Integrated Photonic Devices and Circuits
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Lecture – 04
Evolution of Silicon Photonics Platform

Hello everyone, so far in last few lectures we discussed about evolution of integrated photonics devices and circuits in a very high language. And today I am going to discuss about how the silicon photonics technology platform evolved in course of time. So that now people are thinking about and considering about co integration of photonics and electronics together and people are thinking about on chip optical interconnect integration.

I will just take you through a historical path how this silicon photonics technology evolved in today's lecture. So after that basically we will go to the component level discussions working principle etcetera. So this type of high level understanding overview would help you when we will go through certain kinds of mathematical explanation, mathematical derivations etcetera you will be able to relate. So, let us start evolution of silicon photonics platform, what is that silicon for when we talk about silicon photonics platform what is that? How it is evolved over time.

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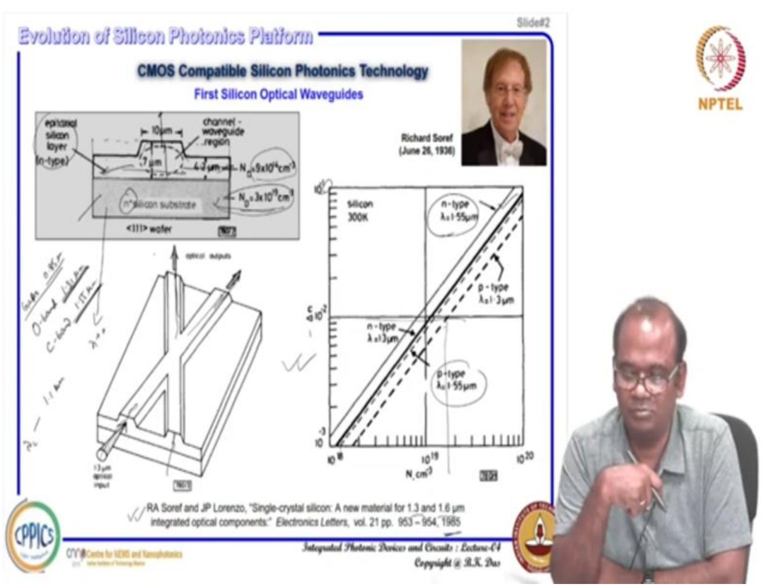

So, if I just survey the literature at RND articles available in published in journals or anywhere else I can see this is the first article it was written by Richard Soref and JP Lorenzo. For the first time they demonstrated optical waveguide in bulk silicon, you know waveguide is the so far it is clear that this waveguide is the basic building block without waveguide low loss waveguide like low loss fiber glass fiber helped for long haul communication.

So, low loss optical waveguide on chip optical waveguide actually opened the prospect of optical interconnect. So that is why it was a challenge 2 fabricate optical waveguide in silicon, this guy first time reported in 1985 so about 35 years ago in single crystal silicon a new material for 1.3 and 1.6 micrometer integrated optical components. So, 1.3 you know it is called O - band it is 1.31 micrometer and C - band it is above 1.55 or 6 micrometer that is the thing.

And another band earlier we have considered that is actually the first laser diode was demonstrated in gallium arsenide that was wavelength was 0.85 micrometer. So, when you see the optical communication optical link was established first with this wavelength 0.85 micrometer and second 1310 nanometer to 1.31 micrometer and third is 1.55 micrometer. So, this is called first generation communication window, second generation optical communication window, third generation optical communication window.

So, thing is how they here fabricated the waveguide which can support both 1.3 micrometer 1.55 micrometer as you know both optical wavelength 1.31 micrometer 1.55 micrometer wavelength the laser light it is transparent in silicon. So, normally cutoff wavelength is around 1.1 micrometer cutoff wavelengths in silicon 1.1 micrometer. So, more than 1.1 micrometer wavelength any electromagnetic wave or laser light that is transparent in silicon.

So that is why he has chosen to test his waveguide fabricated in silicon for this to communication the second generation communication window O – band and C – band how that was done? You see first you take a silicon substrate bulk silicon substrate that can be crystalline silicon and that can be heavily doped n plus it can be consider this is n plus plus heavily doped, then the top layer above 7 micron layer.

You can have you can grow a crystalline silicon epitaxial you can grow epitaxial layer that it is called epitaxial silicon layer that can be n type but it is not heavily doped. For example here heavily doped means doping concentration is 3 into 10 to the power 19 and the top layer doping concentration is 10 to the power 14 much, much lower. So, why is that it can be shown mathematically using Drude model.

If you see this picture if you follow carrier concentration and this is a refractive index higher the carrier concentration you can have this would be negative sign basically refractive index will reduce because you know carrier will be more pre carriers that will actually somehow it will enlarge the dielectric constant. So, refractive index will be reduced so higher carrier concentration refractive index will be if you just see changing the refractive to index in 2 different wavelengths 15, 15 nanometers n type and 15, 15 nanometer p type semiconductor.

