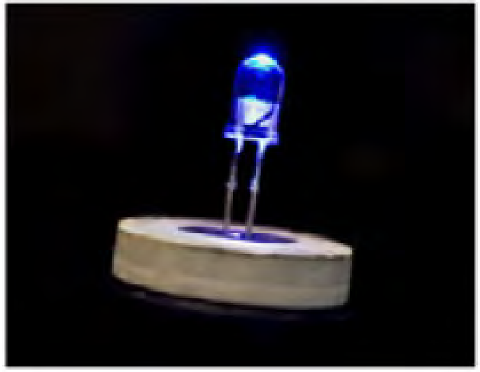
Light Sources

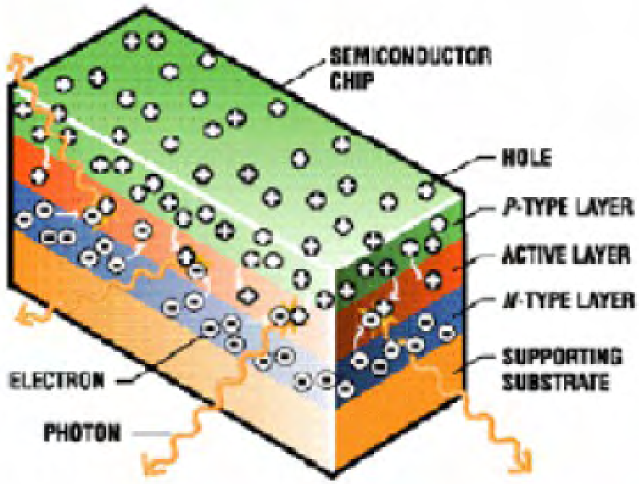
- LED – Light Emitting Diode

Light Emitting Diode

L.E.D.= Light Emitting Diode



Blue LED

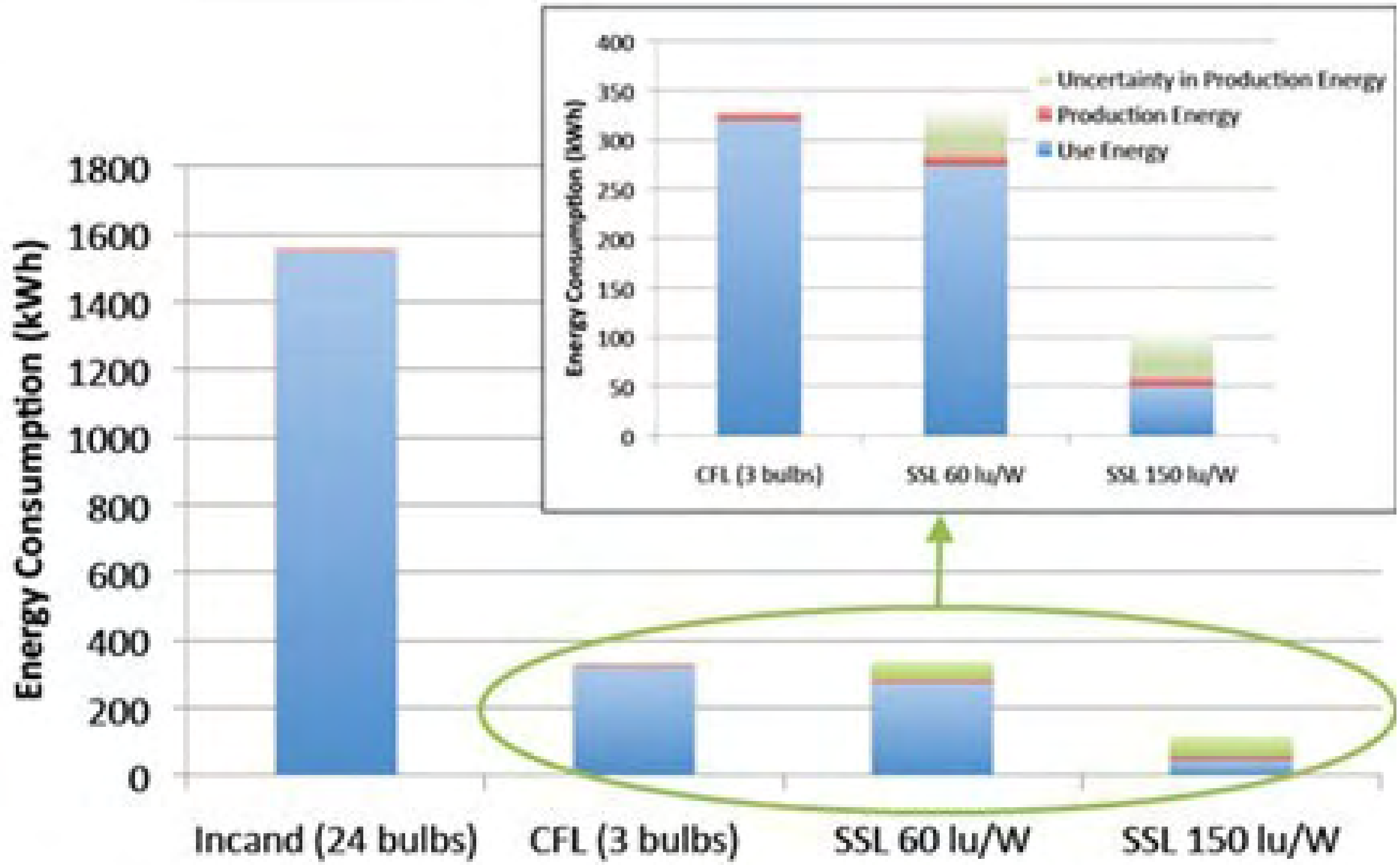


LED produces light by combining
Positive and negative charges inside
Gallium nitride crystal

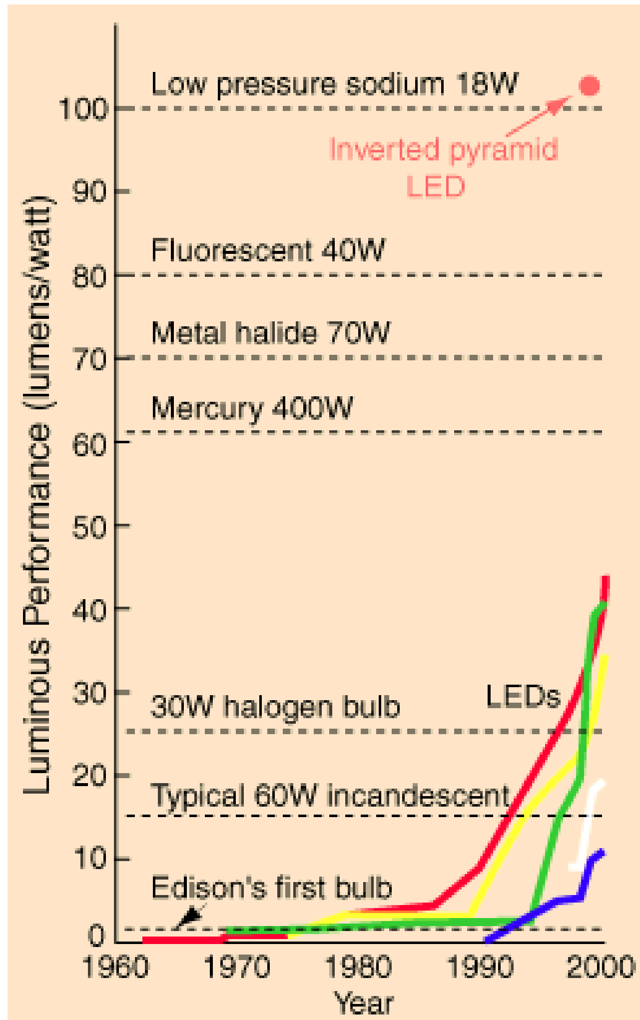
Advantages of LED Lighting

- **Lifetime** – Lifetime can exceed 50,000 Hours as compared to 1,000 Hours for Tungsten bulbs
- **Robustness** – No moving parts, No filaments, No glass
- **Size** – Typical package is 5 mm in diameter
- **Energy Efficiency** – 50-90% less energy used translated into smaller power supply.
- **Toxicity** – No Mercury or Lead.
- **Versatility** – available in a variety of colours and can be pulsed
- **Cool** – Less radiant heat than HID or Incandescent types

Energy Usage Comparison



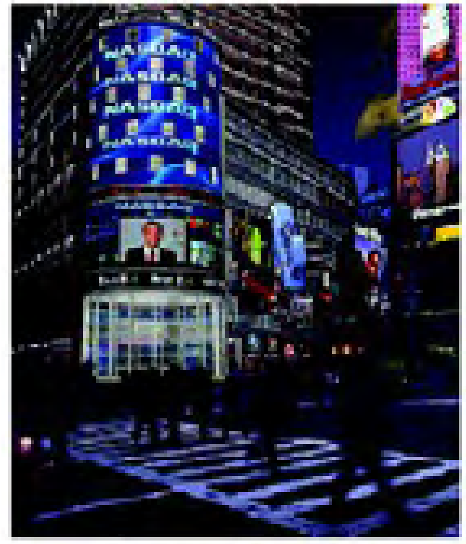
Luminous Performance



Current LED Market 2 B$/Yr

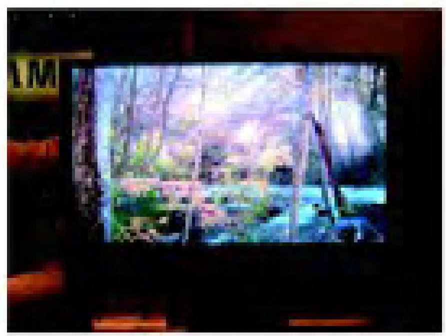
Cellphone
(Nokia)

Traffic signals
(Gelcore)



Large Displays
(NASDAQ)

streetlights



TVs (LED DLP^{tm})
(samsung)

Automotive

LED in Architectural Lighting

Aspire Tower, Doha, Qatar

Takarazuka University, Japan

Car Headlights

Portable Desk/Task Lighting

6 Watt LED Desk Lamp

Halley LED Desk Lamp

Outdoors

Air/Water Purification System

- Fruit and Vegetable Storage Life Extended 1 week
- Water Purification: UV LED to kill bacteria


Mitsubishi Refrigerator MR-W55H,
UV LED 375 nm, 590 nm, Blue LED

UV Water Purifier
(Credit: Hydro-Photon Inc.)

Costs associated with various white lighting

Incandescence
luminous efficacy: low (16lm/W)
light bulbs: inexpensive (0.4$/klm)
very short lifetime (1,000hrs)

Fluorescence
luminous efficacy: high (85lm/W)
long lifetime (10,000 hrs)

High-Intensity Discharges
luminous efficacy: high (90lm/W)
long lifetime: (20,000 hrs)

Solid State Lightning (LED)
high luminous efficacy (>60lm/W)
extremely long lifetime: (>100,000 hrs)

Luminous Efficacy

- Luminous efficacy is a property of light sources, which indicates what portion of the emitted electromagnetic radiation is usable for human vision. **It is the ratio of emitted luminous flux to radiant flux.** Luminous efficacy is related to the overall efficiency of a light source for illumination, but the overall lighting efficiency also depends on how much of the input energy is converted into electromagnetic waves (whether visible or not).
- •In SI, luminous efficacy has units of lumens per watt (lm/W). **Photopic** luminous efficacy has a maximum possible value of 683lm/W, for the case of monochromatic light at a wavelength of 555nm (green). **Scotopic** luminous efficacy reaches a maximum of 1700lm/W for narrowband light of wavelength 507 nm.

