PH 301

ENGINEERING OPTICS

Lecture_Optical Sources_LED_20

Light Emitting Diode

1962

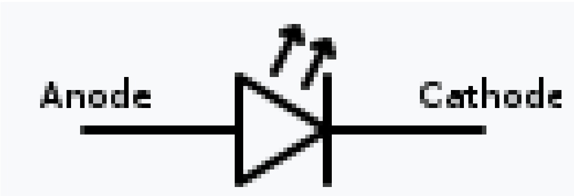
- **A light emitting diode (LED) is a two-lead semiconductor light source.**

- **It is a p-n junction diode that emits light when activated.**

- **When a suitable voltage is applied to the leads, electrons are able to recombine with electron holes within device, releasing energy in the form of photons. This effect is called electroluminescence, & the color of light ($E = h\nu = hc/\lambda$) is determined by energy gap of semiconductor.**

- **LEDs are typically small (less than 1 mm^2) & integrated optical components may be used to shape the radiation pattern.**

Blue, green, & red LEDs

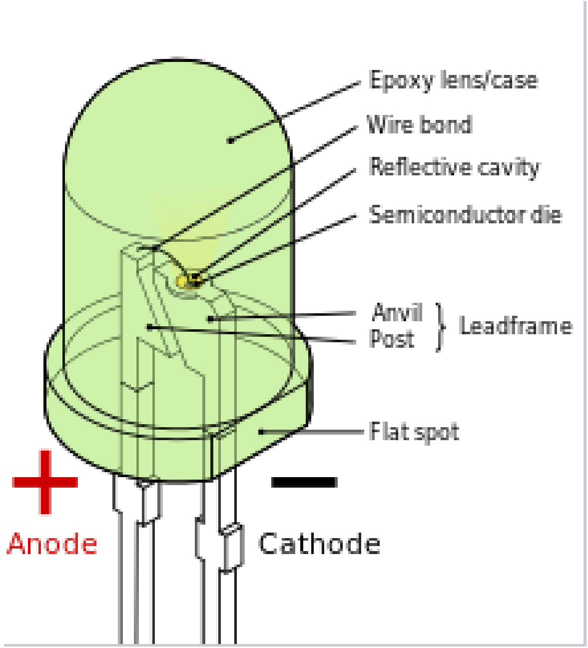


Electronic symbol

- **Earliest LEDs emitted low-intensity IR light (remote control circuits).**

- **Modern LEDs: visible, UV, & IR with very high brightness.**

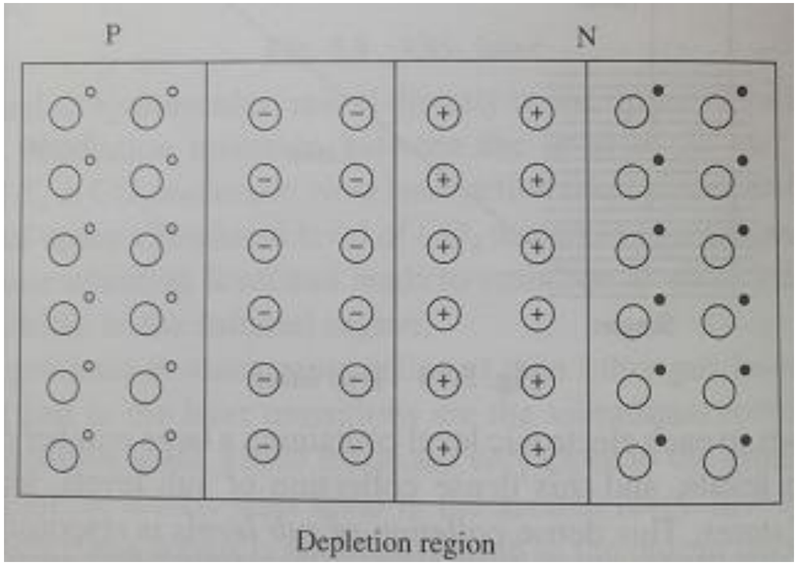
- **Unlike a laser, light emitted from an LED is neither coherent nor monochromatic, but spectrum is narrow with respect to human vision, & for most purposes the light from a simple diode element can be regarded as functionally monochromatic.**



