**Fundamentals of Semiconductor Devices**
**Prof. Digbijoy N. Nath**
**Centre for Nano Science and Engineering**
**Indian Institute of Science, Bangalore**

## Lecture - 47
## Basics of Photo detectors

Welcome back. So, we had concluded solar cells discussion in the last lecture if you recall the various properties and performance matrices of solar cell. Now, we will discuss from today photo detectors, which are very similar to solar cell, but slightly different in some functionalities. You will see there are very subtle difference between solar cell and photo detectors. And photo detectors can of course operate in different wavelengths, you want to detect wavelength of different you know light of different wavelengths, unlike solar cell where the spectra is fixed that is the sun spectra right.

And photo detectors can also be photovoltaic that means, they can also give you electricity without applying any voltage when you shine light, but they are not necessary to you know give you good amount of electricity or to generate power out of that ok, unlike solar cells; we do not connect a load for example. There are many things that are important for photo detectors, the reason I am telling you is, because photo detectors like sensors and sensors are everyone in the around the world, you know all the increasingly important fields like you know IOT and all other sensing technologies.

The news that; you need this sensors and photo sensors or photo detectors are important for a large range of statistics civilian commercial applications, you may not be you know understand knowing it. But there are so many applications that your actually using infrared sensors, and now there are variable UV sensors and so on ok. So, we will start sensors today a photo sensor, sensors today. The next couple of lectures, we will try to finish of photo detectors, so that we can start LED ok. These are opto electronic part of the course under the syllabus ok.

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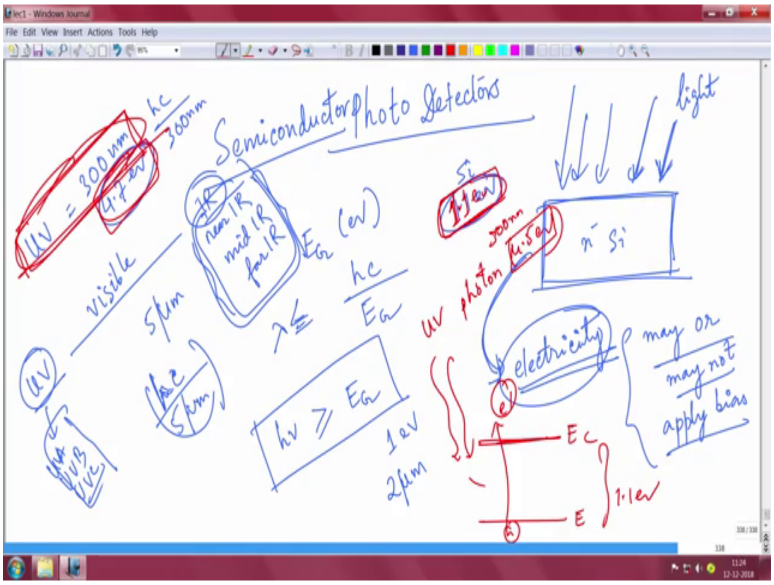


So, we will come to white board here and we will start with photo detectors or photo sensors. We will only consider semiconductor photo detectors which means their other kinds of non-semiconductor based photo detectors also but we will not discuss those. Non-semiconductors photo detectors would include something like vacuum tubes or some photomultiplier tubes and all we do not want to discuss that.

We will only discuss, discuss semiconductor photo detectors. And unlike solar cells which have to be PN junction, which are built in potential. So, the photo detectors need not necessarily be in a PN junction, it may not be a PN junction; it can be just than n minus or an un dope silicon also, can be a solar cell or can be a photo detector.

The difference stems from the fact that a photo detector basically you know, you have light that falls right. You have light that falls, light of different wavelength or (Refer Time: 02:45) and you want to convert that into electricity, not for power generation or power harnessing, but you want to sense. You have light that falls and you want to sense that light, so you and photo detectors will convert that into electricity. So, by the magnitude of the electricity you can find out, the intensity of the light that is falling.

Of course, the material will be sensitive if the only particular range of wavelength. So, you want to detect some particular range of wavelength. So, you can choose a material of the appropriate band gap of for example, this electricity that you get should you know ideal is very small and you do not know, you know data's, because it has to be a very sensitive photo detector, it should be able to detect even faint light of an wavelength.

And photo detectors, I told you need not be necessarily p n junction; it can you know you may or may not apply bias here, depending on the geometry of the photo detector, you may or may not apply bias, unlike solar cell where you definitely do not apply bias yourself, it will self bias for depending on the load. On in photo sensors you may or may not apply bias, which means it may be photovoltaic in nature or it may not be photovoltaic in nature ok.

So, in short for photo detectors take light and convert them into electricity ok, light and when I say for take light and the convert in into electricity, you please remember that the band gap of a semiconductor will decide which wavelengths it will absorbed. So, you know the wavelengths that it can absorb will be hc by E G less than equal to this right, photons of energy.

So, you have photons whose energy h nu is greater than band gap will only be absorbed, and probably give you electricity ok. So, if you have a band gap of 1 electron volt, you cannot absorb a photon of say 2 micron wavelength, because it will pass to the; you know that thing. So, depending on what wavelength you want to detect, you need a band gap appropriately; you want to have the band width at the wavelength or you know less in the more wavelength than that.

So, you know when I say photo detectors, it need not be only visible; visible has only is red, yellow, green, blue and so on. It can also mean infrared, it can also mean UV; infrared and UV are not visible to our eyes you know, we when we cannot detect infrared or UV, but there are sensors photo detectors that can detect infrared and UV. UV also has many part; UV A UV you know sorry, UVA, UVB, UVC we can come to that later different categories.

