XMUT204 Electronic Design

Note 2e: Special Purpose Diodes (LED)

1. 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. We will first look at a few typical examples (there are many more) and then we will look in detail at two types specifically i.e. LEDs and solar cells.

1.1. Zener Diodes

These diodes are manufactured to produce a controlled and repeatable reverse bias breakthrough. Used as voltage references or voltage regulators. We covered this device in the previous section.

1.2. Varactor Diodes

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

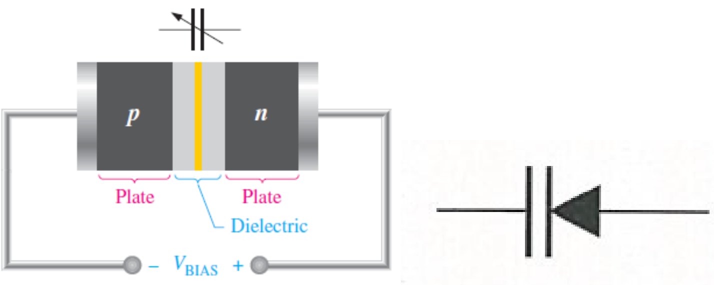


Figure 1: Varactor diodes

1.3. Schottky Diodes

It does not have 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.

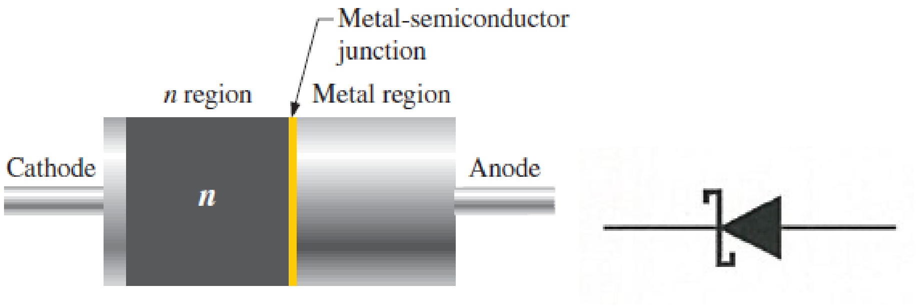


Figure 2: Schottky diode

1.4. Pin Diodes – (p-layer – intrinsic layer – n-layer):

This type of diode 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 i.e. resistance decreases with increasing current. They are typically used as high frequency switches or as photodetectors in optical systems.

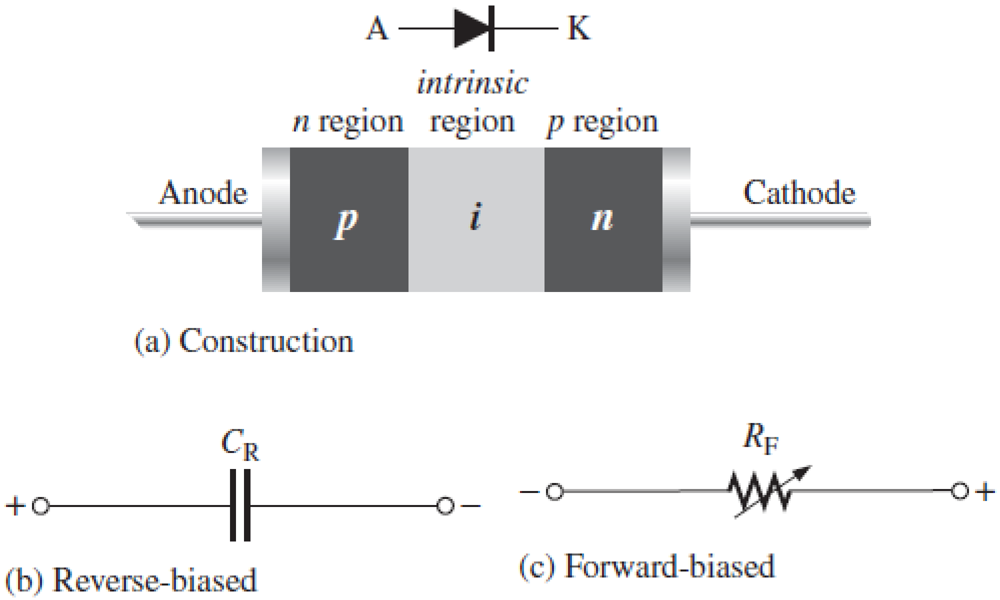


Figure 3: PIN diode

1.5. Photo Diodes

These are used as detectors for incident light, so needs a transparent window in packaging to allow light to fall on semiconductor. These devices are 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.

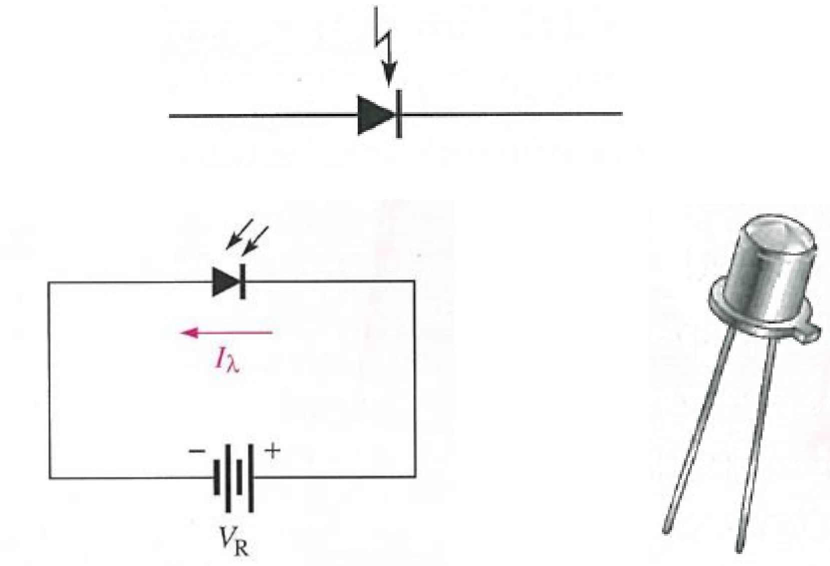


Figure 4: Photodiode

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 cm^2−s), and A is the junction area.

