Processing of Semiconducting Materials
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Lecture - 11
Compound Semiconductors

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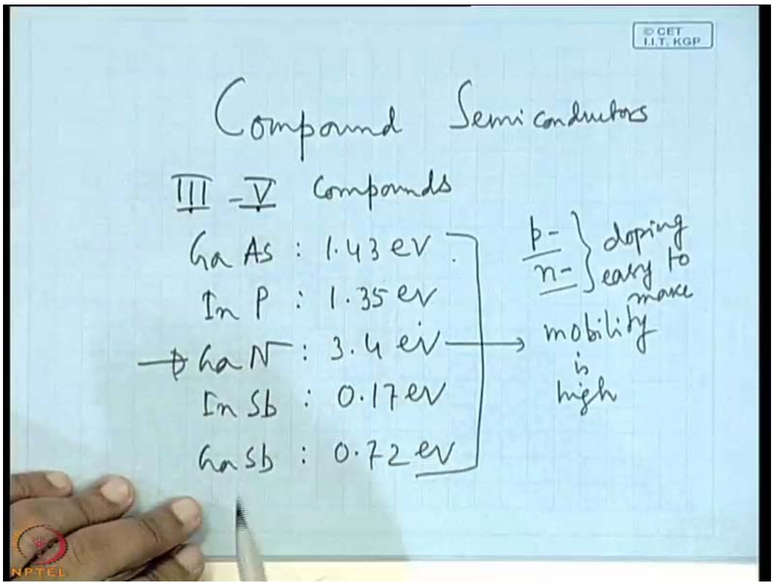

Compound semiconductors; as the name implies these differ from the elemental semiconductor. Elemental semiconductor silicon, charmonium, diamond etcetera. In compound semiconductors they can be formed by using two or more elements from the periodic table, two or more elements from the periodic table. Say, if I talk about 3 5 compounds, if I talk about 3 5 compounds; that means, group 3 of the periodic table warn element from group 3 of the periodic table and other element from group 5 of the periodic table that can be used for the formation of 3 5 compound.

Say gallium arsenide, indium phosphide, gallium nitride, indium antimonide, gallium antimodite and so on and so forth. All those materials are useful in particular applications, In various applications gallium arsenide is band gap is 1.43electron volt, indium phosphide is band gap is 1.35electron volt, What is the band gap of gallium nitride? What is the band gap of gallium nitride? 3.4electron volt. I think. Yes 3.4electron volt, then indium antimonide, what is the band gap of indium antimonide? 0.17electron volt and what is the band gap of gallium antimonide it is 0.72electro volt.

So what you find from these values, what you find? You find that there is a material, say Indium antimonide is whose banding gap is very very less 0.17electron volt. So, that material can be used for application in which region? Infrared region; obviously, if the band gap less, the region where application will be in the infrared region. Similarly say gallium nitride, it is 3.4electron volt. Which region it can 3.4 is basically U V or in blue. In blue also, that means in visible region. Similarly gallium arsenide 1.43 it is in which region? I R, it is also I R. 0.17 is for infrared 0.17 is for infrared and 1.43 and 1.43 is infrared.

So that means a large number of compounds or semiconductor materials are there in compound form in 3 5 groups, which can give you emission in the region from far infrared to ultraviolet say gallium nitride. The advantage of this compound is that they can be made p type as well as n type, unlike wide band gap materials where this doping is very difficult to make or obviously for gallium nitride doping difficult to make because gallium nitride is though it belongs to 3 5 group it is wide band gap.

Why the doping is difficult to make for wide band gap I shall discuss. So, the advantage is that p and n doping can be done and at the same time mobility is high, p and n doping easy to make p and n doping easy to make and mobility is high. So, those can be used for various kinds of application starting from the optical sources to high mobility devices. High mobility, because you I have shown you that the for indium antimonide what is the mobility? The mobility was indium arsenide say 40,000, indium antimonide is 77,000. So, basically high mobility device can be made unlike in elemental semiconductor. In elemental semiconductor the mobility was not very high. Another important aspect of this material is that their direct band of semiconductor.

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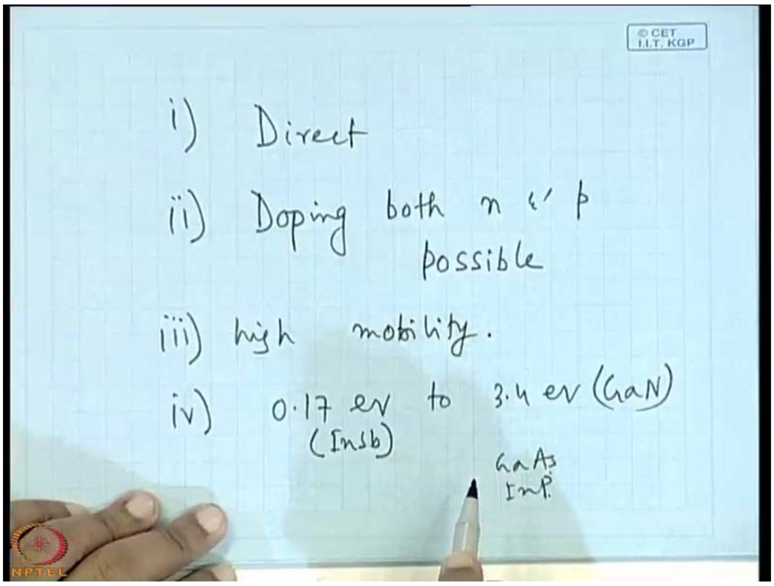

So, 1 is direct, number 2 is doping possible, number 3 is high mobility and number 4 is say 0.17electron volt to 3.04electron volt for say gallium nitride. 1.7 is indium antimonide, long range it can cover right. So, these are the advantages of 3 5 compound semiconductor and the some of the names are gallium arsenide, indium phosphide, gallium nitride, indium antimonide, gallium antimonide, indium arsenide etcetera indium arsenide etcetera. What is the band gap of indium arsenide? It is 0.36electron volt. So you can get narrow band gap, you can made medium band gap, you can made wide band gap materials in 3 5 semiconductors which is not possible for elemental semiconductors, and another application of this compound semiconductor is that particularly this gallium arsenide, indium phosphide et cetera those are available for epitaxial growth substrate. For epitaxial growth you you know that is substrate is required on which the growth takes place.

