ROYAL INSTITUTE OF TECHNOLOGY

Semiconductor Devices
Spring 2019

Lecture 6

This Lecture

- Reading
  - Chapter 4, part II, mainly 4.12 and 4.13
- Concepts:
  - Solar cells, photovoltaic devices
  - Light-emitting diodes (LED)

Blue LEDs

The Nobel Prize in Physics 2014

Photo: Yasuo Nakamura/Meijo University

Isamu Akasaki

Prize share: 1/3

Photo: Nagoya University

Hiroshi Amano

Prize share: 1/3

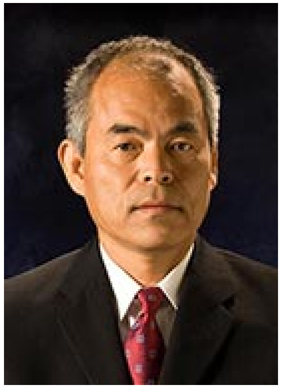


Photo: Randall Lamb, UCSB

Shuji Nakamura

Prize share: 1/3

The Nobel Prize in Physics 2014 was awarded jointly to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura *"for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources"*.

http://www.nobelprize.org/mediaplayer/index.php?id=2370

Part II: Application to Optoelectronic Devices

4.12 Solar Cells

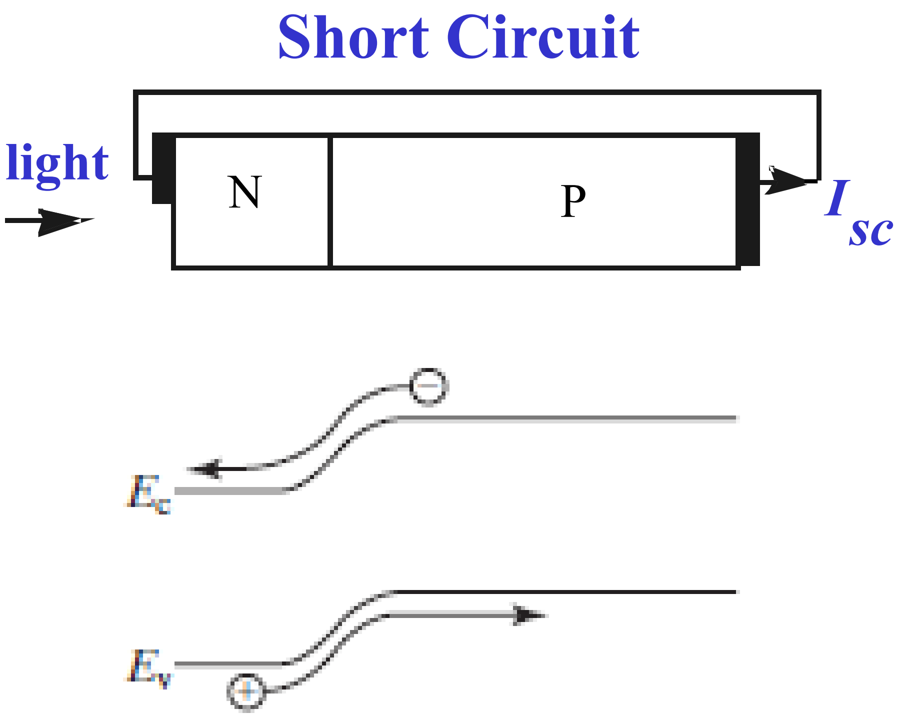
•***Solar Cells*** is also known as ***photovoltaic cells*****.**

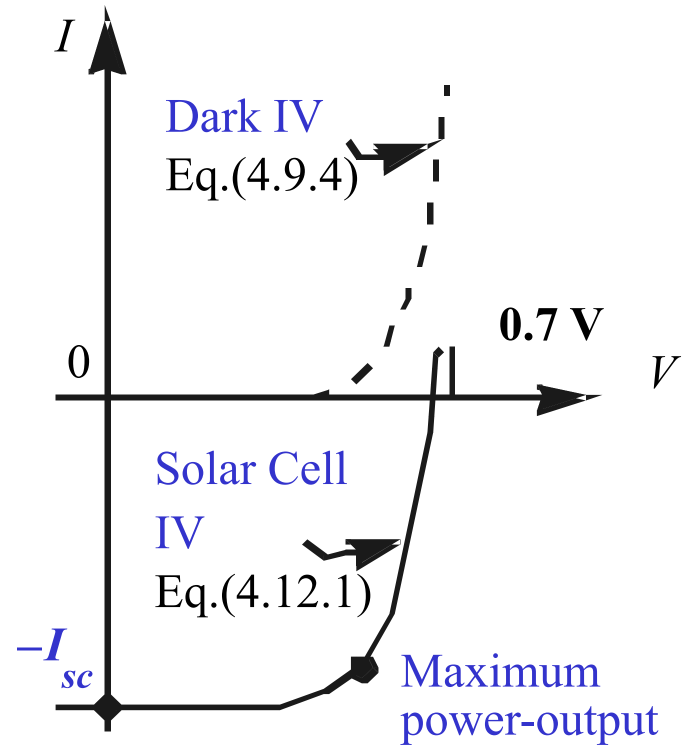
•Converts sunlight to electricity with 10-30% conversion efficiency.

