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XMUT204 Electronics Design

Lecture 2e - Special Purpose Diodes (Photo Diodes and LEDs)

Overview

1. Special purpose diodes
2. Photo diodes
3. Introduction to LED
4. Characteristics of LED
5. Manufacturing of LED

Special Purpose Diodes

- A large number of special function diodes or non-standard diodes can be found in the market.

- These devices show some deviation from the normal p-n junction structure in order to obtain a specific property or device characteristic.

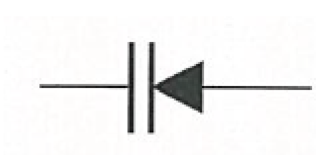
- Will first look at a few typical examples (there are many more) and then we will look in detail at three types specifically – Photo diodes, LEDs, and solar cells.

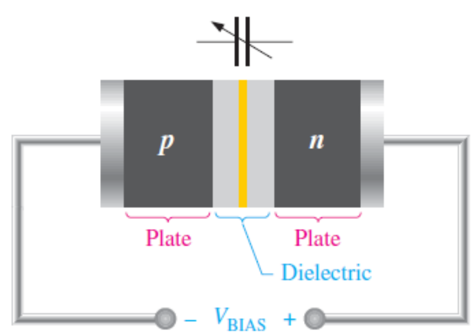
Zener diodes

- Manufactured to produce a controlled and repeatable reverse bias breakthrough.
- Used as voltage references or voltage regulators. Done in previous lecture.

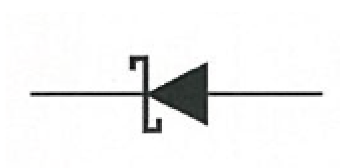
Varactor diodes

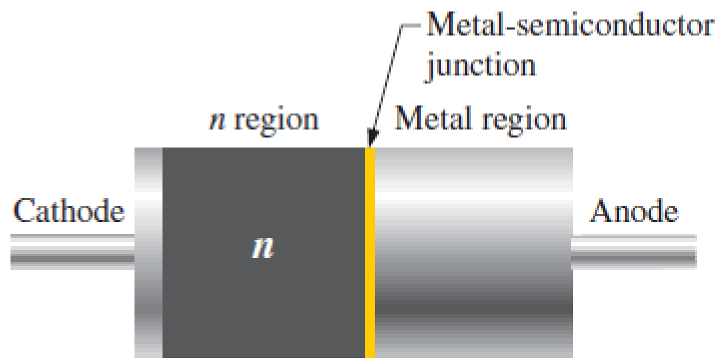
- The depletion layer of the p-n junction acts as a capacitor.
- In reverse bias, we can control the amount of capacitance – thus use a varactor as a voltage controlled capacitor.





Schottky diodes – not a p-n junction but a metal-semiconductor junction that behaves similar to a p-n junction.



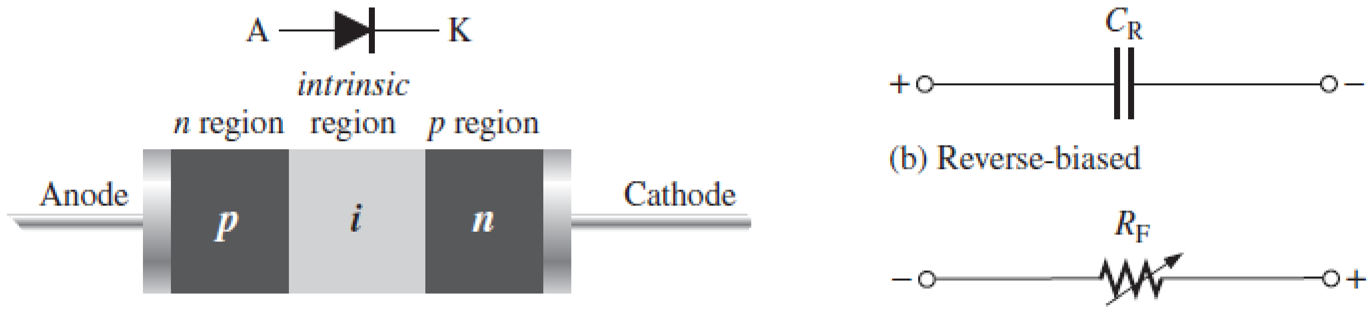


- Typically used in high frequency and fast switching applications (e.g. high speed digital integrated circuits).

- As there is no p-n junction, there is no depletion layer and uses only majority carrier current.

- Voltage drop over the junction is considerably smaller at ~ 0.3 V.

PIN diodes – (p layer – intrinsic layer – n-layer):

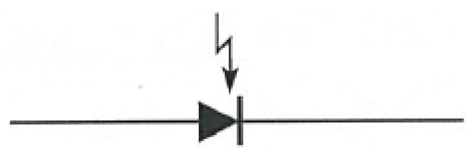


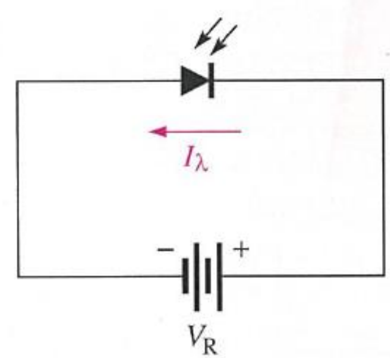
(a) Construction
(b) Reverse-biased
(c) Forward-biased

- Consists of heavily doped p and n regions separated by an intrinsic (undoped) region.
- When in reverse bias, the pin diodes acts as a constant capacitance.
- When in forward bias, the diode acts as a current controlled resistance element – resistance decreases with increasing current.
- Used as high frequency switches or as photodetectors in optical systems.

Photodiodes

- Used as detectors for incident light, so needs a transparent window in packaging to allow light to fall on semiconductor.
- Operated in reverse bias, where p-n junction would typically have a small reverse bias current from thermally generated carriers swept across the depletion region (dark current).
- When light falls on material, the number of carriers will increase and the dark current (or now the light current!) will dramatically increase.



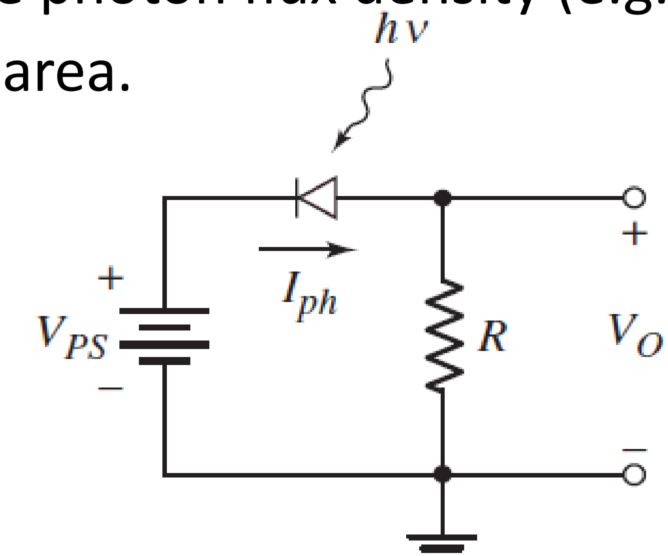


Photodiodes

- For a given photo diode, the photocurrent is:

$$I_{ph} = \eta e \Theta A$$

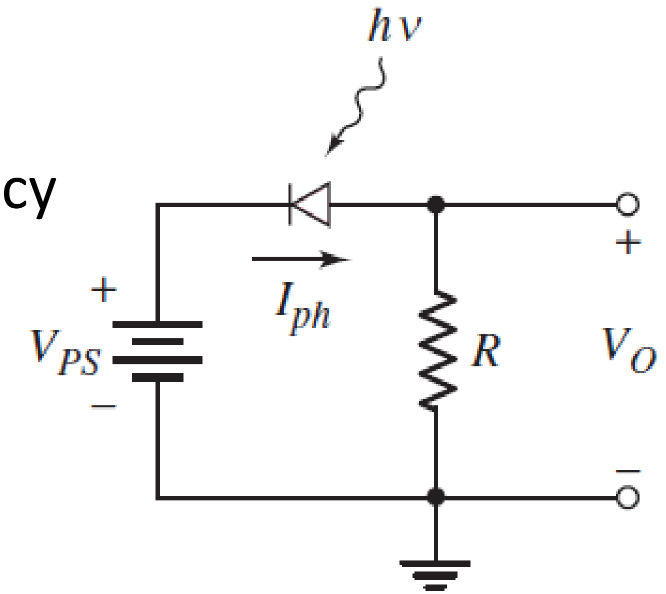
Where: η is the quantum efficiency, e is the electronic charge, Θ is the photon flux density (e.g. in $\mathrm{cm}^2 - \mathrm{s}$), and A is the junction area.