Just now we have we have discussed about the substrate and the layer. So, layer means specifically the epitaxial layer, the very thin layer of single crystal. In bulk you cannot go beyond say 300 micron 400 micron, but in epitaxial you can grow as more as say 1 nanometer, 2 nanometer thickness, 4 nanometer, 10 nanometer thickness that is not possible using bulk. So, if you want grow very thin layer of single crystal, very thin layer of single crystal. So, these are done by epitaxial growth technique epitaxial growth technique. And for all epitaxial growth you need a substrate, and this gallium arsenide , indium phosphide are the most important to materials which are used as substrate in epitaxial growth of 3 5 compound semiconductors, these are the 3 5 semiconductors.

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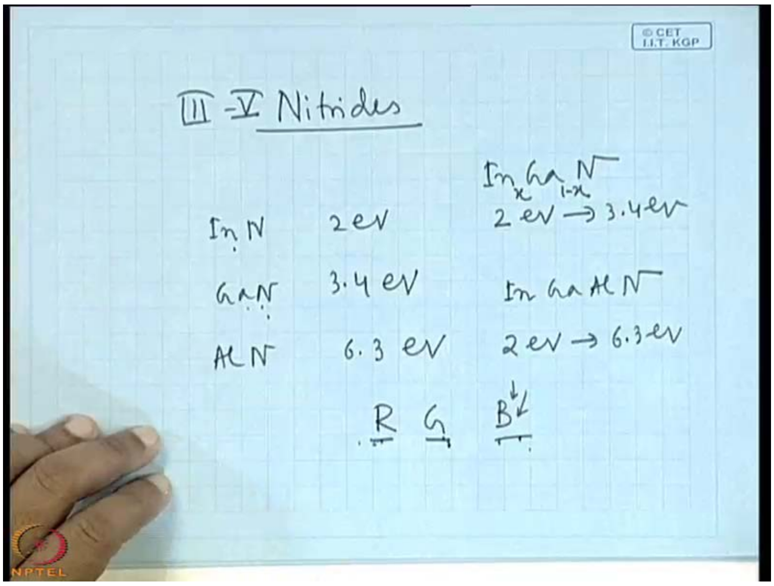

Now, if I talk about say nitrides, 3 5 nitrides; you see that indium nitride it is 2electron volt, aluminum nitride it is 6.3electron volts and gallium nitride it is 3.4electron volt. What you find from this data? This indium nitride is 2electron volt, gallium nitride is 3.4electron volt and aluminum nitride is 6.3electron volt. What to find, that if you grow indium gallium nitride if you grow indium gallium nitride.

Indium gallium nitride, you can tune the band gap from 2electron volt to 3.4electron volt, just by changing say it is x, it is 1 minus x it is 1 minus x you can tune the band gap from 2electron volt to 3.4electron volt or if you change that indium gallium aluminum nitride what you find? You can tune the band gap from 2electron volt to 6.3electron volt. Very large band gap which covers particularly the visible region, because there are many applications particularly the light-emitting diode application or the light in if you if you Japan you will find that they have been using light-emitting diode for their street light, packed panel display for their street light and now you know that the bulb has changed to unconditional lamp now it is being changed to LED lamp.

In the market you will find within next 2 3 months LED lamp will come, why? The advantage is that it consumes less power. Now the people have been tried to save energy, so in that direction you need to make very good light-emitting diode and a panel of light-emitting diode. 10, 20, 100 light-emitting diode, because the intensity of 1 light-emitting diode is not very high. So, if you want to glow this whole room if you want to light this room then say 100 LED's are required, good LED's and different colors particularly the white color and you know that the white color is very difficult to make because the 3 components of white is that the R G B Red Green and Blue.

We have discussed that the red and green, which are the materials using which red and green is used is is fabricated gallium phosphide gallium phosphide, but at that time you have seen that I have not talked about any blue LED because gallium phosphide is not used making blue LED. Blue LED is used is used, gallium nitride, silicon carbide ,aluminum gallium nitride, indium gallium nitride, these are nitride semiconductors are used and using nitride semiconductors if you can zeroing on blue and you have red and green already for; that means, you can make white light; that means, you can make white light.

In that sense this 3 5 nitrides are very important material, only blue can be made using them. Very difficult the very costly also, because the processing technology and doping p n junction is very difficult to make. So, white light can be made out of red green and blue, red and green is available in the market, blue is from 3 5 nitrides. So, now you can make white light out of those 3 LED' s that is mostly used for street lighting and other room lighting et cetera, apart from the flat panel display and apart from these 3 5 nitrides.

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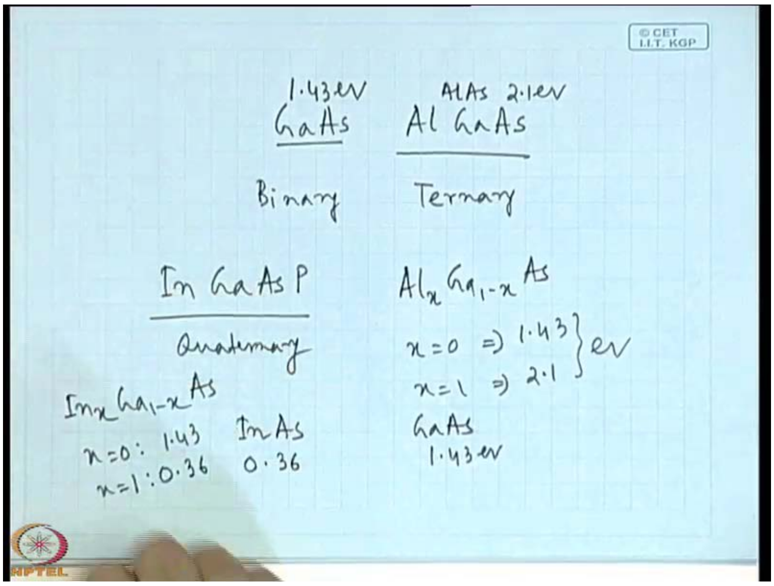

There are other materials, say gallium arsenide, aluminum gallium arsenide. Gallium arsenide, aluminum gallium arsenide; gallium arsenide is 3 5, aluminum gallium arsenide is also 3 5, but that is known as ternary. Gallium arsenide is binary, this is ternary; that means 3 elements are involved, and say indium gallium arsenide phosphide it is known as quaternary; so that means, 3 5 compound semiconductors can be grown as binary, ternary or quaternary.

