

**Integrated Photonics Devices and Circuits**  
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**Lecture - 39**

**Light Sources and Photodetectors for Integrated Photonics: Integrated Photonic Light Sources (Part – 2).**

Hello everyone. In the last lecture, we have discussed about the fundamental principle of waveguide lasers, their working principle and how one can use exploit Bandgap Engineering in compound semiconductors for demonstrating double hetero structure efficient laser sources, semiconductor laser sources. That can be driven by just a current forward current will convert into laser output. And today in this lecture I will try to show that what is the problem in silicon?

Silicon in spite of semiconductor and it is quite a huge success in electronics industry and also photonics, optical waveguides etcetera, it is still in nightmare for technologist and photonics engineers to demonstrate silicon as demonstrated laser source in silicon crystal itself. So, we will just try to discuss about what are the problems and if there is any prospects at all or not. So, and then we will try to see some of the how some of the light sources how present generation of industry and technologist trying to overcome for some practical light sources which can be actually, which is actually in fact integrated on chip for silicon photonics applications.

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The slide, titled "Integrated Photonic Light Sources", compares two semiconductor types. On the left, a "Direct Bandgap Semiconductor" diagram shows the conduction band minimum and valence band maximum at the same  $k=0$  point. A transition from an electron in the conduction band to a hole in the valence band is shown, emitting a photon with energy  $E_g$ . A note states "Photon Emission Probability High". On the right, an "Indirect Bandgap Semiconductor" diagram shows the conduction band minimum at a  $k \neq 0$  point and the valence band maximum at  $k=0$ . A transition from an electron in the conduction band to a hole in the valence band is shown, but it involves the emission of a phonon (represented by a wavy arrow) and a photon. A note states "Photon Emission Probability Poor". A central text box says "Laser Emission requires direct bandgap semiconductor". At the bottom, it states "Silicon is an indirect bandgap semiconductor!". The slide includes logos for NPTEL and CPPIC, and a small photo of Prof. Bijoy Krishna Das in the bottom right corner.

Let us see what is the problem in silicon? Compound semiconductors are good and silicons, silicon crystals, silicon and similar material like germanium semiconductor they are not good for laser emission. If we just try to see that 2 different types of band structure in semiconductors are available, if you just analyze all the semiconductors, you can find 2 different types of energy band structure for electrons.

One type is direct bandgap semiconductors for which if you just try to see energy versus momentum, this E-k diagram so called E-k diagram, k is the momentum vector that means, when electrons moves inside the crystal, it will happen it is like a wave, it is a kind of electron can be conserved considered as a quantum particle and quantum particle means, it is kind of wave nature will be there and for its wave nature to analyze, you need to consider a certain kind of wave vector.

So, that means electron propagation you can express in k space that means momentum space energy momentum space. And if you just see that the energy normally if you just think of energy of a electron we express that  $E = \frac{h^2 k^2}{2m}$ . This is actually nothing but half mv square. Because inside crystal electron when moves kinetic energies with a velocity v kinetic energies half mv square, but v actually this mv normally momentum of whenever you are considering a quantum particle with a vector k.

Then momentum of the quantum particle is expressed by  $hk$  and energy is normally  $\frac{h^2 k^2}{2m}$  that is what we know that. If momentum is  $h k$  normal half mv square can be written as momentum square / 2m. So, that is how p becomes  $\frac{h^2 k^2}{2m}$ . So, that means for free electron if you are just considering a free electron that means energy is  $\frac{h^2 k^2}{2m}$  times k square. This is the value.

So, E-k diagram it should be like a parabola. But when we consider this electron inside crystal inside conduction band inside valance band, this E-k diagram will not be exactly like a parabola. It depends on which direction it is actually electron moving depending on the direction you can see that sometimes the structure instead of simple parabola like these. It can be something like this in a certain direction the energy gain structure.

So, some of the semiconductors you will find in the conduction band. It is the bottom of the conduction band whenever you are just getting an E-k diagram. For example, normally E-k diagram if you see here for free electron it will be like this. So, this is E, this is energy that is actually following this things, but you can think of this similar type of things in electrons in a crystal. And whenever you are considering in the crystal there is a conduction band, there is a valance band.

So, in that case you will see some kind of modification. I am not going into that detail, but when you check that some of the materials you will get conduction band spectrum like this, E-k diagram like this and valance band it will be like this one inverted parabola. Because you know this is actually  $E_v$  and this will be called an  $E_c$ . Earlier we have shown that band like structure that is actually as a function of  $x$  and this is energy. At any position what is the band? Now, we are just expressing the band structure in  $k$  space that means momentum space.

Momentum space that means, at a particular direction  $k$  space in terms of  $k$  we are putting energy and  $k$ . This is the energy and  $x$  and this is the energy and  $k$ . So,  $k$  is a vector wave vector it can have any direction in certain directs and if you move and if you see that this is going like this. And maybe all the energy levels here up to here it is all are field with some electrons there can be some kind of electrons.

And here also all the energy levels if you are just considering as  $k = 0$  means some energy level to consider that is  $k = 0$  means it is a little bit misleading that means  $k = 0$  means momentum equal to 0. And electron will not be able to move like that it is picked it is not like that. So, we will be actually repeated periodic structures. So, in that point of view, if you just study a solid state psics book you can understand more.

But here we can say that this the valance band whatever the electron energy that follow this thing? And normally, this energy is not for electrons instead of that we consider that the energy for the holes we can consider that. Because in the valance band we know in semiconductor particularly some of the electrons can go up to the conduction band and occupy the available

conduction band energies and that is what empty and all other energy levels they are actually occupied.

So, these are many meaning, if you just consider 1 electron here sitting here, it will have certain  $k$  value and this is its energy. And if we are considering this one this is your  $k$  value and this is corresponding, your energy. So, that means as you go for energy higher and higher, lower and lower. So, it will be just occupying this sub site and you go for there you see some of the energy levels electrons are not occupied and that electrons gone to conduction band and that is why it is empty these are called holes.

And in this case, suppose at some point somehow you create that electrons more electrons in the conduction band and more holes in the valence band, more empty space in the valence band. That is what we know that is a population inversion for example, we created we discussed in the previous lecture population inversion something like that you have created. Maybe in PN junction, you have given forward bias and they are actually you see that electrons more electrons in the conduction band, more electrons in the valence band.

And when you talk about more electrons in the conduction band, then they are E-k diagram momentum different energy and what is the corresponding momentum should be it is something like that, and valance band something like that. Population inversion, but they have to follow these things, this energy this dispersion relation they should all the electrons should follow. But normally you know in the conduction band see whenever some electrons are there they will occupy from the bottom energy to the highest energy levels.

And when something will be emptied in the valence band that should be in the bottom top here some empty things will be available here. So, if some electrons from the bottom of the conduction band tries to recombine to the holes that is in the top of the valence band, then you see directly comes and this is the  $k$  axis. So, the same momentum electron here jumps to the conduction band and it does not need to change its momentum and then maybe a little bit of momentum can be changed.

So, in that case, it is actually directly when it comes momentum matching is happening. Because in that case only energy is there energy has to be lost something to be emitted and that energy will be coming like  $h \omega$  radiating energy photon energy. And you know if you just think about photon. Photon is a quantum particle and its energy  $h \omega$  and if you just think of its momentum also, its momentum because photon  $\lambda$  is very large.

