Semiconductor Optoelectronics
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Lecture - 40
General Characteristics of Photodetectors

(Refer Slide Time: 00:40)

So we come to the last part of this course, semiconductor photodetectors. Today, we will discuss the general characteristics of photodetectors. So, photodetectors, photodetectors are broadly classified into two types of photodetectors - photoemissive type, photoemissive, and photo-conductive, so photoemissive type and photo-conductive type.

As the name indicates, photo in, photoemissive type of detectors incident photon results in emission of an electron. A very important example here is the PMT, photo-multiplier tube, widely known as PMT. It is a photoemissive type of detector where the incident photon results in emission of electrons, incident photons result in emission of electrons, which which are subsequently multiplied by avalanche process to get significant amount of current. The very important type of detector, which have has very good sensitivity, sensitivity, it can go down to 10 to the power of minus 19 watts, 10 to the power of minus 19 watts, very, very small, so extremely sensitive detector.

But we are more interested in semiconductor detectors. We will see depending on time we will cover this. Photo-conductive as the name indicates, so this is photoemissive, photo-conductive. The incident photon changes the conductivity, changes the conductivity of the detector. So, photo-conductive refers to detectors where based on change in conductivity, change in conductivity, change in conductivity due to incident photons.

There are three important types of detectors here; the photoconductor, photoconductor, photodiodes, photodiodes, phototransistor. As you can see, that this is not a junction device, this is a simple piece of semiconductor. Probably one of the few applications where you use the semiconductor as it is, otherwise most of the devices are junction devices, p-n junction device, photoconductor, photodiode, phototransistor, phototransistor. In photodiodes, there are the two very important classifications, which is particularly important for optoelectronics in the optical communications are the pin diodes, PIN diodes and APDs, avalanche photodiode; pin, PIN diode and APD, standing for avalanche photodiodes. So, we will focus in the next few lectures on this phototransistor.

There are other detectors, we also have affiliated other detectors, like CCDs. Very important today, CCD, primarily for imaging and then solar cells, solar cells are basically photodiodes, solar cells. There are also another class of detectors, which are called thermopiles, thermopile, thermopiles. As the name indicates, these are certain materials, which, whose temperature changes due to absorption of the incident radiation, particularly used for high energy pulse detection thermopiles. We will not go in this, but we will focus our attention on this and depending on time we will see the other detectors.

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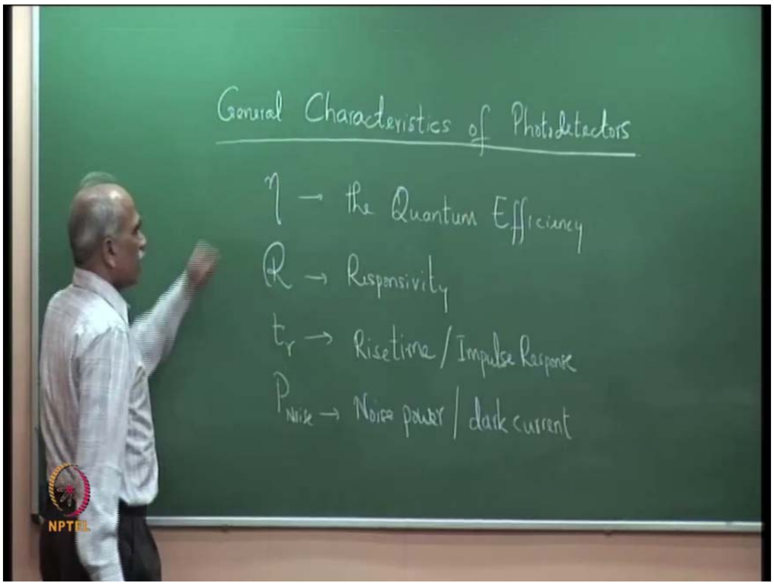

General Characteristics of Photodetectors

η → the Quantum Efficiency

R → Responsivity

t_r → Risetime / Impulse Response

P_{Noise} → Noise power / dark current

So, we begin with general characteristics of photodetectors. What are the general characteristics, which are common to photodetectors? The general characteristics of photodetectors, some of the detectors have gained, we will see this as we go further. The most important detectors used in communication are PIN diodes and APDs. The material issues are similar and we will see again, we will recall the materials and the absorption of these materials.

So, general characteristics of photodiodes, first there are four important parameters. First, eta, the quantum efficiency, quantum efficiency of a photodetector, please see, this is not internal quantum efficiency. We had defined one eta i for semiconductor material, which was the internal quantum efficiency, this is the quantum efficiency, we will define each one of them, quantum efficiency. The second one is responsivity, responisivity, responsivity and third is t r. I have written rise time here, t r standing for rise time, but this is also a measure of the impulse response, impulse response.

The rise time will determine what is, rise time or impulse response will determine what is the bandwidth of the detector, how fast the detector can respond and finally, finally, it is the dark current or noise power. So, p noise, so let me write p noise, noised power oblique dark current, dark current, these are more important for communication. In general, for detection of light these two are more important, but but in the case of communication, high speed communications, the rise time and the noise power are very important.

