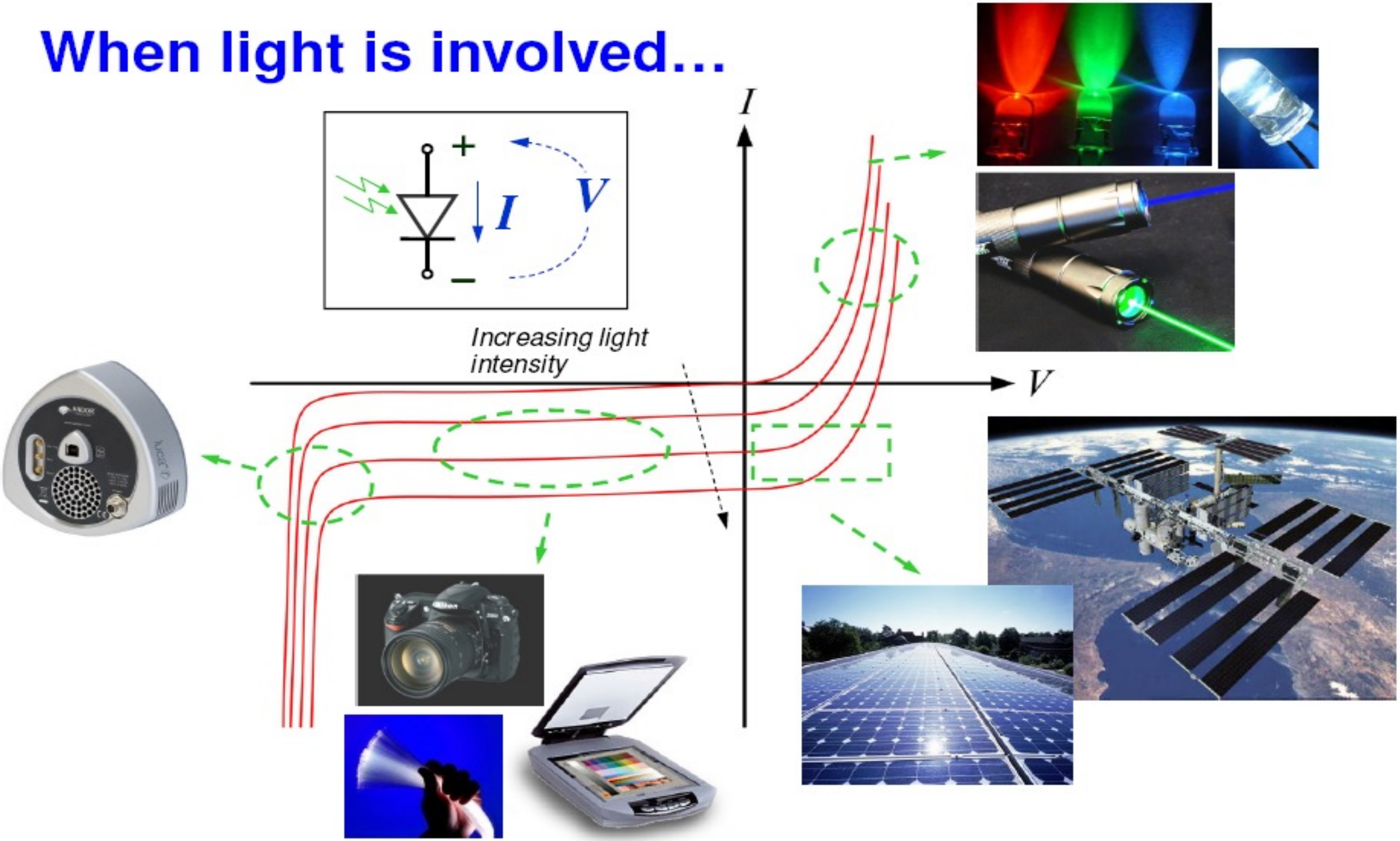
NANYANG TECHNOLOGICAL UNIVERSITY

# *EE2003 Semiconductor Fundamentals*
# (Part III)

# Optoelectronics

# The key is the <u>pn junction</u>

## When light is involved…



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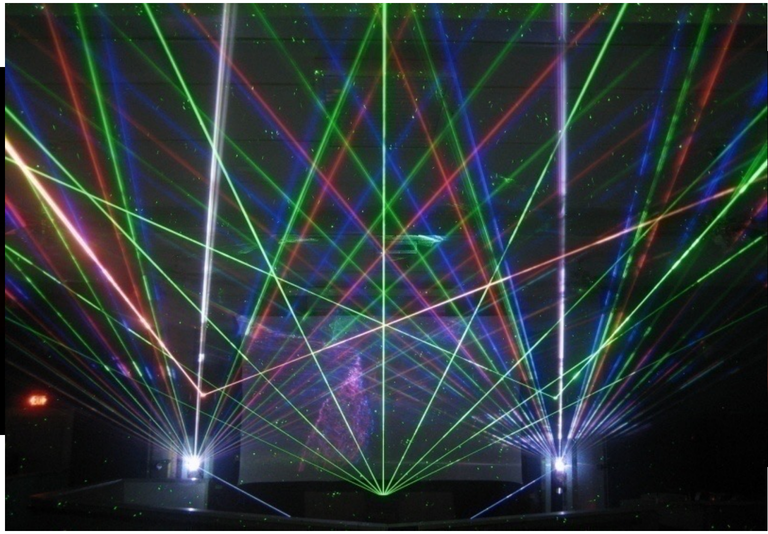
# Lasers and LEDs

# (Lectures 4 - 7)



# What is light ? How to describe it ?

# Wave Nature of Light

- Before the 19th century, light was considered as a stream of particles that either was emitted by the object or emitted from the eyes of the viewer – Newton's particle theory.

- In 1678, Christian Huygens showed that a wave theory of light could also explain reflection and refraction. Theory was not immediately accepted as there is no evidence that light can "bend" around corners.

- In 1801, Thomas Young provided the first demonstration of the wave nature of light - double slit experiment.

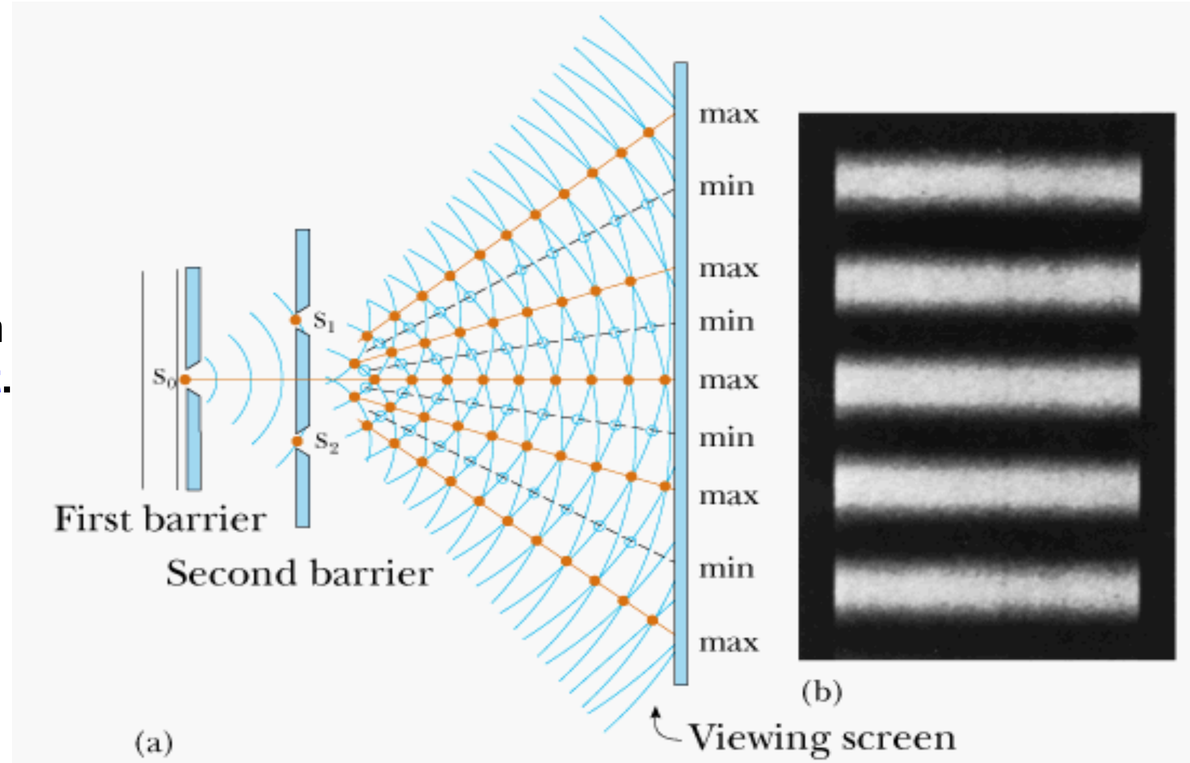



**Figure 2.1: (a) Schematic diagram of Young's double slit experiment. (b) An enlargement of the center of a fringe pattern.**

- In 1873, Maxwell claimed that visible light is a branch of electromagnetic wave.

- In 1887, Hertz provided experimental confirmation of Maxwell's theory by producing and detecting electromagnetic waves that move in the same speed of light.

# Electromagnetic spectrum

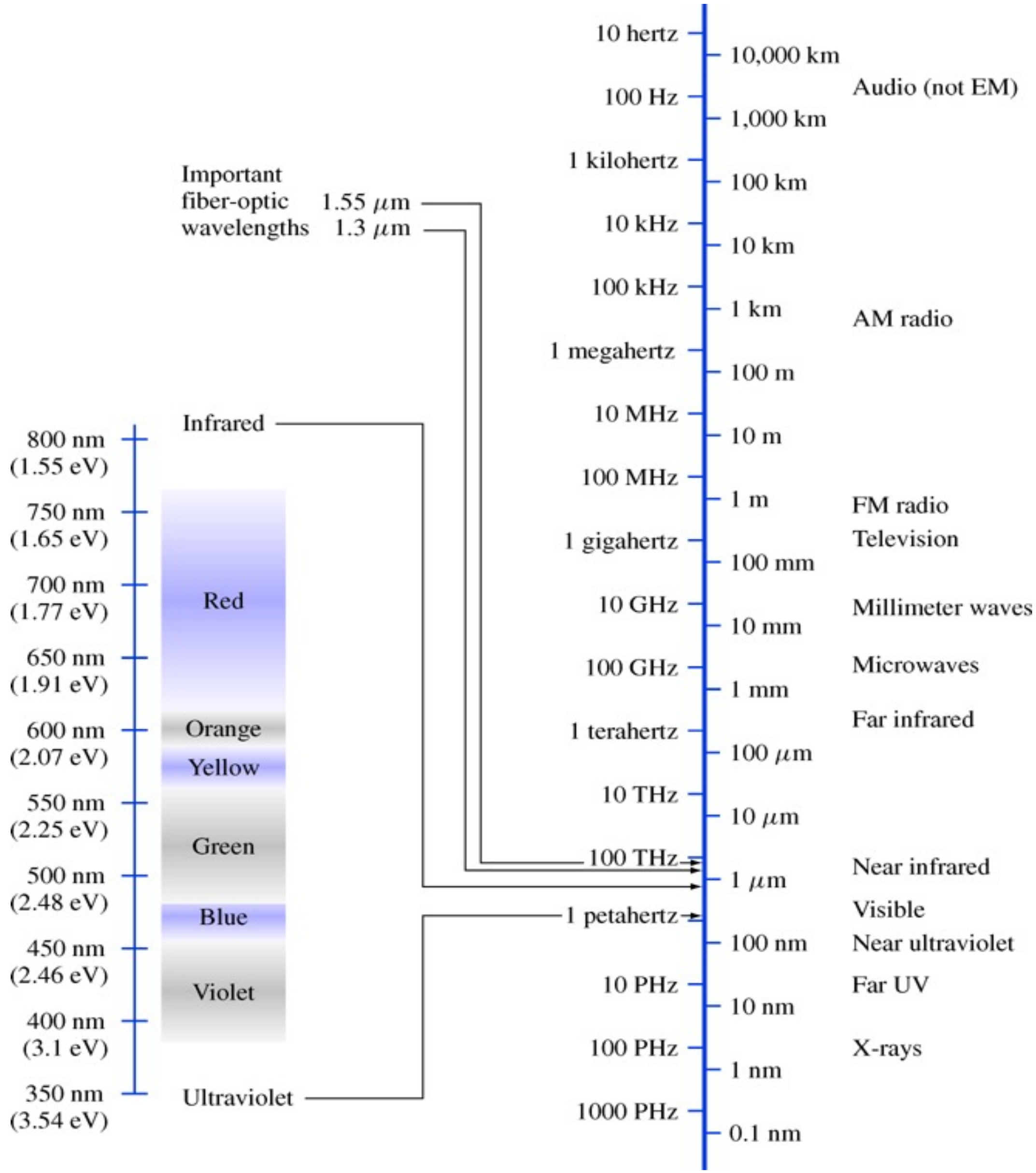



**Figure 2.2 EM spectrum.**

# Particle Nature of Light

- Although the wave model can explain most known properties of light, it cannot explain some subsequent experiments such as the photoelectric effect:

- Light striking a metal surface may eject electrons from the surface and the kinetic energy of the electrons is independent of the light intensity.

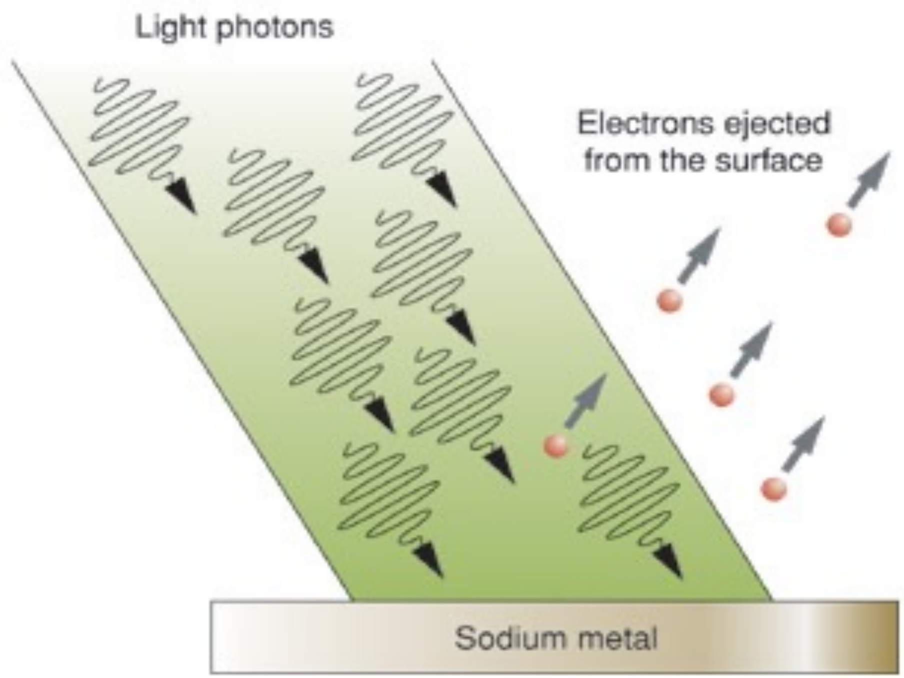



**Figure 2.3 Photoelectric Effect.**

- This finding contradicted the wave theory.

  $\Rightarrow$ more intense beam of light should add more energy to the electrons.

- In 1905, Einstein provided a particle theory that assumes that the energy of the light wave is presented in bundles called *photons*.

- Energy *E* of the photons is quantized and is given by

  $\boxed{E = hf}$ , where *h* is the Planck's constant and *f* is the frequency of the electromagnetic wave.

# Dual Nature of Light

- Light exhibits **characteristics of a wave** in some situations and **characteristics of a particle** in other situations.

- All electromagnetic waves travel through free space (vacuum) with the same speed *c* (3x$10^8$ m/s).

- Unit of light measurement:

  - The radiated power per unit area delivered to a surface is called the irradiance (W/$m^2$ or W/$cm^2$), also called power density or intensity.

# Optoelectronics

- Semiconductor devices designed to interact with electromagnetic radiation in the visible, infrared and UV part of the electromagnetic spectrum.

- Applications can be generally classified into 5 categories:

  1) Stimulated emission (laser diode)
  2) Spontaneous emission (LED)
  3) Photodetection (photodiode etc.)
  4) Photovoltaics (solar cell)
  5) Optical communications (photonics, fiber optics)

# Objectives:

- You will learn how LASERs are created. What are the operation principles?
- You will know the difference between LASERs and LEDs.
- You will learn how many types of lasers are available and what are the differences.
- You will study the characteristics of lasers and LEDs.

# Outline:

2.1 Introduction of Lasers;

**2.1.1 Spontaneous vs stimulated**

**2.1.2 Requirements of lasers**

**2.1.3 Absorption of radiation**

**2.1.4 Laser threshold condition**

2.2 Semiconductor lasers and LEDs;

**2.2.1 Semiconductor lasers**

**2.2.2 LEDs**

2.3 Other types of light emissions;

**2.3.1 Fluorescence and Phosphorescence**

**2.3.2 Plasmon Displays**

**2.3.3 LCDs**

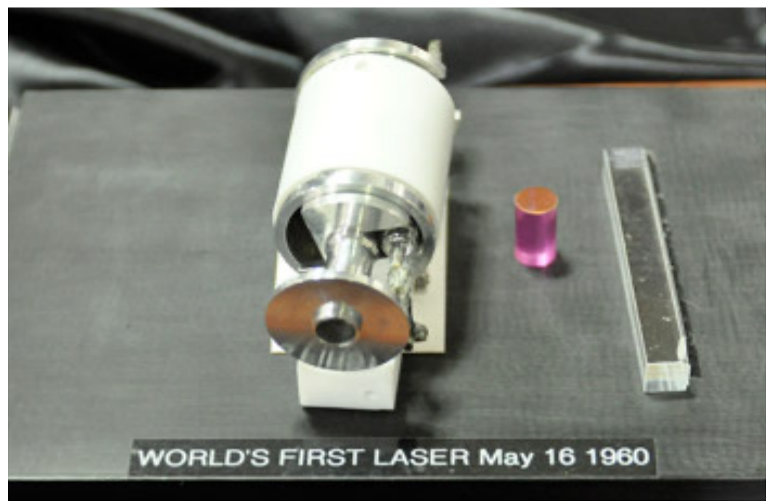
# 2.1 Introduction of lasers

- Laser : Light Amplification by Stimulated Emission of Radiation.

