BASIC OPTOELECTRONIC INTERACTION

In all optoelectronic devices, the basic working process deals with the interaction of optical radiations or electromagnetic waves with materials of interest. With light rays are incident on material, a number of optical processes like **reflection**, **absorption** and **transmission** may occur, as shown in Fig. 2.

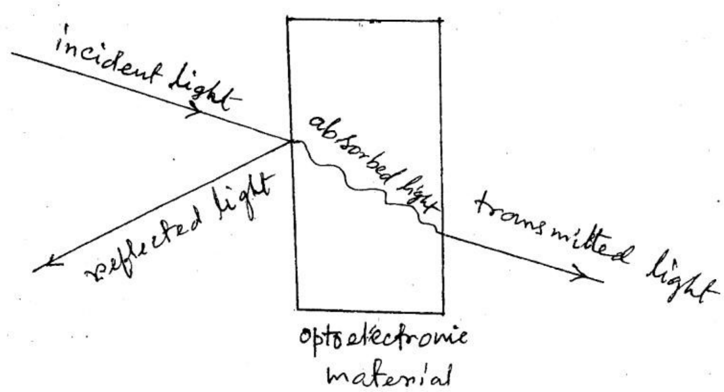

Fig. Types of optical interaction with optoelectronic material.

Out of these processes, mainly the optical absorption magnitude and mechanism have greater significance in **creation and annihilation of electron-hole pairs** and hence, the overall efficiency of optoelectronic devices. By reducing the reflection as well as the transmission loss as minimum to the lowest possible level, one can enhance the absorption amount of the incoming optical signal.

During **light absorption**, the incoming photons provide the necessary impart energy (at least equivalent to bandgap energy) to the filled valence band electrons to take transition into the higher energy sates in the conduction band, leaving behind holes in the valence band. In reverse process, those excited electrons during recombination with holes by **radiative or non-radiative methods** release the excess energy in the form of light radiation. This transition of excited electrons from conduction band to valence band by releasing light is the basic working process of various light sources like **light emitting diode**, **laser** and various display systems, etc.

OPTICAL ABSORPTION AND CARRIER GENERATION IN SEMICONDUCTOR

The excess electrons and holes (in pair-form) are created in the optoelectronic devices by suitable light absorption. The amount of light absorption dictates the carrier generation rate as well as device efficiency. In simplest process of light absorption, the energy quanta of optical radiation or the photons collide with the electrons of semiconductors. If the incoming photon possesses a certain minimum energy ($h\nu \geq E_g$), then by optical absorption the valence band electron gets excited into the conduction band, resulting in the creation of hole in the valence band, as shown in Fig. 3. This phenomenon of conversion of optical energy (by absorption process) into electron-hole pairs is the most common process in optical detectors.

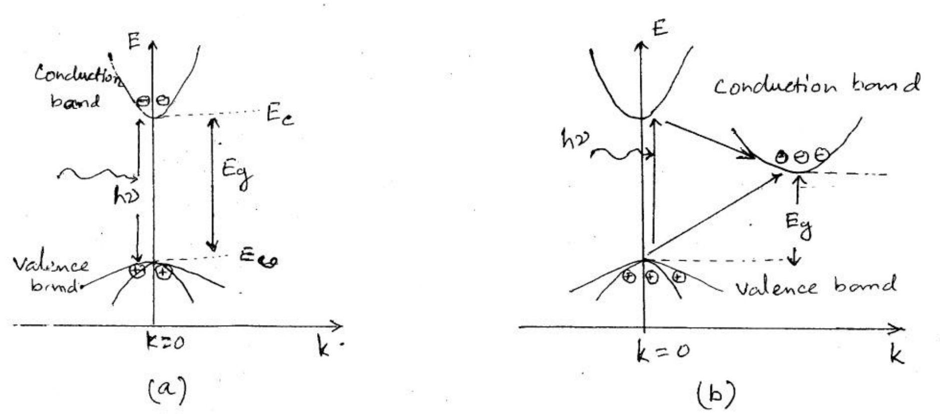

Fig. Carriers generation in (a) direct bandgap and (b) indirect bandgap semiconductors.

