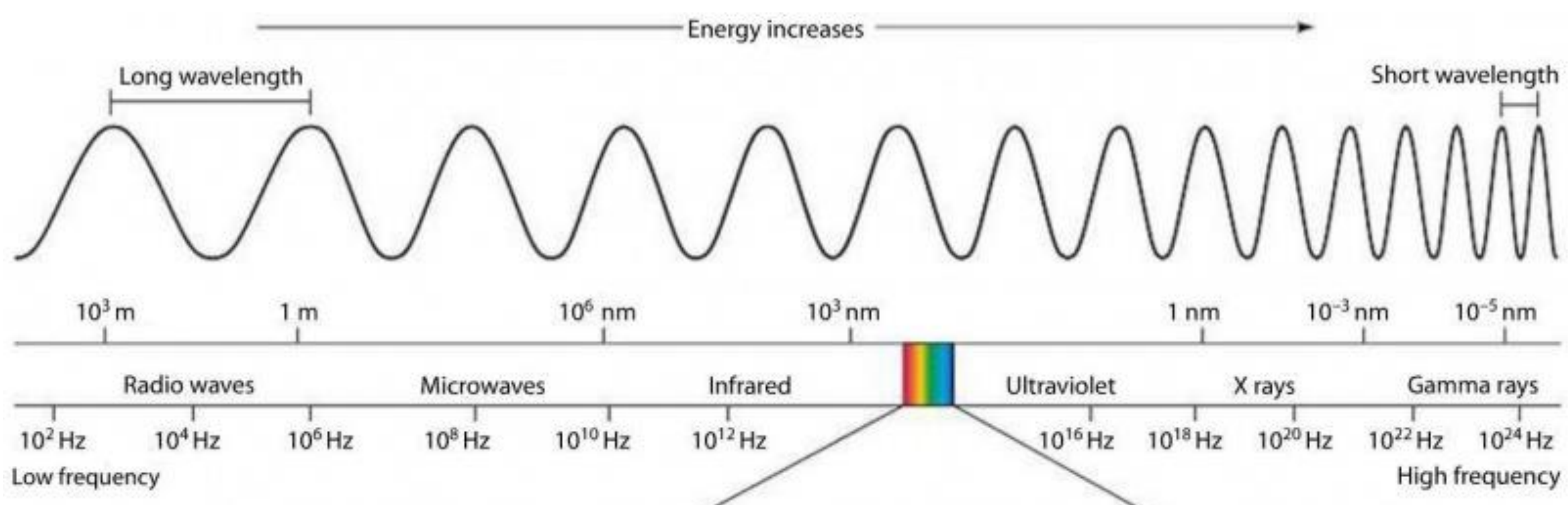


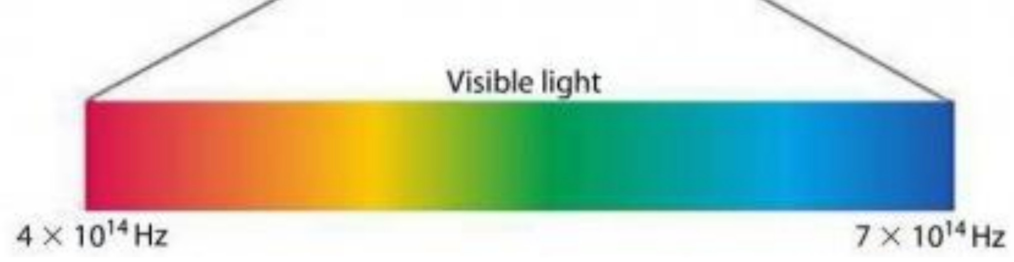




Sources: Textbook, Wikipedia, https://doi.org/10.1007/978-3-030-81576-9_11

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

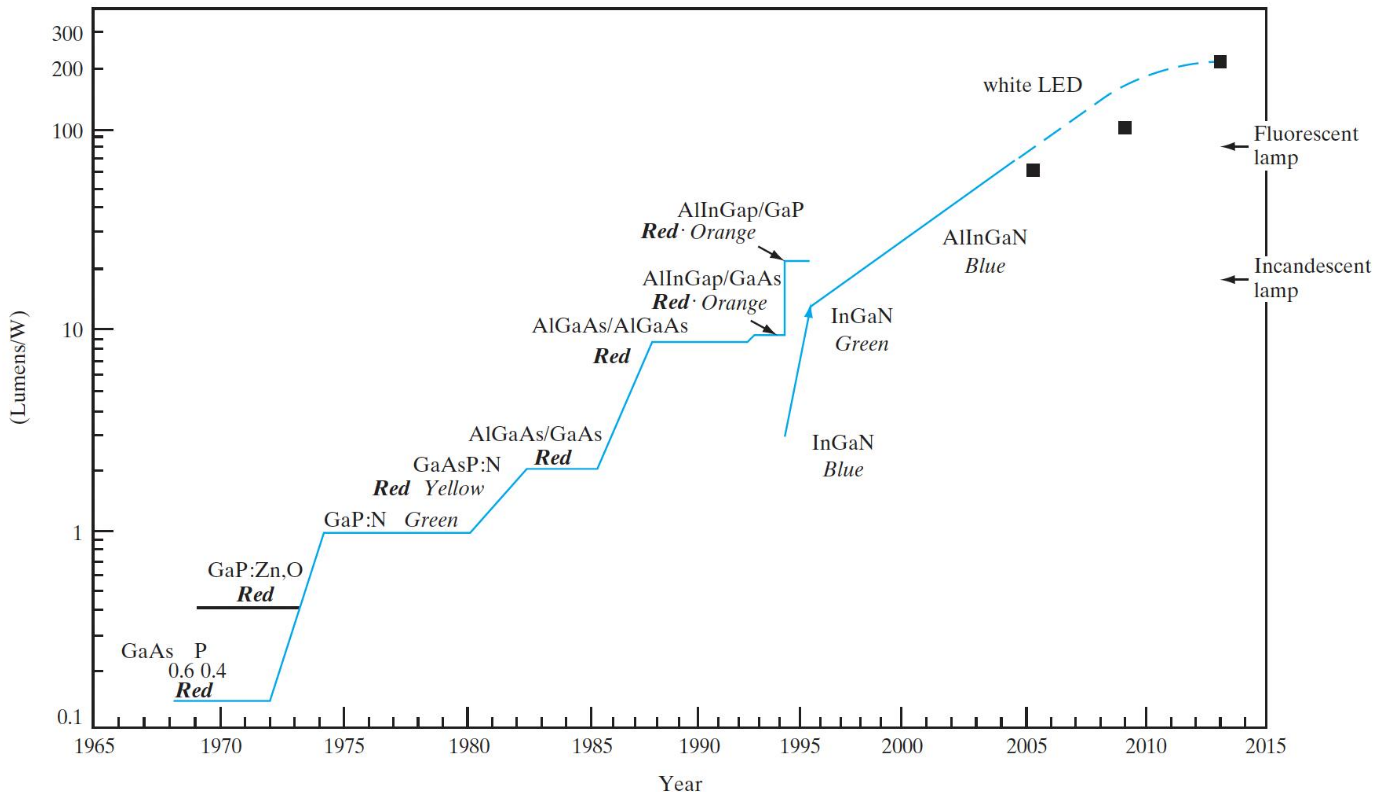
Sources: Principles of Structural Chemistry, Quora, Youtube

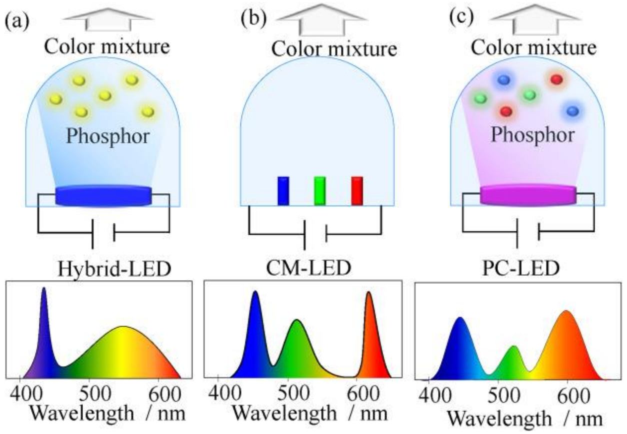
Improvement in luminous intensity of LEDs over time

Luminous intensity: quantity of visible light that is emitted in __________ per ______________

Why so much focus on developing green-blue LEDs?