IR also have many categories like near infrared, mid infrared and far infrared; of course, these are not visible to our eye. They have a lot military and other applications, lot of you know commercial application, lot of security strategy applications, lot of biological medical applications also, these infrared detectors ok, these are not visible to our eyes.

So, you depending on the wavelength that you want to detect you will have a semiconductor of appropriate band gap that you are aware off. For example, if you want to detect an infrared signal of say 5 micron, then your band gap has to be you know h sorry, hc by 5 micron that will give you the band gap, it will be very small may be 0.1, 0.2 volt so on. So, it you will need a narrow band gap material, suppose you want to detect a UV wavelength of 300 nanometer that is UV, then you will need h c by 300 nanometer ok. It will probably be around 4.7 electron volt or so, so that is very large band gap material.

So, you need a very large band gap material for UV detection, a small band very very narrow band gap material for may be higher detect detection and so on. So, I mean of course, but you remember that silicon for example, silicon is a band gap of 1.1 e v, which means it can actually detects signals whose photons or light whose photons are I have energy more than 1.1 e v.

For example, if you want to detect the UV light, if you want to detect a UV light of 300 nanometer, whose band gap you know you said the band gap corresponding to that should be 4.7, 4.5 e v, but silicon's band gap is 1.1 e v which means silicon also can absorbed a photon of 4.7 e v, you see my point. So, silicon has this band gap E c E v and this is 1.1 e v, but if a photon comes if a UV photon comes, whose wavelength is 300 nanometer or whose energy is 4.5 e v. Then the 300 nanometer photon or 4.5 e v photon, will also get absorbed in silicon and general electron hole pair of course, there will be much higher energy electron hole pair, some fraction of that may be able to come out as you know as electricity ok.

So, you can actually use silicon also as a detector in UV, but the problem is that silicon will also detect all the wavelengths, all the photons with energy, whose energy is more than 1.1 e v [FL]. Silicon will also absorb visible, it will absorb green, you know yellow, red near infrared UV everything it will absorb. So, you cannot selectively say whether a light that you are detecting is only from UV 300 nanometer, because silicon also detects visible.

So, visible green, blue, yellow all their photons or energy more than 1.1 e v only, which means silicon will not be selective to UV. So, silicon will absorb everything from its band gap upwards. So, you will not know if their photon your detecting is only for UV or is it for you know or visible or something, so that kind of things are there it depends on application of course, we will come to all these things.

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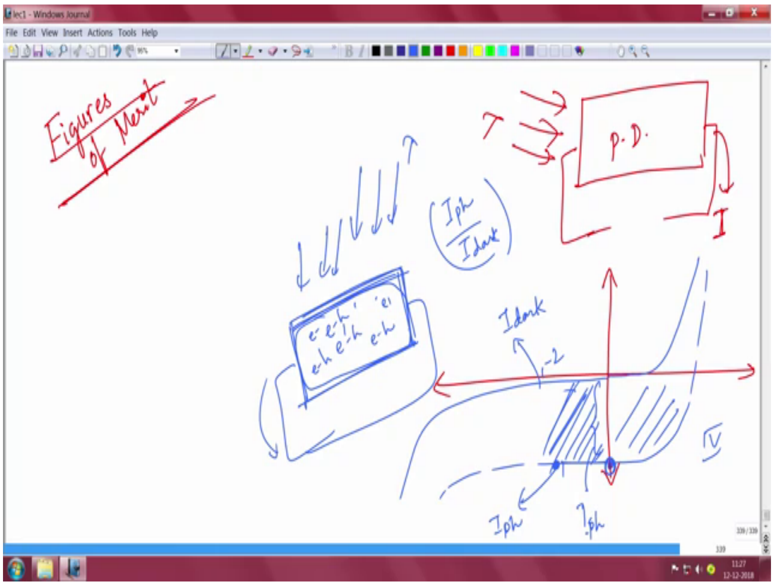


So, now before we go into a working of devices of the photo detectors, we will start understanding the important figures of merit; figures of merit of photo detector. Like what are the important parameters or matrices, which will decide what kind of photo detector; it is how good a photo detector, how bad a photo detector is just like in solar cell you have open circuit voltage, short circuit current, fill factor, efficiency.

Similarly, in photo detectors you have certain things. As of now you think of photo detectors are black box, because it can be a PN junction, it may not be a PN junction, it can be Schottky junction, it could be undope film, it could be dope film, it can be anything; so it is a photo detector I will call it PD. So, essentially you are having light that is falling up of a appropriate wave length corresponding to the band gap and you are going to get electricity some very small electricity. You will probably bias it or you may be not bias it depends [FL].

So, if you there can be photo detectors which could be sort of a PN junctions in such that. So, in unbiased in dark condition when you do not shine any light, you have a characteristic like this that I keep drawing the forward biased; when you shine light, then it becomes something like this right. I told you solar cell is operated in this forth quadrant, because you want to get power out of feed like a battery. At this point of course, you have no voltage applied, but you have good amount of current which we called as photo current or short circuit current, here we will call it photo current only.

A photo detector like a p n junction can be operated at this point definitely or it can be slightly operated in this resume also, slightly you apply a negative bias ok, may be minus 2 volt minus 5 volt. So, you will get some this current that you have here is actually the photo current right, it is called photo current. And this current that you had in the absence of light; you call it dark current right. So, one of the important parameters is photo to dark current ratio I photo by I dark that is a particular voltage may be minus 2 volt or minus 5 volt, whatever.

