# Fundamentals of Semiconductor Devices
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## Lecture - 48
## Photodetectors: figures of merit and types of devices

Welcome back. So, we are discussing Photodetectors; in the last lecture I had introduced what photodetectors are, how they are different from solar cells. Some of the differences will become clear towards the later part of this on the next lecture. I had introduced some figure of merit, efficiencies, responsivity and speed the bandwidth right.

We will continue from there today, we will discuss a few other figures of merit and common times of photodetect common types of photodetector; predominantly p-n junction photodetector and also photoconductive photodetectors. Each has their own characteristics, speed and other things. So, those things will be briefly touch upon and what are the common materials used for different kinds of photodetectors. Those things will you know we will discuss as and when time permits.

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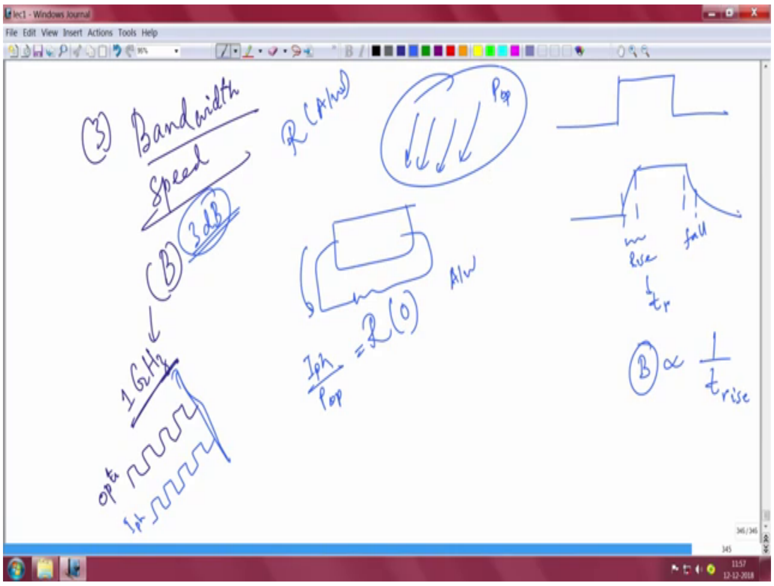

So, let us come to white board here. I had discussed about the bandwidth in the last class or the speed right. I told you about the transient response of the photodetector, how fast they can modulate to an incoming signal. But how do you define bandwidth? And bandwidth it is defined in gigahertz by the way. When I say the bandwidth of a photodetector is 1 gigahertz it means at 1 gigahertz you should be able to replicate faithfully the signal. If you have an a signal that is modulating at 1 gigahertz optical signal, then your the output current should be able to modulate faithfully you know without lag.

So, that basically it means and that is, but there is a you know does it mean that a 2 gigahertz can it replicate? What about 0.5 gigahertz? So, there is an ambiguity here. I cannot just say that is the theoretical definition. What actually it means is that and depends on the geometry of the detector; whether it is a p-n junction detector, whether it is photoconductive detector, there are different mathematical expressions to indicate you know or this thing.

But in other words you see the transient response that I have drawn last time if you have an optical signal like that then electrical signal will be able to follow this like that. So, there was this 10 percent, 90 percent rule I told you; from 90 percent to 10 percent 10 percent to 90 percent what is the rise time and fall time the rise time and fall time right. If this rise time and fall time this rise time is said t r; fall time and rise time are you know in the same order by the way it is not like rise time will be nanosecond and fall time will be second very rarely, but it is typically you know it is in the same order by the way.

And your band width actually is inversely proportional to the rise time by the way rise time because if the rise time is smaller nanosecond, picosecond your bandwidth will become increase increasing and this bandwidth is typically called 3 dB bandwidth. For those of you who are electrical engineers you will understand 3 dB actually is a very holy number sort of thing.

What I mean is that you have a spectral responsivity in amp per Watt this you measure at DC condition. What I mean by DC condition is that, you have a photodetector, your light is shining constantly and you are measuring some current. What is the current you are measuring and what is the light your putting in here that is your responsivity spectral responsivity right. Light is continuously shining. So, I will call this R of 0 [FL] the frequency at which the light is modulating is 0 because there is no frequency, it is constant DC right. You get some value amp per Watt.