•1 m^2 solar cell generate about 150 W peak or 25 W continuous power.

•Low cost and high efficiency are needed for wide deployment.

4.12.1 Solar Cell Basics

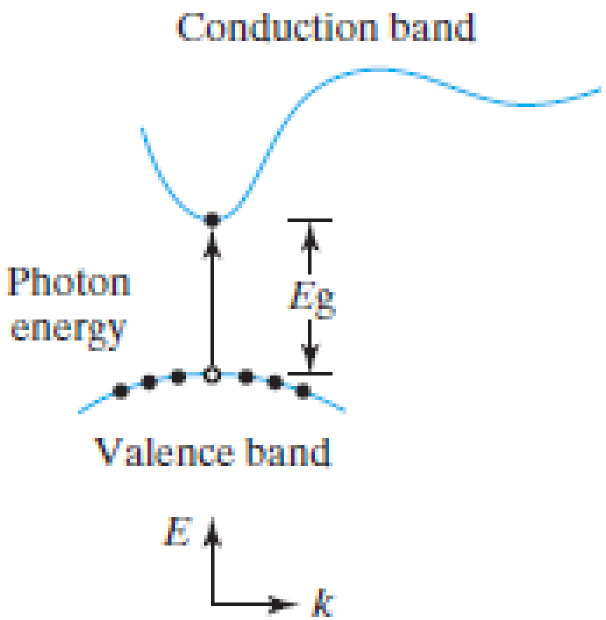




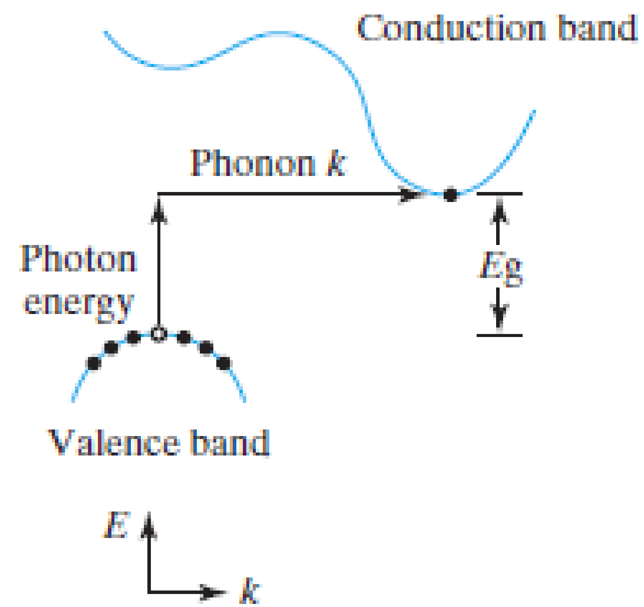
$$I = I_0(e^{qV/kT} - 1) - I_{sc}$$

Direct-Gap and Indirect-Gap Semiconductors

- Electrons have both particle and wave properties.
- An electron has energy E and wave vector k.

