Advanced Optical Communications

Prof. R. K. Shevgaonkar
Department of Electrical Engineering
Indian Institute of Technology, Bombay

Lecture No. # 12

Optical Sources

Up till now we have been discussing the propagation of light inside an optical fiber. We studied various types of optical fibers, and how the signal propagates on these fibers, how signal get distorted on this fibers, and then from that we saw that the single mode optical fiber is the best fiber, because that can support the maximum bandwidth. Let us now discuss the another most important topic of optical communication, and that is optical sources.

We have seen in our earlier discussion that although the light is abundant in nature and there are so many sources of light, these sources are not very suitable for optical communication. And the reason was very simple that many of the sources had very large spectral width; many of the sources could not be switched on and off at a very rapid rate, so they could not be modulated. And as a result, these sources cannot be used for sending information or for carrying information in the optical form. So, before we get in to discussion on the optical sources, first let us spell out what are the characteristics we are looking for an ideal optical source for optical communication.

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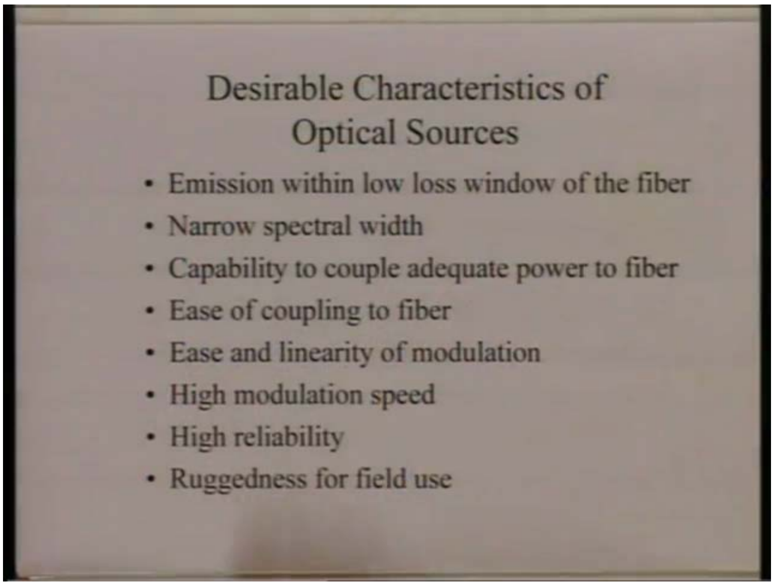

Desirable Characteristics of Optical Sources

- Emission within low loss window of the fiber
- Narrow spectral width
- Capability to couple adequate power to fiber
- Ease of coupling to fiber
- Ease and linearity of modulation
- High modulation speed
- High reliability
- Ruggedness for field use

So, here we have what is called the desirable characteristics of optical sources. We have seen that for propagation of light on optical fiber which is made of glass, there are certain windows where the attenuation is minimum. So, we could use the wavelength either around 850 nanometer or around 1310 nanometer or around 1550 nanometer.

So, as we saw earlier these windows are the first window, second window and third window of optical propagation. So, first it is important that whatever optical source we use, that must have a emission capability within the low loss window of the optical fiber. So, first we have to identify the sources which can give emission either around 1310 nanometer or around 1550 nanometer. As we have seen earlier, 850 nanometer window is not anymore in use. So, essentially we will be discussing optical sources which can give emission in 1310 nanometer or 1550 nanometer.

The second requirement of optical source is that, it should have a narrow spectral width and this is the important aspect because, we have seen that the signal distortion due to dispersion of optical fiber is directly proportional to the spectral width of the source. So, larger the spectral width, smaller will be the data transmission rate on optical fiber and as a result it is desirable that whatever optical source we identify must have as narrow spectral width as possible. In addition to that, there are many other requirements that is capability to couple adequate power to the fiber.

We may have very nice optical source, but if it is not capable of guiding enough power inside the optical fiber which is having a very small dimension, then this optical source may not be of great use to us. So, we require that whatever source we identify must be very compatible with the optical fiber. Also at the same time from practical point of view, we want that the source should be able to couple power adequately. At the same time, it should be able to couple power with great ease so that I should be able to connect or disconnect the optical source to the optical fiber multiple times without losing any efficiency of light launching inside the fiber.

Then, when we are going to modulate this optical source, we want this source to be easily modulatable; that means, I should be able to change the characteristics of light which is emitted by the source. So, we should be able to do that with ease and at the same time, if you are going to use this device for linear modulation, then the source must be a linear source. Also our prime objective here is to send high data rates on the optical fibers. So, essentially we should be able to generate light whose characteristics are changing at a very rapid rate or in other words the speed of modulation should be very high for these optical sources.

And of course, then we are having practical parameters like the source should be highly reliable, it should not be defaulted very easily and also it should be rugged in the field because, when you are going to install this components in the field they are going to see a very large temperature moisture other variations. So, all these devices must be very rugged device. So, leaving these factor which are more like practical aspects of this, even if I concentrate on these two first two ones, that is the emission, should be in a given window and it should have very narrow spectral width. I have very limited choices of optical sources.