So, when you go for ternary or quaternary; that means, some band gap engineering is made; that means, you are changing the band gap of the material. What is the band gap of gallium arsenide? It is 1.43electron volt. What is the band gap of aluminum arsenide aluminum arsenide aluminum arsenide 2.1electron volt aluminum arsenide 2.1electron volt; so that means, if you make Aluminum gallium arsenide you can tune the band gap from, you can tune the band gap from 1.43 when x equals to 0 it is and when x equals to 1 it is 2.1 electron volts; that means, you can tune the band gap from 1.43 to 2.1. Similarly, if you have say Indium gallium arsenide, Indium arsenide and Gallium arsenide; Indium arsenide band gap is how much 0.36 and gallium arsenide 1.43.

So, if you make 1 indium gallium arsenide for x equals to 0 it is 1.43, for x equals to 1 it is 0.46 0.36; so that means, you can tune the band gap from wide range 0.36 to 1.43 electron volt. So that is also possible using the compound semiconductor, you can tune the band gap that is not possible using elemental semiconductor. So you can play around, the area is large compare to elemental semiconductor. Apart from that they are direct band gap, there mobility is high and you can tune the mobility, they can be doped both p and n type that is advantage. But there are disadvantages also; the disadvantages are one of the main disadvantages are that like silicon it cannot oxidize. SiO_2 is very easy to make and SiO_2 is also insulating in nature and it is widely used for processing for gallium arsenide or aluminum gallium arsenide or indium phosphide et cetera you cannot make this oxidation, because you see that in this view graph.

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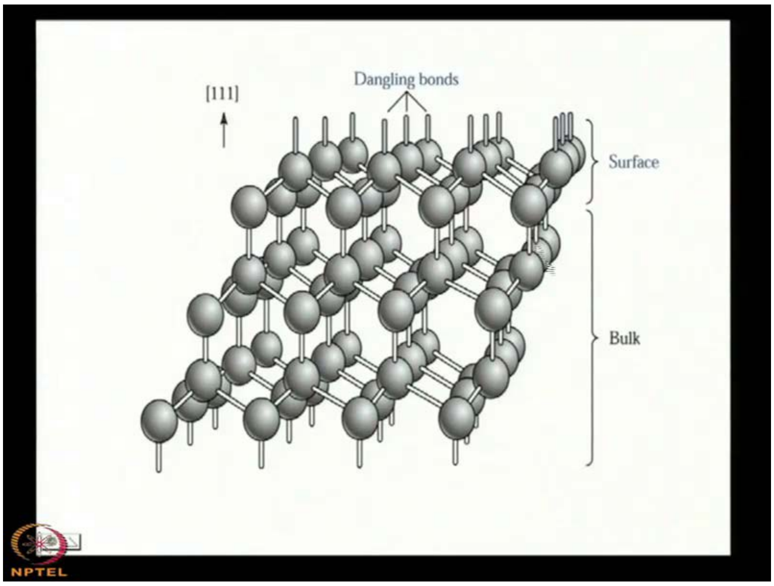

You see that the dangling bonds I have shown you these are the surface this is the bulk. So, in bulk you see that all the bonds are saturated, but at the surface these bonds are unsaturated; that means, they are open. So, they can take off any material particularly the Ariel oxygen. So, gallium arsenide if this material is gallium arsenide this gallium oxide will not be form very easily, there will be some oxide layer obviously, but not exclusively gallium oxide like silicon SiO2 SiO2.

So that is disadvantage for this gallium arsenide or compound semiconductors one part is oxidation. Another important disadvantage is that processing technology; silicon you can dope very easily, you can defuse, you can ion implantation is done, photolithography, all processing technology is very mature. You can handle large wafers in gallium arsenide or indium phosphide you cannot make large wafers are very difficult to handle because they are brittle in nature, they are very soft.

So those are the disadvantages, though it has many advantages it has disadvantages as well. Another disadvantage is the cost; the cost is very high almost 5 to 6 times higher than silicon. If you purchase 1 silicon wafer say it cost is say 12,000, if you cost gallium arsenide wafers its cost will be 50,000, 3 inch it is almost 50,000. In some cases it is higher than that. 3 inch wafer just compared to gallium, silicon is very cheap in that sense and…

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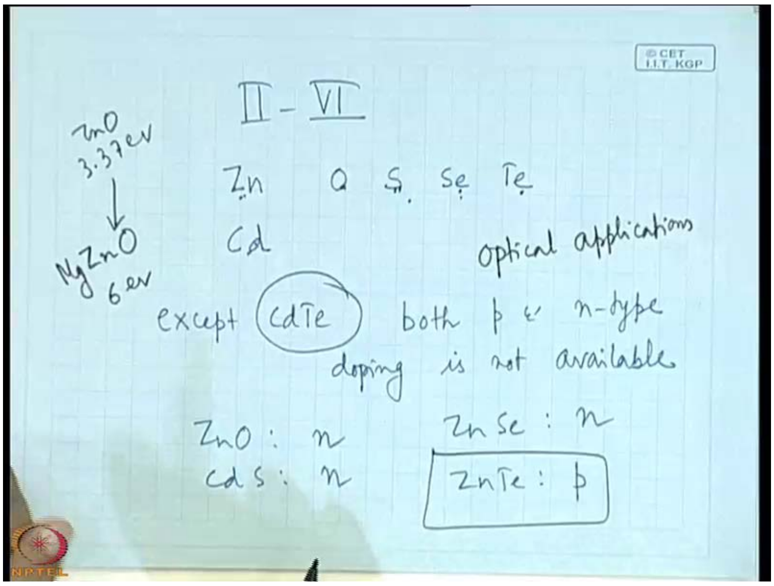

Another thing is that apart from this 3 5 compound you have say 2 6 compound. 2 6 that means,1 element from periodic table 2, 1 element from periodic table 6, say zinc and cadmium and in 6 you have oxygen, sulfur, selenium and tellurium. Group 6 oxygen, sulphur, selenium and tellurium; that means zinc oxide, zinc sulfide, zinc selenide, cadmium oxide, cadmium sulfide, cadmium telluride et cetera.

