Fundamentals of Semiconductor Devices
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Lecture – 49
Junction photodetectors

Welcome back. So, if you recall we were discussing about photodetectors. In the last lecture, I had introduced the most important figures of merit for photodetector and also we discussed a little bit on photoconductive photodetector. The differences of photoconductor photodetectors in solar cells, although they are principal operating principle is quite similar.

Today, I said we shall discuss about Junction photodetectors which are like p-n junction or Schottky junctions. Very much like solar cell with the difference that you may bias this photodetectors at an appropriate voltage depending on application. Photoconductor photodetectors you have to apply bias they are symmetric I V is a symmetric with respect to y axis. Junction photo detectors are like p-n junction diodes like solar cells which are not symmetric and which are vertical devices p on top, n on bottom or vice versa.

I had also talked about Metal Semiconductor Metal MSM sort of a device which is lateral very easy to fabricate, no doping is required in other things and most people who published research data the initially do it on photodetector based on MSM geometry, it is very easy to do that. So, today we shall started p-n junction photo detector and we will hopefully try to wrap up about the photodetector session, so, that we can start LED in the next class ok. So, let us come to white board again here.

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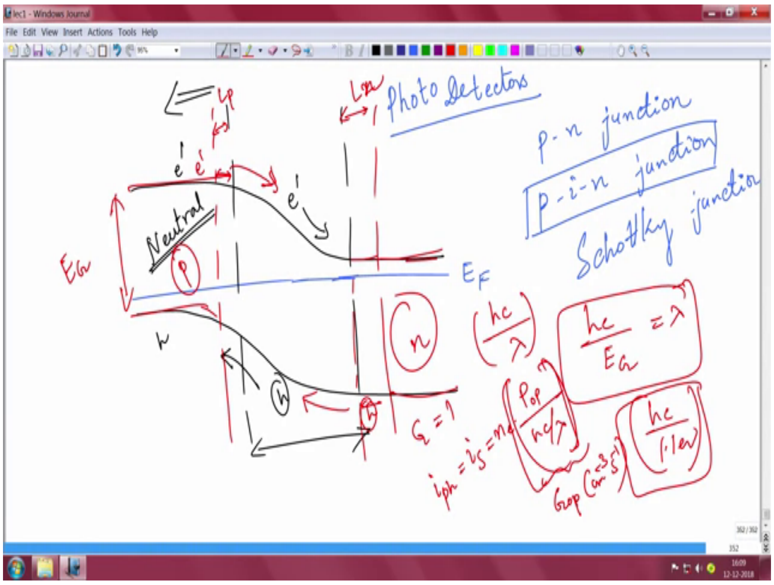

So, what is remaining now is a photodetectors that are based on junctions or when I say junction it can be p-n junctions um. There is a variation of p-n junction it is called p-i-n junction or p-i-n photodiode and then there is Schottky also Schottky junction can be also used as a photo detector.

I am talking about the primary ones. A p-i-n is actually is a p-n junction in where there is an intrinsic layer between p and n; so I will tell you about that. So, we had just discussed p-n junction as solar cell in the last to last class or so, if this is the Fermi level I am sure you have seen this hundreds of time probably.

So, there is nothing much new about here. Just I want to say that the same thing that I have told you in the solar cell class. You want the light to be predominantly absorbed in the depletion region which is this because the field is there. So, any light that is observed that can give you rise to an electron and an hole here. The electron will be swapped this side, hole will be swapped this side.

So, the current will eventually flow in this direction right this area is actually this area is neutral or quasi neutral region and here there is no field. So, any photon that is observed here that gives rise to an electron hole pair is wasted because that will neither drift. They will basically will diffuse and recombined and not contribute to electricity. Same thing applies here except just what is also true in solar cell is also true here that in one diffusion length over here and one diffusion length; one diffusion length L p L n sorry here L n and this is L p in one diffusion length in the neutral region if an electron and or hole comes because this is entire region.

So, here if a minority hole comes somehow in this one diffusion length, then that hole can be swept away and similarly one in minority electron if it comes within the one diffusion length it can be swept away to this side right; so that contributes to current. This is a depletion region and of course, this need not be silicon only. The band gap about the material will decide what wavelength of light you want to detect.

Typically, if you want to detect a light of wavelength lambda, you will go by hc by lambda you know; your E G, hc by E G has to be your band gap that you choose so that the absorption is a band edge in order to get very sharp performance. But silicon can be used for all the wavelengths less than you know hc by 1.1 eV which is close to 1100 nano metre, but it will not selectively absorb a UV or visible it will absorb everything from this nano meter.