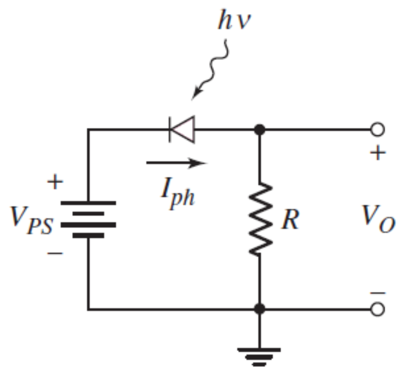


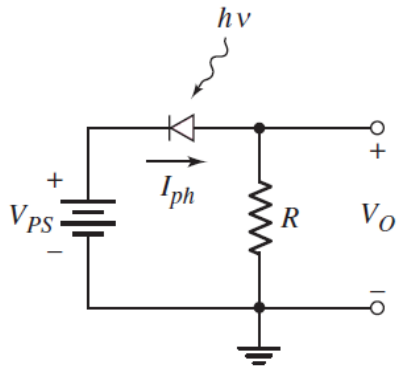
Figure 5: Photo diode circuit

This linear relationship between photocurrent and photon flux is based on the assumption that the reverse-bias voltage across the diode is constant.

This in turn means that the voltage drop across R induced by the photocurrent must be small, or that 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 $10^{-2}\ \text{cm}^2$, and the incident photon flux is $5 \times 10^{17} \text{cm}^{-2} - s^{-1}$.



Calculate the photocurrent generated in a photodiode. [5 marks]

Solution

From the equation below, the photocurrent is

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

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

2. Prequels to LEDs and Solar Cells

In this section, we will look into the mechanisms of photoelectric process built up in semiconductor materials. Similar to the behaviour of conventional diodes, light emitting diode (LED) and solar cells operates using similar principles, albeit different set of processes.

2.1. 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:

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

Where:

h = Planck's constant, 6.62×10^{-34} J.s

f = Frequency of light.

v = Velocity of light.

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}):

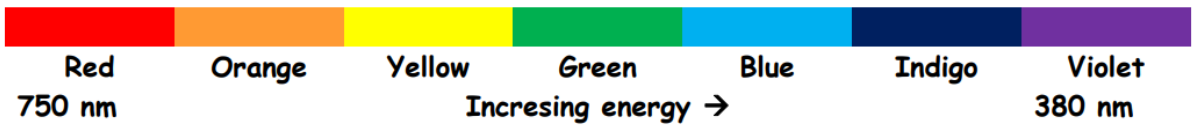
If the energy of incident light is less than the bandgap, it will not be absorbed by the semiconductor.

If it is equal to or greater than the bandgap, it will be strongly absorbed as the optical energy and used to generate electron i.e. hole pairs (EHP), changing the carriers concentration in the material.

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

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:

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

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

2.2. A Typical Transmission Spectrum for a Semiconductor

Given in the graph in the figure below, semiconductor materials have different transmission efficiency depending on their operating wavelength. Observe the change of % transmission at around 400 nm wavelength. This means that the material reacts instantly by transmitting light at that wavelength. Design of the materials for optical application requires careful tuning up of the construction of the devices.

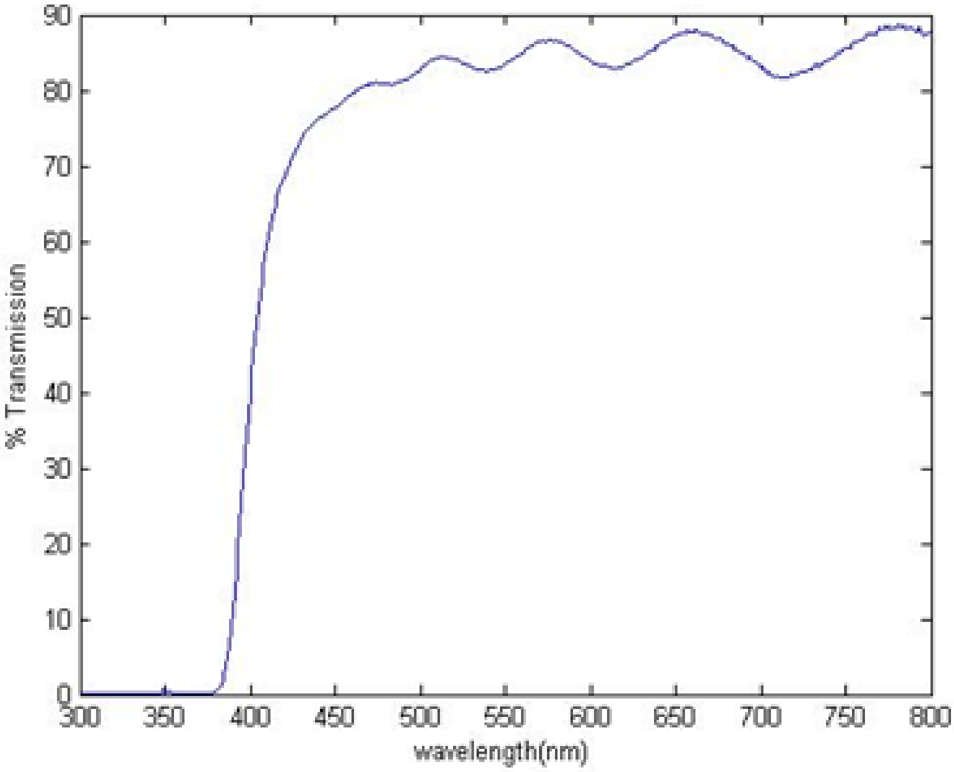


Figure 6: Transmission spectrum of a semiconductor

The reverse process to optical absorption will also happen i.e. when we have an electron hole pair that will recombine, the electron will lose 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 i.e. 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