According to the de Broglie hypothesis, momentum =  $h / \lambda$ ,  $h$  is the Planck constant.  $6.626 \times 10^{-34}$  Joule second, a very small amount. And since  $\lambda$  is very large, momentum is also relatively small compared to  $\lambda$  for the electron. Electron normally quantum particle its  $\lambda$  is very small compared to in the order of angstrom or so, on. When it is considered to wave packet electron wave packet that  $\lambda$  is in the order of angstrom and so, on.

But in case of photon on the  $\lambda$  we are considering corresponding to this energy that is in the order of say maybe 1 micron or so. So, angstrom and 1 micron so in that case photon momentum is very less. So, when photon emits it carries a very little momentum. So, that little momentum it can adjust when it is just a little bit of  $k$  differences there and comes back to the valence band it is matching directly.

So, directly electron can come back from the conduction band that combined to the valence band and you can emit a photon. That is actually conduction that is the thing happens for the direct bandgap semiconductor. But some of the semiconductors you will find that if you see the conduction band  $E-k$  diagram, it is not like simple parabola and where bottom of the conduction band is exactly matching to the top of the valence band rather you see here the values there and adding additional values there in some other  $k$  value.

Which is actually lower energy levels this energy scale lower energy level. So, whenever you are creating a population inversion, so, your electrons in the conduction band will occupy this space with this momentum axis in this momentum axis. But, whenever you see the holes, it will be emptied into the top of the valence band. So, that means, if these electrons wants to recombine,

this is in  $k$  space, remember that this is true for every position, even in the depletion region where you are creating a population inversion.

So, these electrons if tries to recombine, it needs to adjust the momentum of this much. And to adjust this much, then only it can emit a photon. And you know that photon can photon if you just think about this  $\lambda$  corresponding  $\lambda$  and momentum, it is a very little bit of momentum it carries. So, ultimately the momentum mismatch needs to be there if photons to be emitted and that is actually against the law of physics. So, for any transition any reaction to takes place, you have to consider 2 fundamental laws energy conservation, momentum conservation.

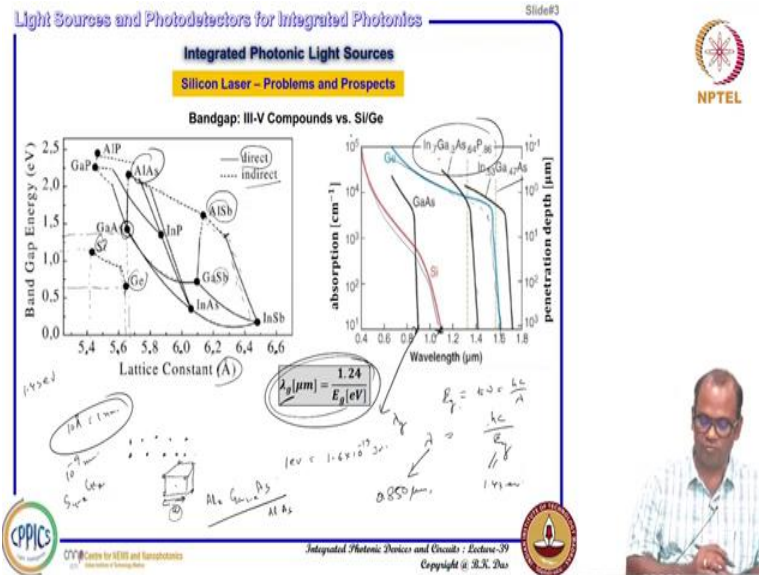
So, since momentum conservation is not there, so, what it does? It does a little bit indirect way it takes help a phonon. Phonon means, it is another type of quantum particle which is nothing but the lattice vibration this actually causes because of the lattice vibration, so, that that actually can have a very little energy, but it has a very small wavelength, it can have very small wavelength also. So, in that case, it can actually give some kind of phonon emission. So, that means, it can acquire some it can lose some momentum to phonon and then it can recombine to the holes.

So, it is an indirect way of re-combinations. And if this electron, the hole and this phonon all this quantum particle and photon, this is also a quantum particle. So, all these 4 quantum particles to act together. So, they should come to a sudden coincidence that this would interact this would have a good overlap so that you can have this type of transition. And because of that photon emission probability is very poor. But in this case, you have to deal with the electron and hold the combined photon comes. So, at least you do not need any wires as phonon wires.

So, that is w phonon emission probabilities high. All the compound semiconductors are having this type of band structure, but silicon and germanium they are having this type of indirect bandgap semiconductors. So, laser emission requires direct bandgap semiconductors, silicon is an indirect bandgap semiconductors is a problem. So, cannot really it is a physics it is a physical . The physics actually prohibiting that it is not easy to have your laser in silicon, but you know this there is some technology we can just try to engineer something.

So, that gets some kind of silicon laser or not to keep on trying for decades and still very close to getting laser in silicon, we will just show how people are overcoming that, but wrong way to go still.

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A little bit of understanding compression of gallium arsenide type III-V semiconductors and silicon germanium type semiconductors which are very good for electronics and for other photonics type devices. If you see that is a compound semiconductors actually people got a lot optoelectronic devices including lasers and photodetectors, because of you know any laser or any photodetector you want to demonstrate, this has to be defined first which wavelength, what is the operating wavelength you want and what is the require accordingly you have to design?

And for that purpose, we know that if you make different types of compounds, we have discussed in the previous lecture. Compound alloying different type of III-V elements in the periodic table and then you can get different type material of different bandgaps. And that type of material you can actually group can get a different type of alloy structure and technology already available today that controlled fraction control alloying composition, you can actually element and composition in alloy you can have and you can control the bandgap.

For example, it is shown here that the bandgap actually depends on normal you know that lattice constant. Whenever some atomic structures are there, in 3 dimensions they actually maintain

some periodic structure. So, these periodic lattices, you can consider like that. Instead of that, it is like whenever you are building a house, you need a brick by brick assembling similarly, when crystal is upon in that case, you can consider some unit cell and that unit cell is extended in all 3 direction then you can get entire crystal.

So, that unit cell or maybe in a unit cell suppose you have a unit cell something like these cubic units cell something you consider where some of the atoms are there some particular locations. And those particular things you are just extending in all 3 directions you get the entire crystal. And for that unit cell the length if it is a cubic length is a particular length  $a$  that is actually called lattice constant. That I think I am not going into the details just giving you some idea.

And if you see that in alloy, that particular type of structures will be created and that particular structure whenever you are just making more and more composition you are replacing some of the gallium with arsenic with the aluminium or arsenic with some kind of phosphorus etcetera then this type of lattice constant also gets changed. When lattice constant changed that periodic things changed then your bandgap will be also changed. So, here it is shown very nicely that lattice constant in the  $x$  axis. This is not comma this is actually 5.4 5.6 5.8 6.0 6.2 6.4 6.6 angstrom and so on so forth.

You know 10 angstrom is equal to 1 nanometer. 1 nanometer means 10 angstrom. 1 nanometer means  $10^{-9}$  meter. So, all these small distance when lattice when crystal is upon their atoms are spaced like that. So, when I concentrate lattice constant you can think about it there is a minimum distance between 2 successive atoms in the crystal. So, you see certain material. For example, let us try to find out in this map gallium arsenide here. Gallium arsenide the lattice constant is somewhere here. It is around 5.7 or so. And what is the bandgap?