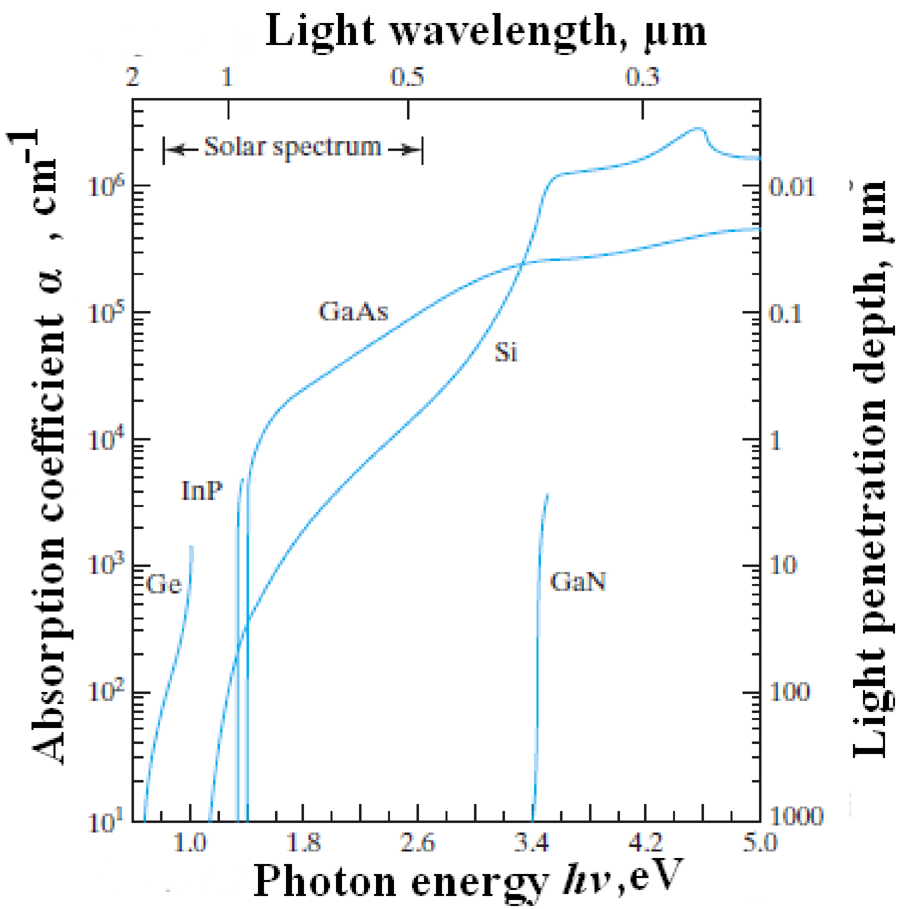


direct-gap semiconductor



indirect-gap semiconductor

4.12.2 Light Absorption



$$\text{Light intensity (x)} \propto e^{-\alpha x}$$

***α(1/cm)*: absorption coefficient**

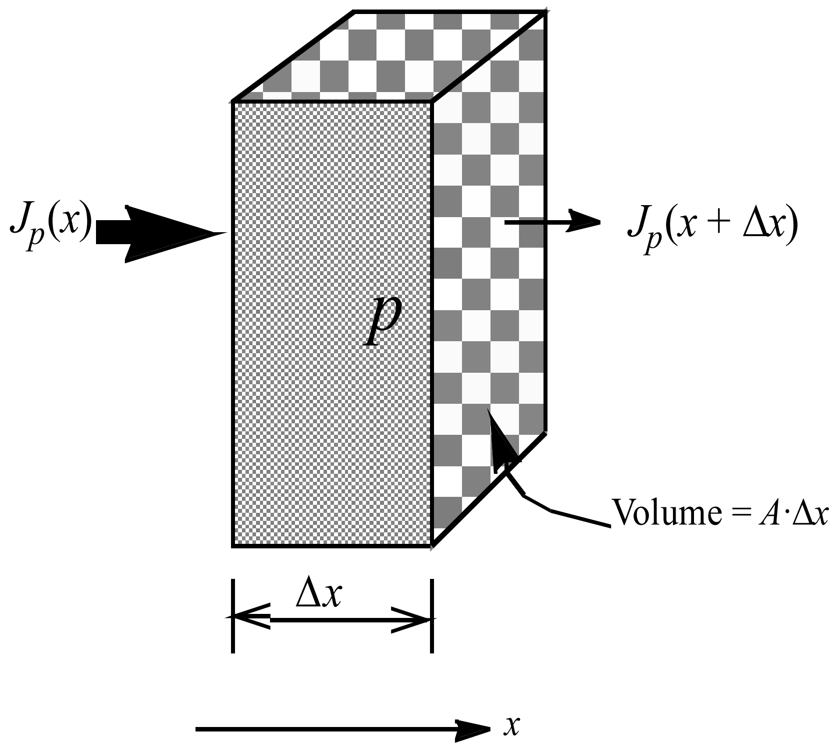
$1/\alpha$: light penetration depth

$$\text{Photon Energy (eV)} = \frac{hc}{\lambda}$$

$$= \frac{1.24}{\lambda} (\mu m)$$

A thinner layer of direct-gap semiconductor can absorb most of solar radiation than indirect-gap semiconductor. But Si…

4.12.3 Short-Circuit Current and Open-Circuit Voltage



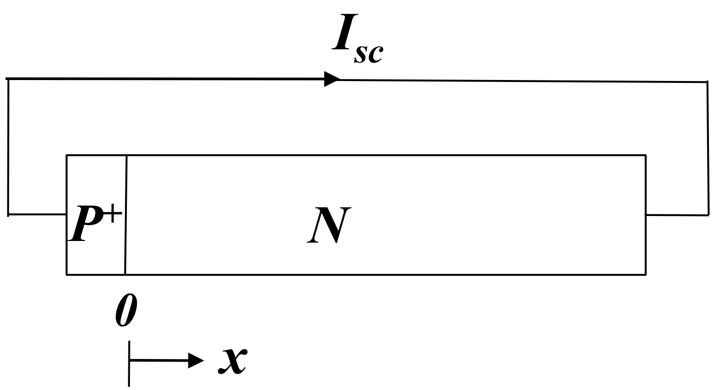
If light shines on the N-type semiconductor and generates holes (and electrons) at the rate of G $s^{-1}cm^{-3}$,

$$\frac{d^2 p'}{dx^2} = \frac{p'}{L_p^2} - \frac{G}{D_p}$$

If the sample is uniform (no PN junction),
$d^2p'/dx^2 = 0 \rightarrow p' = GL_p^2/D_p = G\tau_p$