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





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

LED Design

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

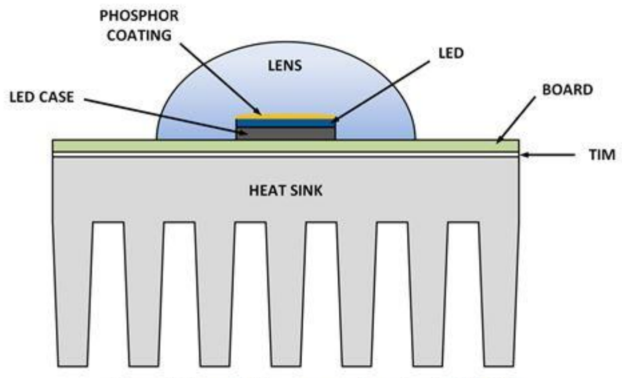
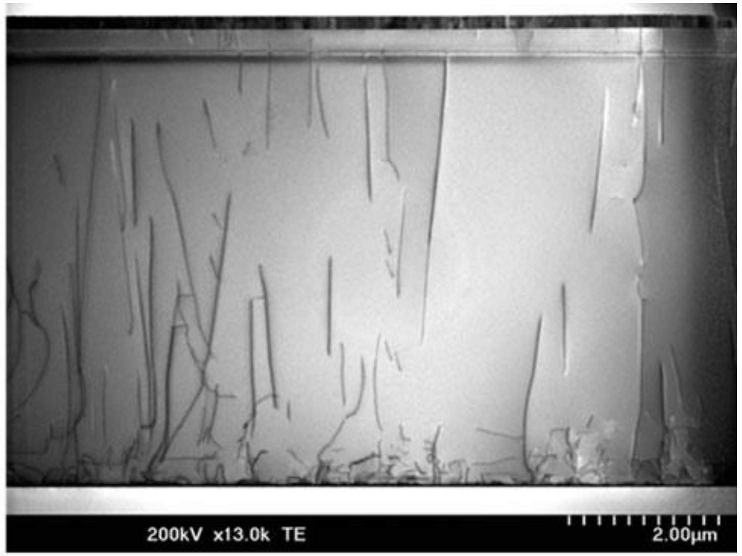


Figure 1 Diagram of the common elements of a LED light

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



- Important: Low dislocation density crystals
  - Defects can cause ________________, and decrease LED photon generation

Sources: Voltimum, EAG Laboratories

Semiconductor Laser Basics

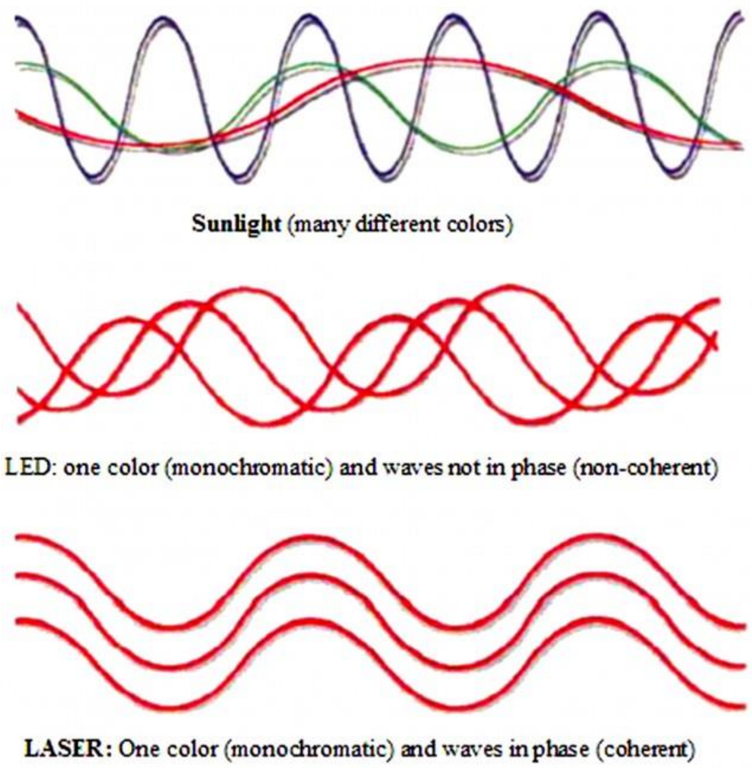
- **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation

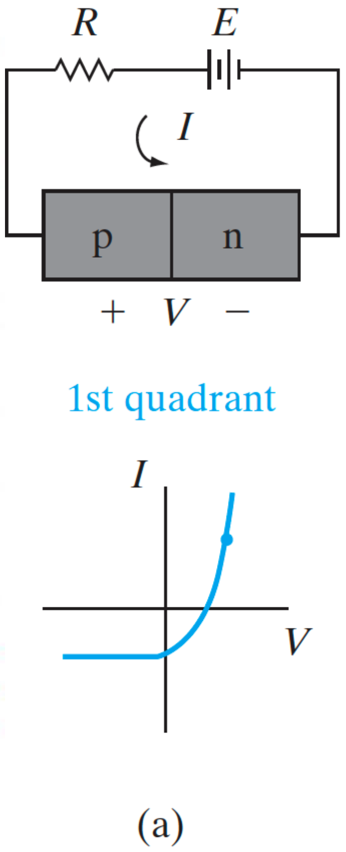
- Laser light is:
  - Highly ________l (unlike LED)
  - Coherent (photons are _________)
  - Monochromatic

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

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

- How do we ____________ emission?

