Semiconductor Optoelectronics
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Lecture - 39
General Characteristics of Photodetectors

Okay so we come to the last part of this course semiconductor photodetectors. Today, we will discuss the general characteristics of a photodetectors.

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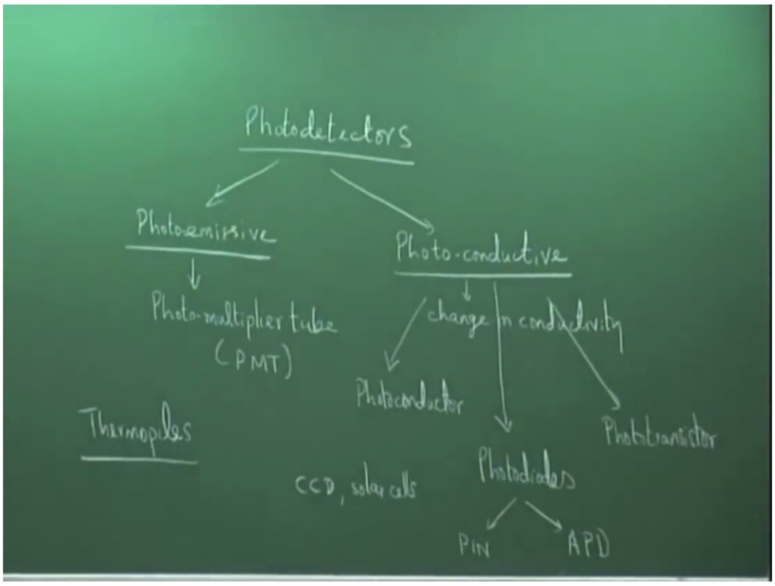

So photodetectors are broadly classified into 2 types of photodetectors, photoemissive type and photoconductive, so photoemissive type and photoconductive type. As the name indicates in photoemissive type of detectors incident photon results in emission of an electron.

A very important example here is the PMT photo-multiplier tube widely known as PMT is a photoemissive type of detector where the incident photon results in emission of electrons which are subsequently multiplied by avalanche process to get significant amount of current. The very important type of detector, which has very good sensitivity, sensitivity it can go down to 10 to the power of -19 watts, 10 to the power of -19 watts very, very small indeed.

So extremely sensitive detector, but we are more interested in semiconductor detectors. We will see depending on time we will cover this. Photoconductive as the name indicates so this is photoemissive, photoconductive. The incident photon changes the conductivity of the detector. So photoconductive refers to detectors were based on change in conductivity due to incident photons.

There are 3 important types of detectors here. The photoconductor, photodiodes, phototransistor. As you can see, 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 p-n junction devices. Photoconductor, photodiode, phototransistor.

In photodiodes, there are 2 very important classifications, which is particularly important for optoelectronics and optical communication are the PIN diodes and APDs avalanche photodiodes. 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 are basically photodiodes. They are also another class of detectors, which are called thermopiles. As the name indicates, these are certain materials 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.

So we begin with general characteristics of photodetectors. What are the general characteristics, which are common to photodetectors?

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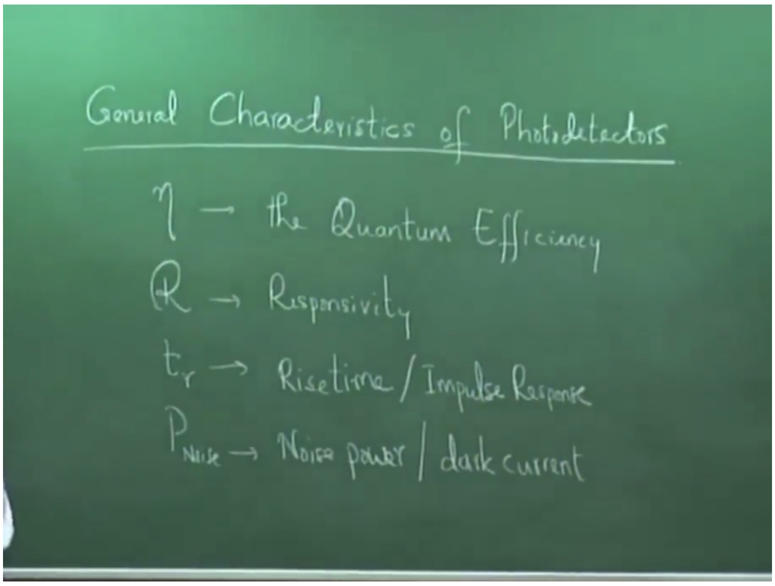