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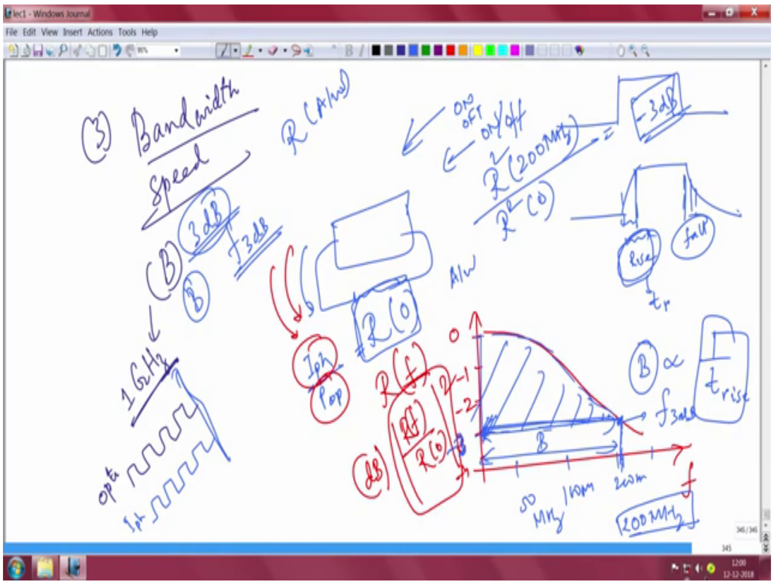

The moment I start to modulate this light, this moment I start to modulate this light which means I turn on and off, on and off this light the current here that I have also will go on and off on and off. Now, if you take the average ratio here that responsivity will not be the same as a responsivity under DC condition, it will be a responsivity as function of frequency.

And you will see that if I take this R of f by R of 0 and if I take the square is like the modulus over frequency; this is frequency in megahertz, gigahertz, whatever kilo hertz does not matter; you will see that your frequency actually falls down sorry, the this ratio falls down. This is caused by the spectral you know normalized spectral response and this is you know sort of the gain you can say dB ok, is the log of this quantity actually; it falls down here. This is dB, this is 0, this is minus 1, this is minus 2, this is minus 3, minus 4 and so on.

With higher what I mean is that, with higher frequency this could be say 50 megahertz, this could be 100 megahertz, this could be 200 megahertz and so on ok. With higher frequency if you switch on and off this light at higher frequency your responsivity also falls down at the frequency. So, when you take the responsivity ratio with respect to the DC responsivity when the light was constant, your normalized responsivity falls down. You see minus 3 dB where this is reached this point know. Your responsivity your spectral responsivity ratio has fallen down with respect to the 0 bias response 0 frequency responsivity.

So, minus 3 dB this is basically the loss in a we can say where it has reached. So, it is a may be 210 giga megahertz or so. So, this is called the 3 dB f 3 dB bandwidth ok. This is called the bandwidth of the device it is called a 3 dB bandwidth of the device which is roughly 200 megahertz in this case. So, that is the; that means, at 200 megahertz your responsivity at 200 megahertz will square of that and responsivity at DC will have fallen down by minus 3 dB, the gain would have come down by minus 3 dB.

So, that is how you define the bandwidth. Let us not go into so much detail. If your rise time is lower and lower your bandwidth will become larger and larger [FL]. So, which means you can operate in this bandwidth very well that is what it means in a way. And for that your rise time and fall time has to be very small so that you have sharp transitions your bandwidth is large. If your rise time and fall time are like 1 second, 1 second which means your bandwidth will be only 1 hertz 1 hertz.

So, your rise time if it is 1 millisecond your bandwidth will be in the range of 1 kilohertz approximately ok; there will be some factors there. So, this is what it means. We will come to this again later when you discuss this specific kinds of photodetector, but this is your bandwidth I call it B or I can call it f 3 dB; it is a 3 dB bandwidth. Higher order 3 dB bandwidth faster is the device, lower is the rise time please keep that in mind. So, this is an important figure of merit that I have discussed.