- Assuming that the reverse-bias voltage across the diode is constant e.g. voltage drop across *R* induced by the photocurrent must be small, or the resistance *R* is small.

Example for Tutorial 1 - Photodiodes

For the photodiode shown in the figure, assume the quantum efficiency is 1, the junction area is $10^{-2}\ \mathrm{cm}^2$, and the incident photon flux is $5 \times 10^{17}\mathrm{cm}^{-2} - s^{-1}$. Calculate the photocurrent generated in a photodiode. [5 marks]



Solution

From the equation below, the photocurrent is

$$I_{ph} = \eta e \Theta A$$

$$= (1)(1.6 \times 10^{-19})(5 \times 10^{17})(10^{-2}) = 0.8\ \mathrm{mA}$$

Prequels to LEDs and solar cells

(1) Optical absorption and emission from semiconductors.

- Up to now considered the generation of carriers by thermal energy. However, carriers can also be generated by optical stimulation.
- Light of wavelength λ will have a photon energy E (note: h = Planck's constant of 6.62 x 10^{-34}, f = frequency, v = speed of light, and λ = photon's wavelength):

$$E = hf = \frac{hv}{\lambda}$$

- If this energy is incident on a semiconductor, the photon energy will be absorbed by the electrons and if the energy is large enough, excitation of electrons from valence band to conduction band will take place.

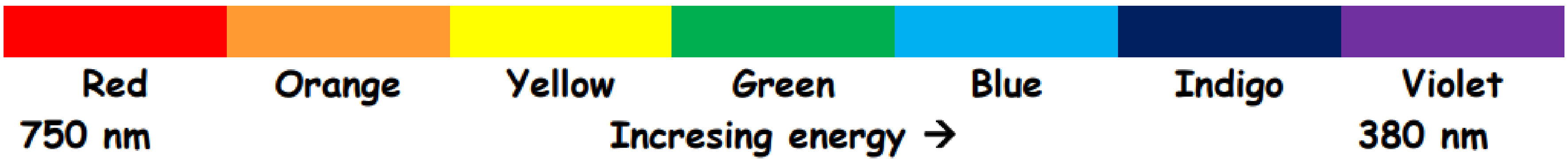
- For optical absorption to take place the incident photon energy must be at least equal the bandgap energy.
- This wavelength is known as the cut-off wavelength (λ_{co}):

$$E_g(eV) = \frac{hv}{\lambda_{CO}}$$

- If the energy of incident light is less than the bandgap, it will not be absorbed by the semiconductor.
- If it is equal to or greater than the bandgap, it will be strongly absorbed as the optical energy and used to generate electron – hole pairs (EHP), changing the carriers concentration in the material.

Example for Tutorial 2 – Energy and Colour in Light

The following figure outlines the colours of the light and their corresponding wavelengths.



a. Green LED has a wavelength of approximately 500 nm. What are the frequency and the energy in Joules of one photon of this light? [5 marks]

b. The yellow light emitted by the sodium lamps in streetlights has wavelengths of 589.6 nm and 589.0 nm. What are the frequency and the energy of one photon of the 589.0 nm light? Comment on the difference with the result obtained in part (a). [7.5 marks]

Answer

a. For the given green LED, λ = 500 nm = 5×10^{-7} m, the frequency of this green light is:

$$f = \frac{v}{\lambda}$$

$$= \frac{3 \times 10^{8}}{5 \times 10^{-7}} = 6.0 \times 10^{14} \text{ Hz}$$

The energy of one photon of green light is:

$$E = hf$$

$$= (6.62 \times 10^{-34})(6.0 \times 10^{14}) = 3.97 \times 10^{-19} \text{ J/photon}$$

b. For the given yellow sodium lamps, λ = 589 nm = 5.89×10^{-7} m, the frequency of the yellow light is:

$$f = \frac{v}{\lambda} = \frac{3 \times 10^{8}}{5.89 \times 10^{-7}} = 5.09 \times 10^{14}\ \text{Hz}$$

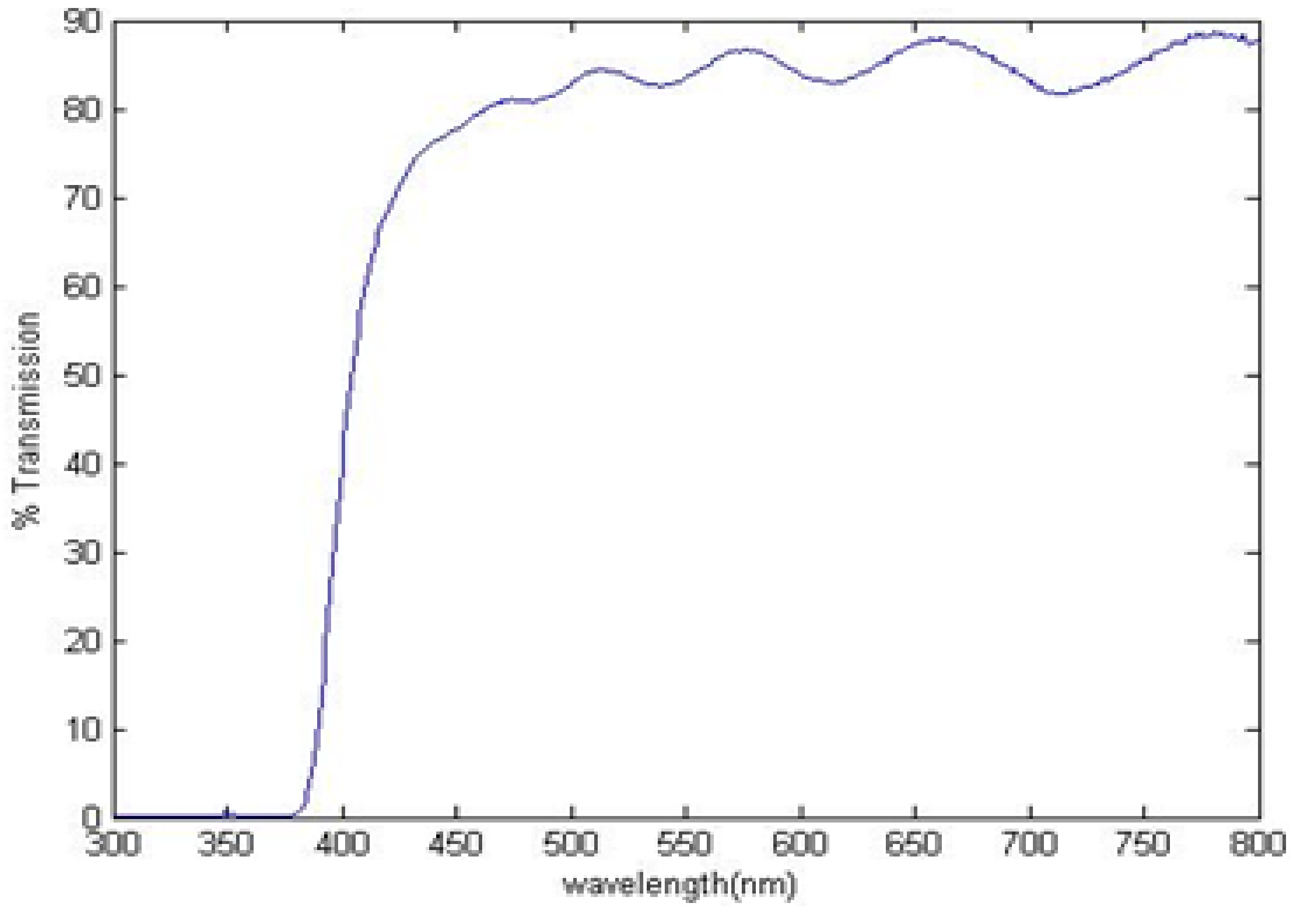
The energy of one photon of yellow light is:

$E = hf$

$= (6.62 \times 10^{-34})(5.09 \times 10^{14}) = 3.37 \times 10^{-19}$ J/photon

As expected, green light has more energy than yellow light.