So those are the 2 6 compounds, here you see that problems, major problems with these materials are; except cadmium telluride, except CdTe both p and n type doping is not available. Both p and n type doping is not available, mostly those are p type in nature n type in nature say zinc oxide it is n type, cadmium sulfide it is n type, zinc sulfide selenide it is n type, almost all of them are n type except zinc telluride which is p type, zinc telluride is p type. All other 2 6 compounds are n type in nature except cadmium telluride which is available as both n type and p type. So, this is the limitation of 2 6 compound.

This is a limitation 2 6 compound in the sense that both type of doping is not obtained. So, unless doping is not obtained then what is the difficulty is that you cannot make a device, the primary requirement for fabrication of a device is a p n junction. There are other revenues, not that this 2 6 compounds are not used they are used, but not very easily. Silicon p n junction is very readily made, gallium arsenide p n junction is very readily made, but this 2 6 compounds zinc oxide or cadmium sulfide or zinc selenide or zinc telluride they are not readily made p n junction. That is disadvantage, why such thing happens? Why there is a problem of doping? What is the difficulty? Difficulty is that.

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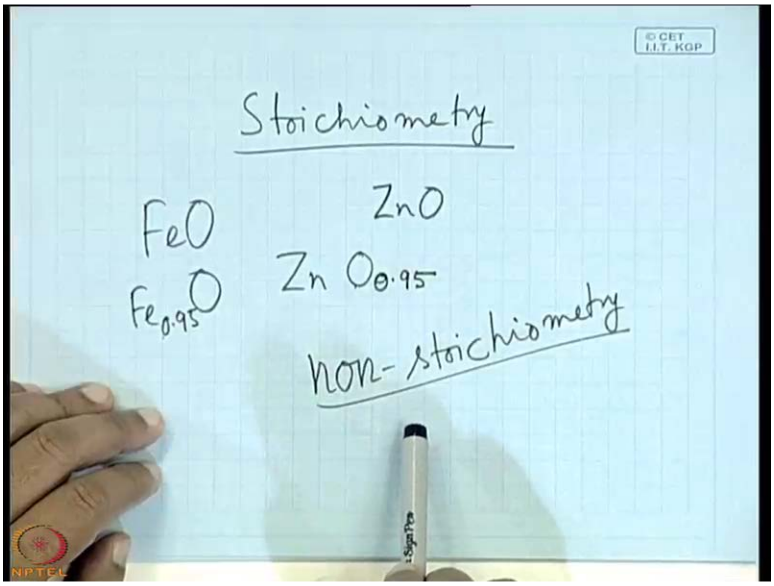

You heard the term stoichiometry, you heard particularly the chemistry student you know that what is this, what is this stoichiometry? Yes chemical balance. So, when you make a material definite proportions of materials are there and if you take the ratio, it gives you a law of definite proportions; that means, say zinc oxide, zinc to oxygen ratio is 1:1, but actually it is not there, here in zinc oxide the oxygen becomes 0.95; that means, there is some deficiency of oxygen in zinc oxide.

Say FeO ferrous oxide, the exact formula is not FeO it is Fe 0.95 at O so; that means, if you take the ratio it is not a natural number, 1 by 0.95, here you see that it 0.95 by 1. Ideally it should be 1 by 1, but there is a deficiency of oxygen here, there is deficiency of iron here. Some materials are their when you grow, because of thermodynamic consideration there will be deficiency of 1 particular element in it and that is the reason that it is known as non- stoichiometry.

So, what is fine in case of zinc oxide, you see that in case of zinc oxide that is a vacancy of oxygen and because of this oxygen vacancy it acts as n type. So, if you try to dope it, say p type what will happen? That dope end will be compensated because already there is vacancy. So, the dope ends will be compensated by the vacancies. So, fast as you go on increasing the doping concentrations there will be compensation, this is known as a self compensation.

Because there is enough vacancy their inside the material and finally what will happen? Finally, when all the vacancies will be full there will be no place for it. So, there will be solid solution, there will be no doping because we have discussed during our doping and diffusion that either it must occupy the interstitial position or it must occupy the vacancy position, defect positions. If there are no positions it will yes where it will be accommodated.

So, then that will be a solid solution, that is not doping. So, that is the reason because of this non- stoichiometry in natural production it is non-stoichiometry in nature, there are oxygen vacancy in there are different types of materials say zinc telluride that may be there is zinc vacancy or tellurium vacancy. So, as you go on increasing the doping concentration in it will first compensated, because of self-compensation the effect of doping will not be observed, will not be visible. Such kind of thing is not there in case of silicon or gallium arsenide or indium phosphide.

So, that is the reason that these materials cannot be dope very easily. There are techniques people have been trying, I have also tried to dope zinc oxide p type we have done, but the problem is stability. After 2 hours, 4 hours, after 2 days, it will come to back to it will back to square one. So, there are several problems, people have been trying. So, these are the major problems associated with the 2 6 compounds, but 2 6 compounds are you see that these 2 6 compounds are widely used for particularly some of the applications in optical applications.

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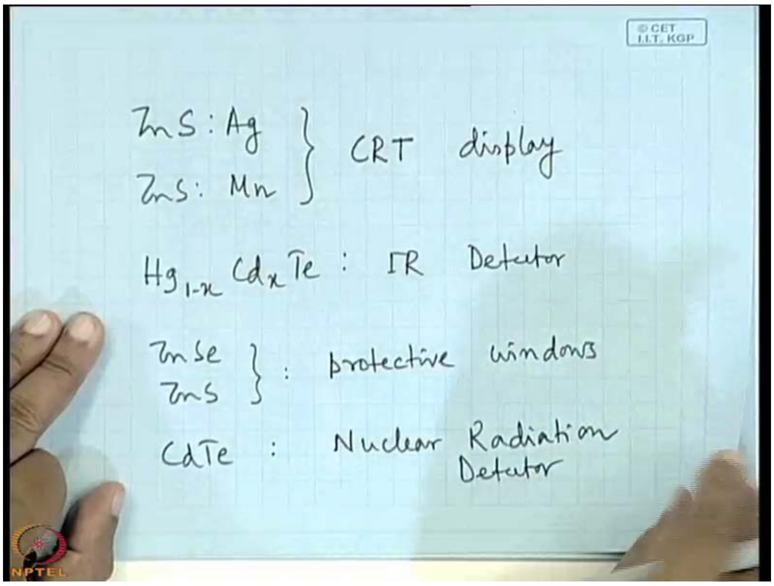

And what are the applications 1 is say zinc sulfide, when you dope with silver or zinc sulfide when you dope with m n, this is CRT Cathode Ray Tube that means display application and mercury cadmium telluride this is IR detector, zinc self and zinc sulfide protective windows, then cadmium telluride nuclear radiation detector, then I have cadmium sulfide and cadmium telluride also, these are used for solar cells.

