Integrated Photonics Devices and Circuits
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Lecture - 40
Light Sources and Photodetectors for Integrated Photonics: Photodetectors for Silicon Photonics

Hi everyone, today we are going to discuss about photo detectors for silicon photonics. What we will do first we will discuss about the working principle of photodiode in general. And then I will be discussing about waveguide photo detectors, especially for silicon photonics applications for photonic integrated circuits with some examples.

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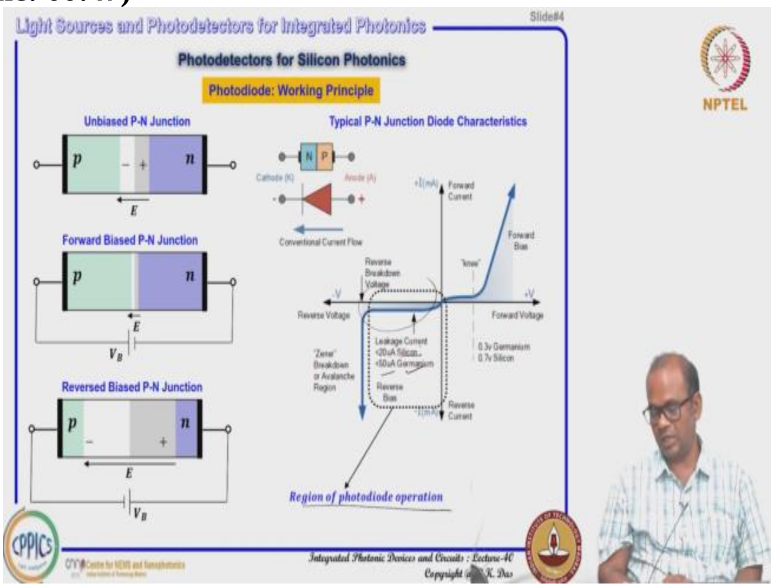

So, let me start with working principle so, as the name suggest photodiode that means a diode. So, basically, when we talk about diode these days that means a semiconductor PN junction diode and we know that how it works for example, a PN junction when it is fabricated as fabricated one side is p type doping and other side is n type doping and then if suppose this is your metallurgical junction then I think normally some of the majority carriers from the inside like electrons will move into the p side.

And then it will actually recombine with some of the holes and then it will create some kind of positive immobile charge in the n side region and vice versa process there will be negative charge immobile charges in the p side and that is how you can get a space charge region. So, where this is plus and this is minus, so, that is why electric field will be in this direction as it is mentioned.

So, there will be space charge field will be there and you must know that even though it is p type doping n type doping there are free holes are there and free electrons are there in the n side, but there in principle charge neutron, but only space charge region will be there electric field will be there. So, because of this electric field, we know that there will be some kind of built in potential we have seen earlier and if you are giving a forward bias this depletion will be reduced and electric field inside will be reduced as well.

Similarly, if you are giving a reverse bias that means, you are just connecting positive to the n side negative to the p side and then this depletion will be widened. So, the depletion will be widened and this electric will also be increased. So, now, what it is done normal PN junction diode if you just see the working principle symbolically sometimes it is represented like that p and n 2 terminal device like this.

Actually whatever way I presented here and p side we can write like these and negative side this is symbolically it is written conventional current flow if you are just giving forward bias then current will be flowing, but reverse bias normal no current will be playing because in the reverse bias you are actually enhancing this built in potential electric field in the depletion region, but in the forward direction, this is actually reducing and that is how if you see the IV characteristics.

Then you can see that in the forward direction in the beginning when you are increasing your voltage the power will be low because you are just overcoming the built in potential already for a PN junction and once you are very close to built in potential then your current will flow in the positive direction exponentially and that current equation we know that this is something like that we can express e to the power qV / kB T - 1 where I 0 is the reverse saturation current B is the applied voltage.

So, following that formula normally in the reverse direction actually you see very little amount of current will be flowing, but when the reverse bias voltage is sufficiently large, then I think some breakdown process takes place a lot of carrier will be generated because of the energetic carrier 1 or 2 carrier available in the depletion region that will actually trigger for generating more electrons.

And a huge amount of current will flow that is actually sometimes called it is Zener breakdown or Avalanche process depending on the different type of condition but in general we know this is the characteristics and as we know that electronic circuits normally when we use PN junction diode basically it is used mostly for your rectifiers purpose and also a little bit of this Zener breakdown region also we used for different applications.

And you see that this reverse direction whatever the reverse direction when the reverse bias is there the current is very small. So, that is the advantage you take use this diode as a rectifier for electronic circuit however, for our photonics applications, we use reverse bias biased PN junction for photo detector operation. So, region of photodiode operations it is shown, that means, you have to apply some reverse bias and then you have to see that if any change is happening in the reverse direction current.

Or if it is increasing depending on the light falling on to it then we can say that how much current is increased in the reverse direction and that actually measures the light intensity. Normally without light in the dark condition if you see if you are giving certain biased voltage some current will be there and that level for silicon diode it is in the order of 20 micro ampere and for germanium it is about 50 micro ampere or something like that. So, micro ampere and sometimes it can be if it is a good diode it can be nano ampere scale also. And so, how we use this reverse biased PN junction per photodiode application? Let us see.