Luminous Efficiency Comparison

Type	Luminous efficacy (lm/W)	Luminous efficiency
Class M star (Antares, Betelgeuse), 3000 K	30	4%
ideal black-body radiator at 4000 K	47.5	7.0%
Class G star (Sun, Capella), 5800 K	80	12%
natural sunlight	93	14%
ideal black-body radiator at 7000 K	95	14%
ideal white light source	242.5	35.5%
ideal monochromatic 555 nm source	683	100%

Flux

- The lumen(symbol: lm) is the SI unit of luminous flux, a measure of the perceived power of light. Luminous flux differs from radiant flux, the measure of the total power of light emitted, in that luminous flux is adjusted to reflect the varying sensitivity of the human eye to different wavelengths of light

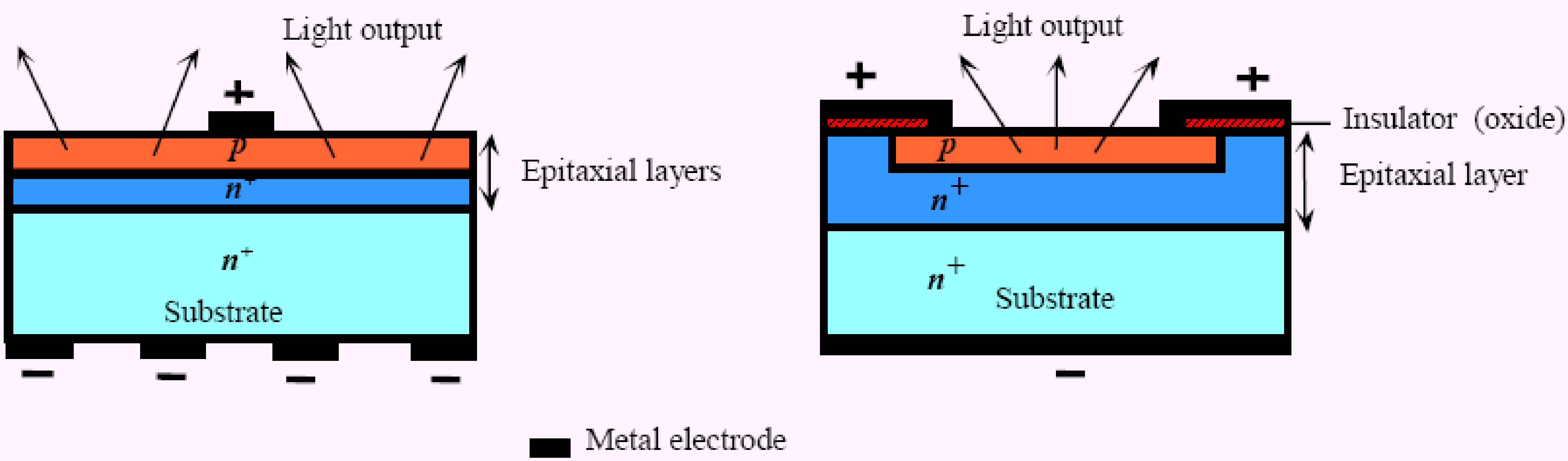
LED Principles

- If forward bias V is applied › voltage drop mainly occurs across the depletion region › Built-in potential Vo is reduced to Vo–V. › Allow the electrons from n+ side to diffuse (or become injected), into the p-side
- The hole injection component from p- into n+ side is much smaller.
- The recombination of injected electrons in the depletion region as well as in the neutral p- side results in photons emission.
- Recombination mainly occurs inside depletion region and within a volume extending over the diffusion length Le of the electrons in the p- side. Recombination zone is called active region.
- The phenomenon of light emission from EH pair recombination as result of minority carrier injection is called **injection electroluminescense**.

LED Structure

- The p- side is on the surface from which light is emitted as is therefore made narrow (a few microns) to allow the photon to escape without being reabsorbed.
- The n- side is heavily doped to ensure that the most of the recombination takes place in the p- side.
- The photons which are emitted toward the n- side become either absorbed or reflected back at the substrate interface depending on the substrate thickness and the exact structure of the LED.

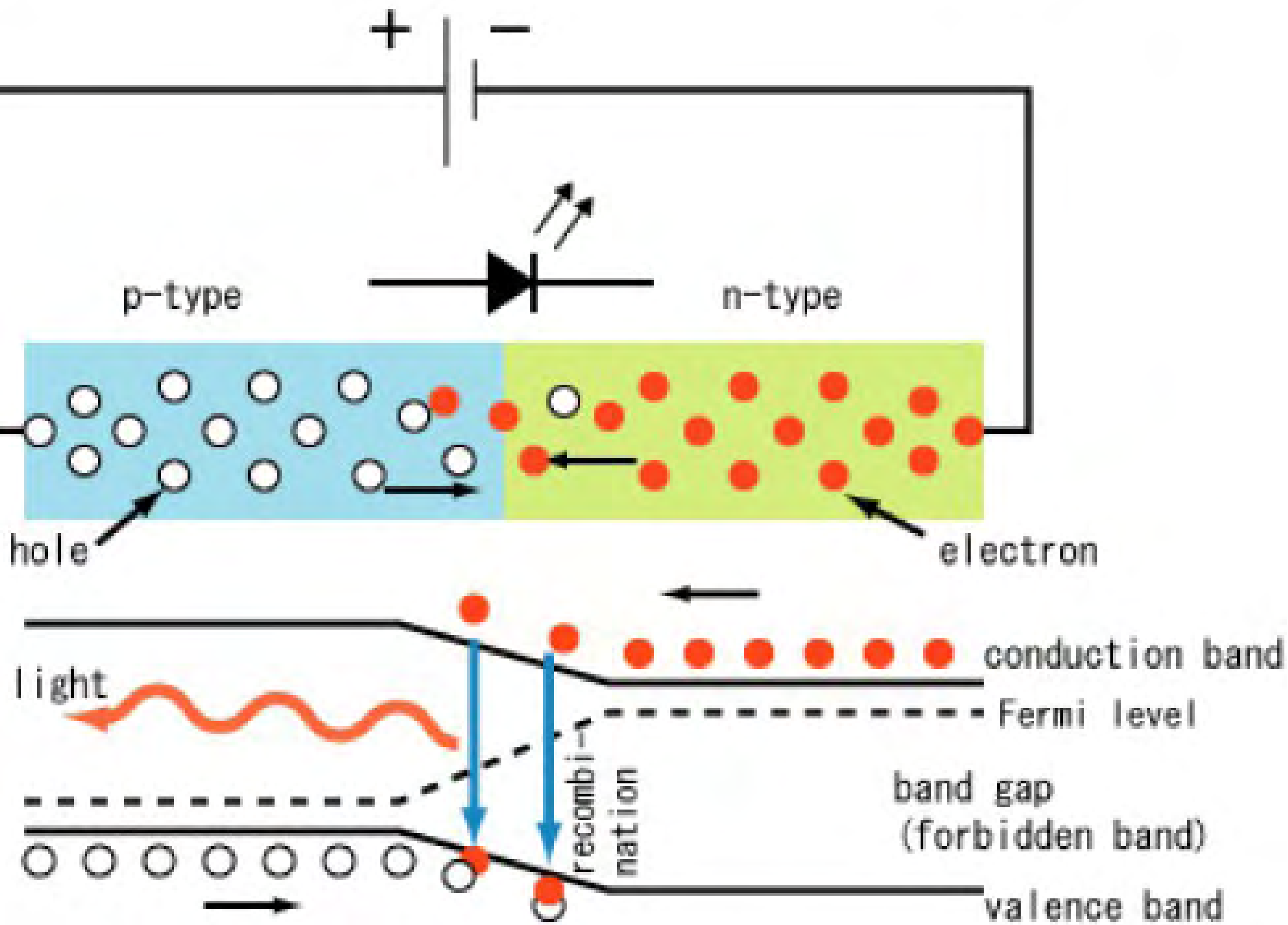
Illustration of typical planar surface emitting LED devices



p-layer grown epitaxially on an *n*+ substrate

First *n*+ is epitaxially grown and then *p* region is formed by dopant diffusion into the epitaxial layer

Inner Workings of a LED



Radiative vs. Non-radiative Recombination

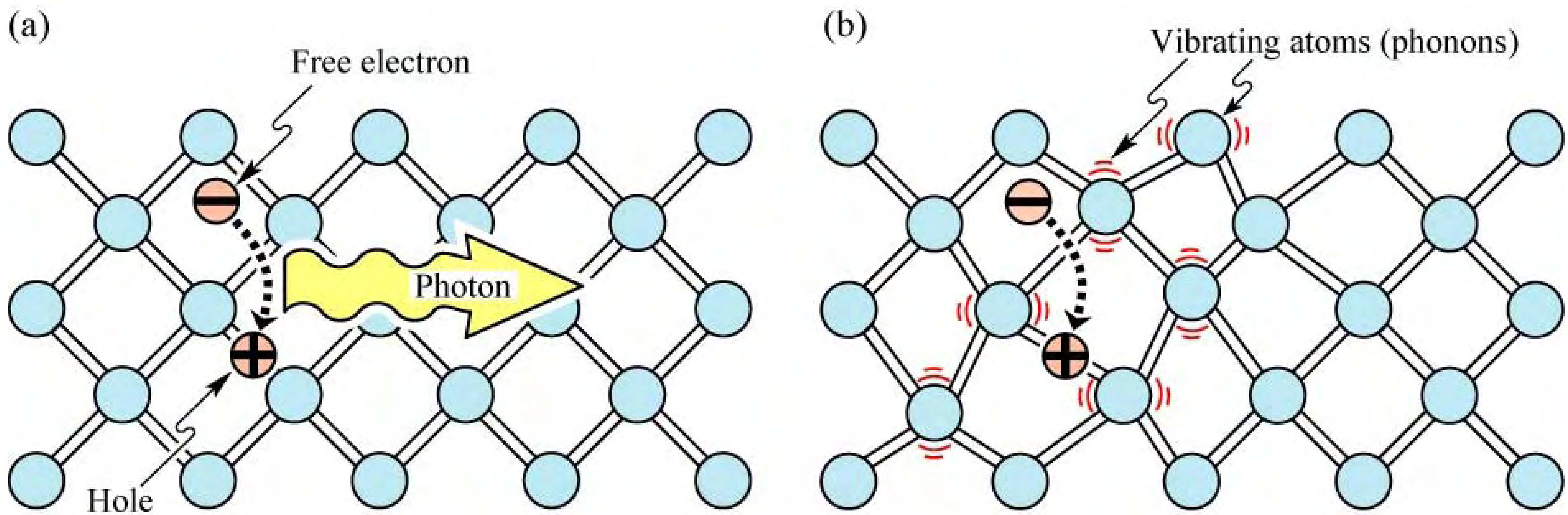


Fig. 2.5. (a) Radiative recombination of an electron-hole pair accompanied by the emission of a photon with energy $h\nu \approx E_g$. (b) In non-radiative recombination events, the energy released during the electron-hole recombination is converted to phonons (adopted from Shockley, 1950).