Now, the thing is p-n junction solar cells typically do not have a gain because this n region and this p region they act as blocking regions that do not allow the carriers to either drift or diffuse across this. So, you can say it is a blocking reasons and so you gain inherently is 1 which means your photo current is actually your signal current which is not the same in your photo conductive detector if you recall and this will be given by a efficiency times the optical power by hc by lambda.

Actually this optical power times hc by lambda is something we call Gop in your solar cell, it is the same thing. It is per centimetre cube how many photons are there per second [FL]. Actually this is the same thing. So, this is optical generation rate. Here I am writing it is a form of power by the wavelength.

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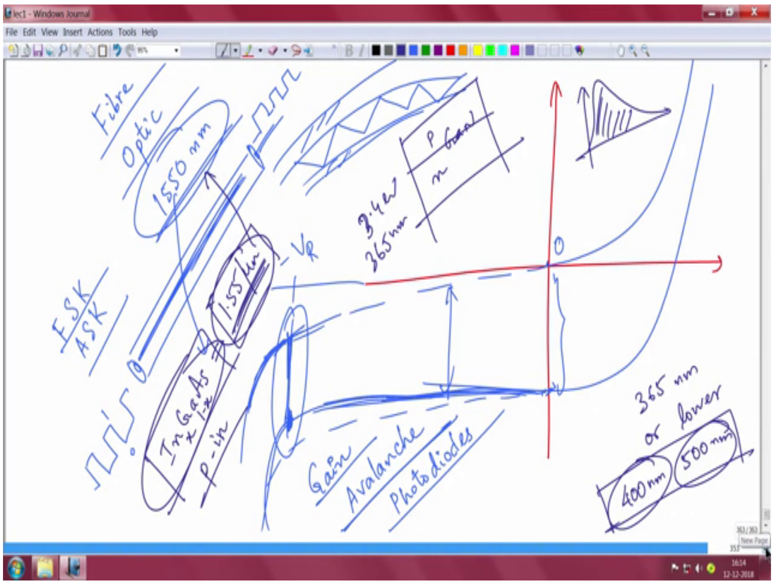

And you might recall that it is the same essentially junction it is a junction one right. So, you will have the same sort of a i v this is your i v and you know this is your zero-bias current. So, even at 0 voltage you will get some current and then it will slowly and eventually it will break down. So, current is mostly flat slowly it might increase if you are sample is leaky it might slowly increase, but that is ok. This is a dark current; this is a dark current right.

So, you want this ratio photo to dark ratio it should be high for a better noise performance and so on and eventually it will break down. Some people operate the device also near break down at this point just before break down you can operate the device. In that cases the gain is high and those are called avalanche photodiodes; if you operate a p-n junction or such a Schottky junction other kind of photodiode near breakdown, just before break down. Then what happens is that this breakdown is happening because of an avalanche multiplication.

If you remember there is a high field; it is the high voltage know high reverse bias, there is a high field in the depletion region that high field will sweep the carriers so fast that energetic carriers will knock off an electron hole pair you know knock of an electron and create an electron hole pair. Those secondary electrons will again accelerate they will create two more pairs and so on, that avalanche starts affecting at near breakdown.

So just not do not go to break down, just before the breakdown use you bias the device and you operate the dark and photo current region here. At that point you can get some high gain, if you operate at such region it is called avalanche photo diodes avalanche photodiodes and you might buy avalanche photo diodes also in market. They will tell you at what voltage you have to operator and so on ok. This can be of silicon this can be of any material.

Please remember, the material you will choose depending on the band the light you want you want. I keep telling you that fibre optic communication for optical cables you know fibre optic communication typically the information is sent at 1550 nano metre that is the wavelength at which the information is sent across the fibre optic cables. You will have this cable know there will be a core; there will be a core along which the light will propagate and then there is a cladding layer I can go through fibre optic text books and classes.

Essentially, you have total internal reflection even if your cable bands your light will total internally get reflected and because the refractive index indices are adjusted accordingly. So, this fibre optic communication typically that brings you the broadband high speed internet. It is actually 1550 nano metre that is the wavelength and the light is modulated very fast if you say 1 Gbps it means the light is modulating at 1 billion times per second.

I told you that many modulation schemes like frequency modulation, amplitude modulation, frequency shift gain amplitude shift gain. There are signal processing things that you can talk about I will not going to that, but your modulation of the signal means 1 and 0 for example and the n outputs are in the other receiving side also you should be able to reproduce; so your detectors has to be very fast.

