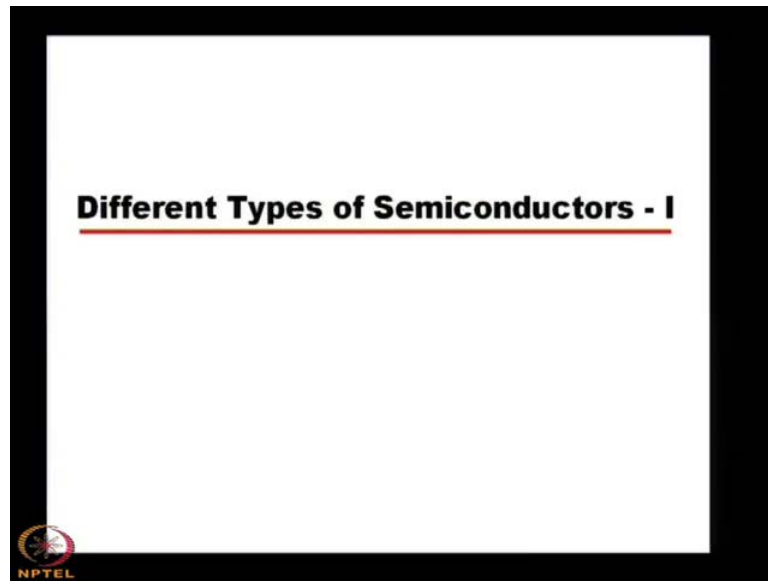


**Processing of Semiconducting Materials**  
**Prof. Pallab Banerji**  
**Department of Materials Science**  
**Indian Institute of Technology, Kharagpur**

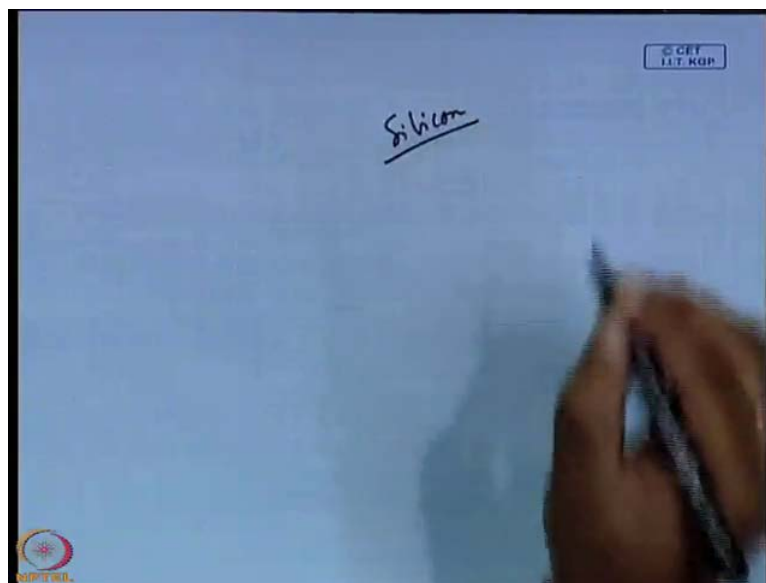
**Lecture - 34**  
**Different Types of Semiconductor - I**

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Earlier, we have used different kinds of semiconductors, but particularly we have mentioned silicon because of its various properties for the IC fabrication technology.

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Now, we shall discuss about different types of semiconductors.

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III-V compound Semiconductors


**GaAs, GaP, GaN, AlAs, InSb, InAs, InP**

**These materials crystallize with a relatively high degree of stoichiometry**

**Can easily be obtained n- and p-type**

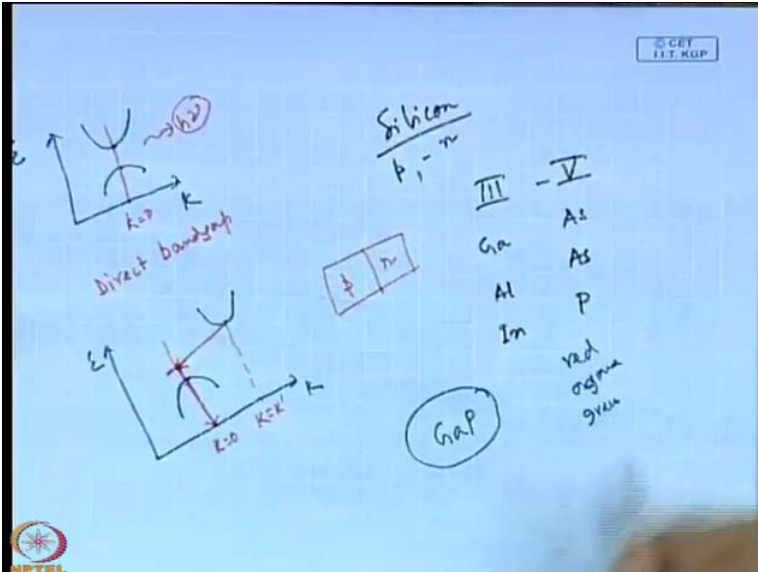
**Have direct energy bandgaps (GaAs, InAs, InP, InSb)**

**High carrier mobilities ( $\mu_{Si} = 1450 \text{ cm}^2/\text{V-s}$  vs  $\mu_{GaAs} = 9200 \text{ cm}^2/\text{V-s}$ )**



In the first phase of this lecture, I shall come across different types of semiconductors namely the 3, 5 compound semiconductors in 3, 5 compound semiconductors. Basically, these are basically the gallium arsenide gallium phosphide, gallium nitride, aluminum arsenide, indium antimonite, indium arsenide and indium phosphide. So, one of this element say belongs to the group three of the periodic table.