Recombination Mechanisms

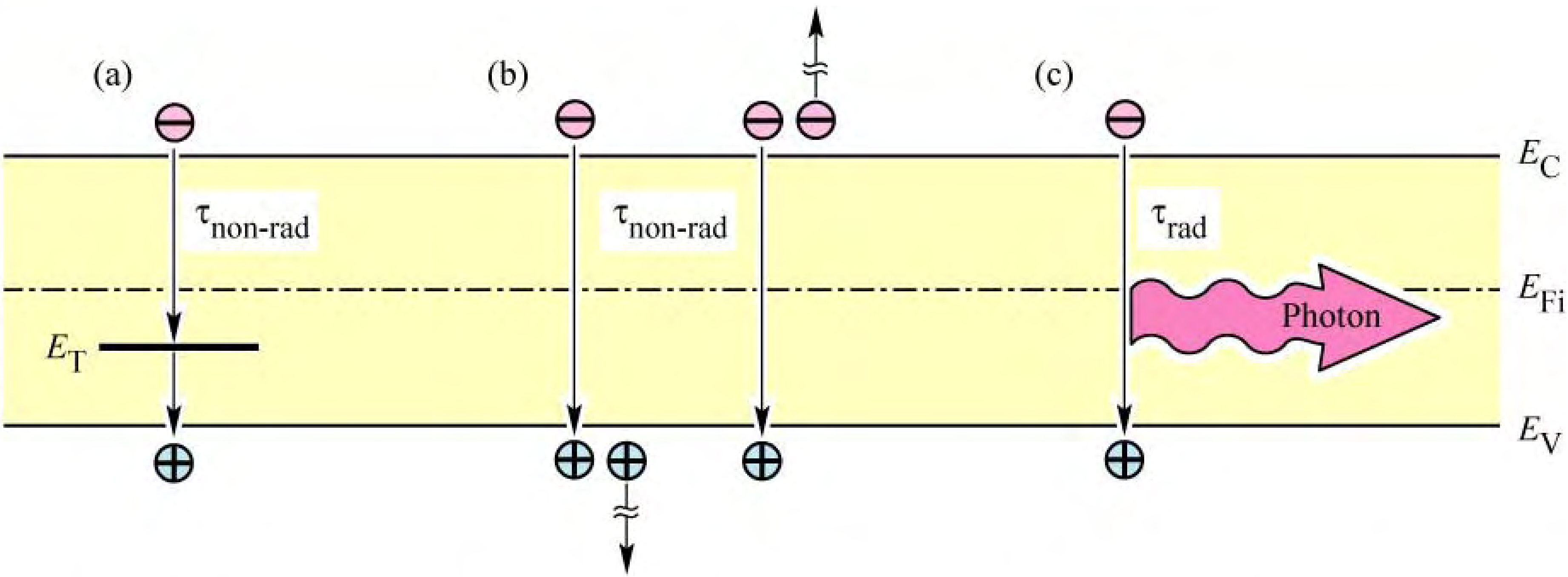
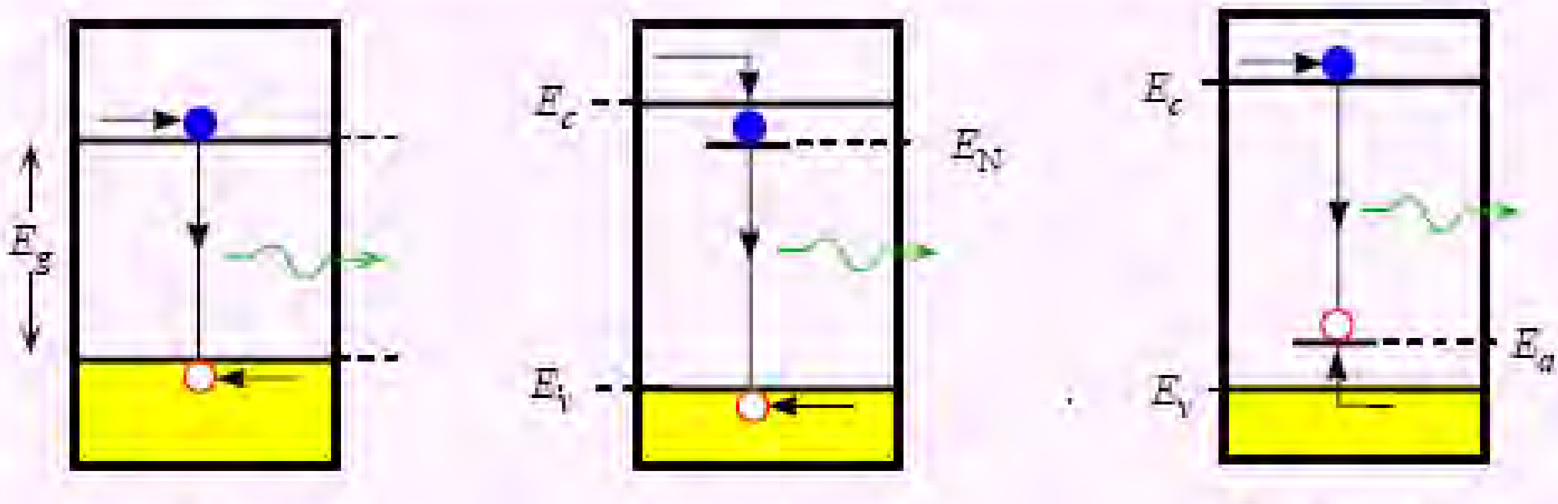


Fig. 2.6. Band diagram illustrating non-radiative recombination: (a) via a deep level, (b) via an Auger process and (c) radiative recombination.

Radiative Recombination



GaAs | N doped GaP | Al doped SiC

Photon emission in a direct bandgap semiconductor

GaP is an indirect bandgap semiconductor. When doped with nitrogen there is an electron trap at E_N. Direct recombination between a trapped electron at E_N and a hole emits a photon.

In *Al* doped *SiC*, EHP recombination is through an acceptor level like E_a.

LED Electrical Basics

Shockley equation for p-n junction diodes

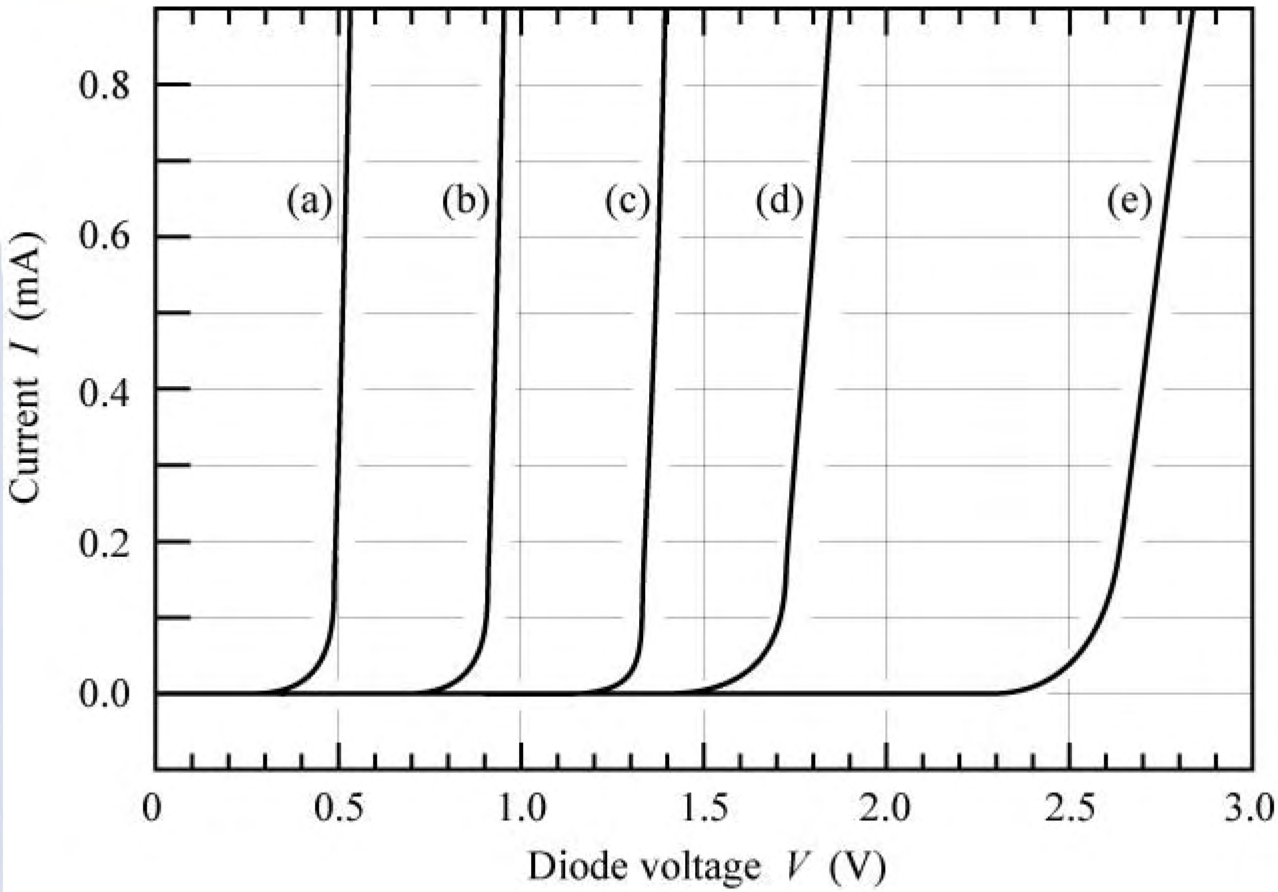
$$I = eA\left(\sqrt{\frac{D_p}{\tau_p}}\,p_{n0} + \sqrt{\frac{D_n}{\tau_n}}\,n_{p0}\right)\left(e^{eV/kT} - 1\right)$$

$$= eA\left(\sqrt{\frac{D_p}{\tau_p}}\,\frac{n_i^2}{N_D} + \sqrt{\frac{D_n}{\tau_n}}\,\frac{n_i^2}{N_A}\right)\left(e^{eV/kT} - 1\right)$$

