Lecture 11d

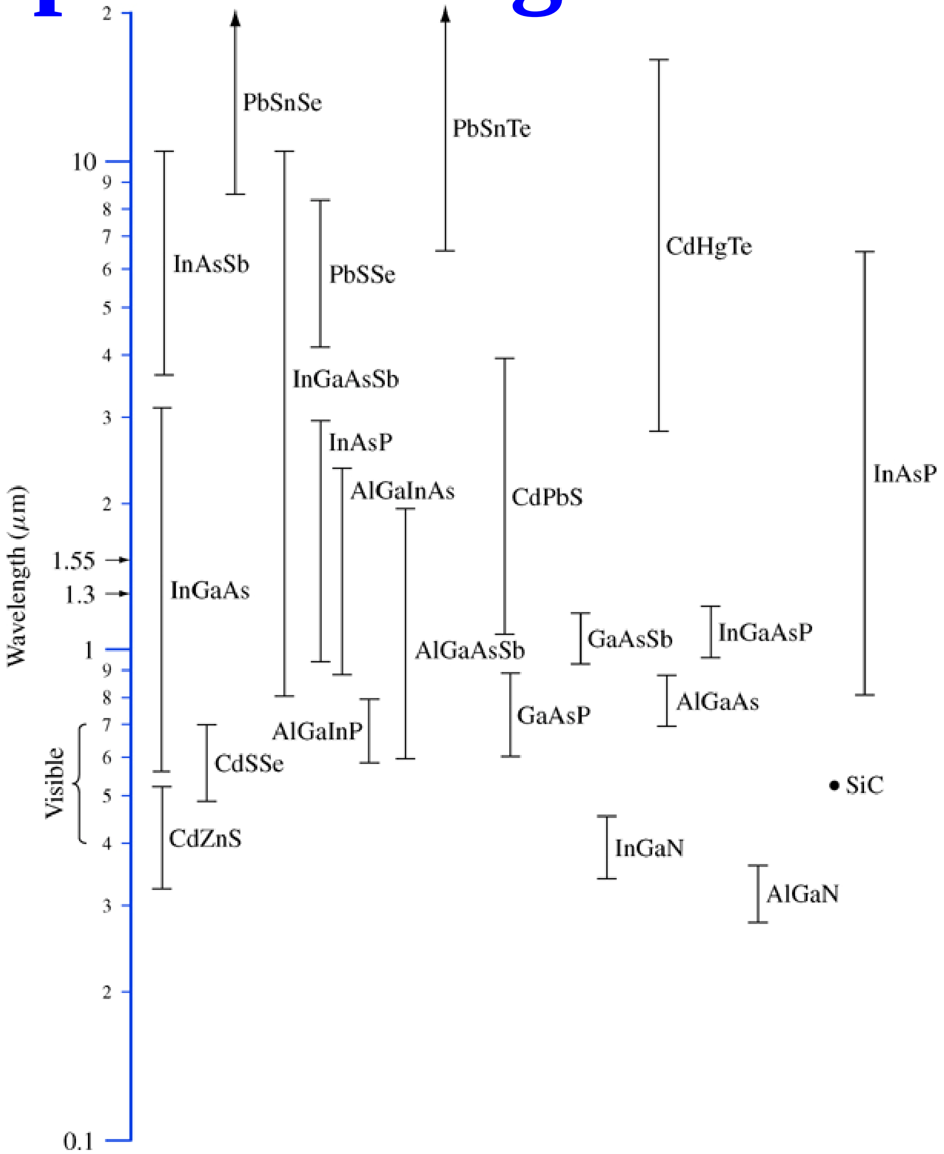
Light Emitting Diodes and Laser Diodes

Reading:

(Cont'd) Notes and Anderson^2 Chapter 11.3-11.4.5

Some images from Anderson and Anderson text

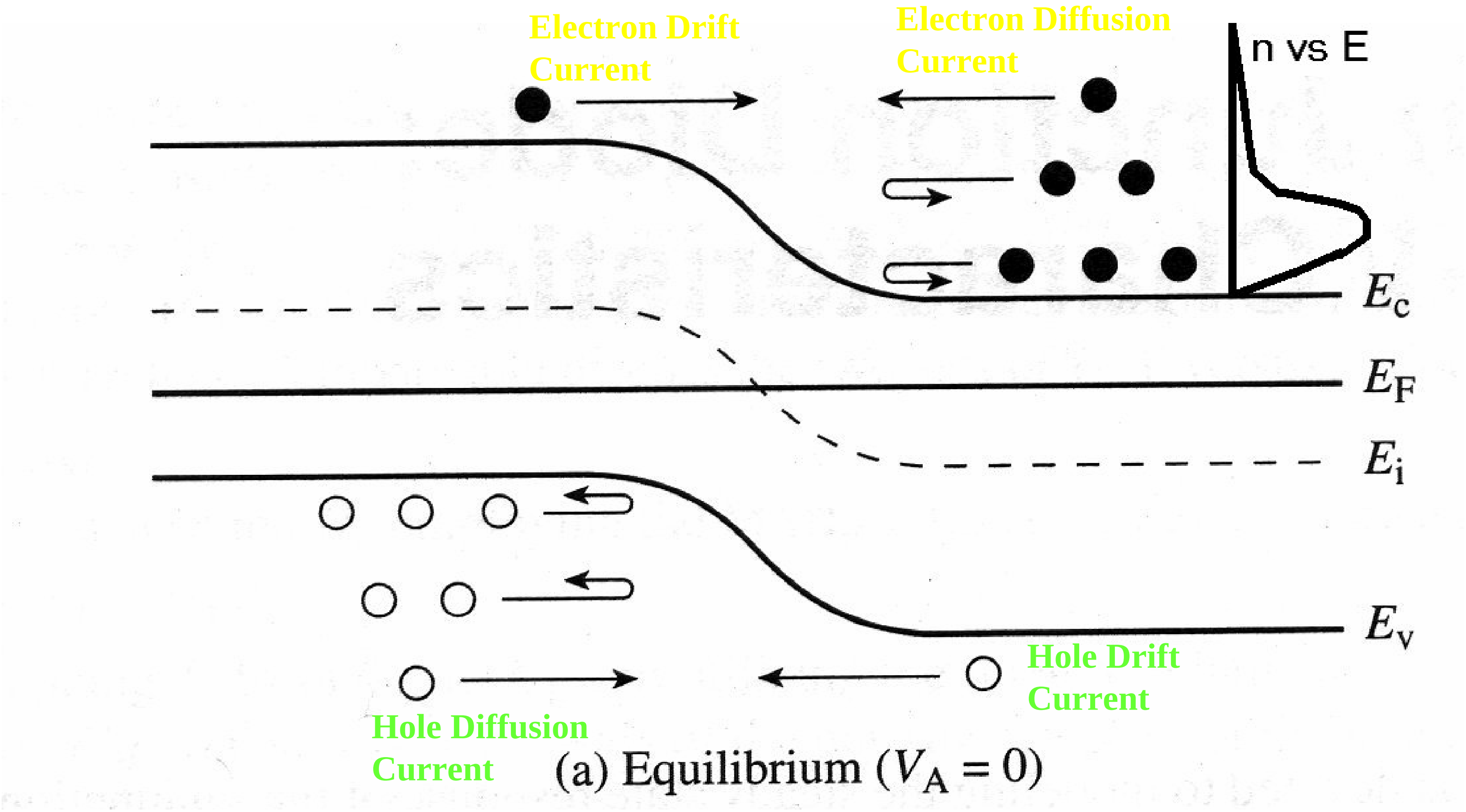
Optical Design Choices



Some semiconductor materials and their wavelength ranges. Based on data from References 3 to 5.

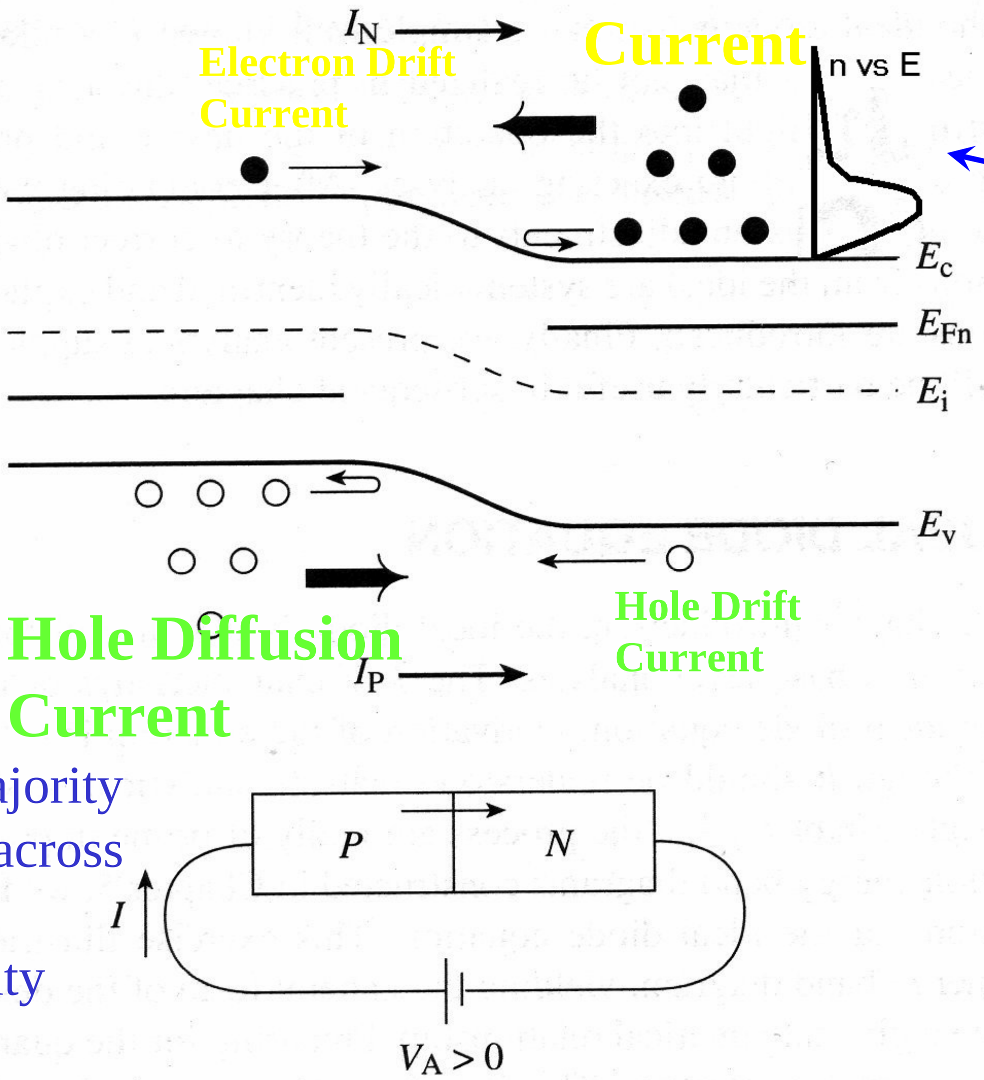
P-n Junction I-V Characteristics

In Equilibrium, the Total current balances due to the sum of the individual components



(a) Equilibrium ($V_A = 0$)

Review: p-n Junction I-V Characteristics



(b) Forward bias ($V_A > 0$)

Electron Diffusion Current

Electron Drift Current

Hole Diffusion Current

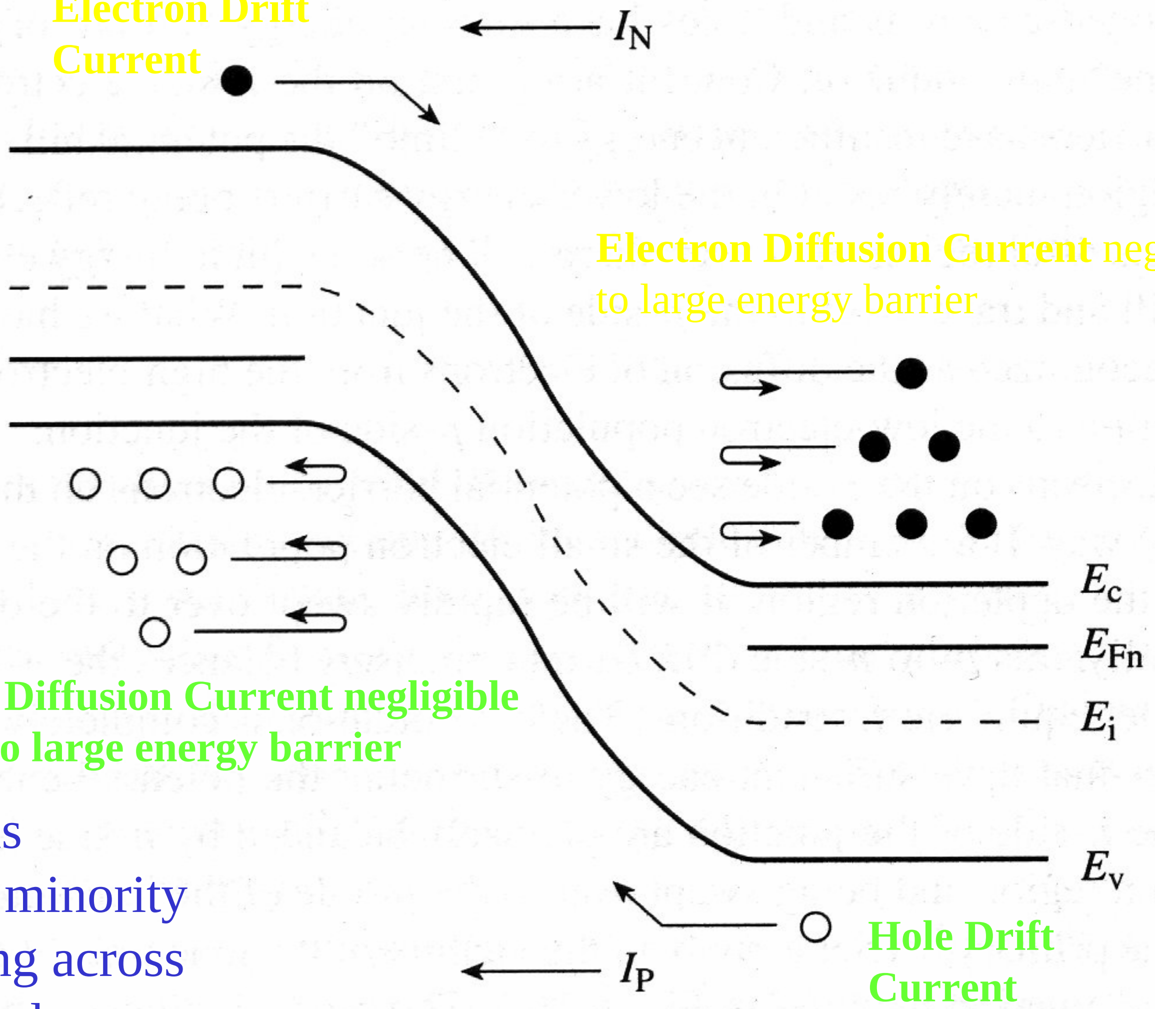
Hole Drift Current

Current flow is proportional to $e^{(Va/Vref)}$ due to the exponential decay of carriers into the majority carrier bands

Current flow is dominated by majority carriers flowing across the junction and becoming minority carriers