So, this is your n type at 15, 15 nanometer how is the refractive index change and if it is p type dope point is there. So, how is the refractive index change? So that means as you increase the carrier concentrate refractive index will be lower. So that can be as low as if you are just going 10 to the power 20 then refractive in exchange can be as high as 10 to the power -1 if you want 10 to the power -2 here so your concentration in our uptrend 10 to the power 19 or so.

And if it is 10 to the 14 or below that will be almost like a bulk. So that means whenever you are getting at this doped region heavily doped region refractive index will be at least 10 to the power -2 lower, then this top layer epitaxial grown silicon layer. So that means if you just see if this is initially if this is a layer for example like this. So, in the top layer you are getting silicon layer with higher refractive index 10 to the power -2 at least 7 micrometer layer.

And bottom is the substrate that can be 1 millimeter few 100 micrometer thickness. So that is lowered refractive index. So that means as you see this lower side refractive index is less and then higher refractive index and in the top there will be air so that means you have lower refractive index, higher refractive index and again lower refractive index. So, you can get 1 dimensional waveguide plan and waveguide.

But if you make this type of structure sustained micrometer and this type of structure rib structure then as I mentioned here you can actually get light confinement both in the x direction as well as y direction. So, 7 micro meter height and 10 micro meter wide this region can act as a waveguide core if you launch suitably light can sit take a shape of guided mode which cannot escape in this direction or in this direction or in this type you can get a solution of that type of mode.

And that particular mode shape it will actually see the guided mode that may likely be guided in the other direction. So that waveguide he fabricated for the first time and reported in electronics later that is one and half page article. Not only that he demonstrated light guiding more than 1.55 micrometer and 1.33 micrometer he also fabricated that time actually imaging technique was not that great.

So, he has to so some kind of scheme 3D scheme actually to fabricate this type of cross waveguide structure. You have 2 input 1 input, another input and 2 output ports. So, this type of structure he has fabricated for power splitting purpose it will launch here and he could so that power is being spitted into 2. So that means you can actually fabricate power splitters. That is the first evidence of the waveguide fabrication in bulk silicon.

Which is the waveguide is a fundamental building block if you can fabricate a waveguide low loss waveguide and on chip of optical interconnect could be fabricated that is the first attempt at successful that is why this we sometimes called the Soref the father of silicon photonics.

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So, waveguide is there the next thing is that modulator what it does modulator it does that your electrical data can convert into optical data right so encoder basically. So, he tried to explore that waveguide is there now another important component for optical interconnect we have seen is the modulator. So, is that possible that if you give a electrical signal then laser light can be modulated if you use a laser light continuous CW means continuous wave laser light.

We can consider lambda equal to 1550 nanometer or 1310 nanometer then if you launch light and you according to the electrical signal if you make certain kinds of structure bulk silicon maybe it can be some diode structure or something like that in diode or transistor if you can create. So, in that case by giving an electrical signal you can control the carrier concentration. So, by controlling carrier concentration you can relax the dielectric constant and you can control the refractive index and you can control the phase velocity of the guided light.

That is how you can have a modulator. And if you have that type of phase modulation that can be also make you can have an input waveguide you can split into 2, 2 half and then you can recombine them this is called like a mergentier inter perimeter. Then if you just create this type of structure here where the electrical signal comes here and you can change the phase so if pi phase it depending on your signal pi phase it if I can create.

Then one hub going this direction another outgoing direction if it is pi phase it is saved when they recombine they will actually create destructive interference. So, you get no light output in this waveguide, but if you withdraw the space then they will construct, they will be coming in phase. So, in this way you can convert electrical data into optical data and he demonstrated that the carrier concentration.

And delta n for FREE HOLED in the axons how refractive index will be changed FREE ELECTRONS how it will be changed for 1.3 micron and this one it has been shown 1.55 micron. So, together which is to done Bennett, Scref demonstrated electro optical effects in silicon first time, normally electro optical effects is a very good material lithium ion modulator we have seen earlier that Professor Camino demonstrated that.

If we apply electric field then the refractive index of the lithium light weight material will change that change the refractive index will modular the guided light that is what we have seen earlier. That is how modulator bandwidth everything was demonstrated and got successful for long haul communication. But if you want to create an on chip modulator silicon is not that type of good electro-optic material you are applying electrical.

And electrical will change the refractive light is not like that in state if you pass some current or give some wires then carrier concentration you can change that carrier concentration actually in turn give refractive index change. So, it is once type of another type of electro-optic effect in silicon. So that is how modulator was demonstrated. So that is also by the Richard Soref and that was demonstrated in 1987. So 2 years later; so first silicon waveguide experimentally demonstrated and then 1987 the modulator.

