Optoelectronic Materials and Devices
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Module - 3
Optoelectronic Device Physics
Lecture - 21
Carrier recombination-generation-I band-to-band transitions

Greetings, today we talk about information age. What is this information age? In other words you can talk about it is an age of electronic devices. Today, you cannot find a person who is not using one or another kind of electronic device in daily life. If you look at that in respect of materials world you can also talk about it as silicon age.

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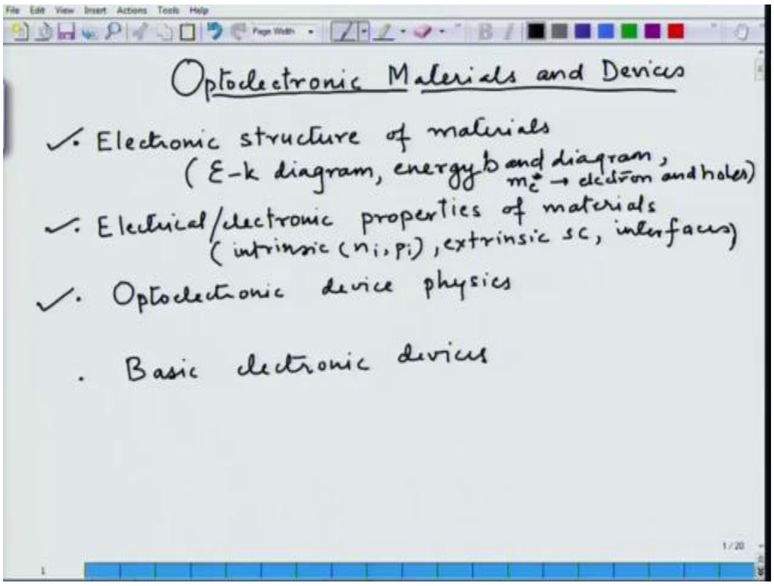

Optoelectronic Materials and Devices

- ✓ Electronic structure of materials
  (E-k diagram, energy band diagram, $m_e^* \rightarrow$ electron and holes)
- ✓ Electrical/electronic properties of materials
  (intrinsic (n_i, p_i), extrinsic sc, interfaces)
- ✓ Optoelectronic device physics
- Basic electronic devices

For last 40, 50 years one can think of advent of electronics and then devices in telecommunications and it is all because of this electronic devices. So, this course is an attempt of trying to bring to you the basic concepts of physics and engineering of a electronic devices. So, far in the course you have looked at electronic structure of materials where you have seen how we can think of electrons in a material, what are the, what is the energy structure or electronic structure of a material.

This you have learned in terms of the E k diagram and this gave you the framework to think about electrons in the material. From there you can, you learnt about energy band diagram and this lead to a very important concept in solid state devices which is related to the effective mass of electrons and the concept of electrons and holes based on the electron dynamics of electrons in the, in each band. Then further from that particular framework of electronic structure in the material what you have done in the next module is about the properties of different materials, metals, semiconductors, dielectrics based on this electronic structure.

Then specifically we went into detail of semiconductor properties, intrinsic semiconductors, calculation of carrier concentration in intrinsic semiconductor, looking at n i, p i; looked at extrinsic semiconductor and how we calculate the equilibrium carrier concentration in these devices. Finally, we also looked at interfaces of different materials based on this electronic structure. Basically, when we bring two materials together based on this electronic structure how do these material align with each other and that is kind of a heart of all electronic devices to some extent.

And then finally, that led to the third module for this course which is if I look at the material in equilibrium and I know the equilibrium carrier concentration, electrons in conduction band, holes in valence band that is not very interesting because material is in equilibrium; that is a charge neutrality condition, nothing is happening. So, when I want to use these materials in some sort of electronic device what is more important is what happens in non equilibrium.

And that is why the third module of this course was dedicated to optoelectronic device physics. And so today we will talk about these optoelectronic device physics, the kind of processes which occur in the non equilibrium situation which then will be used in making some basic electronic devices. So, what happens? In the equilibrium situation in our picture from earlier modules we know in equilibrium situation you have a equilibrium concentration of electrons and holes.

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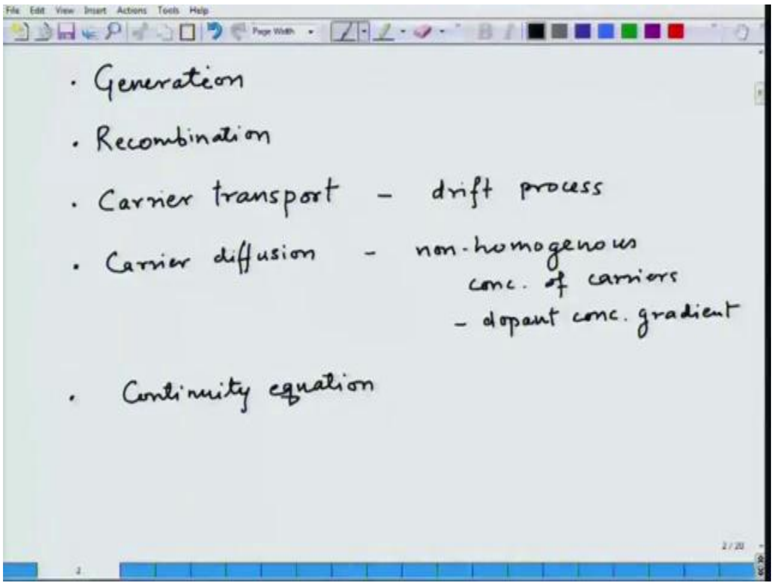