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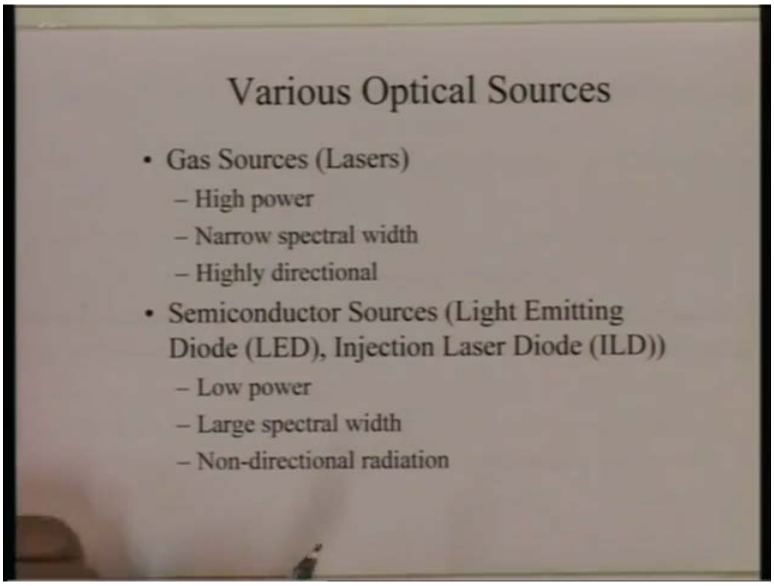

Various Optical Sources

- Gas Sources (Lasers)
  - High power
  - Narrow spectral width
  - Highly directional
- Semiconductor Sources (Light Emitting Diode (LED), Injection Laser Diode (ILD))
  - Low power
  - Large spectral width
  - Non-directional radiation

So, what do you see that from these two desirable features, we can get the optical sources which could be either gas sources which are lasers or they could be semiconductor sources, light emitting diodes or injection laser diodes. For the gas sources of course, we can get a very high power. The gas sources generally have a very narrow spectral width and gas sources are very highly directional. So, they can focus light over a very small region or in other words they can launch light very efficiently inside the optical fiber.

So, if I consider only first two aspects of the optical sources, then the gas sources may be quite appropriate because they satisfy these two criteria very satisfactorily, but if I look at other feature which are looking for an optical sources, it is should be compatible with the optical fiber. It should be also integrable with the electronic circuit which we are going to use then gas sources are not very appropriate sources for optical communication. So, generally we use the sources which are semiconductor base so that they have a integration with the electronics so, all those modulations circuits and all that which we talked, these sources are compatible with the modulation circuit.

So, essentially then our choice reduces to the semiconductor base sources and then we see that there are two sources, one is light emitting diodes what is called LED or other one is called the injection laser diode. Both are diodes, but depending upon their fabrication, their radiation characteristics change and essentially we are going to have a discussion on these two optical sources in the following lecture. So, for a semiconductor source which is a diode the power is rather limited, it can emit only small amount of power.

And later on we will see that if I take a source like LED, it can emit power of microwatts whereas, if I go to the lasers then it can emit power of milliwatts. Intrinsically, because of the nature of the semiconducting material these sources have a rather large spectral width. And as we saw that large spectral width is a rather undesirable feature, because it is direct bearing on the data rate and also these sources are not very directional sources. So, they have a also light launching efficiency problems when they are connected to the optical fibers.

But as we mentioned, considering the compatibility with the electronics and the modulation ease, essentially semiconductor base sources are the one which are most desirable and which are mostly used in the optical communication. So, now we essentially discuss the semiconductor base sources and first we have a discussion of light emitting diodes and then later on, we will see the deficiencies of light emitting diode and then we will go to the laser which is the injection laser diode.

Now, when we are discussing light emitting diode here, we are essentially asking in principle if we take a semiconducting material and if it emit light, what kind of radiation characteristics this material will have? Or in other words, what spectral characteristics the light will have, which is emitted by semiconducting material and also what is the efficiency of the light generation. So, we are asking two fundamental questions, one is the spectral characteristics of the emitted light and second is the efficiency of light generation. Before we get in to the specific questions, first let us say, if I have a semiconducting material then the material is characterized by what is called the band diagram.

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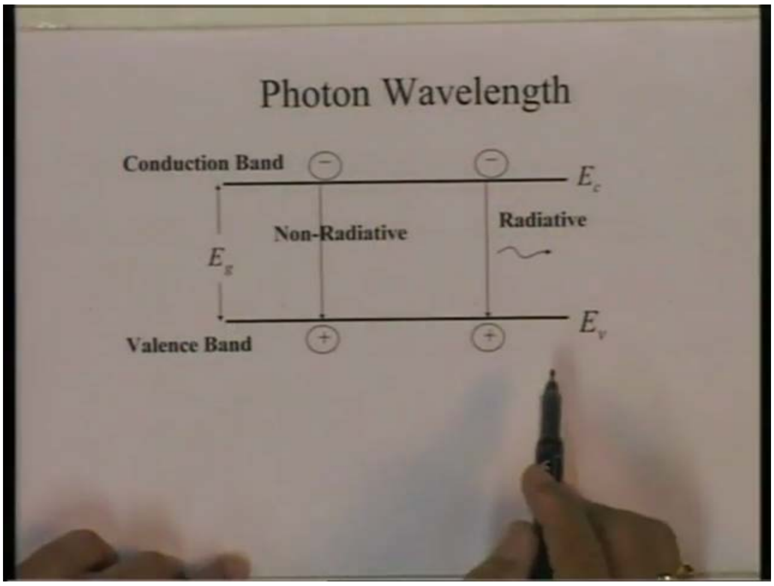

Photon Wavelength

So, if I consider a semiconducting material we have, what is called a valence band and we have a conduction band, this is what is called the forbidden band gap, which is given by energy which is E g. So, you have electrons which are in the conduction band and then you are having vacancy of electrons which we call holes, which is there at the valence band.

