# Emission of light (Optical Source)

- **Emission of light, (in the form of a photon) can take place either <u>spontaneously</u> or it can be <u>stimulated</u> by the presence of another photon of the right energy level.**

- **For spontaneous or stimulated emission to occur, <u>energy must be supplied to boost the electron from its low energy state to a higher energy state.</u>**

- **The energy can come from many sources: Heat (Incandescent light), Electrical Discharge ($D_2$, Hg, Na lamps), Electrical Current (LED, LD), Bioluminescence (Fire fly- luciferase enzyme)**

# OPTICAL SOURCES:

**Optical Source find applications in the area of medical, automotive, analytical equipments, communications and industry.**

**Types of Optical Source**

- **Tungsten, Deuterium, Mercury, Hollow Cathode Lamp**

**Optical Source specifically suited to FO systems are:**

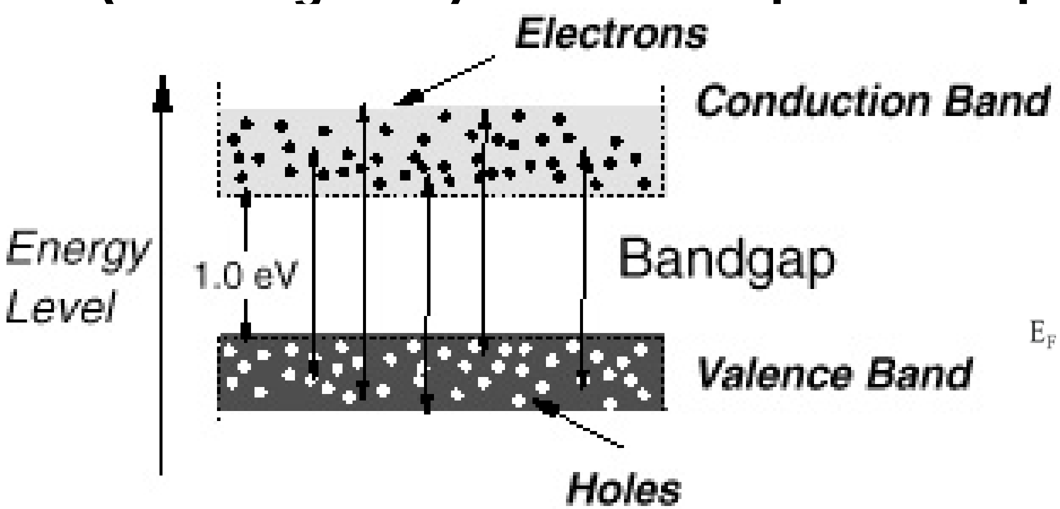
- **Light Emitting Diode (SLED, ELED, SLD)**
- **Laser Diode (DFB, DBR)**

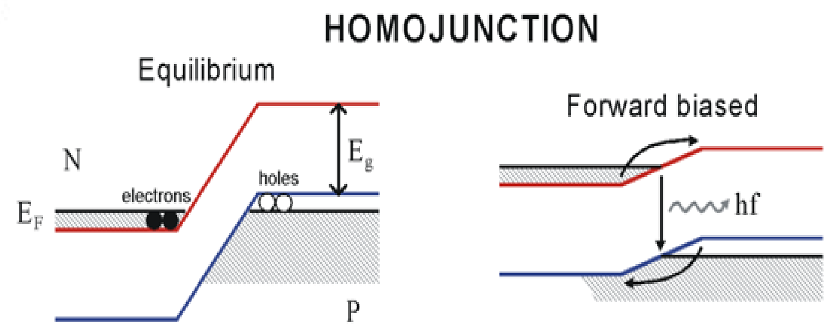
## Optical Source Requirement for Performance (For Fiber Optics)

- **Physical dimensions to suit the optical fiber**
- **Narrow radiation pattern (beam width)**
- **Linearity (output light power proportional to driving current)**
- **Ability to be directly modulated by varying driving current**
- **Fast response time**
- **Adequate output power into the fiber**
- **Narrow spectral width (or line width)**
- **Stability and efficiency**
- **Driving circuit issues**
- **Reliability and cost**

# Basic LED operation

- **A PN junction acts as the active or recombination region.**
- **When the PN junction is forward biased, electrons and holes recombine either radiatively (emitting photons) or non-radiatively (emitting heat). This is simple LED operation.**



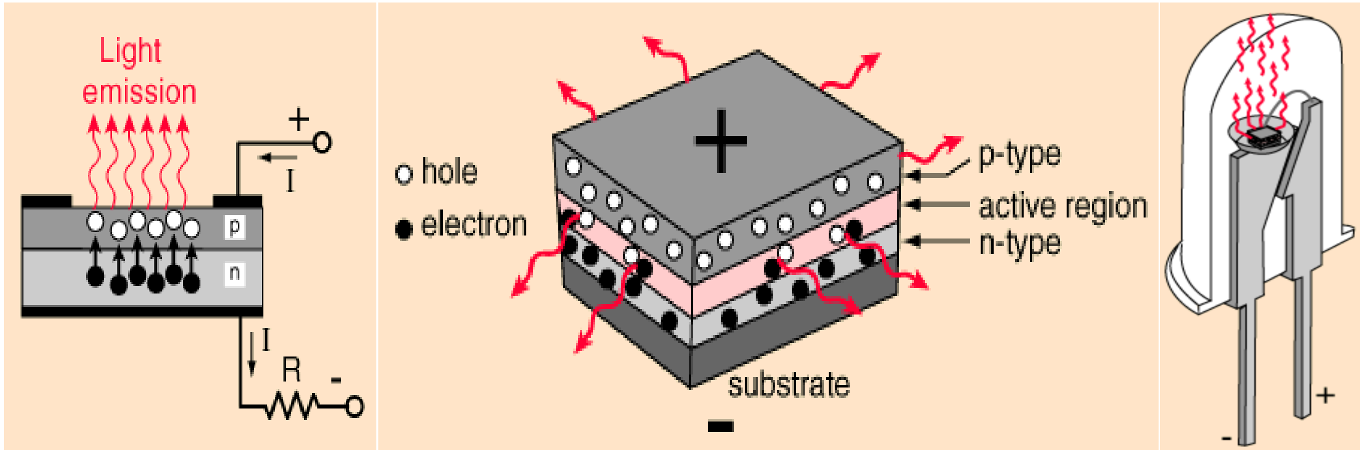



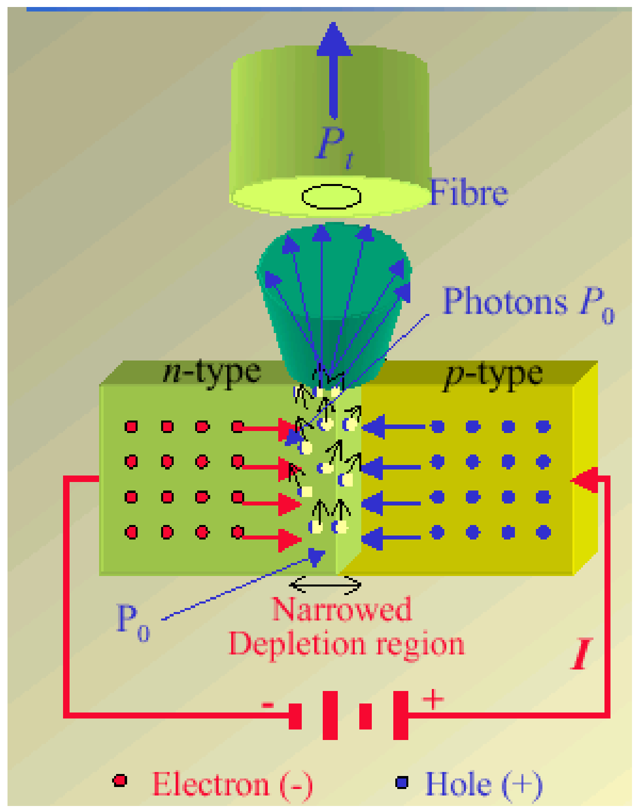

- **Emitted wavelength depends on bandgap energy**
- **Transitions can take place from any energy state in either band to any state in the other band. This results in a range of different wavelengths produced in this spontaneous emission. This accounts for the fact that LEDs produce a range of wavelengths. Typically the range is about 80 nm or so.**

# Light Emitting Semiconductors

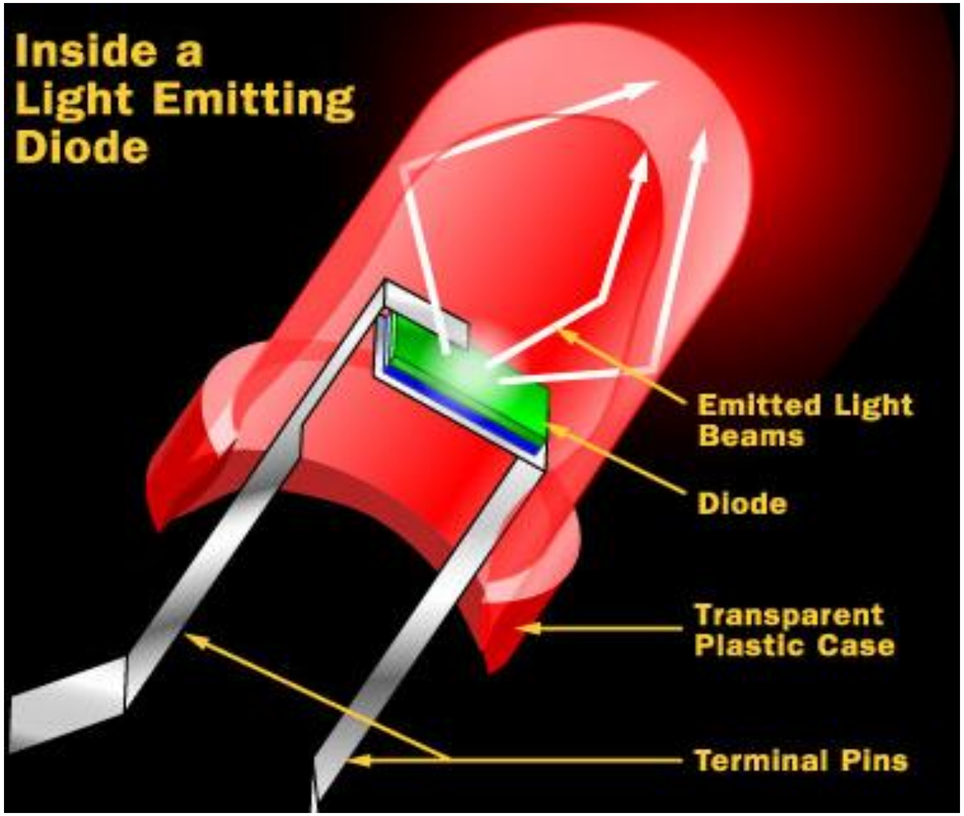
| Material | Wavelength Range (µm) | Bandgap Energy (eV) |
|---|---|---|
| AlGaInP | 0.61 - 0.68 | 1.82 - 1.94 |
| GaAs | 0.9 | 1.4 |
| AlGaAs | 0.8 - 0.9 | 1.4 - 1.55 |
| InGaAs | 1.0 - 1.3 | 0.95 - 1.24 |
| InGaAsP | 0.9 - 1.7 | 0.73 - 1.35 |

# Working of LED



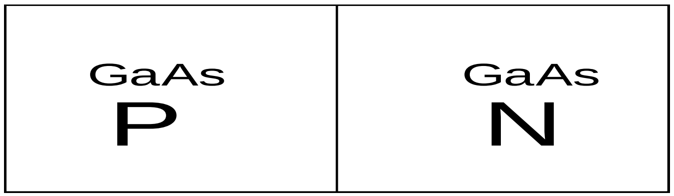



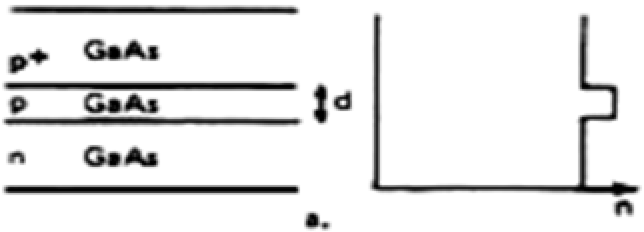
- Light is emitted at site of carrier recombination which is primarily close to the junction.
- However, the amount of radiative recombination and the emission area within the structure is dependent upon the semiconductor materials used and the fabrication of the device.




- Emits incoherent light through spontaneous emission.
- Used for Multimode systems with 100-200 Mb/s rates.
- Broad spectral width and wide output pattern.
- 850nm region: GaAs and AlGaAs
- 1300–1550nm region: InGaAsP and InP

- **Homojunctions**: **P- type and N-type from same material**




- **Carriers are not confined**
- **Light is not confined**

**Structure and index of refraction n in gallium arsenide with a junction width d**

- **<u>LED should have a high radiance (light intensity), fast response time and a high quantum efficiency for FO system</u>**

# Heterojunction

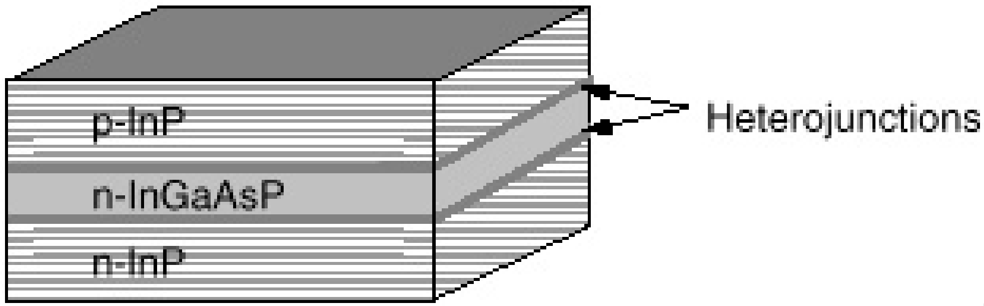
- **Heterojunction is the advanced junction design to reduce diffraction loss in the optical cavity.**
- **This is accomplished by modification in the material to control the index of refraction of the cavity and the width of the junction.**
- **The index of refraction of the material depends upon the impurity used and the doping level.**
- **The Heterojunction region is actually lightly doped with p-type material and has the highest index of refraction.**
- **The n-type material and the more heavily doped p-type material both have lower indices of refraction.**
- **This produces a <u>light pipe effect</u> that helps to confine the light to the active junction region. In the homojunction, however, this index difference is low and much light is lost.**
- **Double or single hetero-structure junction with better light output**

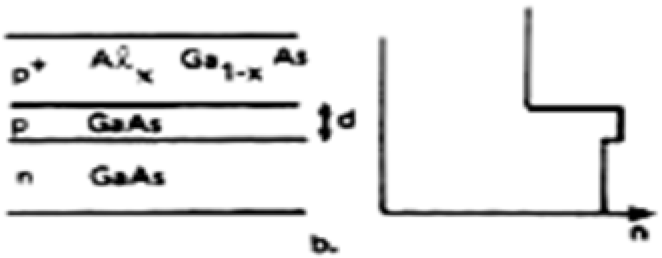
**Heterojunctions:** **Different p- and n- materials**

- **Carriers are confined**
- **Light is also confined**
- **Single Heterojunction, Double Heterojunction.**

➢ **A heterojunction is a junction between two different semiconductors with different bandgap energies.**

➢ **The difference in bandgap energies creates a one-way barrier. Charge carriers (electrons or holes) are attracted over the barrier from the material of higher bandgap energy to the one of lower bandgap energy.**




**Gallium Arsenide-Aluminum Gallium Arsenide single heterojunction**

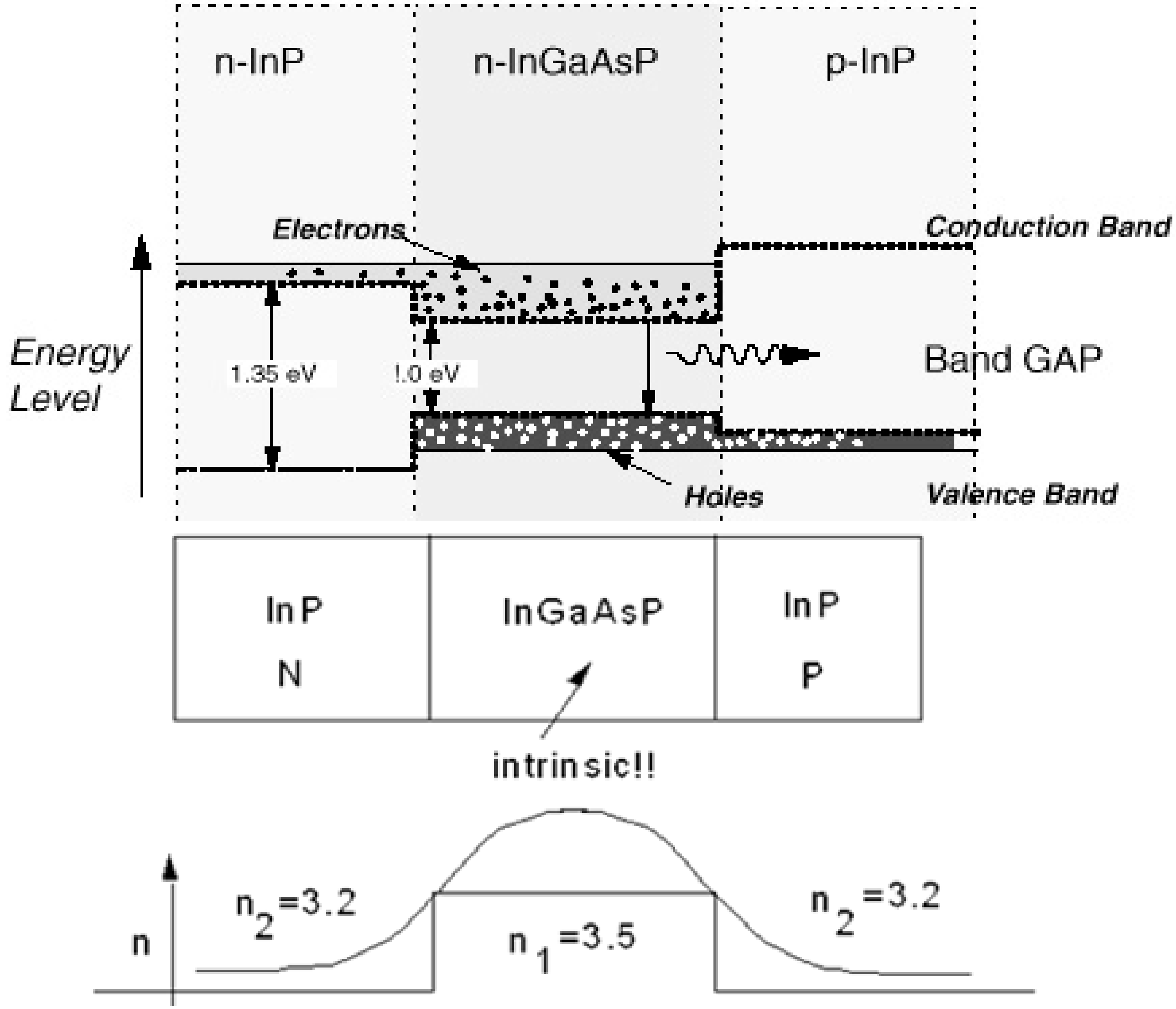
# Double Heterojunction

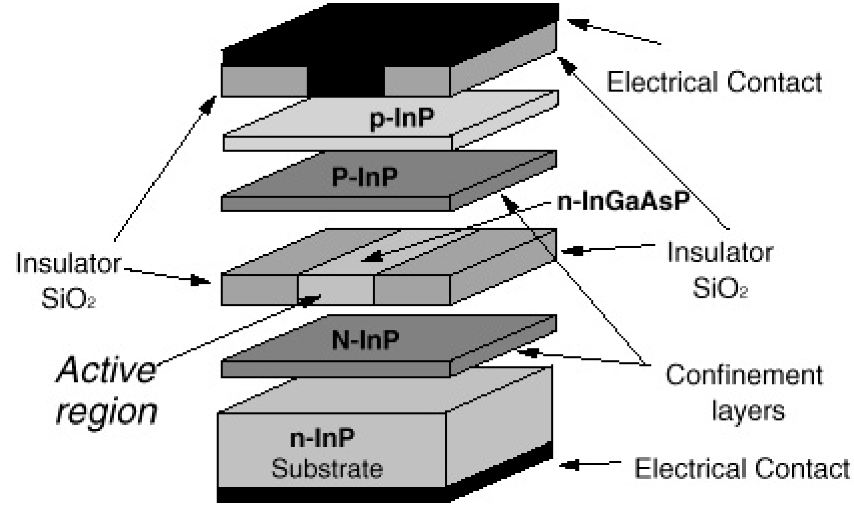
- **When a layer of material with a lower bandgap energy is sandwiched between layers of material with a higher energy bandgap a *double heterojunction* is formed. This is called a double heterojunction because there are two heterojunctions present - one on each side of the active material.**