- Laser light is derived from a form of photon emission known as stimulated emission, theoretically predicted in 1917 by Einstein.

- Not until 1960 was the first laser demonstrated by Maiman. It was a Ruby laser, which was $Al_2O_3$ doped with chromium ions ($Cr_3^+$). Its emission occurs at 694.3nm in the deep red.

Shown in the figure are the polished cylinder and flash lamp, along with the pink ruby a centimeter and a half long, and mirrors on either side.



# Introduction

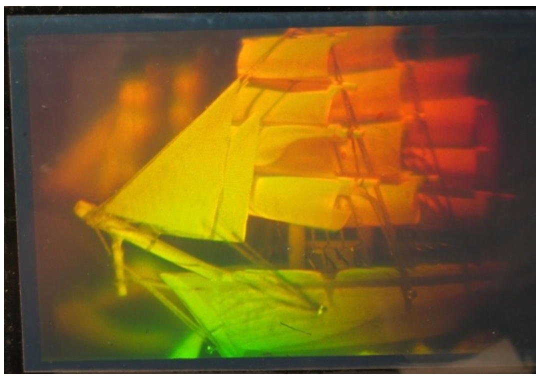
- Laser light is an intense, concentrated, and highly collimated of coherent light.

- Besides solids, laser action can also occur in gases and semiconductors. For semiconductor, laser action is based on direct gap materials where the efficiency for radiative recombination is high.

- Those solids, gases, or semiconductors are called gain medium of the laser, having several discrete energy levels.

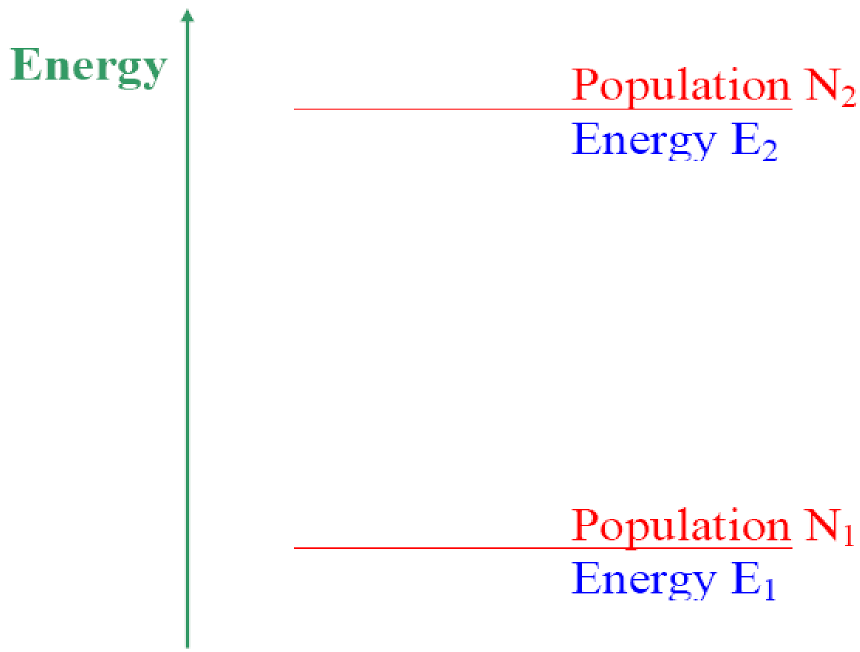
- Light transition takes place among these discrete energy levels.

# Introduction



# Introduction

- Consider in general two energy levels $E_1$ and $E_2$ where radiative recombination can occur in a gain medium.
- There are three transitional processes possible, consisting of (ONE absorption and TWO emissions):

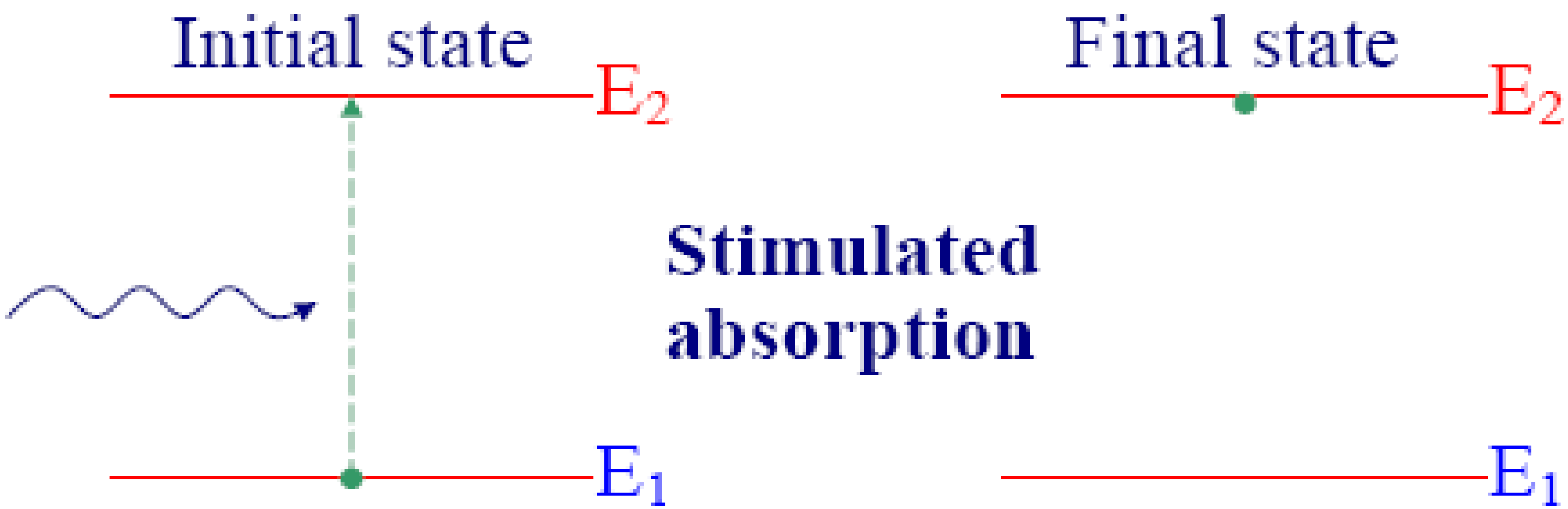



**Two level energy system**

# Introduction

## 1. Stimulated Absorption

An electron in the lower level $E_1$ can be excited to $E_2$ given a photon energy of $hf = E_2 - E_1$. This is an absorption process.



# Introduction

Mathematical description of stimulated absorption

Rate of absorption $R_{ab}$ ( $m^{-3}\ s^{-1}$ ) = $B_{12}\ N_1\ \rho_f$ (A.1)

$N_1$ = No. of electrons per unit vol. with energy $E_1$ ( $m^{-3}$ )

$\rho_f$ = nhf = Photon energy density at frequency f ( $J\ m^{-3}$ )

n = No. of photons per unit vol. with hf = $E_2 - E_1$ ( $m^{-3}$ )

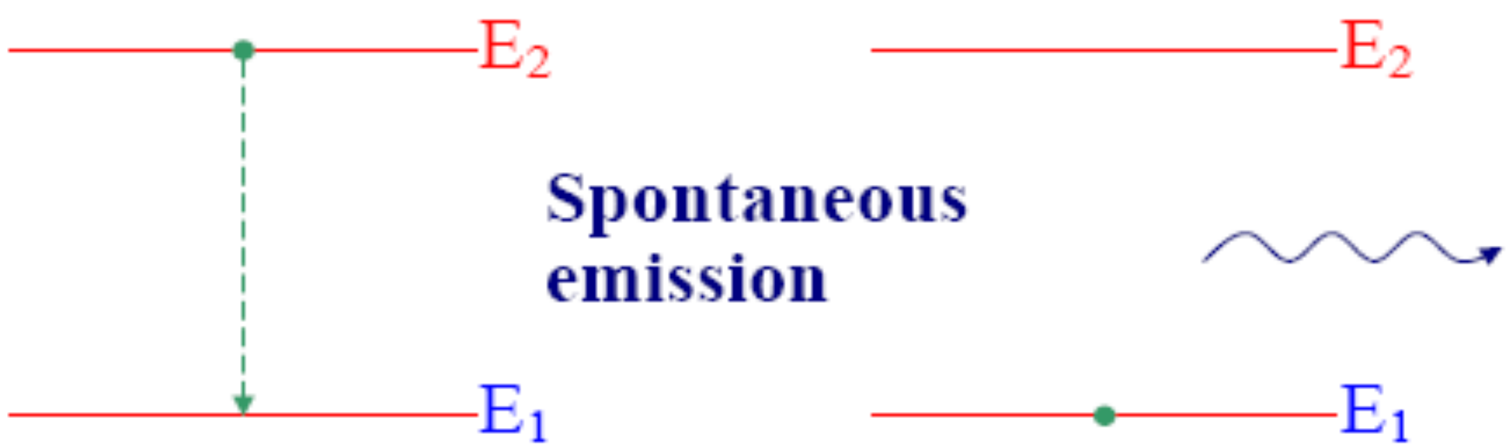
$B_{12}$ = stimulated absorption coefficient

# Introduction

Emissions : An electron in the level $E_2$ can return to the ground state $E_1$ with the emission of a photon with energy hf = $E_2$ - $E_1$. There are two forms:

## 2. Spontaneous Emission

Excited electron decays to $E_1$ in an entirely random way



# Introduction

Mathematical description of spontaneous emission

Rate of spontaneous emission $R_{sp}$ ( $m^{-3}$ $s^{-1}$ ) = $A_{21}$ $N_2$ (A.2)

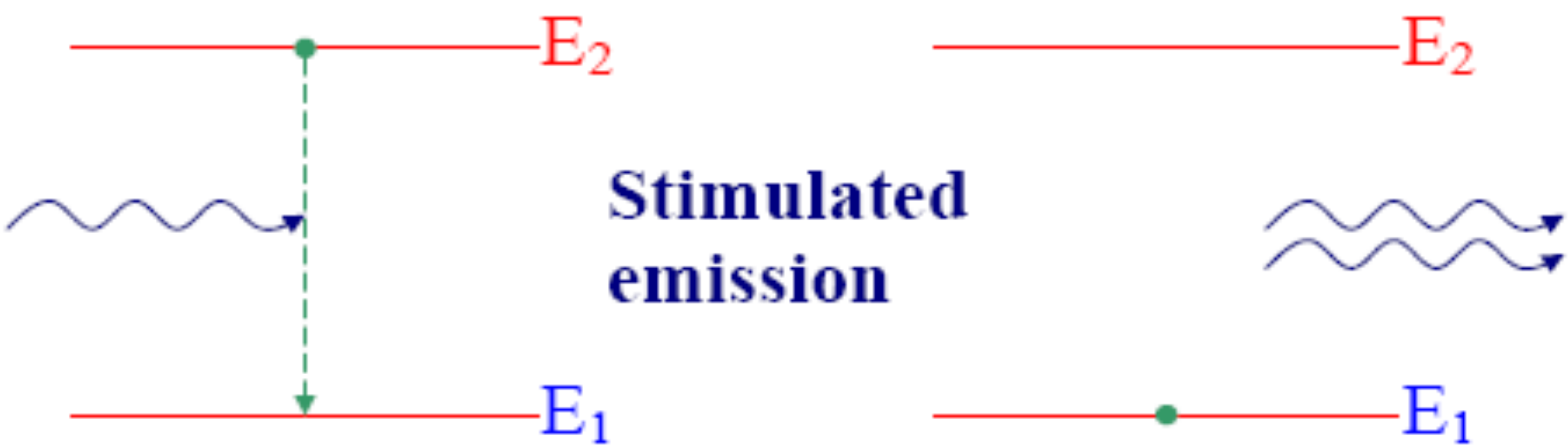
$N_2$ = No. of electrons per unit vol. with energy $E_2$ ( $m^{-3}$ )

$A_{21}$ = spontaneous emission coefficient

# Introduction

## 3. Stimulated Emission

Excited electron is ‘triggered’ to undergo the transition by the presence of photons of energy hf = $E_2$ - $E_1$.



# Introduction

Mathematical description of stimulated emission

Rate of stimulated emission $R_{st}$ ( $m^{-3}$ $s^{-1}$ ) = $B_{21} N_2 \rho_f$ (A.3)

$N_2$ = No. of electrons per unit vol. with energy $E_2$ ( $m^{-3}$ )

$\rho_f$ = nhf = Photon energy density at freq. f ( J $m^{-3}$ )

$B_{21}$ = stimulated emission coefficient

$\mathbf{B_{12}}$, $\mathbf{A_{21}}$ and $\mathbf{B_{21}}$ are the Einstein coefficients.

Comparing the three transition rates from Eqns. (A.1-A.3), we have

$$\frac{R_{st}}{R_{ab}} = \frac{B_{21} N_2 \rho_f}{B_{12} N_1 \rho_f} = \frac{B_{21} N_2}{B_{12} N_1} \qquad \text{(A.4)}$$

$$\frac{R_{st}}{R_{sp}} = \frac{B_{21} N_2 \rho_f}{A_{21} N_2} = \frac{B_{21} \rho_f}{A_{21}} \qquad \text{(A.5)}$$

We can draw the conclusion:

1. For $\mathbf{R_{st} > R_{ab}}$, see Eqn. (A.4), the condition $\mathbf{N_2 > N_1}$ must hold (considering usually $B_{21} = B_{12}$).

   - This is known as population inversion (PI). It cannot be achieved at thermal equilibrium since from Boltzmann's statistics, $\mathbf{N_1 > N_2}$.

2. For $\mathbf{R_{st} > R_{sp}}$, see Eqn. (A.5), a **large photon energy density** $\rho_f$ is required.

# 2.1.1 Spontaneous vs Stimulated

- The stimulated emission process is not observed under normal conditions because the probability of the spontaneous emission happening is much higher.

- Because the spontaneous radiation from any atom is emitted at random, the radiation emitted by a large number of atoms will be incoherent.

- In contrast, the stimulated emission process results in coherent radiation as the waves associated with the stimulating and stimulated photons have identical frequencies.

- Hence; with stimulated emission, the amplitude of an incident wave can grow as it passes through an array of atoms. Thus, an amplification process.

- In spontaneous radiation, any atom is emitted in random in all directions, the radiation emitted by a large number of atoms will be out of phase (incoherent).

- In stimulated emission, emitted photons have the properties:

  1. In phase (coherent) (thus reinforcing with the stimulating photons).
  2. Highly monochromatic (all emitted photons have the same frequency).
  3. Same state of polarization (electric field of the EM waves all vibrating on the same plane).
  4. Directional (travel along the same direction).
  5. Amplification process the amplitude of an incident wave can grow as it passes through an array of atoms.

# 2.1.2 Requirements for lasers

In order to have laser action, i.e. to have stimulated emission dominates, **three requirements** must be met:

1. Population Inversion (PI)

- Population Inversion: the number of electrons in the upper level $\mathbf{E_2}$ should be larger than that in the lower level $\mathbf{E_1}$.

- To achieve PI, some process that will put more electrons into the upper level $\mathbf{E_2}$ (the number of electrons is $N_2$) than the lower level $\mathbf{E_1}$ (the number of electrons is $N_1$) is required.

- This is known as laser pumping.

# Requirements for lasers

- Pumping provides the energy such that **$N_2 > N_1$**. This process is the source of energy for the laser.

- It also results in a non-equilibrium condition as the equilibrium distribution of electrons across different energy levels is disturbed.

- Several pumping techniques are available depending on the types of lasers: optical pumping (e.g. solid-state lasers) and electrical pumping (e.g. semiconductor laser).

# Requirements for lasers

## 2. Optical cavity

- This is to enhance photons building up.
- With population inversion, there are a large number of excited electrons readily to be de-excited back to the lower energy states.

# Requirements for lasers

- Stimulated emission requires photons of energy **$hf = E_2 - E_1$** to trigger the de-excitation.

- Thus, to ensure that most of the excited electrons will undergo stimulated emission, rather than spontaneous emission, a large photon energy density is required.

- The large photon energy density or the stimulated emission can be achieved through an optical cavity (optical feedback):

# Requirements for lasers

➢ That is, add two carefully aligned end mirrors to the laser medium to form a resonant cavity where photon density can build up through multiple reflection.

➢ This type of arrangement is called the Fabry-Perot cavity.