And these electrons and hole can recombine. And when the recombination takes place then there is a possibility that the energy difference of these two can be released in the form of a photon. So firstly, now when we are looking at light as a quantum of energy, you recall in our earlier discussion, we treated light as a ray or we treated light as an electromagnetic wave. Now when we are coming for generation of light or interaction of light with matter, we have to essentially take the quantum model of light that is the light is a collection of photons. Each photon has a energy and that energy is equal to the planks constant time the frequency of the light.

So, essentially what we are saying is, whenever this kind of recombination takes place the energy difference is released and this could be released in the form of a photon. Now there is a possibility that, whatever energy is released in this process, they may not get released in the form of a photon. It may go in to some other form and if that happens then I will not get the emission of light. So, whenever a recombination of electron hole takes place, we may get emission of photon or we may not get emission of photon.

If a photon is released, then we call that recombination process as the radiative recombination process and if the photon is not released, if the energy is gone in to some other form then we say that process is a non radiative recombination process. So, whenever we are having electrons and holes in a semiconducting material and when they recombine, part of the recombination will not produce photons and part will produce photons. The ratio of the recombination which are responsible for photon generation to the total recombination which take place is essentially what is called efficiency factor.

So, we will discuss that later that how many of the total recombination which take place, go in to radiative recombination; however, before we get in to that first, we ask if I consider a semiconducting material, will every semiconducting material give me recombination of electrons and holes and would be capable of generating photon and here we essentially divide the semiconducting material in to two categories what is called the direct band gap material and the indirect band gap material.

And this essentially we characterize by looking at the energy band diagram of the semiconducting materials in the energy momentum space. So, if I consider the energy versus momentum diagram.

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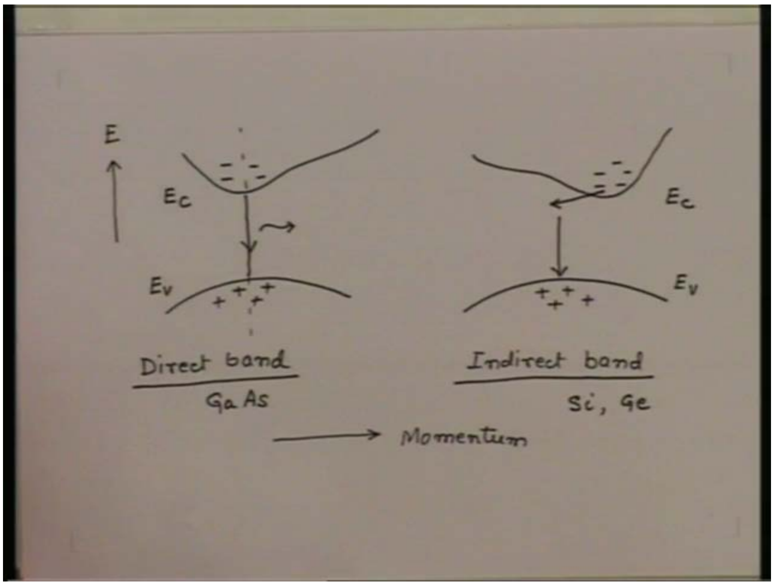

So, if I take the vertical axis is energy, and if I take the horizontal axis as the momentum, and if I draw the energies levels in the conduction and valence band, there are two possibilities, one is that the energy diagram, looks like this or where the maximum of the valence band is aligned in momentum with the bottom of the conduction band. So, this line is aligned.

The other possibility is that I may have the diagram like this, where the bottom of the conduction band is somewhere here whereas maximum of the valence band is somewhere here. So, you are having a difference in the momentum for the conduction band and the valence band. Now we are having holes which are here we are having electrons which are in the conduction band here. Similarly we have holes here and we have electrons which are in conduction band here. So, this is the energy which is the conduction band energy E c and this is the energy say this is E v. So, this is E v, this is E c.

Now in this case, when the recombination of the electron hole takes place, essentially only one process is involved and that is the energy difference of these two carriers. So, these can combine and can give you a corresponding photon out of an energy, which is equal to the difference of these two energies. This material is called as the direct band gap material. Whereas, if I go to the material which is this, where the conduction and the valence band, they are not aligned in the momentum space. Then if the recombination of the electron and hole has to take place, the two processes are involved.

Firstly, that electron whatever is the momentum difference between electron and hole that should be conserved. So, the momentum has to be released and then whatever is the energy difference between these two that should be released in the form of a photon. So, recombination in this phase is equivalent to saying that, we have one process like this, where momentum is released and other process is like this where the energy is released. So, since we are having two processes involved, the probability of two processes taking place simultaneously is much smaller than simply the probability of recombining, when only one process was involved which is this process.