- Generation
- Recombination
- Carrier transport - drift process
- Carrier diffusion - non-homogenous conc. of carriers
  - dopant conc. gradient
- Continuity equation

But if I want to change this concentration which means I will have to generate electrons and holes. So, generation is one process. So, generation by definition is any process by which I am going to create electrons and in the conduction band and holes in the valence band. And then we will define it further what exactly that means. Then what else can I do? I have a equilibrium concentration of electron and holes and I do something’s to reduce that concentration. So, the next process is called recombination which basically removes electrons and holes from a conduction and valence band. So, a electron from the conduction band can recombine with the hole from a, from the valence band and get annihilated.

So, the two carriers are removed from the material. So, any process which leads to that removal of electrons and holes is recombination. Next, the process which is important is if electrons and holes are there and these are charged carriers what will happen if I apply a field? So, what is important is the carrier transport. So, on to a given material if I apply a field what will happen to these electrons and holes? In the field of semiconductor this is referred as drift process. Something else that can happen is because in the semiconductor processing we can control the concentration of dopants in the spatial dimensions and that means that we have a way of changing the spatial concentration of dopant in the material.

Now, this leads to a non homogeneous material. So, far in the earlier modules you have been looking at the properties of a completely homogeneous material and looking at a equilibrium carrier concentration based on that. But if I have a way of making it non equilibrium or introducing a carrier concentration gradient then that would further lead to a process of carrier diffusion which is also a transport process, but not due to the field. But it is being generated because of non homogeneous concentration of carriers and one way of doing that non homogeneous concentration is to introduce dopant concentration gradient.

In a device there are of course, other ways and means of creating this non homogeneous carrier concentration when we have interfaces of two materials, by changing the bias or the electrical field that we apply to the device we can inject access carrier at a certain place and that also creates the non homogeneity. But we will do those special cases later in the next module. And then finally, we will look at all these processes of generation, recombination and how carriers both electrons and hole are transported in the material due to the electric field which is a drift process or due to gradient in the carrier concentration which is the diffusion process. And if you bring all these four things together we can write something which is called as a continuity equation.

Continuity equation is very similar to what many of you from material science background may have seen in heat and mass transport courses. In this case we are talking about transport of carriers, there you talk about transport of mass or transport of heat, but it is basically at any point if I know the generation, if I know the recombination, if I know what is the rate of transport then at any point I can write a equation on how the carrier concentration is changing with time with the given boundary conditions. So, continuity equations for carriers are very similar to continuity equations in other fluid flow topics.

So, this is how we will generate our framework for understanding the devices. Once, we have a continuity equation I can take any device structure, understand the condition at which it is operating, look at the equilibrium structure and then when I apply a bias what happens to this structure. So, if you understand all these five processes then I can analyze any particular device that I have which will be done in the last module. So, let us look at the process of generation

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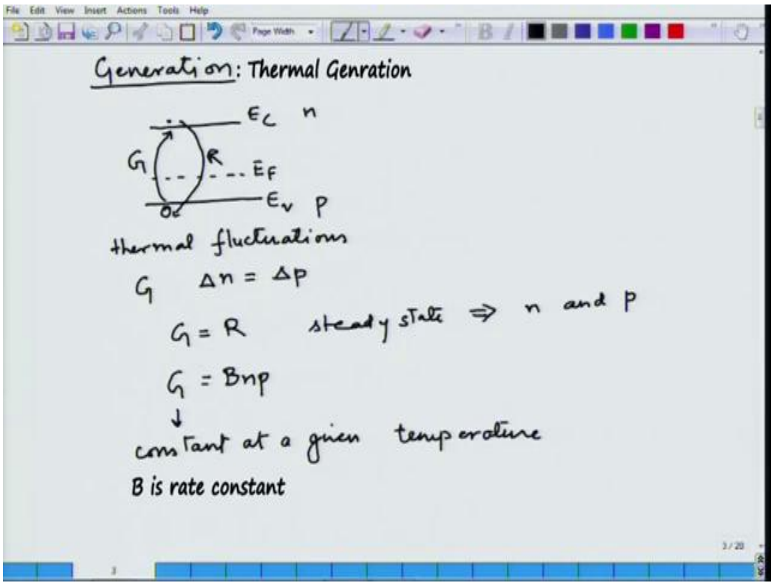

Generation: Thermal Genration

thermal fluctuations

G $\Delta n = \Delta p$

$G = R$ steady state ⇒ n and p

$G = Bnp$

↓

constant at a given temperature

B is rate constant

Yes, so in the generation process we look at equilibrium concentration in a semiconductor. In this case we have the concentration of holes in the valence band and of electrons in the conduction band. In concentration of holes let us say in the valence band is p for electrons, in the conduction band is n and we can assume that this is slightly p type semiconductor and the Fermi level is closer to the valence band h. Now, this we have done earlier in one of the modules, but I will repeat that discussion here because what is happening is that a electron in the valence band due to thermal fluctuations will go to the conduction band.

