Optical Wireless Communications for Beyond 5G Networks and IoT
Prof. Anand Srivastava
Department of Electronics and Communication Engineering
Indraprastha Institute of Information Technology, Delhi

Lecture - 05
Part 1
Photodetectors

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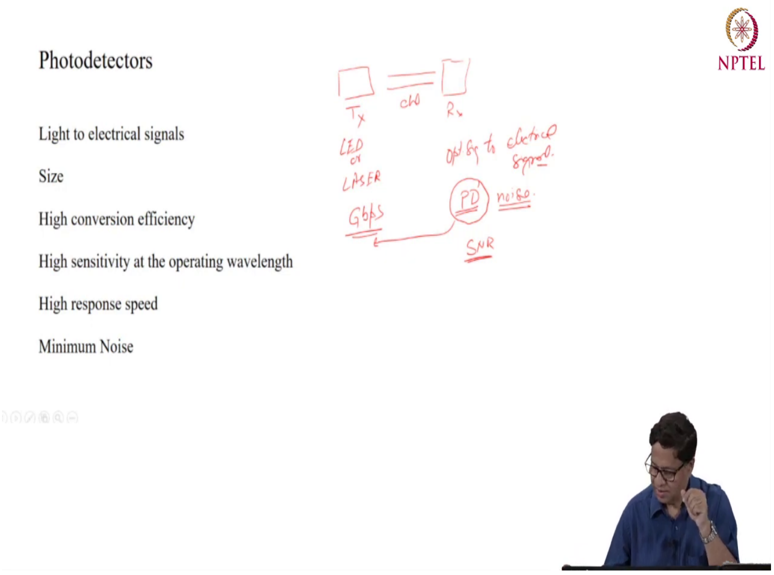

Hi everyone. So, today we are going to discuss about photo detectors. In the last class we had discussed about Optical Sources namely light emitting diode and laser. So, today we are going to discuss about Photodetectors. So, what are the requirements of a photo detector? The first the what does let us first understand what does a photo detector do? So, it basically converts the light power or optical power into electrical energy that is the basic function of photo detector.

So, what we require in photo detector, the size should be small because if you want to mount this may be on your mobile phone or want to use in your you know as an attachment to your laptop, you require that the size of the photo detector should be very small. So, first requirement that the size of the photo detector should be very small.

And it should have high conversion efficiency; meaning whatever light is falling on to it you know most of it should be converted into electrical signal which we are going to process. It should have high sensitivity at the operating wavelength.

So, suppose in a telecommunication scenario, you are working at either 850 nanometer or 1310 nanometers or 1550 nanometers. The kind of detector you should use that it should give you high sensitivity at that particular operating wavelength. If you are using this in a visible light scenario for example, so it will give you a high sensitivity against visible light.

So, you should have depending upon the application you should have a high sensitivity at the operating wavelength. High response speed which means the photo detector should be able to respond at high bandwidth. Because in a typical optical communication system whether it is wired or wireless using optical fiber or wireless you have a transmitter and you have channel here and you have receiver here right.

So, this transmitter is basically combination of either LED or LASER and then receiver is actually converting optical signal whatever is coming through the channel to electrical signal. Now, the goal is to transmit a very high speed from optical transmitter to optical receiver. It could be of the order of say gigabits per second.

So, what we want that the Rx in this case photo detector which we also called as PD should respond at this rate. So, it should have a high response speed. So, we will study in detail about the requirements how one can improve the response speed and photo detector generates you know noise, the sources of noise or the noise generated inside the photo detector. We will study and the idea is to have you know minimum noise. So, that at the receiver your signal to noise ratio is maximized.