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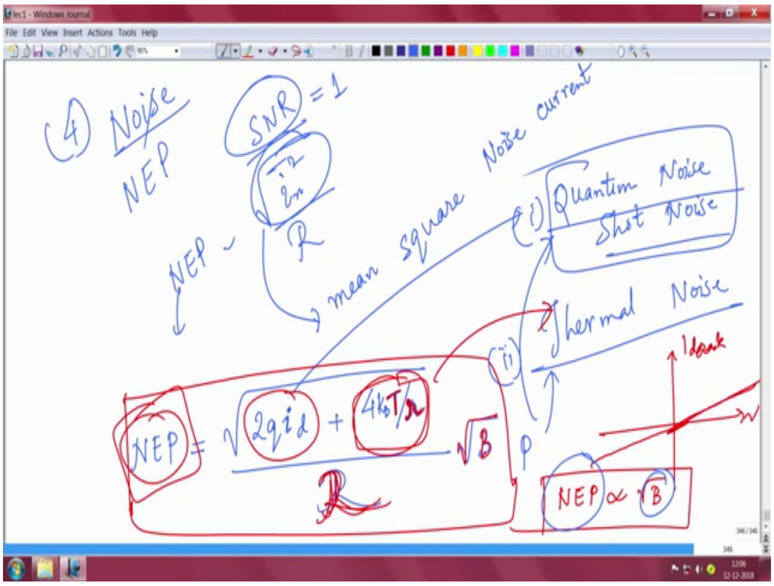

The next figure of merit which is very important connected to this is called noise. What is the performance of a photodetector with noise? There will always be a background noise; there will be always many kinds of noise. What is your photodetectors performance with respect to noise is very important, it is not important for solar cell. In solar cell you deliver high amount of power to the load, you do not care about noise so much. Photodetectors are very important in terms of noise ok.

What is the because in photodetectors you want to detect as faint a signal as you can. What is the faintest signal you can detect very faint coming from outer space or something. So, noise is very important unlike in solar cell. So, noise there is a quantity called noise equivalent power. Please remember, noise equivalent power it means what is that minimum optical input power at which the signal to noise ratio becomes 1, you know SNR Signal to Noise Ratio; that means, in qualitatively you can think that you have a very high amount of input signal.

So, you know there is definitely much higher than the noise the question is if you reduce the input signal keep reducing it keep reducing it keep reducing it. What is that minimum input signal at which the signal and noise will become same ok, that is called noise equivalent power you that is called noise equivalent power, you want it to be very low.

That means you can go too much lower threshold of noise and noise equivalent power noise equivalent power is given by i n square sorry i n square by responsivity, what does it mean? This quantity actually is called mean square noise current; noise will give some current actually. It is called the mean square noise current. You do not have to worry so much about it, we will come to that.

There are essentially two types of noise; one is called the quantum noise quantum noise or also you can call it as shot noise. This noise arises because of the quantum nature of the distribution of electrons holes and the photons and this comes from the statistical nature of that uncertainty principle ok. Your arrival of the electron holes or photons and the generation electron holes has just quantum noise and then there is a thermal noise.

This is one kind of noise and thermal noise this is the other kind of noise thermal noise comes because of the resistance the fluctuation of carriers in the resistance because you will always have some resistance in the device. So, that resistance and thermal radiation thermal fluctuation will lead to some kind of thermal noise. So, there are the two kinds of noise and your essentially the power the noise power that you get will be correlated with this thermal noise as well as the shot noise and this is a very important figure of merit by the way.

So, I will tell you, do not have to worry so much. This noise equivalent power, there are formulas that are derived you do not have to worry this noise equivalent power actually if you look at it, it will go as the square root of 2 times charge of electron times dark current ok. This dark current actually is a kind of a quantum noise. This dark current is the background noise know the background leakage current.

In the absence of light dark current is your leakage current. So, there higher leakage current contributes to higher noise or worse device performance. Even the dark current leakage current to be has lowest possible. That is why this is the dark current 2 q i d plus this is this is because of the; this comes because of the quantum noise.

Then there is a thermal which is 4 this is Boltzmann constant KT by the resistance. This is I will give smaller. This is the resistance of the 0 bias resistance of the device divided by the spectral responsivity into square root of the bandwidth. Please, keep look at this expression carefully. This is noise equivalent power and noise equivalent power tells you what is the minimum; you know the signal that will basically make it equal to noise.

The noise equivalent power goes as it becomes higher if your dark current is higher. Your dark current in a device should be has low as possible because if your dark current is higher, then your noise equivalent power will go high which means your signal that you can detect is a higher signal low you cannot detect a much lower signal. That means, your noise threshold is worse, it is come up. It is also this is a thermal component; this depends on the r smaller which is the resistance of the device. You have to make sure the resistance is as large as possible.

When I say resistance this is the 0 bias resistance of the dark current. So, if you look at the this is the dark current this is the dark current sorry this is voltage this is the dark current iv this slope here this resistance should be as high as possible which means the current dark current should be as low as possible that is another way of saying it ok. So, your noise equivalent power should be you want to minimize the noise equivalent power.