QuickTime Movie

Review: p-n Junction I-V Characteristics



(c) Reverse bias ($V_A < 0$)

Current flow is constant due to thermally generated carriers swept out by E-fields in the depletion region

Electron Drift Current

Electron Diffusion Current negligible due to large energy barrier

Hole Diffusion Current negligible due to large energy barrier

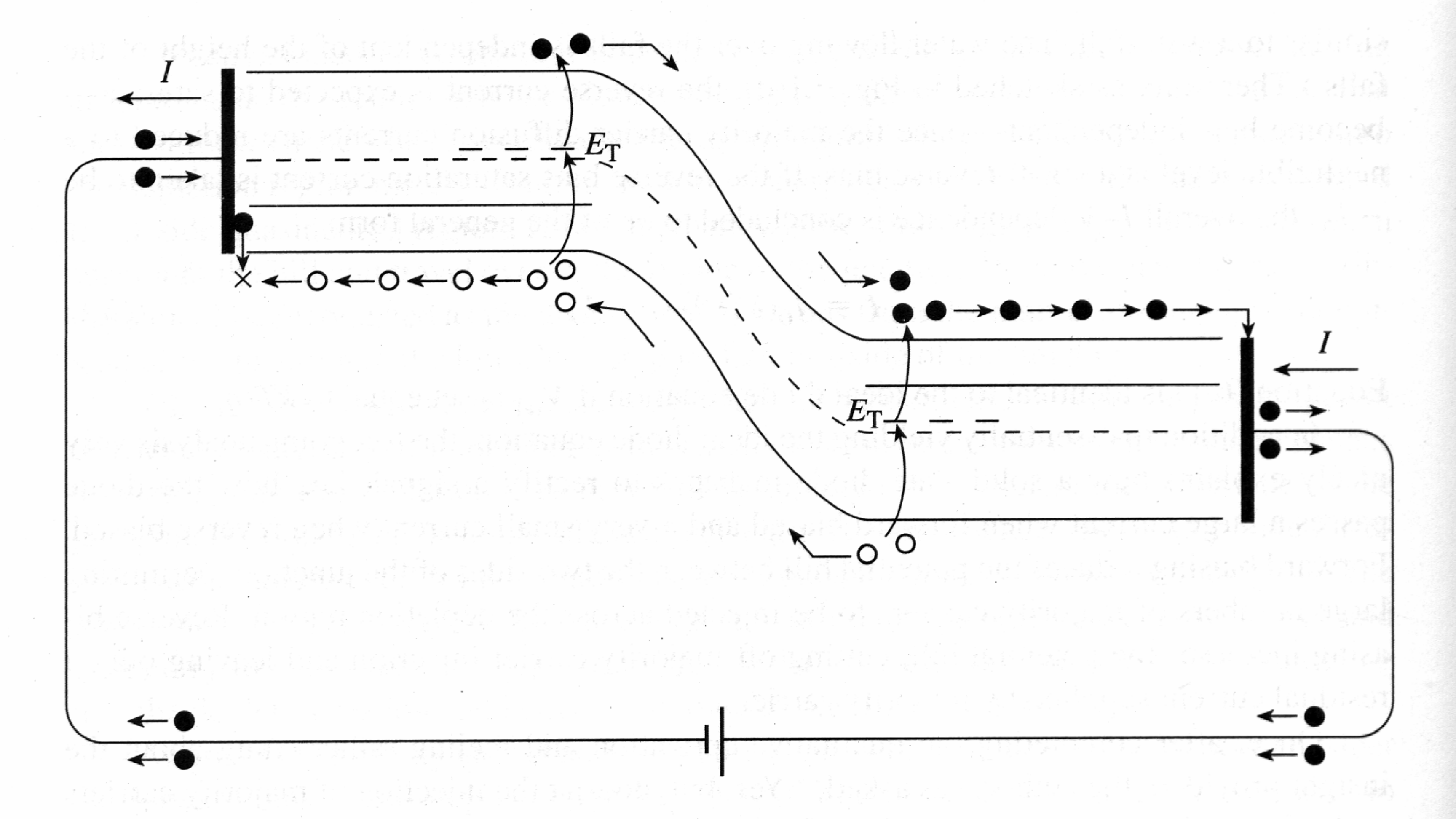
Hole Drift Current

Current flow is dominated by minority carriers flowing across the junction and becoming majority carriers

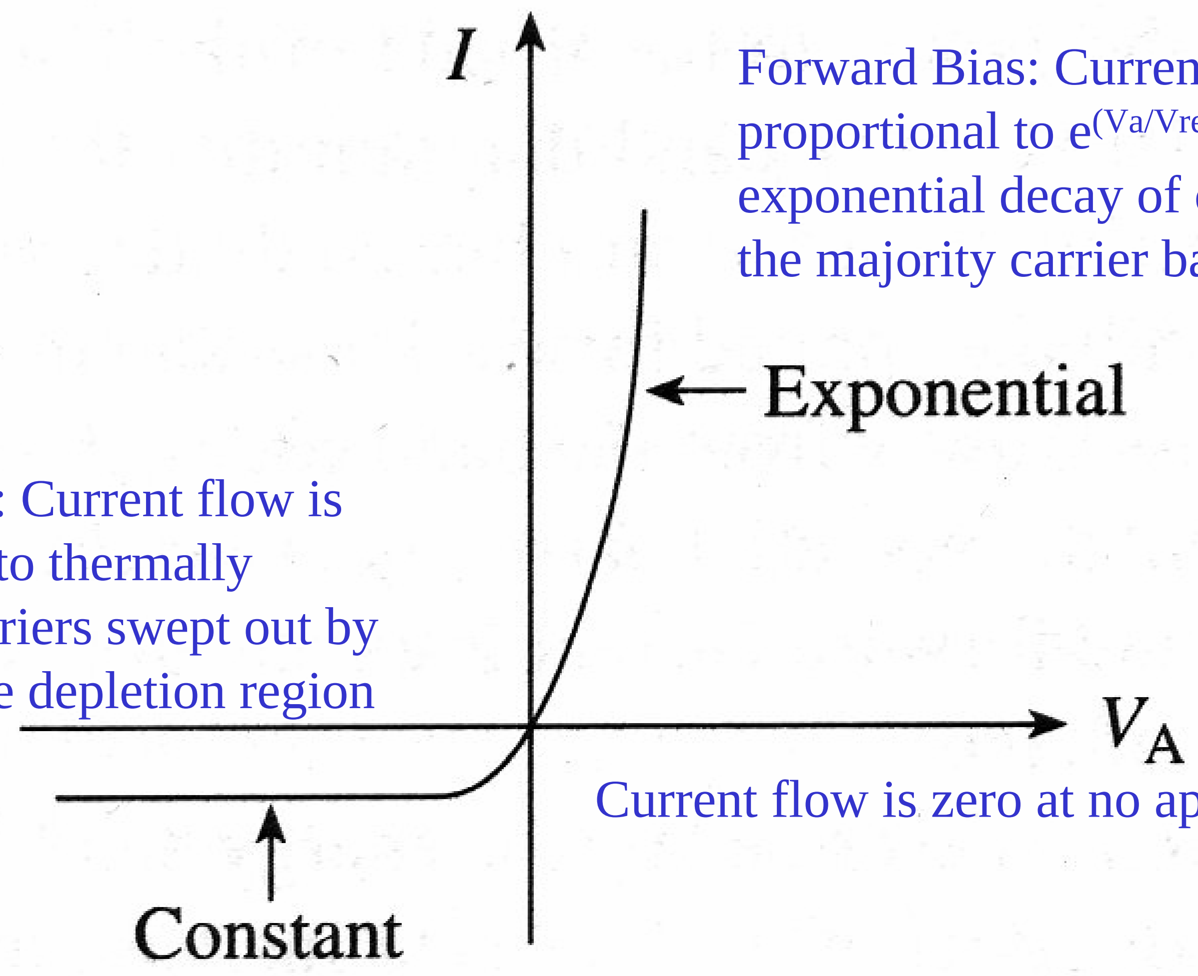
QuickTime Movie

Review: p-n Junction I-V Characteristics

Where does the reverse bias current come from? Generation near the depletion region edges "replenishes" the current source.



Review: p-n Junction I-V Characteristics
Putting it all together



Forward Bias: Current flow is proportional to $e^{(Va/Vref)}$ due to the exponential decay of carriers into the majority carrier bands

Reverse Bias: Current flow is constant due to thermally generated carriers swept out by E-fields in the depletion region

Current flow is zero at no applied voltage

$$I=I_o(e^{Va/Vref} - 1)$$

Light Emitting Devices – Basics

- Emission of photons by recombination of electrons and holes in direct bandgap materials
- **Photoluminescense**: excess electrons and holes required for the radiative recombination are generated by photon absorption
- **Electroluminescense**: excess electrons and holes required for the radiative recombination are result of an electrical current

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Slide Credit to Dr. Oliver Brandt, Ga Tech

LED Applications

LED Displays

LED Text

LED Brake Lights

LED Head Lights

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… and at Georgia Tech?

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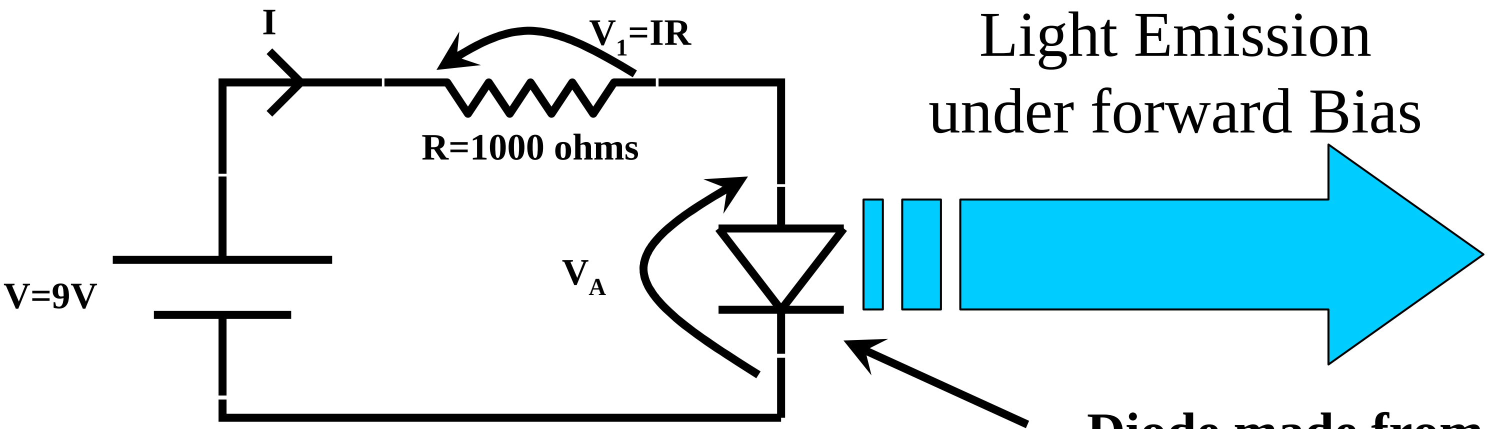
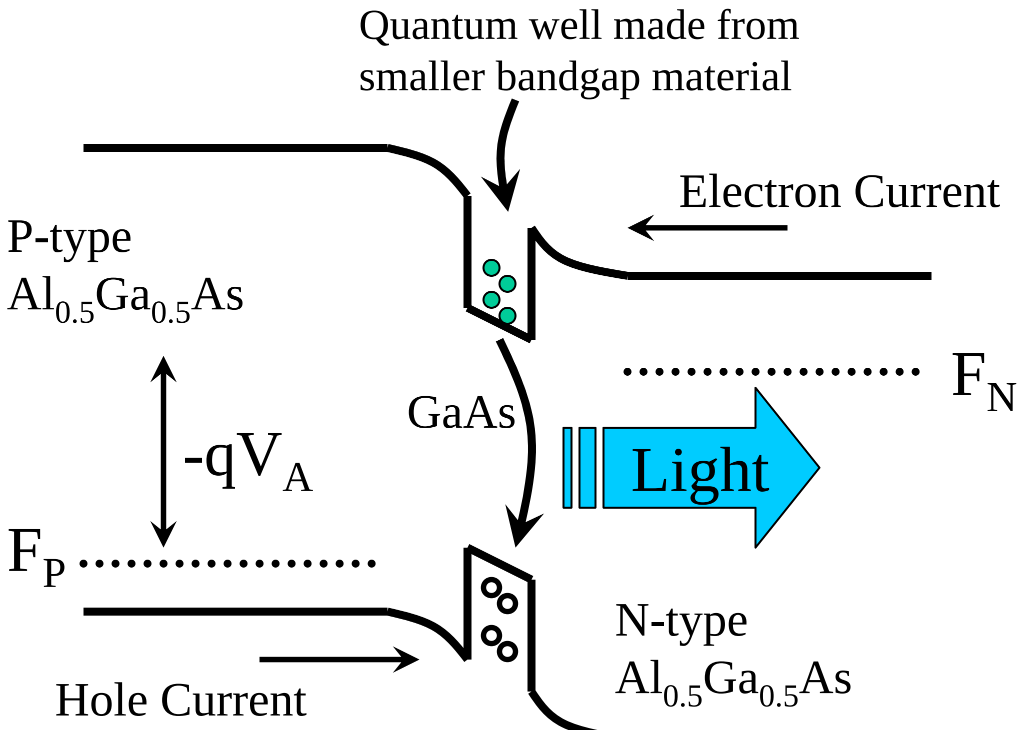
Diode Applications: LED or a Laser Diode



Light Emission
under forward Bias

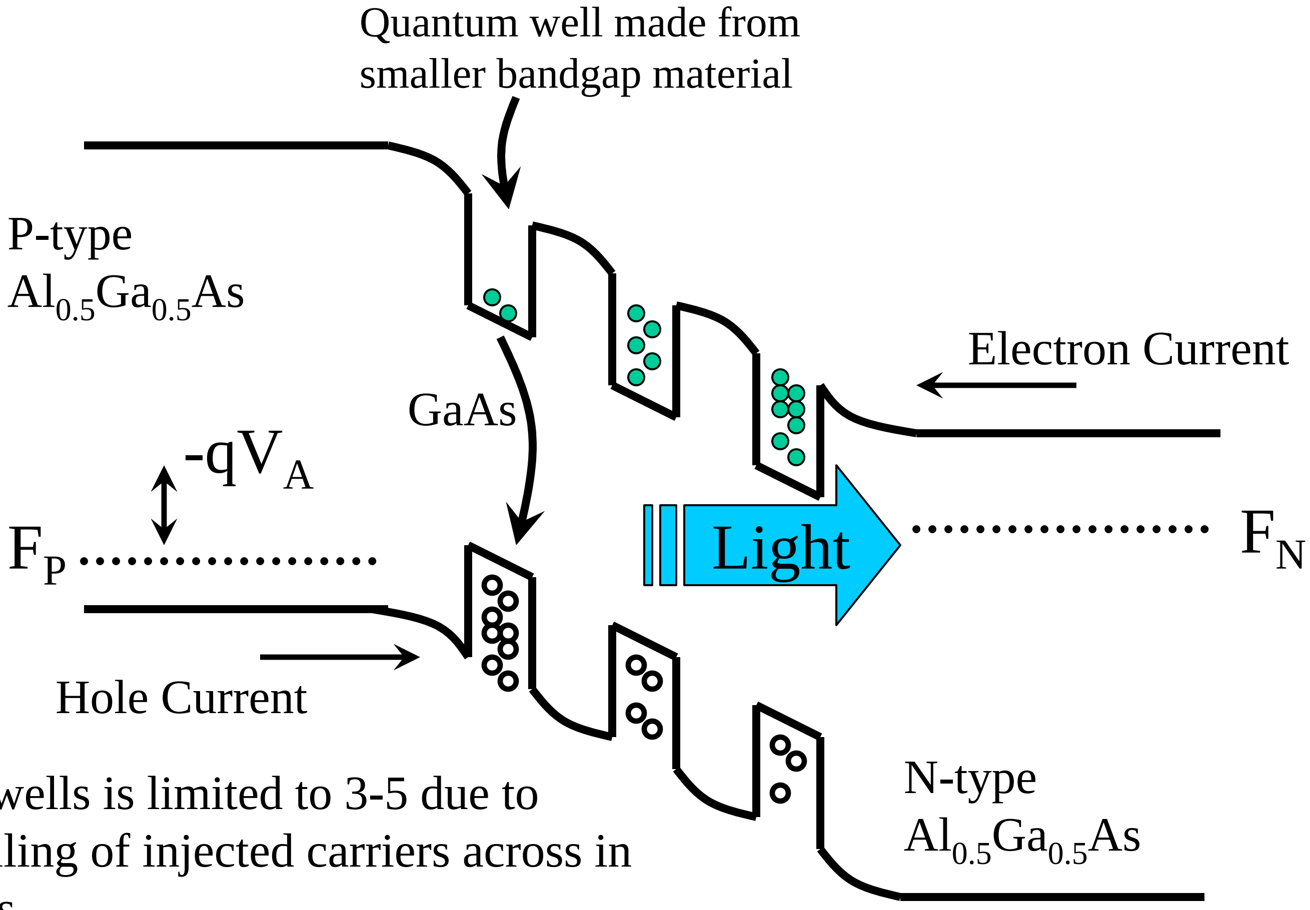
Diode made from a direct bandgap semiconductor.