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

2.3. Direct vs Indirect Bandgaps

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

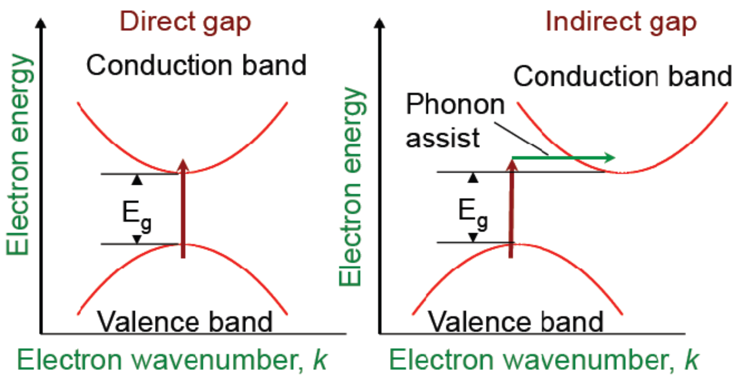


Figure 7: Direct and indirect band gaps

The type of band gap (direct or indirect) determines the ease and efficiency with which optical absorption and emission will take place in the material.

In direct band gap 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 band gap 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 (e.g. a vibration of the lattice = heat).

Any semiconductor with an indirect band gap is thus a poor electro-optical material due to the very low efficiency with which optical radiation is absorbed or emitted.

Silicon, for all its highly desired characteristics which allows us to easily make integrated electronic circuits has an indirect band gap 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 band gap. The wavelength of emission will then be determined by the band gap of the semiconductor material.

2.4. 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 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 and they are used for different applications in electronics.

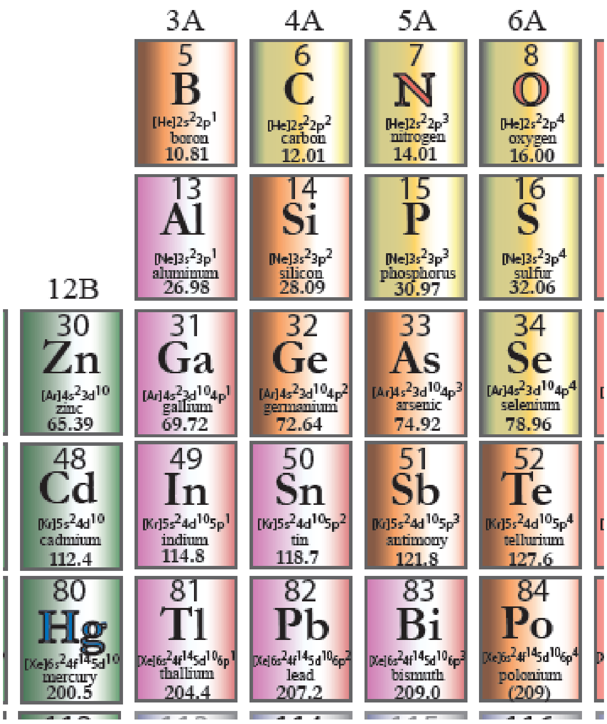


Figure 8: Periodic table of semiconductor materials

Given in the diagram in the figure below, these compounds has different energy gap and wavelength characteristics than their intrinsic counterparts. Notice for example for GaAs which is used for high-voltage/power high speed switching applications as typically this material is more stable at higher temperature and has higher energy band compared with intrinsic Silicon.