- A typical transmission spectrum for a semiconductor.
- Observe change of % transmission at 400 nm wavelength.



Note that spectrum of visible light: Violet (400 nm) <-> Red (700 nm).

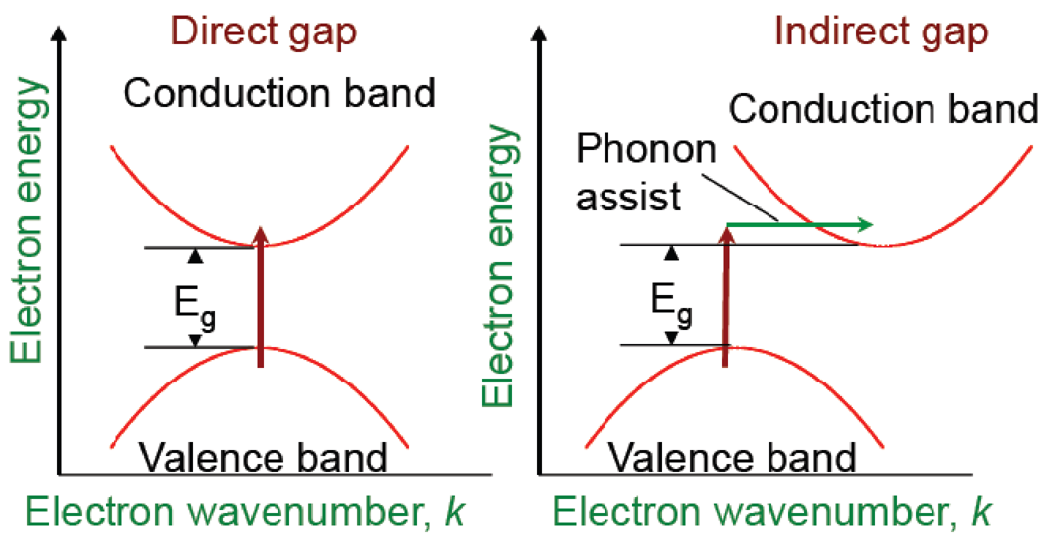
- The reverse process to optical absorption will also happen – when we have an electron hole pair that will recombine, the electron will loose energy by dropping down to the valence band.
- This energy will be emitted as optical radiation.
- As the electron drops from the top bottom of the conduction band to the bottom of the valence band, it will emit light with an energy E_g – characteristic of the valence band of the material.
- As this optical energy is given by $E_g = hf = hv/\lambda$, the emitted radiation will have a wavelength as defined by the energy gap of the material. Again a shortcut formula is:

$$E_g(eV) = \frac{hv}{\lambda_{CO}} = \frac{1.24}{\lambda_{CO}(\mu m)} = \frac{1240}{\lambda_{CO}(nm)}$$

Prequels to LEDs and solar cells

(2) Direct vs Indirect bandgaps.

- Based on their bandgaps, all semiconductors can be classed as either direct bandgap or indirect bandgap materials.
- This describes whether the top of the valence band is aligned with the bottom of the conduction band in momentum space.



- The type of bandgap (direct or indirect) determines the ease and efficiency with which optical absorption and emission will take place in the material.
- In direct bandgap materials, absorption and transmission can take with ease and high efficiency, as the electron does not need a change in momentum to go between valence and conduction band.
- In indirect bandgap materials, optical absorption and emission are relatively difficult and inefficient processes, as the electron will always need a change of momentum to make a transition.
- This momentum change can only come from a phonon assist (a vibration of the lattice = heat).

- Any semiconductor with an indirect bandgap is thus a poor electro-optical material due to the very low efficiency with which optical radiation is absorbed or emitted.
- Silicon, for all it's highly desired characteristics which allows us to easily make integrated electronic circuits has an indirect bandgap and is this not the material we will use to make LEDs from.
- LEDs are typically manufactured from a range of so called compound semiconductors which (nearly all) have a direct bandgap.
- The wavelength of emission will then be determined by the bandgap of the semiconductor material.

Prequels to LEDs and solar cells

(3) Compound semiconductors.

- Compound semiconductors are formed when we combine two or more elements to create binary (two element), ternary (three element), or quaternary (four element) compounds.

- This allows a great deal of flexibility in tuning the properties of these materials, but is also technically very difficult to achieve and most of these compound semiconductors are orders more expensive than Si.

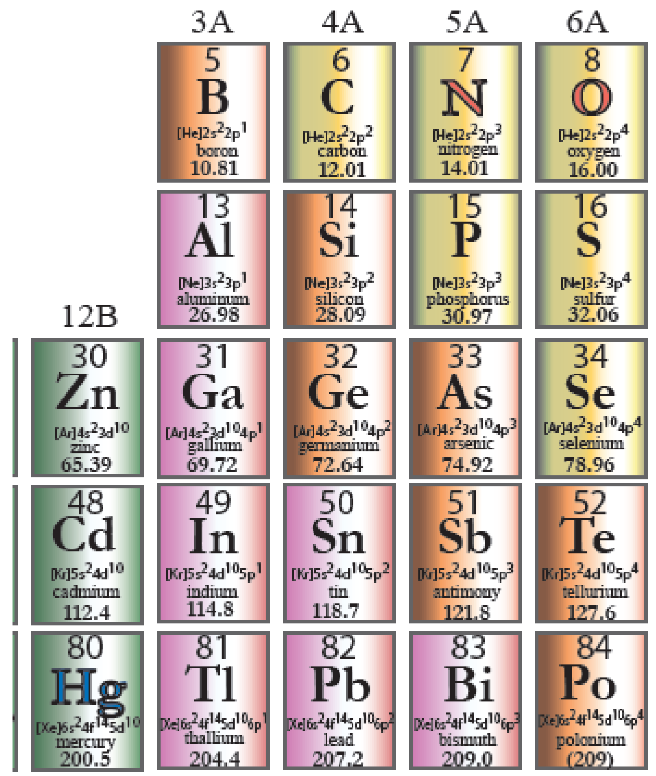
Example: Binary compounds

- We can form binary compounds by combining an element from two different groups of the periodic table:

  Group III and Group V
  GaAs, InSb

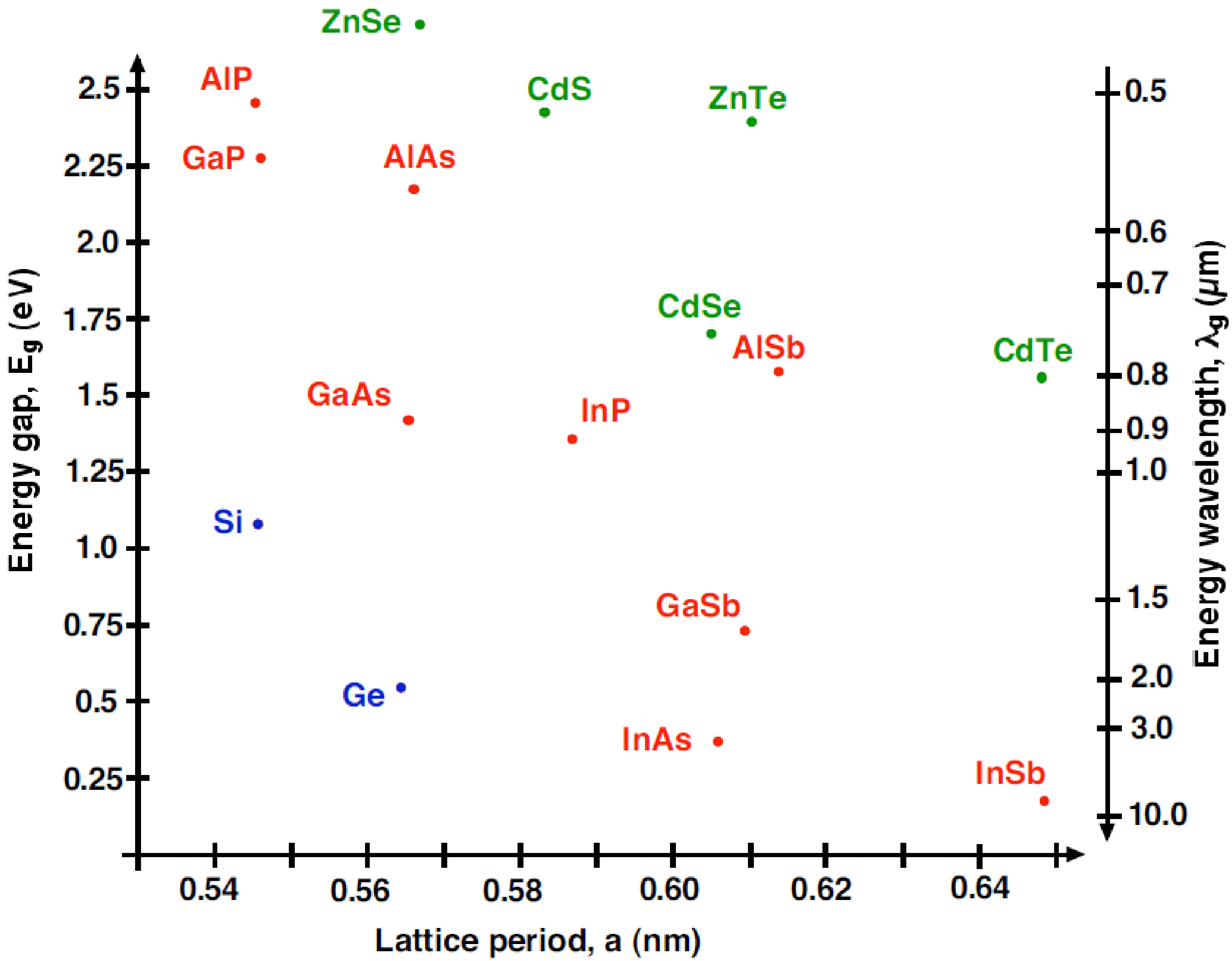
  Group II and Group VI
  ZnS, CdTe

  Group IV and Group VI
  PbS, SnTe



- Some of these are important as specialised semiconductors.

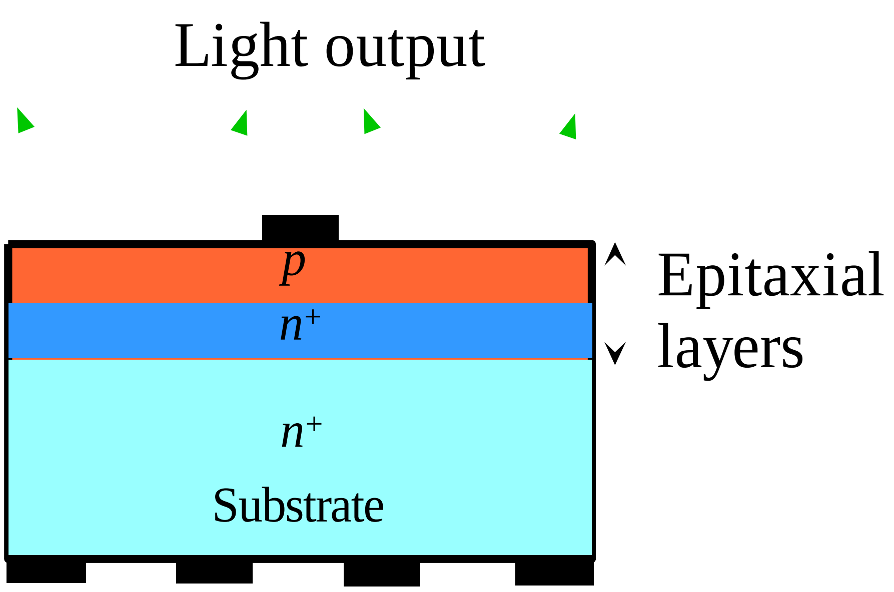
Binary compound semiconductors: Zinc-blende II-V's, II-VI's



Light Emitting Diodes

Structure and Operation

A p-n junction made from a direct bandgap semiconductor, so that electron-hole recombination results in the emission of a photon. The emitted photon energy (hv) is approximately equal to the bandgap E_g.

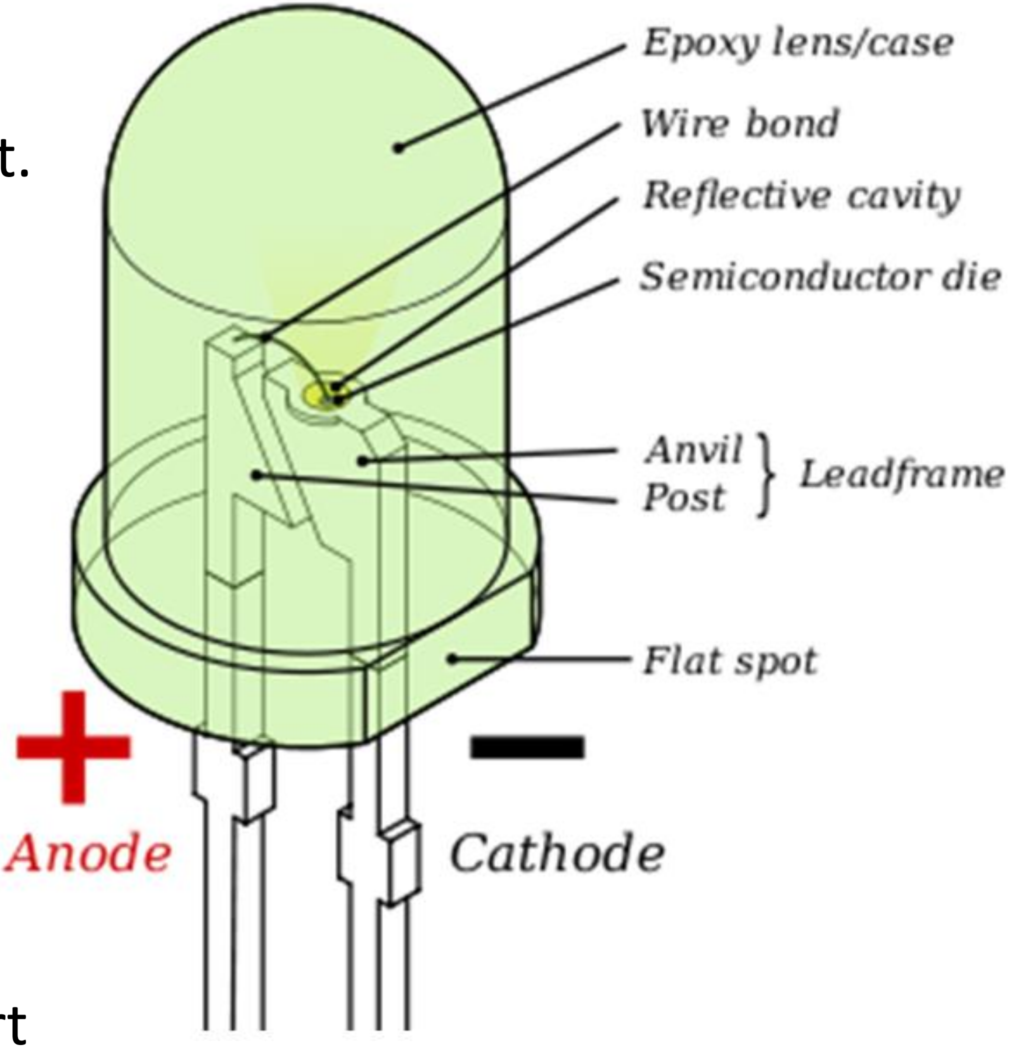


Simple homojunction device structure:

- **Substrate:** Thick semiconductor crystal to serve as mechanical support.
- **n^+ layer:** Heavily doped n layer grown epitaxially to lattice match the substrate.
- **p layer:** Grown epitaxially on n+ layer to form p-n junction.