$$= I_s\left(e^{eV/kT} - 1\right)$$

where I_s is the saturation current

Diode IV Characteristics

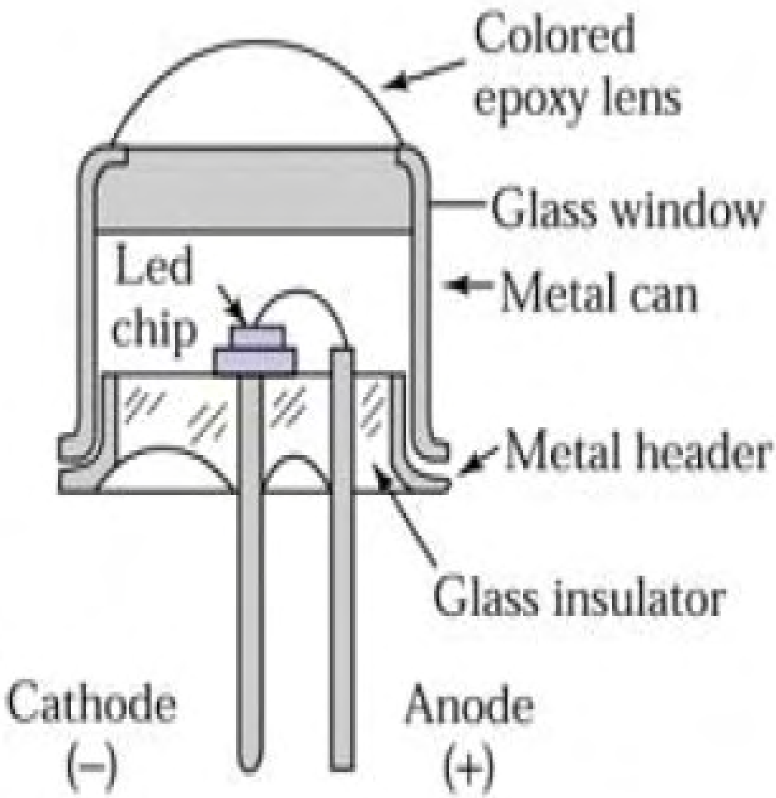


$T = 295$ K

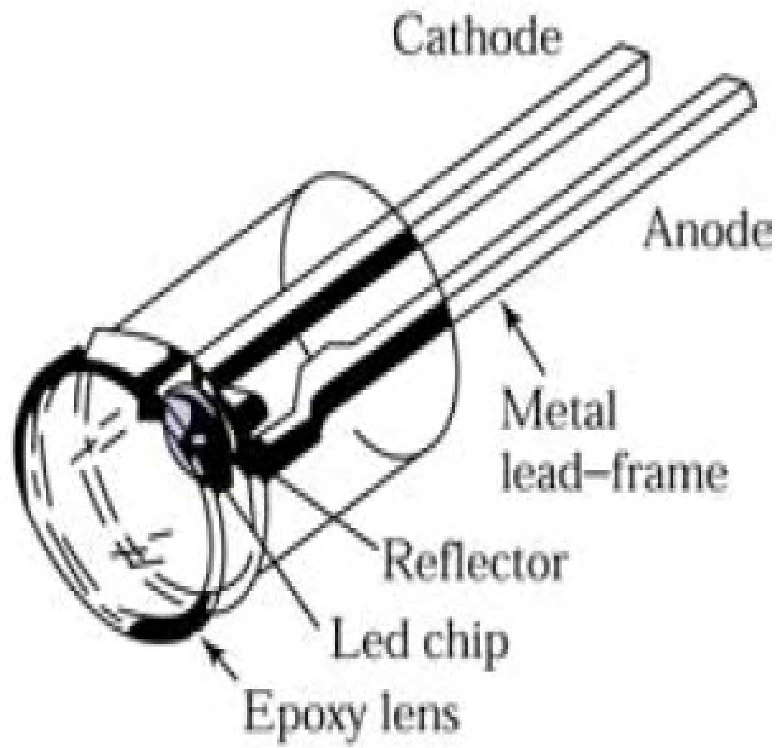
(a)	Ge	$E_g \approx 0.7$ eV
(b)	Si	$E_g \approx 1.1$ eV
(c)	GaAs	$E_g \approx 1.4$ eV
(d)	GaAsP	$E_g \approx 2.0$ eV
(e)	GaInN	$E_g \approx 2.9$ eV

Fig. 4.2. Room-temperature current–voltage characteristics of p-n junctions made from different semiconductors.

LED Structure



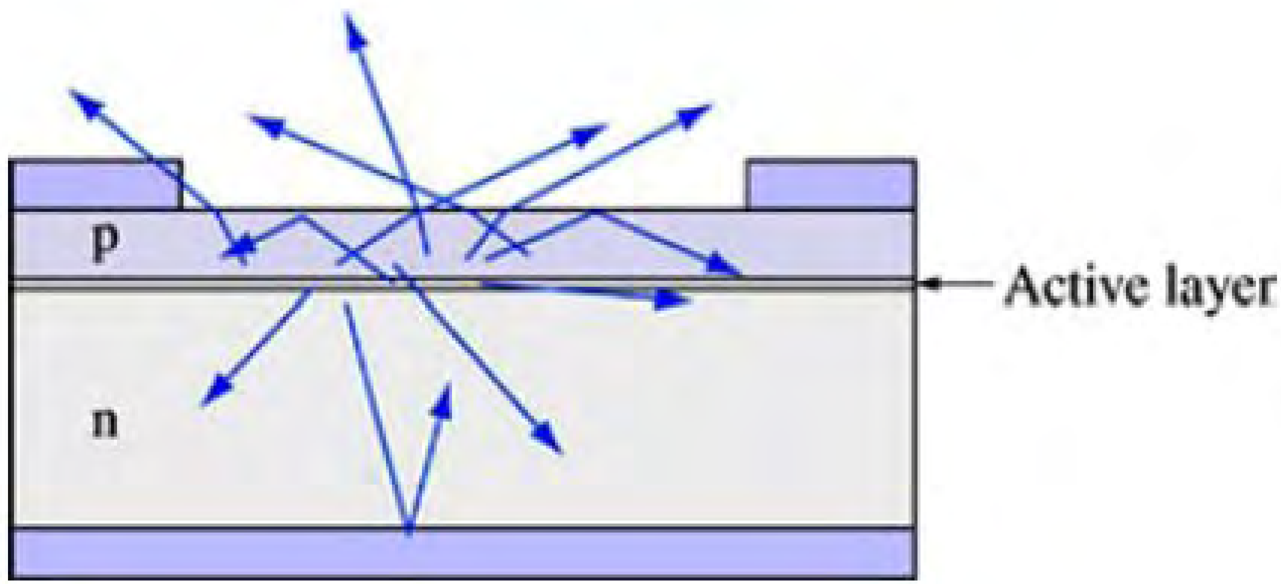
(a)



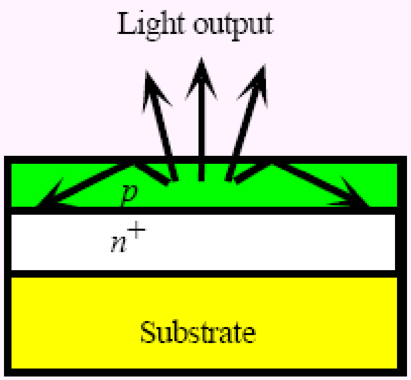
(b)

LED Structure

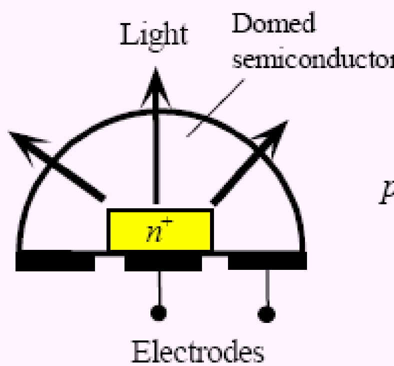
- A generic surface-emitting LED.
  - Some photons are lost by reabsorption in the bulk, Fresnel reflection from the surface, and total internal reflection.



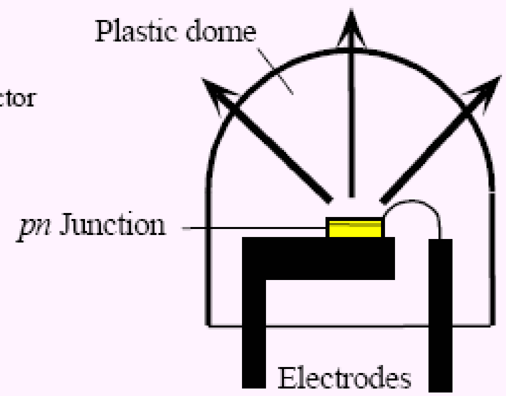
LED Structure



Some light suffers total internal reflection and cannot escape

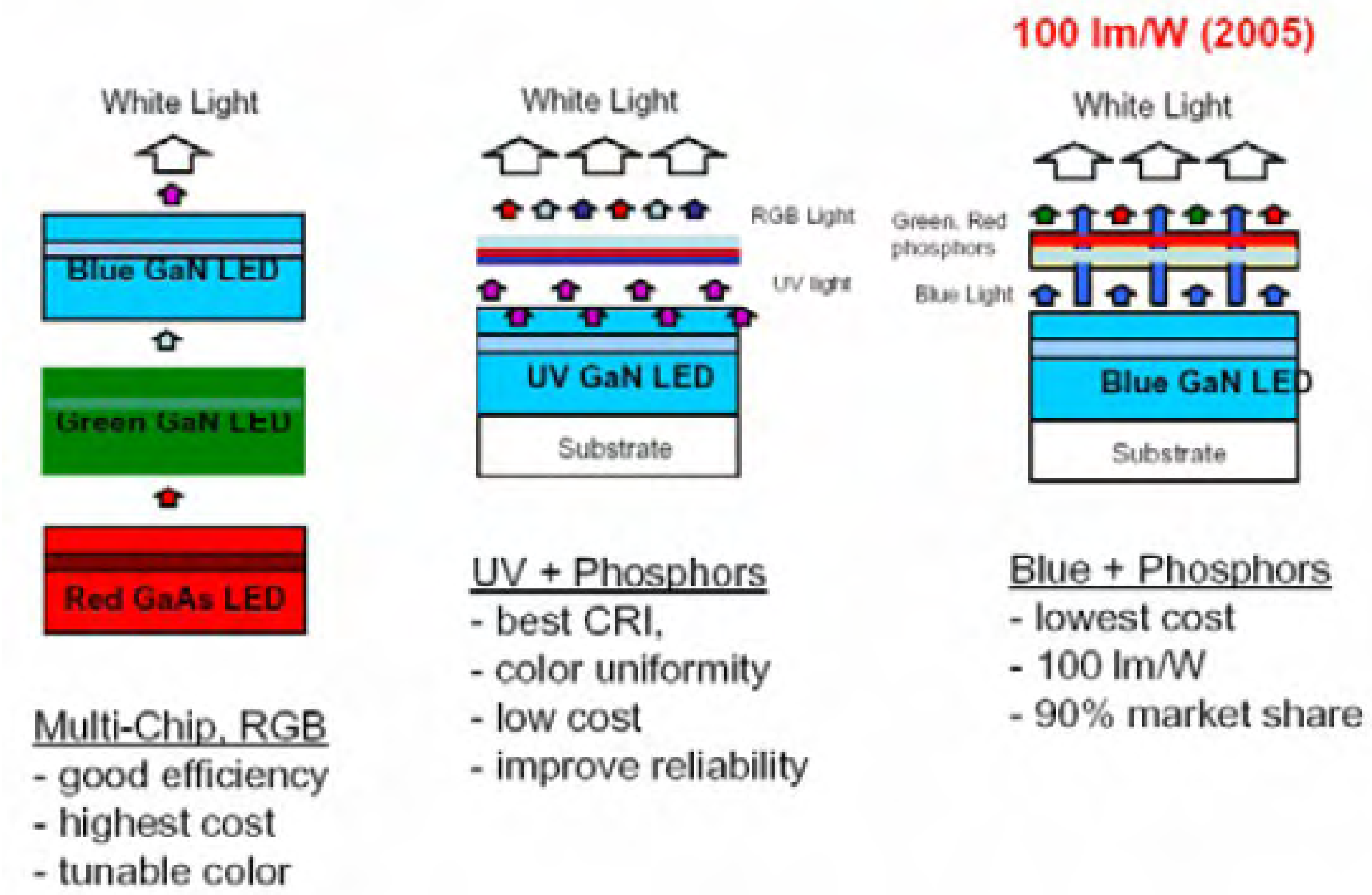


Internal reflections can be reduced and hence more light can be collected by shaping the semiconductor into a dome so that the angles of incidence at the semiconductor-air surface are smaller than the critical angle