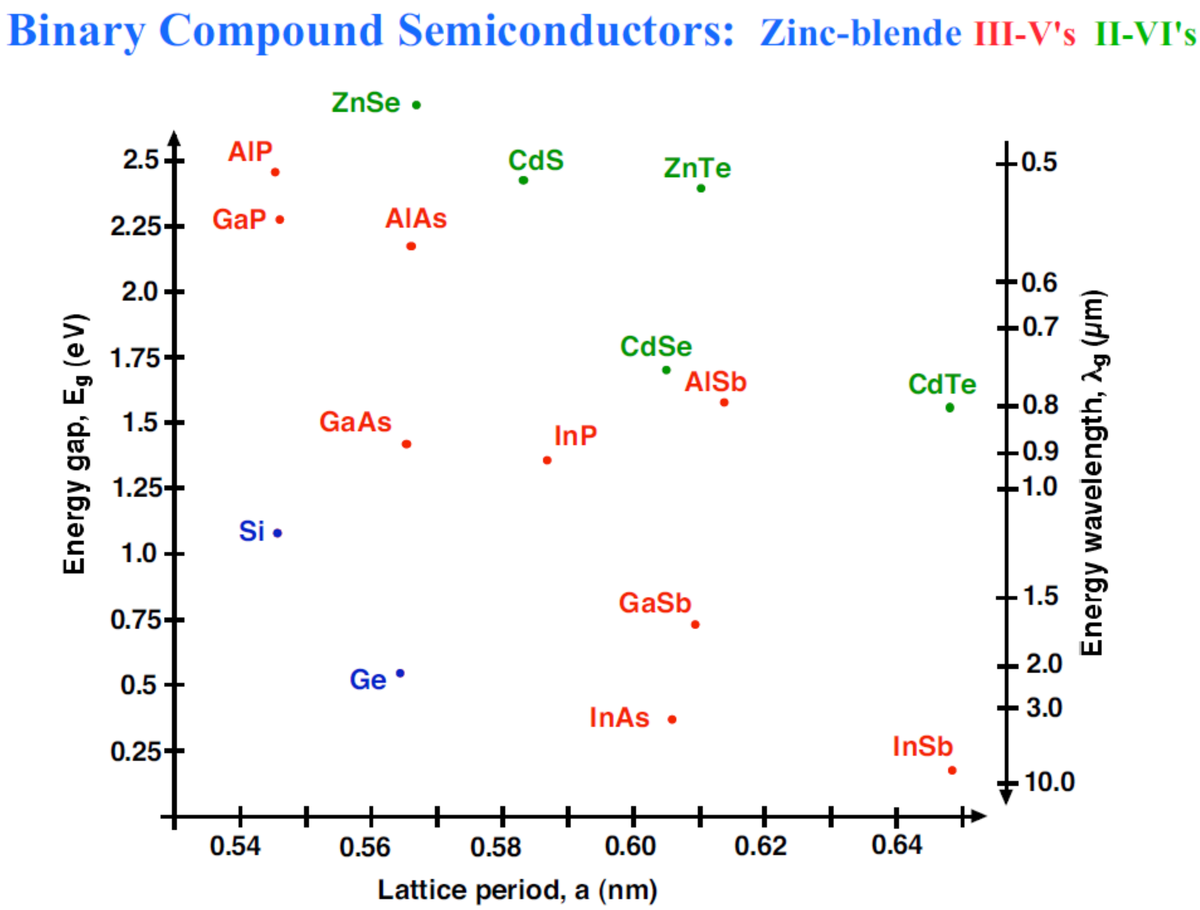


Figure 9: Binary compound semiconductors

Another example is CdTe used for solar panel applications which its band gap (~1.5 eV) is almost a perfect match to the distribution of photons in the solar spectrum in terms of conversion to electricity.

3. Light Emitting Diodes

In this section, we will look into more specifically in the characteristics, design and construction of light emitting diode (LED).

3.1. 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 ($h\nu$) is approximately equal to the bandgap E_g.

As shown in the diagram given below, for a simple homojunction device structure, its substrate is dominated by thick semiconductor crystal to serve as mechanical support. In the n+ layer, it is heavily doped n layer grown epitaxially to lattice match the substrate and on the other hand, its p layer consists of grown epitaxially on n+ layer to form p-n junction.

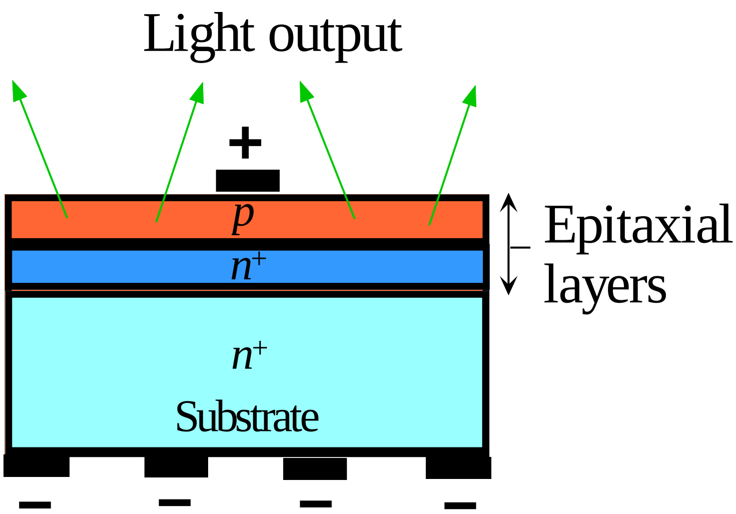


Figure 10: Light emitting diode (LED)

The following diagram shows the mechanical structure of a typical LED. The whole package is encapsulated in an epoxy lens or case, with the semiconductor material is housed in a die inside the case.

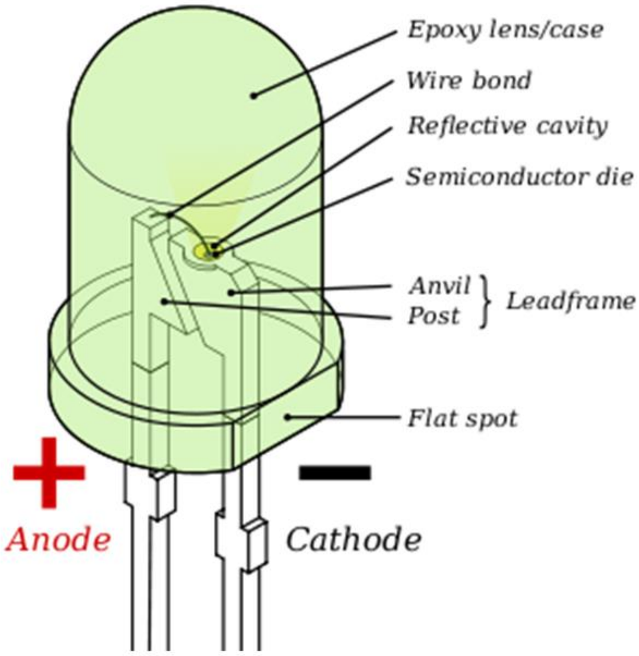


Figure 11: A physical cut out of an LED

Notice from the diagram above that the epoxy lens/case is used to protect the LED from environment and wire bond is to connect the semiconductor die with lead frames. On the other hand, reflective cavity is designed for accumulating and directing lights generated, lead frames that are intended for connecting the LED to circuit, and flat spot which is used to provide support for horizontal set up.

