18ECE322T – OPTOELECTRONICS

UNIT – II

SEMICONDUCTOR PHOTON SOURCES AND DISPLAY DEVICES

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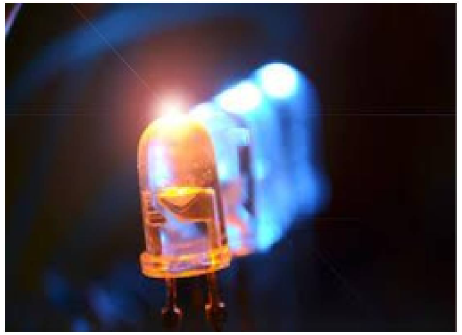
LED Principles- Homojunction LED, Heterostructure LED, Quantum Well High Intensity LEDs, LED Materials and Structures, LED Efficiencies and Luminous Flux, Manufacturing Process and Applications (Solving Problems), LASER: Threshold Condition, Emission and Absorption of Radiation, Population Inversion, Principle of the Laser Diode, Heterostructure Laser Diodes, Device Fabrication, Solving problems, Display Device: Photo Luminescence, Cathode Luminescence, Electro Luminescence, Injection Luminescence, Plasma Displays, LCD, Numeric Displays

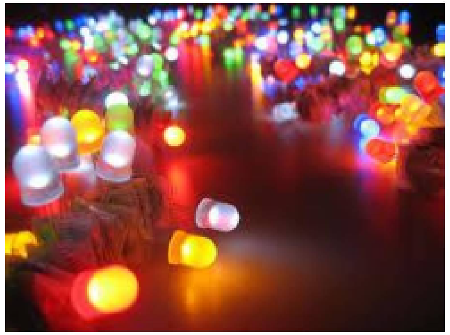
Overview of LEDs, Lasers & other display devices – Working principles, applications, solving basic problems

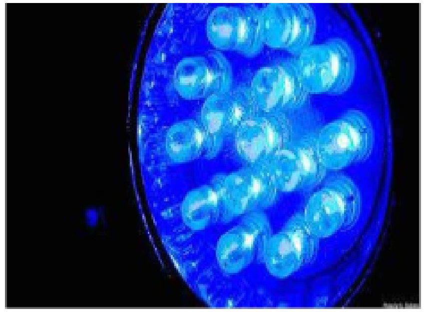
SESSION 1

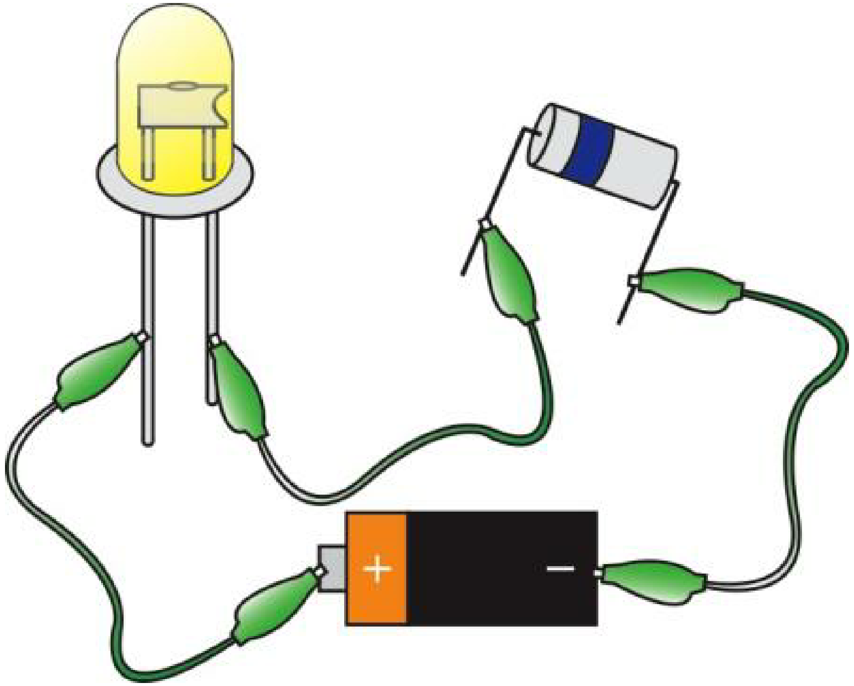
- LED Principles- Homojunction LED, Heterostructure LED
- Quantum Well High Intensity LEDs

Light Emitting Diode







High energy electrons (n-type) fall into low energy holes (p-type)

LED:

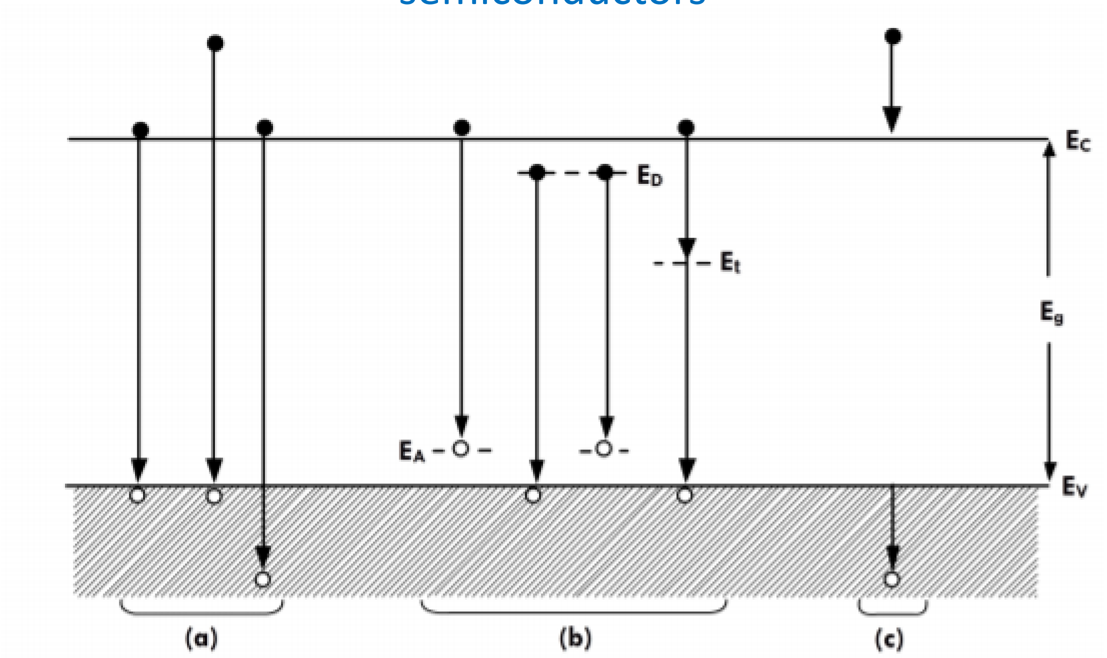
- LEDs belong to the general class of luminescent devices.
- Luminescence is defined as the optical radiation due to electronic excitation.
- When the excited system goes back to the ground state energy is emitted in the form of EM radiation.
- There are different types of luminescence, depending on how the electronic excitation is originally created

1. Photoluminescence - electronic excitation is created by incident light
2. Cathodoluminescence - electronic excitation is created by an electron beam
3. Radioluminescence - electronic excitation is created by ionizing radiation (β-rays)
4. **Electroluminescence - electronic excitation is created by an electrical field.**

LEDs usually work by electroluminescence. Electric current, i.e. electron and holes, are passed to the device by an applied bias. These electrons and holes recombine to emit light.

Radiative transitions

Mechanisms of electron-hole recombination in semiconductors



(a) Interband transitions

(b) Band to localized defect states transitions

(c) Intraband transitions

- In LEDs, electroluminescence (EL) is created by injected carriers, e.g. in a pn junction.
- These recombine to give photons. EL occurs in both direct and indirect band gap semiconductor, though the efficiency of radiative transition is higher in a direct band gap semiconductor.
- EL was first discovered in 1907, but significant advances in practical device development were made after the discovery of pn junctions in 1949.
- Optical efficiency improved after GaAs was used in 1962.

Not all these transitions are radiative. In LEDs the radiative transition must be maximized relative to the nonradiative transition. This can be accomplished by choosing the *right materials* and the *right external bias*.

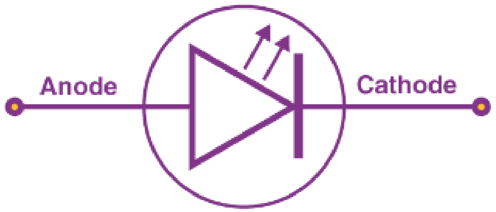
LED Principles- Homojunction LED

- Light-emitting diodes, or LEDs, are widely used as a standard source of light in electrical equipment.
- It has a wide array of applications ranging from your mobile phone to large advertising billboards.
- They find applications in devices for showing what the time is and for displaying different types of data.

What is Light Emitting Diode?

- A light releasing diode is an electric component that emits light when the electric current flows through it.
- It is a light source based on semiconductors.
- When current passes through the LED, the electrons recombine with holes emitting light in the process.
- It is a specific type of diode having similar characteristics as the p-n junction diode.
- This means that an LED allows the flow of current in its forward direction while it blocks the flow in the reverse direction.
- Light-emitting diodes are built using a weak layer of heavily doped semiconductor material.

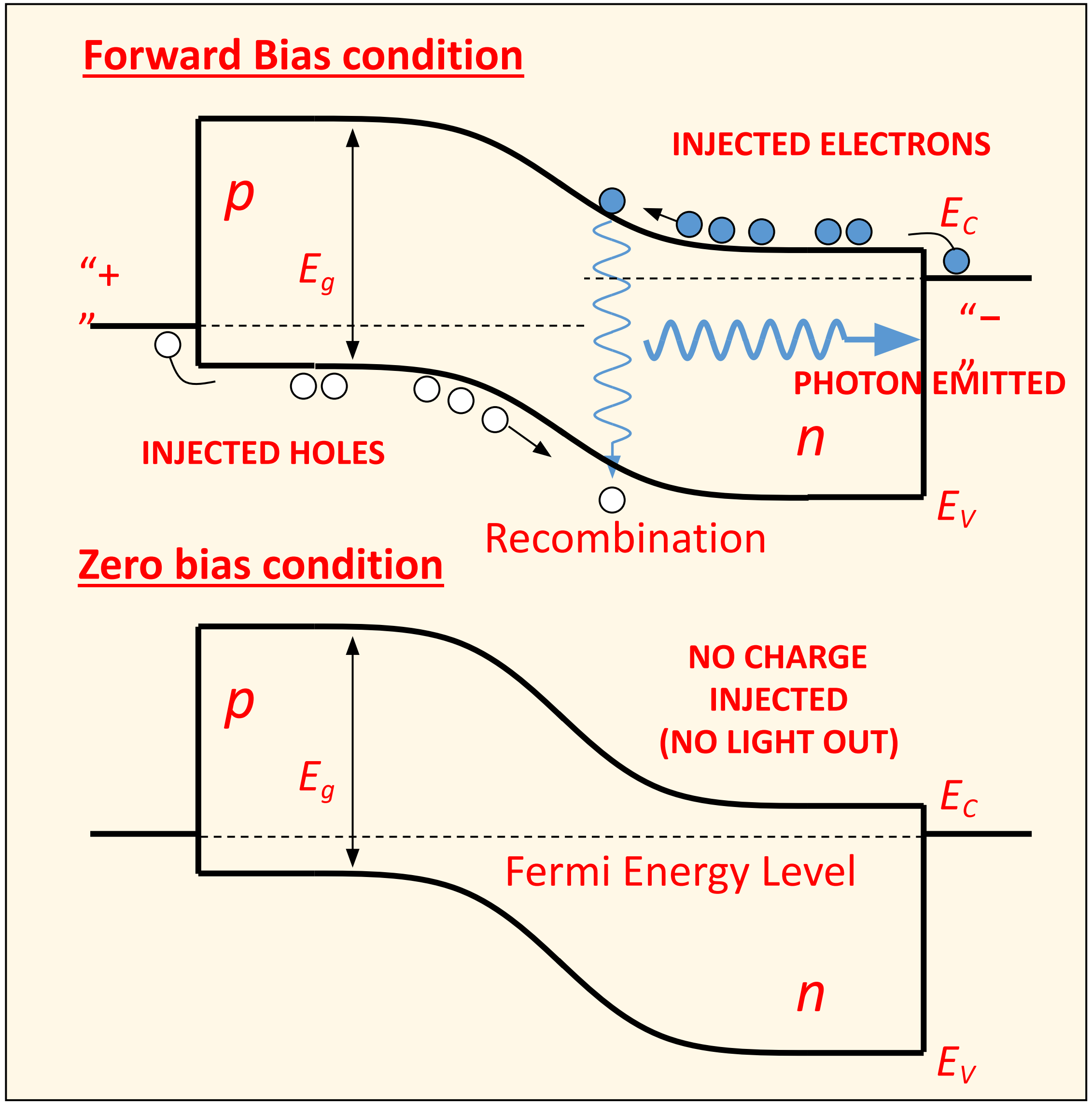
p-n Diode



- Based on the semiconductor material used and the amount of doping, an LED will emit a

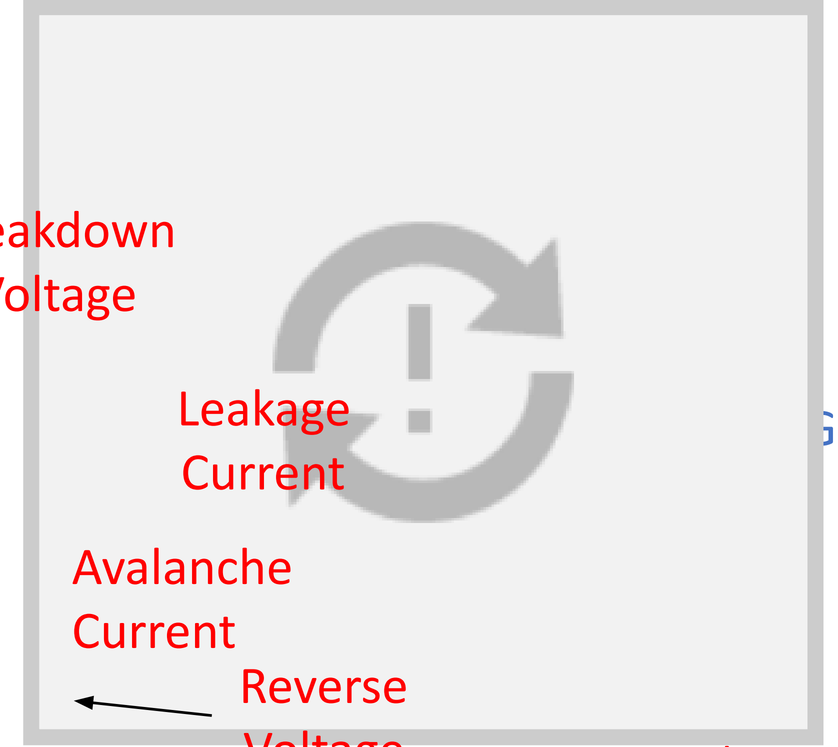
Homojunction p-n Light Emitting Diode

- The holes lie in the valence band, while the free electrons are in the conduction band.
- When there is a forward bias in the p-n junction, the electron which is a part of the n-type semiconductor material would overrun the p-n junction and join with the holes in the p-type semiconductor material.
- Therefore, regarding the holes, the free electrons would be at the higher energy bands.
- When the pn junction is made of the same material then it is called a homojunction.



ELECTRICITY IN □ LIGHT OUT

- When this movement of free electron and hole takes place, there is a change in the energy level as the voltage drops from the conduction band to the valance band.
- There is a release of energy due to the motion of the electron. In standard diodes, the release of energy in the manner of heat. But in LED the release of energy in the form of photons would emit light energy.
- The entire process is known as electroluminescence, and the diodes are known as a light-emitting diode.
- In LED, energy discharged in light form hinges on the forbidden energy gap. One could manipulate the wavelength of the light produced.
- Therefore, from its wavelength, the light colour and its visibility or cannot be controlled. The colour and wavelength of the light emitted can be determined by doping it with several impurities.



Heterojunction LED

- If we can confine the electrons and holes to a small region (like a potential well) then it is possible to increase radiative recombination efficiency.
- This can be achieved by using a heterojunction.
- Double Heterostructure is used to confine the carriers, improving the radiative recombination rate