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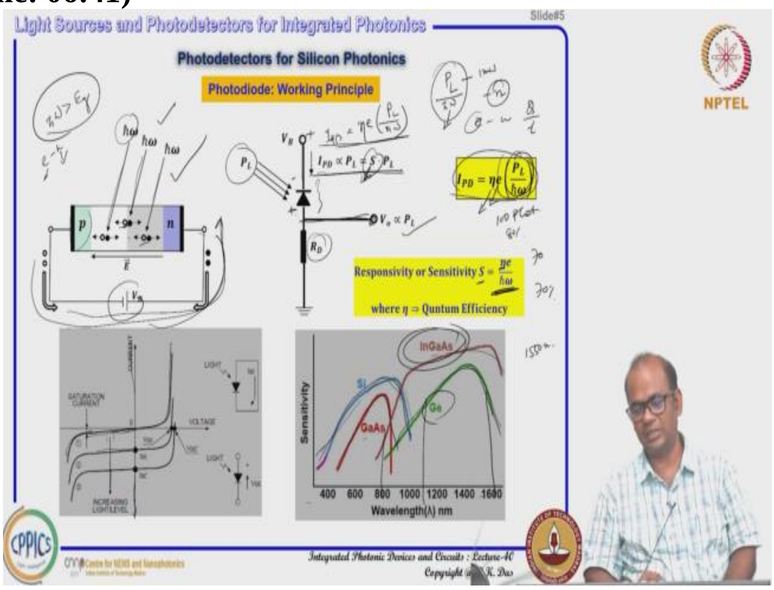

So, how we do it here? For example, if you have it, if you are just illuminating that under reverse bias condition, when your electric field is inside the depletion region will be enhanced depletion will be widened. And in that region if some light comes then what happens if the proton energy of the incident light that is actually quantum of photon energy is h cut omega if that is actually greater than E g bandgap then what happens the electron from the valence band that will absorb 1 photon and can be excited into the conduction band.

So, in the process what you will get? You will be creating an electron hole pair a free electron in the conduction band and a hole left behind in the valance band. So, this electron and hole it is an excess carrier now, in presence of light intensity. So, depending on the light intensity your number of photons will be more so, you can expect more number of electron hole pair will be generated here it is shown as an example 3 electron hole pair it is generated here electron.

And hole the empty circles representing hole and solid circle that is representing electron and what happens since in this depletion region there is a inbuilt electric field is there and that is enhanced by reverse bias what happened this field will actually try to separate this electron and hole in 2 different direction as you know electron negatively charged that will actually travel against the electric field and hole a positive charge that will travel along the electric field direction.

So, they will be separated and hole will be coming to this side and finally, we will see that in the p side region you will get more hole is being coming out from the depletion region and since it is negatively charged, this will be hole is positively charged and that will come out and you can say that it will be reaching towards the negative terminal of the battery. Similarly electron will come this direction and it will reach to the positive terminal of the things. So, in this way you can see a current flow in this direction.

So, in this direction, if it is current is flowing, you can measure that current and depending on that current level you can actually see what is the incident power light power for example, this is shown, that characteristics you see here, this is the characteristics of the normal reverse direction no current forward direction it will be like that, but whenever you are illuminating that increasing the light then you see this negative direction this current will be flowing more.

So reverse saturation current will be increasing that is actually current this negative current actually that means reverse direction. So as you keep on increasing the light intensity, so more current will be flowing in the reverse direction. So, just looking into this increasing light, increase in incremental current you can say that how much light is there you can just calibrate that and you can use that as a photo detector that is what is the major working principle actually.

And you have to see normally a photodiode whatever it is schematically shown here, but normally in textbook if you see the photodiode it is represented like this. So diode and this is a positive terminal that is the p side this is positive and this is the negative side that means n side and then you just give a bias point there plus bias point you are giving there. So, that reverse bias here and when light is illuminated, then current will be flowing and this current can be actually if it is flowing through a load resistance.

Then this can be considered as your load resistance and you can see that current at the output whatever you take it here across this point that will be the output voltage and that voltage should be proportional to the incidental power of the incident light because power of the incident light more is the power you will get more photodiode current that is what it is shown here. And that means photodiode current is proportional to P L and this proportionality constant is here it is mentioned as a S we call it as a sensitivity or responsivity.

Because that depends on many things, what is the area of the photodiode and what is the absorption coefficients of the material you are using particularly the PN junction material. So, depending on that this S actually value of the S can be decided. So, now, let us see, let us try to find out what would be S that is proportional to P L when I say that ultimately, this proportionality constant depends on many things as I mentioned that it is depending on the material property with area etcetera.

If I just a little bit look into it, for example, if you have a P L amount of power it is coming that means this much joule per second power is coming if it is 1 milli watt, suppose P L = 1 milli watt that means 1 joule per second energy is falling into the photodetector. So, that per second energy whatever per second energy we are getting, if you divide by photon energy, if you know the frequency photon energy, then you can get number of photons per second falling on to the photodetector you can find.

So, P L / h cut omega, h cut omega is the photon energy P L / h cut omega is the number of photon energy. So, that means this number of photons, so, all these number of photons, they will be if they are actually absorbed and create a electron hole pair then we can say that the each of these electron and hole they will be travelling in opposite direction to contribute current that means, the number of electron that is actually started conducting current will be n times e.

So, this is your number of electrons and electronic charge that actually per second this much charge will be flowing per second. So, that means, these actually represent this together represent Q / t that means, charge divided by time that is actually current, but, we use additional component called factor like eta that means, whatever the electron hole pair is generated because of the light falling on the depletion region, all of them may not contribute to your current.

