Photonic Integrated Circuit
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Lecture 41
Semiconductor Light Emitting Diodes

Hello everyone. So, we, so far we have looked at important concepts in understanding recombination, absorption and how we can compensate between absorption and an emission, so that we generate photons out, and the rate constants associated with that. And finally concluded from many directions and reconfirmed that you need to have population inversion. So, that means, you need to have more number of particles, in the excited state compared to the ground state particles, atoms or molecules combined together.

So, in order to achieve that, there are multiple platforms one can use, you must have studied about gas lasers, (()) (1:15) dye lasers in other courses, but in this particular case, we are looking at semiconductor type lasers, and particularly whether we can use this in an integrated platform. So, let us look at a very simple system of, of light emitting diodes from a simple pn junction that you can easily make in a semiconductor platform, in a planar circuit platform. So, let us look at that.

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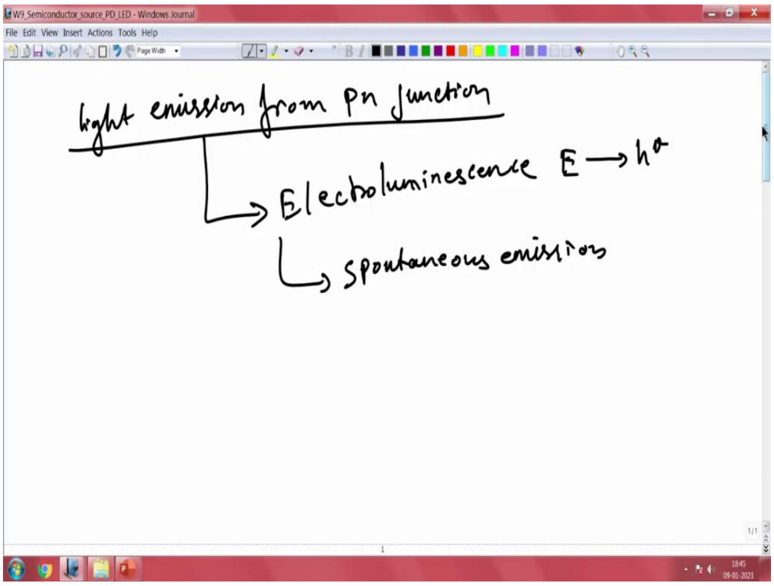
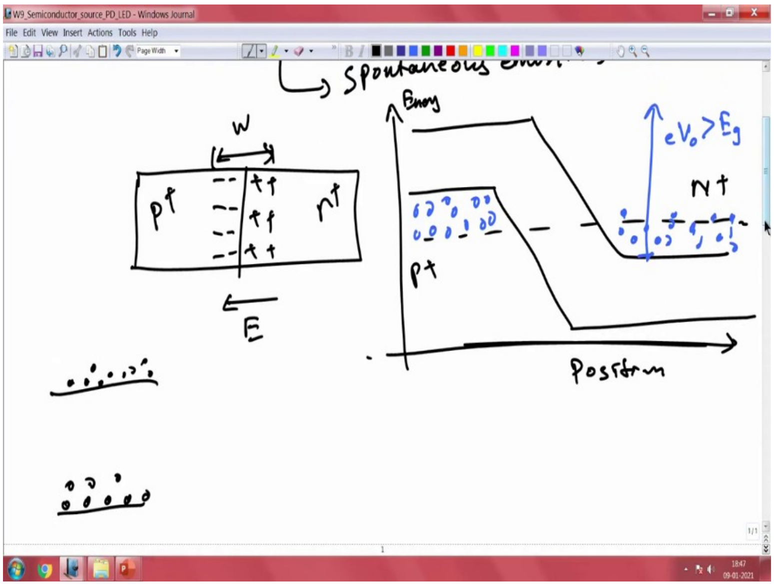


light emission from pn junction

Electroluminescence $E \longrightarrow h^{a}$

spontaneous emission



So, basically what you want is light, light emission from a pn junction is what you are looking for. And this you could achieve on different platforms and in particular, when we say, we want to get it from pn junction, from a semiconductor, is through electro luminescence. So, this is what you are looking at. So, what is electro luminescence? It is basically, the input is electric field. So, you have input electric field and then the output is a photon coming out.

So, that is the electro, electro luminescence. So, this is primarily achieved through spontaneous emission. So, this is spontaneous emission process is what we use in this case. Now, we need to build the circuit or rather the device in order to get photons generated. So, the light emission is primarily occurring because of recombination, in particular, the carrier recombination in the junctions that we have.

So, let us let us quickly recap on the junction, we do not have to go into the detail, because this is something that very basic concept that you must have studied in, in devices course and introduction to photonics as well. So, when you have a simple junction, you create an electric field in this direction and it has a certain width associated with it. So, this is the junction we talk about. So, when you, when you talk about these junctions, so, this will create a band, a bending.