This recombination probability in generation of photon is much smaller than generation of photon in this process. So, if I consider a material which is indirect band material then by injecting electrons and holes, the recombination probability for generation of photon is much smaller than if I consider a direct band material where electrons and holes can recombine easily and can give you a photon out. So, first requirement now for generation of light is that we have to identify the material semiconducting material which is of direct band nature.

Intrinsically, if you look at the materials, we have material like silicon or germanium which are used for electronics, but silicon and germanium both these materials are indirect band gap material. So, both of these material are essentially indirect band gap. What that means is that, if I make a device out of silicon then probability of generation of light by this device is extremely small. So, I cannot make a light emitting diode or a light emitting source by using a material like silicon or germanium.

So, we want to essentially look for materials which are of direct band nature and the most thoroughly investigated material which has direct band nature is the gallium arsenide. So, we have this alloy which is gallium arsenide, which has a direct band nature and that is the reason it has a high efficiency of photon generation. Later on you will see that there are many alloys of type three and type five materials which are capable of generating light because they have a direct band gap nature. So, from this discussion essentially first we conclude that for making light emitting device we have, to identify a proper material, which is of direct band nature. Having done that, then the next question arises that for a direct band material what will be the wavelength of the light emitted.

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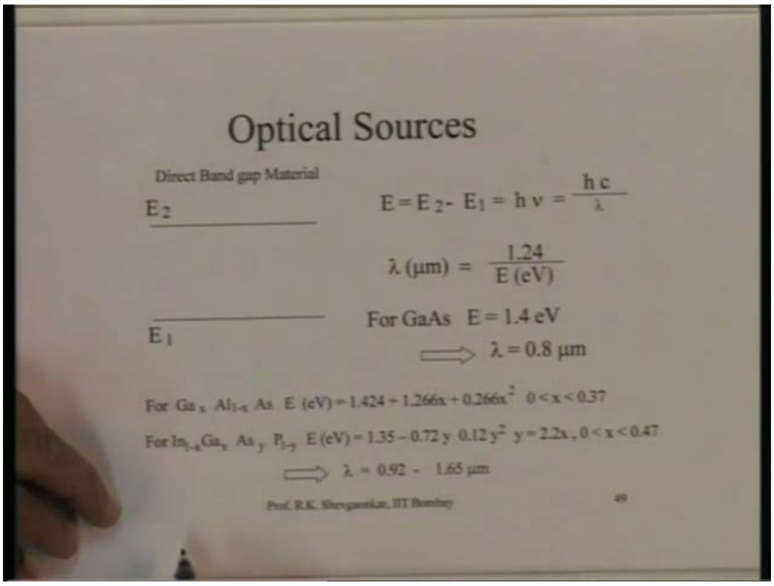

Optical Sources

Direct Band gap Material

E_2

E_1

$E = E_2 - E_1 = h\nu = \frac{hc}{\lambda}$

$\lambda\,(\mu m) = \frac{1.24}{E\,(eV)}$

For GaAs $E = 1.4$ eV

$\Longrightarrow \lambda = 0.8\ \mu m$

For $Ga_x\,Al_{1-x}\,As$ $E\,(eV) = 1.424 + 1.266x + 0.266x^2$ $0 < x < 0.37$

For $In_{1-x}Ga_x\,As_y\,P_{1-y}$ $E\,(eV) = 1.35 - 0.72\,y\ 0.12\,y^2$ $y = 2.2x,\ 0 < x < 0.47$

$\Longrightarrow \lambda = 0.92 - 1.65\ \mu m$

Prof. R.K. Shevgaonkar, IIT Bombay

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So, let us consider two energy levels, let us say you having energy level E 1 here and E 2 here and for semiconducting material this will be very close to E v, the energy in the valence band. Whereas, in the conduction band E 2 will be very close to E c, the conduction band, but in general we can say that if you are having two energy levels and if the recombination takes place between these two energy levels then the difference between these two energies, E 2 minus E 1 is released in the form of a photon and that frequency of the photon is nu than the energy E 2 minus E 1 is equal to h into nu where h is the planks constant and nu is the frequency of the photon.

Since we are dealing with light normally we use the wavelength in optical communication. So, I can write frequency as the velocity of light c divide by the wavelength. So, the energy difference between the two levels or the energy between photon, which is released that is equal to h into c divide by lambda. Now h is the planks constant which is the universal constant, c is velocity of light in vacuum even that is the universal constant. So, we can combine these two together to essentially get constant and then if we use appropriate units, we can get the wavelength lambda in micrometer that is equal to 1.24 divided by the energy of a photon measured in electron volts.

So, if I know the energy difference between the two levels in the electron volts, then very easily I can calculate the wavelength of emission by using this formula. So, if I take the material gallium arsenide which I said has been extensively investigated. The band gap for the gallium arsenide is 1.4 e V. Say if, I substitute 1.4 e V in to this formula, I get the wavelength of emission which is approximately 0.8 micrometer or 800 nanometer. So, you recall when we started discussion on optical communication, we had seen that the process which became available for optical communication had a emission at around 800 nanometer.

And that was because the material which was investigated that time was gallium arsenide. So, in the first generation optical communication systems, the optical fiber had a window relatively low loss window and on 800 nanometer and the sources which were gallium arsenide base had a capability of emitting light at 800 nanometer. So, the optical communication started around 800 nanometer. So, if I use the material gallium arsenide, then intrinsically we will get emission of light in 800 nanometer window.