General Characteristics of Photodetectors

η → the Quantum Efficiency

$\mathcal{R}$ → Responsivity

t_r → Risetime / Impulse Response

P_{Noise} → Noise power / dark current

Some of the detectors have gain; we will see these 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 4 important parameters. First eta, the quantum efficiency of a photodetector.

Please see this is not internal quantum efficiency. We have 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 and third is tr I have written rise time here, tr standing for rise time but this is also a measure of the impulse response.

The rise time or impulse response will determine what is the bandwidth of the detector. How fast the detector can respond and finally it is the dark current or noise power. So P noise so let me write P noise, noise power or dark current. These are more important for communication. In general, for detection of light, these 2 are more important but in the case of high speed communications the rise time and the noise power are very important.

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.

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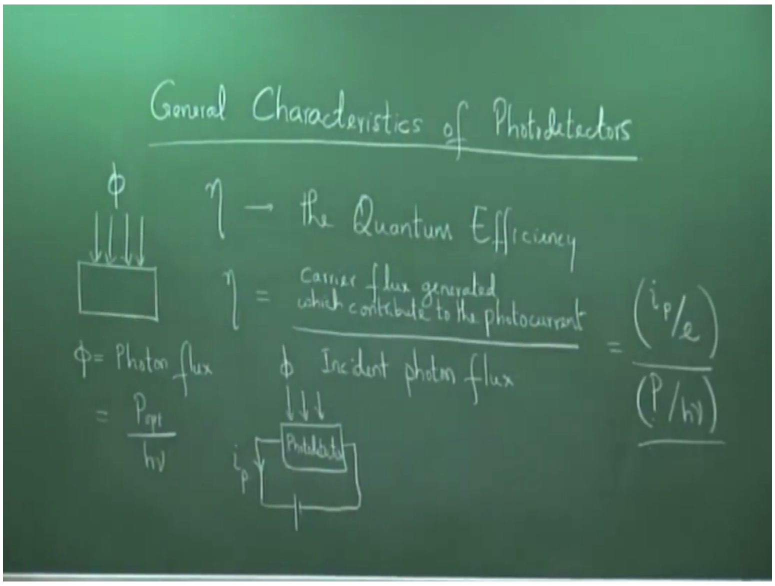

So eta=if you consider a photodetector here and there is a photon flux, which is incident here, photon flux phi, phi is the photon flux. Photon flux means if P optical is the power P optical/h nu energy of one photon. This is the photon flux. Photon flux is the number of photons incident per unit time photon flux.

So if phi is the photon flux then P/h nu gives you phi. Eta is the ratio of the carrier flux generated, which contribute to the photocurrent. Photocurrent refers to the photo generated current/the incident photon flux. Everything will become clear. Carrier flux generated that is number of carrier’s electron hole pairs. An incident photon generates an electron hole pair and the electron hole pairs generated, which contribute.

There is a class here generated, which contribute or that contribute to the photocurrent in the external circuit/the incident photon flux. So what this means is if I is the photocurrent, please see this Ip is the photocurrent generated then the carrier flux is simply photocurrent/e charge of one electron. If I is the current, which is flowing then the carrier flux generated is Ip/e/P/h nu. Ip is the photocurrent in the external circuit. What it insists?

So let me draw here again. So here is the photodetector and you apply a voltage here. Then incident photon flux here. If it leads to a photocurrent, which is a reverse current ip in the external circuit so this is the photodetector. What type of photodetector we do not worry now? It is a photodetector and there is a photon flux phi, which is incident. Then if ip is the measured current in the external circuit then ip/e will give you the carrier flux generated that contribute to the photocurrent in the external circuit/the incident photon flux.