For this 1550 nano metre optical fibre optic communication the receiver will have a detector which is typically made of indium gallium arsenide that the mole fraction of indium and gallium will be tuned such that the band edge or you know the absorption will happen at 1.55 micron, this is the same thing as this right.

This is in gas photodetector in gas p-in diode can be used and in gas p-in diode which is just like a p-n junction except that there is an I layer in between I will come to that very soon. These are commercially available in-gas spin diodes are commercially available at this wavelength. So, even another wavelengths you can buy; so this is your junction, photo photovoltaic junction that you are using for detecting wavelength.

And remember if you use a p-n junction like this with for example, say indium gallium arsenide you are going to get 1.5 micron absorption it will also absorb all the wavelengths that are lower than one wavelength that are higher sorry lower than 1.55 micron corresponding to energy of photons whose energy is higher than the band gap of in gas, that is ok. But, typically it is used at the band edge only.

Similarly, if you take a p-n junction of gallium nitride whose bandgap is 3.4 eV that corresponds to 365 nano metre then this photodetector of gallium nitride will only respond to 365 nano metre or lower wavelengths not higher wavelength. Because, if you shine visible light, for example 400 nanometre is violet or 500 nanometre is green all these light will be not absorbed in the gallium nitride wafer a p-n junction because the band gap is larger than the that of this energy of the photons right.

So, anyways this unlike solar cell where the input spectrum the sun is fixed if you remember that sun spectral looks like this know that sun spectre is fixed then you are going to harness the energy and deliver the power to a load. A photo detector does not have a mandate like that. A photodetector is not expected to deliver power it is expected to detect as faint and weak signal it can and that wavelength at which it has to detect depends on the band gap of the material you are using. There is no fixed inputs solar spectrum sort of thing.

So, there are that is why there is a fundamental differences between solar cell and photo detector. Apart from the fact that solar cell has to be has to have an inbuilt junction field. So, it has to have like a p-n junction sort of thing, but in a photodetector you might apply bias also. So, it can be lateral device without any photovoltaic action.

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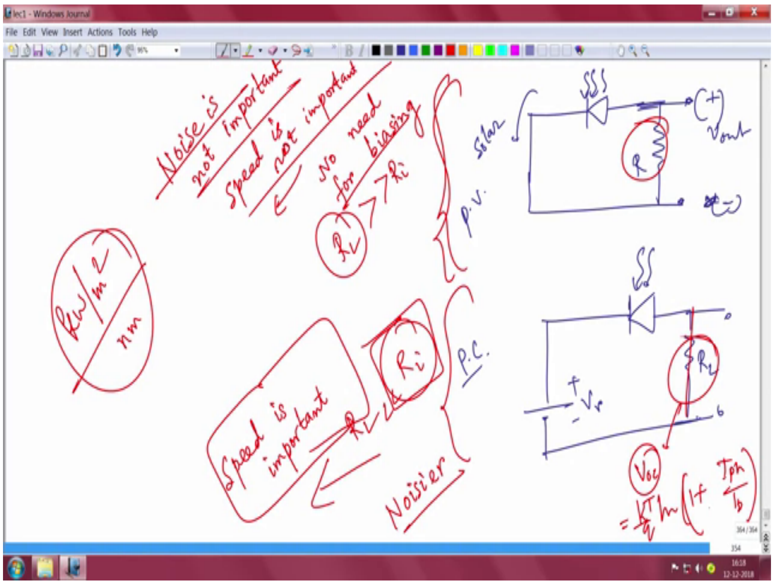

Now, if you recall I had drawn the circuit diagram for a solar cell. A solar cell is essentially like a you know there will be a shining light and you are generating electricity. So, this is this and then there is a load I am not drawing the series and the shunt resistance.

There is a load across which you are basically taking the output voltage right. There is a load that around which you are taking the output voltage. This is a solar cell of photovoltaic mod P V mode. In a photoconductive mode which is P C mode is a photoconductive you might want to apply reverse bias ok. So, you will have a light shine here also this is light and then you have a resistance of course, same thing, but that accept that here you will have a; you will have a reverse bias applied here which will be you know del del be there right.

One important thing is that in case of solar cell which is this in case of solar cell you do not need a bias voltage right. No need for biasing yourself no need for biasing yourself it will forward bias itself based under load resistance. So, you do not have to bias and the load resistance that you are using here is much much large it is much larger than the internal resistance of the device because you want to deliver power here.

