



**SCHOOL OF INNOVATIVE TECHNOLOGIES &  
ENGINEERING**

*Dept. of Industrial Systems Engineering*

**Module Information Pack**

**B.Eng (Hons.) Electronic Engineering Version 3.0**

**Optoelectronics**

**ELEC4105C**

**Academic Year 2024-25 Semester 1**

*Blended Mode (Online and F2F)*

<b>Programme Director:</b>	Mr. Rishi Heerasing
<b>Programme Coordinator</b>	Prof. Vinaye Armoogum (BEE21BFI)
<b>Module Coordinator:</b>	Mr. Rishi Heerasing
<b>Module Convenor:</b>	Mr. Rishi Heerasing
<b>Office:</b>	Room G2.14 Level 2 SITE Block G
<b>Phone:</b>	207 5250 ext. 34
<b>E-mail:</b>	<a href="mailto:rheerasing@utm.ac.mu">rheerasing@utm.ac.mu</a>
<b>Academic Tutoring:</b>	None
<b>Lecture Day and Time:</b>	Mondays: 11:00 – 14:00 BPML 0.02A
<b>Credits &amp; Level:</b>	6 credits, Level 4
<b>Pre-requisites (If applicable):</b>	None
<b>Co-requisites (If applicable):</b>	None
<b>Method of Delivery &amp; Frequency:</b>	45 Hours Blended Mode + 45 Hours Self-Study
<b>Method &amp; Criteria of Assessment:</b>	70% Unseen Exam & 30% Coursework

### **Module Description:**

Electronic and optical processes in semiconductors. p-n junction theory. Light-emitting diodes, Laser: structures, properties and operating principles. Photo-detectors. Optical Fibre Amplifier. Solar cells.

### **Learning Objectives and Outcomes:**

- Understand the major semiconductor optoelectronic devices
- Understand the operating principles, designs, uses, strengths and weaknesses of these devices
- Understand different types of LEDs /lasers and their junction physics
- Identify the different types of optical fibres and understand their properties
- Understand the different types of solar panels and their characteristics

**Tentative Class Schedule (*F2F on odd weeks and online on even Weeks*)**

<b>Week</b>	<b>Date</b>	<b>Topics Covered</b>
1	14/10/24 F2F	Introduction to optoelectronics and optoelectronic devices
2	21/10/24 Online	Atomic Bonding, Type of Solids, Energy Diagram
3	28/10/24 F2F	Carrier Concentration in Semiconductors
4	04/11/24 Online	Carrier Drift and Diffusion
5	11/11/24 Online	Light Emitting Diode
6	18/11/24 Online	Light Emitting Diode
7	25/11/24 F2F	LASER
8	02/12/24 Online	LASER
9	09/12/24 F2F	Photo-Diode
<b>END OF YEAR BREAK</b>		
10	06/01/25 Online	Photo-Diode
11	13/01/25 F2F	Optical Fibre
12	20/01/25 Online	Solar Cell
13	27/01/25 F2F	<b>Open-notes, Open-book, Class Test (30% of module weight)</b>
14	03/02/25 Online	Class Test Post-Mortem
15	10/02/25 Online	Revision

## READING LIST

**RECOMMENDED TEXTS** (as per availability in the UTM Resource Centre):

- Bhattacharya P. (1997) *Semiconductor Optoelectronic Devices*, 2<sup>nd</sup> Edition, Prentice Hall.
- Kasap S. (2012) *Optoelectronics and Photonics: Principles and Practices*, 2<sup>nd</sup> Edition, Pearson

## LECTURE NOTES

The lecture notes are available on **Nefertum's Shrine** at <https://www.rishiheerasing.net>

The notes are in .pdf format so you will need Adobe Acrobat® Reader to view them.

This reader can also be downloaded from the two above-mentioned sites in the Downloads Section.

# Slide Set 0

- Wavelength Utilization
- Growth of Internet Traffic
- Link Capacity Improvements
  - Technological Trends
  - Optoelectronics

## What determines the wavelengths utilized?

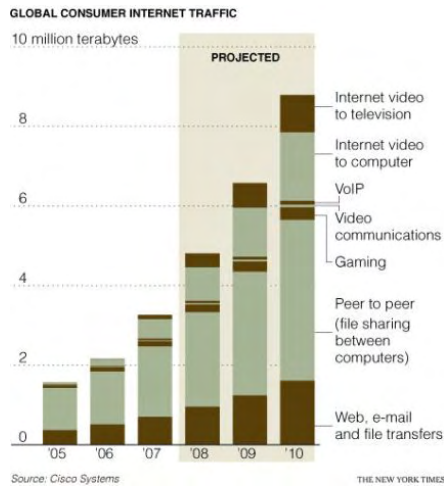
- 1) Human eye response (indicators and displays)
- 2) Transmission media
  - Fibers
  - Atmospheric Transmission
- 3) Source of radiation (detectors)
  - Sun (Solar Spectrum)
  - Black body – T
  - Lasers
- 4) Technologically available materials

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## Growth of Internet Traffic

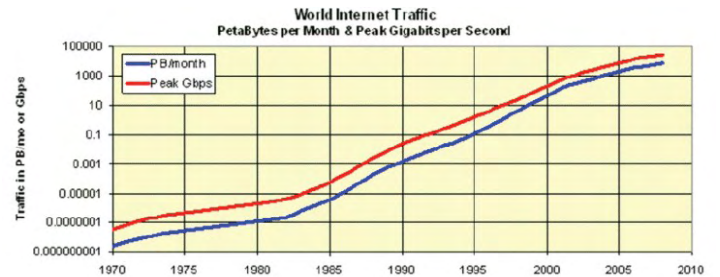


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## Growth of Internet Traffic



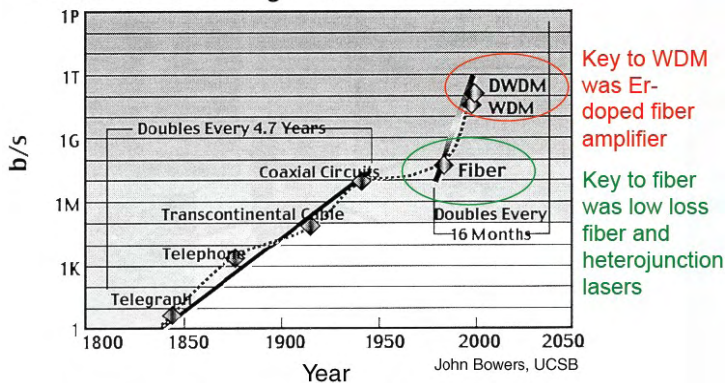
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## Link Capacity Improvements

### Bandwidth of a Single Communications Link



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## SONET/SDH Specifications

Beginner Intermediate Advanced Extreme



**OC-48**  
2.5 Gb/s



**OC-192**  
10 Gb/s



**OC-768**  
40 Gb/s



**OC-3072**  
160 Gb/s

OC – Optical Carrier rate, OC-1 = 51.84 Mbps

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## Technological Trends

### Computer performance continues to follow Moore's Law

- > Doubling of computing power every 18 months
- > Device research indicates exponential growth until 2020

### Network capacity is also increasing exponentially

- > Gilder's Law - "Communication capacity triples every 12 months"
- > Growth at a rate greater than Moore's law requires new integrated, lower cost technologies

### Required network capacity

- > Desktop bandwidth needs limited only by the human eye (~2Gbps)
- > Internet traffic is non local
- > Number of users and hosts is growing exponentially

∴ Need long wavelength, high speed, low cost, vertical-cavity surface-emitting lasers (VCSELs) and integrated photonic ICs with higher functionality

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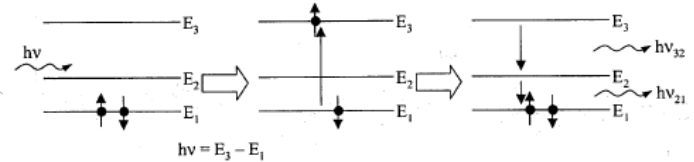
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## What is Optoelectronics?

Involving both electronic and optical (photonic) processes:

- Electronic excitation through photon absorption
- Photon emission through electron relaxation
- Energy converted from electrical to optical or vice versa



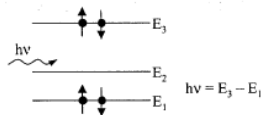
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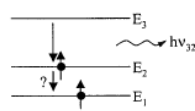
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## Absorption and Emission Issues

- What if  $E_3$  occupied?



- What if  $E_1$  has the same spin?



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## Classification of Optoelectronic Devices

- **Light Emitting Devices**
  - LED, Lasers, LEEC (Light-emitting electrochemical Cell)
- **Light Absorbing Devices**
  - Photodetector, Solar Cell, Photoresistor (LDR)
- **Light Manipulation Devices**
  - Involved in modulation, switching and guiding

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## Applications of Optoelectronic Devices

- **PhotoVoltaics**
  - Convert solar energy into electrical energy (PV)
- **Displays**
  - LCD, LED, TFT, OLED
- **Communications**
  - Optical Communication: Fibre Optics (FO), Free-Space Optics (FSO)
- **Sensing & Monitoring**
  - CCD (Charge-Coupled Device), Infrared

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## Slide Set 1

- Atoms Bonding
- Types of Solids
- Energy Bands

## Atoms and Bonding

- In order to understand the **physics of semiconductor (s/c)** devices, we should first learn **how atoms bond together to form the solids**.
- Atom is composed of a nucleus which contains protons and neutrons; **surrounding the nucleus are the electrons**.
- Atoms can combine with themselves or other atoms. The valence electrons, i.e. the **outermost shell electrons govern the chemistry of atoms**.
- Atoms come together and form gases, liquids or solids depending on the strength of the attractive forces between them.
- The atomic bonding can be classified as **ionic, covalent, metallic, van der Waals, etc.**
- In all types of bonding the **electrostatic force acts between charged particles.**

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## The Periodic Table

GROUP

PERIOD

1 1.0079 H HYDROGEN 2 4.0026 He HELIUM

2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

3 4.0026 Li LITHIUM 6.941 Be BERYLLIUM 9.0122 B BORON 12.0111 C CARBON 14.007 N NITROGEN 15.999 O OXYGEN 18.998 F FLUORINE 20.180 Ne NEON

4 39.098 Na SODIUM 40.078 Mg MAGNESIUM 69.723 Al ALUMINUM 72.64 Si SILICON 74.922 P PHOSPHORUS 78.96 Cl CHLORINE 85.468 Br BROMINE 89.904 Kr KRYPTON

5 85.468 Rb RUBIDIUM 87.62 Sr STRONTIUM 132.91 Yttrium 137.32 Zr ZIRCONIUM 178.48 Hf HAFNIUM 180.948 Ta TANTALUM 186.904 W WOLFRAM 200.59 Pt PLATINUM 200.59 Au GOLD 208.98 Hg MERCURY 208.98 Tl THALLIUM 207.2 Pb LEAD 208.98 Bi BISMUTH 209 Po POLONIUM 209 At ASTATINE 222 Rn RADON

6 138.905 Ba BARIUM 175.10 La LANTHANUM 175.10 Ce CELESIUM 175.10 Pr PRASEODYMIUM 175.10 Nd NEODYMIUM 175.10 Pm PROMETHIUM 175.10 Sm SAMARIUM 175.10 Eu EUROMIUM 175.10 Gd GADOLINIUM 175.10 Tb TERBIUM 175.10 Dy DYSPROSIUM 175.10 Ho HOLEMIUM 175.10 Er ERBIUM 175.10 Yb Ytterbium 175.10 Lu LUTETIUM 175.10 Sc SCANDIUM 175.10 Ti TITANIUM 175.10 V VANADIUM 175.10 Cr CHROMIUM 175.10 Mn MANGANESE 175.10 Fe IRON 175.10 Co COBALT 175.10 Ni NICKEL 175.10 Cu COPPER 175.10 Zn ZINC 175.10 Ga GALLIUM 175.10 Ge GERMANIUM 175.10 As ARSENIC 175.10 Se SELENIUM 175.10 Br BROMINE 175.10 Kr KRYPTON

7 223 Fr FRANCIUM 223 Ra RADIUM 223 Ac ACTINIUM 223 Th THORIUM 223 Pa PROTACTINIUM 223 U URANIUM 223 Np NEPTUNIUM 223 Pu PLUTONIUM 223 Am AMERICIUM 223 Cm CURIUM 223 Bk BERKELIUM 223 Cf CALIFORNIUM 223 Es EISENHOWERIUM 223 Fm FERMIUM 223 Md Mendelevium 223 No Nobeium 223 Lr Lawrencium

Groups 3B, 4B, 5B, 6B, 7B, 8B lie in here

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## The Periodic Table

- Ionic solids
  - Group 1A** (alkali metals) contains lithium (Li), sodium (Na), potassium (K),... and these combine easily with group **7A** (halogens) of fluorine (F), chlorine (Cl), bromine (Br),... to produce ionic solids of NaCl, KCl, KBr, etc.
- Rare (noble) gases
  - Group 8A** elements of noble gases of helium(He), neon (Ne), argon (Ar),... have a full complement of valence electrons and so do not combine easily with other elements.
- Elemental semiconductors
  - Silicon(Si) and Germanium (Ge) belong to **group 4A**.
- Compound semiconductors
  - III-V** compound s/c's; GaP, InAs, AlGaAs (**group 3A-5A**)
  - II-VI** compound s/c's; ZnS, CdS, etc. (**group 2B-6A**)

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## Covalent Bonding

- Elemental semiconductors of **Si, Ge and Carbon (as diamond)** are bonded by this mechanism and these are **purely covalent**.
- The bonding is due to the **sharing of electrons**.
- Covalently bonded solids are hard, high melting points, and insoluble in all ordinary solids.
- Compound s/c's exhibit a mixture of both ionic and covalent bonding.**

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## Ionic Bonding

- Ionic bonding is due to the **electrostatic force of attraction between positively and negatively charged ions** (between 1A and 7A).
- This process leads to electron **transfer and formation of charged ions**; a **positively** charged ion for the atom that has **lost the electron** and a **negatively** charged ion for the atom that has **gained an electron**.
- All ionic compounds are **crystalline solids** at room temperature.
- NaCl and CsCl** are typical examples of ionic bonding.
- Ionic crystals are hard, high melting point, brittle and can be dissolved in ordinary liquids.

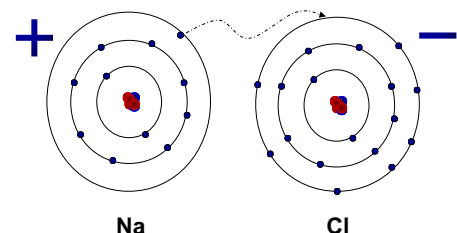
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## Ionic Bonding

The metallic elements have only up to the valence electrons in their outer shell will lose their electrons and become positive ions, whereas electronegative elements tend to acquire additional electrons to complete their octet and become negative ions, or anions.

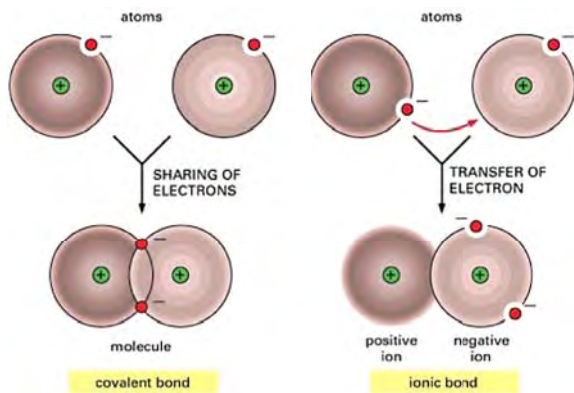


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## Covalent vs. Ionic Bonding

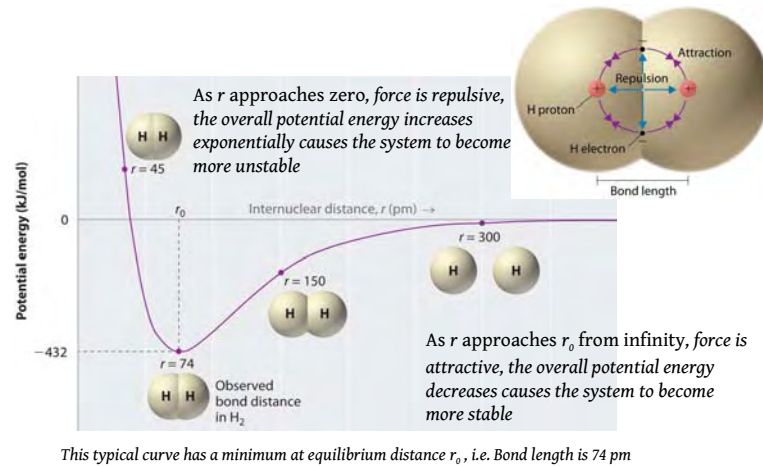


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## Potential Energy Diagram for a Hydrogen Molecule



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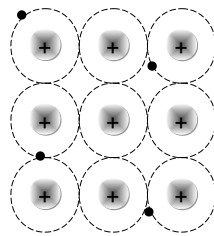
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## Metallic Bonding

❖ Valence electrons are relatively bound to the nucleus and therefore they move freely through the metal and they are spread out among the atoms in the form of a low-density electron cloud.

❖ A metallic bond result from the sharing of a variable number of electrons by a variable number of atoms. A metal may be described as a **cloud of free electrons**.

❖ Therefore, metals have high electrical and thermal conductivity.



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## Metallic Bonding

- All valence electrons in a metal combine to form a “sea” of electrons that **move freely between the atom cores**. The more electrons, the stronger the attraction. This means the melting and boiling points are higher, and the metal is stronger and harder.
- The **positively charged cores** are held together by these **negatively charged electrons**.
- The free electrons act as the bond (or as a “glue”) between the positively charged ions.
- This type of bonding is non-directional and is rather insensitive to structure.
- As a result we have a high ductility of metals - the “bonds” do not “break” when atoms are rearranged – metals can experience a significant degree of plastic deformation.

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## Van Der Waals' Bonding

- It is the **weakest bonding** mechanism.
- It occurs between neutral atoms and molecules.
- The explanation of these weak forces of attraction is that there are **natural fluctuation in the electron density** of all molecules and these cause small temporary dipoles within the molecules. It is these **temporary dipoles that attract one molecule to another**. They are as called van der Waals' forces.
- Such a weak bonding results low melting and boiling points and little mechanical strength.

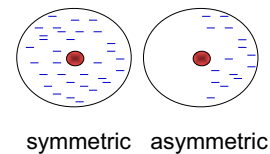
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## Van Der Waals' Bonding

The dipoles can be formed as a result of **unbalanced distribution of electrons in asymmetrical molecules**. This is caused by the instantaneous location of a few more electrons on one side of the nucleus than on the other.



Therefore atoms or molecules containing **dipoles are attracted to each other by electrostatic forces**.

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## Classification of Solids

### SOLID MATERIALS

#### CRYSTALLINE

Single Crystal



e.g. salt

#### POLYCRYSTALLINE



e.g. powder metal

#### AMORPHOUS (Non-crystalline)



e.g. rubber

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## Crystalline Solid

- Crystalline Solid is the solid form of a substance in which the atoms or molecules are arranged in a definite, repeating pattern in three dimension.



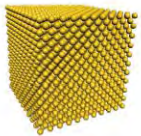
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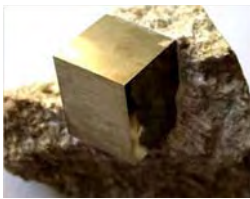
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## Crystalline Solid

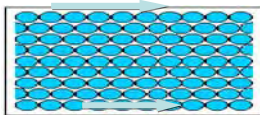
- Single crystal has an atomic structure that repeats periodically across its whole volume. Even at infinite length scales, each atom is related to every other equivalent atom in the structure by translational symmetry



Single Crystal



Single Pyrite Crystal



Amorphous Solid

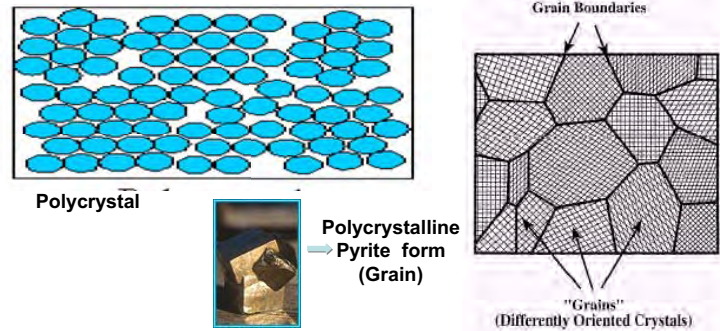
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## Polycrystalline Solids

- Polycrystal is a material made up of an aggregate of many small single crystals (also called crystallites or grains).
- The grains are usually 100 nm - 100 microns in diameter. Polycrystals with grains that are <10 nm in diameter are called *nanocrystalline*



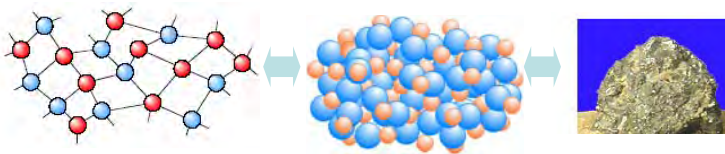
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## Amorphous Solids

- Amorphous (non-crystalline) Solid is composed of randomly orientated atoms, ions, or molecules that do not form defined patterns or lattice structures.



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## Difference between Solids

Crystalline solids	Amorphous solids
1. The internal arrangement of particles is regular & they possess definite and regular geometry.	1. The internal arrangement of particles is irregular. Thus they do not have any definite geometry.
2. They have sharp melting points	2. They do not have sharp melting points
3. There is regularity in the external form when crystals are formed	3. There is no regularity in the external form when amorphous solids are formed
4. Crystalline solids give a regular cut when cut with a sharp-edged knife	4. Amorphous solids give irregular cut.
5. They have characteristic heat of fusion	5. They do not have characteristic heat of fusion
6. Crystalline solids are rigid and their shape is not altered by mild deforming forces	6. Amorphous solids are not very rigid. These can be distorted by bending or compressing forces.
7. Crystalline solids are regarded as true solids	7. Amorphous solids are regarded as super cooled liquids or pseudo solids
8. Crystalline solids are anisotropic. This means that their physical properties like refractive index, conductivity, thermal expansion etc. are different in different directions. This is due to orderly arrangement of particles	8. Amorphous solids are isotropic. This means that their physical properties are same in all the directions. This is because of random arrangement of particles

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## Semiconductors, Insulators and Metals

The electrical properties of metals and insulators are well known to all of us.

Everyday experience has already taught us a lot about the electrical properties of metals and insulators.

But the same cannot be said about "semiconductors".

What happens when we connect a battery to a piece of a silicon;  
would it conduct well ?

Or would it act like an insulator ?



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## Difference between Solids

The name "semiconductor" implies that it conducts somewhere between the two cases (conductors or insulators)

Conductivity :  $\sigma$

$\sigma_{\text{metals}} \sim 10^{10} / \Omega\text{-cm}$

S/C

$\sigma_{\text{insulators}} \sim 10^{-22} / \Omega\text{-cm}$

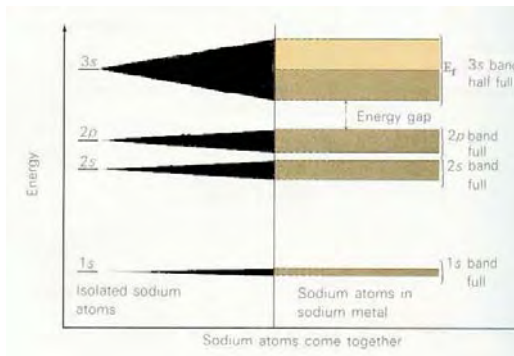
The conductivity ( $\sigma$ ) of a semiconductor (S/C) lies between these two extreme cases.

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## Band Theory of Solids



- The electrons orbiting around the nucleus have certain well-defined energy-levels.
- Electrons don't like to have the same energy in the same potential system.
- The most we could get together in the same energy-level was two, provided that they had opposite spins. This is called **Pauli Exclusion Principle**.

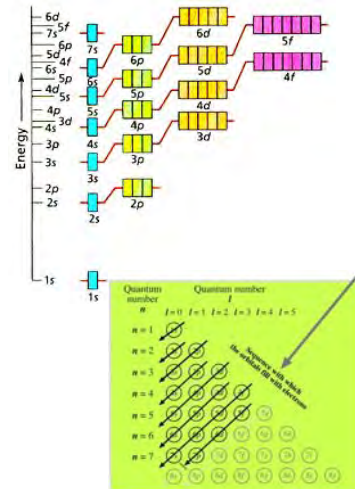
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## Difference between Solids

- The difference in energy between each of these smaller levels is so tiny that it is more reasonable to consider each of these sets of smaller energy-levels as being continuous **bands** of energy, rather than considering the enormous number of discrete individual levels.
- Each **allowed band** is separated from another one by a **forbidden band**.
- Electrons can be found in **allowed bands** but they can not be found in **forbidden bands**.



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## Example

- Consider 1 cm<sup>3</sup> of Silicon. How many atoms does this contain ?
- Solution:

The atomic mass of silicon is 28.1 g which contains Avagadro's number of atoms.

Avagadro's number N is 6.02 x 10<sup>23</sup> atoms/mol .

The density of silicon: 2.3 x 10<sup>3</sup> kg/m<sup>3</sup>

so 1 cm<sup>3</sup> of silicon weighs 2.3 gram and so contains

$$\frac{6.02 \times 10^{23}}{28.1} \times 2.3 = 4.93 \times 10^{22} \text{ atoms}$$

This means that in a piece of silicon just one cubic centimeter in volume, each electron energy-level has split up into 4.93 x 10<sup>22</sup> smaller levels !

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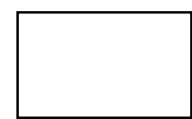
## Semiconductor, Insulators, Conductors



Full band



All energy levels are occupied by electrons



Empty band



All energy levels are empty (no electrons)

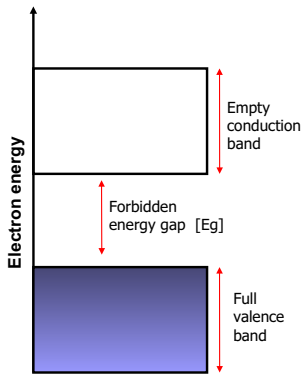
**Both full and empty bands do not partake in electrical conduction.**

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### Semiconductor energy bands at low temperature

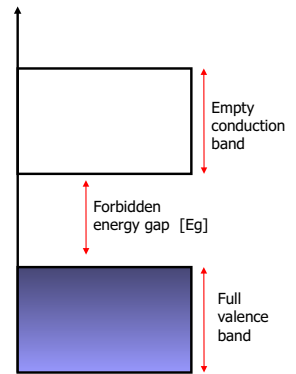


- At low temperatures the valence and the conduction band is empty.
- Recall that a full band can not conduct, and neither can an empty band.
- At low temperatures, s/c's do not conduct, they behave like insulators.
- The **thermal energy** of the electrons sitting at the top of the full band is much lower than that of the **Eg at low temperatures**.