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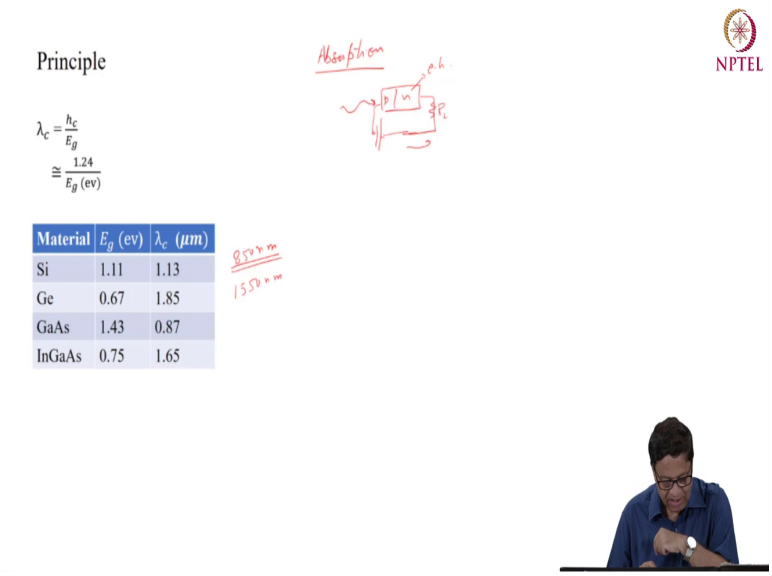

So, what is the basic principle of photo diode. So, it is based on process called absorption. Remember in LED case we had studied about absorption, spontaneous emission and stimulated emission. So, what happens when a light falls on to a semiconductor, the photon energy which is there in the light is absorbed.

It generates electron hole pairs and this device is biased, it is normally reverse biased and those electron hole pairs are actually under the influence of the bias they are swept away or they drift and in the process, they generate current which can be collected through a which can be you can have a R L and the voltage can be developed across RL.

So, you get light the current or the voltage across RL proportional to the intensity of the light. So, that is the basic principle of photo diode. So, you require what kind of wavelength you require because the photon which has energy greater than the band gap of the P N junction only then it will be absorbed and convert into electron hole pairs. So, you require a certain wavelength which will be your light, your wavelength will be sensitive to wavelength which is less than this lambda c or lambda cutoff.

So, this lambda cut off is defined as h c divided by e g this is not subscript this is h Planck's constant and c is velocity flight e g is the band gap of the photo diode junction. So, in terms of you can put the values of Planck's constant and velocity of light then this is approximately equal to 1.24 divided by e g, e g is the band gap energy and it is in electron volts.

So, this is the lambda c or the lambda cut off for different material for silicon the e g is 1.11 [FL] corresponding lambda c is 1.13. So, it is generally sensitive at wavelength less than 1.13 micro meter. So, for example, if you are using 850 nanometer transmission. So, this good can be a good choice.

For germanium the band gap energy is 0.67. The corresponding cutoff wavelength lambda c is 1.85. So, this could be a good candidate for 1550 nanometer transmission. The third one is Gallium arsenide the band gap is 1.43 the corresponding cutoff wavelength is 0.87 and in gas is 0.75 and the corresponding cutoff wavelength is 1.65.

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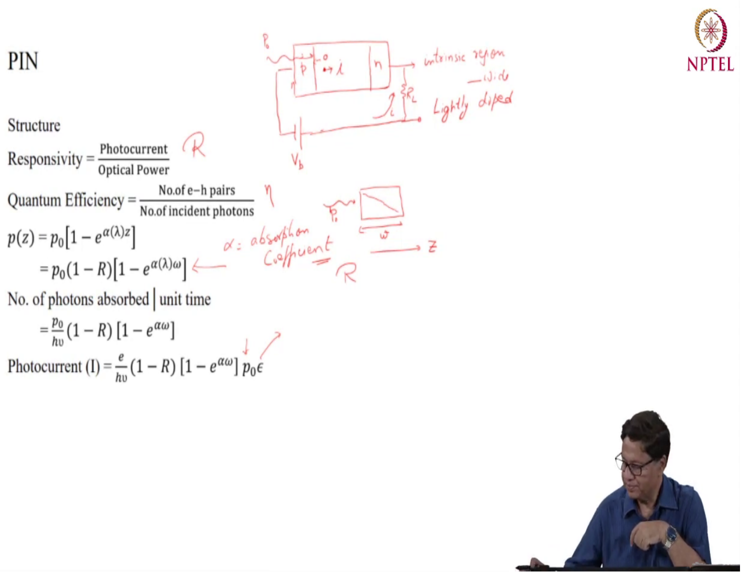

So, let us now understand the specific diode which is used for which is used in optical communication system whether it is fiber based or optical wireless system. So, let us first understand the structure. The structure is actually there is a say PN diode and there is a intrinsic region in between which I am denoting this as I.