- **The double heterojunction forms a barrier which restricts the region of electron-hole recombination to the lower bandgap material. This region is then called the "active" region**

# Double Heterojunction

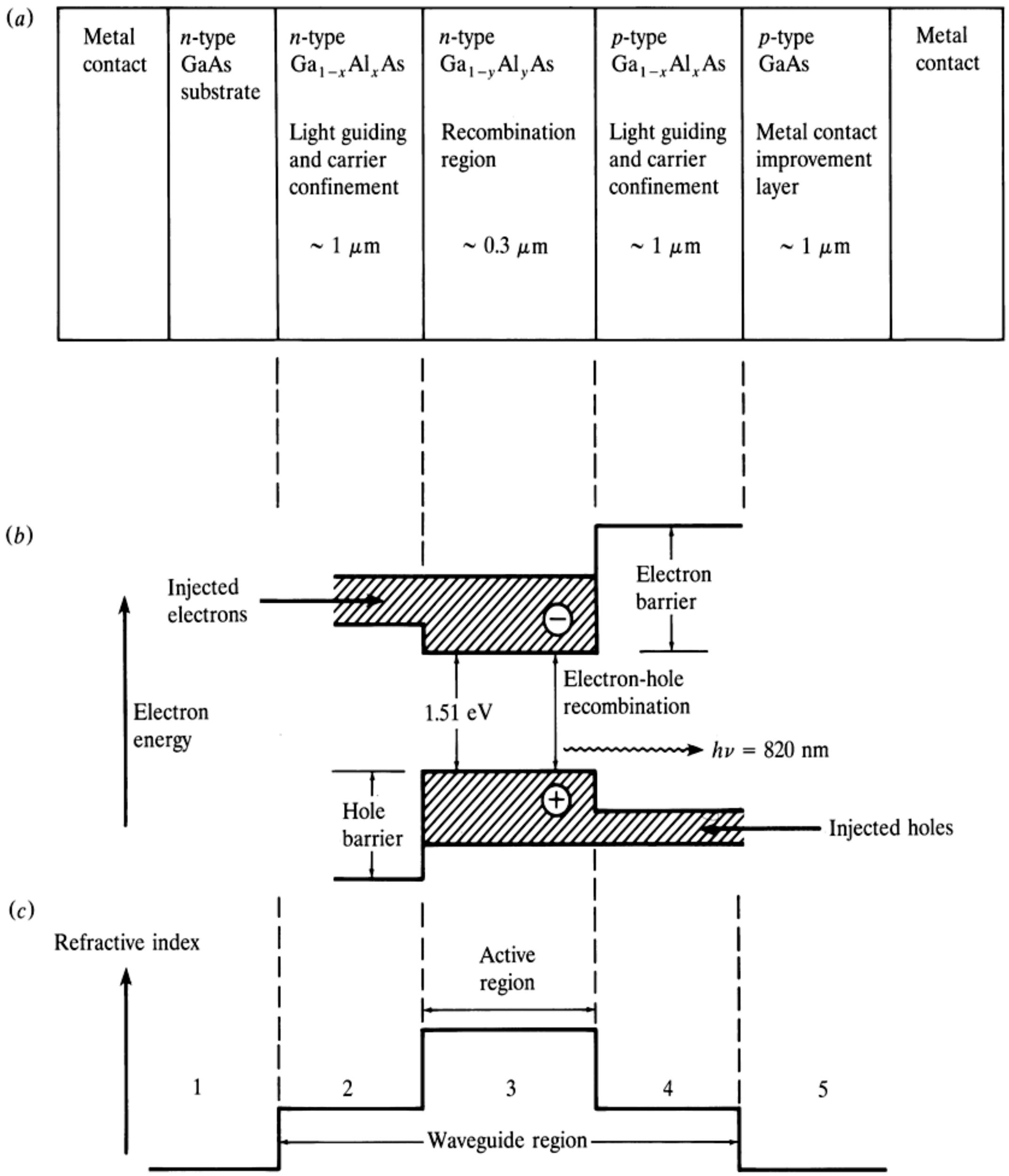
- The valence band of n-InGaAsP is at a higher energy than the valence band of the adjacent n-InP. The conduction band is at a lower energy level.
- p-InP has higher energy levels than n-InP but the bandgap is the same






- Electrons are attracted across the left-hand junction from the n-InP to n-InGaAsP.
- Holes are attracted across the right-hand junction from the p-InP into the n-InGaAsP.
- Recombination takes place in the n-InGaAsP and spontaneous emission occurs.
- The heterojunction allows to have a small active region where the light is produced.
- The material in the active region has a higher refractive index than that of the material surrounding it. This means that a mirror surface effect is created at the junction which helps to confine and direct the light emitted.

# Double Heterojunction



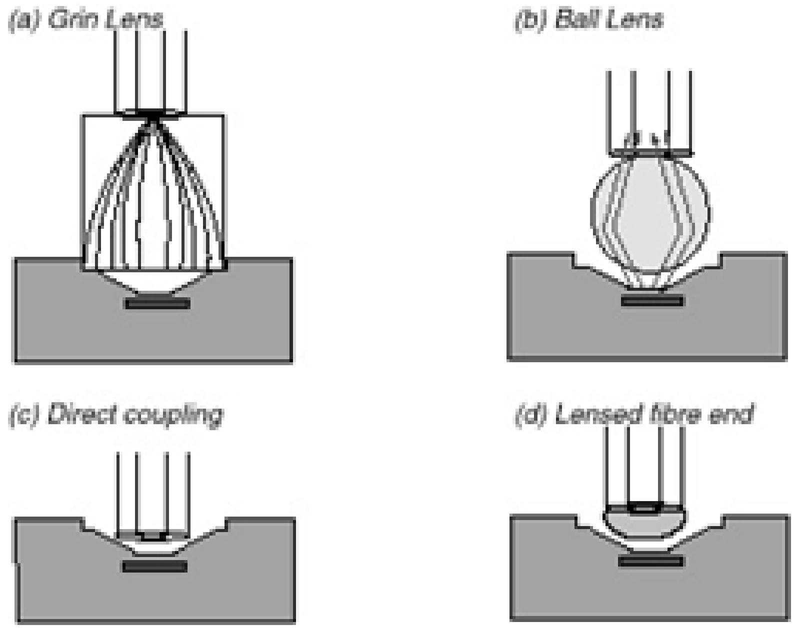

# Confining and Guiding the Light within the Device

- **Within the device the light must be confined and directed to the exit aperture so that it can be directed into the fiber which is done using <u>insulating materials $SiO_2$ to confine the active region and the current path</u>.**

- **The active layer in a heterostructure has a higher refractive index.**

- **This junction forms a mirror layer and helps to confine the light to the <u>active layer</u>. For this reason, the outer layers are often called <u>"confinement layers"</u>**

**Coupling light output to a fiber is the most difficult and costly part of manufacturing a real LED or laser device.**




**Four common methods are used:**

- **Use of a Graded Index Lens (GRIN lens) is fairly common. The lens collects and focuses the light onto the end of the fiber.**
- **A Ball lens is also often used. This is bonded to the surface of the LED with an epoxy resin that has a specific refractive index. However, the RI of the epoxy can't match to both the RI of the fibre and the RI of the semiconductor since the semiconductor will have an RI of around 3.5 and the fiber of around 1.45.**
- **The Direct Coupling method is to mount the fiber end so that it touches the LED directly i.e. to mount the LED inside a connector so that when a fiber is plugged in (mounted in the other half of the connector) one get firm mounting in good position.**
- **To fix a ball lens to the end of the fiber**

# Types of LED Structures

- **Surface Emitting LED's (SLED)**
- **Edge Emitting LED's (EELED)**
- **Superluminescent LED's (SLD)**

## Confining and Guiding the Light within the Device

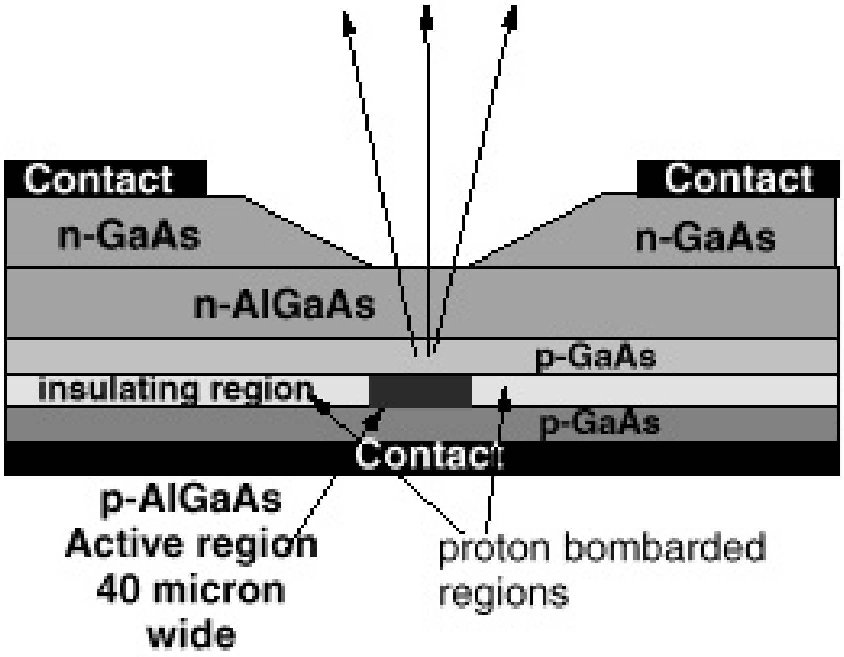
**In both types of LED (SLED and ELED) a combination of insulating materials and junctions is used to:**

1. **Guide the current flow to a small "active region" and**
2. **Guide the light produced out of the device and into an easy position for coupling to a fiber.**

# Surface Emitting LED (SLED)

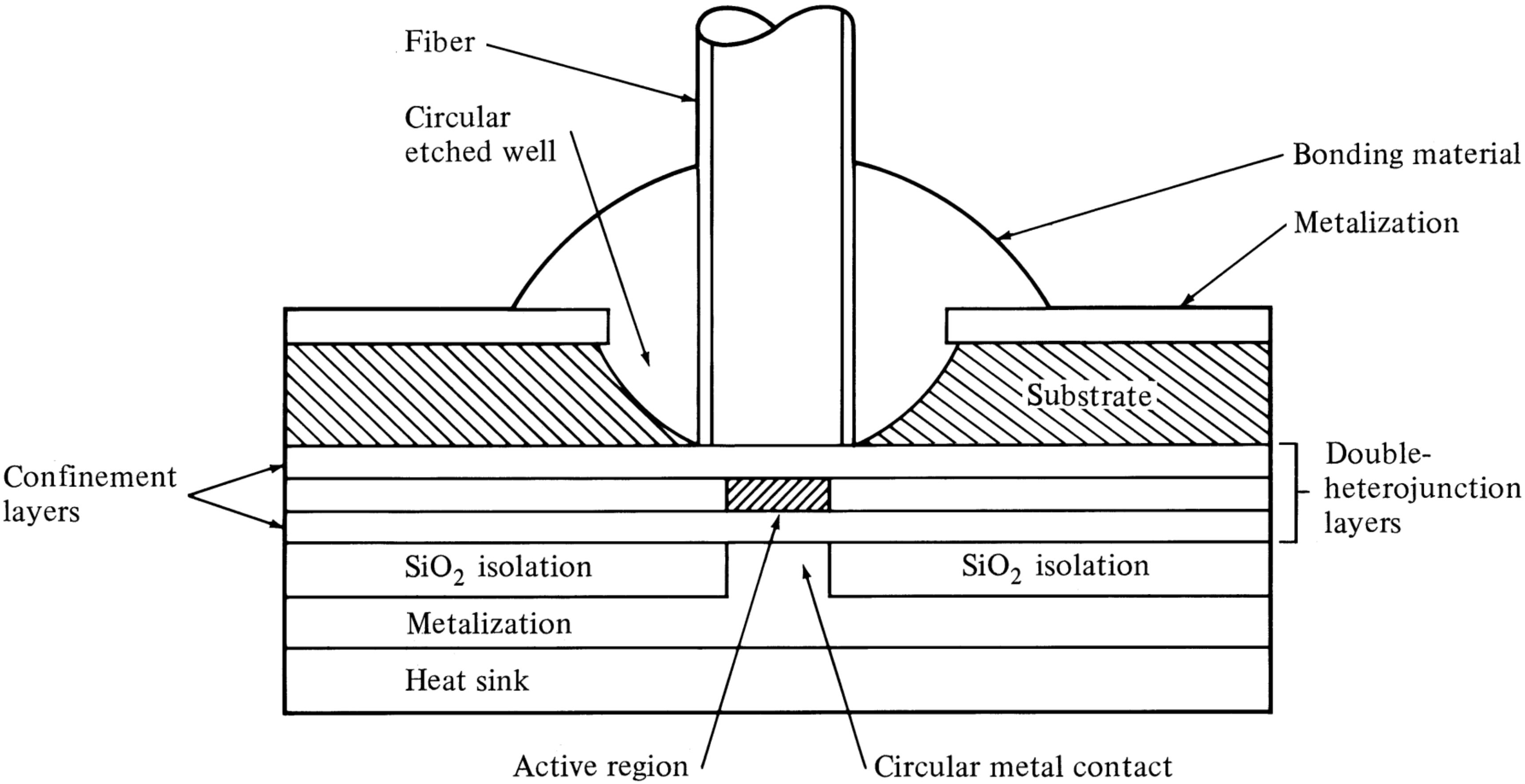
- **Method for obtaining high radiance is to restrict the emission to a small active region within the device – Burrus & Dawson (1970)**

- **Power coupled into the fiber is dependent on many factors; *distance and alignment between emission area and fiber, emission pattern and interfacing medium***
  - **More Power**
  - **Poor Radiance**




- **Coupling lens used to increase efficiency.**
- **Short optical Links with Large NA fibers.**
- **Data rates less than 20 Mbps.**

# Surface-emitting LED

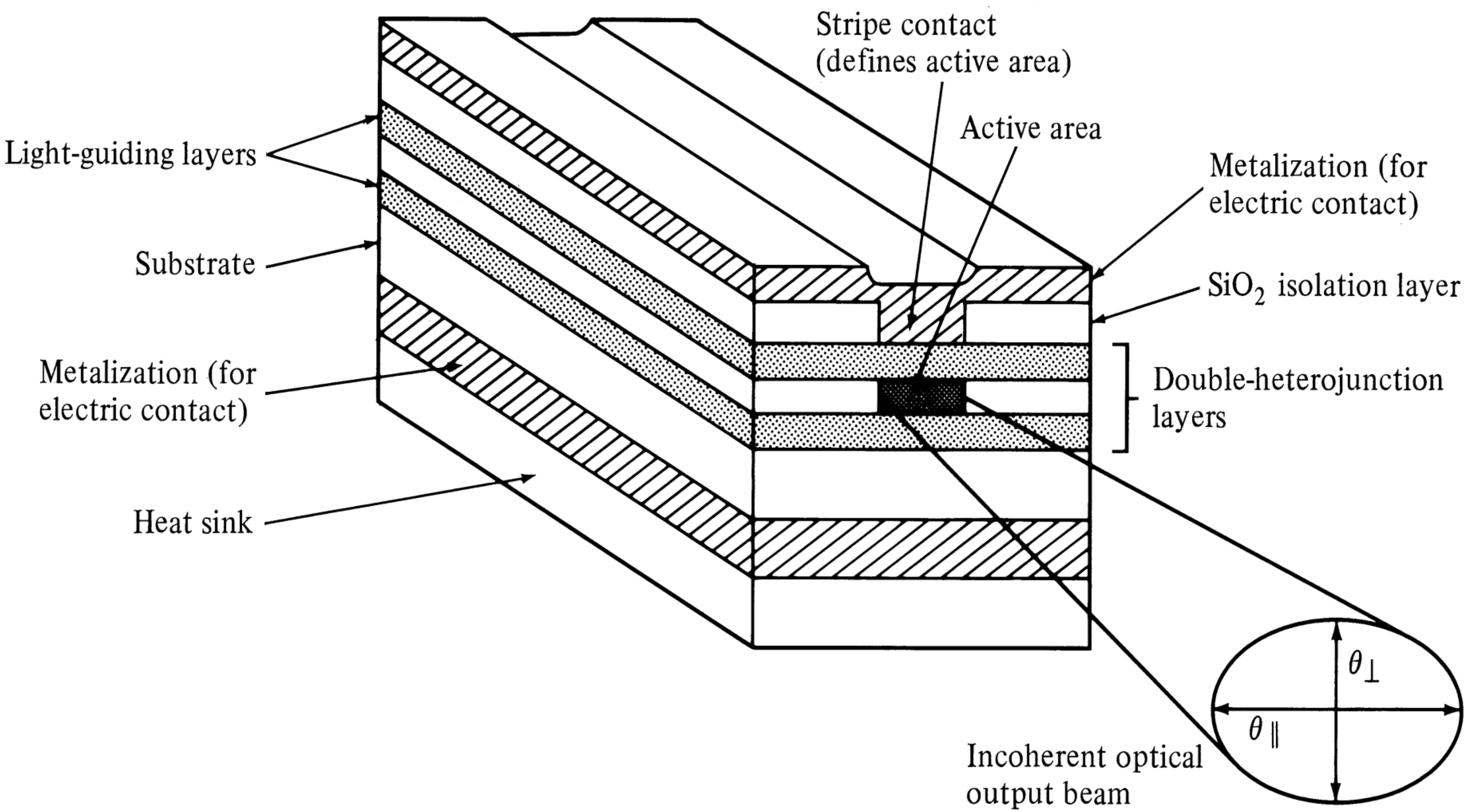



**The active region is limited to a circular section that has an area compatible with the fiber-core end face.**

# Surface Emitting LED

- **The surface-emitting LED is also known as the Burrus LED in honor of C. A. Burrus, its developer.**
- **In SLEDs, the size of the primary active region is limited to a small circular area of 20micron to 50micron in diameter.**
- **The primary active region is below the surface of the semiconductor substrate perpendicular to the axis of the fiber.**
- **A well is etched into the substrate to allow direct coupling of the emitted light to the optical fiber. The etched well allows the optical fiber to come into close contact with the emitting surface.**

# Edge-emitting LED




**Edge-emitting double-heterojunction LED. The output beam is lambertian in the plane of the pn-junction ($\theta_{||}$) and highly directional perpendicular to the pn-junction**

## Edge-emitting LED

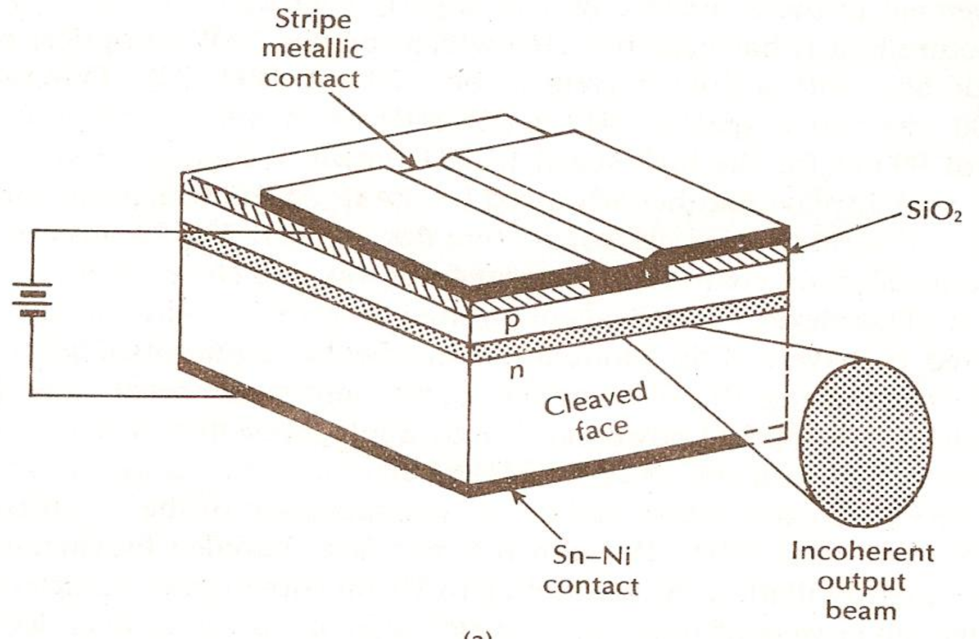
- **Have advantage of transparent guiding layers with a very thin active layer (50 to 100μm). This reduces self absorption and narrows the beam divergence.**
- **Light is emitted at one end face only.**
- **Couple more power to small NA fibers**
- **Higher data rates>100Mbps, better modulation**
- **Multimode and Single Mode fibers**
- **ELEDs provide narrower linewidth than SLED**
- **High radiance**

# Superluminescent LEDs

**Significant benefits over both SLEDs and ELEDs for OFS**

❖ **SLDs Provide**

- **High output power**
- **Directional output beam**
- **Narrow spectral linewidth**




- **One end is made optically lossy to prevent reflections and thus suppress lasing.**
- **Injection current increased until stimulated emission i.e. amplification occurs without feedback.**

# Superluminescent Diode (SLD)

- A superluminescent diode (SLED or SLD) is an edge-emitting semiconductor light source based on superluminnescence.