Assume p-n+ junction with no bias, a typical LED has its depletion layer predominantly on the p-side. In this device, the potential energy barrier, $PE = eV_0$ for electrons to move from n- to p-side and for holes to move from p- to n-side. This potential barrier prevents concentration driven diffusion of majority carriers into depletion region. In this case as shown in the diagram below, V_0 is the built-in voltage across the junction.

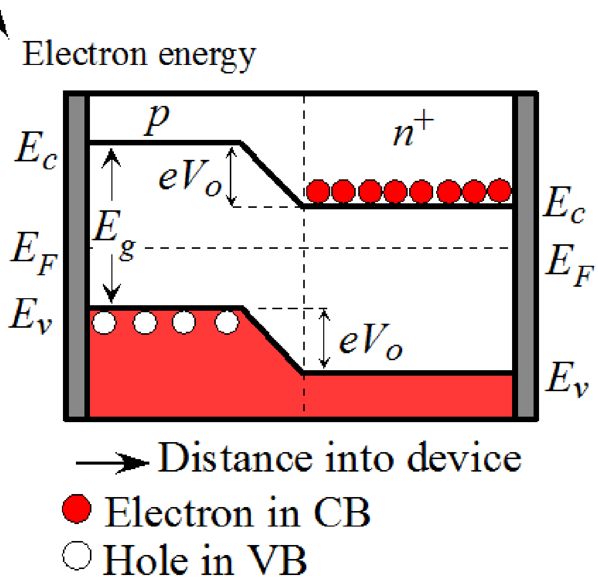


Figure 12: Layers of electron energy in LED materials (preliminary condition)

For a forward biased junction with a given voltage source (V), its built-in potential reduced to $V_0 - V$ and the device allows electrons from n-side to diffuse (injected) into p-side and on the other hand holes injected from p-side is much less due to the difference in doping levels. In this material 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

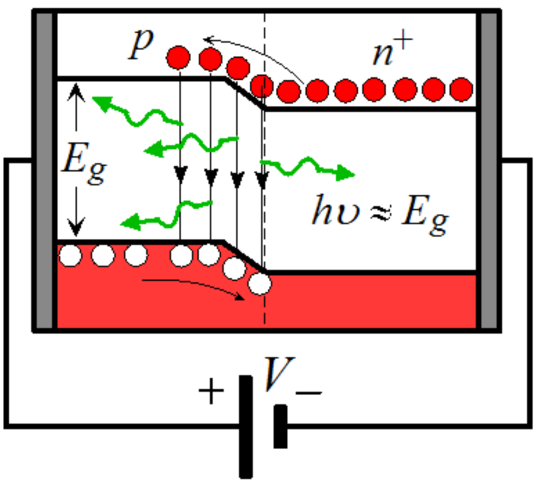


Figure 13: Layers of electron energy in LED materials (excitation condition)

Photons emitted from EHP recombination will be in random direction i.e. LED design has to ensure that maximum light emission from the junction in the desired direction. In this example, firstly we 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 figure below. This is not for examination in the course.