So, some of them will be lost some of them some photons may be lost also that is why we use a term called eta called quantum efficiency. That means, if you are having 100 protons are falling in the photodetector maybe 80 photons contributing to the electron hole pair and then 70 photons maybe contributing to the current then we can say that quantum efficiency is 70%. So, how much power you are how many photons you have just falling and how many of them actually effectively contributing to the current that is called quantum efficiency.

So, that is why current will be your I PD if you just write I PD = eta times e and P L / h cut omega that is the thing. Now, again earlier we have shown I have represented one we have introduced one parameter called sensitivity I PD will be equal to S times P L. So, if I compare this thing I PD and this one the S expression we can find out like this S = eta e / h cut omega. So, that is the sensitivity you know e is the electronic charge h cut is the reduced Planck constant, omega is the frequency of the incident light that they are actually constant.

So, this eta basically the quantum efficiencies that actually depends on your device geometry and material property. So, all these actually count for your sensitivity photodetector. So, first of all sensitivity of a photodetector depends on quantum efficiency and it depends on the frequency that means, energy of the photons of course, now if you see that this sensitivity depends on the photon energy.

Because, the photon energy should be sufficient to create electron hole pair that should be actually greater than the bandgap photon energy must be greater than the bandgap. So, that means, it is bandgap dependent sensitivity is bandgap dependent so, that means, sensitivity is a material dependent different material will have a different bandgap so, it is a bandgap dependent. So, if we see silicon sensitivity silicon sensitivity as a function of wavelength it is shown like this.

So, it is somewhere in the visible region 2800 nanometers this carpet is suing gallium arsenite you see that is also it is narrower, but it is more or less falling something similar to silicon in gallium arsenite whatever the bandgap is there, if you compare indium gallium arsenide, the bandgap must be smaller for that that is why the emission here if you see that goes to longer wavelength range.

So, all this depends on bandgap and if you see the germanium that actually pulse that is the bandgap this sensitivity is higher around say 1200 to 1600 you can say that from here to here, you can use this one for a very broad wavelength range, but if you are using in GaAs you can actually eventually can use visible regions near infrared region to 800 nanometer even broader if you are working with a communication wavelength like around 1550 nanometer.

So, you have to either go for in GaAs material for photodiode design or germanium, but remember that germanium has a sensitivity relatively smaller than indium gallium arsenide. However, in spite of that, people used to use germanium photodetector for silicon photonics application because germanium is compatible CMOS compatible you can actually fabricate germanium photodetector using CMOS technology however, indium gallium arsenide which is actually a 3 type semiconductor compound semiconductors and it is not CMOS compatible.

So, it is very difficult relatively difficult to integrate indium gallium arsenite photodetector in your silicon photonics circuits. So, so far we have just tried to give you a very basic concept of photodetector what is their principle? What is their working principle and what are the important parameters so, far, you see this photo detector it is an area is very huge area actually you can think of photodetector all the figure of merits how you can reduce the figure of merits.

What is the speed and how you can improve the efficiency? And how you can increase the output power? All those type of things are very important, but we will be discussing only those specific figures of merits which is relevant for photonic integrated circuit applications and what is the state of our technology till today.

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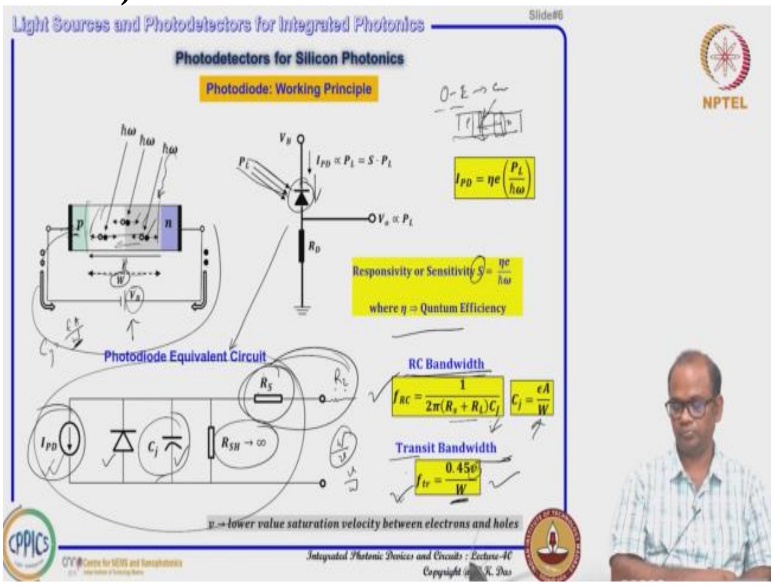

So, now, if you see how we can just find the figure of merit important characteristics of a photo detector. So, to understand that apart from that sensitivity and quantum efficiency, these are actually material property ultimately you have to read out from the current or voltage from the photodetector for actual processing for when you are just thinking photodetector as an OE converter.

OE converter means, it actually converts optical signal into electrical signal or in another word sometimes it can be considered a demodulator if anything any data is encoded in optical signal you just detect that optical signal through a photodetector then you can convert back into electrical signal and you can decode your data. So, that is why sometimes it is called also demodulator sometimes it is called as an optoelectronic optical to electrical converter.

So, to use; that in a bigger circuit how its performance is and also what is your figure of merits like speed and bandwidth etcetera. So, you need to actually see an equivalent circuit of a photodiode if you check it carefully a photodiode when falling when you are making an incident light wave incident on it, then normally you can get a current flow in this direction whether it is a reverse biased or not you can see some kind of current is there.

So, I can say that upon light incidents it is actually can be treated like a current source we have just represented here photodetector here symbolically, but ultimately you can see that actually this is actually showing as a current some certain direction to be sending current that current can be whatever small amount maybe and since, you know this is your junction diode and you are giving a reverse bias.