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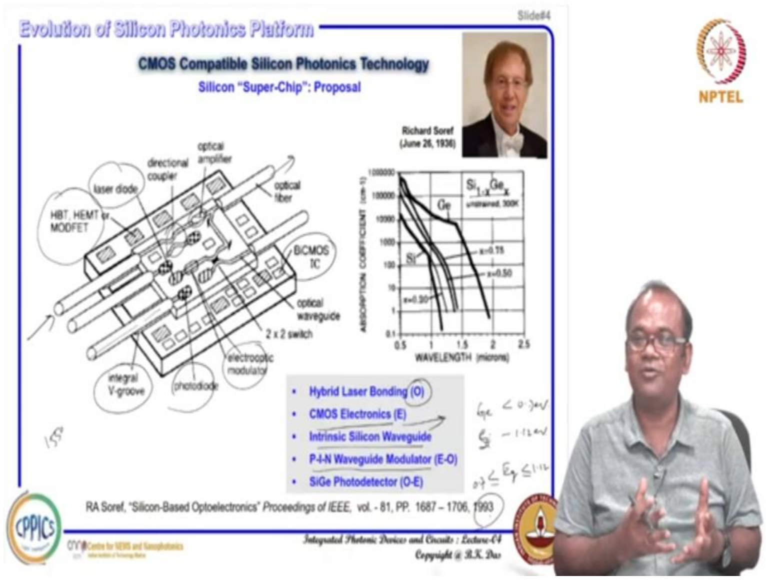

And then same so he was got excited, now we have see the thing still goes like what was done by a similar for integrated optics proposal to a glass waveguide and demonstration a couple of components like that. So, Soref was having certain kind of experimental tools, fabrication process tools using that continuously changing he was continuously changing to prove that silicone is a good material for co-integration.

So, he after demonstrating waveguide after demonstrating modulator he came out with a proposal with him more investigation more research that time hardly anyone else was doing research in silicon photonics silicon waveguides. So, he came out with a proposal that silicon can be a good material candidate for super chip where you can integrate laser diode silicon is a platform laser diode a possible indirect band gap semi conductor that is.

So, you can convert back to some way engineering can do can be direct otherwise you can just somehow hybridization you can do you can have laser source on the silicon substrate. And you can have a directional coupler where you can actually couple light to waveguide comes closer they interact so that light can be tunneled to another waveguide you can make a power splitter that is what he has also demonstrated in each previous paper in electronics later.

And also possibly you can also integrate optical amplifier and you can also have light signal from output using optical fiber input optical fiber output also by CMOS integrated circuit also you can fabricate, electronic modulator demonstrated and some HBT bipolar transistor HEMT MODFET all these electronic devices can also be demonstrated, photodiode of course demonstrated and here integral V-groove.

V-groove means silicon V-groove you can fabricate also using some kind of micro process you can just make a V-groove where you can have you can place your fiber also so that you can get optical interfacing to the chip like electrical interfacing you can do by wave bonding and optical interfaces you can do by fiber bringing fiber together and just attaching with the waveguide. So, he proposed a super chip hybrid laser for optical purpose.

CMOS electronics for electronic data intrinsic silicon for waveguide low loss waveguide. P-I-N waveguide modulator for electronic modulator, silicon germanium photodetector because silicon if you are using a waveguide so it is transparent you cannot make silicon diode for detecting 1550 nanometer wavelength or 1310 nanometer. So, again silicon germanium is a good material he studied that that if you make a silicon germanium alloy.

Somehow some extraction of silicon is replaced by germanium then band gap will be reduced because germanium band gap is in the order of less than 0.7 electron volt and it is actually germanium band gap is less than 0.7 and silicon is about 1.12 electron volt. So, if you make a silicon germanium alloy then you can get a band gap which can be less than 1.12 to greater than 0.7 electron volt. So, by controlling the fraction of germanium you can make a band gap reduction band gap engineering you can do.

And if you reduce the band gap where you want to detect the photo optical signal that can be used as a silicon germanium photo detector here it is shown how the absorption is. So, depending on the absorption you can actually conclude that how much it is getting absorbed to create electron hole pair in that particular point. And if you have a diode and reverse by you can actually carry use you can extract the electron hole pair generation and current.

Just looking into the current you can say how much you like light source high or low and the current you can decode the data. So, he proposed in 1993 it is hardly in just 25 years ago but at the same time electronics industry as I mentioned they were going for silicon on insulator.