So, this I is actually this intrinsic region it is actually kept wide I will tell you why it is kept wide intrinsic it is kept wide and this is lightly doped. So, there are no electron free electron hole pair inside the I region. So, the impedance of this I region is very very high. So, the voltage basically is across the I region and this kind of this PIN photo diode is actually reverse biased.

This is in contrast to LED which was forward biased and that was a P N junction. So, when optical energy falls it is absorbed and it generates electron hole pairs. So, I am denoting this hole as a hole and this has a electron as a dot. So, and because the voltage is across the I region they are drifted away and. In fact, I should make a little change in the diagram little to include resistor. So, this is output and this is resistor the current.

So, this will this electron will go hole will go in this direction, electron will go in this direction and under this influence of reverse bias there is a you know drift current which flows across this device and this is passes through load resistor which is RL and you get a voltage across RL. This is the bias part, let me denote this as a v b. So, this is a basic structure of PIN diode and it is kept wide the I region.

Because we want that photon should have maximum chance of getting absorbed inside the intrinsic region, hence producing electron hole pairs. If it is narrow probably the probability that it generates electron hole pairs is less. So, that is why it is kept high. So, this is a structure of PIN photo diode. There are some quantities which define the property of a photo diode. So, one of them is responsivity which is defined as the photo current divided by the optical power.

So, this optical power let us say this is p naught and the current is I naught here. So, basically how much photo current is produced when you launched optical power p naught. So, that ratio is called as a responsivity. So, this is generally denoted by R, the other quantity which is important is quantum efficiency.

Quantum efficiency is when the photon strikes the PIN junction electron hole pairs are generated, it is not necessary that all photon will generate electron hole pairs, some may be you know they may be recombination or they may be lost. So, some not every photon will result into electron hole pairs.

So, basically the ratio of number of electron hole pair is generated divided by number of incident photon that tells you the quantum efficiency of the photo diode. So, this is defined as eta quantum efficiency. So, now, let us try to understand and find out mathematical expression for responsivity and quantum efficiency. So, inside a semiconductor if I launch power p naught, it is absorbed as the power travels through the semiconductor diode.

This could be for example, w then the power falls because it is getting absorbed. So, as it travels it falls and this can be represented by this is function of z here p z power at point z some point z is equal to p 0 p 0 is the incident power into 1 minus e alpha alpha function of lambda this is function of lambda into z the distance and alpha is the absorption coefficient which is actually function of wavelength. So, this is the power at some point inside the semiconductor.

What happens actually that when you when the power p 0 gets is incident on the p n junction or PIN photo diode then not whole part goes inside the device some part is getting reflected some part gets reflected back. So, let us define that part as the one which is reflected is defined by the reflection coefficient of the device.

So, effectively the power which goes inside the photo diode is p 0 into 1 minus R into 1 minus e alpha which is a function of lambda into the width this is the power you get after travelling a distance of w. So, the number of photons per unit time can be found out this is the power.

So, number of photons will be you have to divide this power by h nu you will get number of photons. So, this is the number of photons per unit time. So, this expression has been divided by h nu. So, this becomes p 0 into h nu 1 minus R, this is because of the reflection and 1 minus e raise to power alpha.

Now, I am not writing this function of lambda this is understood or otherwise unnecessarily it may create some confusion, but this alpha is the absorption coefficient is function of wavelength into the width and the photo current. Because the number of photons absorbed per unit time are this and the photo current I will be you will have to multiply this by e, e by h nu into 1 minus R, 1 minus e alpha into the p 0 this is the incident power p 0 is incident and this factor is actually takes care of the fact that not all photons or will result into electron hole pairs.

So, this factor basically tells you what proportion of photon is converted into electron hole pairs. So, generally this epsilon should be one ideally all the photons should result into electron hole pairs, but in practice does not happen that way. So, this epsilon will be less than 1. So, we have to multiply in order to get the photo current which flows through the resistor or the load is function of this epsilon.