So, you want to actually have a you can cool down the system then t will come down of course, or you can have a higher 0 bias resistance and of course, you want a high responsivity this is spectral responsivity I told you ampere per Watt a high responsivity. In other words a high efficiency also will make sure your noise equivalent power has come down which means you can detect a lower noise equivalent power means that you can detect lower signal of lower magnitude signal with are faint which are week which means your noise floor is little bit low which is good if your noise equivalent power is high it means you can detect only signal of higher magnitude which means your noise floor is high which is not a good thing.

One thing is that it depends square root of bandwidth the noise equivalent power depends square root of bandwidth which means if you have a faster device your bandwidth is more your noise equivalent power also is more it means your noise performance will become worse if your device becomes faster.

So, to minimize the noise you have to make the device slightly slower in other words noise and speed they trade off with each other you cannot get better noise performance and higher speed. At the same time if the carriers have to respond very fast they also give you a higher noise [FL]. So, this is important, but this noise equivalent power is important, but one more important, but see this noise equivalent power does not take into account area.

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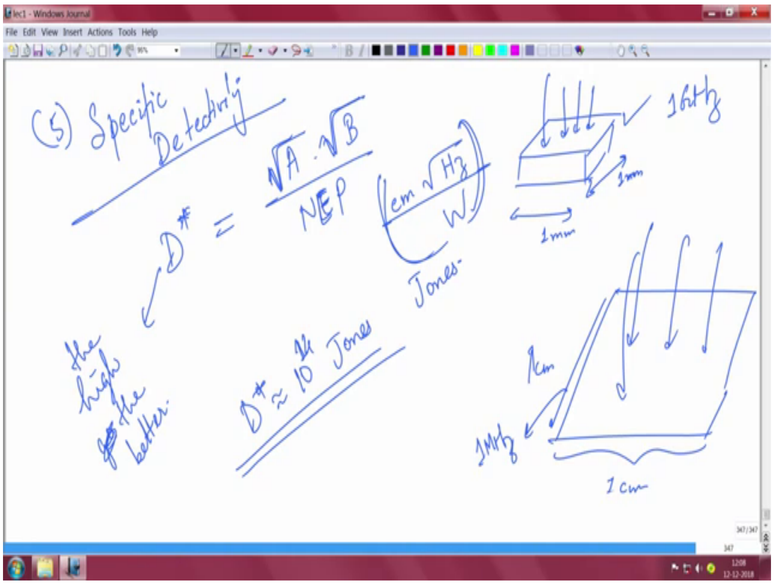

(5) Specific Detectivity

$$D^* = \frac{\sqrt{A}\cdot\sqrt{B}}{NEP}$$

$$\left(\frac{cm\sqrt{Hz}}{W}\right)$$ Jones

the high the better.

$D^* \approx 10^{14}$ Jones

Suppose I have a photodetector which is say you know 1 millimeter by 1 millimeter area. This is the photodetector I have like I can buy commercially, but you have a photodetector which is much large suppose you have it one centimeter by 1 centimeter area the light that you will detect here is much more in quantity because you have large area light I will detect is much smaller area.

So, then this things becomes not so, good. So, you have to normalize that and also you know might your my detector might be working at 1 gigahertz your detector might be such that it works at 1 megahertz. So, then your noise and minors will be so, different; I cannot compare mine with yours because you know our devices size is different at the speed at which they work is different how can you compare noise. So, for that you have under important parameter it is called specific detectivity and it takes into account all of these and so, people nowadays only talk about specific detectivity so, much.

Specific detectivity is basically represented by D star and it is basically your inverse of noise equivalent power. So, which means your specific detectivity should be as high as possible higher the better [FL] the higher the better specific detectivity should be higher. And here you will have a normalizing factor which is square root of the area time square root of the bandwidth; you take into account of bandwidth you take into account the areas square root square root you take so, that that it becomes out of normalized and the unit is centimeter square root of Hertz by Watt.

This quantity is also called Jones and at good detectivity a specific detectivity would be say 10 to the power 14 Jones it is a very good detectivity 10 to the power 10 would be not a good directivity. So, what it means is this is a unit. So, it takes into account the inverse of photo the noise equivalent power also. A higher directivity means that normalise to the area normalize to the bandwidth you are able to detect much fainter signals. So, these are the main important parameters of a figures of merit of a photodetector. So, we have studied them; so we are now aware of that.