And in the process it will leave a hole in the valence band and this is the generation process. And this is happening only due to thermal fluctuations. As you can see that in this process and if I give the generation rate the symbol G, I am always creating same number of extra electrons as same number of extra holes because the process is taking a electron from the valence band and taking it up to the conduction band and in the same process it creates one electron and one hole.

So, the numbers are always equal in a thermal, thermal generation of carriers in this case. But we know in equilibrium that n and p is a constant, we know this from earlier which means that there must be another process which we will do later, which allows this electron to recombine with this hole and this is the recombination process which the symbol is given as R. So, this is a thermal generation process and this is a recombination process and in equilibrium this generation has to be equal to the recombination rate. In this case you will have the steady state situation and this steady state defines the equilibrium n and p concentration.

So, earlier we looked at it all from the point of view of electronic structure and distribution and calculated n and p by looking at the Fermi level and how the electrons and holes are distributed, but one can also look at, look at the same equilibrium electron and hole concentration in terms of a balance of the generation and recombination process due to thermal fluctuations leading to a equilibrium n and p concentration. Generation rate here is completely dependent on the temperature of the sample. It is not dependent on anything else, the fluctuation decide the generation rate.

So, it is kind of taken as a (( )) for a given temperature. This is a constant at a given temperature while recombination will depend on rate constant and how many number of electrons and holes I have in the equilibrium condition. So, this would be the general equation for equilibrium condition when the generation is only due to the thermal fluctuations. Now, then this is not the only way we can create electron and holes in the semiconductor and the more interesting way which are important for devices is by optical means.

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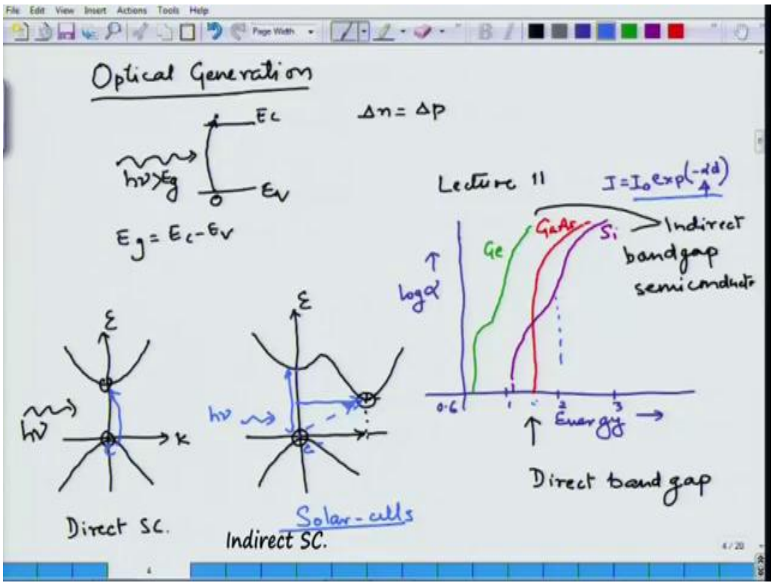

So, one can have optical generation of electron and holes and in this what we have is semiconductor. And the for clarity I am not writing the Fermi level every time, but if I have a semiconductor on which I am shining a light of wave length h nu then if this lights wave length is energy h nu, energy such that it is greater than the band gap of the semiconductor E g. So, band gap of the semiconductor is E g which is E c minus E v. In that case a electron can absorb this energy and can be promoted to the conduction band.

And this will lead to creation of a electron in the conduction band and a hole in the valence band. And again in this process of optical generation as you can see the number of excess electrons you create will always be equal to number of access holes created because a photon absorbed creates one electron and one hole as long as the energy of that particular photon is greater than the band gap. Now, this process also has certain technical details which I would review although you have done it in the lecture 11.

So, more details about optical absorption can be seen in lecture 11, but I will do a bit of review for the sake of completion here. Now, optical generation is dependent on the material. So for example, if I take different kind of semiconducting material and I plot log of absorption coefficient alpha and to remind you what is absorption coefficient if I have intensity of light I naught shining on a material of thickness d then after passing through the thickness d I would have absorbed some of that light into the material and that is decided by the absorption coefficient of that material.

So, if I plot log of the absorption coefficient versus energy on the x axis then I can distinguish different kind of semiconductors by the by their optical generation processes and here I can make a scale for some common semiconductors. So, if I have a gallium arsenide then I would find that gallium arsenide which has a band gap of close to around 1.4, it has a absorption coefficient which increases and then it plateaus that is absorption coefficient increases in this manner. On the other hand if I have silicon than which, whose band gap is around 1.1, absorption coefficient is a small initially. Then at certain value it increases rapidly and becomes similar to gallium arsenide. This is silicon, this is gallium arsenide.

I can take one more example. Let me take germanium which is around 0.67 band gap the absorption coefficient increases, small in the beginning and then again it also increases rapidly later, becoming saturated at closer values to gallium arsenide this is for germanium. And you all understand this with respect to the electronic structure of the material that the significant difference in the electronic structure of germanium, silicon and of gallium arsenide. The way we understand that is gallium arsenide is a direct band gap semiconductor while silicon and germanium are both indirect band gap semiconductor. And the difference in the behavior comes from the E k diagram.