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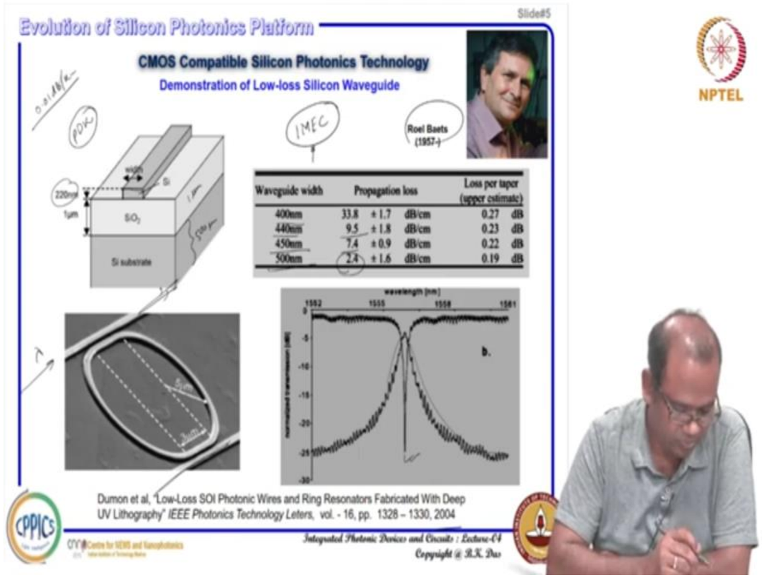

So, after that actually a lot of research went on silicon on insulator wave for came in picture and then a group in Ghent University Belgium led by Roel Baets. So, he actually started exploring the silicon on insulator platform to fabricate photonic device using available CMOS fabrication process in I make so I make a county facility available in Belgium. That is for inter University Consortium. That is a very good fabrication semiconductor fabrication process industries their process boundaries there.

So, by exploiting there that process technology he and his team for the first time demonstrated very low loss silicon waveguide. This is the you see this is silicon substrate the silicon substrate can be in the order of 500 micrometer thickness and box layer here it is mention it is one micrometer later on we will see that this 1 micrometer was not sufficient but when he demonstrated in 2004.

When Intel everything Intel other industries also investigating silicon photonics that time he used 1 micron box layer thickness and then silicon on insulator layer this is the layer which is actually fabricated to form a waveguide structured that is the waveguide structure we have fabricated and he showed that the depending on the width because 220 nanometer wave for once you buy a wave of thickness so he thickness is fix.

So, only controlling parameter is the width W, so by controlling the width he could fabricate devices different waveguide he could fabricate the team fabricated and measure the losses. So, you see loss per centimeter when 400 nanometer that was a very early mode primitive waveguide structure in silicon on insulator. So, it was about 33, 34 dB per centimeter per dB per centimeter you may remember.

If you consider the fiber good low loss fiber you can think about the 0.01 dB per kilometer or something like that. So, such a low loss optical fiber is there but whenever you are coming to waveguide on chip you see 44 dB per centimeter and if you literally increase the width it is about 10 dB and again for that increment 7.4 dB and 500 nanometers it is dramatically low about 2.4 dB per centimeter.

So, relatively higher than optical fiber but optical fiber you use for 1000s of kilometer communication but silicon waveguide you will be using for on chip optical interconnect. So, you need a few 100 microns poly millimeter wave millimeter length or so on. So, in that case this loss can be tolerant. So, this is the past waveguide fabricated on silicon on insulator which promised actually low loss and can be useful for practical device demonstration.

And along with that he also fabricated presented one ring resonator also width 5 micrometer diameter. So, these are the bass waveguide you can launch a light here if that wavelength is resonant to this ring that will be actually stored here and it will be missing in the output side. So that is what they fabricated using their waveguide and clearly they showed that a certain wavelength range actually is missing in the output.

But with another waveguide that wavelength it could be retrieved. So, this type of device will see that this ring resonator we have already seen earlier that this ring resonator was very much instrumental to demonstrate on chip transmitter multi channel multi wavelength multicolor transmitters and that is how interconnect optical interconnect advantage you could get. So, this is the first in 2004 low loss silicon on insulator waveguide was fabricated and demonstrated.

And showed the IMEC guys that you see this what about the device we are fabricating that is actually the CMOS compatible and you can actually think of going to get getting silicon and photonics and indeed they convince and they are the first who actually developed PDK process design kit for silicon photonics in using IMEC foundry all right.