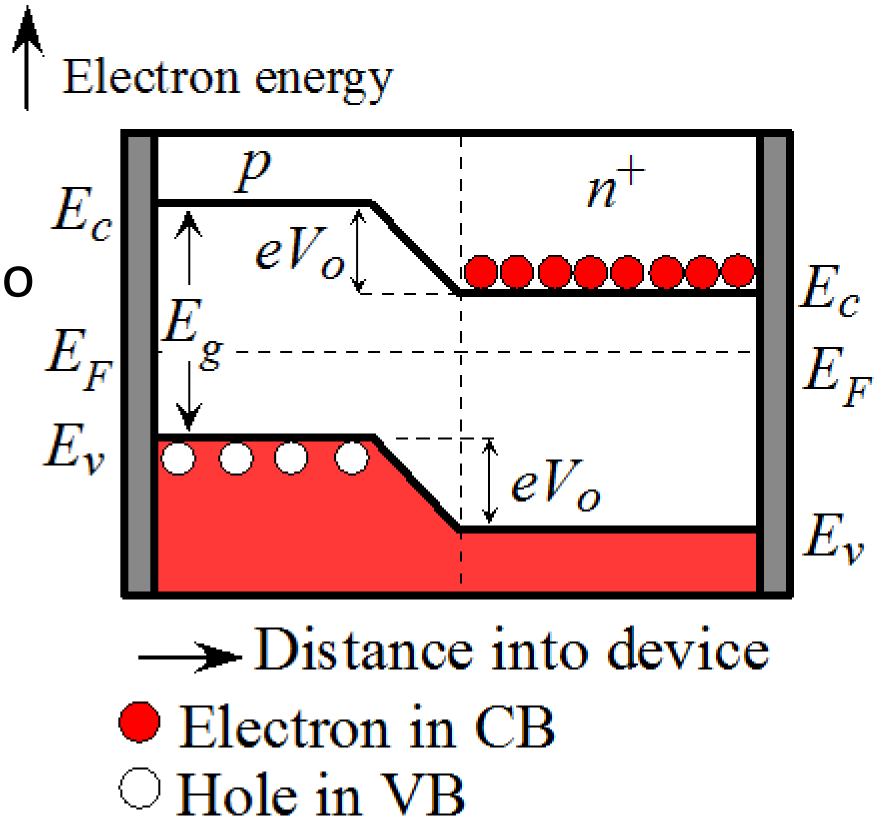
Physical Layout of Light Emitting Diodes

- Epoxy lens/case – protect the LED from environment.
- Wire bond – Connect die with lead frames.
- Reflective cavity – accumulate and direct lights generated.
- Semiconductor die.
- Lead frames – connect to circuit.
- Flat spot – provide support for horizontal set up.



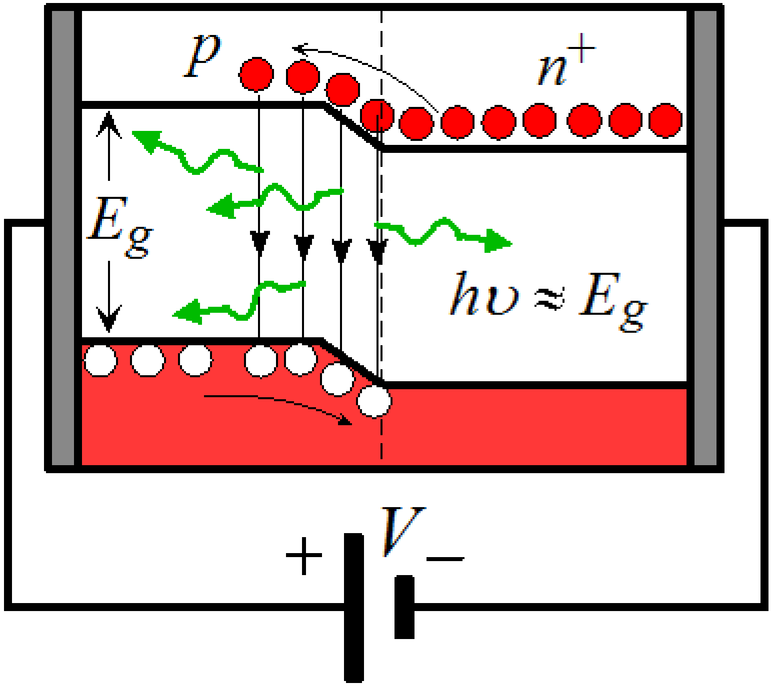
Assume p-n+ junction with no bias:

- Depletion layer predominantly on the p-side.
- Potential energy barrier = eV_0 for electrons to move from n- to p-side and for holes to move from p- to n-side.
- Potential barrier prevents concentration driven diffusion of majority carriers into depletion region.



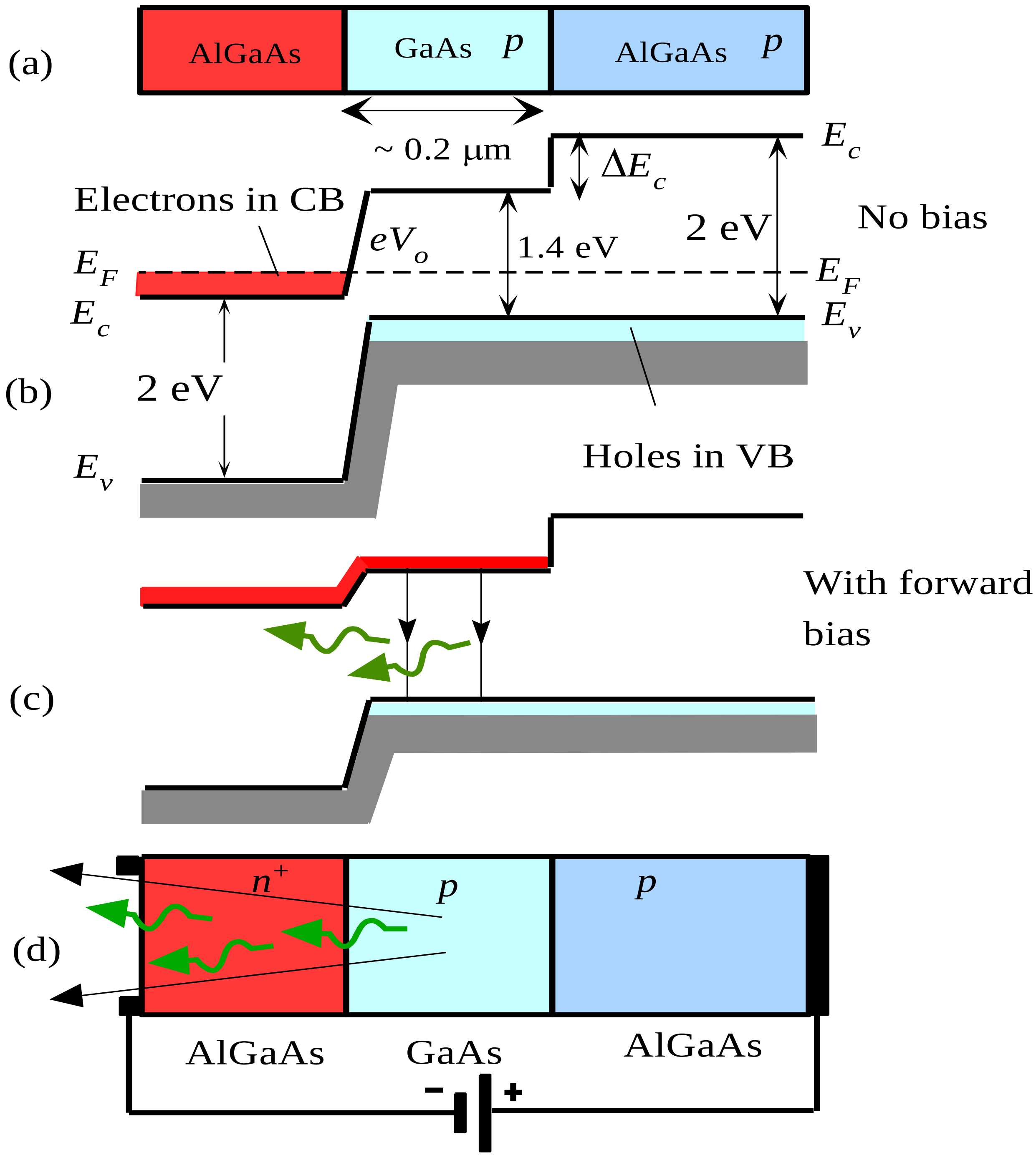
- Voltage V_0 is the built-in voltage across the junction.