This photo to dark current ratio should be very high; you want that ratio to be many orders of magnitude, so that you know your detector is more sensitive. If your photo current is very is almost the same is dark current, then it is not sensitive right; they will be noise and other things, we will come to noise and other things very quickly. So, this is only a p n junction, but it may not be a p n junction also; it could be a photo detector could be also you know such un dope silicon for example, this is silicon which is un doped everywhere.

So, I am connecting a voltage, here you cannot get light if you shine if you cannot get electricity just by shining light, because it is a it is just un dope intrinsic silicon, may be even slightly un doped its silicon is not a problem, but if you have to apply a voltage why? Because if you do not apply a voltage, if you just shine light here. Light of appropriate wavelength which can be absorbed by silicon of course and you want to see the current you know, you will not get any current that is because if it is a uniform elimination, electron hole pairs will be created everywhere you know.

Electron hole pairs will be created everywhere, now the problem is there is no internal electric field here unlike in p n junction. In p n junction, you have a internal electric field that sweeps away, but here there is no electric field, there is no junction p n junction. So while the, if there is no field, then the field there will be nothing to sweep the electrons and holes away to contribute electricity. Also the diffusion will be a same every, because everywhere the uniform electron hole pairs are generating uniform uniformly, there is no diffusion, there is no concentration gradient right.

So, in other words you will not get electricity out just by shining light, you have to apply a voltage ok. So, this kind of detectors also there, these are called photoconductive detectors or we shall definitely come to that.

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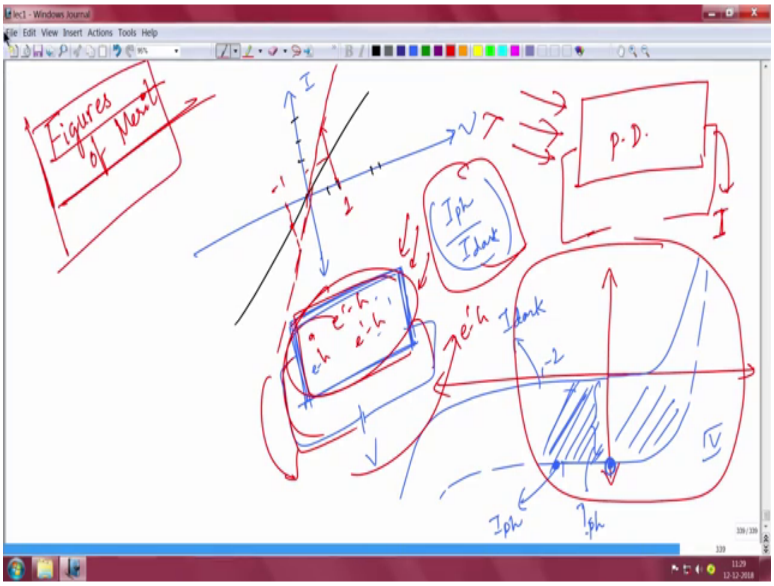

So, if you apply a small voltage for example, if you apply some voltage and there is suppose no light following it is a dark condition, you applying some voltage, this is I, this is V. For example, and suppose I am making an ohmic contact to the silicon somehow, then if I am not applying any if I am not applying any shining any light, I am just a applying a voltage, I will get a current sorry, I will get IV like this ok. So, this is current say micro amp maybe some voltage or milli amp whatever.

The moment I shine light, there will be excess carriers that will generate now, there will be excess carriers that will generate. Now, because you are applying a field a voltage this field will sweep every excess carriers, this field will sweep every excess careers, which were not there before; before it was only intrinsic carrier concentration. Now, it is excess carriers have come in the semiconductor because of the light shining which can be swept away by the externally applied field, so your current will increase.

You see at any volts say 1 volt, initially your current does this again now your current is increased. Similarly, symmetric that minus 1 volt you have a current and dark current here photo current is here. Even here, you want a photo dark current it should be very high, which means this should be ideally varies you know like insulating films, so that the dark current is very low, when you shine light you get a lot of current so that is called photo current or photo current should be very high compared to dark current.

But this is symmetric, in this in a p n junction I I V is not symmetric, but in this kind of photo detector photoconductor detector it is called photoconductor detector, it is actually symmetric ok. So, in a anyway depending on the architecture of the device whether it is p n junction or photo conductor detector sort of thing, you will have different kinds of I V, but the basic figures of merit that I am going to discuss now, we will remain more or less same ok. The figures of merit will remain the same. So, one of them is the photo dark ratio that I keep talking about.

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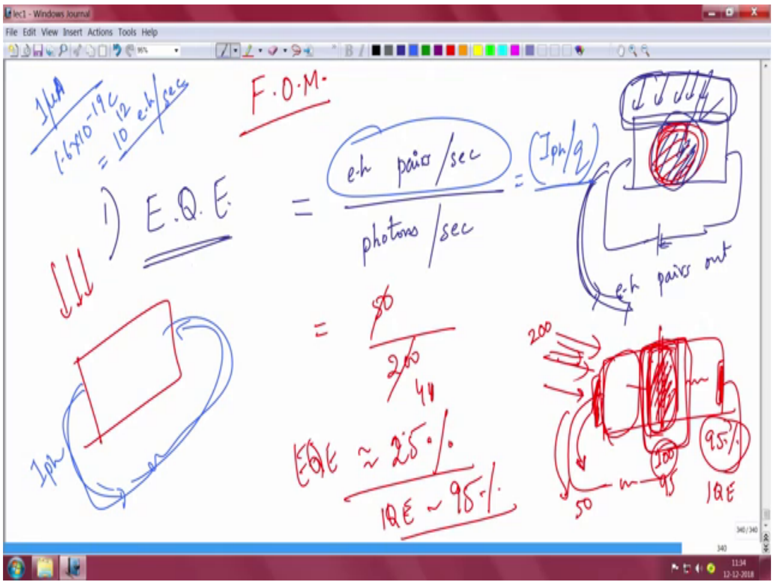