This is about 1.43 electron volts. 1 electron volt is  $1.6 \times 10^{-19}$  joules energy. So, you can have this 1.43 electron volt gallium arsenide. Bandgap is 1.43 that is  $E_g$  you get gallium arsenide this  $E_g$  if you use this formula that means,  $E_g = h \nu = hc / \lambda$ .  $\nu = 2 \pi c / \lambda$   $h \nu = hc / \lambda$ . So, then you can find



out  $\lambda = hc / E$  g. If you put Planck constant velocity of light etcetera then you can get this expression.

Then you can get this  $\lambda$  that corresponding to the bandgap the wavelength. If energy in electron volt gap energy in electron volt, this  $\lambda$  can be micrometer you can find out. So, normally this bandgap if it is 1.43 then  $\lambda$  equal to if it is this one is 1.43 electron volt for gallium arsenide, this  $\lambda$  will be equal to what to call that 850 nanometer or 0.850 micrometer using this expression you can find gallium arsenide. Now, you want to make alloy for example, if you start replacing gallium with aluminium.

So, AlGaAs for example, I just put gallium, a aluminum extraction by replacing gallium extraction and arsenic AlGaAs you are just trying to make. Then what happens you are just your gallium atom whatever the crystallographic structure gallium arsenide is there. I have just show, what is the structure then if fraction of gallium, some of the gallium atoms were replaced by x. So, if  $x = 1$  that means it will be aluminium arsenide. So, keep on increasing the fraction then you will get aluminium arsenide here, gallium arsenite here and aluminium arsenite here.

So, if you keep on increasing the x that means aluminium content if you keep on increasing then you can get slowly to element aluminium arsenide and other type of compound semiconductor, for which you see the lattice constant is also same. But at the same time if you see y axis it is going off that means bandgap be changing. So, if you are just moving from gallium arsenide to aluminium arsenide by changing this extraction then your bandgap keep on increasing and you will reach here.

Now, again if any part you take suppose this gallium arsenide this arsenic if you are just slowly replaced by antimony. For example, this is gallium antimonide then you can see that the bandgap and lattice constant was changing this path curve. And then from here if you want to consider that this gallium being replaced by aluminium again aluminium antimonide then it goes like this path. Or if you want suppose gallium some of the aluminium arsenide here. If you are just slowly increasing aluminium indium arsenide here, it will come like this.

It can happen that different type of material you consider different types of position you will get and different types of composition and you will be getting with different types of lattice constant you will be getting and bandgap will be getting. So, by controlling the composition you can actually engineer the bandgap, but thing is that controlling the compound. For example, if you want to go for gallium arsenide to aluminium arsenide, you see you do not need to change your lattice constant.

When you do not need to change; the lattice constant that type of alloy creation is relatively easier. So, you can get a very good semiconducting material also for that, good quality crystal you can generate and you can engineer the bandgap. So, normally, if you just think of the different types of materials, compound material and if you position they are also in the same chart germanium and silicon it will be germanium position is this one corresponding lattice constant is this one and bandgap if you see it is around 0.67 or 0.7 electron volts.

And silicon if you know it is 1.12 electron volt and band lattice constant is about 5 point. What is lattice constant? I will come a little more details in next slides. So, in this case you see whatever we have shown here in this slide some of the lines if you see is a dashed line and some of the lines are solid line For example, if I try to change aluminium antimonite slowly aluminium being replaced by I Indium then lattice constant is increasing as well as bandgap is reducing. And up to here it is dashed line and then it is shown as a solid line.

So, from here to here solid line means it is actually direct bandgap the material component you will be getting that is a direct bandgap material. And if you are just using in this region a little bit of changing aluminium that will be remaining like a indirect bandgap semiconductor. So, indirect bandgap semiconductor is good for laser action. So, you have to choose a suitable compound so, that it can become a direct bandgap semiconductor here if you see silicon and germanium they are the indirect bandgap semiconductor.

But if you want to make a silicon germanium alloy no way you can get if see slowly you are becoming silicon. For example, you can consider silicon  $1 - x$  germanium  $x$  for example.  $x$  amount of silicon being replaced by germanium then what happens as you keep on increasing.

So, lattice constant is increasing and bandgap is reducing and then again it is changing like this, so lattice constant changing still you will be getting indirect bandgap semiconductor. But nevertheless indirect or direct you can think of that if you are just going back to this structure.

Suppose emission is not possible but what it can happen suppose you have like this if you have some kind of additional photon is coming. So, what happened? Electron from the valence band can actually absorb the photon and can energize and that electron can go to the conduction band and then photon will get absorbed. So, you can see some kind of absorption and this absorption can happen equally whether it is actually direct bandgap or indirect bandgap?

Phonon assistance bandgap is there so, you can actually get absorption also indirect bandgap semiconductor as well. Even though emission probability poor etcetera. But absorption can happen even absorption can happen directly to here also. So, electrons can absorb such sufficient energy from the photon and it can come to electron here and slowly it can settle here also. That type of absorption indirect absorption can happen also.

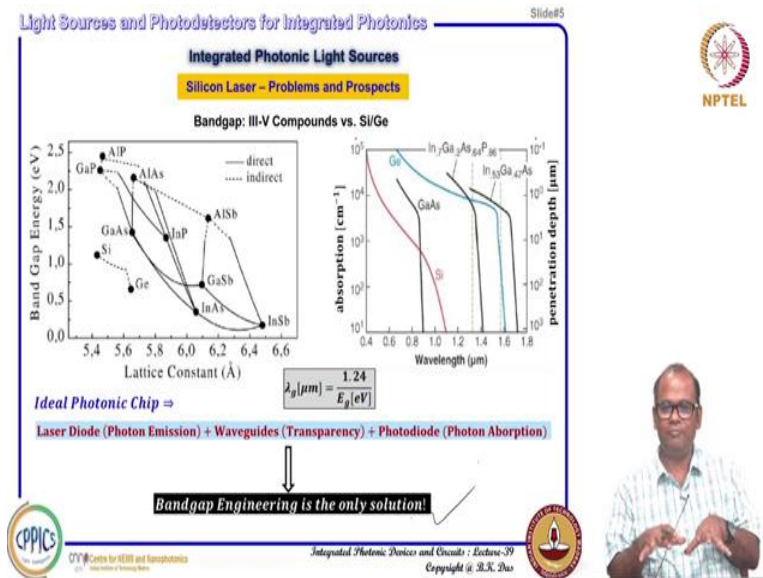
So, if I just only check about absorption, then you see that silicon absorption as you keep on increasing your wavelength up to 1.12. If you see the absorption is getting reduced almost slow and beyond that, no almost no absorption that means, above 1.1 micrometer silicon is showing transparency. Below that it is getting absorbed because photon energy is actually absorbed by electrons from the conduction valence band and go to the conduction band electron jumps to the conduction band.

Similarly for gallium arsenite you see here up to here. So, this is actually corresponding  $\lambda_g$  whatever we calculated. Here this is corresponding to  $\lambda_g$  for silicon and when  $\lambda_g$  is lower than that meaning photon energy is higher. So, that photon will be absorbed. That means, when it absorbed, electron hole pair will be generated, will see that that electron hole pair generation is necessary for photo detection. I will be discussing that thing, but here we are discussing mostly for laser.

