Fiber Optics
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Lecture - 33
Optical Sources and Detectors- I

In the next few lectures we would look into the other segments of an optical communication link it is optical sources on the transmitter side, and optical detectors on the receiver side.

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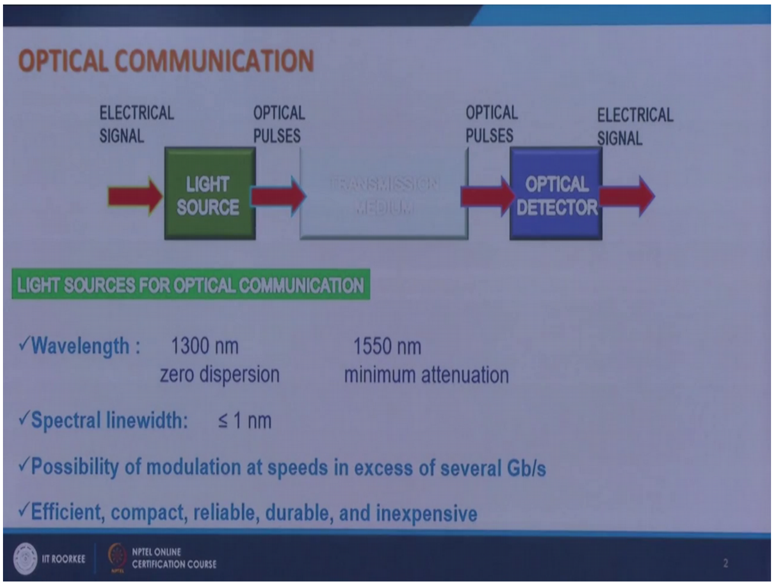

OPTICAL COMMUNICATION

LIGHT SOURCES FOR OPTICAL COMMUNICATION

- ✓Wavelength : 1300 nm zero dispersion; 1550 nm minimum attenuation
- ✓Spectral linewidth: ≤ 1 nm
- ✓Possibility of modulation at speeds in excess of several Gb/s
- ✓Efficient, compact, reliable, durable, and inexpensive

So, if you have this optical communication link then you have electric signal, which modulates the light source this electric signal contains the data. So, it has got electric pulse train, this electric pulse train modulates light source and generates optical pulses. These optical pulses are sent through this transmission medium which is optical fiber, and these optical pulses after travelling through this optical fiber, now are received at optical detector and are converted back into electric signal.

So, in the next few lectures we are going to look into light sources for optical communication and optical detectors. Let us look at light sources what are the requirements. Optical communication is primarily done at 2 wavelengths 1300 nanometer wavelength, which is 0 dispersion wavelength and 1550 nanometer wavelength, which is minimum attenuation wavelength. So, our sources should be able to give me wavelengths this or this.

Then I should have line width as small as possible, typically the line width should be is smaller than or of the order of one nanometer. Third thing is since I am going to use these sources for optical communication. So, I need to modulate them, I need to generate optical pulses from electric pulses. So, these sources should be able to get modulated at speeds in excess of several G b p s, and also with all these qualities the sources should be efficient they should be compact, I would not like to use a source which is this big, I would like to have a source as small as possible.

They should be reliable, there should not be any malfunction during the process while sending the signal, they should be durable I need not to replace them time to time, and on top of all these they should be less expensive because we want to have more and more data, we want to transmit more and more data, but we do not want to pay for it. So, they should be inexpensive they should not add to the cost.

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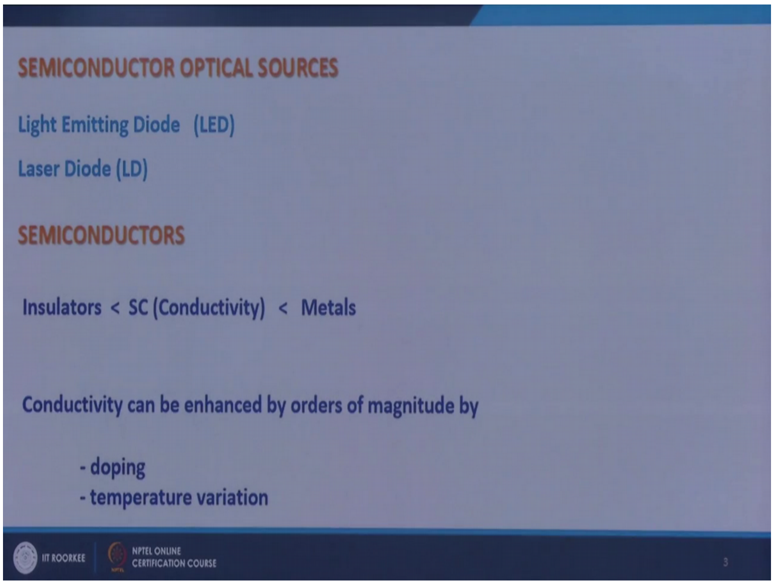

SEMICONDUCTOR OPTICAL SOURCES

Light Emitting Diode (LED)

Laser Diode (LD)

SEMICONDUCTORS

Insulators < SC (Conductivity) < Metals

Conductivity can be enhanced by orders of magnitude by

- doping
- temperature variation

How do we make these sources? These sources are primarily based on semiconductor optical materials.