However as I mentioned earlier, we now look for emission in the window which around 1310 nanometer or 1550 nanometer. So, instead of using simple gallium arsenide, essentially we use what are called the ternary materials, which is a combination of gallium, aluminum and arsenic or indium gallium and arsenic and by mixing them in different proportions essentially the band gap of the material is manipulated. Also for different value of this air mole fraction in which these materials are combined, the material becomes direct band gap or indirect band gap.

So what is shown is that, if you use the value of x between 0 and 0.37 for this material which is gallium, aluminum, arsenic, then the energy of the band is approximately given by this. This is more like a empirical relation and for this value of x, the material is a direct band gap material. Similarly, if I use this ternary material which is indium, gallium, arsenic and also phosphorous, then this is a quaternary material, then again by using the value of x and y, you can manipulate the energy levels and then you can get now the wavelength which can range from 0.92 micrometer to 1.65 micrometer or about 920 nanometer to about 1650 nanometer.

So, you see by using a combination of these materials essentially one can get emission at any desired wavelength, about 1000 nanometer to about 1650 nanometer and that is the window which is of our interest because all our wavelengths lie from 1300 nanometer to about 1600, 1700 nanometer. So, about today's optical devices, essentially the materials which will be used, they will be of this quaternary nature. And then by changing the proportion of their constituents essentially, one can manipulate the band gap of the material and correspondingly one can manipulate the frequency of emission of the light.

So, having now identified the material and then making the electron and hole combine inside the material. Now we say that, we can generate light and let us not worry at the moment, the efficiency aspect. That is how many of these combinations will go in to radiative or non radiative process. Let us say, once the material is direct band gap material, every electron hole pair which is going to recombine is going to produce a photon. Later on we will see that, if every combination does not give you a photon, then we have to account for a non radiative recombination and then the efficiency will be calculated.

So, at the moment let us not worry about the efficiency. Let us simply ask a very basic question, that for a semiconducting material if electron holes recombine, what kind of emission will be delivered by this device?

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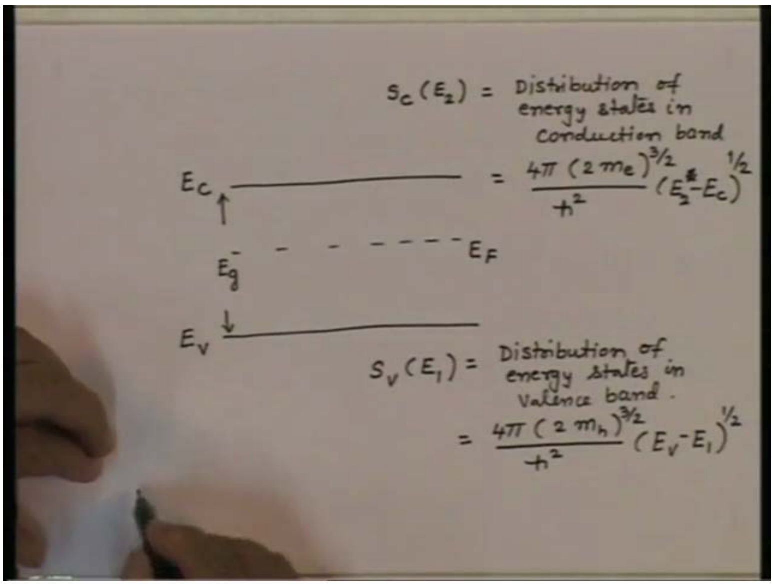

$S_c(E_2)$ = Distribution of energy states in conduction band

$= \frac{4\pi (2m_e)^{3/2}}{h^2} (E_2-E_c)^{1/2}$

$S_v(E_1)$ = Distribution of energy states in valence band.

$= \frac{4\pi (2m_h)^{3/2}}{h^2} (E_v-E_1)^{1/2}$

To ask the question little deeper sense although, we are saying that the semiconducting material is characterized by the band gap. And let us say this is the valence band which is E v this is the conduction band which is E c and the band gap is given by E g. The electrons and holes are not sitting on the edge of this band gaps.

Essentially we have a distribution of electrons and distribution of holes in the conduction and the valence band. And then any electron in the conduction band can recombine with any hole in the valence band. So, what we are saying is there is no preference of any particular electron in the conduction band getting combined with a particular hole in the valence band. So, once the electrons and holes are given, there is a equal probability of any electron getting recombined with any hole.

With that assumption there, one can ask a question, if there is a distribution of electrons in the conduction band and distribution of holes in the valence band and if any electron can recombine with any hole. What kind of spectral distribution we would expect from the semiconducting material? Now having a electron in the conduction band will depend upon two things, one is whether there you are having a energy level present corresponding to that energy. Secondly, even if energy level is present whether the energy level is occupied by an electron; so essentially if you ask what is the density of electrons in the conduction band, they will depend upon two things, one is the energy density function in the conduction band for electrons and the occupancy of the energy level by electron. So, essentially we have two functions one is the energy density function and other one is the occupancy function of the energy level by an electron. Similarly, when I go to the valence band whether you have a hole in the valence band, will depend upon the energy density function inside the valence band and absence of electron in that energy level.