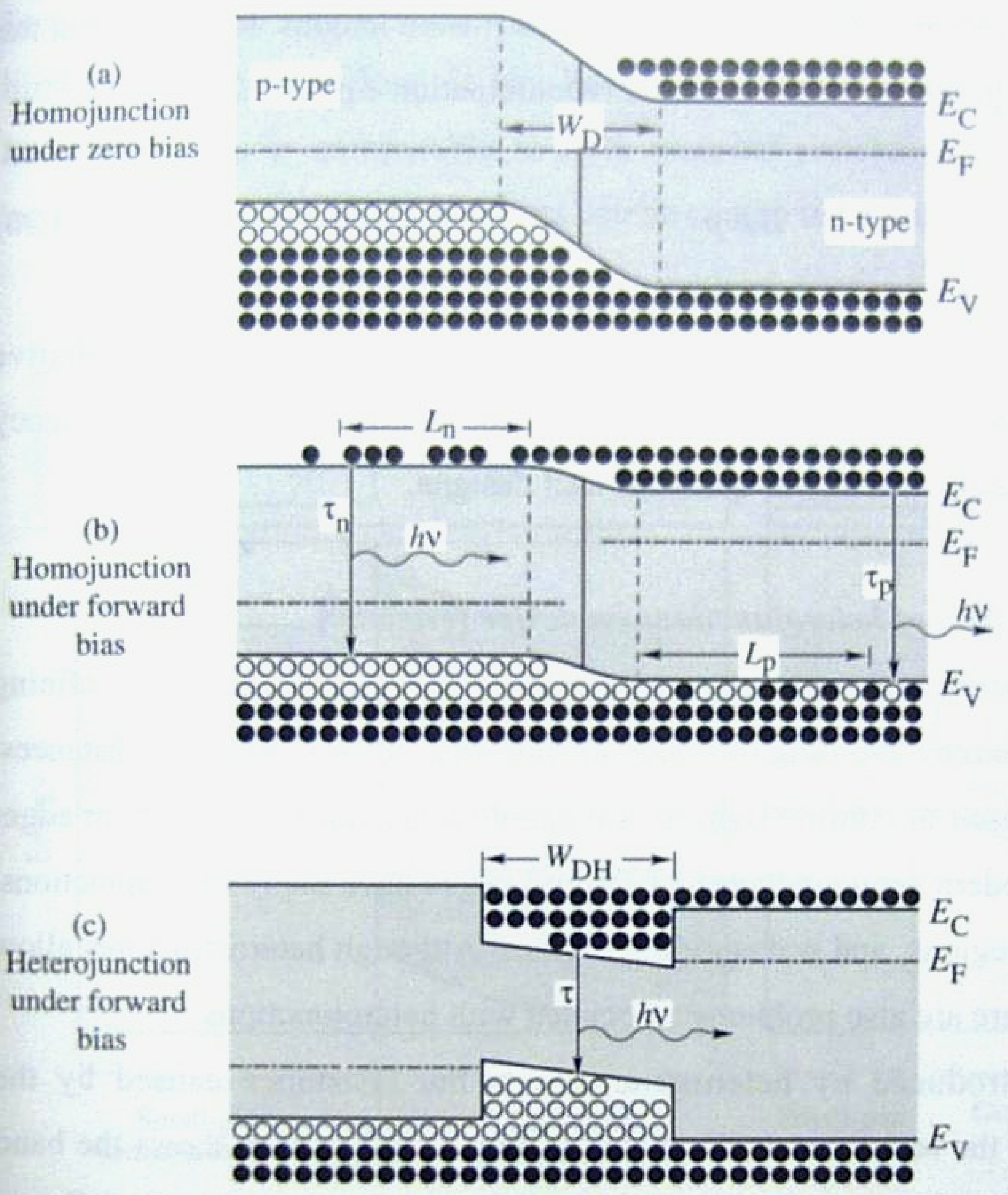


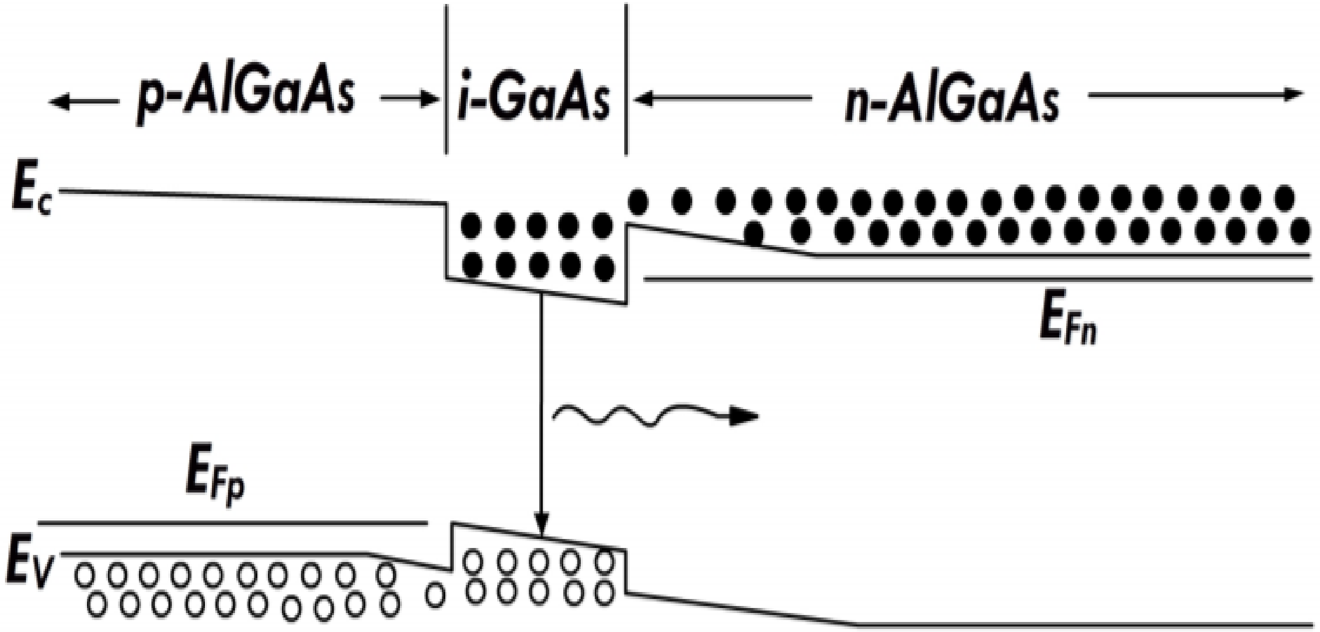
Fig. 4.6. P-n homojunction under (a) zero and (b) forward bias. P-n heterojunction (c) under forward bias. In homojunctions, carriers diffuse, on average, over the diffusion lengths L_n and L_p before recombining. In heterojunctions, carriers are confined by the heterojunction barriers.

From Light-Emitting Diodes, Fred Schubert.

Double Heterostructure LED

- It increase the efficiency by confining the carriers (electrons and holes) in a small spatial region.
- Consider a LED formed by using AlGaAs and GaAs. The structure of this device is shown in figure. AlAs is an indirect semiconductor with a band gap of 2.16 eV and GaAs a direct band semiconductor with a gap of 1.42 eV.
- $Al_xGa_{1-x}As$, formed by substitutional doping of Ga with Al, is a direct band gap for $x < 0.4$ and its band gap depends on x, given by $1.43 + 1.247x$. For $x > 0.4$, this becomes an indirect band gap semiconductor.
- For the heterostructure junction shown in figure the band gap of AlGaAs is 2.0 eV , which corresponds to $x = 0.45$.

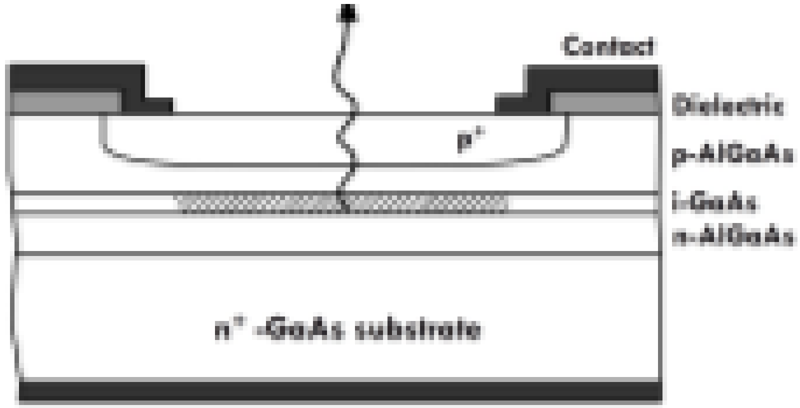
The heterojunction has a higher quantum efficiency since the carriers are localized in GaAs. Thus, recombination occurs only in the i-GaAs region. For both LEDs, the emitted wavelength is the same.



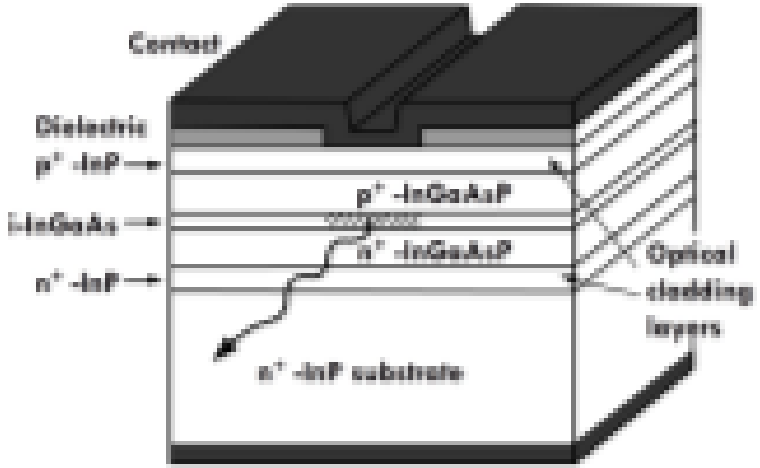
Adapted from Physics of semiconductor devices - S.M. Sze

Double heterostructure device structure

surface emission



edge emission



For surface emission, the top layers are made thin and have low absorption for the emitted radiation. For side emission optical cladding layers are used to confine the light to the emitting layer. A similar principle is also used in solid state lasers.

Adapted from Physics of semiconductor devices - S.M. Sze.

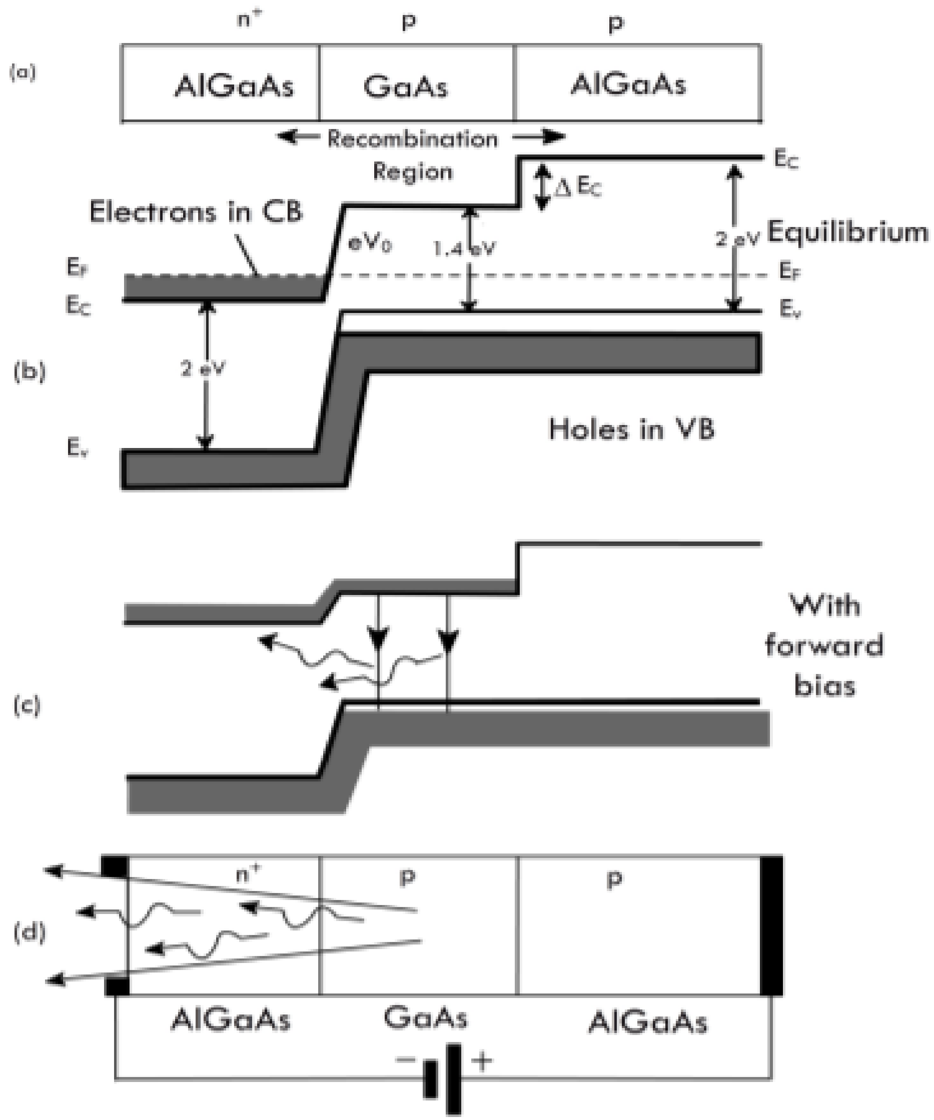
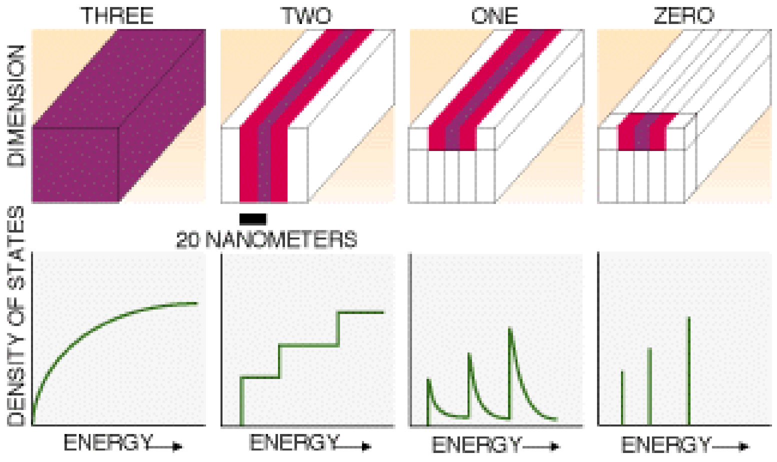


Figure 5: Double heterostructure based LED. (a) Device structure, with a single *pn* heterojunctions and a *p* − *p* isojunction (b) Equilibrium band diagram, with the built-in potential at the *pn* junction (c) In forward bias electrons and holes are injected in the GaAs (d) Light emission, with wavelength depending on the band gap of GaAs. Adapted from *Principles of Electronic materials - S.O. Kasap.*

Quantum confinement

- Trap particles and restrict their motion
- Quantum confinement produces new material behavior/phenomena
- “Engineer confinement”- control for specific applications
- Structures

- Quantum dots (0-D) only confined states, and no freely moving ones
- Nanowires (1-D) particles travel only along the wire
- Quantum wells (2-D) confines particles within a thin layer



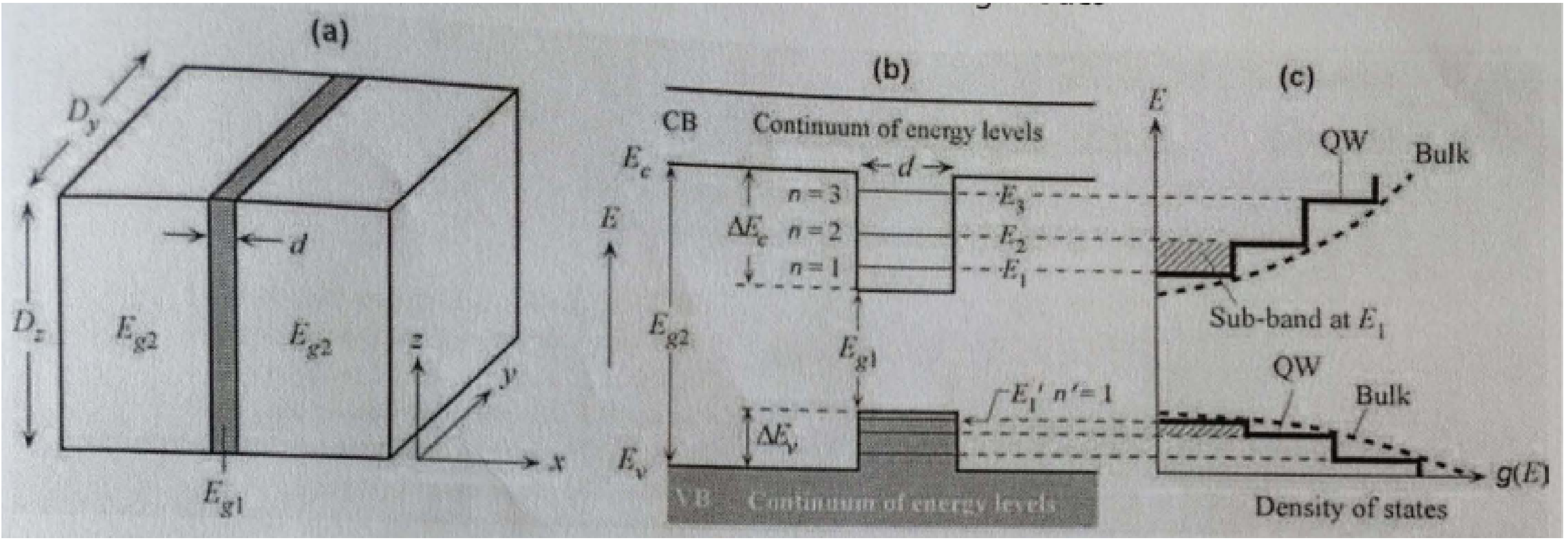
http://www.me.berkeley.edu/nti/englander1.ppt

http://phys.educ.ksu.edu/vqm/index.html

(Scientific American)

Quantum Well High Intensity LEDs

A typical quantum well (QW) device has an ultra-thin, typically less than 50 nm, narrow bandgap semiconductor with a bandgap E_{g1} sandwiched between two wider bandgap semiconductor with a bandgap E_{g2}, as illustrated in Figure (a).



For example. this could be a thin GaAs (E_{g1}) layer sandwiched between two $Al_xGa_{1-x}As$ (E_{g2}) layers.

The wide bandgap layers are called confining layers.

We assume that the two semiconductors are lattice matched in the sense that they have the same crystal structure and lattice parameter a. This means that interface defects due to the mismatch of crystal dimensions between the two semiconductor crystals are minimal; and neglected.

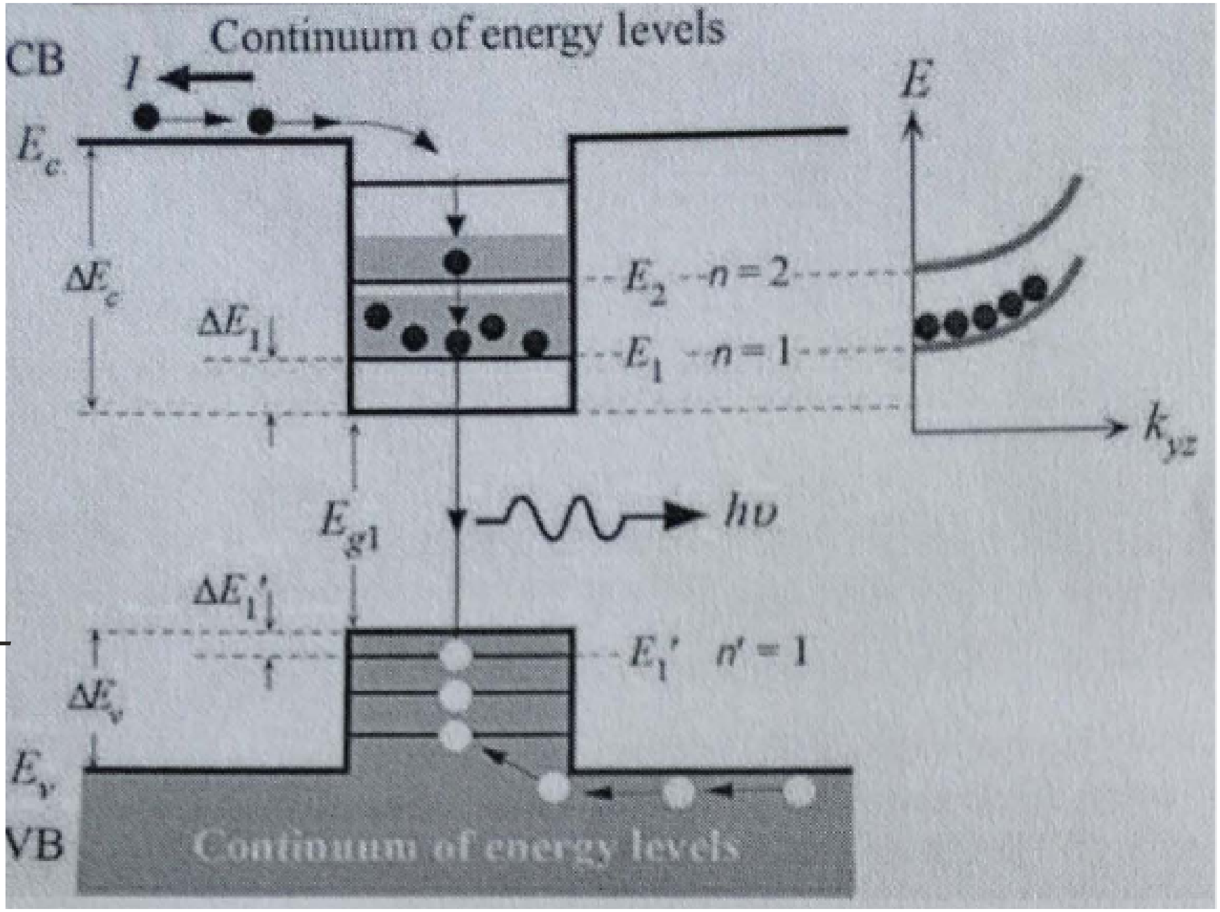
Since the bandgap, E_g, changes at the interface, there are discontinuities in E_e and E_v at the interfaces as before; these discontinuities, ΔE_c and ΔE_v, are shown in Figure. (b). and depend on the semiconductor properties.

Because of the potential energy barrier, ΔE_c conduction electrons in the thin E_{g1} layer are confined in the x-direction.