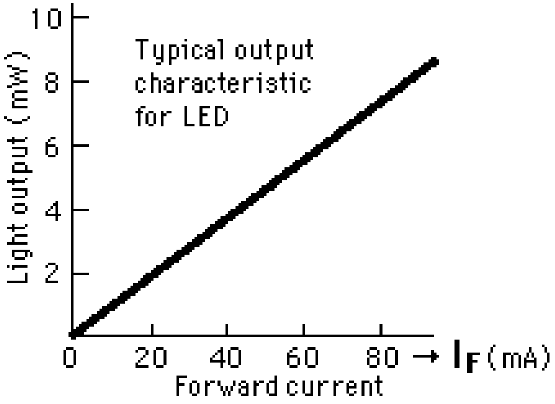
- It combines the high power and brightness of laser diodes with the low coherence of conventional LED.

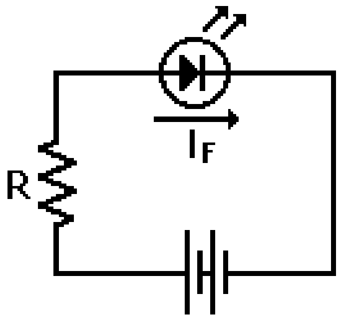
- Its emission band is 5–100 nm wide.

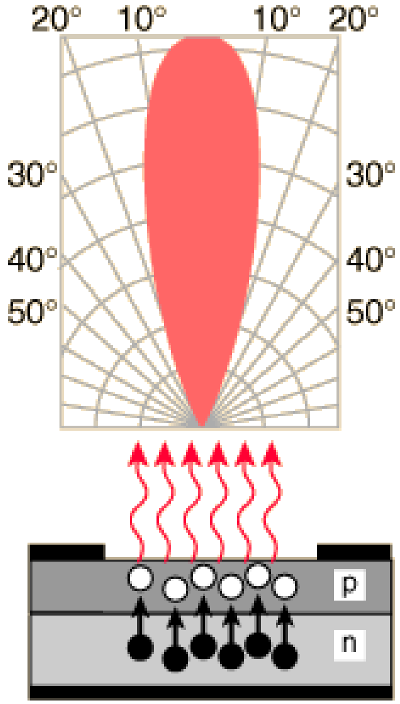
# Comparision : SLEDs Vs ELEDs

- SLED’s generally radiate more power into air (2.5 to 3 times) than ELED’s since the emitted light is less affected by re-absorption.
- SLED’s couples more optical power into large NA (greater than 0.3) than ELED where as the opposite is true for low NA’s.
- Less coupling efficiency in SLED’s as compare to ELED’s.
- ELED’s have better modulation bandwidth than SLED’s
- ELEDs have narrower bandwidth than SLED’s.

# LED Characteristics




- **LED is forward biased, its current increases rapidly and must be controlled to prevent destruction of the device.**
- **The light output is quite linearly proportional to the current, so it can be precisely modulated.**
- **Full Width Half Max, Peak Wavelength, Forward current, Rise time, Luminous intensity (Flux(lm)), LED radiation pattern**

# LED Power & Efficiency

- **Spontaneous emission allows nonradiative recombination to take place within the structure due to imperfections and impurities**
  - **Internal Quantum Efficiency**
    - **50% for simple homojunctions**
    - **60 to 80% with DH structures**

- **Internal quantum efficiency : Ratio of radiative recombination rate to the total recombination rate**

$$\eta_{int} = \frac{r_r}{r_t} = \frac{r_r}{r_r + r_{nr}} = \frac{R_r}{R_t}$$

$R_r$ is the total number of radiative recombination per second

$$R_r = \eta_{int} R_t = \eta_{int} \frac{i}{e}$$

**i - forward biased current to the p-n junction**

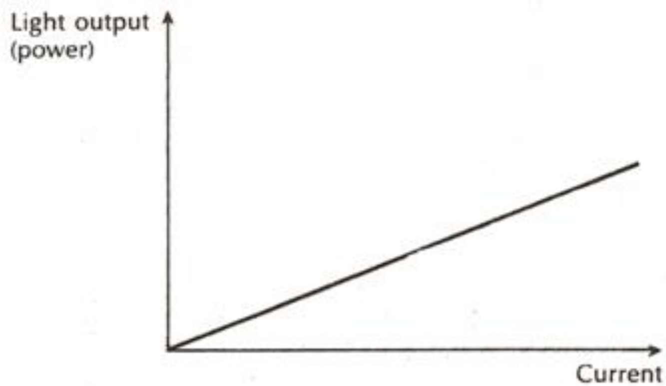
- **$R_r$ is equivalent to number of photons generated per second and each photon has an energy equal to hν, then optical power generated internally by the LED is**

$$P_{\text{int}} = R_r\, h\nu = \eta_{\text{int}} \frac{i}{e} h\nu$$

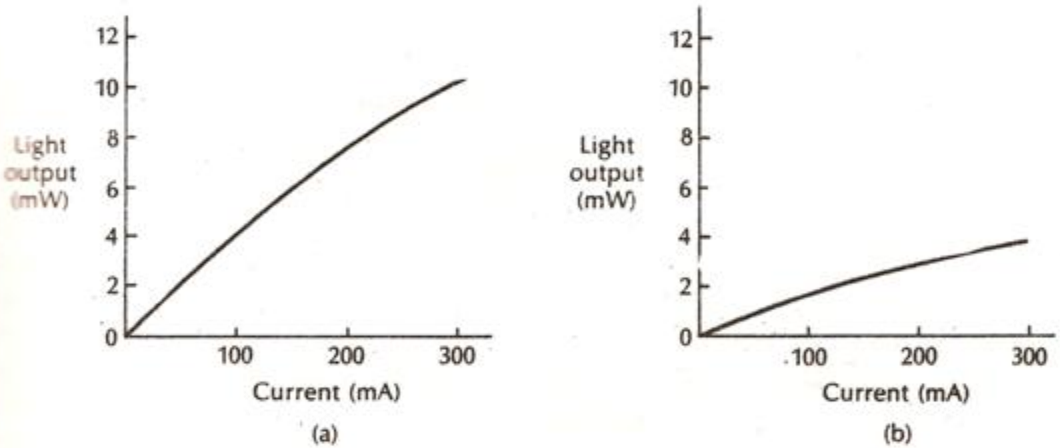
**In terms of wavelength** $$P_{\text{int}} = \eta_{\text{int}} \frac{i\, c}{e\, \lambda} h \;(W)$$

➢ **A linear relationship between the optical power generated in the LED and the drive current into the device**

# Light Output Power




An ideal light output against current characteristic for an LED.

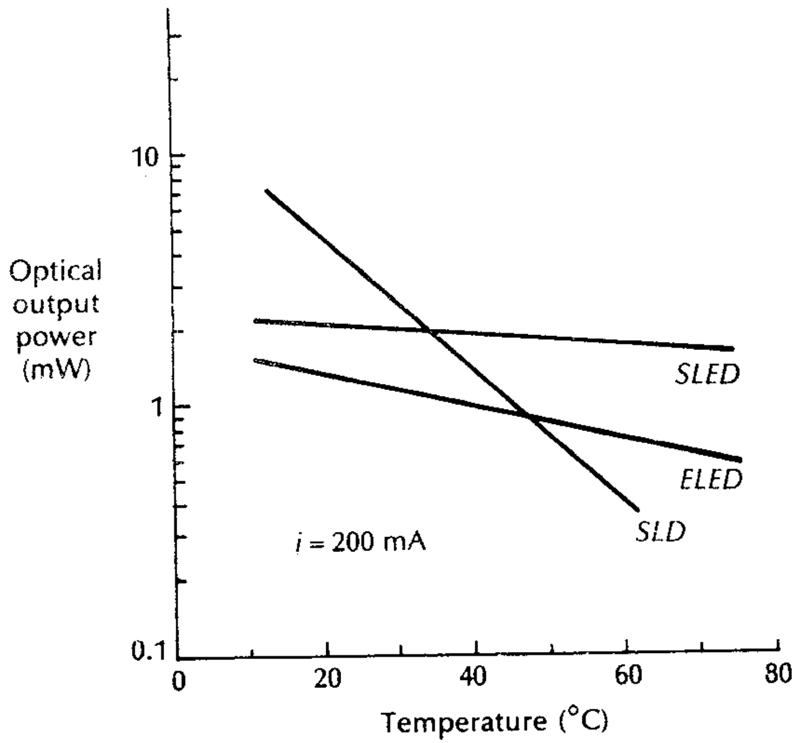



- **Surface emitter radiates significantly more optical power into air than the edge emitter**
- **Both are reasonably linear at moderate drive currents**

**Light ouput (power) into air against d.c. drive current for LED: a) An AlGaAs surface emitter; b) An AlGaAs edge emitter.**

# Temperature Dependence

- **Characteristics show the variation in output <u>at a specific drive current</u> over the temperature range for all the devices.**




**Light output temperature dependence for the three LED structure emitting at a wavelength of 1300 nm**

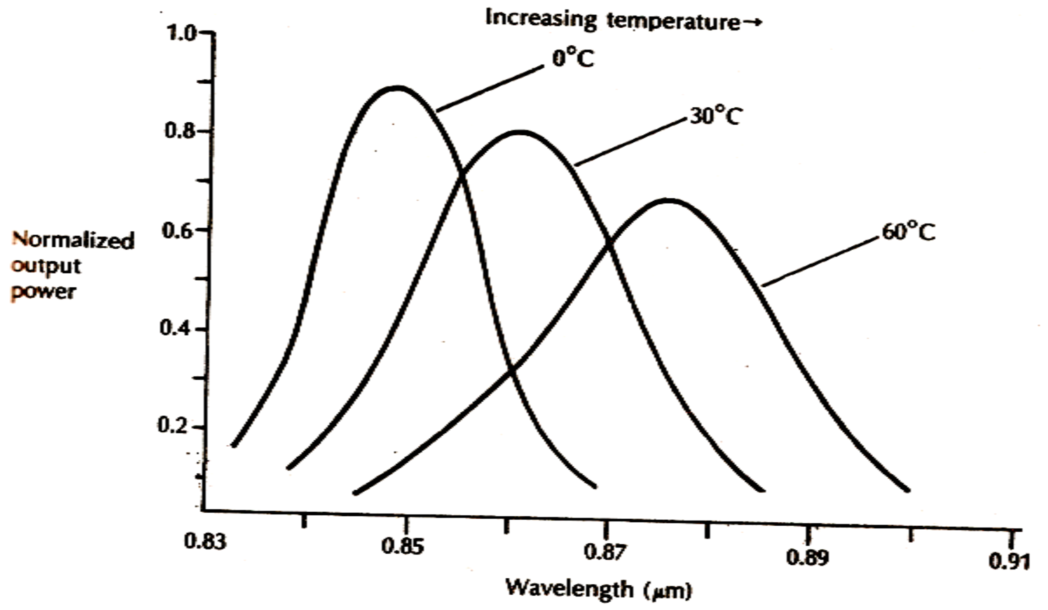
- **Edge emitting device exhibits a greater temperature dependence than the surface emitter and that the <u>output of SLD is strongly dependent on the junction temperature.</u>**

- **To utilize the high power potential of such devices at elevated temperatures, the use of <u>thermoelectric coolers</u> may be necessary.**

# Temperature dependence

- **Spectra tend to broaden with increase in temperature due to greater energy spread in carrier distributions at higher temperatures.**

- **Increase in temperature affect the peak emission wavelength as well.**



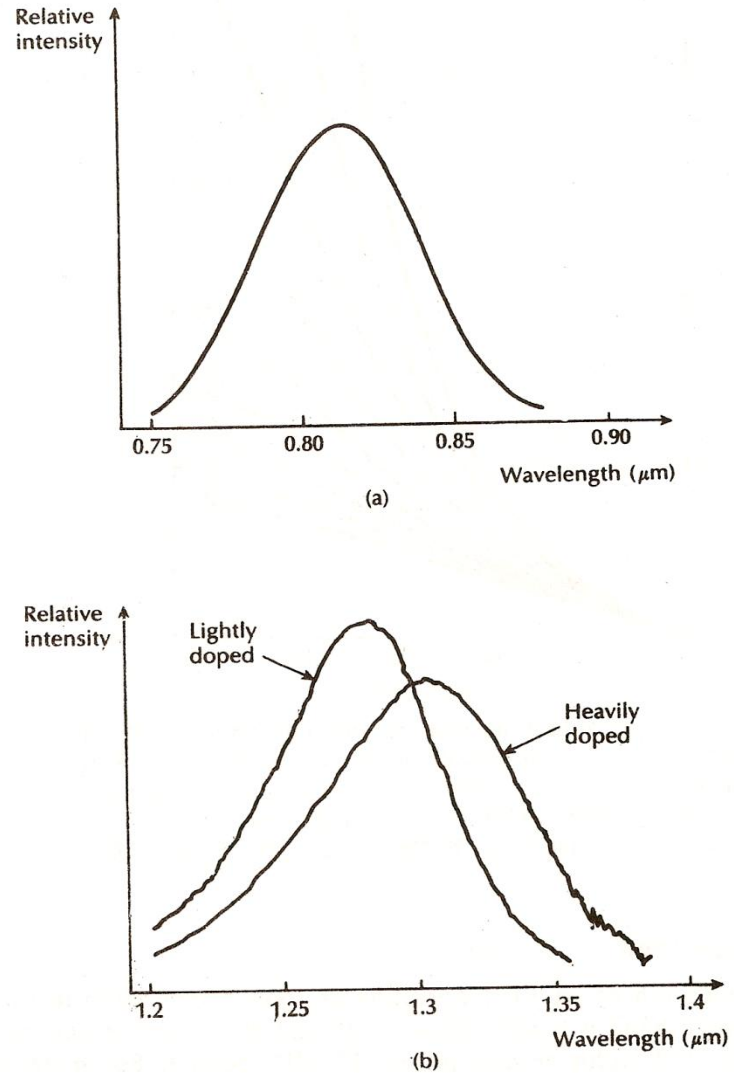

**Spectral variation with temperature for AlGaAs SLED**

# LED: Output Spectrum

**LED Output Spectra:**

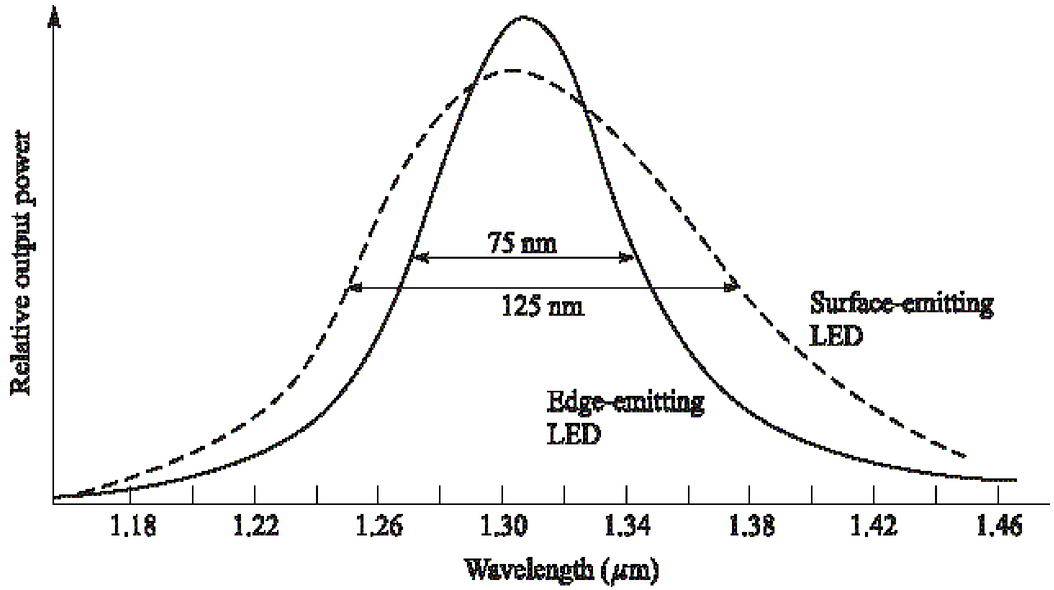
**a) An AlGaAs SLED with doped active region**

**b) InGaAsP SLED with lightly doped and heavily doped cases**




- **Spectral line width of an LED operating at room temperature at 0.85μm is between 25 and 40 nm (FWHM), but vary to 50 to 100 nm in 1550 region.**
- **Increased doping levels leads to increased linewidth also.**