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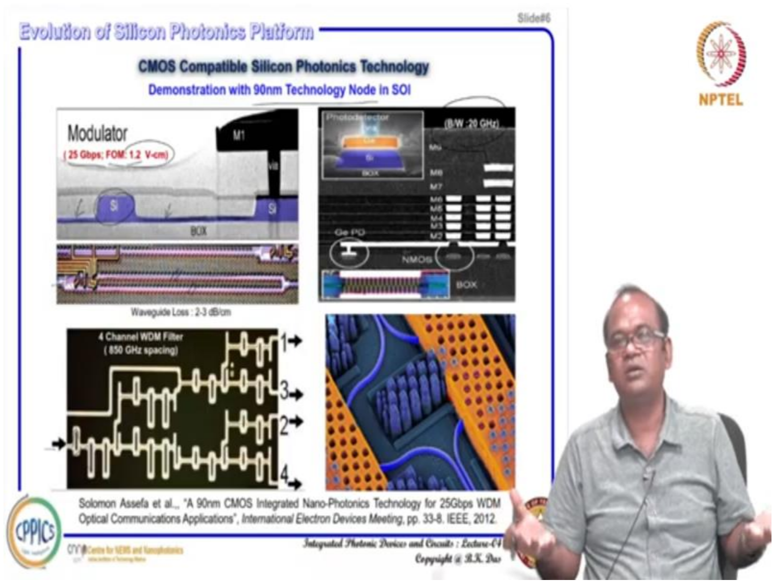

So, later on in 2012 Intel's research actually sold that actual they fabricated using their CMOS technology which the 90 nanometer technology node this modulator they fabricated you see this is the waveguide and this is the slab region we are actually put make doping p type or n type doping so that carrier inside the waveguide region you can control so that refractive index you can actually control and this is the signal with via metal M1 metal you are giving here.

And you can control the refractive index and this is the top view is see this is the top view it is looking like a mergender I have explained earlier it is splitted into 2 arms and again combined. So, mergender modulator they demonstrated which is given 25 Gbps speed data speed. You can send a transmit data with 25 Gbps and this is a FOM figure of merit. That means you need 1.2 volt if your device sizes 1 centimeter.

Normally device size is smaller means you can go for higher voltage particularly 1.2 volt it is shown that is so that the voltage required for driving CMOS circuit is about in the order of 1.5 or 2 volts. So, it is good that if you modulator length is modulated figure of merit is kept within that voltage that would be great and they have demonstrated successfully and they demonstrated 4 channel multiplexer demultiplexer.

You know using different type of unbalanced mergender interferometer is like this unbalanced means if your mergender here it is shown that if you balance both the arms your input guide 2 waveguide it is coming and then combining and both arms are same this arms of this length at the same that is actually used for modulator purpose but you can cascade a different type of mergentator having both arms unbalanced like this.

You say our input and then you have one arm high low and then you can cascade again. So that using this type of circuitry they could demultiplex 4 different color and they could combine also that means it is possible to use 4 different lambda and modulator you can integrate separately to encode data and 4 lambda can be multiplex and also the multiplexer the receiver end, multiplexing the transmitter and receiver you can do multiplex to decode the data.

And they also demonstrated the germanium photo detector which is having about 20 gigahertz bandwidth that is a good enough to detect 25 Gbps data. So that was demonstrated using CMOS process technology 90 nanometer technology node they used for normally 90 nanometer technology still a lot of integrated circuit demonstration it is coming out 180 nanometer 90 nanometer. So, same process technology you can use to demonstrate both silicon and photonics. So, your cost is not that high, so that was Intel demonstrated in 2012 just 10 years back 9 years back.

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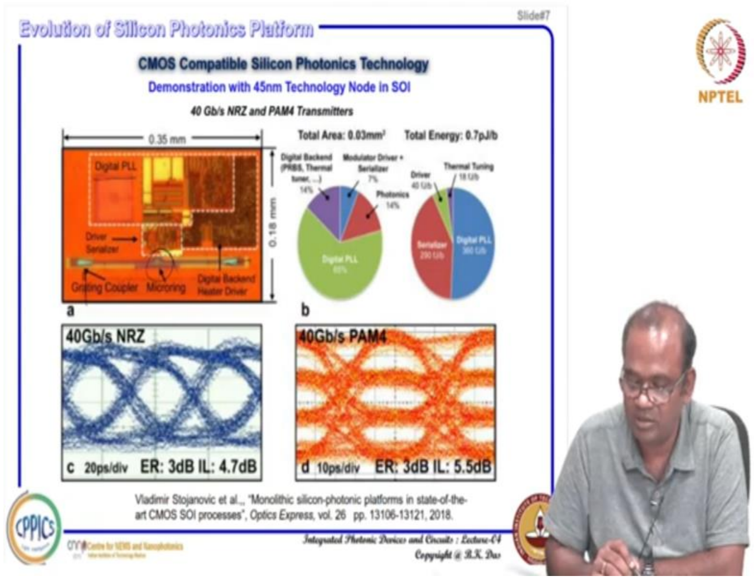

And then the demonstration with 40 nanometer technology note in SOI. So that is happened also with IBM technology IBM actually demonstrated 45 nanometer technology you see parko integration of photonics and electronics you see that is a digital phase locked loop driver serializer you are using all these things serializer this is optical interconnect whenever you are seeing that I will discuss that how they can be serialized in course of time.