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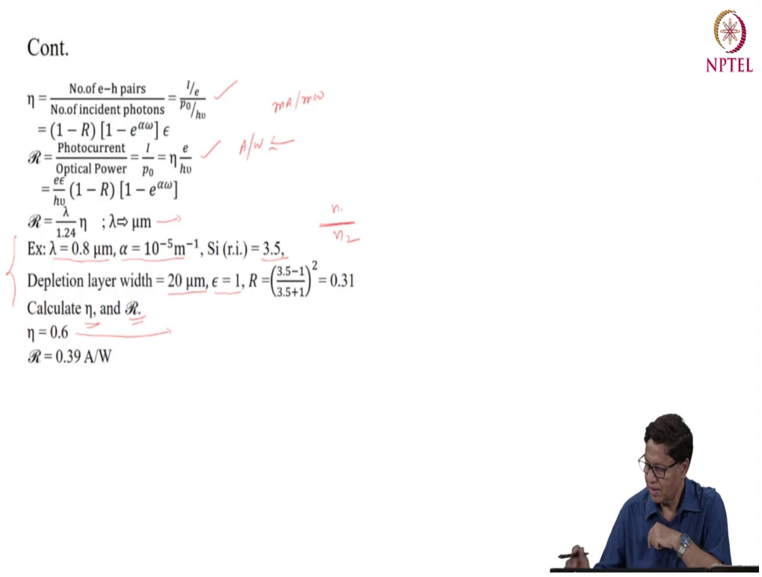

So, as we defined the efficiency earlier which is eta that is the number of electron hole pairs divided by the number of incident photons. So, these are the number of electron hole pairs I divided by e and number of incident photons is the power incident on the photo diode divided by h nu. So, I put the values which I had done calculated last in the earlier discussion.

So, this will become 1 minus R into 1 minus e e raise to alpha w into epsilon. And if I define the responsivity it is defined as photo current divided by the optical powers. The units of responsivity by the way is amperes per watt. How many amperes you generate when you give 1 watt of power. So, generally in optical communication you know you do not generate amperes or watts of power generally you have milli amperes of current and the power is milli watt.

But this R or the responsivity is generally you know represented as amperes per watt. So, photo current divided by optical power; photo current generated was I naught optical power p naught and just manipulating the earlier equations we get responsivity as efficiency into e by h nu.

So, we got expression for efficiency and we got expression for responsivity which can be further simplified here as e epsilon into h nu 1 minus R, 1 minus e raise to the power alpha w and we can also equivalent write in an alternate fashion the responsivity is lambda divided by 1.24 into efficiency where lambda is in micrometers.

So, while calculating the responsivity using this equation you have to put lambda in micrometers and efficiency anyway is dimensionless quantity. So, lambda divided by 1.24 into efficiency will give you the responsivity. So, an example just to give you some feel of the values, if I am operating at lambda is equal to 0.8 micrometer or 800 nanometers and the absorption coefficient is 10 raise to power minus 5 per meter or meter inverse and I am using silicon as the semiconductor material.

The refractive index is 3.5 and the depletion layer width which is the w in my case is 20 micrometer and I assume that sigma that epsilon is 1 where the conversion of all the photons all the photons will result into electron hole pairs and R can be calculated into n 1 minus n 2 divided by n 1 plus n 2 whole square where n 1 is refractive index n 1 at the interface.

So, assuming the n 1 is air and n 2 is 3.5. So, you get R as 0.31 and so, we can calculate the value of efficiency and responsivity; if you are given with these if you are given these parameters. So, in this case if you plug in the values here you get a efficiency of 0.6 or 60 percent and responsivity you get 0.39 amperes per watt. So, each 1 milli watt power which is incident on the photo diode we generate about 0.39 milli amperes of current. So, these are the efficiency and responsivity values for this particular example.

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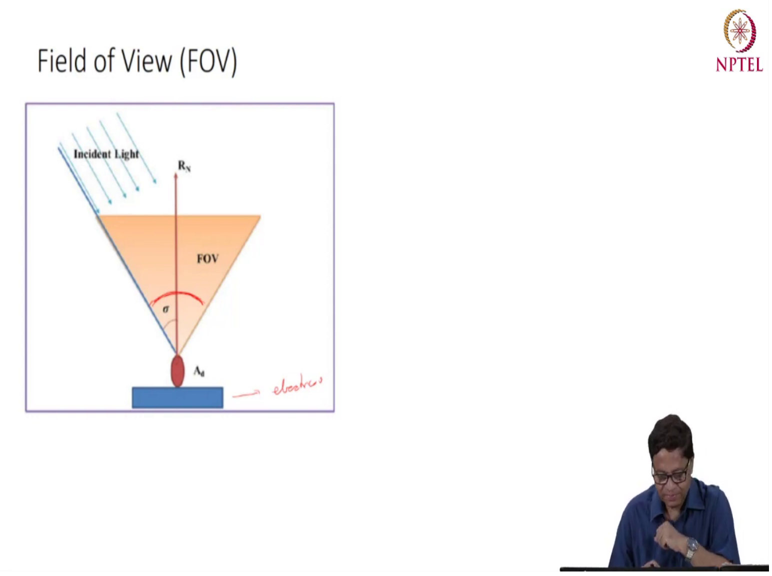