Semiconductor materials and 2 primary sources are light emitting diode LED, and laser diode LD. So, to understand these 2 sources we will discuss about these 2 sources in these lectures. So, to understand the working of these and characteristics of these sources, first let us look at semiconductors let us briefly discuss the basics of semiconductors, which we are going to use in these sources. We know that the semiconductors are the materials whose conductivity lies between the conductivity of the insulators and the metals. Conductivity of semiconductors can be enhanced by order of magnitude by doping and or by temperature variation.

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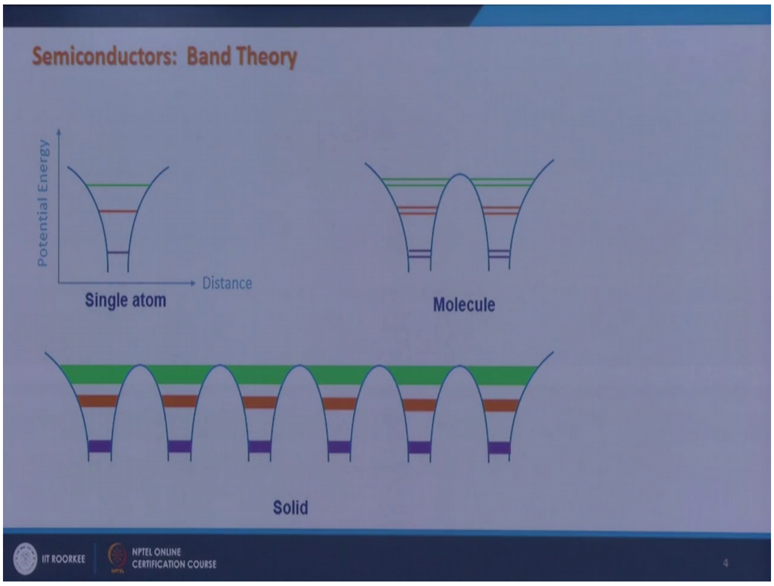

Semiconductors: Band Theory

In semiconductors we have bands, how a semiconductor conducts electricity, how its conductivity changes its temperature, how its conductivity varies with doping, to understand that we will have to look into the energy bands of a semiconductor what are energy bands or energy levels. If we looked at a single atom single isolated atom, then its potential energy is something like this, the electron in an atom experiences the potential something like this the potential energy something like this.

And quantum mechanics tells me that if an electron is subjected to this kind of potential energy, then it has certain bound states. It has discrete energy levels it can occupy this energy or this energy or this energy and no energy in between. We know this from quantum mechanics, but if I have a molecule that is I bring another atom closer to this, then the electron now is shared by both the atoms and it experiences a net potential energy something like this. As a consequence this energy level gets split into 2 and this and this also. So, these energy levels get split if I bring more and more atoms then there would be more and more splitting and these energy levels are then transformed into bands, these are known as energy bands. The highest filled band is the valence band and the immediately next to that is known as conduction band.

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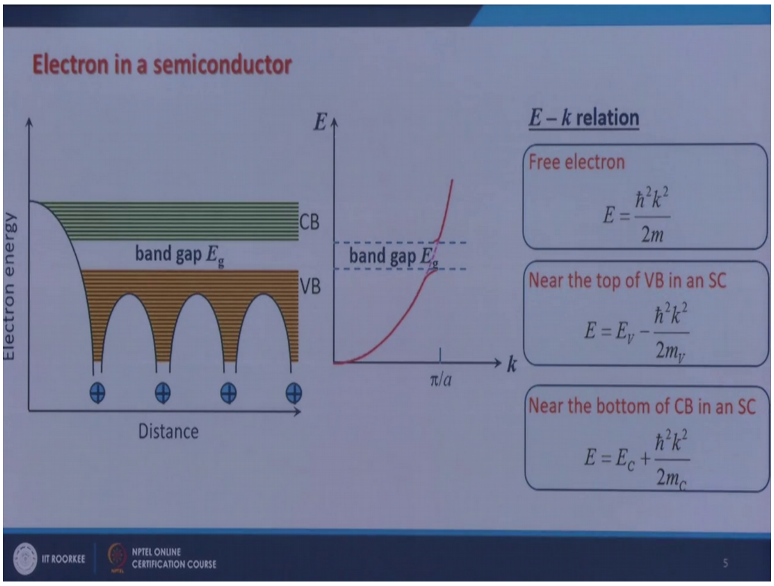

Electron in a semiconductor

$E-k$ relation

Free electron

$$E = \frac{\hbar^2 k^2}{2m}$$

Near the top of VB in an SC

$$E = E_V - \frac{\hbar^2 k^2}{2m_V}$$

Near the bottom of CB in an SC

$$E = E_C + \frac{\hbar^2 k^2}{2m_C}$$

So, what I have? I have a valence band and a conduction band in between I have a gap, that is in between there is energy which electron cannot occupy. So, this is known as band gap and is denoted by E g.

If I have an electron in this kind of solid, then how its energy varies with k; k is the wave vector I know that if an electron is moving then a moving electron has a momentum associated with it, and a moving electron also has a wave associated with it.