The E k diagram of a direct band gap semiconductor has the maxima of the valence band aligning with the minimum of the conduction band. This is for a electronic structure of a direct band gap semiconductor. On the other hand if you have a indirect band gap semiconductor which is a case for silicon and germanium what we find is this is the energy scale. The E k diagram where the maxima of the valence band does not really occur at the same k value as the minima of the conduction band.

So, the difference in and the, in this value of maxima and minima of the valence band and the conduction band is what leads to the behavior, different absorption behavior of these semiconductors. This has been explained earlier. I will just briefly say what happens here is that when I shine light of a wave length equivalent to energy which is higher than the band gap then I am able to excite an electron across the band gap to the conduction band there by immediately absorbing that.

In this process of absorbing the light the electrons momentum, the crystal momentum does not change and it can absorb the light and go to the conduction band and the process is very efficient and hence in gallium arsenide have a very large absorption coefficient. On the other hand when I try to absorb the same light which is higher than the band gap of this indirect band gap semiconductor, this electron can absorb the light, but it has no wave because the momentum of the photon, the photon which is coming in or of the electrons they are all both small.

So, they, it has no way of changing its crystal momentum. It needs to go from this value of same momentum to the momentum of the minimum of conduction band. And for that it requires assistance of a third particle for non or thermal vibrations in this case which have very small amount of energy, but large amount of momentum difference and that process of a photon, a electron in the valence band and the phonon interacting together then leads to absorption in the case of indirect band gap semiconductor.

And hence at the value of the band gap if I take the case of silicon the absorption coefficient initially is very small, but as soon I reach the point where the energy is about the point where I do not need any change in the momentum in order to go from the valence band to the conduction band; at that point again then absorption coefficient increases the way it would have in the case of direct band gap semiconductor. Now, this is a optical generation process and it is very important. Why is it important, because a very important electronic device namely solar cell depends on this particular phenomena. In the solar cell the semiconducting material is chosen such that it will absorb all of the solar spectrum and then by absorbing that light it creates electron and hole pairs and we can then manipulate those electrons and holes such that we can generate power using these materials. Now, as you can see if I, if I use gallium arsenide the absorption coefficient is very large.

I will be able to absorb light of wave length which is higher than the bad gap of the semiconductor. If I use silicon I can still absorb light, but it might take thicker amount of silicon. Remember, in this equation here what we have is we have intensity exponential minus alpha d, so if I, if I want to absorb all the incident light on a solar cell either my alpha should be very large or my thickness should be very large. So, if I have a gallium arsenide device whose alpha is large for wave lengths closer to the, to the band gap of the gallium arsenide I need thinner, thinner amount of material, but if I have silicon and germanium for the same absorption percentage I would require much thicker material layer. So, both materials can be used for making solar cells whether indirect or direct band gap semiconductors except one will have to know exactly how thick should be the material layer in order to absorb most of the solar light. So, this is a second process by which I can generate excess carriers and then use them later in a device.

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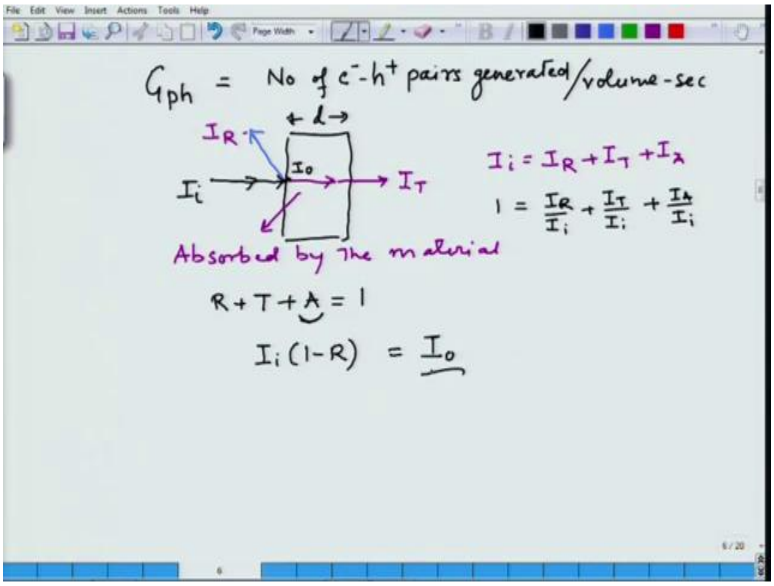

G_{ph} = No of $e^- - h^+$ pairs generated/volume-sec

Absorbed by the material

$$I_i = I_R + I_T + I_A$$

$$1 = \frac{I_R}{I_i} + \frac{I_T}{I_i} + \frac{I_A}{I_i}$$

$$R + T + \underbrace{A} = 1$$

$$I_i(1-R) = \underline{I_0}$$

So, what is this optical generation rate? Let us call it G p h, optical generation rate is basically number of electron hole pairs and I am calling number of electron hole pairs because I already said that in case of optical generation we create same number of electrons as number of holes because of this absorption process which takes the electrons from the valence band and it takes to the conduction band.