Forward biased junction with V



- Built-in potential reduced to $V_0 - V$.
- This allows electrons from n-side to diffuse (injected) into p-side.
- Holes injected from p-side is much less due to the difference in doping levels.
- Electron-hole recombination in depletion region (+ electron drift length based volume from the depletion region) results in photon emission.
- The light emission due to EHP recombination due to the injection of minority carriers is called **injection electroluminescence**

- Photons emitted from EHP recombination will be in random direction – LED design has to ensure that maximum light emission from the junction in the desired direction – firstly make p layer very thin to ensure light is not re-absorbed.
- Much higher intensities can be achieved with **heterojunction** or **double heterojunction (DH) LED structures**. Now use materials with different bandgaps to form the p-n junction.
- A typical diagram for such a DH LED structure shown in the next slide - **not for examination in ECEN204**



(a)
AlGaAs
GaAs p
AlGaAs p
~ 0.2 μm
Electrons in CB
E_F
E_c
eV_o
E_c
ΔE_c
1.4 eV
2 eV
No bias
E_F
E_v
(b)
2 eV
E_v
Holes in VB
With forward bias
(c)
n^+
p
p
(d)
AlGaAs
GaAs
AlGaAs
−
+

Double heterojunction structure

- Fermi level (energy level) is still continuous through structure.
- Potential barrier eV_0 for electrons in in the CB of n+ AlGaAs to diffusing into p GaAs.
- The bandgap change between p AlGaAs and p GaAs results in a step change ΔE_g at this junction.
- This ΔE_g is effectively a potential barrier that prevents any electrons in the CB of the p GaAs from passing into the CB of the p AlGaAs.
- A forward bias will reduce potential barrier between n^+ AlGaAs and p GaAs as normal – allows injection of electrons from CB of n+ AlGaAs to be injected into p GaAs.

- The injected electrons are confined to the CB of the p GaAs as there is a potential barrier between p GaAs and p AlGaAs.

- The p AlGaAs layer then acts as confining layer and restricts injected electrons to the p GaAs layer.

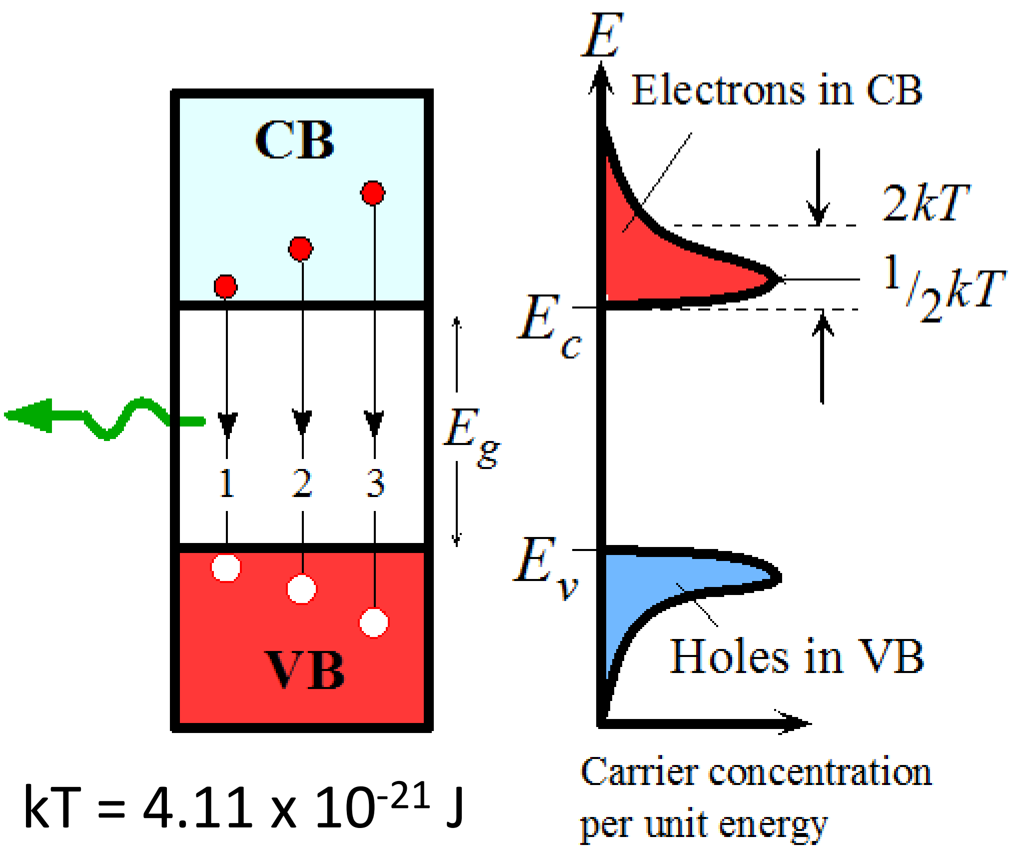
- Recombination of injected electrons with the holes already present in the p GaAs layer results in photon emission.

- Since the bandgap of AlGaAs > bandgap of GaAs, the emitted radiation does nor get reabsorbed in the AlGaAs.

- Light can be reflected at the back surface of the AlGaAs to increase light output.

LED Output Characteristics

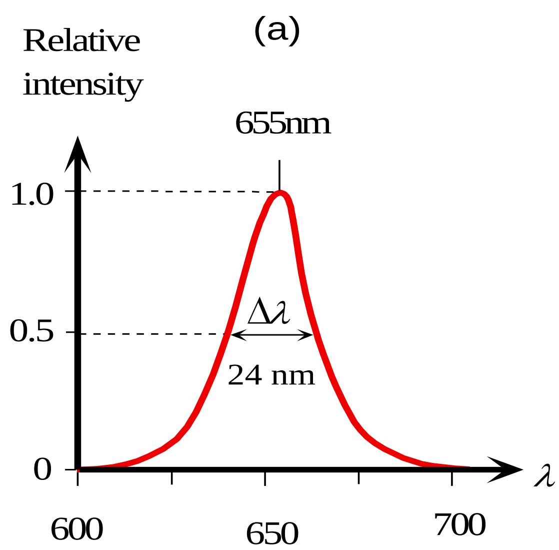
- Have stated initially that the energy of emitted radiation is approximately equal to the bandgap of the material.
- However, both electrons in CB and holes in VB have an energy distribution.



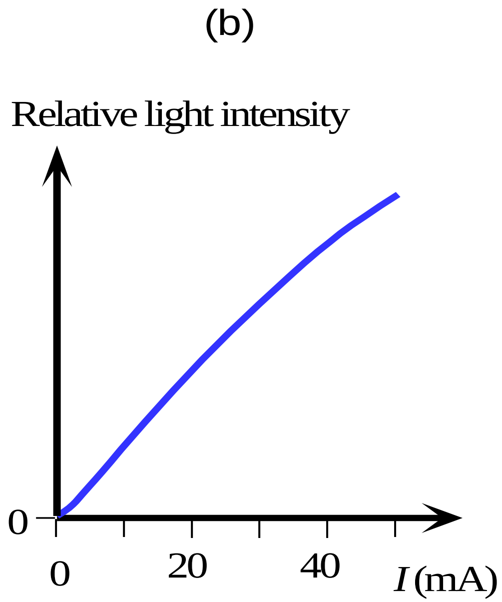
kT = 4.11 x 10^{-21} J

- Actually find concentration of electrons in VB is a maximum $1/2kT$ above bottom of CB.
- Similarly for holes, the concentration is a maximum $1/2kT$ below the VB edge.
- In both cases, spread is non-symmetrical.