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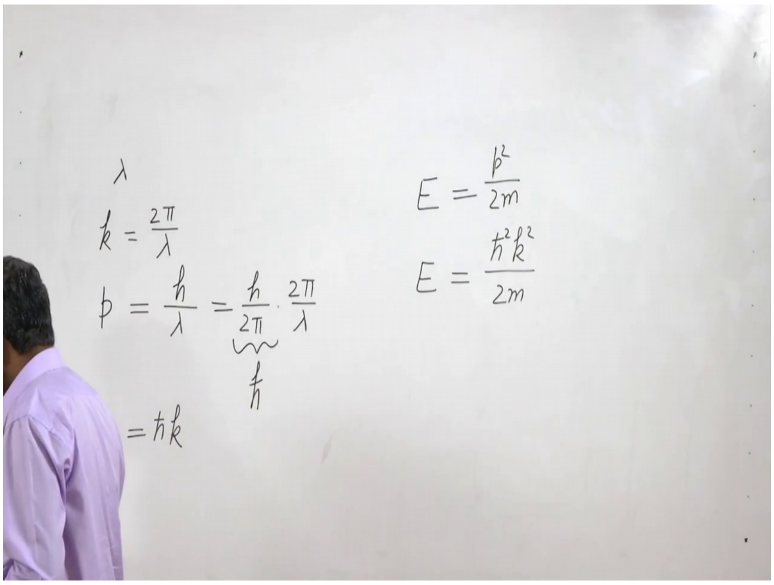

λ

$$k = \frac{2\pi}{\lambda}$$

$$p = \frac{h}{\lambda} = \underbrace{\frac{h}{2\pi}}_{\hbar} \cdot \frac{2\pi}{\lambda}$$

$$= \hbar k$$

$$E = \frac{p^2}{2m}$$

$$E = \frac{\hbar^2 k^2}{2m}$$

If the wavelength of the wave associated with electron is lambda, then k which is the wave vector it is given by 2 pi over lambda, and this the momentum associated with this electron is h over lambda or I can write it down as h over 2 pi times 2 pi over lambda, this is from de Broglie hypothesis. H over 2 pi I represent by a symbol called h cross then this p is equal to h cross k. Now if electron is in free space then its kinetic energy can be given by E is equal to p square over 2 m or I can write down it as E is equal to h cross square k square over 2 m.

In free space any value of energy is possible, because electron is not bound to have certain discrete energies, but it can occupy any energy it is in free space or it is in constant potential, then the relationship between the E energy of the electron and k which is the wave vector associated with the wave of the electron de Broglie wave of the electron is given by E is equal to h cross square k square over 2 m. So, if I plot it then it goes like this it is parabolic. So, electron can occupy any energy. However, if the electron is subjected to this kind of potential energy, then what happens that it can occupy energies here it can occupy energies here, but it cannot occupy energies here then this e k diagram changes.

So, you have energies here in the valence band and the energies here in the conduction band and in between there is a break you cannot have an electron cannot have any energy. So, there is a band gap, then the E k relation is modified as near the top of the valence band the energy is given by E v minus h cross square k square over 2 m v, where m v is the effective mass of the electron in the valence band, and near the bottom of the conduction band in an S c, S c stands for semiconductor, E is equal to E c plus h cross square k square over 2 m c, where m c is the effective mass of the electron in the conduction band.

These E k relations are become very important and become very (Refer Time: 12:28) while understanding the properties of a semiconductor.

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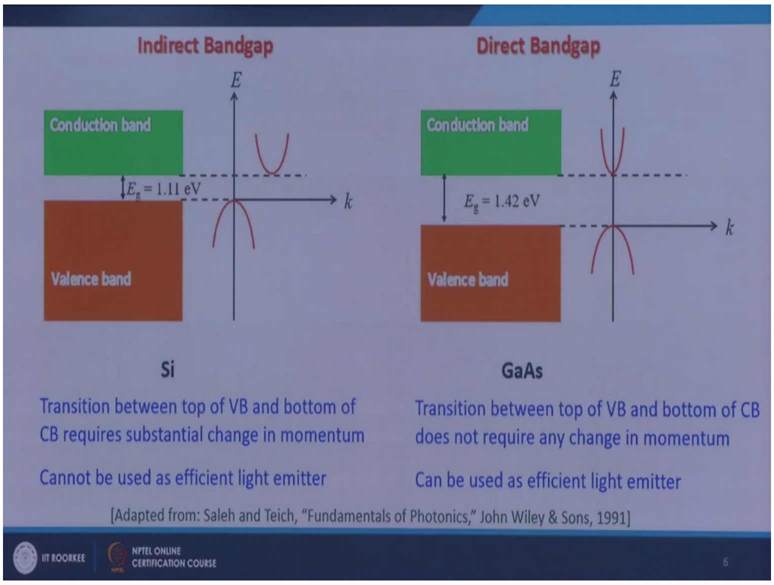

Indirect Bandgap

Si

Transition between top of VB and bottom of CB requires substantial change in momentum

Cannot be used as efficient light emitter

Direct Bandgap

GaAs

Transition between top of VB and bottom of CB does not require any change in momentum

Can be used as efficient light emitter

[Adapted from: Saleh and Teich, "Fundamentals of Photonics," John Wiley & Sons, 1991]

Now, depending upon how the E k diagram of a semiconductor look like, I can have indirect bandgap semiconductor and direct bandgap semiconductor. If a top of valence band and bottom of conduction band they have different k vectors, different values of k that is this one is not on top of this in line, then this kind of semiconductor is known as indirect bandgap semiconductor. Silicon is an example of this, silicon has a bandgap of about 1.1 electron volt, and its conduction band is displaced along k axis with respect to the valence band.