So, number of electron hole pairs generated due to the light per unit volume, per unit time let us say second. So, this is what we want to figure out. What is this optical generation rate is. In order to get to this we first need to figure out how many light photons are absorbed in the material and then we know that each light photon absorbed will result into a one electron hole pair.

So, let us start looking at a example, if this is my semiconductor let us say the dimension in this direction is d and I am making a two dimensional picture, the third dimension for this discussion one can assume infinite and it is not that important and if I have a light shining on this material with intensity, incident intensity E i than what happens at the interface of this material is that the intensity which is coming some of it is going to be reflected back. And that is let us say call it intensity I R, rest of it is going to continue inside the material and then later come out. Let us call that intensity transmitted.

In the process when it is the light is travelling inside the material it is being absorbed by the material. So, we can think of the total intensity which is coming in is divided into one which is reflected plus the one which is transmitted plus the amount which is absorbed by the material or another way of writing the same thing is to normalize it with respect to the incident intensity E i and write that 1 divided by E i is equal to the reflected intensity plus the transmitted from the slab plus the amount that is absorbed in the material. Now, notation for all these coefficient is normally given as reflectance R transmission, absorption (( )) of the material is equal to 1.

So, when we are talking about generation of electron hole pairs it is this absorption that we are interested in and for that purpose we are interested in the light which enters into the material and then comes out as I T. So, we are actually interested in the part of the intensity of incident light which is entering in the material which is going to be at the interface 1 minus R and you are going to call it the light which is entering the semiconducting material as I 0. Now, the discussion on how we come to the terms of getting reflectivity, transmittance and all these is dependent on the optical properties of the material, but here we are more concerned about how much of that light we are going to absorb in the material.

So, we will start with the intensity of light I naught, this is that the light which is at this point after about R of i i is reflected. The light which enters the semiconducting material is I naught intensity. Now, we will work with this I naught intensity and see how we can get a optical generation rate for electron hole pairs.

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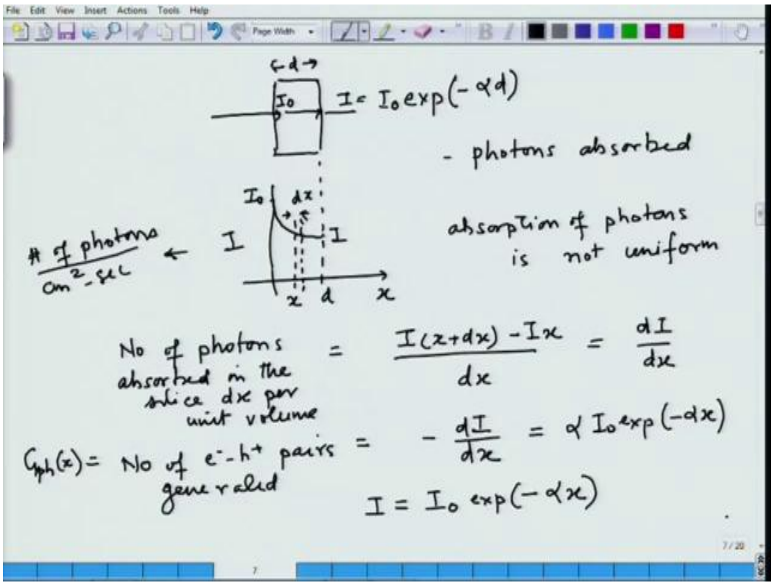

$I = I_0 \exp(-\alpha d)$

- photons absorbed

absorption of photons is not uniform

$\frac{\#\text{ of photons}}{\text{cm}^2\text{-sec}} \leftarrow I$

No of photons absorbed in the slice dx per unit volume $= \frac{I(x+dx) - Ix}{dx} = \frac{dI}{dx}$

$G_{ph}(x) =$ No of e^--h^+ pairs generated $= -\frac{dI}{dx} = \alpha I_0 \exp(-\alpha x)$

$I = I_0 \exp(-\alpha x)$

So, with this I naught information we can proceed and see what happens. So, the light which is coming here is I naught and the one which gets out is I and I, we have already learnt that this can be expressed as absorption coefficient of the material where d is the thickness of this material. Now, the question here is we want to figure out how many photons are absorbed. So, the first thing we want to figure out is how many photons are absorbed in the material. And as you can see if I plot the intensity of light as a function of x when it enters the material it is I naught, when it is coming out of the material it is I and we know that this is not uniform throughout the material. There is more light absorbed at the, at the entering side and it is exponentially decays as the light comes out of the material.

So, basically the absorption is not uniform throughout the material. Absorption of photons is not uniform which also means that a creation of electron hole pairs is not uniform in the material. So, in order to figure out how many electron and hole pairs will be created at any given point let us say x in the material we can think of a slice of the slab which is d x and calculate the number of photons absorbed in the slice d x of the semiconductor is going to be the intensity. And I can do that because I am representing intensity in terms of number of photons incident on the material and then multiplied by 1 minus R after taking care of the reflectivity divided by per unit area per second.