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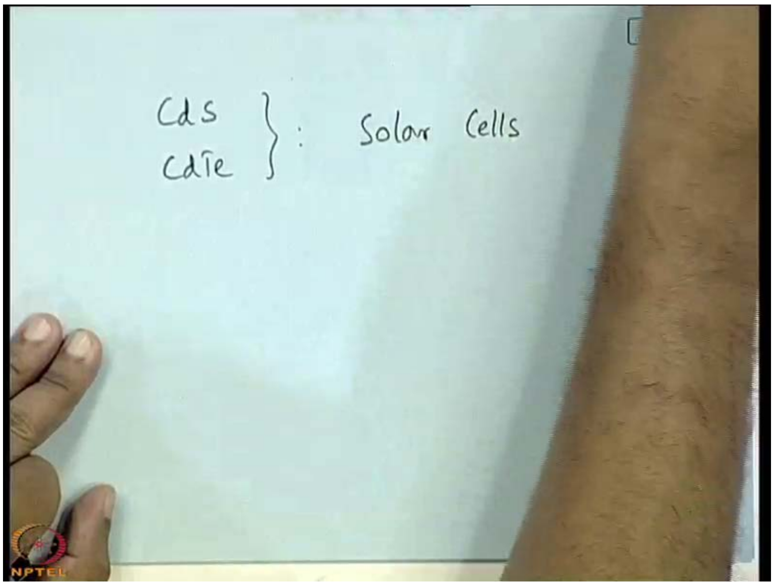

So, these are the various types of applications that can be made out of 2 6 materials. Mostly those are optical in nature, silver and manganese doped zinc sulfide are used at the display devices cathode ray tube and the cathode ray tube there is a thin film coating of zinc sulfide or zinc silver or m n doped, and in cadmium telluride, mercury cadmium telluride; this very important application for IR detector infrared detector, infrared imaging; that means, this is a very ambitious project of DRDO that is handle by SSPL Delhi, Solid State Physics Laboratory and they have been trying to make HgCdTe detector, some success they have got.

So, this is basically to map the battlefield at night, when there will be no light. So, there will be object of metallic object will be there say tank or that type of things. So infrared will some source will be there infrared source, those infrared lights will be reflected back from the surface of the tank or metallic objects and there will be a camera or detector which will detect the positions or the locations of the tanks et cetera.

So that is very ambitious project of our Indian military and they have been trying in SSPL, its very important material cadmium HgCdTe mercury cadmium telluride and this zinc selenide and zinc sulfide it is the protective windows or the optical elements, this cadmium telluride it is nuclear radiation detector say gamma detector et cetera or in case of say CdTe it is used for solar cells also and cadmium sulfide is also for solar cells.

So, these are very important material 2 6 though they has some inherent limitations of doping et cetera, because of it is band gap, nature of the band gap and another important material which we should discuss is the zinc oxide. Zinc oxide is 1 very important material it is excite on binding energy 60 milli-electron volt excite on bending energy. What is the room temperature bending energy generally? 26 milli-electron volt, 26 milli electron volt thermal energy basically. So, 60 means 2.5 times almost 2.2 to 2.3 times.

So that means, even at room temperature the value is higher than room temperature. So, even at high temperature or even at room temperature zinc oxide can be used for fabrication of light emitting diode or laser sources. It is very important material zinc oxide, but problem is that it is not stable and doping is not very easily be made. So, that is the reason that zinc oxide has no commercial applications right now, but the people have been trying. Another thing is that with if you add some magnesium; that means ZnO you add some magnesium, magnesium zinc oxide MgZnO this magnesium zinc oxide it is, if you add some magnesium then you will find that the band gap has increased what is the band gap of zinc oxide is very high zinc oxide is 3.37 electron volt, 3.37 electron volt to if you add magnesium zinc oxide then it will be almost 6 electron; that means, say very large band gap can be tuned from 3.3 to 6 electron volt and what is the main application of this region?

What is the main application of this region of 3.37 to 6 electron volts, it is ultraviolet, it is ultraviolet region and ultraviolet is used for which application? What is the application for ultraviolet? Storage device CD, CD basically storage device because the storage capacity almost inversely proportional to 1 by lambda to the power 4. We have discussed in my first lecture, it is almost varies as 1 by lambda to the power 4. So, if lambda decreases the storage capacity increases. So, present generation storage capacity is red then if you can go to blue or then ultraviolet then many fold it will increase. Then I have introduced your blue ray device, blue ray disc. So, that is very important thing that ultraviolet can be used.

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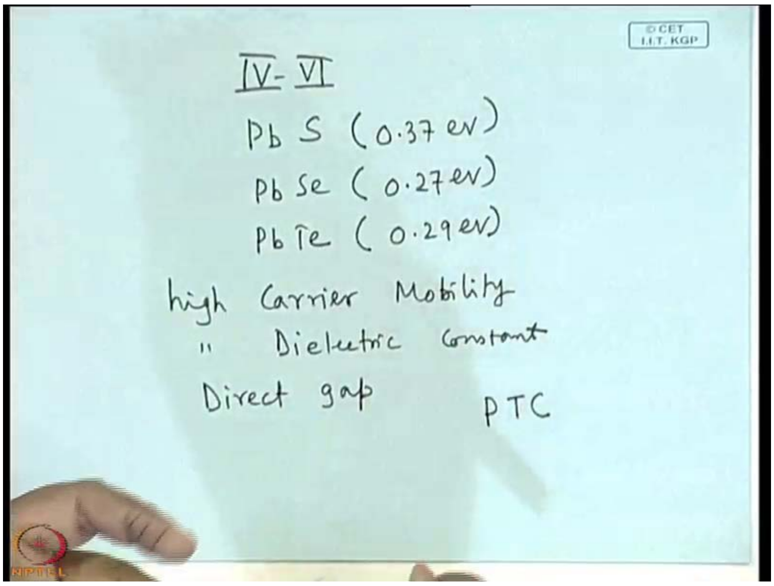

Then there are say 4 6 compound. 4 6 compound is lead sulfide; lead selenide and lead telluride. Lead sulfide is 0.37 electron volt, lead selenide is 0.27electron volt and lead telluride is 0.29electron volt. These are the basically narrow band gap material, band gap you see that the very less it is 0.27, 0.29 and 0.37. It has high carrier mobility, high dielectric constant and direct energy gap; and another important aspect of this lead compounds lead, semiconductor is that it has positive temperature coefficient of band gap. What is positive temperature coefficient of band gap? Generally what happens, generally at room temperature say the band gap value is 1.1 electron volt for silicon if you decrease the temperature the band gap will increase or if you increased the temperature the band gap will decrease; that means, generally negative temperature coefficient is there.