So, for a transition between these 2 that is valence band and conduction band transition between the top of valence band and bottom of conduction band, would now require change in the value of k that is the change in the momentum of the electron. So, this kind of materials since they involve the change in momentum and this is also known as phonon transition then these cannot be used as efficient light emitters.

However, the semiconductor materials whose top of valence band and bottom of conduction band have the same value of k, then the transition between them is direct. This transition does not involve any change in momentum or involvements of phonon then these kinds of materials are known as direct bandgap semiconductors, an example of this is gallium arsenide whose bandgap is 1.42 electron volt, and these kinds of materials can be used as efficient light emitters.

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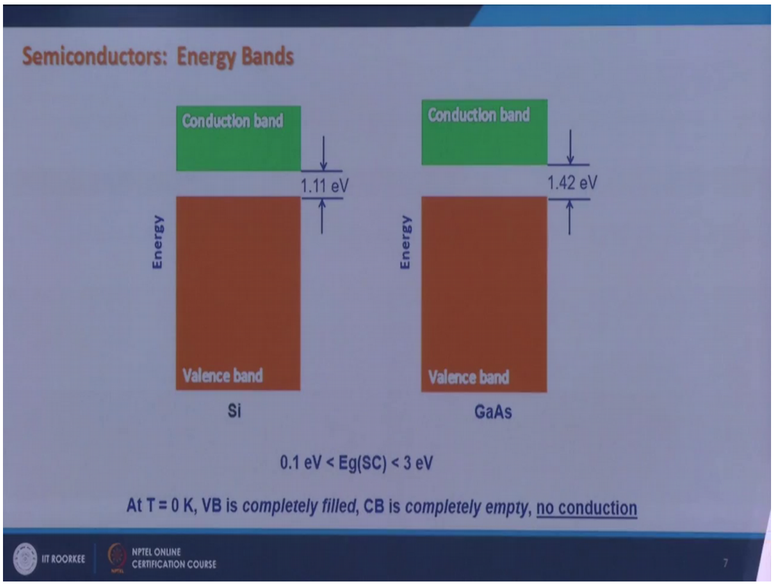

Semiconductors: Energy Bands

0.1 eV < Eg(SC) < 3 eV

At T = 0 K, VB is *completely filled*, CB is *completely empty*, no conduction

So, if I look at a semiconductor at 0 Kelvin, then what I find that the valence band is completely filled and conduction band is completely empty and therefore, since conduction band is completely empty. So, there are no electrons available for conduction and the semiconductor is a perfect insulator at 0 Kelvin. The bandgap of a semiconductor typically lies between 0.1 electron volt and 3 electron volts; for silicon it is 1.1 and for gallium arsenide it is 1.42.

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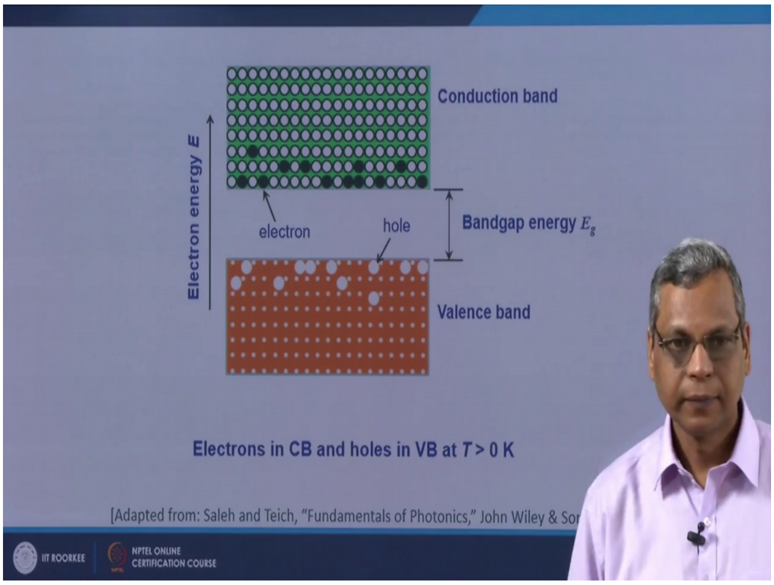

Electrons in CB and holes in VB at $T > 0$ K

[Adapted from: Saleh and Teich, "Fundamentals of Photonics," John Wiley & Sor

However, if I raise the temperature of a semiconductor, then some of the electrons from valence band get thermally excited to the conduction band. So, now, you have some electrons available in the conduction band.