Let us say, if this is a position and this is our energy, the electron energy here. So, your band is going to look something like this. And similarly, that and this is our Fermi here. So, this is too large. So, Fermi is somewhere here, because this is p+ and this is n+. So, we have our electrons in here and then we have holes located here. And the energy difference that we have between here and here is eV_0 which should be greater than the gap that we have.

So, this is in thermal equilibrium. So, in equilibrium we have this very nice simple, band diagram. But now, we want to make these charges to flow because they are separated you see, what you want in a system is a population inversion where you have electrons there populated and then the holes are sitting here. In this case, wherever you look, this inversion is not there. So, we do not have it. So, one way of creating this is by doing forward bias. So, in this heavily doped p+ and n+ region, we are going to do a forward bias.

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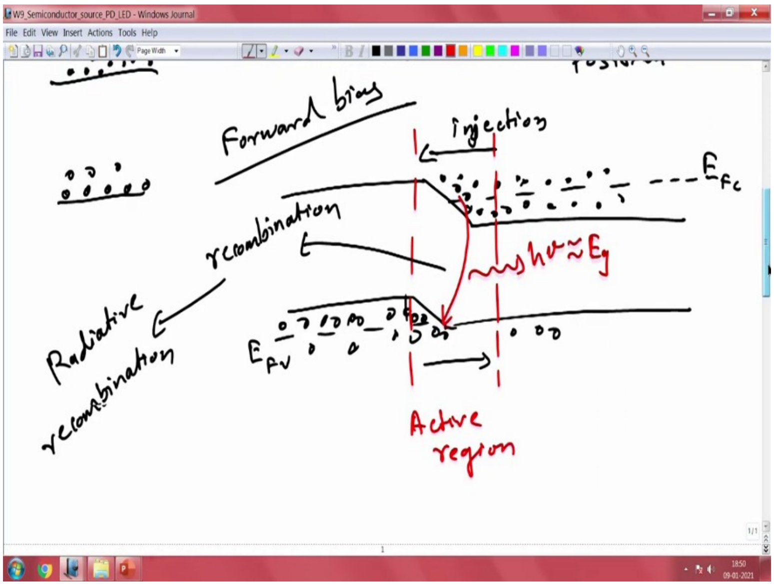

So, when you do a forward bias, when you apply positive to positive and negative to negative. So, that is what we call forward bias. When you do a forward bias the band bending is now reduced. So, the bending is reduced now. So, here we have the Fermi level. So, this is our E_{FV} and then here, here E_{FC}. And now, we have the electrons are trying to flow through the system here and the holes are also here. So, holes can go through.

So, this is forward bias. So, there is a current injection. So, we have charged injection in this direction and the hole injection in this direction. So, when you see this, this particular part, this particular region, where we have the junction, you can see here there is a number density difference that we see here. But at very high injection current density at the junction, or what we call the active region, in the active region, we see a population or a crowding of electrons and holes here.

So, this injection into this, will create the right condition for this electrons to recombine with the holes underneath. So, this recombination is something that we have to enable and that is done through this forward bias. And this forward bias condition helps you, but we need to have radiative recombination. So, this recombination, this recombination that we have should be radiative, radiative recombination.

So, what that means is, when they are coming down it should create a photon, it should create a photon. So, this is what we would like to do, and this generated photon will share the energy. So, this will be close to the, the bandgap energy that we have. So, this is something that we would like to do when you have a junction. So, let us look at different configurations of using this pn junction for various light emitters.

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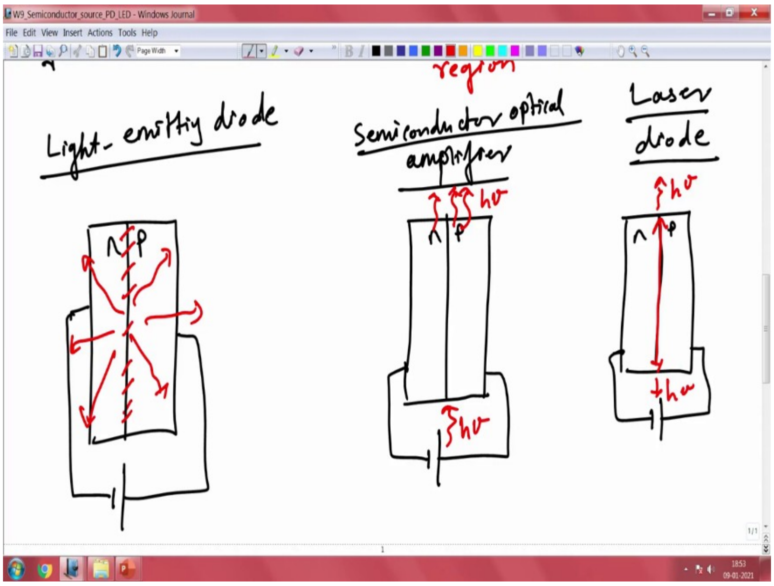

There are three types of light emitters that you could do. One is light emitting diode and then the other one is optical amplifier, semi-, semiconductor optical amplifier. And the third type of device is laser diode. There are three types of devices we can build just by using pn junction. So, let us look at these junctions.