First I will be discussing that why silicon what is the problem we have discussed here and the actual situation why silicon indirect bandgap semiconductor and whether that can be overcome or not. After that we will come back to the photo detection purpose. So, but if you see, germanium rather than here if you see it can actually go up to 1.6 micrometers absorb and beyond that it can attenuate, it is transparent and you can get indium gallium arsenide phosphide, which is actually very good for laser emitting at 1550 nanometer wavelength.

So, here if you see that the bandgap is around 1.4 and laser emission when takes place around before 1 above 1.5 laser emission can happen. So, different type of materiality shown absorption coefficient.

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Now, why I am showing this one interesting part is that for ideal photonic chip, you need laser diode for photon emission waveguide same photon should be transparent. If you can choose a certain bandgap well laser electron photon recombine and gives you photon emission. But on the same material the same photon can get absorbed as well in a reverse process. So, electron holes combines and get give you photon and that photon while travelling it cannot give up energy to the another electron from the valence band and that electron can go to the conduction band again.

So, this is actually contradicting if you want to have a material where you want to have a laser diode photon emission that cannot be good for waveguide. Because the photon can relate job for

a waveguide you need low loss absorption should be free. And at the same time again, photo diode photon absorption require. So, you need material where photon emissions require photon absorption required and also put in transparency require. It is a very difficult to get a material within normal simple structure where you can get all the 3 simultaneously.

So, for ideal optoelectronic circuit where you want to integrate laser diode photodiode waveguides modulator etcetera, it is a very challenging task it is only you can solve by different type of technology. Physics actually is not it is providing that same material can simultaneously give you a laser diode and wave guiding and photodiode already. Obviously, laser diode if you have a laser diode fabricated out of a semiconductor because it is a just emission of photons and photodetector is that just absorption re-absorption.

So, maybe photodetector and laser diode photodiode and laser diode can be fabricated in the same material, but this same material we cannot use for waveguide transparency. So, what is that how that is possible? Bandgap engineering is the only solution. So, Bandgap engineering meaning wherever you need laser source, you just engineer the bandgap so, that photon can be emitted and wherever you need wave guiding you should engineer the bandgap so, that photon can be transparent for bandgap can be just relaxed.

And again whenever you need a photodetector that time that region you need again bandgap engineering for making your detection. So, that means, on chip if you want to have an ideal photonics chip where source photodetectors everything can be integrated. So, you need a must go for bandgap engineering. So, that is actually the technological challenge for the industry for the academicians like you, you have to find out the different types of ways out.

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Slide#8

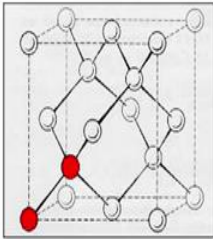
**Light Sources and Photodetectors for Integrated Photonics**

**Integrated Photonic Light Sources**

**Silicon Laser – Problems and Prospects**

**Si-Ge Alloy: Bandgap Engineering?**

Identical Crystallographic Structure

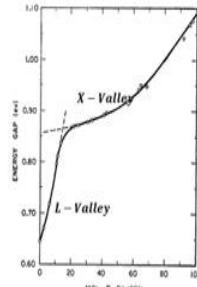


$a_{11} = 0.357 \text{ nm}$ ,  $a_{12} = 0.357 \text{ nm}$

Si:  $1s^2 2s^2 2p^6 3s^2 3p^2$



Ge:  $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^2$

Si-Ge Alloy: Indirect Bandgap Tool!



Braunstein, Rubin, Arnold R. Moore, and Frank Herman. "Intrinsic optical absorption in germanium-silicon alloys." *Physical Review* 109.3 (1958): 695.

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Let us see what is the state of the art? So, now, to discuss about that; how people are thinking to demonstrate silicon laser. We need a little bit of crystallographic structure to understand for silicon whether the silicon germanium alloy bandgap engineering possible to make it certain kinds of possibilities or not. Already, we have shown that even if you are just doing silicon germanium alloy experimental evidence shows that earlier diagram we have shown that they never come up with a direct bandgap semiconductor structures.

But people tried different takes let us see. So, if you see the crystallographic structure for silicon and germanium they are looking like this. Unit cell if you see, it is like a cube as I mentioned that a crystallographic structure is a building block is the unit cell you can extend this x direction, y direction, z direction then it is just you can get it entire structure. And this is cube and this is actually each of these cube distance we consider a called lattice constant. And if you see they if you just consider that some circles these are actually silicon or germanium atoms.

So, these are the position of the silicon or if it is silicon crystal silicon atoms if it is germanium crystal germanium atoms their positions are shown here. And you can consider that you see these are the position if its height is there. So, these atoms, these atoms, these and these atoms, these atoms they are considered like a square of a square if you are consider base point. So, 1 atom is here, 1 atom is here, 1 atom is here, 1 atom in the centre face bottom and identical situation in the top here and this surface also is there.

So, that means, every surface there are 6 surface for the cube, every surfaces there in the centre 1 atom and all the corners of the cube, there will be atoms are there. And apart from that, you see additional 1 atom is there coming like this here that is actually position something like that if you are considering here. So, if total height if this height is 1 if you are considering this atom is around.

All these atoms are 0 position, 00 position, 00 position, 00 position and this height will be this is also 0 position, these height will be 1 fourth position at the height. So, this means this gone to 1 for this side, this 1 fourth and height also 1 fourth on this side. So, basically each of these atomic any proceed they are co violently bonded with 4 other atoms like this. This is the structures and we can consider that this one is a particular lattice point.

This atom and this pattern can be considered combined to consider a particular lattice point with particular lattice point 1 atom is here and other atom is here. And if we just see that every lattice point you can just consider one silicon atom and club to this thing. And then you can consider something like that FCC crystal face centre cubic crystal, face center cubic crystal means, you will have all corners atoms will be there. In the face 1 atom will be there. But you can consider all corner 1 atoms associated with another atom, 2 atoms are there and in the face also 1 atoms associated with another atoms are there.

So, that type of situation if you are considering as a unit cell and that unit cell, you extend x direction, y direction, z direction, then you can get the entire crystal for silicon and germanium. Both silicon germanium crystallographic structures are identical. Only thing is that for silicon the lattice constant this distance is about 5.43 angstrom and for germanium little high 5.66 angstrom, 10 angstrom meaning 1 nanometer. And silicon electronic structure if you see there are 14 electrons and out of them this 4 electrons are actually valence electrons.

And germanium, there are 32 electrons and you see this 4 electrons are the valence electrons. So, germanium atoms are relatively little bit more number of atoms and electrons. And it is size obviously it will be different compared to silicon. So, that is the reason when you see the crystal

graphics the band structure E-k diagram. Then you can see it is a very complicated mathematics it is a kind of quantum mechanically it is normally solved because you know this kind of interaction of this electron interaction.

Suppose electron belongs to this atom that can be interact that can have some kind of influence of the all the neighbouring atoms all the surrounding atoms. So, those things you have to consider. So, in electrons inside the atom it interacts with its nucleus and also it can be influenced by neighboring atoms also. So, how they are arranged depending on that you have to solve. And there are various methods are there one of the methods is k dot p methods, Kronig-Penney models very approximation method tight binding approximations.

And very lately people are using density function theory also DFT density function theory. So, using that people can actually produce the band structures. So, whenever you just consider a E-k diagram energy and k momentum wave vector. This k is your wave vector you can have a different direction. So, different direction you define normally in a crystallographic structure if it is a crystallographic structure, this is your particular direction we call it 100 direction either this direction or this direction, this direction they are identical direction.