So, you need how you can encode the data all the data you can pull from your electronic circuitry and modulate optical data optical signal you can use grating coupler you can have the micro ring resonator for modulator and you can have your output you can take with a fiber grating coupler is there and you can have a digital back and hit a driver sometimes you are ring resonator is fabricate you want it to resonant at a particular wavelength it is not resonating.

So, you can use your micro heater to the tune the wavelength to your design specification. So, they could transmit the data 40 Gbps NRZ 40 Gbps PAM4 all this modulation format actually people use for communication. I am not going to discuss at this point of time but they are quite promising for on chip optical interconnect.

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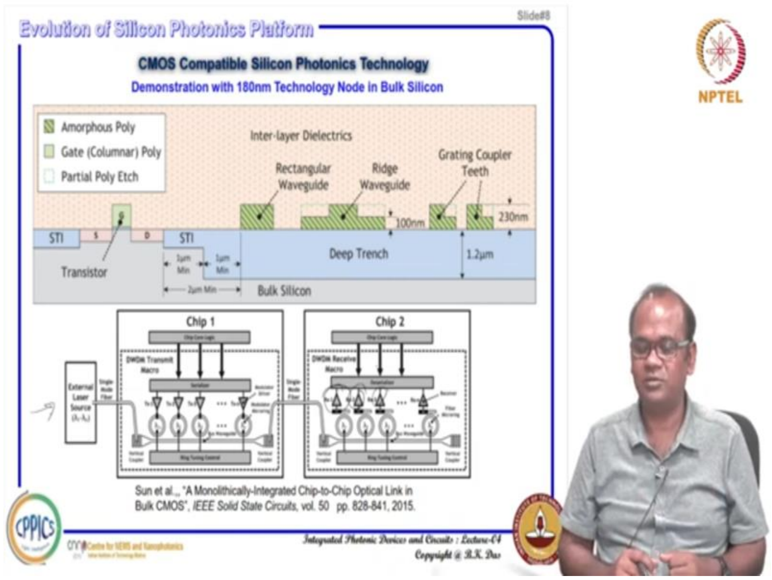

And then as I said that that co integration I showed the figure earlier that photonics and electronics can be co-integrated in using bulk CMOS bulk silicon with CMOS technology and it was also another demonstration from IBM 180 nanometer technology they have used to co integrate this per example transmitter right I think they have used too many more ring resonator it is a lambda 1, lambda 2, lambda 3 you can go for 100s of channels 100 ring resonator.

Then all the laser source you can launch here and you can resonate all the ring resonators here lambda 1 here lambda 2 this one the lambda 3 is this one and each of these ring can be driven by your data coming out of chip here. So, electronics and this photonics part can be co integrated in bulk silicon and in chip do you have a again similar type of rings are there so that you can drop lambda 1 here and you can detect the data here with a photo detector this is the receiver 1 receiver 2.

So, it is these rings lambda 1 to lambda n they are used for multiplexing purpose and these rings they are used for de multiplexing purpose along with the modulator. So, this is a very rugged worst design and the demonstrator date and also experimentally got some success on 2015 that was the IBM technology and this is now advanced it and this IBM technology later on acquired by global foundries.

And we can actually design a circuit and we can use their process design things and we can fabricate chip also from them. So, you can do different type of photonic circuit demonstrations also according to your design.

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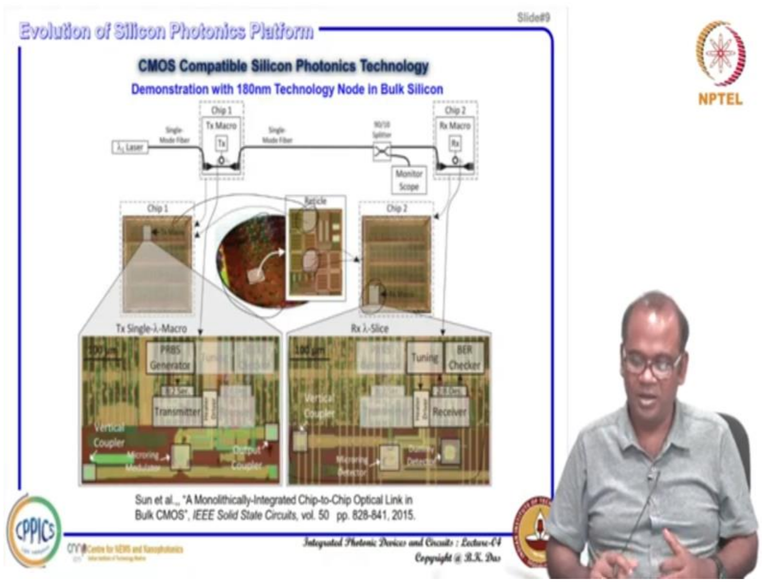

So, this is the same thing when fabricated how they look like you have a wafer this is your wafer and if you see the wafer 1 reticle that is actually is very well known in VLSR technology when you will do photolithography all CMOS technology. So that particular window can be exposed at a time that is actually a reticle that particular reticle by reticle you can just export and process different type of exposure for photolithicol purpose.