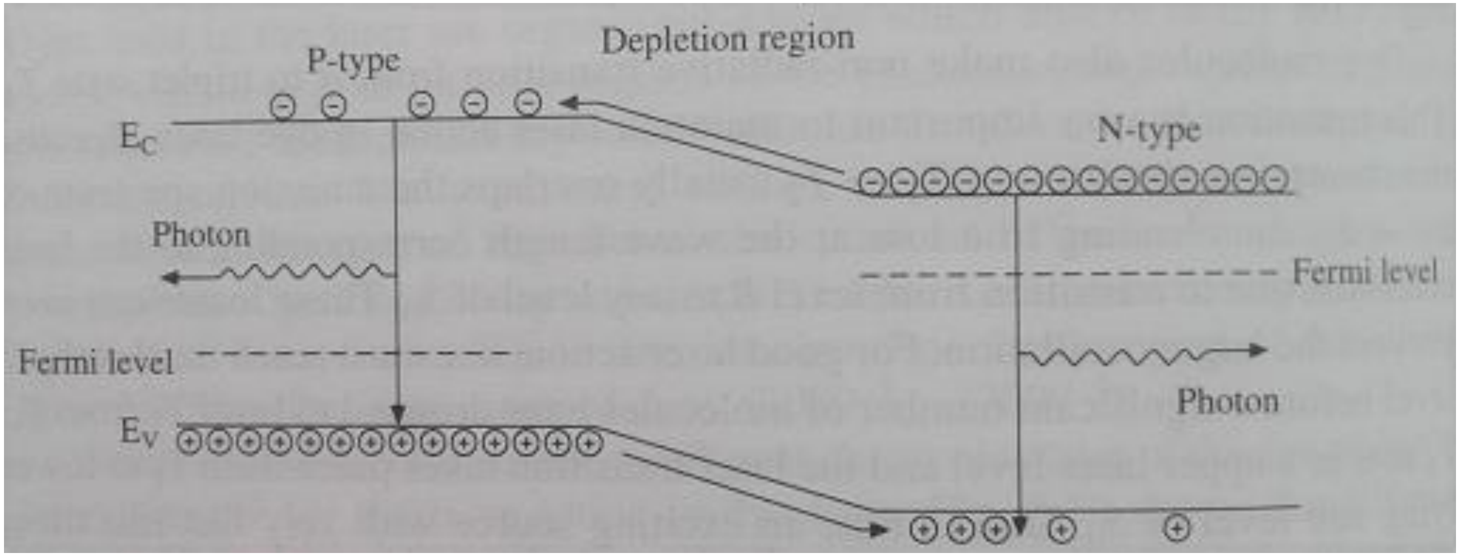
Parts of a conventional LED

Bulb-shaped modern retrofit LED lamp

Semiconductor Light Source



Formation of depletion region in P-N junction



Recombination of carriers under forward bias in P-N junction

Semiconductor Light Source

- **Very small, operate with low power input, & very efficient.**
- **Require merging of two different materials & emission occurs in interface between those two materials.**
- **One of the materials has an excess of electrons (*n*-type) & other has material (*p*-type). [*p*-type has a deficit of electrons or an excess of holes (missing electrons)]**
- **When a forward bias voltage is placed across this junction, electrons are forced into region from *n*-type material & holes are forced into junction from *p*-type material.**
- **These electrons (-ve) & holes (+ve) are attracted to each other & when they collide, they neutralize each other & in the process emit recombination radiation.**

- ❖ **Electrons in *n*-type material exist (at normal operating temp) at a higher energy (conduction band) than holes (valence band).**

- ❖ **Energy difference is designated as *bandgap* of material; amount of energy that is released when recombination radiative process occurs.**