Now, let us come more systematically about the figures of merit, I will call them figures of merit ok. So, the first figure of merit is actually external quantum efficiency. Apart from photo to dark current ratio that you know photo to dark current ratio should be very high that is important to know, but a figure of merit would be external quantum efficiency.

External quantum efficiency is essentially, so you have this; whatever you have photo detector, I mean p n junction, non p n junction whatever, you are shining light, you are getting electricity. This electricity maybe because of a bias voltage or maybe because of inbuilt field like p n junction does not matter you will get some electricity out.

The question is how many electron hole pairs you are getting out per unit time. So, how many electron hole pairs you are getting out of the circuit per unit second or per unit time ok. How many electron hole pairs you are getting out, divided by how many photons your shining per unit time, per unit second ok. You are shining some photons now light.

So, how many photons are falling on the sample per unit time and the ratio of how many electron hole pairs are essentially coming out divided by how many photons are actually following here. The active region will be here and the stand active region is inside, the thing is that not all photons will probably reach the active region; some will get scattered bounds of so that is the different thing. And once the photons reach the active region, they will generate electron hole pair.

So, number of electron hole pairs that are generated in the active region, the number of electron hole pairs that are generated in the active region divided by the number of photons that are absorbed in the active region is I Q E that is the internal. So, suppose you have a p n junction I am just telling you ok, this is the depletion region, your shining light sound of photons will get wasted in the neutral region I told you and only a fractional reach the depletion region which is the active region.

So, how many photons have reached here in the active region ok and whatever suppose 100 photons have reached here, out of the 100 photons that have reached here; how many of them are actually leading to the generation of electron hole pair. Suppose, 95 of the photons are a successful in generating 95 of pairs of electrons and holes in the active region that is why then IQ will be called 95 percent.

Because 95 percent of the photons that are absorbed in the; that are absorbed in the active region are actually converting themselves into electron hole pairs. But remember not all the photons that you are shining here may be able to reach the active region, some will get blocked, some will get absorbed here, reflected, they will be metal contacts that metal contacts also will reflect and other thing, so not all fractional will reach here.

May be your shining 200 photons per unit time, only 100 reach the center here right and out of this 100 they have reached, 95 of them were got converted to electron hole pairs because of the you know of course, when the photon gas absorbed at the same appropriate energy your semiconductor will be saturated electron hole pairs will be generated. So, you are generating 95 percent of IQE Internal Quantum Efficiency, but all the 95 photons that all the 95 pairs of electron holes that are there, may not be able to come out of a circuit.

Some of them the electron hole pairs might be lost here, some the electron hole pairs will lead to extra pairs drop here. So, the number of electron hole pairs that are coming out, the number of electron hole pairs that are coming out of the circuit, may be only 50, 50 electron hole pairs per unit time are coming out of the circuit. So, the EQE will be defined as number of electron hole pairs that are coming out of the circuit which is 50 ok, divided by the number of photons that you are shining per unit time which is 200 right; that is 200 right, so the it will be around 25 percent.

In this particular example, the EQE is 25 percent the external quantum efficiency, [FL] but the I Q E is 95 percent you see, can you see the difference now? External quantum efficiency is 25 percent, but internal quantum efficiency is 95 percent, because internal quantum efficiency tells you, how many electron hole pairs are generated at the active region divided by how many photons are absorbed in the active region. But external quantum efficiency says, how many electron pairs hole pairs have come out of the circuit divided by how many photons are falling on to the device that is there is a difference, because there are losses in between and other things right.

So, now if you suppose you have a photo detector like that you are shining light ok. And the current that is coming out in the circuit, the current that is coming out there is circuit here whatever; the current that is coming out is suppose I photon. So, the number of electron hole pairs coming out per unit time will be actually I photon by the charge of an electron, you agree?

If there is a micro amp of current, then 1 micro amp divided by 1.6 into minus 19 coulomb will give you the number of electron hole pairs per unit time coming out of the circuit, you can do that. If your current photo current is 1 micro amp, you divide it by 1.6 into 10 to the power minus 19 coulomb ok. Ampere is actually coulomb per second, so you will get number of photons it will be probably like 10 to the power 13 or 10 to the power 12 electron hole pairs per unit second ok, I am just telling you ok.