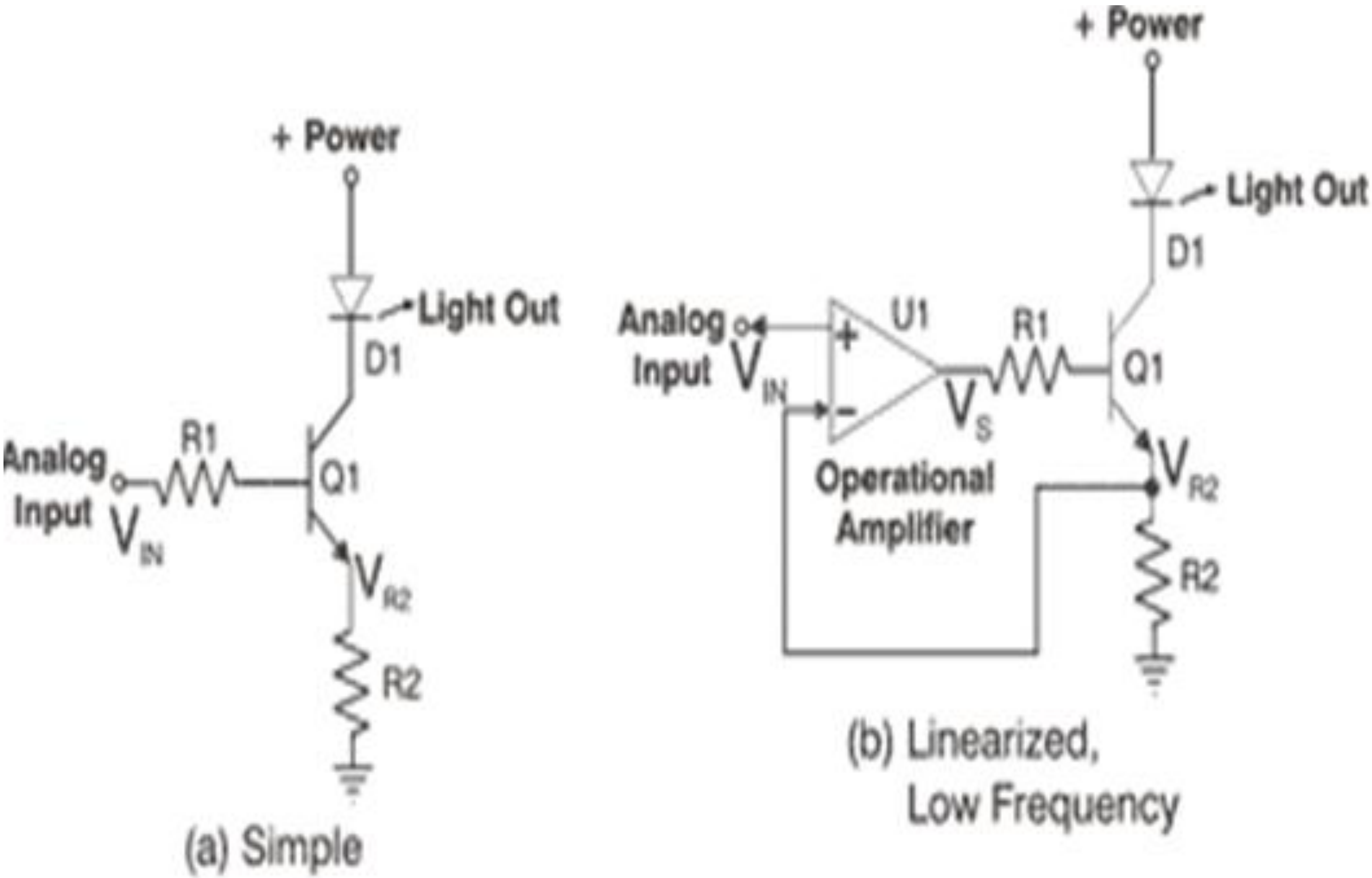
# Spectral Linewidth




**Typical spectral patterns for edge- and surface-emitting LEDs at 1310 nm.**

- **FWHM about 1.6 times smaller for ELED than SLED.**
- **Further narrowed by the Superluminescent operation; linewidth far smaller ≅ 30 nm**
- **The patterns broaden with increasing wavelength and are wider for surface emitters.**

# Analog LED Drive Circuit



# LASER DIODE

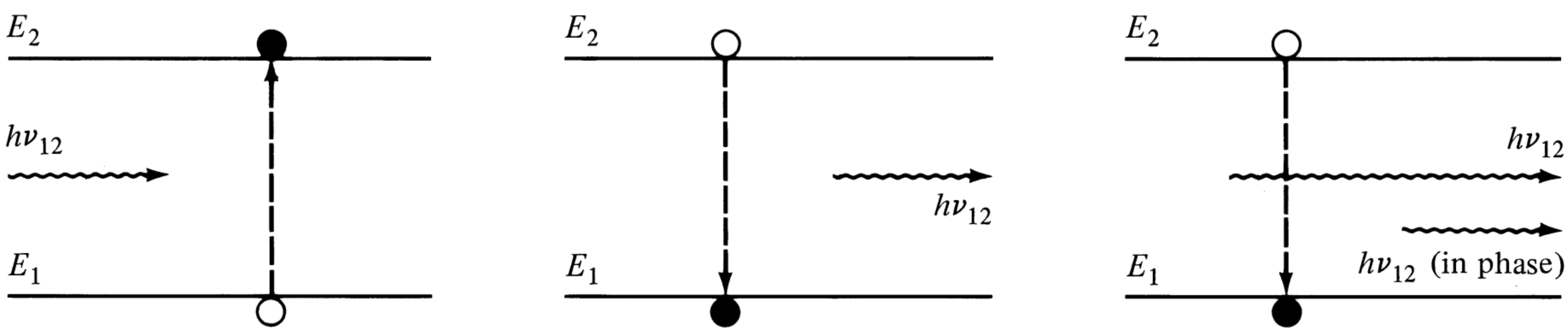
**LASER is an acronym for “Light Amplification by the Stimulated Emission of Radiation”.**

- **Coherent light**
- **Narrow beam width**
- **Lasers can produce high output power. In communication applications, semiconductor lasers of power up to about 20 milliwatts are available.**
- **Because laser light is Coherent, a high percentage (50% to 80%) can be coupled into the fiber.**

# LASER: Basic Operation

## Laser Transition Processes

## (Stimulated and Spontaneous Emission)




(*a*) Absorption (*b*) Spontaneous emission (*c*) Stimulated emission

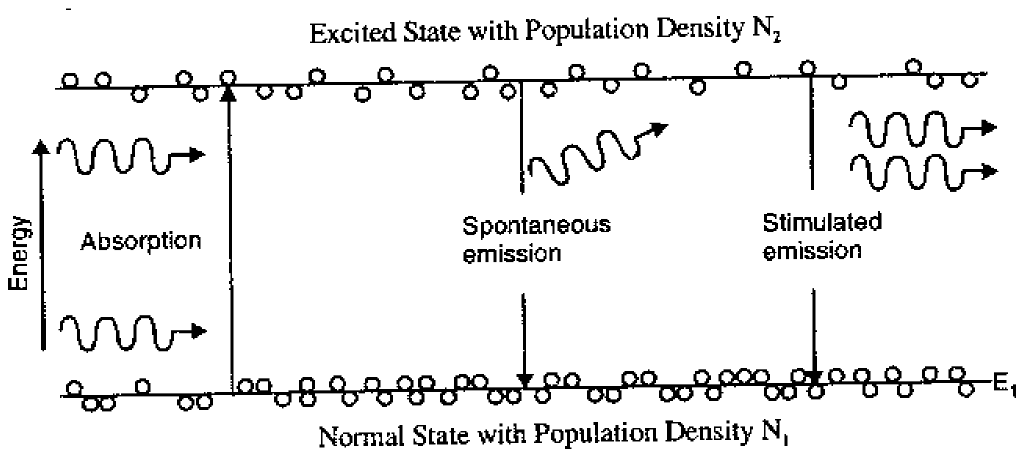
**Energy absorbed from the incoming photon**

**Random release of energy**

**Coherent release of energy**

# Conditions for Large Stimulated Emissions

**All three processes occur together with a balance between absorption and emission.**




**Absorption and Emission process in steady state of material**

- **Two conditions to be satisfied for stimulated emissions to overwhelm the spontaneous emissions are:**
  - **The population of excited level should be greater that that at the lower energy level and**
  - **The radiation density in the medium should be very large.**

# Population Inversion

- **At thermal equilibrium : Photon absorption and emission processes take place side by side, but because $N_1 > N_2$ ; absorption dominates.**
- **Laser operation requires stimulated emission exclusively.**
- **To achieve a high percentage of stimulated emission, a majority of atoms should be at the higher energy level than at the lower level.**
- **Energy is to be supplied somehow to the laser medium to raise atoms from the lower level to the excited level**
- **The process by which atoms are raised from the lower level to the upper level is called <u>pumping</u>.**

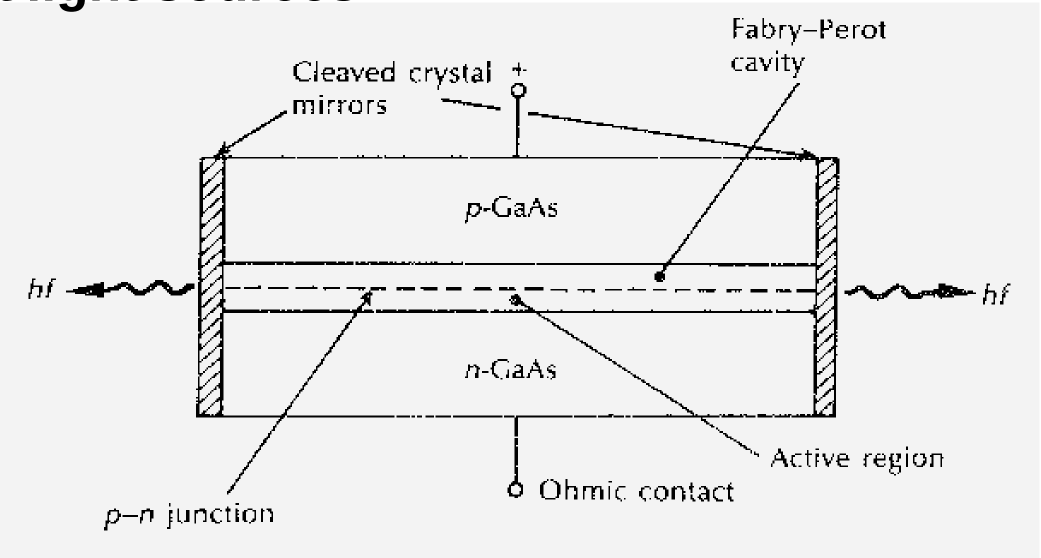
## In Stimulated Emission incident and stimulated photons will have

- Identical energy → Identical wavelength → Narrow linewidth
- Identical direction → Narrow beam width
- Identical phase → Coherence and
- Identical polarization

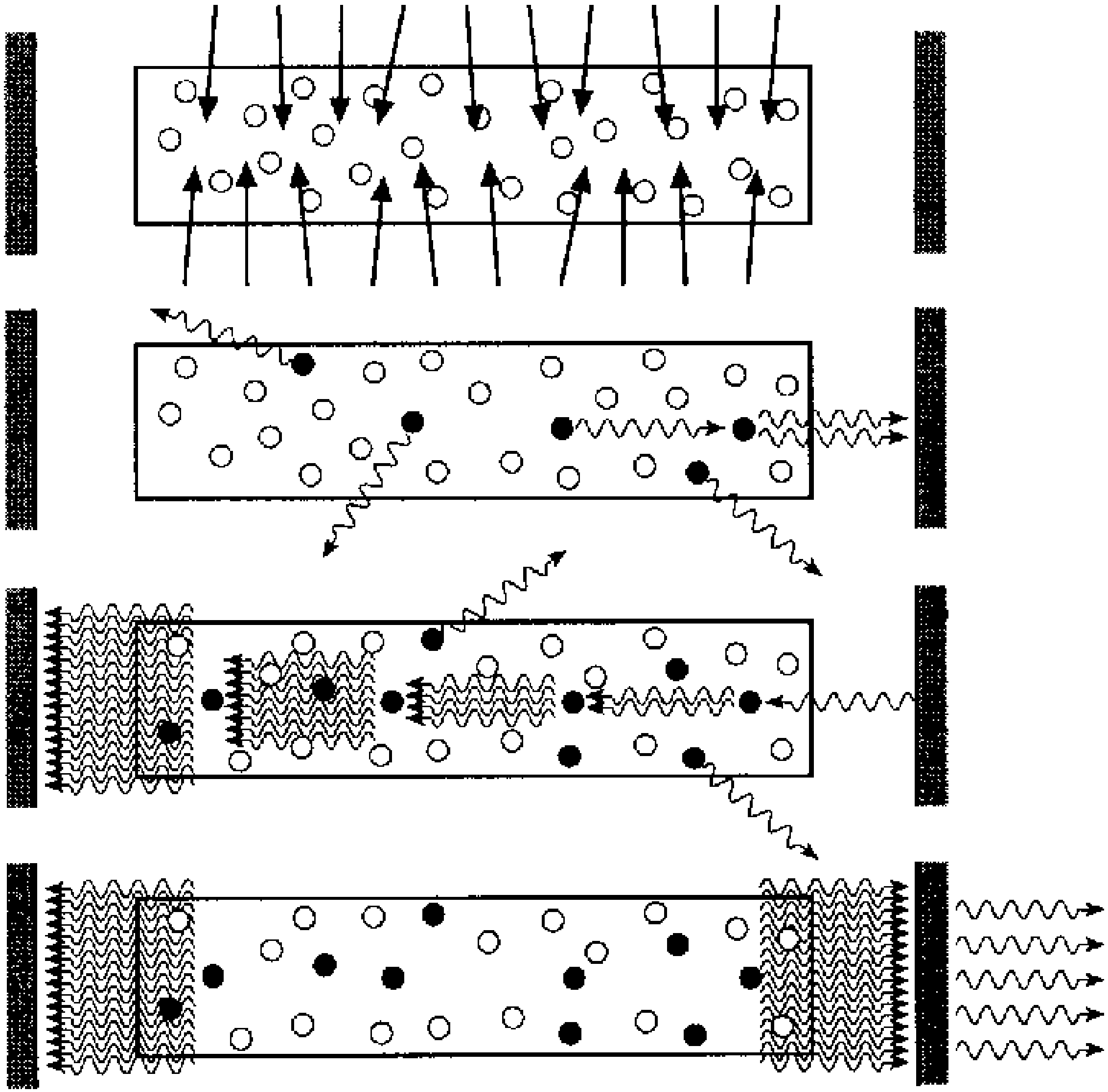
# Basic Structure

- **Homojunction device with cleaved ends demand for high threshold current density ( >$10^4$ A $cm^{-2}$) due to lack of carrier containment - inefficient light sources**

**Schematic diagram of a GaAs homojunction injection laser with a Fabry-Perot cavity**



# How a Laser Works

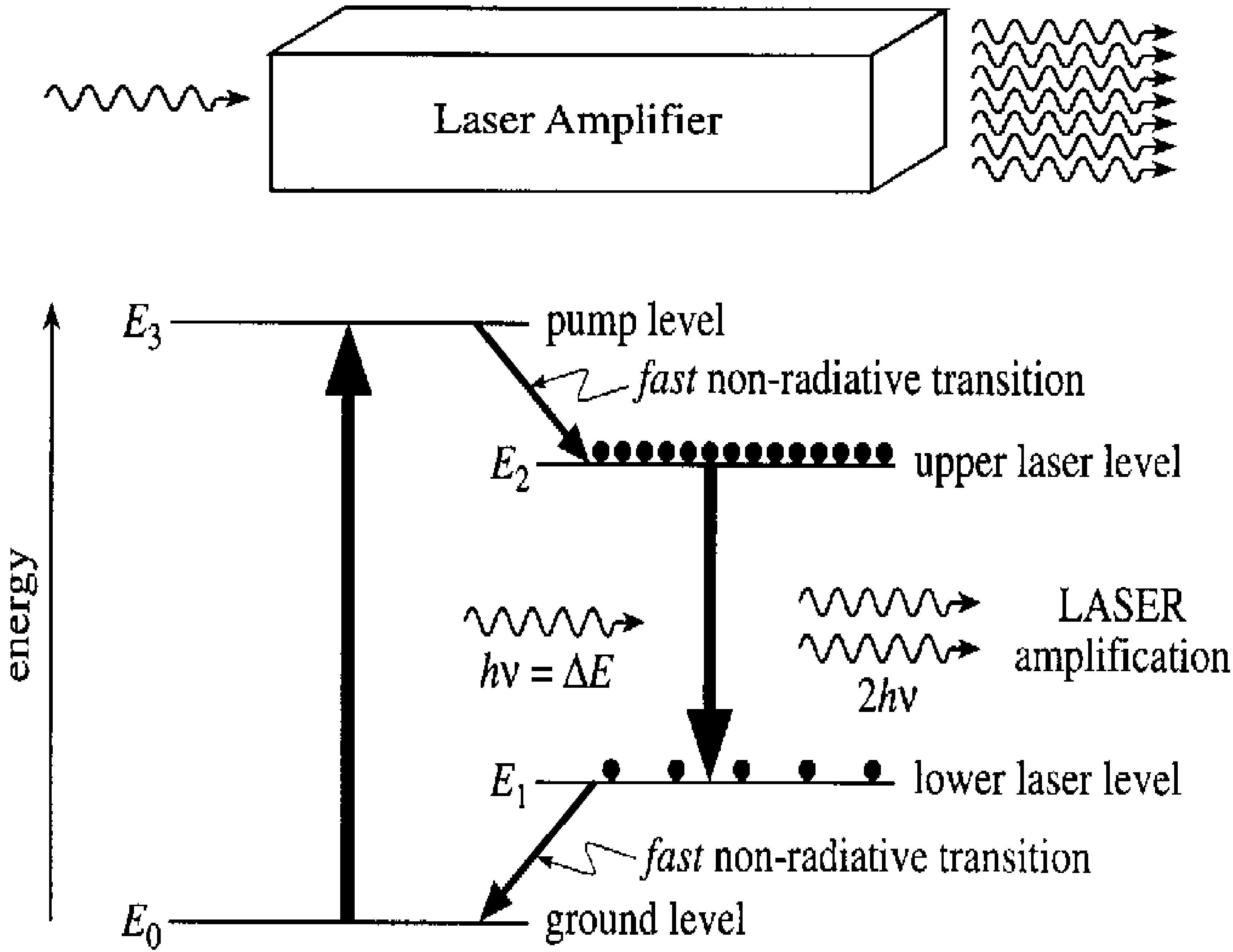


pump on
○ = atoms in excited state

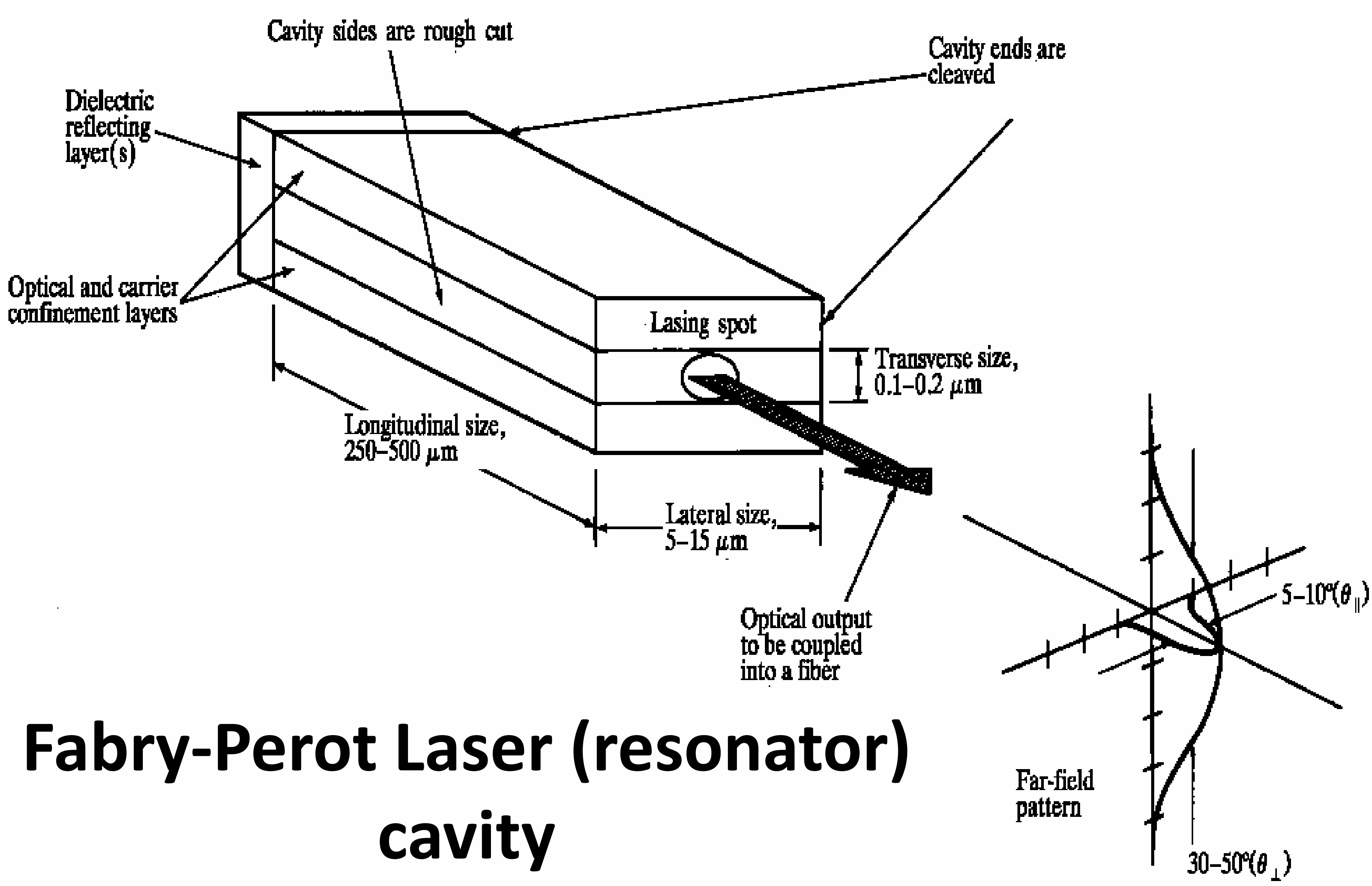
spontaneous emission &
rare stimulated emission

stimulated emission of
light along the laser axis

steady-state
laser operation

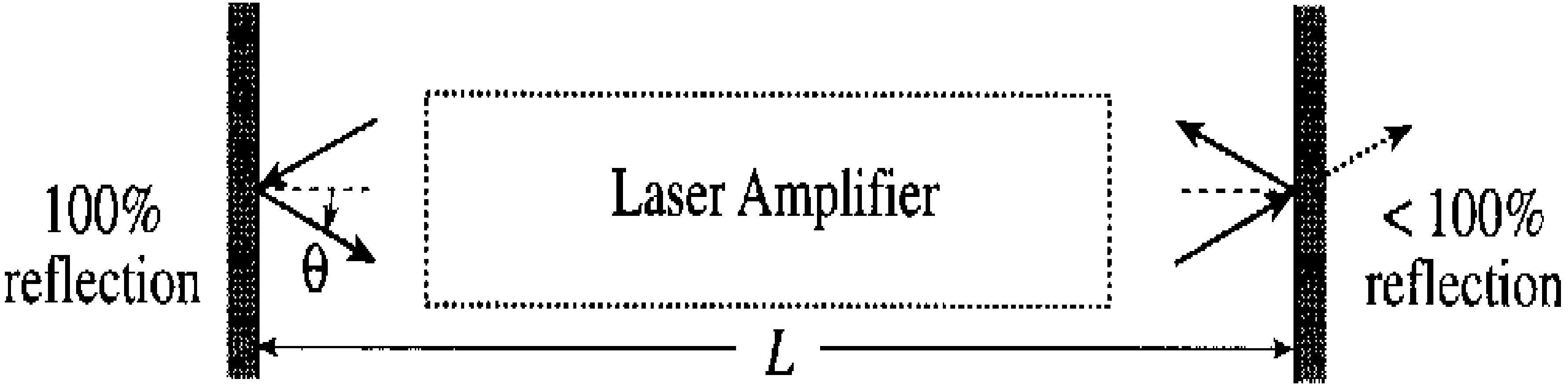


Laser Amplifier
energy
$E_3$
pump level
*fast* non-radiative transition
$E_2$
upper laser level
$h\nu = \Delta E$
LASER
amplification
$2h\nu$
$E_1$
lower laser level
*fast* non-radiative transition
$E_0$
ground level