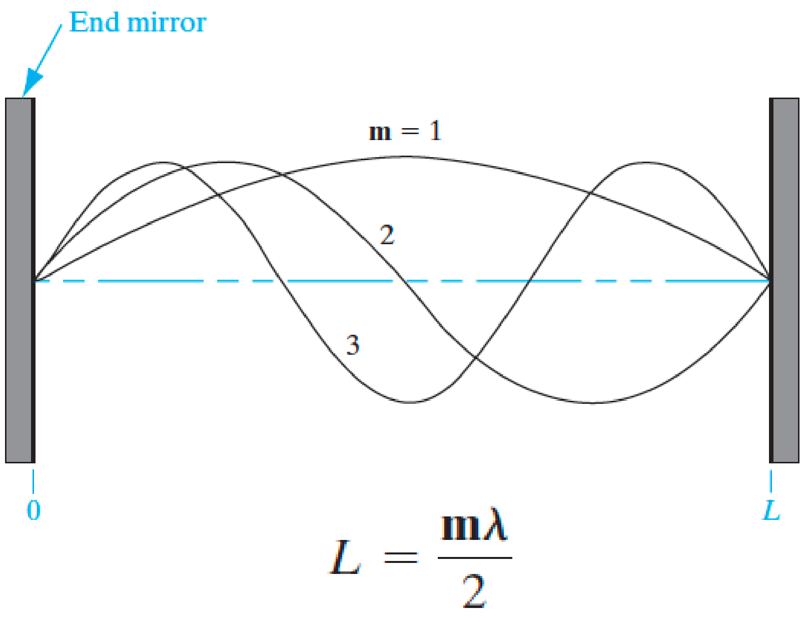


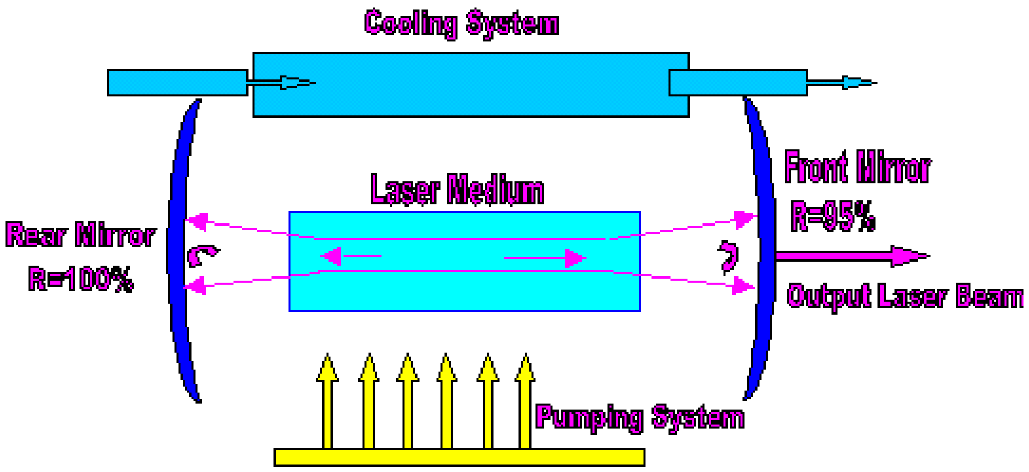


Sources: Textbook, Physics Stack Exchange

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 ________________
- Stimulated emission at $\lambda = \frac{2L}{m}$ where m is an _________
- Parallel mirrors can provide multiple internal ______________
- Fraction of light that "leaks out" of the resonant system is the output of the laser



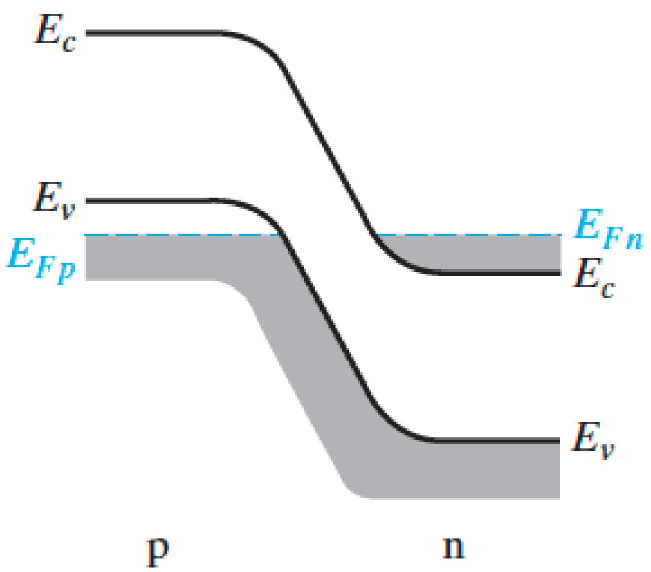


Sources: Textbook, http://www.aml.engineering.columbia.edu/ntm/level1/ch02/html/l1c02s04.html