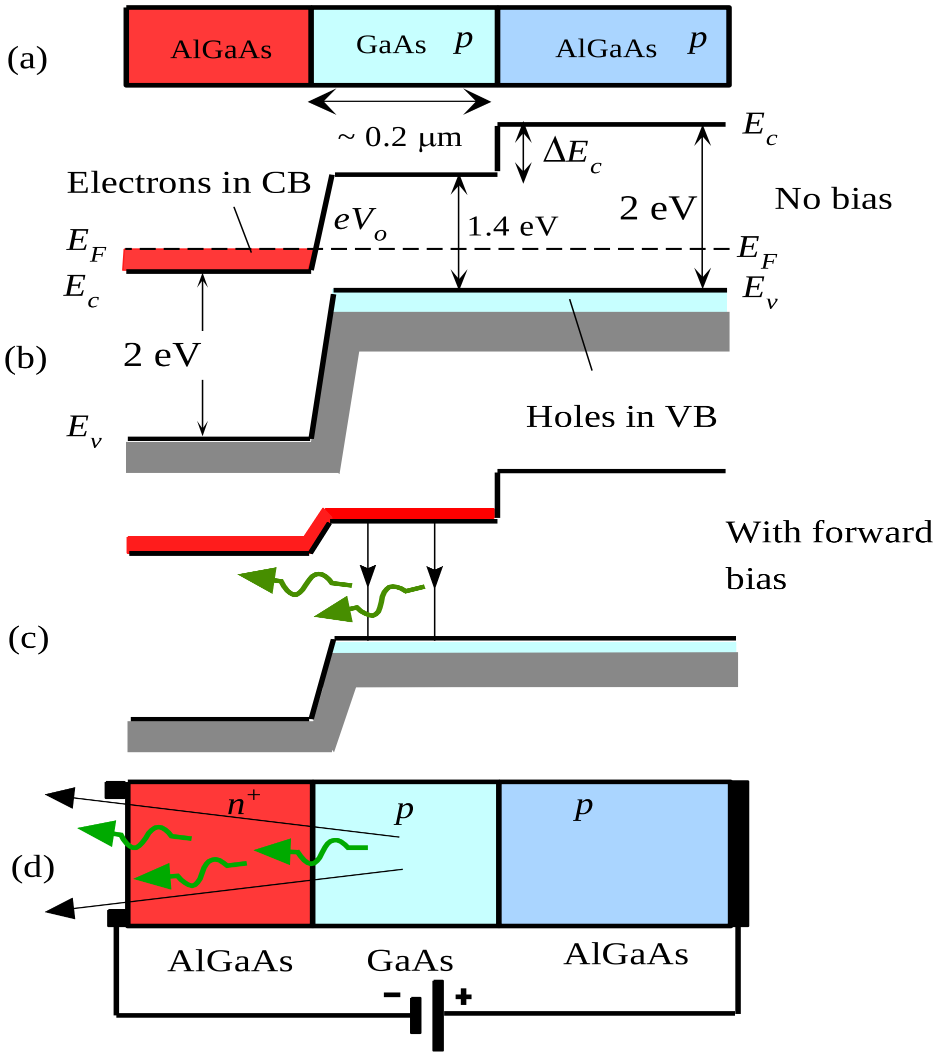


Figure 14: Double-heterojunction LED materials

For a double heterojunction structure, its Fermi level is still continuous through structure and its potential barrier eV_0 for electrons in in the conduction band 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 conduction band of the p GaAs from passing into the conduction band of the p AlGaAs. A forward bias will reduce potential barrier between n^+ AlGaAs and p GaAs as normal. This allows injection of electrons from conduction band of n+ AlGaAs to be injected into p GaAs. The injected electrons are confined to the conduction band 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 not get reabsorbed in the AlGaAs. Furthermore, light can be reflected at the back surface of the AlGaAs to increase light output.

3.2. LED Output Characteristics

We have stated initially that the energy of emitted radiation is approximately equal to the bandgap of the material. However, both electrons in conduction band and holes in valence band have an energy distribution.

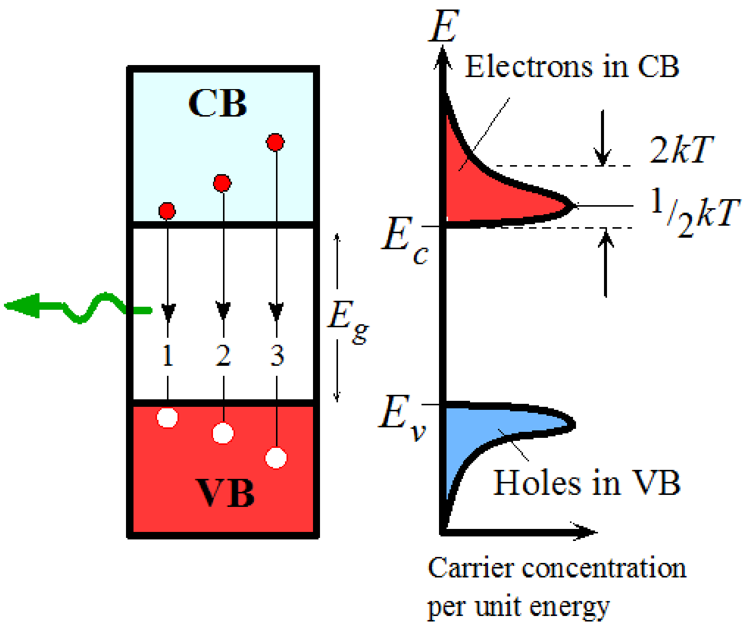


Figure 15: LED output characteristics

Actually, we could find concentration of electrons in valence band is a maximum $1/2kT$ above bottom of conduction band. Similarly, for holes, the concentration is a maximum $1/2kT$ below the valence band edge. For both cases, the spread of the concentration is non-symmetrical as shown in the diagram above.

In this case rate of electron-recombination is proportional to concentration of carriers i.e. most electrons will have energy $1/2kT$ above conduction band edge and most holes will have energy $1/2kT$ below valence band 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 (line width) 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.

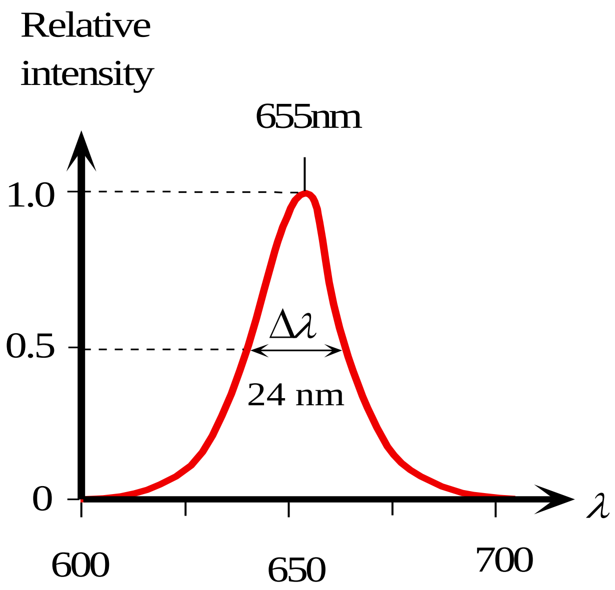


Figure 16: Wavelength of LED materials

The diagram given above is output spectrum of typical red LED, showing less asymmetry than in idealised spectrum. Notice that width of spectrum ~ 24 nm = 2.7 kT.

As in the figure below, LED output light intensity typically increases linearly with current i.e. 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.

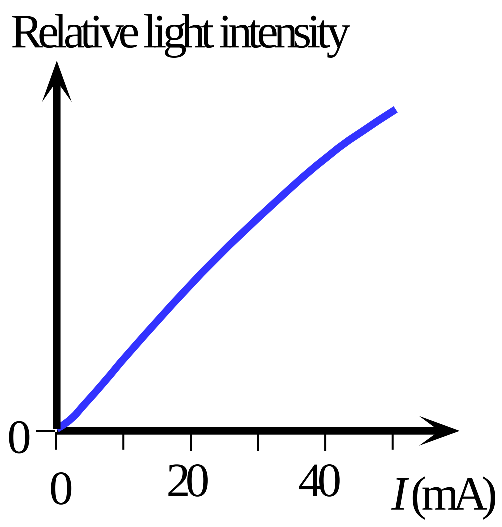


Figure 17: Relative light intensity of LED materials

The diode turn-on voltage will depend on bandgap (colour) and increases with energy gap. It is typically depended on the colour of the LED: Infrared ~ 1 V, Red ~ 1.5 V, Yellow ~ 2 V and Blue ~ 3.5 V.