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### Conduction Electrons

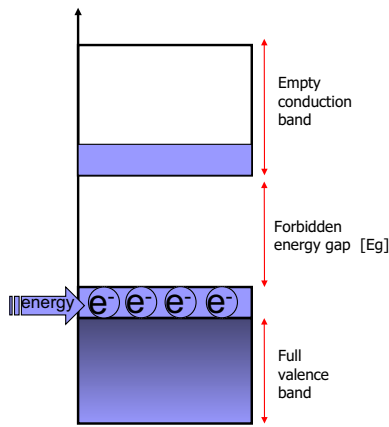
- Assume some kind of energy is provided to the electron (**valence electron**) sitting at the top of the **valence band**.
- This electron gains energy from the applied field and it would like to move into higher energy states.
- This electron contributes to the **conductivity** and this electron is called as a **conduction electron**.
- At 0°K, electron sits at the lowest energy levels. The valence band is the highest filled band at zero kelvin.



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### Semiconductor energy bands at room temperature

- When enough **energy** is supplied to the **e<sup>-</sup>** sitting at the top of the valence band, **e<sup>-</sup>** can make a transition to the bottom of the conduction band.
- When electron makes such a transition it leaves behind a **missing electron state**.
- This missing electron state is called as a **hole**.
- Hole behaves as a **positive charge carrier**.
- Magnitude of its charge is the same with that of the electron but with an opposite sign.



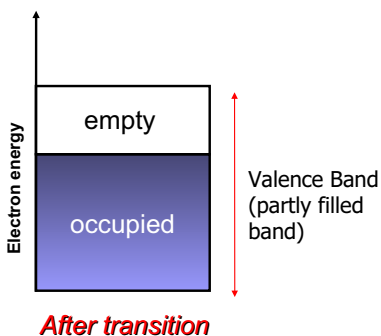
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### Conclusion

- Holes contribute to current in **valence band (VB)** as electrons are able to create current in **conduction band (CB)**.
- Hole is **not** a free particle. It can only exist within the crystal. A hole is simply a vacant electron state.
- A transition results an equal number of e<sup>-</sup> in CB and holes in VB. This is an important property of **intrinsic** or **undoped** semiconductors. For **extrinsic** or **doped** semiconductors this is no longer true.

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### Bipolar (two carrier) conduction



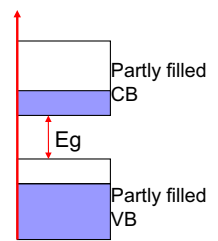
- **After transition**, the valence band is now no longer full, it is **partly filled** and may conduct electric current.
- The **conductivity** is due to both electrons and holes, and this device is called a **bipolar conductor** or **bipolar device**.

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What kind of excitation mechanism can cause an e<sup>-</sup> to make a transition from the top of the valence band (VB) to the minimum or bottom of the conduction band (CB) ?

Answer :

- Thermal energy ?
- Electrical field ?
- Electromagnetic radiation ?



Energy band diagram of a s/c at a finite temperature.

To have a partly filled band configuration in a s/c, one must use one of these excitation mechanisms.

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## 1 - Thermal Energy

Thermal energy at RTP =  $k \times T = 1.38 \times 10^{-23} \text{ J/K} \times 298 \text{ K} = 25.7 \text{ meV}$

Excitation rate = constant  $\times \exp(-E_g / kT)$

Although the thermal energy at room temperature is very small, i.e. 25 meV, a few electrons can be promoted to the CB.

Electrons can be promoted to the CB by means of thermal energy.

This is due to the exponential increase of excitation rate with increasing temperature.

Excitation rate is a strong function of temperature.

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## 2 - Electric Field

- For low fields, this mechanism doesn't promote electrons to the CB in common s/c's such as Si and GaAs.
- An electric field of  $10^{18} \text{ V/m}$  can provide an energy of the order of 1 eV. This field is enormous.

So, the use of the electric field as an excitation mechanism is not useful way to promote electrons in s/c's.

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## 3- Electromagnetic Radiation

$$E = h\nu = \frac{hc}{\lambda} = (6.62 \times 10^{-34} \text{ J} \cdot \text{s}) \times (3 \times 10^8 \text{ m/s}) / \lambda (\text{m}) \Rightarrow E(\text{eV}) = \frac{1.24}{\lambda (\text{in } \mu\text{m})}$$

$$\begin{aligned} h &= 6.62 \times 10^{-34} \text{ Js} \\ c &= 3 \times 10^8 \text{ m/s} \\ 1 \text{ eV} &= 1.6 \times 10^{-19} \text{ J} \end{aligned}$$

Near infrared

for Silicon  $E_g = 1.1 \text{ eV}$        $\lambda (\mu\text{m}) = \frac{1.24}{1.1} = 1.1 \mu\text{m}$

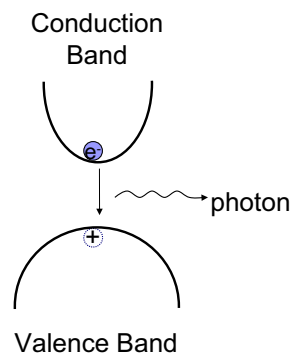
To promote electrons from VB to CB Silicon, the wavelength of the photons must be 1.1  $\mu\text{m}$  or less

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## Direct Band-Gap



- The converse transition can also happen.
- An electron in CB recombines with a hole in VB and generate a photon.
- The energy of the photon will be in the order of  $E_g$ .
- If this happens in a direct band-gap s/c, it forms the basis of LED's and LASERS.

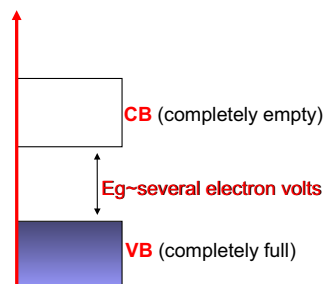
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## Insulators

- The magnitude of the band gap determines the differences between insulators, s/c's and metals.
- The excitation mechanism of thermal is not a useful way to promote an electron to CB even the melting temperature is reached in an insulator.
- Even very high electric fields is also unable to promote electrons across the band gap in an insulator.



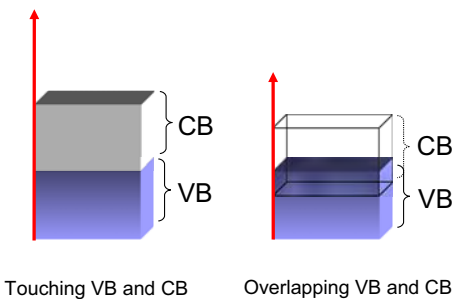
Wide band gaps between VB and CB

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## Metals



- These two bands look like as if partly filled bands and it is known that partly filled bands conducts well.
- This is the reason why metals have high conductivity.

- No gap between **valance band** and **conduction band**

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## The Concept of Effective Mass

### Comparing

#### Free e<sup>-</sup> in vacuum

In an electric field

$$m_0 = 9.1 \times 10^{-31}$$

Free electron mass

#### An e<sup>-</sup> in a crystal

In an electric field

In a crystal

$$m = ?$$

$m^*$  effective mass

- If the same magnitude of **electric field** is applied to both **electrons in vacuum** and inside the **crystal**, the **electrons** will accelerate at a different rate from each other due to the existence of different potentials inside the crystal.
- The **electron inside the crystal** has to try to make its own way.
- So the **electrons inside the crystal** will have a different mass than that of the electron in vacuum.
- This altered mass is called as an **effective-mass**.

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## What is the expression for $m^*$

- Particles of electrons and holes behave as a wave under certain conditions. So one has to consider the *de Broglie* wavelength to link partial behaviour with wave behaviour.
- Particles such as electrons and waves can be diffracted from the crystal just as X-rays .
- Certain electron momentum is not allowed by the crystal lattice. This is the origin of the energy band gaps.

$$n\lambda = 2d \sin\theta$$

$n$  = the order of the diffraction  
 $\lambda$  = the wavelength of the X-ray  
 $d$  = the distance between planes  
 $\theta$  = the incident angle of the X-ray beam

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$$n\lambda = 2d \quad (1)$$

The waves are standing waves

$$\lambda = \frac{2\pi}{k} \quad \text{is the propagation constant}$$

The momentum is

$$P = \hbar k \quad (2)$$

The energy of the free electron can be related to its momentum

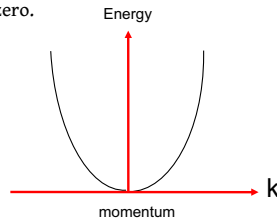
$$E = \frac{P^2}{2m} \quad \left[ P = \frac{h}{\lambda} \right]$$

free e<sup>-</sup> mass,  $m_0$

$$E = \frac{\hbar^2 k^2}{2m} \frac{1}{\lambda^2} = \frac{\hbar^2}{2m} \frac{k^2}{(2\pi)^2}$$

$$\hbar = \frac{h}{2\pi} \quad E = \frac{\hbar^2 k^2}{2m} \quad \text{The energy of the free e<sup>-</sup> is related to the k}$$

By means of equations (1) and (2) certain e<sup>-</sup> momenta are not allowed by the crystal. The velocity of the electron at these momentum values is zero.



E versus k diagram is a parabola.

Energy is continuous with k, i.e, all energy (momentum) values are allowed.

E versus k diagram or Energy versus momentum diagrams

## To find effective mass, $m^*$

We will take the derivative of **energy** with respect to **k** ;

$$\frac{dE}{dk} = \frac{\hbar^2 k}{m}$$

$$\frac{d^2 E}{dk^2} = \frac{\hbar^2}{m}$$

-  $m^*$  is determined by the curvature of the E-k curve

-  $m^*$  is inversely proportional to the curvature

Change  $m^*$  instead of  $m$

$$m^* = \frac{\hbar^2}{d^2 E / dk^2}$$

This formula is the **effective mass** of an electron inside the crystal.

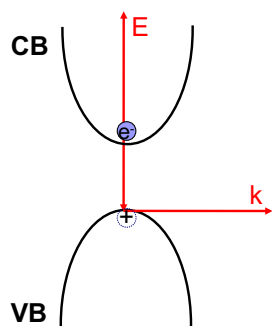
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## Direct-band gap materials

Direct-band gap s/c's (e.g. GaAs, InP, AlGaAs)



- For a **direct-band gap material**, the minimum of the **conduction band** and maximum of the **valence band** lies at the same momentum, k, values.
- When an electron sitting at the bottom of the **CB** recombines with a hole sitting at the top of the **VB**, there will be no change in momentum values.
- Energy is conserved by means of emitting a photon, such transitions are called as **radiative transitions**.

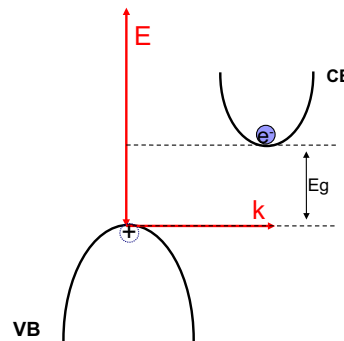
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## Indirect-band gap materials

Indirect-band gap s/c's (e.g. Si and Ge)



- For an **indirect-band gap** material; the minimum of the **CB** and maximum of the **VB** lie at different k-values.
- When an e<sup>-</sup> and hole recombine in an indirect-band gap s/c, **phonons** must be involved to conserve momentum.

### Phonon

- Atoms vibrate about their mean position at a finite temperature. These vibrations produce vibrational waves inside the crystal.
- Phonons are the quanta of these vibrational waves. Phonons travel with a velocity of sound .
- Their wavelength is determined by the crystal lattice constant. Phonons can only exist inside the crystal.

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### Conclusion

- The transition that involves phonons without producing photons are called **non-radiative (radiationless) transitions**.
- These transitions are observed in an **indirect band gap** s/c and result in inefficient photon producing.
- So in order to have efficient LED's and LASER's, one should choose materials having direct band gaps such as compound s/c's of GaAs, AlGaAs, etc...

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### Calculation

- For GaAs, calculate a typical (band gap) photon energy and momentum, and compare this with a typical phonon energy and momentum that might be expected with this material.

photon

phonon

$$E(\text{photon}) = E_g(\text{GaAs}) = 1.43 \text{ eV}$$

$$E(\text{phonon}) = h \nu = h v_s / \lambda = h v_s / a_0$$

$$E(\text{photon}) = h \nu = hc / \lambda$$

$$\lambda(\text{phonon}) - a_0 = \text{lattice constant} = 5.65 \times 10^{-10} \text{ m}$$

$$c = 3 \times 10^8 \text{ m/sec}$$

$$v_s = 5 \times 10^3 \text{ m/sec (velocity of sound)}$$

$$p = h / \lambda \quad h = 6.63 \times 10^{-34} \text{ J-sec}$$

$$E(\text{phonon}) = h v_s / a_0 = 0.037 \text{ eV}$$

$$\lambda(\text{photon}) = 1.24 / 1.43 = 0.88 \mu\text{m}$$

$$p(\text{phonon}) = h / \lambda = h / a_0 = 1.17 \times 10^{-24} \text{ kg-m/sec}$$

$$p(\text{photon}) = h / \lambda = 7.53 \times 10^{-28} \text{ kg-m/sec}$$

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### Phonons vs Photons

- Photon energy = 1.43 eV
- Phonon energy = 37 meV
- Photon momentum =  $7.53 \times 10^{-28} \text{ kg-m/sec}$
- Phonon momentum =  $1.17 \times 10^{-24} \text{ kg-m/sec}$

Photons carry large energies but negligible amount of momentum.

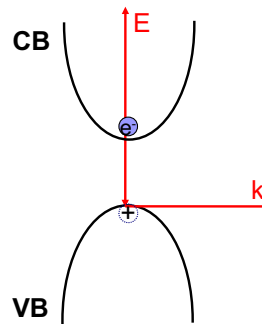
On the other hand, phonons carry very little energy but significant amount of momentum.

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### Positive and Negative effective mass

Direct-band gap s/c's (e.g. GaAs, InP, AlGaAs)

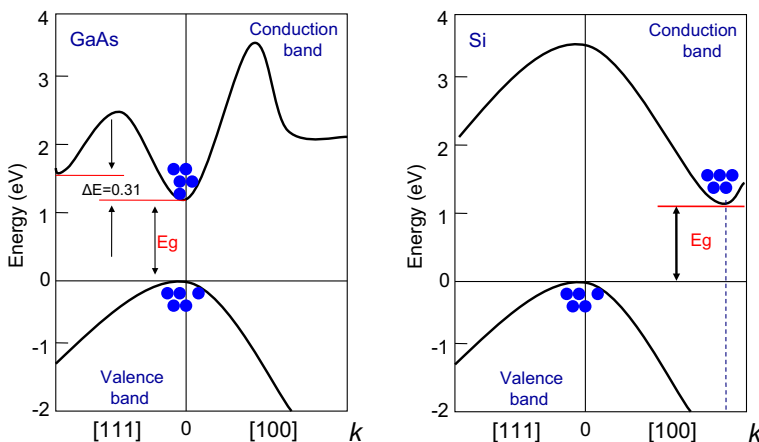
$$m^* = \frac{h^2}{d^2 E / dk^2}$$



- The sign of the effective mass is determined directly from the sign of the curvature of the E-k curve.
- The curvature of a graph at a minimum point is a positive quantity and the curvature of a graph at a maximum point is a negative quantity.
- Particles (electrons) sitting near the minimum have a **positive effective mass**.
- Particles (holes) sitting near the valence band maximum have a **negative effective mass**.
- A negative effective mass implies that a particle will go **'the wrong way'** when an external force is applied.

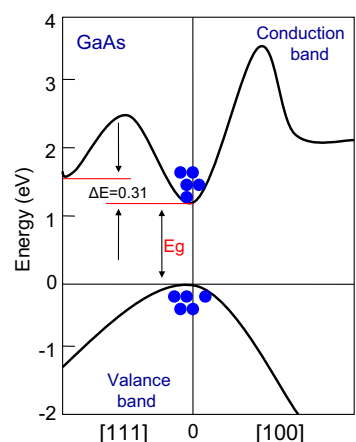
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### Energy band structures of GaAs and Si



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### Energy band structure of GaAs



Band gap is the smallest energy separation between the valence and conduction band edges.

The smallest energy difference occurs at the same momentum value



Direct-band gap semiconductor

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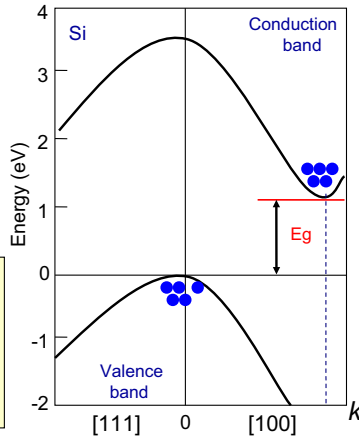
### Energy band structure of Si

The smallest energy gap is between the top of the VB at  $k=0$  and one of the CB minima away from  $k=0$

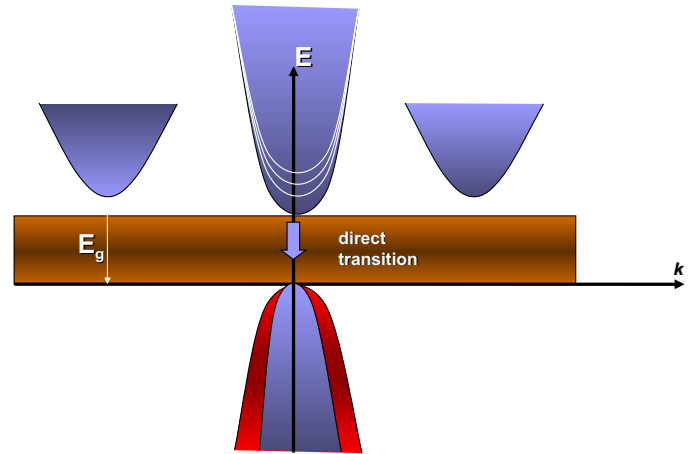


Indirect band gap semiconductor

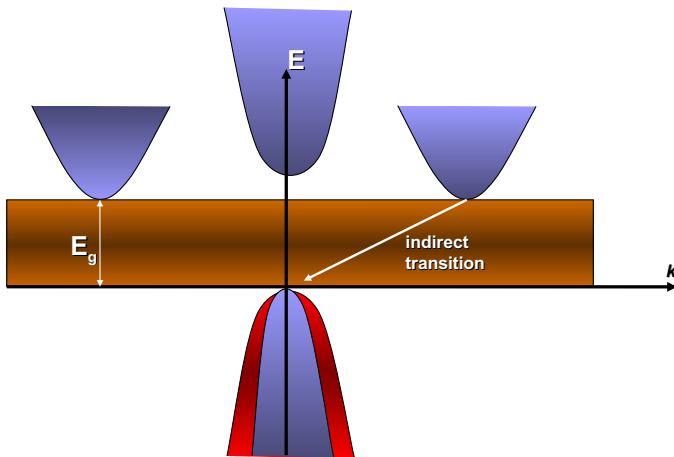
- Band structure of AlGaAs?
- Effective masses of CB satellites?
- Heavy- and light-hole masses in VB?



### Direct transition



### Indirect transition



## Slide Set 2

### Carrier Concentration in Semiconductors

## CARRIER CONCENTRATIONS IN SEMICONDUCTORS

### Donors and Acceptors

Fermi level,  $E_f$

Carrier concentration equations

Donors and acceptors both present

### Donors and Acceptors

The conductivity of a pure (intrinsic) s/c is low due to the low number of free carriers.

■ The number of carriers are generated by thermally or electromagnetic radiation for a pure s/c.

- For an **intrinsic semiconductor**

$$n = p = n_i$$

$n$  = concentration of electrons per unit volume

$p$  = concentration of holes per unit volume

$n_i$  = the intrinsic carrier concentration of the semiconductor under consideration.

$$n \cdot p = n_i^2$$

$$n = p$$

number of e<sup>-</sup>s in CB = number of holes in VB

- This is due to the fact that when an e<sup>-</sup> makes a transition to the CB, it leaves a hole behind in VB. We have a bipolar (two carrier) conduction and the **number of holes and e<sup>-</sup>s are equal.**

$$n \cdot p = n_i^2$$

This equation is known as **mass-action law.**

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$$n \cdot p = n_i^2$$

The intrinsic carrier concentration  $n_i$  depends on; the **semiconductor material**, and the **temperature.**

- For silicon at 300 K,  $n_i$  has a value of  $1.4 \times 10^{10} \text{ cm}^{-3}$ .
- Clearly, equation ( $n = p = n_i$ ) can be written as

$$n \cdot p = n_i^2$$

- This equation is valid for **extrinsic** as well as **intrinsic** material.

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## What are doping and dopants impurities ?

To increase the conductivity, one can dope pure s/c with atoms from column III or V of periodic table. This process is called as **doping** and the added atoms are called as **dopants impurities.**

There are two types of doped or extrinsic s/c's;

- n-type
- p-type

**Addition of different atoms modify the conductivity of the intrinsic semiconductor.**

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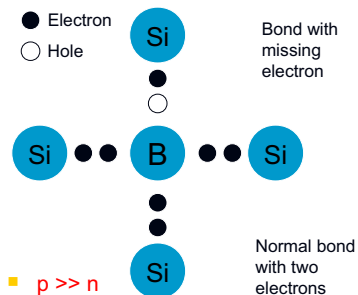
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## P-type doped semiconductor

- Si + Column III impurity atoms

Have four valence electrons

Boron (B) has three valence electrons



- Boron bonding in Silicon
- Boron sits on a lattice site

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## P-type doped semiconductor

**Boron (column III)** atoms have three valence electrons, there is a deficiency of electron or missing electron to complete the outer shell.

This means that each added or doped **Boron** atom introduces a **single hole** in the crystal.

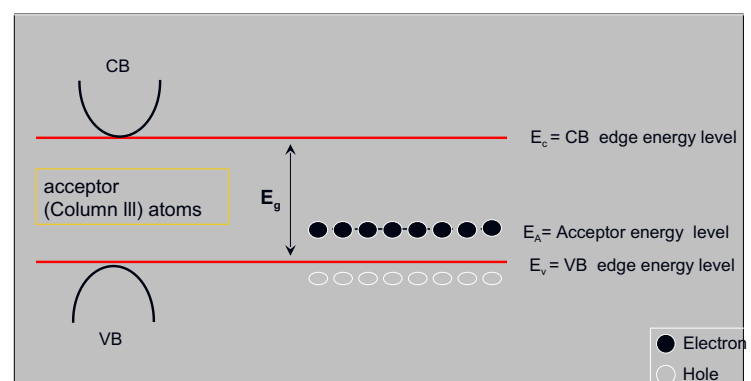
- There are two ways of producing holes
  - Promote electrons from VB to CB,
  - Add column III impurities to the s/c.

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## Energy Diagram for a P-type s/c



The energy gap is forbidden only for pure material, i.e. Intrinsic material.

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## P-type semiconductor

- The impurity atoms from column III occupy at an energy level within  $E_g$ . These levels can be:

  - Shallow levels which is close to the band edge,
  - Deep levels which lies almost at the mid of the band gap.
- If the  $E_A$  level is shallow i.e. close to the VB edge, each added boron atom accepts an  $e^-$  from VB and have a full configuration of  $e^-$ 's at the outer shell.
- These atoms are called as acceptor atoms since they accept an  $e^-$  from VB to complete its bonding. So each acceptor atom gives rise a hole in VB.
- The current is mostly due to holes since the number of holes are made greater than  $e^-$ 's.

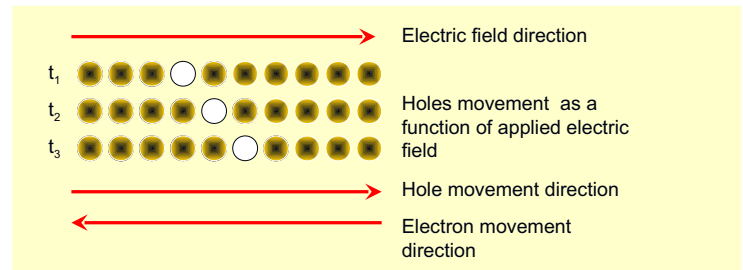
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## Majority & Minority carrier in a P-type semiconductor

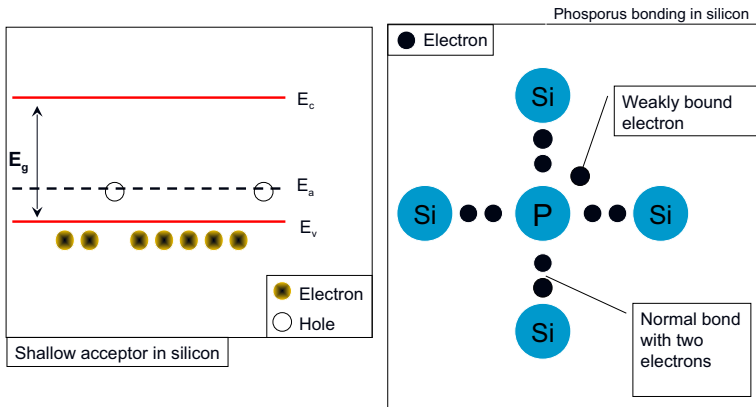
Holes =  $p$  = majority carriers  
 Electrons =  $n$  = minority carriers



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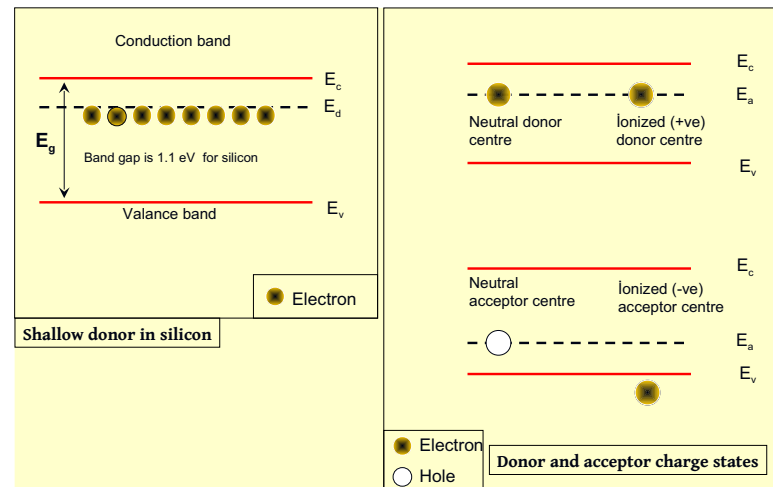
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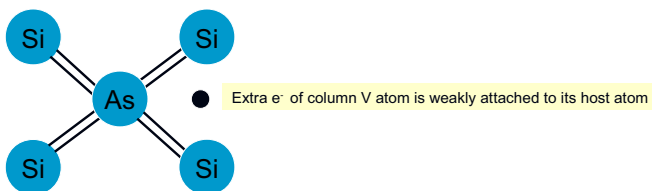


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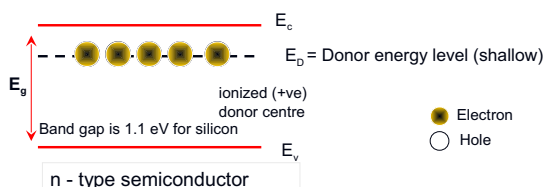
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## N-type doped semiconductor



Si + column V (with five valance  $e^-$ )



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## Np vs. Pn semiconductors

n-type,  $n \gg p$ ;  $n$  is the majority carrier concentration  $n_n$   
 $p$  is the minority carrier concentration  $p_n$   
 p-type,  $p \gg n$ ;  $p$  is the majority carrier concentration  $p_p$   
 $n$  is the minority carrier concentration  $n_p$

$n_p$                        $p_n$

Type of semiconductor

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## Calculation

Calculate the hole and electron densities in a piece of P-type silicon that has been doped with  $5 \times 10^{16}$  acceptor atoms per  $\text{cm}^3$ .

$$n_i = 1.4 \times 10^{10} \text{ cm}^{-3} \quad (\text{at room temperature})$$

### Undoped

$$n = p = n_i$$

P-type ;  $p \gg n$

$$n, p = n_i^2 \quad N_A = 5 \times 10^{16} \quad p = N_A = 5 \times 10^{16} \text{ cm}^{-3}$$

$$n = \frac{n_i^2}{p} = \frac{(1.4 \times 10^{10} \text{ cm}^{-3})^2}{5 \times 10^{16} \text{ cm}^{-3}} = 3.9 \times 10^3 \text{ electrons per cm}^3$$

$p \gg n_i$  and  $n \ll n_i$  in a p-type material. The more holes you put in the less electrons you have and vice versa.