The first type is a simple pn junction. We have n type and p type, and I am going to positively bias this. And when we do this, you are going to generate photons in all possible directions. So, you will generate light. This is, this is natural because you have the junction here and this junction is going to generate photons. And the next type of device that we are interested in is an amplifier. So, again you have n and p type, we are going to forward bias this.

And in this case, I am going to put a photon in, I am going to put a photon in. So, there is a photon of energy h nu, but then when it comes out it, it has more photons of same frequency. And this is in a directional form. So, this is what we call optical amplifier. And then you could have another type of device, where we create the diode here to be highly directional, the light generation is along only in this direction. And the emission is confined within this and that would result in photons coming out only in this direction.

So, this is what the laser diode is all about. So, a light emitting diode, that we have here primarily is a spontaneous emission process. It is spontaneous emission is what you see in a light LED structure. But in a, in an amplifier and then a laser diode you have stimulated emission. So, in order to have this process happen in these material, in n type and p type material, we use a direct bandgap material.

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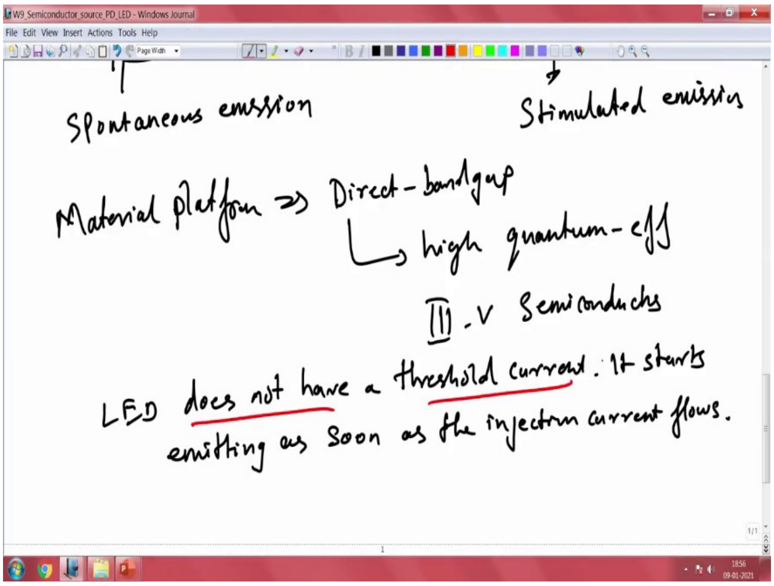
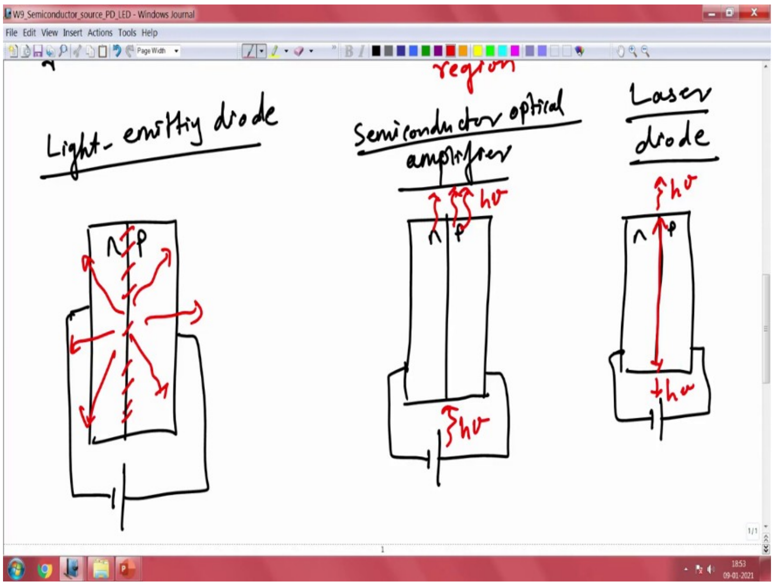