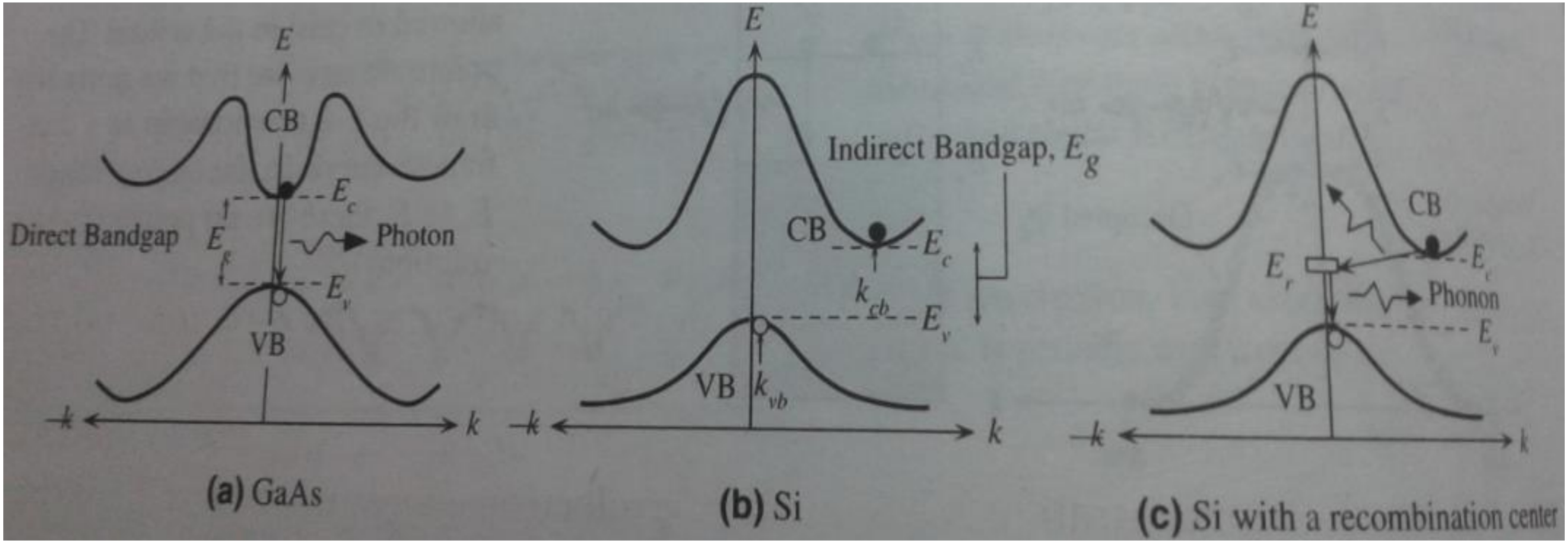
- ❖ **Different material combinations have different bandgaps & thus emit different wavelengths of light.**

- ❖ **When forward bias voltage is applied across junction, it produces a current flow in the form of electrons (& holes) flowing into junction. If current is low, incoherent light is emitted from the junction when recombination process occurs – <u>Light Emitting Diode</u> (LED).**

- ❖ **If current is high enough that there are more electrons in conduction band at a given energy than in valence band, then a population inversion exists & gain is produced.**

(a) In GaAs, minimum of conduction band is directly above maximum of valence band. GaAs is a direct bandgap semiconductor.

(c) Recombination of an electron & a hole in Si involves a recombination centre.



(a) GaAs (b) Si (c) Si with a recombination center

(b) In Si, minimum of conduction band is displaced from maximum of valence band. Si is an indirect bandgap semiconductor.

Advantages

- **Lower energy consumption (energy efficient),**
- **Longer lifetime,**
- **Improved physical robustness,**
- **Smaller size,**
- **Faster switching, &**
- **Fewer environmental concerns linked to disposal**

Applications

- **Aviation lighting,**
- **Automotive headlamps,**
- **Advertising,**
- **General lighting,**
- **Traffic signals,**
- **Camera flashes,**
- **Lighted wallpaper, …**

Electroluminescence

- 1907: Electroluminescence was discovered by H. J. Round (British) using a crystal of silicon carbide & cat's-whisker detector.
- 1927: Oleg Losev (Russian) reported creation of 1st LED.
- 1953: Kurt Lehovec, Carl Accardo, & Edward Jamgochian (SiC).
- 1955: Rubin Braunstein, IR using GaAs
- 1957: Braunstein demonstrated that rudimentary devices could be used for non-radio communication across a short distance.
- 1961: James R. Biard & Gary Pittman discovered near-IR emission from a tunnel diode (GaAs substrate).
- 1962: Nick Holonyak at GE, red LED

Braunstein "…had set up a simple optical communications link: Music emerging from a record player was used via suitable electronics to modulate the forward current of a GaAs diode. The emitted light was detected by a PbS diode some distance away. This signal was fed into an audio amplifier and played back by a loudspeaker. Intercepting the beam stopped the music." This setup presaged the use of LEDs for optical communication applications.

Until 1968, VIS & IR LEDs were extremely costly - US $200 per unit & so had little practical use.