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## Fermi level , $E_F$

This is a reference energy level at which the probability of occupation by an electron is  $\frac{1}{2}$ .

Since  $E_f$  is a reference level therefore it can appear anywhere in the energy level diagram of a S/C .

Fermi energy level is not fixed.

Occupation probability of an electron and hole can be determined by Fermi-Dirac distribution function,  $F_{FD}$  ;

$$F_{FD} = \frac{1}{1 + \exp\left(\frac{E - E_F}{k_B T}\right)}$$

$E_F$  = Fermi energy level

$k_B$  = Boltzman constant

T = Temperature

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## Fermi level , $E_F$

$$F_{FD} = \frac{1}{1 + \exp\left(\frac{E - E_F}{k_B T}\right)}$$

E is the energy level under investigation.

$F_{FD}$  determines the probability of the energy level E being occupied by electron.

$$\text{if } E = E_F \rightarrow f_{FD} = \frac{1}{1 + \exp 0} = \frac{1}{2}$$

$1 - f_{FD}$  determines the probability of not finding an electron at an energy level E; the probability of finding a hole .

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## Carrier concentration equations

The number density, i.e., the number of electrons available for conduction in CB is

$$n = 2 \left( \frac{2\pi m_n^* kT}{h^2} \right)^{3/2} \exp\left(-\frac{E_C - E_F}{kT}\right)$$

$$n = N_C \exp\left(-\frac{E_C - E_F}{kT}\right) \quad n = n_i \exp\left(\frac{E_F - E_i}{kT}\right)$$

The number density, i.e., the number of holes available for conduction in VB is

$$p = 2 \left( \frac{2\pi m_p^* kT}{h^2} \right)^{3/2} \exp\left(-\frac{E_F - E_V}{kT}\right)$$

$$p = N_V \exp\left(-\frac{E_F - E_V}{kT}\right) \quad p = n_i \exp\left(\frac{E_i - E_F}{kT}\right)$$

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## Donors and acceptors both present

Both donors and acceptors present in a s/c in general. However one will outnumber the other one.

In an n-type material the number of donor concentration is significantly greater than that of the acceptor concentration.

Similarly, in a p-type material the number of acceptor concentration is significantly greater than that of the donor concentration.

A p-type material can be converted to an n-type material or vice versa by means of adding proper type of dopant atoms. This is in fact how p-n junction diodes are actually fabricated.

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## Example

How does the position of the Fermi Level change with

- increasing **donor concentration**, and
- increasing **acceptor concentration** ?

(a) We shall use equation

$$n = N_C \exp\left(-\frac{E_C - E_F}{kT}\right)$$

If  $n$  is increasing then the quantity  $E_C - E_F$  must be decreasing **i.e.** as the donor concentration goes up the Fermi level moves towards the conduction band edge  $E_C$ .

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### Example

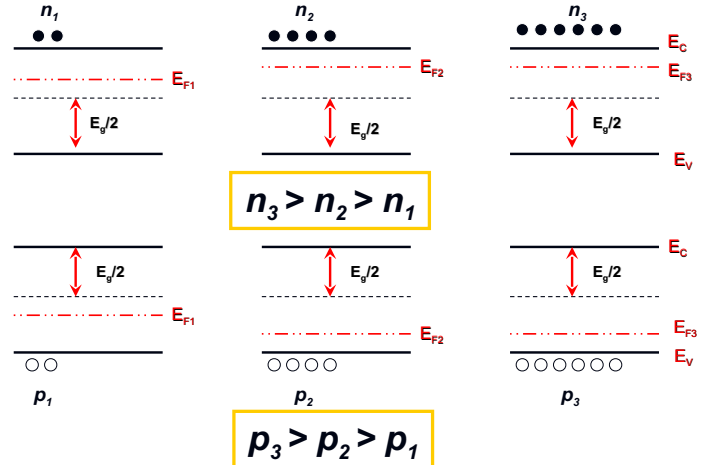
But the carrier density equations such as;

$$n = 2 \left( \frac{2\pi m_n^* kT}{h^2} \right)^{\frac{3}{2}} \exp\left(-\frac{E_c - E_F}{kT}\right) \text{ and}$$

$$p = n_i \exp\left(\frac{E_i - E_F}{kT}\right)$$

aren't valid for all doping concentrations! As the fermi-level comes to within about  $3kT$  of either band edge the equations are no longer valid, because they were derived by assuming the simpler **Maxwell Boltzmann statistics** rather than the proper **Fermi-Dirac statistic**.

### Example



### Example

(b) Considering the density of holes in valence band;

$$p = N_v \exp\left(-\frac{E_F - E_V}{kT}\right)$$

It is seen that as the acceptor concentration increases, Fermi-level moves towards the *valance band edge*. These results will be used in the construction of device (energy) band diagrams.

### Donors and acceptor both present

- In general, both donors and acceptors are present in a piece of a semiconductor although one will outnumber the other one.
- The impurities are incorporated unintentionally during the growth of the semiconductor crystal causing both types of impurities being present in a piece of a semiconductor.
- How do we handle such a piece of s/c?

1) Assume that the shallow donor concentration is significantly greater than that of the shallow acceptor concentration. In this case the material behaves as an n-type material and

$$n_n = N_D - N_A$$

2) Similarly, when the number of shallow acceptor concentration is significantly greater than the shallow donor concentration in a piece of a s/c, it can be considered as a p-type s/c and

$$p_p = N_A - N_D$$

### Donors and acceptor both present

For the case  $N_A > N_D$ , i.e. for p-type material

$$n_p \cdot p_p = n_i^2$$

$$n_p + N_A^- = N_D^+ + p_p \Rightarrow p_p + N_D - n_p - N_A = 0$$

$$p_p \times \left[ p_p + N_D - \frac{n_i^2}{p_p} - N_A \right] = 0 \Rightarrow p_p^2 + (N_D - N_A)p_p - n_i^2 = 0$$

### Donors and acceptor both present

$$p_p^2 + (N_D - N_A)p_p - n_i^2 = 0, \text{ solving for } p_p; x_{1,2} = \frac{-b \mp \sqrt{b^2 - 4ac}}{2a}$$

$$p_p = \frac{1}{2} \left( N_A - N_D + \left[ (N_A - N_D)^2 + 4n_i^2 \right]^{\frac{1}{2}} \right) \quad \text{majority}$$

$$n_p = \frac{n_i^2}{p_p} \quad \text{minority}$$

## Donors and acceptor both present

For the case  $N_D > N_A$ , i.e. n-type material

$$n_n \cdot p_n = n_i^2 \Rightarrow p_n = \frac{n_i^2}{n_n}$$

$$n_n + N_A = N_D + p_n \Rightarrow n_n + N_A - p_n - N_D = 0$$

$$n_n \times \left[ n_n + N_A - \frac{n_i^2}{n_n} - N_D = 0 \right] \Rightarrow n_n^2 + (N_A - N_D)n_n - n_i^2 = 0$$

$$\text{solving for } n_n : x_{1,2} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$n_n = \frac{1}{2} \left( N_D - N_A + \left[ (N_D - N_A)^2 + 4n_i^2 \right]^{1/2} \right)$$

$$p_n = \frac{n_i^2}{n_n}$$

## Slide Set 3

- Carrier drift
- Carrier mobility
- Saturated drift velocity
- Mobility variation with temperature
- Drift current equations
- Band diagrams with an electric field present
  - Carrier diffusion
  - Flux equation
  - Einstein relation
- Total current density
- Carrier recombination and diffusion length

## Drift and Diffusion

We now have some idea of the number density of charge carriers (electrons and holes) present in a semiconductor material from the last slide set. Since **current is the rate of flow of charge**, we shall be able calculate currents flowing in real devices since we know the number of charge carriers. There are **two current mechanisms** which **cause charges to move** in semiconductors. These two mechanisms are **drift and diffusion**.

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Slide Set 3

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## Carrier Drift

- Electron and holes **will move under the influence of an applied electric field** since the **field exert a force** on charge carriers (electrons and holes).

$$F = qE$$

- These movements result a current of  $I_d$

$$I_d = nqV_d A$$

$I_d$  : drift current                       $n$  : number of charge carriers per unit volume

$V_d$  : drift velocity of charge carrier     $q$  : charge of the electron

$A$  : area **presented** in the direction of the flow of charge carriers

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## Carrier Mobility $\mu$

$$V_d = \mu E$$

$E$  : applied field

$\mu$  : mobility of charge carrier

$$[\mu] = \left[ \frac{cm^2}{Vs} \right]$$

$\mu$  is a proportionality factor

$$\mu = \left[ \frac{V_d}{E} \right]$$

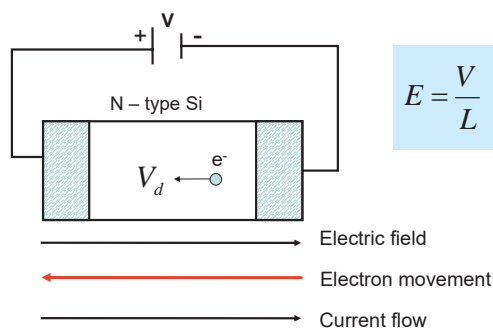
❖ So  $\mu$  is **a measure how easily charge carriers move** under the influence of an applied field or  $\mu$  determines **how mobile the charge carriers** are.

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## N - type Silicon



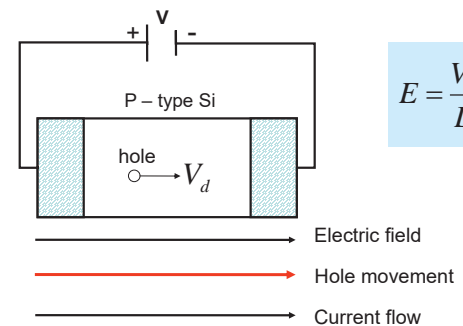
Current carriers are mostly electrons.

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## P - type Silicon



Current carriers are mostly holes.

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## Carrier Mobility

Macroscopic understanding

$$\mu = \frac{V_d}{E}$$

In a perfect Crystal

$$\rho = 0$$

$$\sigma \rightarrow \infty$$

It is a superconductor

Microscopic understanding? (what the carriers themselves are doing?)

$$\mu = \frac{q\tau}{m^*}$$

$$m_e^* < m_h^* \text{ in general}$$

$$m_e^* : \text{N-type}$$

$$m_h^* : \text{P-type}$$

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## $\mu$

- A *perfect crystal has a perfect periodicity* and therefore the potential seen by a carrier in a perfect crystal is completely periodic.
- So the *crystal has no resistance to current flow* and behaves as a *superconductor*. The perfect periodic potential does not *impede the movement of the charge carriers*. However, in a real device or specimen, the presence of impurities, interstitials, substitutionals, temperature, etc. creates a resistance to current flow.
- The presence of all these *upsets the periodicity of the potential* seen by a charge carrier.

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## Mobility has two components

Mobility has two components



Lattice interaction component

Impurity interaction component

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## Thermal Velocity

- Assume that s/c crystal is at thermodynamic equilibrium (i.e. there is no applied field). What will be the energy of the electron at a finite temperature?
- The electron will have a thermal energy of  $kT/2$  per degree of freedom. So, in 3D, electron will have a thermal energy of

$$E = \frac{3kT}{2} \Rightarrow \frac{1}{2}m^*v_{th}^2 = \frac{3kT}{2} \Rightarrow V_{th} = \sqrt{\frac{3kT}{m^*}}$$

$V_{th}$  : thermal velocity of electron or hole  
 $V_{th}$  is proportional to  $T^{1/2}$   
 $V_{th}$  is inversely proportional to  $(m^*)^{1/2}$

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## Random motion result no current.

- Since there is no applied field, the movement of the charge carriers will be completely random. This randomness result no net current flow. As a result of thermal energy there are almost an equal number of carriers moving right as left, in as out or up as down.

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## Calculation

Calculate the velocity of an electron in a piece of n-type silicon due to its thermal energy at RT and due to the application of an electric field of 1000 V/m across the piece of silicon.

$$V_{th} = ? \quad RT = 300 \text{ K} \quad m_e^* = 1.18 m_0$$

$$V_d = ? \quad E = 1000 \text{ V/m} \quad \mu = 0.15 \text{ m}^2 / (\text{V} \cdot \text{s})$$

$$V_{th} = \sqrt{\frac{3kT}{m^*}} \Rightarrow V_{th} = 1.08 \times 10^5 \text{ m/sec}$$

$$V_d = \mu E \Rightarrow V_d = 150 \text{ m/sec}$$

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## Microscopic understanding of mobility?

How long does a carrier move in time before collision ?

The average time taken between collisions is referred to as relaxation time or mean free time:  $\tau$  (small Greek symbol Tau)

How far does a carrier move in space before a collision?

The average distance taken between collisions is called as mean free path:  $\zeta$  (small Greek symbol Zeta)

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## Calculation

Drift velocity=Acceleration x Mean free time

$$V_d = \frac{F}{m^*} \times \tau$$

Force is due to the applied field,  $F=qE$

$$V_d = \frac{F}{m^*} \times \tau = \frac{qE}{m^*} \tau$$

$$V_d = \mu E \Rightarrow \mu = \frac{q\tau}{m^*}$$

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## Calculation

Calculate the mean free time and mean free path for electrons in a piece of N-type silicon and for holes in a piece of P-type silicon.

$$\tau = ? \quad l = ? \quad m_e^* = 1.18 m_0 \quad m_h^* = 0.59 m_0$$

$$\mu_e = 0.15 \text{ m}^2 / (V - s) \quad \mu_h = 0.0458 \text{ m}^2 / (V - s)$$

$$\tau_e = \frac{\mu_e m_e^*}{q} = 10^{-12} \text{ sec} \quad \tau_h = \frac{\mu_h m_h^*}{q} = 1.54 \times 10^{-13} \text{ sec}$$

$$v_{th_{elec}} = 1.08 \times 10^5 \text{ m/s} \quad v_{th_{hole}} = 1.52 \times 10^5 \text{ m/s}$$

$$l_e = v_{th_{elec}} \tau_e = (1.08 \times 10^5 \text{ m/s})(10^{-12} \text{ s}) = 10^{-7} \text{ m}$$

$$l_h = v_{th_{hole}} \tau_h = (1.52 \times 10^5 \text{ m/s})(1.54 \times 10^{-13} \text{ sec}) = 2.34 \times 10^{-8} \text{ m}$$

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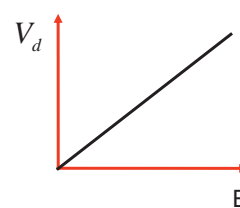
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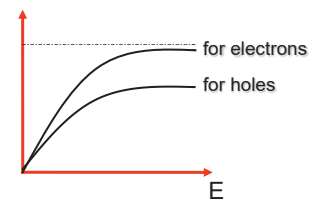
## Saturated Drift Velocities

$$V_d = \mu E$$

So one can make a carrier go as fast as we like just by increasing the electric field beyond the speed of light ☺



(a) implication of above eqn.



(b) Saturation drift velocity

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## Saturated Drift Velocities

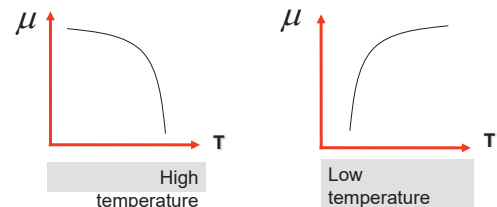
- The equation of  $V_d = \mu E$  does not imply that  $V_d$  increases linearly with applied field  $E$ .
- $V_d$  increases linearly for low values of  $E$  and then it saturates at some value of  $V_d$  which is close  $V_{th}$  at higher values of  $E$ .
- Any further increase in  $E$  after saturation point does not increase  $V_d$  instead warms up the crystal.

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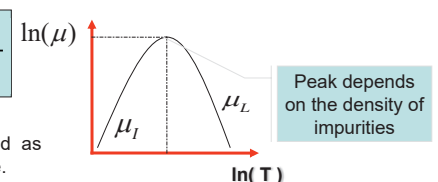
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## Mobility variation with Temperature



$$\frac{1}{\mu_T} = \frac{1}{\mu_L} + \frac{1}{\mu_I}$$

This equation is called as Mattheisen's rule.



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## Variation of mobility with temperature

At high temperature as the lattice warms up  $\Rightarrow \mu_L$  component becomes significant.

$\mu_L$  decreases when temperature increases.

$$\mu_L = C_1 \times T^{-\frac{3}{2}} \Rightarrow T^{-\frac{3}{2}} \quad C_1 \text{ is a constant.}$$

It is called as a  $T^{-1.5}$  power law.

Carriers are more likely scattered by the lattice atoms.

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## Variation of mobility with temperature

At low temperatures  $\Rightarrow \mu_I$  component is significant.

$\mu_I$  decreases when temperature decreases.

$$\mu_I = C_2 \times T^{\frac{3}{2}} \quad C_2 \text{ is a constant.}$$

Carriers are more likely scattered by ionized impurities.

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## Variation of mobility with temperature

The peak of the mobility curve depends on the number density of ionized impurities.

Highly doped samples will therefore cause more scattering, and have a lower mobility, than low doped samples.

This fact is used in high speed devices called High Electron Mobility Transistors (HEMTs) where electrons are made to move in undoped material, with the resulting high carrier mobilities!

HEMTs are high speed devices.

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## A Derivation of Ohm's Law

$$I_d = nqV_dA$$

$$V_d = \mu E$$

$$J_d = \frac{I_d}{A}$$

$$\mu = \frac{q\tau}{m^*}$$

$$J_x = nqV_d = nq\mu E$$

$$J_x = \left( \frac{nq^2\tau}{m^*} \right) E_x$$

$$\sigma = \frac{nq^2\tau}{m^*}$$

$$J_x = \sigma E_x$$

$$\rho = \frac{1}{\sigma}$$

$$[\rho] = [\Omega - m]$$

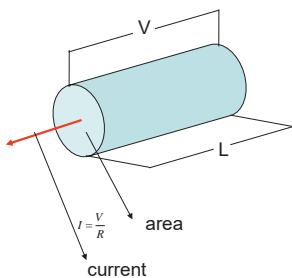
$$[\sigma] = [1/(\Omega - m)]$$

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## A Derivation of Ohm's Law



This is in fact ohm's law which is written slightly in a different form.

$$J_x = \sigma E_x \quad \frac{I_x}{A} = \sigma \frac{V}{L} \Rightarrow \frac{I_x}{A} = \frac{1}{\rho} \frac{V}{L} \quad I = \frac{VA}{\rho L} = \frac{V}{R}$$

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## Drift Current Equations

For undoped or intrinsic semiconductor ;  $n=p=n_i$

For electron

$$J_n = nqE\mu_n$$

drift current for electrons

number of free electrons per unit volume

mobility of electron

For hole

$$J_p = pqE\mu_p$$

drift current for holes

number of free holes per unit volume

mobility of holes

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## Drift Current Equations

Total current density

$$J_i = J_e + J_h$$

$$J_i = nqE\mu_n + pqE\mu_p$$

since  $n = p = n_i$

$$J_i = n_i q (\mu_n + \mu_p) E$$

For a pure intrinsic semiconductor

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## Drift Current Equations

$$J_{total} = ? \text{ for doped or extrinsic semiconductor}$$

n-type semiconductor;

$$n \gg p \Rightarrow J_T \cong nq\mu_n E = N_D q \mu_n E$$

where  $N_D$  is the shallow donor concentration

p-type semiconductor;

$$p \gg n \Rightarrow J_T \cong pq\mu_p E = N_A q \mu_p E$$

where  $N_A$  is the shallow acceptor concentration

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## Variation of resistivity with temperature

Why does the *resistivity of a metal increases* with increasing temperature whereas the *resistivity of a semiconductor decreases* with increasing temperature?

$$\rho = \frac{1}{\sigma} = \frac{1}{nq\mu}$$

This fact is used in a real semiconductor device called a **thermistor**, which is used as a temperature sensing element.

The thermistor is a temperature – sensitive resistor; that is its terminal resistance is related to its body temperature. It has a negative temperature coefficient, indicating that its resistance will decrease with an increase in its body temperature.

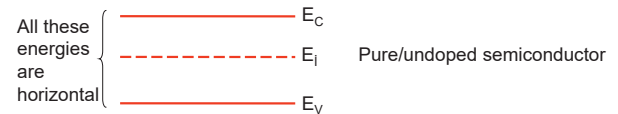
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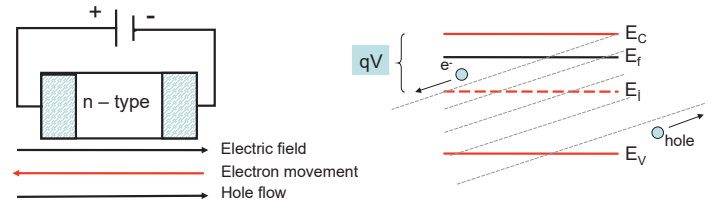
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## Band Diagrams with Electric Field Present

At equilibrium ( with no external field )



How these energies will change with an applied field ?



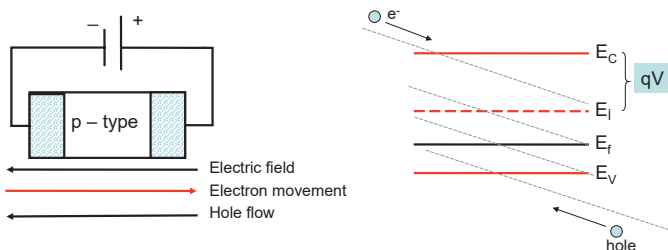
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## Band Diagrams with Electric Field Present

• With an applied bias the band energies slope down for the given semiconductor. Electrons flow from left to right and holes flow from right to left to have their minimum energies for a p-type semiconductor biased as below.



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## Under drift conditions

• **Under drift conditions**; holes **float** and electrons **sink**. Since there is an applied voltage, currents are flowing and this current is called as **drift current**.

• There is a certain slope in energy diagrams and the depth of the slope is given by  $qV$ , where  $V$  is the **battery voltage**.

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## Work done on the charge carriers

Work = Force x distance = electrostatic force x distance

$$\text{work} = -qE \times L$$

$$= -q \frac{V}{L} \times L \Rightarrow \text{work} = -qV = \text{gain in energy}$$

$$\text{Slope of the band} = -\frac{qV}{L} = -qE = \text{Force on the electron}$$

$$E = \frac{V}{L}$$

where L is the length of the s/c.

Since there is a certain slope in the energies, i.e. the energies are not horizontal, the currents are able to flow.

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## Work done on the charge carriers

$$\text{Electrostatic Force} = -\text{gradient of potential energy} = -\frac{dV}{dx}$$

$$-qE_x = -\frac{dE_i}{dx} \Rightarrow E_x = \frac{1}{q} \cdot \frac{dE_i}{dx} \quad (1)$$

one can define electron's electrostatic potential as

$$E_x = -\frac{dV_n}{dx} \quad (2)$$

comparison of equations (1) and (2) gives,

$$V_n = -\frac{E_i}{q} \quad \text{is a relation between } V_n \text{ and } E_i$$

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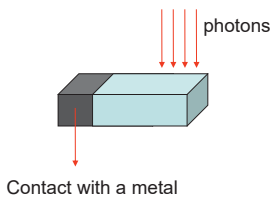
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## Carrier Diffusion

Current mechanisms

Drift      Diffusion



$$P = n k T$$

$$\frac{dP}{dx} = \frac{dn}{dx} k T$$

$$\frac{dn}{dx} = \frac{1}{k T} \frac{dP}{dx}$$

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## Carrier Diffusion

➤ Diffusion current is due to the movement of the carriers from high concentration region towards to low concentration region. As the carriers diffuse, a diffusion current flows. The force behind the diffusion current is the **random thermal motion of carriers**.

$$\frac{dn}{dx} = \frac{1}{k T} \cdot \frac{dP}{dx}$$

➤ A concentration gradient produces a pressure gradient which produces the force on the charge carriers causing to move them.

How can we produce a concentration gradient in a semiconductor?

- 1) By making a semiconductor or metal contact.
- 2) By illuminating a portion of the semiconductor with light.

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## Illuminating a portion of the semiconductor with light

❖ By means of illumination, **electron-hole pairs** can be produced when the **photon energy**  $> E_g$ .

❖ So the increased number of **electron-hole pairs** move towards to the lower concentration region until they reach to their equilibrium values. So there is a number of charge carriers crossing per unit area per unit time, which is called as flux. Flux is proportional to the concentration gradient,  $dn/dx$ .

$$\text{Flux} = -D_n \frac{dn}{dx}$$

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## Flux

$$[\text{Flux}] = m^{-2} - s^{-1}$$

$$D = v_n t, [D] = m^2/s$$

The current densities for electrons and holes

$$J_n = -q \left( -D_n \frac{dn}{dx} \right) = q D_n \frac{dn}{dx} \quad \text{for electrons}$$

$$J_p = +q \left( -D_p \frac{dp}{dx} \right) = -q D_p \frac{dp}{dx} \quad \text{for holes}$$

$$[J_{n,p}] = [A/m^2]$$

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## Einstein Relation

Einstein relation relates the two independent current mechanism of mobility with diffusion;

$$\frac{D_n}{\mu_n} = \frac{kT}{q} \quad \text{and} \quad \frac{D_p}{\mu_p} = \frac{kT}{q} \quad \text{for electrons and holes}$$

Constant value at a fixed temperature

$$\frac{\text{cm}^2/\text{sec}}{\text{cm}^2/\text{V} - \text{sec}} = \text{volt} \quad \frac{kT}{q} = \frac{(J/K)(K)}{C} = \text{volt}$$

$$\frac{kT}{q} = 25 \text{ mV} \quad \text{at room temperature}$$

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## Total Current Density

When both electric field (gradient of electric potential) and concentration gradient present, the total current density ;

$$J_n = q\mu_n nE + qD_n \frac{dn}{dx}$$

$$J_p = q\mu_p pE - qD_p \frac{dp}{dx}$$

$$J_{total} = J_n + J_p$$

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## Carrier Recombination and Diffusion Length

- By means of introducing excess carriers into an intrinsic s/c, the number of majority carriers hardly changes, but the number of minority carriers increases from a low- to high-value.
- When we illuminate our sample (n-type silicon with  $10^{15} \text{ cm}^{-3}$ ) with light that produces  $10^{14} \text{ cm}^{-3}$  electron-hole pairs.
- The electron concentration (majority carriers) hardly changes, however hole concentration (minority carriers) goes from  $1.96 \times 10^5$  to  $10^{14} \text{ cm}^{-3}$ .

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## Recombination Rate

- Minority carriers find themselves surrounded by very high concentration of majority carriers and will readily recombine with them.
- The recombination rate is proportional to excess carrier density,  $\delta_p$ .

$$\frac{d\delta p}{dt} = -\frac{1}{\tau_p} \delta p \Rightarrow \delta p(t) = \delta p(0) \exp\left(-\frac{t}{\tau}\right)$$

Lifetime of holes

Excess hole concentration when t=0

Excess hole concentration decay exponentially with time.