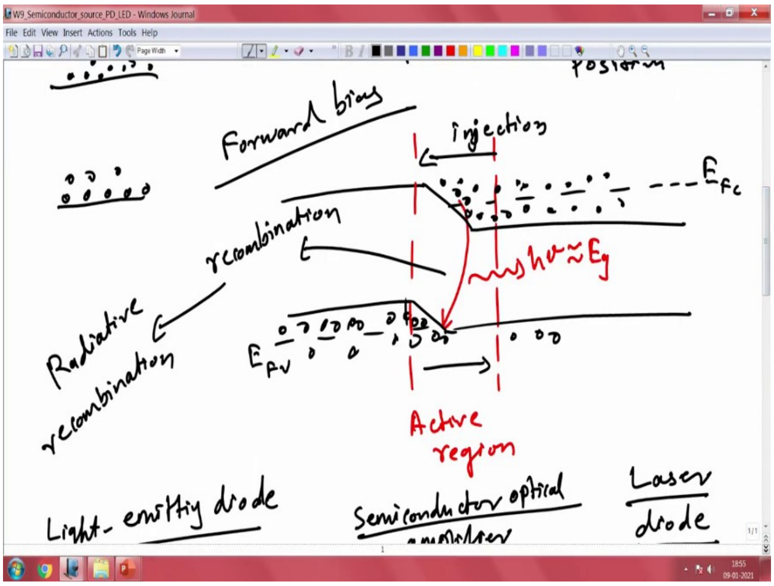
Spontaneous emission

Stimulated emission

Material platform => Direct-bandgap
↳ high quantum-eff
III-V Semiconductors

LED does not have a threshold current. It starts emitting as soon as the injection current flows.





It is important that the material platform should be direct bandgap material. So, this will ensure high quantum efficiency of emission. So, normally we use III-V group semiconductors for this kind of light emitters. So, as I already mentioned in our earlier lectures, the spontaneous emission is going to be, really unpolarized or randomly polarized, incoherent light that is going to come out from an LED. And the LEDs they do not have any kind of threshold. It starts emitting as soon as you start conducting.

So, as long as the current is flowing through, you will start emitting light from an LED. So, the LEDs are much, much easier to, to start off unlike the other two. So, we need to understand how much flux is required. So, let me put that important point here. So, LED does not have a threshold, threshold current let us say. It starts, it starts emitting as soon as the injection current flows. So, this is an important thing that you may want to keep in mind.

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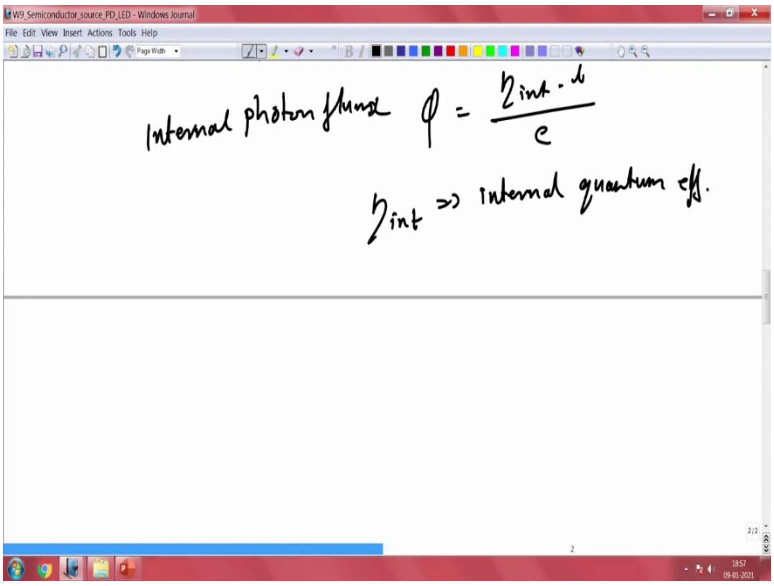

Internal photon flux $\varphi = \frac{\eta_{int} \cdot i}{e}$

$\eta_{int} \Rightarrow$ internal quantum eff.

So, once you start generating the photon what, what is the efficiency of generation? So, you need to understand the internal photon flux. So, what is the internal photon flux, basically your efficiency related, so that is φ. So, what is it internal photon flux? Depends on internal efficiency, injection current times the charge. So, this is injection, electro luminescence. So, here $\eta_{internal}$ is internal quantum efficiency.