This is the incident photon flux. So straightforward, 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 does this eta depend on? I will explain what it means this second part here which contribute 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. So this is the definition of eta quantum efficiency.

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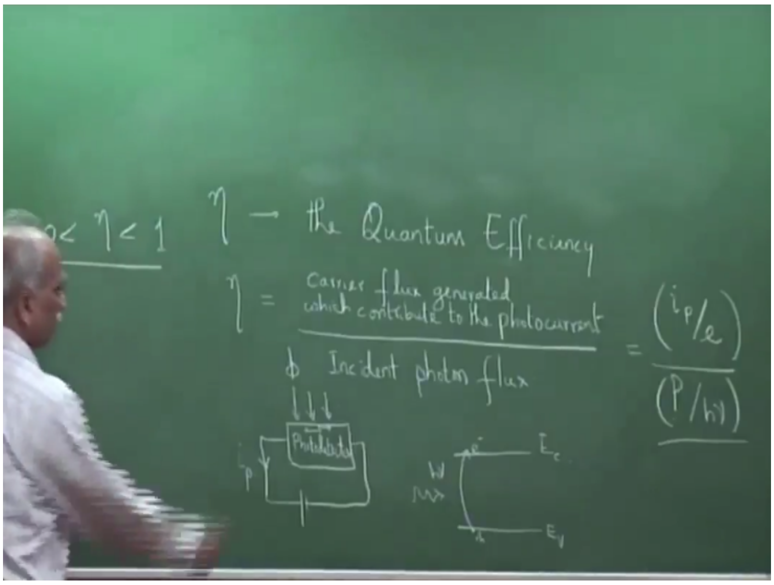

Obviously, eta is<1 so 0<=eta<=1 at best or in general I do not even use this 0<eta<1 because it is a fraction. Every incident photon this is number of photons. Photon flex is number of photons incident per unit time and this is number carriers generated. Every incident photon will generate one electron 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 nonlinear optics. We are in the regime of linear optics where you have the material of band gap so Ev, Ec. There is a photon which is incident here h nu, then an electron sitting here would go here to create an electron hole pair e-h pair. You can show that 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 that is electron hole pair, one electron hole pair moving inside the semiconductor=one electron charge E moving in the external circuit. This can be shown from Ramo's 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 but what does eta depend on and we need to maximize this eta quantum efficiency. Why we need to maximize this quantum efficiency.

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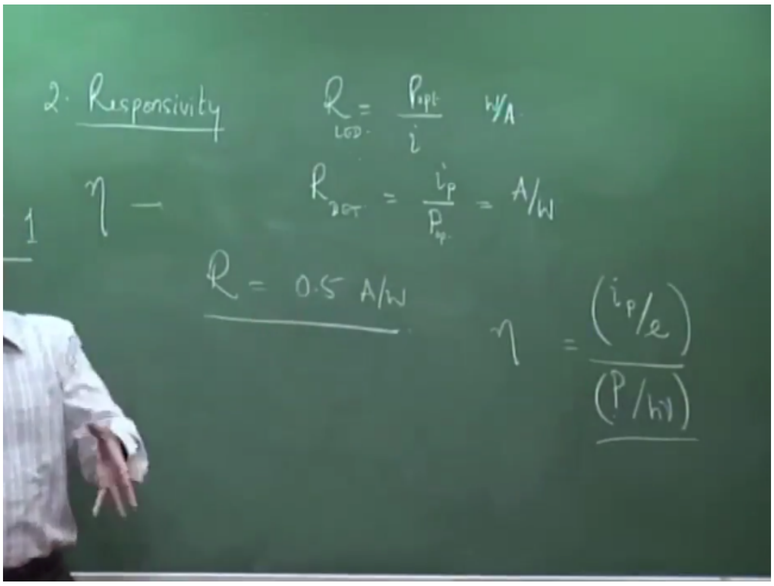

So before I proceed to eta let me look at the expression for eta again. The second parameter which I had written was responsivity. We talked of responsivity in the case of an LED if you remember that if you pass a certain current i what is the optical power generated? So responsivity in the case of an LED was R=optical power generated so responsivity was optical P opt/current i.