3.3. LED Materials

Most important materials for LEDs are based on Group III-V ternary alloy semiconductors. As shown in the diagram given below, for the InGaN/GaN materials, the wavelength of the green LED is at 505-525 nm and blue is at 466-470 nm. Whereas for InGaAIP materials, green LED wavelength is at 560-570 nm, yellow is at 587 nm, and so forth.

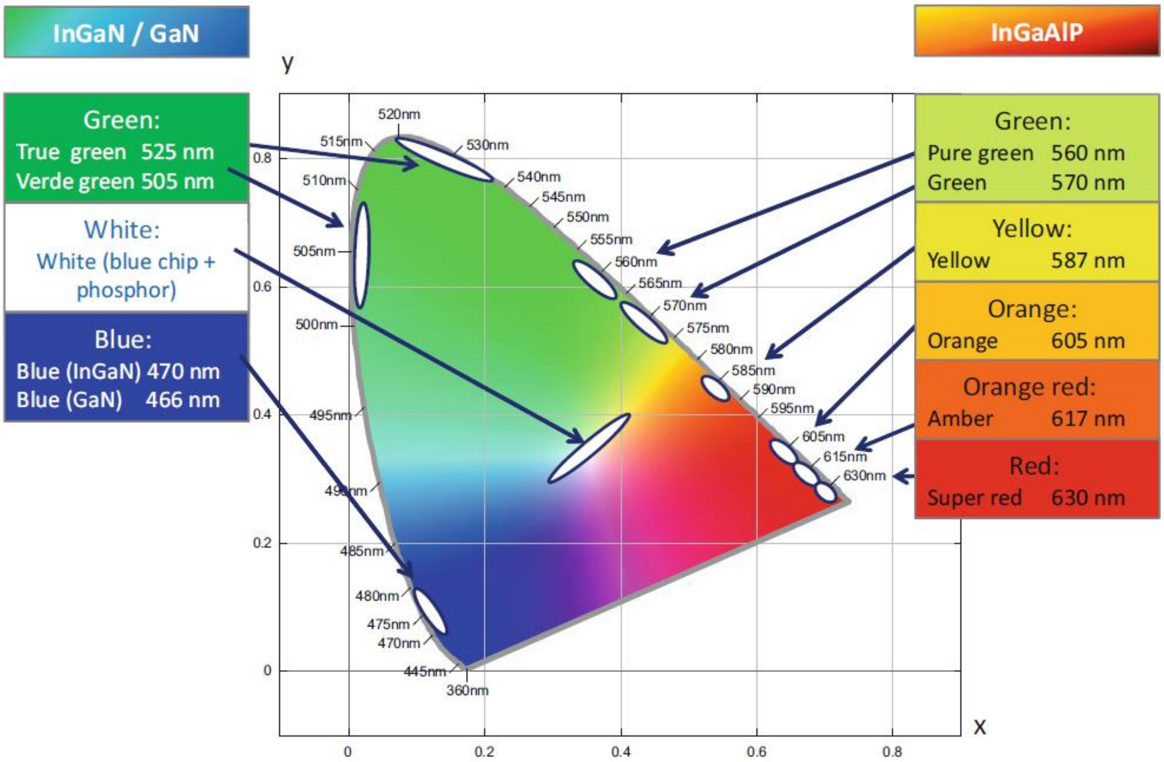


Figure 18: Wavelengths of various LED materials

Nobel prize for physics 2014 was for the invention of the Blue LED and it was awarded to Shuji Nakamura, Isamu Akasaki and Hiroshi Amano. See the following link for further details: 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? This is an important question and this is related to how do we make white LEDs (see diagram above) i.e. of vital importance to sustainable energy systems!

3.4. LED Colours

As shown in the following table, the colours of LED 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

Table 1: Materials, wavelength, and forward voltage of several coloured LED

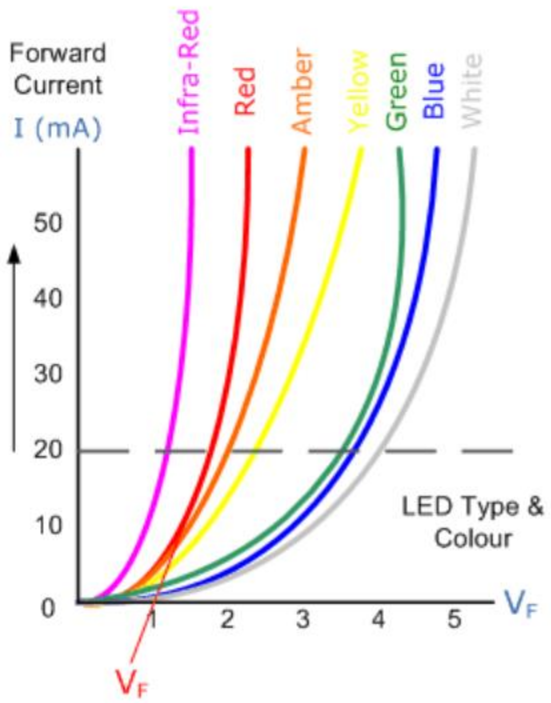


Figure 19: Forward voltages of several coloured LEDs

3.4.1. A bi-colour light emitting diode

In bi-colour LED, two LEDs chips connected together in “inverse parallel” (one forwards, one backwards) combined in one single package.