Note: These devices may not be a simple p-n type diode, but behave electrically identical to a p-n junction diode.



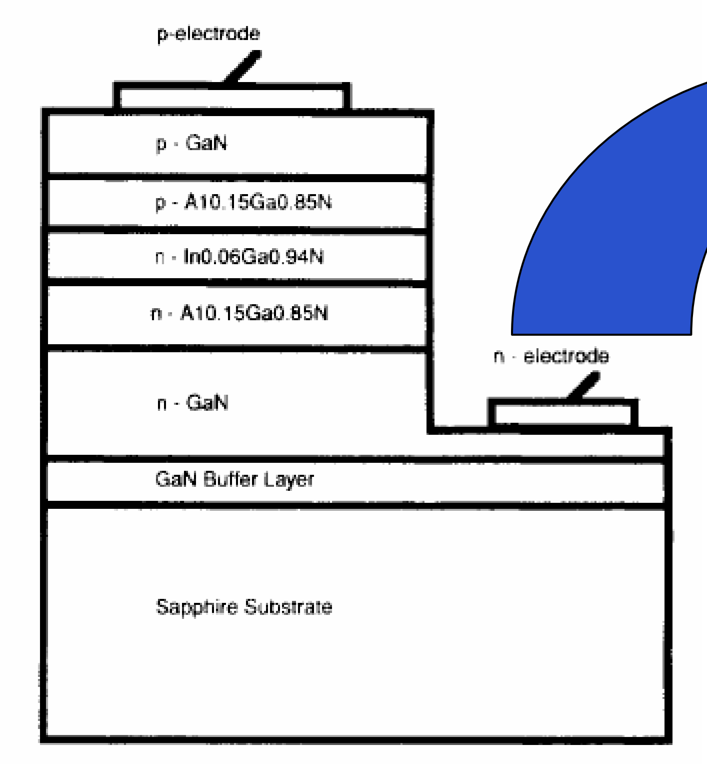
Majority Carriers that are injected to the opposite side of the diode under forward bias become minority carriers and recombine. In a direct bandgap material, this recombination can result in the creation of photons. In a real device, special areas are used to trap electrons and holes to increase the rate at which they recombine. These areas are called quantum wells.

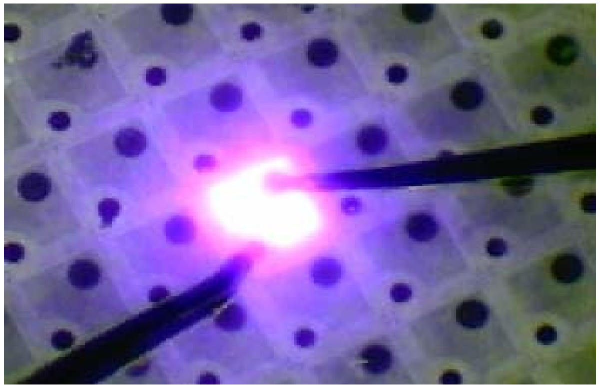
MQW LED Design Considerations

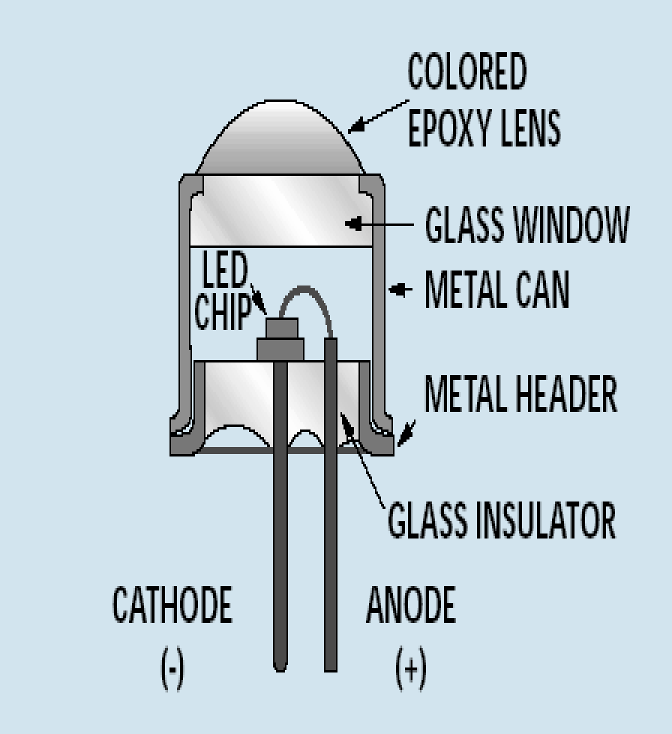


- Number of wells is limited to 3-5 due to inefficient filling of injected carriers across in last few wells.
- Light wavelength can be tuned by quantum confined energy state effect discussed earlier (only useful for very narrow wells).

MQW LED Design Considerations



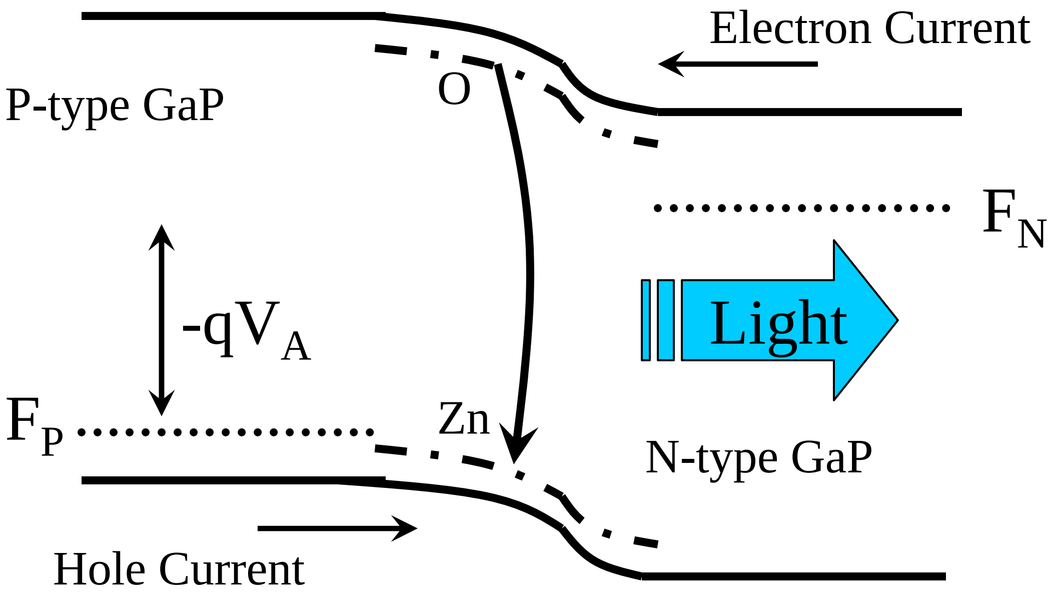




- The shape of the "die" (chip) can greatly aid light extraction by minimizing internal reflections

Nakamura, S. *et al.*, "**High-power InGaN single-quantum-well-structure blue and violet light-emitting diodes,**" *Appl. Phys. Lett* **67**, 1868 (1995).

Homojunction LED Design Considerations



- Efficient light generation results from Donor-Acceptor pair transition – requires high doping level so Donor and acceptor are “close to each other”.

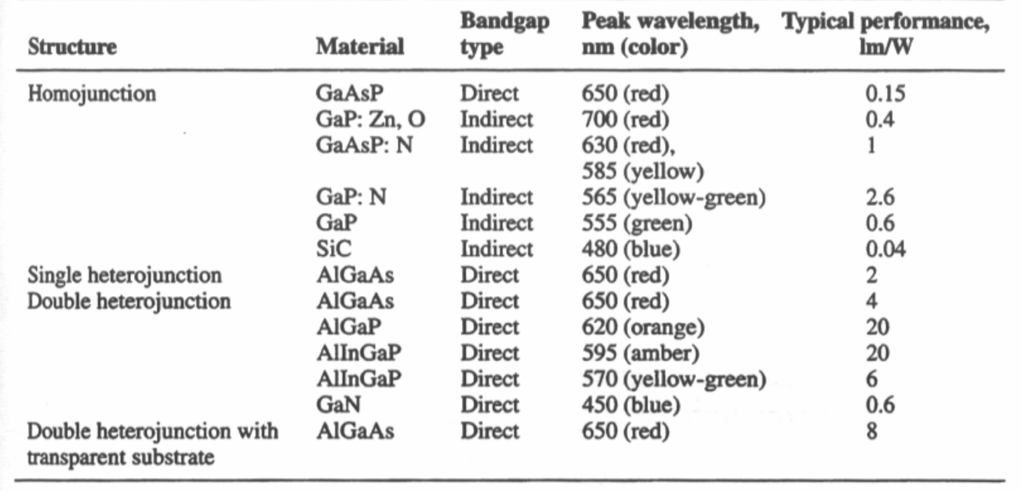
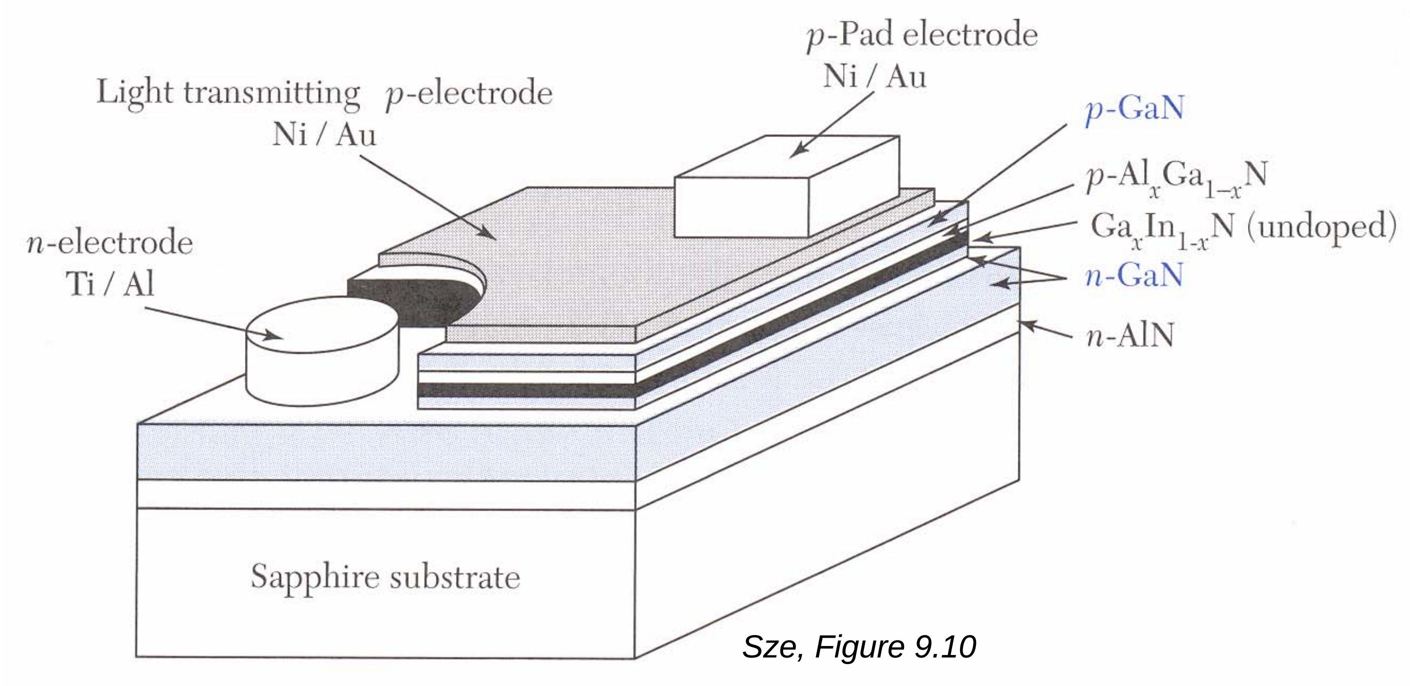


Table 5.1 CHARACTERISTICS OF VISIBLE LIGHT-EMITTING DIODES (from M. G. Craford, “LEDs Challenge the Incandescents,” *IEEE Circuits and Devices Magazine*, September 1992).