Similarly, for electrons;

$$\frac{d\delta n}{dt} = -\frac{1}{\tau_n} \delta n \Rightarrow \delta n(t) = \delta n(0) \exp\left(-\frac{t}{\tau}\right)$$

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## Diffusion Length $L$

When excess carriers are generated in a specimen, the minority carriers diffuse a distance, a characteristic length, over which minority carriers can diffuse before recombining majority carriers. This is called as a diffusion length,  $L$ .

Excess minority carriers decay exponentially with diffusion distance.

$$\delta n(x) = \delta n(0) \exp\left(-\frac{x}{L_n}\right)$$

Excess electron concentration when x=0

$$\delta p(x) = \delta p(0) \exp\left(-\frac{x}{L_p}\right)$$

Diffusion length for holes

Diffusion length for electrons

$$L_n = \sqrt{D_n \tau_n}$$

$$L_p = \sqrt{D_p \tau_p}$$

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## Light Sources

### LED – Light Emitting Diode

## Solid State Lighting (SSL)

Solid-state lighting (SSL) is a type of lighting that uses semiconductor light-emitting diodes (LEDs). Organic light-emitting diodes (OLED), or polymer light-emitting diodes (PLED) as sources of illumination rather than electrical filaments, plasma (used in arc lamps such as fluorescent lamps), or gas.

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## Advantages of LED Lighting

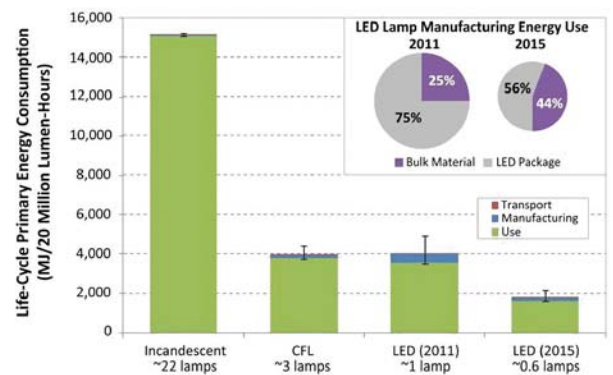
- **Lifespan** – Lifespan can exceed 50,000 Hours as compared to 1,000 Hours for filament bulbs
- **Robustness** – No moving parts, No filaments, No glass
- **Size** – compact package typically 5 mm in diameter
- **Energy Efficiency** – 30-70% less energy than other light sources.
- **Environmental Safety** – No Mercury or Lead. Easy to dispose
- **Versatility** – available in a variety of colours and can be tuned
- **Cool** – Less radiant heat than HID or Incandescent types
- **Luminous Efficacy** – LED can produce up to 300 lumens/Watt

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## Energy Usage Comparison

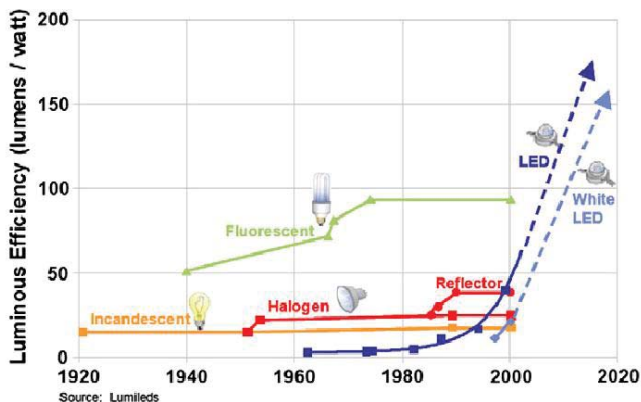


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## Luminous Performance Evolution



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## Global LED Market approx. 90 B\$ in 2024



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### LED in Architectural Lighting



Aspire Tower, Doha, Qatar



Takarazuka University, Japan

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### Car Headlights



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### Portable Desk/Task Lighting



6 Watt LED Desk Lamp



Halley LED Desk Lamp

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### Indoor market 3 times larger than Outdoor



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### Air/Water Purification System

- Fruit and Vegetable Storage Life Extended 1 week
- Water Purification: UV LED to kill bacteria



Mitsubishi Refrigerator MR-W55H, UV LED 375 nm, 590 nm, Blue LED



UV Water Purifier (Credit: Hydro-Photon Inc.)

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### Costs associated with various white lighting

•**Incandescent**

Traditional bulbs that are inefficient, wasting 90% of their energy as heat. They emit about 15 lumens per watt and have a lifespan of around 1,200 hours. Cost: \$1

•**Halogen**

A type of incandescent lighting that's more efficient than traditional incandescent bulbs, but less efficient than LED and CFL bulbs. They emit about 25 lumens per watt and have a lifespan of around 2,500 hours. Cost: \$15

•**HID**

High-intensity discharge bulbs that are brighter and more efficient than halogens. They are used as running lights on vehicles. They have a lifespan of up to 15,000 hours. Cost: \$40

•**CFL**

Compact fluorescent lamps that are more energy efficient than incandescent bulbs. They emit 60 lumens per watt and have a lifespan of around 10,000 to 15,000 hours. Cost: \$30

•**LED**

Light emitting diodes that are the most energy efficient of all the light bulbs. They emit around 75 lumens per watt and can last up to 50,000 hours. Cost: \$5

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## Luminous Efficacy

- Luminous efficacy is a property of light sources, which indicates what portion of the emitted electromagnetic radiation is usable for human vision. **It is the ratio of emitted luminous flux to radiant flux.** Luminous efficacy is related to the overall efficiency of a light source for illumination, but the overall lighting efficiency also depends on how much of the input energy is converted into electromagnetic waves (whether visible or not).
- In SI, luminous efficacy has units of lumens per watt (lm/W). **Photopic** luminous efficacy (daylight) has a maximum possible value of 683 lm/W, for the case of monochromatic light at a wavelength of 555nm (green). **Scotopic** luminous efficacy (night) reaches a maximum of 1700 lm/W for narrowband light of wavelength 507 nm.

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## Luminous Efficiency Comparison

Type	Luminous efficacy (lm/W)	Luminous Efficiency
Tungsten light bulb, typical, 2800 K	15	2%
Class M star (Antares, Betelgeuse), 3300 K	30	4%
Black body, 4000 K, ideal	47.5	7%
Class G star (Sun, Capella), 5800 K	93	13.60%
Black body, 7000 K, ideal	95	14%
Ideal monochromatic source: 555 nm (in air)	683	100%

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## Flux

- The lumen (lm) is the SI unit of luminous flux, a measure of the perceived power of light is equal to the amount of light emitted per second in a unit solid angle of one steradian from a light source of 1 candela.
- Luminous flux differs from radiant flux, the measure of the total power of light emitted, in that luminous flux is adjusted to reflect the varying sensitivity of the human eye to different wavelengths of light

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## LED Principles

- If forward bias  $V$  is applied  $\rightarrow$  voltage drop mainly occurs across the depletion region  $\rightarrow$  Built-in potential  $V_0$  is reduced to  $V_0 - V$ .  $\rightarrow$  Allow the electrons from  $n^+$  side to diffuse (or become injected), into the  $p$ -side
- The hole injection component from  $p$ - into  $n^+$  side is much smaller.
- The recombination of injected electrons in the depletion region as well as in the neutral  $p$ - side results in photons emission.
- Recombination mainly occurs inside depletion region and within a volume extending over the diffusion length  $L_e$  of the electrons in the  $p$ - side. Recombination zone is called active region.
- The phenomenon of light emission from EH pair recombination as result of minority carrier injection is called **injection electroluminescence**.

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## LED Structure

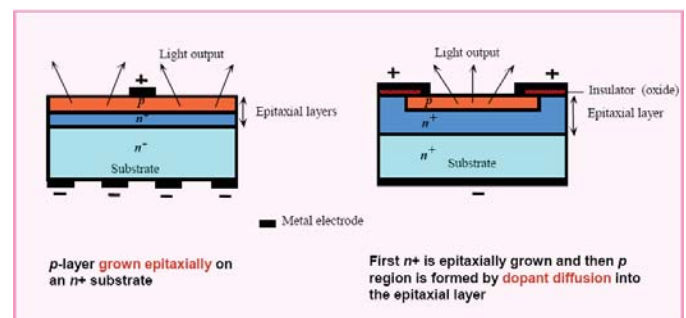
- The  $p$ - side is on the surface from which light is emitted as is therefore made narrow (a few microns) to allow the photon to escape without being reabsorbed.
- The  $n$ - side is heavily doped to ensure that the most of the recombination takes place in the  $p$ - side.
- The photons which are emitted 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.

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## Illustration of typical planar surface emitting LED devices

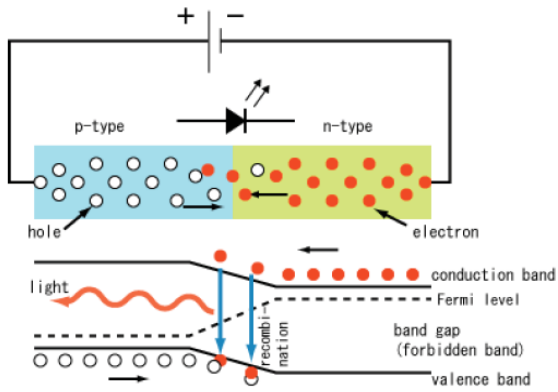


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### Inner Workings of a LED



### Radiative vs. Non-radiative Recombination

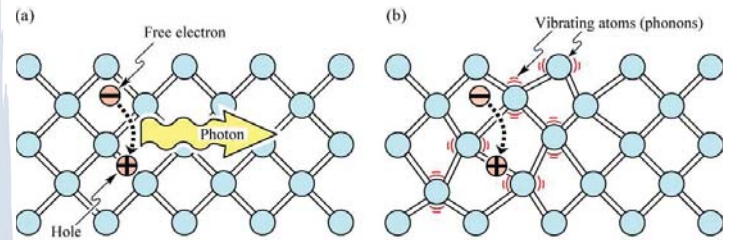


Fig. 2.5. (a) Radiative recombination of an electron-hole pair accompanied by the emission of a photon with energy  $h\nu = E_g$ . (b) In non-radiative recombination events, the energy released during the electron-hole recombination is converted to phonons (adopted from Shockley, 1950).

### Recombination Mechanisms

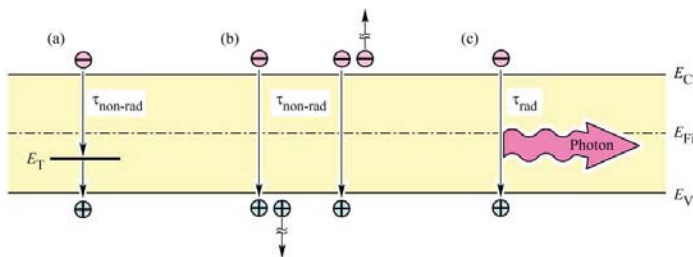
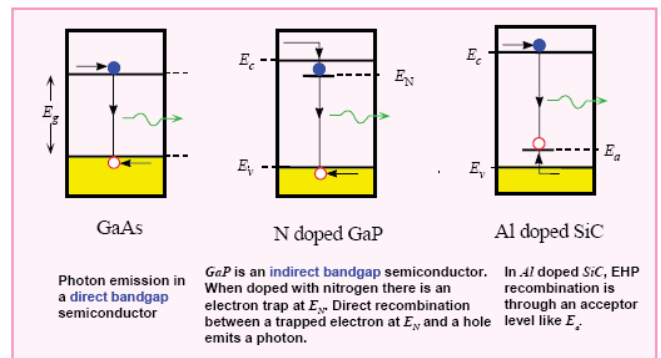


Fig. 2.6. Band diagram illustrating non-radiative recombination: (a) via a deep level, (b) via an Auger process and (c) radiative recombination.

### Radiative Recombination



Photon emission in a direct bandgap semiconductor

GaP is an indirect bandgap semiconductor. When doped with nitrogen there is an electron trap at  $E_N$ . Direct recombination between a trapped electron at  $E_N$  and a hole emits a photon.

In Al doped SiC, EHP recombination is through an acceptor level like  $E_A$ .

### LED Electrical Basics

Shockley equation for p-n junction diodes

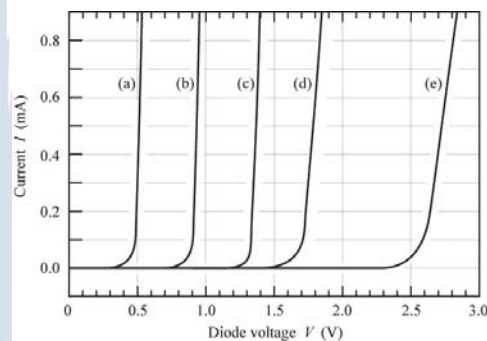
$$I = eA \left( \sqrt{\frac{D_p}{\tau_p}} p_{n0} + \sqrt{\frac{D_n}{\tau_n}} n_{p0} \right) (e^{eV/kT} - 1)$$

$$= eA \left( \sqrt{\frac{D_p}{\tau_p}} \frac{n_i^2}{N_D} + \sqrt{\frac{D_n}{\tau_n}} \frac{n_i^2}{N_A} \right) (e^{eV/kT} - 1)$$

$$= I_s (e^{eV/kT} - 1)$$

where  $I_s$  is the saturation current

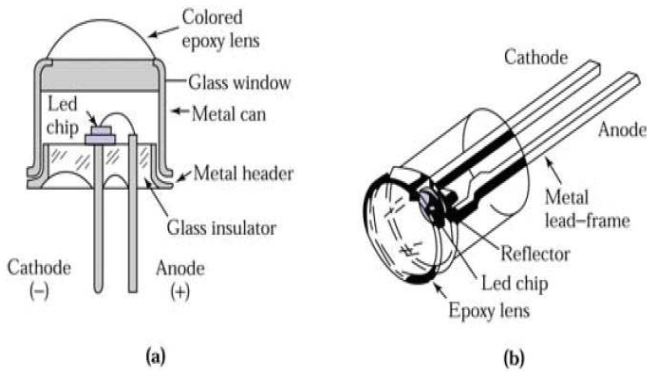
### Diode IV Characteristics



- $T = 295 \text{ K}$
- (a) Ge  $E_g = 0.7 \text{ eV}$
  - (b) Si  $E_g = 1.1 \text{ eV}$
  - (c) GaAs  $E_g = 1.4 \text{ eV}$
  - (d) GaAsP  $E_g = 2.0 \text{ eV}$
  - (e) GaInN  $E_g = 2.9 \text{ eV}$

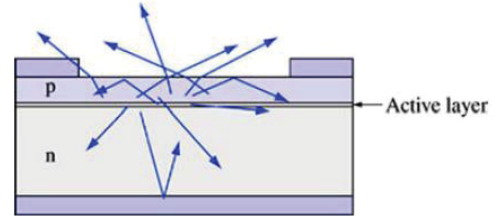
Fig. 4.2. Room-temperature current-voltage characteristics of p-n junctions made from different semiconductors.

### LED Structure

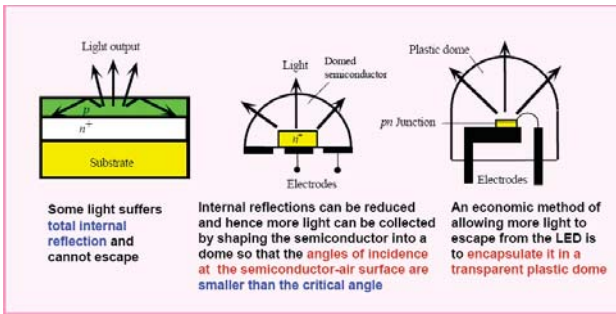


### LED Structure

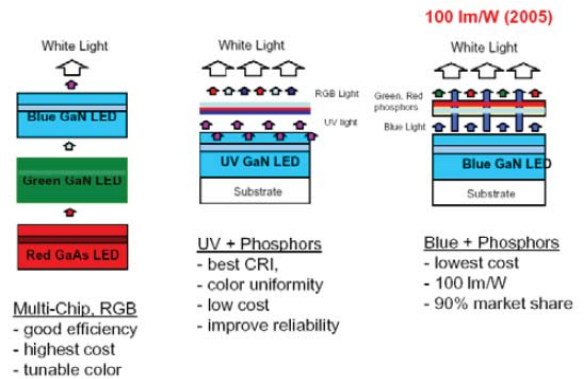
- A generic surface-emitting LED.
- Some photons are lost by **reabsorption in the bulk**, **Fresnel reflection from the surface**, and **total internal reflection**.



### LED Structure



### Methods for Generating white light



### LED Materials

- There are various direct bandgap semiconductor materials that can be readily doped to make commercial pn junction LEDs that emit radiation in the red and infrared range of wavelengths.
- Class of commercial semiconductor materials that cover visible spectrum is the **III-V ternary alloys** (three elements) based on alloying GaAs and GaP, which are denoted as  $GaAs_{1-y}P_y$ .
- When  $y < 0.45$ , this alloy is a direct bandgap semiconductor and hence the EHP recombination process is direct (fig. a).
- The emitted wavelengths are 630 nm ( $y = 0.45$ ) – 870 nm ( $y = 0$ ).
- For indirect bandgap,  $y > 0.45$ , EHP recombination processes occur through recombination centers and involve lattice vibrations (phonon).
- **Isoelectronic impurities**, such as nitrogen (in the same group V as P) → some N atoms substitute for P atoms.

### LED Materials

- Positive nucleus of N is less shielded → conduction electron in the neighborhood of an N atom will be attracted and may be trapped at this site. → N atom then have localized energy levels, or electron traps,  $E_N$ , near the conduction band (fig b).
- The trapped electron then can attract a hole in its vicinity → recombine with it and emit a photon.
- The emitted photon energy is slightly less than  $E_g$ .
- The recombination process depends on N doping → less efficient.
- Mainly used from green, yellow, and orange LEDs.
- Two types of blue LED materials: GaN alloy (InGaN) and Al doped SiC.
- The localized energy level captures a hole from the valence band and a conduction electron then recombines with this hole to emit a photon (fig c).
- More efficient blue LEDs using direct bandgap compound II-VI semiconductors, such as ZnSe.

# LED Materials

Color	Wavelength [nm]	Semiconductor material
Infrared	$\lambda > 760$	Gallium arsenide (GaAs) Aluminum gallium arsenide (AlGaAs)
Red	$610 < \lambda < 760$	Aluminum gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP) Aluminum gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Orange	$590 < \lambda < 610$	Gallium arsenide phosphide (GaAsP) Aluminum gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Yellow	$570 < \lambda < 590$	Gallium arsenide phosphide (GaAsP) Aluminum gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
Green	$500 < \lambda < 570$	<b>Traditional green:</b> Gallium(III) phosphide (GaP) Aluminum gallium indium phosphide (AlGaInP) Aluminum gallium phosphide (AlGaP) <b>Pure green:</b> Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN)
Blue	$450 < \lambda < 500$	Zinc selenide (ZnSe) Indium gallium nitride (InGaN) Silicon carbide (SiC) as substrate Silicon (Si) as substrate—under development
Violet	$400 < \lambda < 450$	Indium gallium nitride (InGaN)
Purple	multiple types	Dual blue/red LEDs, blue with red phosphor, or white with purple plastic
Ultraviolet	$\lambda < 400$	Diamond (235 nm) Boron nitride (215 nm) Aluminum nitride (AlN) (210 nm) Aluminum gallium nitride (AlGaN) Aluminum gallium indium nitride (AlGaInN)—down to 210 nm
Pink	multiple types	Blue with one or two phosphor layers: yellow with red, orange or pink phosphor added afterwards, or white with pink pigment or dye.
White	Broad spectrum	Blue/UV diode with yellow phosphor

# LED Materials

- Other various commercial direct bandgap semiconductor material that emit the red and infrared wavelengths: ternary, quaternary alloys based on III and V elements.
- Emitted radiation ranges from 640 – 870 nm (from deep red light to infrared).
- External efficiency  $\eta_{\text{external}}$  of an LED: efficiency of conversion of electrical energy into an emitted external energy.

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

- The input power: product of diode current and voltage.

# LED External Conversion Efficiency

The external power or conversion efficiency  $\eta_{\text{ext}}$  is defined as

$$\eta_{\text{ext}} = \frac{\text{Optical power output}}{\text{Electrical power input}} = \frac{P_o}{IV}$$

One of the major factors reducing the external power efficiency is the loss of photons in extracting the emitted photons which suffer reabsorption in the pn junction materials, absorption outside the semiconductors and various reflections at interfaces.

The total light output power from a particular AlGaAs red LED is 2.5 mW when the current is 50 mA and the voltage is 1.6 V.

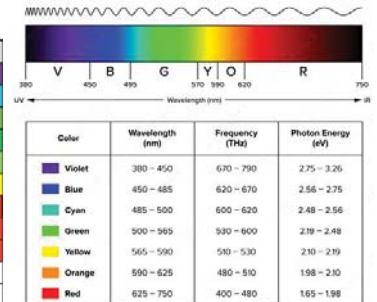
Calculate its external conversion efficiency.

**Solution**

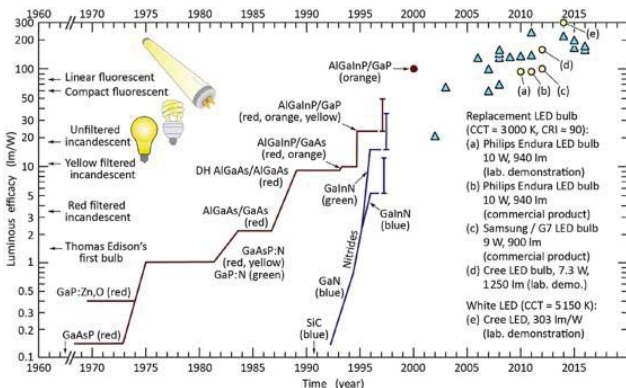
$$\eta_{\text{ext}} = \frac{P_o}{IV} = \frac{2.5 \times 10^{-3} \text{ W}}{(50 \times 10^{-3} \text{ A})(1.6 \text{ V})} = 0.03125 = 3.125 \%$$

# LED Materials and Colour

Materials	Wavelength	Colour
GaNN	370	Violet
GaNN	450	Blue
GaNN	525	Green
InGaAlP/GaAs	562	Yellow
InGaAlP/GaAs	574	Yellow
InGaAlP/GaP	590	Yellow
InGaAlP	644	Orange
GaAlAs/GaAs	660	Red
GaP	700	Red
GaAlAs	880	IR
GaAs	940	IR



# Historical Development of LEDs



# Quaternary alloy Example

## InGaAsP on InP substrate

The quaternary alloy  $\text{In}_{1-x}\text{Ga}_x\text{As}_{1-y}\text{P}_y$  grown on an InP crystal substrate is a suitable commercial semiconductor material for infrared LED and laser diode applications. The device requires that the InGaAsP layer is lattice matched to the InP crystal substrate to avoid crystal defects in the InGaAsP layer. This in turn requires that  $y = 2.2x$ . The bandgap energy  $E_g$  of the alloy in eV is given by the empirical relationship:

$$E_g = 1.35 - 0.72y + 0.12y^2 \quad ; 0 \leq x \leq 0.47$$

Calculate the composition of InGaAsP alloy for peak emission wavelength of 1.3  $\mu\text{m}$ .

( $h = 6.626 \times 10^{-34} \text{ J}\cdot\text{s}$ ,  $k_B T = 0.0259 \text{ eV}$  at 300K,  $c = 3 \times 10^8 \text{ m/s}$ ,  $q = 1.6 \times 10^{-19} \text{ C}$ )

The photon energy at peak emission is:  $\frac{hc}{\lambda} = E_g + k_B T$  in Joules

Rewriting equation in eV:  $E_g = \frac{hc}{\lambda q} - 0.0259$  where  $\lambda = 1.3 \times 10^{-6} \text{ m}$ ,  $T = 300\text{K}$

$$E_g = \frac{6.626 \times 10^{-34} \cdot 3 \times 10^8}{1.3 \times 10^{-6} \cdot 1.6 \times 10^{-19}} - 0.0259 = 0.928 \text{ eV}$$

The InGaAsP alloy must therefore satisfy:  $0.928 = 1.35 - 0.72y + 0.12y^2$

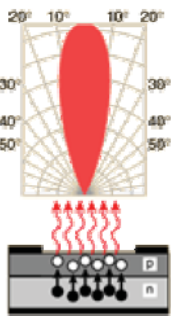
$$0.12y^2 - 0.72y + 0.422 = 0$$

Solving:  $y = 0.66$  and  $x = 0.66/2.2 = 0.3$

The quaternary alloy composition is  $\text{In}_{0.7}\text{Ga}_{0.3}\text{As}_{0.34}\text{P}_{0.66}$

## Radiation Pattern

### LED radiation pattern



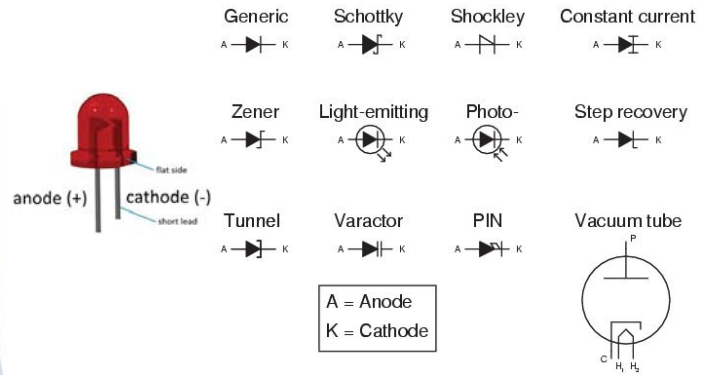
- > An LED is a **directional light source**, with the maximum emitted power in the direction perpendicular to the emitting surface.
- > The typical radiation pattern shows that most of the energy is emitted within 20° of the direction of maximum light.
- > Some packages for LEDs include plastic lenses to spread the light for a greater angle of visibility.

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## LED Symbols

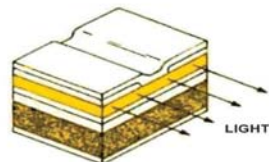
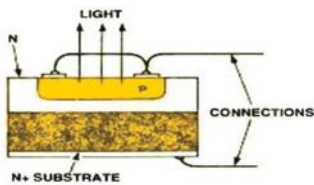


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## Light Emitting Diode Types



Structure of a surface-emitting diode.

Structure of an edge-emitting diode

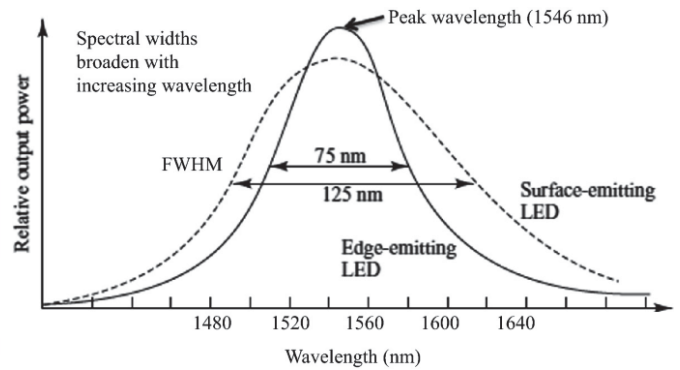
Easy to fabricate	Less modulation bandwidth	Difficult to fabricate	Better modulation bandwidth
Easy to mount and handle	Less optical power coupling into low NA fiber	Difficult to mount and handle	More optical power coupling into low NA fiber
Require less critical tolerances	Light emitted from surface of active layer	Need critical tolerance on fabrication	Light emitted from edge of active layer
Less Reliable	Wider spectral width	Highly Reliable	Narrow spectral width
Lower system performance	Maximum Internal Quantum Efficiency is up to 60%	Higher system performance	Internal Quantum Efficiency is in the range of 60 to 80%

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## LED Spectral Patterns

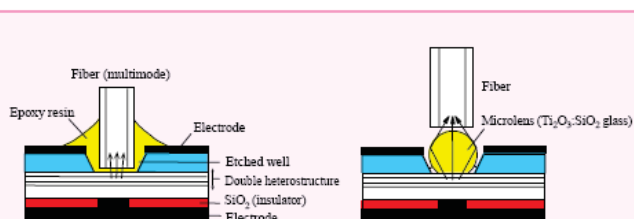


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## Optical Fibre coupling for Surface Emitting LED



Light is coupled from a surface emitting LED into a **multimode fiber** using an index matching epoxy. The fiber is bonded to the LED structure.