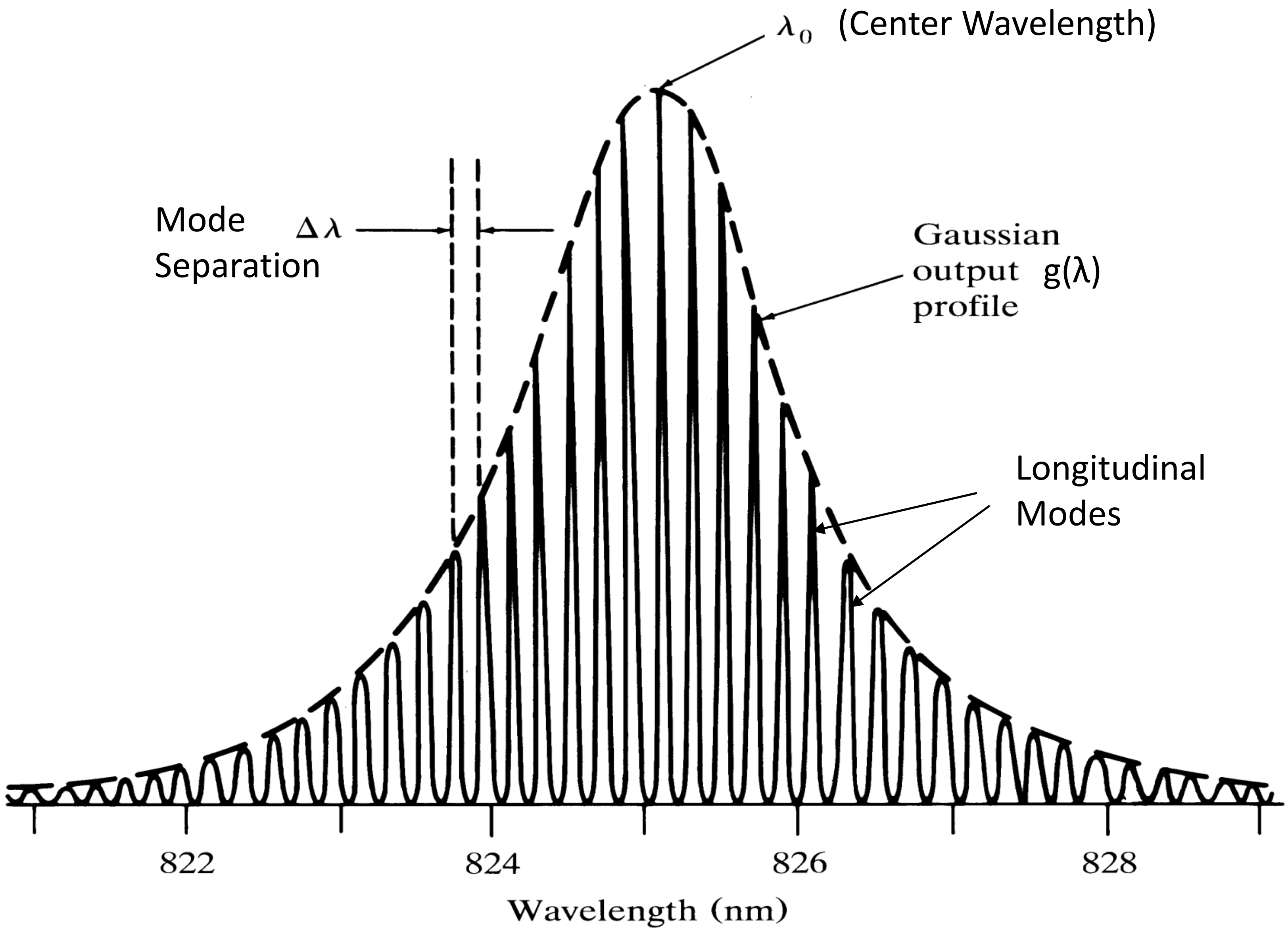



# Fabry-Perot Laser (resonator) cavity

# Mirror Reflections



# Laser Output Spectrum



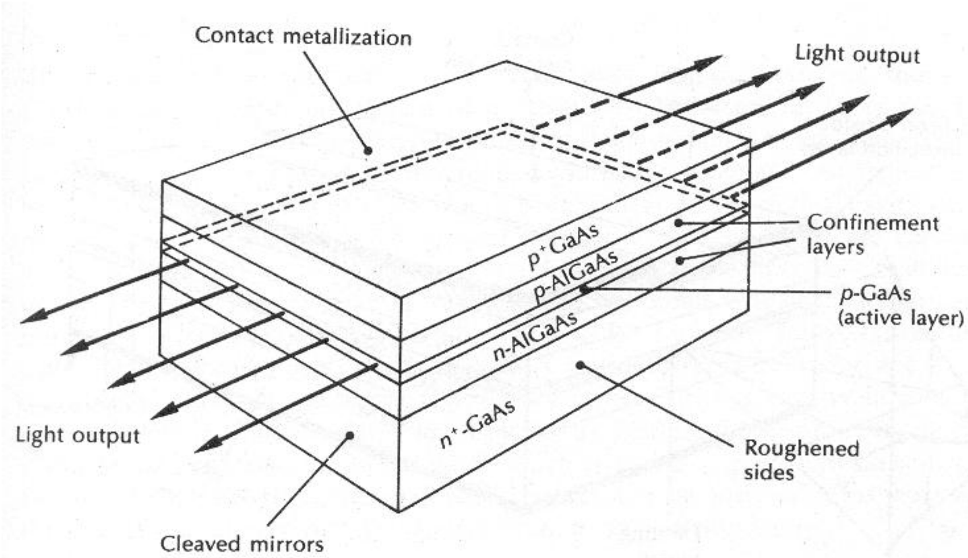
- ***Heterojunction structures*** **: Improved carrier confinement and thus lower current densities (≈ $10^3$ A $cm^{-2}$ )**
- **DH ILD fabricated from lattice matched III-V alloys provided both carrier and optical confinement on both sides of the p-n junction, giving the injection laser a greatly enhanced performance.**

# Stripe Geometry

**DH laser structure provides optical confinement in the vertical direction through the refractive index step at the heterojunction interfaces, but lasing takes place across the whole width of the device.**

**Broad Area <u>DH laser</u>**

- **Sides of cavity simply formed by roughening the edges of the device**
- **Reduce unwanted emission in these directions**
- **Limit the number of horizontal transverse modes**




**broad area GaAs/AlGaAs DH injection laser**

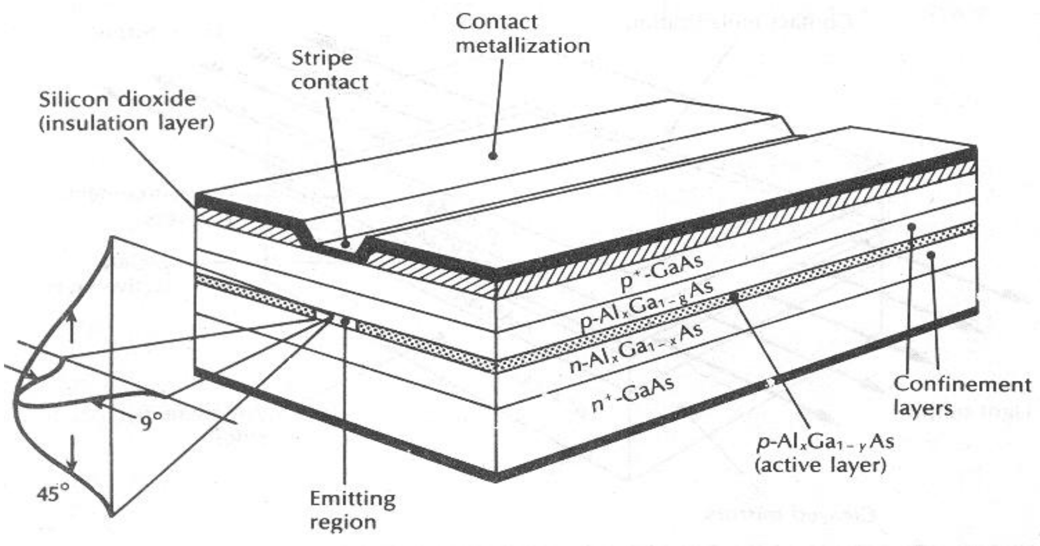
- **Broad emission area creates several problems including difficult heat sinking, relatively wide active area, unsuitable light output geometry for efficient coupling to fibers etc.**

# DH Stripe Contact Laser

- **To overcome broad emission problems whilst also reducing the required threshold currents**
  - **laser structures in which active region does not extend to the edges of the device were developed.**

- **In this structure, the major current flow through the device and hence the active region is within the stripe.**

- **Generally, stripe is formed by creation of high resistance areas on either side by techniques such as *Proton Bombardment* or *Oxide Isolation*.**




**Schematic representation of an oxide stripe AlGaAs DH injection laser.**

**The stripe therefore acts as a guiding mechanism which overcomes the major problems of the broad area device.**

# Distributed Feedback Laser

- **A distributed feedback laser (DFB) is a type of laser diode where the active region of the device is periodically structured as a diffraction grating.**

- **The structure builds a one-dimensional interference grating (Bragg Scattering) and the grating provides optical feedback for the laser.**

- **DFB laser diodes do not use two discrete mirrors to form the optical cavity (as they are used in conventional laser designs).**

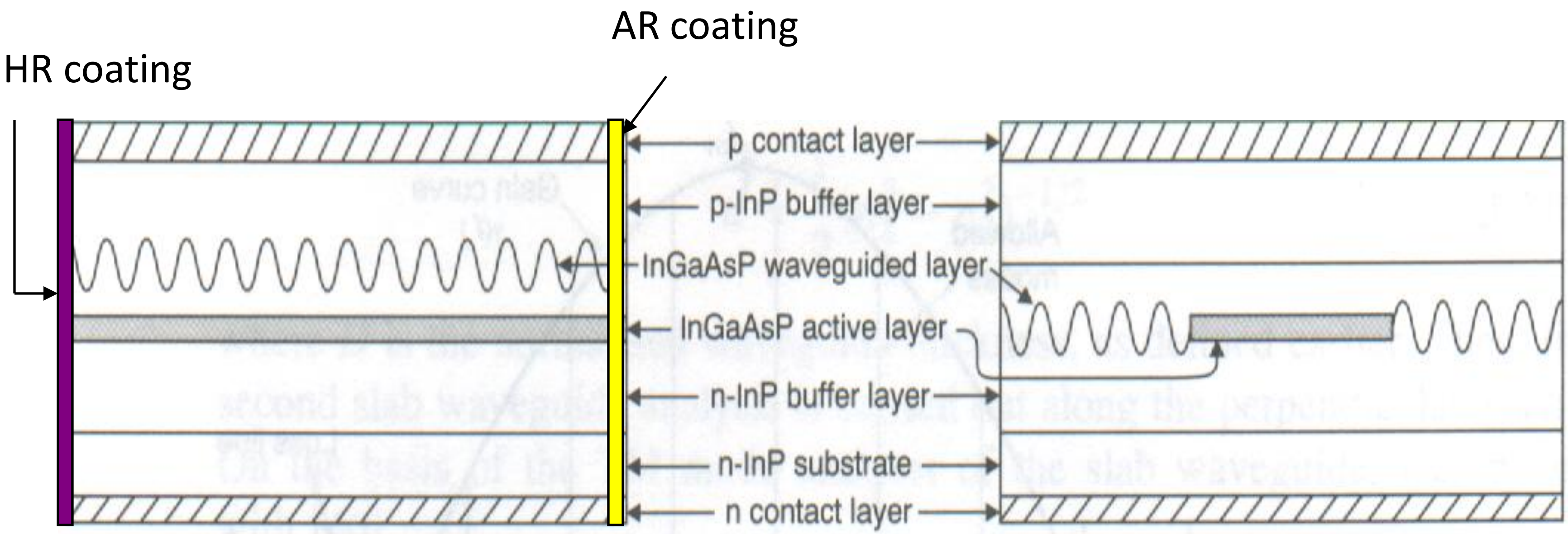
- **The grating acts as the wavelength selective element for at least one of the mirrors and provides the feedback, reflecting light back into the cavity to form the resonator.**

- **The grating is constructed so as to reflect only a narrow band of wavelength, and thus produce a single longitudinal lasing mode.**

- **This is in contrast to a Fabry-Perot Laser, where the facets of the chip form the two mirrors and provide the feedback.**

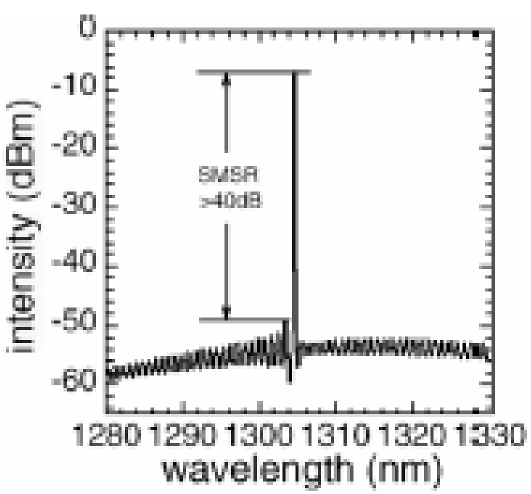
- **Altering the temperature of the device causes the pitch of the grating to change due to the dependence of refractive index on temperature. This dependence is caused by a change in the semiconductor laser's bandgap with temperature and thermal expansion.**
- **A change in the refractive index alters the wavelength selection of the grating structure and thus the wavelength of the laser output, producing a Tunable Diode Laser.**
- **DFBs are antireflection coated on one side of the cavity and coated for high reflectivity on the other side (AR/HR).**
- **In this case the grating forms the distributed mirror on the antireflection coated side, while the semiconductor facet on the high reflectivity side forms the other mirror.**
- **These lasers generally have higher output power since the light is taken from the AR side, and the HR side prevents power being lost from the back side.**