And when it is reverse bias this width will be increased and this thing actually in the diode junction region as long as the depletion width is there you can think of that, that for AC signal you can see the space charge actually contributing a junction capacitance. So, we have shown that junction capacitance which is just shown as a variable because it can be changed as a function of voltage.

So, as you increase the reverse bias voltage, this junction width depletion width will be increasing and when the junction width is increased this capacitance for this, the junction capacitance C j can be written as epsilon / W. So, when W is increasing as a function of reverse bias voltage the capacitance will be dropping. So, that capacitance I have shown as a parallel to this diode.

So, diode current, current source upon elimination under biased condition and illumination you get a certain current we just model this one like this capacitance for that bias condition like this and you can think of that if it is a diode you can see some kind of specific conductance or stand resistance you can apply that one across that I think normally it is intrinsic and for an ideal diode case the stand resistances must be very high that means it should be highly conducting.

But suppose 2 diode is sending current so, we be considering conducting and then we because once the current flowing in this direction, you can think of that some resistance will be there in series in the contact from the p side to the negative terminal of the battery and n side to the positive terminal of the battery that contact points etcetera everything that will give you some kind of series resistance you can consider that series resistance like this.

And of course, if the series resistance, this is actually the diode you can see the output and if you want to use this diode output to read out or give an input to a load that is called load resistance, then you can just say that, this is some load is there additional load is there typically that load can be 50 ohm and so, on. So, in that case you can see ultimately it is some kind of total R resistance R S + R L and this capacitance.

So, if you try to find out that if you are interested to know how fast this photodetector can work actually that will be limited by this R C constant basically. So, if it is the R C constant R C bandwidth will be typically 1 over 2pi R S + R L times C j capacitance. So, by controlling the junction capacitance, you can actually control the bandwidth, what is the junction capacitance? You can have higher is the bandwidth the lower is the series resistance you can have higher bandwidth.

So, because series resistance once it is fabricated you cannot change the series resistance contact everything you cannot just change that is actually fakes. So, what is in your hand is that you can actively control that is the capacitance. So, this junction capacitance can be increased can be decreased by giving more reverse bias. So, higher the reverse bias then you can operate at a higher speed.

But you cannot operate a diode at higher reverse bias at your will because as you have seen earlier that higher point reverse bias you can end up with a breakdown. So you want to avoid this breakdown because you are interested to see how this reverse saturation current is increasing as a function of light that is making incident on the photodiode and apart from the R C bandwidth, so, sometimes what happens the R C bandwidth is like that.

So, as we understand that if you increase W this junction capacitance if you want to increase that means you have to increase the B BI so, in that case it will be breakdown voltage. So, sometimes what happens you can have a pin structure pin photodiode so, you can have a p type side and n side and you can have an intrinsic region. So, you can have here one field it will be created junction field here will be created junction field and light will be falling.

So, in that case this junction capacitance will be lower for normally instead of PN junction if you have a PIN diode then this junction capacitance can be lower and once it is lower, so, you can have very high speed operation and when you are introducing certain length again one thing you should keep in mind that this carrier from the generated by the photo illumination that carrier how fast it can travel from this junction region to the terminal contact point.

So, that also controls how fast your modulated signal can come in how fast you can make your diode on off because of the light intensity. So, that means your bandwidth also depends on the mobility carrier velocity. So, that is called the bandwidth by transit, transit bandwidth this is actually R C bandwidth and this will be called transit bandwidth and transit bandwidth actually you can define by normally if your width of the depletion region is W that is shown here depletion region width.

And V is the velocity the velocity is the lower value saturation velocity between electrons and holes you know in this current both electrons and holes they are actually contributing for your photocurrent. But, in this derivations, you will find that this transit bandwidth actually limited by the velocity which is lower if you compare saturation velocity of electrons and holes, but electrons and holes saturation velocity will not be similar here you have to consider the velocity of which one is smaller that number you have to give.

So, in that case normally if you just say that if is the width is a W and then W / V that means, the saturation velocity that means transit time. So, this transit time whatever you will consider your transit time and inverse of that one V / W if you just take that can be considered as a frequency that the inverse of transit time that can be considered as a frequency bandwidth, but here instead of just considering V / W.

You have to consider 0.45, 0.45 in that sense because you know that this always is not that your electron hole pair is generating at the junction region it can be somewhere anywhere it will be created. So, if you just take the effect of electron hole pair generated in different positions and different section of the depletion regions and try to see their overall effect then you will end up with using 0.45 actually 45% of whatever the transit time inverse of the transit time that actually controls the bandwidth.

So, what I mean to say that the bandwidth of a junction PN junction diode or PIN junction diode that actually that is limited by one is by R C constant and another is by because of the transit bandwidth which is actually lower that is actually your ultimate bandwidth will be of the photodiode so, far so, good.