- Rate of electron – recombination is proportional to concentration of carriers - most electrons will have energy $1/2kT$ above CB edge and most holes will have energy $1/2kT$ below VB edge.
- Most frequent (intense) recombination will then occur with energy difference $E_g + kT$.
- Recombination with other energies are less frequent and will then be less intense.
- Half-peak width (linewidth) of radiation ~ 2.5 – 3 kT.



- In a real LED, the output spectrum depends not only on the LED material, but also on the structure of the p-n junction.
- Output spectrum of typical red LED, showing less asymmetry than in idealised spectrum.
- Width of spectrum ~ 24 nm = 2.7 kT.



- LED output light intensity typically increases linearly with current – increase in current increases the injected minority carrier concentration and thus increasing the recombination rate and light output.
- This will become non-linear at high currents.

- The diode turn-on voltage will depend on bandgap (colour) and increases with energy gap

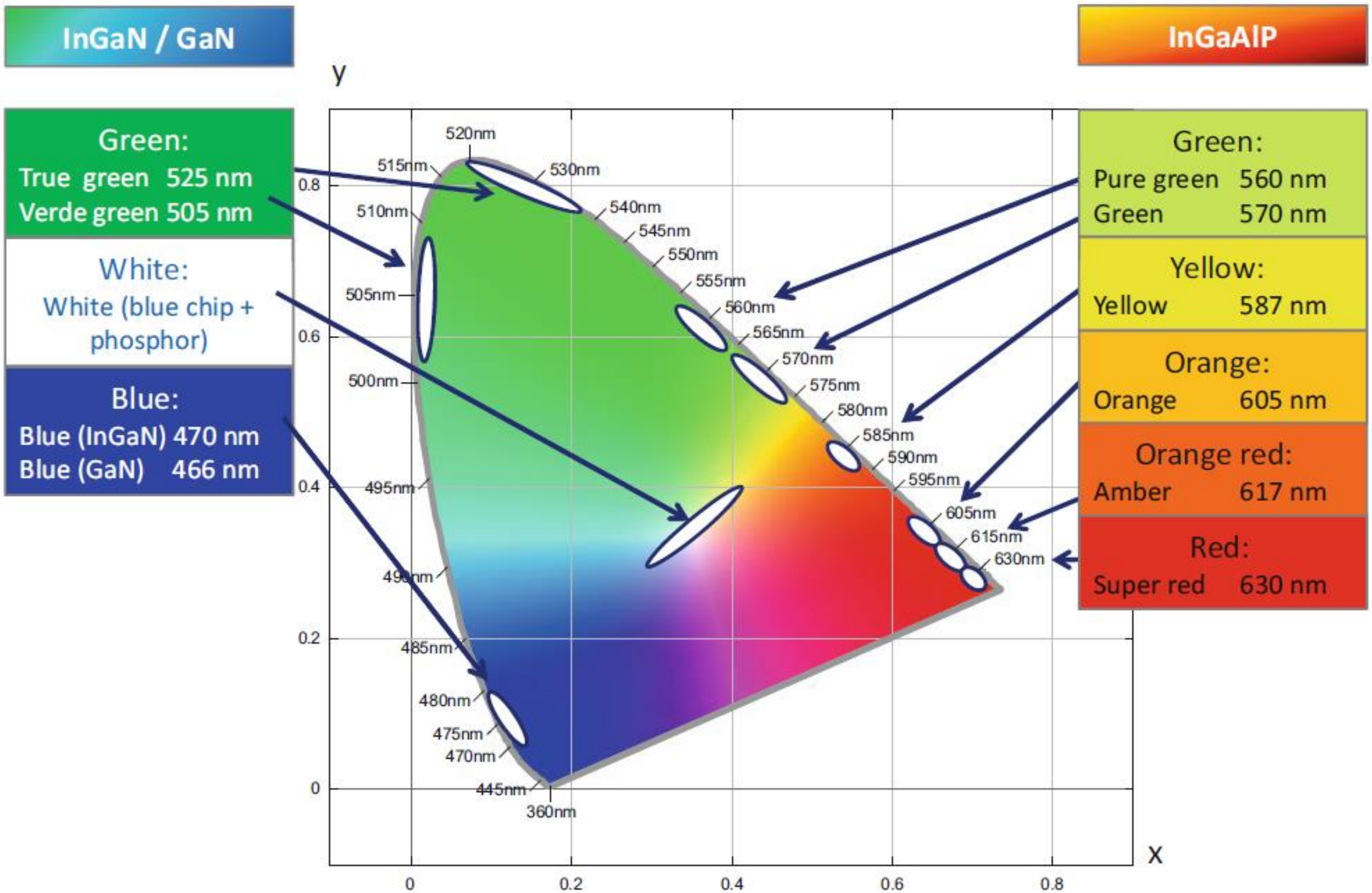
  Infra Red ~ 1V

  Red ~ 1.5 V

  Yellow ~ 2V

  Blue ~ 3.5 V

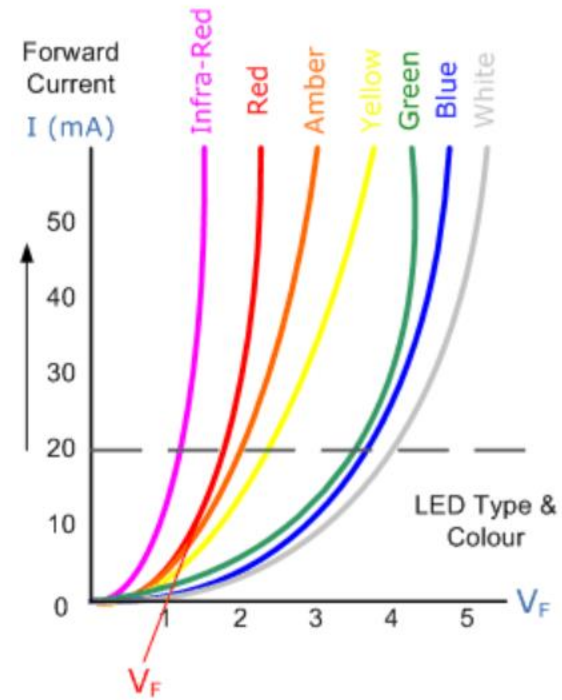
LED Materials: Most important materials for LEDs are based on Group III-V ternary alloy semiconductors.



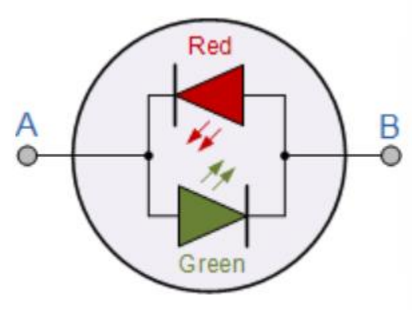
LED Colours

Colours depend on the wavelength and forward voltage.

Semiconductor Material	Wavelength	Colour	V_F @ 20mA
GaAs	850-940nm	Infra-Red	1.2v
GaAsP	630-660nm	Red	1.8v
GaAsP	605-620nm	Amber	2.0v
GaAsP:N	585-595nm	Yellow	2.2v
AlGaP	550-570nm	Green	3.5v
SiC	430-505nm	Blue	3.6v
GaInN	450nm	White	4.0v



A bi-colour light emitting diode:



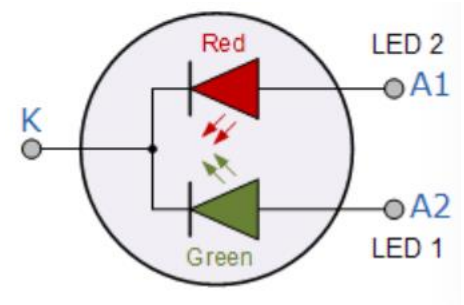
- Two LEDs chips connected together in “inverse parallel” (one forwards, one backwards) combined in one single package.