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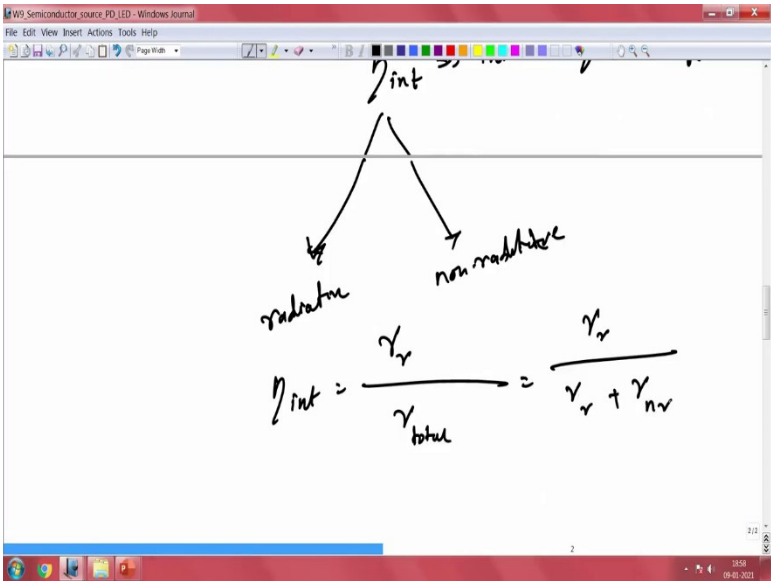
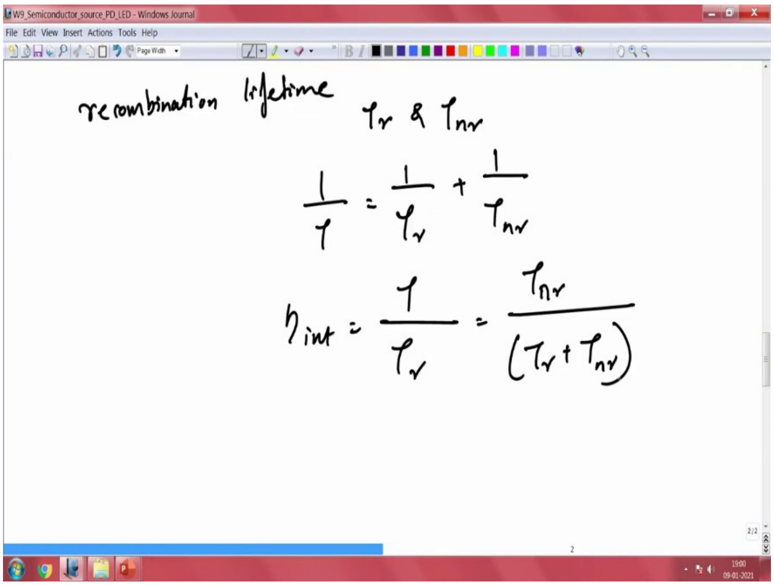


$$\eta_{int} = \frac{\gamma_r}{\gamma_{total}} = \frac{\gamma_r}{\gamma_r + \gamma_{nr}}$$



recombination lifetime τ_r & τ_{nr}

$$\frac{1}{\tau} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

$$\eta_{int} = \frac{\tau}{\tau_r} = \frac{\tau_{nr}}{(\tau_r + \tau_{nr})}$$

So, this internal quantum efficiency that we have, depends on many factors. And it is basically given by the electron hole recombination. So, when the recombination, the radiative recombination, so, this primarily depends on radiative and non-radiative. So, you have two recombination, radiative recombination and non-radiative recombination. So, the light generation primarily depends on how much recombination that you have as proportion to radiative or non-radiative.

So, the internal quantum efficiency depends on the radiative recombination to total recombination. And radiative recombination to radiative plus non-radiative. So, the n_r is the non-radiative and r_r is the radiative. So, this is, is the factor that defines this internal and external quantum efficiency. The other important factor is about this radiative recombination and non-radiative recombination rates, so, they depend on the lifetime of the carriers in their system. So, what you can write is the radiative and non-radiative light, lifetimes are going to be important.

So, that means that recombination lifetime, so the recombination lifetime is inversely proportional to the, the radiative and the non-radiative rates that we just saw. So, that is nothing but τ_r and τ_{nr}. So, the total recombination lifetime is simple addition of radiative and non-radiative recombination lifetimes. So, these two are, are the important factors here. And the internal quantum efficiency can be now written as the lifetimes now. So, non-radiative recombination lifetime to the total lifetime that you have.

So, normally this, the internal quantum efficiency for semiconductors are pretty high. So, this can be very large because the lifetimes are very small. So, the radiative, the total time recombination lifetime can be very small.

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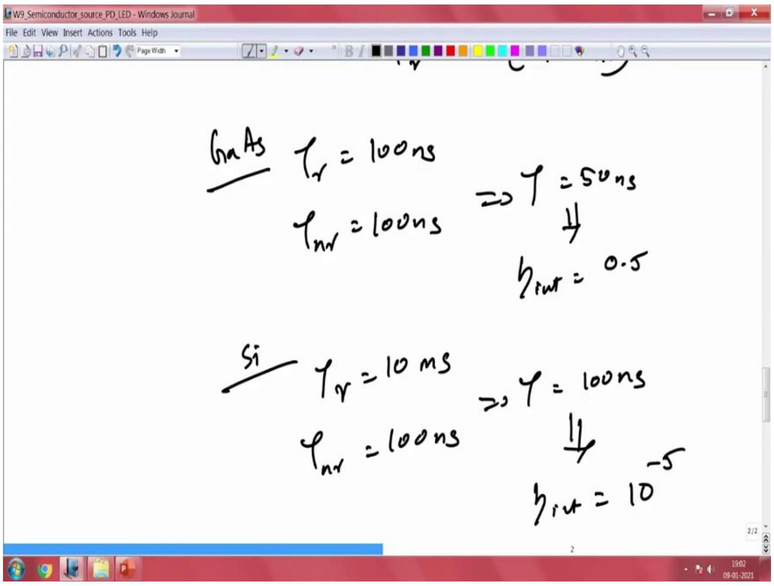