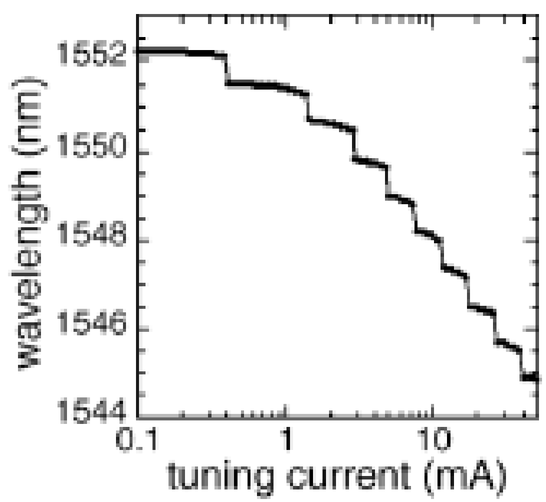
# DFB and DBR lasers



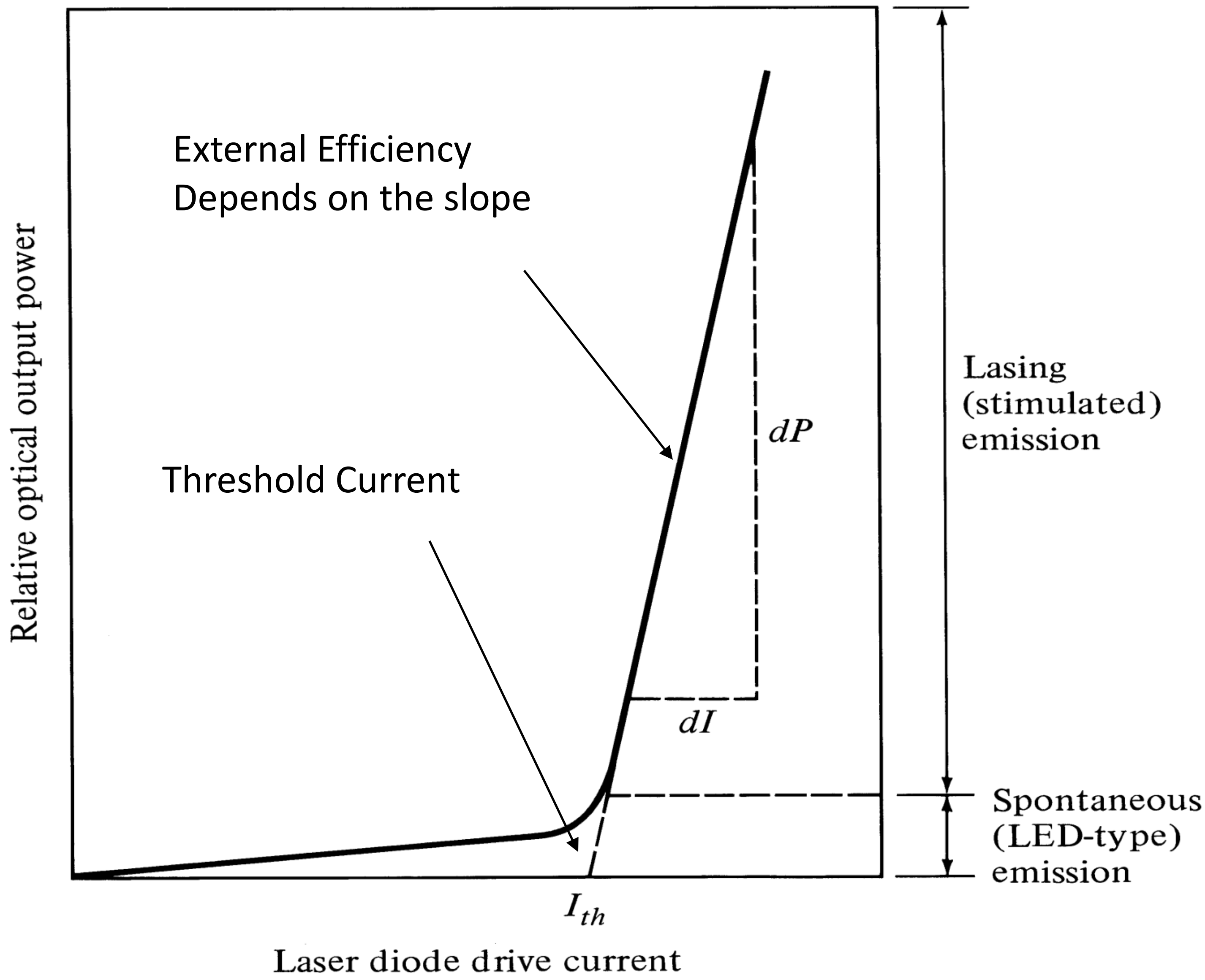

DFB

DBR

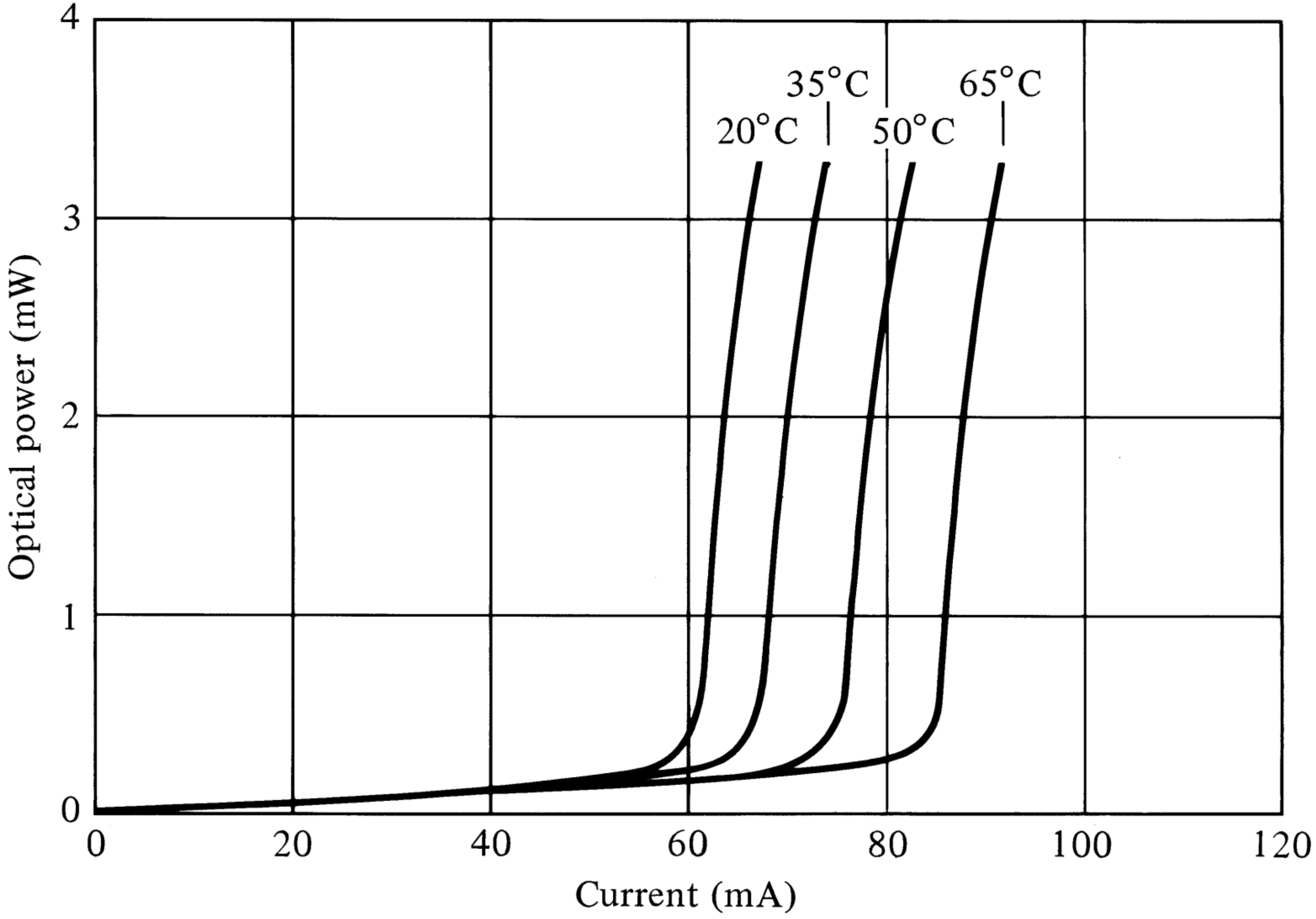


# Optical output vs. drive current of a laser

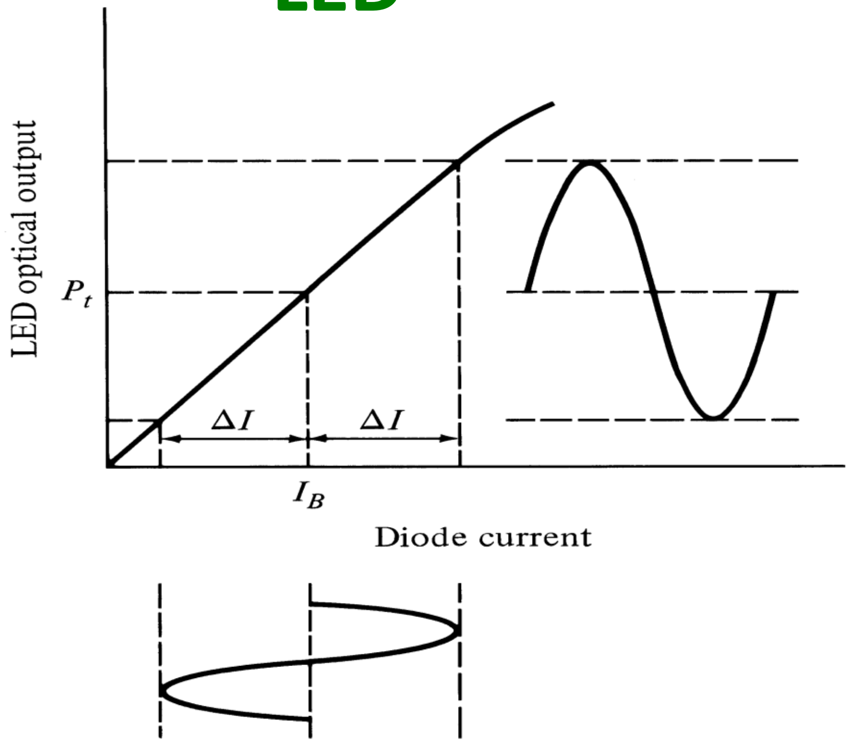


# Laser threshold depends on Temperature

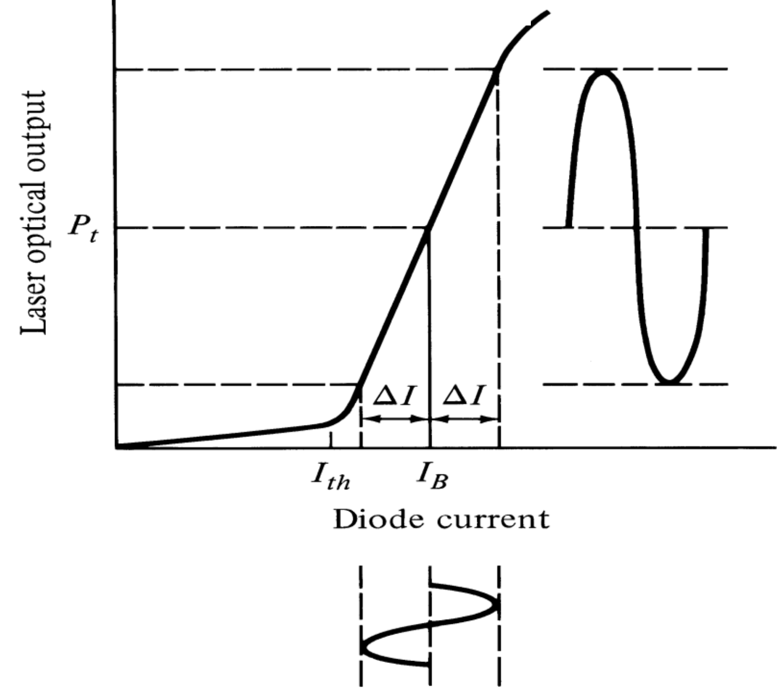


# Analog Modulation

## LED

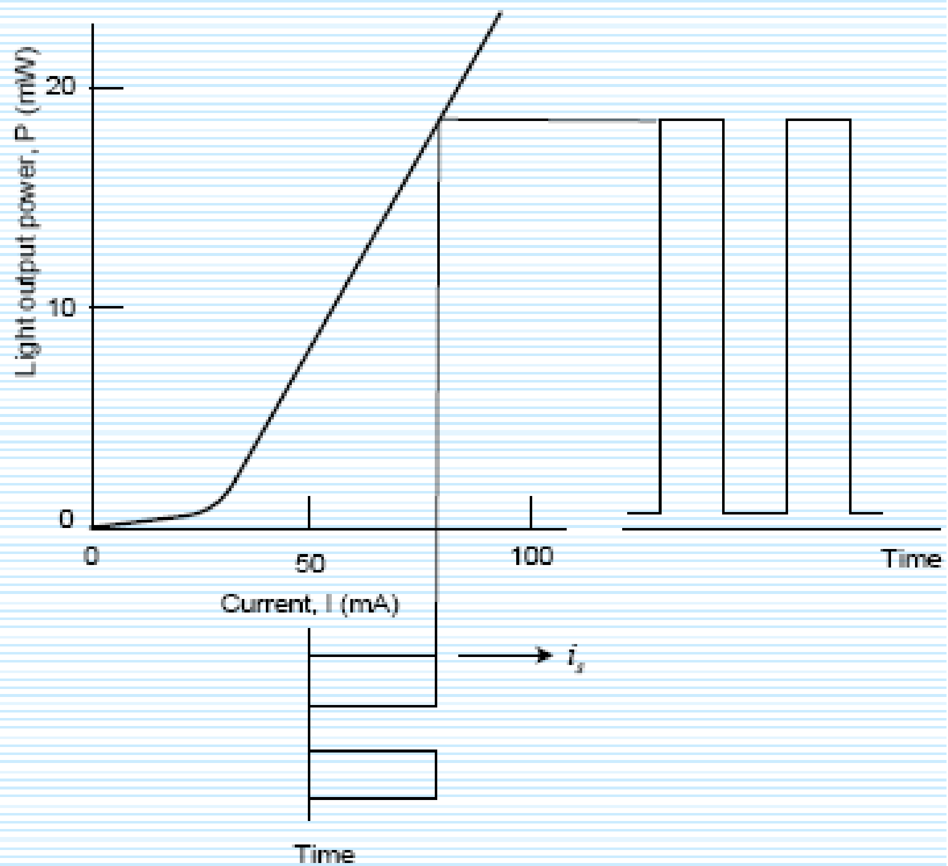


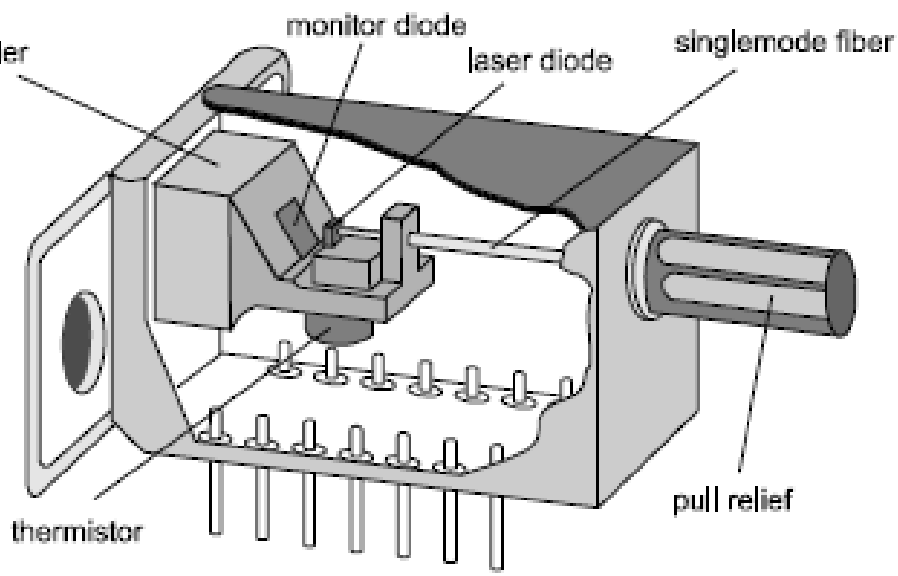

## LASER



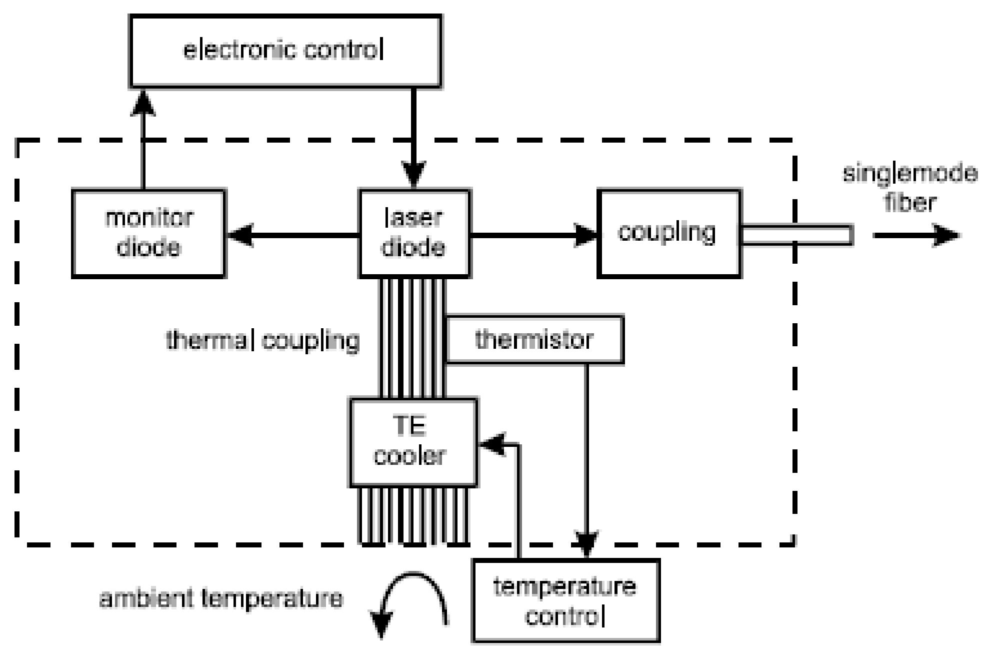
# Laser Digital Modulation

Digital modulation:



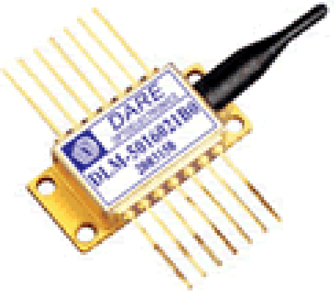



**DIL-14 package with laser diode, monitor diode thermistor, TE cooler and fiber coupling**




**Set-up of a laser module**

# Commercial DFB




| Parameters | Symbo l | Min | Typ | Max | Unit |
|---|---|---|---|---|---|
| CW Output power(25C) | Pf | 10 | --- | 30 | mW |
| Threshold current | It h | -- | 25 | 60 | mA |
| Operating current | If | -- | 300 | -- | mA |
| Forward voltage | Vf | -- | 2.0 | 3.0 | V |
| Center Wavelength | λc | 1540 | 1550 | 1570 | nm |
| Linewidth | Δ λ | -- | 2 | -- | MHz |
| Monitor Current | Im | -- | 200 | -- | μA |
| Monitor dark current(Vr=-5V) | Id | -- | -- | 100 | nA |
| Isolation(Optional) | Iso | -30 | -- | -- | dB |
| TEC current | ITEC | -- | 1.2 | -- | A |
| TEC voltage | VTEC | -- | 3.2 | -- | V |
| Thermistor resistance(at 25℃) | Rt h | 9.5 | 10 | 10.5 | kΩ |
| Operating Temperature Range | To | -20 | -- | 65 | C |
| Storage temperature | Tst g | -40 | -- | 85 | C |

- **Components**
  - DFB diode
  - Thermoelectric cooler
  - Thermistor
  - Photodiode
  - Optical isolator
  - Fiber-coupled lens

## Applications

- CATV
- Long Haul Telecommunication

## Features

- Use the High Reliability Qualified Chip
- High Kink Free Power up to 30mW
- Use YAG Laser Welding Technique
- Hermetic 14-pin Butterfly Package
- Built-in Temperature Control
- Internal Optical Isolator(optional)

# Comparison between LED and LASER

**LED**

- Low efficiency
- Slow response time
- Lower data transmission rate
- Broad output spectrum
- In-coherent beam
- Low launch power
- Higher distortion level at the output
- Suitable for shorter transmission distances.
- Higher dispersion
- Less temperature dependent
- Simple construction
- Life time $10^7$ hours

**Laser Diode**

- High efficiency
- Fast response time
- Higher data transmission rate
- Narrow output spectrum
- Coherent output beam
- Higher bit rate
- High launch power
- Less distortion
- Suitable for longer transmission distances
- Lower dispersion
- More temperature dependent
- Construction is complicated
- Life time $10^7$ hours

# PHOTODETECTORS:

**Photodetectors find applications in the area of medical, automotive, safety and analytical equipments, cameras, communications, astronomy and industry.**

## Types of Photodetectors

- **Photodiode, Photodiode Array, Light Dependent Resistor**
- **Avalanche Photodiode**
- **Photomultiplier Tube, Microchannel Plate, Image Intensifier**
- **Position Sensitive Detector**
- **CCD**

# Photodetector Requirements for Performance

- High sensitivity at the operating wavelength of the source
- Short response time to obtain a desirable bandwidth
- Minimum noise contribution
- Compatible size for efficient coupling and packaging
- Linear response over a wide range of light intensity
- Stability of performance characteristics
- Low bias voltage
- Low cost

# Photodetection Mechanisms

**Photodetector converts light (power) into electrical signals (photocurrent)**

**There are two distinct photodetection mechanisms**

## 1 External photoelectric effect :

- **Photomultiplier Tubes (PMT)**

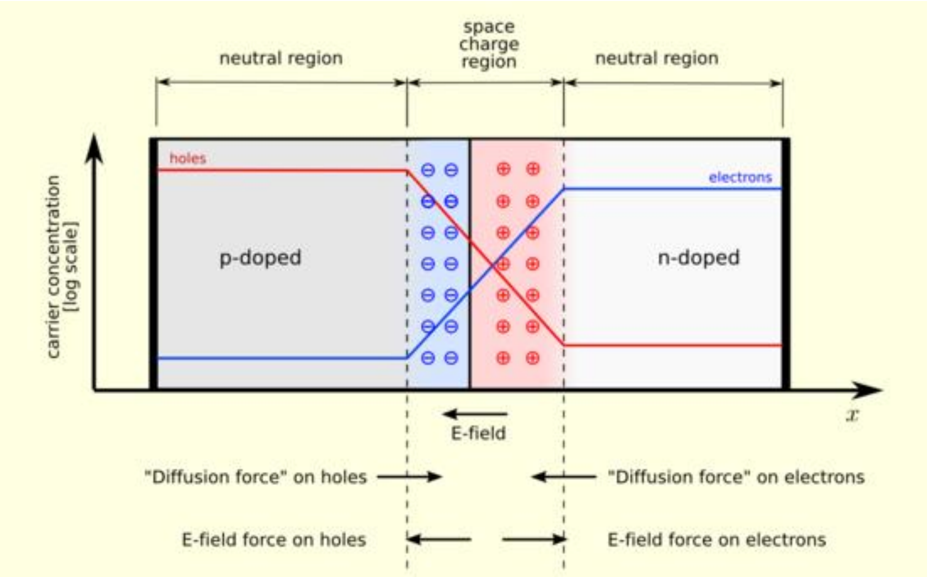
## 2 Internal photoelectric effect :