On the other end in a photo conductor in a photodetector mode your load resistance that you are using here is much smaller because you do not want to unnecessarily drop power there ok. Your internal resistance R i is the internal resistance of the device actually is larger. So, in photodetectors speed is important how fast you can actually on and off the photo detector from you know the light following can you turn on and off the detector. In solar cells speed is not important right, sunlight is there. Sunlight is not important. Sunlight is not going to be switched on and off in the day like so fast millisecond on nanosecond sunlight is there.

So, you do not have to worry about the speed of solar cell, but in here photodetector you have to worry about the speed. Secondly, photodetectors are also nosier devices because your intrinsic resistances are high; intrinsic resistance are high. You have to talk about the noise floor because the noise can severely limit the impact of the photo detector. You want to detect a faint signal.

But, in case of solar cell the solar spectrum is fixed it is kilo watt per metre square their noise floor is not like that. So, solar cells do not worry about noise. Noise is not relevant so much ok. Noise is not important in solar cell because, solar cell are nothing to do with noise. There will be thermal you know resistances is there be shot noise quantum fluctuations they do not care; solar cell is very high you know the suns intensity that is falling is kilowatt per metre square right per nanometre.

So, there is a solar spectre falling you know the sunlight following, do not worry about the noise and all. But, in case of photodetector your signal can be very weak coming from a distance star. For example, you wanted to do mid IR astronomy or UV astronomy. The signals that come from these will be very fine faint right. So, you need to detect very faint signals not like kilowatt per metre square; that is why noise is very important in photodetectors.

The expression for photo you know corresponding output voltage in a this thing is also like the open circuit voltage in a solar cell only, except that where the wavelength is not the wavelength corresponding to sunlight. But the source maybe IR, maybe mid IR, may be ultraviolet whatever you know, but otherwise this expression is similar you know. It is a junction photovoltage only 1 plus the photo current by the dark current; it is the same thing ok, nothing fancy. Photo detectors have you know very low dark current, they are very small you know load resistance and so on right.

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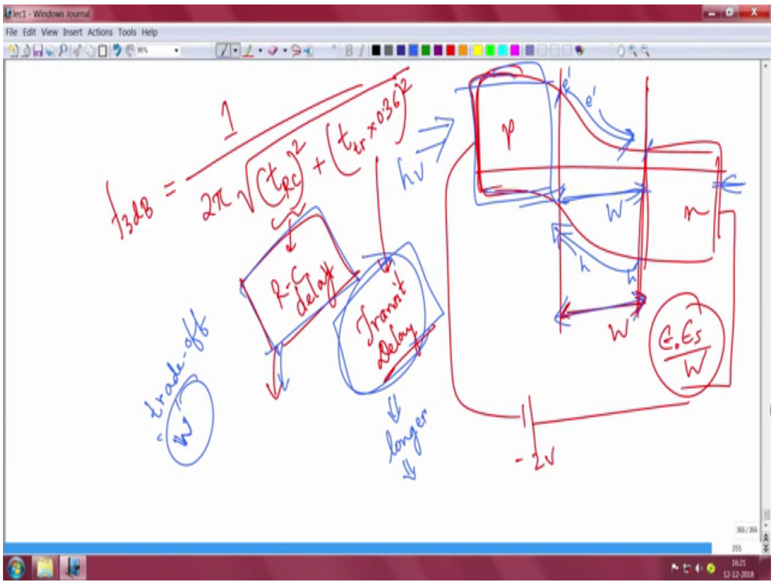

So, you know in case of this junction photodetectors like a p-n junction, when you have like you have a p-n junction photo detector like this; this is the depletion region. You will operate it at either 0 volt or a very this is p this is n. So, you are either operator it at a 0 volt or a slightly more negative voltage like minus 2 volt or minus 3 volt or minus 1 volt, whatever.

So, this is a you know a junction photo detector and there is a depletion layer the speed of this detector which is corresponding to the 3 dB bandwidth. Remember 3 dB band width from last class? You will remember it is actually how fast that can operate what is the bandwidth in gigahertz or megahertz is given by 1 by 2 pi into square root of the you know the there is a time constant associated with RC delay plus there is a time constant associated with transit delay which is multiplied by 0.36 for some reason do not have to worry about the right now.