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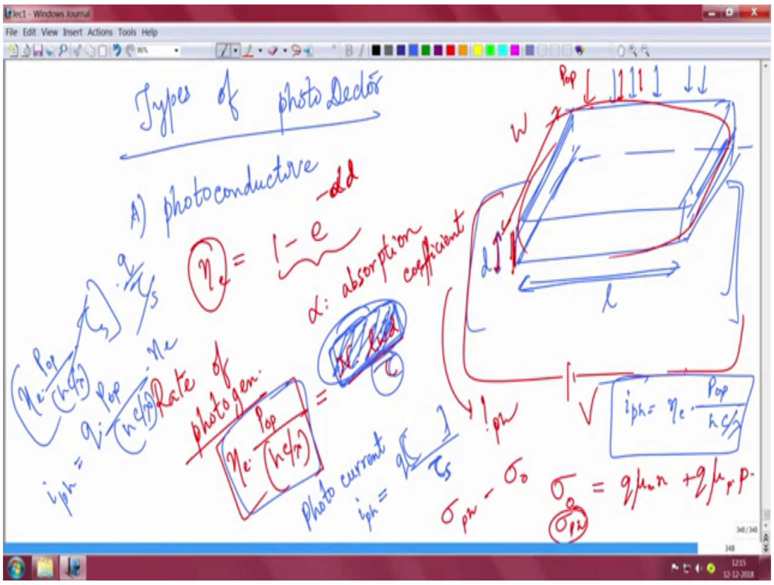

So, you know now, I will come to the types of photodetector types of photodetector in semiconductor photodetector. There are many kinds of photodetector one is photoconductive detector which means it is like a photoconductor; it is like a photoconductor you have a it is like a photoconductor here it is a photoconductor here you can assume that you are making an Ohmic contact here and you know you are shining light and getting electricity out from here, you have both electrons and holes in this and that light of appropriate wavelengths can be absorbed here ok.

So, I can say that you know I am making an Ohmic contact on this side Ohmic contact on this side I will apply voltage that is why this way like that. I can assume that this is the distance over which electrons and holes shining light will come from the top everywhere in from light will come from the top.

The photoelectrons holes electrons will be generated they will be swept away by this applied field you have to apply field this length is l; the length over which electrons and holes have to drift to come out of the circuit. The thickness of the slab is suppose d and your the width the width of this device along this is suppose w. So, now you are applying a voltage as I told you might be applying a voltage maybe V around it applying voltage your shining light you will be getting some electricity what is this i photon this is called like a photoconductive detector this is called a photoconductive detector it can be high resistance detector.

But you are assuming that you are making an Ohmic contact. The resistance of this the conductivity of this will be q mu of electron into n plus holes also would be there because you will have excess holes any shine light cube p times p this is your conductivity. In dark it will be a conductivity in photo it will photoconductivity if this is your dark conductivity, then photoconductivity will be sigma ph that under the light your photoconductivity will be increase the difference between the total conductivity minus the dark conductivity will be your true photoconductivity.

So, now, if I have this suppose I am shining light from the top how much light is getting absorbed here you know that actually tells you this is the thickness is d. Please remember this thickness is d in general if you take a slab of material whose thickness is d and your shining light. The light intensity decreases as the thickness increases right because it will get absorbed there is this Lambert, Beer Lambert laws if you recall.

So, essentially the light that is absorbed there is directly proportional to the external quantum efficiency which is 1 minus e to the power minus alpha d this d is the thickness of this material and alpha is basically the absorption coefficient how well the material absorbs your light. And absorption coefficient will be better or higher for direct band gap material and lower or worse for indirect band gap material.

So, alpha 1minus 1 minus e to the power alpha d gives you the fraction of light that is absorbed in a thickness material of thickness d, it is a measure of the external quantum efficiency by the way. So, you know if I am shining a light of say Pop that is the intensity optical intensity I am giving you and if the efficiency of the eternal quantum efficiency is you know eta of e. Then the rate in this kind of a device this is a photoconductive detector rate of you know the generation the photo generation the rate at which you are generating carriers will be equal to the efficiency times the optical signal that you are shining by hc by lambda.

That has to be equal to the total photo carriers that are generated in this block divided by the lifetime the total carriers that are generated there is n; n is the you know the total the optical generation rate you can say into the volume per centimeter cube into centimeter cube that will be l wd by life time that is your this is your rate of photo generation actually ok.

And the number if you if you this quantity that is there if you multiply by if you multiply by this life time; then you get this quantity which is essentially the number of photo generated free carriers. This quantity represents the number of photo generated free carriers that is divided by the lifetime to give you the rate of photo generated carriers ok.