- **PN junction photodiodes**
- **PIN photodiodes**
- **Avalanche photodiodes**

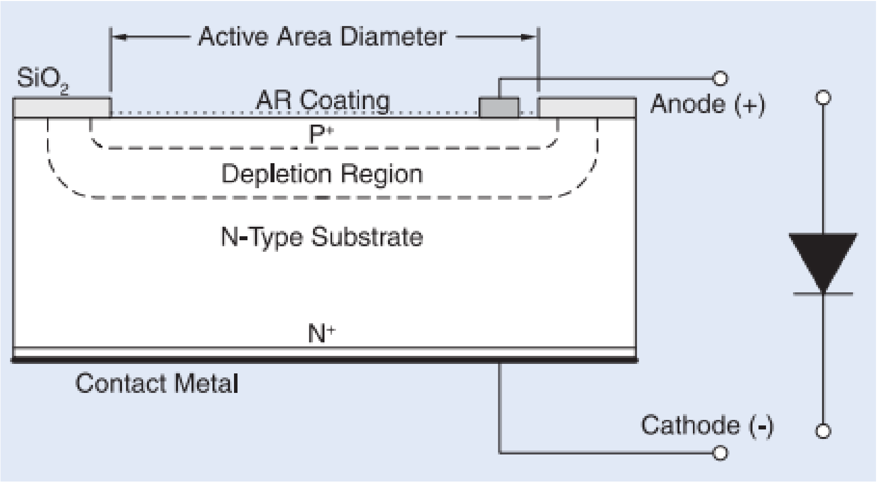
# Principle of Photodetection (In Semiconductor)

- In semiconductors, conduction band and valence band are separated by a forbidden band gap.
- Electrons at the valance band are bound. The electrons in the conduction band are free and when small voltage is applied they move and causes current flow
- Populating the conduction band with electrons causes the semiconductor to conduct current.
- The value of band gap $E_g$ determines the conductive properties of semiconductor

# Photodetection

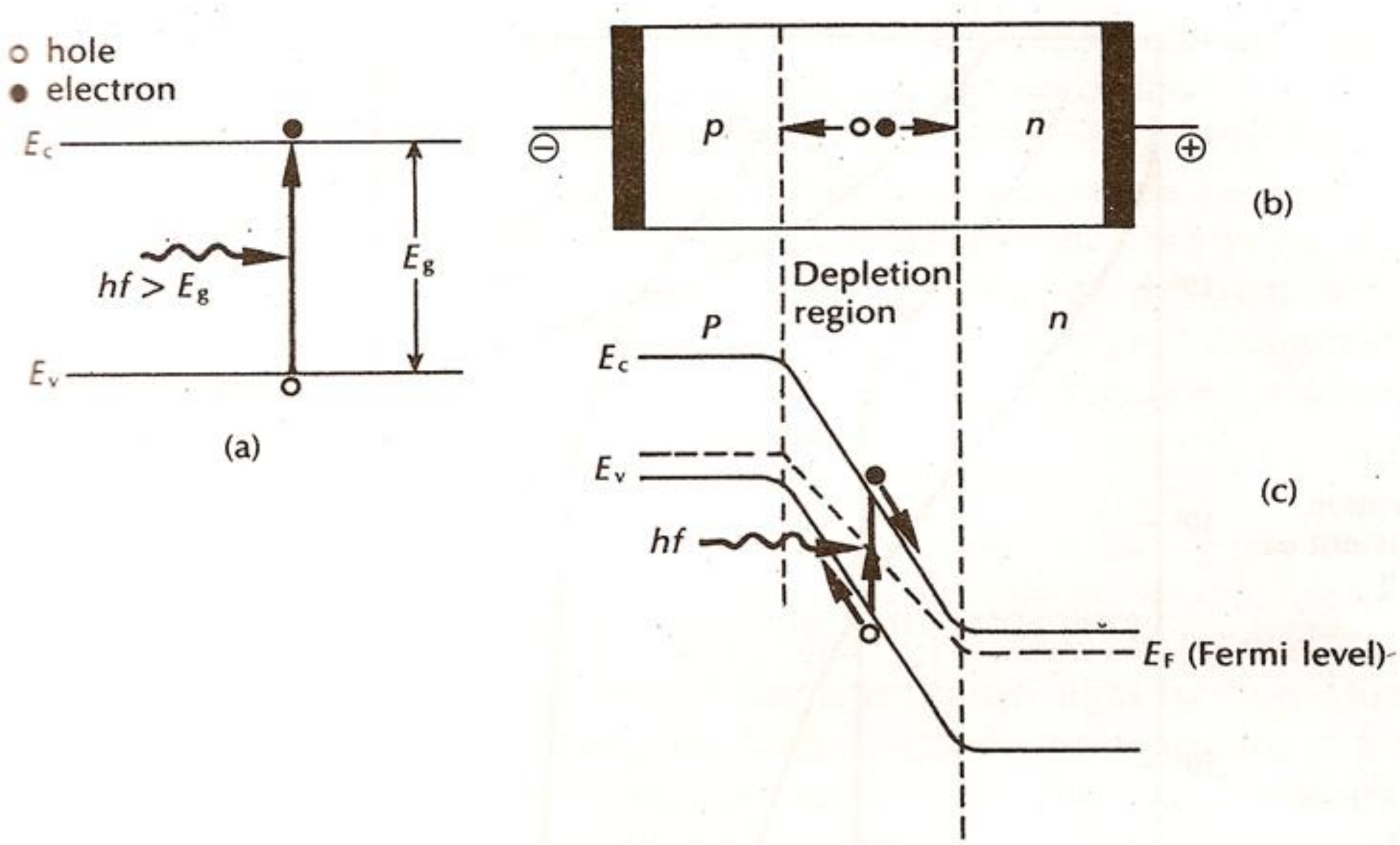



**p–n junction in thermal equilibrium with zero bias voltage**




**A PN junction can be formed by diffusing either a P-type impurity such as Boron, into a N-type bulk silicon wafer, or a N-type impurity, such as Phosphorous, into a P-type bulk silicon wafer.**

# Photodetection




**(a) Photogeneration of e-h pair**

**(b) Reverse biased p-n junction with carrier drift in depletion region**

**(c) Energy band diagram showing photogeneration and separation of e-h pair**

- **All semiconductor photodetectors use photon absorption in depletion region to convert photons into electron hole pairs, and then sense them.**

- **When a semiconductor is illuminated by light having an energy E = hγ greater than its band gap energy $E_g$ the light is absorbed in the semiconductor and electron hole pairs are generated. γ is the frequency of light.**

- **Incident photon after passing through p-region will be absorbed in the depletion layer. The absorbed energy creates EHP, Electron raises to conduction band and hole fall to valance band. The free electron travel down the barrier and the free hole will travel up the barrier to constitute current flow.**

- **The photon absorbed in the neutral p or n regions, outside the depletion region create EHP, but these free charges will not move quickly due to lack of strong electric field. Most of the free charges will diffuse slowly through the diode and may recombine before reaching the junction. These charges produce negligible current, thus reducing the detector's responsivity.**

- **EHP created close to the depletion layer can diffuse and subsequently be swept across the junction by the large electric field due to applied reverse biased voltage. An external current is produced but it is delayed with respect to variations in the incident optical power**

- **It is desirable that photon be absorbed in the depletion layer so that it can contribute maximum in generation of photocurrent.**

- **Typical pn photodiodes have a rise time of the order of microseconds making them unsuitable for high speed optical systems.**

- **The existence of electric field across the junction facilitate the rise of photocurrent**

- **The primary operating wavelength regions for FO communication systems are 850nm, 1310nm and 1550 nm. The photodetectors which are used in these systems are :**

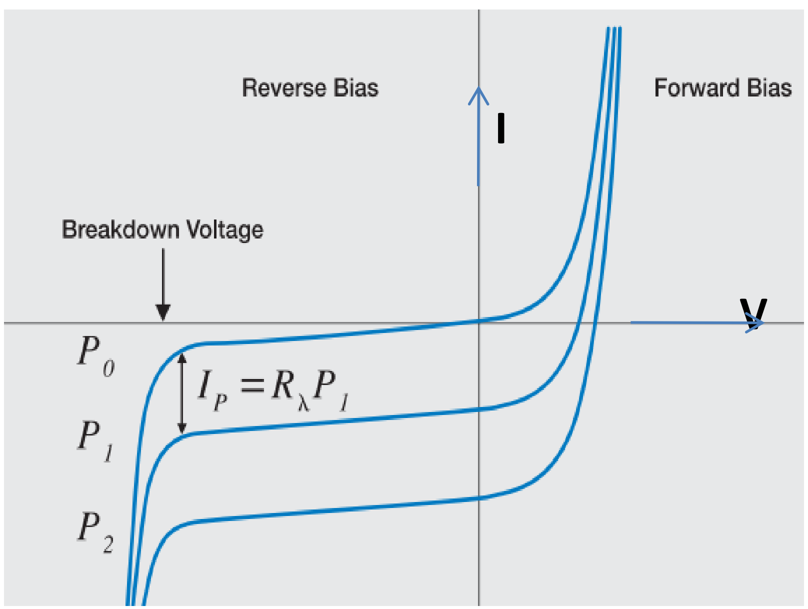
  **- PN junction photodiodes**
  **- PIN photodiodes**
  **- Avalanche photodiode**

# Photodetector I-V curve under Illumination

**The I-V characteristic of a photodiode with no incident light is similar to a rectifying diode. When the photodiode is forward biased, there is an exponential increase in the current. When a reverse bias is applied, a small reverse saturation current appears. It is related to dark current as**

$$I_D = I_{SAT}\left(e^{\frac{qV_A}{k_B T}} - 1\right)$$

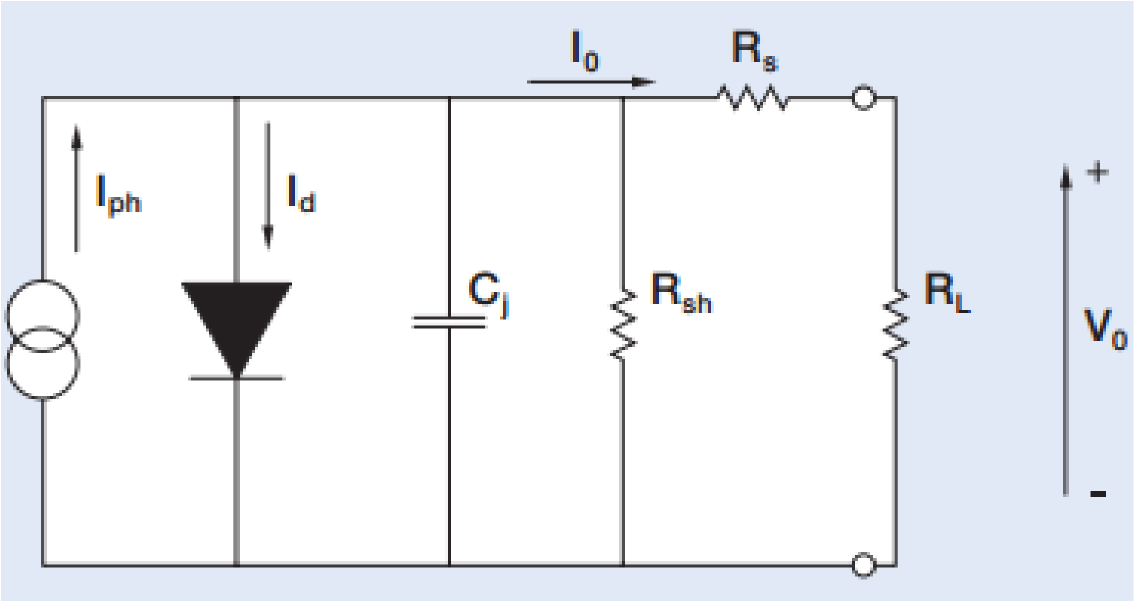
**where $I_D$ is the photodiode dark current, $I_{SAT}$ is the reverse saturation current representing thermally generated free carriers which flow through the junction, q is the electron charge, $V_A$ is the applied bias voltage, $k_B = 1.38 \times 10^{-23}$ J/K, is the Boltzmann Constant and T is the absolute temperature (273 K= 0$^o$C)**




$$I_{TOTAL} = I_{SAT}\left(e^{\frac{qV_A}{k_B T}} - 1\right) - I_P$$

**Illuminating the photodiode with optical radiation, shifts the I-V curve by the amount of photocurrent ($I_P$)**

# Photodiode Characteristics (Electrical)




**A silicon photodiode can be represented by a current source in parallel with an ideal diode. The diode represents the p-n junction, $C_j$ junction capacitance, $R_{SH}$ shunt resistance, $R_S$ Series resistance, $R_L$ load resistance**

**Shunt resistance**: An ideal photodiode should have an infinite $R_{SH}$, but actual values range from 10's to 1000's of Mega ohms. $R_{SH}$ is used to determine the noise current in the photodiode

**Series resistance:** $R_S$ of a photodiode arises from the resistance of the contacts and the resistance of the undepleted silicon and its value ranges from 10 to 1000 Ω's. This is used to define the linearity of photodiode.

**Junction capacitance**: The boundaries of the depletion region acts as the plates of a parallel plate capacitor. The junction capacitance is directly proportional to the diffused area and inversely proportional to the width of the depletion region. Junction capacitance is used to determine the speed of the response of the photodiode

**Response Time:** There are three factors defining the response time of a photodiode:

1. $t_{DRIFT}$, the charge collection time of the carriers in the depleted region of the photodiode.

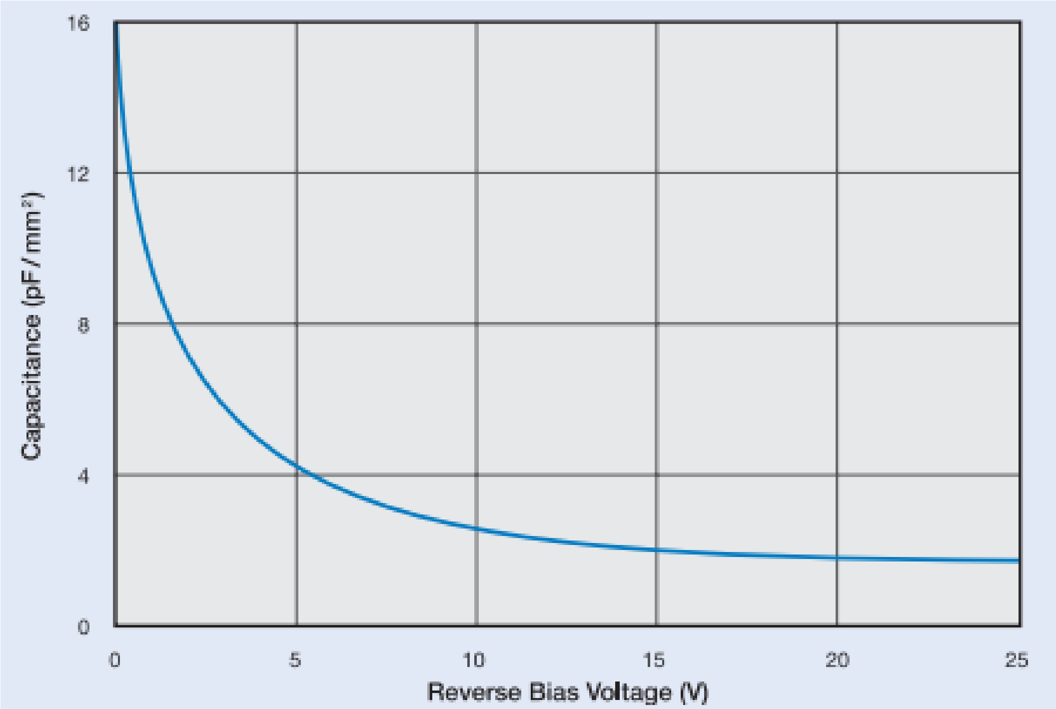
2. $t_{DIFFUSED}$, the charge collection time of the carriers in the undepleted region of the photodiode.

3. $t_{RC}$, the RC time constant of the diode-circuit combination.

$t_{RC}$=2.2RC, where R, is the sum of the diode series resistance and the load resistance ($R_S + R_L$), and C, is the sum of the photodiode junction and the stray capacitances ($C_j+C_S$). Since the junction capacitance ($C_j$) is dependent on the diffused area of the photodiode and the applied reverse bias, faster rise times are obtained with smaller diffused area photodiodes, and larger applied reverse biases.

The total rise time is determined by

$$t_R = \sqrt{t_{DRIFT}^2 + t_{DIFFUSED}^2 + t_{RC}^2}$$



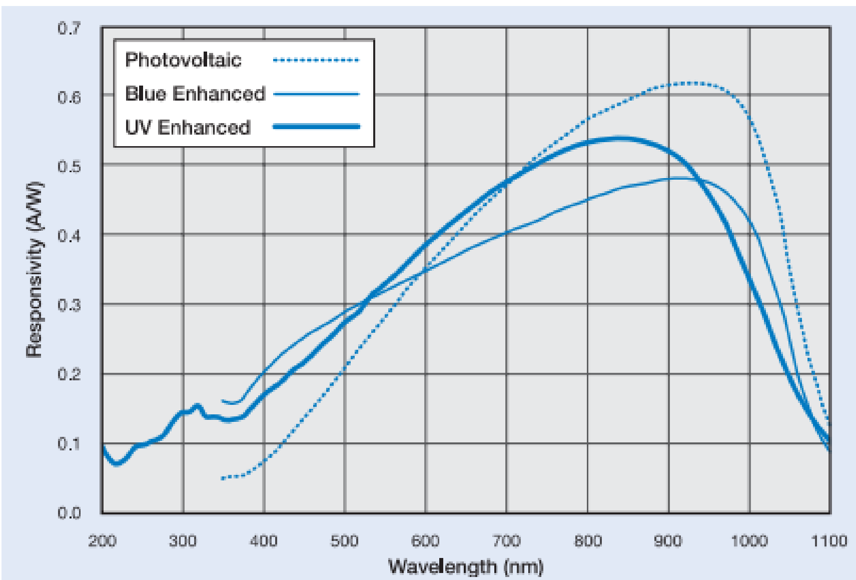

Capacitance of Photoconductive Devices versus Reverse Bias Voltage

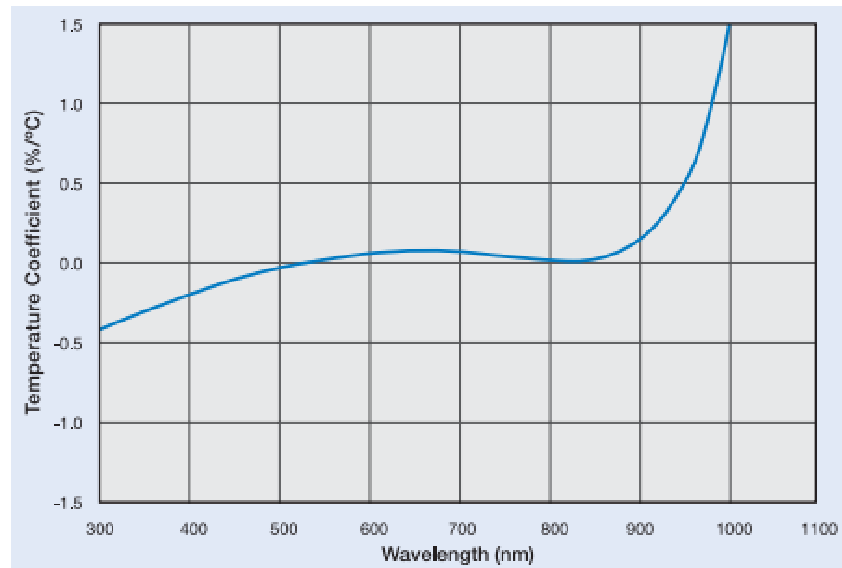
# Photodiode Characteristics (Optical)