When you pass a current i what is the optical power generated? So unit was watt per ampere. So this is for source LED. In the case of a photodetector, 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 optical power generates how much current.

Therefore, responsivity of a detector is defined as ip/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 photodetector, there will be this parameter will be there responsivity R=0.5 amperes per watt typical number. For a silicon photodetector, responsivity is 0.5 amperes per watt. This is very important for the design engineer.

Because if he is dealing with few milliwatts of power, this will tell him how much current will be generated. In a particular application, he may be using 10 microwatts. In another application one may be using milliwatts and in another application one may be using 100s of milliwatts of optical power and the responsivity will tell him 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 Ip/P it is here Ip/P so responsivity.

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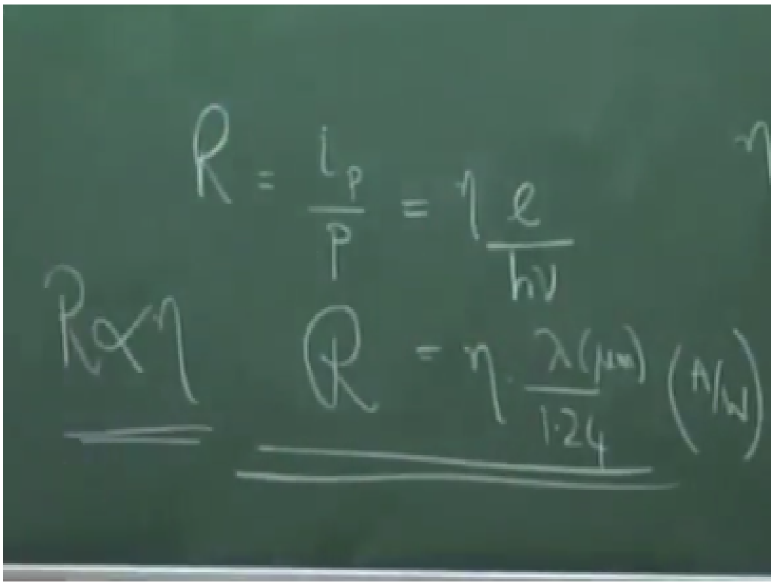

$$R = \frac{i_p}{P} = \eta \frac{e}{h\nu}$$

$$R \propto \eta \qquad R = \eta \cdot \frac{\lambda(\mu m)}{1.24} \ (A/W)$$

So I now have the expression. For responsivity=ip/P=so I take this here then eta*h nu, this was already in the denominator so h nu comes to numerator so eta*e/h nu responsivity=ip/P, this e was in the denominator h nu was so there it is eta*this and this is=eta this is our familiar what is that so this nu is C/lambda, lambda goes to the numerator and therefore this is eta*lambda/1.24, lambda in micrometer.

So responsivity=if you substitute lambda in micrometer responsivity is so many 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 photocurrent 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. 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.

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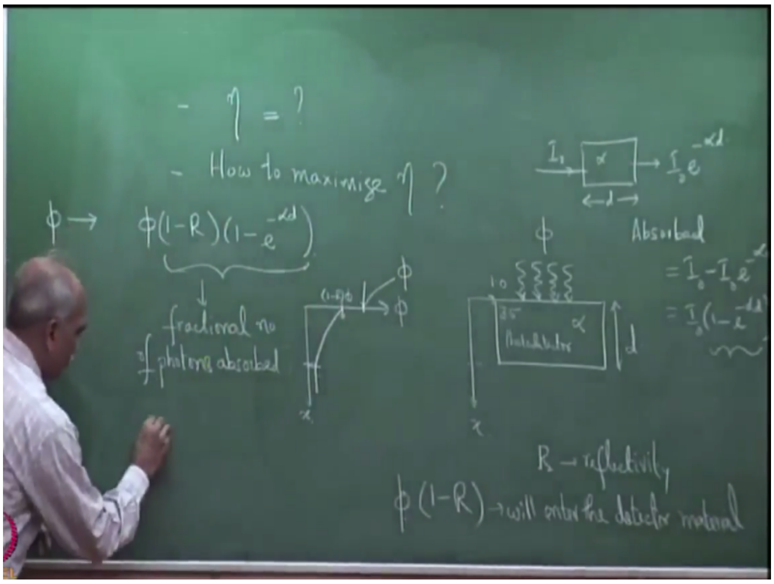