Once you are having these two distributions for electrons in the conduction band and holes in the valence band, there one can have a probability of recombination and from there essentially we get probability of photon generation. So what we are saying now is that, first write down the electron densities inside the conduction band, the hole densities inside the valence band and then the probability of photon generation will be proportional to product of these two densities because any electron can combine with any hole with equal probability.

So essentially what we are saying is that, we have let us say a function called S c is the energy density function and let us say all the energy which are representing in the conduction band are given by 2. So, this is the distribution of energy states in conduction band, this is given as 4 pi 2 into m e which is the mass of the electron divided by h square where h is the planks constant into E square minus E c or E 2 minus E c whole square. Similarly, I can get the distribution of energy states in the valence band.

So, let us say that is given by S v and let us say the energy is in the valence band are denoted by E 1. So, S v E 1 will be distribution of energy states in valence band and that is given by 4 phi 2 times m h, which is the effective mass of the hole to the power 3 by 2 divided by h square into E v minus E 1 to the power half, this should be E to the power half whole square. So, essentially we are having the energy density, which are distributed in the conduction band and the valence band.

And what we see from here is that, when E 2 is equal to E c this quantity is 0 and when E 2 becomes higher and higher essentially, the density of states increases. So, you have no energy states just on the edge of the conduction band and as I go deeper inside the conduction band the energy states increase and they increase rather slowly because this function is only a square root function. So, gradually they density of the energy states increases as you go inside the conduction band.

Similar thing happens when I go inside the valence band that the density of the energy states on the edge of the valence band is 0 and as we go deep inside the valence band, again the density of the energy states increases. Next thing now is that, once the energy state is given then what is the probability that a particular energy state has been occupied by an electron. And that essentially is given by the Fermi distribution. So, if I know the Fermi level then, I can find out the probability that a particular energy level is occupied by an electron.

So, let us say if a Fermi energy level is given by this E F and if you take a intrinsic semiconducting material then the Fermi level is midway between the conduction and the valence band, then I can get the Fermi distribution F of E which is equal to1 upon 1 plus e to the power E minus E F, where E is the Fermi energy divided by k T where k is the Boltzmann constant and t is the absolute temperature. So, to find now the availability of electron in the conduction band, we have to take essentially product of these two because this is telling me the availability of energy state and this function is telling me the occupancy of the energy state.

So, if I take product of these two then that will tell me the probability of having an electron at that energy which is E 2. Similarly, when I go inside the valence band then the Fermi function gives me the occupancy of the state. So, if I take 1 minus F E that will give me the probability of that state not occupied by the electron or presence of the hole. So, if I take a product of this function and one minus F E inside the valence band then that gives me the probability of having a hole at that energy level. Then I can take a product of these two and find out the probability of the photon generation. Now, before I do in to that. Firstly, I have to make now the electrons and hole available for recombination.

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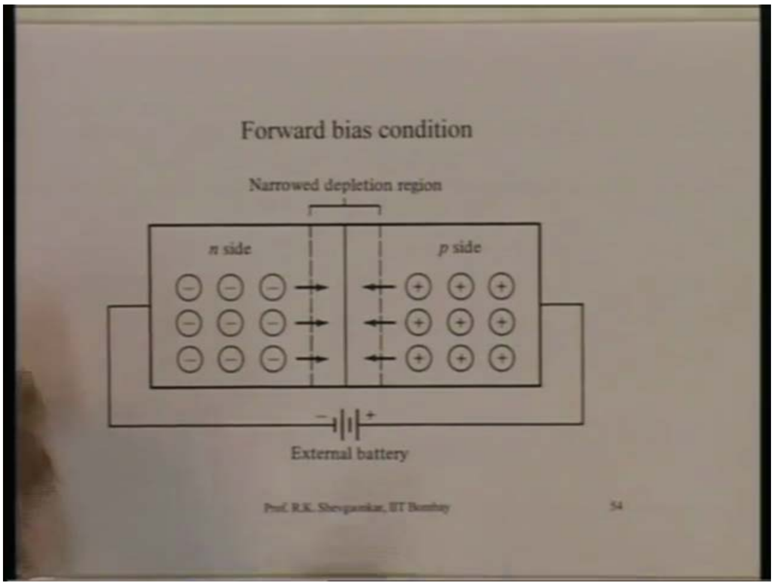

Forward bias condition

Prof. R.K. Shevgaonkar, IIT Bombay

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And the easiest way of doing that is, essentially creating what is called a p n junction and if the p n junction is forward bias. Then the electrons and holes are injected in to the depletion region, they recombine in the depletion region. And the recombination of the electrons and holes will take place and then that may produce the photons. So, essentially for making a p n junction, first you have to make a material which is doped with p type impurities, you have to make a material which is doped with n type impurities and then you have to make a junction out of it.

And as we know when the material is doped with these impurities the Fermi level shifts. See, if I take a n type material then the Fermi level is very close to the conduction band; whereas, if I take the p type material then the fermi level will be very close to the valence band.