And some vacancies are created in the valence band. So, these electrons now can move in the conduction band if you apply electric field, and these vacancies can be filled by the nearby electrons. So, the electron can move from here. So, it will create a vacancy here then from here to here then it will create a vacancy here. So, movement of electron in this direction is equivalent to movement of vacancy in the opposite direction, and since the electron is leaving a vacancy; so in the vacancy I can say it has got equivalent positive charge and this is known as hole.

So, I have free electrons now available in the conduction band and holes are available in the valence bands which contribute towards conduction. So, I can enhance the conductivity of a semiconductor if I raise the temperature.

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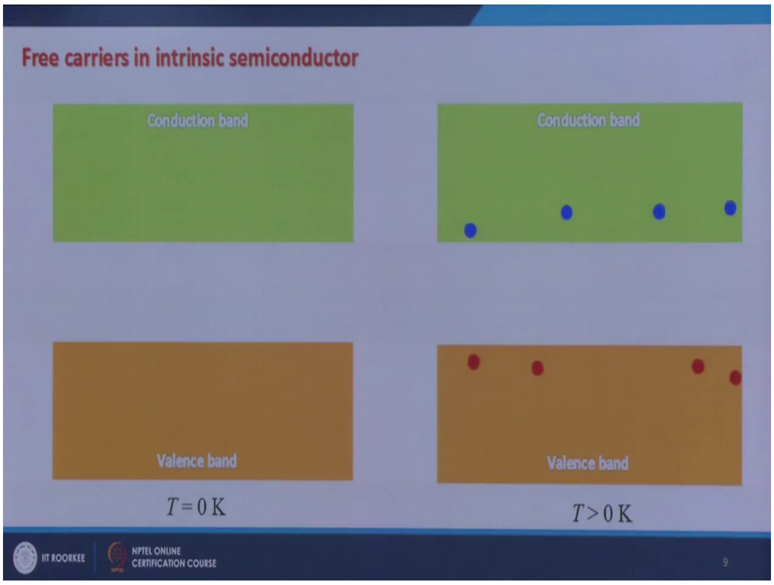

Free carriers in intrinsic semiconductor

Conduction band

Conduction band

Valence band

Valence band

$T = 0\ \mathrm{K}$

$T > 0\ \mathrm{K}$

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Another way of increasing the conductivity is by doping, I will talk about that later. So, if I look at free carriers in an intrinsic semiconductor which is not doped, then that T is equal to 0 Kelvin, I do not have any free carriers in the valence band or in the conduction band. However, at elevated temperatures I have some holes available in the valence band and some electrons available in the conduction band, these blue circles represent here electrons and red circles here represent holes.

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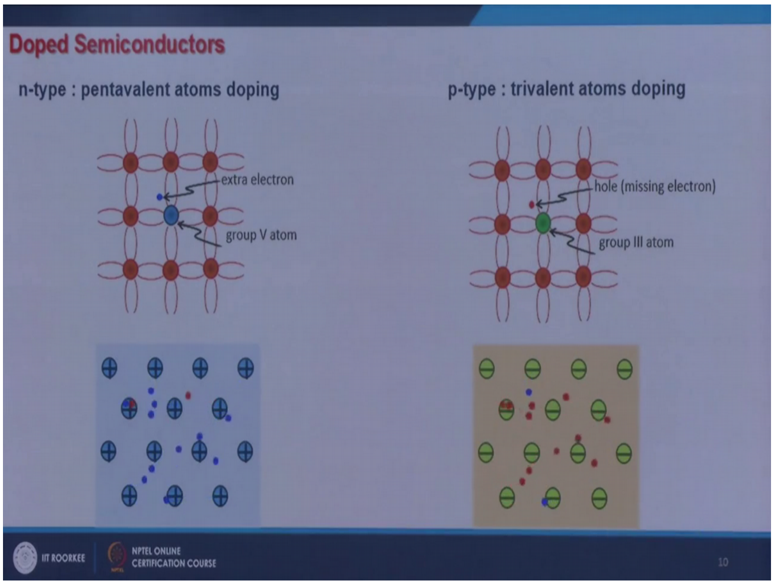

Doped Semiconductors

n-type : pentavalent atoms doping

p-type : trivalent atoms doping

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I can also increase the conductivity of the semiconductors by doping, and I can dope the semiconductor either by pentavalent atoms or by trivalent atoms. If I doping of pentavalent atoms then 4out of 5 valence electrons of this pentavalent atom, may bond with the semiconductor materials 4 4 valence electrons of semiconductor material, and one electron is now available it is left which is now available for conduction. So, equivalently what I have? I have a positive ion code because this electron is not associated with the atom now. So, atom has given out this electron.

So, effectively I have this positive ion core and large number of these electrons available depending upon the doping level for conduction. And this kind of material is known as p type semiconductor. I am sorry this type of semiconductor is then known as n type semiconductor because now you have negative charge electron available for conduction. If you dope it with trivalent atoms then three valence electrons of these atoms make bond with three electrons of the semiconductor and one vacancy is left ok.

Fourth one does not get bonded. So, a vacancy is left. So, this vacancy is hole a missing electron which is equivalent to a positive charge. So, this can be thought of as some negative ion core with some positive charges, whose charge is exactly the same as that of electron. So, you have positive charges holes available here for conduction in the negative ion core. So, this kind of semiconductor material is known as p type semiconductor.