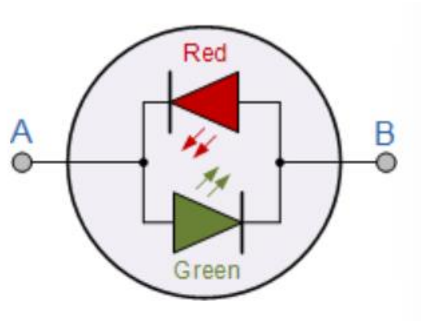


Figure 20: Bicolour LED

The bi-colour LED produces 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.

The bi-colour LED is useful for giving polarity indication, e.g. the correct connection of batteries or power supplies etc.

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

Table 2: Operational state conditions of bicolour LED

3.4.2. Tricolour light emitting diode

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

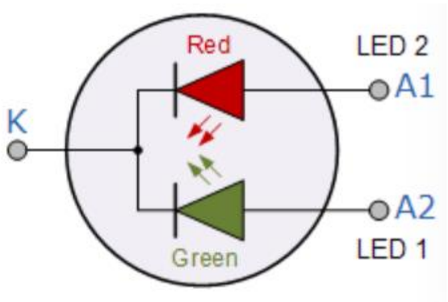


Figure 21: Tricolour LED

The tricolour LED gives out a single red or a green colour by turning "ON" only one LED at a time. It 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.

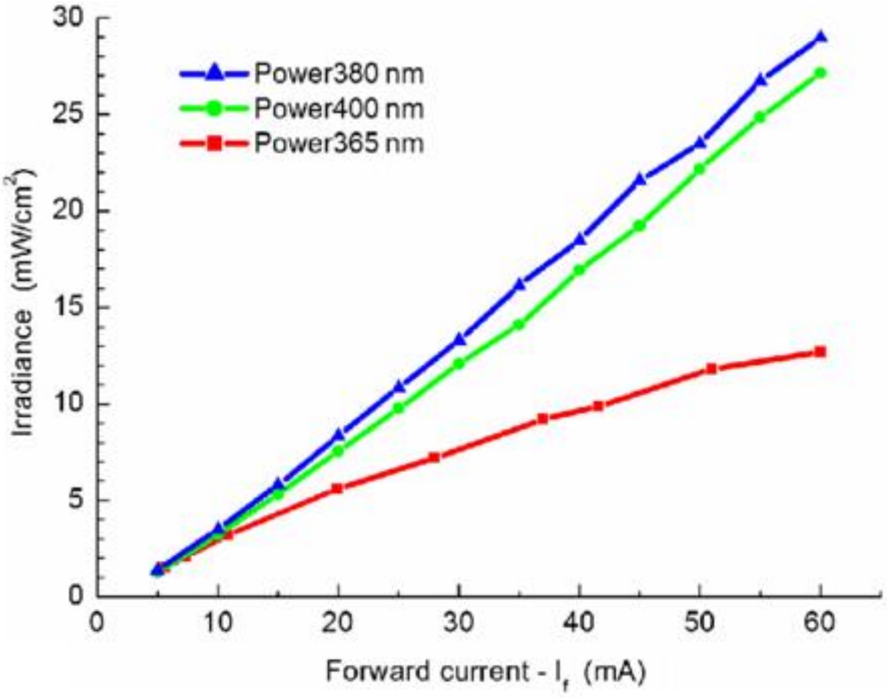
	Red	Orange	Yellow	Green
LED 1	0	5 mA	9.5 mA	15 mA
LED 2	10 mA	6.5 mA	3.5 mA	0

Table 3: Operational state conditions of tricolour LED

Example for Tutorial 3 – Light Emitting Diode (LED)

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]



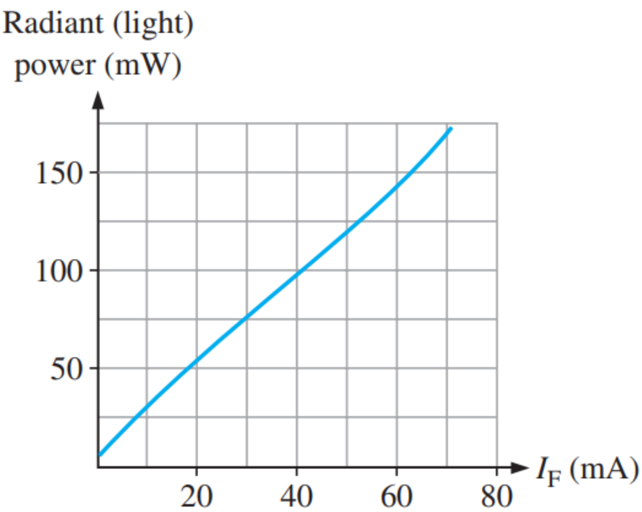
Answer:

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.

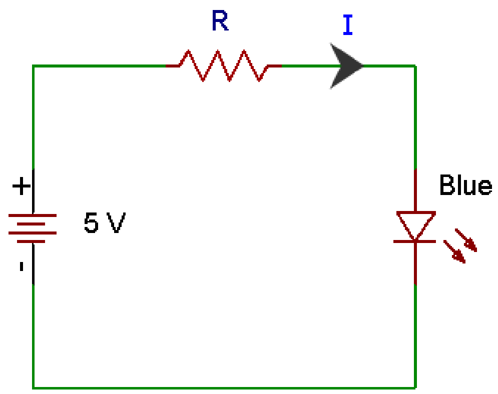


a. Calculate the resistor value that will produce a light output of 100 mW. [5 marks]

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 that flows in the circuit is: [2.5]

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

This will give power:

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

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

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

This will give power:

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