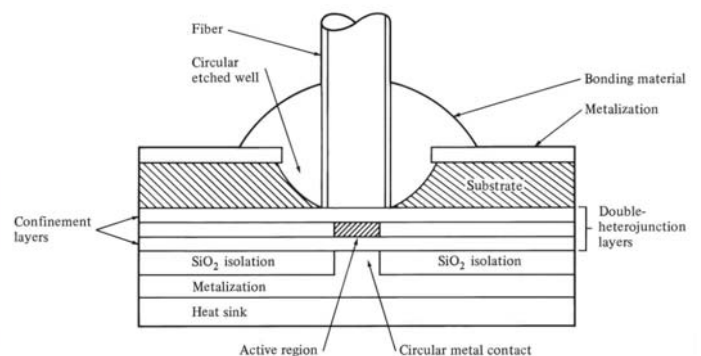
A **microlens** focuses diverging light from a surface emitting LED into a multimode optical fiber.

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## Surface Emitting LED Optical Coupling



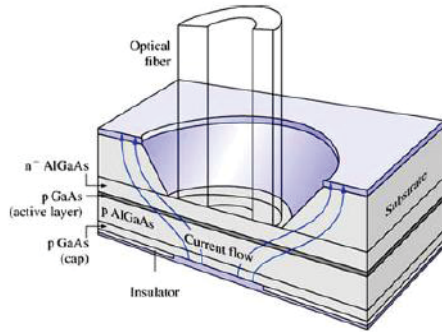
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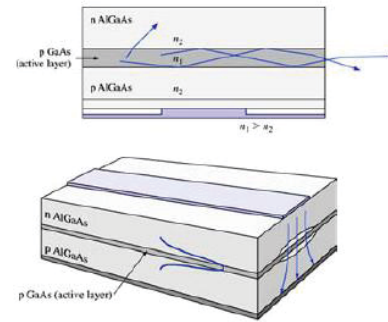
### Burrus Type LED

A Burrus-type LED. This one uses a Double Heterostructure to confine the carriers, making recombination more efficient. The etched opening in the LED helps align and couple an optical fiber.



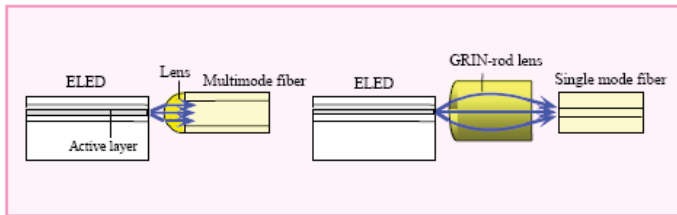
### Edge Emitting LED

In an Edge-emitting LED, the higher-index active layer acts as a waveguide for photons traveling at less than the critical angle.



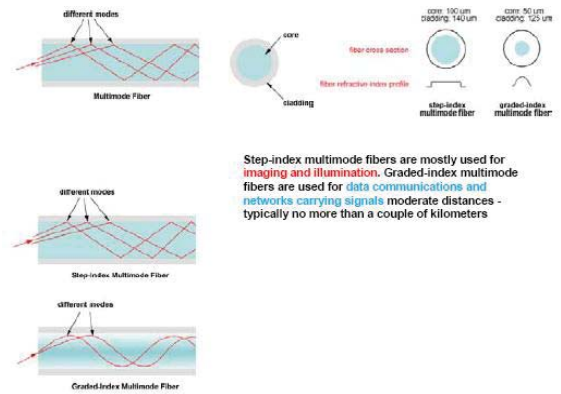
### Optical Fibre Coupling in Edge Emitted LED

Light from an Edge emitting LED is coupled into a fiber typically by using a lens or a GRIN rod lens



GRIN = Gradient Index

### Type of Multimode Fibre



Step-index multimode fibers are mostly used for **imaging and illumination**. Graded-index multimode fibers are used for **data communications and networks carrying signals** moderate distances - typically no more than a couple of kilometers

### Fibre Coupling Efficiency

#### LED-Fiber coupling Efficiency

- It is found that approximately 200  $\mu\text{W}$  is coupled into a multimode step index fiber from a surface emitting LED when the current is 75 mA and the voltage across the LED is about 1.5 V. What is the overall efficiency of operation?
- Experiments are carried out on coupling light from a 1310 nm ELED-Edge emitting LED in multimode and single mode fibers.
  - At room temperature, when the ELED current is 120 mA, the voltage is 1.3 V and light power coupled into a 50  $\mu\text{m}$  multimode fiber with NA = 0.2 is 48  $\mu\text{W}$ . What is the overall efficiency?
  - At room temperature, when the ELED current is 120 mA, the voltage is 1.3 V and light power coupled into a 9  $\mu\text{m}$  single mode fiber is 7  $\mu\text{W}$ . What is the overall efficiency?

**Solution**

- $\eta_{\text{overall}} = \frac{P_{\text{out}}}{IV} = \frac{200 \times 10^{-6} \text{ W}}{(75 \times 10^{-3} \text{ A})(1.5 \text{ V})} = 1.8 \times 10^{-3} = 0.18 \%$
- $\eta_{\text{overall}} = \frac{P_{\text{out}}}{IV} = \frac{48 \times 10^{-6} \text{ W}}{(120 \times 10^{-3} \text{ A})(1.3 \text{ V})} = 0.0307\%$
  - $\eta_{\text{overall}} = \frac{P_{\text{out}}}{IV} = \frac{7 \times 10^{-6} \text{ W}}{(120 \times 10^{-3} \text{ A})(1.3 \text{ V})} = 0.0045\%$

3.11. Internal quantum efficiency. The internal efficiency  $\eta_{\text{int}}$  gauges what fraction of electron hole recombinations in the forward biased pn junction are radiative and emit close to photon emission. Nonradiative transitions are those in which an electron and hole recombine through a recombination center such as a crystal defect or an impurity and emit phonons (lattice vibrations). By definition,

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

or

$$\eta_{\text{int}} = \frac{1}{\frac{1}{\tau_r} + \frac{1}{\tau_{nr}}}$$

where  $\tau_r$  is the mean lifetime of a minority carrier before it recombines radiatively and  $\tau_{nr}$  is the mean lifetime before it recombines via a recombination center without emitting a photon. The total current  $I$  is determined by the total rate of recombinations whereas the number of photons emitted per second ( $\Phi_{ph}$ ) is determined by the rate of radiative recombinations.

Photons emitted per second  $\Phi_{ph} = \frac{P_{\text{optical}}}{h\nu}$   
 Total carriers lost per second  $= \frac{I}{e} = \frac{I}{1.6 \times 10^{-19} \text{ C}}$

where  $P_{\text{optical}}$  is the optical power generated internally (not yet extracted).  
 For a particular AlGaAs LED emitting at 830 nm it is found that  $\tau_r = 50 \text{ ns}$  and  $\tau_{nr} = 100 \text{ ns}$ . What is the internal optical power generated at a current of 100 mA?

**Solution**

$$\eta_{\text{int}} = \frac{1}{\frac{1}{\tau_r} + \frac{1}{\tau_{nr}}} = \frac{1}{\frac{1}{50 \text{ ns}} + \frac{1}{100 \text{ ns}}} = 0.667 = 66.7 \%$$

From

$$P_{\text{optical}} = \eta_{\text{int}} \left( \frac{I}{e} \right) h\nu = (0.667) \left( \frac{100 \times 10^{-3} \text{ A}}{1.6 \times 10^{-19} \text{ C}} \right) (6.63 \times 10^{-34} \text{ J} \times 10^9) = 0.097 \text{ W or } 97 \text{ mW}$$

## Light Sources

### LASER

## Contents

- ▣ Lasers
  - Basic Principles
  - Applications
- ▣ Gas Lasers
- ▣ Semiconductor Lasers
- ▣ Semiconductor Lasers in Optical Networks
- ▣ Improvement in Basic Design
- ▣ Recent Advances

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## Lasers: Basic Principle

### Light Amplification by Stimulated Emission of Radiation

#### Key Terms:

- Stimulated Emission
- Metastable State
- Population Inversion

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## Properties of LASERS

- ▣ Monochromaticity
- ▣ Coherence
- ▣ Beam Divergence
- ▣ High Irradiance
- ▣ Properties vary with type of Lasers:
  - Gas, Solid, Semiconductor

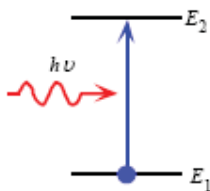
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## Spontaneous vs. Stimulated Emission

An electron in an atom can be excited from one energy level  $E_1$  to a higher energy level  $E_2$  by absorption  $\rightarrow$  photon absorption  $h\nu = E_2 - E_1$ . Note:  $\nu$  is lowercase nu representing frequency.



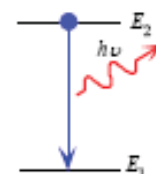
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## Spontaneous vs. Stimulated Emission

- Two possibilities of emission (an electron moves/transits down in energy to an unoccupied energy level  $\rightarrow$  emits a photon)
  - Spontaneous
  - Induced (Stimulated)
- Spontaneous emission: random direction  $\rightarrow$  random photon.
- Transition for  $E_2$  to  $E_1$  as if the electron is oscillating with a frequency  $\nu$



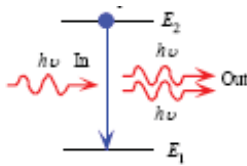
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## Spontaneous vs. Stimulated Emission

- Stimulated emission: incoming photon of energy  $h\nu = E_2 - E_1$  stimulates the whole emission process by inducing the electron at  $E_2$  to transit down to  $E_1$ .
- Emitted photon: in phase, same direction, same polarization, same energy with incoming photon  $\rightarrow$  two outgoing photons.
- To obtain stimulated emission  $\rightarrow$  the incoming photon should not be absorbed by another atom at  $E_1$ .



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## Spontaneous vs. Stimulated Emission

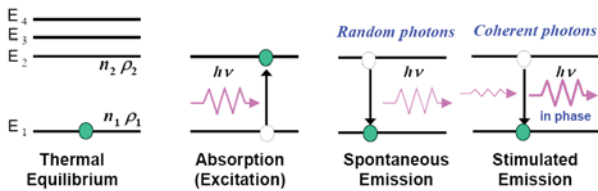
- Although we consider transitions of an electron in an atom, we could have just well described photon absorption, spontaneous and stimulated emission in term of energy transitions of the atom itself in which case  $E_1$  and  $E_2$  represent the energy levels of the atom.
- Consider the collection of atoms to amplify light  $\rightarrow$  we must have the majority of atoms at the energy level  $E_2$ . Otherwise the incoming photon will be absorbed by the atom at  $E_1$ .
- Population inversion:** more atoms at  $E_2$  than at  $E_1$ .
- In steady state incoming photon will cause as many upward excitations as downward stimulated emissions  $\rightarrow$  for only two energy levels  $\rightarrow$  we can never achieve atom population at  $E_2$  greater than  $E_1$ .

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## Lasers: Basic Principle



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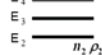
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## Lasers: Basic Principle

### Absorption and Radiation Processes

$\rho$  : Density of State



### Boltzmann Distribution

$$\text{Number of electron at } E_1, n_1 = \rho_1 f(E_1) = \rho_1 e^{-(E_1 - E_f)/kT}$$

$$\text{Number of electron at } E_2, n_2 = \rho_2 f(E_2) = \rho_2 e^{-(E_2 - E_f)/kT}$$

Thermal Equilibrium

$$\frac{f(E_2)}{f(E_1)} = \frac{n_2 \rho_1}{n_1 \rho_2} = e^{-(E_2 - E_1)/kT} \rightarrow \left(\frac{n_2}{\rho_2}\right) = \left(\frac{n_1}{\rho_1}\right) e^{-(E_2 - E_1)/kT}$$

$$> (E_2 - E_1) > 0 \rightarrow \left(\frac{n_2}{\rho_2}\right) < \left(\frac{n_1}{\rho_1}\right)$$

$$> \text{If } \left(\frac{n_2}{\rho_2}\right) > \left(\frac{n_1}{\rho_1}\right) \text{ can be achieved by pumping,}$$

$$\rightarrow kT < 0 \quad (\text{negative temperature: Population inversion})$$

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## Lasers: Basic Principle

### "Negative" Temperature concept

Question: What negative temperature would describe a system in which the population of the upper energy level exceeds that of the lower level by 10% and the energy difference between the two levels is 2.26 eV?

Answer:

$$\text{Number of atoms in } \alpha \text{ excited state } N_\alpha = N_0 e^{-(E_\alpha - E_0)/kT}$$

$$\therefore \frac{N_2}{N_0} = e^{-(E_2 - E_0)/kT}$$

$$\ln\left(\frac{N_2}{N_0}\right) = -(E_2 - E_0)/kT$$

$$\text{or } -T = \frac{E_2 - E_0}{k \ln\left(\frac{N_2}{N_0}\right)}$$

Now,

$$E_2 - E_0 = 2.26 \text{ eV} \quad \frac{N_2}{N_0} = 1.10, k = 8.62$$

Therefore,

$$-T = \frac{2.26 \text{ eV}}{(8.62 \times 10^{-5} \text{ eV/e}) \ln(1.10)}$$

$$\boxed{T = -2.75 \times 10^5 \text{ K}}$$

Answer: Negative temperature of  $2.75 \times 10^5 \text{ K}$  or  $2K$  will describe a system.

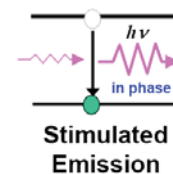
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## Lasers: Basic Principle

### Absorption and Radiation Processes



**Coherent photons**  
**In phase**  
**Same energy**  
**Same direction**  
**Same polarization**

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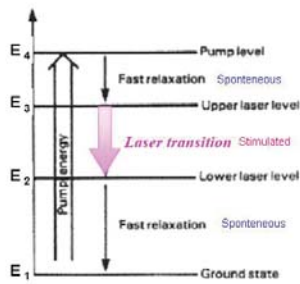
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### Laser: Basic Principle

#### 4-Level Laser Example

Meta-Stable state

Population inversion between E3 and E2

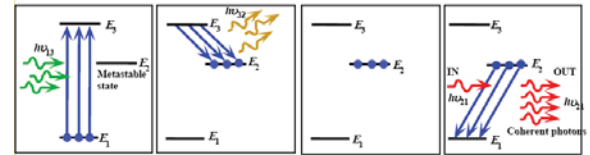


Basic requirement for Lasing action:  
 Metastable state, Population inversion, Optical resonant cavity

### Laser: Basic Principle

#### Lasing Action

#### 3-Level Laser Example



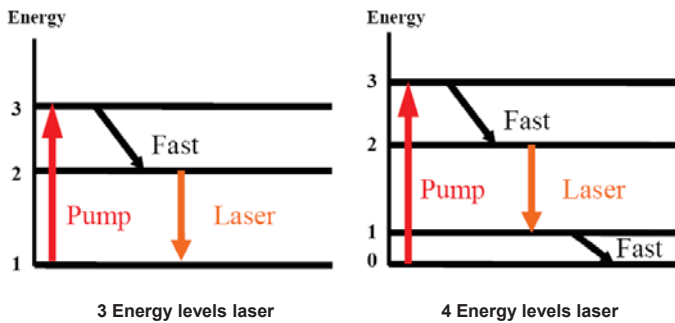
Atoms in the ground state are pumped up to the energy level  $E_3$  by incoming photons of energy  $h\nu_{13} = E_3 - E_1$ .

Atoms at  $E_3$  rapidly decay to the metastable state at energy level  $E_2$  by emitting photons or emitting lattice vibrations;  $h\nu_{32} = E_3 - E_2$ .

As the states at  $E_2$  are long-lived, they quickly become populated and there is a population inversion between  $E_2$  and  $E_1$ .

A random photon (from a spontaneous decay) of energy  $h\nu_{21} = E_2 - E_1$  can initiate **stimulated emission**. Photons from this stimulated emission can themselves further stimulate emissions leading to an avalanche of stimulated emissions and coherent photons being emitted.

### Laser: Basic Principle



3 Energy levels laser

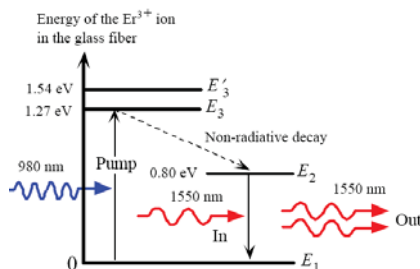
4 Energy levels laser

### Optical Fibre Amplifier

- A light signal traveling long distances will suffer attenuation. → It is necessary to regenerate the light signal at certain intervals for long haul communications over several thousand miles.
- Practical optical amplifier is based on the **erbium ion (Er3+) doped fiber amplifier (EDFA)**.
- The core region of an optical fiber is doped with Er3+ or with neodymium ion (Nd3+).
- The host fiber material is a glass based on SiO<sub>3</sub>-GeO<sub>2</sub> or Al<sub>2</sub>O<sub>3</sub>. → Easily fused to a single mode long distance optical fiber by technique called splicing.

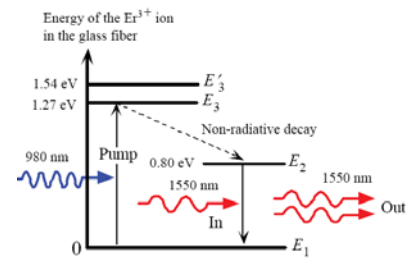
### Optical Fibre Amplifier

- Er3+ has energy level as indicated in the figure below.
- Er3+ is optically pumped from laser diode to excite them to E3.
- The Er3+ ions decay rapidly from E3 to E2 (**long-lived**) energy level ~ 10 ms.
- The decay from E3 to E2 involves energy losses by radiation-less transition (phonon emission).



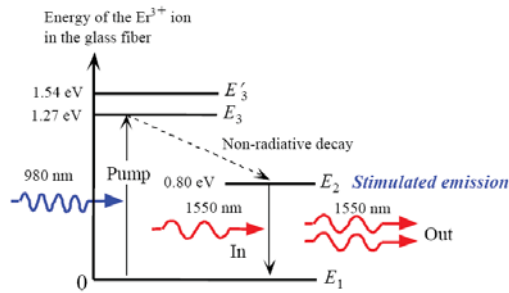
### Optical Fibre Amplifier

- The accumulated Er3+ ions at E2 leads to a population inversion between E2 and E1.
- Signal photons at 1550 nm have energy of 0.80 eV (E2 – E1), and give rise to **stimulated transitions** of Er3+ ions from E2 to E1.
- Meanwhile, any Er3+ ions left at E1 will **absorb** in incoming 1550 nm photons to reach E2.



## Optical Fibre Amplifier

### EDFA: Er-doped Optical Amplifier



Energy diagram for the  $Er^{3+}$  ion in the glass fiber medium and light amplification by stimulated emission from  $E_2$  to  $E_1$ . Dashed arrows indicate radiationless transitions (energy emission by lattice vibrations)

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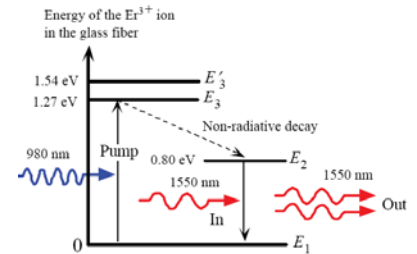
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## Optical Fibre Amplifier

- Thus, to achieve light amplification we must have stimulated emission exceeding absorption.
- Only possible if more  $Er^{3+}$  ions at  $E_2$  ( $N_2$ ) than at  $E_1$  ( $N_1$ ).

- The net optical gain  $G_{op}$ : where  $K$  is a constant which depends on the pumping intensity

$$G_{op} = K(N_2 - N_1)$$

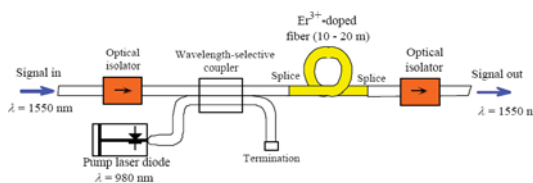


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## Optical Fibre Amplifier



A simplified schematic illustration of an EDFA (optical amplifier). The erbium-ion doped fiber is pumped by feeding the light from a laser pump diode, through a coupler, into the erbium ion doped fiber.

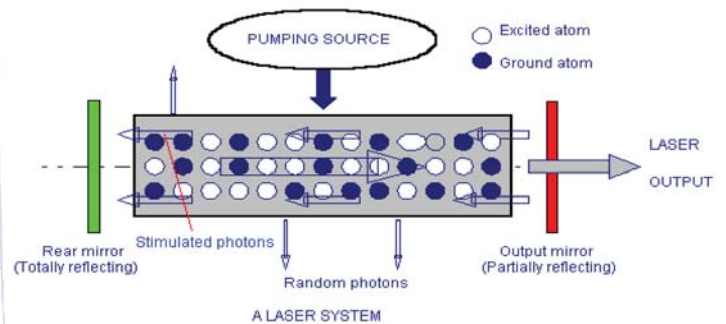
- Optical oscillators are inserted at the entry and exit to allow ONLY optical signals at 1550 nm to pass in one direction and prevent the 980 nm pump light from propagating back or forward into the communication system.
- Energy level  $E_1$ ,  $E_2$ , and  $E_3$  are not single unit levels, but rather consists of closely spaced collection of several levels  $\rightarrow$  range of stimulated transitions from  $E_2$  to  $E_1$  (1525 – 1565 nm) with 40 nm optical bandwidth  $\rightarrow$  wavelength division multiplexed system (WDM) systems.

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## Laser: Basic Principle



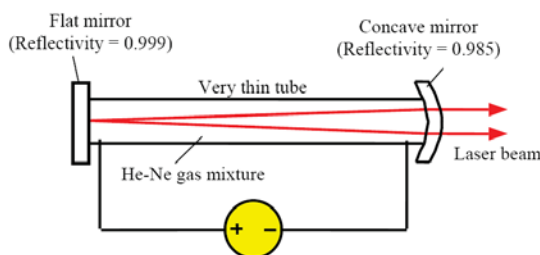
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## Laser: Gas Lasers

### He-Ne Lasers



Current regulated HV DC/RF power supply  
He atom to become excited by collision with drifting electrons

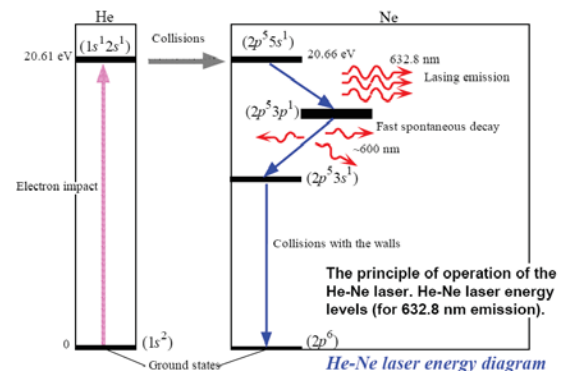
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## Laser: Gas Lasers

### He-Ne Lasers

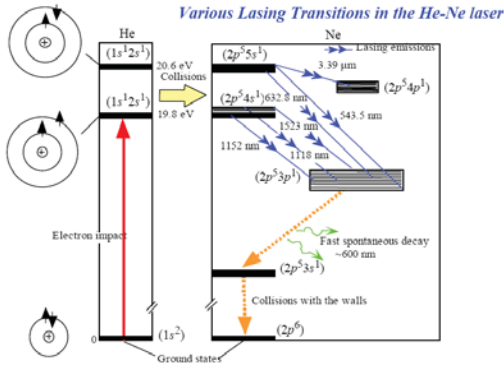


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### Laser: Gas Lasers



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### Overall Efficiency

$$\text{Overall efficiency} = \frac{\text{Optical Power Output}}{\text{Electrical Power Input}} \times 100\%$$

Typical commercial He-Ne laser characteristics

Wavelength (nm)	543.5	594.1	612	632.8	1523
	Green	Yellow		Red	Infrared
Optical output power (mW)	1.5	2	4	5	1
Typical current (mA)	6.5	6.5	6.5	6.5	6
Typical voltage	2750	2070	2070	1910	3380
Overall efficiency = $P_{out}/IV$	0.0084 %	0.015 %	0.030 %	0.040 %	0.005 %

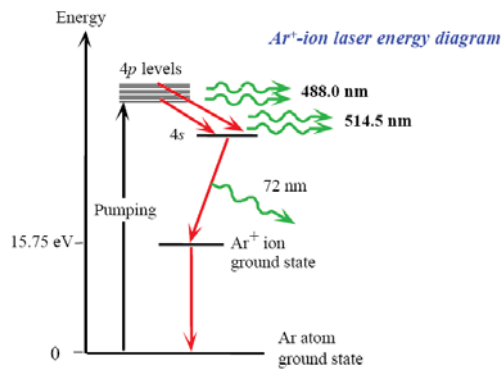
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### Laser: Gas Lasers

#### Ar<sup>+</sup>-ion Lasers



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### Laser: He-Ne Gas Lasers

- By using dc or RF high voltage, **electrical discharge** is obtained within the tube which causes the He atoms to become excited by collisions with the drifting electrons,  $\text{He} + e^- \rightarrow \text{He}^* + e^-$
- The excited He atom, He\*, cannot spontaneously emit a photon  $\rightarrow$  large number of He\* atoms build up during the electrical discharge.
- When He\* collides with a Ne atom, it transfers its energy to the Ne atom by resonance energy exchange.  $\text{He}^* + \text{Ne} \rightarrow \text{He} + \text{Ne}^*$
- A spontaneous emission of a photon from one Ne\* atom gives rise to an **avalanche of stimulated emission process**  $\rightarrow$  lasing emission with a wavelength 632.8 nm in the red.

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### Gas Laser Output Spectrum

- Doppler effect**  $\rightarrow$  resulting the broadening of the emitted spectrum  $\rightarrow$  output radiation from gas laser covers a spectrum of wavelengths with a central peak.
- Given the average K.E. of  $(3/2)kT$ , radiation freq.  $\nu_0$  (as source frequency), due to Doppler effect, **when gas atom is moving away from the observer**, the latter detects a lower frequency  $\nu_1$

$$\nu_1 = \nu_0 \left(1 - \frac{v_x}{c}\right)$$

where  $v_x$  is the relative velocity of the atom along the laser tube (x-axis) with respect to observer.