	Terminal+	Terminal-	AC
LED1	ON	OFF	ON
LED2	OFF	ON	ON
	Green	Red	Yellow

- Produce any one of colours e.g. a red colour when connected with current flowing in one direction and a green colour when biased in the other direction.
- Useful for giving polarity indication, e.g. the correct connection of batteries or power supplies etc.

Tricolour light emitting diode:

- A single Red and a Green LED combined in one package with their cathode terminals connected together producing a three terminal device.



	Red	Orange	Yellow	Green
LED1	0	5 mA	9.5 mA	15 mA
LED2	10 mA	6.5 mA	3.5 mA	0

- Give out a single red or a green colour by turning "ON" only one LED at a time.
- Can also generate additional shades of their primary colours (the third colour) such as Orange or Yellow by turning "ON" the two LEDs in different ratios of forward current.

Nobel prize for physics 2014 – the Blue LED

- Shuji Nakamura, Isamu Akasaki and Hiroshi Amano
- See further the article on their invention:

http://spectrum.ieee.org/semiconductors/optoelectronics/nobel-prize-puts-blue-leds-in-spotlight/?utm_source=techalert&utm_medium=email&utm_campaign=100914

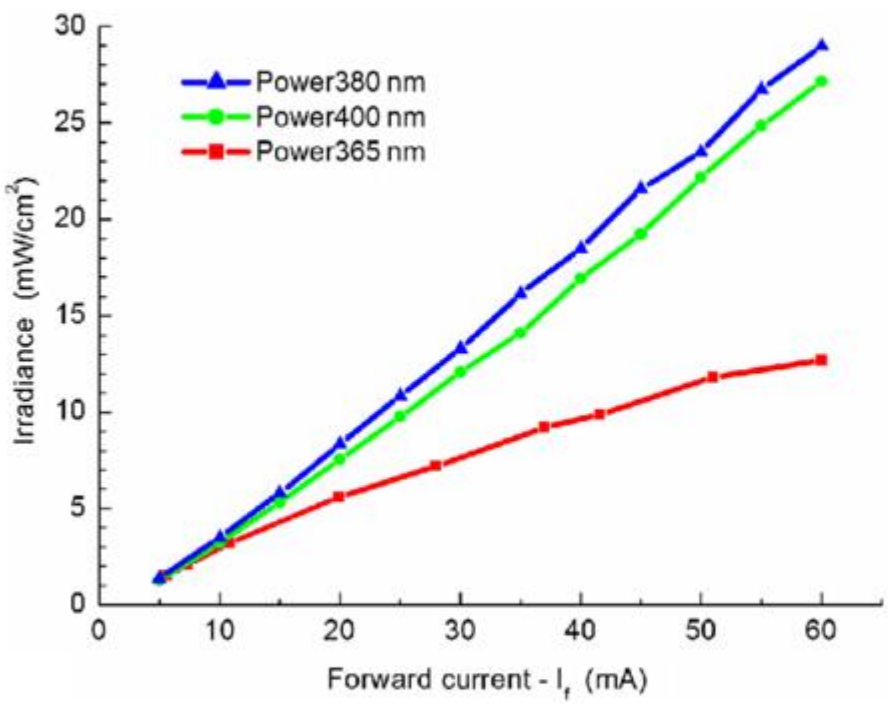
- Why was this so significant ?
- **Important question:** So how do we make white LEDs – of vital importance to sustainable energy systems !

Example for Tutorial 3 – LED Diode

1. An LED is connected in series with a 1 kΩ limiting resistor and 12 V voltage source. It has a light-producing characteristic as shown in the figure below.

   Taking into account the forward voltage drop of a red LED (V_f = 2.2 V), determine the amount of radiant (light) power produced in mW/m^2.

   [5 marks]



Answer:

Assuming $V_F = 2.2$ V for a red LED used in the circuit, the forward current is: [2.5]

$$I_F = \frac{12\text{ V} - 2.2\text{ V}}{1\text{ k}\Omega} = 9.8\text{ mA}$$

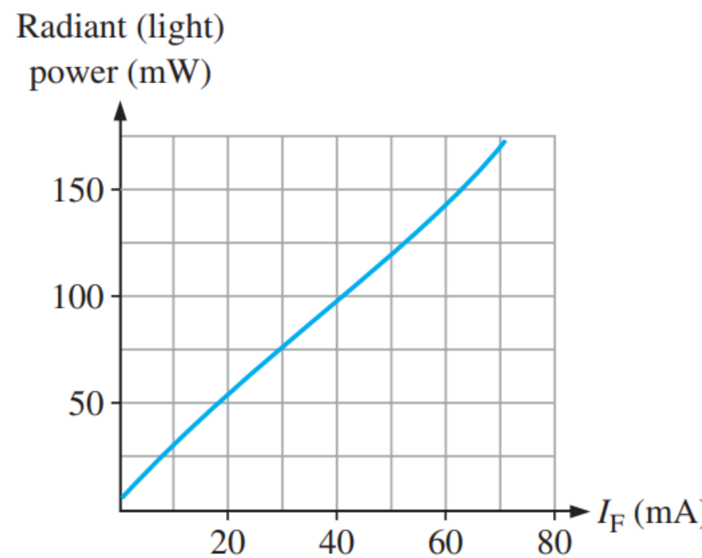
From the graph given above, the radiant power for forward current = 9.8 mA is approximately 2.5 – 3.0 mW/cm^2.

[2.5]

2. A blue LED (V_f = 3.5 V) is connected with a series limiting resistor and a 5 V voltage source. It has a light output power dependant on diode current as shown in the figure below.

a. Calculate the resistor value that will produce a light output of 100 mW. [5 marks]

b. Choose a resistor from the E12 series and calculate the actual current and light power of the LED. [5 marks]

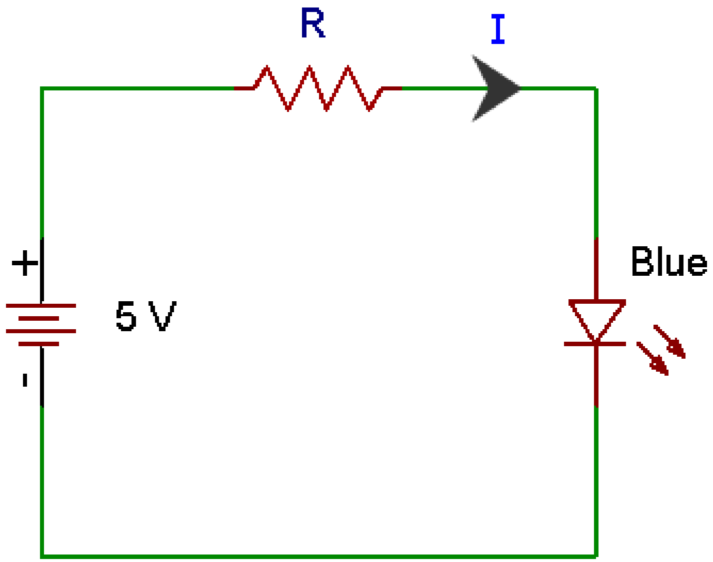


Answer

a. For 100 mW light output, from the graph above, the LED needs ~ 40 mA of current. [2.5]

Apply KVL on the circuit given above, the resistor value is: [2.5]

$$R = \frac{5\ \text{V} - 3.5\ \text{V}}{40\ \text{mA}} = 37.5\ \Omega$$



b. Choose either 33 Ω or 39 Ω (from E12 resistor series). This will give either slightly more/less light intensity.

For 33 Ω resistor, the current in the circuit is: [2.5]

$$I = \frac{5\ \mathrm{V} - 3.5\ \mathrm{V}}{33\ \Omega} = 45\ \mathrm{mA}$$

This will give power:

$$P = (I)^2 R = (0.045)^2(33) = 110\ \mathrm{mW}$$

For 39 Ω resistor, the current in the circuit is: [2.5]

$$I = \frac{5\ \mathrm{V} - 3.5\ \mathrm{V}}{39\ \Omega} = 38.5\ \mathrm{mA}$$

This will give power:

$$P = (I)^2 R = (0.0385)^2(39) = 95\ \mathrm{mW}$$