Monsanto Company: Visible LEDs, using gallium arsenide phosphide (GaAsP) to produce red LEDs suitable for indicators.

Hewlett-Packard: Red LEDs, these were bright enough only for use as indicators, as light output was not enough to illuminate an area.

Fairchild Optoelectronics.

- **1994: 1st high-brightness blue LED - Shuji Nakamura, InGaN (Indium Gallium Nitride).**

  In parallel, Isamu Akasaki & Hiroshi Amano in Nagoya were working on developing important GaN nucleation on sapphire substrates & demonstration of p-type doping of GaN.

- **2014: Nakamura, Akasaki, & Amano, Nobel prize in Physics.**

White LED

- **In white LED, a $Y_3Al_5O_{12}$:Ce (known as YAG) phosphor coating on the emitter absorbs some of the blue emission & produces yellow light through fluorescence. Combination of that yellow with remaining blue light appears white.**

  However, using different phosphors (fluorescent materials) it also became possible to instead produce green & red light.

Working Principle

- **A P-N junction can convert absorbed light energy into a proportional electric current. This process is reversed here (i.e. P-N junction emits light when electrical energy is applied to it). This phenomenon is called electroluminescence.**

- **Electroluminescence can be defined as emission of light from a semiconductor under the influence of an electric field.**

- **Charge carriers recombine in a forward-biased P-N junction as the electrons cross from N-region & recombine with holes existing in P-region.**

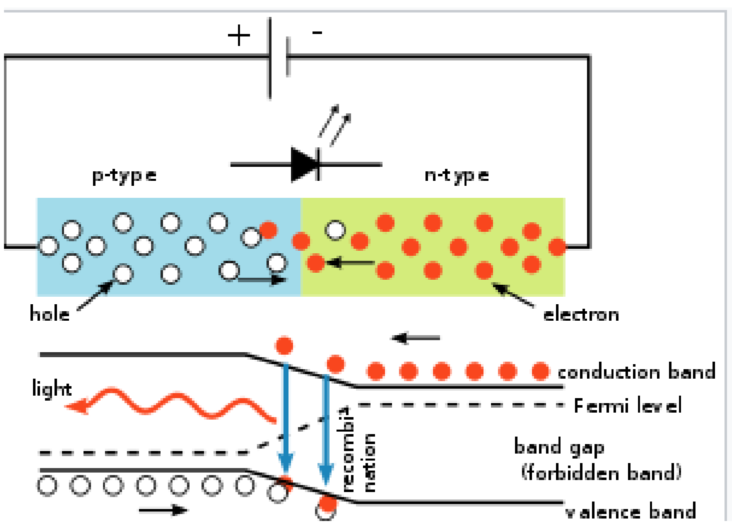
- **Free electrons are in conduction band of energy levels, while holes are in valence energy band. Thus energy level of holes is less than energy levels of electrons.**

  Some portion of energy must be dissipated to recombine electrons & holes. This energy is emitted in the form of heat & light.

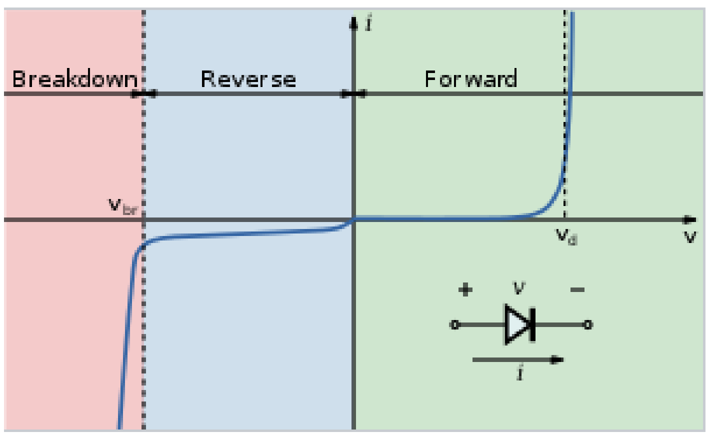
Working Principle

Electrons dissipate energy in the form of heat for silicon & germanium diodes but in gallium arsenide phosphide (GaAsP) & gallium phosphide (GaP) semiconductors, electrons dissipate energy by emitting photons.

If semiconductor is translucent (semi-transparent – allowing light but not detailed shapes), junction becomes source of light as it is emitted, thus becoming an LED. However, when junction is reverse biased, LED produces no light & if the potential is great enough, the device is damaged.