**Responsivity:** **The responsivity of a silicon photodiode is a measure of the sensitivity to light, and is defined as the ratio of the photocurrent $I_P$ to the incident light power P at a given wavelength.**

$$R_\lambda = \frac{I_P}{P}$$

**<u>It varies with the wavelength of the incident light as well as applied reverse bias and temperature</u>. It is a measure of the effectiveness of the conversion of the light power into electrical current.**




**Temperature Coefficient of Responsivity Vs. Wavelength For Silicon Photodiode**

**The responsivity variations due to change in temperature is due to decrease or increase of the band gap, because of increase or decrease in the temperature respectively**

# Quantum Efficiency (Q.E.)

**Quantum efficiency is defined as the fraction of the incident photons that contribute to photocurrent.**

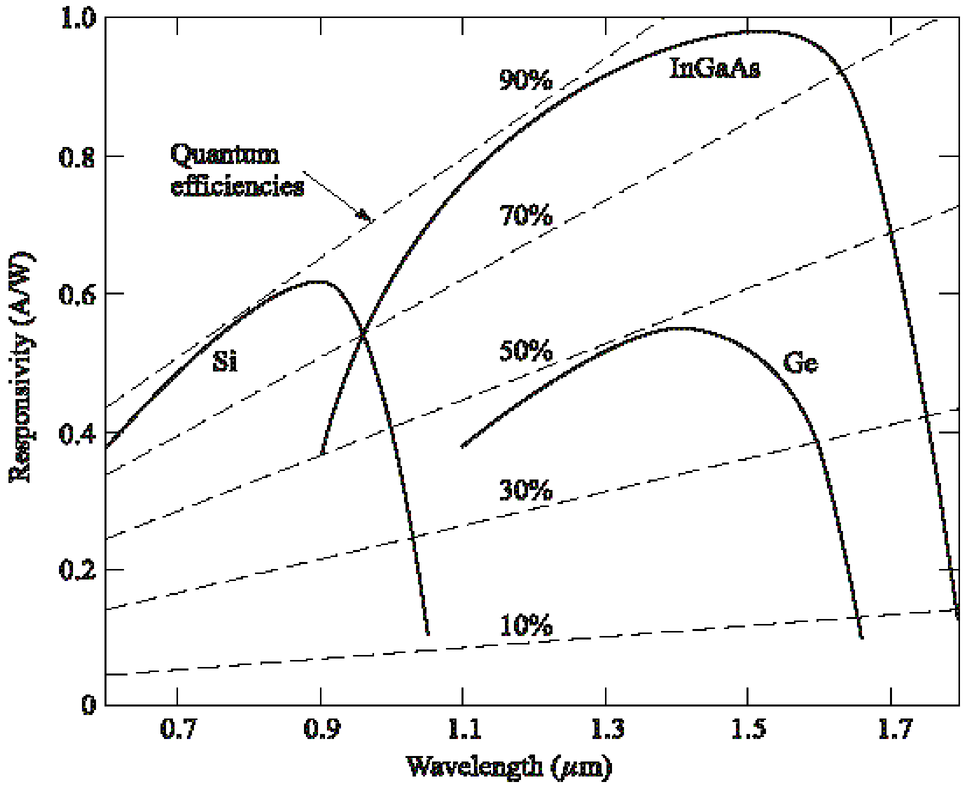
$$\eta = \frac{\text{number of emitted electrons}}{\text{number of incident photons}}$$

**One of the major factor which determine the quantum efficiency is the absorption coefficient of the semiconductor material used within photodetector. $\eta < 1$ quoted as a percentage say 85% i.e. 85 electrons collected per 100 incident photons**

**It is related to responsivity by**

$$Q.E. = R_\lambda \frac{hc}{\lambda q}$$

# Responsivity & Quantum efficiency



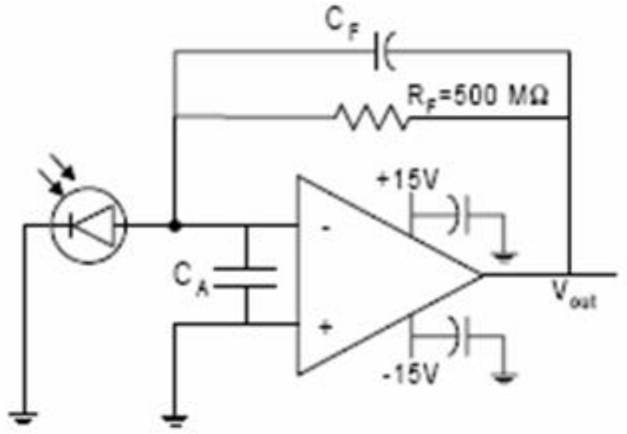

Comparison of the responsivity and QE as a function of wavelength for photodiodes constructed of different materials.

- Quantum Efficiency is not constant at all wavelengths- varies according to photon energy.
- For a given material, as the wavelength of the incident photon becomes larger, the photon energy becomes less than that required to excite an electron from the valence band to the conduction band.
- Responsivity falls off rapidly beyond cutoff wavelength.

# Biasing Photodiode

## Photovoltaic Mode

**The photovoltaic mode of operation (unbiased) is preferred when a photodiode is used in low frequency applications as well as ultra low light level applications. The photocurrents in this mode have less variations in responsivity with temperature.**




Photovoltaic mode of operation circuit

**For stability, select $C_F$ such that**

$$\sqrt{\frac{GBP}{2\pi R_F (C_J + C_F + C_A)}} > \frac{1}{2\pi R_F C_F}$$

**Operating bandwidth after gain peaking compensation is**

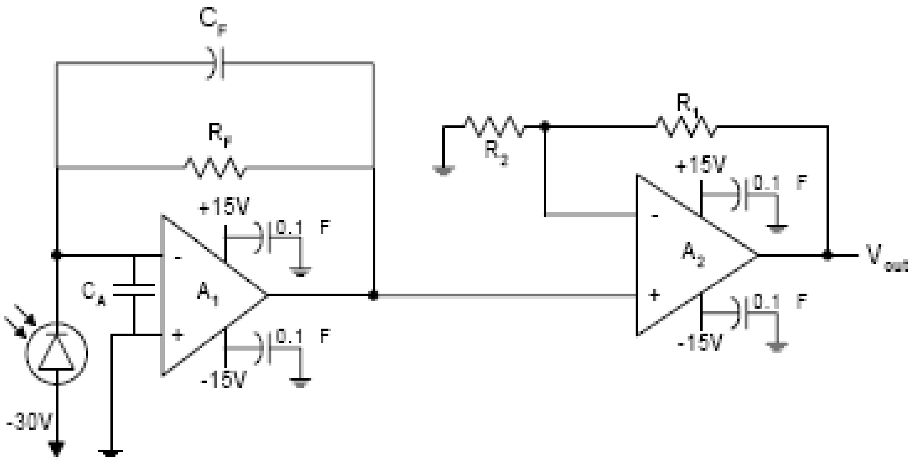
$$f_{OP}(Hz) = \frac{1}{2\pi R_F C_F}$$

# Photoconductive Mode

**Application of a reverse bias improves the speed of response.**

**<u>Effect of reverse bias</u>**

- **Increase in the depletion region width**
- **Decrease in junction capacitance.**
- **Increase in the dark and noise currents.**
- **Decrease in rise time ($t_r$).**




Photoconductive mode of operation circuit

$$f_{3dB\mathrm{Max}}[Hz] = \sqrt{\frac{GBP}{2\pi R_F (C_J + C_F + C_A)}}$$

**Where GBP is the Gain Bandwidth Product of amplifier (A1) and $C_A$ is the amplifier input capacitance.**

**A feedback capacitor ($C_F$) will limit the frequency response and avoids gain peaking**

# Noise Sources in Photodiode:

**Shot noise is related to the statistical fluctuation in both the photocurrent and the dark current.**

$$I_{sn} = \sqrt{2q\left(I_P + I_D\right)\Delta f}$$

**Where q=1.6x10-19C, is the electron charge, $I_P$ is the photogenerated current, $I_D$ is the photodetector dark current and $\Delta f$ is the noise measurement bandwidth. Shot noise is the dominating source when operating in photoconductive (biased) mode.**

**Thermal or Johnson Noise The shunt resistance in a photodetector has a Johnson noise associated with it. This is due to the thermal generation of carriers.**

$$I_{jn} = \sqrt{\frac{4k_B T\Delta f}{R_{SH}}}$$

**Where k= $1.38 \times 10^{-23}$ J/ºK, is the Boltzmann Constant, $T$, is the absolute temperature in degrees Kelvin, $\Delta f$ is the noise measurement bandwidth and $R_{SH}$ , is the shunt resistance of the photodiode. This type of noise is the dominant current noise in photovoltaic (unbiased) operation mode.**

**All resistors have a Johnson noise associated with them, including the load resistor.**

**Various figure of merit parameters** have been used to asses the noise performance of optical detectors. most commonly used are Noise equivalent power (NEP), Detectivity (D) and Specific detectivity ($D^*$).

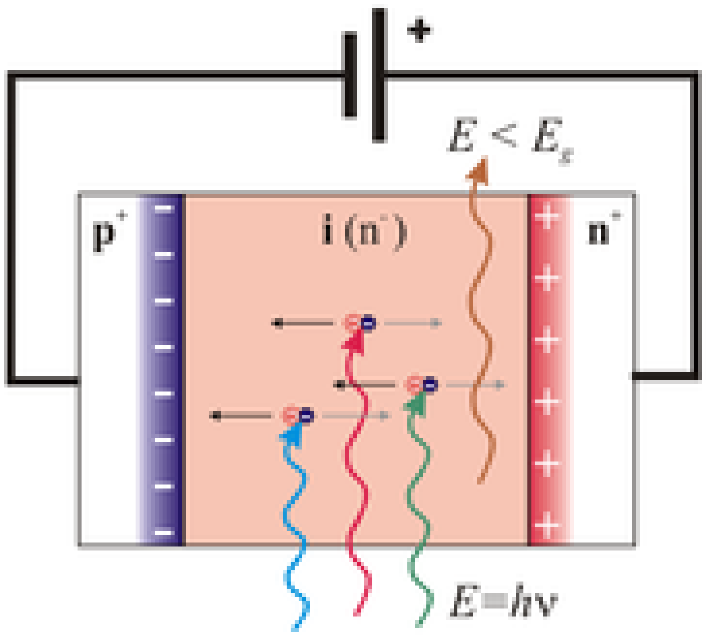
**Noise Equivalent Power (NEP):** The minimum input optical power required to generate photocurrent, equal to the rms noise current in a 1Hz bandwidth. NEP is essentially the minimum detectable power.

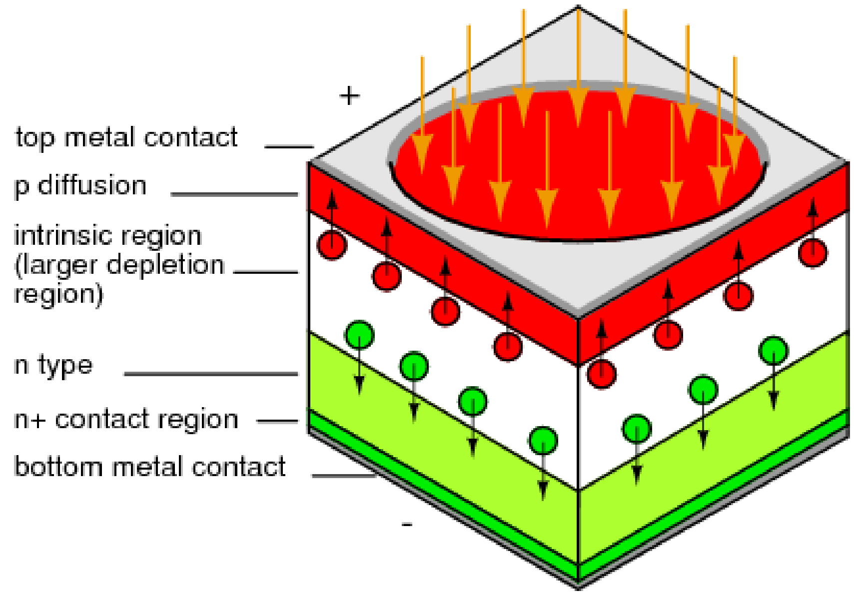
**Detectivity(D):** The characteristic detectivity (D) is the inverse of NEP, 1/NEP.

**Specific Detectivity (D*):** It is detectivity multiplied by the square root of the area (A) of the photodetector, ($D^*=D\sqrt{A}$) for a 1Hz bandwidth.

D* allows different photodetectors to be compared independent of sensor area and system bandwidth; a higher detectivity value indicates a low-noise device

# PIN Photodiode




*PIN photodiode.*

**The P-Intrinsic-N structure increases the distance between the P and N conductive layers, decreasing capacitance, increasing speed. The volume of the photo sensitive region also increases, enhancing conversion efficiency. The bandwidth can extend to 10's of GHz. PIN photodiodes are the preferred for high sensitivity, and high speed at moderate cost.**

# P-i-N PHOTODIODE

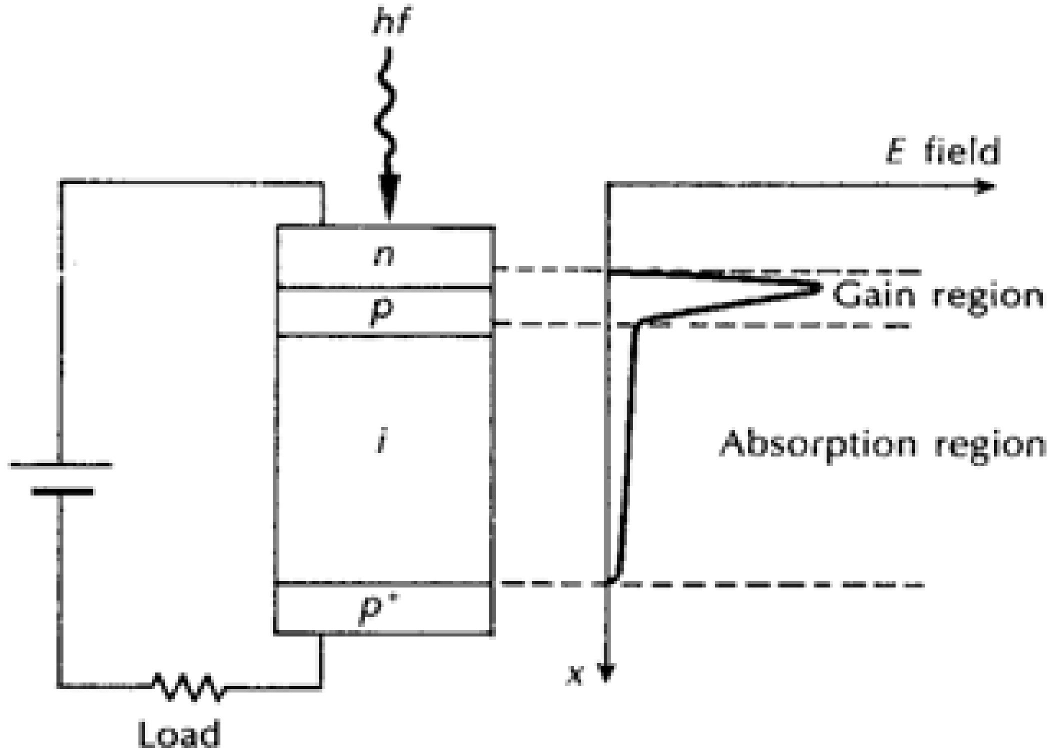
- **A typical P-i-N photodiode consists of a highly-doped transparent *p*-type contact layer on top of an undoped absorbing layer (i) and an *n*-type highly doped contact layer on the bottom.**

- **This diode is evolved mainly from one basic requirement: light should be absorbed in the depletion region of the diode to ensure that the electrons and holes are separated in the electric field and contribute to the photocurrent, while the transit time must be minimal.**

- **This implies that a depletion region larger than the absorption length must exist in the detector. This is easily assured by making the absorbing layer undoped. Only a very small voltage is required to deplete the undoped region.**

- **An added advantage is that the recombination/generation time constant is longest for undoped material, which provides a minimal thermal generation current.**

# Avalanche Photodiodes (APD) – Photodetector with Internal gain




**Avalanche photodiode showing high electric field region**

- **Photodiode with Internal gain: Internally multiply the primary signal photocurrent before it enters the input circuitry of the amplifier.**
- **Increases receiver sensitivity: the photocurrent is multiplied before encountering the thermal noise associated with the receiver circuit.**
- **For carrier multiplication, the photogenerated carriers must traverse a region where a very high electric field is present.**

- **In the high field region, a photogenerated electron or hole can gain enough energy so that it ionizes bonds in the valence band upon colliding with them. This is known as <u>Impact Ionization</u>**

- **The newly created carriers are also accelerated by the high electric field, gaining enough energy to cause further impact ionization. This phenomenon is the <u>Avalanche Effect</u>**

- **Create an extremely high electric field region (approximately 3 x $10^5$ V/cm)**

- **Requires high reverse bias voltages (100 to 400 V) in order that the new carriers created by impact ionization**

- **Carrier multiplication factors as great as $10^4$ may be obtained**

- When carriers are generated in undepleted material, they are collected somewhat slowly by the diffusion process. This has the effect of producing a long 'diffusion tail' on a short optical pulse.
- When the APD is fully depleted by employing high electric fields, all the carriers drift at saturation-limited velocities.
- The response time for the device is limited by three factors:
  - the transit time of the carriers across the absorption region (i.e. the depletion width)
  - the time taken by the carriers to perform the avalanche multiplication process
  - the RC time constant incurred by the junction capacitance of the diode and its load
- At low gain the transit time and RC effects dominate giving a definitive response time and hence constant bandwidth for the device
- At high gain the avalanche build-up time dominates and therefore the device bandwidth decreases proportionately with increasing gain

- **The rise time between 150-200ps and fall time of 1ns or more are quite common and this *limits the overall response of the device***

- **Multiplication factor M is a measure of the internal gain provided by the APD and is defined as**

$$M=I_M/I_P$$

  **where $I_M$ is the average value of the total multiplied output current and $I_P$ is the primary photocurrent.**

- **The avalanche mechanism is a statistical process, and not every carrier pair generated in the APD experiences the same multiplication. Thus, the measured value of M is expressed as an average quantity which is as great as $10^4$ .**

# Advantages & Drawbacks of APDs

## Advantages

- Provides an increase in sensitivity of between 5 dB to 15dB over p-i-n photodiodes i.e. detection of very low level light signals.

- Wider dynamic range as a result of their gain variation with response time and reverse bias

## Drawbacks

- Fabrication difficulties due to their more complex structure and hence increased cost.

- The random nature of the gain mechanism which gives an additional noise contribution.

- Often high bias voltages required (50 to 400 V)

- The variation of the gain (multiplication factor) with temperature i.e. temperature compensation is necessary to stabilize the operation of the device.

# Photodetectors

- APD vs *p-i-n* diode

**Typical Performance Characteristics of Photodetectors**

| | Silicon | | Germanium | | InGaAs | |
|---|---|---|---|---|---|---|
| **Parameter** | **PIN** | **APD** | **PIN** | **APD** | **PIN** | **APD** |
| Wavelength range (nm) | 400–1100 | | 800–1800 | | 900–1700 | |
| Peak (nm) | 900 | 830 | 1550 | 1300 | 1300 (1550) | 1300 (1550) |
| Responsivity *R* (A/W) | 0.6 | 77–130 | 0.65–0.7 | 3–28 | 0.63–0.8 (0.75–0.97) | |
| Quantum efficiency (%) | 65–90 | 77 | 50–55 | 55–75 | 60–70 | 60–70 |
| Gain | 1 | 150–250 | 1 | 5–40 | 1 | 10–30 |
| Excess noise factor | — | 0.3–0.5 | — | 0.95–1 | — | 0.7 |
| Bias voltage (V) | 45–100 | 220 | 6–10 | 20–35 | 5 | <30 |
| Dark current (nA) | 1–10 | 0.1–1.0 | 50–500 | 10–500 | 1–20 | 1–5 |
| Capacitance (pF) | 1.2–3 | 1.3–2 | 2–5 | 2–5 | 0.5–2 | 0.5 |
| Rise time (ns) | 0.5–1 | 0.1–2 | 0.1–0.5 | 0.5–0.8 | 0.06–0.5 | 0.1–0.5 |

# Thank You