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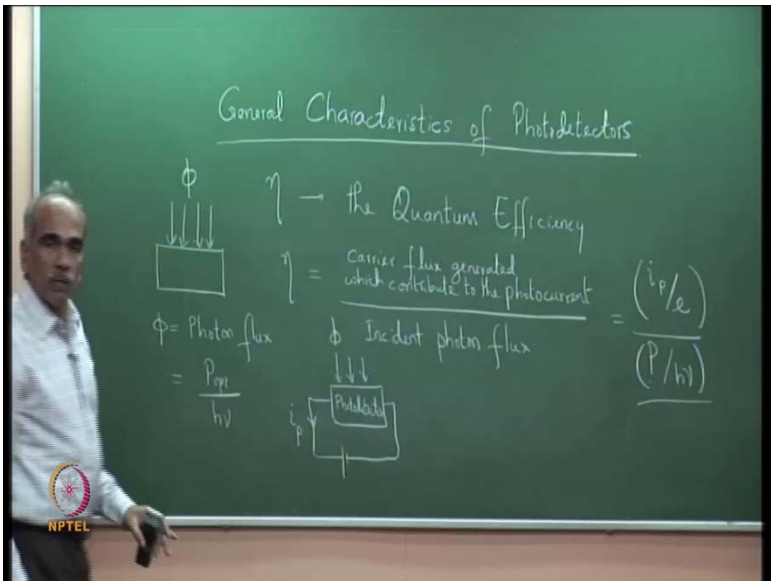

General Characteristics of Photodetectors

$\eta \rightarrow$ the Quantum Efficiency

$$\eta = \frac{\text{Carrier flux generated which contribute to the photocurrent}}{\phi \text{ Incident photon flux}} = \frac{(i_p/e)}{(P/h\nu)}$$

ϕ = Photon flux $= \frac{P_{opt}}{h\nu}$

So, we start with the quantum efficiency of a detector. What is the quantum efficiency? Quantum efficiency refers to the fraction of the fractional number of carriers generated per incident photon, fractional number of carriers generated, so eta is equal to, if you consider a photodetector here and there is a photon flux, which is incident here, photon flux, phi, phi is the photon flux, photon flux, photon flux. Photon flux means, if p optical is the power, p optical divided by h nu, energy of one photon, this is the photon flux.

Photon flux is the number of photons incident per unit time, photon flux. So, if phi is the photon flux, then p divided by h nu gives you. phi eta is the ratio of the carrier flux, carrier flux generated, generated, which, which contribute, contributes to the photocurrent, to the photocurrent. Photocurrent refers to the photon generated current divided by the incident photon flux, incident photon flux; everything will become clear, incident photon flux. Carrier flux generated, that is, number of carrier electron-hole pairs. An incident photon generates an electron-hole pair and the electron-hole pairs generated, which contribute, there is a clause here, generated, which contribute or that contributes to the photocurrent in the external circuit divided by the incident photon flux.

So, what this means is, if i is the photocurrent, we see, this i p is the photo current generated, then the carrier flux is simply, photocurrent divided by e, charge of one electron. If i is the current, which is flowing, then the carrier flux generated is i p by e divided by p divided by h nu; i p is the photo current in the external circuit. What it becomes is, so let me draw here again. So, here is the photo-detector and you apply a voltage here, then incident photon flux here, if it leads to photocurrent, which is a reverse current i p in the external circuit, so this is the photo-detector.

What type of photo-detector we do not worry, now it is a photo-detector and there is a photon flux phi, which is incident, then if i p is the measured current in the external circuit, then i p by e will give you the carrier flux generated, that contributes to the photo current in the external circuit divided by the incident photon flux. This is the incident photon flux. So, straight forward keep the picture clear and you do not have to remember anything if you keep the picture clear, things will be alright. Now, let us see what, what, does this eta depend on? I will explain what it means. This second part here, which contributes to the photocurrent because obviously, that means all the electron-hole pairs generated need not contribute to the current in the external circuit. So, we will come to that in a minute.

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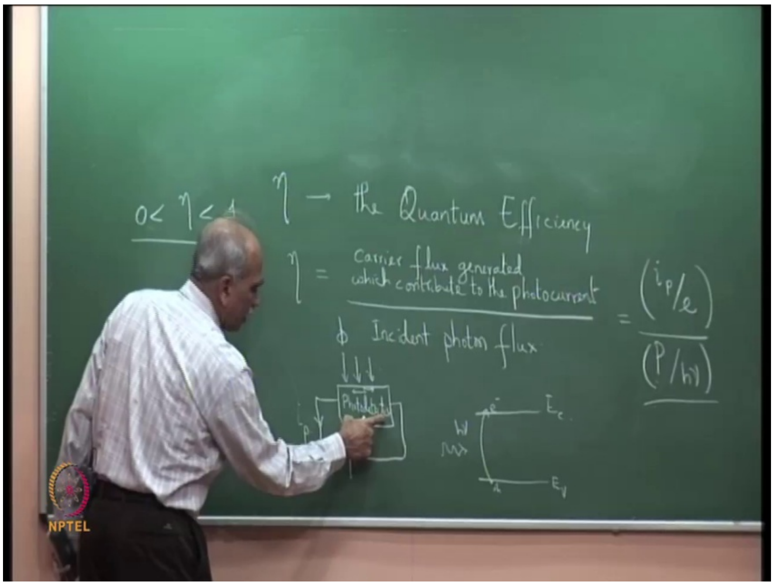

This is the definition of eta quantum efficiency, obviously eta is less than 1, so 0 less than or equal to eta less than or equal to 1 at best or in general, I do not even use this 0 less than or eta less than equal because it is a fraction. Every incident photon, this is number of photons, photon flux is number of photons incident per unit time and this is number of carriers generated. Every incident photon will generate 1 electron-hole pair that is all at best. All incident photons may not generate electron-hole pairs, but at best one incident photon.

We are not in the regime of non-linear optics, we are in the regime of linear optics where you have the material of band gap, so E v, E c, there is a photon, which is incident here, h nu. Then an electron sitting here would go here to get an electron-hole pair, e-h pair. You can show that motion of an electron, the motion of an electron and hole simultaneously inside the semiconductor is equivalent to one charge e, which is moving in the external circuit. This we can show the motion of electron inside, that is, electron-hole pair, one electron-hole pair moving inside the semiconductor is equal to one charge, electron charge e moving in the external circuit. This can be shown from (( )) theorem, we will see, depending on time we will get into that, but right now I hope this part is clear. And what is the expression for this eta? We find out the expression for eta. This is in terms of the incident optical power and the photocurrent generated incident optical power and photocurrent, but what does eta depend on and we need to maximize this eta.