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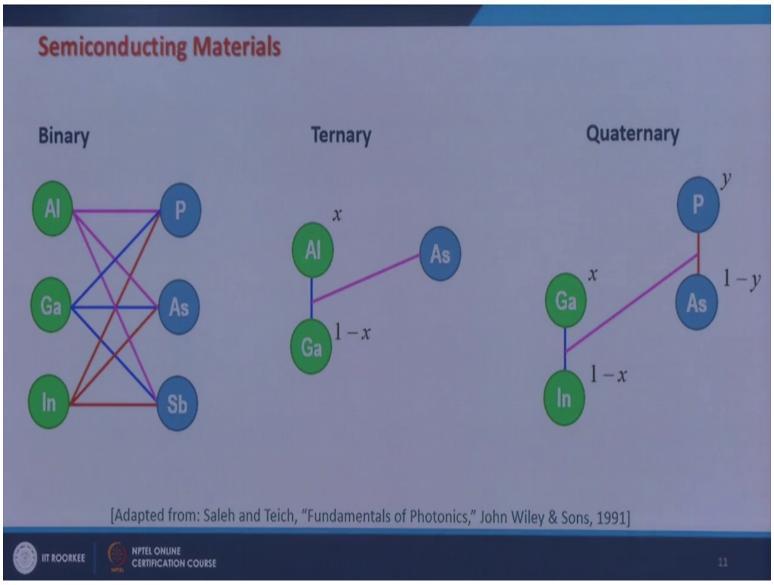

Semiconducting Materials

[Adapted from: Saleh and Teich, "Fundamentals of Photonics," John Wiley & Sons, 1991]

So, apart from these silicon germanium these kind of semiconductors, which have just one element from fourth group I can make semiconductor by mixing the elements from fifth group and third group. So, what I can do? I can take the elements from third group of periodic table like aluminum gallium and indium, and I can take from fifth group of the periodic table like phosphorous arsenic and antimony. I can take one from here and one from here and make a semiconductor which is known as binary semiconductor. Gallium arsenide is one example of this aluminum phosphide is another example gallium antimonite is another example, indium phosphide yet another example. Then these are binary semiconductors I can also have 2 elements from third group in different proportion and one from fifth group.

So, if x fraction of aluminum if combined with one minus x fraction of gallium from third group, and then with arsenic of fifth group then I can make aluminum gallium arsenide this is a ternary semiconductor. You can also have 2 from third group and 2 from fifth group. So, x fraction of this 1 minus x fraction of this from third group, and y fraction of this from fifth group and one minus y fraction of this from fifth group then I can make what is known as quaternary semiconductors.

What is the advantage of doing this? The advantage of doing this is that I can tune the bandgap when I change the composition then the bandgap of the material changes. So, I can tune the bandgap.

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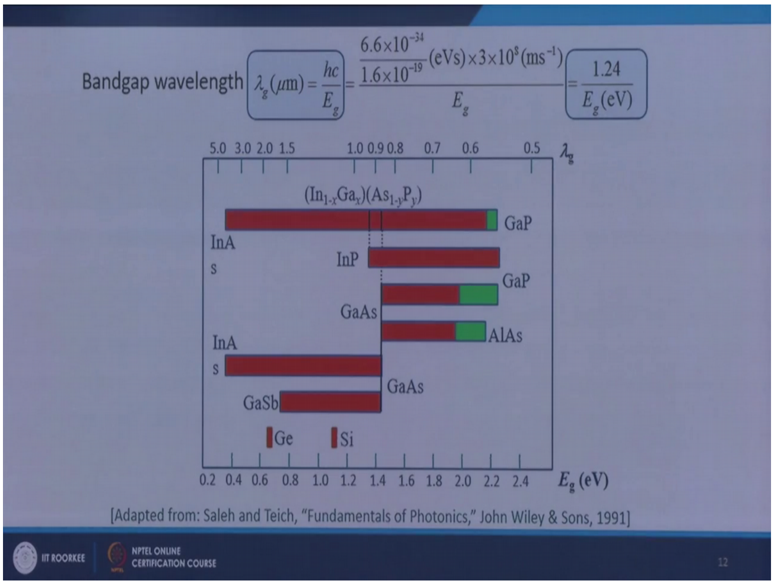

Bandgap wavelength $\boxed{\lambda_g(\mu m) = \frac{hc}{E_g}} = \frac{\frac{6.6\times10^{-34}}{1.6\times10^{-19}}(eVs)\times3\times10^{8}(ms^{-1})}{E_g} = \boxed{\frac{1.24}{E_g(eV)}}$

[Adapted from: Saleh and Teich, "Fundamentals of Photonics," John Wiley & Sons, 1991]

So, here what has been plotted is the composition of various semiconductors, whether it is quaternary ternary or binary, their bandgap energy and bandgap wavelength corresponding bandgap wavelength I would like to mention here, that in in this lecture and in the subsequent few lectures I have adopted several illustrations from the book (Refer Time: 23:35) which is the textbook, I have recommended fundamentals of photonics. So, you can refer to that book also. So, if I now find out the bandgap wavelength corresponding to this bandgap energy. So, it is given by h c over E g when it is convenient to write it in this particular form how.