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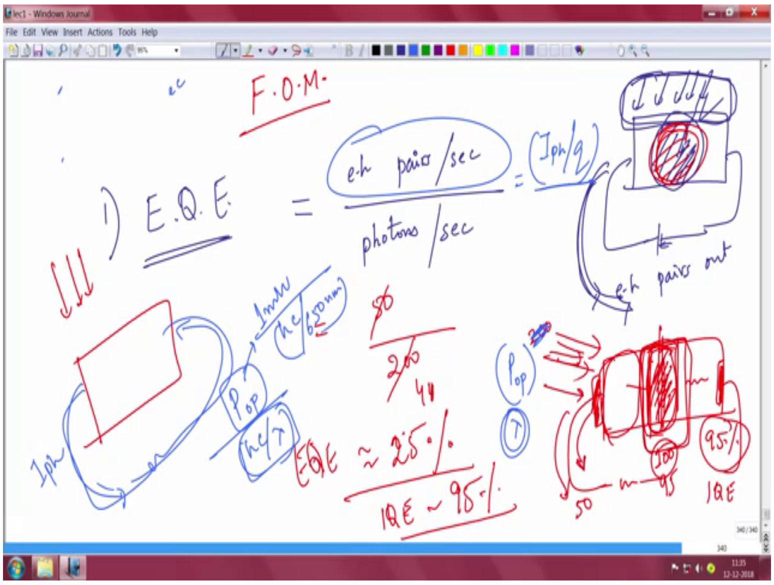


And basically you are shining light of some energy P op that is called Optical Power Density it is watt per centimeter square or whatever ok. So, you are shining some light there and the you are shining a light of monochromatic wavelength, which means there is only one wavelength of the light, your light does not have multiple wavelength otherwise it becomes difficult ok. Anyways in photo detectors there is not a spectra of like sunlight to detect, a photo detector sensually will detect a wavelength of a particular light of a particular wavelength only that is the idea.

So, you want to basically have a light that has a particular wavelength of lambda, then the number of photons per unit time that is shining on the device is the optical power divided by h c by lambda, h c by lambda is the energy of each photon, P op is the total power. So, if you divide that by h c by lambda, you will get a number of photons per unit time you can do the math.

Suppose, the your shining 1 milli Watt of optical power and wavelength of light is suppose red. So, hc by red is 650 nanometer, if you do that you will find out a large number that number is basically number of photons per unit time ok. So, if I come to the next slide here and I will show you, what I mean.

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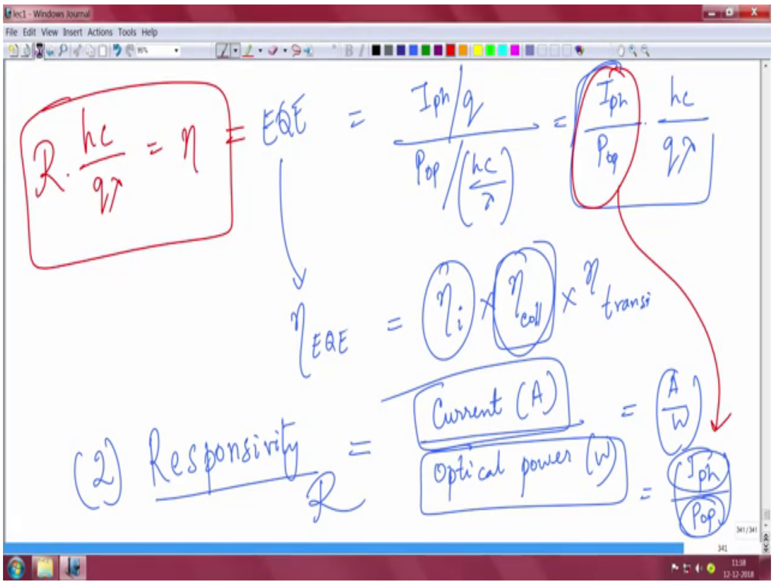


So, EQE this is a figure of merit by the way that is why I am telling you know EQE, is actually the total photo current by the charge of an electron divided by the total optical power by hc by lambda. What it will become is that I photon photo current divided by optical power into hc by q lambda ok. This is your external quantum efficiency, this is a very important property, this is a very important figure of merit for your photo detector.

And I told you the external quantum efficiency I will call it n EQE, actually is internal quantum efficiency times the efficiency that is limited because of collection, not all the you know not all the photons, not all the electron hole pairs generated in this device can come out I told you. Some of them will go waste and get lost and heat dissipation and other things, so that efficiency also reduces.

So, internal quantum efficiency is 95 percent remember with that you have to multiply the efficiency of the collection into efficiency of transmission. Because all the photons that you are shining may not reach the active region, some of that get might get lost in the neutral region, some of them might be bounced off from the metal contact and so on right.

So, this is your expression for external quantum efficiency, but you have to remember that it is connected very much to the second most important figure of merit, which is called responsivity and this is a very critical figure of merit for photo detector. Responsivity in a way is defined as how much photocurrent you are getting out of the device in ampere or milli ampere whatever, divided by how much optical power you are shining, how much optical power Watt or you know whatever. So, it is basically ampere per Watt the unit is ampere per Watt. So, how much of optical power you are shining at a particular wavelength and how much current you are getting out of that because of that light you are shining ok.

And this is definitely the photo current that your measuring divided by input optical power that you are giving. And thus responsivity is represented by a symbol of like stylish R ok. So, essentially how much photo current you are getting divided by what is the optical power you are giving, this is very important.

If you recall this quantity, this quantity in external efficiency is actually responsivity. So, then can I write this that EQE is basically responsibility in to h c by q lambda, this is equal to your EQE efficiency, can I write that? I can write that right.