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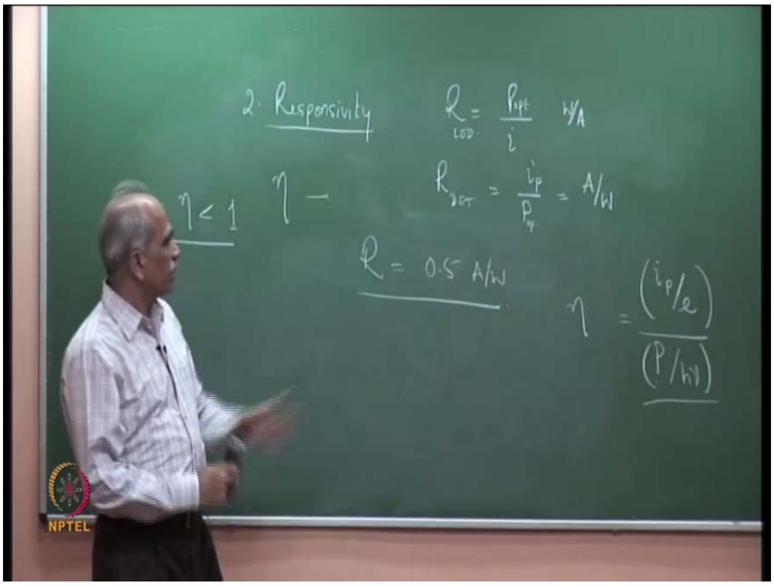

Quantum efficiency, why we need to maximize this quantum efficiency? So, before I proceed to eta let me look at the expression for eta again. The second parameter, which I had written was responsivity, responsivity. We talked of responsivity in the case of a LED. If you remember, that if you pass a certain current i what is the optical power generated. So, responsivity in the case of a LED was R equal to optical power generated. So, responsivity was optical, p opt divided by current i. When you pass a current i what is the optical power generated? So, it was, unit was watt per ampere in the case of a photo-detector.

So, this, for source LED or a source in the case of a photo-detector, the response is the photocurrent, incident is the power, response is the photocurrent. In the case of a source you pass a current and see how much power is generated. In this case, incident photo-detector, photo optical power generates how much current? Therefore, responsivity of a detector is defined as i p divided by p, p optical. Always I am talking about optical power, so this is in amperes per watt.

You will see, if you take a data sheet of any photo detector, there will be, this parameter will be there responsivity R equal to 0.5 amperes per watt, typical number for a silicon photo-detector, responsivity is 0.5 amperes per watt. This is very important for the design engineer because if he is dealing with the few milli-watts of power, this will tell him how much current will be generated in a particular application. He may be using 10 micro-watts in another application, one may be using milli-watts and in another application one may be using hundreds of milli-watts of optical power and the responsivity will tell you how much is the current generated, that is very important to design the electronic circuit, what is the current generated, so responsivity is this. So, if you see, therefore, therefore, i p divided by p, it is here, i p by p, so responsivity.

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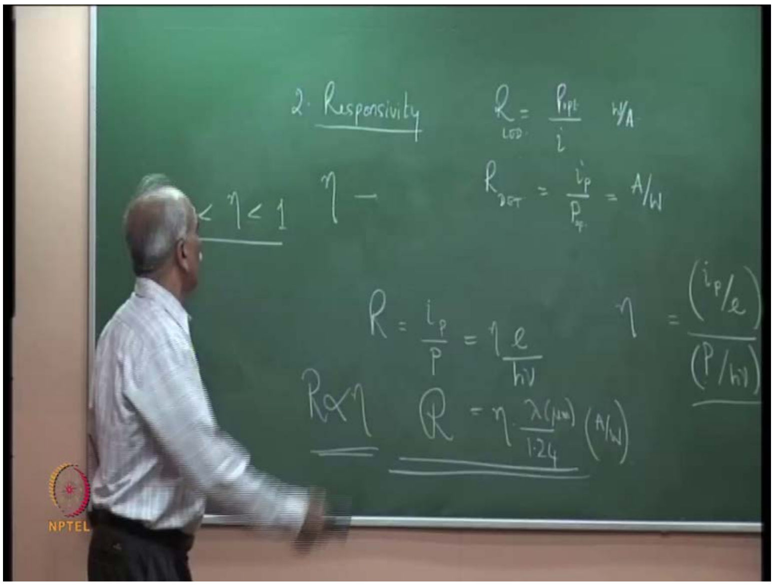

So, I now have the expression for responsivity equal to i p by p, is equal to i p by p. So, I take this here, then eta into h nu, oh this was already in the denominator, so it is, h nu comes to the numerator, so eta into e divided by h nu. Responsivity equal to i p by p, i p by p. This e was in the denominator, h nu was, so there it is eta into this and this is equal to eta. This is we our familiar, what is that? So, this is, nu is c by lambda, lambda goes to the numerator and therefore, therefore, this is eta into lambda divided by 1.24 lambda micrometer.

So, responsivity is equal to, if you substitute lambda in micrometer, responsivity is so many amperes per watt, amperes per watt. What we see is the, responsivity is proportional to eta, so responsivity, this clearly tells us, that responsivity is proportional to eta. If you want to maximize the responsivity, which means, for an incident optical power if you want to get maximum photo current generated, you have to maximize eta because about this you cannot do anything. This is a constant, lambda is the wavelength that we are using, so eta is the only one, which you can maximize if you want to maximize responsivity.