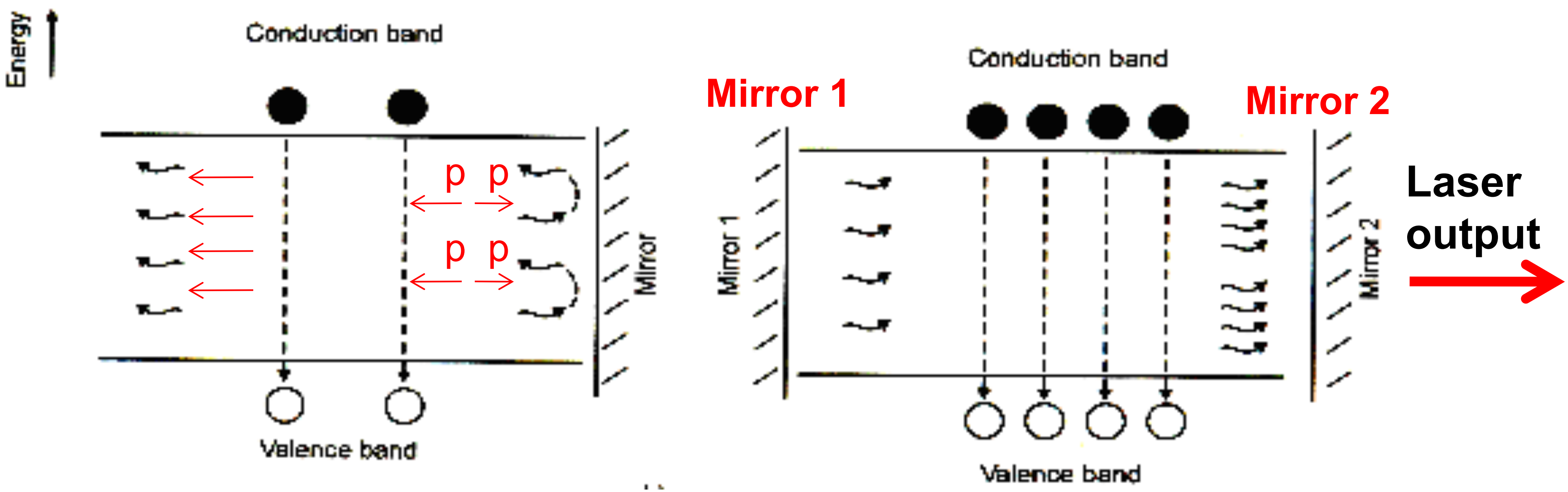



Figure 2.4 Fabry-Perot cavity

# Fabry-Perot cavity

In the Fabry-Perot cavity, usually one mirror (Mirror 2 in the figure in the last slide) is made less reflective so that some photons can get transmitted out of the medium.

This small percentage of light transmitted is the laser output.

# Requirements for lasers

## 3. Optical gain > optical loss

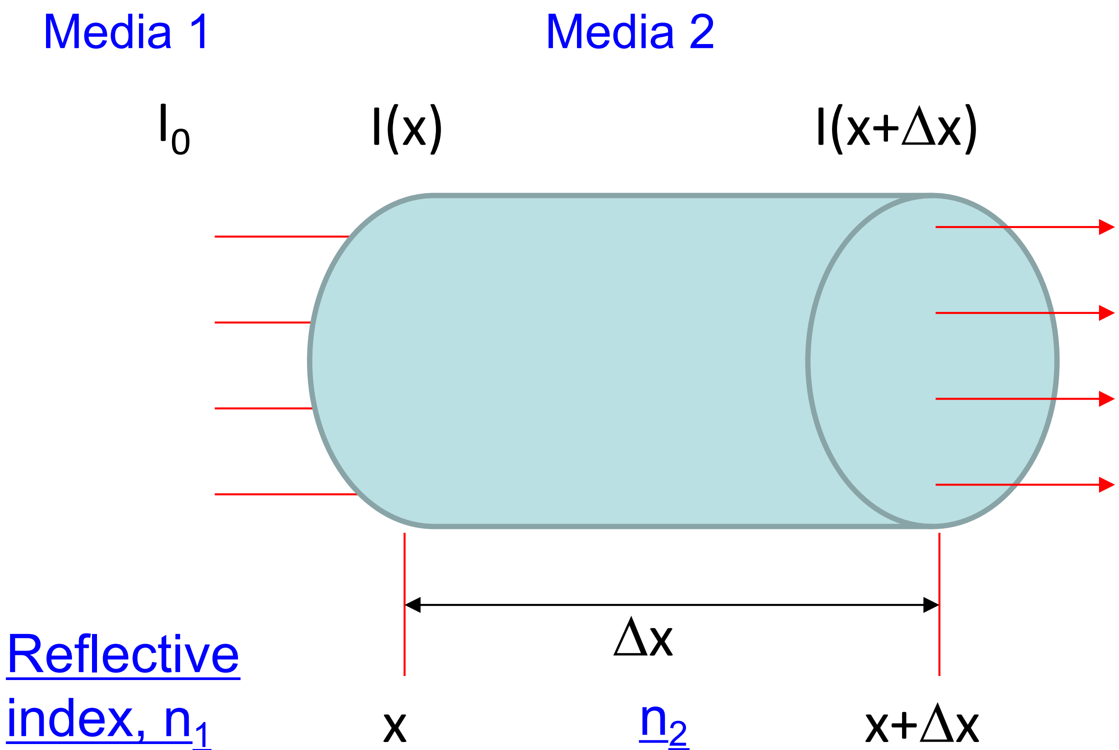
- This is to allow laser operated above the threshold condition.

- We will discuss about this requirement in the later part of this chapter.

## Summary

- Up to now, you should know what is a laser.
- You should learn what are the requirements to achieve lasing actions.
- You should know what is population inversion, and how to achieve that.
- You should learn the difference between spontaneous emission and stimulated emission.
- You should know why an optical cavity is used.

# 2.1.3 Absorption of radiation




- Speed of light in any material ($v$) is smaller than that in vacuum ($c$) → refractive index $n = c/v$ or $v = c/n$.

# Absorption of radiation

- Consider a beam of monochromatic radiation, perfectly collimated of unity cross-sectional area passing through an absorbing medium.

- When a material, e.g. semiconductor, is illuminated with light, some of the photons will transmit, some of them will be reflected, some of them may be absorbed.

- Normally, medium 1 refers to air.

# Absorption of radiation

**1)** If without considering the reflection at the interface between the Medium 1 and Medium 2 (the absorption material).

In passing through, if the photon energy is larger than the bandgap of the semiconductor, electron transitions can occur between energy levels $E_1$ and $E_2$. Then:

$$\Delta I(x) = I(x + \Delta x) - I(x)$$

$\Delta I(x)$ = Change in irradiance of the beam as a function of distance.

$I(x)$ = Original light irradiance in the medium.

$I(x+\Delta x)$ = Final light irradiance in the medium.

# Absorption of radiation

For homogeneous medium; $\Delta I(x)$ is LINEAR proportional to both $\Delta x$ and $I(x)$. Hence;

$$\Delta I(x) = -\alpha I(x) \Delta x$$

$\alpha$ = Absorption coefficient ($m^{-1}$ or $cm^{-1}$)

The irradiance is reduced due to absorption, hence the negative sign. Hence, divide $\Delta x$ on each side, we have

$$\frac{dI(x)}{dx} = -\alpha I(x)$$

# Absorption of radiation

Integrating the above equation gives

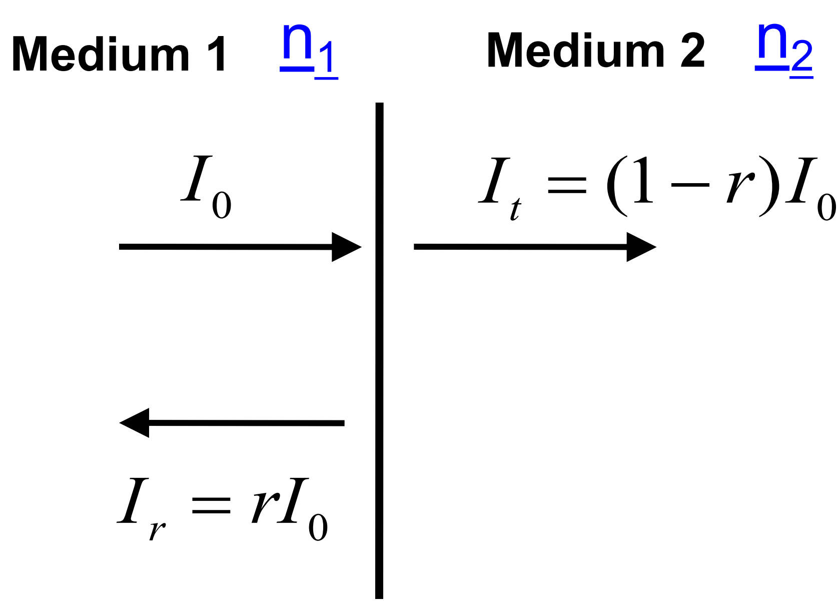
$$\boxed{I(x) = I_t e^{-\alpha x}} \qquad (2.1)$$

where $I_t$ is the incident irradiance in Medium 2.

# Fresnel reflection

**2)** If with consideration of the reflection at the interface between the Medium 1 and Medium 2 (the absorption material).

Due to the difference in the refractive index, part of $\mathbf{I_o}$ will be reflected and the remaining will be transmitted. This reflection is known as Fresnel reflection.



# Fresnel reflection

With consideration of the Fresnel reflection, the reflected power $I_r$, at the interface between Medium 1 and 2, can be expressed as:

$$\boxed{I_r = rI_0 = I_0\left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2} \qquad (2.2)$$

where *r* is the reflectivity.

# Fresnel reflection

Then the transmitted power $I_t$ is :

$$\boxed{I_t = (1 - r) I_0} \qquad (2.3)$$

# Example 1:

Consider light radiation of **hf** = 1.2eV (infrared) with intensity 100mW/$m^2$ incidence normally from air onto a Si wafer.

Calculate (a) the reflected intensity

(b) the intensity absorbed in Si upon traveling the first 20$\mu$m

For Si, take n = 3.56 and $\alpha$ = 3.4x$10^3$ $m^{-1}$ for **hf** = 1.2eV,

# Example 1:

(a) At 1.2eV (it is larger than the bandgap of Si of 1.12 eV, so the light will be absorbed in Silicon),

$n_1$ = 1 (air) and $n_2$ = 3.56 (Si), using Eqn (2.2)

$$r = \left(\frac{1-3.56}{1+3.56}\right)^2 = 0.315$$

$$I_r = 0.315 \times 100 = 31.5 \text{ mW/m}^2$$

# Example 1:

(b) For 1.2 eV, intensity transmitted into Si:

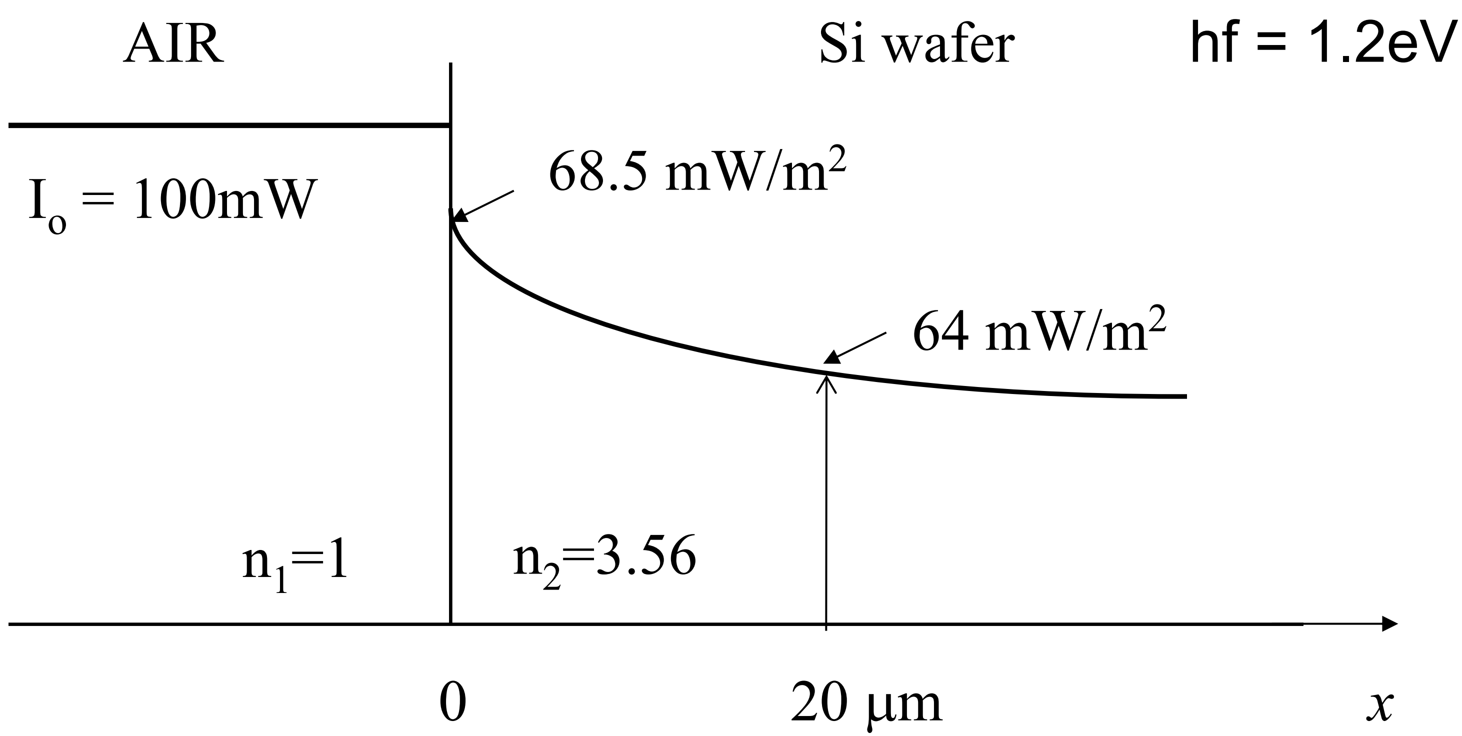
$I_t$ = 100 – 31.5 = 68.5 mW/m$^2$
Using Eqn (2.1), at 20μm in Si, the intensity drops to

$$I(x = 20\mu m) = I_t e^{-\alpha x}$$

$$= 68.5 \times \exp(-3.4 \times 10^3 \times 20 \times 10^{-6}) = 64 \text{ mW/m}^2$$

Intensity absorbed over the first 20 μm is: $I_{abs}$ = 68.5 – 64 = 4.5 mW/m$^2$

# Example 1:


AIR
Si wafer
hf = 1.2eV
68.5 mW/m²
I$_o$ = 100mW
64 mW/m²
n$_1$=1
n$_2$=3.56
0
20 μm
x

# Example 2:

Similar to example 1, but the light radiation is at the photon energy, 2eV (red), with intensity 100mW/m$^2$ incidence normally from air onto a Si wafer.

Calculate (a) the reflected intensity

(b) the intensity absorbed in Si upon traveling the first 20$\mu$m

For Si, take n = 3.91 and $\alpha$ = 4.5x10$^5$m$^{-1}$ for **hf** = 2eV.

# Example 2:

(a) At 2eV (it is larger than the bandgap of Si of 1.12 eV, so the light will be absorbed in Silicon),

$n_1$ = 1 (air) and $n_2$ = 3.91 (Si), using Eqn (2.2)

$$r = \left(\frac{1-3.91}{1+3.91}\right)^2 = 0.351$$

$$I_r = 0.351 \times 100 = 35.1 \quad \text{mW/m}^2$$

# Example 2:

(b) For 2 eV, intensity transmitted into Si:

$I_t$ = 100 – 35.1 = 64.9 mW/m$^2$

Using Eqn (1), at 20μm in Si, the intensity drops to

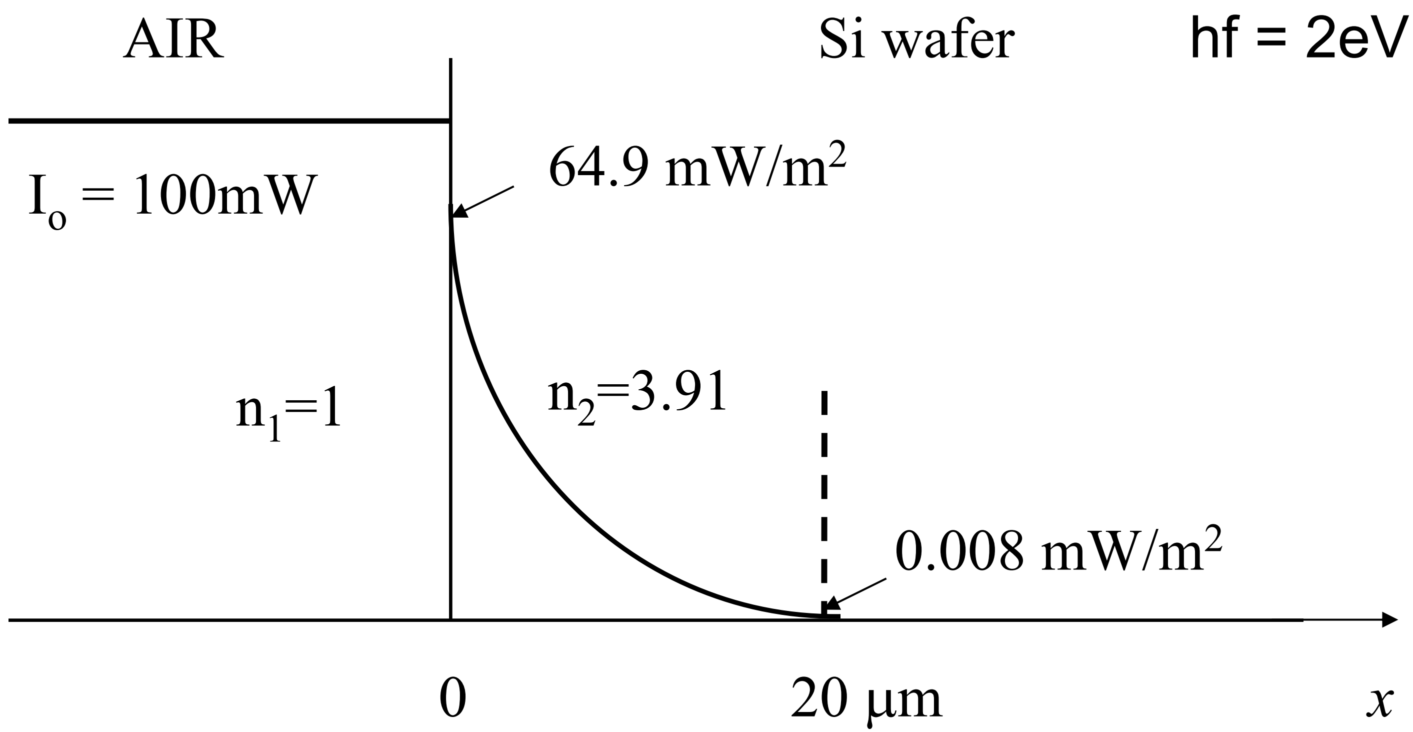
$$I(x = 20\mu m) = I_t e^{-\alpha x}$$

$$= 64.9 \times \exp(-4.5 \times 10^5 \times 20 \times 10^{-6}) = 0.008 \text{ mW/m}^2$$

Intensity absorbed over the first 20 μm is:

$I_{abs}$ = 64.9 – 0.008 ≈ 64.9 mW/m$^2$

# Example 2:




Note: Due to the larger value of $\alpha$ at the higher photon energy of 2eV ($E_g$=1.12eV for Si), light is almost entirely absorbed in the first 20μm.