Another important thing which we will use quite frequently while you know finding out the power which is or the power collected by the photo diode is field of view. So, each photo diode has certain field of view the light falling in this cone this is actually a solid angle. So, you have to visualize this in three dimension will get absorbed and will get converted into electrical current. So, this cone or this solid angle is referred as the field of view.

So, you can make the field of view you know very narrow you can make it wide if you want to collect light from all possible angles and if it is a point-to-point transmission you will try to make it narrow. So, this field of view is very important when you are designing a optical wireless communication system.

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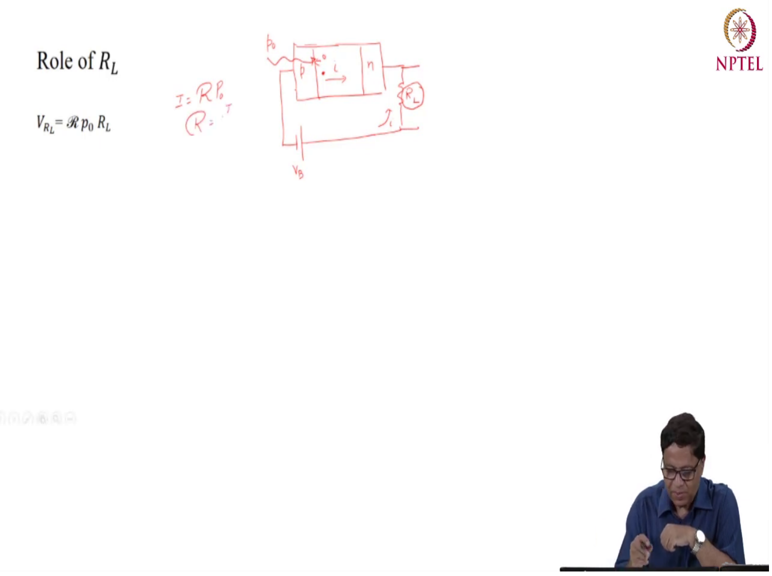

So, now let us understand the role of R L the load resistor which we had discussed when we were discussing about the P I N diode. So, again I will redraw this picture of PIN diode. So, this is P, this is my I region, this is n region and this is reverse biased and there is a resistor here, the current flows and let us denote this as R L and again there are hole and electron.

They are generated as a result of incident photon energy and this hole will move in this direction; this it will be swept away in this direction and this electron will be swept away in this direction. So, what is the what should what value of RL you should select? So, let us understand this RL here.

So, initially when there is no current or no photon energy flowing the whole bias voltage vb let us say is across the I region and when the current when the photon energy is incident on this PIN diode, it will result into some current and then it will there will be a voltage across RL and that voltage is actually V RL is equal to responsivity of the photo diode into p naught the power incident which is actually current because I is equal to R over p naught or responsivity is sorry responsivity I should write.

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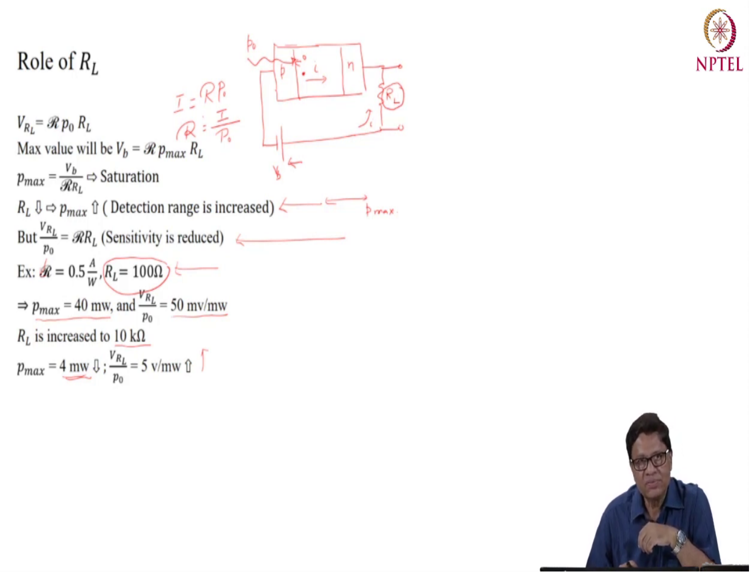

The current is actually equal to responsivity over p naught. Because we know we had defined responsivity as the current photo current divided by the power incident. So, this is I into RL. So, this is the VRL which is across the load resistor. So, what is the maximum value it can have?