Except these materials, except these lead materials; that means, 4 6 compound, in this 4 6 compounds if you increase the temperature band gap increases. That is the unique feature of this 4 6 compound, in other materials you will not find this thing, exactly the opposite happens. Another advantages are that it has high carrier mobility, its dielectric constant is very high, it has direct band gap.

So, some advantages are there, but positive temperature coefficient is there and its main application is in the detector material; that means, infrared detector because you see that the band gap is very, very low. So, infrared detector and another application is thermoelectric application, because lead telluride or lead sulfide these are used for thermoelectric application. So, many materials are there and these compound semiconductors are used for different kinds of applications.

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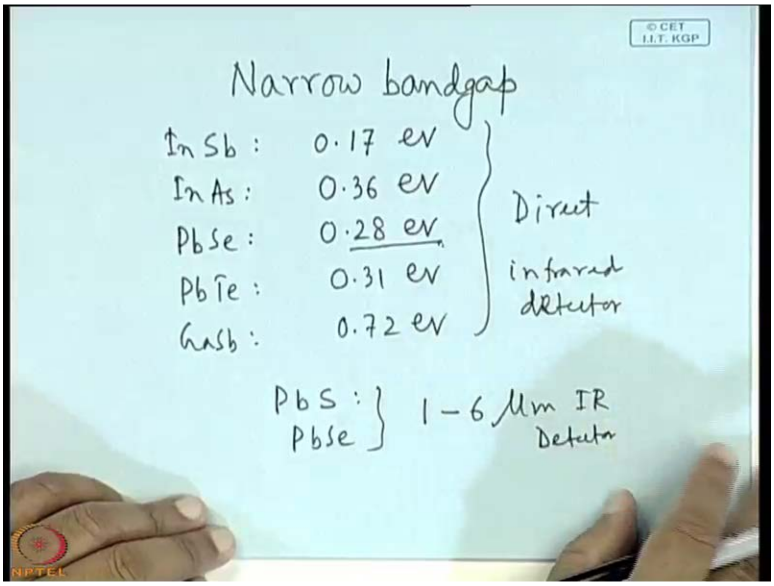

Next we shall concentrate our discussion on say narrow band gap semiconductor. Narrow band gap semiconductor say indium antimonide, it has 0.17electron volt then indium arsenide it has 0.36electron volt, then lead selenide it has 0.28electron volt, lead telluride it has 0.31electron volt and so on and so forth. There are other materials also which can be say gallium antimonide it is 0.72electron volt et cetera.

So, these are all narrow band gap material and these narrow band gap materials are almost all are in direct nature. Remember that if the band gap is direct in nature then it can be used in optoelectronics that is special point it can be used optoelectronics for detector as well as for sources there are other constants like doping et cetera, but first constant is that it must be direct then you can cross the minimum barrier and these are basically materials which are used for infrared detector. And say lead selenide and lead selenide, lead sulfide or lead selenide.

You see that the band gap is. So, less that is 0.28electron volt; you will find that it can be used for 1 to 6 micron infrared detector I R detector. What is 1 to 6 micron? 1 to 6 micron is, it can absorb 1 micron to 6 micron wave length light. 1 micron to 6 micron wave length light, where it is used such micron? 1 to 1.5 micron is we know that it is in fiber optic communication, 1 to 1.5 say 1.3 micron 1.55 micron we have discussed it is used in fiber optic communication, but this 3 micron, 4 micron, 5 micron, 6 micron, in yes in a remote sensing application say in say atmospheric there are the different kinds of gases et cetera affluent gases. So, carbon monoxide carbon dioxide sulfuric So2 etcetera, sulfur dioxide et cetera. So, for detection of those gases et cetera this high infrared region is used.

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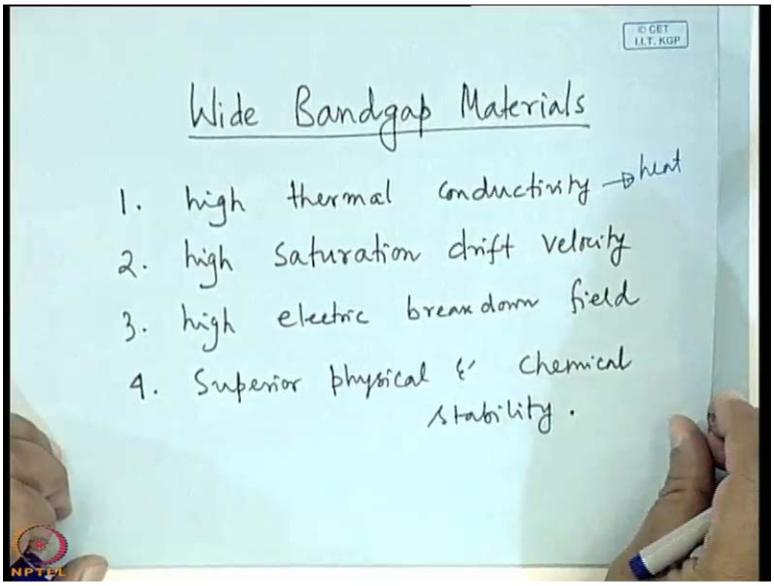

Now, the important part is the wide band gap semiconductor, where we shall divert some time. Wide band gap semiconductor; wide band gap materials, 1 is that it has high thermal conductivity, high saturation drift velocity, high electric break down field and number 4 is that superior physical and chemical stability.