We can consider this is like 100 direction either x axis, y axis, z axis they are identical situation for this. But if it is diagonal direction you are considering that is actually 111 direction and different direction crystallographic structures are there but here in this course, I am not going into the detail just you can consider the different direction if electron if you try to transport electron in different direction it will see different type of periodicity, different type of situation. So, different types of energy k E-k diagram.

If you are energizing electron to move in a certain direction it will see different type of dispersion relation and if it is going another direction different types of situations. So, here it is shown that around 100, direction if you see the valance band will have also different type of curve will be there electron can follow this curve or maybe these 2 curve very fine structures are there. All these are coming from complicated mathematical solutions normally Computer aided solutions are required.



I am not going into that detail again and you see this E-k diagram it is not like a parabola I have shown earlier. It is a completely different one side is symmetric one side means it is showing in the x direction another side is not minus x direction. Because x direction minus x direction is identical. If you go for different direction say that is called 111, direction that means diagonal direction then you can see that minimum is coming and 110 are this minima is coming.

And you get a maxima where the energy alloyed energy is highest here that particular point which called gamma point. And along 111, direction you can find a particular k value that will be minimum here and its value it is minimum here. And then next higher band if you are just trying to see then also you can get different types of features for germanium here it is shown. And you see that one next higher band structure the E-k diagram.

It is showing that see there is a value exactly matching to the gamma point here, this is a gamma point it is shown. And it is the energy of electrons is minimum but if the electron if you see the k vector you are considering along 11 direction you see this is the coming down like a valley but this valley is lower than this 1. So, that means this is kind of indirect bandgap semiconductor because top of the valence band and bottom of the conduction band this is a bottom minima.

If you see this is also minimum but this one also minimum lower than this 1. So, we have to consider any electrons in the conduction band they will try to occupy this valley first. So, bottom of the conduction band and top of the valence band not matching exactly at same k position. This is actually k along the x direction this is a along 111 direction 100 direction. If you want to know what this direction defines different direction means you can just again consult any solid state physics book maybe key tell solid state physics book you can also check that one.

So, this indirect bandgap semiconductor similarly for silicon if you see compared to if you see that valley of the conduction band that is along in the x direction 100 direction 11 direction just remember that 100 direction is a class of direction. It means it involves either x direction, y direction or z direction all direction or 100 class they are identical. But other than this direction if you are just considering any other direction like the diagonal direction called 111 direction.

So, that is actually will be another minima you will be getting here also you are getting minima but conduction band you will see in the along the x direction. So, that is the difference basically for silicon and germanium. The conduction band minima happens in silicon along x direction. In the k space by the way this x direction means when I consider 100 direction that means k xi would consider. That means x component of the k vector. So, both silicon and germanium is indirect bandgap semiconductor but their E-k diagram band structures are not identical.

This is not identical because they are electronic structures are different, the lattice constants are different. That is why you are getting this thing. So, if you analyze different types of semiconductor, different type of crystal, different type of band structure you will be getting these are very complicated. So, I think if you are starting solid state physics you can go much more details but for this course for engineering purpose you can take this is all about whatever it is shown here that is true which is granted.

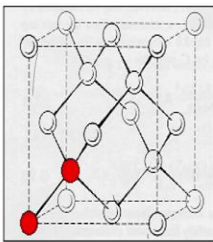
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Light Sources and Photodetectors for Integrated Photonics Slide#8

**Integrated Photonic Light Sources**  
**Silicon Laser – Problems and Prospects**

Si-Ge Alloy: Bandgap Engineering?

Identical Crystallographic Structure

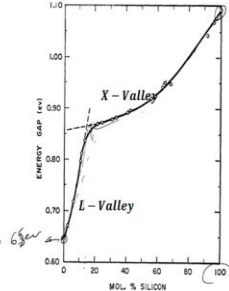


$a_{Si} = 0.357 \text{ nm}$ ;  $a_{Ge} = 0.357 \text{ nm}$

Si:  $1s^2 2s^2 2p^6 3s^2 3p^2$





Ge:  $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^2$

Si-Ge Alloy: Indirect Bandgap Tool



Braunstein, Rubin, Arnold R. Moore, and Frank Herman, "Intrinsic optical absorption in germanium-silicon alloys." *Physical Review* 109.3 (1958): 695.

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So, now we will see as I shown earlier that as if you are making a silicon germanium alloy as you consider this silicon content. For example if you start with the germanium and keep on increasing silicon content then you see if silicon content is 0 then you can get bandgap is around 0.67 electron volt or something like that 0.65 electron volt or something like that. As you keep on increasing silicon because, germanium normally the bandgap if you just check here this is the

bandgap this will be called as a your bandgap this is your energy in electron hole this is 0 and it is about 6 point bandgap.

But for silicon the bandgap is this one E g bandgap is this one this is about 1.12 electron volt. So, when you are actually increasing your silicon content initially starting from 0 your bandgap is 0.65 electron volt. Now increasing silicon that means you get back your energy valley still will be this one and keep on increasing silicon content more and more and more then what happens this thing slowly the alloy whenever you are just increasing germanium to silicon. So, the property moves from germanium property to silicon dominating property.

So, silicon dominating property maybe it will come to this valley X valley. This is called X valley bottom of the conduction band this is the L valley of the conduction band. And that is the reason you see initially your bandgap is increasing but with a certain slope and at this point actually what is happening it is a confused state. So, whenever silicon percentage is around 20% and so, on that means which value will be dominating because silicon content is slowly increasing even 20% of silicon content that pull the band structure to the x value that means 100 directions the bandgap will be there and the slope is different.

But bandgap is increasing and up to 1.10 it is 1 means percentage it is when silicon is completely germanium atoms are completely replaced all the atoms of germanium component, germanium atoms are replaced by silicon that means silicon crystal. So, bandgap will be 1.12 electron volt. If you want to know a little more about that just to go to this paper and download that thing and to how it is calculated band structure etcetera will be able to learn that thing it is very old paper 1958. So, about 40 to about 65 years ago, 60 years ago.

Now, very recently so, now what we conclude that even if you do alloy it is not like compound semiconductor some of the fractions you will see the direct bandgap semiconductor. You indeed see bandgap engineering. But this bandgap is moving from L valley to X valley the conduction band. And valance band it is remaining identical. So, that means even if you are making alloy bandgap is moving from 0.65 electron volt 1.1 to electron volt that is fine.

But it is only conduction minima just moved from L valley to X valley remain identical indirect bandgap semiconductor. So, there is no way that some of the compound semiconductor like I have shown earlier that if you just make some alloy you can get some fractions it can give you direct bandgap semiconductor. And some composition can give you indirect bandgap but silicon germanium it is not possible. So, unless and until you get a silicon germanium direct bandgap in silicon or silicon germanium alloy we are talking about silicon germanium alloy?

Because silicon and germanium this type of alloy is well known for CMOS industry and they are used largely used for various types of electronic devices. So, it is CMOS compatible so, first try would be just go for bandgap engineering particularly for photodetector designing extra. But what we understand that is not giving you direct bandgap semiconductor so laser also not possible. So, what is the alternative way? So, people are trying that with these indirect bandgap semiconductors? That is because of this basal crystallographic structure.