This confinement length d, the width of the thin E_{g1} semiconductor, is so small that we can treat the

The energy of the electron in the QW must reflect its 1D quantization in the x-direction, and its freedom in the *yz* plane. If E_n is the electron energy in the well, then

$$E_n = E_c + \frac{h^2 n^2}{8 m_e^* d^2} + \frac{\hbar^2 k_y^2}{2 m_e^*} + \frac{\hbar^2 k_z^2}{2 m_e^*}$$



n is a quantum number having the values 1, 2, 3, ...

k_y and k_z are the wave vectors of the electron along *y*- and z-directions

For any given *n* value, we have a sub-band of energies due to k_y and k_z terms

The separation between the energy levels associated with motion in the *yz* plane in a sub-band is so . mall that the electron is free to move in the *yz* plane as if it were in the bulk semiconductor; we assume a continuum of energy as shown in Figure

Therefore have a *two-dimensional electron gas* which is confined in the x-direction.

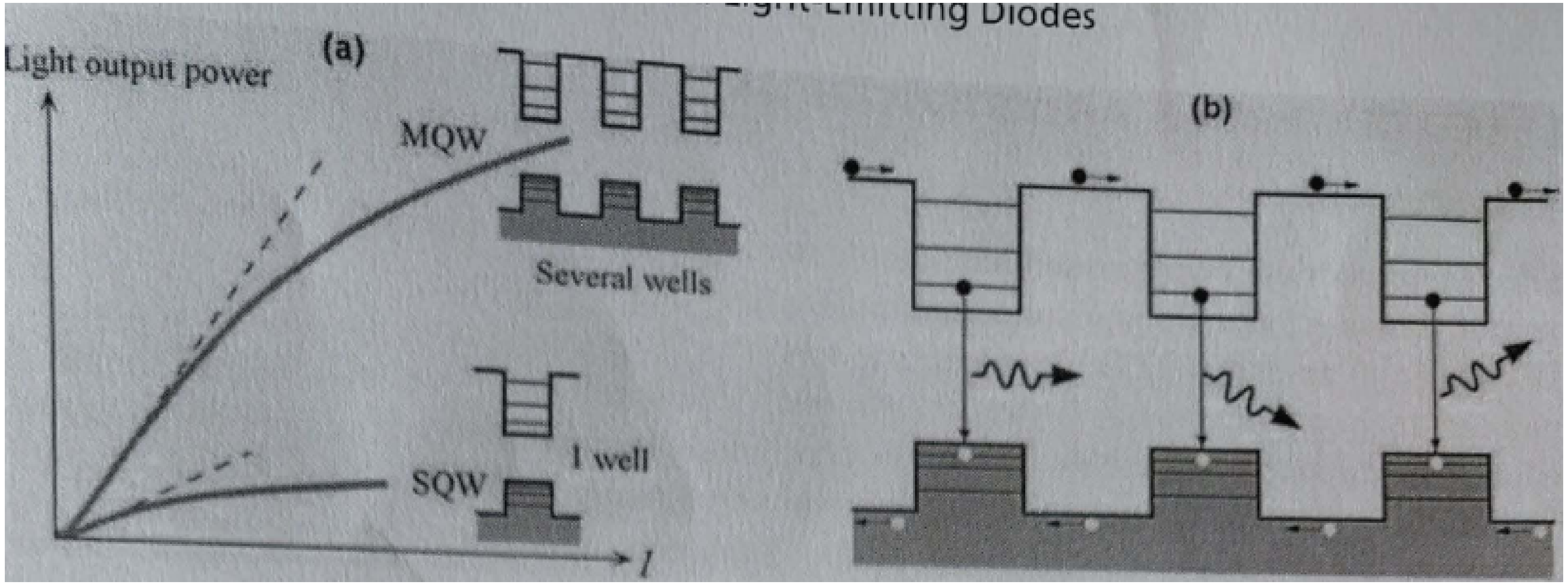
A QW structure that shows the energy level in the wells and how charge carriers that are brought in by the current fall into the lowest energy level in the well and then recombine, emitting a photon.

The electrons at a particular energy level also have kinetic energies in the yz plane, which is not quantized. The electrons are therefore spread in energy above E_n as shown. The same notion also applies to holes in the ΔE_v well.

since the majority of electrons are spread around E_1 and holes around E_1', the range of emitted photon energies can be narrower than the emission spectrum in the corresponding bulk device

Since at E_1 there is a finite and substantial density of states, the electrons in the conduction band do not have to spread as far in energy as in the bulk to find states.

Under a forward bias, as indicated in Figure, electrons are injected into the conduction band of the E_{g1}-*layer,* which serves as the *active layer*. The injected electrons readily populate the ample number of states at E_1 which means that the
electron concentration at E_1 increases rapidly with the current. The direct recombination rate, that is, the radiative recombination rate, which determines the rate of photon emission, depends on the product *np,* the concentration of electrons *and* holes. Thus, the radiative transitions occur much more readily in the quantum well for the same current as in the bulk device.



A schematic illustration of the comparison of light power output vs. current characteristics for a single Quantum Well (SQW) and an Multi Quantum Well (MQW) LED.

The main problem with the single quantum well (SQW) heterostructure LEDs is that under a sufficiently large current, the well can be flooded with charge carriers and can overflow. For example, electron can flood the QW ΔE_c and the well will overflow.

The advantages of the QW action (such as confinement that increases the electron concentration n) would be lost. The light output will no longer increase proportionally to the current, and will fall behind the increase in the current as indicated in Figure previously.

This problem can be resolved by using multiple quantum wells (MQWs), in which electrons are shared by a number of quantum wells.

SESSION 2

- LED Materials and Structures
- LED Efficiencies and Luminous Flux

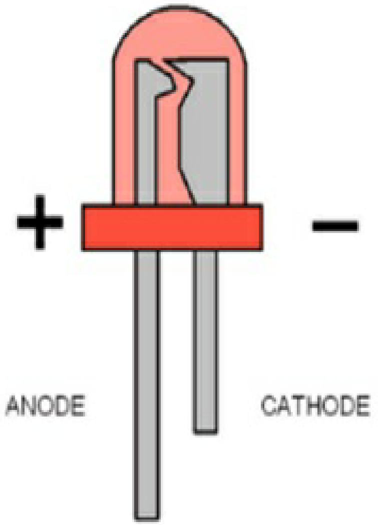
What is LED?

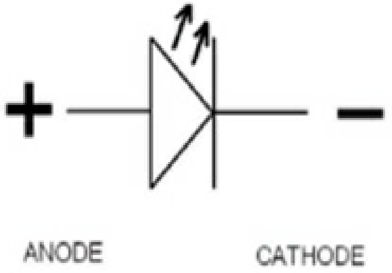
- Light-emitting diode (LED) is a semiconductor device that emits light when an electric current is passed through it.
- Light is produced when the particles that carry the current (known as electrons and holes) combine together within the semiconductor material.
- Since light is generated within the solid semiconductor material, LEDs are described as solid-state devices.
- The term solid-state lighting, which also encompasses organic LEDs (OLEDs), distinguishes this lighting technology from other sources that use heated filaments (incandescent and tungsten halogen lamps) or gas discharge (fluorescent lamps).

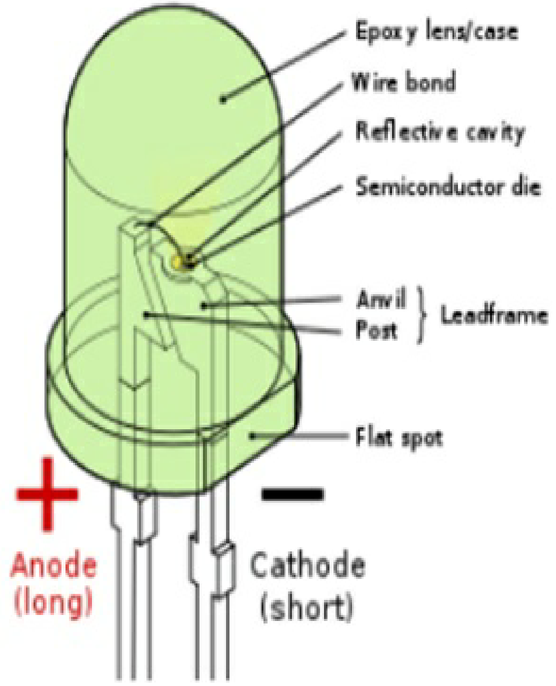
- The separation of the bands (i.e. the bandgap) determines the energy of the photons (light particles) that are emitted by the LED.
- The photon energy determines the wavelength of the emitted light, and hence its color.
- Different semiconductor materials with different bandgaps produce different colors of light. The precise wavelength (color) can be tuned by altering the composition of the light-emitting, or active, region.

LEDs are comprised of compound semiconductor materials, which are made up of elements from group III and group V of the periodic table (these are known as III-V materials). Examples: GaAs, GaP

DIFFERENT COLORS







Main LED Materials

The main semiconductor materials used to manufacture LEDs are:

- **Indium gallium nitride (InGaN):** blue, green and ultraviolet high-brightness LEDs
- **Aluminum gallium indium phosphide (AlGaInP):** yellow, orange and red high-brightness LEDs
- **Aluminum gallium arsenide (AlGaAs):** red and infrared LEDs
- **Gallium phosphide (GaP):** yellow and green LEDs
- Various direct band gap semiconductor materials that can be readily doped to make commercial pn junction LEDs which emit radiation in the red and infrared range of wavelengths are available.
- The fabrication of an actual LED would require that the doped crystal layers with the required band gap can be grown on a suitable substrate crystal.
- Requirement:

  substrate crystal and the LED material will have to be lattice matched(i.e) they must have the same crystal structure and very close lattice parameters to avoid creating dislocations at the interface.

- Commercial semiconductor materials that cover the visible spectrum is **III–V ternary alloys based on alloying GaAs and GaP, which are denoted as $GaAs_{1-y}P_y$.**
- When $y < 0.45$, **$GaAs_{1-y}P_y$** ***is*** direct bandgap semiconductor ,EHP recombination process is direct and efficient.

  630 nm, red, for $y = 0.45$ ($GaAs_{0.55}P_{0.45}$)

  870 nm for $y = 0$, GaAs.
- *When*, $y>0.45$, The EHP recombination processes occur through recombination centers and involve lattice vibrations rather than photon emission.
- Isoelectronic impurities such as nitrogen into the semiconductor crystal then the N-dopants can act as recombination centers.
- An electron is first captured by the N-center, the excess energy is lost to phonons, and then while at the N-center, it recombines with a hole in a radiative transition.
- Nitrogen-doped indirect bandgap $GaAs_{1-y}P_y$ alloys are widely used in inexpensive green, yellow and orange LEDs.

- There are various commercially important direct bandgap semiconductor materials that
- emit in the red and infrared wavelengths which are typically **ternary (containing three elements)** and **quaternary (four elements) alloys based on Group III and V elements, so-called III–V alloys.**
- For example, GaAs with a bandgap of about 1.42 eV emits radiation at around 870 nm in the infrared.
- AlGaInP is a quaternary III–V alloy (In, Ga, Al from III, and P from V) that has a direct bandgap variation with composition over the visible range.
- used in the high-intensity visible LED range, especially for the red, amber, and yellow.
- GaN is a direct bandgap semiconductor with an *Eg of 3.4 eV. The blue GaN LEDs actually* use the GaN alloy InGaN with a bandgap

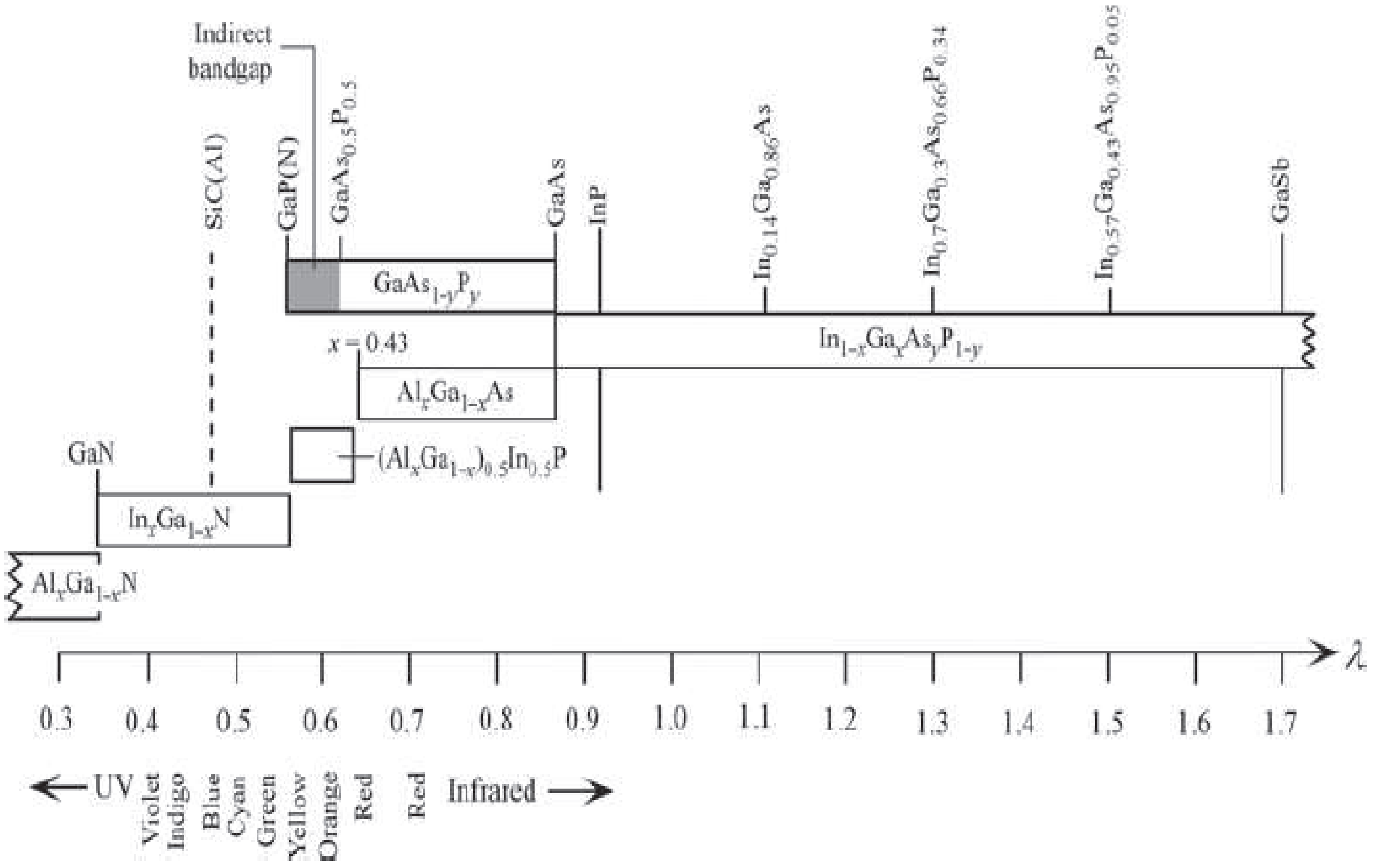
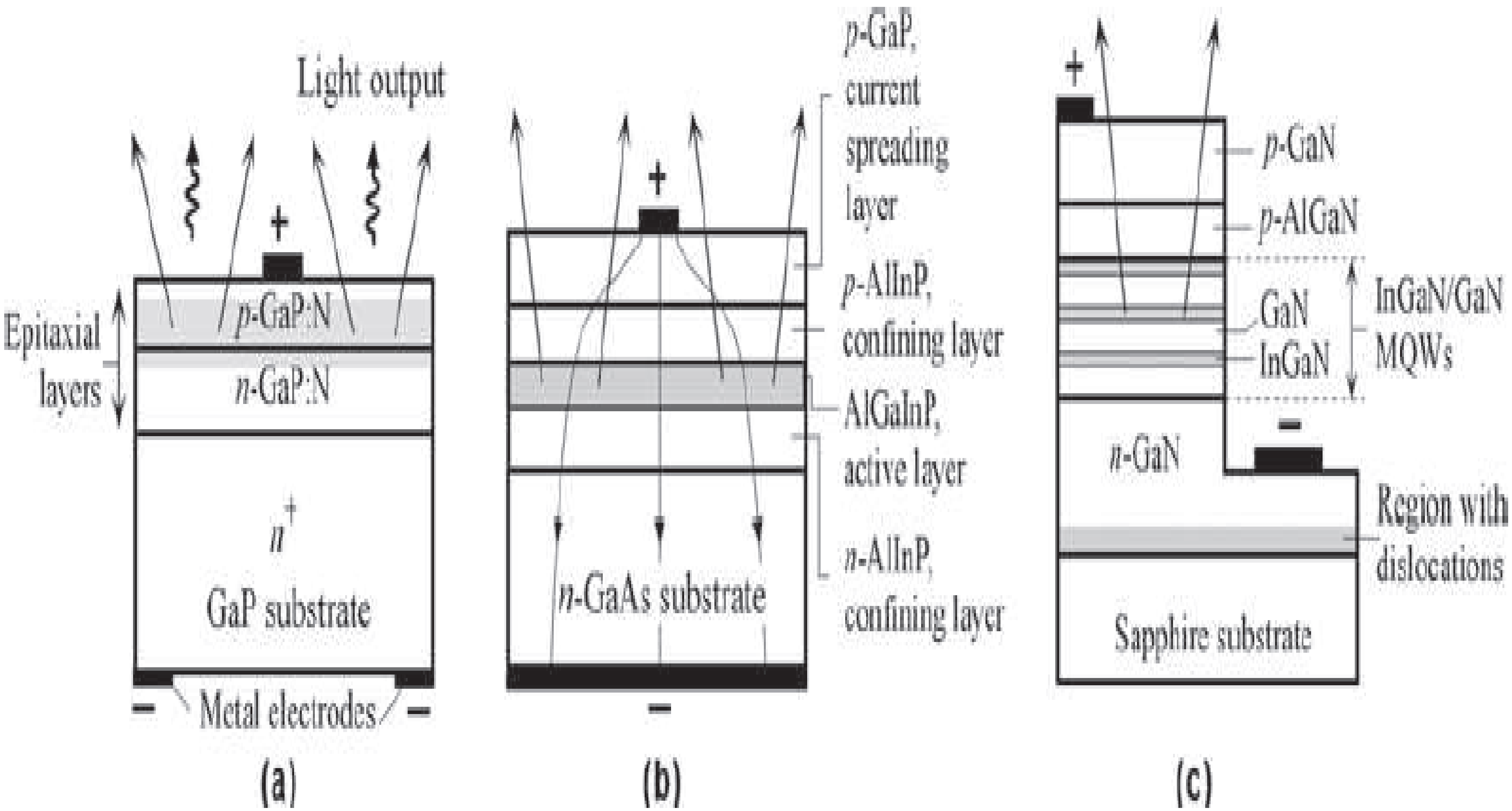


FIGURE Free-space wavelength coverage by different LED materials from the visible spectrum to the infrared, including wavelengths used in optical communications. Grey region and dashed lines are indirect E_g materials. Only material compositions of importance have been shown.

LED Structure

- LEDs are typically fabricated by epitaxially growing doped semiconductor layers on a suitable substrate (e.g., GaAs or GaP).
- This type of planar pn junction is formed by the epitaxial growth of first the n-layer and then the p-layer.
- The substrate is essentially a mechanical support for the pn junction device (the layers) and can be of different crystal.
- The p-side is on the surface from which light is emitted and is therefore made narrow (a few microns) to allow the photons to escape without being reabsorbed.