Essentially this is your R-C delay speed I am talking about the speed, what are the delays. And this is your transit delay. What do you mean by that? The speed of at which detector can operate will depend on R-C delay because a photo detector will have parasitic resistances, series resistance, some parasitic capacitances will be there. This is a p-n junction. So, it of course, has a capacitance know. Their capacitance is given by epsilon naught epsilon s the material by W; W is the depletion layer.

So, if your depletion layer is large then what will happen your capacitance will come down if your depression is large. If your capacitance comes down then your R-C delay also comes down which means your detector should become faster ok. This is a charging discharging delay associated with the photoconductor being a p-n junction. So, it is like a junction capacitance if you recall we have studied that it is a p-n junction which is which acts as a capacitor and there will of course, be resistances associated.

So, you have a charging discharging delay of the p-n junction that gives rise to this R-C delay which does not matter in solar cell, but it definitely matters in photodetector that is the R-C delay. Then there is transit delay essentially an electron will take some time to go, a hole will take some time to go, but on an average you take electron taking a time from going from this point this point. So, what is the total time here a hole? We will from here to here what is the total time their that is called transit time because the electrons and holes have to physically move to the edge of the depletion region to get swapped away you know develop in the process of sweeping them away; so that is a transit delay.

Now, if this depletion region W is larger that transit time will became longer because the electrons and holes have to travel longer now. And so, your transit delay become longer will lead to a slower device, but your larger depletion width will lead to a smaller RC delay. So, there is a trade off; there is a trade off. You have to play on the depletion width W. You cannot have a depletion width W very large, otherwise your transit delay will be so much that your device will become slow.

You cannot have the depletion with very narrow because your R-C delay will become very large going to a large capacitance and you will again lose the speed. Also the depletion region is the region where you want all the photos to be absorbed. If your depletion region is narrow then the fraction of protons you are absorbing will also be small and so, your efficiency also will come down. So, if there is a trade off that you have to play.

Of course, light will shine from here or from here and that light do not; you do not want that light to be absorbed in this useless region p. So, you might want to use heterostructure such that p is slightly wide bandgap so that it is not observed in the light that is falling on the intrinsic region. Do you follow what I am saying you? I will come to that. Anyways I was talking about 3 dB bandwidth here.

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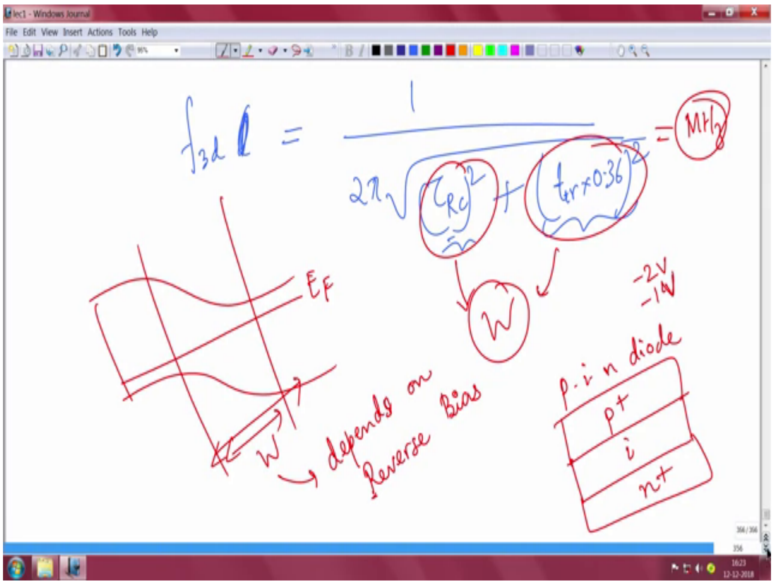

I was talking about 3 dB bandwidth there. So, your 3 dB bandwidth in this will be giga Hertz, mega Hertz or whatever will be equal to 1 by 2 pi square root of your RC delay right plus your transit time delay into some 0.36 it comes from some frequency response and other things. So, that comes from that.

So, you know if this component is larger than one component dominates if this is larger than your RC delay dominance right. So, it is all this things you have done and the best delay will happen when this quantity is; this quantity is equal to this quantity then your time will there be your frequency will be the fastest. So, those things you can understand there. Now, you see this both of these delays depends on W.

And if you look at the band diagram again this is your; this is your depletion region W. You see the depletion region W depends on the what? It depends on the reverse bias that you are applying. It depends on the reverse bias that you are applying, if the reverse bias is more the depletion region will become larger right if a device bias reverse bias is reduced depletion become smaller.