That is the FCC crystallographic structure per center cubic this type of unit cell if you can grow silicon crystal little bit differently technologically if you just grow this natural silicon. If you grow a silicon crystal, silicon is of course normally whenever you use in electronics industry and photon industry that silicon crystal you have to grow but this growth taking natural growth technique is like this cubic crystal something like that. Now people try it that if we can grow a little bit differently different arrangement of atoms if that is possible or not.

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Light Sources and Photodetectors for Integrated Photonics Slide#9

**Integrated Photonic Light Sources**  
**Silicon Laser – Problems and Prospects**

Hexagonal Crystallographic Structure for Si and Ge: New Hope?

Example: Hexagonal ZnO Crystal

γ = 120°

Fadaly, E.M.T., Dijkstra, A., Suckert, J.R. et al. *Nature* 580, 205–209 (2020).

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So, people tried instead of cubic crystal growth like whenever you see cubic silicon the band structures are looking like this. This is a valence band and this is your conduction this is silicon conduction band will be coming like this. And cubic germanium if you grow the structure is shown here this a gamma point this side is zone x this side is L normally you know this is your zone x and this L it is actually reverse process here in this paper you can find a detail in this paper this was recently published in nature 2020.

So, they calculated band structure of a cubic silicon using density function theory and this is this side is shown L because it is your silicon alone. So, silicon this is actually L direction and this is X valley here is your band valley is coming along the x direction and this one actually 1.12 electron volts and for germanium if you see this one actually these to these that is actually your bandgap. And that is bandgap is equal to less than 1 it is about 0.6 electron 0.65 electron volts. So, this is actually L Valley.

For germanium you have L valley in the conduction band and silicon this is actually silicon here and silicon what you get here is actually silicon. So, here you see in the L valley germanium is there in the conduction band. But if you can actually somehow grow silicon and germanium with hexagonal crystallographic structure. What is that hexagonal crystallographic structure? It is something like that hexagonal crystal like zinc oxide, if you see crystallographic structure of zinc oxide then atomic arrangement if you see that it takes a hexagonal shape.

If you say this one this is your lattice constant here all the hexagonal something like this type of shape will take atomic positions it takes like this. So, if you can grow silicon and germanium like that is also possible it depends on your crystal growth technique. If you somehow engineer your crystal growth taking normally all the silicon crystals most of the crystals they are actually grown using Czochralski method that is a well known method Czochralski method and that is a natural process whatever I have shown here cubic crystal growth.

But if you have some kind of special type of seeding mechanism is there so that you can grow all the atomic positions or like a hexagonal structure like this. So, here it is shown zinc position and oxide position and in case of silicon this all zinc and oxygen all will be like a silicon atoms. So, this white dots and white balls and black balls they are shown as the atomic positions so instead of zinc and oxide you will be getting always silicon crystal or if it is germanium you will be getting germanium crystal if you can grow like that then if you again calculate your density function theory for a band structure.

Then you can see that the band cycle structure is completely different. How it is for silicon if you see that you will have another particular locations all these points are actually defined points in the case space. I am not going into the details of those space but what you see that your valance band is somehow a little bit modified compared to this one you see valance band it is modified like that and your conduction band you see the minima instead of X valley you will see M valley some other location other direction you will see.

Hexagonally few just grew and if you just grew hexagonal germanium. Then what happened this type of crystallographic structure if you grow then also your band structure different this is you are all the fine lines all these corresponding to the valance band this is around gamma point. And in Germanium instead of instead of your valley in the L in the modified structure if you see that the valley comes here directly here exactly at the gamma point.

So, it is looking like as if it is something like coming like a direct bandgap semiconductor for germanium. So, actually if you actually speaking if you see all the structures if you seek

ultimately it is very difficult to grow the direct bandgap some semiconductor even if it is hexagonal it has been shown that the silicon and germanium they are basically indirect bandgap semiconductor. So, what is the way out?

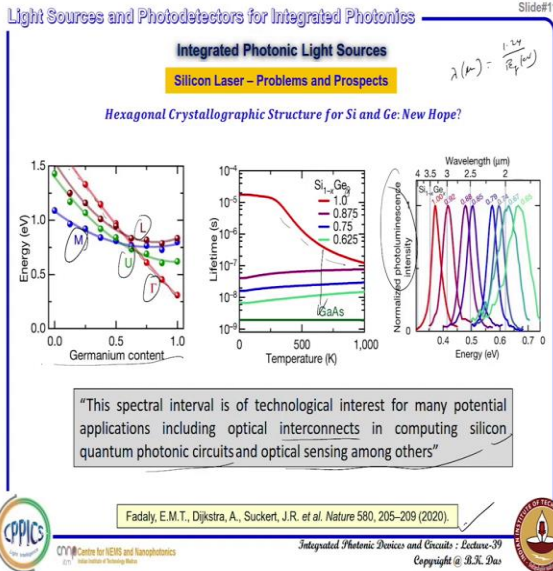
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The slide, titled "Integrated Photonic Light Sources" and "Silicon Laser – Problems and Prospects", discusses the "Hexagonal Crystallographic Structure for Si and Ge. New Hope?". It features four band structure plots (a, b, c, d) showing Energy (eV) versus momentum along high-symmetry directions (Γ-X-Γ-L-A-Γ-M-U-L). Plots (a) and (b) are for Silicon (Si), showing indirect bandgaps for Cub-Si and Hex-Si. Plots (c) and (d) are for Germanium (Ge), showing indirect bandgaps for Cub-Ge and Hex-Ge. A scanning electron micrograph (SEM) shows a hexagonal array of pillars. A quote states: "Clearly, a direct bandgap is predicted at the  $\Gamma$ -point for  $x > 0.65$  (red curve) with a magnitude that is tunable across the energy range 0.3–0.7 eV". The slide is attributed to Fadaly, E.M.T., Dijkstra, A., Suckert, J.R. et al. Nature 580, 205–209 (2020).

If you make an alloy now if you make alloy structure like silicon extraction you remove and germanium extraction you remove and you grow a crystal silicon germanium alloy. You get a hexagonal crystal like this you see according to these are the pillars grown. And it has been shown that is if  $x$  is somehow greater than 0.65. That means if germanium content is more silicon extraction reduced germanium content is more than bandgap engineering is possible at the same time he can get a direct bandgap semiconductor.

So, in this lecture what we try to make you convince that just silicon crystal indirect bandgap FCC cubic crystal, silicon crystal, germanium crystal let us say indirect bandgap semiconductor. But if you grow with a hexagonal structures like this atomic arrangement such that the band structure can be engineered and even after engineering you cannot get also direct bandgap semiconductor but if you can try to make silicon germanium alloy with hexagonal structure then you can get a direct bandgap semiconductor and clearly direct bandgap is predicted or the gamma point with a magnitude that is tunable across 0.3 electron volt 2.7 electron volt.

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So, if you see all this point these are the valley points M Valley, L Valley, U valley gamma valley in the conduction band. If you increase your germanium content the gamma valley actually if you see increasing germanium content gamma value will be lowering down this is gamma red one U valley, L valley, M valley that means you can actually engineer the bandgap. And if you make a population inversion that means electrons in the conduction band more and holes in the valence band more than radiative recombination will take place electron and hole.

