High Speed Devices and Circuits

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Lecture – 4

Ternary Compound Semiconductors and their Applications

Last time we discussed some aspects of the compound semiconductors and we saw that there are II - VI, III - V, IV - IV. We have named all of them and we finally came to the ternary compound semiconductors and we have also discussed everything about or most of the things about III - V compound semiconductors. Now, we just began our discussion on ternary compound semiconductors. So, that is why, this lecture will be on ternary compound semiconductors and some of their applications because it is interesting to see instead of just seeing listed out those materials see where they are useful. In fact we will see that they emphasize on some of the devices or materials are on photonic devices that also we will touch upon.

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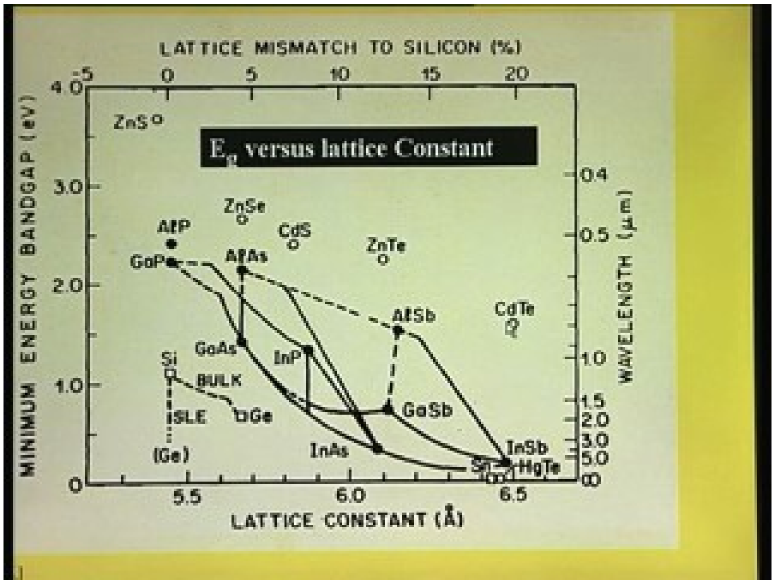

So, now you can see that here, this is the entire picture of the ternary compound and compound semiconductors given. Actually what you see is mainly III - V semiconductors and II-VI semiconductors joined by some lines. So, we can see, go from the top here. All these compounds are the II-VI compounds which we have virtually eliminated from the microelectronics agenda because their mobilities are low; their band gaps are excellent, much higher than that of silicon in all cases, but we do not want it for microelectronics but they are useful for optical Opto-Electronics or Photonic devices.

Now, let us see the ternary compounds. You can see here in this diagram, just I want to tell you something about this diagram. You have on x-axis the lattice constant of each of those materials. See, for example, if you see gallium arsenide, it is about 5.63 Angstroms or 5.65 Angstroms or so for gallium arsenide. Now, if it is indium arsenide, it is quite different. We can see it is more than 6.1, slightly less than 6.1 Angstroms bigger atom. Indium is bigger compared to gallium. Gallium is 1.26 Angstroms and indium is 1.44 Angstroms. So that way it is bigger, that way lattice constant is big compared to that. So on x-axis you have that. On the y-axis, you have the minimum energy band gap. When I say minimum energy band gap, the meaning is, it is actually the band gap which is coming into picture. We have seen yesterday, there is direct band gap and there is indirect band gap also. There had been both band gaps, minima in the conduction band. What we talk of is the minima of the minimum. Minimum of the minimum. There are two minima which is lower, so that is why it is called. It is actually the band gap. On the right hand side, you see the wavelength. This is the wavelength that corresponds to the band gap. If it can emit light, it will emit light corresponding to that band gap guided by the formula energy is equal to h mu. So, if you substitute for h and mu is equal to velocity by lambda. Lambda will be related to energy as we will write down that afterwards as 1.24 divided by energy. So this number that you get here on the right hand side is actually is 1.24 divided by the band gap in microns. When you express energy in electron volts that will be in micron. If you want to write down that, see for example E:

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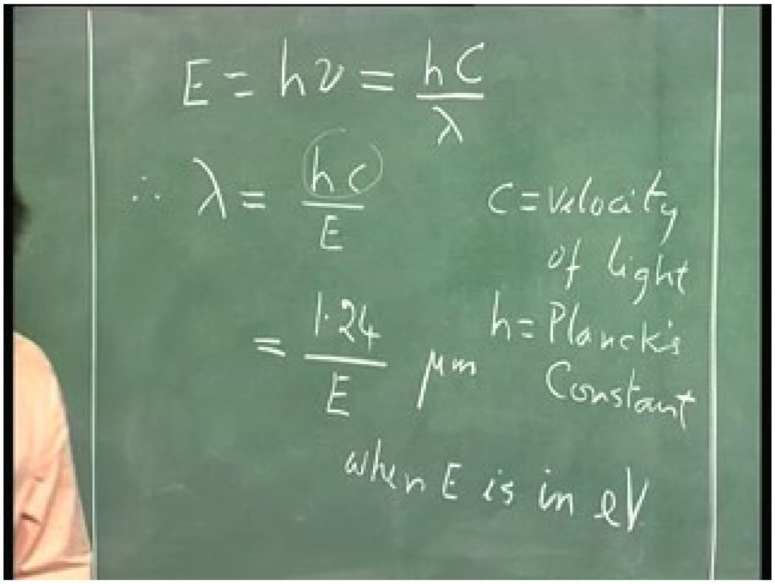

$$E = h\nu = \frac{hC}{\lambda}$$

$$\therefore \lambda = \frac{hc}{E}$$

$$= \frac{1.24}{E}\ \mu m$$

C = Velocity of light

h = Planck's Constant

when E is in eV

E is h mu where mu is the frequency, h is the famous law you cannot forget Planck’s constant that is at h into v velocity of light, to avoid confusion I am putting C divided by lambda, wavelength. Therefore lambda is equal to hc by E. We substitute C is the velocity of light and h is Planck’s constant. We substitute for those two quantities together and then this turns out to be in fact it is worthwhile remembering the relationship between energy and lambda.1.24 divided by E. So many microns where when E is in electron volts, so we can see if gallium arsenide has got band gap of 1.43 electron volts, automatically you will know how much is the lambda correspondingly to that is. It will actually be equal to about 0.87 or so, the wavelength corresponding to that divided by this 1.24 divided by 1.43 about 0.87 wavelength. So if we use gallium arsenide for realizing the light emitting diode, how do you make light emitting diodes? Make a pn junction forward bias it, pump in current that injects carriers into it. For example, if it is n plus p diode, electrons are injected into p region, those electrons are minority carriers which will recombine and when it recombines the electron drops from the conduction band to the valence band. So, if your energy band diagram is like this.