The higher the refractive index of the absorption medium, the higher the reflection at the interface.

# 2.1.4 Laser Threshold Condition

- Population inversion is a necessary condition for laser action.

- However, it is not a sufficient one because the minimum or threshold value of gain coefficient must be large enough to overcome the losses and sustain oscillations.

- A steady-state level of oscillation will be reached when the rate of amplification is balanced by the rate of loss.

# Laser Threshold Condition

Important losses of the laser system are:

1) Absorption in the laser medium due to transitions other than the desired transitions.

2) Scattering due to optical inhomogeneities in the laser medium.

3) Transmission at the mirrors: – the transmission from one of the mirrors usually provides the useful output (useful "loss"), the other mirror is made as reflective as possible to minimize losses.

4) Absorption and scattering at the mirrors.

5) Diffraction losses at the mirrors.

# Laser Threshold Condition

- The loss effects (except the mirror loss, loss item 1 in the last slide) can be modeled by a loss coefficient $\gamma$ (unit $cm^{-1}$) , i.e. **$I = I_o \exp(-\gamma L)$** ( $\gamma > 0$ ), where L is the cavity length.

- The gain medium provides gain (amplification) to the generated light.

- Overall, if we define the gain of the material as ***k*** (unit $cm^{-1}$), then the irradiance will vary as

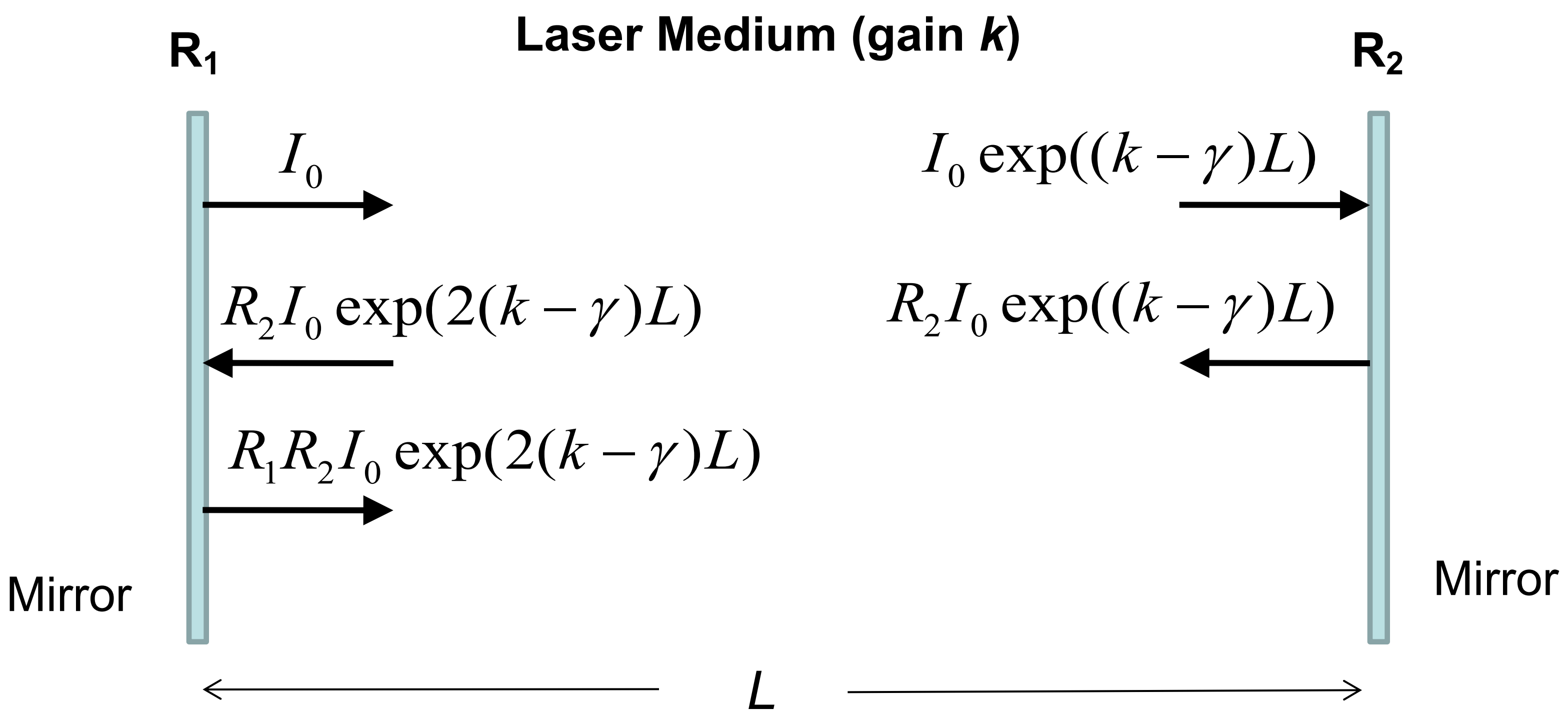
$$I = I_0 \exp((k - \gamma)L)$$

# Laser Threshold Condition

- We define an overall gain coefficient in the medium given by **( *k* -** $\gamma$ **)**.
- For a net build up of irradiance, the gain ***k*** must be large enough to cover $\gamma$ , and the mirror losses.
- The gain ***k*** is normally a function of the pumping strength (e.g. pumping current), and the wavelength.
- This condition determines the laser action and hence how strongly should the system be pumped.

# Laser Threshold Condition

**In a cavity**, we shall determine the threshold gain by considering the change in irradiance of a beam of light undergoing a round trip within the laser cavity.




where $R_1$ and $R_2$ = mirror reflectance
L = cavity length

# Laser Threshold Condition

- After one round trip, the irradiance changes from $\mathbf{I_o}$ to

$$I = R_1 \, R_2 \, I_0 \exp(2(k-\gamma)L)$$

- Then we can define round trip gain **G** as

$$G = \frac{I}{I_0}$$

$$= R_1 \, R_2 \exp(2(k-\gamma)L) \qquad (2.4)$$

# Laser Threshold Condition

- If $G > 1$, there will be net amplification and the laser oscillations will grow.
- If $G < 1$, the oscillations will die out.
- The threshold condition for gain is:

$$G = R_1 R_2 e^{2(k_{th} - \gamma)L} = 1$$

# Laser Threshold Condition

We have not considered the mirror loss. If we consider this loss, we have

**(mirror loss also needs to be considered)**

$k_{th}$ = threshold gain $= \gamma +$ useful loss (mirror loss)

$$= \gamma + \boxed{\frac{1}{2L}\ln\left(\frac{1}{R_1 R_2}\right)}$$

Unit: $cm^{-1}$ (2.5)

$\gamma$ is the cavity loss.

*Not necessary to know how to derive it in this course*

# Laser Threshold Condition

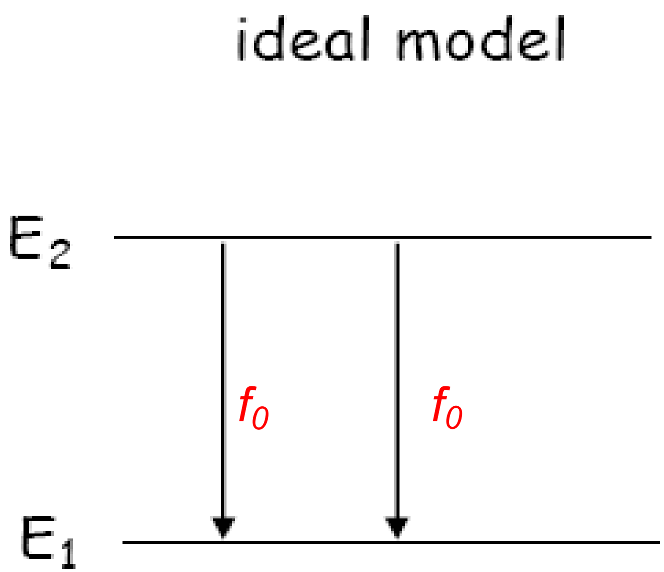
- The threshold condition is also the steady state condition since the irradiance is maintained constant, and is neither building up nor decaying.

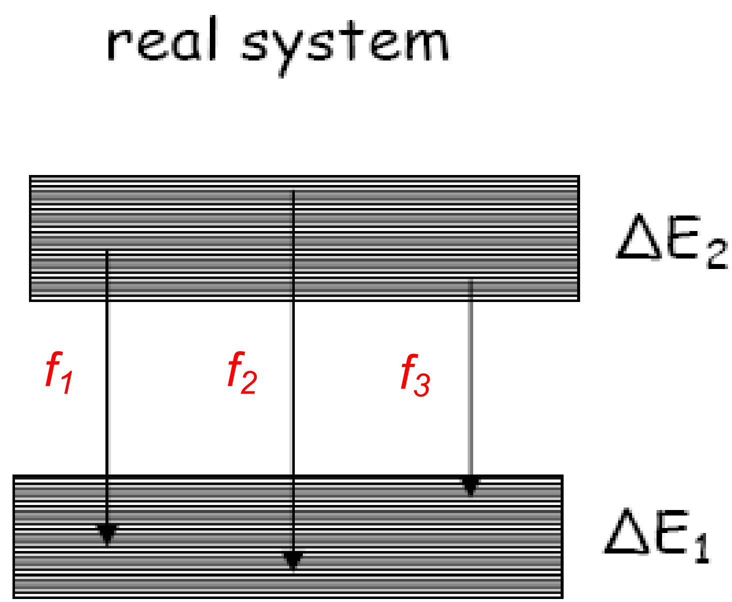
- At this condition, the optical gain $\mathbf{k_{th}}$ is exactly equal to the total losses, which consists of the medium loss $\gamma$ and the mirror loss $\alpha_m = 1/(2L) \times \ln(1/(R_1 R_2))$.

# Lineshape Function

➢ It has been assumed that all the atoms in either the upper or lower levels will be able to interact with the perfectly monochromatic beam.

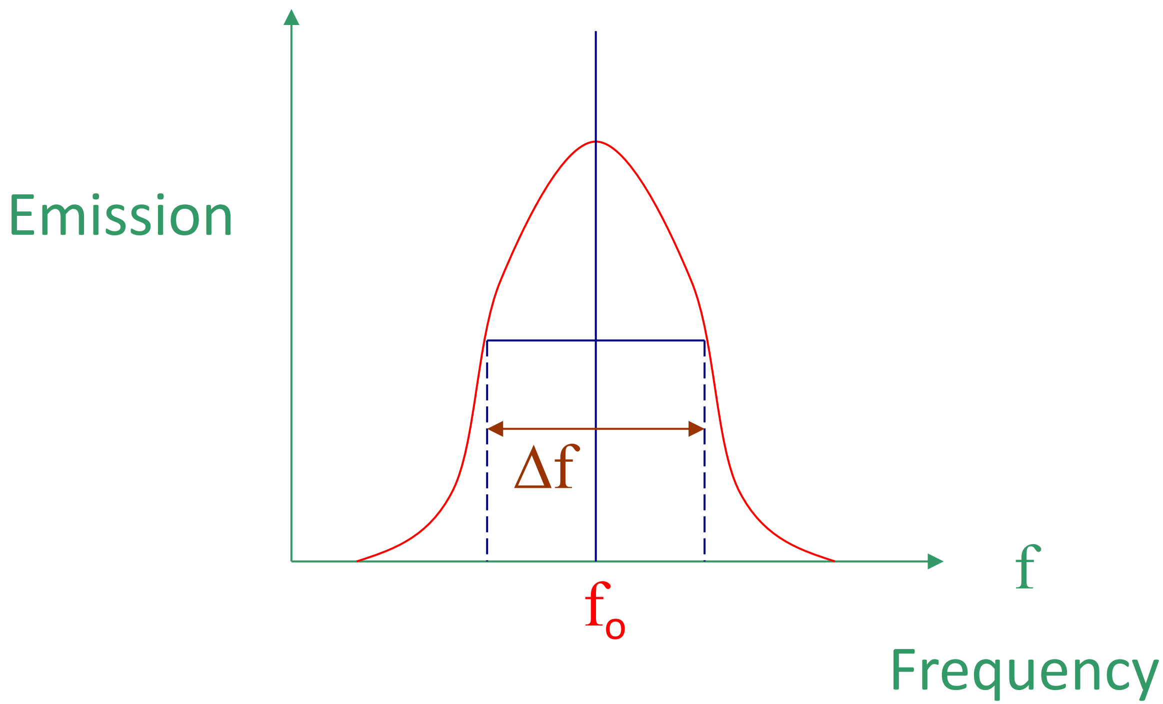
➢ In practice, spectral lines have a finite wavelength (or frequency) spread known as <u>spectral linewidth (lineshape)</u>.



# Lineshape Function

This results in an emission curve like:




**Emission curve for transitions between $E_2$ and and $E_1$**

# Lineshape Function

- The shape of this curve is described by the lineshape function $g(f)$.

- $g(f)$ defines the probability that a given transition between the 2 energy levels will result in the emission (or absorption) of a photon whose frequency lies between $f_0-\Delta f/2$ and $f_0+\Delta f/2$.

- g(f) defines that the stimulated photon will have an energy between $f_0-\Delta f/2$ and $f_0+\Delta f/2$.

# Summary

- To achieve lasing action, population inversion is the necessary condition. One also has to make sure the gain of the medium is higher than the total losses.

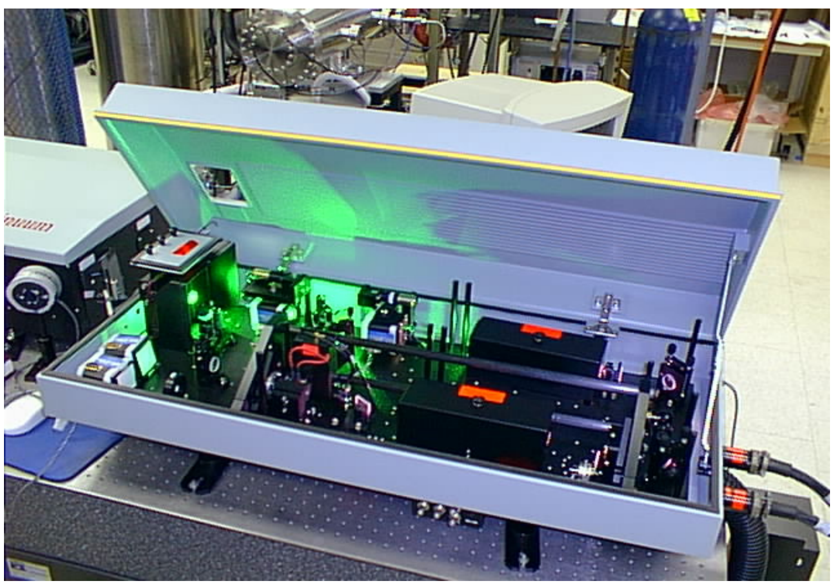
- The losses normally consists of the cavity loss and the mirror loss, where the mirror loss is a “useful” loss.

- In practice, lasers have a finite wavelength (or frequency) spread, a finite linewidth or lineshape.

# Classes of Lasers

## a) Solid-state laser

- Active medium consists of atoms in crystalline form with impurity atoms intentionally doped during growth.
- Rugged, and capable of delivering high power.
- Typical examples: Nd: YAG lasers are more widely used, at 1.06 μm. Optically pumped (e.g. flash lamp).

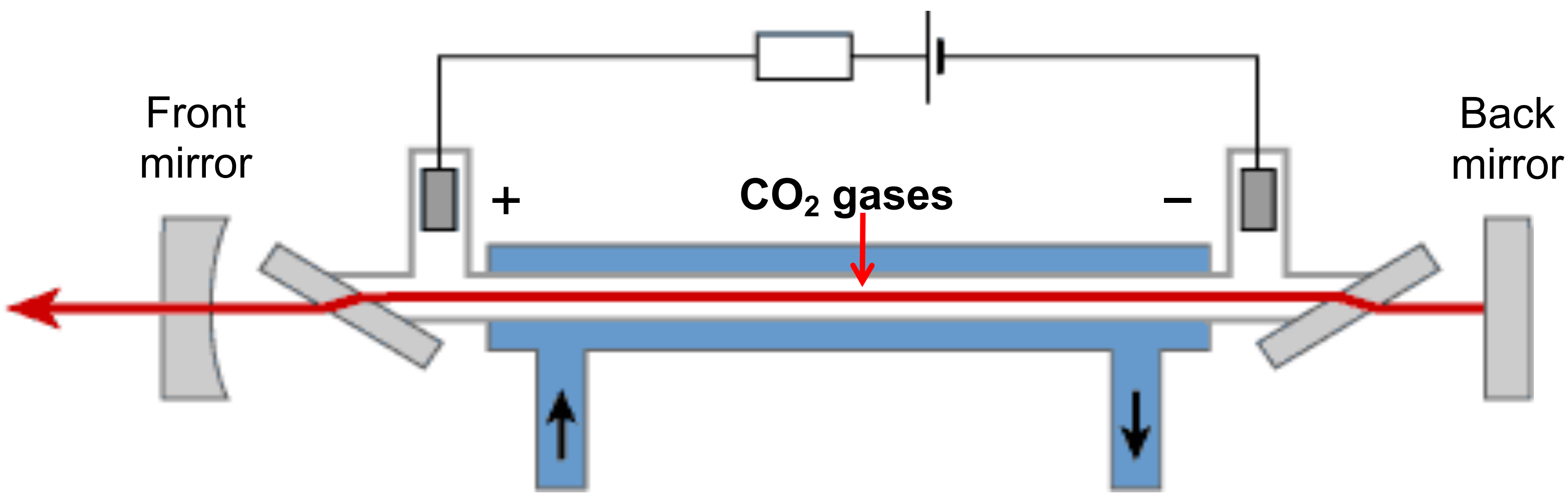


Nd:YAG laser with lid open showing frequency-doubled 532 nm green light

# b) Gas Lasers

- Widely used in industries (e.g. high power $CO_2$ lasers, kW) and laboratories (e.g. low power He-Ne laser, medium power Ar ion laser).