So, if the depletion do with W changes with bias, then your delaying and your speed in bandwidth in giga Hertz or mega Hertz also will change with bias which is not a good thing. Sometimes you might want to bias it at minus 2 volt sometimes minus 1 volt. You do not want the speed to change so much, but it will change.

So, the solution is to go for a p-i-n diode. In a p-i-n diode you use a highly doped p plus layer on top of an undoped layer and this can be any material silicon gallium arsenide, gallium phosphide you know ferrous oxides can be p doped gallium nitride and whatever and you use a very highly n plus doped region. If what if this is the case then what will happen you know; I will show you now.

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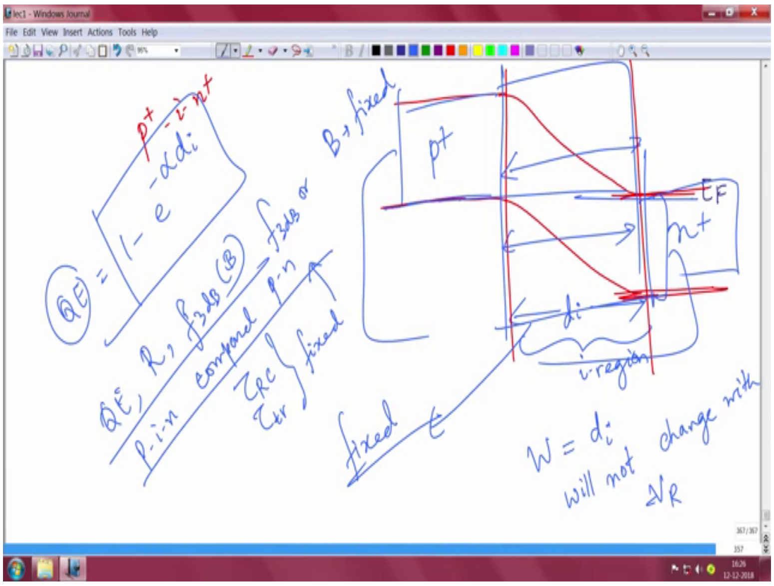

So, if you use a p plus i and n plus this is called p-i-n junction. What happen will happen is that you have this Fermi level the p plus is very heavily doped. So, the Fermi level will almost balance here n plus is very highly doped Fermi level almost here and depletion will not extend towards p and n. Whatever depletion is complete only dropping across the is dropping across the i-region this is your sorry this is your sorry I am not a good drawing person.

This is your i-region; so this is your Fermi level ok. This is your i-region and your depression width is fixed at the thickness of the i-region this is d i this thickness of the i-region is the depletion your depression width will not change. This will not change which apply reverse bias V R. No matter what you apply here your reverse bias your depletion thickness will not change because this side is p plus, so, depression cannot go to p plus. This side is n plus so, depletion region cannot go to n plus it is very highly doped you.

Remember, if you have a very high doping depletion will not extended there. So, the depletion has to be on the i which means your depletion region thickness is not fixed. If your depression region thickness is fixed then your transit capacitance RC delay time and you transit time delays are also fixed which means your 3 dB frequency or your bandwidth it is also fixed.

So, that is a flexibility you have and that is why people go for p-i-n diodes only now. Your capacitances is also fixed right; so that is a good time. So, you know advantage of p-i-n is there, your quantum efficiency your quantum efficiency also depends by the way on 1 minus exponential of minus alpha times the depletion where you are absorbing. In a normal p-n junction this depletion keeps changing with bias.

So, you do not know what efficiency you are going to get at minus 2 volt minus 3 to calculate, but in p-i-n depletion does not change it is fixed at d i which is the thickness of the i-region. So, your efficiency can be fixed; so in terms of designing your quantum efficiency hence responsivity, hence you also your 3 dB frequency and so on speed and band width and so on your p-i-n device will definitely be better compared to your p-n devices because you can fix this numbers beforehand. You can design this number is better [FL] that is why you use that.