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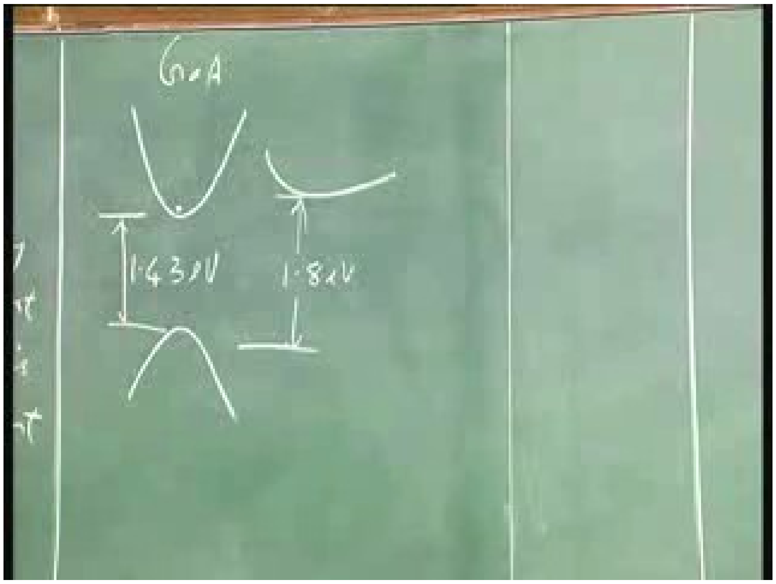

That is the satellite valley which is gallium arsenide. If I have this as 1.43 electron volts that is gallium arsenide. You will have this as 1.8 electron volts. You do not care about that because the electrons tend to occupy the minimum energy position that is that. It will not occupy this position, unless you give enough energy by some external means like electric field. Then you scatter it from here to here. Otherwise, it will remain here. So, if you make a pn junction like that, N P, N plus heavily doped n region and p and if I forward bias and pump in current.

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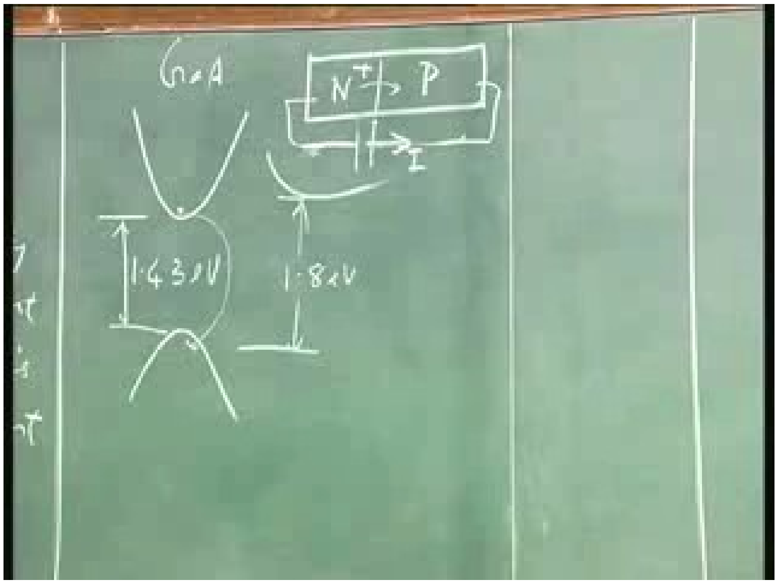

If it is gallium arsenide device the electron or whatever gallium arsenide or silicon it will inject electrons into this. Those electrons will be recombining by dropping down like this, recombination means electrons getting recombining the holes, so transfer of electrons from conduction band to the valence band. So you forward bias the diode. Current is injected and when current is injected electrons are injected and current is flowing actually in this direction. That means electrons are injected in that region p region. Electrons injection is in this direction. So, there is recombine. When they recombine they lose the energy and that energy is given to the light that is the light emitting diode. Now if you use gallium arsenide, the wave length you will get will be 1.24 by E that is about 0.87 microns. 0.87 microns is something which cannot see. It is not a visible light. It is infra red radiation. It cannot be used for making light emitting diodes, but the wavelength that is projected here on the right-hand side of this diagram (Refer Slide Time: 10:26) is actually the wavelength corresponding to, if there is a transition like this, that will be corresponding to that band gap. So, let us see and this diagram that you have drawn is actually a diagram for gallium arsenide direct band gap and also we have said the minimum band gap is put there, implied that this is the minimum compared to that. If you transfer the electrons from here to here, if there were there then it should have been indirect transition. I just am trying to point out some of these things which are in this diagram. At this side we get the wavelength which is actually on 1.24 divided by energy.

Now you can see there are number of things put here. Gallium phosphide, it gives what is its lattice constant. It gives what is the band gap for that is minimum band gap and then you have got gallium arsenide here.

Now, between those two gallium phosphide and gallium arsenide a line is drawn. In fact between each of those semiconductors, III-V semiconductors in this diagram lines are drawn. Some of them are solid lines, some of them are broken lines. Now, let us take this gallium phosphide and gallium arsenide. You can make a compound which consists of gallium arsenic and phosphorus, gallium arsenide phosphide, or gallium arsenic phosphide whichever way you want to call it ternary. So, what is shown here is you can make ternary using gallium phosphide and gallium arsenide. Now remember gallium arsenide is a direct band gap semiconductor. They had been explained all that direct band gap semiconductor; whereas, gallium phosphide is an indirect band gap semiconductor. So, if you mix them together what happens is the mixture of them. For example, if you take here, that is gallium arsenic phosphide into the… if you see that, this is solid line implying from aluminum arsenide is direct band gap. If I go on adding phosphorus to that gallium arsenide, it becomes more and more towards gallium arsenic phosphide. If you go all the way down it is gallium phosphide that becomes the indirect band gap. That means from direct band gap materials, it will move towards the indirect band gap semiconductor, at some point it will become indirect. For example, there it becomes indirect. Beyond that point if I move that dotted line indicates that that will be indirect band gap. The solid line indicates it is direct band gap.

Take a look at this for example, gallium arsenide direct band gap and indium arsenide direct band gap. You can make alloys of gallium, indium, and arsenide. Ternary compound consisting of gallium, indium, and arsenic. It is called gallium indium arsenide. Now you can see the band gap of gallium arsenide 1.43, band gap of indium phosphide is something like 0.36. If you mix them together, you can get material whose band gap is anywhere from 1.43 right down to 0.36. Whether you are interested in that band gap whatever reason it depends upon the particular application.

For example, I can just adjust the concentration of the indium. This is gallium arsenide. I keep on adding indium to the gallium arsenide; it will replace gallium with the indium. Increase the mole fraction of the indium, then at a particular point it reaches there. Now you can see a solid line is made here. That is you can use that component the entire thing is solid line here because the entire thing is, indium arsenide is direct band gap, gallium arsenide is direct band gap, so any combination is direct band gap. Now, you can have here, indium phosphide which is actually a slightly higher band gap compared to that here. That is also direct band gap. I can mix gallium indium arsenide of this composition with indium phosphide or I can grow gallium indium arsenide on indium phosphide. See that vertical line indicates that there is lattice match between the two compounds. This diagram is actually I have just one slide here contains so much packed information here.

You can change this material, at this point it has 5.85 or something like that, lattice constant. If you take indium phosphide the line is vertically up. It has the same lattice constant. So, I can grow gallium indium arsenide of that composition on indium phosphide. The vertical line indicates that they are lattice match and you can grow one over the other. Similarly, here you can see and the whole thing is of course direct band gap. Similarly, here you can see gallium arsenide. Lattice constant is practically same as that of aluminum arsenide. You can mix gallium arsenide with aluminum arsenide. Aluminum arsenide is indirect band gap. So if I mix that it will go up increasing aluminum content, it becomes some direct to indirect. But again what you are telling is you can have gallium arsenide on the top of that. You can have a compound made up of any composition from here to here. On the gallium arsenide, I can have aluminum gallium arsenide that is I have to keep on adding aluminum to gallium arsenide it becomes aluminum gallium arsenide, I can have that.