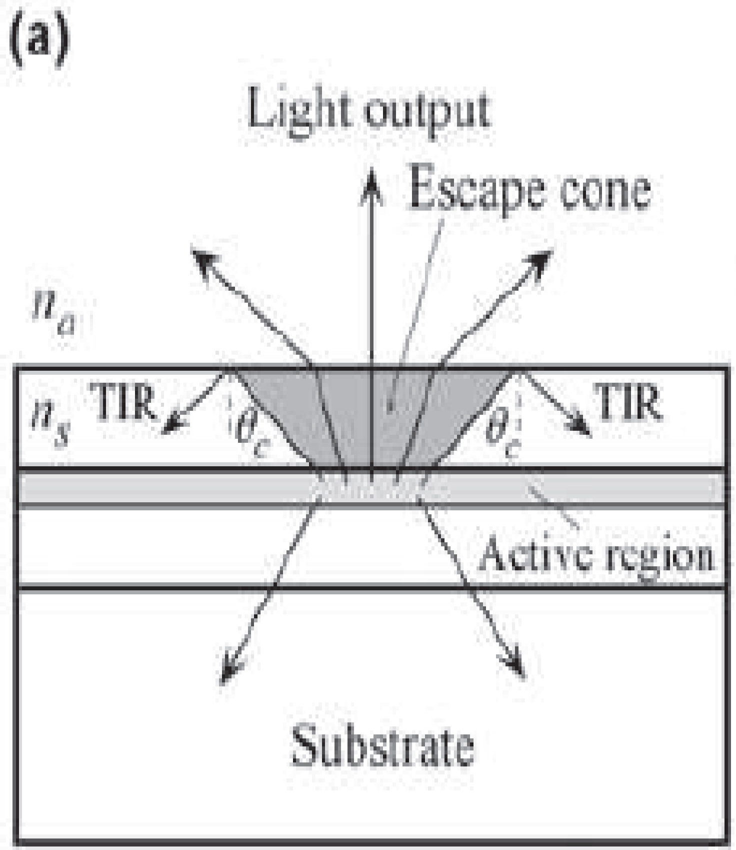


A schematic illustration of various typical LED structures. (a) A planar surface-emitting homojunction green GaP:N LED. (b) AlGaInP high-intensity heterostructure LED. (c) III-Nitride-based (GaN/InGaN) MQW LED for emission from the UV to green.

- To ensure that most of the recombination takes place in the p-side, the n-side is heavily doped (n+).
- Those photons that 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.
- The use of a segmented back electrode as in Figure (a) will encourage reflections from the semiconductor–air interface.
- If the epitaxial layer and the substrate crystals have different crystal lattice parameters, then there is a lattice mismatch between the two crystal structures.
- This causes lattice strain in the LED layer and hence leads to crystal defects. Such crystal defects encourage radiationless EHP recombinations. That is, a defect acts as a recombination center.
- Such defects are reduced by lattice matching the LED epitaxial layer to the substrate crystal. It is therefore important to lattice-match the LED layers to the substrate crystal.
- MQW LED that can be used for emission in the blue as well as green. With some modification to compositions, it can also emit inthe UV.

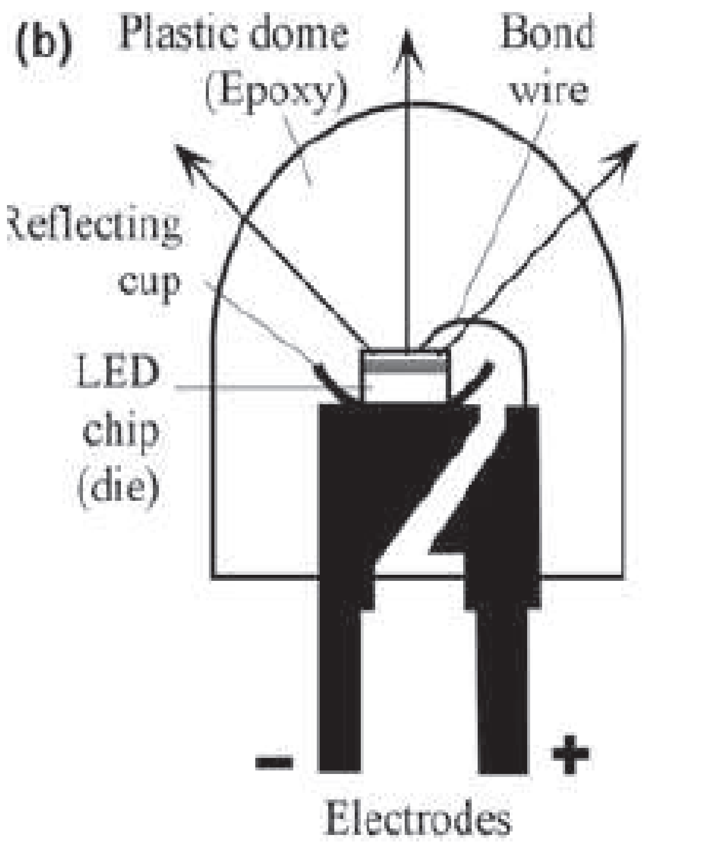
To avoid total internal reflection

- Not all light rays reaching the semiconductor–air interface, however, can escape because of total internal reflection (TIR). Those rays with angles of incidence greater than the critical angle become reflected as illustrated in Figure (a).
- For the GaAs–air interface, for example, Is only 17°, which means that much of the light suffers TIR.
- It is possible to shape the surface of the semiconductor into a dome, or hemisphere, so that light rays strike the surface at angles less than critical angle and therefore do not experience TIR.



DRAWBACK

- The main drawback, however, is the additional difficult process in fabricating such domed LEDs and the associated increase in expense.
- An inexpensive and common procedure that reduces TIR is the encapsulation of the semiconductor junction within a transparent plastic medium (an epoxy) which has a higher refractive index than air and,
- a domed surface on the emission side of the LED chip as shown in fig (b).

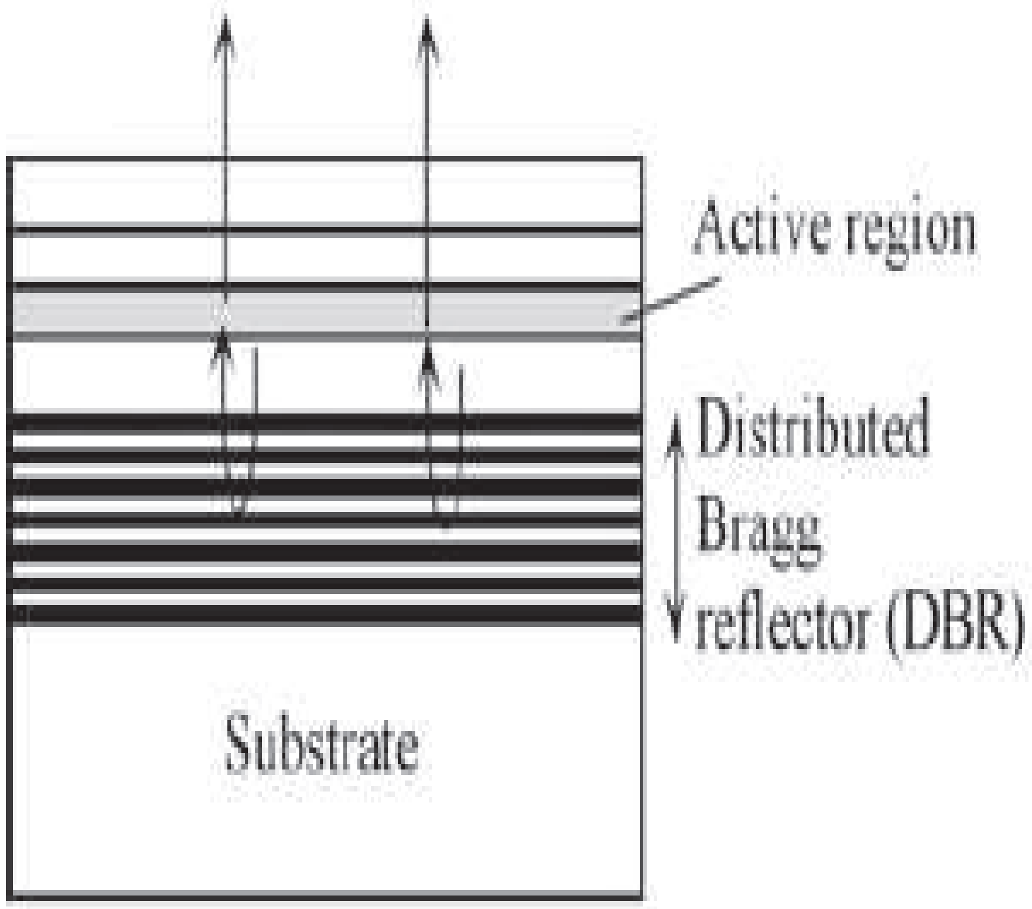


ENCAPSULATION

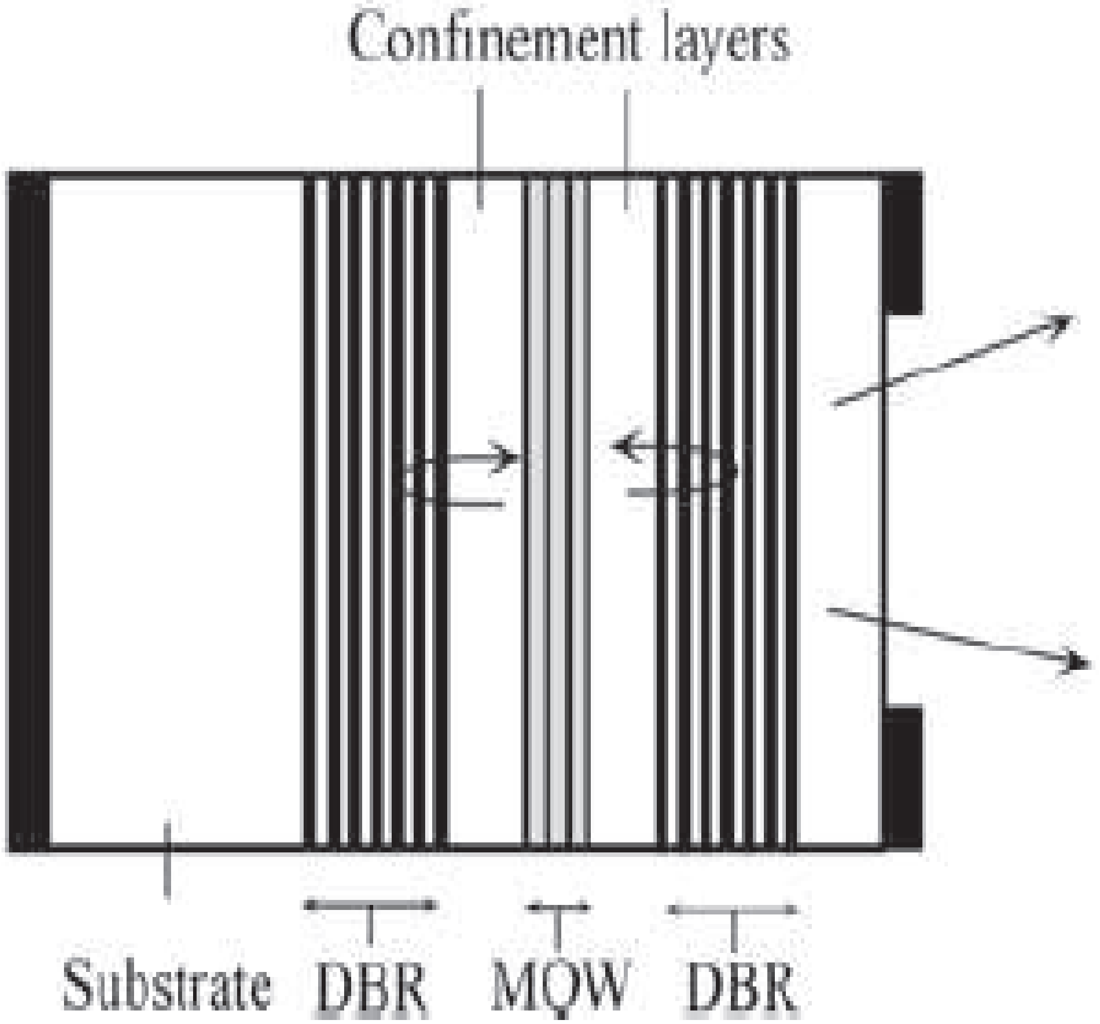
- A simple structure that overcomes the TIR problem by placing the LED chip at the centre of a hemispherical plastic dome.
- The epoxy is refractive index matched to the semiconductor and the rays reaching the dome's surface do not suffer TIR.

To Improve Light Extraction Ratio

A distributed Bragg reflector (DBR) under the confining layer (below the active region in grey) acts as a dielectric mirror, and increases the extraction ratio.



An RCLED is an LED with an optical resonant cavity (RC) formed by two DBRs has a narrower emission spectrum.



LED Efficiencies

- To compare different LED materials and device structures requires internal &external quantum efficiency.
- internal quantum efficiency (IQE) h_{IQE} gauges what fraction of electron hole recombination in the forward-biased pn junction are radiative and therefore lead to photon emission.
- Non-radiative 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).
- t_r - mean lifetime of a minority carrier before it recombines radiatively
- T_{nr} - mean lifetime before it recombines via a recombination center (or a defect) without emitting a photon.

Internal quantum efficiency

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

or

Internal quantum efficiency

$$\eta_{\mathrm{IQE}} = \frac{\tau_r^{-1}}{\tau_r^{-1} + \tau_{nr}^{-1}}$$

The rate of nonradiative recombination rate $(1/\tau_{nr})$ would also include the recombination of injected carriers at the interfaces of heterostructures between different crystals: an important loss mechanism that would reduce η_{IQE}.

The total current I is determined by the total rate of recombinations whereas the number of photons emitted per second, the **photon flux** Φ_{ph}, is determined by the rate of radiative recombinations.

Internal quantum efficiency

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

where $P_{o(\text{int})}$ is the *optical* power generated internally (not yet extracted).

The **external quantum efficiency** (EQE) η_{EQE} of an LED represents the efficiency of conversion from electrical quanta, *i.e.*, electrons, that flow into the LED to optical quanta, *i.e.*, photons, that are emitted into the outside world. It incorporates the "internal" efficiency of the radiative recombination process [embedded in Eq. (3.14.1)] and the subsequent efficiency of photon extraction from the device. Suppose that the actual optical power emitted to the ambient, called the **radiant flux**, is P_o. (Φ_e is also used in the literature.) $P_o/h\upsilon$ is the number of emitted photons per second. Since the number of electrons flowing into the LED is I/e, we have

External quantum efficiency

$$\eta_{EQE} = \frac{P_o/h\upsilon}{I/e}$$

- external QE to meaningfully compare different LED efficiencies
- Internal QE in comparing different LED materials.
- indirect bandgap semiconductors η_{EQE} are generally less than 1% whereas for direct bandgap semiconductors with the right device structure, η_{EQE} can be substantial, for example 30–40%

The light **extraction ratio**, or the **extraction efficiency** (EE), η_{EE}, is the fraction of light that is extracted to the ambient from the internally generated light, that is,

$$\eta_{EE} = \frac{\text{Photons emitted externally from the device}}{\text{Photons generated internally by recombination}}$$

Extraction efficiency

the emitted optical output power, the radiant flux, is

$$P_o = \eta_{EE} P_{o(\text{int})} = h\upsilon \eta_{EE} \eta_{IQE} (I/e)$$

Emitted optical power

The **power conversion efficiency** (PCE), η_{PCE}, or simply the **power efficiency**, gauges the overall efficiency of conversion from the input of electrical power to the output of optical power, *i.e.*,

$$\eta_{PCE} = \frac{\text{Optical output power}}{\text{Electrical input power}} = \frac{P_o}{IV} \approx \eta_{EQE}\left(\frac{E_g}{eV}\right)$$

Power efficiency

The **luminous flux** Φ_v is a measure of *visual* **brightness**, in lumens (lm), and is defined by

$$\Phi_v = P_o \times (633 \text{ lm W}^{-1}) \times V(\lambda)$$

where P_o is the radiant flux or the radiation power emitted (in watts) and $V(\lambda)$ is the **relative luminous efficiency** (or the relative sensitivity) of an average light-adapted (photopic) eye, which depends on the wavelength and hence λ in parenthesis. The function $V(\lambda)$ is also called the **luminosity function** and the **visibility function**.

PROBLEM NO:1

A particular 870 nm IR LED for use in optical links and instrumentation has a GaAs chip. Active layer that has been doped *p*-type with $2 \times 10^{17}\,\text{cm}^{-3}$ of acceptors and the nonradiative lifetime is about 100 ns. At a forward current of 30 mA, the voltage across it is 1.35 V, and the emitted optical power is 6.5 mW. Calculate the IQE, EQE, and PCE, and estimate the light extraction ratio. For GaAs, $B \approx 2 \times 10^{-16}\,\text{m}^2\,\text{s}^{-1}$.

SOLUTION

The radiative lifetime $\tau_r = 1/BN_a = 1/\left[(2 \times 10^{-16}\,\mathrm{m^3\,s^{-1}})(2 \times 10^{23}\,\mathrm{m^{-23}})\right] = 2.5 \times 10^{-8}\,\mathrm{s}$ or 25 ns. IQE is,

$$\eta_{\mathrm{IQE}} = \frac{\tau_r^{-1}}{\tau_r^{-1} + \tau_{nr}^{-1}} = \frac{(25\,\mathrm{ns})^{-1}}{(25\,\mathrm{ns})^{-1} + (100\,\mathrm{ns})^{-1}} = 0.80 \quad \text{or} \quad 80\%$$

The emitted photon energy $h\upsilon = hc/\lambda \approx 1.43$ eV. Thus the EQE is

$$\begin{aligned}\eta_{\mathrm{EQE}} &= (P_o/h\upsilon)/(I/e) \\ &= \left[(6.5 \times 10^{-3}\,\mathrm{W})/(1.43\,\mathrm{eV} \times 1.6 \times 10^{-19}\,\mathrm{J\,eV^{-1}})\right]/\left[(30 \times 10^{-3}\,\mathrm{A})/(1.6 \times 10^{-19}\,\mathrm{C})\right] \\ &= 0.15 \quad \text{or} \quad 15\%\end{aligned}$$

The PCE is simply P_o/IV or $(6.5\,\mathrm{mW})/\left[(30\,\mathrm{mA})(1.35\,\mathrm{V})\right]$, that is, 0.16, *i.e.*, 16%.
using $P_o = h\upsilon\eta_{\mathrm{EE}}\eta_{\mathrm{IQE}}(I/e)$,

$$6.5 \times 10^{-3}\,\mathrm{W} = (1.43\,\mathrm{eV} \times 1.6 \times 10^{-19}\,\mathrm{J\,eV^{-1}})\eta_{\mathrm{EE}}(0.80)(30 \times 10^{-3}\,\mathrm{A}/1.6 \times 10^{-19}\,\mathrm{C})$$

solving the above gives $\eta_{\mathrm{EE}} = 0.19$ or 19%.

PROBLEM NO:2

- Consider two LEDs, one red, with an optical output power (radiant flux) of 10 mW, emitting at 650 nm, and the other, a weaker 5 mW green LED, emitting at 532 nm. Find the luminous flux emitted by each LED.

Note: take luminous efficiency as 0.10 , 0.87 for Red,Green LED respectively

SOLUTION

For the red LED, at $\lambda = 650$nm,

$$\Phi_v = P_o \times (633\,\text{lm W}^{-1}) \times V = (10 \times 10^{-3}\,\text{W})(633\,\text{lm W}^{-1})(0.10) = 0.63\,\text{lm}$$

For the green LED, $\lambda = 532$ nm,

$$\Phi_v = P_o \times (633\,\text{lm W}^{-1}) \times V = (5 \times 10^{-3}\,\text{W})(633\,\text{lm W}^{-1})(0.87) = 2.8\,\text{lm}$$

Clearly the green LED at half the optical power is 4 times brighter than the red LED.