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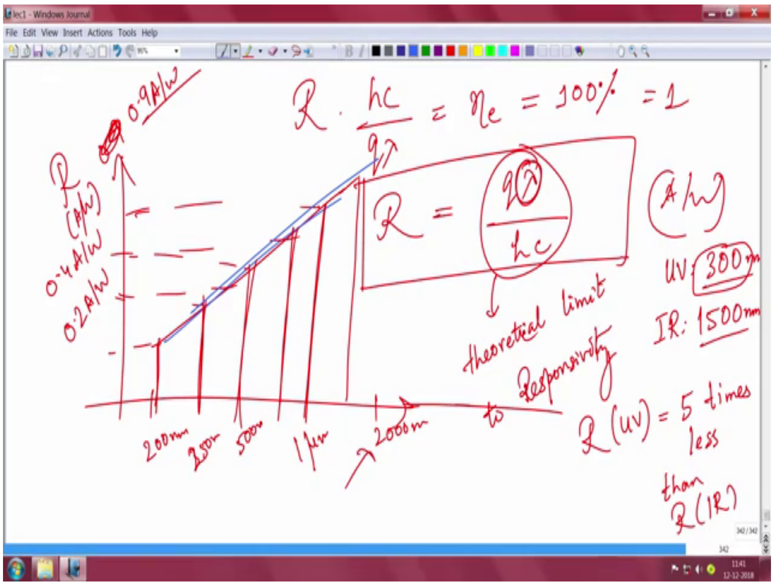


So, let me write here. So, responsivity into hc by q lambda equal to external quantum efficiency. If I assume; if I assume that the external quantum efficiency is 100 percent so hypothetically assuming that is the best you can get, then your this is 1 that means 100 percent, then your responsivity is given by q lambda by hc, this is ampere Watt ok. What does it mean? It means the responsivity of a photo detector. This is the theoretical limit sorry, this is the theoretical limit to responsivity of a photo detector, this is the theoretical limit of a responsivity photodetector.

Surprisingly this depends on lambda, which means if I use a UV light; if I talk about a UV detector of 300 nanometer wavelength, then whatever responsivity I get ok. And compare that with an infrared detector I am using of wavelength, suppose 1500 nanometer, then the responsivity; the theoretical responsivity for UV will be almost here it will be it is lambda directly proportional know; 5 times less than the responsivity at infrared. I mean here it is 300 and 1500 it can be anything, it can be 300 3000 whatever I am just talking about ok, what I am trying to say is that the theoretical limit to responsivity in ampere Watt is depend on lambda.

So, if I use a UV light which means a short wavelength, my responsivity also will be low theoretically. If I use an infrared light of a higher wavelength like 1500 nanometer 2 amp 2 micron 3 micron and so on, then the responsivity also will be theoretically high, which means the theoretically achievable maximum responsivity in ampere Watt. If I plot with respect to lambda, then it will be like a linear plot; this is say 200 nanometer, I am just saying this is say 2000 nanometer 2 micron, it can go to many much higher 3 micron, 4 micron I am just giving you a range.

So, you see red will have higher responsivity than green, green will have higher than blue, blue will have higher than UV will have very low, red will have higher here infrared will have even more higher. So, theoretical responsivity will be high and you can actually calculate the value here.

You can plug in the value h c by lambda this thing q h c by lambda. For example, if you have around 250 nanometer I know the value, it is around 0.2 ampere Watt that 500 nanometer wavelength, it will probably were on 0.4 ampere Watt ok. At 1 micron, which is almost silicon band gap, you will have probably like 0.9 sorry, 9; 0.9 ampere watt right, so many and so.

So, the actual responsivity is actually increasing the real the theoretical limit to responsivity increases it wavelength. This is; this does not mean that you know your UV detectors will always have lowers, I mean this will always have lower spectra responsivity than IR. It does not mean that you know, you should not work at lower wavelength that is not the point. The point is that if I use there do you know where what is the physical reason behind is by the way? Why is that this is coming out like that? And responsivity is a very important parameter of photo detector.

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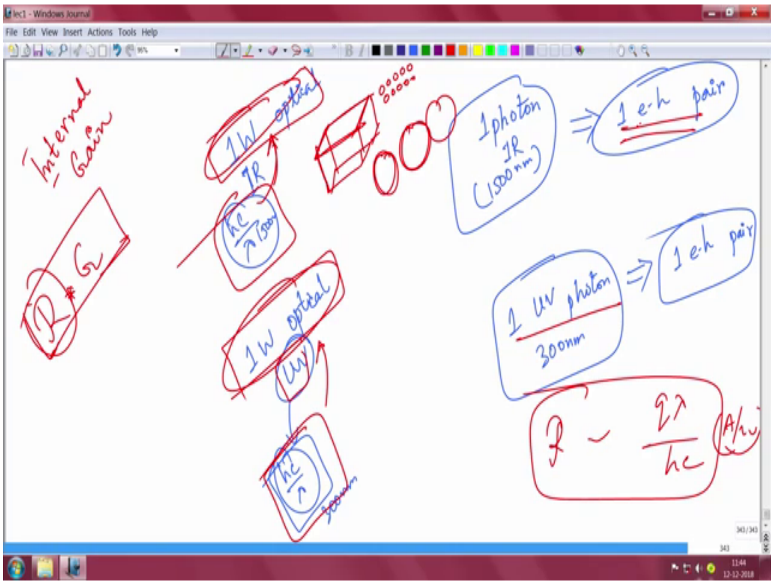


It is because if you take 1 photon of IR infrared; say you know I will talk about say 1500 nanometer wavelength photon, when it if it is absorbed in a material at completely, it can give rise to 1 electron hole pair right. Similarly, 1 UV photon which is say 300 nanometer 1 single photon, if it is absorbed completely, it also gives one electron hole pair; no discrimination here. 1 IR photon will also give 1 electron hole pair best case, 1 UV photon also will give 1 electron hole pair best case.