It looks at this stage, that we are just playing with different materials but that is the technology for compound semiconductors. We can mix compounds, realize whatever band gap you want and you can use one material or one band gap. For example 1.43 here, mix with aluminum arsenide whose band gap is something like 2. So, 1.43 band gap gallium arsenide, aluminum gallium arsenide band gap of 2. We can make one substrate of one material may be that is n type just as an example. On the top, you can have aluminum gallium arsenide which is p type or you can take p type gallium arsenide and n type aluminum gallium arsenide that is the hetero junction. Conventionally what we talk of is silicon on silicon. Silicon p type material, silicon n type material that is a homo junction, material is same. But, if you have gallium arsenide p type, aluminum gallium arsenide on that n type that is a hetero-junction. So you make hetero-junctions but we should careful do when you making hetero-junctions. What is the thing that should be careful? Lattice match. So that is why you should go up when you mix for making junctions vertically down like that. Now, let us take a look at some of the materials which are useful for photonic applications. For example, light emitting diodes maybe lasers. I will just take up this example where you mix gallium phosphide and gallium arsenide. Let us draw that diagram now. So, I will take this diagram out.

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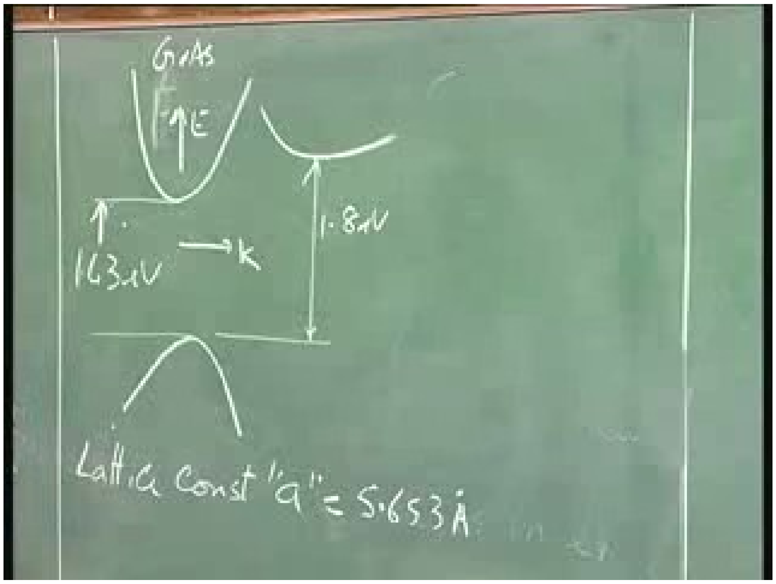

Let me redraw this here. So, you got gallium arsenide satellite valley, the energy versus this momentum and conduction band valence band that is understood, it is a direct band gap semi conductor and then, you have got this is 1.43. I am rewriting what I have written there earlier and this quantity is 1.8 electron volts. Now the lattice constant a, hereafter, I will write only a means lattice constant which is 5.653 Angstroms for gallium arsenide. Now you take a look at the other material that is gallium phosphide.

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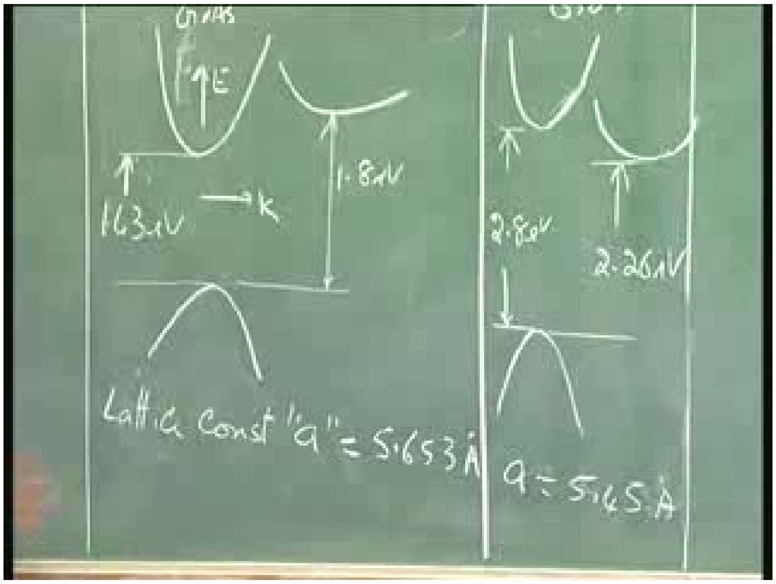

Gallium phosphide has got indirect band gap materials so that has got, we will see this here. We have got gallium phosphide, which is coming like that and something like this and that is 2.8 electron volt. It is not a direct band gap semiconductor. It is an indirect band semiconductor which would mean you will have a satellite valley which is below that. So, that is actually somewhere here 2.26 electron volt and a for this case is actually 5.45 Angstroms. So, that is shown also in the diagram here. The value is shown there, 5.45 and 5.653. Now let us see what would happen if you mix up these two. Let us put this diagram, we can see when you mix these two you can get material called gallium arsenic 1 minus y phosphide. You can mix them; you can get the ternary compound which is very useful for light emitting diodes. Now let us put that diagram here.

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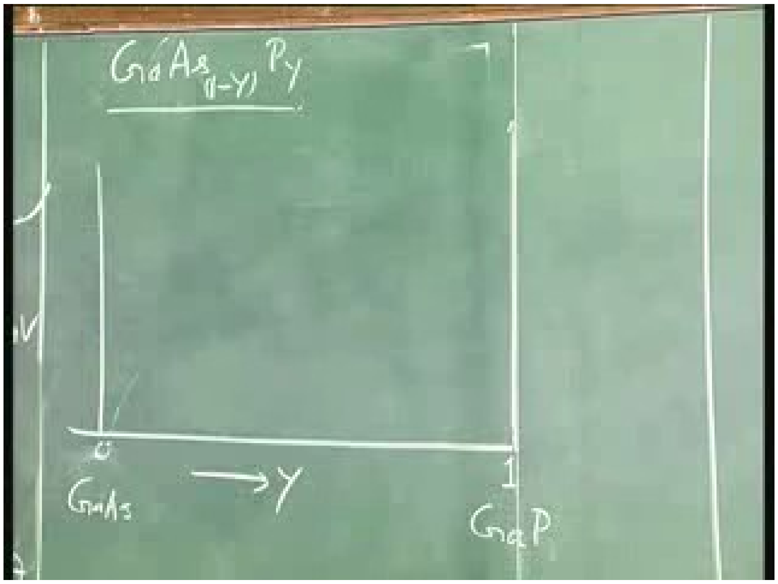

So, on this side I have got gallium arsenide. I will vary y that y. When y is equal to 0 that material is gallium arsenide. That is y equal to 0 that is gallium arsenide then y is equal to 1 that is gallium phosphide and whole material here you can call it as gallium arsenic 1 minus y phosphide y. What we are doing is, go on adding phosphorus to gallium arsenide so disturb the stoichiometry to get a total number of arsenic and phosphorus atom equal to gallium atoms that is the stoichiometry.