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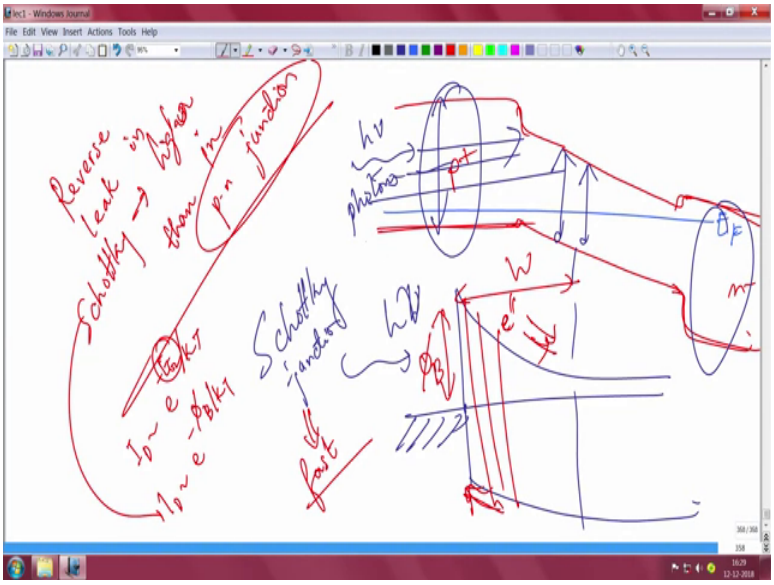

And I also told you that sometimes you might want to use a slightly high band gap materials so that you know if you have your Fermi level like that, you might want to use a slightly higher band gap material, slightly higher band gap material. So, what will happen this is p plus and this is n minus; your band gap on the p side is slightly bigger than on the i side band gap on the n side also is slightly bigger than i side.

So, any photons that are coming here these are h nu photons this photons that corresponds to the band gap here will not get absorbed here because this is a wider band gap. So, all the photons that shining that corresponds to the band gap in the intrinsic layer will definitely passed through very easily. It will not get absorbed in the p-type layer or n-type layer which will not lead to any useless waste of the carriers.

So, these are slightly heterojunction photo detectors also used their advantages and disadvantages are also of course, in any case. And similarly you have this Schottky junction photodetectors which is the same as you know p-i-n junction except that these are Schottky. So, you have some think like say metal work function and then have a barrier like this right.

So, if you shine light from the top then in this depletion region; in this depletion region whatever is absorbed will immediately go this and that way. Of course, in most of this will get absorbed in a nearest surface. We do not talk about hole so much we talk about electrons and because only electrons go you know on transit here. So, this Schottky detectors can be quiet fast because anywhere that you have only electron transport and not hole transport the device tends to become faster.

So, Schottky device is also is very similar to p-n junction device in terms of operations speed and all these things ah. So, you do not have to worry you know Schottky junctions also used, but the dark current in Schottky junction will not be as good or as low p-i-n junction because reverse leakage in Schottky junction you know from your other earlier classes. Reverse leakage in Schottky is always higher than in is higher is leakage is higher sorry, higher than leakage in what? P-n junction.

Remember, of the same material I am talking about same material. You cannot compare Schottky junction of gallium nitride with p-n junction of silicon about the same material. In p-n junction the barrier the dark current [FL] barrier goes as e to the power minus E G, the band gap by KT. In Schottky the barrier the leakage current goes e to the power minus Schottky barrier by KT. Schottky barrier is this a Schottky barrier will never be as big as a p-n junction and the band gap sorry the band gap.

So, your leakage in the Schottky junction is slightly higher. You can get faster devices, but little nosier. So, dependents on application that you are looking at you can (Refer Time: 25:09) like that.

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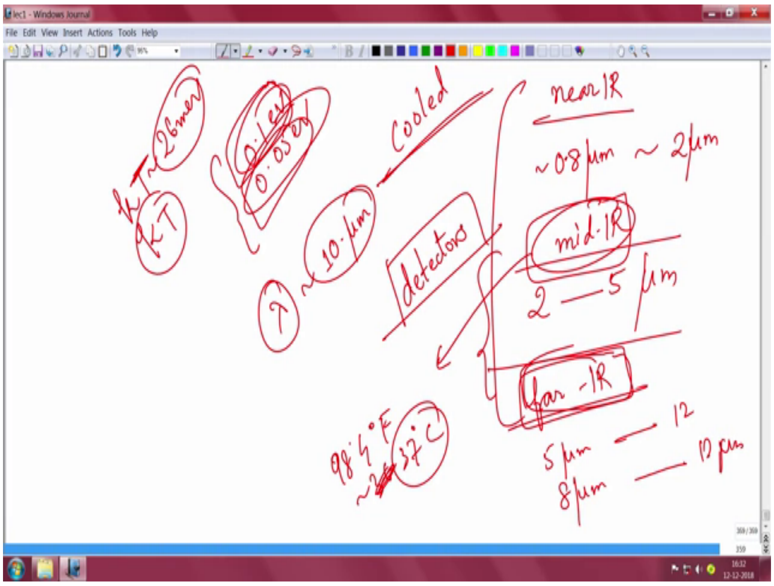

So, I told you different materials are used for photo detectors for near see this near IR photo detection the near IR wavelength stretches from of just after human eye sensitivity and set around 700.