Just in the high language if you are interested you can take any VLSR cost you can understand how they are fabricated normally they are fabricated using CMOS versus like. So, within the reticle if you see there are different structures. So, one structure again they are showing like this is actually chip 2 and another structure they are taking from other so this one, this one within the reticle this is another chip 1 and this reticle.

So, each of them are chip they are zoomed and they are shown here right. So, within the chip again if you see this particular area that is actually you are this thing where you have particle couplers you have micro ring detector dummy detectors receiver and this is 2 is to 8 days that means DC sterilizer, electronic DC sterilizer, studies of type of electronic circuit is required and PRBS generator this chip all those type of in they could integrate.

That means I am trying to give you that it is actual practically feasible and people are demonstrating. So, it is no more issue for integrated optics because it is silicon waveguide actually could demonstrate in silicon on insulator both in silicon on insulator and bulk and all the technology node is being exploited to demonstrate or co-integrate electronics and photonics.

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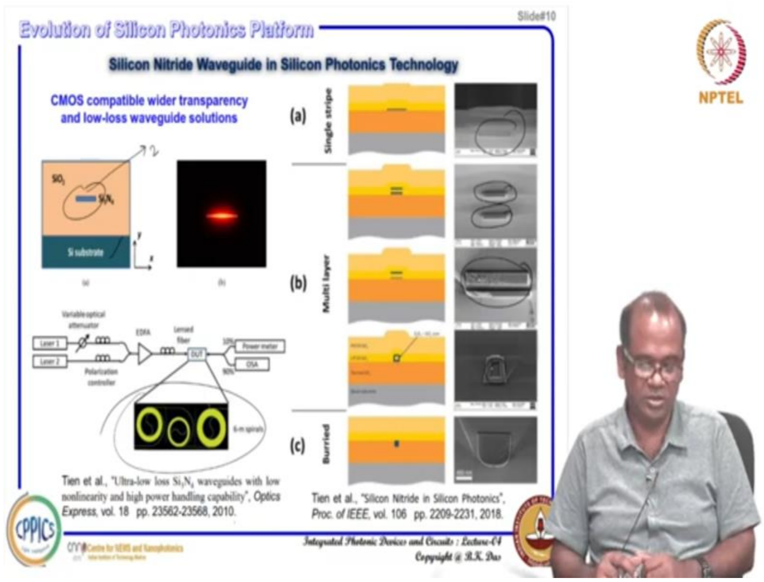

So, and other than that silicon so you know still silicon had certain kinds of limitations, you know few limitation is that first limitation I would say you are restricted to use a wavelength 1.1 micrometer greater than 1.1 micrometer you are using only 1.31 micro meter or 1.55 micro meter per second communication window third communication window if you want to demonstrate some device which can be visible like for example.

Let us say 500 nanometer wavelength for example Green Blue all this visibility and you want to use those wavelength is not useful for silicon photonics applications. Sometimes those types of wavelengths are useful for spectroscopic application purpose. So that is the reason people are trying to see if any alternative material platform is there to demonstrate waveguide and silicon platform of course.

And another issue is that sometimes for some certain application quantum photonic application you need high power nonlinear application non linearity needed high power to be launched in the waveguide. So, when you are launching 1.55 micrometer wavelength and high power then what happens 2 photon join together and give up energy to a single electron in the balance band and then electron hole pair can generate.

So that is why this TPA so called 2 photon absorption it is causing a lot of problem cell phase modulation, cross phase modulations all those type of issues are there. So, silicon some problems are there for high energy application high power applications as well as also losses also silicon because you have silicon waveguide and you have bottom silicon dioxide and top edge also silicon dioxide and this is silicon.

So, silicon refractive index is 3.47, silicon dioxide is 1.47, contrast is 2. So, such a high contrast if little bit fabrication related roughnesses they are in the surface that will cause a lot of losses. So, these few things are there so people are also exploring if there is any other alternative to have low loss waveguide in CMOS platform. So, people explore that with a silicon nitride, silicon nitride material is frequently used for IC technology for a passivation purpose insulation purpose etcetera.

Same silicon nitride which is having refractive index is in the order of 2 and surrounding silicon dioxide and silicon substrate. So, you can use the silicon nitride as a core and you can actually see that light can become find also it is shown here. So, this is a report in 2010 first time people demonstrated like Tian at el Ultra Low loss silicon nitride waveguide with low non linearity and high power handling capability.