Now, if I take 1 Watt of power optical power 1 Watt of optical power in IR ok, 1 Watt of optical power in IR. And then I take separately 1 Watt of optical power in UV, because the UV photons have more energy hc by lambda, where lambda is 300 nanometer. This photon has more energy than air photon hc by lambda, lambda is 1500 nanometer right. So, this so this IR photon has lower energy, 1 photon has lower energy, then UV 1 photon; so same power 1 Watt, 1 Watt.

If you do if you find out how many IR photons are there in 1 Watt, then number will be more compared to how many UV protons are there in 1 Watt, you see my point. 1 watt is fixed, but the number of photons that can be accommodated in 1 Watt is more in IR than in UV, because IR photon energy is less. It is like you know you have only a fixed amount of 1 Watt, you can think of a one fixed volume in one fixed you know trunk of you know box, the volume is fixed.

Now, you can either fit in only few footballs or you can fill in many small marbles, because the size of which marble is small, the size of each football is large, but the volume on the trunk is fixed. So, 1 Watt is fixed, but the number of IR photons will be more than the number of UV photons there. And 1 photon gives you 1 electron hole pair that is why more IR protons in 1 Watt, means that you will get more electricity out of 1 Watt of IR power then in 1 Watt of UV power and that is why spectral responsivity goes as q lambda by h c amp per Watt for 100 percent efficiency ok, but this is the theoretical limit.

In some cases, there can be an internal gain in the device internal gain in the device. If there is an internal gain, then your responsivity will be multiplied by the gain. The gain can come because of many factors, level and so many other traps and other things do not worry about that. But there can be a gain and efficiency of a photo detector can be more than 100 percent, which means the responsivity can be more than the theoretical limit. Why is that possible? There can be gain, there are physics behind it. There can be gain ok, track related gain and other things let us not come to that so much now, but please understand that. So, two figures of merit we have discussed.

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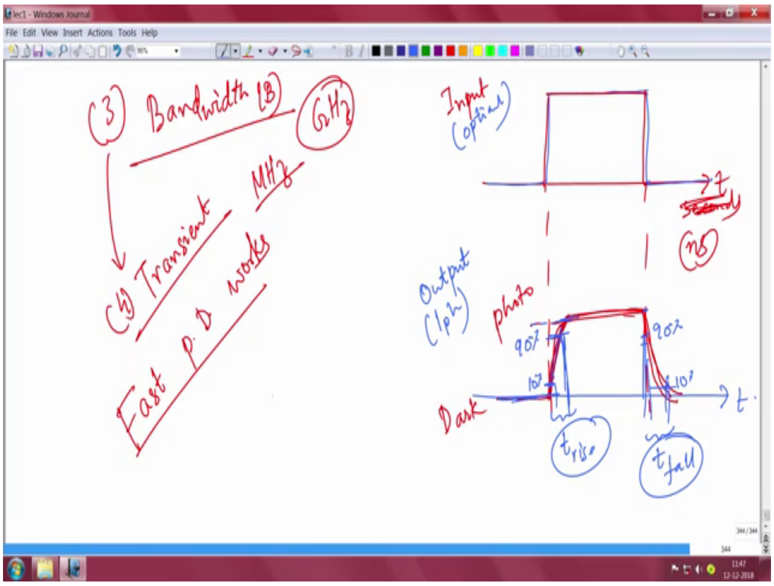


These are important figures of merit for photo detector we will need then actually that is why I am talk talking about them here in details. One figure of merit is called bandwidth, so bandwidth is essentially represented by B and it is basically speed, how many gigahertz or megahertz the device can work at. When I say gigahertz and megahertz I do not mean the optical signal, the optical signal red, blue, green is not gigahertz or something; they are thousands of terahertz or something the optical signal.

These gigahertz or megahertz, this bandwidth basically means how fast the device can operate ok. And so with respect to this also, another quantity is related actually both of them in a way that is called transient response, essentially both of them tell you how fast your photo detector is how fast your photo detector works, I will come to that.

So, essentially what means is that, if you have a photo detector and you are putting a light signal input light signal, suppose the in this is time, time axis suppose the input line signal is 0, suddenly you switch on the light; suddenly you switch on the light and you kept the light on for may be whatever time, then you switch off the light abruptly and go, now this is the input.

Now, output of a photo detector has to given electricity, this is input optical power, but the output has to be electricity IR photon. So, this is time, will the at this time and at this time, the photo detector will not give the electricity abruptly, it will take some time to rise, then it will be there. And once you switch off the light, it will again some take some time to fall off, so that speed at which it can operate how abruptly can it turn on, off that is basically the speed at which that that determines the bandwidth also.

Now, if this time scale is in range of seconds now of course photo detectors is very slow it can operate, and of course, but it is in the case of nano second. If you are turning on and off the light in 1 nanosecond, can the photocurrent rise to the this is the dark current, this is the photo current. Can the photo detectors current rise from dark current photocurrent in 1 nanosecond, then again come back in 1 nanosecond or 1 picosecond, 1 microsecond that determines the speed and the bandwidth of the device. The band width will be inversely proportional to that right.

So, if it can actually go in 1 nanosecond turn on and off, then you say it is very fast detector, its bandwidth it is so high. And if it cannot, then you know it is slow. I mean depends on what time you are putting millisecond, microsecond and so on ok. So, essentially what you do is that the way we define is that if this is your photocurrent, then there is a 90 percent of the photo current is here ok. And this is the dark current, this dark current is not 0 by the way; it will be very small like pico amps or fem to amps.