The maximum value it can have is vb which is the bias. This can be written as capital B and this is equivalent to R responsivity into p max. So, that is the maximum power; because if you incident more power than this you will not get any additional current. It will get saturated. So, that is the maximum power you can give to the device into R L.

So, that is the maximum value of vb. So, p max of a photo diode which actually tells you the range in which the photo diode will respond in terms of power. So, p max will be vb I mean it is better to change at one place. So, this is vb. So, let me write this as b vb p max will be vb by responsivity into R L. Now, if RL decreases, if I reduce the value of RL this p max will increase; which means my detection range is increased. I am able to detect you know wide value of power because this p max has increased alright.

On the other hand, if I see the sensitivity that is the ratio of the voltage which is developed across RL, divided by the incident power is given as responsivity into RL. So, this is the sensitivity part. So, if I decrease RL, this sensitivity also decreases. So, by decreasing RL, I was able to increase the p max the detection range, but at the same time I have compromised on the sensitivity. So, you have to decide the value of RL depending upon whether you want a good detection range or you want good sensitivity.

So, let us see this one of the example, if the responsivity is 0.5 amperes per watt and let us initially have RL as 100 ohms. Then the p max if RL is 100 ohms is actually 40 milli watts. If you give power more than 50 milliwatts it will get saturated, it will not respond. So, p max is 40 milli wat and if you see the sensitivity, it is 50 milli volt per milli watt. Now, let us see when I increase this RL, what happens to these values?

So, I have increased the RL to 10 kilo ohms and if I calculate p max this is 4 milli watt my detection range has decreased. Whereas, if I see the sensitivity part, it becomes 5 volt per milli watt; that means, my sensitivity has increased. I am able to get 5 volts per milli watt; which was earlier 50 milliwatts per milli watt. This is 5 volts per milli watt. So, RL was 50 milli volts per watt.

So, depending upon your sensitivity or the detection range you select the value of RL. So, RL plays a very important role in the design of a receiver based on photo diode.

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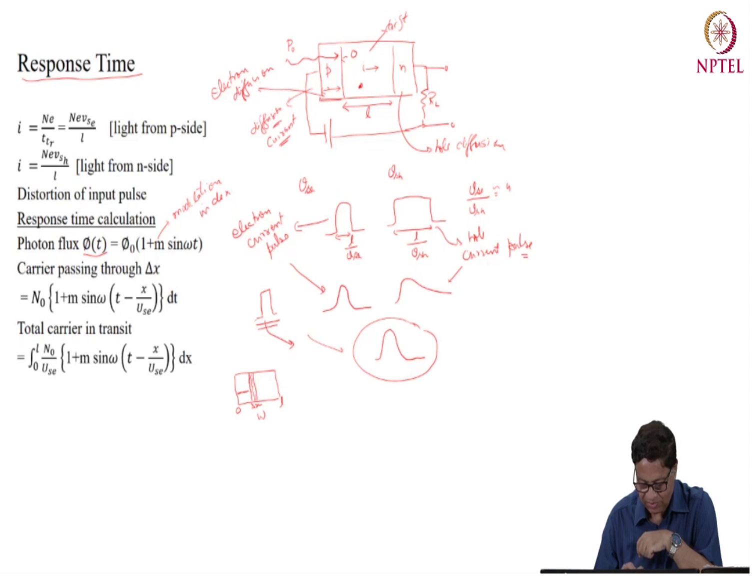

Now, let us understand the response time. So, response time understanding again we will have to draw our p n structure sorry. So, let me again redraw and then we will discuss about the response time. So, this is p this is n, this is reverse biased and then you have the RL here and these are the where you draw the voltage.