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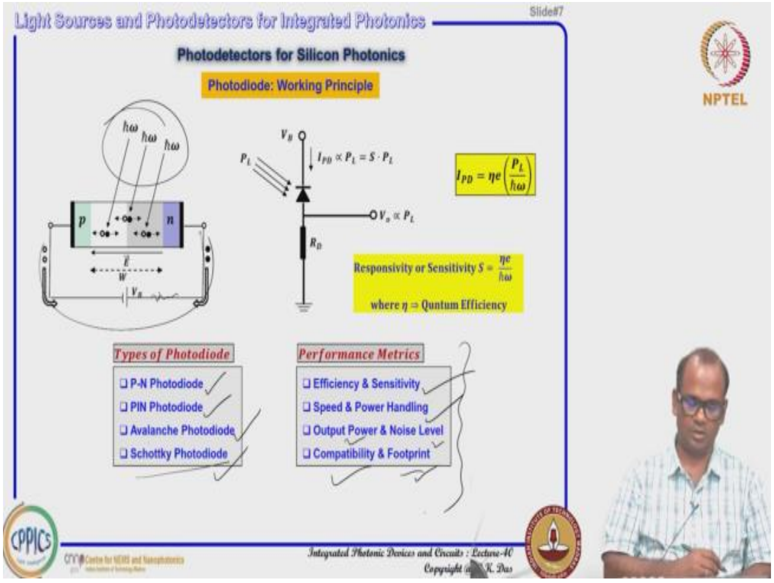

Now, let us see that what are the types of photodiode? Because you have to see first thing is that we have to see what could be the bandwidth, what could be the bandwidth of the photo diode? How fast you can operate? Because ultimately you want to use this photodiode as a demodulator that means your data stream when it is coming how fast a data stream how much Gbps data you can actually deserve by your photo detector that depends on the bandwidth of the photo detector.

So, to control the bandwidth, normally as I mentioned that instead of PN junction diode sometimes people use PIN photodiode, and sometimes the generated current maybe not sufficient. So what happens in that case we use a photon avalanche process where you can see that one, under reverse bias condition, if you want to detect a very low signal of light, so, maybe 1 or 2 photons just getting absorbed and electron hole pair is getting generated.

So, once this electron hole pair is generated here and if you have a sufficiently large reverse bias voltage, then this electron so, when it rush through with a saturation velocity V, it will acquire sufficient high kinetic energy and that kinetic energy is good enough to knock additional electron from the core of the atoms then you can it will create 1 more electron. So, 1 electron will create 2 electrons.

Now, 2 electrons again will acquire energy and create 4 electrons and 4 electrons again acquire energy because of the high electric field here energy that will create 8 electrons. So, in this way, avalanche process you can get many more electrons generation it can start from one single photon single electron hole pair and single electron hole pair that can actually accelerate and get energy and can cascade to generate more electron hole pairs.

And it will give you a huge amount of electron hole pair as it travel across the junction and then you can get a large amount of current. So, very weak signal if you want to detect then you should go for this avalanche photodiode however, you know this avalanche process actually contributes a lot of noises you may end up with signal to noise ratio drop, so, that we have to also take care and another type of photodiode also used that is called Schottky photodiode.

So, Schottky photodiode is relatively fast in operation, because you want to reduce this transit time to reduce the transit time sometimes it is better to instead of using PN junction at longer distance, you can use a semiconductor metal junction Schottky contact so, that any electron hole pair generated that can be quickly transferred to the contacts and you can get very quick current and you are not limited by your so called transit bandwidth. So, in that case, this Schottky photodiodes are normally used.

And so, as I mentioned that we have discussed few of the figures of merits. So, if you just talk about the overall performance of a photonic integrated circuit, you have to think not only for only speed, you have to think about the efficiency or sensitivity speed power handling, how much power it can handle. So, how many photons it can incident at once and electron hole pair will be generated and the device will be protected it will not be burned at all.

So, that thing also you have to take care and then output power whenever you are just a current is flowing here. So, if you have a load resistance here, so, current and voltage drop here whatever it is happening you just multiply you were getting the output power basically. So, that output power if it is very low, it may not be useful for certain applications particularly for micro photonic applications, you need this port to detected power should be large enough so, that you can actually get significant amount of R F power also.

So, that is also another big figure of merits and of course, noise level as I mentioned that your process whenever you are making magnifications and also making it high speed or maybe external magnification amplification you are doing so, that will add a lot of noise. So, your signal to noise ratio can be dropped also. So, that is another important figure of merits you should keep in mind.

And then compatibility and footprint compatibility means, I mean to say that, whenever you were designing a certain photo detector, which may be efficient, which may be highly sensitive, which may be high speed and which can handle very high power and it can generate also very good output power that is everything is fine, but it may not be compatible for fabricating photonics devices along with this high speed photo detector and high performing photo detector using CMOS technology.

So, that also you have to look into it and overall footprint how compact the photodiode because in a photonic integrated circuit you may have to integrate a large number of photodetectors maybe 100s. So, their footprint is also very important on cheap print if it is compact, then you can go for a large scale integration as well. So, all these figure of merits you have to just think whenever you are designing a photo detector particularly for photonic integrated circuit and that is to silicon photonic platform.

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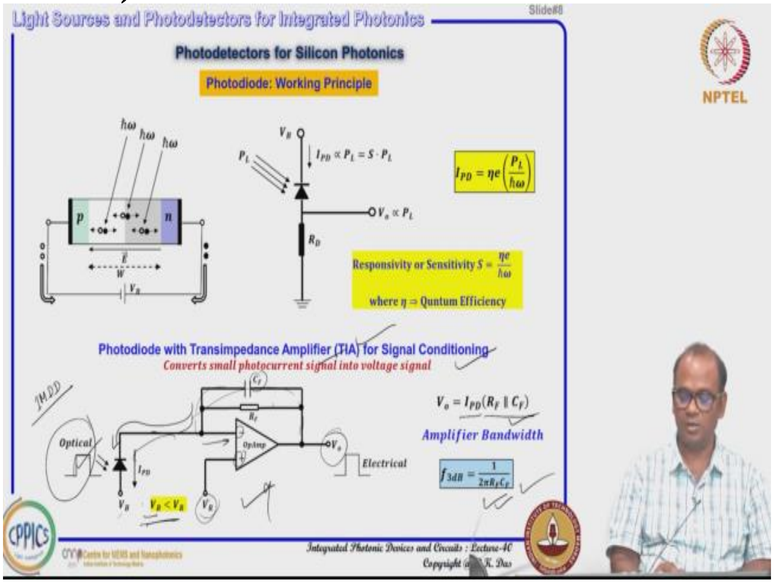