So, the number of photon absorbed in the slice of d x would be I at x plus d x minus I x and if I want to change this from per unit area to per unit volume I should divide by d x. So, this can be thought of as if I now take this small slab of d x and make it infinite decimally small then this can be written as the light absorbed at any point x as a function of x. Now, I want to change this number of photon absorbed into number of electron and hole pair generated which is going to be same as number of electrons except in the case of photons you are losing, they are absorbed. That is a negative number and number of electron and hole pairs generated would be a positive number because a photon absorbed, a loss of photon is resulting in generation of electron hole pairs.

So, this would be negative of this issue and so what is I? I if I write in a generalize term is nothing but I naught exponential, absorption coefficient x at any point x, if I take the differentiation of this, this gives me alpha I naught exponential minus alpha x. So, this is my generation rate, generation rate at any point x for a given wave length of light for which I know the absorption coefficient is going to be given by alpha times the I naught which is the light entering the semiconductor exponential minus alpha x. Now, if I want to calculate what is the total generation of electron hole pairs start in the material I basically need to integrate this expression for a given wave length of light from 0 to d. So, that is further can be done if needed.

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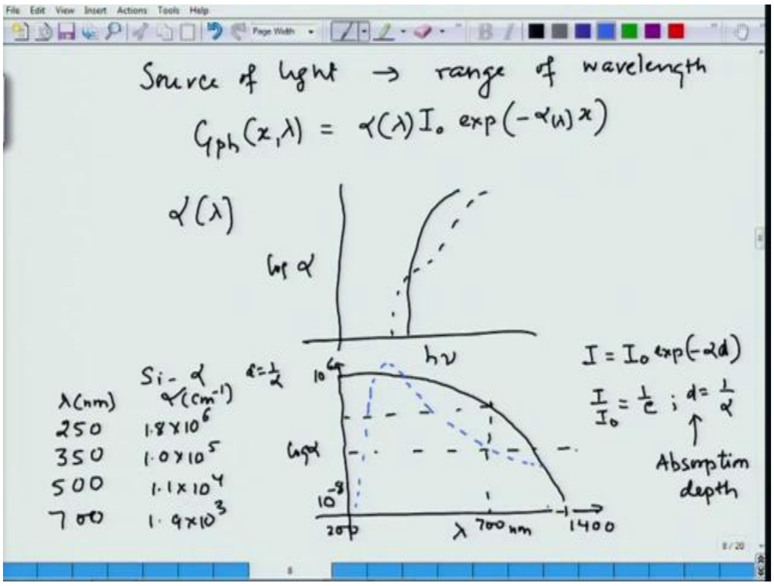

Source of light → range of wavelength

$$G_{ph}(x,\lambda) = \alpha(\lambda) I_o \exp(-\alpha(\lambda) x)$$

$\alpha(\lambda)$

Si - α

$d = \frac{1}{\alpha}$

λ(nm)	α(cm^{-1})
250	1.8×10^6
350	1.0×10^5
500	1.1×10^4
700	1.9×10^3

$I = I_o \exp(-\alpha d)$

$\frac{I}{I_o} = \frac{1}{e}$; $d = \frac{1}{\alpha}$

↑

Absorption depth

Now, what is; what one needs to remember is that when we are calculating electron hole pair generation we have just considered so far a particular wave length, but generally the source of light is not monochromatic, it has a range of wave length. And hence one should write a generalized term for generation of carriers in terms of x and wavelength of the source of light should be written as absorption coefficient which is dependent on the wave length light I naught exponential absorption coefficient which is a function of lambda times x. And then this would be a general expression and if I, if I have a spectrum for example, in the case of solar cell which has many wave lengths one will have to integrate this expression for all wave lengths to get the total number of electron hole pairs generated when the semiconductor is irradiated by the light.

So, this is what gives rise to the generation of electron hole pairs. Let us look at what is alpha? Alpha I said is a function of lambda. Let us see, what is the nature of alpha? We have already seen it in a different context. What we showed you in case of materials, alpha as a absorption coefficient h nu if shown cases where this is for direct semiconductor and then you have for indirect semiconductor. Same thing if we plot rather than plotting it as energy if we plot it as a function of wave length, let me take the example of case of let us say silicon alpha numbers. Then if I plot it for wave length region 200 to say about 1400, let us get some idea of these numbers; so for wave length numbers in the range of 250, 350, 500 nanometer and 700 nanometer.

Remember the visible light is in the range of 300 to 700 nanometer and the alpha values given in the units of centimeter inverse are in the range of about 1.8 10 to the power 6, 1.0 10 to the power 5, 1.1 10 to the power 3. So, if I take this and plot it in the log of alpha this is also plotted as log of alpha then what I find here is that starting from value of about 250 which is in the range of 10 to the power 6, this is the inverse of the energy diagram and if we are plotting it in a, in wave length goes fairly, down fairly sharply. This is where it is about 10 to the power 3. We can say this is at around 700 nanometer.

This is not exactly up to the scale. You can get these numbers from any standard hand book of absorption coefficient of various semiconductors. I am just giving some typical numbers, but for a numericals one can get this data easily available from standard text books. So, if this is the absorption coefficient which ranges all the way from 10 to the power 6 to 10 to power minus 8 most of the absorption being a high absorption coefficient being in the range of 10 to the power 6 to 1 and then going suddenly dropping as we reach the band edge of the indirect semiconductor silicon in this case.