- When atom moving towards the observer**, the detected freq  $\nu_2$  is higher:

$$\nu_2 = \nu_0 \left(1 + \frac{v_x}{c}\right)$$

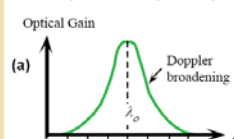
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### Gas Laser Output Spectrum

- Since the atoms are in random motion the observer will detect a range of frequencies due to Doppler effect.
- Resulting the frequency or wavelength of the output radiation from a gas laser will have a **"linewidth"**  $\Delta\nu = \nu_2 - \nu_1$ . It is called **Doppler broadened linewidth**.
- $\rightarrow$  Stimulated emission wavelength of lasing medium or **optical gain** has distribution around  $\lambda_0 = c/\nu_0$ .
- The full width at half maximum **FWHM** in the output intensity vs. frequency spectrum is:



$$\Delta\nu_{1,2} = 2\nu_0 \sqrt{\frac{2kT \ln(2)}{Mc^2}}$$

where M is mass of lasing atom or molecule

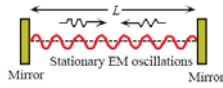
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### Gas Laser Output Spectrum

- Let consider an **optical cavity of length L** with parallel end mirrors (etalon – Fabry-Perot optical resonator).



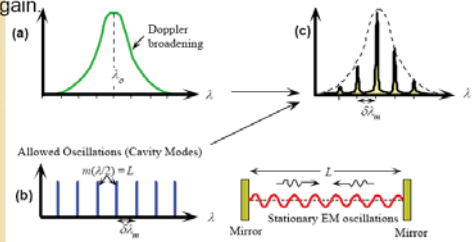
- Any standing wave in the cavity must have an integer number of half-wavelengths  $\lambda/2$  that fit into the cavity length L,

$$m \left( \frac{\lambda}{2} \right) = L \quad \text{where } m \text{ is mode number of the standing wave.}$$

- Cavity mode:** each possible standing wave within the cavity (laser tube) which satisfy the above equation.
- Axial (longitudinal) modes:** existing modes along the cavity axis.

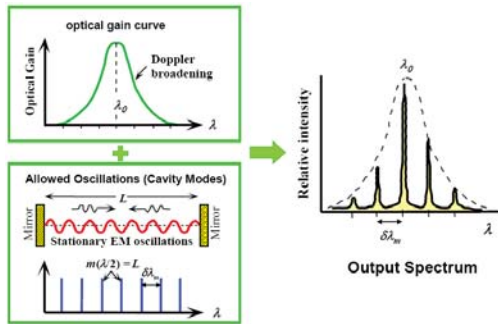
### Gas Laser Output Spectrum

- The laser output thus has broad spectrum with peaks at certain wavelengths corresponding to various cavity modes existing within the Doppler broadened optical gain.

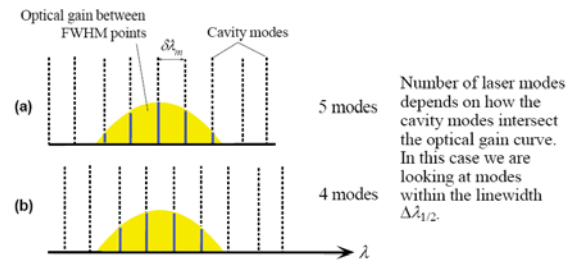


The output spectrum is determined by satisfying (a) and (b) simultaneously.

### Gas Laser Output Spectrum



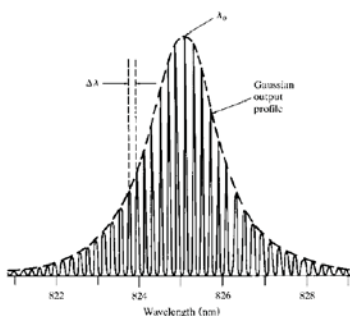
### Optical Gain



Number of laser modes depends on how the cavity modes intersect the optical gain curve. In this case we are looking at modes within the linewidth  $\Delta\lambda_{1/2}$ .

### Optical Gain

#### Fabry-Perot laser spectrum



### Example

A typical low power 5mW He-Ne laser tube operate at a DC voltage of 2000V and carrier a current of 7mA . What is the efficiency of the laser?

Solution:

$$\begin{aligned} \text{Efficiency} &= \text{output light power} / \text{Input Electric power} \\ &= 5 \times 10^{-3} \text{W} / (7 \times 10^{-3} \text{A})(2000\text{V}) \\ &= 0.036\% \end{aligned}$$

Note that 5mW over a beam diameter of 1mm is  $6.4 \text{kW/m}^2$

### Example

**4.2 The He-Ne Laser** A particular He-Ne laser operating at 632.8 nm has a tube that is 50 cm long. The operating temperature is 130 °C

- a** Estimate the Doppler broadened linewidth ( $\Delta\lambda$  in the output spectrum).
- b** What are the mode number  $m$  values that satisfy the resonant cavity condition? How many modes are therefore allowed?
- c** What is the separation  $\Delta\nu_m$  in the frequencies of the modes? What is the mode separation  $\Delta\lambda_m$  in wavelength.

### Solution

**a** The central emission frequency is  $\nu_0 = c/\lambda_0 = (3 \times 10^8 \text{ m s}^{-1}) / (632.8 \times 10^{-9} \text{ m}) = 4.74 \times 10^{14} \text{ s}^{-1}$ .

The FWHM width of the frequencies  $\Delta\nu_{1/2}$  observed will be given by Eq. (3)

$$\Delta\nu_{1/2} = 2\nu_0 \sqrt{\frac{2k_B T \ln(2)}{Mc^2}} = 2(4.748 \times 10^{14}) \sqrt{\frac{2(1.38 \times 10^{-23})(130+273)\ln(2)}{(3.35 \times 10^{-26})(3 \times 10^8)^2}}$$

$$= 1.515 \text{ GHz}$$

To get FWHM wavelength width  $\Delta\lambda_{1/2}$ , differentiate  $\lambda = c/\nu$

$$\frac{d\lambda}{d\nu} = \frac{c}{\nu^2} = \frac{\lambda}{\nu}$$

so that  $\Delta\lambda_{1/2} \approx \Delta\nu_{1/2} \lambda / \nu = (1.515 \times 10^9 \text{ Hz})(632.8 \times 10^{-9} \text{ m}) / (4.74 \times 10^{14} \text{ s}^{-1})$

or  $\Delta\lambda_{1/2} \approx 2.02 \times 10^{-12} \text{ m}$  or 0.00202 nm.

This width is between the half-points of the spectrum.

### Solution

**b** For  $\lambda = \lambda_0 = 632.8 \text{ nm}$ , the corresponding mode number  $m$  is,  $m_0 = 2L / \lambda_0 = (2 \times 0.5 \text{ m}) / (632.8 \times 10^{-9} \text{ m}) = 1580278.1$  and actual  $m$  has to be the closest integer value to 1580278.1, that is 1580278

Consider the minimum and maximum wavelengths corresponding to the extremes of the spectrum at the half-power points:

$$\lambda_{\min} = \lambda_0 - \frac{1}{2} \Delta\lambda = 632.798987$$

and  $\lambda_{\max} = \lambda_0 + \frac{1}{2} \Delta\lambda = 632.801012$

**c** The frequency separation  $\Delta\nu_m$  of two consecutive modes is

$$\Delta\nu_m = \nu_{m+1} - \nu_m = \frac{c}{\lambda_{m+1}} - \frac{c}{\lambda_m} = \frac{c}{\frac{2L}{m+1}} - \frac{c}{\frac{2L}{m}} = \frac{c}{2L} \left( \frac{m+1}{m+1} - \frac{m}{m} \right) = \frac{c}{2L}$$

or  $\Delta\nu_m = \frac{c}{2L} = \frac{3 \times 10^8}{2(0.5)} = 3 \times 10^8 \text{ Hz}$ .

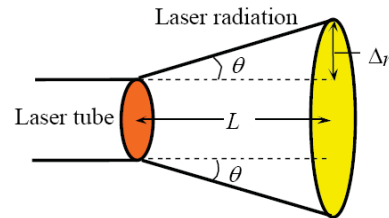
The wavelength separation of two consecutive modes is

$$\Delta\lambda_m = \frac{\lambda^2}{2L} = \frac{(632.8 \times 10^{-9})^2}{2(0.5)} = 4.004 \times 10^{-13} \text{ m} \text{ or } 0.4004 \text{ pm}.$$

Note:

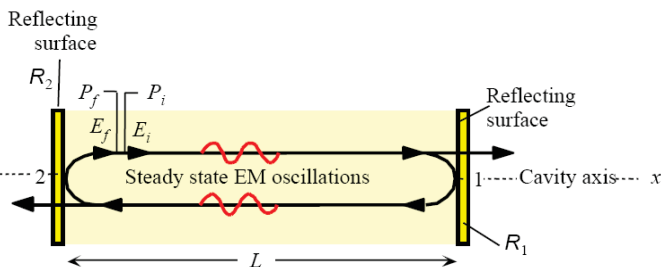
$$\text{Modes} = \frac{\text{Linewidth of spectrum}}{\text{Separation of two modes}} \approx \frac{\Delta\lambda_{1/2}}{\Delta\lambda_m} = \frac{2.02 \text{ pm}}{0.4004 \text{ pm}} = 5.04.$$

### Laser Beam Divergence

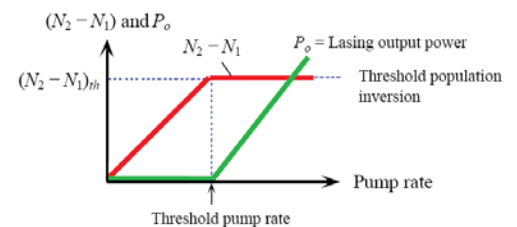


The output laser beam has a divergence characterized by the angle  $2\theta$  (highly exaggerated in the figure)  $\Delta r = L \tan \theta$ . What is the diameter of the beam at a distance of 10m, if divergence is 1mrad?

### Optical Cavity Resonator



### Laser Oscillator



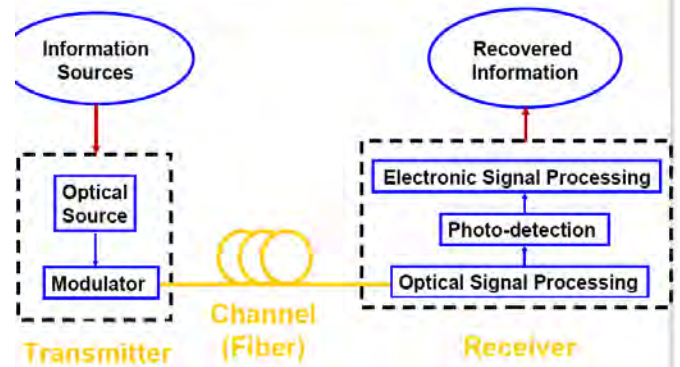
Simplified description of a laser oscillator.  $(N_2 - N_1)$  and coherent output power ( $P_o$ ) vs. pump rate under continuous wave steady state operation.

# Photodetectors

## Photodiodes



# 1. Introduction



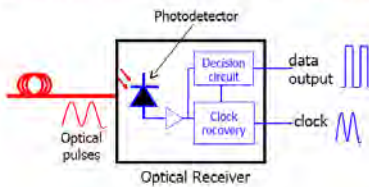
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# 4. Photodetector

- Convert an optical signal into an electrical signal
  - **Photodetectors** made of semiconductor materials **absorb** incident photons and produces electrons
  - If electric field imposed on photodetector an electric current (**photocurrent**) is produced  $\Rightarrow$  **photodiode**



# 4. Photodetector

- Basic requirements of a photodetector
  - **Sensitivity** at the required wavelength
  - **Efficient conversion** of photons to electrons
  - **Fast response** to operate at high frequencies
  - **Low noise** for reduced errors
  - **Sufficient area** for efficient coupling to optical fiber
  - **High reliability**
  - **Low cost**

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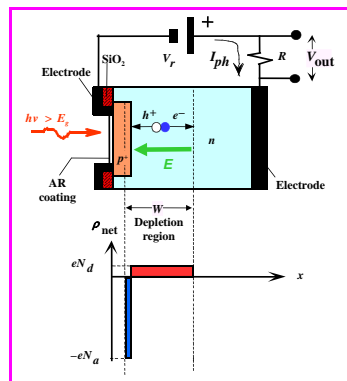
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## Photo-detectors: Principle of the P-N junction photo-diode

- Schematic diagram of a **reverse biased p-n junction photodiode**
  - Photocurrent is depend on number of EHP and drift velocity.
  - The electrode do not inject carriers but allow excess carriers in the sample to leave and become collected by the battery.
- **Net space charge** across the diode in the depletion region.  $N_d$  and  $N_a$  are the donor and acceptor concentrations in the  $p$  and  $n$  sides.



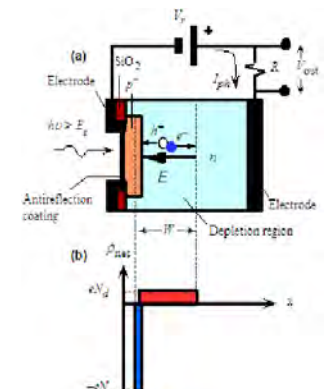
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## Principle of pn junction photodiode

- (a) **Reversed biased pn junction photodiode.**
  - Annular electrode to allow photon to enter the device.
  - Anti-reflection coating ( $\text{Si}_3\text{N}_4$ ) to reduce the reflection.
  - The  $p$ -side thickness  $< 1 \mu\text{m}$ .
- (b) Net space charge distribution, within SCL.



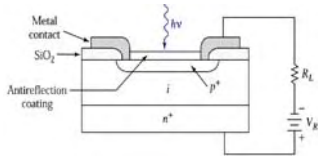
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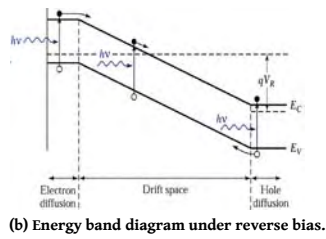
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### Photo-detectors: Principle of the p-n junction Photo-diode

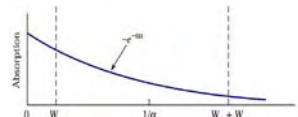
❑ Operation of a photo-diode



(a) Cross-section view of a photo-diode



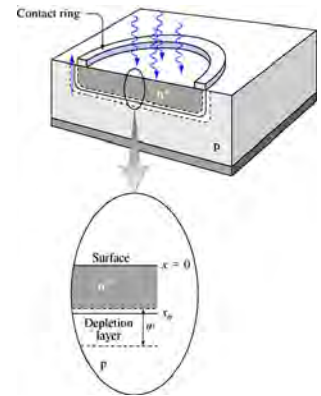
(b) Energy band diagram under reverse bias.



(c) Carrier absorption characteristics.

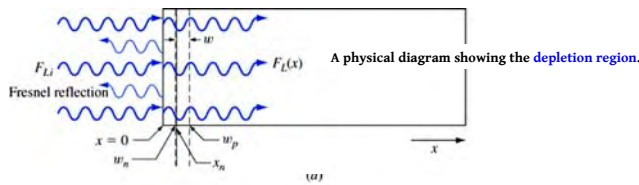
### Photodetectors: Principle of the p-n junction Photo-diode

❑ A generic photo-diode

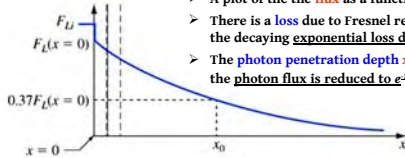


### Photodetectors: Principle of the p-n junction Photo-diode

❑ Variation of photon flux with distance.



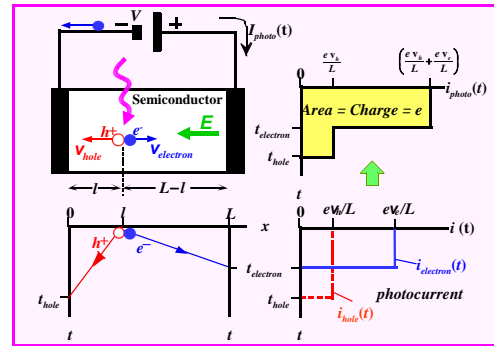
A physical diagram showing the depletion region.



- A plot of the flux as a function of distance.
- There is a loss due to Fresnel reflection at the surface, followed by the decaying exponential loss due to absorption.
- The photon penetration depth  $x_0$  is defined as the depth at which the photon flux is reduced to  $e^{-1}$  of its surface value.

### Photo-detectors: RAMO'S Theorem and External Photo-current

- An EHP is photogenerated at  $x = l$ . The electron and the hole drift in opposite directions with drift velocities  $v_e$  and  $v_h$ .
- The electron arrives at time  $t_{electron} = (L-l)/v_e$  and the hole arrives at time  $t_{hole} = l/v_h$ .



### Photo-detectors: RAMO'S Theorem and External Photo-current

- As the electron and hole drift, each generates  $i_{electron}(t)$  and  $i_{hole}(t)$ .
- The total photocurrent is the sum of hole and electron photocurrents each lasting a duration  $t_e$  and  $t_h$  respectively.

$$t_e(t) = \frac{L-l}{v_e} \text{ and } t_h(t) = \frac{l}{v_h} \quad \text{Transit time}$$

$$\text{Work done} = e \cdot E \cdot dx = V \cdot i_e(t) dt \quad \left( E = \frac{V}{L}, v_e = \frac{dx}{dt} \right)$$

$$i_e(t) = \frac{e v_e}{L}; t < t_e \quad i_h(t) = \frac{e v_h}{L}; t < t_h \quad \text{Photocurrent}$$

$$Q_{collected} = \int_0^{t_e} i_e(t) dt + \int_0^{t_h} i_h(t) dt = e \quad \text{The collected charge is not } 2e \text{ but just "one electron".}$$

If a charge  $q$  is being drifted with a velocity  $v_d(t)$  by a field between two biased electrodes separated by  $L$ , the motion of  $q$  generates an external current given by

$$i(t) = \frac{e v_d(t)}{L}; t < t_{transit} \quad \text{Ramo's Theorem}$$

### Photo-detectors: Absorption Coefficient & Photo-diode Materials

❑ Absorbed Photon create Electron-Hole Pair.

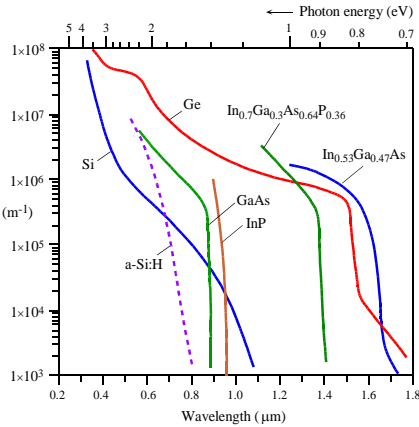
$$\lambda_g [\mu m] = \frac{1.24}{E_g [eV]} \quad \text{Cut-off wavelength vs. Energy bandgap}$$

- ❑ Incident photons become absorbed as they travel in the semiconductor and light intensity decays exponentially with distance into the semiconductor.

$$I(x) = I_0 \cdot e^{-\alpha x} \quad \text{Absorption coefficient}$$

### Absorption Coefficient

- Absorption coefficient  $\alpha$  is a material property.
- Most of the photon absorption (63%) occurs over a distance  $1/\alpha$  (it is called **penetration depth  $\delta$** )



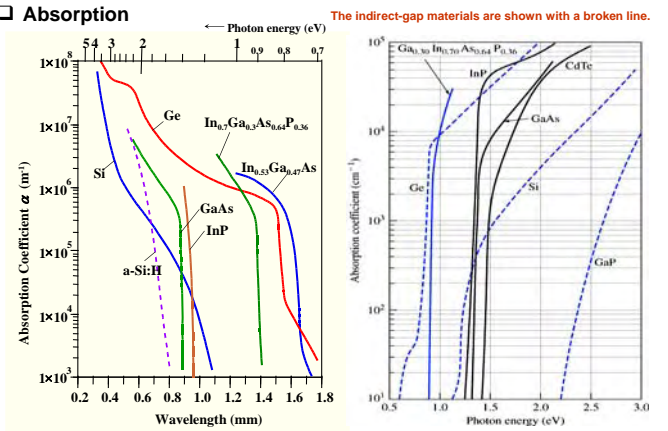
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### Photo-detectors: Absorption Coefficient & Photo-diode Materials

#### □ Absorption



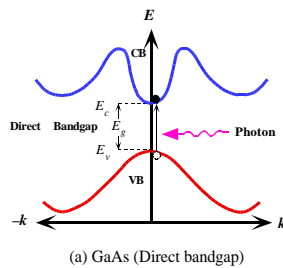
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### Absorption Coefficient

- Direct bandgap semiconductors (GaAs, InAs, InP, GaSb, InGaAs, GaAsSb), the photon absorption **does not require assistant from lattice vibrations**. The photon is absorbed and the electron is excited directly from the VB to CB without a change in its k-vector (crystal momentum  $\hbar k$ ), since photon momentum is very small.



$$\hbar k_{CB} - \hbar k_{VB} = \text{photon momentum} \approx 0$$

- Absorption coefficient  $\alpha$  for direct band-gap semiconductors rise sharply with decreasing wavelength from  $\lambda_g$  (GaAs and InP).

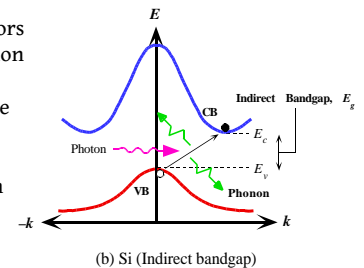
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### Absorption Coefficient

- Indirect band-gap semiconductors (Si and Ge), the photon absorption **requires assistant from lattice vibrations (phonon)**. If  $K$  is wave vector of lattice wave, then  $\hbar K$  represents the momentum associated with lattice vibration  $\rightarrow \hbar K$  is a **phonon momentum**.



$$\hbar k_{CB} - \hbar k_{VB} = \text{phonon momentum} = \hbar K$$

- Thus the probability of photon absorption is not as high as in a direct transition and the  $\lambda_g$  is not as sharp as for direct band-gap semiconductors.

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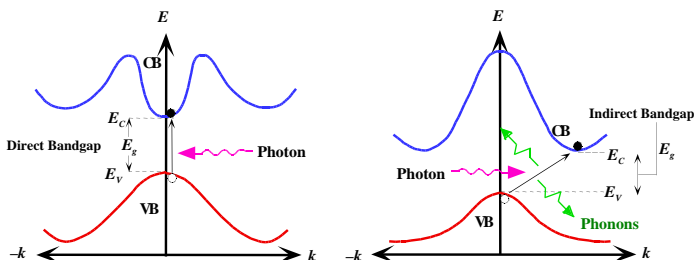
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### Photo-detectors: Absorption Coefficient & Photo-diode Materials

Photon absorption in a **direct bandgap** semiconductor.

Photon absorption in an **indirect bandgap** semiconductor



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### Photo-detectors: Quantum Efficiency and Responsivity

#### □ External Quantum Efficiency

$$\eta = \frac{\text{Number of EHP generated and collected}}{\text{Number of incident photons}} = \frac{I_{ph}/e}{P_0/h\nu}$$

#### □ Responsivity

$$R = \frac{\text{Photocurrent (A)}}{\text{Incident Optical Power (W)}} = \frac{I_{ph}}{P_0}$$

$$R = \eta \frac{e}{h\nu} = \eta \frac{e\lambda}{hc} \quad \text{Spectral Responsivity}$$

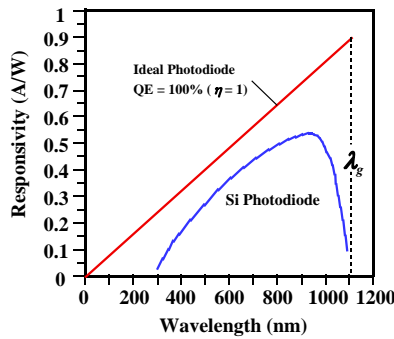
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### Photo-detectors

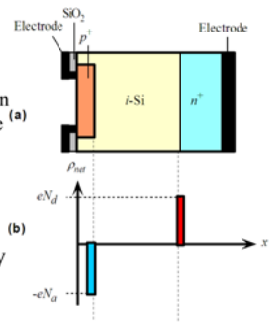
□ Responsivity vs. wavelength for a typical Si photo-diode



### The pin Photo-diode

• The *pn* junction photo-diode has **two drawbacks**:

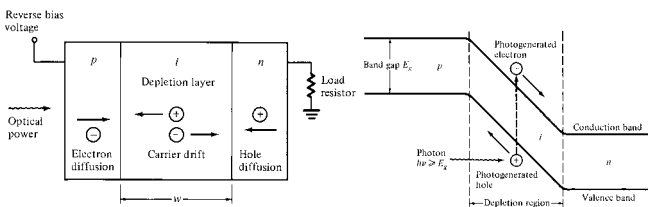
- Depletion layer capacitance is not sufficiently small to allow photodetection at high modulation frequencies (RC time constant limitation).
  - Narrow SCL (at most a few microns) → long wavelengths incident photons are absorbed outside SCL → low QE
- The *pin* photo-diode can significantly reduce these problems.



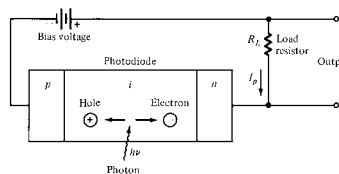
■ Intrinsic layer has less doping and wider region (5 – 50 μm).

### Photo-detectors: PIN Photo-diode

□ Reverse-biased *p-i-n* photodiode □ *pin* energy-band diagram

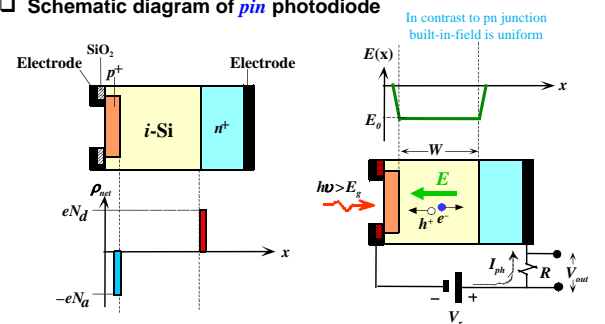


□ *pin* photodiode circuit



### Photo-detectors: PIN Photo-diode

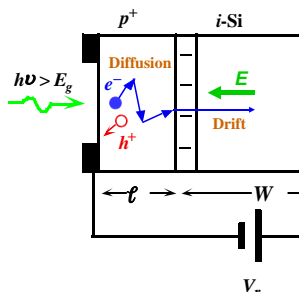
□ Schematic diagram of *pin* photodiode



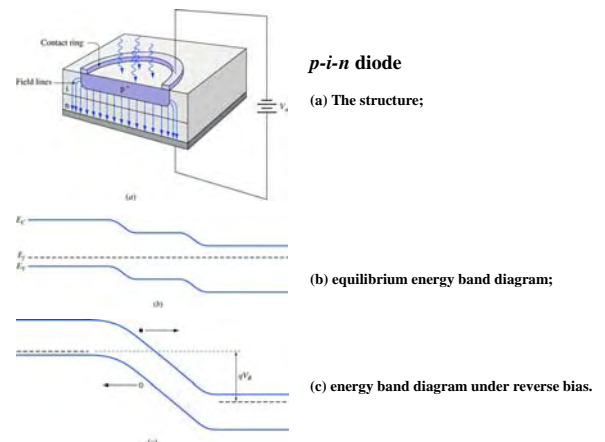
- > Small depletion layer capacitance gives high modulation frequencies.
- > High Quantum efficiency.

### Photo-detectors: PIN Photo-diode

- > A reverse biased *pin* photodiode is illuminated with a short wavelength photon that is absorbed very near the surface.
- > The photogenerated electron has to diffuse to the depletion region where it is swept into the *i*-layer and drifted across.