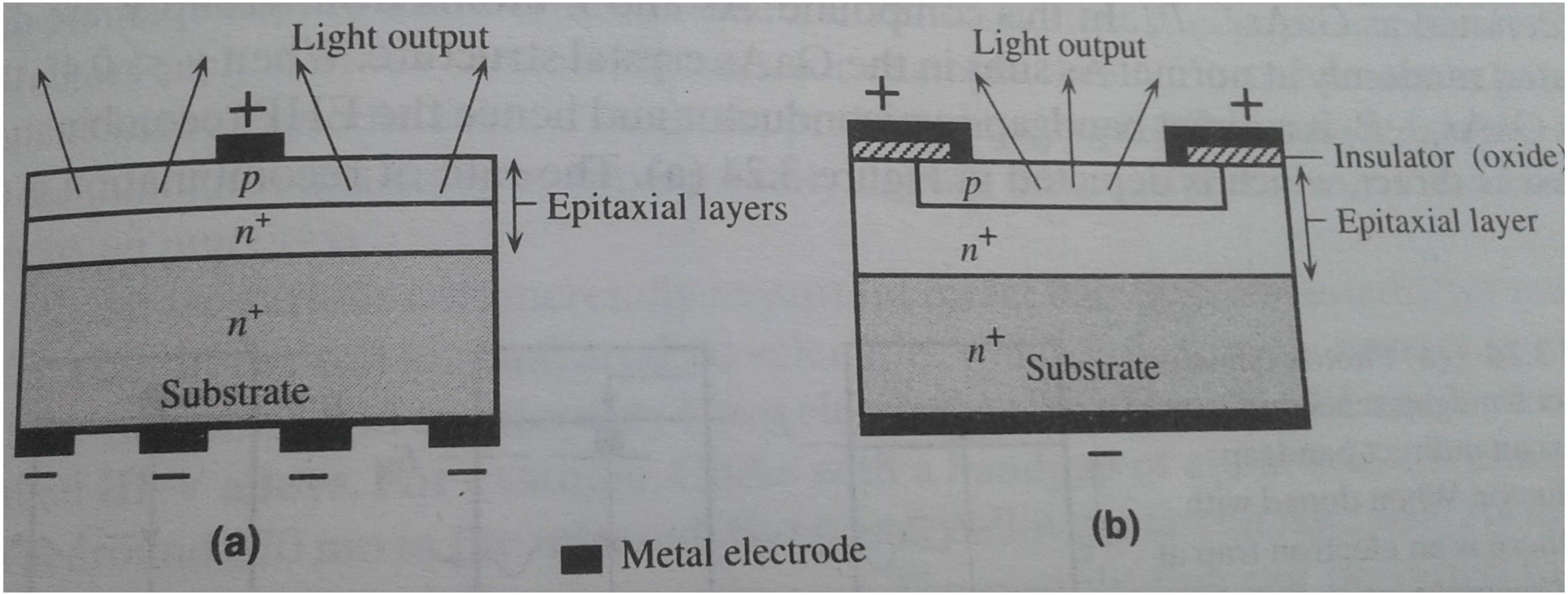
Inner working of an LED



I-V diagram of a diode. LED begins to emit light when more than 2 or 3 volts are applied.

Device Structure

LEDs are fabricated by epitaxially growing doped semiconductor layers on a suitable substrate (eg. GaAs or GaP).



Schematic illustration of typical planar surface emitting LED.
(a) *p*-layer grown epitaxially on an n^+ substrate &
(b) 1st n^+ is epitaxially grown & then *p* region is formed by dopant diffusion into epitaxial layer.

- **Not all light rays reaching semiconductor-air interface can escape because of total internal reflection (TIR).**

- **Rays with angles of incidence greater than critical angle θ_c become reflected.**