So, the photo current in other words if you look in this expression carefully the photo current I photo current is actually defined as q times the total number of photo generated carriers which is this divided by the lifetime what is the number of photo generated carriers. And this is per not per centimeter cube this is absolute number divided by the lifetime with which we are decaying that is your photo current. Now this quantity is actually this quantity which is n a Pop by h c by lambda into tau into tau you agree. So, the tau will actually cancel out here and this quantity will have to be multiplied by q by tau s.

So, that will come out here. So, the photo current is actually given by q the optical power by hc by lambda into efficiency can I add it again? Photo current is equal to efficiency into the optical power that you are shining divided by h c by lambda this is your photo current this is the photo current which you will be getting; please remember that this will be photo current that you will be getting. Now the photo current will be different from the signal current actually the moment because you are also applying a voltage you are applying a voltage.

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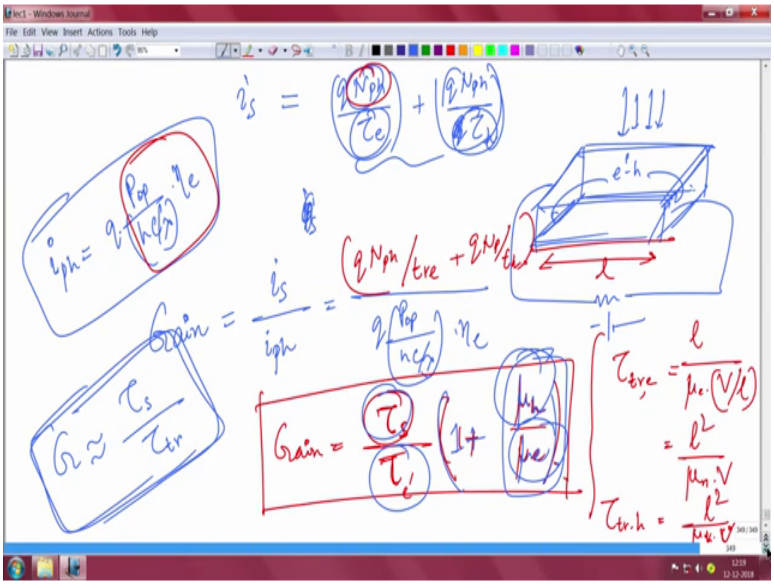

$$i_s = \frac{qN_{ph}}{\tau_e} + \frac{qN_{ph}}{\tau_h}$$

$$i_{ph} = q\cdot\frac{P_{op}}{hc/\lambda}\cdot\eta_e$$

$$\text{Gain} = \frac{i_s}{i_{ph}} = \frac{qN_{ph}/t_{re} + qN_{ph}/t_{rh}}{q\frac{P_{op}}{hc/\lambda}\cdot\eta_e}$$

$$\text{Gain} = \frac{\tau_s}{\tau_e}\left(1+\frac{\mu_h}{\mu_e}\right)$$

$$G \approx \frac{\tau_s}{\tau_{tr}}$$

$$\tau_{tre} = \frac{l}{\mu_e\cdot(V/l)} = \frac{l^2}{\mu_n\cdot V}$$

$$\tau_{tr.h} = \frac{l^2}{\mu_h\cdot V}$$

So, you will get a signal current also ok. And that signal current is basically how much total carriers you have divided by the electron transit time plus how much photo carriers you have divided by the whole transit time sorry hole transit time do not worry about that. That means, how fast the electrons and holes bringing the current out of this particular block. You remember this block in the last slide right your light is shining from here the expression that I had given for a photo current in the previous slide was this. This is the photo current the photo current is basically the charge times your optical power that your shining divided by h c by lambda this is the number of photons into efficiency ok.

This is your photo current but because you are applying a voltage also know when you are shining light because you are applying a voltage here. So, you will get some signal current also the electron hole pairs that are generated how fast are they moving out. So, how fast are they moving out? So, that transit this is the transit time not the life time by the way if you do some simple math, you will be able to find out the signal and we will assume that some of the things like electrons and holes might drift with the you know the mobility might be same or so and so forth.

So, the gain of a device this is a photo conducting photoconductor the gain is actually defined as how much signal current are you getting when you are shining light and applying voltage divided by what is the true photo current that you should ideally get ok. So, the true photo current will be q this quantity Pop by hc by lambda into efficiency and this will be by the way this quantity this quantity is actually this quantity here.