Structure	Material	Bandgap type	Peak wavelength, nm (color)	Typical performance, lm/W
Homojunction	GaAsP	Direct	650 (red)	0.15
	GaP: Zn, O	Indirect	700 (red)	0.4
	GaAsP: N	Indirect	630 (red), 585 (yellow)	1
	GaP: N	Indirect	565 (yellow-green)	2.6
	GaP	Indirect	555 (green)	0.6
	SiC	Indirect	480 (blue)	0.04
Single heterojunction	AlGaAs	Direct	650 (red)	2
Double heterojunction	AlGaAs	Direct	650 (red)	4
	AlGaP	Direct	620 (orange)	20
	AlInGaP	Direct	595 (amber)	20
	AlInGaP	Direct	570 (yellow-green)	6
	GaN	Direct	450 (blue)	0.6
Double heterojunction with transparent substrate	AlGaAs	Direct	650 (red)	8

Blue LED based on AlGaInN



Sze, Figure 9.10

- AlGaInN: direct bandgap ranging from 0.65 eV to 6.2 eV corresponding to wavelength from 1.9 µm to 0.2 µm
- Challenge: find lattice-matched substrate
  Solution: sapphire substrate with AlN buffer layer
- Because sapphire is non-conducting, both contacts are from the surface
- Blue light originates from radiative recombination in the $\text{Ga}_x\text{In}_{1-x}\text{N}$ layer

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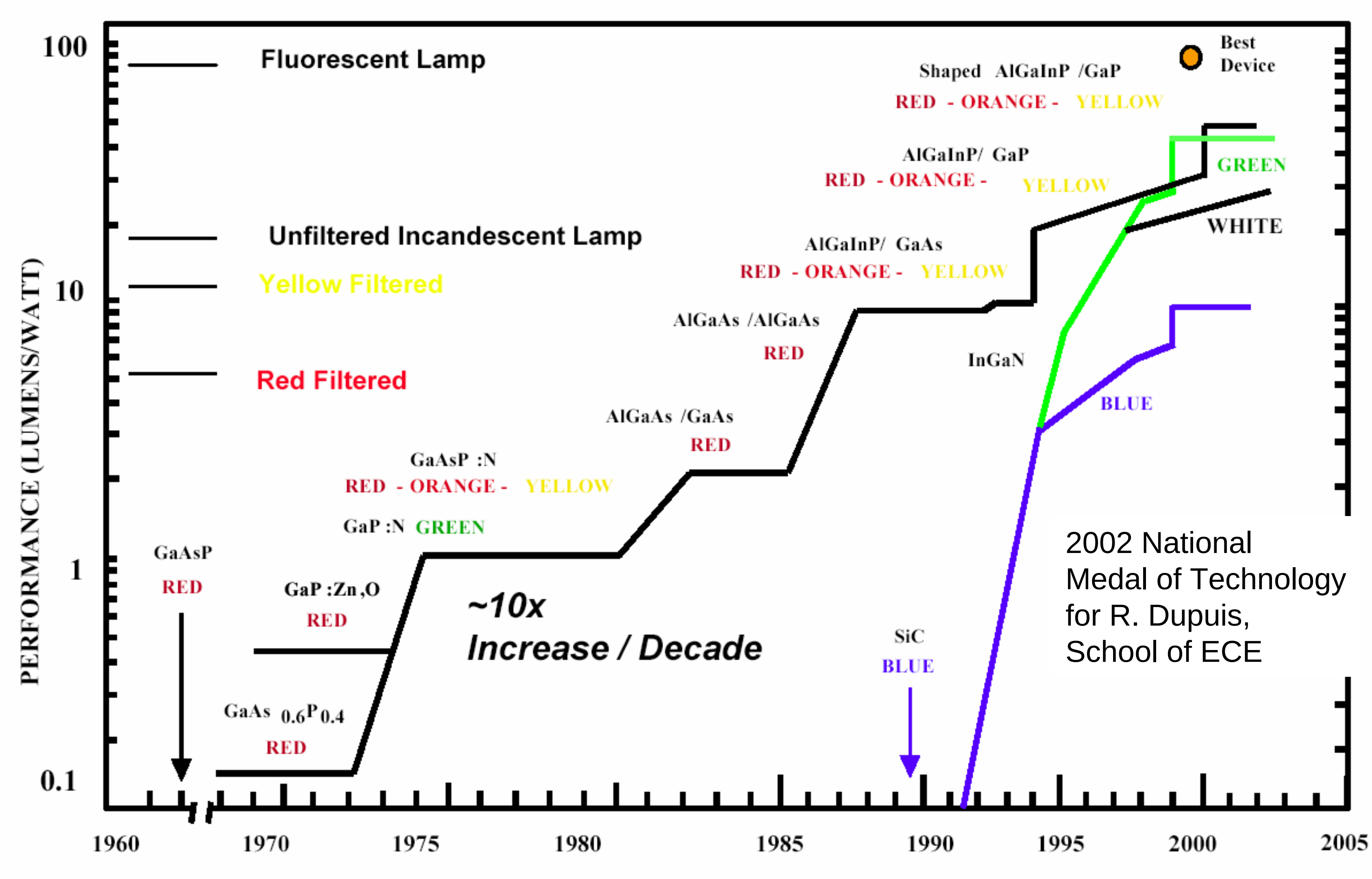
The LED Development



2002 National
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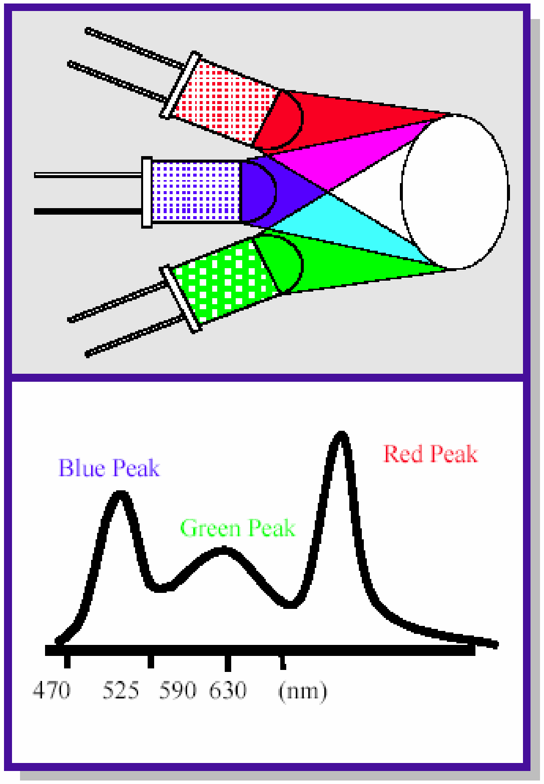
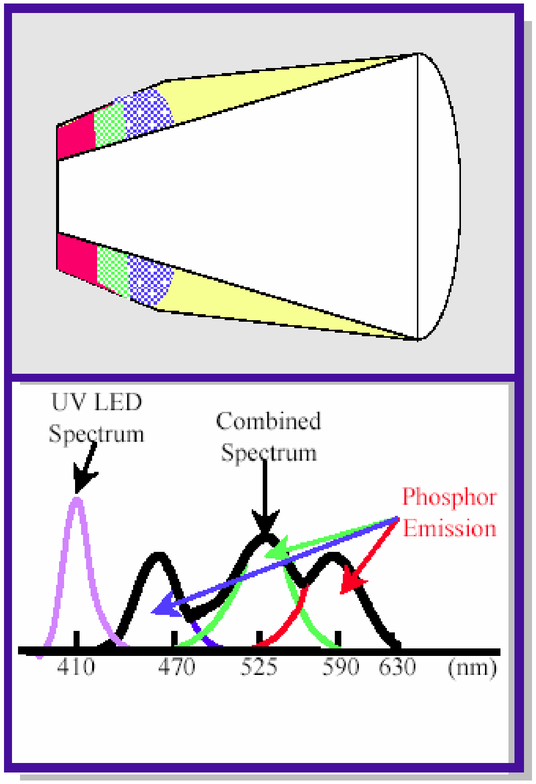
How to Make White LEDs?

Red + Green + Blue LEDs



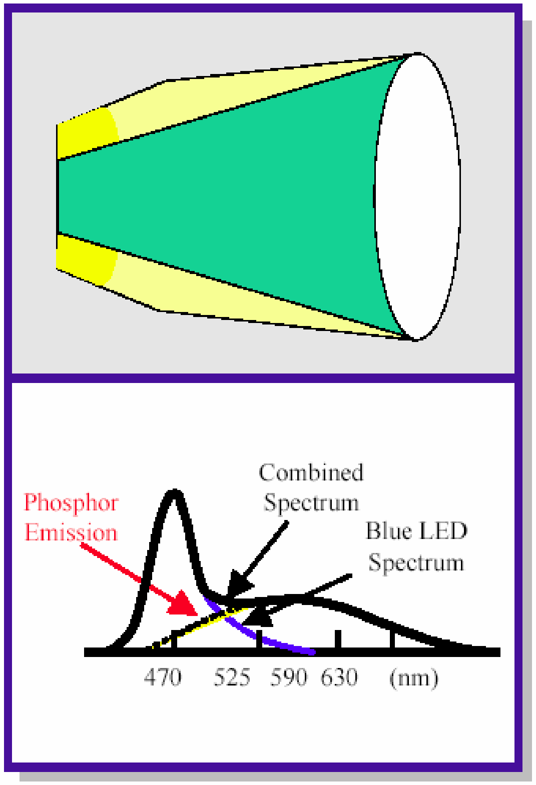
RGB LEDs

UV LED + RGB Phosphor



UV LED + RGB phosphor

Binary Complimentary



Blue LED
+
Yellow phosphor

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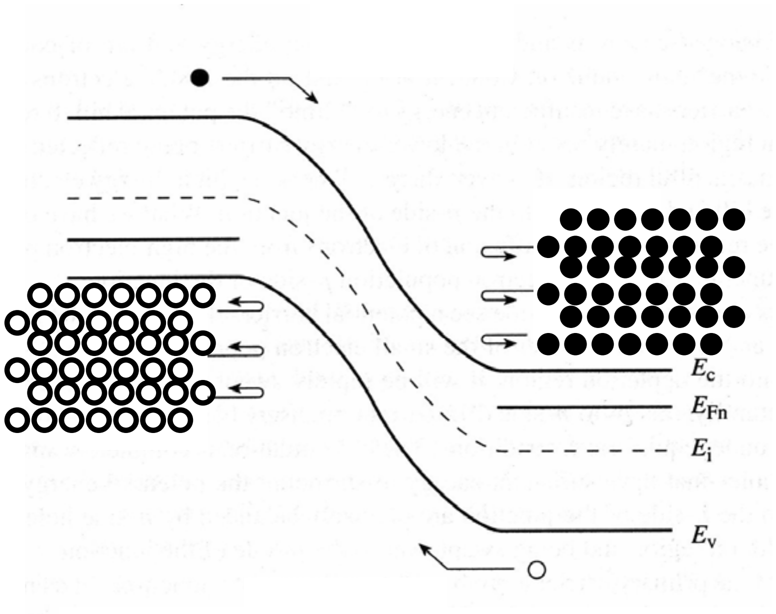
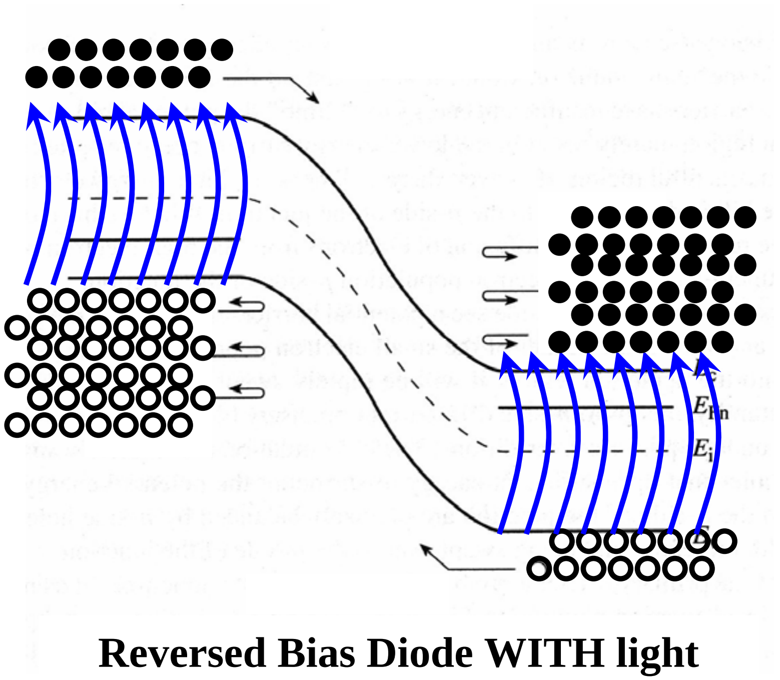
Photodiode



Reversed Bias Diode with no light illumination



Reversed Bias Diode WITH light illumination results in "extra" drift current due to photogenerated ehp's that can reach the junction.

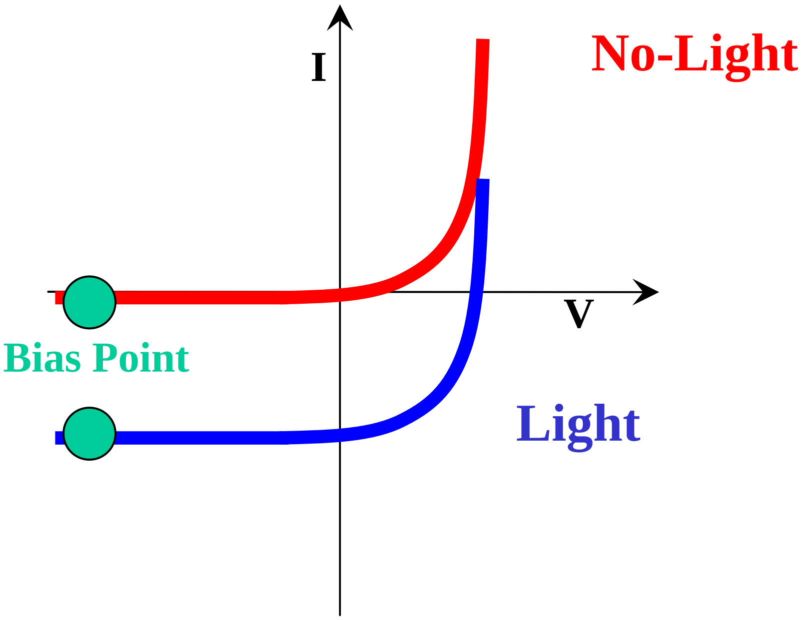
Photodiode

$$I_{total} = I_{dark} + I_{Due\ to\ Light}$$

$$I_{total} = I_o\left(e^{\left(V_D/V_T\right)} - 1\right) + I_{Due\ to\ Light}$$

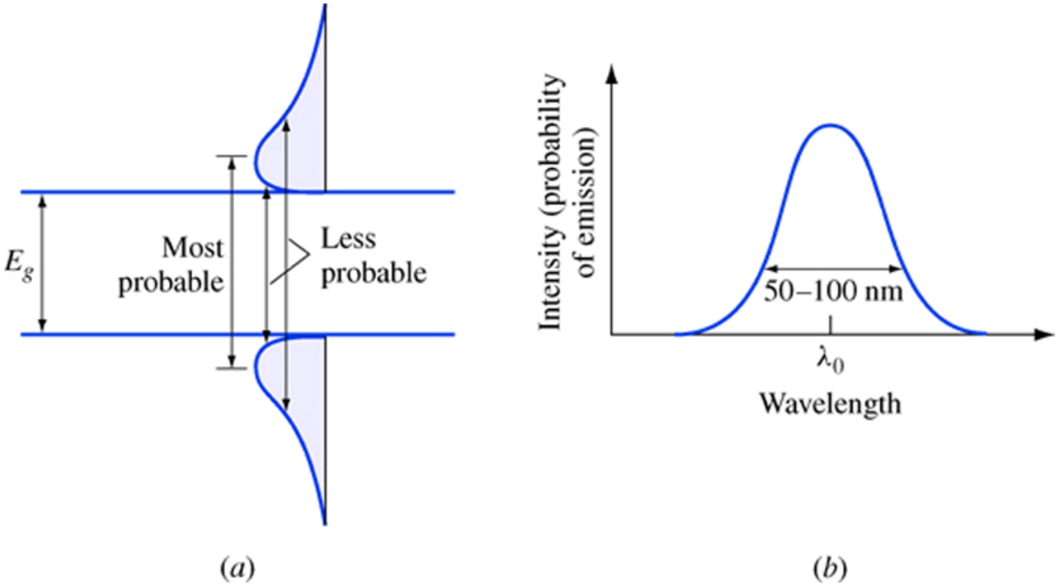
$$I_{total} = \underbrace{\left(I_o e^{\left(V_D/V_T\right)} - I_o\right)}_{\text{No-Light}} + \underbrace{(-qA)\overbrace{(L_N + W + L_P)}G_L}_{\text{Light}}$$

Every EHP created within the depletion region (W) and within a diffusion length away from the depletion region is collected (swept across the junction by the electric field) as photocurrent (current resulting from light). All other EHP's recombine before they can be collected.