Solar Cell Short-Circuit Current, I_{sc}

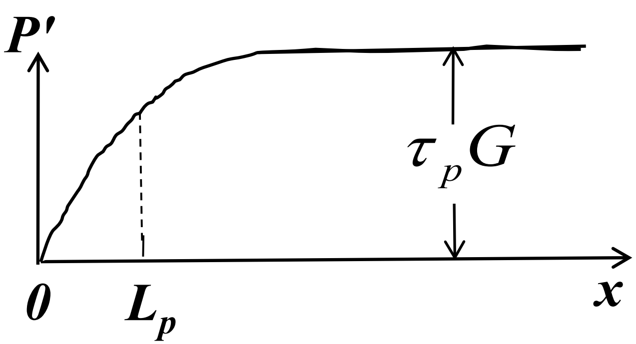
Assume very thin P+ layer and carrier generation in N region only.



$$p'(\infty) = L_p^2 \frac{G}{D_p} = \tau_p G$$

$$p'(0) = 0$$

$$p'(x) = \tau_p G(1 - e^{-x/L_p})$$



$$J_p = -qD_p \frac{dp'(x)}{dx} = q\frac{D_p}{L_p}\tau_p G e^{-x/L_p}$$

$$I_{sc} = AJ_p(0) = AqL_p G$$

G is really not uniform. L_p needs be larger than the light penetration depth to collect most of the generated carriers.

Open-Circuit Voltage

- Total current is I_{SC} plus the PV diode (dark) current:

$$I = Aq\frac{n_i^2}{N_d}\frac{D_p}{L_p}(e^{qV/kT} - 1) - AqL_pG$$

- Solve for the open-circuit voltage (V_{oc}) by setting *I=0*

(assuming $e^{qV_{oc}/kT} >> 1$)

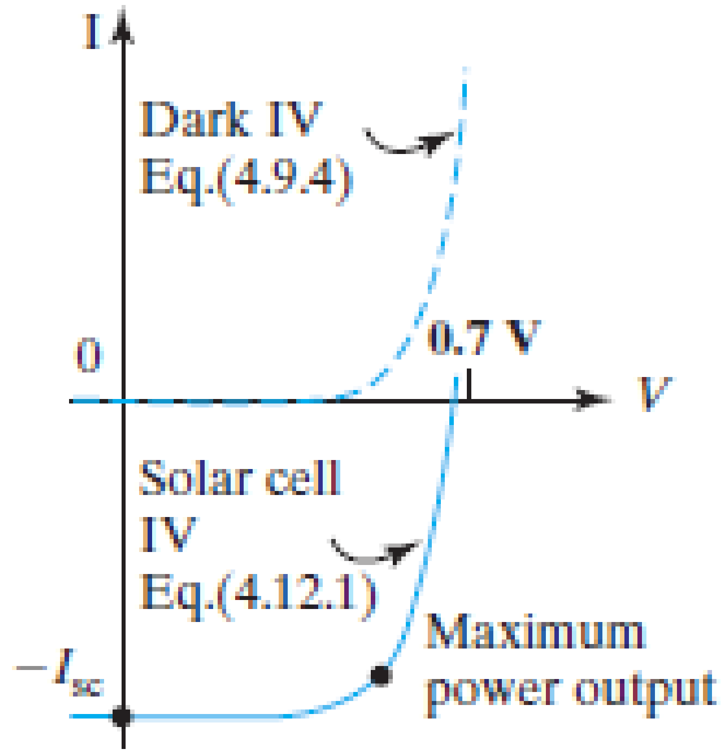
$$0 = \frac{n_i^2}{N_d}\frac{D_p}{L_p}e^{qV_{oc}/kT} - L_pG$$

$$V_{oc} = \frac{kT}{q}\ln(\tau_p G N_d / n_i^2)$$

How to raise V_{oc}?

4.12.4 Output Power

A particular operating point on the solar cell I-V curve maximizes the output power (I ×V).



$$\text{Output Power} = I_{sc} \times V_{oc} \times FF$$

•Si solar cell with 15-20% efficiency dominates the market now

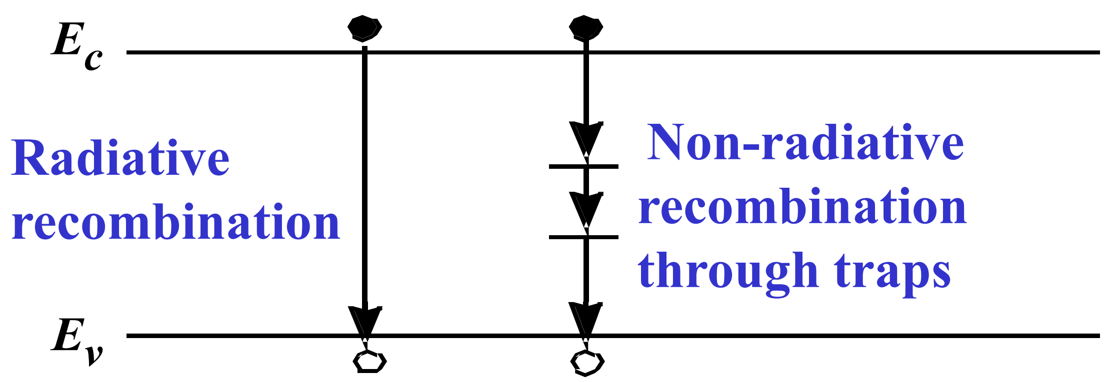
•Theoretically, the highest efficiency (~24%) can be obtained with 1.9eV >Eg>1.2eV. Larger Eg lead to too low Isc (low light absorption); smaller Eg leads to too low Voc.