So, depending on the x fraction  $x = 1.875, 0.75, 0.625$  if you go on increasing decreasing x value up to 0.625 more than that means all the x greater than 0.65 we have shown then you see that lifetime recombination lifetime or radiative lifetime that means how much time it takes for radiating a photon it is slowly coming closer to the gallium arsenide and gallium arsenide you know that is actually like a direct bandgap semiconductor will not poly laser show that means if you make a silicon germanium structure.

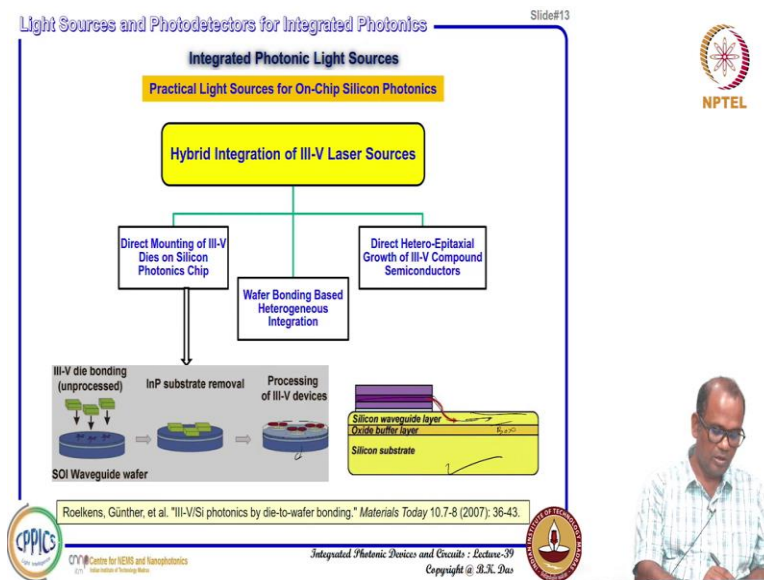
And bandgap engineer with hexagonal crystallographic growth then you can get laser emission. And it is calculated and it is shown that you see as a function of x. Then what is the transition luminous electron photon emission whatever coming out of that type of silicon germanium crystal. Different energy level different energy you can calculate already electron volt is there that means lambda you can calculate in micrometer that already 1.24 by whatever  $E_g$  electron volt.



So, corresponding energy corresponding lambda you can find out that emission will be there. So, that comment I just pointed out from this paper it is this nice paper recently published if you are interested in one load and read this paper the spectral interval is of technological interest for many potential applicants including optical interconnects in computing silicon quantum photonic circuits and optical sensing among others. So, this is very including interconnects all this type of thing I mean to say that so, this is a very new prospect for a silicon laser.

But so far this is still it is you see this is just coming out technology I hope it will be dominating in future it is upcoming technology for sure but for the industry application purpose it is now still it is long way to go.

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Normally people used to have different types of integration technique that means hybrid integration of III-V layer sources now people are considering. So, there are 3 different techniques people are using for hybrid integration what are those so, you can have for silicon photonics photonic integrated circuits I mean to say the practical light sources for on chip silicon photonics so, direct mounting of III-V dies.

So, you make your III-V wafer compound semiconductor which is capable of certain laser emission of interest that dies you can just put directly on the top of the silicon photonics chip.

And then you can bond them it is kind of pick and place precisely. And then you can actually fabricate, you can structure your laser by different type of process technology. And then you can bios wherein everything you can do and then light can emit and coupled into the silicon waveguide and so that.

And another thing is that wafer bonding based on heterogeneous integration you can do that. Silicon wafer and then you can grow, you can actually bond III-V semiconductors directly on to 8 and then you can get a structure your laser and you can make also photonic waveguide in the silicon. So, all this type of thing hybrid integration means as I mentioned that you cannot find a suitable material.

Where you can have laser photodetector and waveguide would low loss waveguide so if getting the same material platform. So, that is the one problem only possibilities that bandgap engineering efforts are going on alternatively people are thinking that optimal laser or on chip brid integration. So, 3 different techniques are used and 1 of them I will be just explaining here how it is coming like that if you see this waveguide that is just bonded here indium phosphide substrate removal and then processing III-V devices.

So, you can have a compound semiconductor grow on indium phosphide crystal for necessary bandgap engineer bandgap compound semiconductor and then you just bond it and then indium phosphide back layer sacrificial layer you remove and then you can structure them, process them and make a laser device and that laser if you fabricate if you just see SOI substrate this is your SOI substrate silicon substrate buried oxide box and this is a waveguide layer. And you can have some kind of mechanism so, that laser emitted laser can be coupled into the waveguide layer.

So, this things actually known for a long time since 2007 about 15 years ago and that is still continuing and technology is becoming more and more matured so, that people are getting on chip laser sources.

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Slide#14

### Integrated Photonic Light Sources

Practical Light Sources for On-Chip Silicon Photonics

Hybrid Integration of III-V Laser Sources

Direct Mounting of III-V Dies on Silicon Photonics Chip

Wafer Bonding Based Heterogeneous Integration

Direct Hetero-Epitaxial Growth of III-V Compound Semiconductors

Roelkens, Günther, et al. "III-V/Si photonics by die-to-wafer bonding." *Materials Today* 10.7-8 (2007): 36-43.

So, you see sometimes you see the Fabry-Perot laser diode how it is just mounted here and this is your SOI waveguide inverse taper is there. So, light from the normally laser when it emits like cross section is in the order of micrometer or so on but you know silicon photonic where the cross section is submicron. So, normally inverse taper you do the spot size converter and the top of the cladding of the inverse taper region is just some kind of polymer waveguide they use and then emitted laser light slowly coupled into the silicon layer.

So, this is kind of expensive technology and precise alignments all those type of things are required. But still people have optimized to those type of solutions and they are getting coming out with products also.

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Light Sources and Photodetectors for Integrated Photonics Slide#15

**Integrated Photonic Light Sources**  
**Practical Light Sources for On-Chip Silicon Photonics**

**Hybrid Integration of III-V Laser Sources**

- Direct Mounting of III-V Dies on Silicon Photonics Chip
- Wafer Bonding Based Heterogeneous Integration
- Direct Hetero-Epitaxial Growth of III-V Compound Semiconductors

III-V die bonding (unprocessed) SOI Waveguide wafer  
 InP substrate removal  
 Processing of III-V devices

Roelkens, Günther, et al. "III-V/Si photonics by die-to-wafer bonding." *Materials Today* 10.7-8 (2007): 36-43.

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And you see this, this is the after on chip laser mounting etcetera processing it is shown that as a function of current how much power actually being coupled into the silicon waveguides.  
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Light Sources and Photodetectors for Integrated Photonics Slide#16

**Integrated Photonic Light Sources**  
**Practical Light Sources for On-Chip Silicon Photonics**

**Photonic Wire Bonding – A New Approach!**

3D structuring by two-photon polymerization  
 Photonic wire bond  
 Chip 1  
 Chip 2  
 Submount  
 Resist

The PWB structures were written in MicroChem SU-8 2073 photoresist (refractive index  $n = 1.57$  at 1550 nm) using a commercially available 3D laser lithography system based on an inverted microscope (Photonic Professional, Nanoscribe GmbH)

Transmission (dB) vs Wavelength (nm)

Photonic wire bond  
 SOI waveguides  
 Chip 1  
 Chip 2  
 10  $\mu$ m

Lindenmann, N., G. Balhassar, D. Hillerkuss, R. Schmogrow, M. Jordan, Juerg Leuthold, W. Freude, and C. Koos. "Photonic wire bonding: a novel concept for chip-scale interconnects." *Optics Express* 20, 17667-17677 (2012).