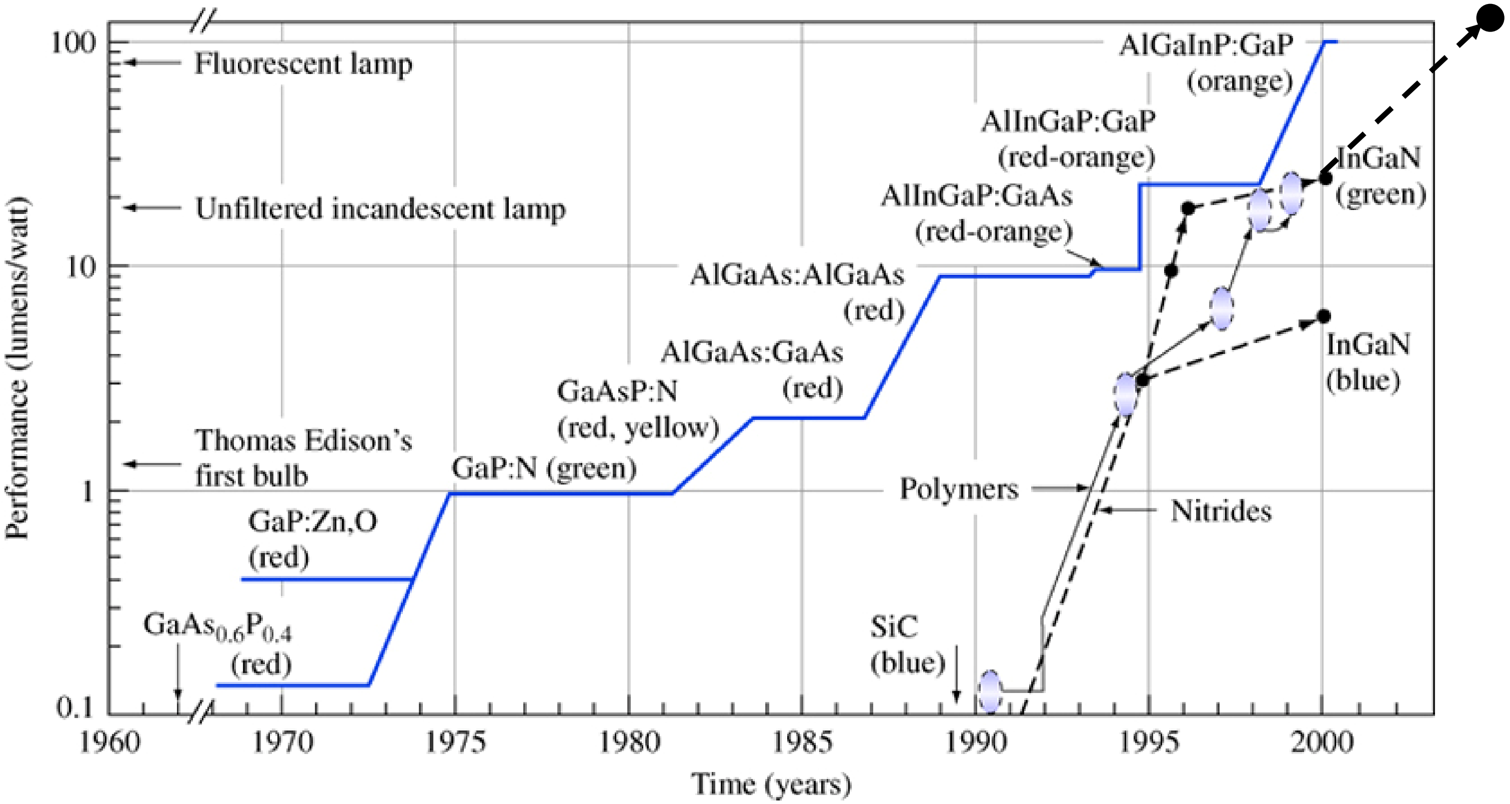
Semiconductor LED vs LASER?

- Light Emitting Diode
  - Light is mostly monochromatic (narrow energy spread comparable to the distribution of electrons/hole populations in the band edges)
  - Light is from spontaneous emission (random events in time and thus phase).
  - Light diverges significantly



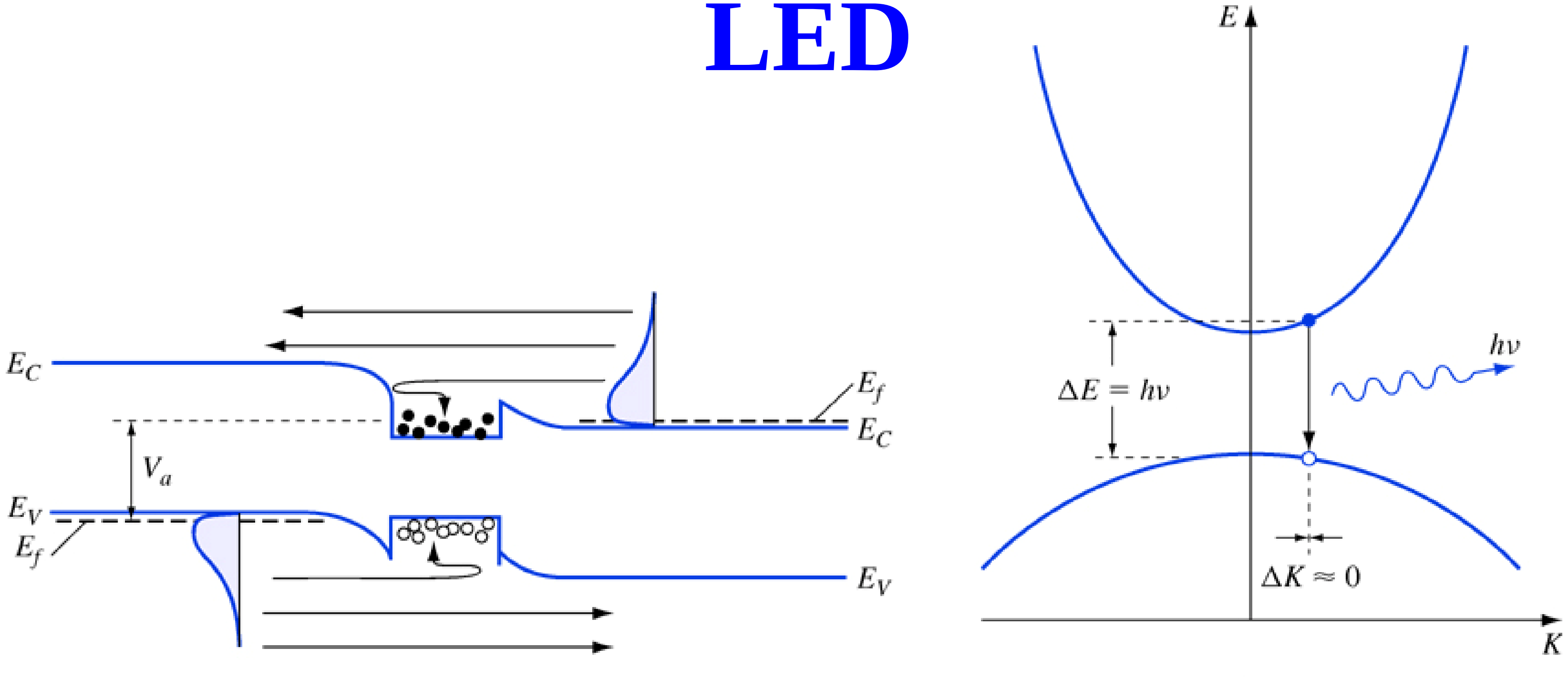
- LASER
  - Light is essentially single wavelength (highly monochromatic)
  - Light is from “stimulated emission” (timed to be in phase with other photons
  - Light has significantly lower divergence (Semiconductor versions have more than gas lasers though).

LED History



Present LED technology is more efficient than even fluorescent lamps! However, it will take some time before the cost comes down enough to replace light bulbs.

LED

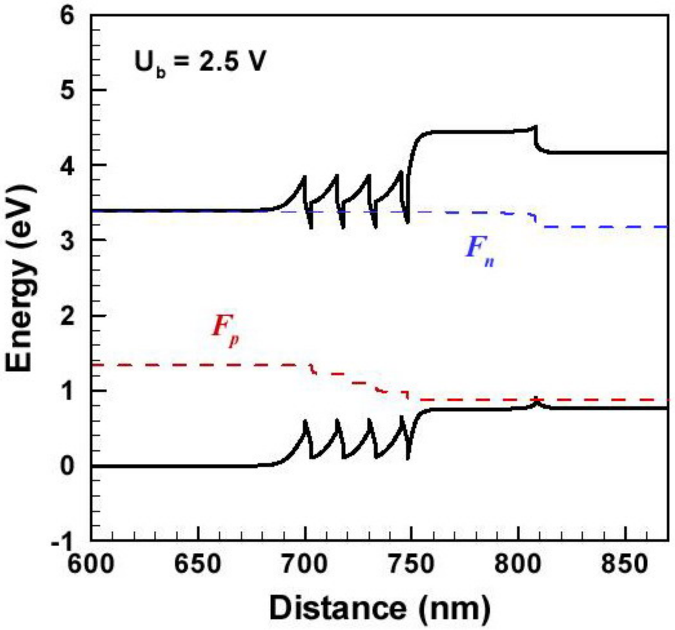


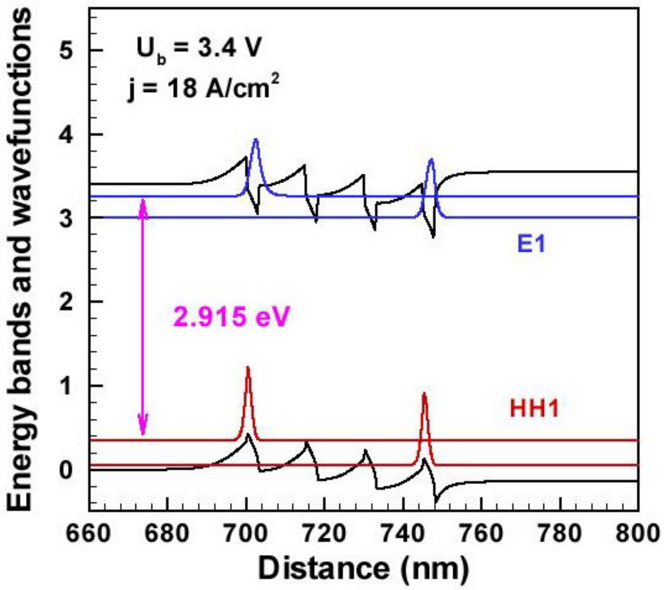
(a)

(b)

- A pn junction in a direct bandgap material will produce light when forward biased. However, re-absorption (photon recycling) is likely and thus should be avoided.
- Use of quantum wells in the “active region” (region where minority carriers are injected and recombine from the “majority carrier” anode (source of holes) and cathode (source of electrons) results in minimal re-absorption since the emitted light is below the bandgap of the cladding layers (higher bandgap regions).
- The quantum well also strongly confines the electrons and holes to the same region of the material enhancing the probability of recombination and thus enhancing the radiation efficiency (light power out/electrical power in).

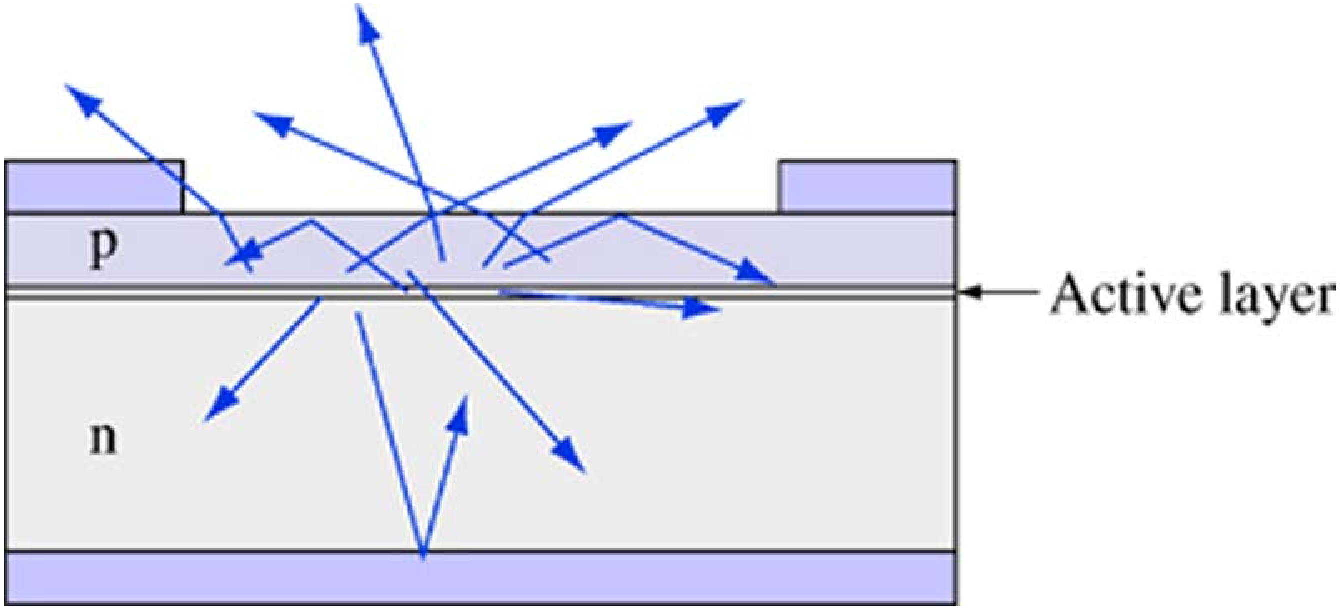
LED





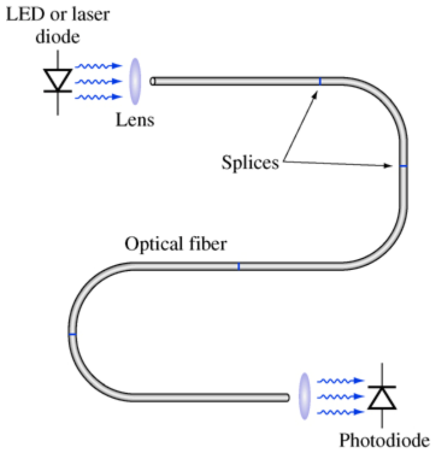
- •Often Multiple QWs are used to insure radiation efficiency. Typically 3-5 QWs maximize the light output since holes are injected from the p-side and electrons from the n-side and thus would get trapped in different wells if we had too many QWs.
- •Some real effects to consider:
  - – Some semiconductors (Nitrides and Carbides) are polar materials. Thus, heterojunctions must contend with polarization discontinuities (changes in polarization) at the interfaces. This leads to spikes in the band diagrams and strong electric fields in the QW that can partially separate the electron wave function from the hole wave function lowering radiation efficiency.
  - – Often, an electron blocking layer is introduced via a wide bandgap layer near the anode (p-side). This prevents electrons (which have higher diffusivity than holes) from entering the anode (p-side) thus limiting recombination “at the wrong wavelength” enhancing color purity and desired light power efficiency.