SESSION 3

- Manufacturing Process and Applications
- Solving Problems

$\left.\begin{array}{l}\\ \\ \end{array}\right\}$ See other ppt

SESSION 4 & 5

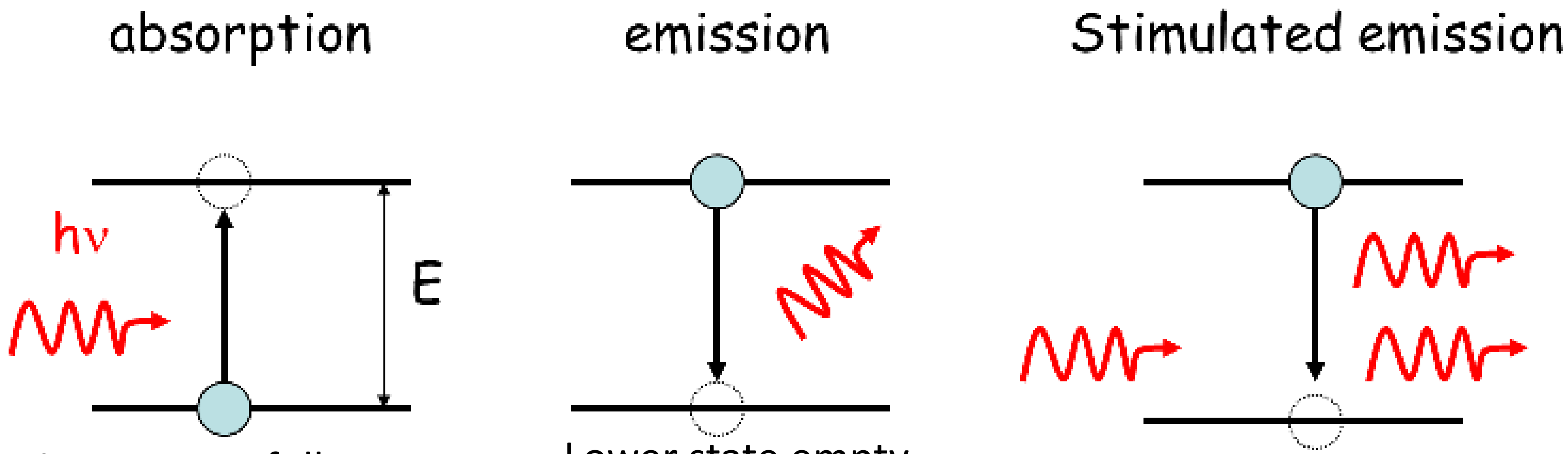
- LASER: Threshold Condition
- Emission and Absorption of Radiation
- Population Inversion
- Principle of the Laser Diode

Fundamentals of Lasers

Light amplification by stimulated emission of radiation

Einstein 1917

Electron transitions between energy levels



Lower state full
Upper state empty
Light absorbed

Lower state empty
Upper state full
MORE light emitted

Amplification:
Need more electrons at high energy than at low energy.

No one thought this could be done

stimulated emission just a theoretical curiosity for about 30 years!

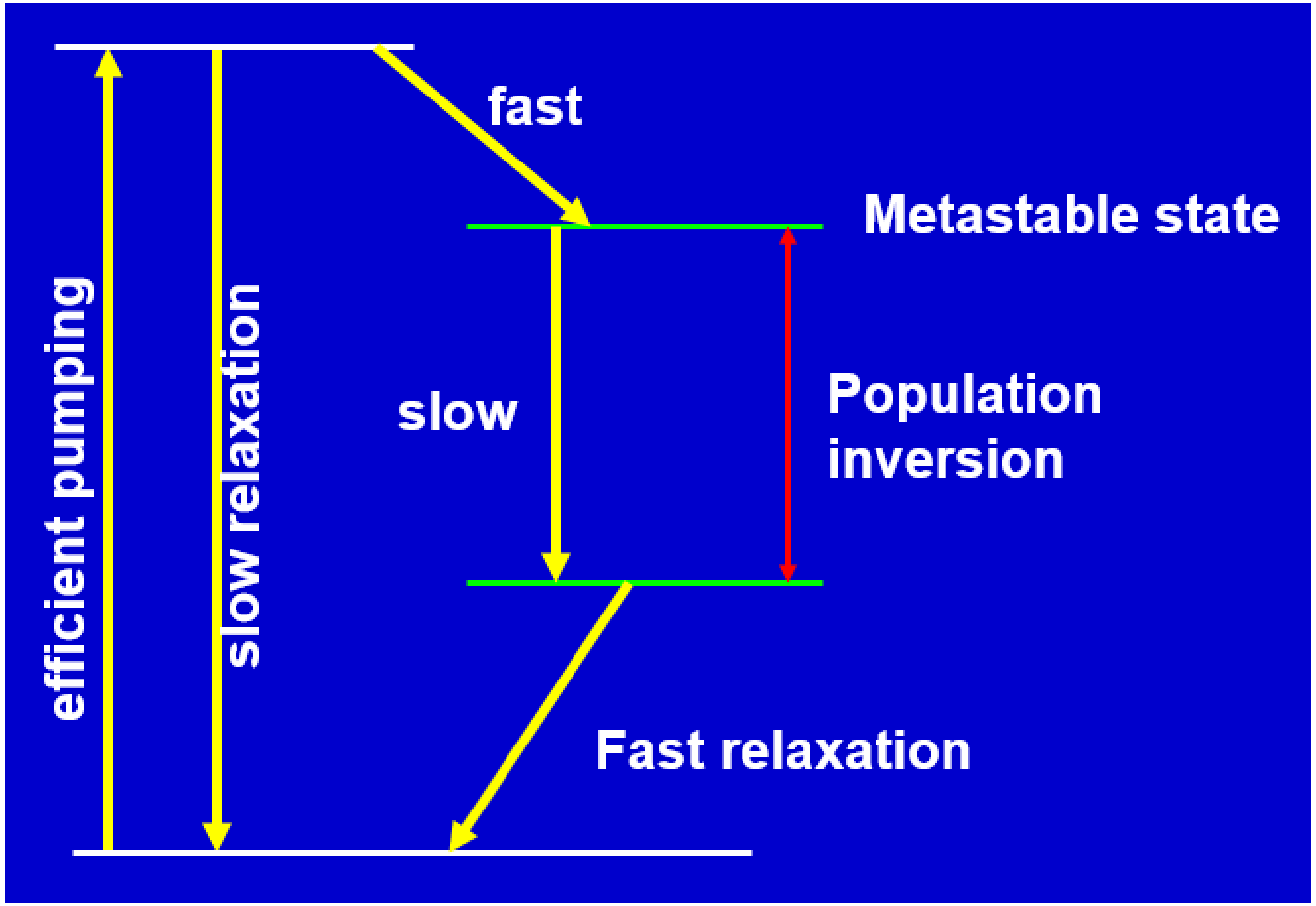
Even with very a intense pump source, the best one can achieve with a two-level system is

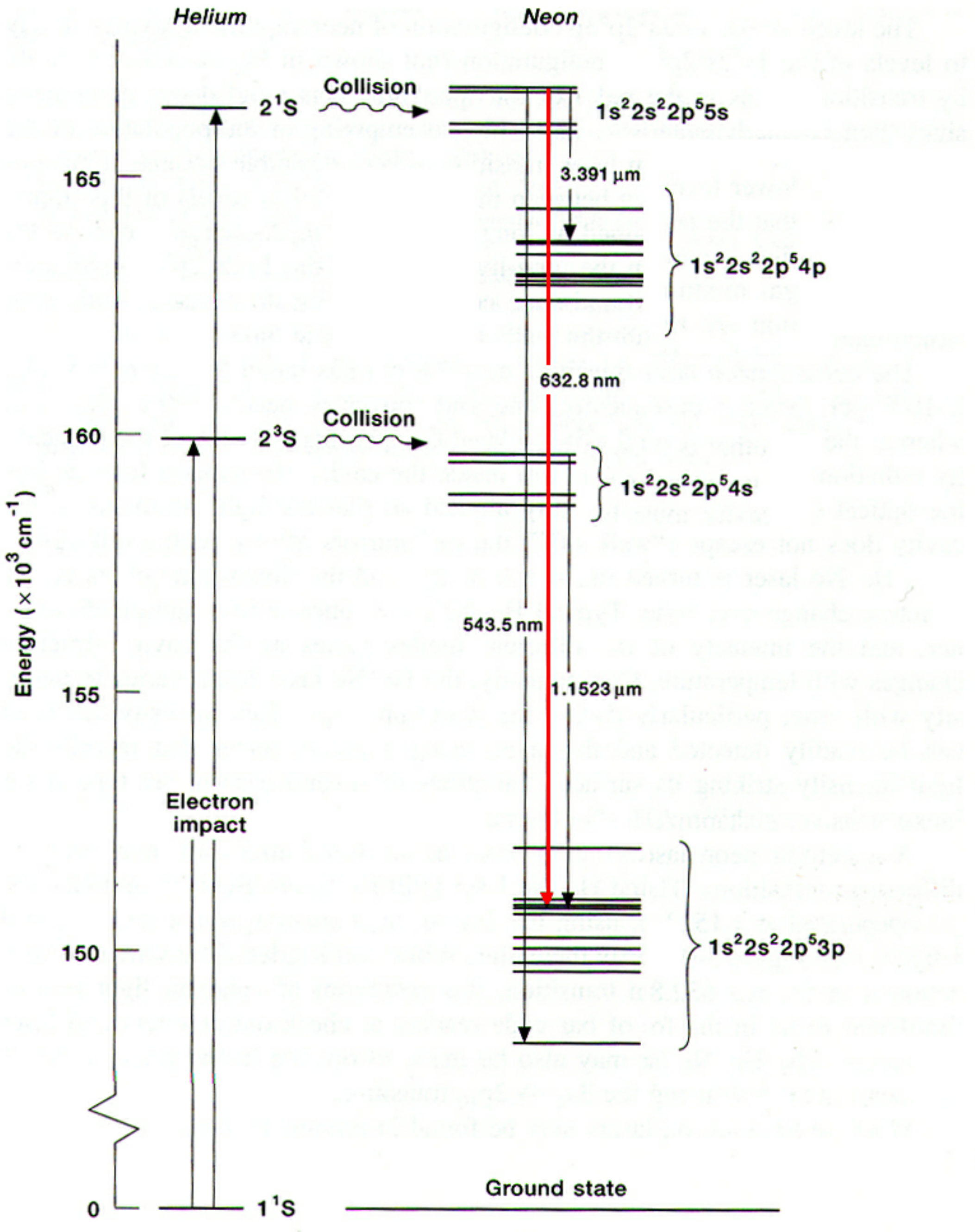
excited state population = ground state population

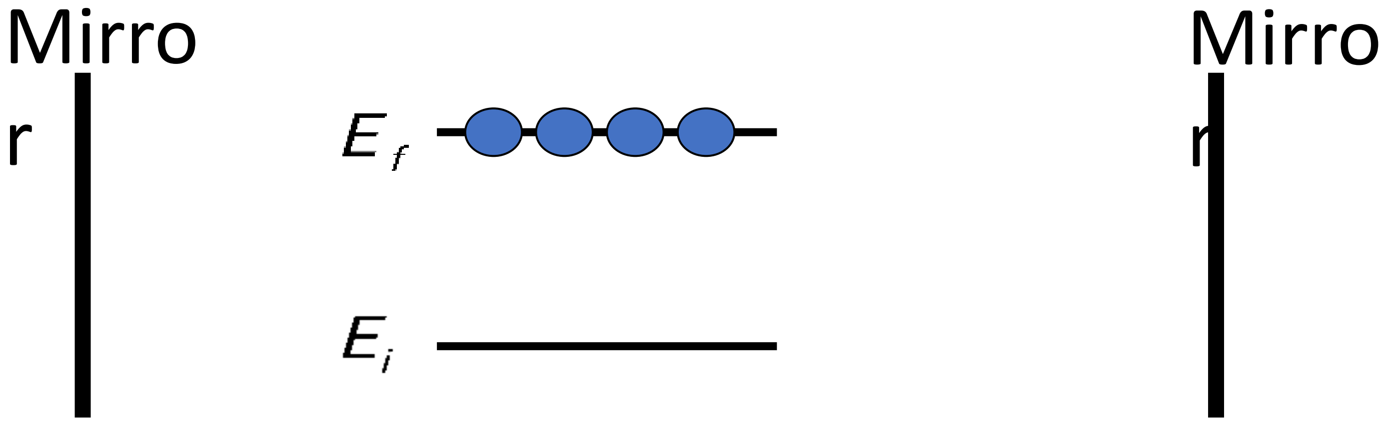
Laser: Four-Level System

He-Ne laser

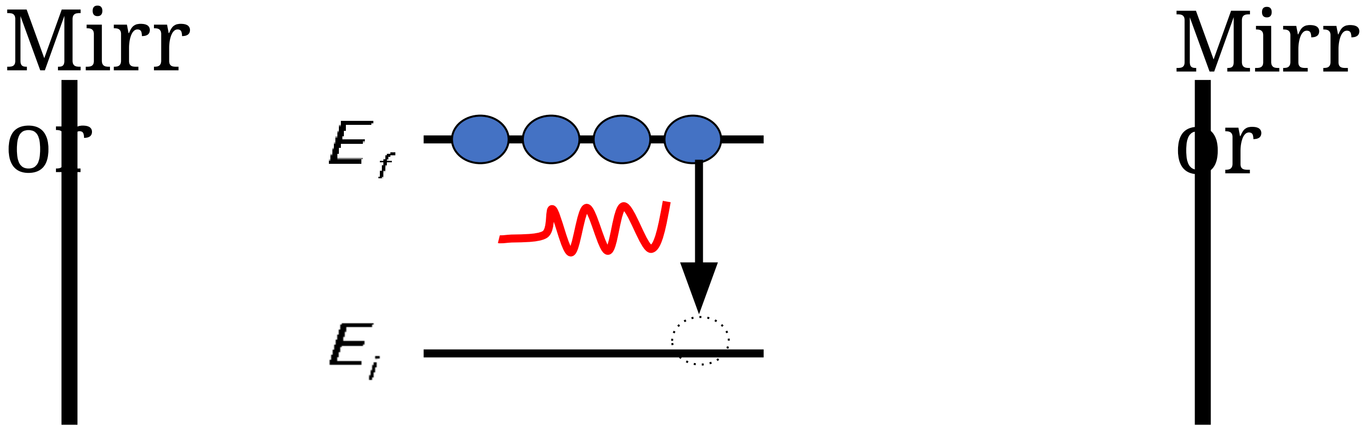
Requirements for Laser Action



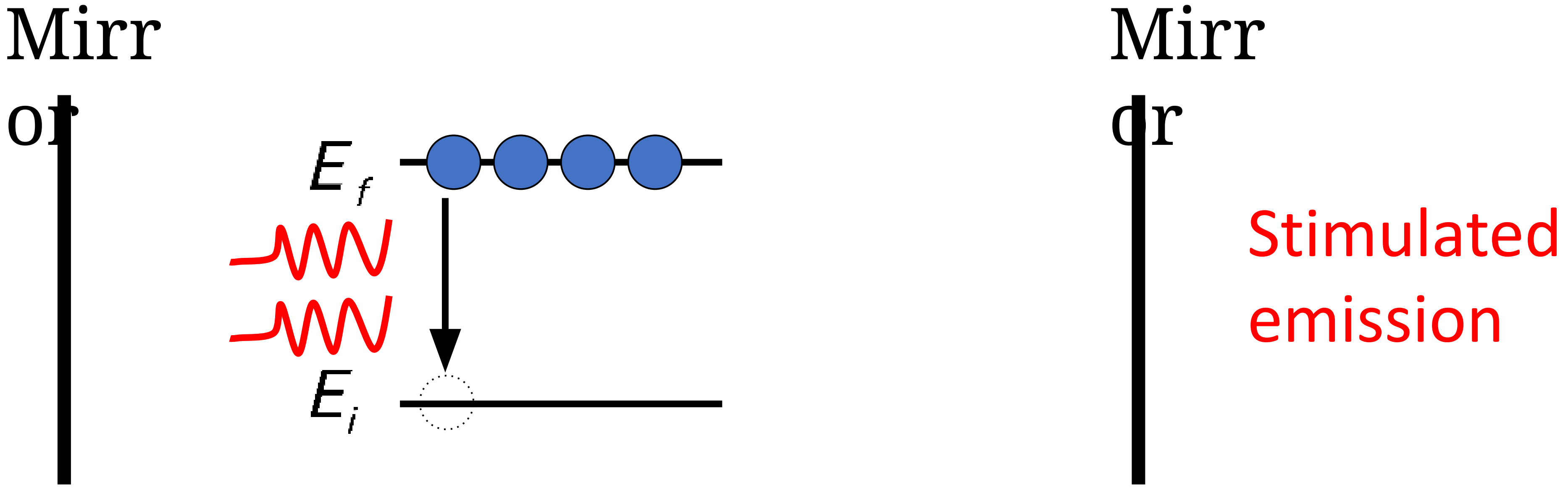




Population inversion



Spontaneous emission


Mirr
or
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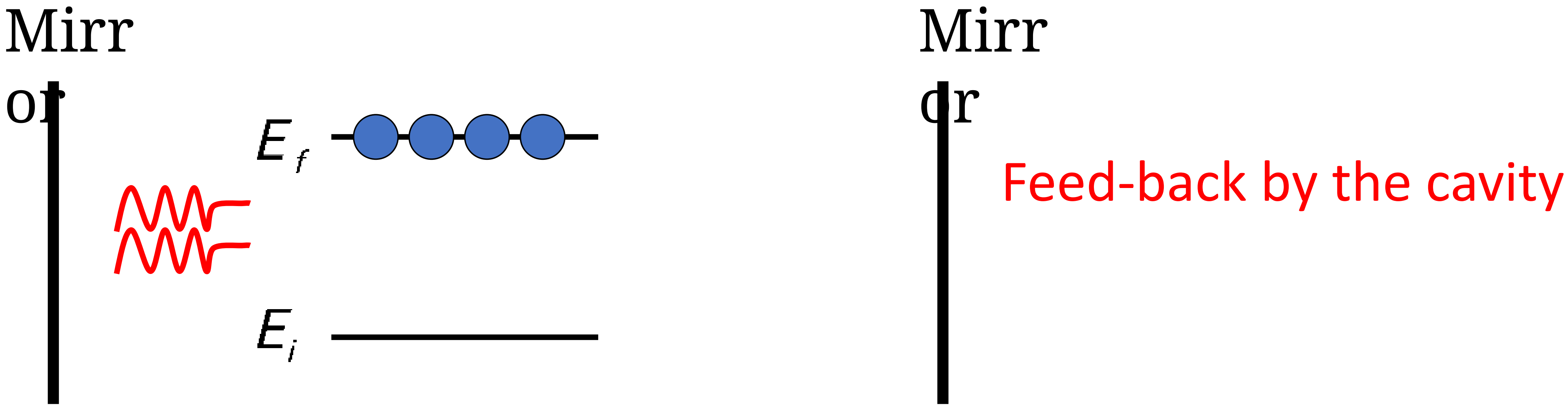
Stimulated
emission