An economic method of allowing more light to escape from the LED is to encapsulate it in a transparent plastic dome

Methods for Generating white light



LED Materials

- There are various direct bandgap semiconductor materials that can be readily doped to make commercial pn juction LEDs that emit radiation in the red and infrared range of wavelengths.
- Class of commercial semiconductor materials that cover visible spectrum is the **III-V ternary alloys** (three elements) based on alloying GaAs and GaP, which are denoted as $GaAs_{1-y}P_y$.
- When $y < 0.45$, this alloy is a direct bandgap semiconductor and hence the EHP recombination process is direct (fig. a).
- The emitted wavelengths are 630 nm ($y = 0.45$) – 870 nm ($y = 0$).
- For indirect bandgap, $y > 0.45$, EHP recombination processes occur through recombination centers and invlve lattice vibrations (phonon).
- **Isoelectronic impurities**, such as nitrogen (in the same group V as P) → some N atoms substitute for P atoms.

LED Materials

- Positive nucleus of N is less shielded → conduction electron in the neighborhood of an N atom will be attracted and may traped at this site. → N atom then have localized energy levels, or electron traps, E_N, near the conduction band (fig b).
- The trapped electron then can attract a hole in its vicinity → recombine with it and emit a photon.
- The emitted photon energy is slightly less than E_g.
- The recombination process depends on N doping → less efficient.
- Mainly used from green, yellow, and orange LEDs.
- Two types of blue LED materials: GaN alloy (InGaN) and Al doped SiC.
- The localized energy level captures a hole from the valence band and a conduction electron then recombines with this hole to emit a photon (fig c).
- More efficient blue LEDs using direct bandgap compound II-VI semiconductors, such as ZnSe.

LED Materials

Color	Wavelength (nm)	Voltage (V)	Semi-conductor Material
Infrared	$\lambda > 760$	$\Delta V < 1,9$	Gallium arsenide (GaAs) Aluminium gallium arsenide (AlGaAs)
Red	$610 < \lambda < 760$	$1,63 < \Delta V < 2,03$	Aluminium gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP)
Orange	$590 < \lambda < 610$	$2,03 < \Delta V < 2,10$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP)
Yellow	$570 < \lambda < 590$	$2,10 < \Delta V < 2,18$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP)
Green	$500 < \lambda < 570$	$2,18 < \Delta V < 4,0$	Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN) Gallium(III) phosphide (GaP) Aluminium gallium indium phosphide (AlGaInP) Aluminium gallium phosphide (AlGaP)
Blue	$450 < \lambda < 500$	$2,48 < \Delta V < 3,7$	Zinc selenide (ZnSe) Indium gallium nitride (InGaN) Silicon carbide (SiC) as substrate Silicon (Si) as substrate — (under development)
Violet	$400 < \lambda < 450$	$2,76 < \Delta V < 4,0$	Indium gallium nitride (InGaN)
Ultraviolet	$\lambda < 400$	$3,1 < \Delta V < 4,4$	diamond (C) Aluminium nitride (AlN) Aluminium gallium nitride (AlGaN) (AlGaInN) — (down to 210 nm[17])
White	Broad spectrum	$\Delta V = 3,5$	Blue/UV diode with phosphor

LED Materials

- Other various commercial direct bandgap semiconductor material that emit the red and infrared wavelengths: ternary, quartenary alloys based on III and V elements.
- Emitted radiation ranges from 640 – 870 nm (from deep red light to infrared).
- External efficiency $\eta_{external}$ of an LED: efficiency of conversion of electrical energy into an emitted external external energy.

$$\eta_{external} = \frac{P_{out}\,(\text{Optical})}{IV} \times 100\%$$

- The input power: product of diode current and voltage.

LED External Conversion Efficiency

The external power or conversion efficiency η_{ext} is defined as

$$\eta_{ext} = \frac{\text{Optical power output}}{\text{Electrical power input}} = \frac{P_o}{IV}$$

One of the major factors reducing the external power efficiency is the loss of photons in extracting the emitted photons which suffer reabsorption in the pn junction materials, absorption outside the semiconductors and various reflections at interfaces.

The total light output power from a particular AlGaAs red LED is 2.5 mW when the current is 50 mA and the voltage is 1.6 V.

Calculate its external conversion efficiency.

Solution

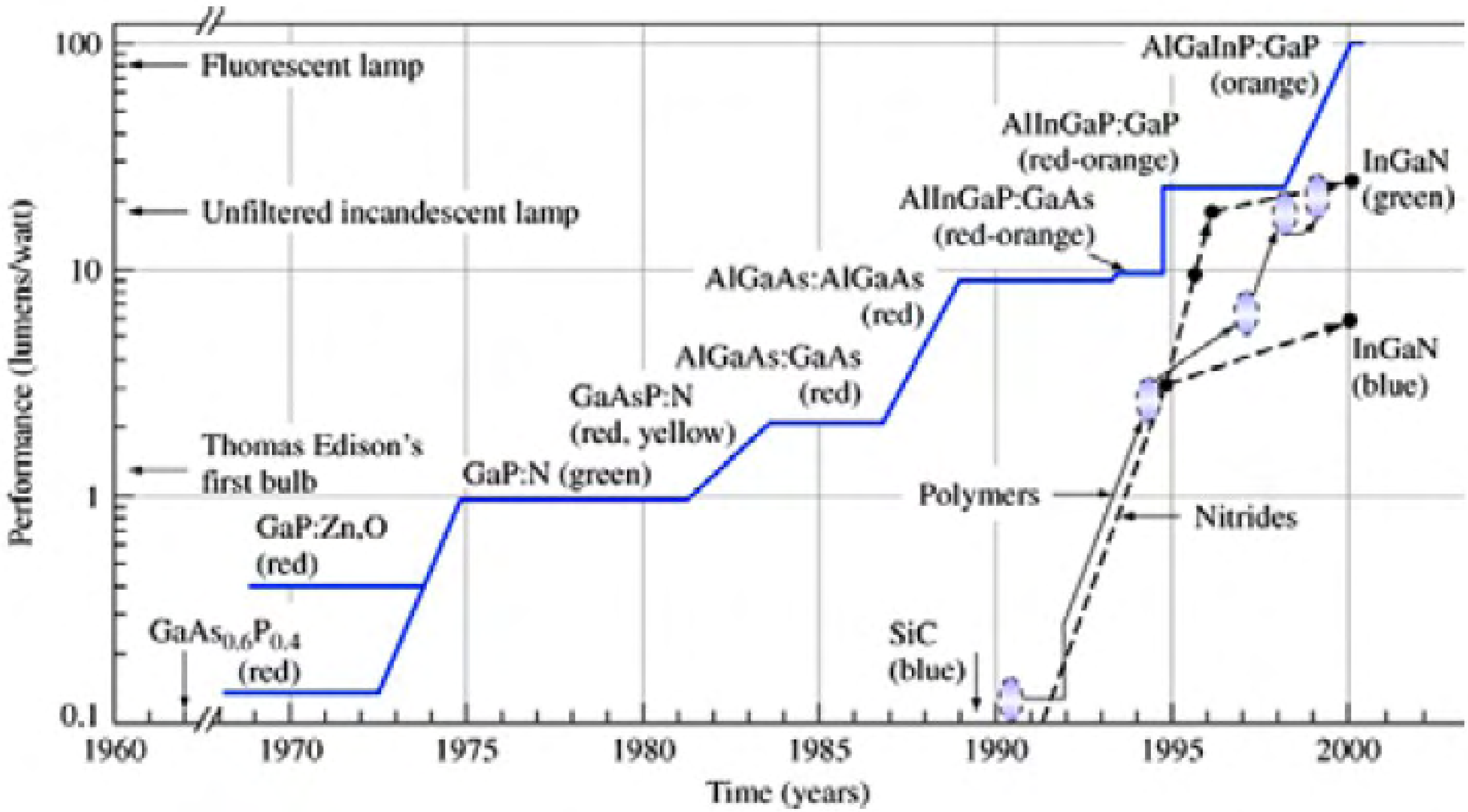
$$\eta_{ext} = \frac{P_o}{IV} = \frac{2.5 \times 10^{-3}\ \text{W}}{(50 \times 10^{-3}\ \text{A})(1.6\ \text{V})} = 0.03125 = \mathbf{3.125\ \%}$$

LED Characteristics

Wavelength vs. Typical Materials

Materials	Wavelength	Color
GaInN	*370*	purple
GaInN	*450*	blue
GaInN	*525*	green
InGaAlP/GaAs	*562*	green
InGaAlP/GaAs	*574*	yellow green
InGaAlP/GaP	*590*	yellow
InGaAlP	*644*	red
GaAlAs/GaAs	*660*	red
GaP/GaP	*700*	red
GaAlAs	*880*	UV
GaAs	*940*	UV

Historical Development of LEDs



Quaternary alloy Example

InGaAsP on InP substrate

The quaternary alloy $In_{1-x}Ga_xAs_{1-y}P_y$ grown on an InP crystal substrate is a suitable commercial semiconductor material for infrared LED and laser diode applications. The device requires that the InGaAsP layer is lattice matched to the InP crystal substrate to avoid crystal defects in the InGaAsP layer. This turn requires that $y \approx 2.2x$. The bandgap energy E_g of the ternary alloy in eV is then given by the empirical relationship,

$$E_g \approx 1.35 - 0.72y + 0.12y^2 \;:\; 0 \leq x \leq 0.47$$

Calculate the compositions of InGaAsP ternary alloys for peak emission a a wavelength of 1.3 µm. (h= 6.626x10-34 joule-sec, kB= 8.617x10-5 eV/K, kBT= 0.0259 eV (T=300K), c= 3x108 m/sec, q= 1.6x10-19 coul)