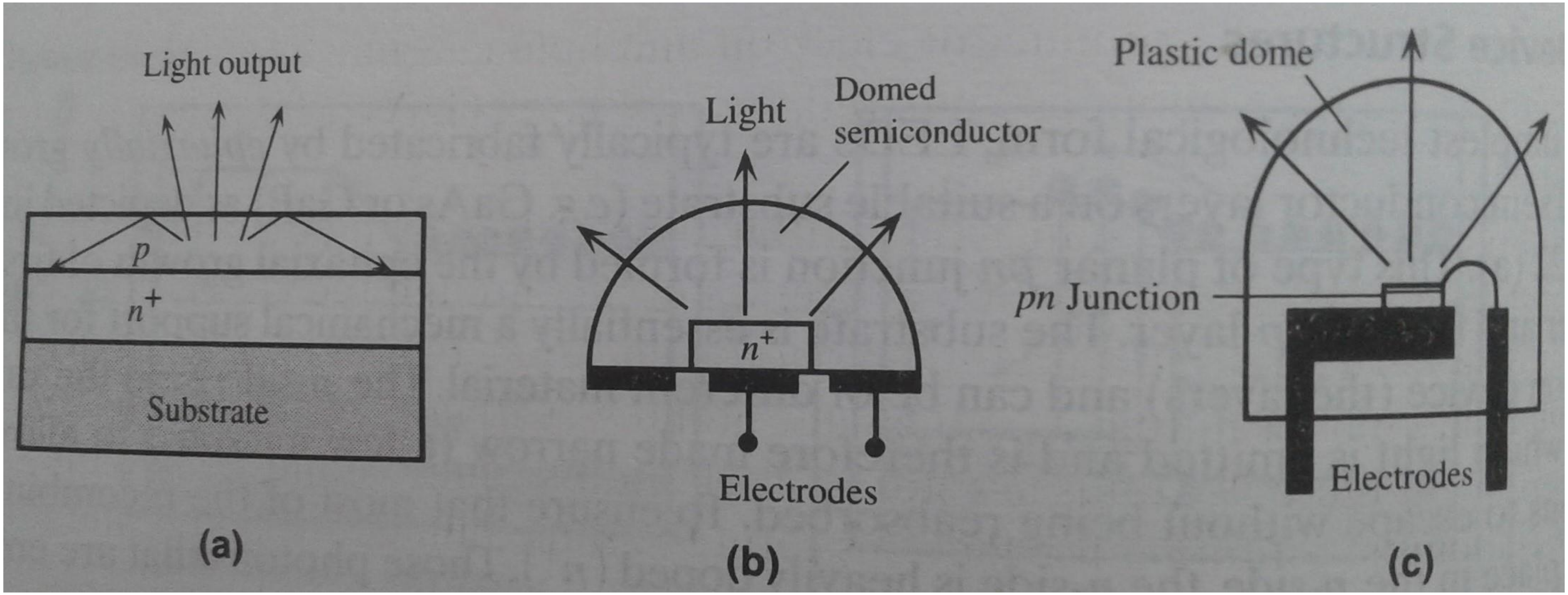
- **For GaAs-air interface, θ_c is only 16º, which means that much of light suffers TIR.**

- **It is possible to shape the surface of semiconductor into a dome or hemisphere so that light rays strike surface at angles less than θ_c therefore do not experience TIR.**

- **A common procedure that reduces TIR is encapsulation of semiconductor junction within a transparent plastic medium that has a higher refractive index than air & further also has a domed surface on one side of *pn* junction.**

(a) Some light suffers TIR & cannot escape.

(c) Common method of allowing more light to escape from LED is to encapsulate it in a transparent plastic dome.