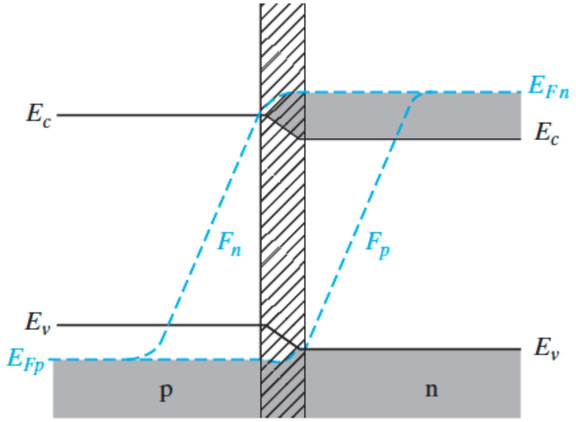
Population Inversion

- We can _____________ *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 ________________ junction
- Instead of depleting junction region, we have a _________ population of carriers around the junction
- AKA there are more e- in the ___________ band than in the valence band!
- If concentrations around junction are large enough, the condition of population inversion is met -> called _______________

Equilibrium



Strong forward bias



Sources: Textbook

Population Inversion Continued

- Our carrier concentrations can still be found as a function of ____________:

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

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

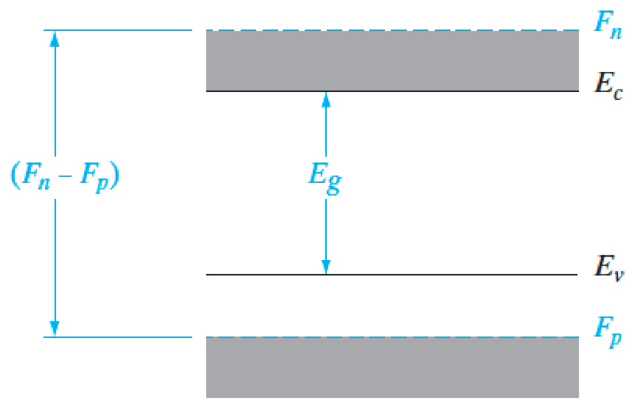
- Where the __________ carrier concentration that allows for population inverse occurs when $F_n - F_p = E_g$
- Normally a range of transition energies, from

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

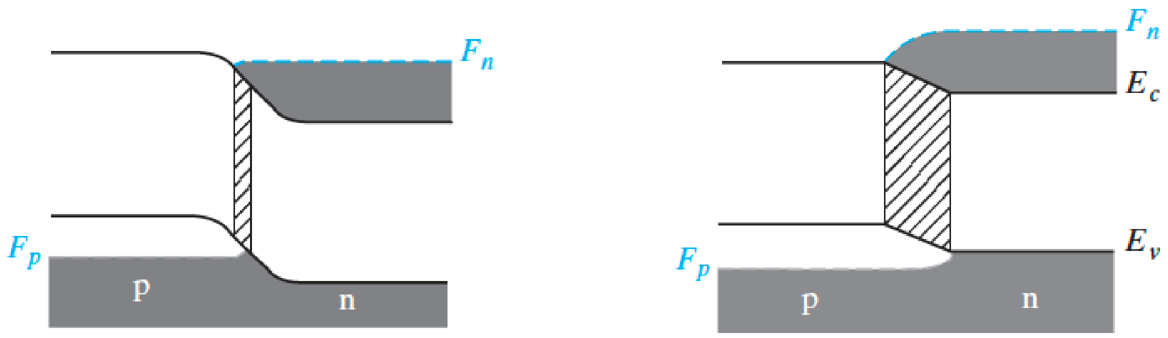
- What does this mean for the emission spectra?

Condition for population inversion:

$$(F_n - F_p) > E_g$$



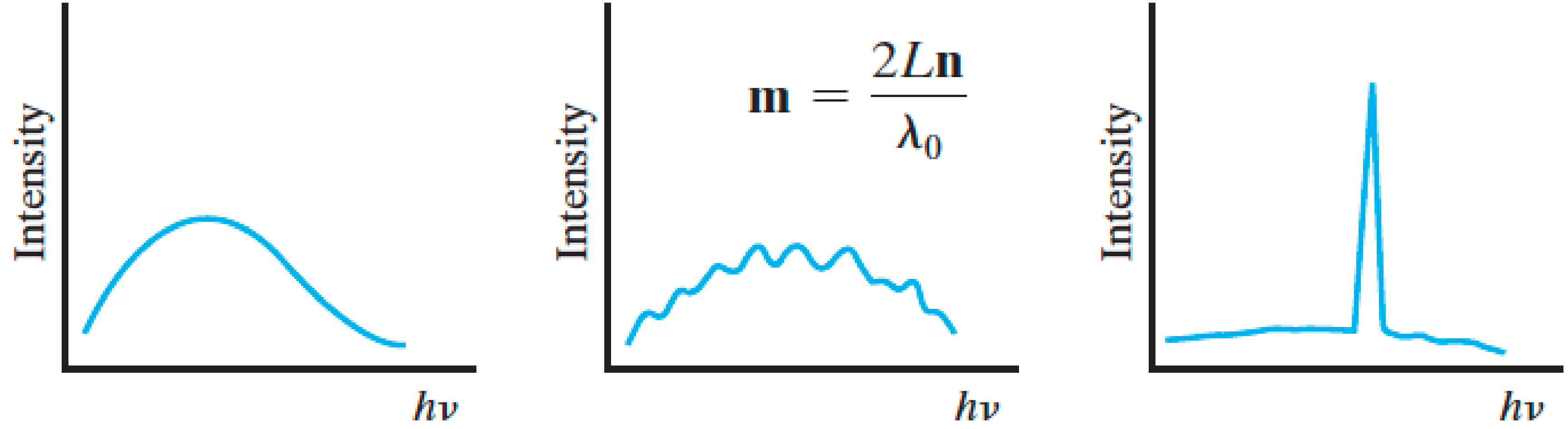
Variation of inversion-region width with forward bias V(a) < V(b):