The photon energy at peak emission is $\frac{h \cdot c}{\lambda} = E_g + k_B T$

Then $E_g[eV] = \frac{h \cdot c}{e\lambda} - \frac{k_B T}{e}$ $\quad \lambda = 1.3 \times 10^{-6} m, \quad T = 300K$

$$E_g = \frac{(3 \times 10^8)(6.626 \times 10^{-34})}{(1.6 \times 10^{-19})(1.3 \times 10^{-6})} - 0.0259\, eV = 0.928\, eV$$

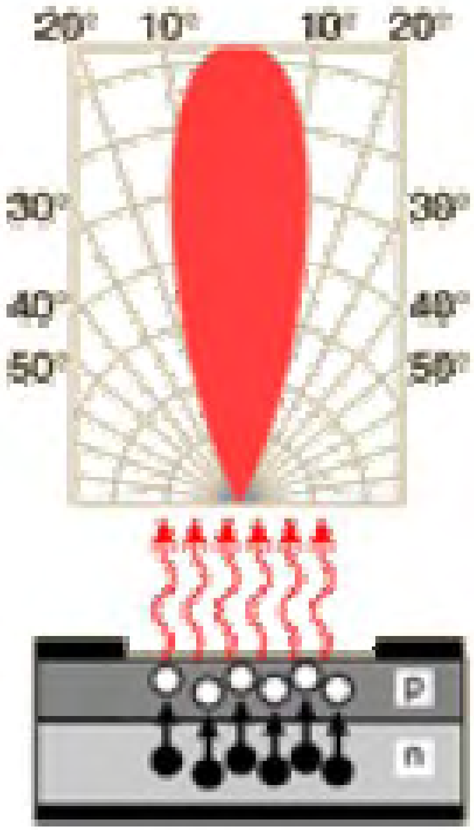
The InGaAsP then must have y satisfying $0.928 = 1.35 - 0.72y + 0.12y^2$

$$y = 0.66, \quad x = \frac{0.66}{2.2} = 0.3$$

The quaternary alloy is $In_{0.7}Ga_{0.3}As_{0.34}P_{0.66}$

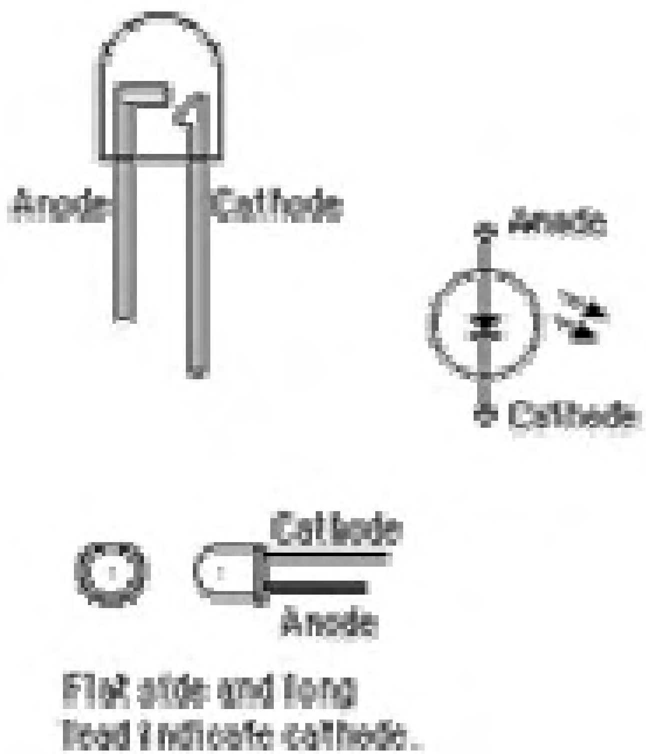
Radiation Pattern

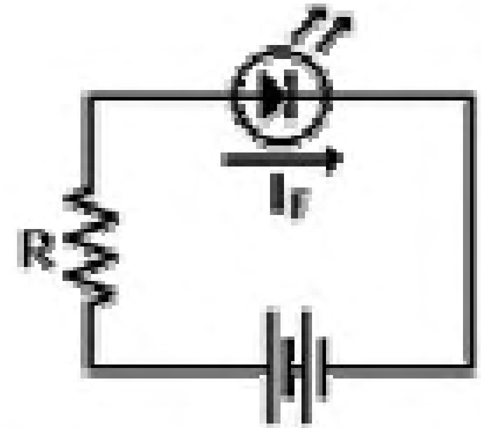
LED **radiation pattern**



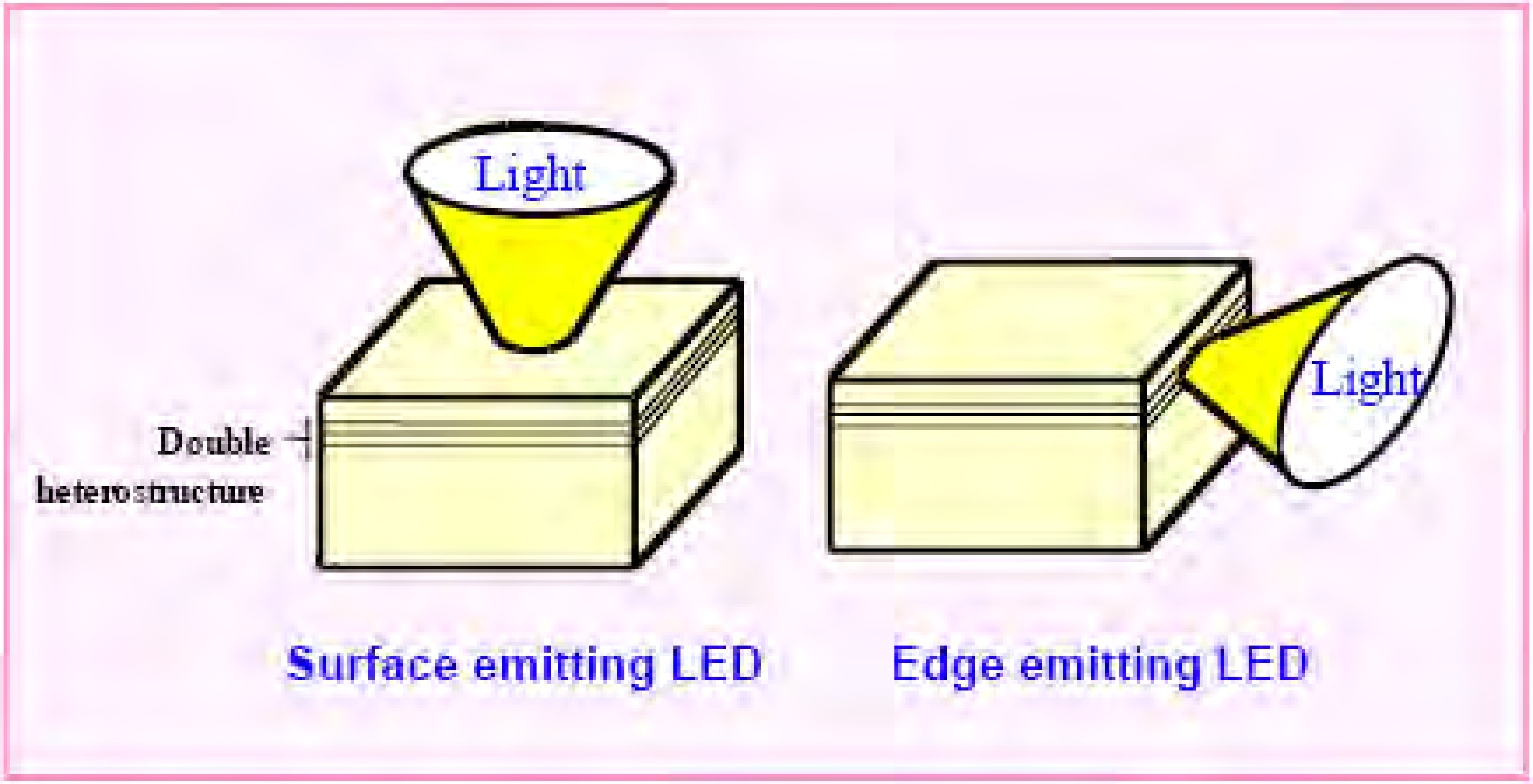
- An LED is a directional light source, with the maximum emitted power in the direction perpendicular to the emitting surface.
- The typical radiation pattern shows that most of the energy is emitted within 20°of the direction of maximum light.
- Some packages for LEDs include plastic lenses to spread the light for a greater angle of visibility.

LED Symbols

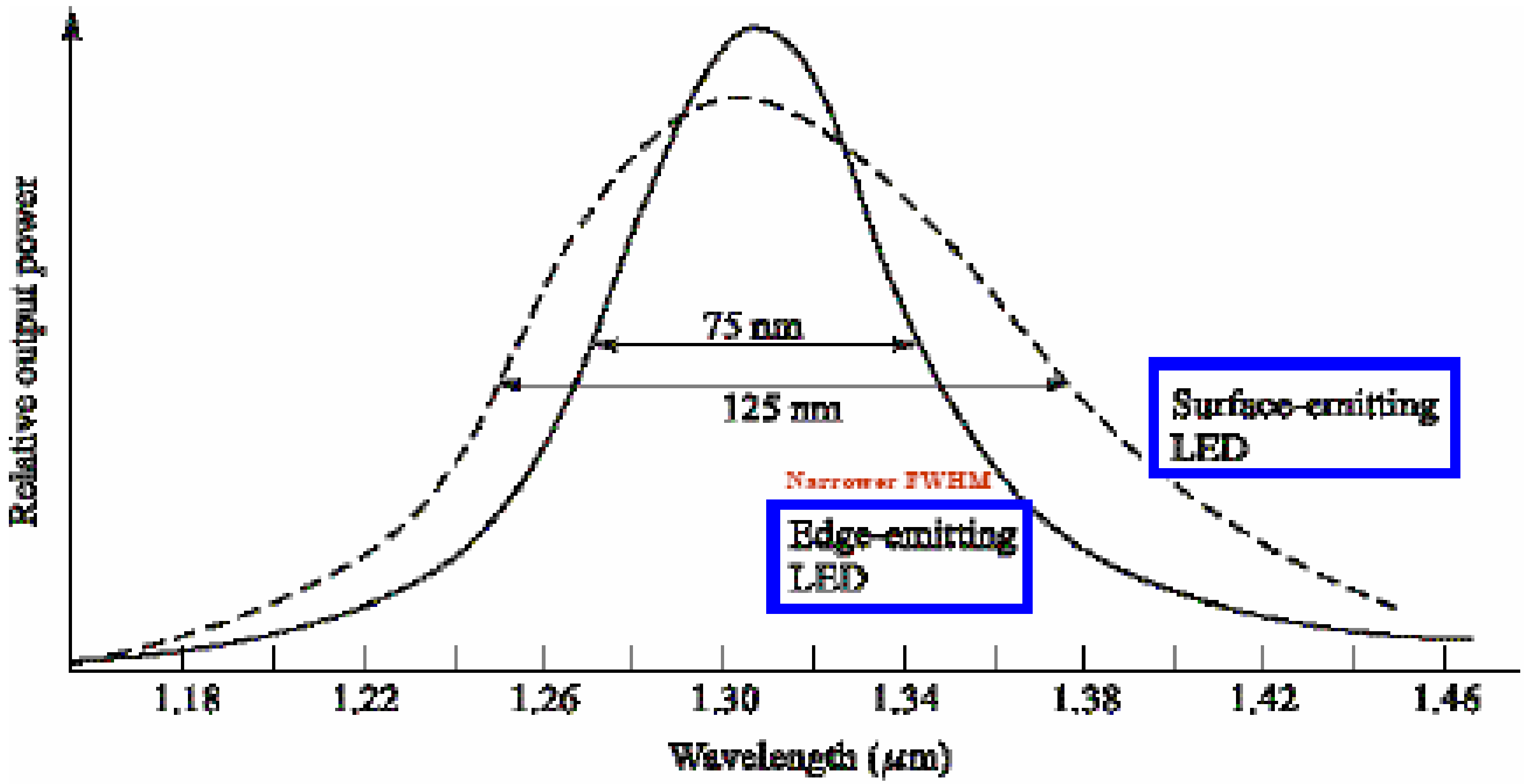

Anode
Cathode
Anode
Cathode
Cathode
Anode
Flat side and long
lead indicate cathode.