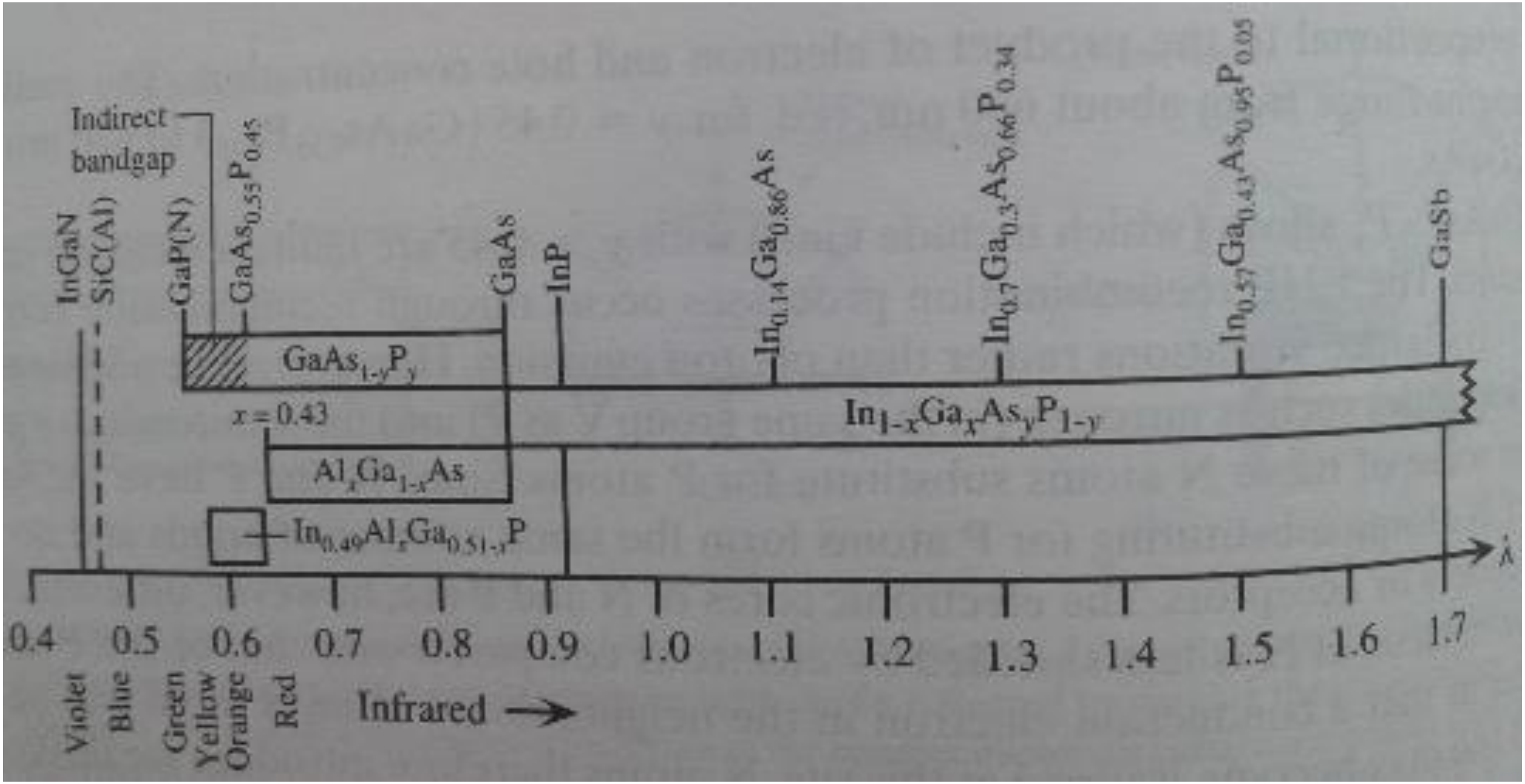
(b) Internal reflections can be reduced & hence more light can be collected by shaping semiconductor into a dome so that angles of incidence at semiconductor-air interface are smaller than critical angle.

Technology

- **LED consists of a chip of semiconducting material doped with impurities to create a p-n junction.**
- **Current flows easily from p-side, or anode, to n-side, or cathode, but not in reverse direction.**
- **Charge-carriers - electrons & holes - flow into junction from electrodes with different voltages.**
- **When an electron meets a hole, it falls into a lower energy level & releases energy in the form of a photon.**
- **Wavelength of emitted light, & thus its color, depends on band gap energy of materials forming *p-n junction*.**
- **Si/Ge diodes - electrons & holes recombine by a *non-radiative transition*, because these are indirect band gap materials.**
- **Materials used for LED have a direct band gap with energies corresponding to near-IR, visible, or near-UV light.**

LED Materials

Commercial semiconductor materials for visible spectrum is III-V ternary alloys based on alloying GaAs & Gap.



Free space wavelength coverage by different LED materials from visible to IR.

Lifetime & Failure

- Solid-state devices such as LEDs are subject to very limited wear & tear if operated at low currents & at low temperatures.

- Typical lifetimes are 25,000 to 100,000 hrs, but heat & current settings can extend or shorten this time significantly.

- Most common symptom of LED (& diode laser) failure is gradual lowering of light output & loss of efficiency.

- Whereas in most sources of light (incandescent lamps, discharge lamps, & those that burn combustible fuel, e.g. candles & oil lamps) light results from heat, LEDs only operate if they are kept cool enough.