•***Tandem solar cells*** gets 35% efficiency using large ***and*** small Eg materials tailored to the short and long wavelength solar light.

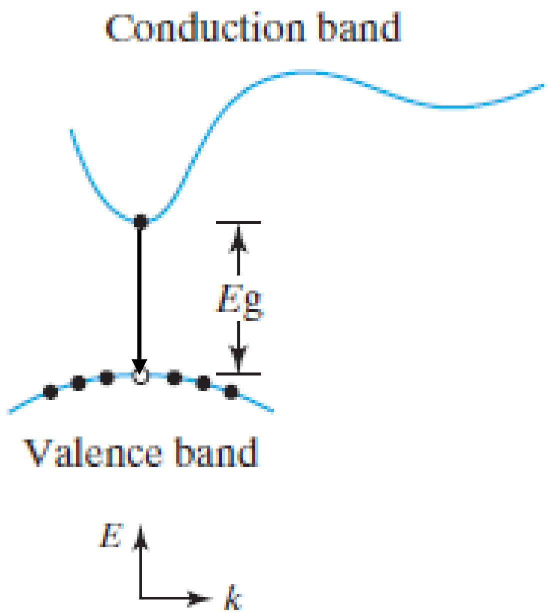
4.13 Light Emitting Diodes and Solid-State Lighting

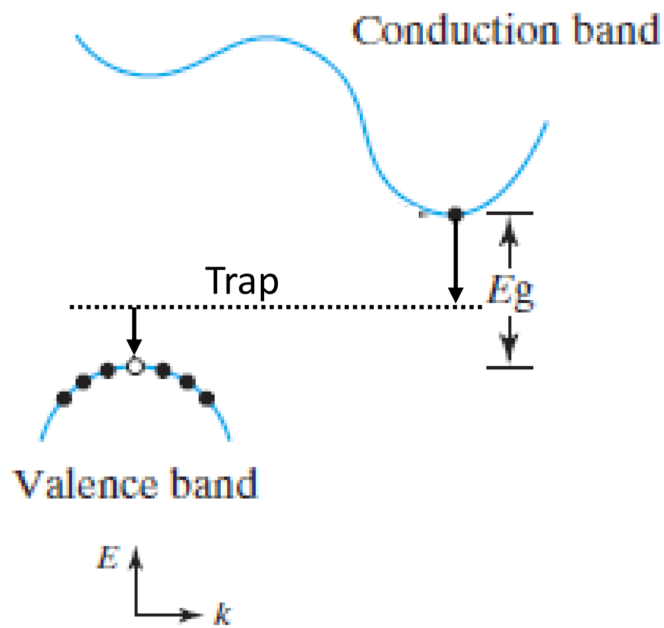
Light emitting diodes (LEDs)

- LEDs are made of compound semiconductors such as InP and GaN.
- Light is emitted when electron and hole undergo ***radiative recombination***.



Direct and Indirect Band Gap





Direct band gap
Example: GaAs

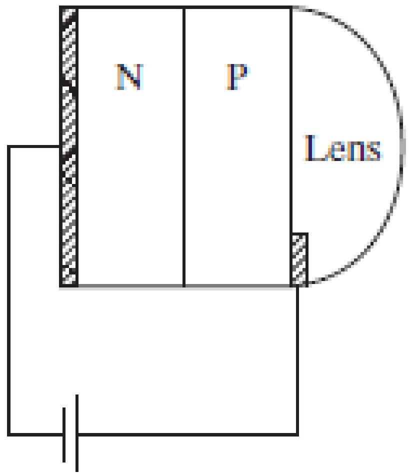
Direct recombination is efficient as k conservation is satisfied.

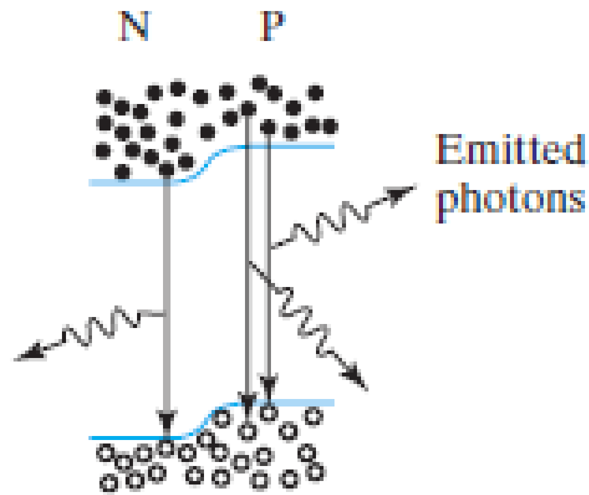
Indirect band gap
Example: Si

Direct recombination is rare as k conservation is not satisfied

Modern Semiconductor Devices for Integrated Circuits (C. Hu)