Since, the absorption process is basically a collision or scattering process between electron and photon, both energy and momentum are conserved. The photon momentum being extremely small (~ zero) as compared to that of electron, makes a requirement for the conservation of momentum that the electron (electron) transition is most favored in vertical (i.e., same) *k*-space (i.e., momentum space) which is available only in **direct bandgap materials** like GaAs, InP, GaAlAs, etc.

On the other hand, for **indirect semiconductors** (like Si, Ge, GaP, AlAs, etc.) as the top of the valence band and minimum of the conduction band do not arise at the same *k*-space [Fig.3.(b)], the inter-band (i.e., from valence band to conduction band) electron transition always assisted by phonon (i.e., the lattice vibration energy quanta) creation or annihilation.

LIGHT EMITING DIODE (LED)

Since the discovery of the **light emitting diode (LED)** in the early 1900s, it is one the oldest and simplest optoelectronic devices which have found tremendous scientific and industrial applications in display systems, optical communication networks, sensors, logic devices, tail light in automobiles and many more. LEDs alongwith lasers are basically **electroluminescence** type of devices, where light emission supported by generation of excess carriers by electric field or current injection into the devices.

From the mid-1950s, the entire effort on designing efficient LEDs rests on alloy materials of III-V (like GaAs, GaP, GaN, AlGaAs, GaAsP, GaInP, GaInP, AlGaInP, etc.) and II-VI (like ZnS, ZnTe etc.) semiconductors. These materials, being direct bandgap by nature, support primarily radiative light emission, and hence ensure higher efficiency. Moreover, the light emission from these binary, ternary or quaternary semiconducting materials covers a wide range of light starting from infrared (IR) to visible (white light or single colour light such as green blue, red, yellow, etc.) as well as ultra violet (UV) region. Nowadays, with the advent of **modern semiconductor growth techniques** like **molecular beam epitaxy (MBE)**, **metal organic chemical vapor deposition (MOCVD)**, etc. alongwith bandgap engineering using compound semiconductors, it is possible to fabricate various solid state light sources including LEDs and lasers which are active in visible, UV and IR region of the spectrum as shown in Fig. 4.

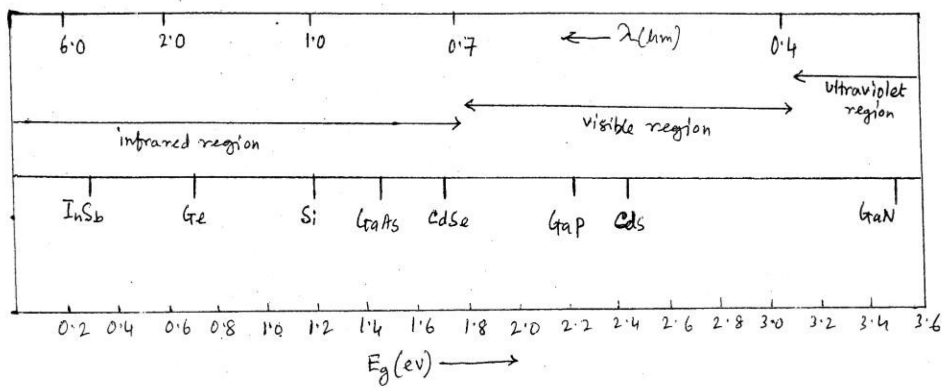

Fig. Emission wavelength and bandgap energy of the most usable semiconductors.

It is well known that LEDs are not technologically glamorous like semiconductor laser diodes, in terms of quality of light source. But the later device (i.e., laser diode) needs special care in fabrication alongwith requires more complex drive and cooling circuitry. The relative merits and demerits of LED and laser diodes are given in Table 1.

Table 1 Comparison between LED and Laser Systems

LED	Laser
1. It emits the light by spontaneous emission.	1. Here, the light is by stimulated emission.
2. The emitted light is incoherent, i.e., the photons are in the random phase among themselves.	2. It possesses a coherent beam with identical phase relation of emitted photons.
3. The emitted light power is relatively low.	3. The output power is high (few mW to GW).
4. The light output has larger spectral broadening (~ 30 - 50 nm) and supports many optical modes, i.e., multimode optical source.	4. It has relatively smaller spectral broadening with less numbers of modes.
5. It requires smaller applied bias and	5. It requires relatively higher driving

operates under relatively lower current densities.	power and higher injected current density is required.
6. It possesses a simple structural design and does not require optical cavity and mirror facets like laser, as it operates under relatively lower power.	6. Its fabrication requires more steps and special care in comparison to an LED.
7. It does not suffer catastrophic degradation and is more reliable in uses.	7. It has relatively higher degradation chances during long period operation.
8. It exhibits linear light-current characteristic and suitable for analog modulation.	8. The light-current characteristics for it are highly sensitive to operating temperature.