So, anyways; so if you do that and this will be q N p h by the transit time of electron plus q N p h the transit time of holes. If you do that then you will get an expression for gain which will look like the lifetime divided by the transit time of electron transit time of electron how fast the electrons can move this is the lifetime by the way into 1 plus mobility of holes by mobility of electrons it will look like that if you do some things like for how do you get there.

For example, that transit time the transit time of electrons for example, the transit time of electron will basically be the length that has to cover which is l divided by the velocity which is mobility times the field; field is nothing , but v by l. So, this will be l square by mu electron velocity similarly transit time of holes will be equal to l square by mu holes times ls v.

So, if you do all this map then you will get this expression that is a gain of the device if there is a gain in the device that is the ratio of the lifetime the ratio of the lifetime of the carriers divided by the transit time of electron into 1 plus the ratio of mobility hole by mobility of electron. This is your gain of the device this is called the photoconductive gain of the device. And in general if your hole mobility is very very lower compared to electron mobility then you might actually cancel this part out. And then your gain will be basically given by the lifetime divided by the transit time of electron ok.

Lifetime by transit time gives you the gain for a photoconductive detector. Now this is a photoconductive detector this is not a p n junction it is just a block; it is just like a block of insulating material on which you are applying a voltage and your getting some current by moment your shine light, you get some more current that is signal current. So, this is basically what it means this is a photoconductive detector you do not have to worry. So, much, but this is your gain of a photoconductive detector the lifetime divided by the transit time the lifetime divided by transit time.

Now, this is one kind of, but the practically you can actually go ahead and make this speed will be you know I will come to this figure again you know if you practically think of this device.

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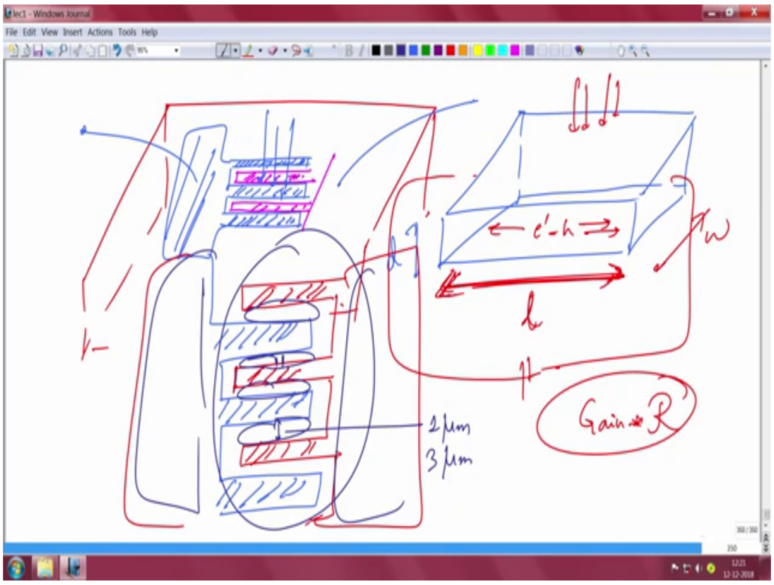

You have like a block like this right you have a block like this is your thickness d light is shining here from the top, this is your width l this is the length l this is the width w your electron holes are coming to this circuit here.

You know this l; this l is the very large length if it is the large length then the electrons and holes will take much longer time to transit and your gain will be low if your gain is low your total responsivity also is low because gain times responsivity is the actual measured responsivity. So, you want if you want a higher gain you have to reduce this l. So, what people do is that they use you want to reduce that l. So, what you do is that you make small small fingers. So, for example, if you have this I am drawing this is the this thing top view here.

If you have this things like that then you make a device such that instead of you know you do not have this the carrier transit everywhere what is do is that you have this small fingers this is a small metallic finger you have to make a metal contact anyways. Then you have another metal finger then you have another metal finger and the spacing between them is very very small.

So, you can have many of this fingers and then you might have you might have another set of fingers which comes in between you have the another set of fingers they will not short with each other; there will be a gap small gap there will be a small gap here and then there will be connected to a bigger pad here.

Similarly, this will be connected to a bigger pad here. So, you can probe the voltage here on this pad and this pad you can apply, but actually you are shining light onto this area. So, from the top it will look like this is one figure finger metal finger this is one metal finger this is one metal finger. On the other side you have this is one metal finger this is one metal finger similarly keep going. So, what will happen is that when you shine light please look at it carefully from the top this is again another metal finger similarly this is another metal finger so, on and so, forth. So, this will be another pad this will be another pad.