External Efficiency of an LED

- **It quantifies efficiency of conversion of electrical energy into an emitted external optical energy.**

- **It incorporates internal efficiency of radiative recombination process & subsequent efficiency of photon extraction from device.**

- **Input of electrical power into an LED is diode current & diode voltage product (IV). If P_{out} is optical power emitted by device then**

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

- **For indirect bandgap semiconductors efficiencies are generally less than 1% whereas for direct bandgap semiconductors with right device structure, efficiencies can be substantial.**

Organic Light Emitting Diode

- OLED: electroluminescent material comprising emissive layer of diode is an organic compound.
- Organic material is electrically conductive due to delocalization of pi electrons caused by conjugation over all or part of the molecule, & material therefore functions as an organic semiconductor.
- Organic materials can be small organic molecules in a crystalline phase, or polymers.
- Advantages: thin, low-cost displays with a low driving voltage, wide viewing angle, & high contrast & color gamut.
- Polymer LEDs have added benefit of printable & flexible displays.
- Applications: visual displays for portable electronic devices; cellphones, digital cameras, MP3 players, lighting, & televisions.

Quantum dot LEDs

- Quantum dots (QD) are semiconductor nanocrystals in which emission color be tuned from visible to IR.

- QD-LEDs can create almost any color on the CIE diagram. They provide more color options than white LEDs since emission spectrum is much narrower, characteristic of quantum confined states.

- Two types of schemes for QD excitation; one uses photo excitation with a primary light source LED (typically blue or UV LEDs are used) & other is direct electrical excitation.

- Structure of QD-LEDs used for electrical-excitation scheme is similar to basic design of OLEDs.
  A layer of QDs is sandwiched between layers of electron-transporting & hole-transporting materials. An applied electric field causes electrons & holes to move into QD layer & recombine forming an exciton that excites a QD.

Semiconductor Laser & LED

LED	Semiconductor Laser
▪ Operate at lower current densities, below threshold current.	▪ Starts lasing action above threshold current only.
▪ Incoherent optical source (emitted photons have random phases due to spontaneous emission).	▪ Coherent source of light (stimulated emission).
▪ Wider spectral line width (energy of emitted photon is roughly equal to E_g of semiconductor material).	▪ Line width is very narrow.
▪ Multimode source (supports many optical modes within its structure).	▪ Monomode source.
▪ Low internal quantum efficiency.	▪ Very high internal quantum efficiency.
▪ Light emission is very weak.	▪ Light emission is very intense.

LED device offers hope in hair-loss battle

Stewart Wills, Opt. Photon News, Sept. 2018

Korean researchers showed that treating shaved mice with a flexible vertical micro-LED patch developed in their lab regrew hair faster than no treatment (Con) or minoxidil injections (MNX).

A micro-LED approach

- Researchers led by Keon Jae Lee of Korea Advanced Institute of Science and Technology (KAIST) demonstrated a smaller-footprint, wearable photostimulator. They created flexible thin-film vertical micro-LEDs (f-VLEDs).

- Team started by growing layers of high-purity AlGaInP LEDs on a GaAs wafer using metal-organic chemical vapor deposition, & next employing photoresists, RF sputtering & conventional photolithography processes to mark out individual micro-LEDs & add electrodes. Researchers then selectively etched away wafer substrate.

- Produced 900-LED square array with a thickness of 20 µm & an active-layer thickness of 3 µm.

- Device can produce 10 pulses of 650-nm light per second with a total output of around 30 mW/mm^2 & at a low forward voltage of 2.8 V.

Taming (mouse) baldness

- **Device can be attached to human skin without overheating or cracking. Additional tests revealed that the device remained mechanically reliable after being bent & unbent 10,000 times at a 5-mm bending radius.**

- **To see if the device could help tame the dreaded bald spot, team shaved hair off the backs of 12 mice & applied the device to shaved area of four of them, with another four receiving minoxidil (active ingredient in Rogaine & other oral hair-growth treatments) & the remaining four receiving no treatment. After 20 days of periodic irradiation with red LEDs (@ 15 minutes a day), mice treated with micro-LED patch showed significantly faster hair growth, a wider regrowth area & longer hairs relative to minoxidil & control mice.**

- **Clinical potential of f-VLED patches in real-time phototherapy. Other applications could be wound healing, acne care, skin lightening & other areas in which phototherapeutic approaches have shown promise.**

Given than the width of the relative light intensity versus photon energy spectrum of an LED is typically around ~ $3k_BT$. What is the linewidth $\Delta\lambda$ in the output spectrum in terms of wavelength?