Now, this much of absorption coefficient, how far does the light go into the material; if you want to calculate that we can see that this is nothing but if I look at this equation the light, the light is going to be reduced to about 1 over e value, I over I naught will become 1 over e when d is equal to 1 over alpha and this thickness we call as absorption depth. So, if I want to list the absorption depth d that is 1 over alpha what I find is that it is also going to change in the range of to the order of 2 to 3 magnitude in the wave length range which I am interested in figuring out how thick should my material be.

So, question that one could ask is how should, how thick should be the cell if you want to make, if you want to absorb as much light as possible. Now, the answer to that question is that it should be as thick as possible because if you look at the solar cell spectrum, typically solar cell spectrum peaks at in the visible range at around 400, 500 nanometer and then a lot of it is beyond a silicon band edge. But if you take any particular wave length what one finds it you need smaller thickness to absorb lower wave lengths, but as you go towards larger wavelength you need much thicker silicon substrate. And obviously if you want to absorb all of it you need a much larger value of the silicon thickness to absorb most of the sun light.

So, ideally as thick silicon wafer would be better for as possible would be better for the solar cell, but then there are going to be limitations from other parts which we will see later. You cannot make the solar cell very thick because it may absorb all light, but you may not be able to collect the electricity from it, but from, just from optical point of view if you want to capture all the light, you want your material to be as thick as possible or you want a material which has very high absorption coefficient. So, this would be related later when we discuss solar cells.

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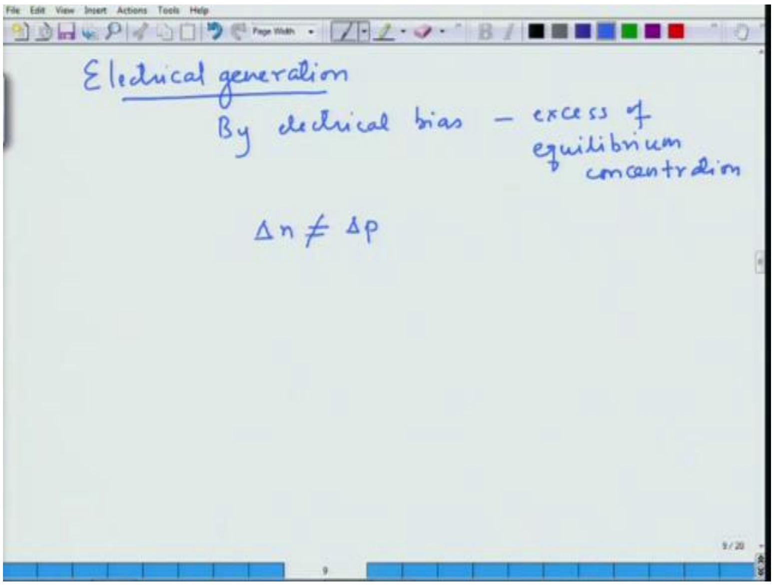

Electrical generation

By electrical bias – excess of equilibrium concentration

$\Delta n \neq \Delta p$

Now, coming to the third way of generating, for generation of carriers; that is known as electrical generation. Now, by applying a electrical bias one can create carriers in excess of, one can create carriers in excess of equilibrium concentration. Now, this is possible because when we apply bias to different structures, different junctions, one has the equilibrium concentration when the bias is changed, one is able to inject carriers from one side to the other side.

Now, details of this discussion we will take up after we have talked about the transport of carriers because it is about injection of carriers and at this point it we will just leave that this is another way of creating excess carriers, excess electrons in the conduction band and excess holes in the valence band. But in this particular process of creating this excess carriers it is not necessary that it should be equal unlike the processes that we discussed earlier which was thermal generation of electron and hole pairs and optical generation of electron and hole pairs.

So, with this now we know three ways of generating electron hole pairs by, by taking a electron from valence band giving it extra energy to take it to the conduction band. Now, let us look at the process exactly opposite to it which is recombination.

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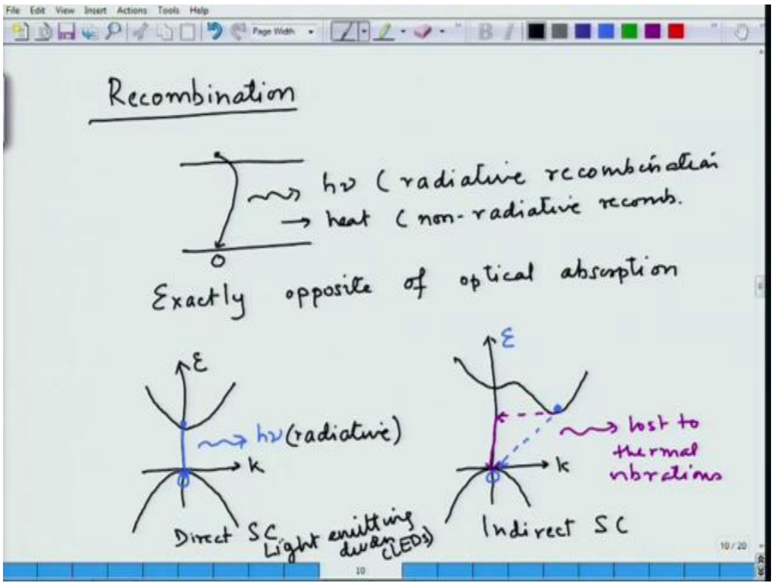

Recombination

hν (radiative recombination

heat (non-radiative recomb.