Mirr
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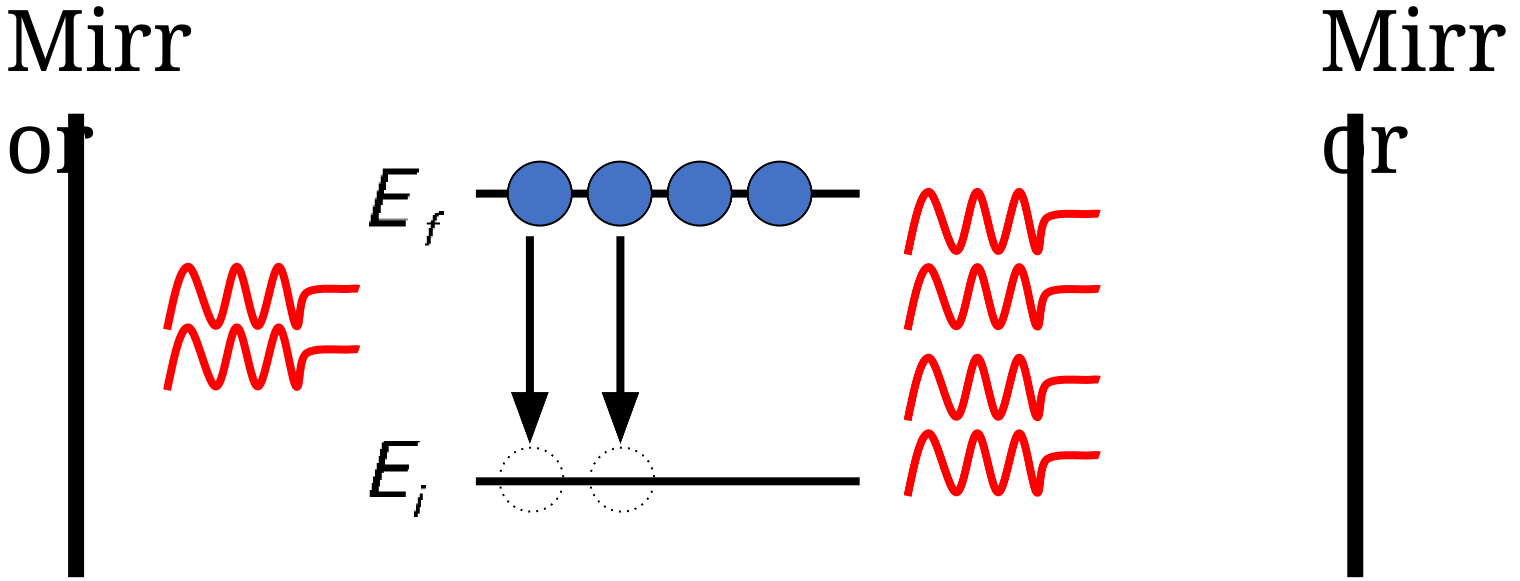
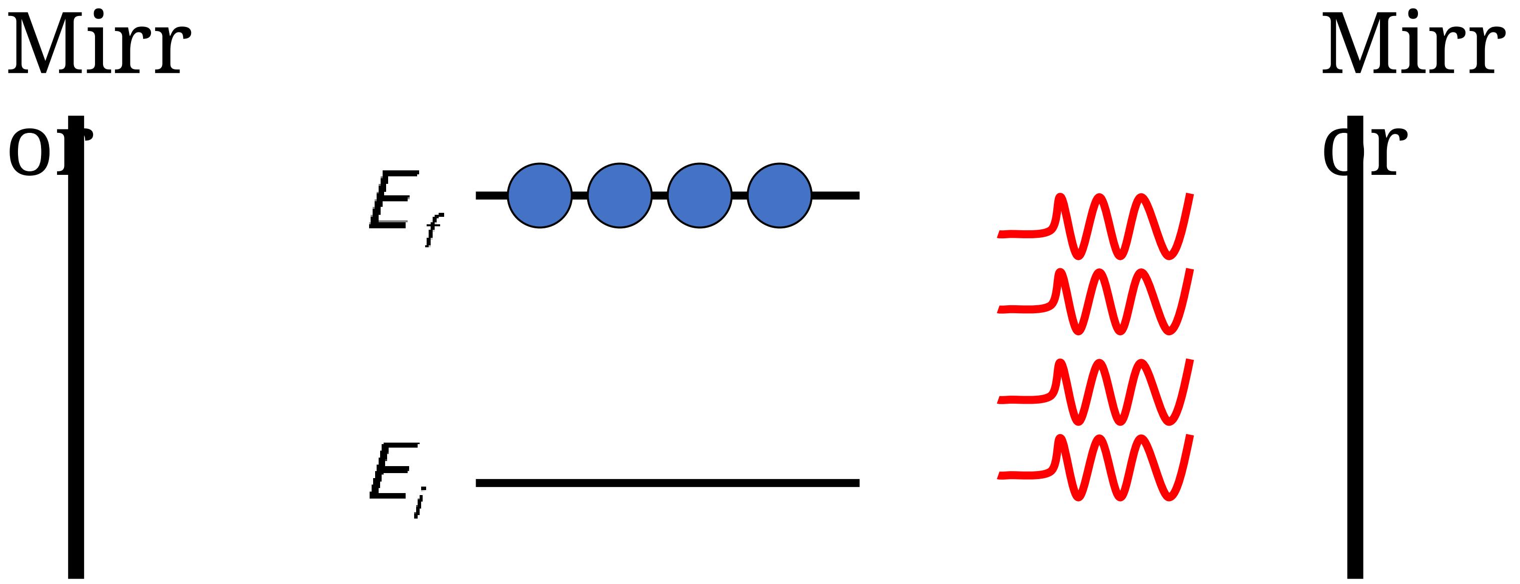
Feed-back by the cavity

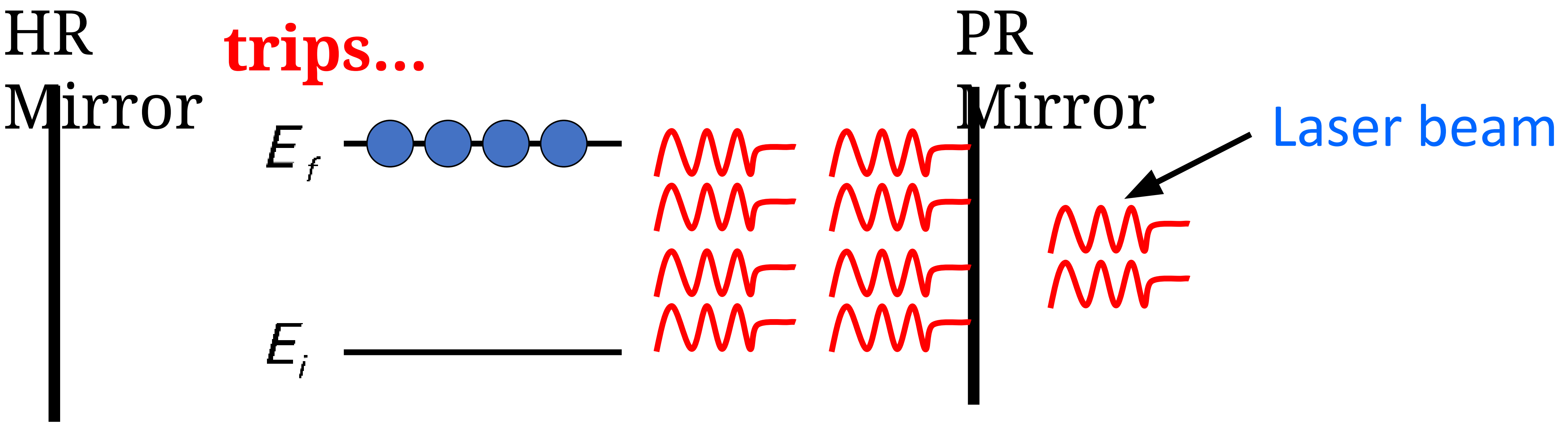


Stimulated emission



Feed-back by the cavity

After several round trips...

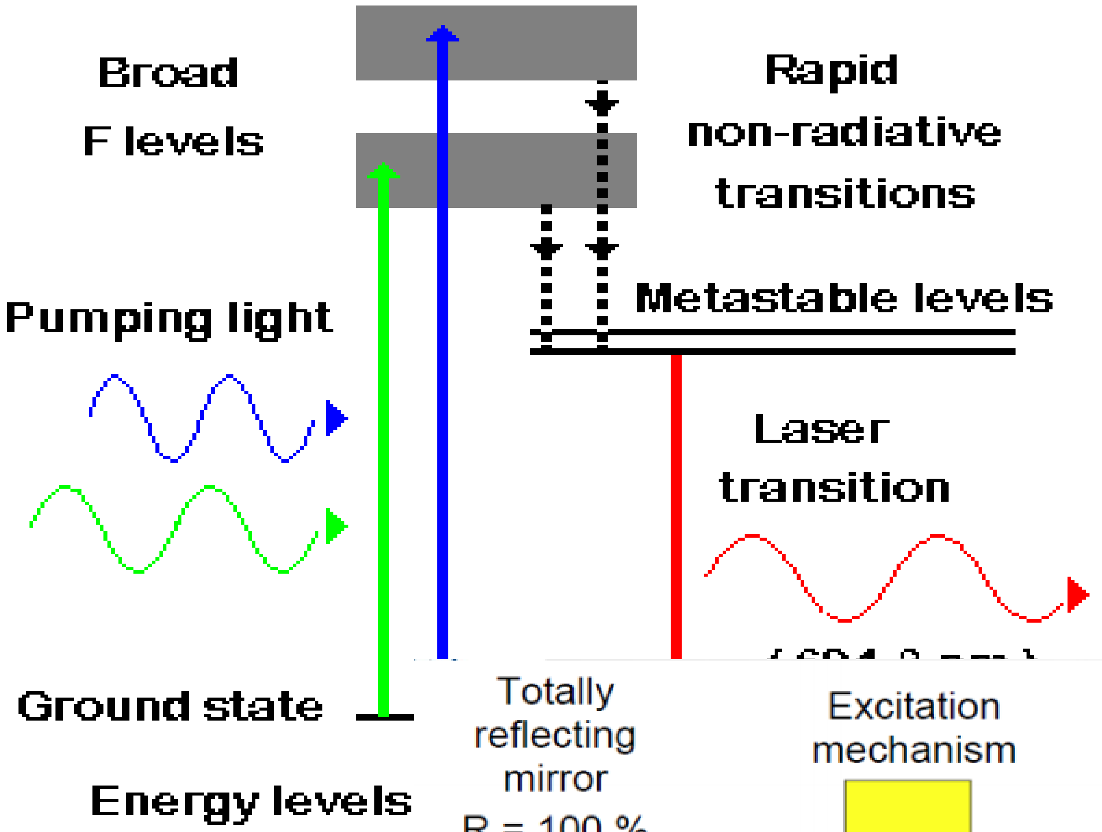


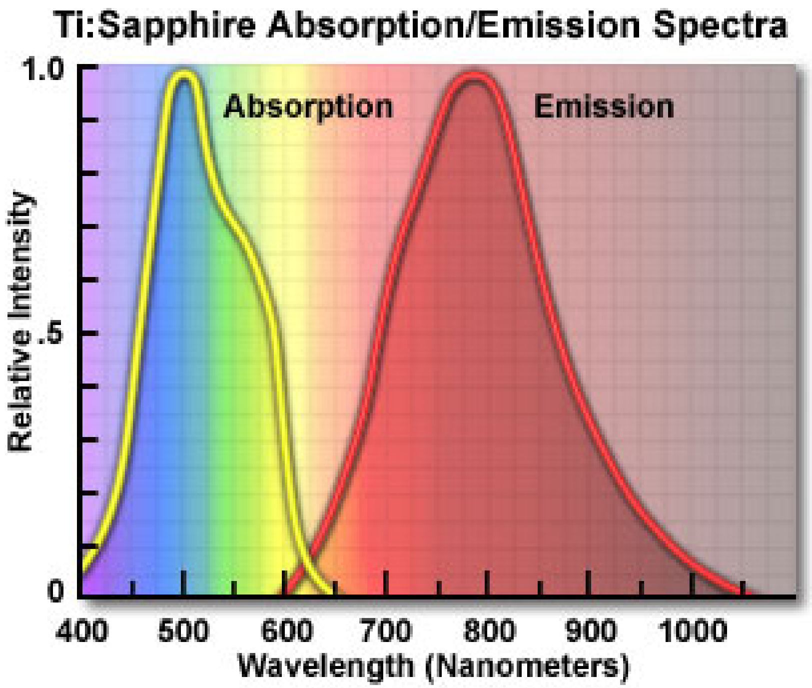
Photons with:

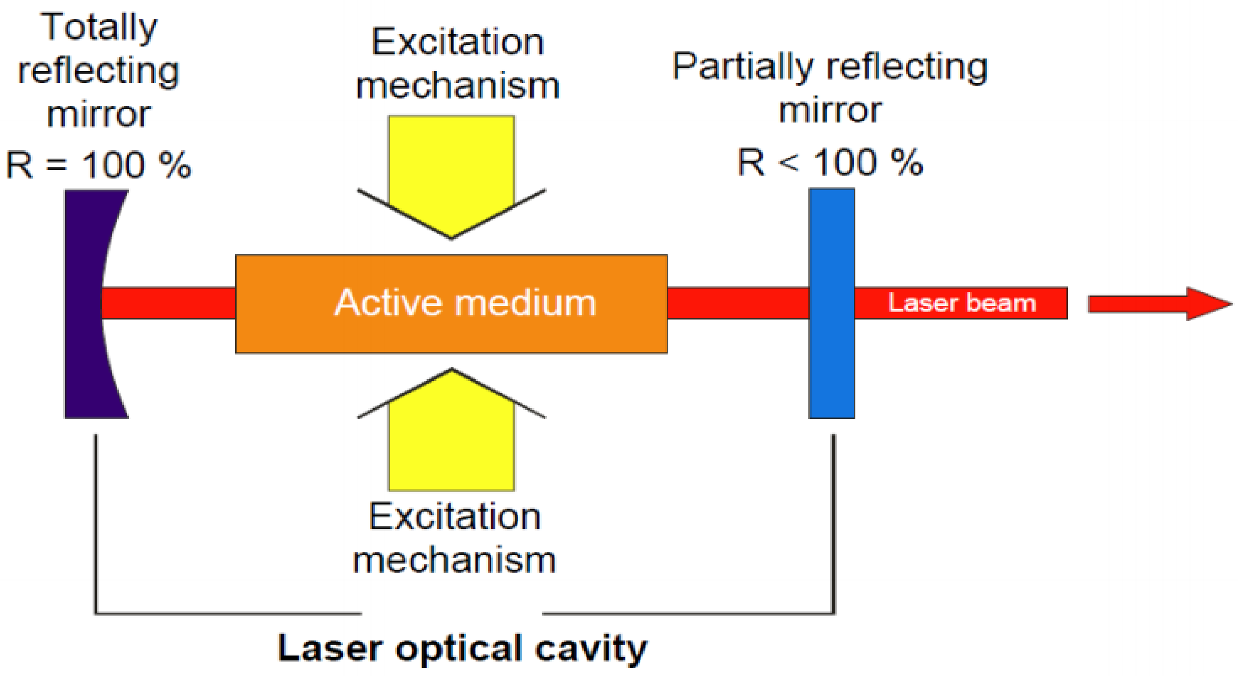
- **same energy : Monochromatic**
- **same direction of propagation : Spatial coherence, collimated**
- **all in synchrony: Temporal coherence, in-phased**

Characteristics of Laser Light

- **INTENSE MONOCHROMATIC COLLIMATED COHERENT**







J. Kim, Adv. In Optics and Photonics (2016)

Stimulated vs Spontaneous Emission

Stimulated emission requires the presence of a photon. An "incoming" photon stimulates a molecule in an excited state to decay to the ground state by emitting a photon. The stimulated photons travel in the same direction as the incoming photon.

Spontaneous emission does not require the presence of a photon. Instead a molecule in the excited state can relax to the ground state by spontaneously emitting a photon. Spontaneously emitted photons are emitted in all directions.

When light travels through an absorbing medium, the medium absorbs the light; the amount of light absorbed is determined by Beer's Law.

For a medium to operate as a lasing medium, the transmitted light intensity should be greater than the intensity of light incident on the material.

How can a population inversion be created?

- By excitation of the lasing atoms or molecules - this is called PUMPING.
- If the pump source is very intense, the number of atoms or molecules excited can be large.
- However, once excited, the atoms and molecules must say in the excited state long enough to create an excited population > ground state population
- For stimulated emission to be the dominant process, the excited state population must be larger than the lower state population.
- In other words, for a medium to produce laser light, there must be a "population inversion" where $N_{upper} > N_{lower}$
- How can a population inversion be created when the population in the ground state is always greater that the population in the excited state?
- What kinds of materials will "allow" for an inversion of population in its electronic states?

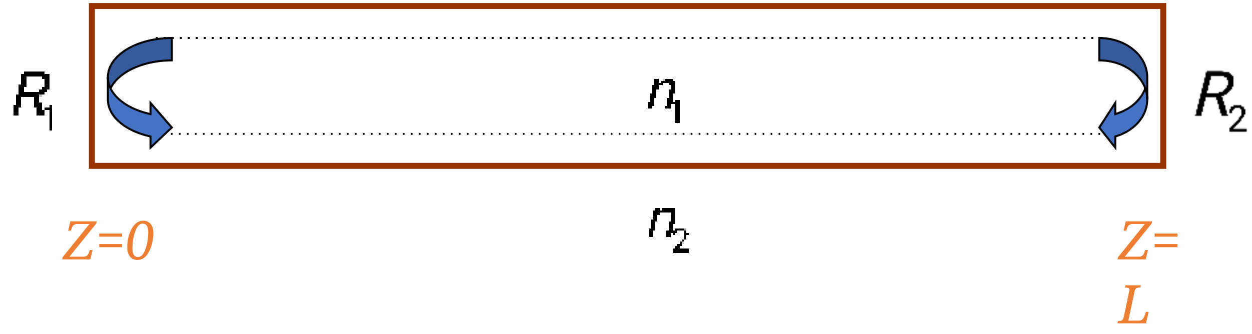
Laser Operation & Lasing Condition

- To determine the lasing condition and resonant frequencies, we should focus on the optical wave propagation along the longitudinal direction, *z*-axis. The optical field intensity, *I*, can be written as:

$$I(z,t) = I(z)e^{j(\omega t-\beta z)} \quad [1]$$

- Lasing is the condition at which light amplification becomes possible by virtue of population inversion. Then, stimulated emission rate into a given EM mode is proportional to the intensity of the optical radiation in that mode. In this case, the loss and gain of the optical field in the optical path determine the lasing condition. The radiation intensity of a photon at energy $h\upsilon$ varies exponentially with a distance z amplified by factor *g*, and attenuated by factor $\bar{\alpha}$ according to the following relationship:

$$I(z) = I(0)\exp\left[\left(\Gamma g(h\upsilon) - \bar{\alpha}(h\upsilon)\right)z\right] \quad [2]$$



$$I(2L) = I(0) R_1 R_2 \exp\left[\left(\Gamma g(h\upsilon) - \bar{\alpha}(h\upsilon)\right)(2L)\right] \qquad [3]$$

Γ : Optical confinement factor, g : gain coefficient

$\bar{\alpha}$: effective absorption coefficient, $R = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2$

Lasing Conditions:

$$\boxed{\begin{aligned} I(2L) &= I(0) \\ \exp(-j2\beta L) &= 1 \end{aligned}} \qquad [4]$$