The successes of the design and operation of efficient LEDs depend on several fabrication as well as operational parameters. In reality, various LEDs like **simple p-n junction LED** alongwith most efficient class of LEDs such as **double heterostructure (DH) LED**, **surface emitting LED**, **edge emitting LED**, **resonant-cavity LED**, **white LED**, etc. can be designed for various purpose.

WORKING PROCESS OF SIMPLE p-n JUNCTION LED

The simplicity in the fabrication (in p-n junction diode form) and driving circuitry of LED makes it very attractive as solid state light source in a wide variety of technical as well as commercial applications. The LED converts input electrical energy into **spontaneous optical radiation** through the injection luminescence or electroluminescence process. During its normal operation, the electrons and holes are injected as minority carriers into the p- and n-sides of forward bias p-n junction diode respectively, as shown in Fig. 5.

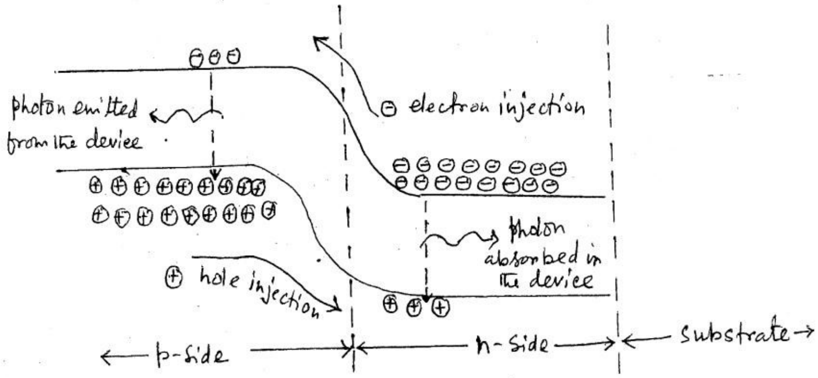

Fig. Carrier injection in forward bias p-n junction diode leading towards spontaneous emission.

The injected excess minority carriers are then try to diffuse away quickly from the junction and subsequently recombine with majority carriers either by radiative and non-radiative ways. The diode should be designed in such a way that it can support the radiative recombination as strong as possible. Under such case, the emitted spontaneous radiation photon energy be given by $\boldsymbol{hv = E_g}$. The list of the most usable materials for LED design is shown in Table 2.

Table 2 Most usable LED materials used in different spectral region.

Material	Dopant	Emission Colour	Wavelength	Region
GaP	N (< 10^{14} $cm^{-3)}$	green	~ 550 nm	visible
	N (>> 10^{14} $cm^{-3)}$	yellow	~ 590 nm	visible
GaP	Zn and O simultaneously	red	~ 690 nm	visible
GaN	Zn	blue	~ 465 nm	visible
$GaAs_{0.60}P_{0.40}$	N	red	~ 690 nm	visible
$GaAs_{0.35}P_{0.65}$	N	orange	~ 620 nm	visible

$GaAs_{0.15}P_{0.85}$	N	yellow	~ 590 nm	visible
SiC	B Al Sc	yellow blue green	~ 590 nm ~ 465 nm ~ 550 nm	visible visible visible
ZnS, ZnSe, ZnTe, CdTe, HgTe, etc.	different doping	green t ored	~ 460-690 nm	visible
GaAS	Zn, Si	-	~ 860 nm	NIR
$In_{1-x}Ga_xAs$, $In_xGa_{1-x}P_yAs_{1-y}$	-	-	~ 1.1 – 1.6 µm	NIR
GaSb, InSb	-	-	-	FIR
$Ga_xAl_{1-x}As$ ($1<x<0.7$)	Si	-	~880 nm	NIR

LED STRUCTURAL DESIGN AND EFFICIENCY

Among various LEDs, the most simple and widely used one is planar surface type as shown in Fig.6. A p-n^+ junction with very thin p-layer (top emitting side) as compared to heavily doped wide n^+ layer, is grown on low resistive and lattice matched n^+-substrate. The external bias is applied through the ohmic contact layers present at the top and bottom while the emitted light comes from the thin p-layer as indicated.