(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.**

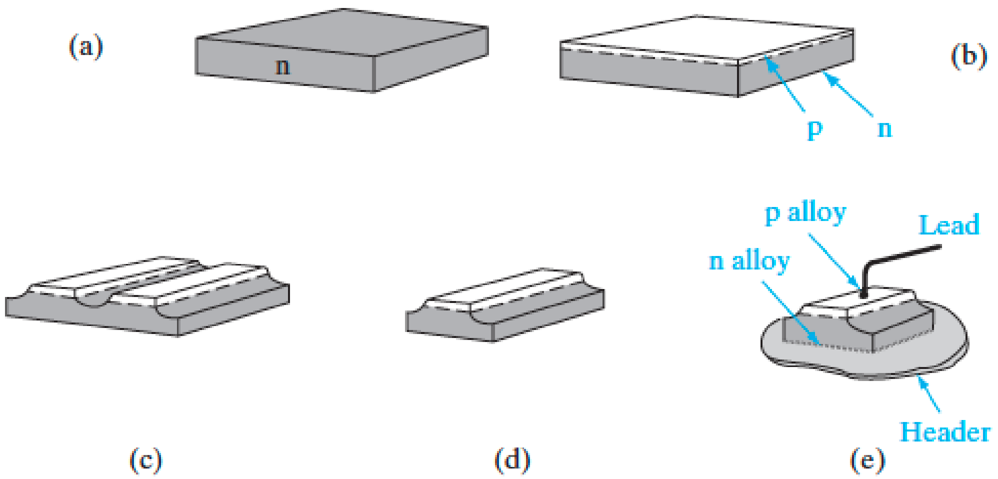
(c) **Higher forward bias: Preferred mode will dominate and is the main laser output. Nearly monochromatic.**

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

Sources: Textbook

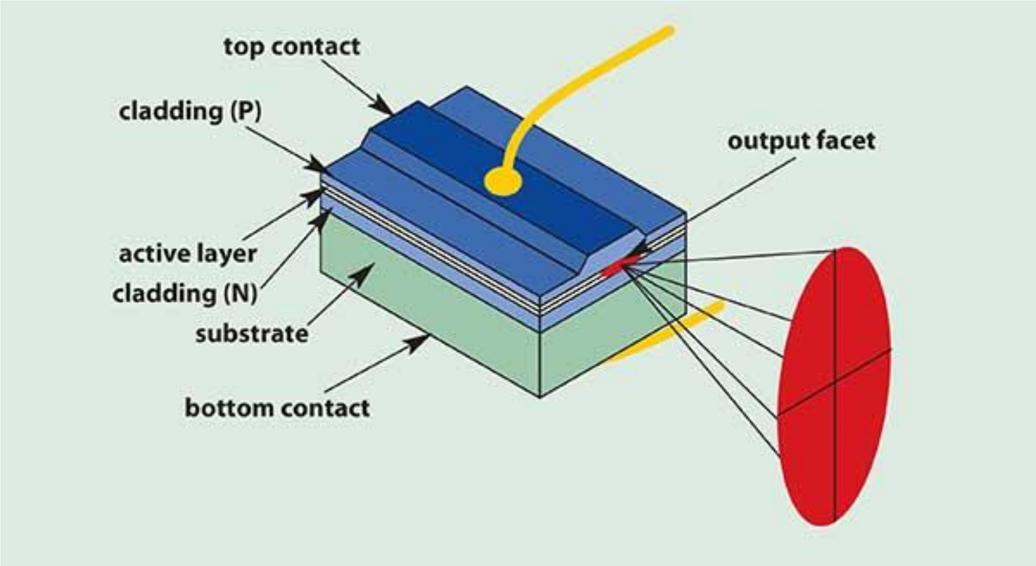
Semiconductor Laser Design and Fab

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



- Important: front and back faces must be _______ and ________ (resonant cavity)