Threshold gain & current density

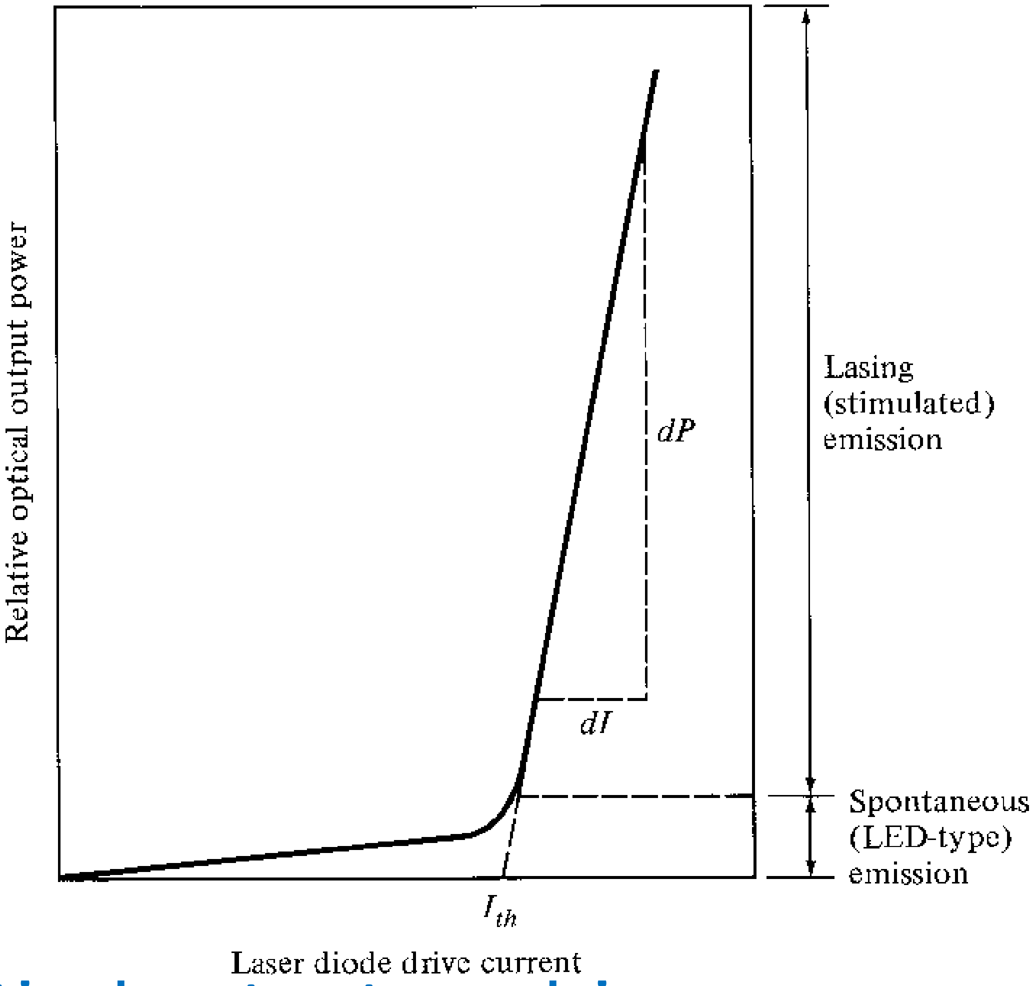
$$\Gamma g_{th} = \bar{\alpha} + \frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)$$ [5]

$$\text{Laser starts to "lase" iff}: g \geq g_{th}$$

For laser structure with strong carrier confinement, the threshold current density for stimulated emission can be well approximated by:

$$g_{th} = \beta J_{th}$$ [6]

β : constant depends on specific device construction



Optical output vs. drive current

Optical Fiber communications, 3rd ed.,G.Keiser,McGrawHill, 2000

Semiconductor Diode laser rate equations

- Rate equations relate the optical output power, or # of photons per unit volume, Φ, to the diode drive current or # of injected electrons per unit volume, *n*. For active (carrier confinement) region of depth *d*, the rate equations are:

$$\frac{d\Phi}{dt} = Cn\Phi + R_{sp} - \frac{\Phi}{\tau_{ph}} \qquad [7]$$

Photon rate = stimulated emission + spontaneous emission + photon loss

$$\frac{dn}{dt} = \frac{J}{qd} - \frac{n}{\tau_{sp}} - Cn\Phi \qquad [8]$$

electron rate = injection + spontaneous recombination + stimulated emission

C: Coefficient expressing the intensity of the optical emission & absorption process

R_{sp}: rate of spontaneous emission into the lasing mode

τ_{ph}: photon life time

J: Injection current density

Threshold current Density & excess electron density

- At the threshold of lasing: $\Phi \approx 0,\ d\Phi / dt \geq 0,\ R_{sp} \approx 0$

$$\text{from eq. [7]} \Rightarrow\ Cn\Phi - \Phi/\tau_{ph} \geq 0 \Rightarrow \boxed{n \geq \frac{1}{C\tau_{ph}} = n_{th}}$$ [9]

- The threshold current needed to maintain a steady state threshold concentration of the excess electron, is found from electron rate equation under steady state condition *dn/dt=0* when the laser is just about to lase:

$$0 = \frac{J_{th}}{qd} - \frac{n_{th}}{\tau_{sp}} \Rightarrow \boxed{J_{th} = qd\frac{n_{th}}{\tau_{sp}}}$$ [10]

Laser operation beyond the threshold $J > J_{th}$

The solution of the rate equations [7] gives the steady state photon density, resulting from stimulated emission and spontaneous emission as follows:

$$\boxed{\Phi_s = \frac{\tau_{ph}}{qd}(J - J_{th}) + \tau_{ph}R_{sp}}$$ [11]

External quantum efficiency

- Number of photons emitted per radiative electron-hole pair recombination above threshold, gives us the external quantum efficiency.

$$\eta_{ext} = \frac{\eta_i (g_{th} - \bar{\alpha})}{g_{th}}$$

$$= \frac{q}{E_g} \frac{dP}{dI} = 0.8065\lambda[\mu m] \frac{dP(\text{mW})}{dI(\text{mA})} \qquad [12]$$

- Note that: $\eta_i \approx 60\% - 70\%; \qquad \eta_{ext} \approx 15\% - 40\%$

Laser Resonant Frequencies

- Lasing condition, namely eq. [4]: $\exp(-j2\beta L) = 1 \Rightarrow \qquad 2\beta L = 2m\pi, \quad m = 1,2,3,\ldots$

- Assuming $\beta = \dfrac{2\pi n}{\lambda}$ the resonant frequency of the m^{th} mode is:

$$\boxed{\upsilon_m = \frac{mc}{2Ln}} \qquad m = 1,2,3,\ldots \qquad [13]$$

$$\Delta\upsilon = \upsilon_m - \upsilon_{m-1} = \frac{c}{2Ln} \Leftrightarrow \boxed{\Delta\lambda = \frac{\lambda^2}{2Ln}} \qquad [14]$$

Problem: Efficiency of the HeNe laser

A typical low-power 5 mW He-No laser tube operates at a de voltage of 2000 V and carries a current of 7 mA, What is the efficiency of the laser?

From the definition of efficiency,

$$\text{Efficiency} = \text{Output optical power / Input electrical power} = \frac{5 \times 10^{-3}\ W}{(7\times 10^{-3} A)(2\times 10^{3}\ V)} = 0.036\%$$

Typically He-Ne efficiencies are less than 0.1 %.

What is important is the high concentration of coherent photons. Note that 5 mW over a beam diameter of 1 mm is 6.4 kW m^{-2},

SESSION 6

- Heterostructure Laser Diodes
- Device Fabrication

Heterostructure Laser Diodes

- First we can confine the injected electrons and holes to a narrow region around the junction. This narrowing of the active region means that less current is needed to establish the necessary concentration of carriers for population inversion.

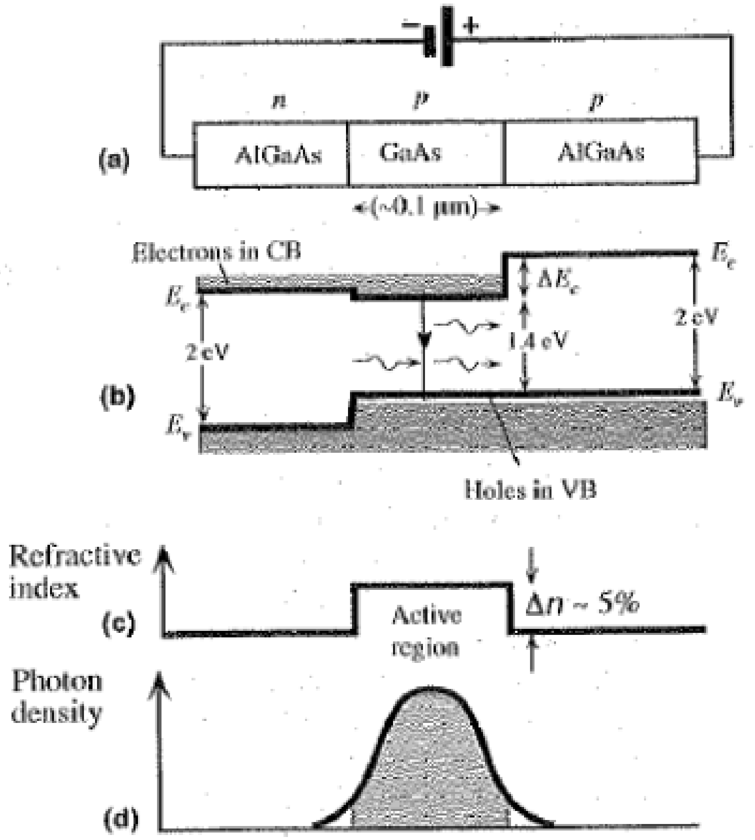
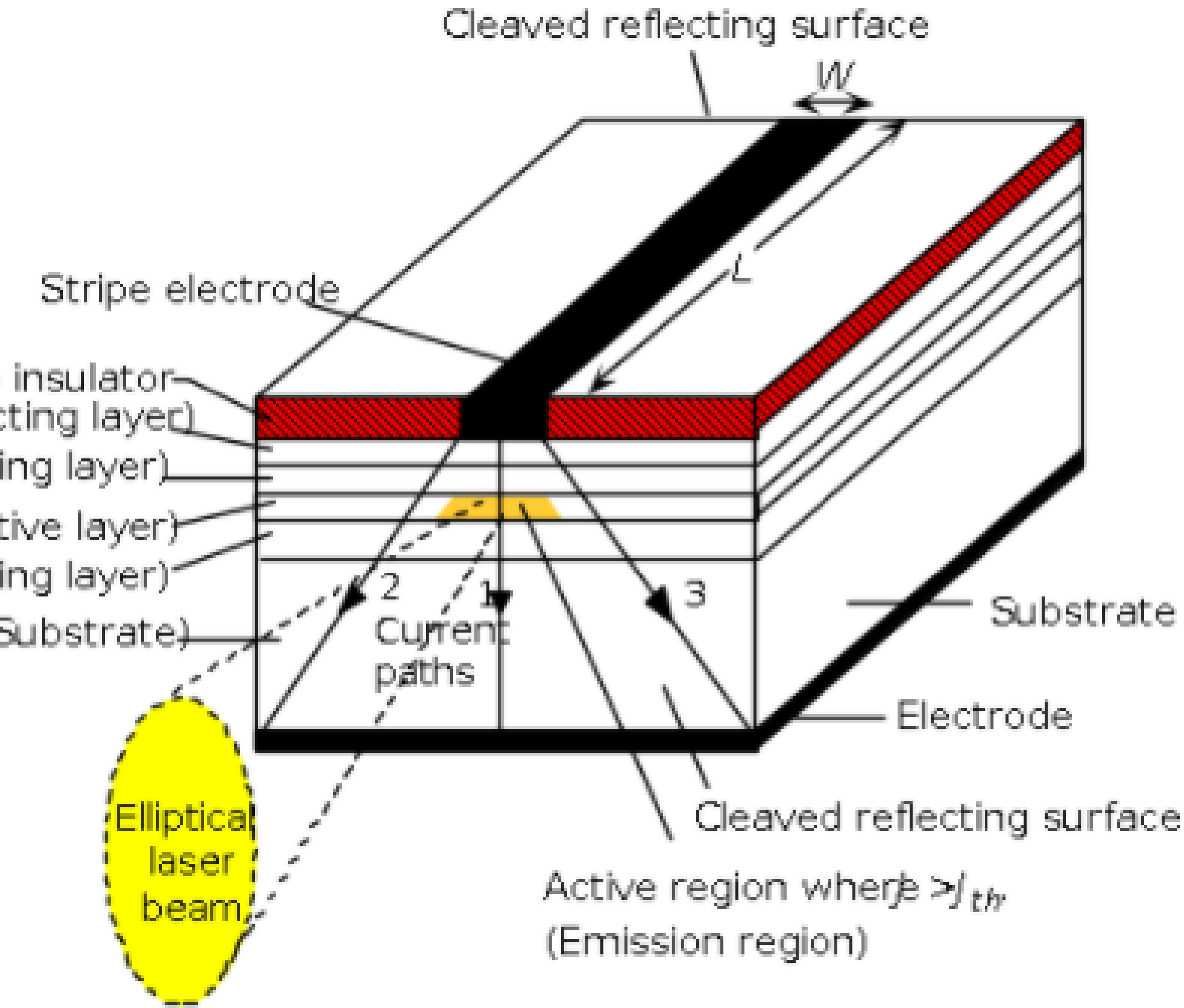


FIGURE 4.18 (a) A double heterostructure diode has two junctions which are between two different bandgap semiconductors (GaAs and AlGaAs). (b) Simplified energy band diagram under a large forward bias. Lasing recombination takes place in the *p*-GaAs layer, the *active layer*. (c) Higher bandgap materials have a lower refractive index. (d) AlGaAs layers provide lateral optical confinement.

- Secondly, we can build a dielectric waveguide around the optical gain region to increase the photon concentration and hence the probability of stimulated emission. This way we can reduce the loss of photons traveling off the cavity axis. We therefore need both carrier confinement and photon confinement.
- Both of these requirements are readily achieved in modern laser diodes by the use of heterostructured devices as in the case of high-intensity double heterostructure LEDs.
- However, in the case of laser diodes, there is an additional requirement for maintaining a good optical cavity that will increase stimulated emissions over spontaneous emissions.

Heterostructure Laser Diodes

- ⇒ Substrate is n-GaAs
- ⇒ Confining layers are n-AlGaAs and p-AlGaAs
- ⇒ Active layer is p-GaAs (870-900nm)
- ⇒ Additional contacting layer is p-GaAs (allows better electrode contact and avoids Schottky junctions which limit current.
- ⇒ The p and n-AlGaAs layers provide carrier and optical confinement by forming heterojunctions with the p-GaAs.



Advantage of AlGaAs/GaAs heterojunction is that they offer a small lattice mismatch between their crystal structures.

This introduces negligible strain induced interfacial defects (dislocations).

Defects of this nature act as non-radiative recombination centers.

Heterostructure Laser Diodes

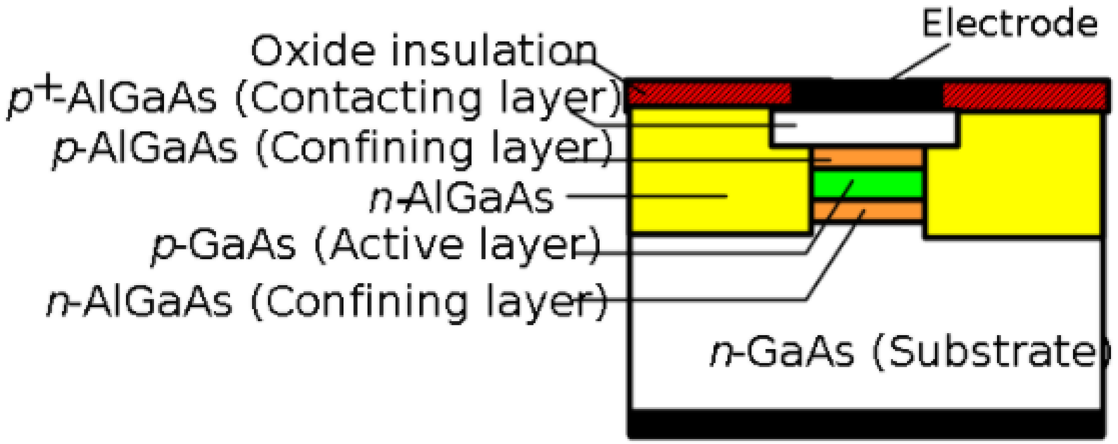
Stripe Geometry:

=>current density J is not uniform laterally from the stripe contact.

=>current is maximum along the central path and diminishes on either side with confinement between path 2 and 3. (gain guided)

=>population inversion and therefore optical gain occurs where current density exceeds threshold current values.

Adavantages of stripe geometry: 1. Reduced contact reduces threshold current. 2. Reduced emission area makes light coupling to fibre easier. (ex. Stripe widths of a few microns develop threshold currents of tens of milliamperes)



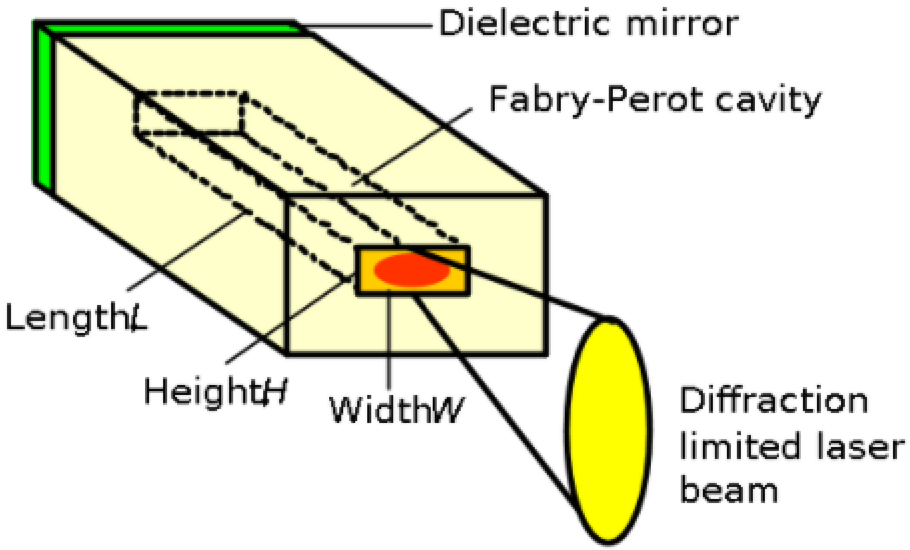
What factors determine LD output spectrum?

1. The neature of the optical resonator that develops laser oscillations.
2. The optical gain curve (line-shape of active medium).

=>Optical resonator is a Fabry-Perot cavity.

=>length determines longitudinal modes where width and height of the cavity determines transverse or lateral modes.

=>with a sufficiently small W and H only the lowest transverse mode exits (TEM_{00}).



SESSION 7 & 8

- Solving problems
- Display Device: Photo Luminescence
- Cathode Luminescence, Electro Luminescence
- Injection Luminescence

See other ppt

Problem :01

Consider a He-Ne gas laser operating at the wavelength 632.8 nm (equivalent to $\upsilon_0 = 473.8\,\text{THz}$). The tube length $L = 40$ cm and mirror reflectances are approximately 95% and 100%. The linewidth $\Delta\upsilon$ is 1.5 GHz, the loss coefficient α_s is $0.05\,\text{m}^{-1}$, the spontaneous decay time constant τ_{sp} is roughly 100 ns, and $n \approx 1$. What are the threshold gain coefficient and threshold population inversion?

Solution :01

The threshold gain coefficient i

$$g_{\text{th}} = \alpha_s + \frac{1}{2L}\ln\left(\frac{1}{R_1R_2}\right) = (0.05\ \text{m}^{-1}) + \frac{1}{2(0.4\ \text{m})}\ln\left[\frac{1}{(0.95)(1)}\right] = 0.114\ \text{m}^{-1}$$

The threshold population inversion :

$$\Delta N_{\text{th}} \approx g_{\text{th}}\frac{8\pi n^2 \upsilon_o^2 \tau_{\text{sp}} \Delta\upsilon}{c^2}$$

$$= (0.114\ \text{m}^{-1})\frac{8\pi(1)^2(473.8\times10^{12}\ \text{s}^{-1})^2(100\times10^{-9}\ \text{s})(1.5\times10^9\ \text{s}^{-1})}{(3\times10^8\ \text{m s}^{-1})^2}$$

$$= 1.1\times10^{15}\text{m}^{-3}$$

Problem :02

Consider the He-Ne laser in that has a tube length of 40 cm and $R_1 = 0.95$ and $R_2 = 1$. Suppose that the tube diameter is 0.8 mm, and the output power is 2.5 mW. What are the photon cavity lifetime and the photon concentration inside the cavity? (The emission frequency υ_o is 474 THz.)