Exactly opposite of optical absorption

So, recombination is any process which takes the excess electron and hole concentration which is an excess of equilibrium and recombines them, any process that does that is called recombination process and the simplest one which we can think of is when you have a excess electron in the conduction band and hole in the valence band, they recombine and they can in this process give out light. This would be a radiative recombination. Sometimes, they do not give out light, rather they give out heat and this is known as a non radiative recombination.

Now, in this process the; just the energy diagram does not tell the whole story because when does the material give out a radiative photon or when does it result in to just heat in the material or being lost in thermal vibrations. That depends on the E k diagram. So, this process is exactly opposite of what we discussed for optical absorption in semiconductors. So, the process here is exactly opposite of optical absorption and here also if we think of a direct band gap semiconductor with E k diagram such that the minimum of the conduction band is aligning with the maximum of the valence band. In that case if you have a electron and a hole in the valence and conduction band then it can easily recombine with the hole without any change required in the crystal momentum or k value.

And in this process this is, in this process it is easier, this energy exchange can come out as a radiative photon. On the other hand if I have a indirect band gap semiconductor and which has a electron in the conduction band and a hole in the valence band. And it now needs to recombine with the hole. Now, it cannot recombine with the hole. In the energy diagrams it is simple to see that it will be recombine with the hole, but when you look at also the, the E k diagram you can see that it cannot easily recombine with the hole because the crystal momentum do not conserve which basically means it has to interact with another entity called phonon.

Phonons are nothing but quantized thermal vibrations or thermal energy of the lattice and then it can reduce its energy to the value of the valence band. So, in this process the energy does come out, but it is lost to thermal vibrations. So, just as in the case of absorption, in the case of direct semiconductor when we have recombination from conduction band to valence band it is possible to get radiative light, radiative emission, but when you have a indirect semiconductor and we have recombination of electron in the conduction band with the hole in the valence band. Then very often this light, this light will be lost as heat not as radiative emission.

What are the implications of this? The implications of this are that a direct band gap semiconductor like gallium arsenide can be used for making light emitting diodes. These, these can be used for making light emitting diodes also known as LED’s in the short form, while indirect semiconductors are not the right material for light emitting diodes. So, you have light emitting diodes of gallium arsenide, but not of silicon and germanium. So, recombination process has also implications for the type of material that one can use and then its application. What is then recombination rate?

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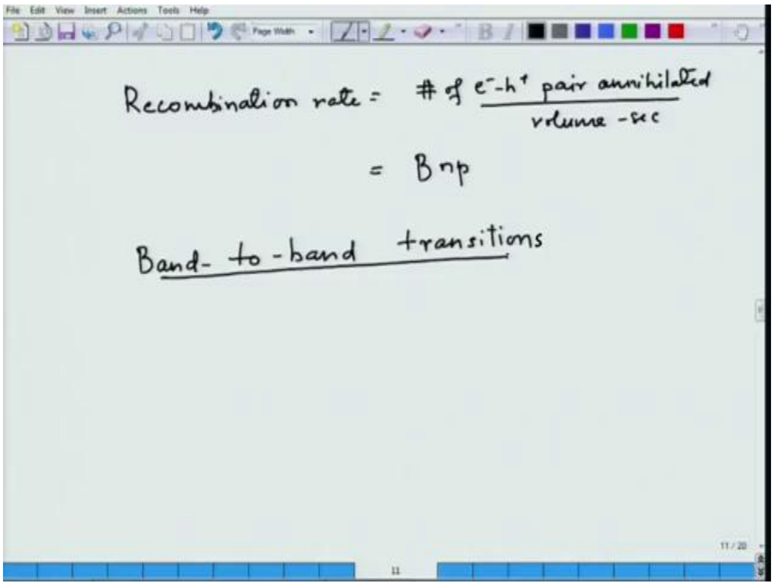

$$\text{Recombination rate} = \frac{\#\text{ of } e^- - h^+ \text{ pair annihilated}}{\text{volume - sec}}$$

$$= Bnp$$

Band- to - band transitions

Recombination rate is then defined as the number of electron hole pairs annihilated per unit volume per second. And the general expression for this is given as some rate constant multiplied by the carrier concentration in the conduction band and the carrier concentration in the valence band of electrons and holes. So, this would be a general expression which in the special cases we, we, we will find later much brief expression of recombination rate.

So, so far we have discussed generation and recombination of carriers. All the processes that we have discussed so far are band to band transition which basically means that I assume that the electron is in valence band and then it transfers to the conduction band thereby creating a electron hole pair. And I also assumed that there was a electron in the conduction band and a hole in the valence band and they recombined and thereby getting annihilated for the recombination process. But this is not the only way for excess carriers to be generated in semiconductors, band to band transition is not the only process that generates electron hole pairs or annihilates electron hole pairs. There are many other processes and that is what we will take up in the next lecture and at any given time all the processes are possible in a semiconductor, but given in a situation or conditions may be one or two will dominate the process.