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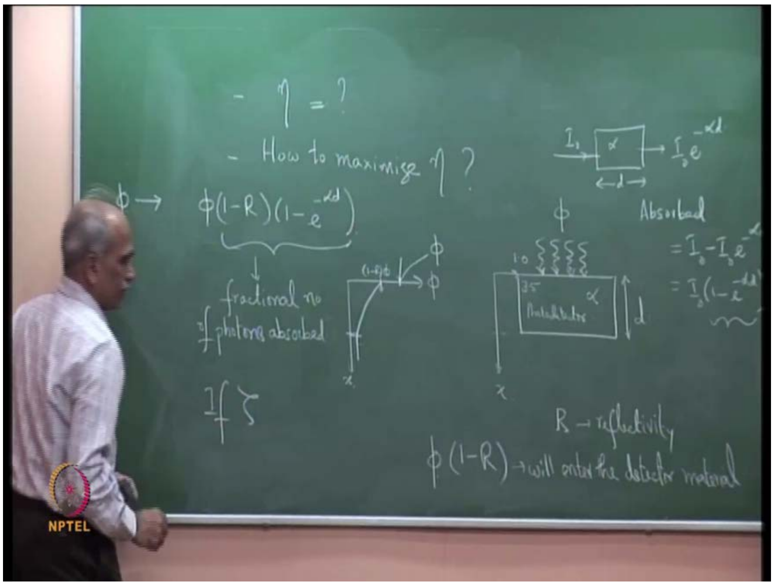

So, what does eta depend on? We have given a definition, but what does physically eta depend on? So, let us discuss about this. So, I have simultaneously taken both the parameters at hand. Responsivity is proportional to eta and we have to focus on maximizing the responsivity, which means, maximizing eta. So, eta equal to, what is eta and how to maximize? So, what is eta and how to maximize, these are the two questions, which we want to address; how to maximize, what is eta and how to maximize? Consider a photo-detector surface, here is a photo-detector, this is of thickness d. So, this is a photo-detector, which is basically a semiconductor material. So, photo-detector, in this case a semi-conductor material of thickness d and photons are incident, light is incident from here. A photon flux phi is incident here; photon flux phi is incident.

Now, out of the incident photon flux, if you see this as the depth direction, this is the surface and this is the depth, so let me call this as x. x is the depth, depth direction, then incident photon, so here this is, phi is the photon flux incident. If I consider phi as the photon flux here, so this is photon flux phi, then out of this, refractive index here is 1, refractive index here may be 3.5, a semiconductor. Then a fraction of light photon flux is nothing but light that is incident, is reflected back because of the index difference.

So, if r is the reflectivity, oh this r, I have to use some other r, what r will I use, small r is for amplitude reflectivity, by convention capital R is, let me write the roman capital R, so this is reflectivity. If R is the reflectivity, reflectivity R is the reflectivity, please see wherever i have written this r, i usually write like this, responsivity, this is flower r, this is the roman capital R, that is, reflectivity. So, if R is the reflectivity, r into phi will be reflected back. If R is the reflectivity, reflectivity like in the semiconductor laser we had seen, that it is 0.32, if you take a 3.5 and this, this will, this will come out to be approximately 0.3, that is, 30 percent is reflected back, so only 70 percent is entering. Therefore, the amount, which is entering, so phi is the photon flux, but what is entering here will be, how much will this be, what is entering here. Please see, incident is phi, what will enter the material, what will enter the material means, 1 minus r into phi, phi will enter the semiconductor, the detector material.

Things will become clear, just see this. So, this is 1 minus r, r times has gone, so this is 1 minus r into phi is the value here out of this. As it enters, the photon flux will decrease exponentially inside the material. Why it receives the semiconductor, which has an absorption coefficient alpha. If I 0 is the intensity, which is incident and if this thickness is d, then the output is I 0 into e to the power minus alpha d. So, inside this medium intensity is exponentially decaying, is that alright. It is exponentially decaying because alpha is the absorption coefficient of the semiconductor, alpha is the absorption coefficient of this semiconductor here, alpha.

Therefore, once it enters… What I am plotting here? I am plotting photon flux phi as a function of x depth, incident is phi, right. At the interface 30 percent is reflected back over all times, phi is reflected back, therefore what is entering is 1 minus r times phi and that is now exponentially decaying by a factor e to the power minus alpha x, is that alright. So, that is why, I have shown the photon flux decaying like this.

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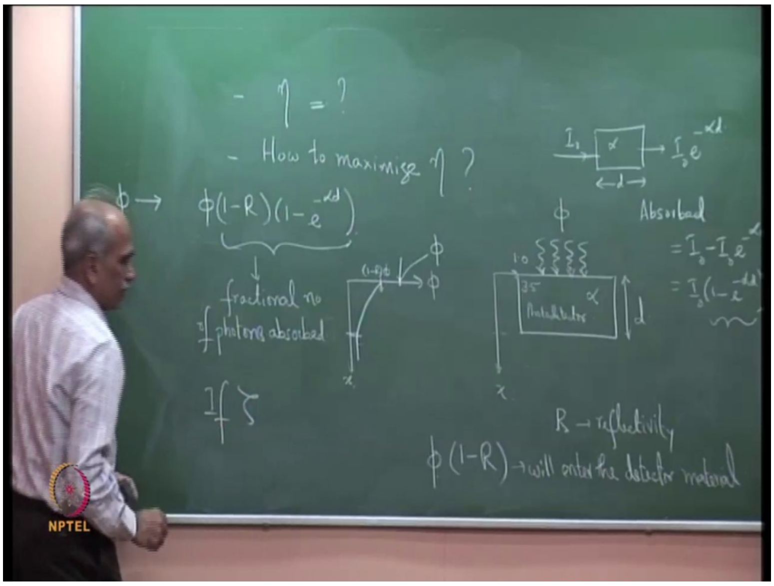

So, if you are up to d, so up to d, so d is here, then the exponential decay will come here and then from here it is constant, it is into the air. So, what I have plotted is photon flux inside, here photons are continuously getting absorbed up to d. So, what would be the amount of photons absorbed? 1 minus r into phi was entering, please see, 1 minus r into phi was entering and then at d, this is e to the power minus alpha z. Please see, this is coming out, so what is absorbed?