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And here another interesting technique is very recently so known for a couple of years that it is something like that if you have a III-V semiconductor laser and you have a photonics chip optical waveguide silicon photonic devices are there if you want to coupled light why not like something like that electronic wire bonding whenever you do you go for packaging electronics chip normally you have to bond your devices. You have to wire bond from one device to your outside world.

You need some kind of pins like a pump you see there are pins out outside inside there is a bonding methods are there, but there is a electrical connection is there electrical wire you are just bonding that technology is there. So, people have been trying to have similar type of bonding technique so, waveguide bonding so, that means one waveguide to another waveguide how you can couple light. So, can we have some kind of technique that you just touch something and somewhere type that optical wire optical waveguide wire?

You can have you can just bond in one waveguide you can have a contact pack and then you can bring it to another waveguide and you can couple that thing so, in that case if you have 2 different chip one is III-V semiconductor chip where you have photodetector and laser is there and another chip is silicon photonics, if you want to get laser output from there and directly connect into the another chip just with a machine if you can do that would be fantastic. So, there is a machine actually that lithographic technique called 3D lithographic technique.

So, 3D lithographic technique means you can have a laser source and that laser source normally when we do photolithography, photolithography you know that normally you have a substrate and then suppose this is your substrate then you have a photoresist you do coating and then whenever light is falling if it is a positive resist that positive resist is here and actually it will be hard and rest of the regions actually it will be dissolved in a developer and you get a structure that means photon actually activate this polymer like photoresist it is kind of polymer and that particular structure will be hardened.

And other this is your photon coming this is photon beam or light beam is coming and that that region hard and rest of the region will be developed and to get a particular structure defined structure where you want to do for etching and so on you can do that. Similarly this type of machine is being invented has been invented where actually whenever you were focusing a laser light in a certain type of polymer the focus region that polymer will be actually polymer chain will be modified and that will be hardened and if you develop that particular region will stay.

And rest of the things can be developed and this machine actually it is called 2 photon polymerization TPP. So, when you focus a high energy pulse laser, and focus it then 2 photon

jointly transfer energy to the polymer molecule and when 2 photons transfer the energy to the polymer molecules that polymer molecule will be modified, hardened and wherever that is hardened it is a focused laser beam using an inverted microscope some microscope is there, objective is there we are just tightly focusing the laser source.

And because of the 2 photon polymerization you can actually modify, now you can control the beam spot by computer programming. And you can actually wherever it can be 3 dimensional you can actually define your structure. So, what it is done for example, you have a chip 2 here and this is chip one let us consider that this is your III-V laser made out of gallium arsenide or indium phosphide and this is your silicon photonics chip. So, what they do? They do that entire region the coat with a polymer thick polymer.

In this case it is AC weight is a special type of polymer is used for a lot of structuring and different types of micro what to call them microfluidic channels etcetera people use that type of polymer. So, that type of polymer it will cover thick maybe a couple of microns or so, now this laser beam comes here so, you can use this laser spot size to define a certain type of polymerization 2 photon polymerization you see this pink colour things are there.

So, as you move your spots size focused beam as you move your focus beam from this region to this region for example this contact pad region then you can see that particular region will be polymerized. And if you put in a developer then rest of the region it will be removed only that hardened person will be staying back and you see the technology is so precisely optimized you can see that this side one waveguide is there, this side another waveguide is there, on the top you have one waveguide it is coming like it is a bonded.

This is a polymer waveguide and comes here and in this there you see 2 chips separated by the gap here and you can have connecting here. And then when light comes here that can be mono centric coupled to this this type of polymer waveguide which is actually can be fabricated using photonic wire bonding so, called photonic wire bonding method and you can get this type of thing it as like as easy like whatever you use for electronics chip bonding.

Actually in PCB whenever you are mounting a electronic chip in PCB printed circuit board. There also you need to bond the different types of contact points of the electronic chip you can bond with a PCB or maybe chip to chip you can do that type of technology is well known and widely used for electronic industry. Now, similar type of technologies actually demonstrated for photonics industry where you can have, you can actually combine, you can actually bond from one particular photonic chip to another particular photonic chip.

So, in that case, you do not need to go for all this type of complicated integration methods etcetera. And here it is shown that the coupling between one waveguide to another waveguide that polymer waveguide to photonic wire wave guide it is a coupling loss transmission, if you see less than 0.1 dbm so on for entire wavelength range. So, that is a very promising technique that is w I thought of sharing with you so, that in future whenever you are learning and going for research in different direction that would be helpful for you.

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Light Sources and Photodetectors for Integrated Photonics
Slide#17

**Integrated Photonic Light Sources**

**Practical Light Sources for On-Chip Silicon Photonics**

*Photonic Wire Bonding – A New Approach!*

Center for Nanoscale and Nanophotonics  
Institute of Technology, Delhi

Billah, Muhammad Rodin, et al. "Hybrid integration of silicon photonics circuits and InP lasers by photonic wire bonding." *Optica* 5, 7, 876-883 (2018).

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And using this technology it is just they have already demonstrated some kind of so called photonic wire bonding for DWDM application purpose if you see different type of lasers they are fabricated out of indium phosphide chip so that they can be different color maybe 16, 24, 32 and so on different types of color they can be emitting and you can actually bond with modulator silicon photonics modulator chip you say modulators can always you can fabricate a very good low loss waveguides.

And modulators in silicon and you can bond here and then again you can use another chip where you can actually use for multiplexing purpose normally added arrayed waveguide grating structure is used. Suppose you have 100 sub channels or they are 100 of modulator fabricated in silicon chip where you can actually encode all your data you can actually multiplex into them together into a single mode fiber and you can take it as a use it as for long all communication purpose.

So, this is some kind of state of the art futuristic artistic think people are talking about and very recently it is coming up very nicely optimization etcetera. And it is shown that this type of bonding this photonic wire bonding PWB means photonic wire bonding how they are they can precisely control with computer nowadays computer technologies programming is so fast so, that they can precisely control your focused beam. And then you can bond you see this how nicely it is bonded polymer waveguide into the silicon chip photonic chip is shown here.

And you say this how angle precisely 85 degrees controlled and they have fabricated you see they have 2 different chips where lasers are there and this is the photonics chip and they try to bond maybe 1 2 3 4 4 different chips bonded here and they have just shown how there incessant loss that means, whatever power on chip it is emitting here. And how much being coupled to the silicon photonics shown just losses in this case 0.6 dB 0.6 dB 0.4 dB as low as 0.4 dB loss coupling loss 0.4 dB only.

That is actually very phenomenal results basically whenever you talk about fiber coupling for example, standard single mode fiber coupling into silicon photonics chip I think losses is 6 DB, 7 DB and the best possible loss people reported so far is 3 dB or so on. But in this case you see that this coupling loss is very small just 0.4 dB as small as 0.4 dB. So, that is very interesting technology coming forward so, in next few years I hope this technology is being flourishing is going to be flourished with this I just stopped this lecture today.

And in the last lecture I will be discussing about how one can integrate the photodetector that is the first final things. So, you need passive devices, silicon photonics passive devices, modulators,



lasers and then final thing is the photodetector and that is how we will be closing our courses.  
Thank you very much.