4.13.1 LED Materials and Structure





$$\text{LED wavelength}\,(\mu\,\text{m}) = \frac{1.24}{\text{photon energy}} \approx \frac{1.24}{E_g(eV)}$$

4.13.1 LED Materials and Structure

	$E_g(eV)$	Wavelength (μm)	Color	Lattice constant (Å)
InAs	0.36	3.44		6.05
InN	0.65	1.91	infrared	3.45
InP	1.36	0.92		5.87
GaAs	1.42	0.87	Red Yellow	5.66
GaP	2.26	0.55	Green Blue	5.46
AlP	3.39	0.51		5.45
GaN	2.45	0.37		3.19
AlN	6.20	0.20	UV	3.11

Light-emitting diode materials

compound semiconductors

binary semiconductors:

- Ex: GaAs, efficient emitter

ternary semiconductor :

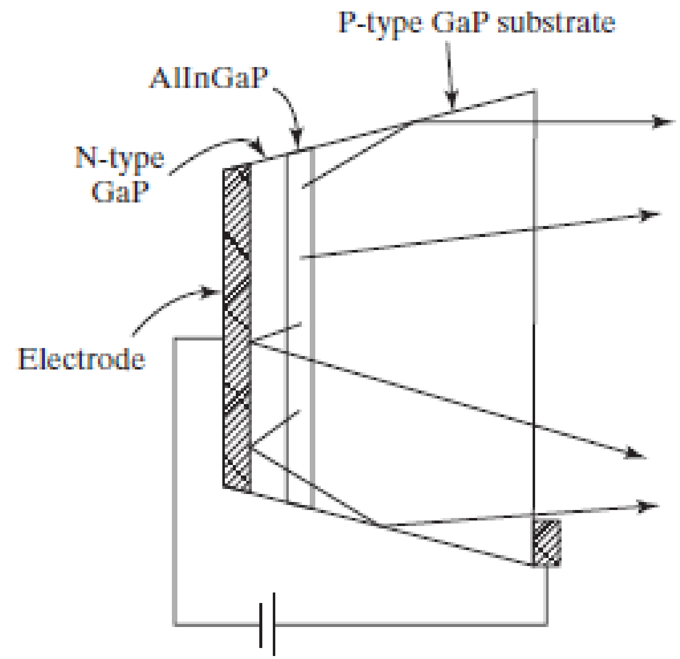
- Ex: $GaAs_{1-x}P_x$, tunable E_g (to vary the color)

quaternary semiconductors:

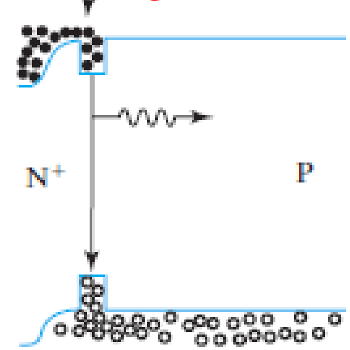
- Ex: AlInGaP , tunable E_g and lattice constant (for growing high quality epitaxial films on inexpensive substrates)

Common LEDs

Spectral range	Material System	Substrate	Example Applications
Infrared	InGaAsP	InP	Optical communication
Infrared -Red	GaAsP	GaAs	Indicator lamps. Remote control
Red-Yellow	AlInGaP	GaA or GaP	Optical communication. High-brightness traffic signal lights
Green-Blue	InGaN	GaN or sapphire	High brightness signal lights. Video billboards
Blue-UV	AlInGaN	GaN or sapphire	Solid-state lighting
Red-Blue	Organic semicon-ductors	glass	Displays



AlInGaP Quantun Well



4.13.2 Solid-State Lighting

luminosity (lumen, lm): a measure of visible light energy normalized to the sensitivity of the human eye at different wavelengths

Incandescent lamp	Compact fluorescent lamp	Tube fluorescent lamp	**White LED**	Theoretical limit at peak of eye sensitivity (λ=555nm)	Theoretical limit (white light)
17	**60**	**50-100**	**90-?**	**683**	**~340**

Luminous efficacy of lamps in lumen/watt

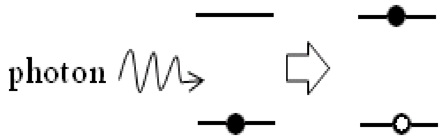
Organic Light Emitting Diodes (OLED) :
has lower efficacy than nitride or aluminide based compound semiconductor LEDs.