So, one important electronic circuit used to convert photo current into a voltage signal that is called actually transient impedance amplifier for signal conditioning you need for example, whatever photo current is being used that photo current you have to convert into a suitable value in terms of voltage, so that, that can be a good input for further driving circuit or so on. So, you need to whatever signal you are detecting you have to condition it you have to convert into voltage and you need a certain voltage height.

So, that if it is a very small voltage it may not be useful you need to have certain kinds of voltage output. So, that thing is called signal conditioning and that signal conditioning is done using a transimpedance amplifier. So, transimpedance amplifier it is actually explained here with a very, very simple example with operational amplifier. Here in this case, it is a simplest example of a transimpedance amplifier you can design much more complicated circuits there are a lot of literature available how to design how to improve those type of thing.

But this is the simplest one to explain you that how signal can be conditioned how to detect a signal current signal can be conditioned into a specific voltage signal with base specific voltage peak to peak power up let us consider your optical signal it is a digital data it is kind of on off intensity modulation on off signal that is how you have encoded using intensity modulator all the data comes so, that and you may want to use that for direct detection IMDD for example Intensity Modulation Direct Detection method you want to use.

So, for example, here I have shown that the one bit that needs a pulse of this optical thing that is counted as a one bit for example, and if there is no high output optical power that means it is a 0 and so on. So, when power is on that means like power is coming then your current will be flowing and then when off then your current will not be flowing. So, that means your current the optical signal will be directly converting into electrical signal or just 1 to 1 manner.

So, this will be flowing a current and then this is the OpAmp circuit and it is a bias here and the OpAmp circuit we are giving a positive sorry negative feedback this is the inverting port and this is a non inverting port. So, positive feedback with sorry again this is negative feedback you are giving for stability purpose you can add a capacitance also in parallel with the feedback resistance, but this sometimes this capacitor even if you do not add in circuit you have to show it sometimes.

Because sometimes this whenever you are using your feedback resistance that feedback resistance there can be some kind of parasitic capacitance involved that capacitance you can consider as a C F. And this non inverting port actually you can ground it or you can give a certain reference voltage, but this reference voltage should be such that V B should be less than V R such that your photodetector is reverse biased basically.

So, in this condition actually you are ensuring that your photodiode is reverse biased and then what is happening in the output what you will be getting in the output some suppose photodiode current is I PD and that is flowing through this in that case the voltage here you will be seeing here whatever the voltage you will be seeing here that means with respect to V 0 with respect to V R, that actually is proportional to current flowing multiplied by the equivalent impedance of R F and C F.

Because current will be flowing whatever the current will be flowing no current no significant current goes into the OpAmp. So, all the current will be flowing in this direction here in this path. So, that means total voltage you will be seeing here with respect to V R that will be this one I PD, R F parallel to C F. So, that means, this you can find out what is the value of R F parallel to C F and then if you just see that will be actually frequency dependent because capacitance is there.

So, capacity impedance is frequency dependent. So, amplifier bandwidth can be again it will be actually R C limited we will find 3 dB bandwidth is the 2 / R F C F. So, you can actually enhance your signal but whenever you are adding you can enhance means you can convert the current into voltage and you can use this voltage strength, the amount of voltage strength you can amplify depending on the feedback resistance etcetera but at the same time you are using additional electronics operation amplifier that may add certain kinds of noises.

And also that has certain kind of bandwidth any amplifier will have a bandwidth that additional bandwidth limitation will be coming also. However, most of the time you cannot avoid you have to use this type of circuitry because whatever the photo detected signal comes that is because of the reverse bias and you know reverse bias current is very, very weak in the range of microwatt and so on. Unless and until you condition your signal you will not be effectively using them for different applications.

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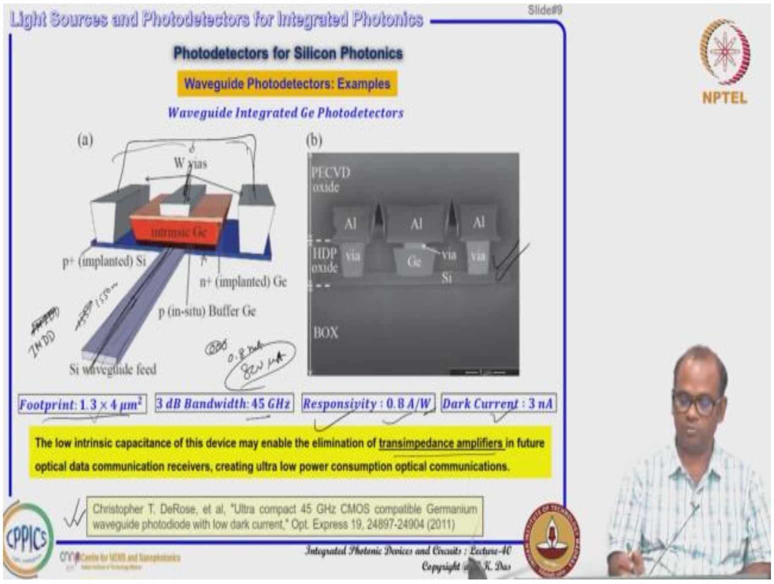

So, here it is one example of how this waveguide photodetector germanium is integrated into silicon photonic waveguide for photodetector purpose. So, you see here is an example schematically shown this is your silicon waveguide where light is coming for example, it can be carrying some data it can be IMDD data or any other coherent data thing is there intensity modulated sorry, this is not IMDD intensity modulated direct detection it is coming.