GaAs $\tau_r = 100\,ns$

$\tau_{nr} = 100\,ns$ $\Rightarrow \tau = 50\,ns$

$\Downarrow$

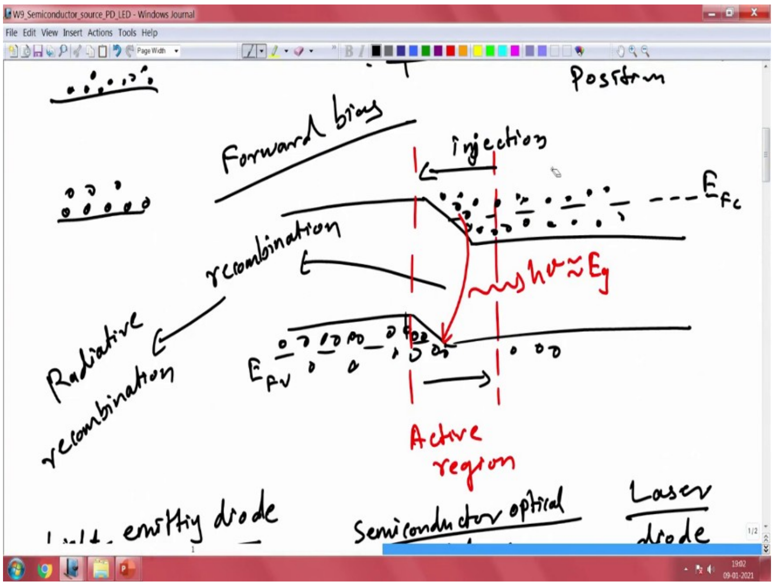
$\eta_{int} = 0.5$

Si $\tau_r = 10\,ms$

$\tau_{nr} = 100\,ns$ $\Rightarrow \tau = 100\,ns$

$\Downarrow$

$\eta_{int} = 10^{-5}$



So, just to give you an example for gallium arsenide your τ_r, so, the radiative recombination is about 100 nanoseconds, while your non-radiative recombination is also in that same order. So, this would result in a total recombination lifetime of about 50 nanosecond, which would result in, which would result in internal quantum efficiency of 0.5, which is just quite high. So, the, the recombination, the radiative recombination lifetime are very important to, to get a good quantum efficiency.

For example, if you take silicon, your radiative recombination rate is in milliseconds, while your non-radiative recombination is in nanoseconds. So, this would result in radiation, total radiative lifetime, radiation lifetime of, in terms of nanoseconds. So, this would 100 nanoseconds. So, this would result in, internal quantum efficiency of very small. So, this is going to be 10^{-5} or 10^{-6}. So, this is the reason why silicon is not a good emitter at all and it is a, again it is an indirect bandgap material.

So, we need to make sure that you use a direct bandgap material at the same time your radiative lifetimes are low enough in order to enable light generation in the system. So, the internal quantum flux that we saw here, depends on your internal quantum efficiency, but at the same time, we need to also look at the carrier generation here as well. So, how quickly we can generate these carriers. So, the carrier generation is primarily coming from our injection here. So, we had this injection here. So, how much injection, what is the injection rate we have, based on that we could actually find the internal quantum efficiency, which is related to our injection rate.

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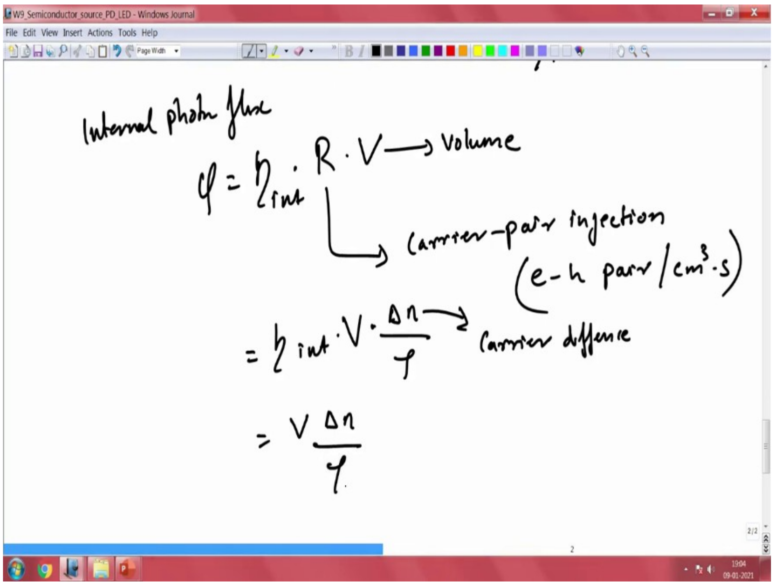