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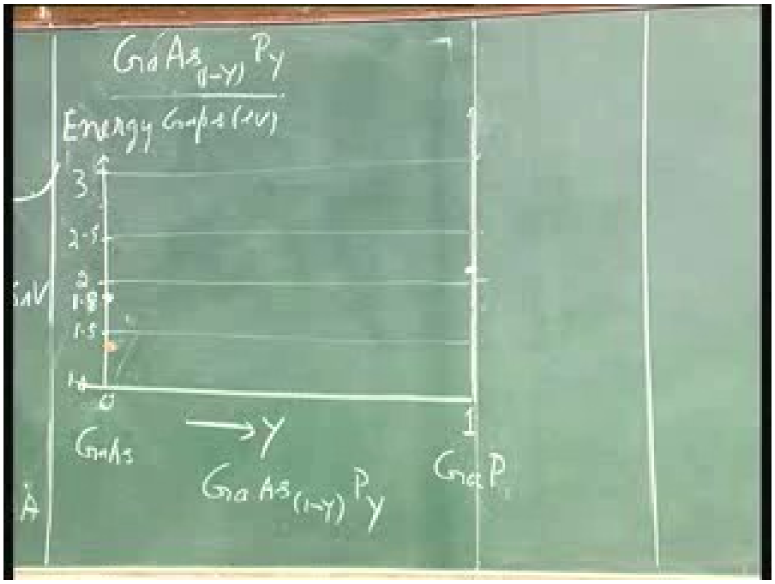

Now you can just see put this x here. You will represent energy gap E_g. Let me put it like this. Energy gaps in electron volts that is what I put there. Now you plot this. Put that number there. You can put this is 1, 1.5, 2, 2.5, 3. Now, if you take a look at gallium arsenide you have got direct band gap of 1.43. That I will mark it as here and put it in some color here and if you take a look at this gap that is 1.8 that is somewhere here. So, I have marked those two points there. If you go to the other end gallium phosphide has got 2.26 as the indirect band gap. I can just put it down here like this. Somewhere here that is actually the indirect band gap. That is actually the band gap of gallium phosphide. So, if you make y equal to 0 the minimum band gap is 1.43. If I take y equal to 1, the minimum band gap is 2.26 direct band gap, indirect band gap, and minimum band gap.

Now what happens is when you mix them together, the lattice constants almost linearly changes. Similarly, the interaction between the two takes place. Without getting down to the physics of that, what happens is the direct band gap links with the direct band gap here. Almost linearly not exactly linear, almost linearly it varies. So that means actually if I mix at this direct band gap here is 2.8. You have got 2.8 there. When you mix them together what turns out is from here to there you will have the band gap this keeping on widening and ultimately it becomes that. This whatever 1.8 is there that keeps on widening ultimately becomes that.

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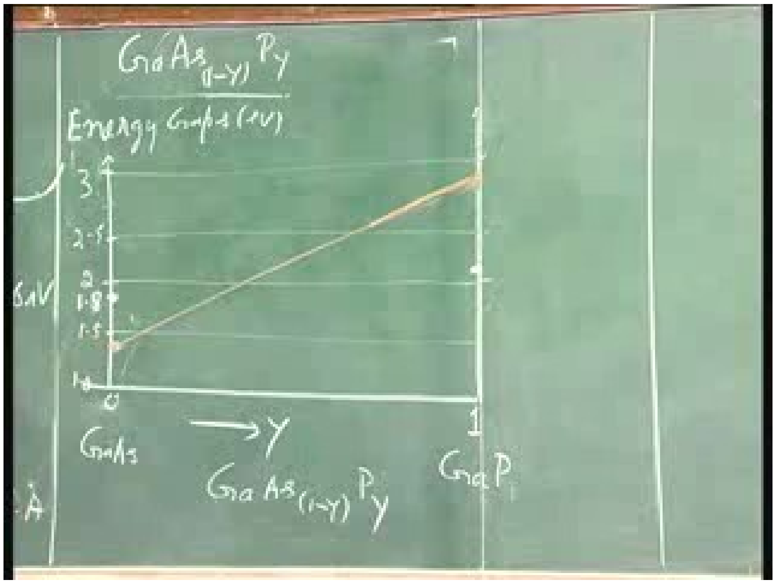

So, this is almost linear from here to here, almost linear that the direct band gap varies like that, because the lattice constant almost linearly varies. Now the indirect band gap corresponding to that, this latches on to that. That also will vary linearly.

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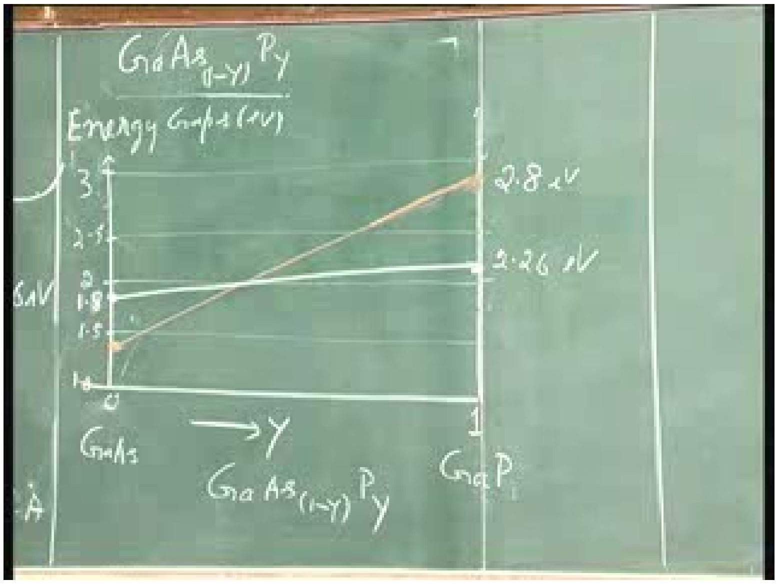

So, what you have finally is something like, I am just trying to keep track of where that 0.5 thing is, so somewhere here. That is the indirect band gap vary 0.8 to 2.26 and here it is 2.8. So, it is very interesting to see as you keep on varying that y the difference between this and this narrows and at a particular point the direct band gap and indirect band gap both remain the same. That means actually the electrons will be there, some of them ________ and some of them will be there in that point.

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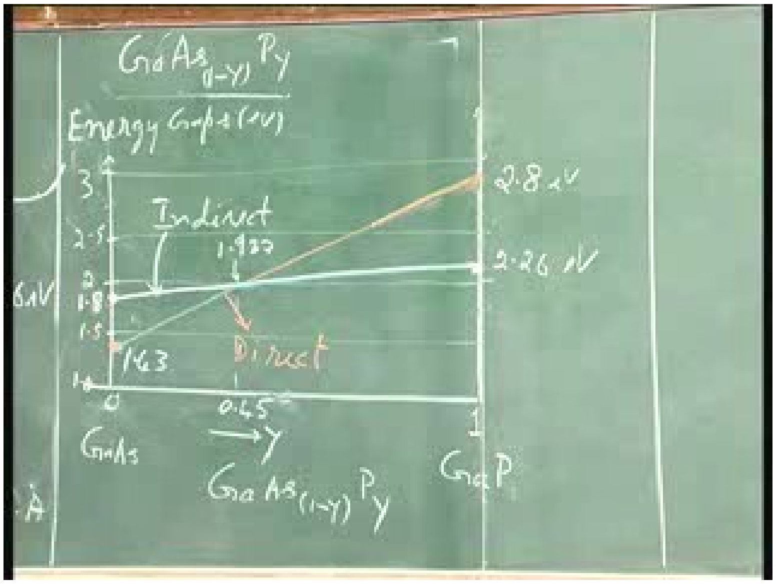

So, transition can takes place from either of them. The most interesting part is, if you see this combined which is actually the band gap now? Here the band gap is this one minimum band gap, direct band gap. It will go here up this is indirect and this one is direct. If you vary the band gap ultimately what you get is that is the minimum. So up to that point it is direct band gap. Go into this you will move from gallium arsenide towards indium phosphide up to that point, it is direct. Beyond that point it is indirect. What has happened? From here between the two band gaps this is smaller. So, it turns out to be like this. So the final band gap of this material you vary from 1.48, 1.43, and at this point, it will be 1.97 here that will be 1.977 and this will be actually 0.45. This is 0.47 or 0.45. When y is 0.45 the transition from direct to indirect takes place that is the key thing here. So, the most interesting part of this diagram is or this exercise is, you can make use of ternary compound semiconductors by mixing binary. Whether it is direct or indirect depends upon the composition. Here y that is the phosphorus mole fraction has varied from 0 to 1 you will go from direct to indirect. What is the key thing here? Now you can actually use… If I want to make light emitting diode which portion of this diagram will be used? The answer will be immediately spontaneous because direct band gap. Direct band gap gives transition like that. Indirect band gap actually transition like this will not emit light. The last time we mentioned it will be the two step process and because of momentum difference. So, if there are no intermediate levels, it will be like this, this portion which you choose.