Terms: **luminosity** measured in **lumens**. **luminous efficacy,**

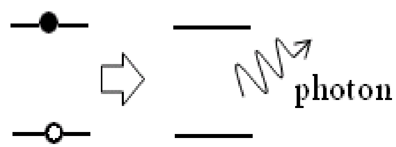
4.14 Diode Lasers

4.14.1 Light Amplification

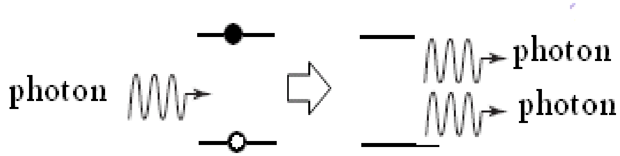
(a) Absorption



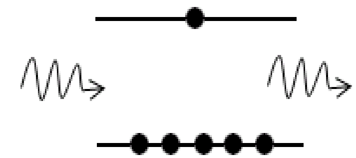
(b) Spontaneous Emission



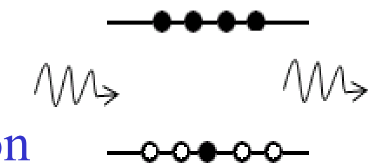
(c) Stimulated Emission



(d) Net Light Absorption



(e) Net Light Amplification



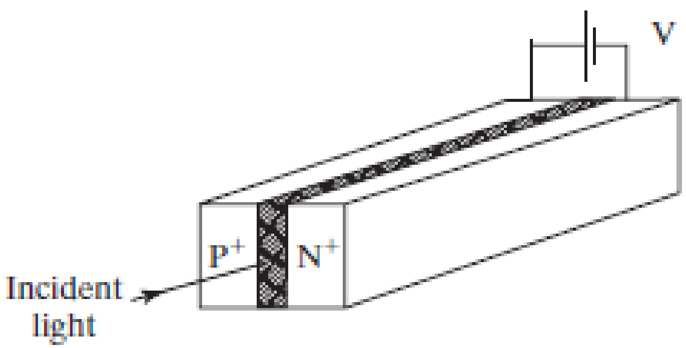
Light amplification requires *population inversion*: electron occupation probability is larger for higher E states than lower E states.

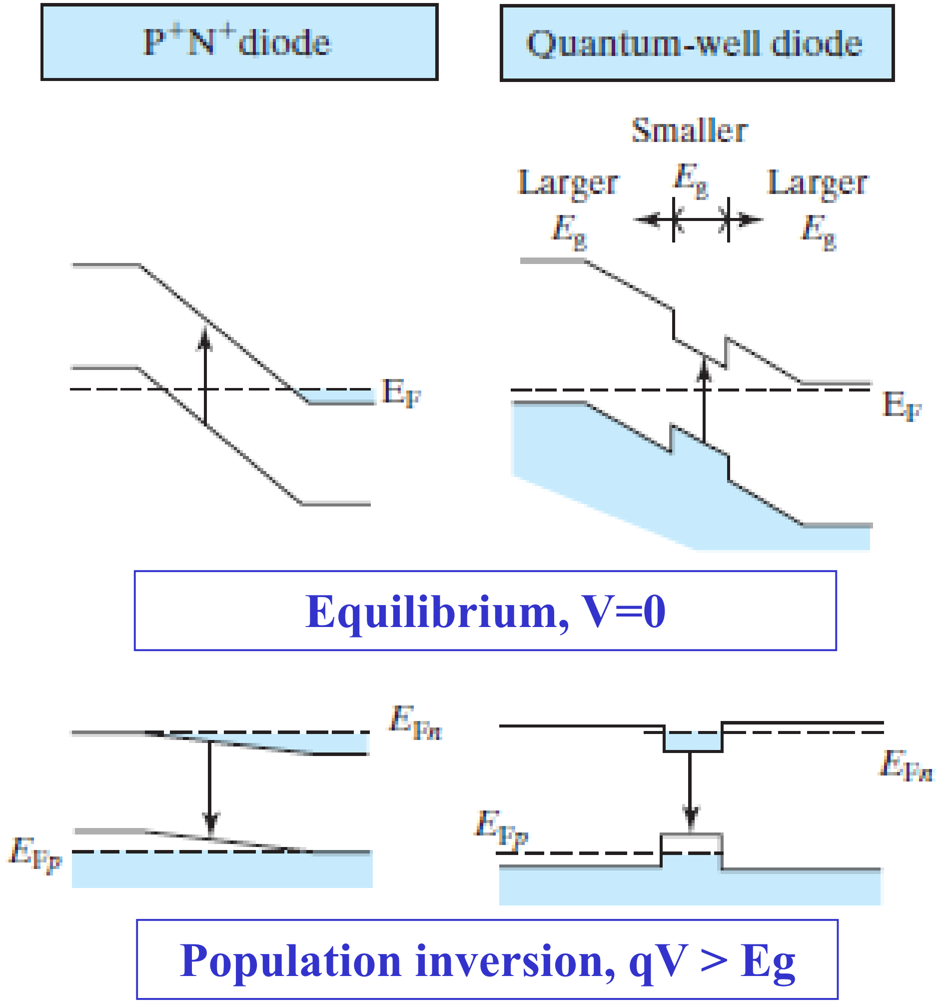
Stimulated emission: emitted photon has identical frequency and directionality as the stimulating photon; light wave is amplified.