R
I_F

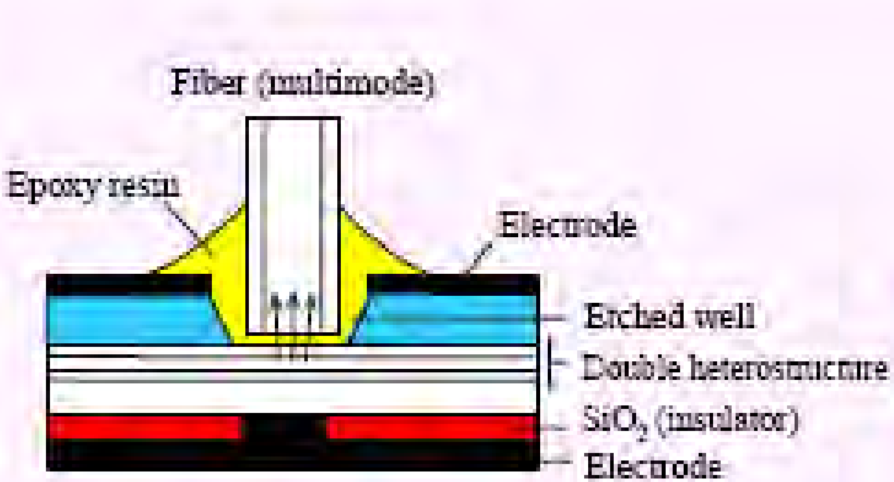
Emitting Diode Types



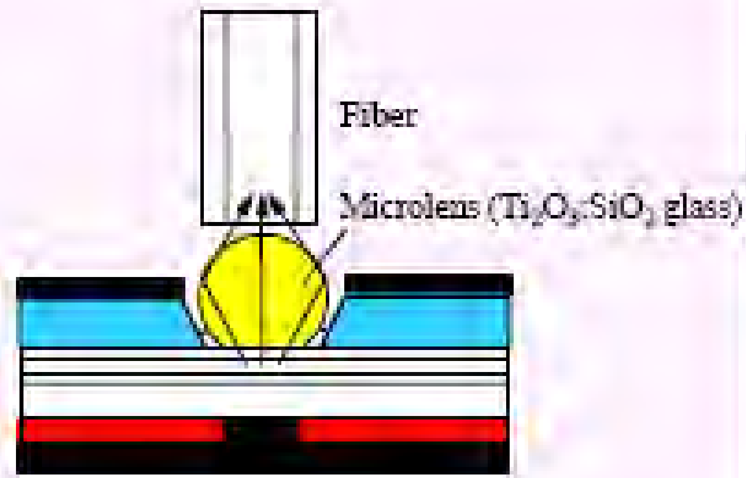
LED Spectral Patterns



Optical Fibre coupling for Surface Emitting LED

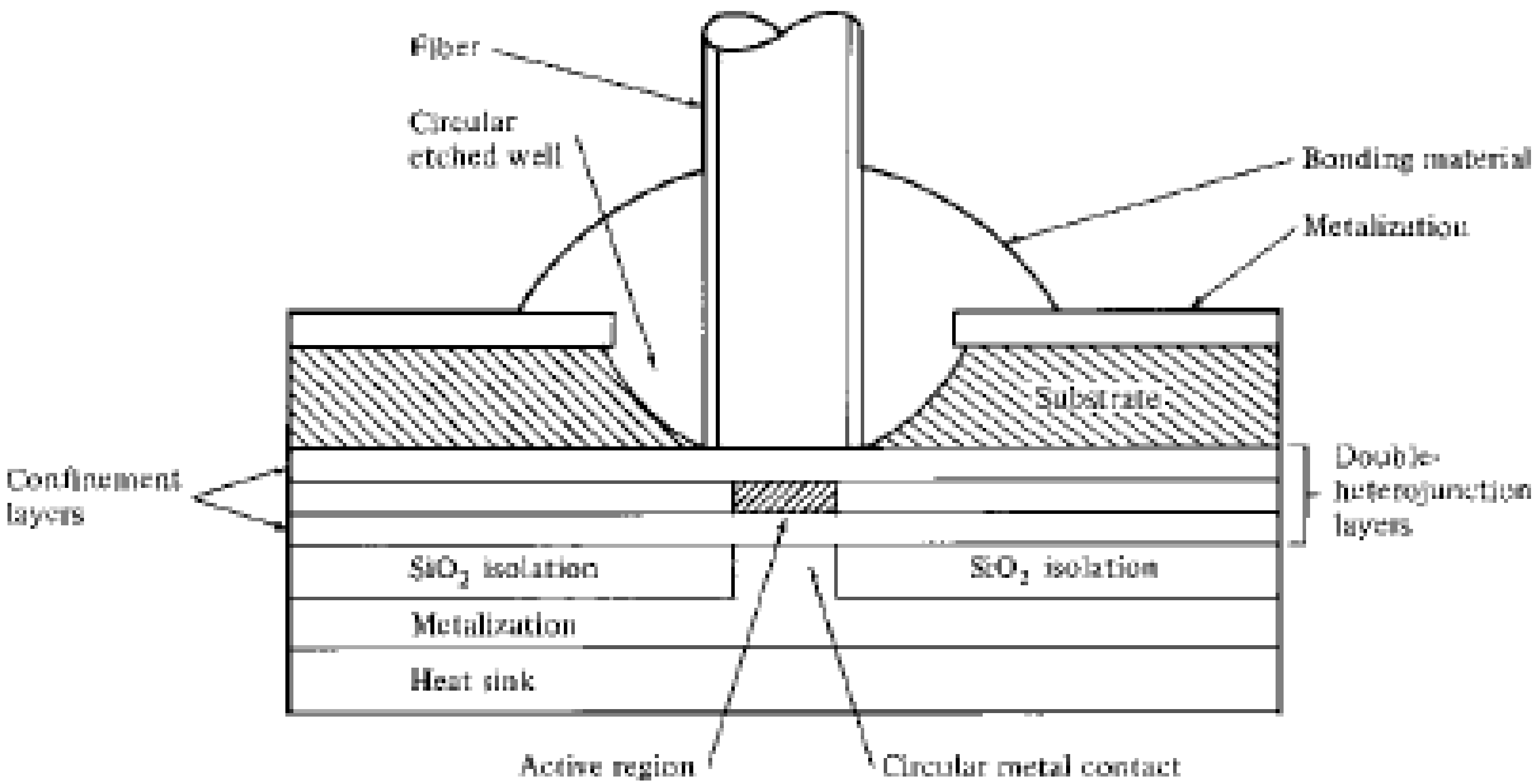


Light is coupled from a surface emitting LED into a multimode fiber using an index matching epoxy. The fiber is bonded to the LED structure.



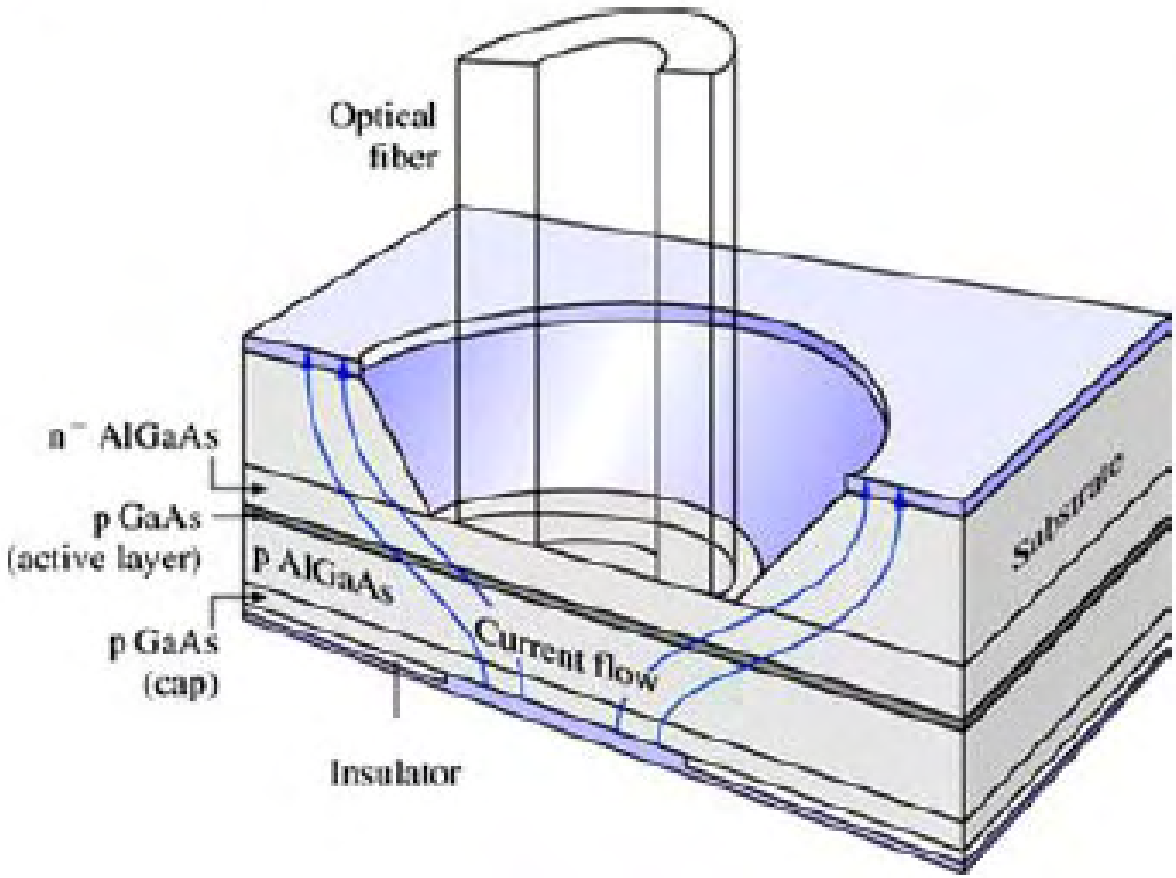
A microlens focuses diverging light from a surface emitting LED into a multimode optical fiber.