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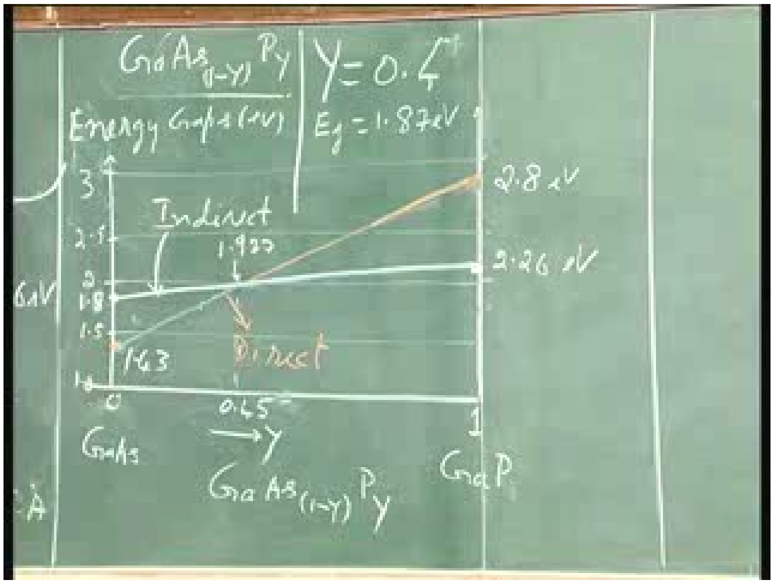

So, what people have done is they have made use of y equal to 0.4 somewhere here. Y equal to 0.4 gallium arsenic phosphide, if you would take that gives you E_g equal to 1.87 electron volts here somewhere here 0.4 and that is 1.87 direct band gap. You make a diode with that pn junction with that it can be used when you forward bias, it can be used as light emitting diode. What is the wavelength corresponding to that? 1.24 divided by 1.87 so many microns. So lambda optical emission for this case actually turns out to be 0.66 microns. What is that?

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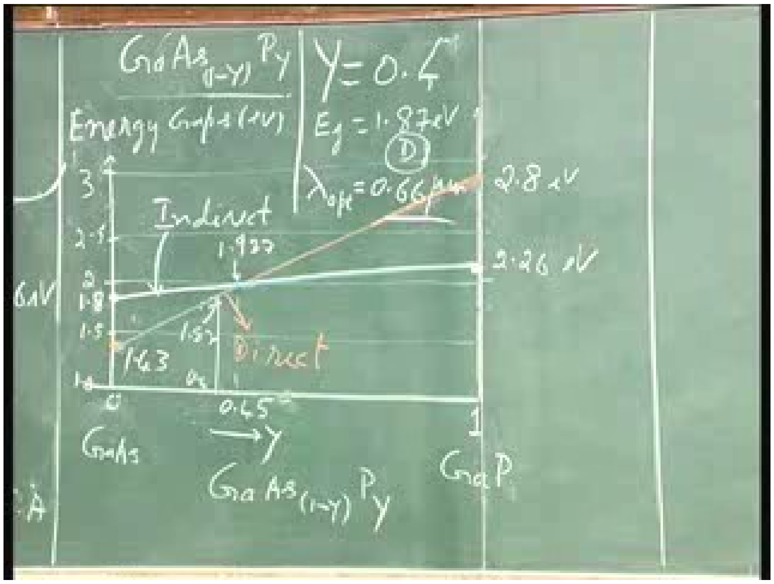

That is red light. I am overwriting here, but you have got red light. We can make red LEDs that is light emitting diode LED in case you know the abbreviation. So you can make light emitting diodes LEDs with red emission by gallium arsenic phosphide with phosphorus mole fraction equal to 0.4, because that is very popular in the desk calculators. Some of the calculators which we were using that is what the one very popular. Now, next thing that I would like to highlight here is the aspect of… can we make use of this portion or making light emitting diodes? After all for emitting light what should be the wavelength? Visible light anywhere from 0.4 to 0.7, which would actually mean you need something like 0.31 or so. You need a wave length which is corresponding to… actually you can work out for visible light, lambda should be 0.4 to 0.7 roughly microns ________ energy corresponding to that 1.24 divided by 0.4 that is about 3.1 electron volts and 0.7 of course, you will have 1.24 divided by 0.7 so that you must have energies which are more one electron volts. So you can just work out and find out those things. What we are trying to point out is if you go to this region we have band gap which are actually more than1.9277, more than 1.977 band gap you have got that means, you will get if I reduce that transition region.

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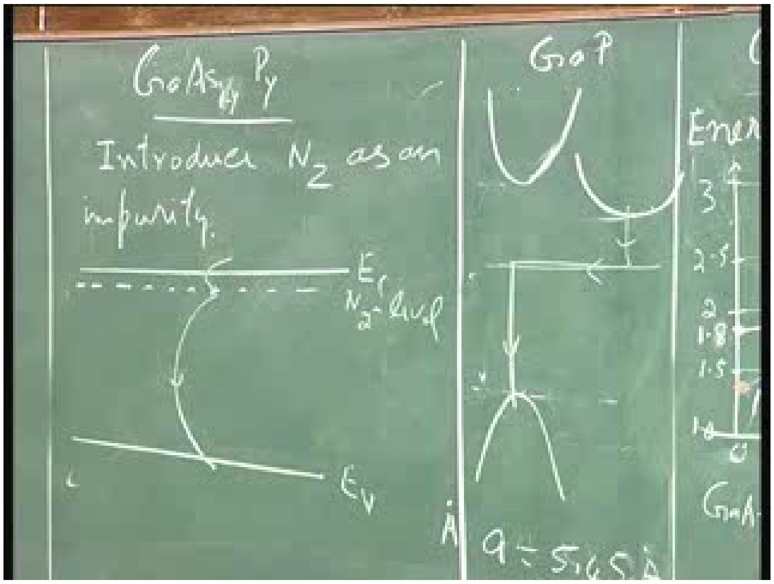

Suppose I introduce into gallium arsenic phosphide 1 minus y, for that introduce nitrogen as impurity then what happens is E_c and E_v. If I vary y, I can vary this here. If I vary y in this portion is indirect band gap, I am varying that band gap. Now I introduce nitrogen as an impurity which introduces the level which is very close to here, nitrogen level, level corresponding to the nitrogen impurity. Now what will you do? If it is indirect band gap semiconductor, you know that the direct transition you cannot have light emission of the band gap. But if I introduce a level here, then what I am doing is, let me remove this thing. What we are doing is, we are introducing a level here which has a diffused momentum in the sense you capture the electrons, destroy their momentum then make a transition like this. So, it will capture here and then a transition. If I introduce an impurity like nitrogen, the momentum difference will be destroyed by that impurity level. So, once momentum level is destroyed; if this energy gap is sufficiently large, I can get light in the visible region. With that thing what I am trying to point out now is, we can make use of this region, vary the band gap from 1.977 to 2.26 by varying y. In each of those compounds, if you introduce nitrogen that nitrogen introduces the level very close to the conduction band with some gap that means you get a transition which will emit light of energy which is close to this band gap. We have to repeat if I move from here to here, I am varying the band gap, but in each one of those materials if I introduce nitrogen, I will have an effective transition gap which is very close to that but slightly smaller than that.