Well h is equal to 6.6 into 10 to the power minus 34 which is planks constant, it is in joules second. So, I can convert it into electron volt second if I divide it by 1.6 into 10 to the power minus 19 which is the charge of an electron, then c is three into 10 to the power 8 meters per second, then I can have this as 1.24 divided by Eg. This will give you this will give you 1.24 into 10 to the power minus 6. So, 10 to the power minus 6 will give you wavelength in micrometer, and then this E v basically reflects here that is E g will have to now input in E v.

So, you can immediately find out the bandgap wavelength, if you divide 1.24 by E g, where E g is in electron volts and then the wavelength you will get in micrometer. So, you can see that you can have a variety of E g and correspondingly different bandgap wavelengths.

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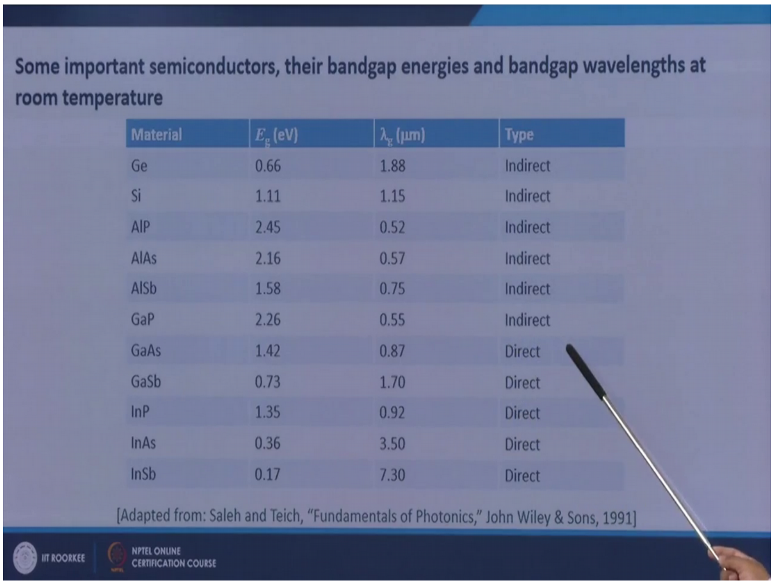

Some important semiconductors, their bandgap energies and bandgap wavelengths at room temperature

Material	E_g (eV)	λ_g (μm)	Type
Ge	0.66	1.88	Indirect
Si	1.11	1.15	Indirect
AlP	2.45	0.52	Indirect
AlAs	2.16	0.57	Indirect
AlSb	1.58	0.75	Indirect
GaP	2.26	0.55	Indirect
GaAs	1.42	0.87	Direct
GaSb	0.73	1.70	Direct
InP	1.35	0.92	Direct
InAs	0.36	3.50	Direct
InSb	0.17	7.30	Direct

[Adapted from: Saleh and Teich, "Fundamentals of Photonics," John Wiley & Sons, 1991]

These are some important semiconductors their bandgap energies and bandgap wavelengths. So, and also the type of the semiconductor, you can see germanium has a bandgap energy of about 6.6 electron volt, which corresponds to bandgap wavelength of 1.88 micrometer and it is indirect semiconductor. Well silicon has a bandgap energy of 1.1 electron volt, corresponding bandgap wavelength 1.15 it is also indirect semiconductor. You can look at gallium arsenide which has bandgap energy of 1.42 electron volt.

Bandgap wavelength of 0.87 micrometer, it is direct bandgap semiconductor. Indium phosphide 1.35 electron volt bandgap energy, 0.92 micrometer bandgap wavelength, it is direct bandgap semiconductor.

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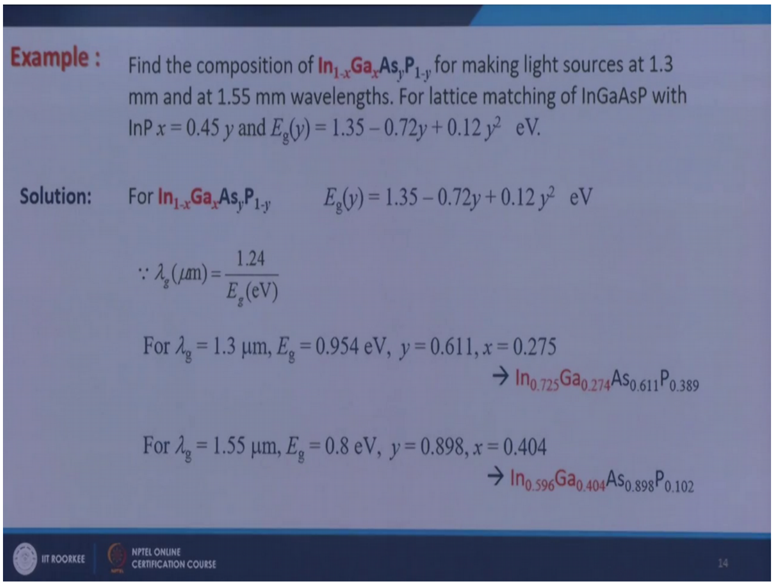

Example : Find the composition of $In_{1-x}Ga_xAs_yP_{1-y}$ for making light sources at 1.3 mm and at 1.55 mm wavelengths. For lattice matching of InGaAsP with InP $x = 0.45\,y$ and $E_g(y) = 1.35 - 0.72y + 0.12\,y^2$ eV.