- Electrically pumped (electron collisions in a gas discharge).




**Schematic structure of a $CO_2$ laser emitting at 10.6 μm.**

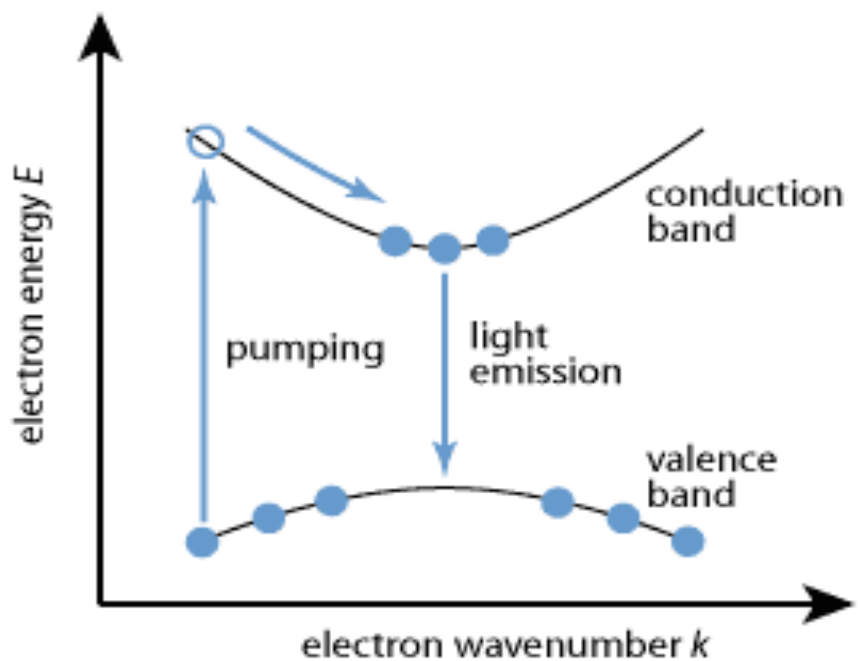
# c) Semiconductor Lasers (or diode lasers)

- The active medium is formed by a semiconductor pn junction.
- They are electrically pumped light sources, compact, low-cost, high pump efficiency lasers.
- They can cover a wavelength range from visible to the infrared.
- It is widely used for optical communications, CD writers, and as pump lasers for other laser sources.

# 2.2 Semiconductor lasers and LEDs

- Recall that radiative recombination in semiconductors occurs when electrons from conduction band (**CB**) undergo **direct recombination** with holes in the valence band (**VB**).

- Both lasers and LEDs are based on radiative recombination in semiconductors.



# 2.2.1 Semiconductor Lasers

- First fabricated in 1962. Also called laser diode (LD). It has attractive characteristics such as compact size and low cost. It is the ultimate optoelectronic source.

- To have high efficiency radiative recombination, only direct gap semiconductors (e.g. GaAs) are used as active media for LD. Indirect bandgap semiconductors (e.g. Ge and Si) are not used.

- The LD working principle is exactly the same as discussed before. We need an active medium (direct gap semiconductor), population inversion (PI) and an optical resonant cavity.

- PI in semiconductors corresponds to the condition where there are many excited electrons in the **CB** and many holes in the **VB** present together, readily to recombine radiatively.

- This can be achieved by having a both p and n sides <u>heavily doped pn junction</u> under <u>strong forward bias (FB).</u>

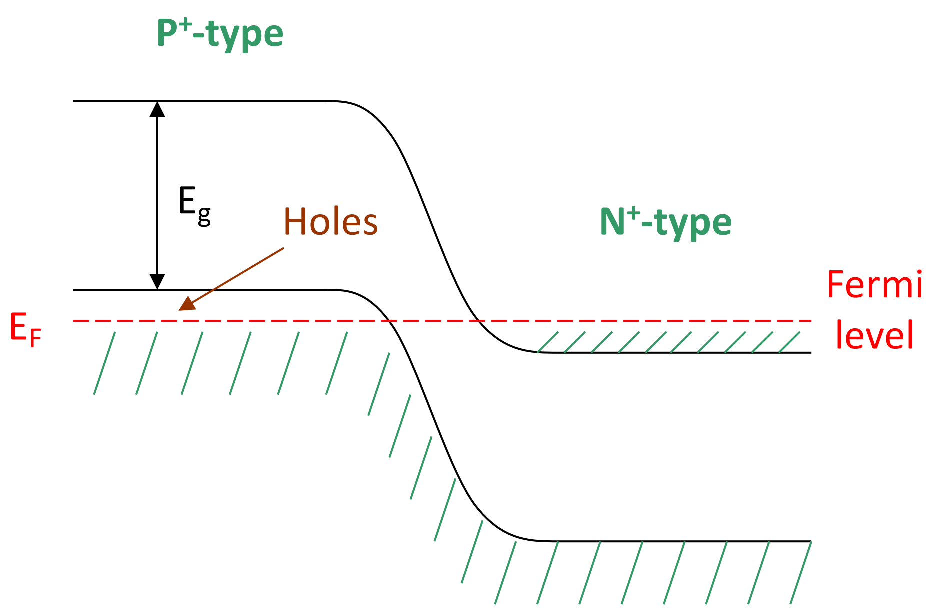
- Recall that under FB, we have minority carrier injection, where majority carriers are injected across the depletion region **W** to the opposite side as minority carriers.

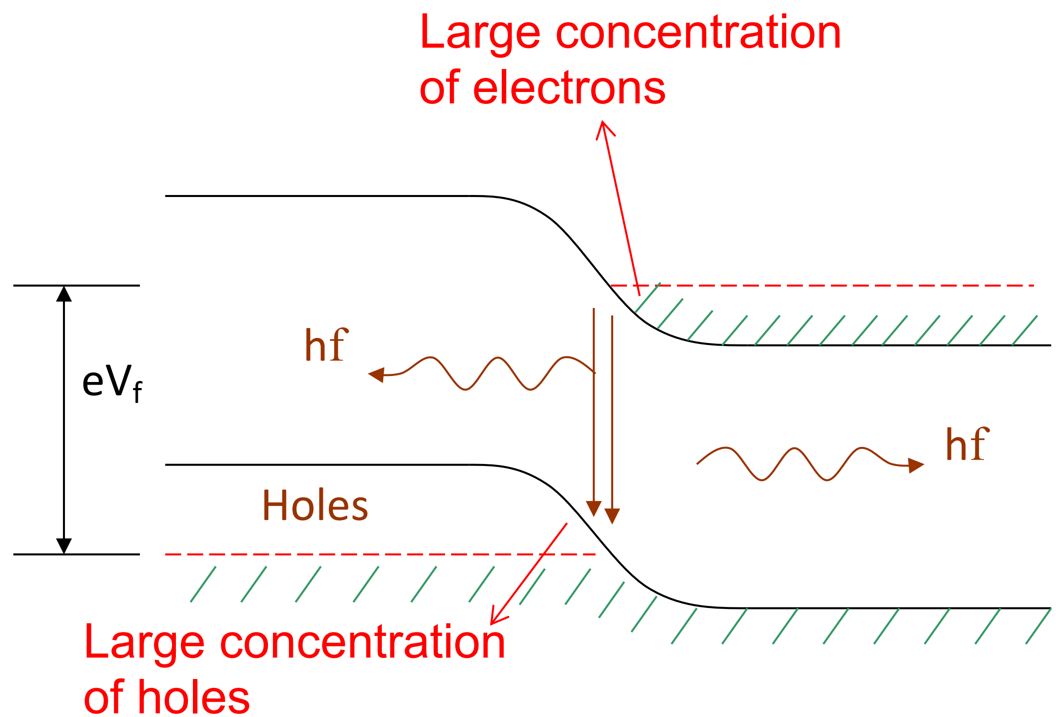
- Once injected across, <u>the minority carriers diffuse</u> inwards into the bulk neutral regions and <u>recombine with the majority carriers</u>.

- If the semiconductor is of direct gap material, then the recombination process will be direct, giving out photons as a result.

# Energy band diagrams of a LD

It can be shown that the doping must be so heavy that the Fermi levels lie above the band edges. i.e. $\mathbf{E_{Fn} > E_c}$ at the n-side and $\mathbf{E_{Fp} < E_v}$ at the p-side.

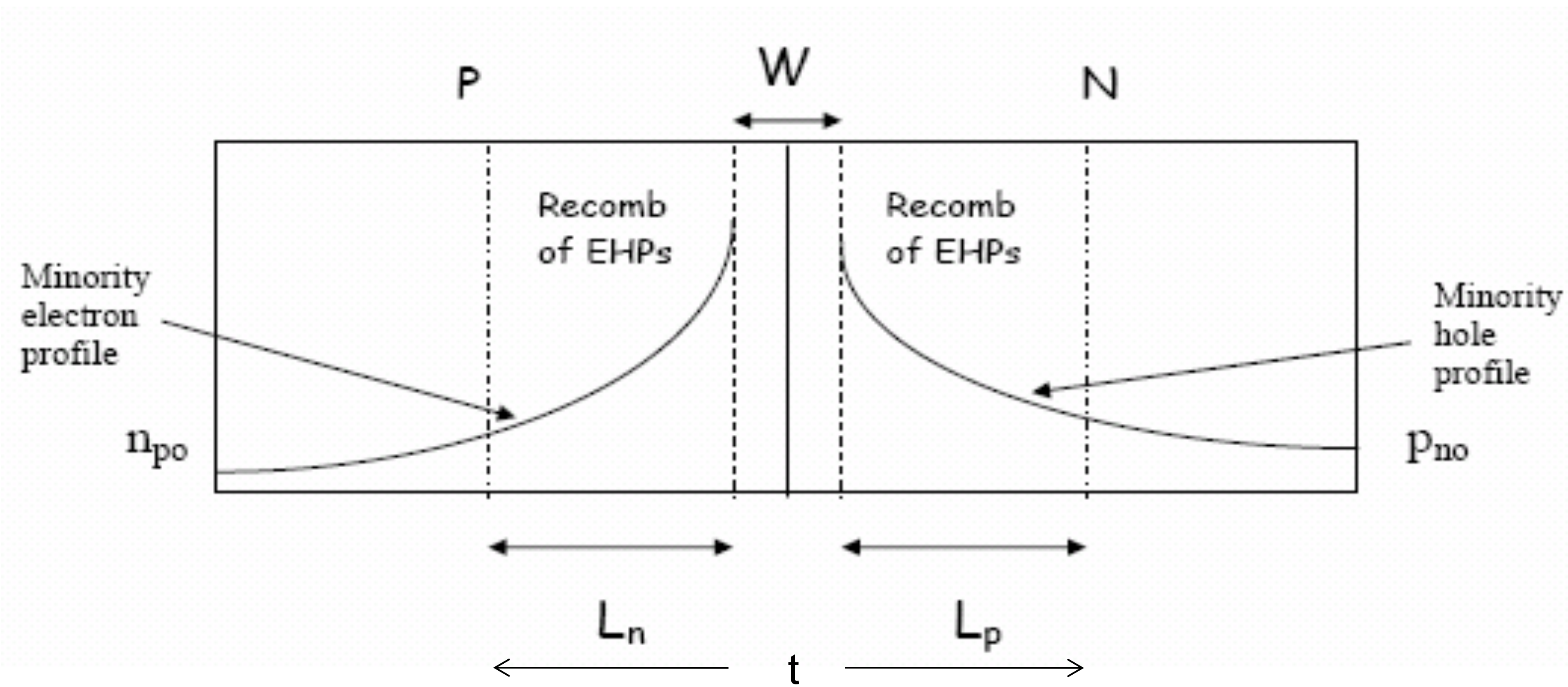



p+-n+ junction in equilibrium

p+-n+ junction under forward bias

- Recall that on average, the minority carriers will only survive over their minority carrier diffusion length, before they recombine with the majority carriers.
- Hence on average, photon emission will only occur over a distance equal to the minority carrier diffusion length from the edge of **W**, $\mathbf{L_p}$ at the n-side and $\mathbf{L_n}$ the p-side.



- Thus, in LDs, PI is only achieved somewhere near the junction where there are many electrons and holes present together.

- This region with thickness $\mathbf{t \approx L_n + L_p}$ is called the active region. Only this region has optical gain with PI.

- The pn junction needs to be heavily doped on both sides and also under strong FB so as to achieve strong PI.

- For such a junction, there will be a large number of minority electrons injected into the p–side which has many holes.

- Similarly, a large number of minority holes are injected into the n–side which has many electrons.

- Thus there will be a lot of recombination occurring.

- With direct gap semiconductors used, the recombination will result in photons being emitted.

# Summary

**1 )** The pn junction is the active medium for laser action.

**2 )** The forward biasing of the pn junction which results in the injection of minority carriers to achieve PI is the pumping process.

If we just have a heavily doped pn junction under FB as described above, with PI built-up but with no resonant cavity, there will be no stimulated emission, but only spontaneous emission. This gives rise to LEDs.

**3 )** To have laser action, a resonant cavity formed with 2 end mirrors is necessary to reflect photons back into the active medium to induce stimulated emission.

# Semiconductor Lasers (cont)

- To prevent radiation emitting from the opposite surface, the reflectivity is sometimes increased to nearly 100% by having some optical coatings.
- Ideally, the photon flux should be confined within the active region where PI exists in order to induce stimulated emission. However, in practice the photons are not well confined and are spread out of the active region.
- Those photons spread out is a form of loss and will reduce the optical gain and hence makes it more difficult to achieve laser action.

# Diagram of Semiconductor Lasers

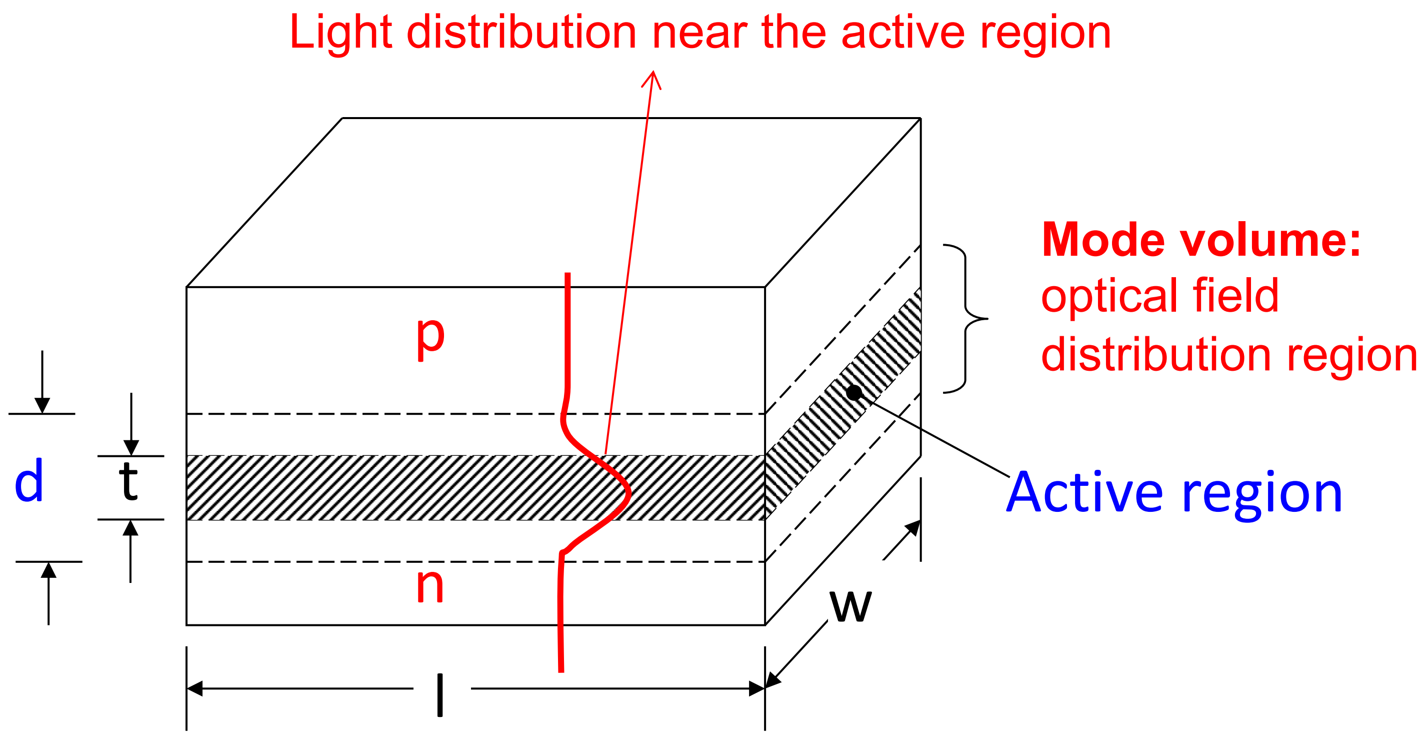



Diagram showing the active region and mode volume of a semiconductor laser

Note: optical intensity is the highest in the middle of the active region (i.e. high optical confinement in the active region). We will explain it in the later section.