So, they demonstrated silicon photonics chip but core is silicon nitride and they could demonstrate waveguide which will be very long 6 meter long spiral waveguide like circular spiral waveguide for nonlinear photonic application purpose, we will come to know later but that was demonstrated. So, sometimes in silicon platform along with your silicon core waveguide you can think of silicon nitride waveguide also which can offer low loss and not only low loss silicon nitride is having a very band gap is very wide

So, transparencies wider, so visibility and wavelength also can be transmitted. So, you can design some waveguide structure device structure which can operator much, much lower wavelength. So that is how silicon nitride waveguide is also coming into picture and there are some boundary also being developed. So, called damascene process you can different type of process and this is a 2 line silicon nitride silicon nitride in between silicon dioxide this type of structure.

And sometimes silicon nitride will be in this type of rectangular rumbas structure this region is silicon nitride and in the core salvage a silicon oxide that type of waveguide structure also fabricated for microwave photonics engineering purpose all these type of things this technology also getting match you are also and people are exploring that how to get low loss waveguide and how to improve the functionalities more and more complex design. So that cost and energy efficiency everything can be predicted nicely.

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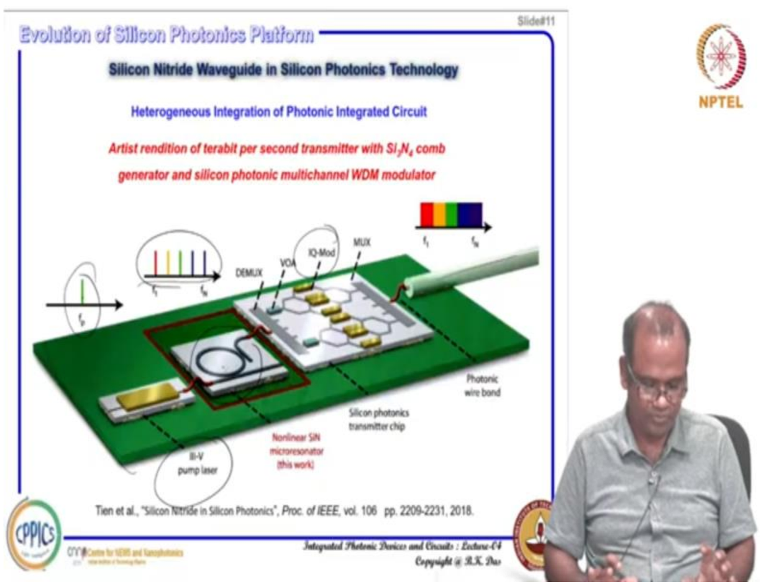

And this is the thing, so people think that sometimes silicon waveguide has certain kinds of limitations but your demand is very high scalable photonics integrated circuits for various application programmable photonic circuit, so that you can design a circuit you can program for various application programmable photonic circuit you can do. So that for that purpose you have you can think this is just kind of artistic viewpoint.

So, they kind of photonics on chip system in package or something like that. So, you can have 3 different chips it is earlier first chip is the 3 pipe pump laser 3 pipe conductor for laser purpose and then another chip which is offering here the waveguide silicon nitride waveguide that can be useful for your nonlinear photonic application low loss purpose everything it is used for some certain kind of so called here if yours pump it is giving your only one signal.

And because of the silicon nitride non linearity you can get different frequency generation here, once from the single laser source you can have multiple lines ledger lines and multiple laser lines you can divide into different arms of the mergender interferometer and you can do all the IQ modulation intensity modulation you can do and so that you can encode data for example one frequency from one laser you can convert into 5 frequencies here 5 colours you can generate because of the silicon nitride waveguide.

And then you can use your silicon chip actual silicon waveguide chip for your transmitter purpose and then you combine them to you can transmit to the fiber. So that means you can have a global things and then you can just put chip side by side. So, you can have 3 types of conductor silicon nitride, waveguide chip and silicon actual silicon chip. So, you can get a system in chip applications.

So, nowadays you can individually you get 3 pipe semiconductor foundries, you can get individual new silicon nitride foundries you can have silicon waveguide from silicon photonics foundries so all these chip you can design and you can fabricate out of different foundries and you can assemble and you can make a system in package also and you can think of some kind of new type of application and cost effective production.

So, with this I just have given the technology aspects of the silicon wafer platform silicon photonics platform how it is being progressed of course it is in high language and different type of technologies being still growing still improving all this type of thing will be learning in course of time. And in the next lecture I will be entering into the actual property when I am just talking about waveguide, waveguide device, ring resonator, mergender modulator, although staple things how actually they work what is their figure of merit how you can improve their design everything. So, some theoretical aspects will be just learning in next lectures.