Solution: For $In_{1-x}Ga_xAs_yP_{1-y}$ $E_g(y) = 1.35 - 0.72y + 0.12\,y^2$ eV

$$\because \lambda_g(\mu m) = \frac{1.24}{E_g(eV)}$$

For $\lambda_g = 1.3\ \mu m$, $E_g = 0.954$ eV, $y = 0.611, x = 0.275$

→ $In_{0.725}Ga_{0.274}As_{0.611}P_{0.389}$

For $\lambda_g = 1.55\ \mu m$, $E_g = 0.8$ eV, $y = 0.898, x = 0.404$

→ $In_{0.596}Ga_{0.404}As_{0.898}P_{0.102}$

By changing the composition of the material, I can have whatever wavelength I want in a particular range. For example, I can find the composition of indium gallium arsenide phosphide for making light sources at 1.3 micrometer, this should be micrometer and this also micrometer; so at 1.3 micrometer and 1.55 micrometer wavelengths. So, I can find the composition of indium gallium arsenide phosphide, for making light sources at 1.3 micrometer and 1.55 micrometer wavelengths. I know and it is given that for lattice matching of indium gallium arsenide phosphide with indium phosphide x should be equal to zero point four five y and the bandgap energy of this material is given by 1.35 minus 0.72 y plus 0.12 y square in electron volts.

So, how to get the composition? So, since e g is given by this and I know that lambda g is equal to 1.24 divided by E g. So, if I want to make a source at 1.3 micrometer wavelength. So, I can find out E g corresponding to 1.3 micrometer here. So, this gives me E g is equal to 0.954 electron volt.

If I put it back into this equation this is a quadratic equation, I can solve it and get the values of y. This will give you of course, 2 values of y and you will have to discard the value which is larger than one, because y is a fraction it cannot be greater than one the other value comes out to be 0.611 and it gives you x is equal to 0.275 because x is equal to 0.45 y. So, I can have the complete composition of indium gallium arsenide phosphide for lambda g is equal to 1.3 micrometer. I can do the same for 1.55 micrometer. So, for 1.55micrometer E g will come out to be 0.8 electron volts, and this will give you the composition of indium gallium arsenide phosphide like this.

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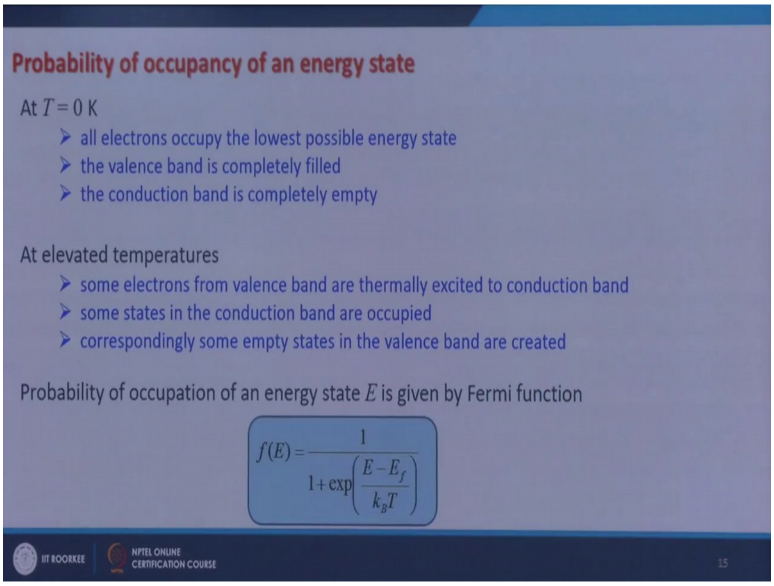

Probability of occupancy of an energy state

At $T = 0$ K

- all electrons occupy the lowest possible energy state
- the valence band is completely filled
- the conduction band is completely empty

At elevated temperatures

- some electrons from valence band are thermally excited to conduction band
- some states in the conduction band are occupied
- correspondingly some empty states in the valence band are created

Probability of occupation of an energy state E is given by Fermi function

$$f(E) = \frac{1}{1 + \exp\left(\dfrac{E - E_f}{k_B T}\right)}$$

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So, now what is the probability of occupation of an energy state, k at absolute 0 temperature, all the electrons will occupy the lowest possible energy state because they are not agitated thermally agitated.

So, the valence band would be completely filled and the conduction band is completely empty. If you elevate the temperature then some electrons from valence band are thermally excited to the conduction band, and some states in conduction bands are occupied, correspondingly you have some empty states in the valence band. Then the probability of occupation of energy state E is given by a function which is known as Fermi function and is given by f E is equal to 1 over 1 plus exponential E minus E f over k B T. This kind of statistical distribution helps us to understand the properties of a semiconductor, and electrical and optical characteristics of a semiconductor.

So, we will look into the characteristics of semiconductor and how we can make LED out of these semiconductors in the next lecture.

Thank you.