If that is the thing I can get a light out of it, in this transition I can get light I can make LED which will give the wavelength corresponding to close to this. So that is how they are able to make use of even gallium phosphide which is 2.26 and add nitrogen impurity to that and then you get a wavelength corresponding to…

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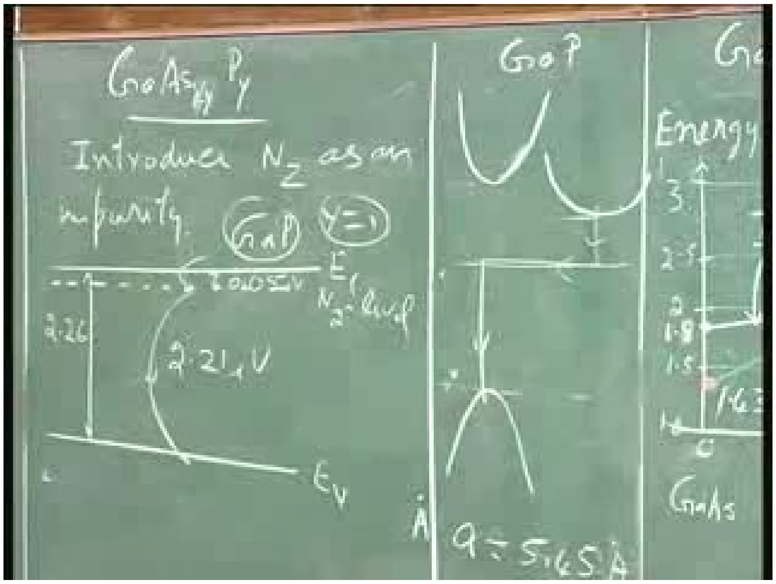

See for example, if I take this as gallium phosphide y equal to 1 and if I take extreme example this is actually 2.26 and this is actually 0.05 electron volt, so what you get there is actually how much 2.21. What I am trying to point out is gallium phosphide is indirect band gap. It will not emit light of the wavelength that you will require, because it is not able to make the transition, but if you introduce a level like this, it will make a transition from in a two-step process where momentum is conserved in the first step, in the second step, the energy is conserved by emitting light and that wavelength corresponds to 2.21 electron volts and this will give you lambda equal to 1.24 divided by 2.21 microns and that turns out to be actually 0.56 microns. What is that? Anybody guess who is expert in ________. So, you can make use of gallium phosphide which is indirect band gap semiconductor. Add impurity like nitrogen which introduces level at 0.05 below the conduction band, 0.05 electron volts. Force a transition through that and force the emission of light that very high quantum efficiency can be obtained. That is for each photon making transition, one each electron making transition you can get light emitting.

So, you can get wavelength corresponding to that which is green. So, if I use the materials which are of different band gap here, what I get is 2.26 minus 0.05, I get here, somewhere here 2 minus 0.5. So, we can get light of varying length. This is a very powerful material where you can get light from green, yellow, orange, and red, entire wave length you can get, so red, orange, yellow, and green. The whole idea is actually through the question is what are the criteria for collecting the impurity? To introduce the impurity, you should know where it will introduce the level. For example, in this case, the nitrogen is known to introduce impurities, which is about 0.05 E_v below the conduction band, for all those materials. So, it is fortunate that you are able to force that light wavelength corresponding to this level and this. Now let us just put that diagram.

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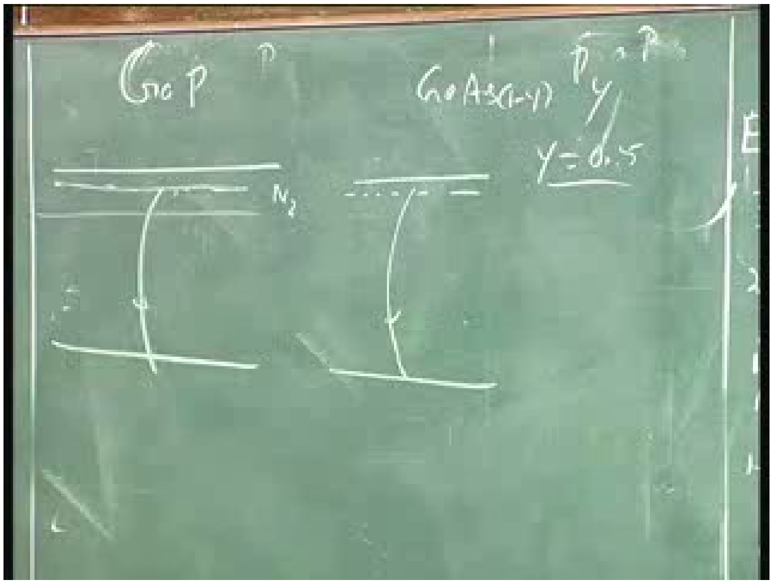

In fact I will just put a series of diagrams now. Gallium phosphide there if I introduce a level like this here, nitrogen the transition is corresponding to this. That is 2.21. If I choose somewhere here that is 2.0 that is gallium arsenic y and y is equal to something like 0.5 or so, some number m storing and passing out some number then what happens to the band gap? Compared to…here, band gap is reduced so that is somewhere here. This does not change practically. The difference between the two. So, if that band gap reduces, nitrogen actually enjoys the same position practically 0.05. So the transition now is from here to here which are that much now has reduced. Energy is reduced which means the wavelength has gone up. If you go down here, you go from green to red that is the idea. You can actually use some other impurities. For example, there is a very famous impurity which is used for making red light, red LED that is zinc oxide. It is introduced into gallium phosphide which introduces at the trap level at the bottom at 0.3 E_c minus 0.3. If I take this, if I introduce some other impurity that will introduce an impurity there, zinc oxide that wave length will be reduced. The energy will be reduced. The wavelength will go up. We can force it to the red light 2.26 minus 0.3 that is the band gap transition, so that is the thing. But now, how good is the light emitted light? How much light is emitted for that particular wavelength depends upon how many impurities are present there. There may be unwanted impurities. If unwanted impurities I have put two levels here. When you put this level, you want to ensure if you want green light you must have only the nitrogen impurity because that wave length. If I have one more impurity what will happen? Then some transition will be taking from through this. So, you will have unwanted emission. So that is why when you make light emitting diodes, it is important that you have a pure material. Growth must be really pure and you must be able to introduce the impurity which you want to introduce that is the thing. Now, this is about the gallium arsenic phosphide. If I had nitrogen actually gives you a quantum efficiency which is much higher, when you introduce nitrogen here and the indirect band gap.

In the sense, quantum efficiency means photons which are generated for one, for the photons generated divided by whole electron pairs for one whole electron pair which is recombining how many photons are generated on an average that is the thing that is the quantum efficiency, for the light emitting diode. Now there is one more vey interesting application which actually we have been working out in our laboratory in IIT that is detector. I am just citing out some of the applications when we are discussing this.