# GaAs Semiconductor Lasers

- Because of the low probability of radiative recombination in Si (being an indirect band gap semiconductor), there is a high chance of non-radiative recombination occurring, and the light output is poor.

- The high probability of radiative recombination in GaAs makes the light emission process dominant.

- Emission from a GaAs p-n junction mainly occurs in the p-type region.

# GaAs Semiconductor Lasers

- This is due to the higher mobility of the electrons causing rapid diffusion across the junction into the p side, where most of the recombination takes place.

- Depending on the doping level, the electron diffusion results in recombination and light output may penetrate several μm into the p side.

- The recombination radiation (emitted photons) may interact with valence band electrons and be absorbed (give loss), or interact with electrons in the conduction band (give gain) through stimulated emission at the same frequency.

# GaAs Semiconductor Lasers

- If the injected carrier concentration becomes large enough (population inverted), the stimulated emission can exceed the absorption, so that optical gain is achieved in the active region.

- Laser oscillations occur when the round trip gain exceeds the total losses.

# GaAs Semiconductor Lasers

Some points on GaAs LD as shown in Fig. 2.5

- The emission is centered at the band gap of GaAs, which is 1.43eV (870nm), so emission is in the infrared.

- In GaAs, as the minority electrons have a longer diffusion length ( $L_n > L_p$ ), the light emitting volume is not symmetrical with respect to the junction. It is greater at the p-side than at the n-side.

- If $N_D >> N_A$, the diode current will be mainly carried by electrons injecting into the p-side. Radiative recombination will now mainly occur at the p-side, and the thickness of the active region $t \approx L_n$. (For heavily doped GaAs at 300K, $L_n$ is 1-3μm )

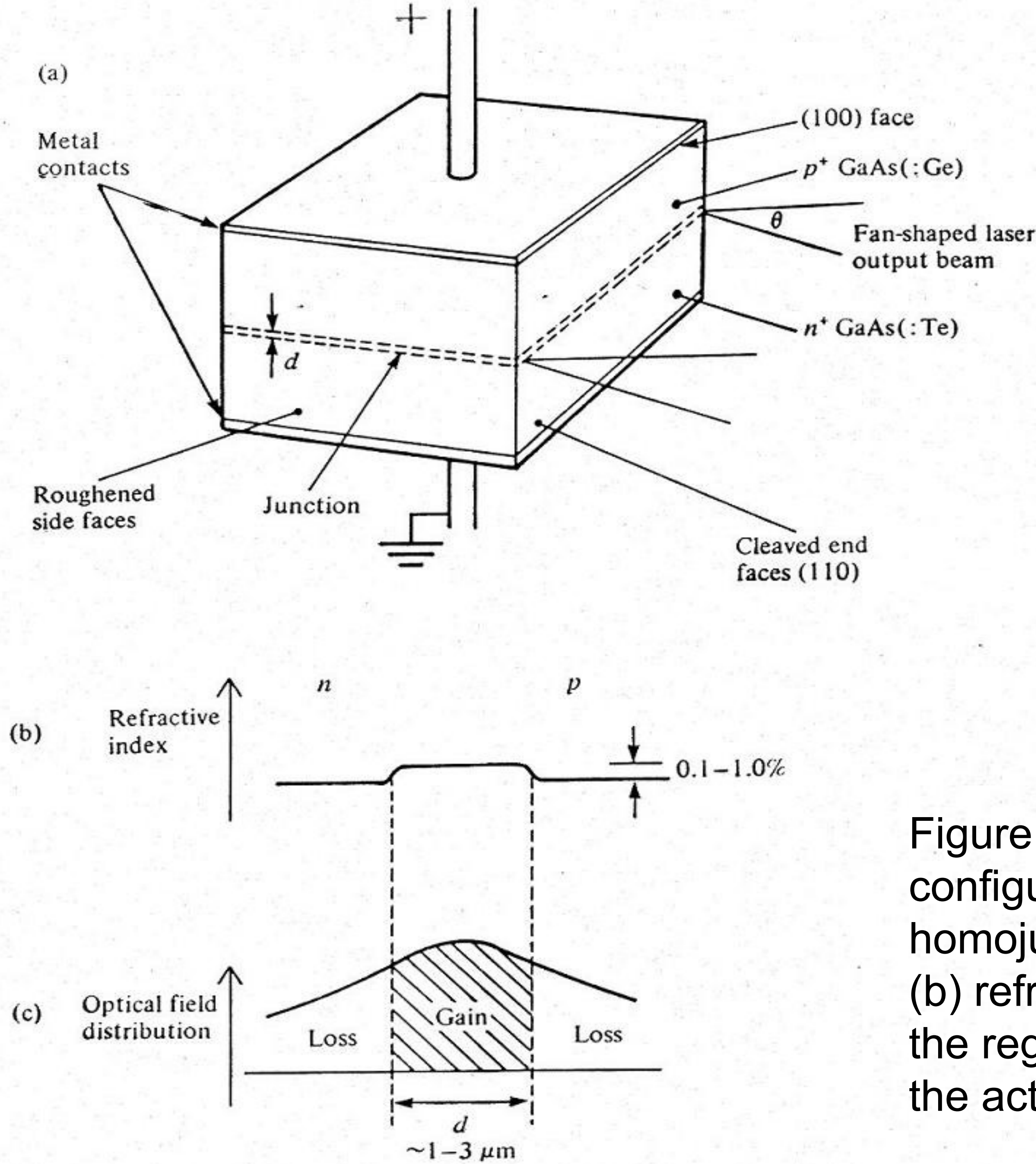



Figure 2.5 (a) Schematic configuration of a GaAs homojunction semiconductor laser; (b) refractive index change across the region; (c) mode confinement in the active region.

# GaAs Semiconductor Lasers

- Due to the higher density of carriers present in the active region, its refractive index (RI) is slightly higher than that of the surrounding medium.

- This difference in RI leads to Fresnel reflection and hence some confinement of radiation over a mode volume of thickness d where d > t.

- The larger the difference in the refractive index between the two materials, the higher the reflection. Thus, the higher the confinement of radiation.

- Nevertheless, the confinement is rather ineffective. Eg. In GaAs, the RI difference is only about 0.02.

# GaAs Semiconductor Lasers

- Inefficient wave guiding in homo-junction LDs requires strong pumping to maintain laser action (the higher the pumping, the higher the gain). Therefore, the threshold current density is usually quite high.

- The onset of laser action at the threshold current density is detected by an sudden increase in the light output, see Fig. 2.6

- Energy is channeled into one mode (one lasing frequency, with the highest gain). This mode is the first to achieve stimulated emission, thus consuming most of the electrons in the upper energy states, see Fig. 2.7.

- So that only this lasing frequency is observed, resulting in a significant decrease in spectral linewidth, above the threshold.

# Light output vs. current of a LD

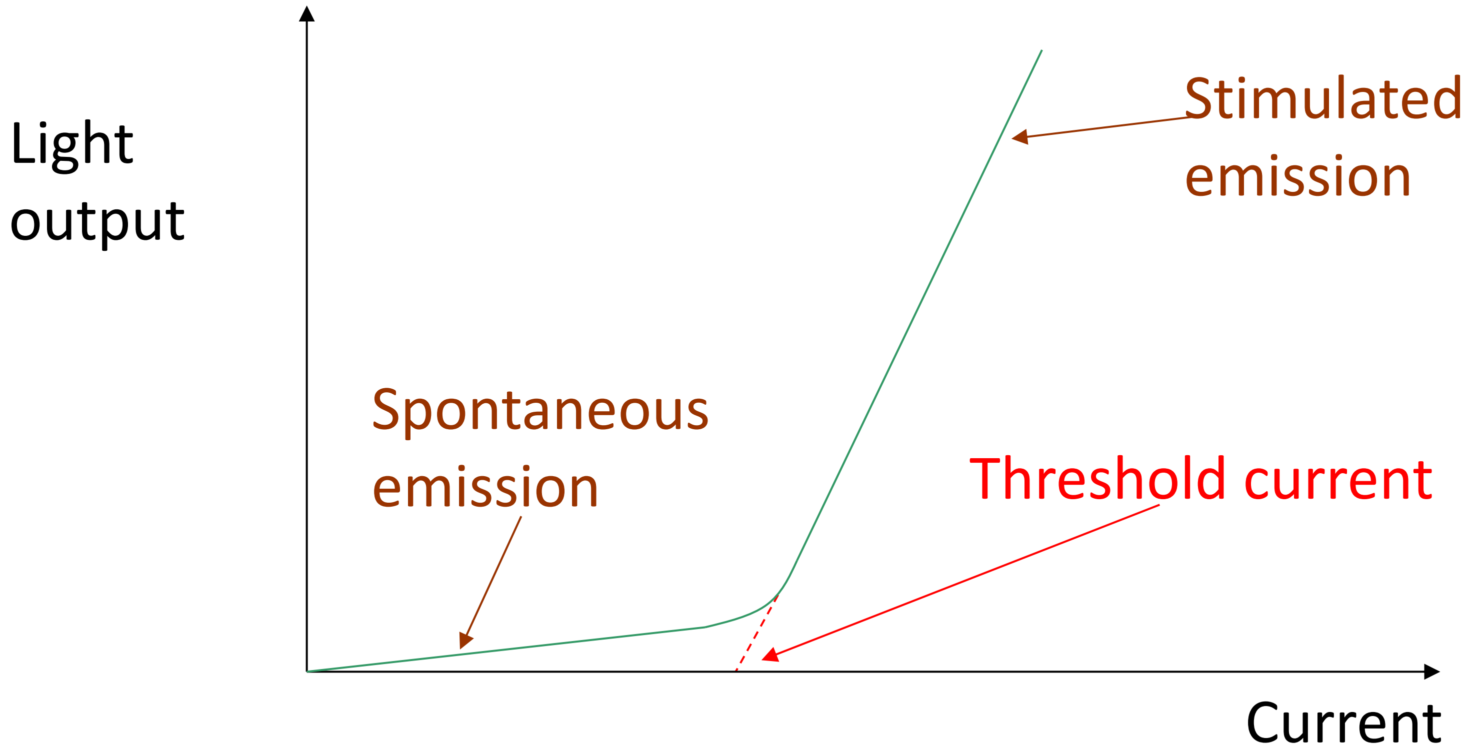
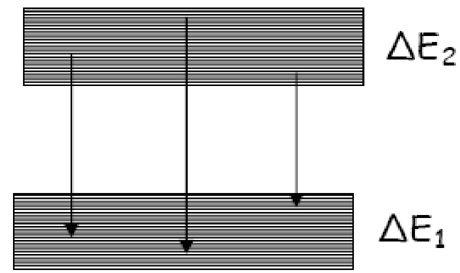
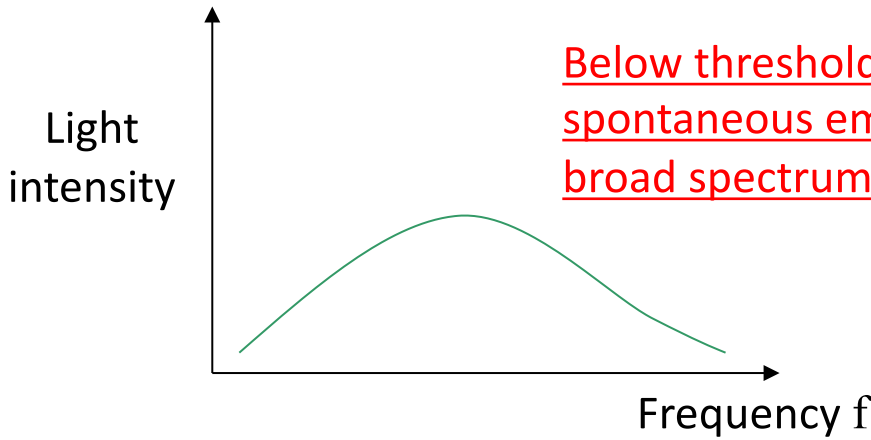



**Fig. 2.6 Light output *vs.* current characteristic of a LD**

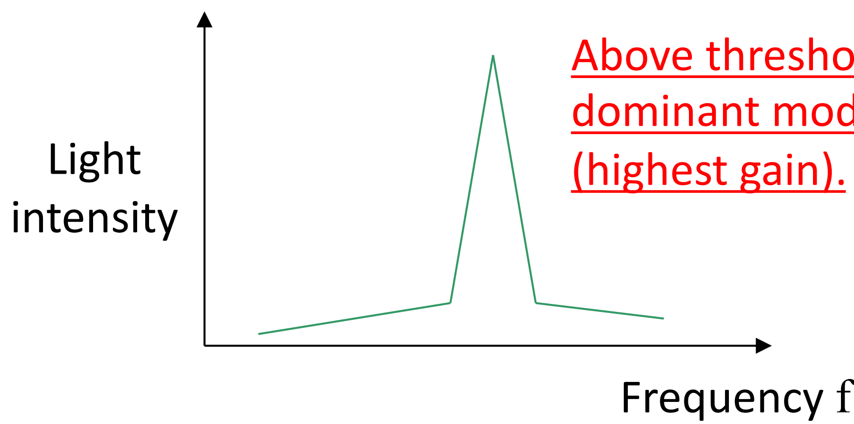
# Laser Spectra of a LD

real system




Below threshold: spontaneous emission, broad spectrum




Above threshold: single dominant mode appear (highest gain).

## Fig. 2.7 LD lasing spectra

# Summary

- Semiconductor lasers are nothing but heavily doped pn junction under strong forward-bias conditions.
- Semiconductor lasers can only be realized in direct bandgap semiconductors.
- You should know the light-current and spectra characteristics of a semiconductor laser.
- You should know the energy band diagram and schematic structure of a semiconductor laser.
- Semiconductor lasers have wide applications in various fields.

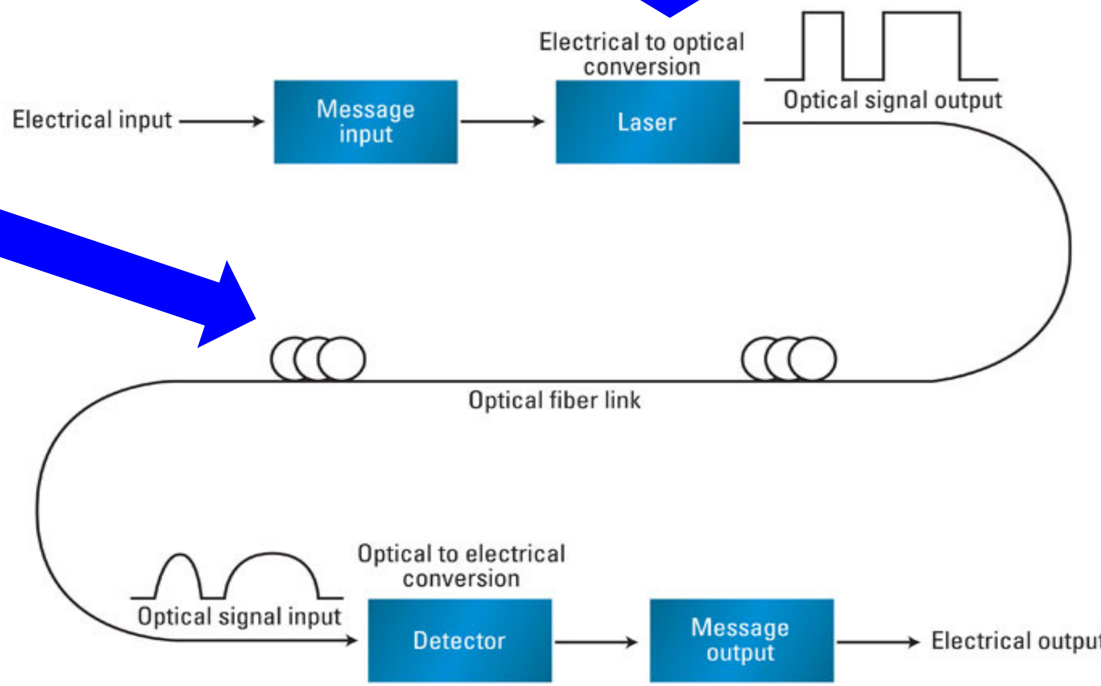
# Semiconductor Laser Applications

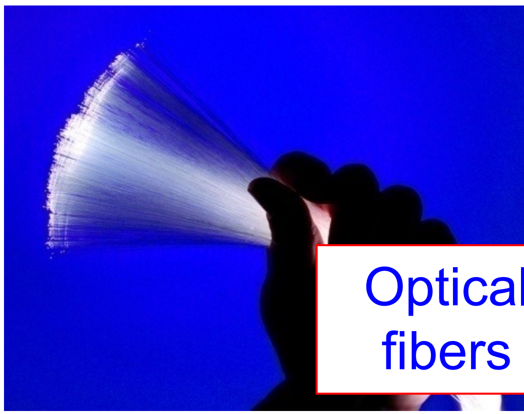
- Optical Communication
- CD Player
- Laser Surgery
- Laser Processing
- Holography
- etc.

Coherent, narrow, intense beam from a laser: a unique feature

# Optical Communication

Semiconductor light sources as the signal generator



Optical fibers

Semiconductor optical detectors

Light source in an optical fiber communication system and a bundle of optic fibres.