You take 10 percent of this value here, this is 10 percent. What is the time that the detector takes for it to rise from 10 percent of the value of photo current to the 90 percent of the volume of the photo current that time is called a rise time.

Similarly, this is 90 percent of the peak value, this is 10 percent of the peak value; how much time does it take, to come from 90 percent to 10 percent is called the fall time. So, these are called rise time and fall time of the detectors. If the rise time and fall times are very small, very you know when nanosecond whatever, you say detector is very fast; if it takes a long time, then you know it is small, it is very slow.

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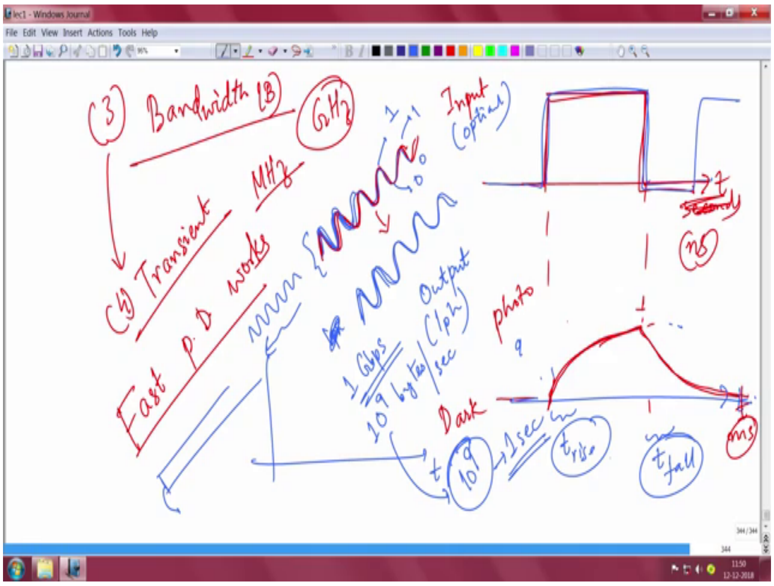


For example, it may be so happened that this is time, you have switched on and off the device. So, let me do that again, you have switched on and off the device, but your photo detector may not be able to respond only, at this point it is slowly increase to rise; it did not even reach the value, it was rising, rising, rising; when you switched off, it again fail, fail slowly take so much time. It could not even rise its value completely, this is the slow detector, but again it depends on time scale are you talking about millisecond, are you talking about nanosecond, whatever you know that depends.

If it is working like this a nanosecond maybe and millisecond it will be fast. So, depends on that way ok, so that bandwidth is basically up to what frequency of modulation of the signal. You see, this signal can be modulated the input optical signal can be modulated at some frequency. It is not the please remember this is not the frequency of the light, light is you know infrared or red or violet whatever that is like thousands of terahertz probably, that is not the frequency of light I am talking about.

I am talking about light on and off, on and off, on and off, there is a this is called modulation frequency ok. You are modulating the light on and off, on and off in certain speed or frequency. This is scan the photo detectors photo current also follow this signal on and off, on and off as fast as the light signal that represents the bandwidth or the speed of the photo detector ok.

Because; and this is important, because this on and off, on and off these are actually used in frequency modulation, amplitude modulation, sort of thing signal processing in optics fiber optic cable. The way you get internet data in your home from fiber optic cable is because of this by the way.

Infrared light is central silica fiber you know that fiber optic silica code. There actually on and off, on and off is modulated; on is suppose this is a digital 1, this is a digital 0 1 0 like that right. So, you have to send a signal that means, there has to be a light source like an LED or laser diode which can on and off very fast. So, you know 0 1 0 1 whatever. On the detector side of the fiber optical also you need a detector, a photo detector in infrared that will be able to respond to that so fast on and off, on and off only then you will be able to get all the digital data right, which constitutes your internet your Facebook everything right.

And your internet in fiber optic cable if it works at a speed of 1 Gbps; it means 10 to the power 9 bytes; 10 to the power 9 bytes per second are coming to you. Actually, 10 to the power 9 bytes means that 10 to the power 9 times, your light has to switch on and off per in 1 second please remember that. 10 to the power 9 times your light has to signal on and off in 1 second, your detected that you have on the other and the fiber optic should be able to respond to 10 to the power 9 or 1 billion the light that your optical fiber cable is detecting.

You know the light that is coming is changing 1 billion times in 1 second; your photo detector should be able to respond to that 1 billion times a second, otherwise your internet will not work, otherwise you will not be able to get the data your broadband data.

Your light will be on and off 1billion times, your photo current should be able to respond to that, your photo detector should be able to respond to that as fast as you can as fast, as the light comes; only then you will be able to reproduce your data right that is true right, so that is true. So, this is about the speed and bandwidth and there other things also with respect to speed and bandwidth. So, what we will do is that we will end the class here today; we have discussed enough of photo detectors for today's class.

We have introduced the concept of photo detector detectors and different kinds can be there. I told you what are the basic differences solar cell, I introduced in the concepts of figures of merit, efficiency, spectral response, bandwidth, transient time, it is a lot more things to do. We will not go into much depth, but we should be aware and familiar with the basic terminologies, basic working.

So, what we will do in the next class is that we will continue with the figures of merit. I will talk about a little bit about more or transient response, noise and detectivity; specific detectivity it is very important. All these things or figures of merit and after that we will be discussing some sample cases of photoconductive detectors, p n junction detectors, what is the speed, what is the responsivity and so on, so that we can understand the working of photo detectors ok. So, we will end the class here today.

Thank you.