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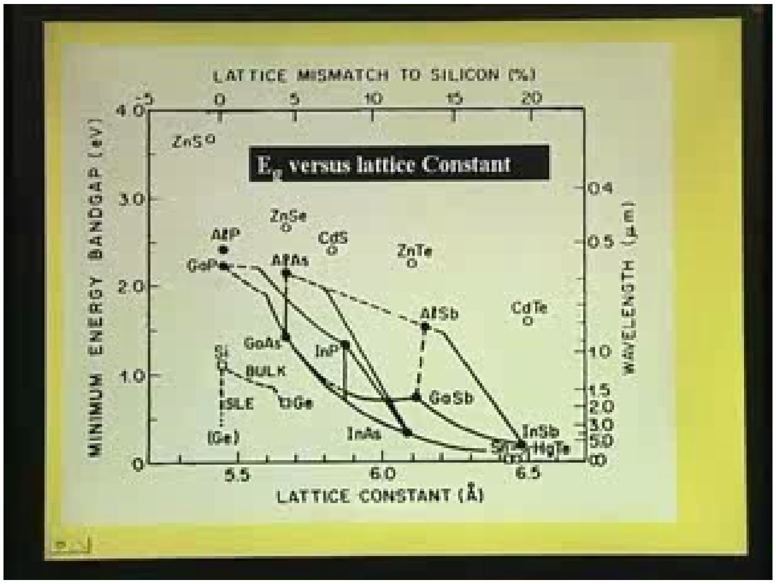

We can use a material like gallium indium arsenide, if you go down here and make a detector which is suitable for optoelectronic applications. When I use a fiber optic communication, what you do? You have the entire information transmitted through light. Now ultimately at the receiving end you must convert the light signal into electrical signal. There must be detector. At the transmitting part, you must have the laser. At the receiving part, you must have a detector and that detector should detect best at the wavelength that it comes out. So, for fiber optic it is about 1.3 electron volts in that range that is the best wavelength that people are working 1.3 to 1.5.

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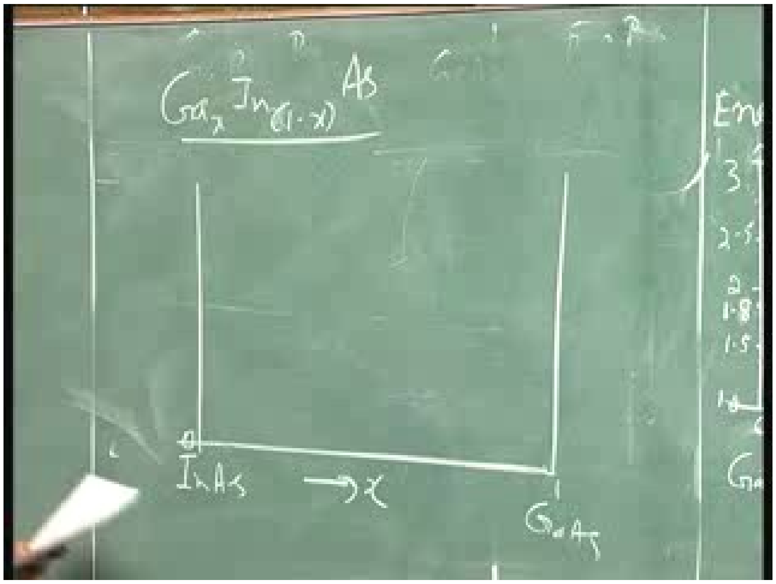

Now, if you take gallium indium arsenide, there what is happening is you have got… I will draw it a bit faster now because you know this x is mole fraction of gallium and here you have got indium arsenide, x equal to 0 gives indium arsenide, x equal to 1 gives you gallium arsenide.

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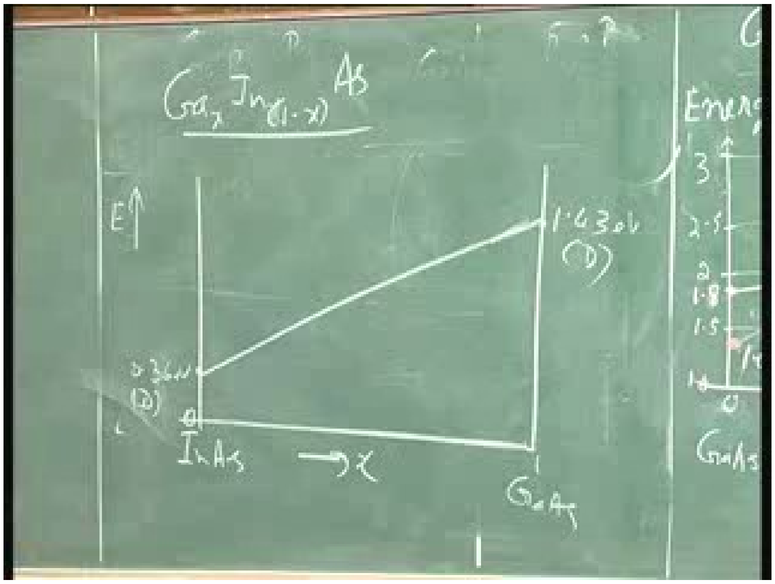

Now here you have got 0.36 direct band gap and gallium arsenide has got 1.43. Both are direct, you have got this is indirect, that is also direct band gap. You mix them together and that is it. Choose the composition you get the band gap, all direct.

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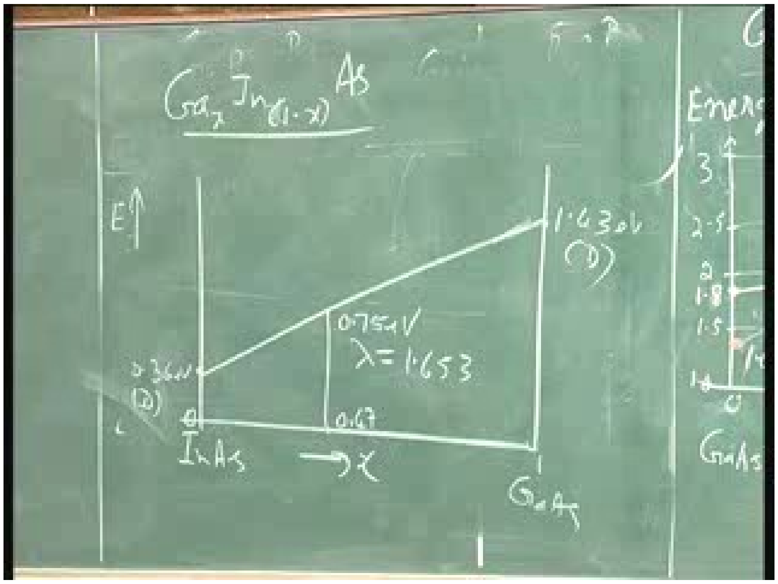

See for example, if you use this as 0.47, use that as 0.47 then you will get around 0.75. The wavelength corresponding to that is actually equal to 1.653. Now my question is, what we want to point out here is, this diagram is straight forward no indirect.

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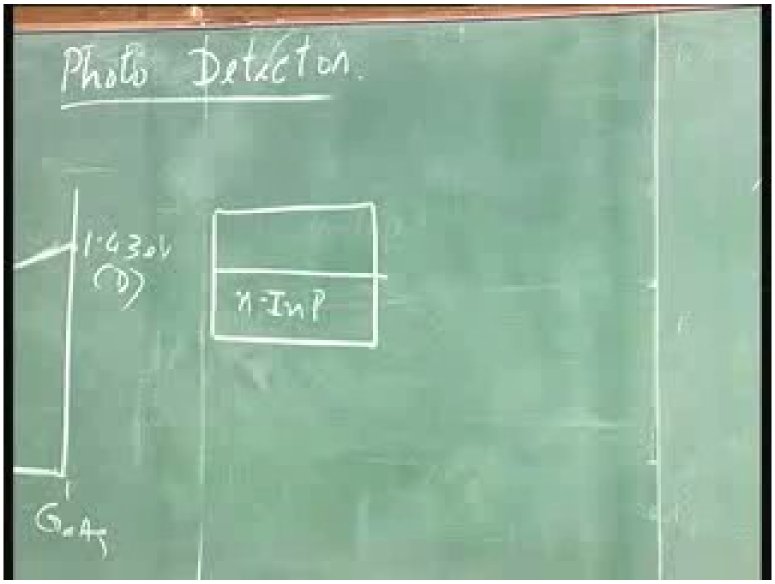

So, you make a diode like this. This is called detector or a photo diode if you make what you do is take indium phosphide n type. This is reverse of the LED. In a LED what you do? You forward bias it. Force recombination light emission. In the detector, light is falling, it is absorbed and you get the current. Electron holes are generated, you reverse bias, you will get the current, draw the current out not forward bias. Here what you do is a new p type or I type intrinsic or closed intrinsic, indium gallium, indium arsenide of this composition where x is 0.47. If you choose that you will get a band gap of 0.73 electron volts, 0.75 electron volts, and this will be p plus p plus gallium indium arsenide.