Light Scattering in an LED

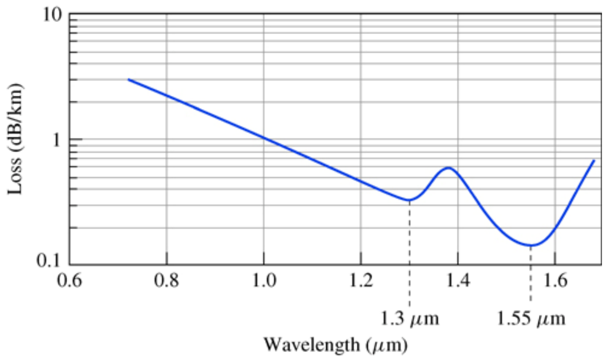


A generic surface-emitting LED. Some photons are lost by re-absorption in the bulk, Fresnel reflection from the surface, and total internal reflection.

A fiber coupled LED

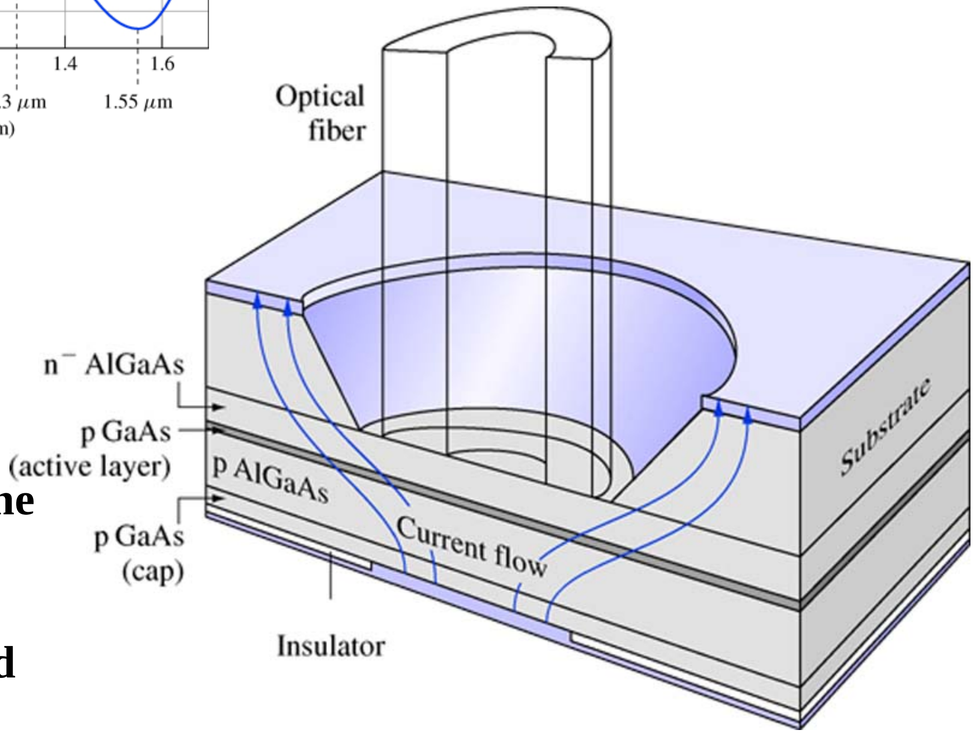


(a)

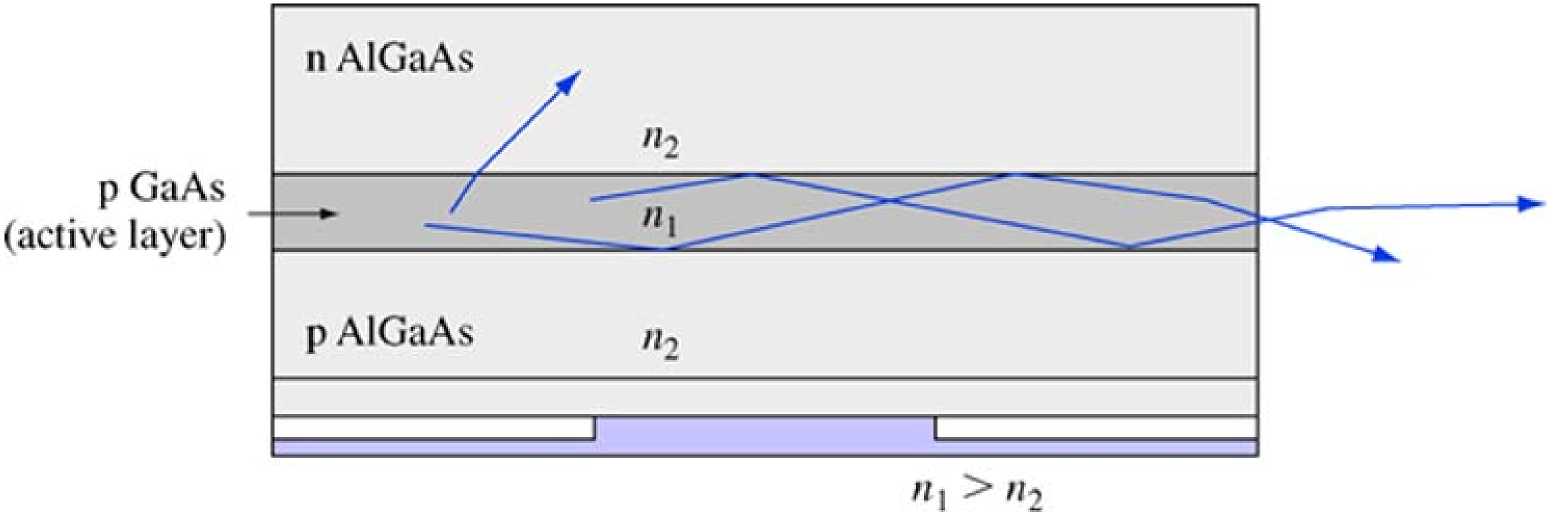


(b)

- A Burrus-type LED. This one uses a double heterostructure to confine the carriers, making recombination
- more efficient. The etched opening in the LED helps align and couple an optical fiber.
- Typically InGaAs active layers are used to produce the IR light necessary to transmit in a fiber with minimal loss in the fiber.

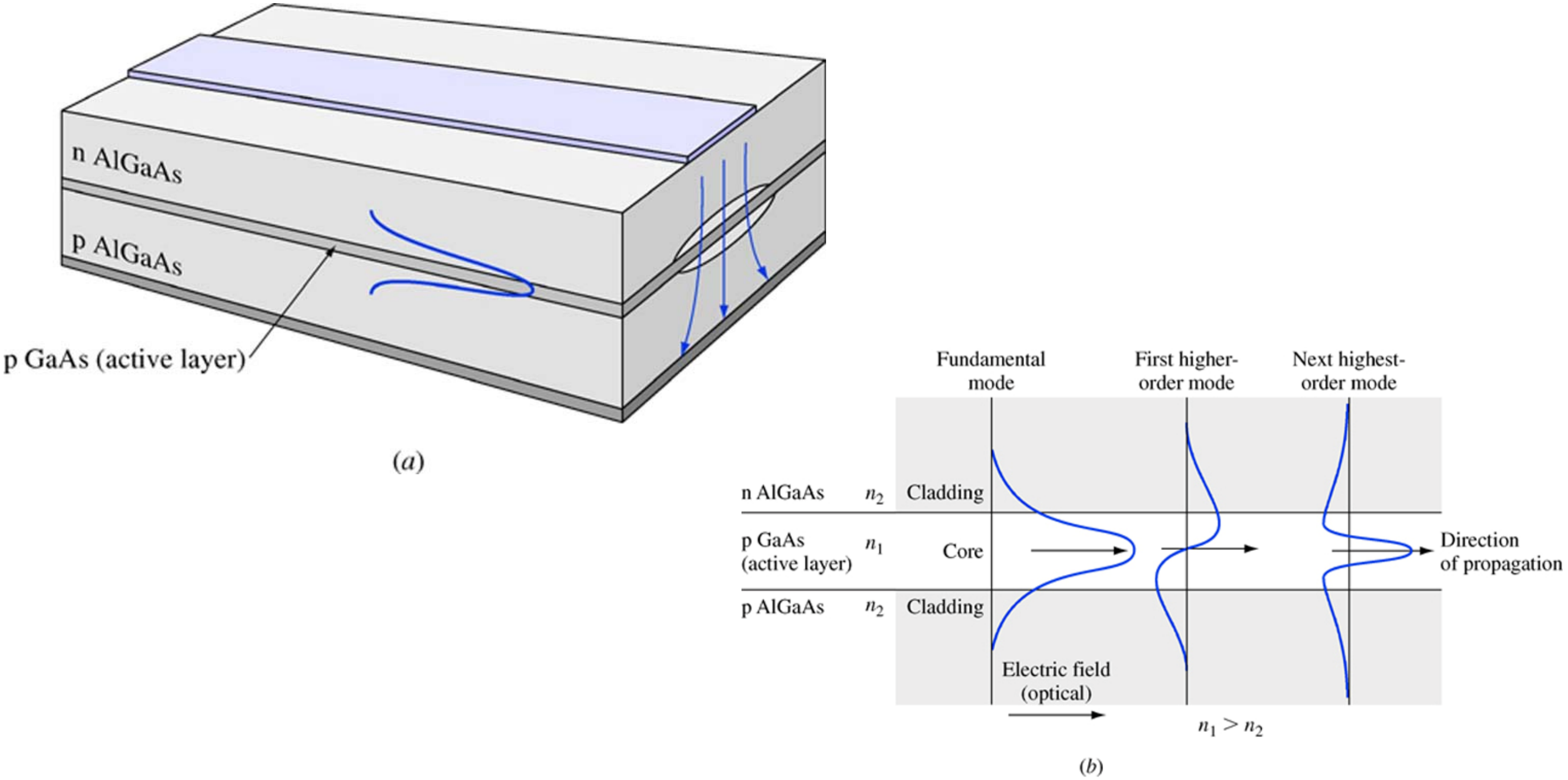


Light Channeling (Waveguiding) in a LED



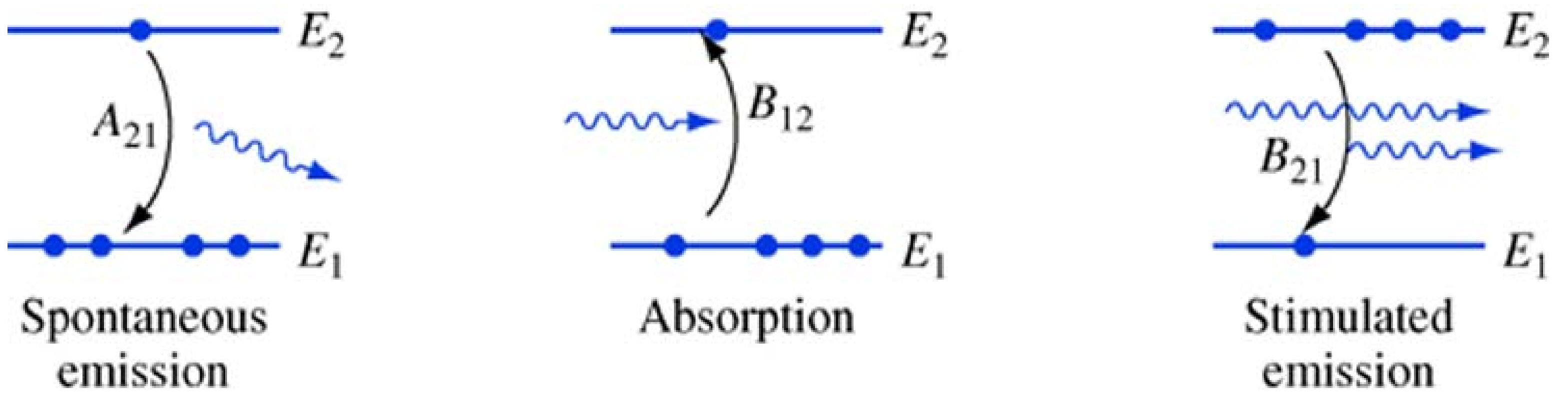
- **In an edge-emitting LED, the higher refractive index active layer acts as a waveguide for photons traveling at less than the critical angle.**
- **Why is re-absorption not a huge concern? …**

LED Waveguides (edge emitting LED)



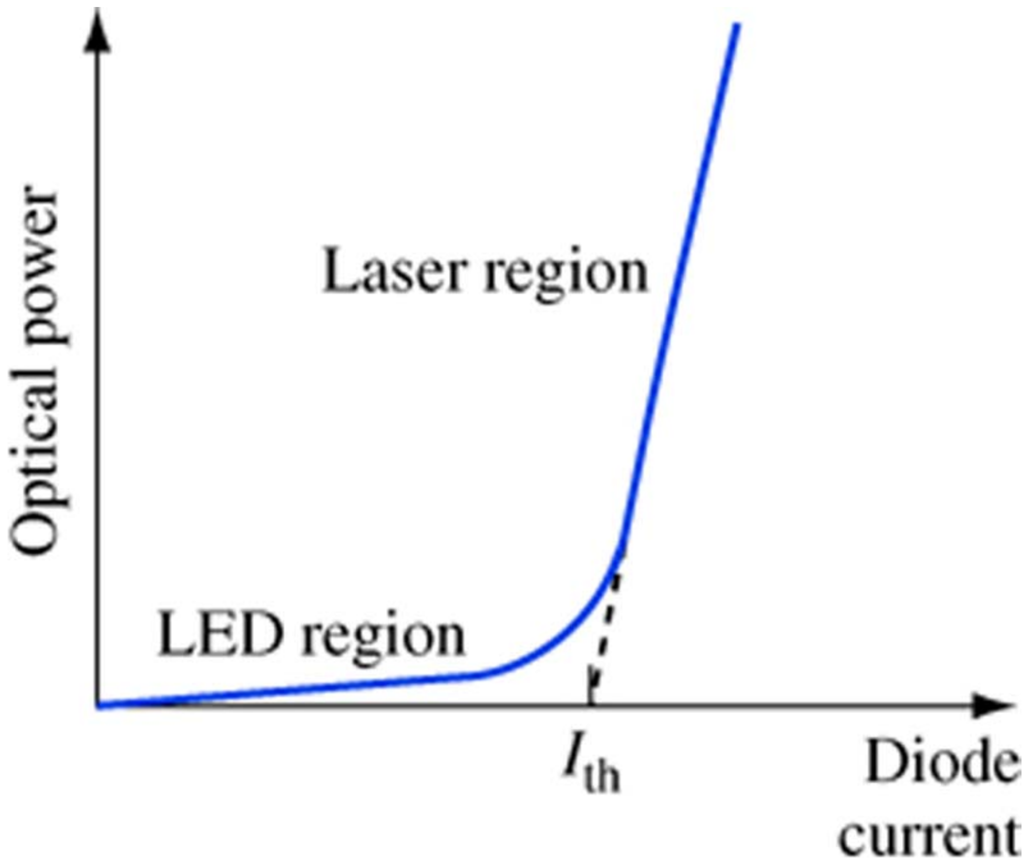
- The edge-emitting LED’s waveguide (a) supports only certain transverse modes, whose field distributions are shown in (b). In practice, only the first mode is allowed. It is not completely confined to the active layer, thus its absorption is reduced.