So eta=what is eta and how to maximize? These are the 2 questions, which we want to address how to maximize eta okay. What is eta and how to maximize eta? Consider a photodetector surface, here is a photodetector okay. This is of thickness d, so this is a photodetector, which is basically a semiconductor material. So photodetector in this case is semiconductor material of thickness d and photons are incident. Light is incident from here.

A photon flux phi is incident here. Now out of the incident photon flux if you see this as the depth direction, so this is the surface and this is the depth so let me call this as x, x is the depth okay depth direction then incident photon so here this 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 maybe 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, 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 okay let me right roman capital R okay. So this is reflectivity. If 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 okay that is reflectivity.

So if R is the reflectivity R*phi will be reflected back, if R is the reflectivity, reflectivity like in the semiconductor laser we had seen there it is 0.32. If you take a 3.5 and this, this will come out to be approximately 0.3 that is 30% is reflected back. So only 70% 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? Please see incident is phi, what will enter the material?

What will enter the material is 1-R*phi will enter the semiconductor, the detector material. Things will become clear, just see this. So this is 1-R R times has gone so this is 1-R*phi is the value here. Out of this as it enters, the photon flux will decrease exponentially inside the material. Why? If this is the semiconductor which has an absorption coefficient alpha, if I0 is the intensity which is incident and if this thickness is d, then the output is I0*e to the power –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 interphase 30% is reflected back where R times phi is reflected back.

Therefore, what is entering is 1-R times phi and that is now exponentially decaying by a factor e to the power –alpha x. Is that alright? So that is why I have shown the photon flux decaying like this. 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-R*phi was entering, please see, 1-R*phi was entering and then at d this is e to the power –alpha z please see, this is coming out so what is absorbed? Absorbed energy=I0-I0 e to the power –alpha d which is=I0*1- e to the power –alpha d. If I0 enters I0*e power –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*this because I0 is incident and this fraction is absorbed and therefore this*1-e to the power –alpha d. 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 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 entered 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?

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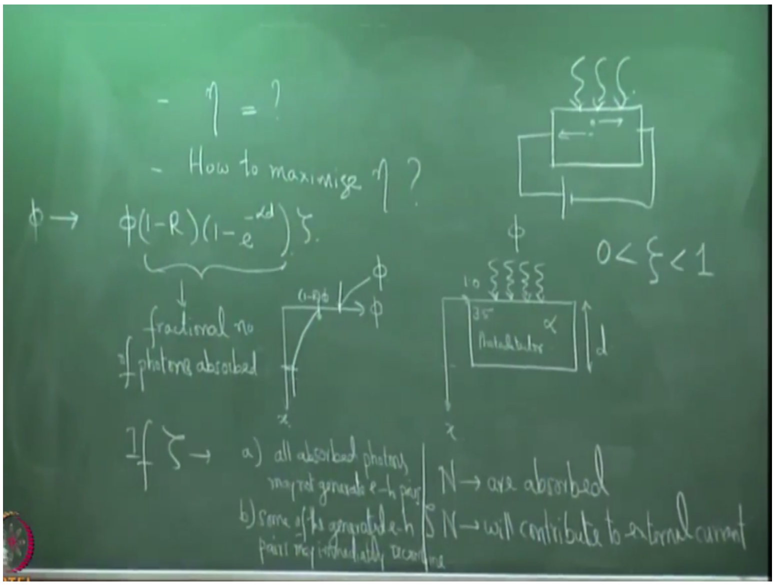

If zeta is that fraction, if zeta is the fractional number of photons that are absorbed and that generate so zeta fractional number. Zeta comprises of 2 components, please see this, one out of all the photons which are absorbed all may not lead to generation of electron hole pairs. Why? What would happen to the rest? Some of them may just generate phonons, it is not necessary that they 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 may get absorbed in lifting this. This is not a free carrier, so some of the energy may 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.