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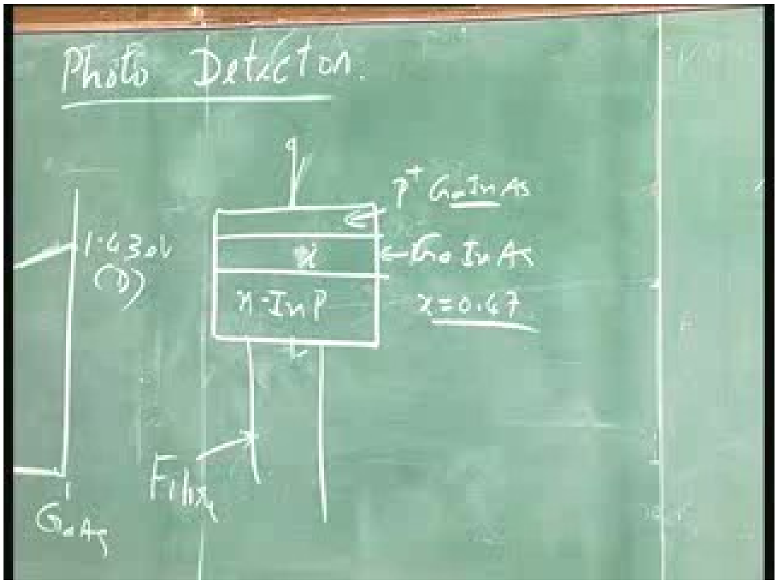

Connected it to… of course, you can bias it. This is the fiber. A fiber connected from this piece indium phosphide side. Light is falling on this. A fiber is coupled to that; you must make arrangement to couple it together. The light is falling on that. Now the idea is, if light is falling on that, what will happen when it falls on to the indium phosphide? If, I plot the photon current, can I take this of now? If I will take this of know, put the other diagram.

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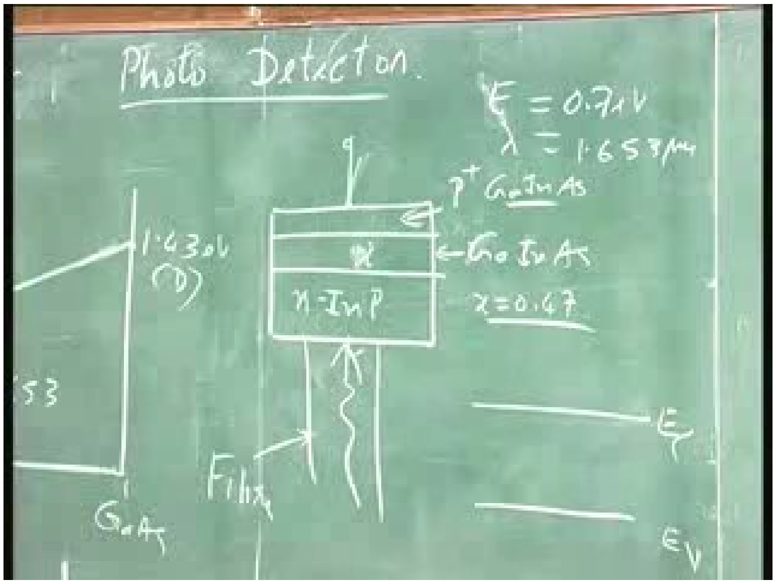

Remember this 0.75 E is equal to 0.75 electron volts, lambda corresponding those 1.6 by 3 microns. What does it mean? What does it mean, when I say for a detector the wavelength is 1.653 microns? Which means actually like this; which means, if I have the band gap like this, if the light is falling it should knock out electrons from here to here. It must create whole electron pairs when the light is falling on that. Now, whether it can knock out electrons or not depends upon the energy. If the energy is less than 1.653 electron volts, it will not knock out electrons. What will happen? It will be just be transmitted. If you take indium phosphide, indium phosphide has got a cutoff wavelength which is actually a 0.92. Indium phosphide, this one that is E_g is actually equal to 1.35 electron volts which correspond to lambda equals to 0.92 microns. Now when the light is falling here from the back side, it sees the indium phosphide first. So, if the energy of the light that is coming is greater than 1.35 electron volts, if the energy of the light that is coming is greater than 1.35 electron volts, which means if the wavelength is smaller than 0.93 electron volts, it will be absorbed by that and this is a thick layer. This is very thin 0.2 microns or 1 micron. So, if this is 100 micron or 200 micron whatever light is falling here is absorbed here. It is just absorbing in the bulk, whole electron pairs are there in the bulk, what happens? If you generate whole electron pairs, they just recombine and fallback, no effect. That is all. It is converted into heat, in fact heat there when it recombines. So that is nothing happening here. But, if the energy is more than that or if the energy is less than that; if the energy is more than that, it will be absorbed. What we are telling is? We quickly put that diagram.

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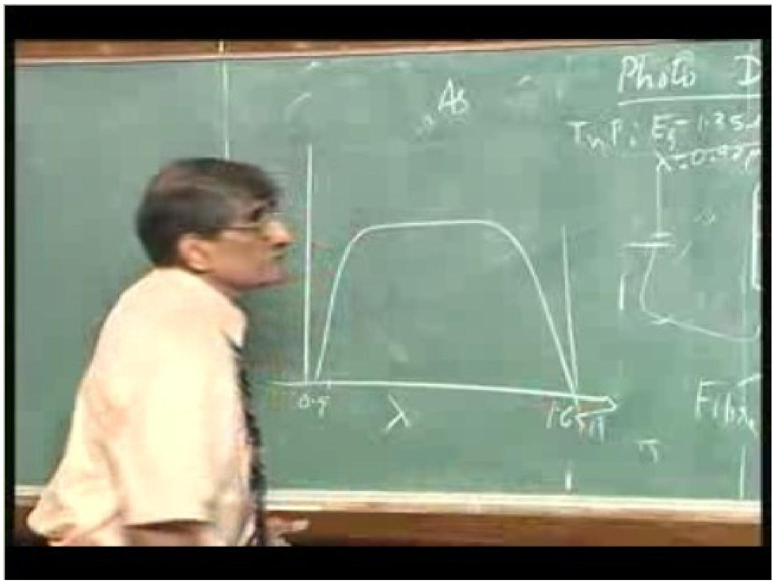

If I see lambda versus current I connect it like this, reverse bias like this. There will be current versus lambda if you say when the wavelength is 0.9, up to that point, nothing will be absorbed. When the wavelength becomes more than that, this will not absorb. This will act as a window. It will fall on this. This will absorb whenever the energy is right up to 0.7, so up from 0.9 to up to 1.6 microns this layer will appear. In fact I think I should continue on this in my next discussion. In more detailed, it will come like this. This is 1.65 Angstroms. So, what I am trying to point out is if the wavelength is small, this absorbs it and no effect. If the wavelength is more than that, this absorbs it and that gives rise to current. If the wavelength is more than that, energy is less than that, no current. So it acts as a very good window. We will continue on this particular discussion few more aspects of this ________ next lecture.