4.14.1 Light Amplification in PN Diode

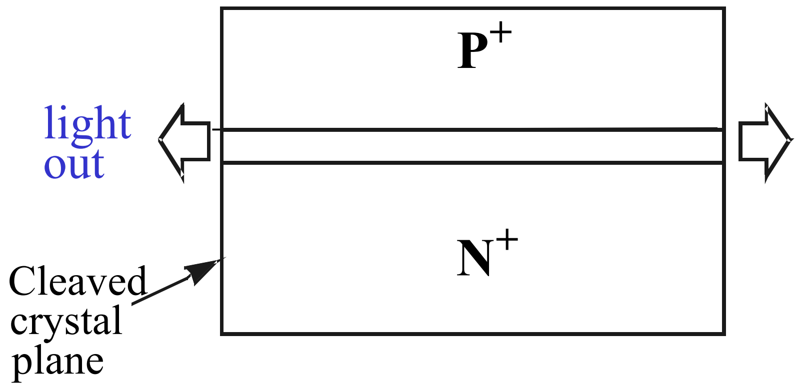
Population inversion is achieved when

$$qV = E_{fn} - E_{fp} > E_g$$





4.14.2 Optical Feedback and Laser



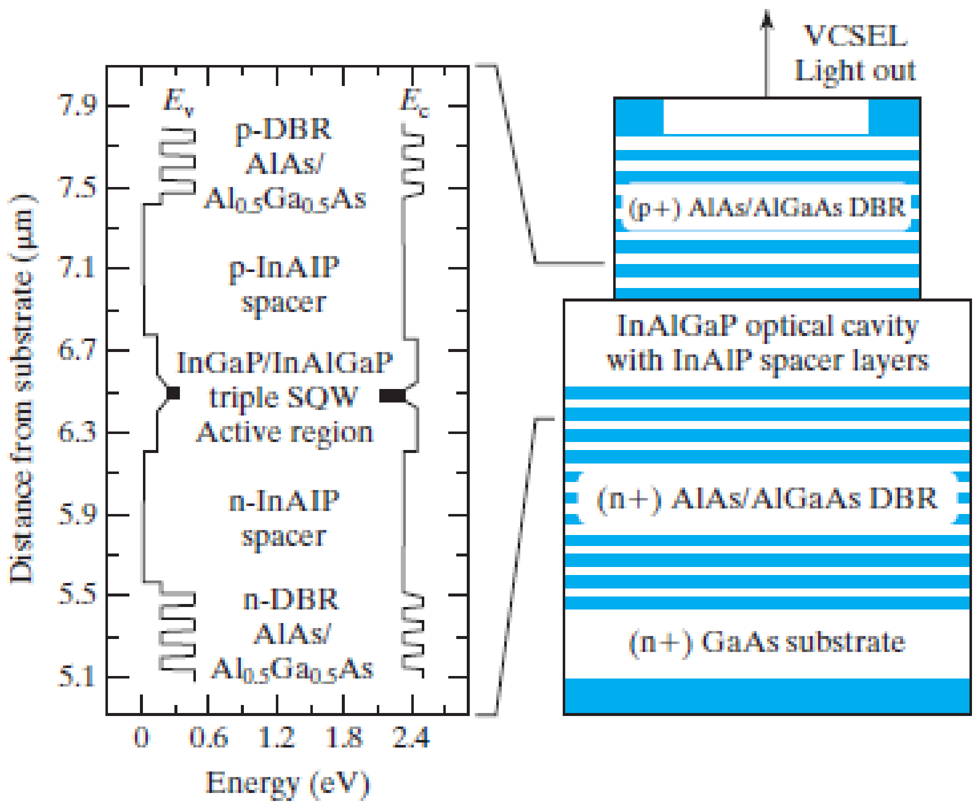
***Laser threshold* is reached (light intensity grows by feedback) when**

$$R_1 \times R_2 \times G \geq 1$$

•**R1, R2**: reflectivities of the two ends
•**G** : light amplification factor (gain) for a round-trip travel of the light through the diode

Light intensity grows until $R_1 \times R_2 \times G = 1$, when the light intensity is just large enough to stimulate carrier recombinations at the same rate the carriers are injected by the diode current.

4.14.2 Optical Feedback and Laser Diode



- ***Distributed Bragg reflector (DBR)*** **reflects light with multi-layers of semiconductors.**
- ***Vertical-cavity surface-emitting laser (VCSEL)*** **is shown on the left.**
- **Quantum-well laser has smaller threshold current because fewer carriers are needed to achieve population inversion in the small volume of the thin small-*Eg* well.**

4.14.3 Laser Applications

***Red* diode lasers**: *CD, DVD reader/writer*

***Blue* diode lasers**: *Blu-ray DVD (higher storage density)*

***1.55 µm infrared* diode lasers:** *Fiber-optic communication*

4.15 Photodiodes

Photodiodes: Reverse biased PN diode. Detects photo-generated current (similar to Isc of solar cell) for optical communication, DVD reader, etc.

Avalanche photodiodes: Photodiodes operating near avalanche breakdown amplifies photocurrent by impact ionization.