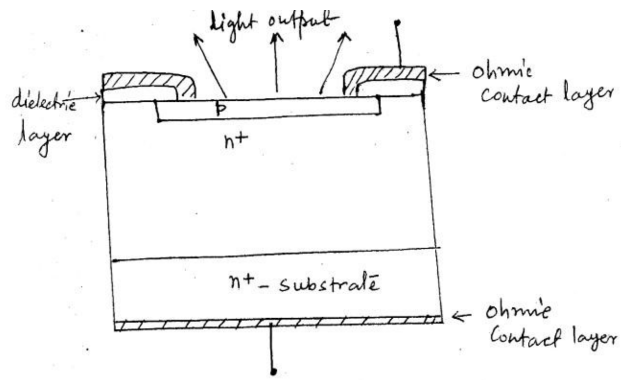

Fig. Structural view of planer surface LED.

The top or the active layer (p-region) is made thinner than the heavily doped n^+ layer for higher efficiency of LED. By using p-n^+ structure (rather than simple p-n junction), the depletion region can be pushed into p-region of the junction (i.e., nearer to the top layer) where major carrier recombination takes place. Thus, the emitted photon has the minimum chance to be reabsorbed by the device material. In addition, by using very high quality (e.g., defect-free except doping atoms) material, the trap assisted recombination current is made nearly negligible. Then, the LED carrier injection efficiency approaches to unity.

The ultimate or overall device efficiency η_{iult} depends on three different steps of operational processes of LED such as

(a) Forward bias minority carrier generation across the junction through carrier injection efficiency η_{inj} ;

(b) Photon generation by minority carrier recombination through **internal quantum efficiency** $\boldsymbol{\eta_{int}}$ and

(c) Quick transmission of generated photons through the active thin top p-layer to the outside of the device for external sensation represented by extraction efficiency η_{ext}

Combining all those, the **overall device efficiency** becomes $\boldsymbol{\eta_{iult} = \eta_{inj}\ \eta_{int}\ \eta_{ex}}$ In the ideal condition, the carrier injection efficiency η_{inj} should be unity but in real situation due to doping, temperature and other fabrication limitations, the best experimentally reported results for two important LED materials have observed its values for GaAs ~ 0.8 and for GaP ~ 0.6 - 0.8. As compare to η_{inj}, the measured values of internal quantum efficiency η_{int} are very less due to carrier recombination for GaP (a) with Zn, O doping η_{int} ~ 0.3 or 30 % and (b) with N doping η_{int} ~ 0.03 or 3 %. Such poor internal quantum efficiency is attributed to unwanted **non-radiative carrier recombination** from various effects like presence of bulk and surface defect states, etc.

Even such high appreciable (30 – 80 %) values of carrier injection efficiency η_{inj} and recombination efficiency η_{int} do not ensure large overall device efficiency η_{iult}. By taking maximum care in device fabrication, the typical values of overall device efficiency η_{iult} of common LEDs come in the range of only 1% to 5%. The main reason for such poor performance of device overall efficiency is due to very low value of its **photon extraction efficiency η_{ext}.**

Again, the very low value of photon extraction in LED after generation through recombination process, depends on three distinct optical loss mechanisms like -

(a) Loss of certain portion of emitted photons due to re-absorption by the LED material itself to recreate the electron–hole pair;

(b)Loss of generated photon during its vertical incident at the semiconductor-air interface and

(c) Photon loss due to its total internal reflection at incidence upon LED top planer surface with angles greater than the critical angles.

To minimize the loss of photon due to reabsorption process (first category), the top p- layer of LED is made thin that prevents the traveling of the emitted photons to the long distance of its exposed planer layer. The second and third types of loss mechanism can be minimized by using **dome-shaped LED**.

In real case, the external power efficiency of LED can be further improved by using several special class of LEDs like -

(a) Double heterojunction (DH) LED

(b) High efficiency double heterojunction LED

(c) Resonant cavity LED

(d) Edge emitting LED

(e) Surface emitting LED

(f) White LED.

These advanced LEDs have higher efficiency with low to high radiance and are widely used in optical communication, optical fiber-based instrumentation systems, general illumination, etc.