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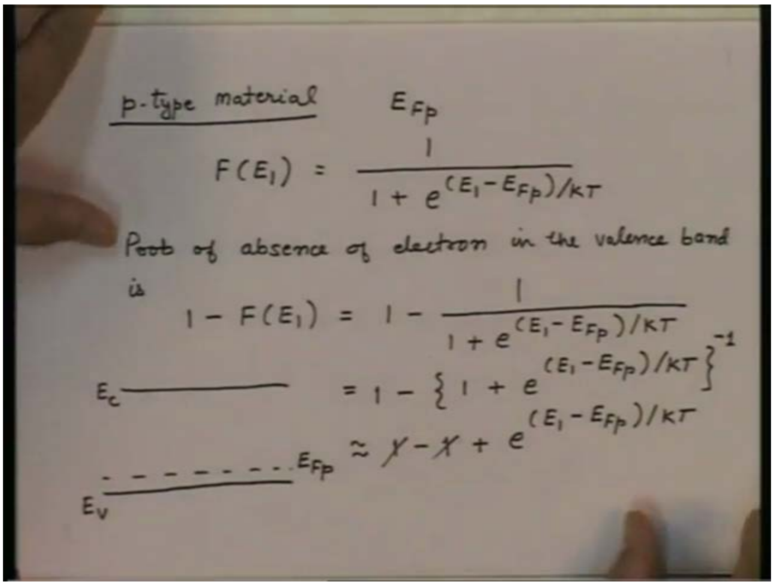

p-type material E_{Fp}

$$F(E_1) = \frac{1}{1 + e^{(E_1 - E_{Fp})/kT}}$$

Prob of absence of electron in the valence band is

$$1 - F(E_1) = 1 - \frac{1}{1 + e^{(E_1 - E_{Fp})/kT}}$$

$$= 1 - \left\{1 + e^{(E_1 - E_{Fp})/kT}\right\}^{-1}$$

$$\approx \cancel{1} - \cancel{1} + e^{(E_1 - E_{Fp})/kT}$$

So, let us say I take the p type material and let us say the Fermi level for this is given as E F p, then the occupancy of the energy level in the valence band is given by F of E 1 will be equal to 1 upon 1 plus e to the power E 1 minus E F p divided by K T. But we are looking for a probability of non occupancy, because we are looking for the availability of a hole for a given energy. So, we are looking for a function which is 1 minus F E 1. So, we say probability of absence of electron in the valence band is 1 minus F of E 1 that is equal to one minus one upon one plus e to the power E 1 minus E Fp divided by K T. Now notice here that the material is not very heavily doped the Fermi level is shifted towards the valence band, but still the energy which you are talking about the E 1 they are much smaller compared to this quantity.

So, what we are saying is, if I consider the semiconducting material which is type this is E c this is E v and the Fermi level is shifted here, which is close to the conduction band or valence band E Fp . So since, E 1 is much smaller compared to this quantity, here you see that this quantity is much smaller compared to 1. So, I can make an approximation that this is a small quantity. So, I can say this is one plus this small quantity to the power minus 1 which can be expanded and can be retained only the first order terms.

So, you get 1 minus 1 plus e to the power E 1 minus E Fp divided by k T to the power minus 1 since this quantity is very small and if I retain only the first order term, this is approximately you can write as 1 minus 1, this minus 1 will come here, this will become plus. So, this is plus e to the power E 1 minus E Fp divided by k T, this will cancel. So, essentially we have the probability of absence of an electron or probability of having a hole with energy E 1 that is essentially given by this quantity.

Similar exercise now we can do for the conduction band also or in the n type material.

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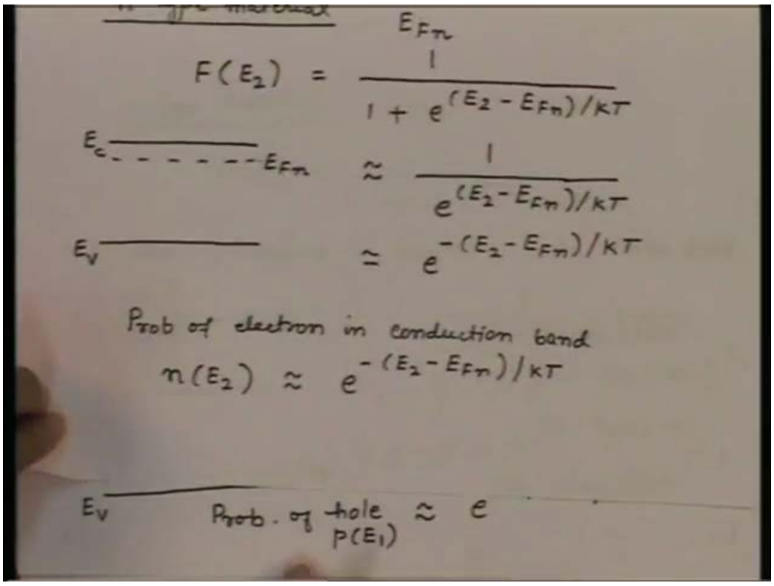

E_{Fn}

$$F(E_2) = \frac{1}{1 + e^{(E_2 - E_{Fn})/KT}}$$

$$\approx \frac{1}{e^{(E_2 - E_{Fn})/KT}}$$

$$\simeq e^{-(E_2 - E_{Fn})/KT}$$

Prob of electron in conduction band

$$n(E_2) \approx e^{-(E_2 - E_{Fn})/KT}$$

Prob. of hole $p(E_1)$ $\approx e$

So, if I consider now the n type material and let us say for n type material, the fermi level is given by E Fn. So, the fermi function in the conduction band and here the energies are denoted by E 2 that will be equal to 1 upon 1 plus e to the power E 2 minus E Fn divided by K T, again saying that for this material now the Fermi level is shifted closer to the conduction band E c there is E v the Fermi level is somewhere here.