And then on the both side here you have a reed waveguide structure you can have a intrinsic germanium you are depositing directly onto the top of the silicon waveguide and in the silicon this side is p plus doped and here this germanium and the top you can have a n plus doping and this side also p plus doping in silicon p plus doping both side and germanium in the top you have n plus doping and you are giving a contact here and these 2 thing you can just sort it.

So, that you can give a reverse bias here this is p side reverse bias here with respect to this one we were just giving with respect to this one we are giving some bias. So, this 2 is sorted and here you are giving bias. So, whenever light is propagating through this waveguide as it propagates, you know, germanium is also refractive index is closer to silicon waveguide. So, the waveguide mode propagating here that will be disturbed that will be expanded that will be penetrated into the germanium layer and germanium layer.

You know, any wave propagating at 1550 nanometers, which is transparent, which is sorry lambda = 1550 nanometer which is transparent in silicon, but that is not transparent in germanium. So, that would be absorbed and electron hole pair will be generated and that electron hole pair can contribute to the current and the both terminal of the photodetector. So, some of the fabricated devices it is shown here.

And the important part is that this is the first germanium photo detector integrated in silicon having a very high bandwidth in the order of 3 dB bandwidth in the order of 45 gigahertz and that is to possible with a footprint of such a small footprint 1.3 micron / 4 micrometre. So, length is 4 micrometre which is 1.3 micrometre that is the footprint and responsibility as good as like a normal silicon photodetectors.

So, like a 0.8 ampere per watt 1 watt power going inside then you can get 0.8 ampere current. So, 1 milliwatt means you will be getting suppose instead of 1 watt if it is 1 milliwatt that means 0.00 that means, you can consider 0.8 milli ampere for 1 milliwatt you will be getting 0.8 milli ampere that means it is milli ampere means 800 micro ampere or so, in such a device also as a dark current is only 3 nano ampere.

So, dark current is 3 nano ampere and whenever you are launching 1 milliwatt power you are getting 800 micro ampere current. So, that means it is a very good sensitive photodetector first time fabricated and not only that, not only it is a very good responsivity very low dark current very small footprint and it is also because its sensitivity is very high. So, it is just commented in this paper.

This paper if you just want to learn a little more about this type of photodetector you just download this paper ultra compact 45 gigahertz CMOS compatible germanium waveguide photodiode with a low dark current. So, this paper you will download a couple of pages are there and then you can understand how nicely they have fabricated and they demonstrated for the first time very high speed around 2011, 45 gigahertz the first time CMOS compatible.

I mean to the CMOS compatible photodetecting silicon photonics platform that was demonstrated, and one important conclusion as I mentioned that this low intrinsic capacitance of this device may enable the elimination of the transimpedance amplifiers as I mentioned earlier, you need to do some kind of signal conditioning once you detect your photocurrent you need to condition it so that you can use it effectively.

But in this case, the sensitivity and the capacitance of this device is so good. So, as I mentioned the low intrinsic capacitance it is very low. So you are going for high speed and also responsibilities of a significant high. So you may not need actually transimpedance amplifier they commented.

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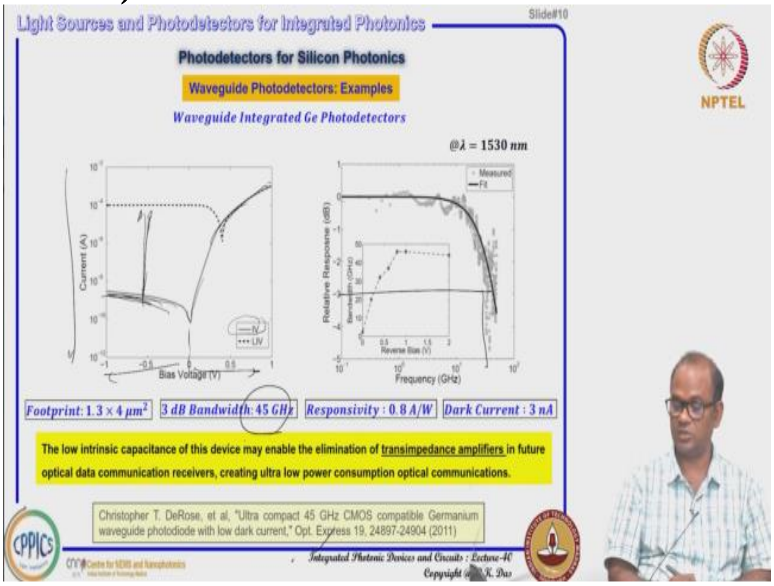

Some of the characteristics I would say that you see whatever the characteristics shown here. The same device, same group I have just taken from this paper. You see this is your 0 bias voltage. This is forward bias direction this is your reverse bias direction. So, as you go for reverse bias your current this is in the log scale it is shown here. So, current will be this much in the 10 to the power -9 ampere in that range in nano ampere range and whenever we are going for forward bias the current is increasing like this.