Absorbed energy is equal to I naught minus I 0 e to the power minus alpha d, which is equal to I 0 into 1 minus e to the power minus alpha d . If I naught enters, I naught into e power minus alpha d comes out, which means, the difference between this is absorbed in the medium. I am interested in how much energy is absorbed because it is the absorbed photons that will generate carrier pairs, which will contribute to my current in the circuit and therefore, this is what is absorbed. So, what is the fraction that is absorbed is 1 into this because I naught is incident and this fraction is absorbed and therefore, this into 1 minus e to the power minus alpha d.

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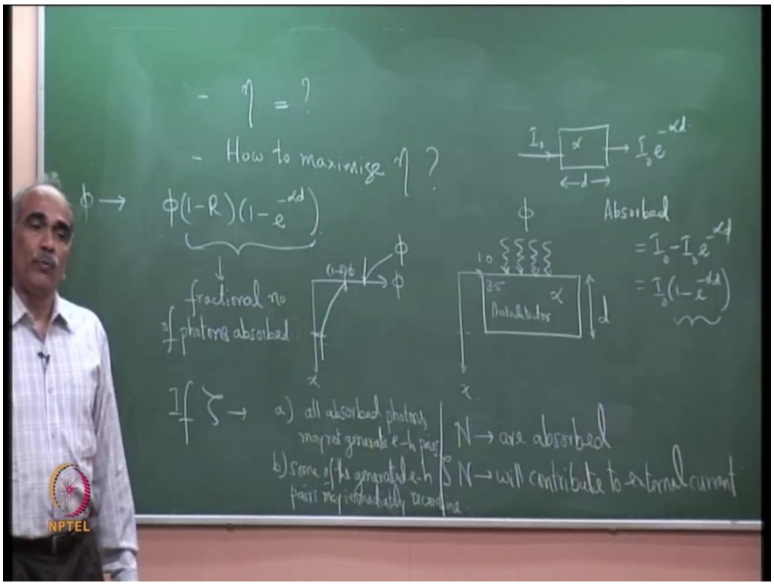

What am I showing? My incident was phi, after coming out here this is the fractional number of photons, which are absorbed. So, what I have written here is the fractional number of photons absorbed, fractional number of photons absorbed other than phi because phi if I put, it will tell me the total number of photons absorbed. This is the fraction, which is absorbed. This is entering out of the (( )), this fraction is absorbed, this is not sufficient. What was our definition? Out of this how many of them will result in the generation of carriers and how many of them will contribute to the current?

In the external circuit if zeta is that fraction, if zeta is the fractional number, is the fractional number of photons that are absorbed and that generates. So, zeta fractional number, zeta comprises of two components. Please see this one, out of all the photons, which are absorbed, all may not lead to generation of electron-hole pairs. Why, what would happen to the rest? Some of them may just generate phonons, it is not necessary, that they should, they can give energy to the lattice.

Also, some of the photons may give energy to the lattice and get absorbed; some of the photons may get absorbed in traps. There may be trap states, so a photon will get absorbed in lifting this. This is not a free carrier, so some of the energy may be out of the all photons, which are incident. If n number of photons are incident, absorbed, n are absorbed only a fraction zeta times, n will contribute to the external current; contribute to external current. So, zeta comprises of two parts, one all photons, all absorbed photons. All absorbed photons may not, may not generate, generate e-h pairs, e-h pairs, e-h pairs.

Second, the generated e-h pairs may immediately recombine some of the generated e-h pairs may immediately recombine due to defects or surface states. So, some of them, some of the generated e-h pairs, e-h pairs may immediately recombine. I hope you can see this, immediately recombine, which means even though n photons are absorbed, only a fraction of them will lead to generation of carrier pairs, electron-hole pairs, which are contributing to the current in the external circuit.

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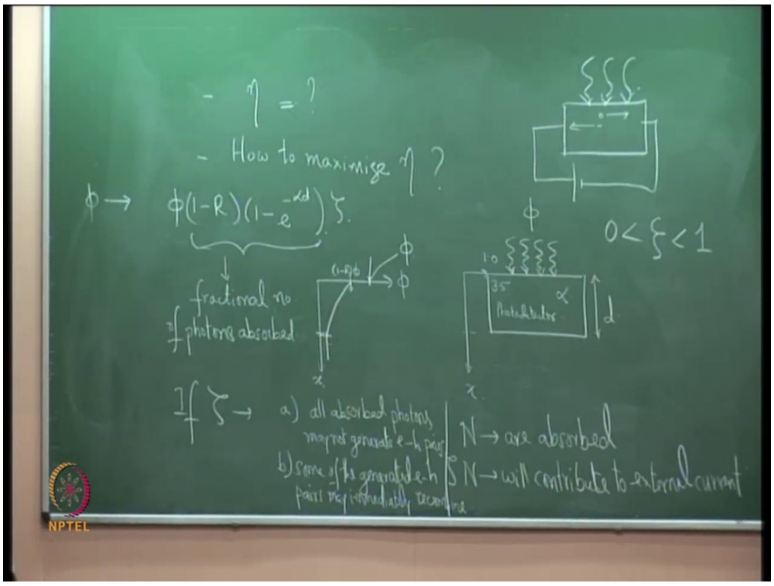

Please see, I had drawn a circuit like this. Let me make it clear what am I referring to. So, here is the incident photon flux, here it generates, let us say, an incident. Photon creates an electron-hole pair in the semiconductor. The electron will start moving towards this and hole will start moving here. So long as the electron and holes are moving, they are contributing to the current in the external circuit, but the generated electron-holes may immediately recombine due to the presence of surface states or defect states in the medium. And if they, the moment they recombine, they are no more contributing to this. Do you follow?

Out of all absorbed photons every photon may not lead to generation of carrier pairs. And second, even though they lead to generation of pairs, the generated pairs may immediately recombine and therefore, the actual number of carrier whole pairs, which are contributing to the external circuit will the less than the generated number of carrier hole pairs, which means, zeta. So, 0 less than zeta less than 1, so n are absorbed; n is the number of photons absorbed. Zeta times n will only contribute to the current and therefore, this needs to be multiplied by a factor zeta, that is all.