Use He-Ne laser in problem :01

Solution :02

Using $L = 40$ cm, $R_1 = 0.95$, $R_2 = 1$, $\alpha_s = 0.05\ \text{m}^{-1}$ gives

$$\alpha_t = \alpha_s + (1/2L)\ln(R_1R_2)^{-1} = 0.05\ \text{m}^{-1} + \left[2(0.4\ \text{m})\right]^{-1}\ln\left[(0.95 \times 1)\right]^{-1} = 0.114\ \text{m}^{-1}$$

and hence

$$\tau_{ph} = \left[(2)(1)(0.4)\right]/\left[(3 \times 10^8)(1 - e^{-2\times0.114\times0.4})\right] = 30.6\ \text{ns}$$

To find the photon concentration,

$$P_o = (0.0025\ \text{W}) \approx \frac{1}{2}A(1 - R_1)h\upsilon_o N_{ph}c/n$$

$$= \frac{1}{2}\left[\pi(8 \times 10^{-3}/2)^2\right](1 - 0.95)(6.62 \times 10^{-34})(474 \times 10^{12})N_{ph}(3 \times 10^8)/(1)$$

which gives $N_{ph} \approx 2.1 \times 10^{15}$ photons m^{-3}.

Problem :03

- For an InGaAsP laser operating at a wavelength of 1.3 μm, calculate the mode spacing in nanometer for a cavity of 300 μm, assuming that the group refractive index is 3.4.

$$\Delta\lambda = \frac{\lambda^2}{2nL}\Delta m,$$

for the neighboring modes $(\Delta m = 1)$ we obtain $\Delta\lambda = 8.3$ Å.

Problem :04

Assuming that the refractive index depends on the wavelength as $n = n_0 + dn/d\lambda(\lambda - \lambda_0)$, find the separation $\Delta\lambda$ between the allowed modes for a GaAs laser at $\lambda_0 = 0.89\ \mu$m, $L = 300\ \mu$m, $n_0 = 3.58$, $dn/d\lambda = 2.5\ \mu\text{m}^{-1}$.

Differentiating the condition for the resonance modes

$$m\frac{\lambda}{2n} = L,$$

we obtain that

$$\Delta\lambda = \frac{\lambda_0^2}{2L(n_0 - \lambda_0 dn/d\lambda)} = 9.7\ \text{Å}.$$

Problem :05

An InGaAsP Fabry-Perot laser operating at a wavelength of 1.3 μm has a cavity length of 300 μm. The refractive index of InGaAsP is 3.9. If one of the laser facets is coated to produce 90 % reflectivity, what should be the minimum gain for lasing, assuming the absorption coefficient of the material α to be 10 cm^{-1}?

The minimum gain for lasing is

$$g_{min} = \alpha + \frac{1}{2L} \ln\left(\frac{1}{R_1 R_2}\right).$$

Here, $R_1 = 0.9$. The reflectivity of the noncoated facet is

$$R_2 = \left(\frac{n-1}{n+1}\right)^2 = 0.35.$$

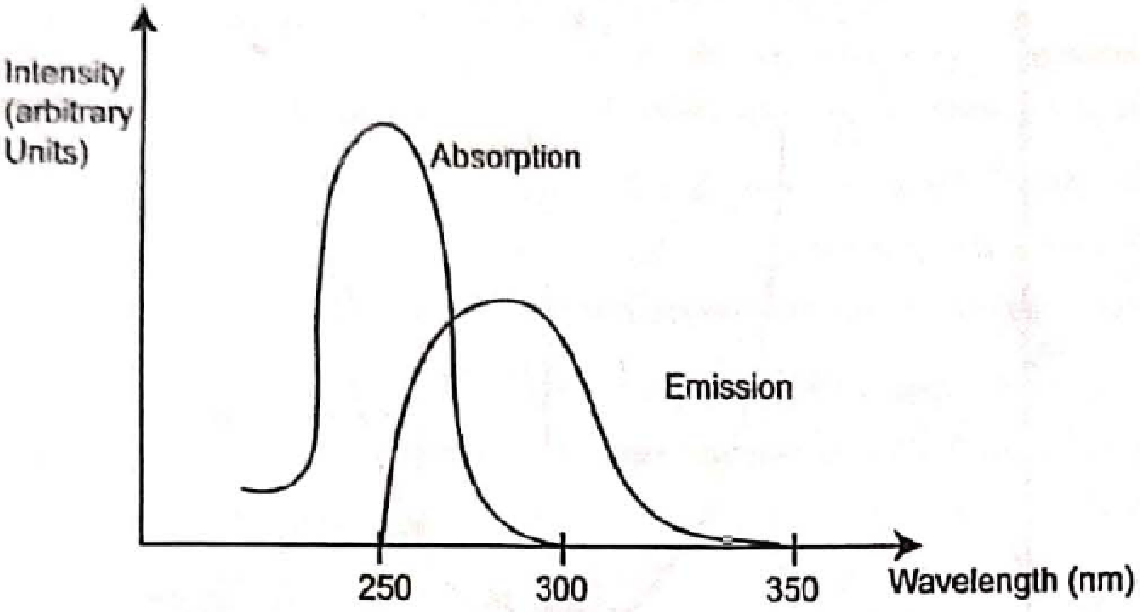
Finally, we get that $g_{min} = 29.3$ cm^{-1}.

SESSION 9

- Plasma Displays
- LCD, Numeric Displays

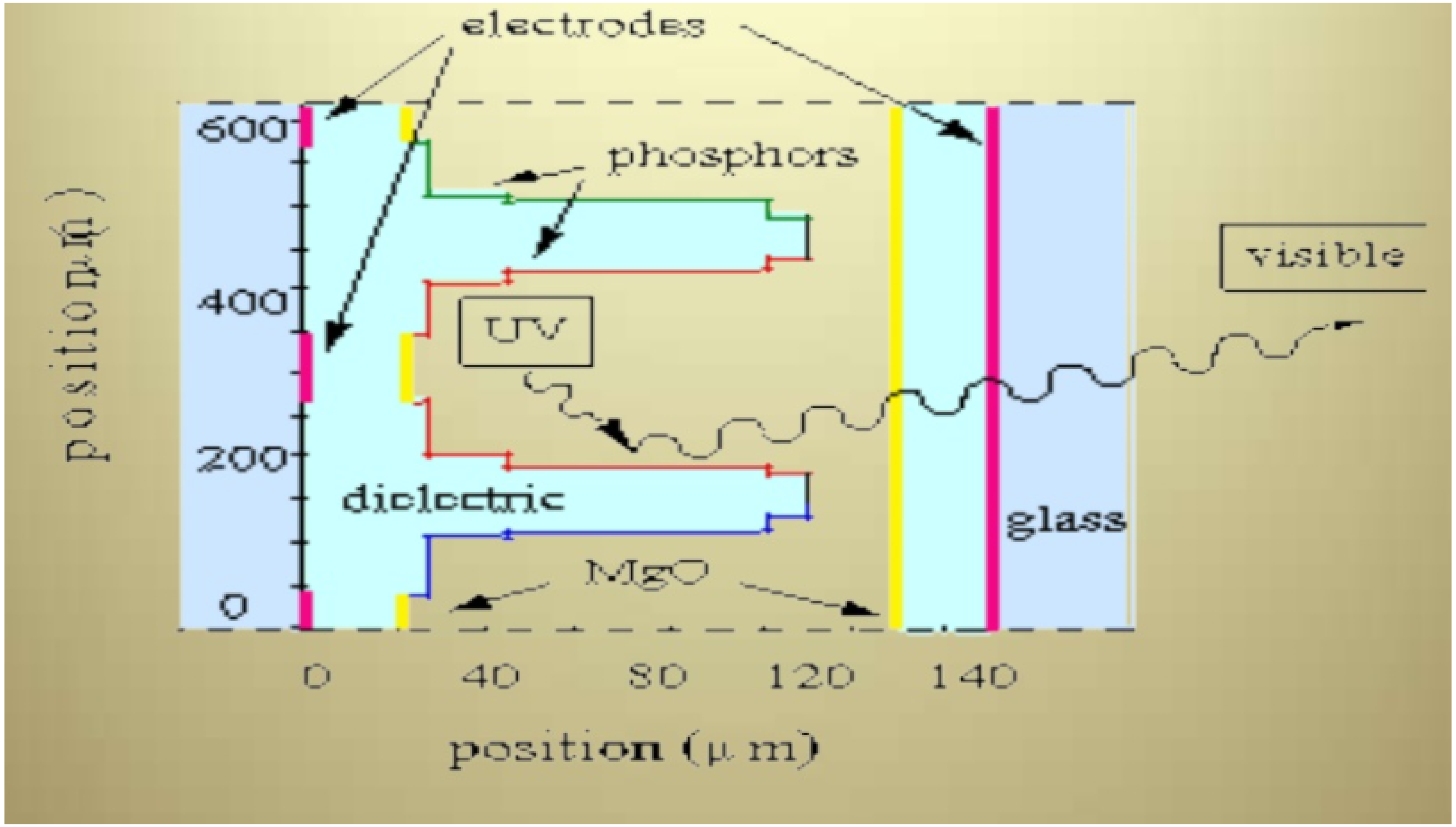
Plasma Displays

- Plasma device is a computer video display in which each pixel on the screen is illuminated by a tiny bit of Plasma or charge gas somewhat like a tiny neon light.
- Plasma displays are thinner than cathode ray tube (CRT) display and brighter than liquid crystal displays (LCD)
- A Plasma display panel is a type of flat panel display common to large TV displays 30 inch or larger
- They are called plasma displays because the technology utilises small cells containing electrically charged ionized gases or what are the essence Chambers more commonly known as fluorescent lamps.



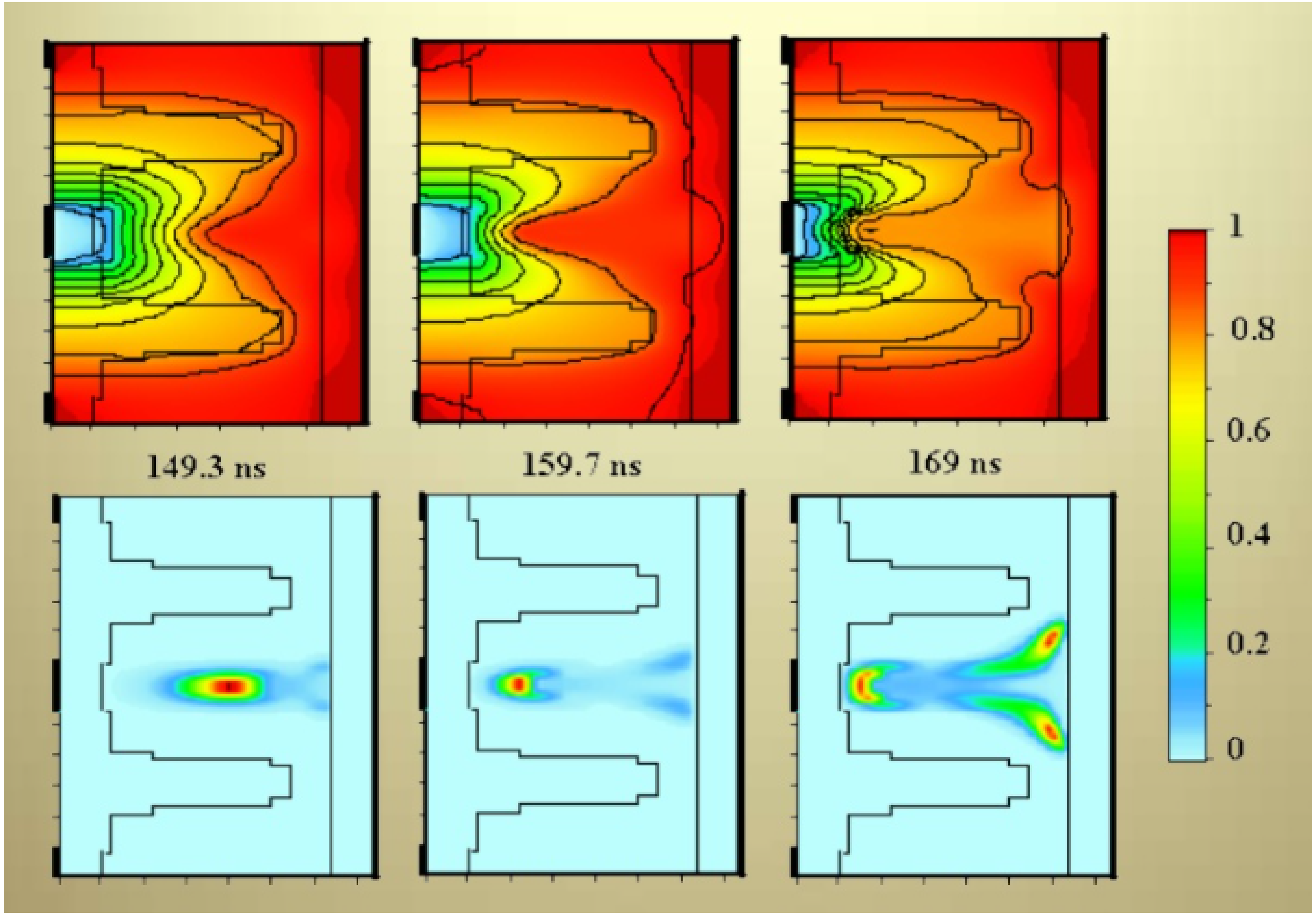
Principle of Plasma display panels

- In Plasma display panels the light of each picture element is emitted from plasma created by an electric discharge.
- The dimension of the discharge are in 100 micrometre range at a pressure of a few hundred torrs and the voltage applied between electrodes is in the 100 to 200 V range



Simulated domain including one cell and two half cells

Space and time variation of the electric potential and Xenon excitation in the cell



General characteristics

- Plasma displays are bright 100 locks or higher for the module
- They have a wide colour range
- They can be produced in fairly large sizes up to 3.8 metres diagonally
- They have very low-luminance "dark room" black level compared with the lighter grey of the unilluminated parts of an LCD screen (i.e. the blacks are blacker on plasma and grayer on LCD screen)
- The display panel itself is about 6 cm think, generally the devices total thickness to be less than 10 cm.
- Power consumption is 400 Watts for a 127 cm (50 inch) screen.
- 200 to 310 watts for a 127 cm display when set to cinema mode
- Most screens are set to 'shop mode' by default which draws at least twice the power of a home setting or less extreme brightness

Native Resolution

Plasma TVs scale the video image to each incoming signal to the native resolution of the display panel

ED resolution

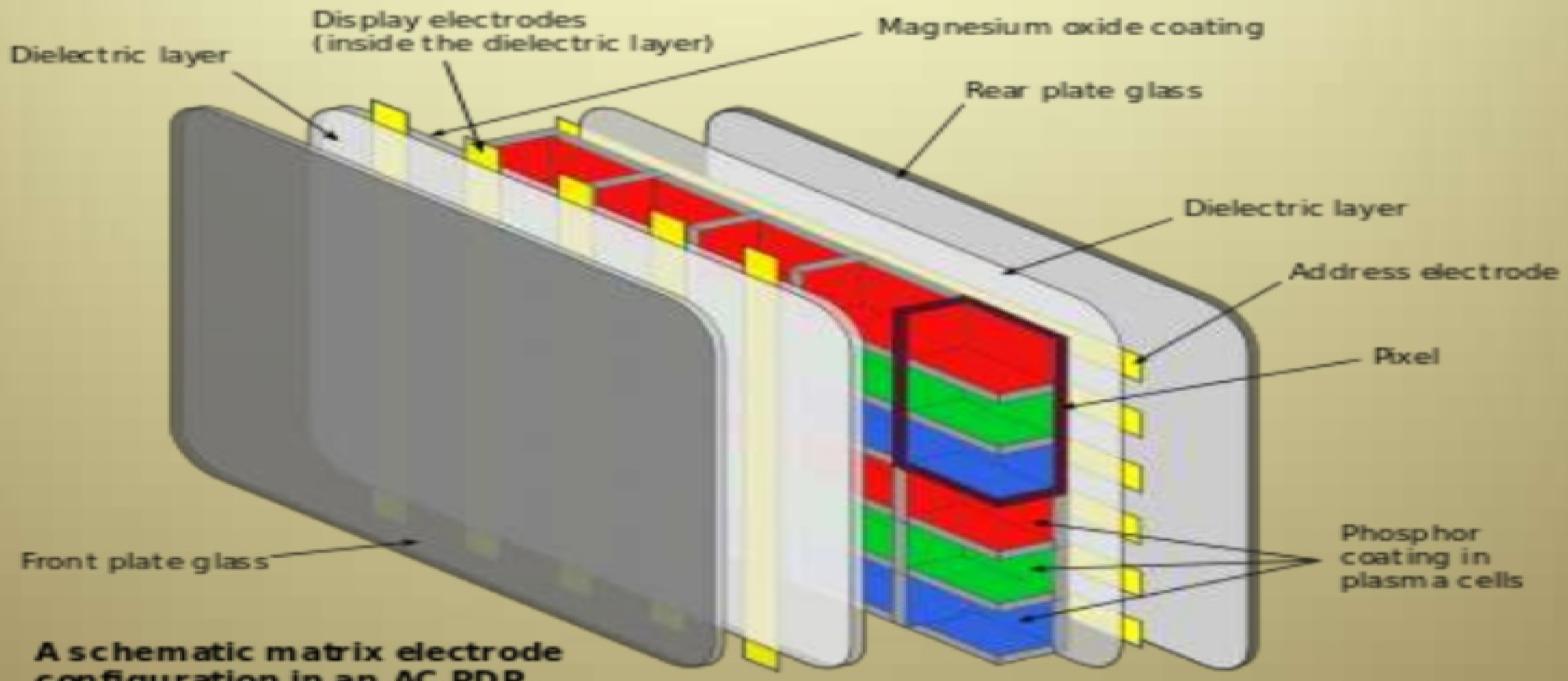
- 840 480
- 853 480

HD resolutions

- 1024 1024
- 1024 768
- 1280 768
- 1366 768
- 1280 1080
- 1920 1080

- This is the trend towards large screen Television Technology, the 32 inch screen is rapidly disappearing.
- Though considered bulky and thick compared with their LCD counterparts, some sets such as Panasonic's Z1 and Samsung's B860 series are as slim as 2.5 cm thick making them comparable to LCDs in this respect.
- Competing display Technologies include cathode ray tube (CRT), Organic light emitting diode (OLED), AMLCD, Digital Light Processing DLP, SED-TV, LED Display, Field Emission display (FED), and Quantum dot display (QLED)

WORKING OF A PLASMA DISPLAY



A schematic matrix electrode configuration in an AC PDP

Advantages

- Picture quality
  - Capable of producing deeper blacks allowing for superior contrast ratio
  - Wider viewing angles then those of LCD; images do not suffer from degradation at high angle like LCDs
  - Less visible monitor blur, very high refresh rates and a faster response time, contributing to superior performance when displaying content

Disadvantages

- Use more electrical power, on an average, then an LCD TV
- Does not work well at high altitudes above 2 kilometres due to pressure difference between the gases inside the screen and the air pressure at altitude.
- It may cause a buzzing noise. for those who wish to listen to AM radio, or are amateur radio operators (HAMs) or shortwave listeners (SWL), the radio frequency interference from these devices can be irritating or disabling.

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