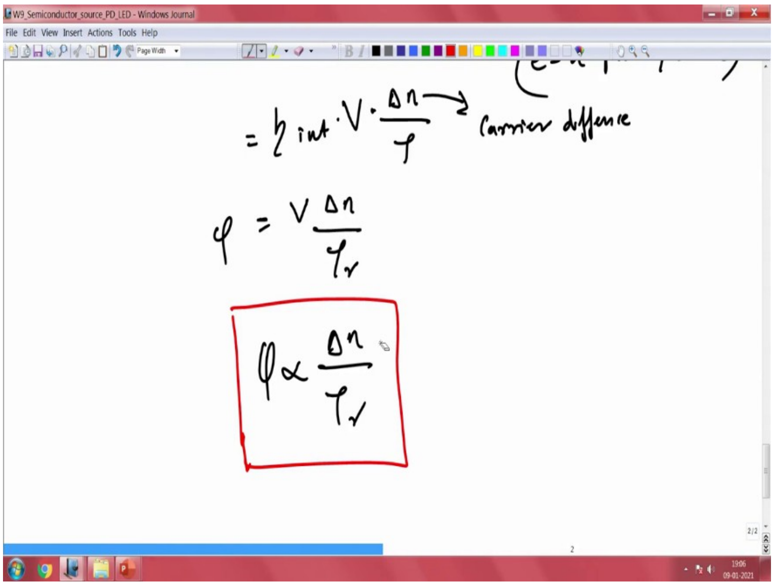
Internal photon flux

$\varphi = \eta_{int} \cdot R \cdot V \longrightarrow$ Volume

$R \longrightarrow$ Carrier-pair injection (e-h pair/cm^3·s)

$= \eta_{int} \cdot V \cdot \frac{\Delta n}{\tau} \longrightarrow$ Carrier diffence

$= V \frac{\Delta n}{\tau}$



$= \eta_{int} \cdot V \cdot \frac{\Delta n}{\tau} \longrightarrow$ Carrier diffence

$\varphi = V \frac{\Delta n}{\tau_r}$

$\boxed{\varphi \propto \frac{\Delta n}{\tau_r}}$

So, your internal photon flux, φ, is related to your quantum efficiency times R times V. So, what is R? R is our carrier pair injection. So, how much injection we have or in other terms electron hole pair per centimeter cube per second. So, this is, what this injection is. And V is the volume, material volume, how large the material volume is. And if you, if you look at it finally, you can deduce this to our earlier equation or 'I' times e if we want. So, you could write this as $\frac{\eta_{\int ¿V\Delta n}}{\tau}¿$.

So, this is another way of writing it because it, the recombination lifetime also plays a role in your rate. So, that, the rate here depends on the change in the number density, your Δ, Δn is a carrier difference because of the injection and which is equal to $\frac{V\Delta n}{\tau \square_r}$.

So, these are all various forms of, of representing our photon flux. So, on the whole, this photon flux depends on the number of charge carriers you have and then your recombination lifetime. And also we can just write this as a proportionality constant and this is basically it. So, your photon flux depends on the, the carrier density change and your lifetime. So, you want your lifetime to be shorter, at the same time you want your charge injection to be higher. So, how do we achieve this, the scenario?

So, your recombination rate as intrinsic to the material, but then you can play with this injection. So, the injection or the current carriers that you have, can be increased by putting more current into the system, but you cannot increase the current as you like because there is a limit to the material itself. So, it will break down because you do not have much carriers to follow through. But you can increase the density of carriers. So, that is something that you can do.

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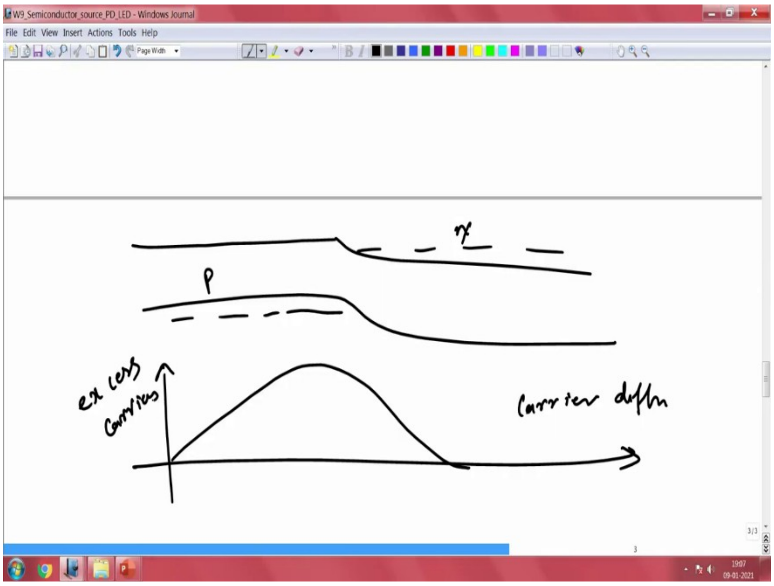