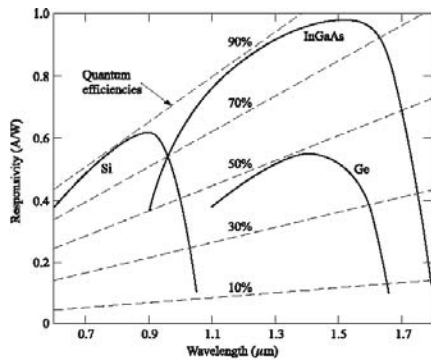


### Photo-detectors: PIN Photo-diode



### Photo-detectors: PIN Photo-diode

□ The responsivity of PIN photodiodes



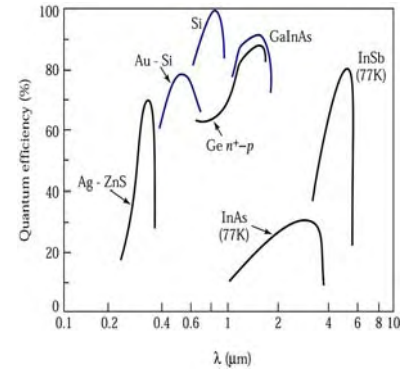
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### Photo-detectors: Photo-conductive Detectors and Gain

□ Quantum efficiency versus wavelength for various photo-detectors



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### Photo-detectors: PIN Photo-diode

□ Junction capacitance of pin

$$C_{dep} = \frac{\epsilon_0 \epsilon_r A}{W}$$

> Small capacitance: High modulation frequency  
>  $RC_{dep}$  time constant is ~ 50 psec.

□ Electric field of biased pin

$$E = E_0 + \frac{V_r}{W} \approx \frac{V_r}{W}$$

□ Response time

$$t_{drift} = \frac{W}{v_d}$$

$$v_d = \mu_d E$$

The speed of pin photodiodes are invariably limited by the transit time of photogenerated carriers across the i-Si layer.

For i-Si layer of width 10 μm, the drift time is about is about 0.1 nsec.

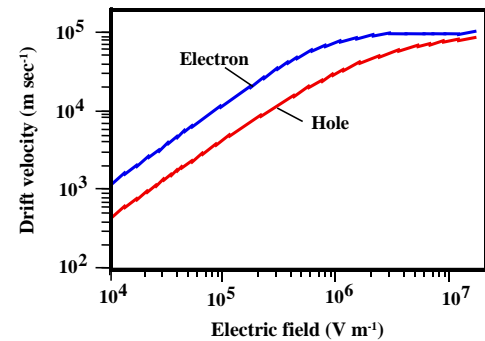
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### Photo-detectors: PIN Photo-diode

□ Drift velocity vs. electric field for holes and electrons in Silicon.



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A Si pin photodiode has an i-Si layer of width 20 μm. The p<sup>+</sup> layer on the illumination side is very thin (0.1 μm). The pin is reverse biased by a voltage of 100 V and then illuminated with a very short optical pulse of wavelength 900 nm. What is the duration of the photocurrent if absorption occurs over the whole i-Si layer?

**Solution** The absorption coefficient at 900 nm is  $\sim 3 \times 10^4 \text{ m}^{-1}$  so that the absorption depth is  $\sim 33 \text{ μm}$  as apparent in Figure 5.3. We can assume that absorption and hence photogeneration occurs over the entire width  $W$  of the i-Si layer. The field in the i-Si layer is

$$E \approx V_r/W = (100 \text{ V})/(20 \times 10^{-6} \text{ m}) = 5 \times 10^6 \text{ V m}^{-1}.$$

At this field the electron drift velocity  $v_e$  is very near its saturation at  $10^5 \text{ m s}^{-1}$ , whereas the hole drift velocity  $v_h$  is about  $7 \times 10^4 \text{ m s}^{-1}$  as shown in Figure 5.7. Holes are slightly slower than the electrons. The transit time  $t_h$  of holes across the i-Si layer is

$$t_h = W/v_h = (20 \times 10^{-6} \text{ m})/(7 \times 10^4 \text{ m s}^{-1}) = 2.86 \times 10^{-10} \text{ s or } 0.3 \text{ ns.}$$

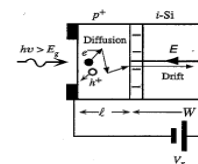
This is the response time of the pin as determined by the transit time of the slowest carriers, holes, across the i-Si layer. To improve the response time the width of the i-Si layer has to be narrowed but this decreases the quantity of absorbed photons and hence reduces the responsivity. There is therefore a trade off between speed and responsivity.

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A reverse biased pin photodiode is illuminated with a short wavelength photon that is absorbed very near the surface as shown in Figure 5.8. The photogenerated electron has to diffuse to the depletion region where it is swept into the i-layer and drifted across. What is the speed of response of this photodiode if the i-Si layer is 20 μm and the p<sup>+</sup> layer is 1 μm and the applied voltage is 120 V? The diffusion coefficient ( $D_n$ ) of electrons in the heavily doped p<sup>+</sup> region is approximately  $3 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ .



**FIGURE 5.8** A reverse biased pin photodiode is illuminated with a short wavelength photon that is absorbed very near the surface. The photogenerated electron has to diffuse to the depletion region where it is swept into the i-layer and drifted across.

**Solution** There is no electric field in the p<sup>+</sup> side outside the depletion region as shown in Figure 5.8. The photogenerated electrons have to make it across to the p<sup>+</sup> side to give rise to a photocurrent. In the p<sup>+</sup> side, the electrons move by diffusion. In time  $t$ , an electron, on average, diffuses a distance  $\epsilon$  given by<sup>2</sup>

$$\epsilon = [2D_n t]^{1/2}$$

The diffusion time  $t_{diff}$  is the time it takes for an electron to diffuse across the p<sup>+</sup> side (of length  $\epsilon$ ) to reach the depletion layer is

$$t_{diff} = \epsilon^2/(2D_n) = (1 \times 10^{-6} \text{ m})^2/[2(3 \times 10^{-4} \text{ m}^2 \text{ s}^{-1})] = 1.67 \times 10^{-6} \text{ s or } 1.67 \text{ ns.}$$

On the other hand, once the electron reaches the depletion region, it becomes drifted across the width  $W$  of the i-Si layer at the saturation drift velocity since the electric field here is  $E = V_r/W = 120 \text{ V}/20 \text{ μm} = 6 \times 10^6 \text{ V m}^{-1}$  and at this field the electron drift velocity  $v_e$  saturates at  $10^5 \text{ m s}^{-1}$ . The drift time across the i-Si layer is

$$t_{drift} = W/v_e = (20 \times 10^{-6} \text{ m})/(1 \times 10^5 \text{ m s}^{-1}) = 2.0 \times 10^{-10} \text{ s or } 0.2 \text{ ns.}$$

Thus, the response time of the pin to a pulse of short wavelength radiation that is absorbed near the surface is about  $t_{diff} + t_{drift}$  or 1.87 ns.

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A Si *pin* photodiode has an active light receiving area of diameter 0.4 mm. When radiation of wavelength 700 nm (red light) and intensity  $0.1 \text{ mW cm}^{-2}$  is incident it generates a photocurrent of 56.6 nA. What is the responsivity and QE of the photodiode at 700 nm?

**Solution** The incident light intensity  $I = 0.1 \text{ mW cm}^{-2}$  means that the incident power for conversion is

$$P_o = AI = \pi(0.02 \text{ cm})^2(1 \times 10^{-3} \text{ W cm}^{-2}) = 1.26 \times 10^{-7} \text{ W or } 0.126 \mu\text{W.}$$

The responsivity is

$$R = I_{ph}/P_o = (56.6 \times 10^{-9} \text{ A})/(1.26 \times 10^{-7} \text{ W}) = 0.45 \text{ A W}^{-1}$$

The QE can be found from

$$\eta = R \frac{hc}{e\lambda} = (0.45 \text{ A W}^{-1}) \frac{(6.62 \times 10^{-34} \text{ J s})(3 \times 10^8 \text{ m s}^{-1})}{(1.6 \times 10^{-19} \text{ C})(700 \times 10^{-9} \text{ m})} = 0.80 = 80\%$$

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### Example

#### Bandgap and photodetection

- (a) Determine the maximum value of the **energy gap** which a semiconductor, used as a photoconductor, can have if it is to be sensitive to yellow light (600 nm).  
 (b) A photodetector whose area is  $5 \times 10^{-2} \text{ cm}^2$  is irradiated with yellow light whose intensity is  $20 \text{ mW cm}^{-2}$ . Assuming that each photon generates one electron-hole pair, calculate the **number of pairs generated per second**.

#### Solution

(a) Given,  $\lambda = 600 \text{ nm}$ , we need  $E_{ph} = h\nu = E_g$  so that,  
 $E_g = hc/\lambda = (6.626 \times 10^{-34} \text{ J s})(3 \times 10^8 \text{ m s}^{-1})/(600 \times 10^{-9} \text{ m}) = 2.07 \text{ eV}$

(b)  $Area = 5 \times 10^{-2} \text{ cm}^2$  and  $I_{light} = 20 \times 10^{-3} \text{ W/cm}^2$ .

The received power is

$$P = Area \times I_{light} = (5 \times 10^{-2} \text{ cm}^2)(20 \times 10^{-3} \text{ W/cm}^2) = 10^{-3} \text{ W}$$

$$N_{ph} = \text{number of photons arriving per second} = P/E_{ph} \\ = (10^{-3} \text{ W})/(2.059 \times 1.60218 \times 10^{-19} \text{ J/eV}) \\ = 2.9787 \times 10^{15} \text{ photons s}^{-1} = 2.9787 \times 10^{15} \text{ EHP s}^{-1}.$$

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### Example

#### Bandgap and Photodetection

- (c) From the known energy gap of the semiconductor GaAs ( $E_g = 1.42 \text{ eV}$ ), calculate the primary **wavelength** of photons emitted from this crystal as a result of electron-hole recombination. Is this wavelength in the visible?  
 (d) Will a **silicon photodetector** be sensitive to the radiation from a **GaAs laser**? Why?

#### Solution

(c) For GaAs,  $E_g = 1.42 \text{ eV}$  and the corresponding wavelength is  $\lambda = hc/E_g = (6.626 \times 10^{-34} \text{ J s})(3 \times 10^8 \text{ m s}^{-1})/(1.42 \text{ eV} \times 1.6 \times 10^{-19} \text{ J/eV}) = 873 \text{ nm}$  (invisible IR). The wavelength of emitted radiation due to EHP recombination is **873 nm**.

(d) For Si,  $E_g = 1.1 \text{ eV}$  and the corresponding cut-off wavelength is  $\lambda_c = hc/E_g = (6.626 \times 10^{-34} \text{ J s})(3 \times 10^8 \text{ m s}^{-1})/(1.1 \text{ eV} \times 1.6 \times 10^{-19} \text{ J/eV}) = 1120 \text{ nm}$ . Since the 873 nm wavelength is shorter than the cut-off wavelength of 1120 nm, the Si photodetector can detect the 873 nm radiation (Put differently, the photon energy corresponding to 873 nm, 1.42 eV, is larger than the  $E_g$ , 1.1 eV, of Si which mean that the **Si photodetector can indeed detect the 873 nm radiation**)

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### Example

#### Absorption coefficient

- (a) If  $d$  is the thickness of a photodetector material,  $I_o$  is the intensity of the incoming radiation, the **number of photons absorbed per unit volume of sample** is

$$n_{ph} = \frac{I_o[1 - \exp(-\alpha \cdot d)]}{d h\nu}$$

#### Solution

(a) If  $I_o$  is the intensity of incoming radiation (energy flowing per unit area per second),  $I_o \exp(-\alpha d)$  is the **transmitted intensity** through the specimen with thickness  $d$  and thus  $I_o \exp(-\alpha d)$  is the "absorbed" intensity

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### Example

- (b) What is the **thickness** of a Ge and  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$  crystal layer that is needed for absorbing 90% of the incident radiation at  $1.5 \mu\text{m}$ ?

For Ge,  $\alpha \approx 5.2 \times 10^5 \text{ m}^{-1}$  at  $1.5 \mu\text{m}$  incident radiation.

For  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ ,  $\alpha \approx 7.5 \times 10^5 \text{ m}^{-1}$  at  $1.5 \mu\text{m}$  incident radiation.

- (b) For Ge,  $\alpha \approx 5.2 \times 10^5 \text{ m}^{-1}$  at  $1.5 \mu\text{m}$  incident radiation.

$$\therefore 1 - \exp(-\alpha \cdot d) = 0.9$$

$$d = \frac{1}{\alpha} \ln\left(\frac{1}{1-0.9}\right) = \frac{1}{5.2 \times 10^5} \ln\left(\frac{1}{1-0.9}\right) = 4.428 \times 10^{-6} \text{ m} = 4.428 \mu\text{m}$$

For  $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ ,  $\alpha \approx 7.5 \times 10^5 \text{ m}^{-1}$  at  $1.5 \mu\text{m}$  incident radiation.

$$d = \frac{1}{7.5 \times 10^5} \ln\left(\frac{1}{1-0.9}\right) = 3.07 \times 10^{-6} \text{ m} = 3.07 \mu\text{m}$$

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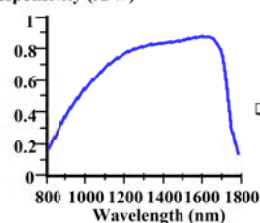
### Example

#### InGaAs *pin* Photodiodes

Consider a commercial InGaAs *pin* photodiode whose responsivity is shown below. Its dark current is 5 nA.

- (a) What optical power at a wavelength of  $1.55 \mu\text{m}$  would give a photocurrent that is twice the dark current? What is the QE of the photodetector at  $1.55 \mu\text{m}$ ?  
 (b) What would be the photocurrent if the incident power in (a) was at  $1.3 \mu\text{m}$ ? What is the QE at  $1.3 \mu\text{m}$  operation?

Responsivity (A/W)



□ The responsivity of an InGaAs *pin* photodiode

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## Solution

- (a) At  $\lambda = 1.55 \times 10^{-6} \text{ m}$ , from the responsivity vs. wavelength curve we have  $R \approx 0.87 \text{ A/W}$ . From the definition of responsivity,

$$R = \frac{\text{Photocurrent (A)}}{\text{Incident Optical Power (W)}} = \frac{I_{ph}}{P_0}$$

we have  $P_0 = \frac{I_{ph}}{R} = \frac{2I_{dark}}{R} = \frac{2 \times 5 \times 10^{-9} \text{ (A)}}{0.87 \text{ A/W}} = 11.5 \text{ nW}$

From the definitions of quantum efficiency  $\eta$  and responsivity,

$$R = \eta \frac{e}{h\nu} = \eta \frac{e\lambda}{hc}$$

$$\eta = \frac{hcR}{e\lambda} = \frac{(6.62 \times 10^{-34} \text{ J} \cdot \text{sec})(3 \times 10^8 \text{ m/s})(0.87 \text{ A/W})}{(1.6 \times 10^{-19} \text{ coul})(1.55 \times 10^{-6} \text{ m})} = 0.70 \text{ (70\%)}$$

Note the following dimensional identities:  $A = C \text{ s}^{-1}$  and  $W = J \text{ s}^{-1}$  so that  $A \text{ W}^{-1} = C \text{ J}^{-1}$ . Thus, responsivity in terms of photocurrent per unit incident optical power is also charge collected per unit incident energy.

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## Solution

- (b) At  $\lambda = 1.3 \times 10^{-6} \text{ m}$ , from the responsivity vs. wavelength curve,  $R = 0.82 \text{ A/W}$ .

Since  $P_0$  is the same and  $11.5 \text{ nW}$  as in (a),

$$I_{ph} = R \cdot P_0 = (0.82 \text{ A/W})(11.5 \text{ nW}) = 9.43 \text{ nA}$$

The QE at  $\lambda = 1.3 \text{ } \mu\text{m}$  is

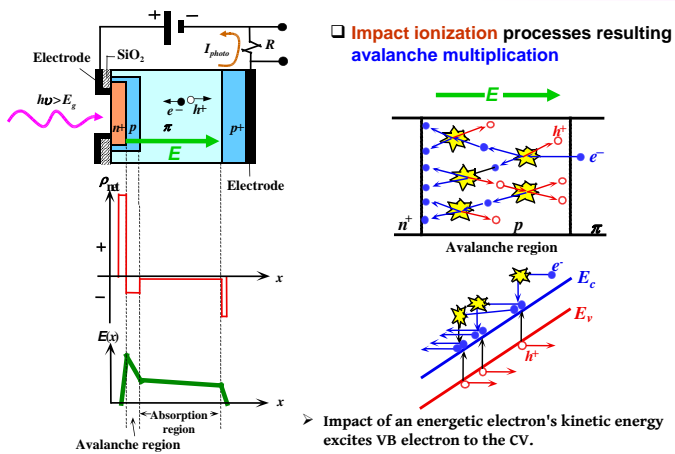
$$\eta = \frac{hcR}{e\lambda} = \frac{(6.62 \times 10^{-34} \text{ J} \cdot \text{sec})(3 \times 10^8 \text{ m/s})(0.82 \text{ A/W})}{(1.6 \times 10^{-19} \text{ coul})(1.3 \times 10^{-6} \text{ m})} \approx 0.78 \text{ (78\%)}$$

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## Photo-detectors: Avalanche Photo-diode (APD)



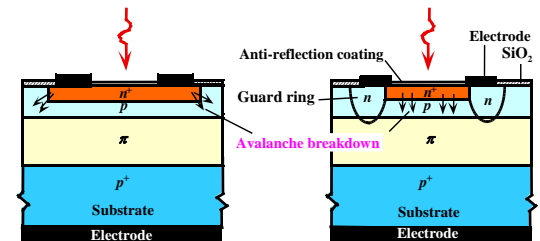
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Slide Set 6

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## Photo detectors: Avalanche Photo-diode (APD)

- Schematic diagram of typical Si APD.



Si APD structure without a guard ring

More practical Si APD

- Breakdown voltage around periphery is higher and avalanche is confined more to illuminated region (n<sup>+</sup>p junction).

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## Photodetectors

### Solar Cell

- Solar energy spectrum
- Photovoltaic device principles
  - I-V Characteristics

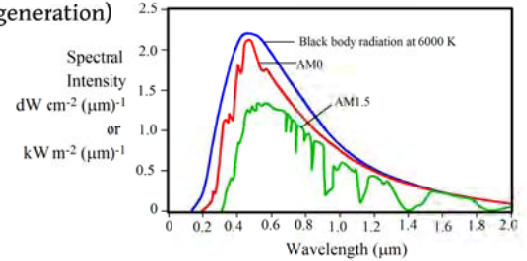
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Slide Set 7

1

## Solar Energy Spectrum

- Photovoltaic devices (solar cells) convert the incident solar radiation energy into electrical energy.
- Absorbed photons  $\rightarrow$  photogeneration  $\rightarrow$  current (photo-current) in external circuit
- Power range: from  $<$  mW (calculator) to few MW (photovoltaic power generation)



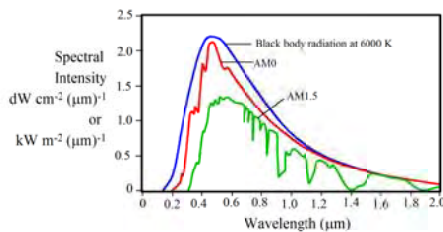
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2

## Solar Energy Spectrum

- Spectral intensity  $I_\lambda$ : Intensity per wavelength.
- $I_\lambda \delta\lambda$ : intensity in a small interval  $\delta\lambda$ .
- Total intensity  $I$ : integration of  $I_\lambda$  over the whole spectrum.
- **Solar constant** or **air-mass zero (AM0)**: the total intensity above earth's atmosphere, approx. constant at  $1.353 \text{ kW m}^{-2}$ .



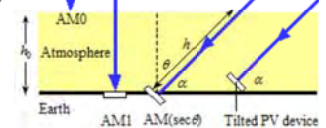
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## Solar Energy Spectrum

- On sunny day, light intensity on earth's surface is about 70% of the intensity above the atmosphere.
- Absorption and scattering effects increase with the sun beam's path through the atmosphere.
- The shortest path through the atmosphere is when the sun is directly above that location and the received spectrum is called **air mass one (AM1)**.
- **Air mass  $m$  (AM $m$ )**: the ratio of the actual radiation path  $h$  to the shortest path  $h_0$ ,  $m = h/h_0$ . Since  $h = h_0 \sec\theta$ , AM $m$  is  $\text{AM} \sec\theta$ .



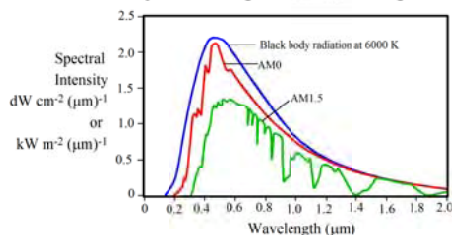
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## Solar Energy Spectrum

- The spectral distribution AM1.5 has several sharp absorption peaks at certain wavelengths which are due to those wavelength being absorbed by various molecule in the atmosphere, such as ozone, air, and water vapor molecules.
- Dust particles scatter the sun light  $\rightarrow$  reduces the intensity and gives rise to the sun's rays arriving at random angle.



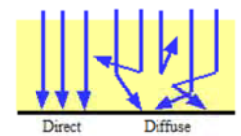
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## Solar Energy Spectrum

- Thus, the terrestrial light has a **diffuse** component in addition to **direct** component.
- Cloud and sun position  $\rightarrow$  increase diffuse component  $\rightarrow$  spectrum shifted toward the blue light.
- Scattering also increase with decreasing wavelength.
- On a clear day, diffusion component can be about 20% of the total radiation.
- The amount of incident radiation depends on the position of the sun. Flat photovoltaic device flat will receive less solar energy by factor  $\cos\theta$ . However it can be tilted to directly face the sun to maximize the collection efficiency.



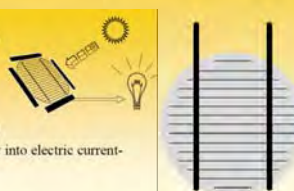
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### Definitions: PV Cell

- Cell:** The basic photovoltaic device that is the building block for PV modules.
- Thin wafers of silicon
  - Similar to computer chips
  - much bigger
  - much cheaper!
- Silicon is abundant (sand)
  - Non-toxic, safe
- Light carries energy into cell
- Cells convert sunlight energy into electric current- they do not store energy
- Sunlight is the "fuel"



PV Cells have efficiencies approaching 21.5%

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Slide Set 7

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### Definitions: PV Module

- Module:** A group of PV cells connected in series and/or parallel and encapsulated in an environmentally protective laminate.

PV Modules have efficiencies approaching 17%



Solarex MSX60  
60 watt polycrystalline

Siemens SP75  
75 watt single crystal


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### Definitions: PV Panel

- Panel:** A group of modules that is the basic building block of a PV array.




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### Definitions: PV Array

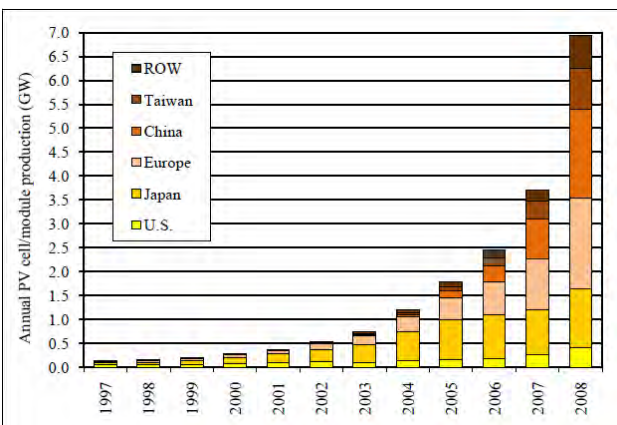
- Array:** A group of panels that comprises the complete PV generating unit.



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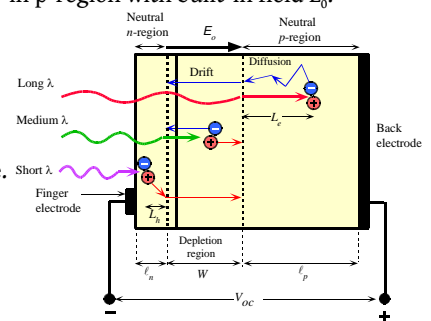
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### Photovoltaic Device Principles

- Consider pn<sup>+</sup> junction with very narrow n-region.
- The illumination is through then thin n-side.
- The SCL extend mainly in p-region with built-in field  $E_0$ .
- Electrode at n-side must allow illumination to enter the device and at the same time result in a small series resistance.
- This electrode is formed from array of finger electrodes.



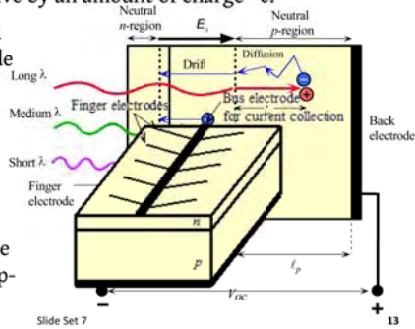
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### Photovoltaic Device Principles

- Photons are absorbed in SCL within the neutral p-side ( $L_p$ ) → photogenerated EHP in this region.
- The electron drifts and reaches the neutral n' side whereupon it makes this region negative by an amount of charge  $-e$ .
- Similarly, hole drifts and reaches the neutral p-side and thereby makes this side positive → **open circuit voltage** between terminals of the device.
- If there is external load, electron will travel through it and recombine with the excess holes in p-side.



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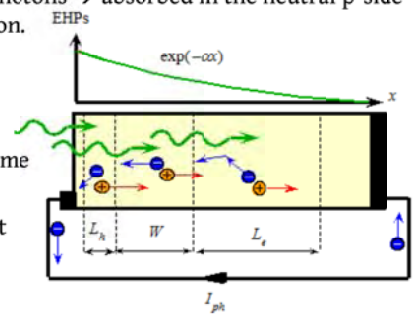
Slide Set 7

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### Photovoltaic Device Principles

- Therefore the existence of built-in field  $E_0$  is important to create accumulated electrons in the n-side and holes in the p-side.
- For long wavelength photons → absorbed in the neutral p-side → no E field → diffusion.
- Minority carrier diffusion length  $L_e$ .  

$$L_e = \sqrt{2D_e \tau_e}$$
- $\tau_e$ : recombination lifetime of electron.
- $D_e$ : diffusion coefficient in the p-side.



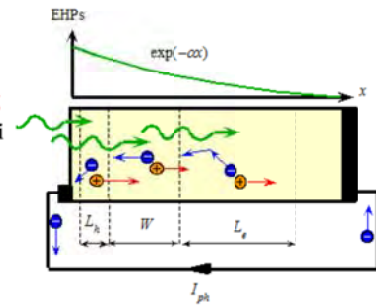
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### Role of Diffusion Length

- Only those EHPs photogenerated within the  $L_e$  to the depletion layer can contribute to the photovoltaic effect.
- Those photogenerated EHPs further away from SCL than  $L_e$  are lost by recombination.
- Thus, it is important to have the **minority carrier diffusion length  $L_e$  as long as possible**. By choosing Si pn junction to be p-type which makes electrons to be minority carriers; the **electron diffuse length in Si > the hole diffusion length**.



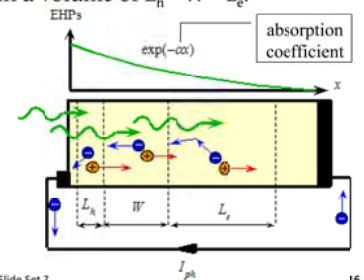
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### Role of hole diffusion length and s/c current

- For EHPs photogenerated by short-wavelength photons absorbed in the n-side, within **diffusion length  $L_h$** , can reach SCL and swept across to the p-side.
- The photogenerated of EHPs that contribute to the photovoltaic effect occurs in a volume of  $L_h + W + L_e$ .
- If the terminals are shorted then the excess electrons in the n-side can flow through the external circuit to neutralize the excess holes in the p-side → this current is called **photocurrent**.