Spontaneous Light Emission



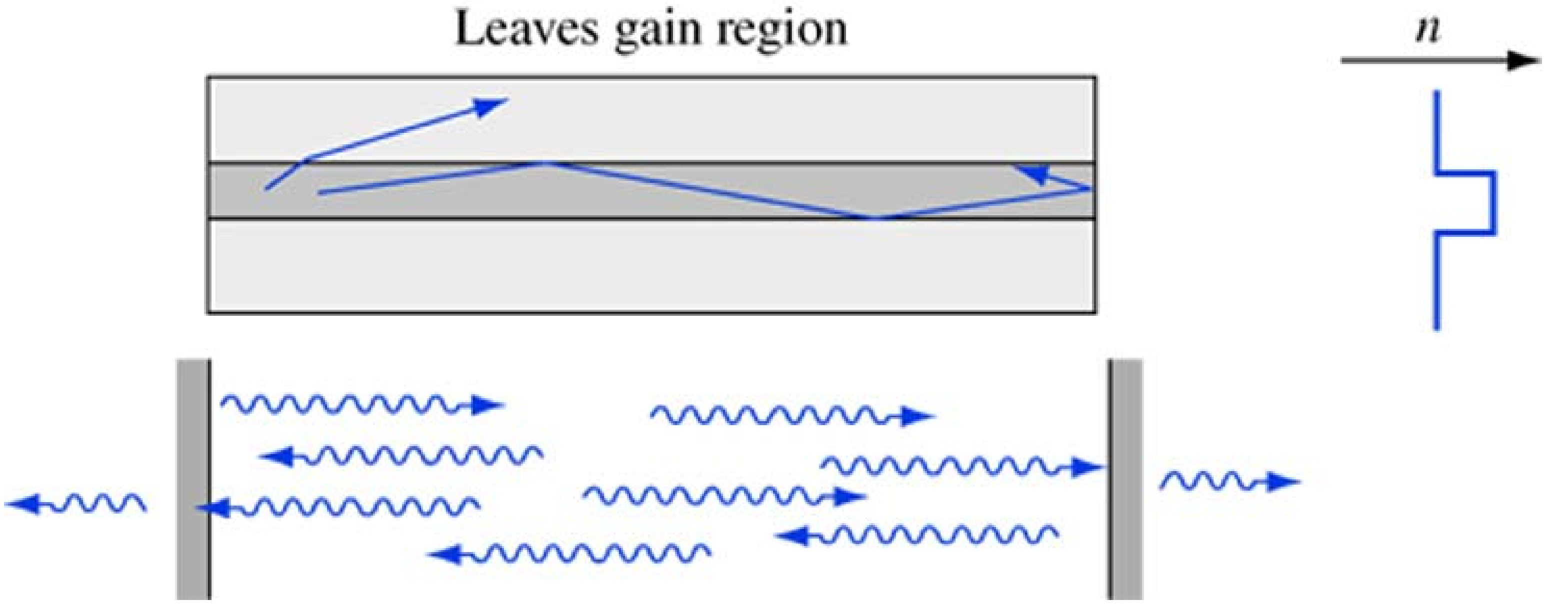
- We can add to our understanding of absorption and spontaneous radiation due to random recombination another form of radiation – Stimulated emission.
- Stimulated emission can occur when we have a “population inversion”, i.e. when we have injected so many minority carriers that in some regions there are more “excited carriers” (electrons) than “ground state” carriers (holes).
- Given an incident photon of the bandgap energy, a second photon will be “stimulated” by the first photon resulting in two photons with the same energy (wavelength) <u>and phase</u>.
- This phase coherence results in minimal divergence of the optical beam resulting in a directed light source.

Spontaneous vs Stimulated Light Emission



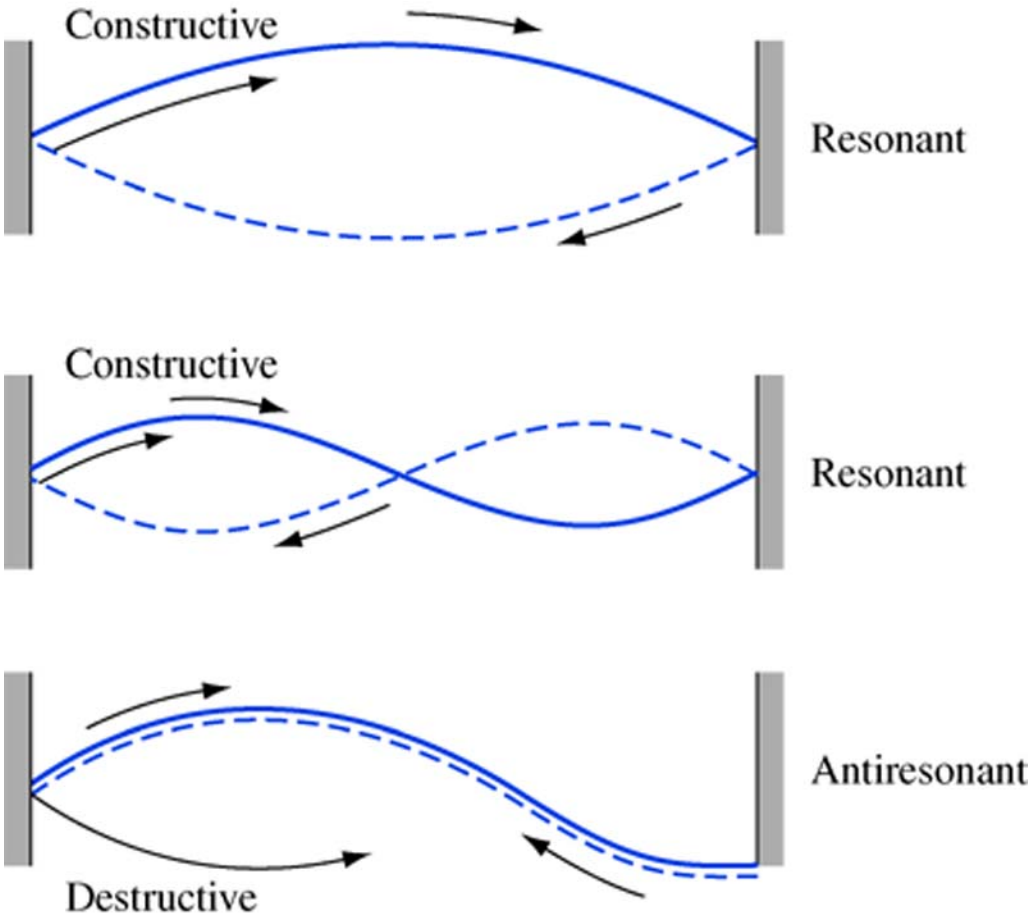
The power-current curve of a laser diode. Below threshold, the diode is an LED. Above threshold, the population is inverted and the light output increases rapidly.

Using Mirrors and Optical Gain (through Stimulated emission) to "Amplify the Light"



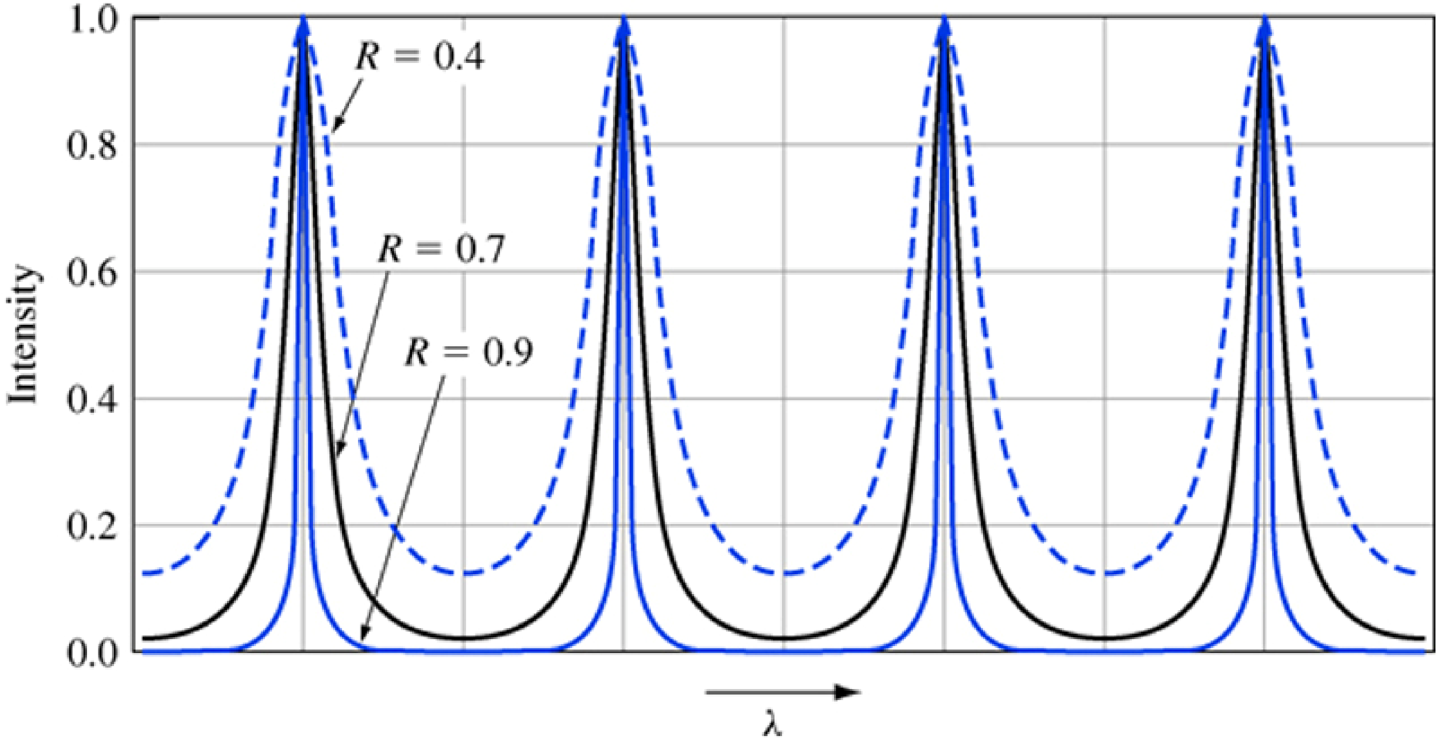
The ends of the chip form partially reflective mirrors, which allows the photons to be reflected back and forth and thus be exposed to gain for a longer period of time.

Cavity Modes used in Wavelength Selection



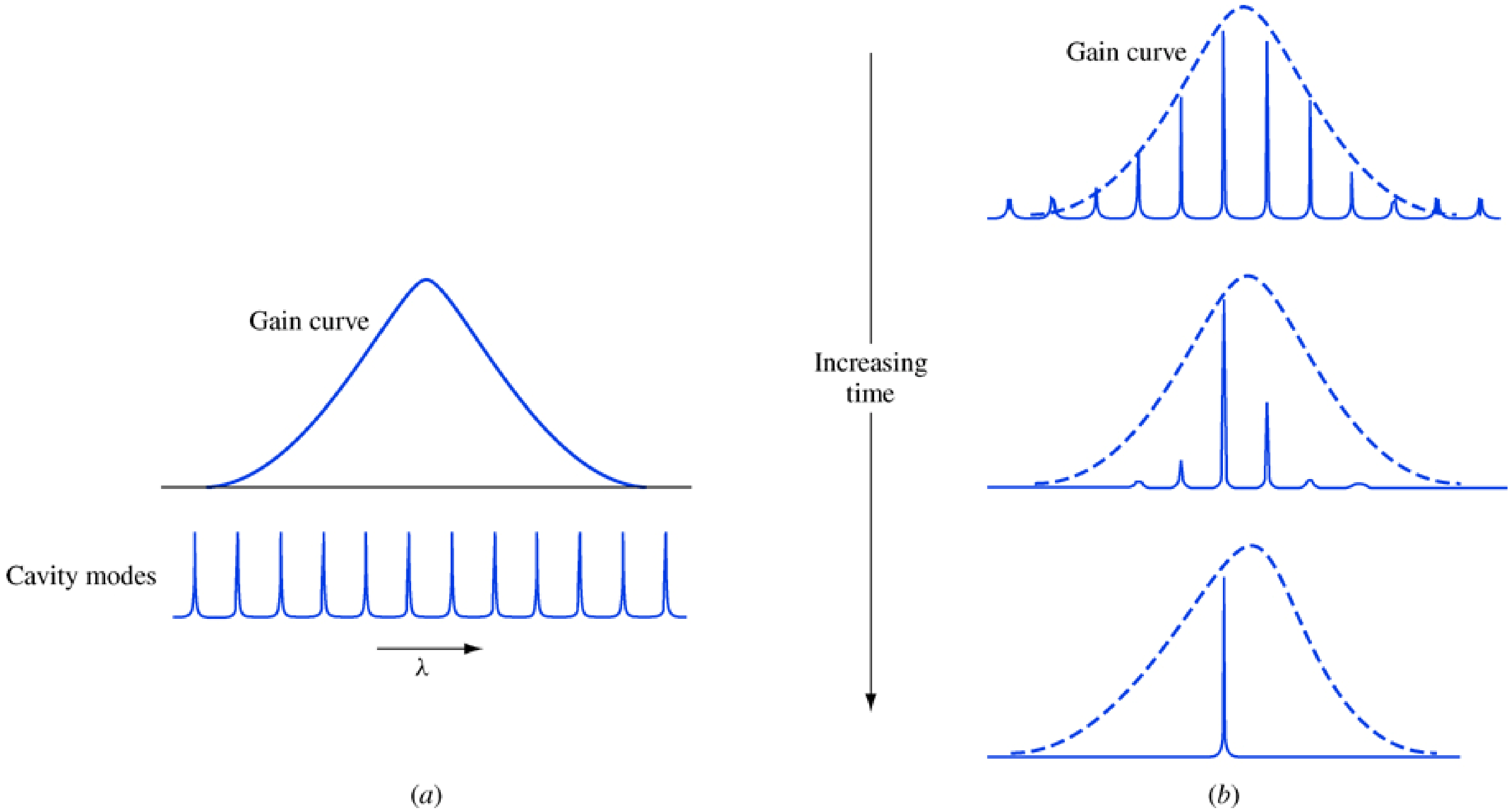
Wavelengths that are integer multiples of half the cavity's length can resonate, interfering constructively. Other wavelengths die out eventually.