But still the energy which we are having which are in the conduction band are much larger compared to E Fn, this quantity is a positive quantity and much greater than 1. So, we can say that this quantity is much greater than 1. So, we can neglect 1 in this case approximately. So, we can say that in this case approximately you have a function which is one upon e to the power E 2 minus E Fn divided by K T or I can bring it to the numerator. So, this will be e to the power minus E 2 minus E Fn divided by K T.

This is now nothing, but the probability of electron being present in the energy level E 2. Now, as we earlier said that essentially now the presence of electron is given by the probability of this distribution function and the occupancy function which is given by the

Fermi distribution. However, assuming that this function is a very slowly varying function of energy this is only going as a square root. Let us assume that this function is practically constant in a region where the recombination takes place.

So, you are having certain energy levels here, certain energy levels here. The recombination is going to take place on electrons and holes. So, let us assume that this function is not varying very rapidly which is the energy density function. Only the Fermi distribution or the availability of electron or absence of electron in a valence band which is presence of hole, that is the one which is dominating this recombination process. So, for simplicity what we can do is we can assume that although there is a variation of the density of energy states inside the conduction and valence band for a very simple analysis, we can assume that the density states are uniformly distributed inside the conduction and valence band.

If that happens then essentially the probability of a photon generation will be product of these two quantities which is this quantity here and this quantity here. So, let us say probability of having electron which is given, is denoted by probability of electron in conduction band. Let us denote that by n E 2 that is approximately given by e to the power minus E 2 minus E Fn divided by K T and probability of having a hole in the valence band is approximately given as e to the power of e 1.

So, let us say this is you call it p of E 1, E 1 minus E Fp divided by K T. So, I have now the probability of electrons in the conduction band, I have probability of hole in the valence band. And then if I say that any electron can recombine with any hole to give you the photon out than the probability of photon generation will be product of these two.

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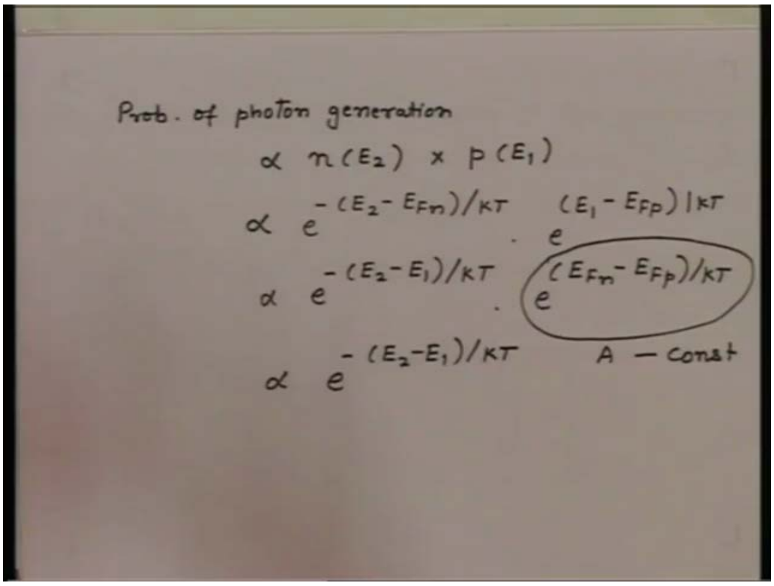

Prob. of photon generation

$$\propto n(E_2) \times p(E_1)$$

$$\propto e^{-(E_2 - E_{Fn})/KT} \cdot e^{(E_1 - E_{Fp})/KT}$$

$$\propto e^{-(E_2 - E_1)/KT} \cdot \boxed{e^{(E_{Fn} - E_{Fp})/KT}}$$

A — const

$$\propto e^{-(E_2 - E_1)/KT}$$

So, we have probability of photon generation will be proportional to n of E 2 multiplied by p of E 1. Say if, I substitute this now, this quantity and E 2 and E 1, essentially we get is proportional to e to the power minus E 2 minus E Fn divided by K T multiplied by e to the power of E 1 minus E Fp divided by K T.

I can rearrange this to write that e to the power minus E 2 minus E 1 divided by K T multiplied by e to the power of E Fn minus E Fp divided by K T, for a given doping this quantity is constant. So we can say, let us say this, quantity is some constant which is given as A. So, the probability of photon generation for a given doping concentration is essentially proportional to this quantity here. So, you have here proportionality this is A is constant proportional to e to the power minus E 2 minus E 1 by K t.

Now, if you want to find out the total number of photons which are going to be generated essentially we have to integrate now in the conduction and valence band and that will essentially give us the spectral distribution. So, what we are saying is, if I consider now that any electron can recombine with equal probability with any hole then just check that electron hole pair and find out all possible electron hole pair which will having the same energy difference and that essentially will give you total number of photons which will be generated for a given frequency or given energy.

So, we will continue with this and next time when we meet, essentially we take this expression here integrate over the energies in the conduction and the valence band. And then from there we find out the relative photon number which will be generated by recombination of electrons and holes in the semiconducting material. And that will give us essentially the spectral distribution of the optical source created out of a semiconducting material.