So, when you shine light when you shine light in this area then the photo generate this will metals will block. But there are exposed areas like this area photons will be generated electrons electron hole pairs will be generated this area this area this area. But this areas are very small this may be you know 1 micron or 3 micron or 2 micron whatever. So, essentially the field the voltage that you apply on this big pad and this big pad there will be the voltage will drop across very small spacing you see my point the voltage will drop across very small spacing.

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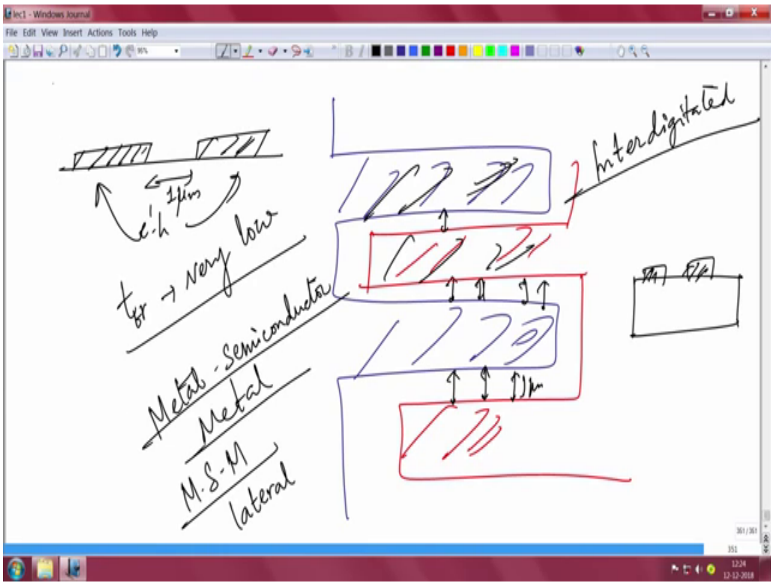

It is like this is one finger this is one finger right and on the other hand I have this 1 finger and this 1 finger you see the spacing between these fingers is very small this is the 1 micron or 2 micron or whatever even less we can make.

So, when you shine light under photo generated carriers are there if you look at the side view this will be 1 finger there will be another finger here which is one of this and this can be 1 micron or 2 micron. Then whatever electron hole pairs are generated their that their transit time will be very low their transit time will be very low. Because these are very very closely spaced this kind of detectors are called metal this is a metal layer know again you have semiconductor below and again metal here another metal.

So, these are called Metal Semiconductor Metal kind of MSM sort of photodetectors these are lateral devices which means it is not like a top down device like a p n junction you have a block of material you have metal and then metal. So, it is like a metal semiconductor metal device you have to apply bias these are symmetric mostly because if the both metals are same it will be symmetry both metals are different it will be asymmetric.

It is very easy to fabricate you do not need doping you do not need hatching you do not need completed fabrication steps you just put down the metals it is a metal semiconductor metal device it can be very easily done lot of research papers have published on this you can take any new material. And put an MSM device this speed here is limited by carrier lifetime people typically use semi insulating or high resistive material.

So, that the dark current is low and once you shine light photo current is expected to be high you know you can have this these are call interdigitated fingers; interdigitated fingers and this interdigitated fingers can be spaced events sub micron. So, that your transit time is low and your gain is very high.

Your transit time is low your gain is very high and the transit time gives you the speed of this device also; so that is important to understand [FL]. So, we will end the class here today we have finished most of the part of photodetectors I had discussed about you know the other parameters of photodetector like the bandwidth the noise the specific detectivity.

And finally, we have come to photoconductive detectors, I told your metal semiconductor metal detectors and the properties you know it is very easy to fabricate and you can bring the metal electrodes close as close as you want which is called interdigitated sort of a geometry. So, these are very widely used you have to apply a voltage by the way this will not work without voltage that is why that is these are not photovolaarode to another electrode [FL].

So, these are photoconductive and you know MSM sort of detectors one last thing is remaining that is junction photodetectors which are sort of p n junctions or Schottky junction that are can be used as photodetectors it is just like solar cell except that you can have a p n junction of different material like gallium arsenide gallium nitride gallium telluride and so, on the band gap will be different.

So, the wavelength of light it can detect also is different and once you have those kind of detectors you can operate them in photovoltaic mode or self powered mode which means you do not have to apply any voltage the expression for the speed there is slightly different. So, this we will cover in next class and if time permits we shall also sort leds in the next class because that is the final thing in the optoelectronic portion of the course how light emission takes place we are talking about light detection. Now we should talk also about light emission then so.

Thank you for your time. I will see you in the next class.