Cavity Modes used in Wavelength Selection



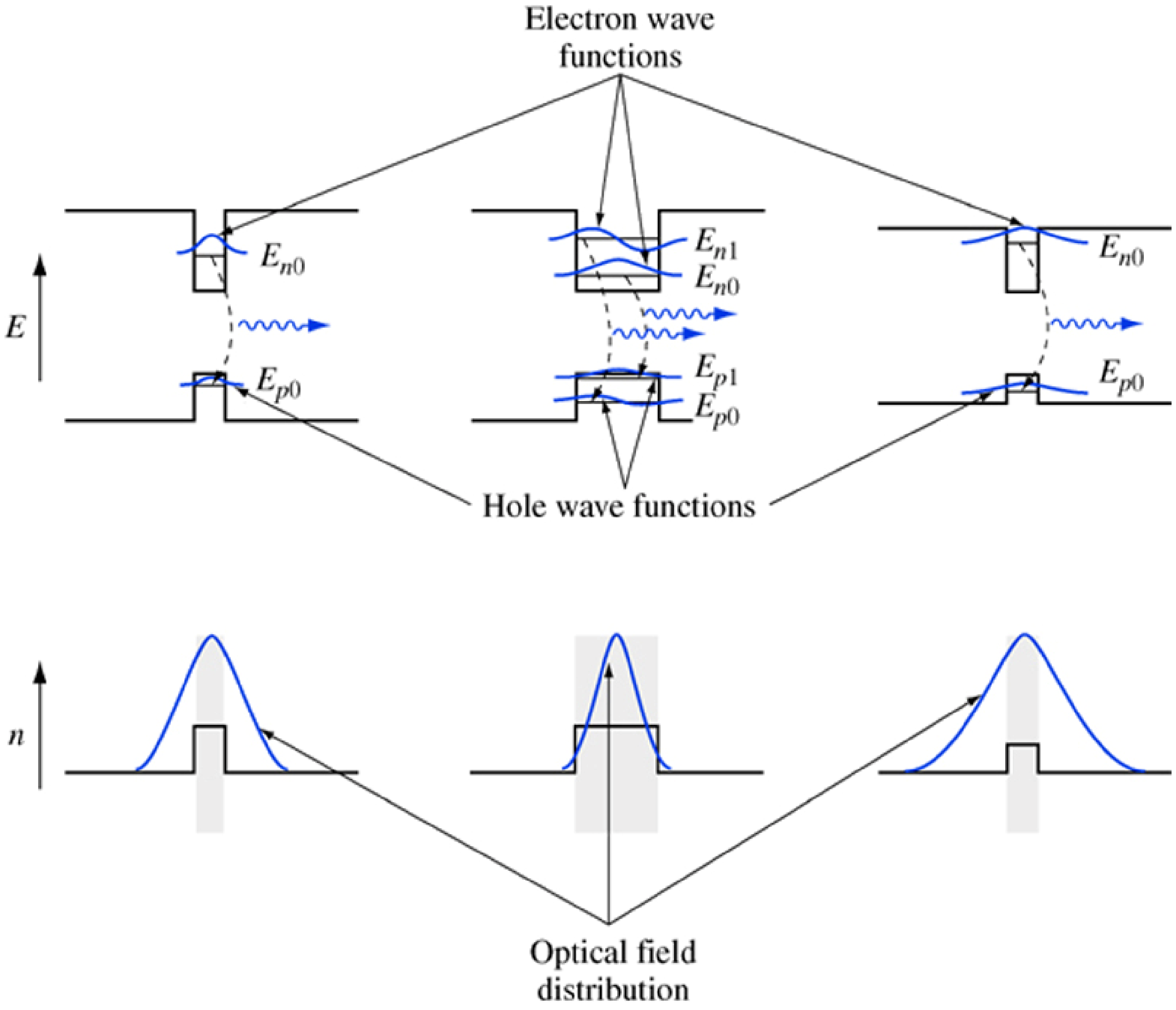
The resonances of a Fabry-Perot cavity. The width of the resonances depends on the reflectivity *R* of the mirrors.

Cavity Modes + Gain Result in Wavelength Selection



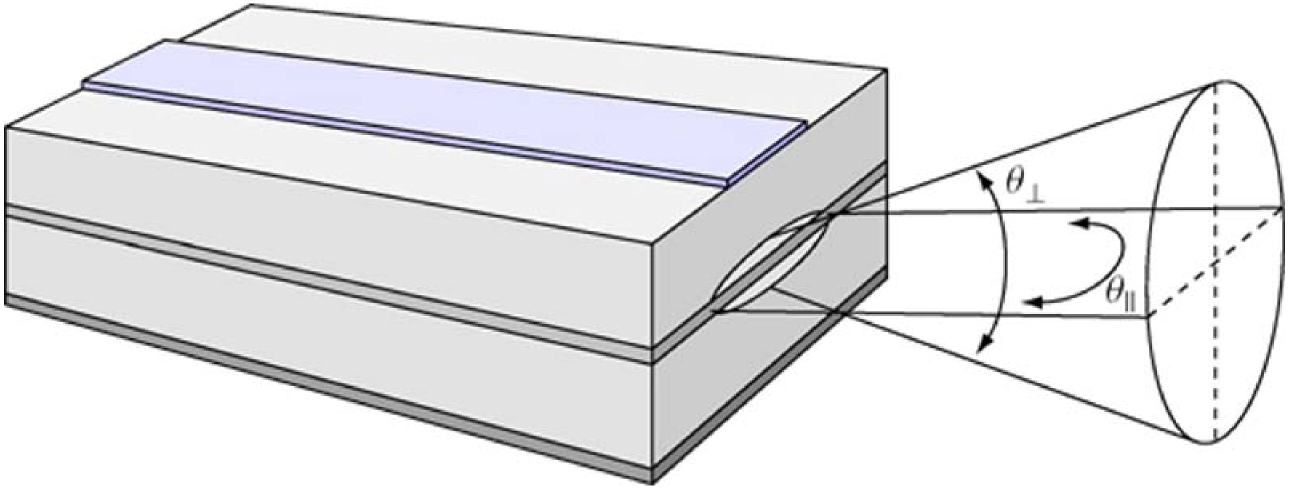
Development of lasing. (a) The gain distribution is the same as the spontaneous emission spectrum. (b) Only the photons at the resonance will amplify. The ones near the center of the gain curve will amplify the fastest.

LASER Wavelength Design



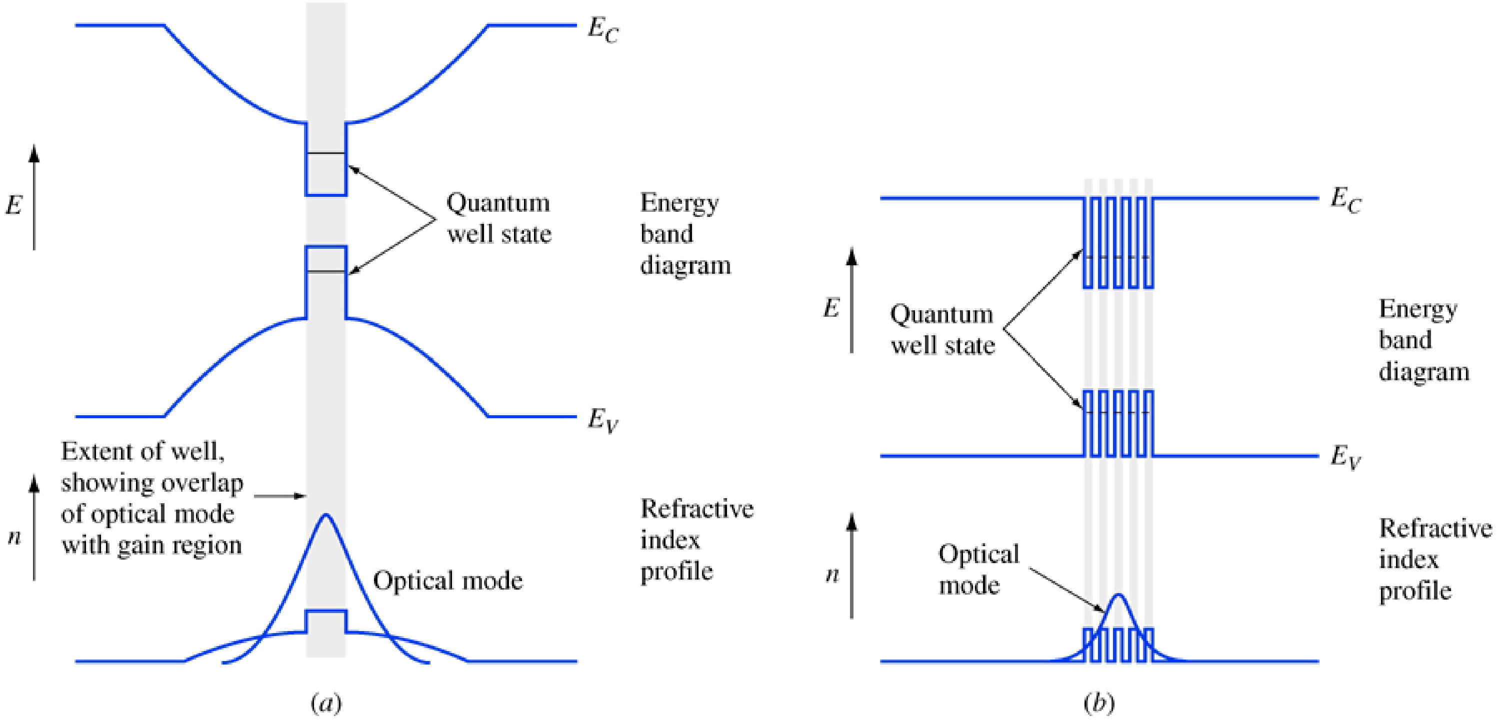
Adjusting the depth and width of quantum wells to select the wavelength of emission is one form of band-gap engineering. The shaded areas indicate the width of the well to illustrate the degree of confinement of the mode.

Stripline or Edge Emitting LASER



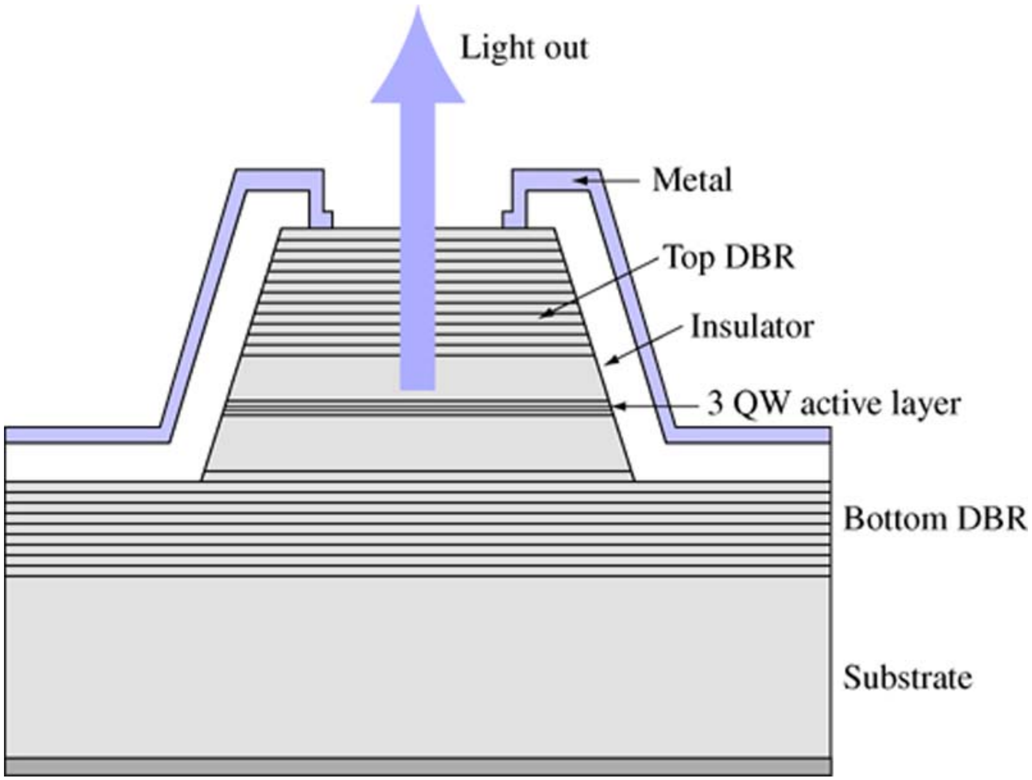
The output pattern of a simple "stripline", edge-emitting laser is elliptical and widely divergent.

Advanced LASER Wavelength Design



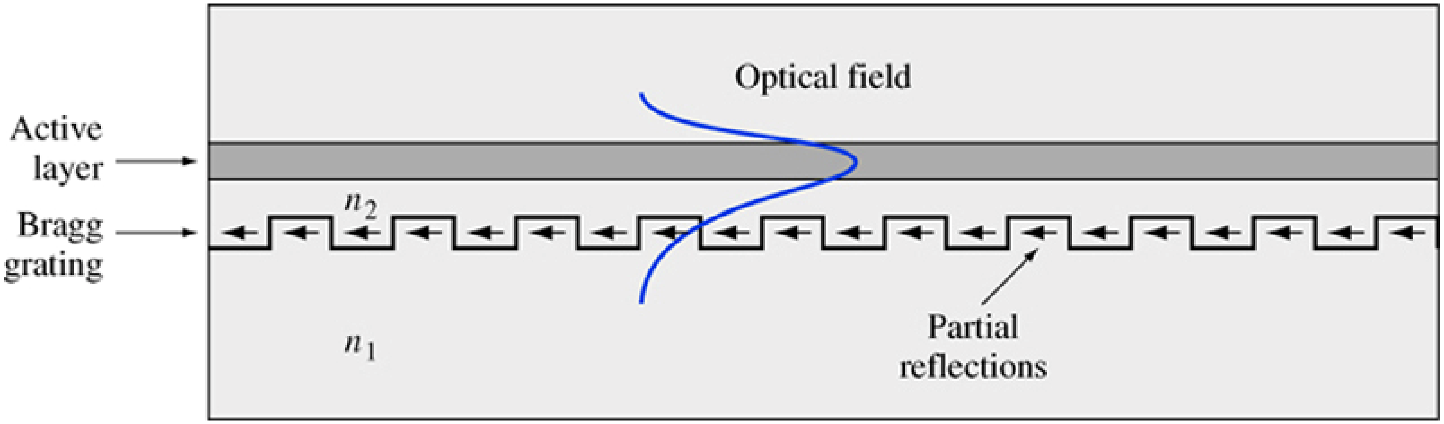
- **(a) A GRINSCH structure helps funnel the carriers into the wells to improve the probability of recombination. Additionally, the graded refractive index helps confine the optical mode in the near-well region. Requires very precise control over layers due to grading. Almost always implemented via MBE**
- **(b) A multiple quantum well structure has improves carrier capture.**
- **Sometimes the two are combined to give a "digitally graded" device where only two compositions are used but the well thicknesses are varied to implement an effective "index grade"**

Vertical Cavity Surface Emitting Laser (VECSEL)



- A vertical cavity surface-emitting laser. (After Ueki et al., *IEEE Photonics Technology Letters*, 11, no. 12, pp. 1539–1541, 1999, © IEEE.)
- Distributed Bragg Reflectors (DBR) mirrors require very precise growth control. Refreactive index is varied as much as possible (while still remaining electrically conductive) and must be a precise fraction of a wavelength

DFB LASER



The distributed feedback (DFB) laser uses a grating to provide continuous feedback along the laser cavity.