So, this is again log scale, but, that is when this curve means, that is actually IV characteristics when there is no illumination when there is no light launched into silicon waveguide, but whenever you have sudden light then you see the reverse saturation current is increased many fold it is reached up to 10 to the power -4 that means, it is at least it is more than 10 to the power 4 times it is increased however in the forward direction no current is being changed much.

So, you just change see what is the current is increased and you can calibrate to see that what is the power in the waveguide watch? And here also frequency dependent relative response it is shown as a function of frequency you see for lower frequency it is almost a response, the response is almost constant. So, as you go for higher frequency it is dropping, but nevertheless, if you see 3 dB bandwidth as I mentioned this 45 gigahertz so that it is clear.

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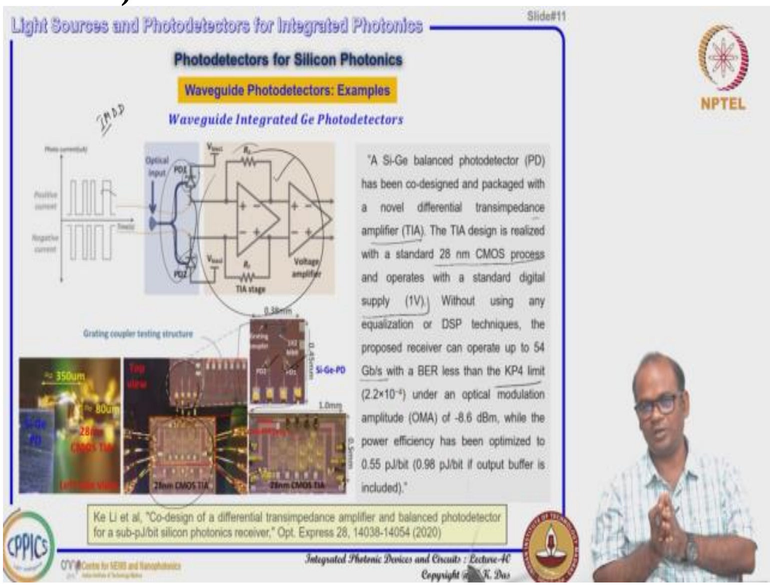

Then very recently into 2020 just last year, I think Li et al I think that is a suggestive group from Southampton university, they actually showed that they actually demonstrated a very nice balance, I think they say that this is a balanced photo detector, photo detector and also integrated transimpedance amplifier for detecting IMDD signal, IM intensity modulated direct detection signal purpose they have fabricated.

So, in 2020 this Southampton group they have demonstrated waveguide photodetectors using germanium photodetectors I would say and they have demonstrated kind of so called balanced photodetector. So, whatever optical input comes with a data you can split into 2 parts and one will be integrated with a photodetector 1 identical photodetector 2 also this side. So, that they are organised in such a passion that any data comes the current will be generated here positive current will be generated with one photo detector.

And another about is coming here that will be actually giving a negative current generated here. So, this type of signal generation and if you detect and if you do some kind of differential transimpedance amplifier, so, your non inverting input port is giving one positive current and inverting port you are giving negative current and then you can also condition them with further voltage amplifier and it would be very efficient.

And I has read out as they commented in their paper which is actually very attractive to me I find it very attractive, what they say that a silicon germanium balance photodetector has been co-designed and packaged with a novel differential transimpedance amplifier the TIA transimpedance amplifier design is realised with a standard 28 nanometer CMOS process very advanced CMOS technology they have used and operates with a standard digital supply of 1 volt.

So, only 1 volt reverse bias is sufficient for detecting this optical signals without using any equaliser or DSP digital signal processing techniques additional things we did not use and without that even they could actually recover data transmission up to 54 Gbps, 54 gigabit per second data they could actually detect with a bit error rate actually less than 10 to the power -4 or so something like that this is called KP4 limit.

And also another important things which must be noted that while the power efficiency has been optimised to 0.55 pico joules per bit that means your data transmission as I mentioned that it is very important that per bit data transmission how much power you are consuming for the entire circuit in your receiver that is very important also they say that it is conjunction is about 0.55 pico joule per bit.

And in fact this was 0.98 pico joule per bit if output buffer is included. So if you have a buffer in the output, output circuit is there, then it will be little bit worse a little more power need to be consumed. So, here they have shown also some of the pictures you see here, this is the region we are getting coupler and all this schematically shown things it is shown here and these are the balanced photodetector, photodetector 1, photo detector 2.

And then rest of the things is that all this electronic circuit that means, differential transimpedance amplifier that is actually in built here using 28 nanometer CMOS circuitry and a little bit of it says the 1 millimetre / 0.5 millimetre area this one actually it is shown here and your this thing is that this photonics part actually it is 0.45 millimetre / 3.38 millimetres. So, with this I just close this chapter as well as I want to close this course integrated photonic devices and circuits.

And I hope in this course, I think we have covered up to 40 lectures till today and starting from the very fundamental basic electromagnetics to the waveguide theory to the couple mode equation and plot of passive devices, active devices and also we have discussed about how integrated photonic modulator can be designed and how can we optimise the performance and then we have also discussed how one can integrate laser sources possible silicon laser how to proceed how to fabricate those type of silicon lasers.

By considering hexagonal growth hexagonal crystallographic structure of silicon, silicon germanium alloy, it has been shown that it is a very, very perspective, for futuristic laser integration using CMOS technology and today we have just discussed how what is the state of the our technology for integrating germanium photodetector using CMOS technology to the photonics integrated circuits in silicon I mean to say silicon photonics technology platform. Thank you very much.