## CD Player

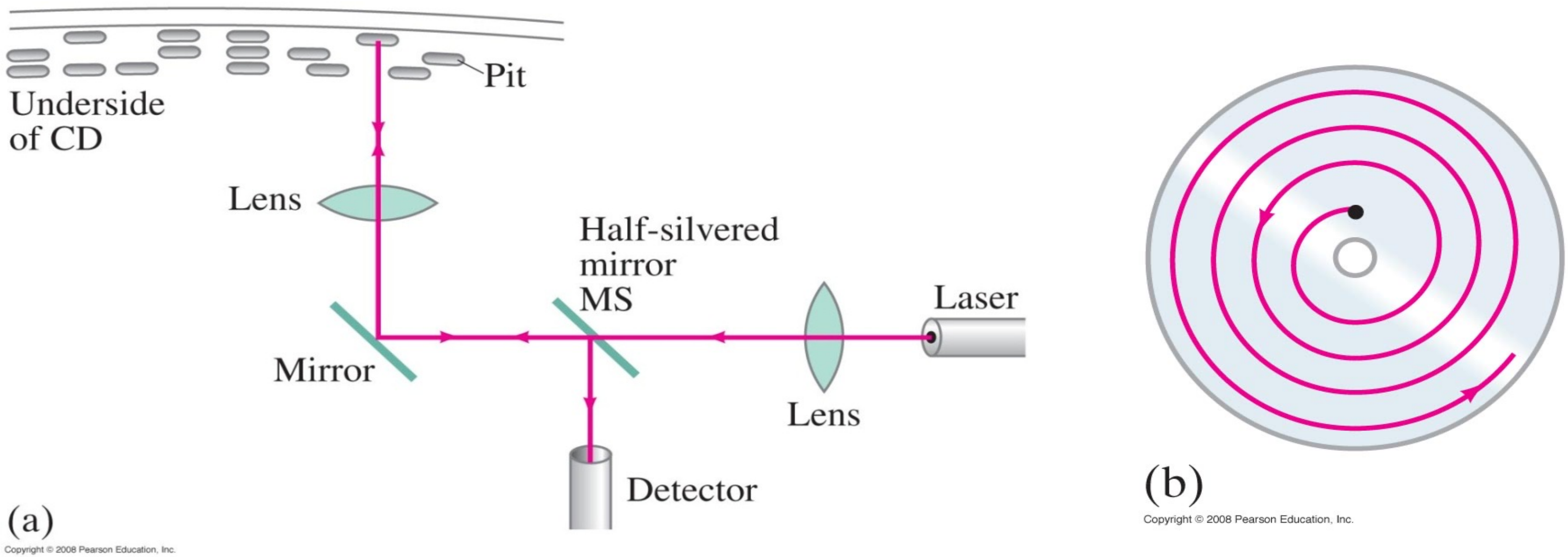



Figure 2.8 operational principle of a CD player

# CD Player

- The recorded information on a CD or DVD is a series of pits and spaces representing 0s and 1s.

- The laser beam reflects off the spaces of a bar-code, and off the tiny pits, shown in Fig. 2.8 (a).

- The signal is then detected by an optical detector to check whether 0s or 1s.

- The laser of a CD player starts reading at the inside of a disc, shown in Fig. 2.8 (b).

- An 1-hour CD has a track roughly 5 km long;

- The distance between pits is about 800 nm;

# 2.2.2. Light Emitting Diode (LED)

An LED is a semiconductor device that produces incoherent light. The device consists of a p-n junction with a forward bias applied.

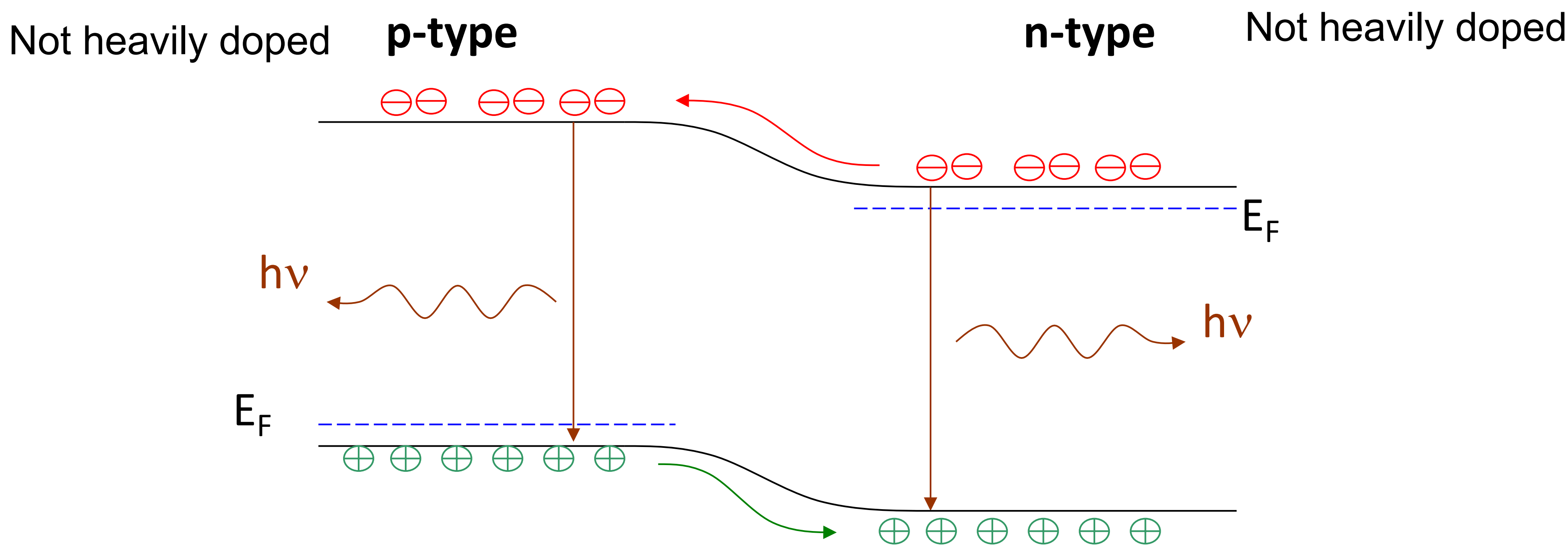



**Low energy consumption**

http://www.youtube.com/watch?v=WxP1ToZhLeU

# Light Emitting Diode (LED)

Basic structure giving injection luminescence is a p-n junction under the forward-bias condition.




Energy band diagram of an LED under forward bias

# Light Emitting Diode (LED)

- In an ideal LED, every injected electron takes part in radiative recombination, and hence gives rise to an emitted photon.

- In practice this is not so, and the efficiency of the device is described by its quantum efficiency (<1); which is the rate of photon emission divided by the rate of supply of electrons.

# Current-Voltage Characteristics

In reverse bias, no carrier injection takes place, and no light is emitted.

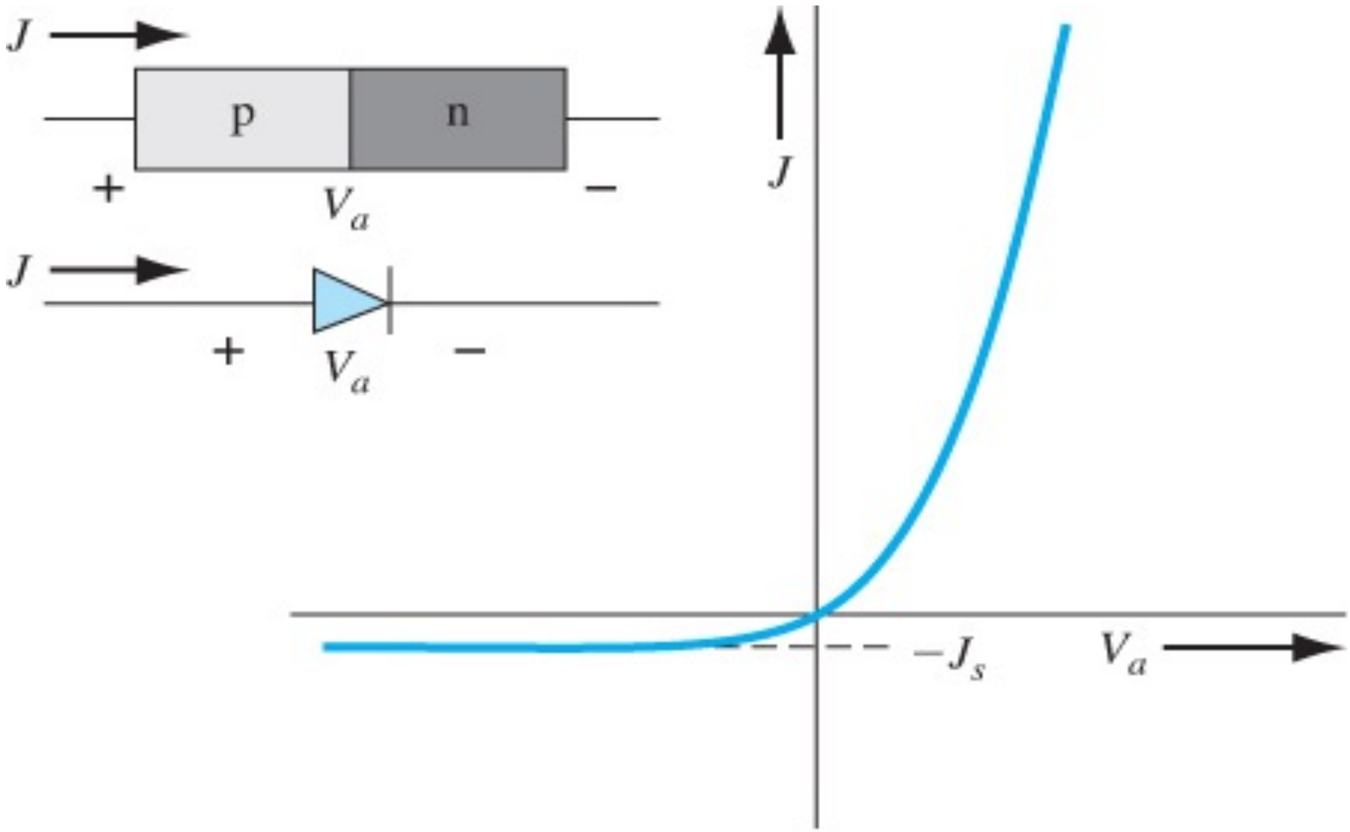
We know, for an LED (pn junction), the I-V relation can normally be written as:

$$I = I_S \left[ \exp\left( \frac{qV}{kT} \right) - 1 \right] \qquad V > 0 \qquad (2.6)$$

**Derived from a pn junction (see next slide)**

$I_S$ = reverse saturation current (a constant).

# Recall the current density vs voltage of a pn junction




$$J = J_S\left[\exp\left(\frac{qV_a}{kT}\right) - 1\right]$$

## Emission Wavelength

Emission wavelength λ of the LED is given by:

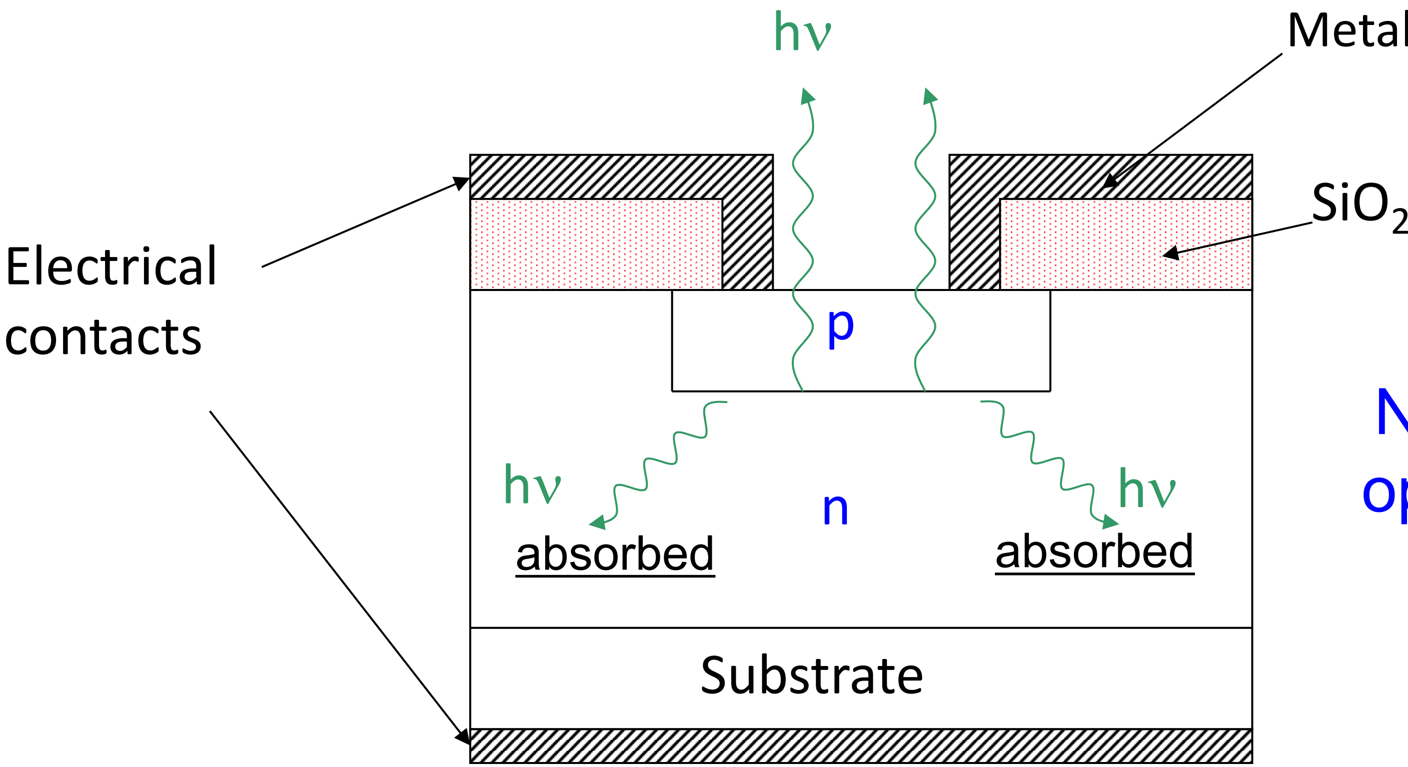
$$\frac{\mathrm{hc}}{\lambda} = \mathrm{E_c} - \mathrm{E_v} = \mathrm{E_g}$$

$$\underline{\underline{\lambda = \frac{hc}{E_g}}}$$

e.g. for GaAs, $E_g$ = 1.44 eV

∴ λ = 0.86 μm.

# Schematic structure of LED




Simple LED Structure

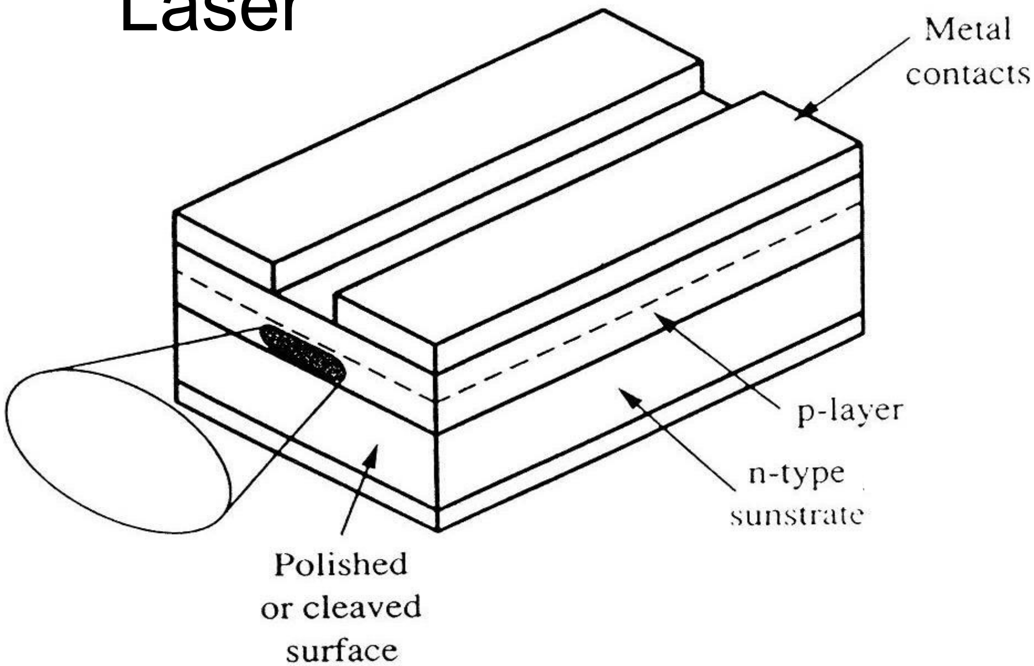
NOTED: No optical cavity is formed

- Top and bottom electrical contacts for injection of holes and electrons, respectively.

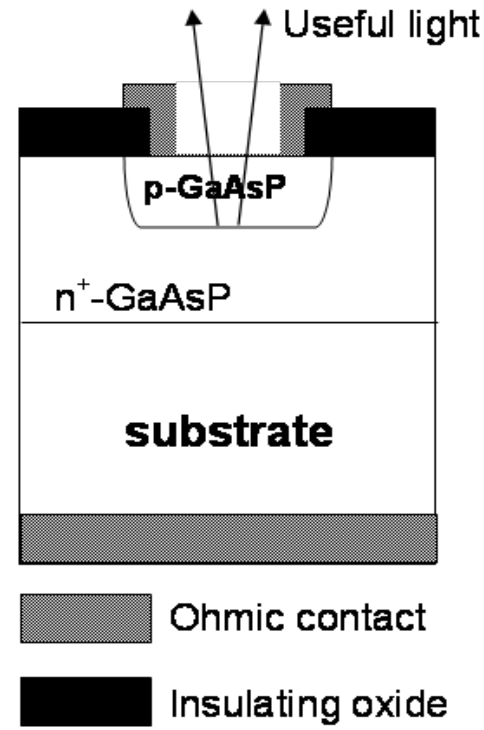
- A $SiO_2$ insulation layer is used to avoid "shortcut" between top and bottom metal layers.