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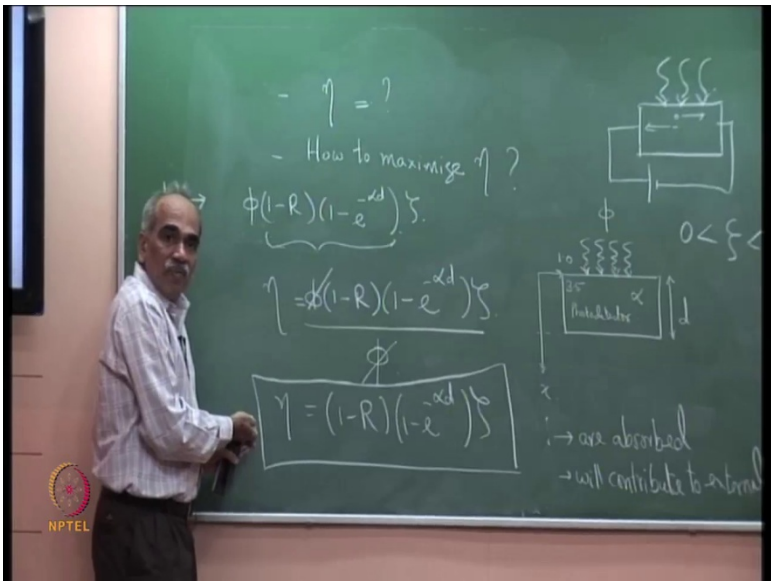

So, what is this? This is, I had written the definition of eta as the number of eta is equal to 1 minus half. The internal quantum efficiency equal to 1 minus half into 1 minus e to the power minus alpha d into zeta because this is phi divided by incident photon flux phi. So, phi, phi cancels, incident photon flux is phi, phi into this 1 minus R enters the semiconductor. Phi into 1 minus R into 1 minus e power minus alpha d is absorbed in the medium. This into this into this into this will be the fractional number of carriers, which are contributing to the current. Therefore, the definition of eta is, this I by e divided by the photon flux. So, phi, phi cancels, so eta is simply equal to 1 minus T into 1 minus e to the power minus alpha d into zeta.

Why did I write this in this form? Earlier also I had written an expression for eta in terms of the optical power and the current, which is the practical thing. Power is incident, you know, that this much power is incident, this much current is generated, that is what an engineer would like to see. But unless you know what factors contribute to eta, you cannot maximize eta.

Now, let me tell you how to maximize. Once I have written this expression I know how to maximize this, how to maximize? If I can make R equal to 0, this will be very large. If I can make this equal to 0, this will be maximum. If I can make this equal to 1, that will be maximum. Therefore, the question is how to make R equal to 0, how to make this term equal to 0 and how to make this term equal to 1. What will affect these things? So, that is what the device engineer will need, the one who makes the device, not the one who uses the device, one who uses the device wants to get very good responsivity. That is all how you, how you get very good responsivity.

We have to maximize eta, who will maximize eta? The device fabricating engineer, he has to maximize eta. So, how to maximize? So, the question I had written, see how to maximize eta is the question. How can we make R equal to 0, R equal to 0? If I can make R is equal to 0, then this quantity will become 1. If I can make this equal to 0, this quantity will be 1. If I can make this equal to 1, this will also be 1 and eta will become 1.

Quantum efficiency of 100 percent, in practice one can get quantum efficiency of 90, 95 percent, it is possible. So, ideally, if everything is taken care, you will get quantum efficiency 1, but normally around 0.9 is the quantum efficiency.

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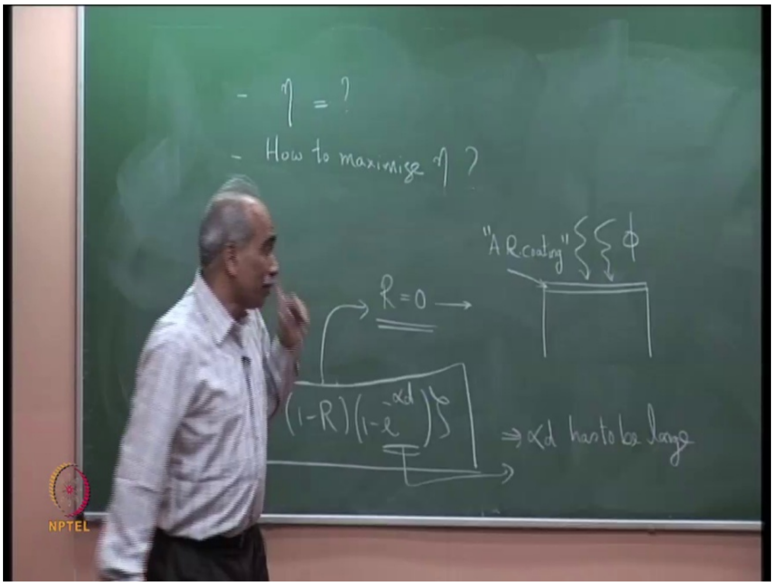

So, R has to be 0, R equal to 0, how to do R equal to 0? Yes, we need to put the material with an antireflection coating. So, incident photon flux here, so phi is the incident photon flux. If you coat an antireflection coating, AR coating, I think we have discussed enough about this importance of AR coating, antireflection coating, then there will be no reflection. So, R is equal to 0. Of course, in general, you can make antireflection coatings. At one particular wavelength it is not possible to make antireflection for all wavelengths.