So zeta comprises of 2 parts, one all photons all absorbed photons may not generate 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 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 read to generation of carrier pairs, electron hole pairs which are contributing to the current in the external circuit. Please see I had drawn a circuit like this. Let me make it clear what I am 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 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 hole pairs, which are contributing to the external circuit will be<the generated number of carrier hole pairs, which means zeta so 0<zeta<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. So what is this?

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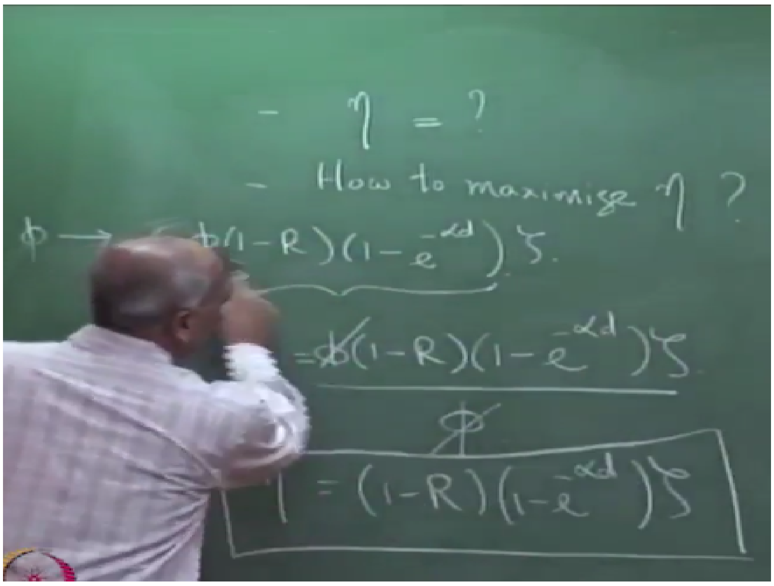

This is I had written the definition of eta as the number of so eta=1-R the internal quantum efficiency=1-R*1-e to the power –alpha d*zeta because this is phi/incident photon flux phi, so phi phi cancels. Incident photon flux is phi, phi*this 1-R enters the semiconductor, phi*1-R*1-e power –alpha d is absorbed in the medium. This*this*this*this will be the fractional number of carriers which are contributing to the current.

And therefore the definition of eta is this i/e/the photon flux so phi phi cancels so eta is simply=1-R*1-e to the power –alpha d*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 practice thing. Power is incident you know that this much power is incident and 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=0, this will be very large. If I can make this=0, this will be maximum. If I can make this=1 that will be maximum. Therefore, the question is how to make R=0? How to make this term=0 and how to make this term=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 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=0? If I can make R=0 then this quantity will become 1. If I can make this=0 this quantity will be 1. If I can make this=1, this will also be 1 and eta will become 1 quantum efficiency of 100%. In practice, one can get quantum efficiency of 90, 95% 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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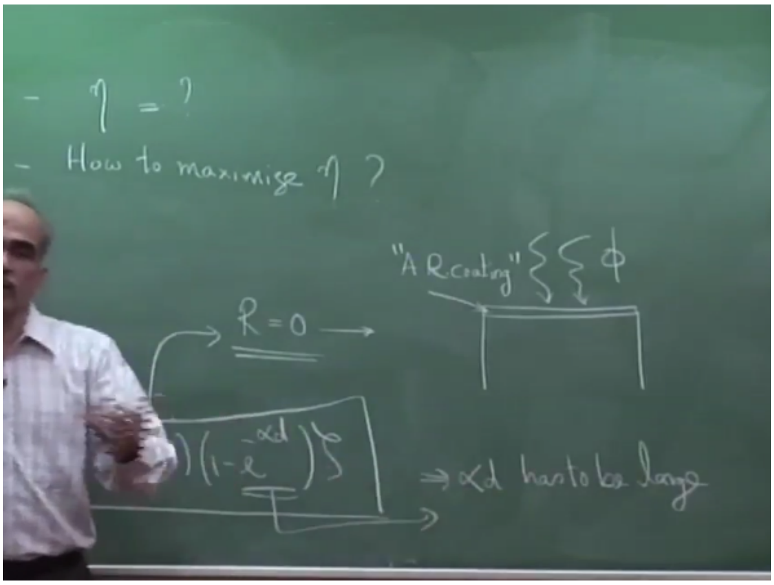