# Difference between a LD and an LED

Laser




LED




An optical cavity is formed

No optical cavity is formed:
Other than the surface emission, the light emission in the other directions are absorbed.

The light paths in lasers and LEDs are different

# Difference between a LD and LED

## In a LD

- The main difference between a LD and an LED is the way the optical signal is generated and manipulated.

- In a LD, the emitted photons may initially travel in arbitrary directions, but for the ones that traverse along the optical axis, when they reach the cleaved edges, they are reflected back into the semiconductor and continue generating photons.

- This helps stimulate more radiative transitions (stimulated emission).

➢ When gain > losses, oscillation starts and laser action eventually reaches a steady-state value.

➢ Hence a LD, compared to an LED, has the following features (due to stimulated emission):

1. It generates coherent light output.
2. It has a narrow emission linewidth as it is highly monochromatic (all photons have the same frequency).
3. The output is polarized (electric field of the EM waves all vibrating on the same plane).
4. The light output is directional.
5. The light output is higher due to the amplification process.

# In an LED

- In an LED, light is emitted in all directions.

- There is no optical waveguiding to guide the light in any specific direction, and there is no optical cavity to enhance stimulated emission.

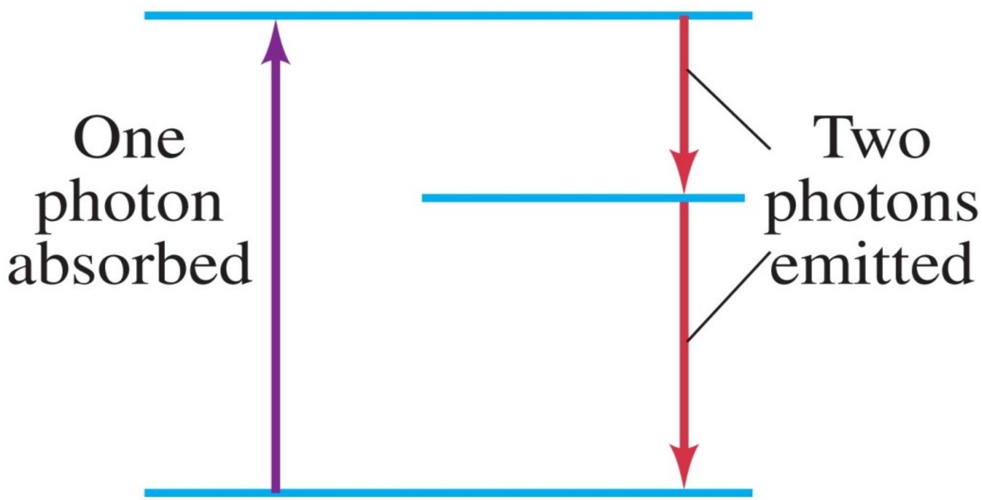
- Whatever fraction of light can escape from the front surface of the semiconductor appears as useful light.

- LEDs are easier to make than LDs, and are obviously cheaper.

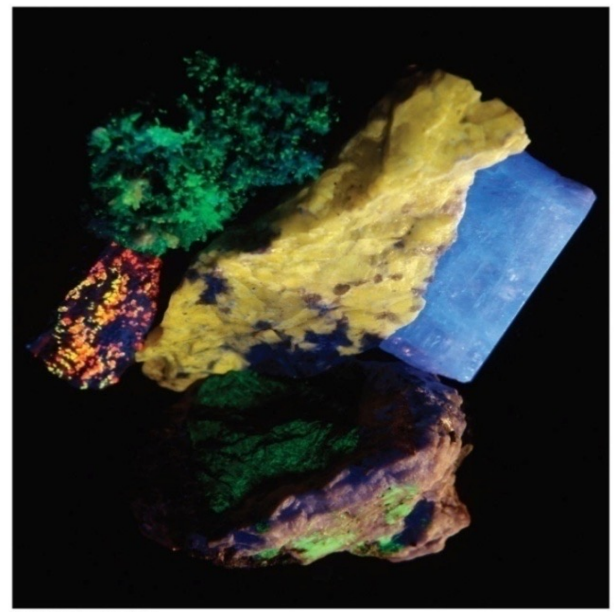
# 2.3 Other types of light emissions

## Fluorescence and Phosphorescence

If an electron is excited to a higher energy state, it may emit two or more photons of longer wavelength as it returns to the lower level.







When UV light illuminates, they fluoresce in the visible range

# Fluorescence and Phosphorescence

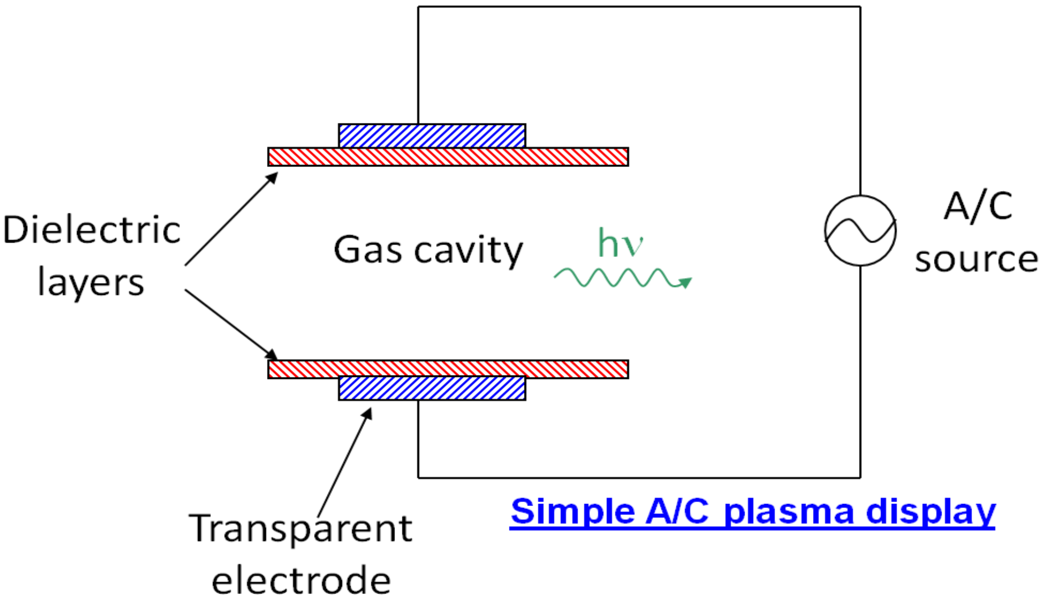
- **Fluorescence** occurs when the absorbed photon is ultraviolet and the emitted photons are in the visible range.

  Because the emission frequencies are different for different materials, fluorescence is a powerful tool for identification of compounds.

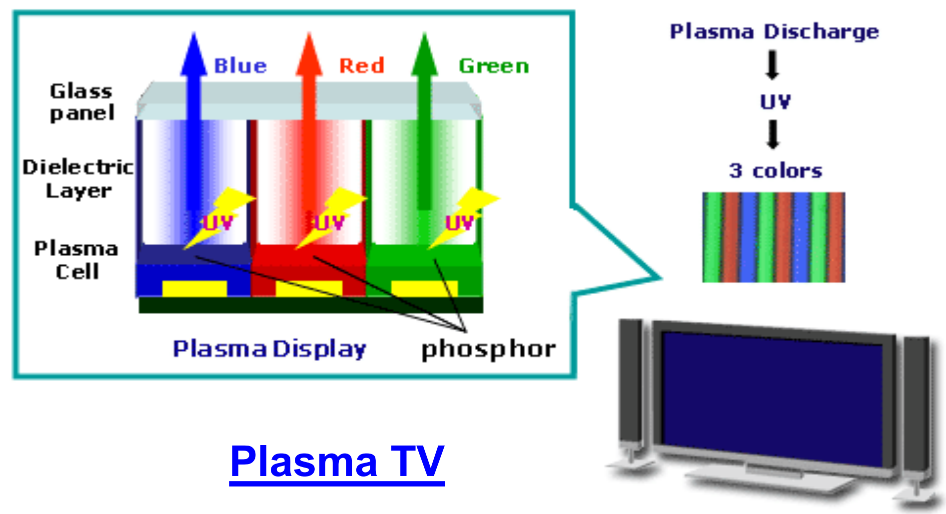
- **Phosphorescence** occurs when the electron is excited to a metastable state; it can take seconds or longer to return to the lower state. The emission sustains for a longer time.

  E.g. your luminous watch dials: after you put your luminous watch dial to a bright lamp, it lasts for a long time.

# Plasma Displays




Simple A/C plasma display




Plasma TV

Heating a gas may ionize its molecules or atoms, turning it into **a plasma**, which contains positive ions and negative electrons.

Not popular: rather clumsy due to the usage of gas.

# Plasma Displays

- Rely on the radiation produced when an electrical current passes through a gas (usually neon).

- Under the external electric field, the $e^-$ acquired a higher kinetic energy and when they collide with the gas atoms, they transfer this energy to the atoms, thereby exciting them into higher energy levels above the ground state.

- The atom may lose energy radiatively and return to the ground state. Similar to the concept of gas laser (but without an optical cavity).

- In a plasma TV, the plasma radiation is in the UV range, which is then used to excite different phosphor compounds for generation of RGB colors.

# Liquid Crystal Displays (LCDs)

- The liquid crystal displays (LCDs) have their optical activity changed by the applied electric field potential across different parts of the display. Application: e.g. LCD TVs.

- Made from liquid crystal materials that have rodlike molecules with electric dipole moments along the molecular axes.

LCD TVs, the most widely produced and sold TV displays


Industry standard LCD display with black characters and green background

# Liquid Crystal Displays (LCDs)

## a) Without applied voltage

- Liquid crystal molecules are aligned parallel to the surface but with a 90° rotation from the front surface to the back surface.

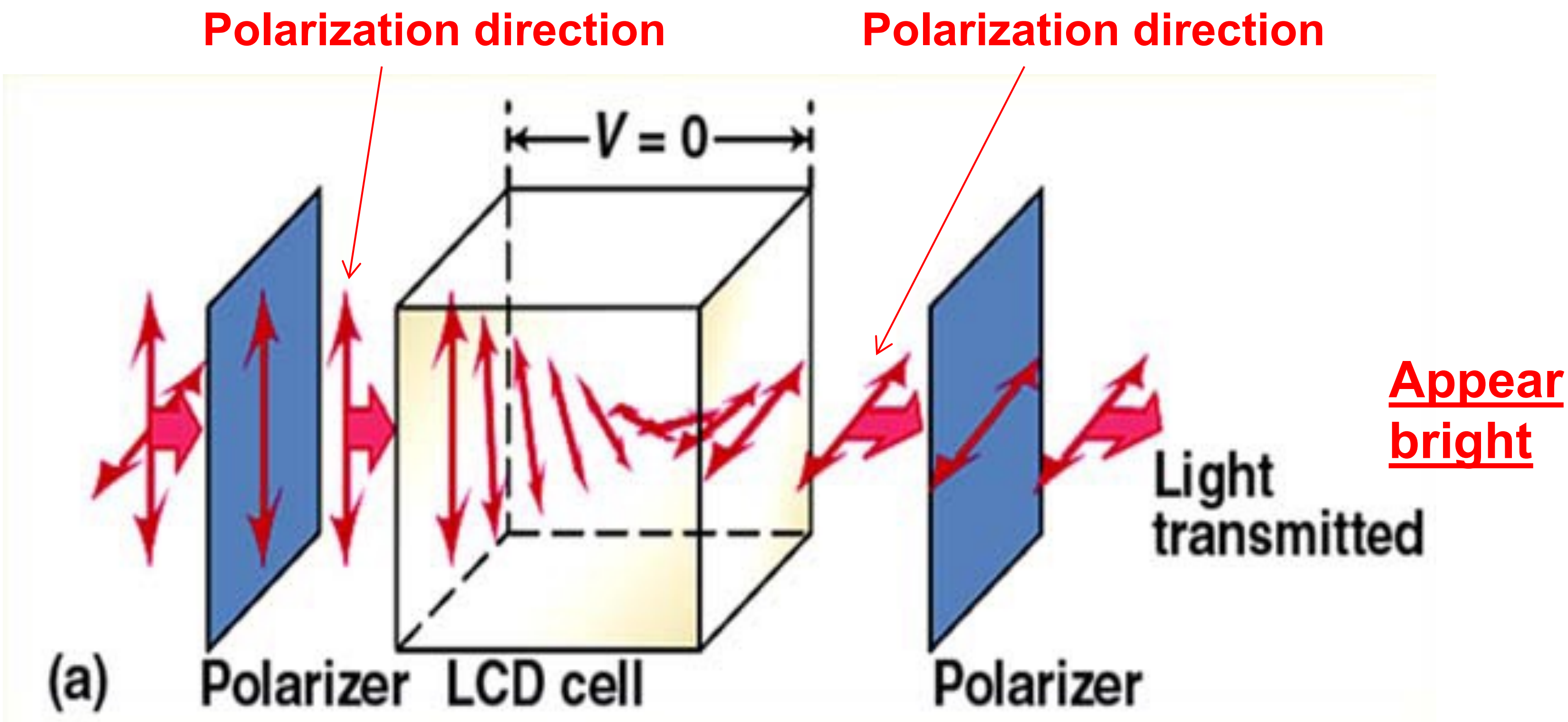
- Light incident on the display is linearly polarized by the first polarizer.

- Polarization plane of the light is rotated through 90° as it passes through the material, i.e. the molecules affect the polarization of the light.

- Now, light can pass through the second polarizer (90° rotated to the first one)

→ display is clear.

# Without Voltage




**The plane of polarization is rotated when no voltage is applied to the cell.**

# Liquid Crystal Displays (LCDs)

## b) When voltage is applied

- With voltage applied, the molecules rotate to align with the resulting electric field (from the left to the right).

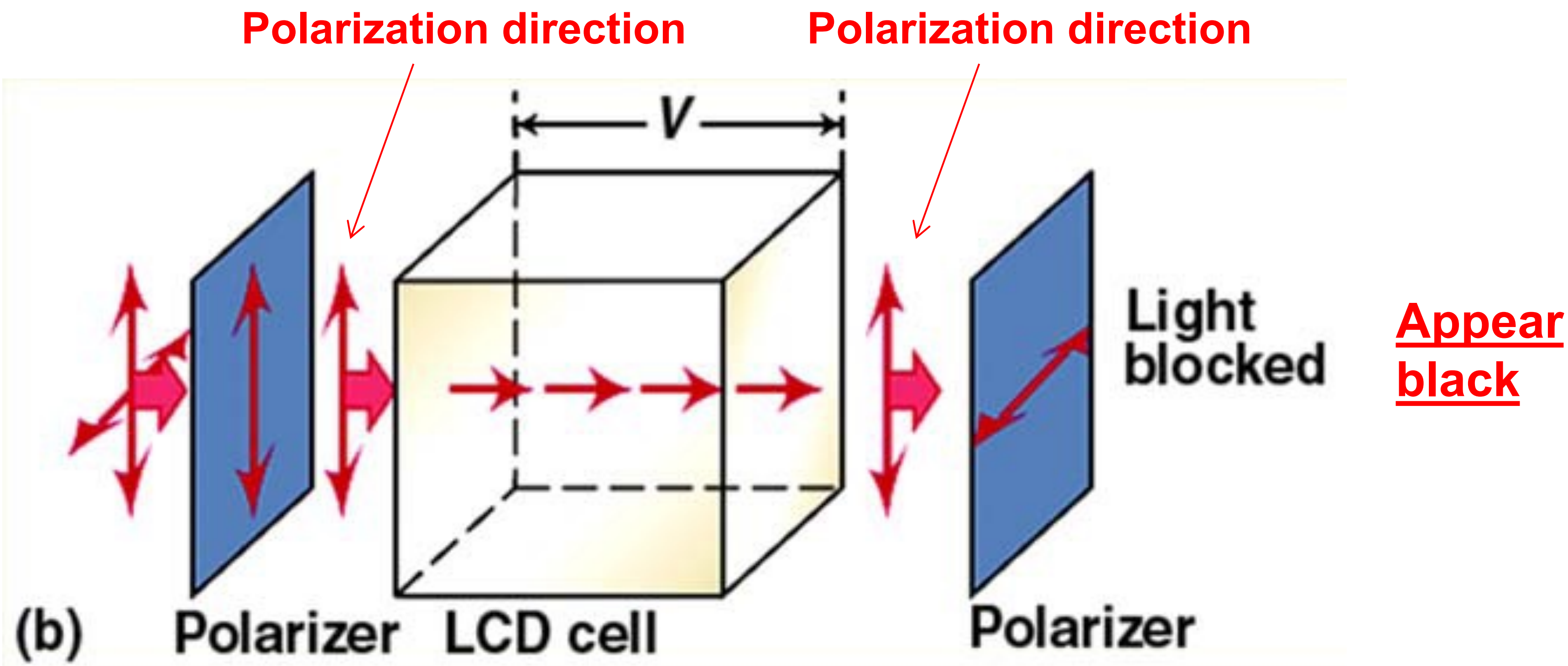
- In this case, the molecules have no effects on the incident light.

- Thus, linearly polarized light no longer rotates as it traverses the liquid crystal material.

- The second polarizer blocks the light.

⇨ segment appears black on a light background

# With applied Voltage




When voltage is applied across the cell, the molecules of the liquid crystal is changed so that light passes through with no change in its polarization.

# Summary

- You should know how semiconductor lasers are used in different applications.

- You should know what are the different characteristics between semiconductor lasers and LEDs.

- You should know the operation principles of other types of light emissions, such as plasma displays and LCDs.