So, if you are using a general photo-detector with a power meter, for example, for a general purpose measurement, then you may, you may probably measure the visible region, the I R region and then it is a range of wavelengths and in such cases it is not possible to make an AR coating. But if your application is specific, like for example, optical communication, your wavelength is around 1.55. Yes, you can have AR coating, which is almost, which will cut down R down to 0. So, AR coating will lead to R equal to 0. So, this is first point. Second, how to make this 0? e to the power minus alpha d, this implies either alpha, this term has to be very large, so implies alpha. d has to be large, which means, either alpha has to be large or d has to be large or both have to be large. You remember, we had…

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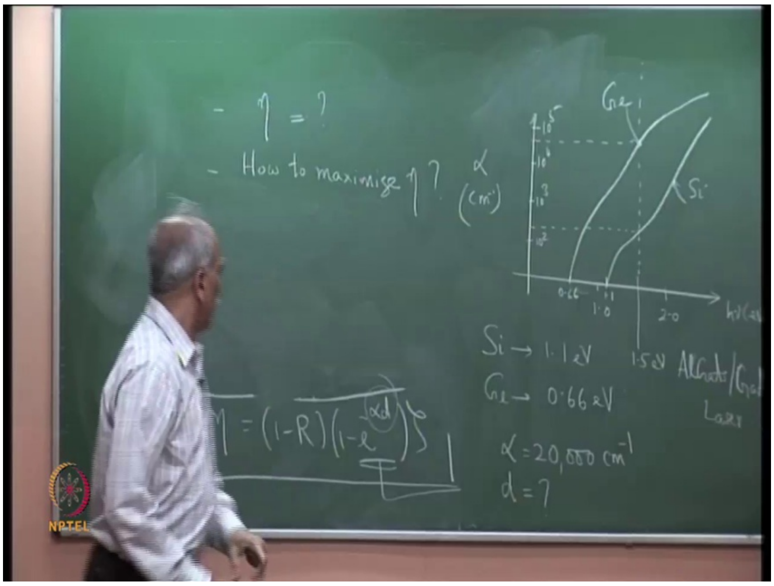

Ok, let us recall the absorption curve that we had drawn. So, here is h nu in Ev, Ev, then here is alpha centimeter inverse. So, you may recall, that we had numbers like 10 to the power of 2, 10 to the power of 3, 10 power 4, 10 power 5 centimeter inverse and we had 1 Electron-volt, 2 Electron-volt and so on. So, if I take two important materials of semiconductor, namely silicon, which has a band gap of 1.1 eV and germanium, which has a band gap of about 0.66 eV, then absorption will start right at e g, as you know, so 6 0.6 here. So, germanium absorption coefficient starts something like this and then it goes up. So, this is for germanium, for germanium and for silicon starts at 1.1.

So, let us say this is 1.1, this is 0.65, 0.66 and this is 1.1 for silicon. So, silicon also goes… Approximately, I have drawn the absorption curves for silicon and germanium. You may recall that both of them are direct band gap semiconductors. For direct band gap semiconductors, the absorption curve shoots almost vertically up, whereas for indirect band gap it increases a little slowly. And if I take, let us say, I am using a laser, which is corresponding to 1.5 eV, the laser, which is emitting at h nu equal to 1.5 eV, typical of gallium arsenide lasers, algas, algas lasers. So, aluminum gallium arsenide, a, l, g, a, s, so gallium arsenide laser emitting at 1point h nu, then you can see, that at this value.

So, the coefficient, absorption coefficient, these are approximate numbers or, so germanium has a very large absorption coefficient, so 10 to the power and 10 to the power of 5. So, approximately, for germanium alpha is equal to, let us say, 20000, 20000 centimeter inverse, 2 into 10 power 4, 10 power 4 is here, is a log scale, so 2 into 10 power 4 I have written is about or may be 3 into 10 to the power of 4 centimeter inverse. And for silicon it is a few hundred, few hundred centimeter inverse. So, for this wavelength germanium has a very high absorption coefficient.

For example, if I take this alpha what is the d required, d equal to, so that this number is very large? Please see, the thickness of the material required will depend on the value of alpha. We want alpha d to be very large, alpha d to be very large, which means, either alpha has to be large or d has to be large. Alpha is a parameter, which is characteristic of the material; for a given material, here is the alpha variation at a given wavelength. Therefore, if a good quantity of the incident photon has to be absorbed, you have to choose the right value of d.

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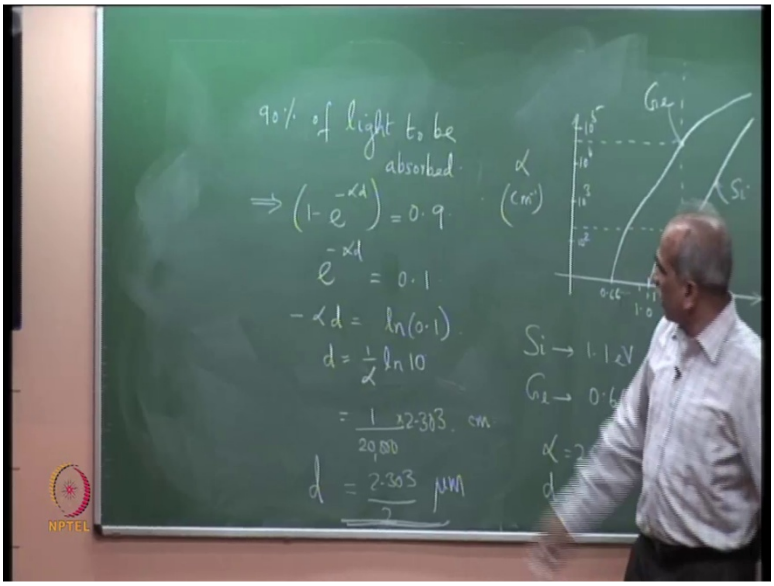

Let me take an example. For example, I want that 90 percent of light has to be absorbed. So, if I want 90 percent of light has to be absorbed, to be absorbed, this implies, 1 minus e to the power minus alpha d must be equal to 0.9. 90 percent has to be absorbed, so this is the fractional number, so this must be equal to 0.9 or e to the power minus alpha d must be equal to, this will go here, so it is 0.1 minus 0.1 minus 0.1. This will go here and this is 0.1 and therefore, alpha d, if you take log, so this will give you alpha d. Alpha d minus alpha d is equal to ln 0.1, 0.1 or 1 by 10 or alpha d. Therefore, you can find out d is equal to ln 0.1 or I can write this as 1 by 10, so it will become minus 1. And therefore, I have d is equal to 1 by alpha into ln 10. Is this correct? d is equal to 1 over alpha into ln 10, so this is equal to my, this is 20000 centimeter inverse.