So R has to be 0, R=0 how to do R=0? Yes, we need to coat the material with an antireflection coating. So incident photon flux here, so phi is the incident photon flux. If you coat an antireflection coating, AR coating I think we have discussed enough about this, importance of AR coating, antireflection coating. Then there will be no reflection, so R=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 photodetector with a power meter for example, for a general purpose measurement then you may probably measure the visible region the IR 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 an AR coating which is almost which will cut down R down to 0. So AR coating will lead to R=0. So this is first point. Second, how to make this 0? E to the power –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.

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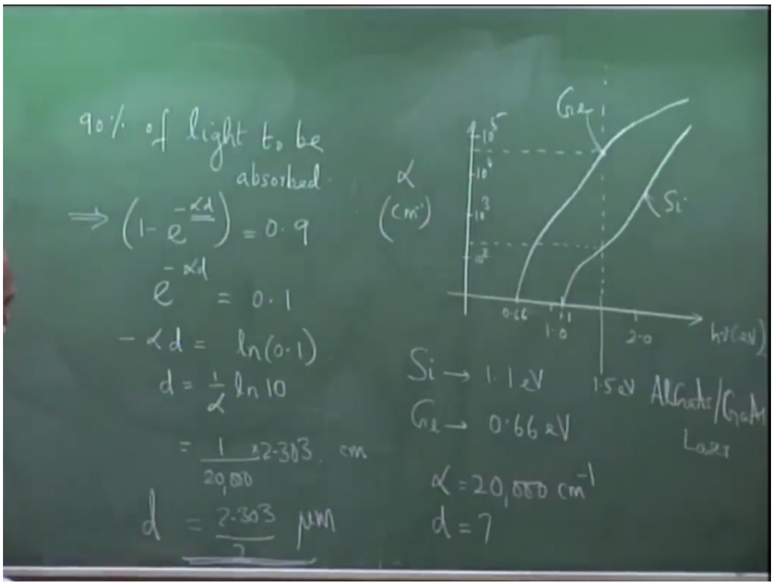

You remember we had, okay let us recall the absorption curve that we have drawn. So here is h nu in eV and here is alpha centimeter inverse. So you may recall that we had numbers like 10 to the power of 2, 10 to the power of 3, 10 power 4, 10 power 5 centimeter inverse and we had 1 electron volt, 2 electron volt and so on.

So if I take 2 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 eG as you know so 6.6 is here so germanium absorption coefficient starts something like this and then goes up. So this is 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 indirect band gap semiconductors. For direct band gap semiconductor, 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.

A laser which is emitting at h nu=1.5 eV, typical of a gallium arsenide lasers AlGaAs lasers, GaAs AlGaAs so aluminium gallium arsenide AlGaAs, gallium arsenide laser emitting at 1.0

h nu then you can see that at this value so the absorption coefficient these are approximate numbers, 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=let us say 20,000 centimeter inverse, 2*10 power 4 okay 10 power 4 is here, this is a log scale so 2*10 power 4 I have written is about or maybe 3*10 to the power of 4 centimeter inverse and for silicon it is a 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= 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 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. Let me take an example. For example, I want that 90% of light has to be absorbed. So if I want 90% of light to be absorbed, this implies 1-e to the power –alpha d must be=0.9, 90% has to be absorbed so this is the fractional number, so this must be=0.9 or e to the power –alpha d must be=this will go here so it is 0.1, -0.1.