Now this is P region this is I. So, there are holes and there are electrons which are generated as a result of this incident light of power say p 0 and hole will move in this direction and I will move in this direction alright. So, if these electron hole pairs are generated in this region, in this region; they will it is called diffusion. So, this process is called diffusion and they it is a slow process.

So, electron hole pairs will take some time to generate current. If that happens in a; in this region where there is a voltage. So, this electron hole pairs they are swept away and they generate current and this is called as drift current. So, you have two parts, one is drift current and the diffusion current. So, we want actually this p n n to be very very small.

So, that the diffusion component is much less. So, that you know we will see that it will not degrade your response time. So, what want that all the photon electron. So, electron hole pairs should be generated within the I region and they are drifted with a drift velocity and the delay component is much less and the response time of the device is very high.

So, I can call this as here hole diffusion this will be hole diffusion and this is electron diffusion and let us see the length of this device is or the I region is l; where I want the whole you know activity happening in this I in this l region. So, when electron actually when is swept towards the which constitute the current because of the drift it will attains some velocity which is called as a saturation velocity.

Let me define that as vse. So, that electron pulse which will generate will be something like this. So, this will be l over vse and similarly, the hole will contribute to the current and if and that will attain some velocity vsh and we know the ratio of vs e and the vs h the saturation hole velocity is approximately 4. So, this will generate into a current pulse which will be little wider and this will be l divided by vsh.

So, this is how it will be generated. Electron current pulse let me denote this as electron current pulse, electron current pulse and this is hole current pulse hole current. So, if this electron hole pairs are generated in the middle each one will travel l by two distance, but in actual practice electron hole pairs can be generated anywhere inside the I region.

So, effective pulse which you launch here, if you see the electron current pulse because of you know the optical pulse which is launched in this fashion then it will be little distorted. So, this will be something like this and similarly the hole pulse because it is generated throughout the I region and if you take the you know sort of average of it will be something like this.

So, this is the corresponding hole current pulse and this is the electron pulse and because both are contributing to the current. So, this pulse which was launched like this and if you try if you add the add them up and including the diffusion part then what you get is not this kind of pulse. But you get a distorted pulse. So, because of the diffusion the drift nature of this device your pulse gets distorted and this is what you get at the output right.

So, this is going to limit your response time. Because if the distortion is too much then there may be interference with the next pulse and the response time gets reduced. So, if I see the current which is generated when the light falls from the p side is n number of electrons into e divided by the transit time; the time it takes to travel the device which for electron is n into e t a t t tr t transit is vse divided by l.

And if the light is from the n side then the current which is generated gives you n into e vs h. This is the saturation velocity of the hole vsh this is the saturation velocity of the electron is ne vsh divided by l. So, this will result as I explained you the distortion of the input pulse which I had discussed here.

This the input pulse gets distorted because of this diffusion and the drift phenomena which I have explained in detail here. So, now let us try to calculate the response time what is what is the maximum bandwidth I can achieve in a photo diode and if I want to improve what are the ways of improving it.

So, let us try to do some calculations to understand the response time. So, let us assume that the photon flux which is incident on the PIN diode is say phi t which is some sinusoidal or some modulation modulated signal which is given as phi 0 into 1 plus m sin omega t m is the frequency and m is the modulation index. This is the photon flux which is incident on the photo diode.

Now, let us try to understand let me break this photo diode into a smaller structure which is something like this. So, this will be width is this thing and let me take a slice here which I called as delta x. So, let me see how many what is the carrier number of carrier which are passing through this small portion delta x and then we will try to integrate this from 0 to whatever the length is suppose the length is l up to l right and then find out the total carrier passing total carrier which are generated.

So, if I want to calculate the carrier passing through this delta x which is a thin slice here of width delta x. This is given by n 0, n 0 is the initial number of electron carriers generated into 1 plus m sin omega t and this t minus x divided by velocity saturation velocity of the electron is what all electrons which are generated prior to this will actually contribute to the electrons which are passing through this thin slice which is delta x.

So, this the electron which are generated in in this region in this region will contribute the number of electrons passing through this delta x. So, this is represented as n 0 into 1 plus m, m is the modulation index sin omega t minus x by vse saturation velocity into d t. The total carrier in the transit will have to integrate from 0 to l. So, this I am integrating from 0 to l into n 0 divided by saturation velocity into 1 plus m sin omega t t minus x v s e into dx.