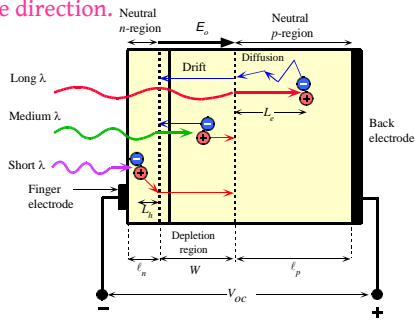
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### Photovoltaic Device Principles

- Under steady state operation → no net current through an **open circuit solar cell** → Photocurrent inside the device due to **photo generated carriers must be balanced by a flow of carriers in the opposite direction**.
- Those are minority carriers that become injected by the appearance of the photovoltaic voltage across the pn junction as in normal diode.



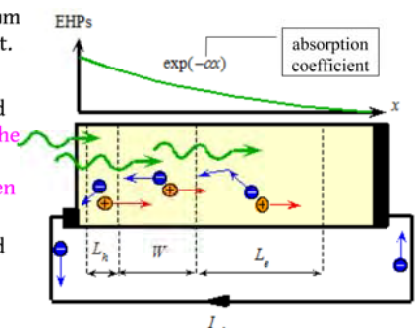
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### Device optimization and carrier losses

- For long wavelengths, 1 - 1.2  $\mu\text{m}$ ,  $\alpha$  is small → absorption depth  $1/\alpha$  is typically greater than 100  $\mu\text{m}$ . → Need a thick p-side and long minority carrier diffusion length  $L_e$ .
- Thus, p-side is 200 - 500  $\mu\text{m}$  and  $L_e$  is shorter than that.
- Si has  $E_g = 1.1 \text{ eV}$  → correspond to a threshold wavelength of 1.1  $\mu\text{m}$  → **The incident energy with wavelength > 1.1  $\mu\text{m}$  is then wasted (~ 25%)**.
- Photons are absorbed and recombined near the crystal surface → losses.



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Slide Set 7

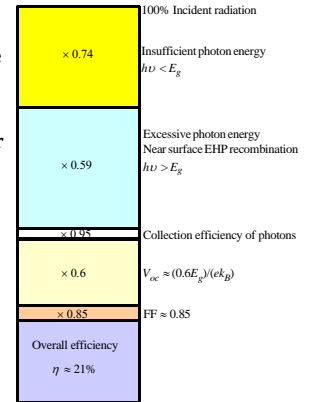
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### Sources of carrier losses

- Photons are absorbed and recombined near the crystal surface → losses → severely reduce efficiency.
- Crystal surface and interface contain high concentration of **recombination-center**.
- Those facilitate the recombination of photogenerated EHP near the surface.
- The losses due to this event as high as ~ 40%.
- These combined effect bring the efficiency down to about 45%.
- Anti-reflection coating is also contributing the reduction of photons collection due to imperfection with factor of 0.8 – 0.9.
- And including the limitation of photovoltaic action the upper limit to a photovoltaic device that uses single crystal of Si is about 24 – 26% at room temperature.

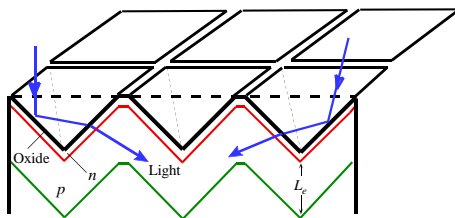
### Solar Cells Materials, Devices & Efficiencies

- For a given solar spectrum, conversion efficiency depends on the semiconductor material properties and the device structure.
- Si based solar cell efficiencies 18% for polycrystalline and 22 – 24% for single crystal devices.
- About 25% solar energy is wasted → not enough energy → unable to generate EHPs.
- Considering all losses, the maximum electrical output power is ~20% for a high efficiency Si solar cell.



### Solar Cells Materials, Devices & Efficiencies

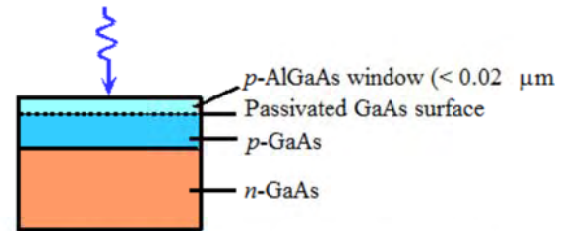
- Si homojunction solar cell efficiencies ~24%. Single crystal PERL (Passivated Emitter Rear Locally-diffused) cells.



Inverted pyramid textured surface substantially reduces reflection losses and increases absorption probability in the device

### Solar Cells Materials, Devices & Efficiencies

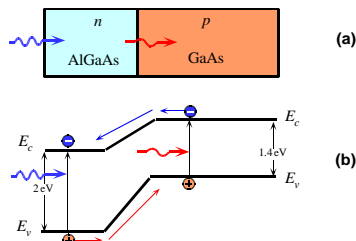
- Semiconductor alloy III-V → different bandgap with the same lattice constant → Heterojunction.



AlGaAs window layer on GaAs passivates the surface states and thereby increases the low wavelength photogeneration efficiency

### Solar Cells Materials, Devices & Efficiencies

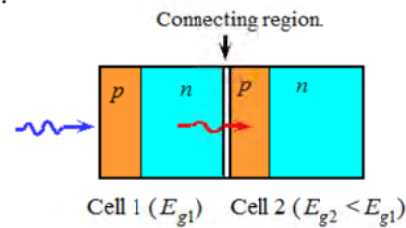
- Example n-AlGaAs with p-GaAs.



A heterojunction solar cell between two different bandgap semiconductors (GaAs and AlGaAs)

### Solar Cells Materials, Devices & Efficiencies

- To further increase the absorbed photons → tandem or cascade cells (use two or more cells in tandem), such as GaAs – GaSb.



A tandem cell. Cell 1 has a wider bandgap and absorbs energetic photons with  $h\nu > E_{g1}$ . Cell 2 absorbs photons that pass cell 1 and have  $h\nu > E_{g2}$ .



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## B.Eng (Hons.) Electronic Engineering

Cohort: BEE/09/FT

### Examinations for 2012 – 2013 / Semester 2

MODULE: OPTOELECTRONICS

MODULE CODE: ELEEC4105

Duration: 2½ Hours

Reading time: None

#### Instructions to Candidates:

1. Attempt ALL **FOUR** questions.
2. Start your answer to each question on a fresh page.
3. All questions carry **equal** marks.
4. Maximum Marks = **100**
5. Silent calculators are allowed in the Examination Room.
6. Appendix is provided.

This question paper contains **4** questions and **5** pages.

Page 1 of 5

#### **ATTEMPT ALL FOUR QUESTIONS**

#### **QUESTION 1: (25 MARKS)**

- a) Describe **two** mechanisms by which electrons can be excited from the valence band to the conduction band?  
(4 marks)
- b) Given that the direct-band gap energy for Gallium Nitride (**GaN**) is **3.4 eV** at room temperature, calculate the phonon energy and phonon momentum that you can expect from such a material with a lattice constant of **3.186 Å** and velocity of sound of **5x10<sup>3</sup> m/s**.  
(3+2 marks)
- c) Given a **P-type** semiconductor with  $N_A$  and  $N_D$  atom concentrations of **8x10<sup>11</sup> cm<sup>-3</sup>** and **3x10<sup>3</sup> cm<sup>-3</sup>** respectively, calculate the electron concentration assuming  $n_i = 1.4 \times 10^{10}$  cm<sup>-3</sup>.  
(3 marks)
- d) What do you understand by the Fermi Level of a crystal? According to the Fermi-Dirac function, what is the temperature at which there is **1%** probability that a state, with an energy **0.5 eV** above the Fermi energy, will be occupied by an electron?  
(7 marks)
- e) Given a piece of **N-type** silicon at **0 °C**,
- i. Calculate the thermal velocity of an electron with an effective mass of **1.18m<sub>0</sub>** and a mobility of **0.25 m<sup>2</sup>V<sup>-1</sup>s<sup>-1</sup>**.
  - ii. What is the electric field that needs to be applied to make the electron drift at a velocity of **1000 ms<sup>-1</sup>**?  
(4+2 marks)

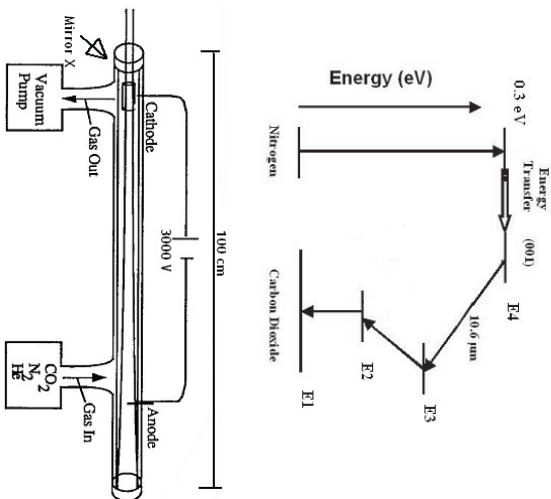
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**QUESTION 2: (25 Marks)**

- a) Describe **five** advantages of LED lighting over conventional incandescent lighting. **(5 marks)**
- b) State **two** impairments that reduces the radiant flux of a surface-emitting LED. Illustrate one way how any one of these impairments may be addressed? **(4 marks)**
- c) Illustrate how white light can be generated using a blue Gallium Nitride (GaN) LED. **(3 marks)**
- d) Find the composition of the quaternary alloy  $In_{1-x}Ga_xAs_yP_{1-y}$  for making semiconductor LEDs operating at **1.27 $\mu$ m**. The bandgap energy  $E_g$  of the quaternary alloy in eV is then given by the empirical relationship  $E_g = 1.35 - 0.72y + 0.12y^2$  where  $y=2.2x$ . **(6 marks)**
- e) Given a particular Gallium Nitride (GaN) Edge-emitting LED drawing a current **50 mA** when the voltage is **1.5 V** and operating at **450 nm** wavelength with light power of **5  $\mu$ W** coupled with a **9  $\mu$ m** single-mode fibre.
  - i) What is the colour of the light emitted from the LED?
  - ii) Calculate the overall efficiency of the LED.
  - iii) Calculate its internal quantum efficiency given that  $T_r = 50ms$  and  $T_{nr} = 70 ns$ .
  - iv) Hence, calculate the internal optical power generated by the LED. **(1+2+1+3 marks)**

**QUESTION 3: (25 Marks)**

- a) State **four** general properties of lasers. **(4 marks)**
- b) Describe why 'population inversion' is a necessary condition for sustained lasing action? **(4 marks)**
- c) Consider a **400 mW** nitrogen-carbon dioxide laser operating at **10.6  $\mu$ m**. The operating temperature is **350 °C** and the current is **20 mA**. (*Mass of CO<sub>2</sub> molecule = 7.16x10<sup>-26</sup> kg*)
  - i) Calculate the energy value at level E3 in eV and state which level is meta-stable?
  - ii) Describe Mirror X in the diagram above and calculate the efficiency of the laser?
  - iii) Estimate the Doppler broadened linewidth ( $\Delta\nu$ ) in the output spectrum.
  - iv) What are the mode number m values that satisfy the resonant cavity condition?
  - v) What are the mode separations in frequency ( $\Delta\nu_m$ ) and wavelength ( $\Delta\lambda_m$ )? **(4+3+4+2+4 marks)**



**QUESTION 4: (25 Marks)**

a) State **six** desirable requirements of a generic photo-detector. (6 marks)

b) A gallium arsenide *pin* photo-diode has an intrinsic layer of width **1 μm**. The diode is reverse-biased by a voltage of **3 V** and then illuminated with short optical pulse of wavelength **800 nm**.

- i) Deduce the penetration depth to know if absorption will occur across the whole width.
- ii) Calculate the electric field across the intrinsic layer width.
- iii) Estimate the electron drift velocity.
- iv) Estimate the duration of the photo-current across the whole width of the diode.

(4x2 marks)

c) A photo-diode has an active circular area with radius **2 mm**. When radiation of wavelength **800 nm** and intensity **0.25 mW/cm<sup>2</sup>** is incident it generates a photo-current of **0.3 μA**. What is the responsivity and quantum efficiency of the photo-diode at **800 nm**? (4+2 marks)

d) A **0.5 cm<sup>2</sup>** photo-detector is shone with **850 nm** light of intensity **75 mW/cm<sup>2</sup>**. Assume that each photon generates one EHP, calculate the number of EH pairs created per second. (3 marks)

e) What is the thickness of a Germanium crystal layer that is needed for absorbing **85%** of the incident radiation at **1 μm**? (2 marks)

\*\*\*END OF EXAM PAPER\*\*\*



**B.Eng (Hons.) Electronic Engineering**

**Cohort: BEE/10A/FT**

**Examinations for 2013 / Semester 2**

**MODULE: OPTOELECTRONICS**  
**MODULE CODE: ELEC4105**  
**Duration: 2½ Hours**  
**Reading time: None**

**Instructions to Candidates:**

- Attempt ALL **FOUR** questions.
- Start your answer to each question on a fresh page.
- All questions carry equal marks.
- Maximum Marks = **100**
- Silent calculators are allowed in the Examination Room.
- Appendix provided

This question paper contains 4 questions and 5 pages.

**ATTEMPT ALL FOUR QUESTIONS****QUESTION 1: (25 MARKS)**

- a) Describe three mechanisms by which electrons can be excited from the valence band to the conduction band? **(6 marks)**
- b) Given that the band gap energy for Indium Phosphide (*InP*) is 1.344 eV at 300K, calculate the photon momentum that you can expect from such a material. **(3 marks)**
- c) Given a N-type semiconductor with  $N_A$  and  $N_D$  concentrations of  $1 \times 10^{17}$  atoms  $\text{cm}^{-3}$  and  $3 \times 10^{16}$   $\text{cm}^{-3}$  respectively, calculate the electron concentration assuming  $n_i = 1.4 \times 10^{10}$   $\text{cm}^{-3}$ . **(3 marks)**
- d) What do you understand by the Fermi Level of a crystal? According to the Fermi-Dirac function, at what temperature can we expect a 40% probability that electrons in Gold will have an energy which is 5% above the Fermi level? ( $E_F$  (Gold) = 5.5 eV) **(6 marks)**
- e) An electron is moving in a piece of lightly doped silicon under an applied field at 27 °C so that its drift velocity is one-tenth of its thermal velocity.
- Calculate the average number of collisions it will experience while drifting a region 1  $\mu\text{m}$  wide given  $m_e^* = 0.26m_0$  and electron mobility =  $0.1414 \text{ m}^2\text{V}^{-1}\text{s}^{-1}$ .
  - What is the applied voltage across this region? **(5+2 marks)**

Page 2 of 5

**QUESTION 2: (25 Marks)**

- a) Describe five advantages of LED lighting over conventional incandescent lighting. **(5 marks)**
- b) Describe two ways to reduce loss of radiant flux in an LED due to total internal reflection of photons at the output interface. **(4 marks)**
- c) Explain how white light can be generated using a UV LED. **(3 marks)**
- d) Find the composition of the quaternary alloy  $\text{In}_{1-x}\text{Ga}_x\text{As}_{1-y}\text{P}_y$  for making semiconductor LEDs operating at 1.5  $\mu\text{m}$ . The bandgap energy  $E_g$  of the quaternary alloy in eV is then given by the empirical relationship  $E_g = 1.35 - 0.72y + 0.12y^2$  where  $x=0.5y$ . **(6 marks)**
- e) Given a particular Gallium Nitride (GaN) LED drawing a current 75 mA when the voltage is 3 V with an external conversion efficiency of 10% and operating at 400 nm wavelength.
- What is the colour of the light emitted from the LED?
  - Calculate its external optical power output.
  - Calculate its internal quantum efficiency given that  $T_r = 3.5 \text{ ns}$  and  $T_{nr} = 50 \text{ ns}$ .
  - Hence, calculate the internal optical power generated by the LED. **(1+2+1+3 marks)**

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**QUESTION 3: (25 Marks)**

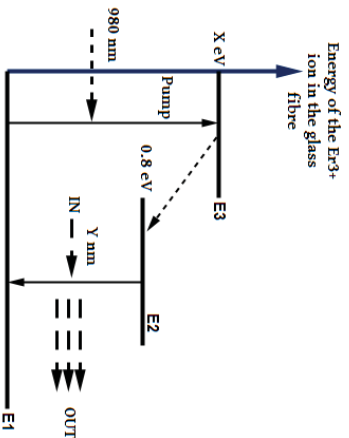
a) State **four** general properties of lasers.

**(4 marks)**

b) Why is 'population inversion' necessary for sustained lasing action?

**(4 marks)**

c) Consider a hypothetical Er<sup>3+</sup> doped optical fibre amplifier (EDFA) below:



i) Calculate the value of X in eV at level E3.

ii) Describe what happens between level E3 and E2 as shown by the dotted arrow?

iii) Calculate the value of Y in nm between level E2 and E1?

**(2+4+2 marks)**

d) A particular 2 Watt Krypton laser operating at 400 nm has a tube that is 30 cm long. The operating temperature is at 400 K at a voltage of 110 V drawing a current of 10 A. (Mass of Krypton atom =  $1.39 \times 10^{-25}$  kg)

i) What is the efficiency of the laser?

ii) Estimate the Doppler Broadened linewidth ( $\Delta\nu$ ) in the output spectrum.

iii) What are the mode number  $m$  values that satisfy the resonant cavity condition?

iv) What are the mode separations in frequency ( $\Delta\nu_m$ ) and wavelength ( $\Delta\lambda_m$ )?

**(1+3+1+4 marks)****Page 4 of 5****QUESTION 4: (25 Marks)**

a) State **five** desirable requirements of a generic photo-detector.

**(5 marks)**

b) Describe **two** drawbacks that are addressed by **pin** photo-diode compared to conventional **pn** junction photo-diode.

**(2 marks)**

c) An AlGaAs/GaAs *pin* photo-diode has an intrinsic GaAs layer of width 1  $\mu\text{m}$ . The p<sup>+</sup> layer is very small at 10  $\mu\text{m}$ . The diode is reverse-biased by a voltage of 1.75 V and then illuminated with short optical pulse of wavelength 700 nm.

i) Estimate the absorption coefficient of the photo-diode.

ii) Deduce the penetration depth to know if absorption will occur across the whole width.

iii) Calculate the electric field across the intrinsic layer width

iv) Estimate the hole drift velocity

v) Hence, calculate the duration of the photo-current across the whole width of the diode.

**(2+1+2+1+2 marks)**

d) A photo-diode has an active light receiving area of 15  $\text{mm}^2$ . When radiation of wavelength 650 nm and intensity 0.5  $\text{mW}/\text{cm}^2$  is incident on it, it generates a photo-current of 0.2  $\mu\text{A}$ . What is the responsivity and quantum efficiency of the photo-diode at 650 nm?

**(3+2 marks)**

e) A 0.5  $\text{cm}^2$  photo-detector is irradiated with 750 nm light of intensity 75  $\text{mW}/\text{cm}^2$ . Assuming that each photon generates one EHP, calculate the number of pairs created per second.

**(3 marks)**

f) What is the thickness of a Germanium crystal layer that is needed for absorbing 75% of the incident radiation at 1.5  $\mu\text{m}$ ? (For Ge,  $\alpha = 5.2 \times 10^5 \text{ m}^{-1}$  at 1.5  $\mu\text{m}$  incident radiation)

**(2 marks)****\*\*\*END OF EXAM PAPER\*\*\*****Page 5 of 5**



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## B.Eng (Hons.) Electronic Engineering

Cohort: BEE/13/FT

### Examinations for 2016 – 2017 / Semester 2

MODULE: OPTOELECTRONICS

MODULE CODE: ELEC4105

Duration: 2½ Hours

Reading time: None

#### Instructions to Candidates:

1. Attempt ALL **FOUR** questions.
2. Start your answer to each question on a fresh page.
3. All questions carry equal marks.
4. Maximum Marks = **100**
5. Silent calculators are allowed in the Examination Room.
6. Appendix is provided.

This question paper contains 4 questions and 5 pages.

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#### ATTEMPT ALL FOUR QUESTIONS

#### QUESTION 1: (25 MARKS)

- a) Describe **two** mechanisms by which electrons can be excited from the valence band to the conduction band?  
(4 marks)
- b) Given that the direct-band gap energy for Zinc Phosphide ( $Zn_3P_2$ ) is **1.5 eV** at room temperature, calculate the phonon energy and momentum that you can expect from such a material with a lattice constant of **0.0899 Å** and velocity of sound of **330 m/s**.  
(3+2 marks)
- c) Given a **n-type** semiconductor with  $N_A$  and  $N_D$  atom concentrations of  $3 \times 10^{19} \text{ cm}^{-3}$  and  $7 \times 10^{18} \text{ cm}^{-3}$  respectively, calculate the hole concentration assuming  $n_i = 1.4 \times 10^{10} \text{ cm}^{-3}$ .  
(3 marks)
- d) What do you understand by the Fermi Level of a crystal? According to the Fermi-Dirac function, what is the temperature at which there is **5%** probability that a state, with an energy **0.5 eV** above the Fermi energy, will be occupied by an electron?  
(7 marks)
- e) Given a piece of **p-type** silicon at **300 °K**,
- i. Calculate the thermal velocity of a hole with an effective mass of **1.15** $m_0$  and a mobility of **0.045**  $\text{m}^2\text{V}^{-1}\text{s}^{-1}$ .
  - ii. What is the electric field that needs to be applied to make a hole drift at a velocity of **90**  $\text{ms}^{-1}$ ?  
(4+2 marks)

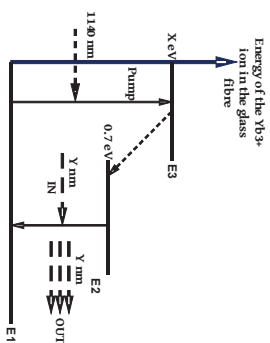
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**QUESTION 2: (25 Marks)**

- a) Describe **three** advantages of LED lighting over conventional incandescent lighting. **(3 marks)**
- b) State **two** impairments that reduces the radiant flux of a surface-emitting LED. Illustrate one way how any one of these impairments may be addressed? **(4 marks)**
- c) Illustrate how white light can be generated using a Blue Gallium Nitride (GaN) LED. Give **two** advantages of this technique. **(3+2 marks)**
- d) The bandgap energy  $E_g$  in eV for  $In_{1-x}Ga_xAs_yP_{1-y}$  lattice-matched to  $InP$  is given by the empirical relationship  $E_g = 1.35 - 0.72y + 0.12y^2$  where  $y=2.15(1-x)$ . Calculate the fraction of **Gallium** suitable for a **1.15  $\mu\text{m}$**  emitter. **(6 marks)**
- e) Given a particular Indium Gallium Aluminium Phosphide ( $InGaAlP$ ) edge-emitting LED drawing a current **50 mA** when the voltage is **1.5 V** and operating at **560 nm** wavelength with optical power that is coupled in a multi-mode fibre through a lens is **1.5 mW**.
  - i) What is the colour of the light emitted from the LED?
  - ii) Calculate the overall efficiency of the LED.
  - iii) Calculate its internal quantum efficiency given that  $T_r = 15 \text{ ns}$  and  $T_{nr} = 40 \text{ ns}$ .
  - iv) Hence, calculate the internal optical power generated by the LED. **(1+2+1+3 marks)**

**QUESTION 3: (25 Marks)**

- a) State **four** general properties of lasers. **(4 marks)**
- b) Describe why 'population inversion' is a necessary condition for sustained lasing action? **(4 marks)**
- c) Consider a hypothetical Ytterbium Doped optical Fibre Amplifier (YDFA) below.



- i) Calculate the value of X in eV at level E3.
- ii) Which level is the meta-stable state?
- iii) Explain what happens between level E3 and E2 as shown by the slanted dotted arrow.
- iv) Calculate the value of Y in nm between level E2 and E1? **(2+1+3+2 marks)**
- d) A particular 50 W Krypton-Fluoride laser operating at 248 nm has a tube that is 50 cm long. The operating temperature is at 75 °C. It operates at a voltage of 2 kV and carries a current of 500 mA. (Mass of an Krypton atom =  $1.39 \times 10^{-25}$  kg)
  - i) What is the efficiency of the laser?
  - ii) Estimate the Doppler broadened linewidth ( $\Delta\nu$ ) in the output spectrum.
  - iii) What are the mode number **m** values that satisfy the resonant cavity condition?
  - iv) What are the mode separations in frequency ( $\Delta\nu_m$ ) and wavelength ( $\Delta\lambda_m$ )? **(1+3+1+4 marks)**

**QUESTION 4: (25 Marks)**

- a) State five desirable requirements of a generic photo-detector. (5 marks)
  
- b) A silicon *pin* photo-diode has an intrinsic layer of width 20  $\mu\text{m}$ . The p' layer is very small at 0.5  $\mu\text{m}$ . The diode is reverse-biased by a voltage of 100 V and then illuminated with short optical pulse of wavelength 900 nm.
  - i) Estimate the absorption coefficient of the photo-diode.
  - ii) Deduce the penetration depth to know if absorption will occur across the whole width.
  - iii) Calculate the electric field across the intrinsic layer width
  - iv) Estimate the hole drift velocity
  - v) Hence, calculate the duration of the photo-current across the whole width of the diode. (2+2+2+2+2 marks)
  
- c) A photo-diode has an active light receiving area with diameter 1 mm. When radiation of wavelength 900 nm and intensity 0.3 mW/cm<sup>2</sup> is incident it generates a photo-current of 0.25  $\mu\text{A}$ . What is the responsivity and quantum efficiency of the photo-diode at 900 nm? (3+2 marks)
  
- d) A 0.5 cm<sup>2</sup> photo-detector is irradiated with 840 nm light of intensity 40 mW/cm<sup>2</sup>. Assuming that each photon generates one EHP, calculate the number of pairs created per second. (3 marks)
  
- e) What is the thickness of a Germanium crystal layer that is needed for absorbing 90% of the incident radiation at 1.5  $\mu\text{m}$ ? *(For Ge,  $\alpha = 5.2 \times 10^5 \text{ m}^{-1}$  at 1.5  $\mu\text{m}$  incident radiation)* (2 marks)

\*\*\*END OF EXAM PAPER\*\*\*

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**Constants:**

- $h = 6.626 \times 10^{-34} \text{ m}^2\text{kg/s}$
- $V_T = kT/q = 25 \text{ mV @ } 300\text{K}$
- $q = 1.6 \times 10^{-19} \text{ C}$
- $k = 1.38 \times 10^{-23} \text{ J/K}$
- $m_0 = 9.1 \times 10^{-31} \text{ kg}$
- $c = 3 \times 10^8 \text{ m/s}$
- $N_A = 6.02 \times 10^{23} \text{ mol}^{-1}$

**Miscellaneous Formulae:**

- $n = p = n_i$
- $f(E) = \frac{1}{e^{-E/kT} + 1}$
- $P_D = \frac{1}{2} [N_A - N_D + \sqrt{(N_A - N_D)^2 + 4n_i^2}]$
- $I_D = nqV_{th}A$
- $V_{th} = \sqrt{\frac{3kT}{m^*}}$
- $\delta V = 2V_0 \sqrt{\frac{2kT \ln 2}{Mc^2}}$
- $E_g = \frac{hc}{\lambda} - k_B T$
- $\eta_{int} = \frac{R_{hvc}}{eI_0}$
- $R = \frac{I_{ph}}{I_0}$

Appendix - ELECA105