“Professor - student conversation starts.” This will go here and this will come here so 0.1 okay **“Professor - student conversation ends.”** and therefore alpha d if you take log so this will give you -alpha d=ln 0.1 or 1/10 or alpha d therefore you can find out d=ln 0.1 or I can write this as 1/10, so it will become -1 and therefore I have d=1/alpha*ln 10. Is this correct? d=1/alpha*ln 10 so this is=this is 20,000 centimeter inverse.

So if I want to write this in micrometer inverse per micrometer it will be simply 2, 2 micrometer inverse or 20,000 whatever. So 20,000 here, my unit will be centimeter ln 10, ln 10 is how much? 2.303*log of 10 which is 1 so this is simply=2.303 centimeter which is=if I take this onto the numerator, it is 10 to the power so this will come out to be 2.303/2 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% of the light. Please see the logic that how to detect. This factor is so important because if you want to minimize this down to 0 you need to maximize this, even with 1 micron we get 90% absorbed. If I make this as 10 microns 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 absorbing at a later value of h nu so depending on the material you have to choose the point is chosen the right material and right thickness so that this goes down to 0, our objective is to maximize eta alright. We come to the last point that is how to maximize zeta?

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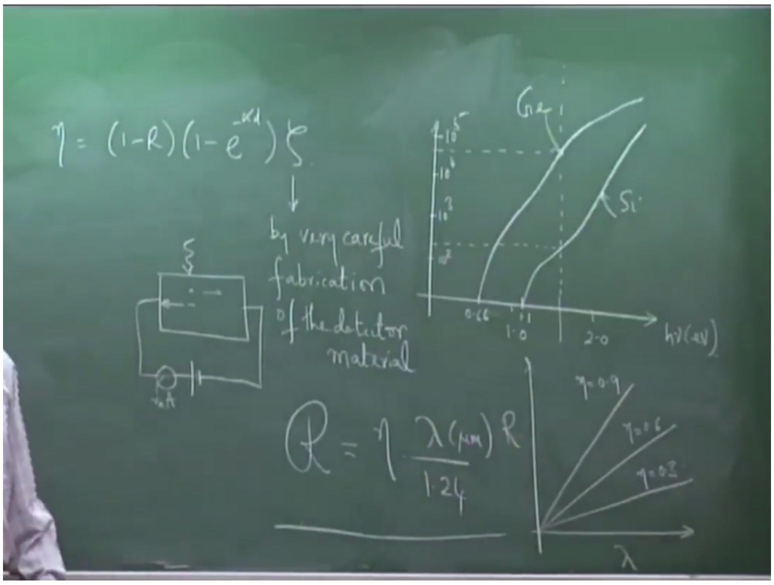

So eta recall that eta=1-R*1-e to the power –alpha d*zeta. Zeta is the fractional number of absorbed photons that will generate electron hole pairs, which contribute to the current in the external circuit, which means first it has to generate electron hole pairs and second it has to contribute which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

If you take a photodetector here, let us say a photon is incident, there is an electron and hole which is generated. If you simply connect to this outside a mA 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 this will travel here and hole will travel here. If they start traveling, 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, may be as a photon. So you have to apply a bias.

Second to generated electron hole pairs can recombine very quickly if there are defects in the material because defects are traps act like recombination centers, which lead to recombination of the generated carriers and therefore the material fabrication zeta can be maximized by very careful fabrication of the detector material, careful here I am referring to very high quality detector materials, which are free of defects or minimum defected 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 2 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=eta*1.241*lambda/1.24. Lambda has to be substituted in micrometers. If you plot R versus lambda, I 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=0.9, eta=0.6 eta=0.3 fixed eta, but we will see in the next class that eta is not a constant, 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 responsivity 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 APDs.