Surface Emitting LED Optical Coupling



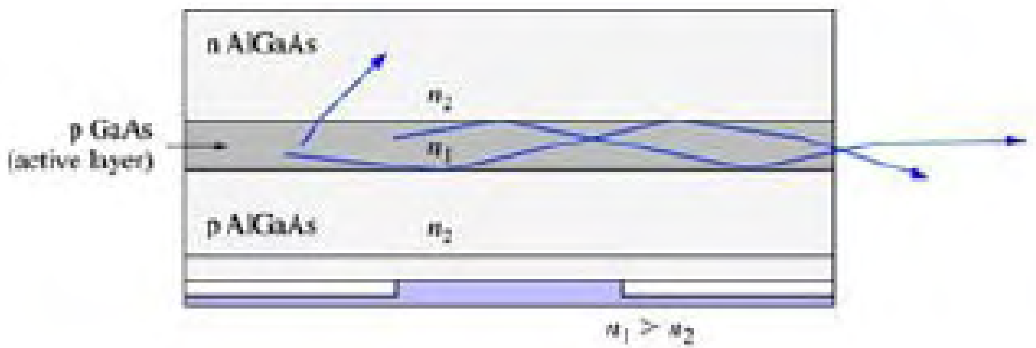
Burrus Type LED

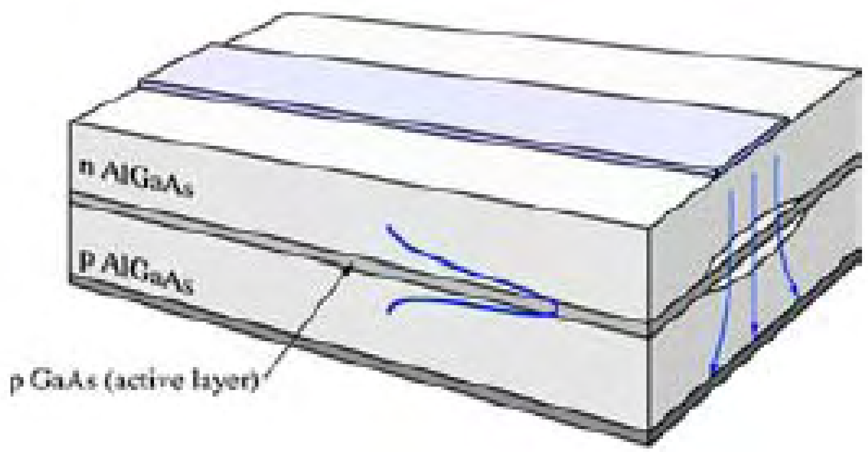
A Burrus-type LED. This one uses a Double Heterostructure to confine the carriers, making recombination more efficient. The etched opening in the LED helps align and couple an optical fiber.



Edge Emitting LED

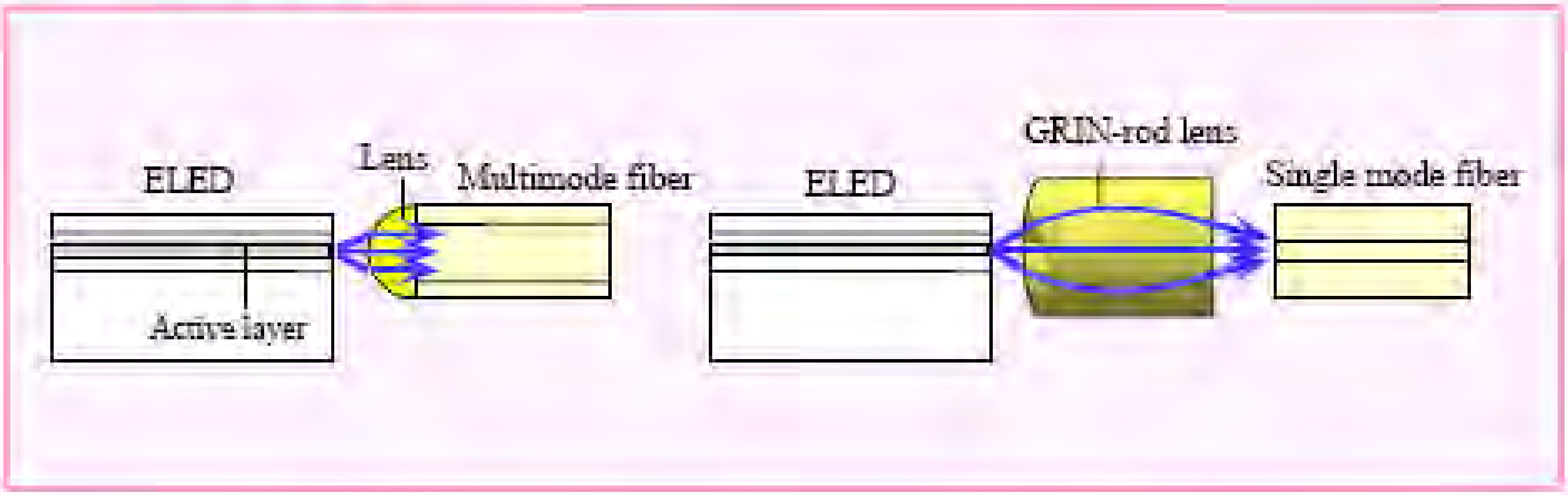
- In an Edge-emitting LED, the higher-index active layer acts as a waveguide for photons traveling at less than the critical angle.





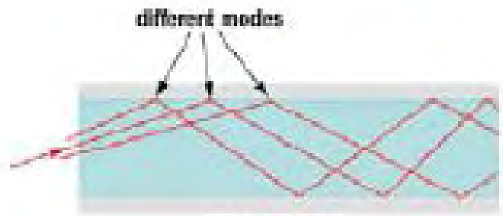
Optical Fibre Coupling in Edge Emitted LED

- Light from an Edge emitting LED is coupled into a fiber typically by using a lens or a GRIN rod lens

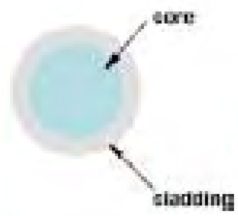


GRIN = Gradient Index

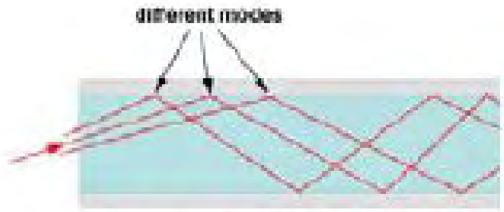
Type of Multimode Fibre



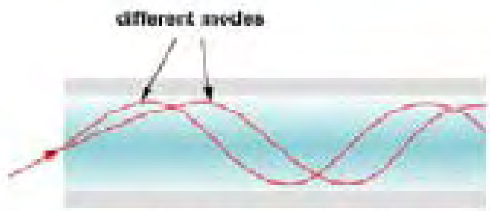
Multimode Fiber



Step-index multimode fibers are mostly used for imaging and illumination. Graded-index multimode fibers are used for data communications and networks carrying signals moderate distances - typically no more than a couple of kilometers



Step-index Multimode Fiber



Graded-index Multimode Fiber

Fibre Coupling Efficiency

LED-Fiber coupling Efficiency

a) It is found that approximately 200 μW is coupled into a multimode step index fiber from a surface emitting LED when the current is 75 mA and the voltage across the LED is about 1.5 V. What is the overall <u>efficiency</u> of operation?

b) Experiments are carried out on coupling light from a 1310 nm ELED-Edge emitting LED in multimode and single mode fibers.

(i) At room temperature, when the ELED current is 120 mA, the voltage is 1.3 V and light power coupled into a 50 μm multimode fiber with NA = 0.2 is 48 μW. What is the overall <u>efficiency</u>?

(ii) At room temperature, when the ELED current is 120 mA, the voltage is 1.3 V and light power coupled into a 9 μm single mode fiber is 7 μW. What is the overall <u>efficiency</u>?

Solution

a) $$\eta_{overall} = \frac{P_o}{IV} = \frac{200 \times 10^{-6} \text{ W}}{(75 \times 10^{-3} \text{ A})(1.5 \text{ V})} = 1.8\text{x}10^{-3} = \mathbf{0.18\ \%}$$

b) i) $$\eta_{overall} = \frac{P_o}{IV} = \frac{48 \times 10^{-6} \text{ W}}{(120 \times 10^{-3} \text{ A})(1.3 \text{ V})} = \mathbf{0.0307\%}$$

ii) $$\eta_{overall} = \frac{P_o}{IV} = \frac{7 \times 10^{-6} \text{ W}}{(120 \times 10^{-3} \text{ A})(1.3 \text{ V})} = \mathbf{0.0045\%}$$

3.11 Internal quantum efficiency The internal efficiency η_{int} gauges what fraction of electron hole recombinations in the forward biased *pn* junction are radiative and therefore lead to photon emission. Nonradiative transitions are those in which an electron and a hole recombine through a recombination center such as a crystal defect or an impurity and emit phonons (lattice vibrations). By definition,

$$\eta_{int} = \frac{\text{Rate of radiative recombination}}{\text{Total rate of recombination (radiative and nonradiative)}}$$

or

$$\eta_{int} = \frac{\frac{1}{\tau_r}}{\frac{1}{\tau_r} + \frac{1}{\tau_{nr}}}$$

where τ_r is the mean lifetime of a minority carrier before it recombines radiatively and τ_{nr} is the mean lifetime before it recombines via a recombination center without emitting a photon. The total current I is determined by the total rate of recombinations whereas the number of photons emitted per second (Φ_{ph}) is determined by the rate of radiative recombinations.

$$\eta_{int} = \frac{\text{Photons emitted per second}}{\textit{Total carriers lost per second}} = \frac{\Phi_{ph}}{I/e} = \frac{P_{op(int)}/h\upsilon}{I/e}$$

where $P_{op(int)}$ is the optical power generated internally (not yet extracted).

For a particular AlGaAs LED emitting at 850 nm it is found that τ_r = 50 ns and τ_{nr} = 100 ns. What is the internal optical power generated at a current of 100 mA?

Solution

Consider

$$\eta_{int} = \frac{\frac{1}{\tau_r}}{\frac{1}{\tau_r} + \frac{1}{\tau_{nr}}} = \frac{\frac{1}{50\ \text{ns}}}{\frac{1}{50\ \text{ns}} + \frac{1}{100\ \text{ns}}} = 0.667 = \mathbf{66.7\ \%}$$

From

$$\eta_{int} = \frac{P_{op(int)}/h\upsilon}{I/e}$$

$$P_{op(int)} = \eta_{int}\left(\frac{I}{e}\right)h\upsilon = \eta_{int}\frac{Ihc}{e\lambda} = (0.667)\frac{(100\times10^{-3})(6.626\times10^{-34})(3\times10^{8})}{(1.6\times10^{-19})(850\times10^{-9})}$$

$$= 0.097\ \text{W or } \mathbf{97\ mW}$$