So, these are the important points or the common property of wide band gap materials. Any wide band gap materials have these 4 common property. 1 is that it has high thermal conductivity, number 2 is that it has high saturation drift velocity, number 3 is that it has high electric break down field and number 4 is that superior physical and chemical stability, apart from that the band gap is wide apart from that the band gap is wide. Now where we use those materials? What are the specific applications of this wide band gap material?

1 is that is high thermal conductivity. What is the advantage of high thermal conductivity? Heat dissipation bright so; that means, you know that for particularly high power applications, high power transistor or in say high restore type of application where high current is involved the circuit basically is heated, then there is heat sink there is heat sink metallic heat sinks are there, generally aluminum is used or copper is used, but since the thermal conductivity is very high so they dissipate the heat very easily, without taking help of other kinds of heat sink or if you get heat sinks then if you if you can use heat sinks then it will be another type of advantage, but you see that this high thermal conductivity makes it the most important heat resistance device, then high saturation drift velocity.

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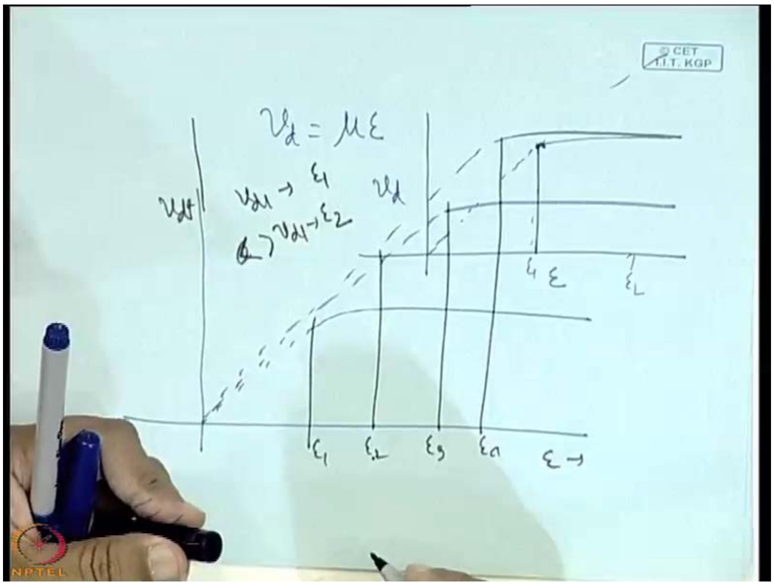

What is high saturation drift velocity? What is high saturation drift velocity that that high velocity of the, then what is the why it is important? What is the implication of this velocity? Mass maximum, no actually v d equals to mu e mu e, v d is the drift velocity, mu is the mobility, is the electric field. So, if you plot e verses v d, then first it increases then it saturates then it saturates.

We want that the velocity saturation calms at very high electric field, say if this electric filed is say E 1 we want that it calms at say E 2 or E 3. So, because of this thing we prefer that the saturation drift velocity is becomes high. This is a saturation on set of saturation is here, now this if you plot say this curve and then second one is like this one and third one is say this one so you see that the saturation values are E 1, E 2, E 3, E 4 etcetera. So, high saturated drift velocity means if the velocity saturates at high electric field.

This is particularly important for high power device, this is particularly important for high power device, because for high power the electric field associated is very high and if the drift velocity saturates then some of the properties you will not find. Some of the applications you will not make. If it is saturates in a very low field then for in high field it will not work basically, try it because we want that the electrons will be, will be as movable as in the low field region. See if the drift velocity is say v d 1 at electric field E 1, we want that at electric field E 2 it must be v d 1 at least, right, by it becomes if it becomes greater then v d 1 then it is better so; that means, the saturation must calm not in the early stage, but in a later stage. So that you can make use of this phenomena for particular application, remember that this wide band gap material is used for high power devices.

High power transistor in electrical devices and another important aspects of the saturation drift velocity is that high frequency application, that is also very important; that means, say R F you if you would like make 1 R F amplifier radio frequency amplifier or micro F sources then the saturation drift velocity must be very high otherwise the operation of the frequency limit.

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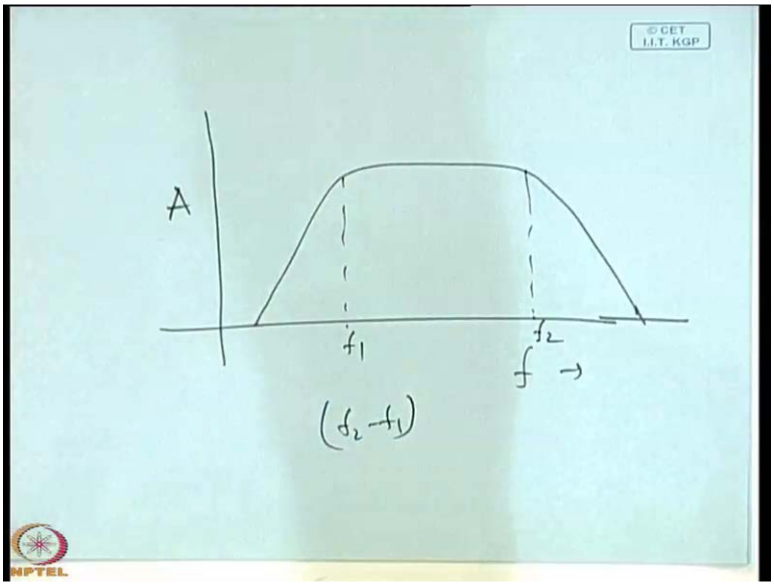

That means, if you plot the frequency verses amplification, then you will get this kind of a curve that is its band width band width it is say it is f 2 it is f 1. So, f 2 minus f 1 is the band width of this material. So, if the band width is becomes very large if you want that the band width becomes large then the drift velocity must be very high. Saturation should not come at very early stage. So, that is important parameter.