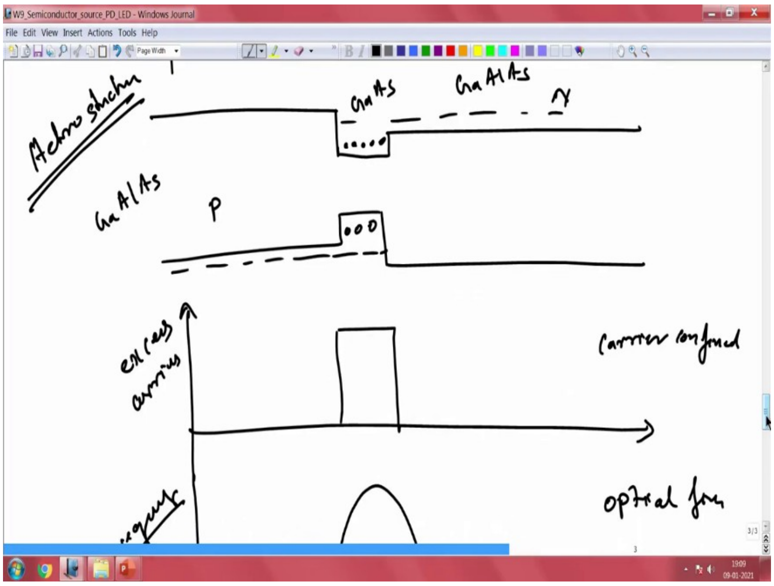

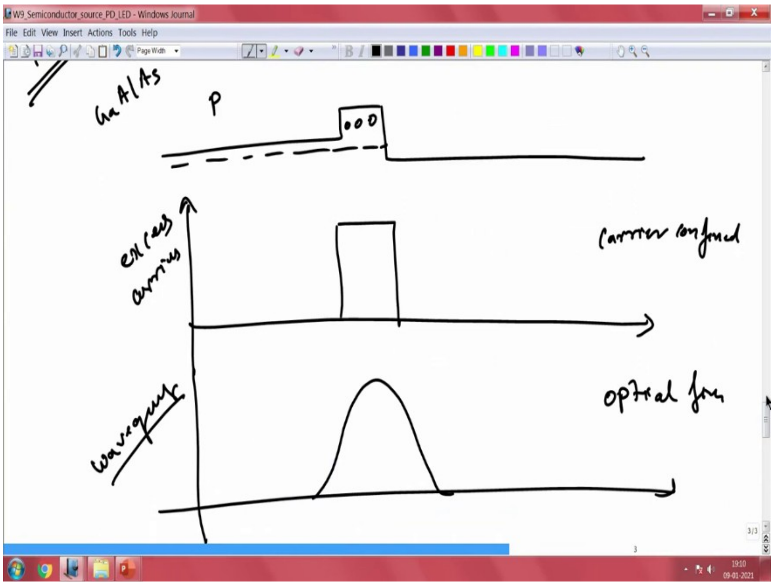

So, let us look at a very simple diode carrier distribution. So, let us, let us look at that carrier here. So, this is our very simple diode and then your carrier diffusion is going to be. So, this is our p side and this is our n side. So, your carrier diffusion is something like this, it is too much. This is carrier diffusion and this is excess, excess carriers. But instead of having such a big distribution, what one could do is by using an hetero structure. So, instead of having a band like this, so, we could have a band structure, it could be like this.

So, in this case, we have gallium aluminum arsenide and gallium arsenide and gallium aluminum arsenide. So, you can say this is the p side and this is our n side. So, when you have this kind of structure where we are using three different, two different type of material you can see there is a different in the bandgap that will result in carrier confinement. So, this is our carrier confined. So, this is excess carriers. So, in this particular region you, you can confine the carriers and by confining the carriers we are increasing your Δn in this.

And by increasing that Δn, we could effectively generate the photons out of this system. And another important aspect of this is the light emission itself, the optical field. This is optical field will be only in this particular region. So, what you see is a, a light guiding. So, by using this kind of hetero structure, we should be able to generate light in this very confined region.

So, that we can have wave guiding. So, this, this becomes an important stack in order to realize waveguide along with light generation.

However, if you take a simple pn junction, the, the carrier distribution is very large and you are not having any confinement in the charges and also optical field. So, a hetero structure is something that, that is essential if you want to improve your light generation or flux density inside the optical medium. So, with this discussion, we have come to a basic understanding of how one could create sandwich of stacks by using different material platforms. For example, a low bandgap material and a high bandgap material.

So, by putting a low bandgap material between two high bandgap materials, you can create a carrier confinement and this carrier confinement would result in light, efficient light generation. And the reason for that is, you are confining the carriers not only confining the carriers, your generation is also confined, you are not generating carriers across the structure it is confined. But this bandgap difference that you have between a small, a narrower bandgap and large bandgap you are generating refractive index difference as well.

And this refractive index difference is also going to help you in light confinement. The narrow bandgap material, they have higher refractive index. So, the higher refractive index will confine the light and that is the reason why in a hetero structure you have light confinement in the narrow bandgap material. So, by confining the light and also confining your charges in this region, we can efficiently harness the charge injection. So, with that understanding, we would like to go to generating this charges and trying to create a cavities out of this. So, that is something that we will see in the following lectures. Thank you very much for listening.