So, if I want to write this in micrometer inverse, for micrometer it will be simply, 2, 2 micrometer inverse or 20000, whatever. So, 20000 here, 20000, my unit will be centimeter. ln 10, ln 10 is how much? 2.303 into log of 10, which is 1, so this is simply equal to 2.303 centimeter, which is equal to, if I take this on to the numerator, it is 10 to the power, so this will come out to be 2.303 divided by 2 micrometer, about 1 micrometer. See, such a nice thing, that this tells you, that if you take germanium, which is only 1 micron thick, that will absorb 90 percent of the light.

Please see the logic, that how to detect this is, so this factor is so important because if you want to minimize this down to 0, you need to maximize them. Even with 1 micron will get 90 percent absorbed. If I make this as 10 micron, then this will almost go down to 0. So, if you take appropriate thickness and but if you had taken silicon as the detector at this wavelength, you would have required a thicker material at this wavelength. But somewhere later you will see, that silicon will be highly absorbed at a later value of h. So, it depends, depending on the material you have to choose. The point is, choose the (( )) material and right thickness, so that this goes down to 0. Our objective is to maximize zeta, alright.

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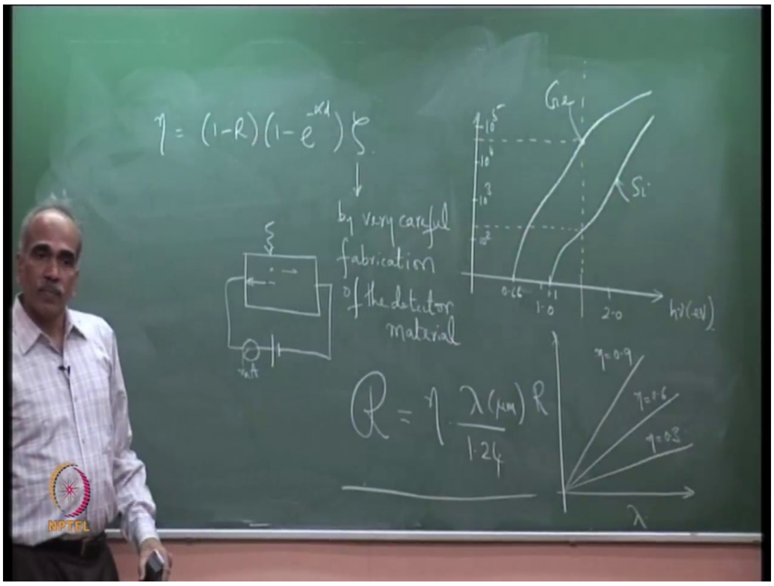

We come to the last point, that is, how to maximize zeta, how to maximize zeta. So, eta, recall, that eta is equal to 1 minus R into 1 minus e to the power minus alpha d into zeta. Zeta is the fractional number of absorbed photons, absorbed photons, that will generate electron-hole pairs, which contribute to the current in the external circuit, which means, first it has to generate electron-hole pairs and second, it has to contribute, which means, the electron-hole pairs have to remain alive as that, we do not want them to combine immediately.

If you take a photo-detector here, let us say, a photon is incident, there is an electron and a hole, which is generated. If you simply, current, connect to this outside, if m a, then there is, this is a piece of semiconductor, which you have connected here. There is nothing, which is driving these; there is nothing that is driving. Only if you apply a potential from outside, if you connect it to a battery, then only it will immediately, if I put positive and negative here, then immediately, the electron disc will travel here and hole will travel here. If they start travelling, then only there will be a current in the circuit.

So, first thing is, you apply a bias, an appropriate bias if it is a p-n junction. We will see later, that you have to apply a reverse bias. If it is a photoconductor, then there is no junction. You simply need to apply a bias, there is nothing like forward and reverse, so you just, so that the generated carriers immediately start moving away. If they do not move away immediately, they can always recombine. They can be wandering and they can recombine the electron and hole can recombine again giving out the energy, may be to the lattice, maybe as a photon, so you have to apply a bias.

Second, the generated electron-hole pairs can recombine very quickly if there are defects in the material because defects or traps act like the recombination centers, which lead to recombination of the generated carriers and therefore, the material fabrication zeta can be maximized by very careful fabrication, careful, very careful fabrication of the detected material. Be careful here, I am referring to very high quality, very high quality detector material, which are free of defects or minimum defect densities within the material of the detector material. High purity detector materials will minimize the defect densities and avoid recombination and then an applied bias from outside will maximize zeta.

So, these are the two factors, which will contribute to a maximum value of zeta if the generated carriers are immediately swept apart, then you are likely to collect, it contributes to the current in the circuit. So, in these, considering each one of them, please see, how I have built the expression for eta just from definitions. There is nothing to remember here, it is just from definitions.

We have got eta like this and eta need to be maximized because our objective is to have a maximum responsivity, which is equal to eta into 1.24, one minute, into lambda divided by 1.24. Lambda has to be substituted in micrometers. If you plot R versus lambda, we will stop in a minute, so if you plot responsivity versus lambda for different values of eta, it will be linear. So, R versus lambda if you plot you will get graphs. Say for example, eta equal to 0.9, eta equal to 0.6, eta equal to 0.3, fixed eta, but we will see in the next class, that eta is not a constant, eta is…

So, this is assuming, that eta is a constant; the responsivity is directly proportional to lambda. If eta is a constant, R is directly proportional to lambda and you will get straight responivities of, for example, you can put some numbers and find out what is the responsivity, but eta is not going to be constant. We will discuss this in the next class and in the next class I will also discuss about p-n diodes, PIN diodes and FEDs.