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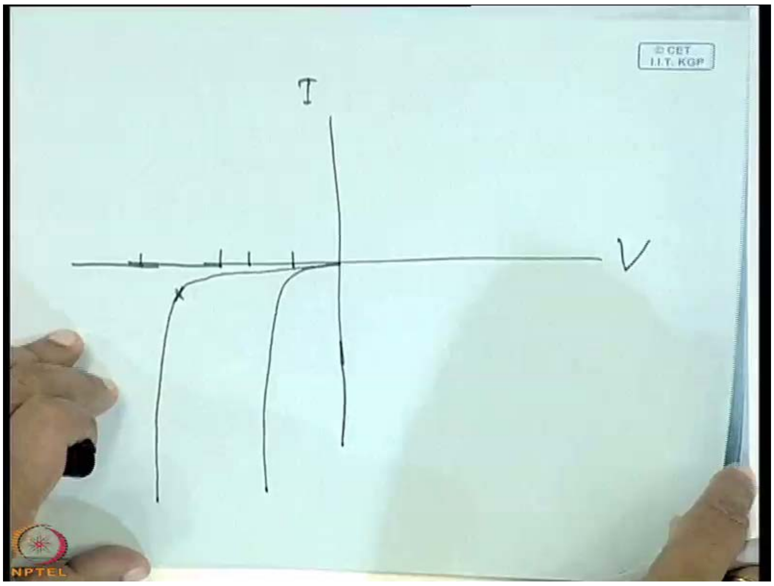

Another is high break down field that we have discussed, then what is this break down field? What is break down? Break down you know that if you consider the p n junction characteristics I v characteristics of a p n junction in the reverse wise, what you will find in the reverse wise, what we will find? Basically it will be, then it will break down; this is the point where the break down occurs, right.

Now if you if your break down occurs at this point then it is known as the early break down it is known as the early what we want actually, we want that the break down occurs at in a later stage in very high voltage say it is minus 1volt then minus 2 volt minus 3 volt and so on, 10, 15, 150 better safe it become 220, your line voltage. So, that is very important thing that if you use a silicon device if you use a silicon device then the break down field is within 5 to 10 volt, minus 5 to 10volt, but if it is a wide band gap material then its break down field is 50 to 60volt. Some of the applications are their where in the positive cycle it is positive voltage is going, but in the negative cycle the reverse voltage will be there in the p n junction making it a reverse wise and at that point if break down occurs then your circuit will be broken, your purpose will be failed.

So, that is the important thing which we should consider for wide band gap semiconductor. So, these are the 4 important points, 1 high thermal conductivity, 1 is high saturation drift velocity, high electric break down field and superior physical and chemical stability and what are, can you name some of the wide band gap semiconductors? Nitrides are wide band gap semiconductor not all nitrides, but some of the nitrides; then silicon carbide is a wide band gap of semiconductor right silicon carbide. Say some of the name of the wide band gap semiconductors is diamond, carbon

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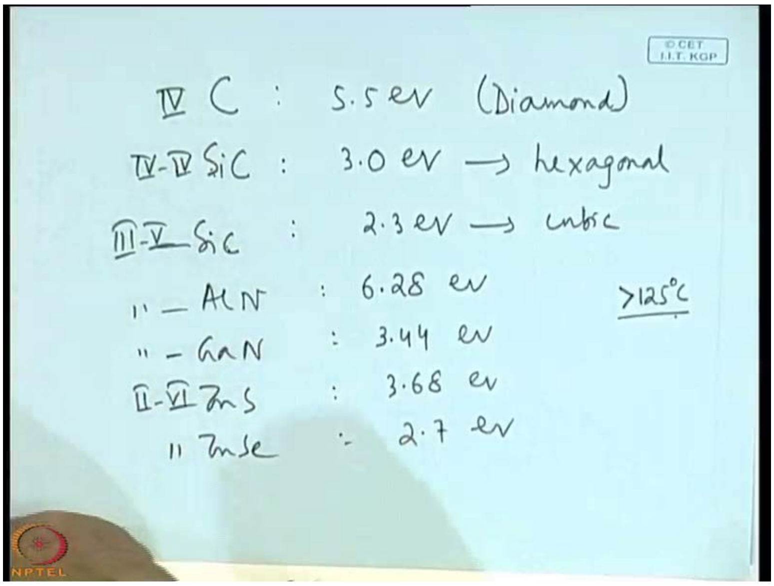

It is 5.5 electron volt it is diamond, then silicon carbide; silicon carbide had 2 band gap 1 is 3 and another is 2.3 electron volt. Why silicon carbide has two band gaps? Why silicon carbide has two band gaps that why because silicon carbide can be crystallize in 2 different forms, 1 is cubic another is hexagonal. One one is cubic another is hexagonal. So, if it is hexagonal, then its band gap is this. If it is cubic, then its band gap is not in true sense is white.

Then aluminum nitride it is 6.28, gallium nitride it is 3.44, zinc sulfide it is 3.68, zinc selenide it is 2.7. So, these are the wide band gap semiconductors which are readily available and it is used also in different kinds of applications. Generally you can greater than 125 degree centigrade you can use those devices, greater than 125 degree centigrade. And it will consume power. So, heat will be there. So, heat dissipation will be in a faster rate forward band gap semiconductor.

So, wide band gap semiconductor is very useful materials in electronic industry particularly for high power devices high power devices and where that heat conduction is required, and where your this high temperature withstand is required, then this is very important material. And also one important material is silicon carbide or nitride that can be the band gap can be tuned up to this visible range, that is also important thing that blue material can be used blue device can be used using silicon carbide or gallium nitride.

Silicon carbide or gallium nitride blue LED or blue laser is used and for say white light fabrication of white light these materials has very important. So, if we conclude our discussion that first we have taken that elemental semiconductor, next we have considered the compound semiconductor; for compound semiconductor we have say 3 5, then we have 2 6, then we have lead materials that is 4 6 compound, then we have this wide band gap then narrow band gap etcetera. In wide band gap you see that it forms of different group, silicon carbide which group silicon carbide which group? 4 right, 4 4 then carbon a diamond is group 4, silicon carbide 4, aluminum nitride 35, then zinc sulfide 2626, this is also 26, these are all 3 5 this is all 35.

So, these are the various groups; that means, not necessary that a particular group is useful almost all materials are useful and they have different applications; obviously, this wide band gap semiconductors are not used for making integrated circuit like silicon obviously, but this they have some other applications. 3 5 semiconductors are not used for optoelectronic for are not used for integrated circuit they are used for optoelectronic devices. So, they have different kinds of applications and I shall show you during our discussions that many materials are their which are used for solar cell applications or a large number of materials we used for making very good solar cell or light-emitting diode or laser etcetera.

Thank you.