So, from 0.8 micron to may be around 2 micron, the definition can slightly vary depending on whom you are talking to. And then mid IR which stretches typically from 2 to 5 micron sometimes people also have a slightly different range and then you have far IR. Far IR will go from like 5 micron to much more may be 12 micron or more or even sometimes people call it 8 micron and 12 micron. These are the rangers you have to go to progressively lower and lower band gap materials.

Mid IR for example, in detectors mid IR detectors have extremely high importance in military surveillance, in night vision, in technical and strategic things like in airport security. If you want to if you do an mid IR imaging you will be able to see who has a concealed weapon; you can also detect very dangerous gases; in the night time we can see enemy movement. So, mid IR detectors are very strategically important and that why important mid IR detector is very restricted and it is purely military you know a lot of security and other things. Besides that mid IR detectors can also detect things like some scan skin cancer and tissues and cells and all; so these are very important and promising devices.

Far IR is also very important for many of these industrial waste monitoring and other things. There is always a black body radiation you know human body temperature is around 98 degree Fahrenheit, 98.4 degree Fahrenheit or around say 36, 37 degree Celsius; 37 degree Celsius is the human body temperature. Everything there is at a finite temperature emits a black body radiation now. So, human body you know Wien's displacement law.

You have learnt about Wien's displacement law. You can find out what is the wavelength at which human body is at normal temperature will emit. It will emit at around I guess 10 micron or 10 point something micron that is the wavelength of mid IR, far IR, infrared signature of human beings animals also depends on the temperature.

So, if you have this far IR detectors you can detect all these things. So, there is a lot of applications of course, this devices have to be cool down. Not only the devices, the entire lengths the electronics everything has to be cooled down because you know if consider the band gap; the band gap will be like 0.1 eV 0.05 eV. So, the room temperature thermal energy is so high 26 milli electron volt that the probability of this thermal acceleration generating carriers in this material is very high.

So, your dark current is ridiculously high. You will not be able to differentiate the signal from a noise. So, that is why you cool down so that KT becomes very low 77 Kelvin, 50 Kelvin, 4 Kelvin. Your system becomes so cool that your KT becomes comes lower and compared to KT this signal will now be bigger. So, you cannot get a noise will come down. So, this is one form of IR.

So, this mid IR and IR detectors are very important for a lot of applications you know military and strategic visible detectors also can build, silicon can do most of the visible detection if you want or human eye also detects also visible. Of course, the magnitude of the light that you can detect with photodetectors you can make it much more sensitive than the human eye and also it has UV detectors from many other applications and other things. So, these are different categories of UV detectors and you know applications of various detectors that are there mid IR and IR detectors have large number of application. Please remember that apart from this things.

So, we shall end up our lecture here today. Now, we are done with photodetectors. We have finished the proto detectors discussion the various categories of detectors I have briefly discussed about also the speed about how fast you can operate a junction proto detector. There are two limiting factors; one is that there is an R-C delay, because of the capacitance charging, one is the transit delay electrons and holes have to take to reach each other in the other ends; so both of the delays matter in deciding how fast the detector can operate.

If you want to operate at a one giga Hertz for example, the delay has to be less than nanosecond for example, right. So, all these things are important in designing photodetectors, heterojunction photodetectors are there, avalanche photodetectors are there when you operators at near gain. Photodetectors are a vast topic again like any other topic BJTs, MOSFET and all. Within this syllabus we cannot do justice to a lot of these things. Each of the topics in photodetectors can cover many many lectures.

For example in avalanche photodetector itself there are so many things to understand in terms of gain, noise and bandwidth ok, the trade off. There is something call SAM – Separate Avalanche Multiplication photodiodes, but the kind of architectural design that you can do for enhancing the gain. There are so many threats that we can discuss about even it transfers speed and everything.

There is also quick quantum value infrared photodetector, mercury cadmium detector and so many detectors are there. You can definitely read up discuss with me and other things over email you know, but here in the course we will only restrict to whatever we have discussed till now.

So, we shall end up photodetectors here. From next class we shall start with light emission which is LED ok.

Thank you for your time.