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



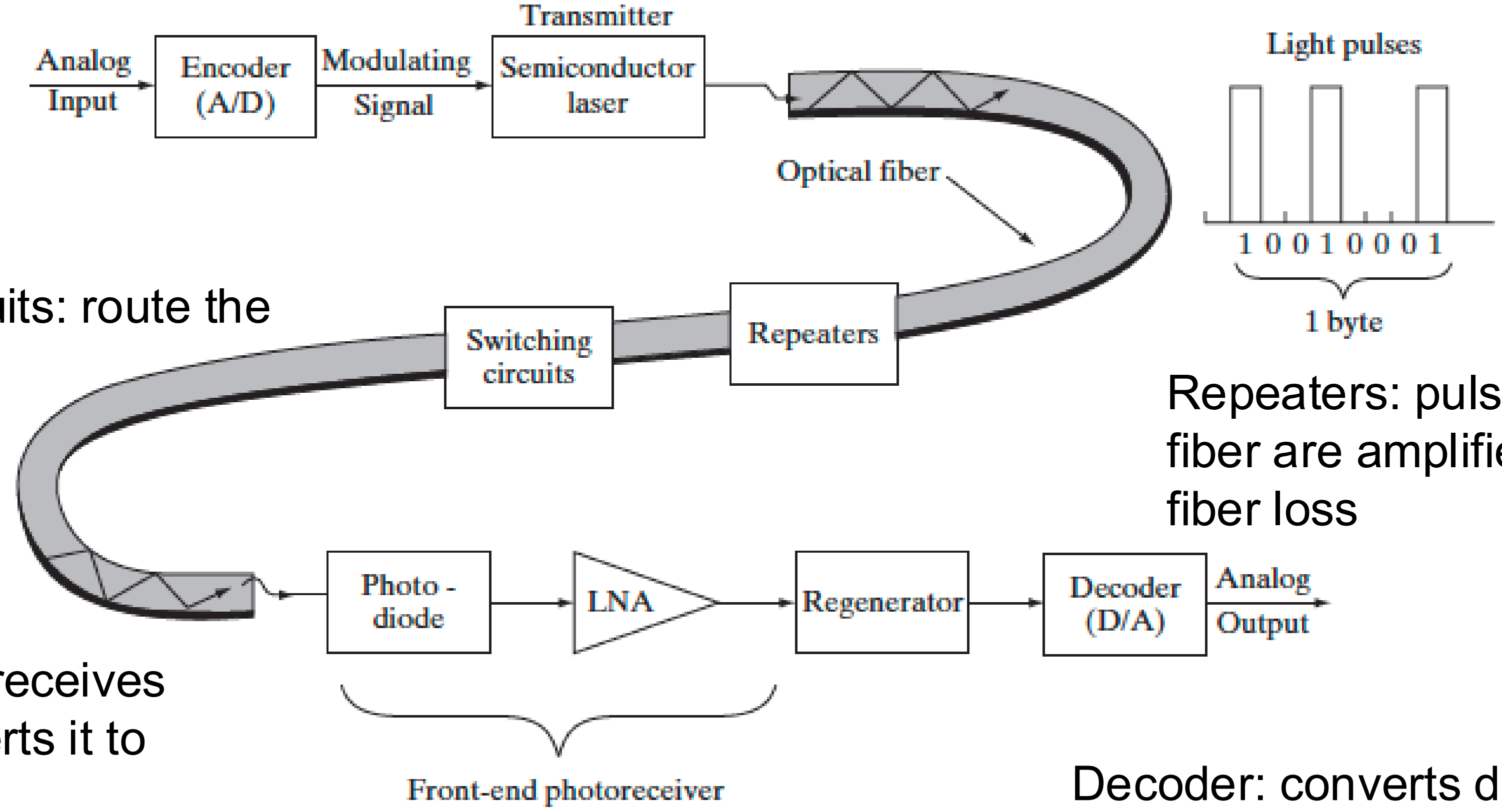
Sources: Textbook, Photonics.com

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

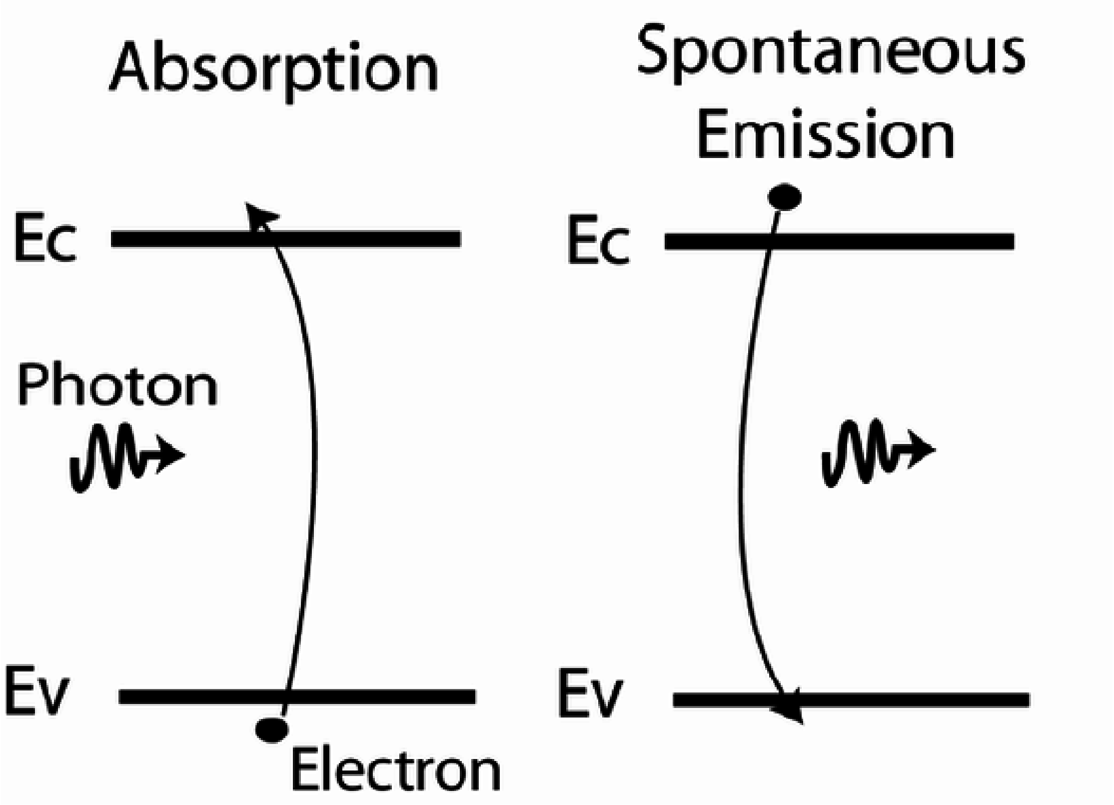
Decoder: converts digital signal back to analog

Regenerator: Corrects propagation distortion

Sources: Textbook

Summary: Interaction of Light with Semiconductors

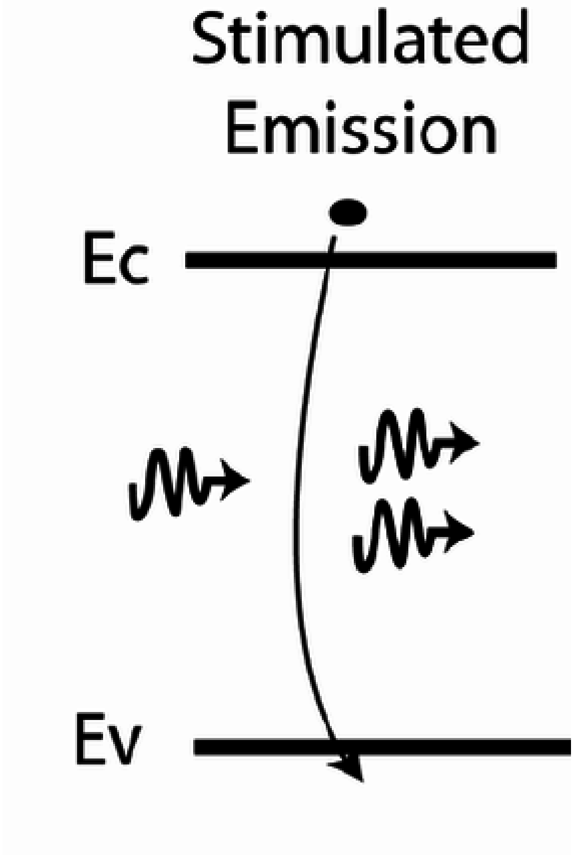
- Absorption: High probability that light (photons) with energy ______ are absorbed by the atoms. e- are excited from ___ to ____
- Spontaneous emission: If atoms are in an excited state, spontaneous decay events cause e- to “fall” from ____ to ____, and emit a photon with E _____



Sources: Textbook, Photonics.com

Summary: Interaction of Light with Semiconductors

- e- already in the excited state can be agitated by the passage of a photon that has E ______. The excited e- relaxes to the ground state, e- ”falls” from ____ to _____, and produces a **second photon** with energy ____
  - What happens to the original photon
  - Results: _____ photons of the same frequency are emitted (_______________)
  - Population inversion is necessary condition, because it ensures that there are ______ e- in an excited state than in the ground state, allows for a ______________ of photon emission



Sources: Textbook, Photonics.com