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Another group five of the periodic table, say if we take the example of gallium arsenide, gallium belongs to group three and arsenide belongs to group five. Here, aluminum arsenide or say indium phosphide indium belongs to group three and phosphorous belongs to group five of the periodic table. So, this compound semiconductor has some unique advantage over the silicon particularly in the area of optoelectronic devices and both in as a light emitting diode and as a detector. These the advantages of these materials are that these materials crystallize with a relatively high degree of stoichiometry and it can easily be obtained n and p type.

If you consider various type of semiconductors you know that silicon which is doped both p and n type because in a device particularly for a making a diode or transistor or FET or MOSFET basically it is a p n junction diode. So, both type of carrier is required for making the device so in that sense that it can easily be obtained both n and p type. It has direct energy band gaps particularly gallium arsenide, indium arsenide, indium phosphide and indium antimonite, they have direct band gap.

So, let me very quickly refresh your memory that there are two types of band gaps one is the direct band gap semiconductor. Here, if you plot the band in the E k diagram E versus k E in the y axis k the wave vector in the x axis which is nothing but the carrier momentum. Then, you see that when the conduction band minima and the valence band maxima they lie on the same k value say it is k equals to 0. Then, it is known as the direct band gap semiconductor and in this case in direct band gap semiconductor, it is very easily they can contribute in the fabrication of the light emitting diode because of the same momentum.

Now, if you plot the indirect band gap semiconductor in the same frame means E versus k then this has different k value the conduction band minima or the valence band maxima this conduction band minima and the valence band maximum. They have different k value say it is equals to k equals it is k equals to 0, it is k equals to k dash, now what happens that normally when electron moves from the valence band to the conduction band. Then, they again come back to recombine with the holes in the valence band electromagnetic radiation is emitted and this gives rise to the light. This is the basic principle of the light emitting diode which is one of the most important components in optoelectronics.

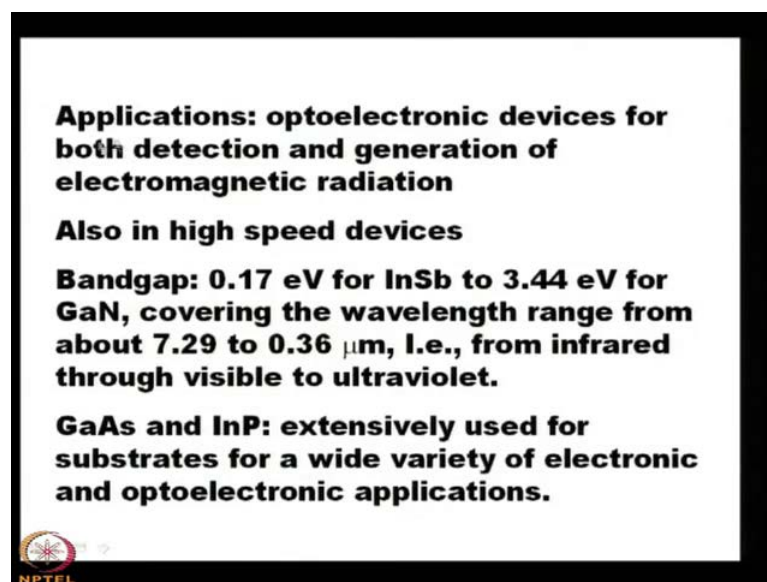
In this case, for the indirect band gap semiconductor because the momentum is different, so conservation of momentum is required. So, first what happens that the carriers from the

conduction band come to the trap state or the impurity state and then they acquire the same momentum? Finally, recombine with the holes in the valence band for the emission so normally this indirect band gap semiconductor is not used through there is several examples where we use the indirect band gap semiconductor particularly. The example of gallium phosphide, which is used for or making light emitting diode in the region of red orange and green this is due to the impurity adding with the gallium phosphide material.

Now, this direct band gap material this gallium arsenide indium arsenide indium phosphide indium antimonite they have direct band gap. So, these are the better material for making the optoelectronic sources and also they have high carrier mobilities. You see that they have higher carrier mobilities which is the  $\mu_{Si}$  that is the mobility of the silicon which is at room temperature 1,450 centimeter square per volt second.

You can compare this with the mobility of gallium arsenide at room temperature which is 9,200 centimeter square per volt second. So, it is manifold the mobility of gallium arsenide is manifold higher than the mobility of silicon, so we see that obviously that 3,5 compounds semiconductors have certain advantages over the silicon for optoelectronic devices.

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**Applications: optoelectronic devices for both detection and generation of electromagnetic radiation**

**Also in high speed devices**

**Bandgap: 0.17 eV for InSb to 3.44 eV for GaN, covering the wavelength range from about 7.29 to 0.36  $\mu\text{m}$ , i.e., from infrared through visible to ultraviolet.**

**GaAs and InP: extensively used for substrates for a wide variety of electronic and optoelectronic applications.**

 NPTEL

Now, as mentioned earlier that the applications of these materials are in optoelectronic devices for both detection and generation of electromagnetic radiation. And when we talk about the electromagnetic radiation you know that in electromagnetic radiation.

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$$E = h\nu = \frac{hc}{\lambda}$$
$$\lambda (\text{nm}) = \frac{1240}{E_g (\text{eV})}$$

↑ emission wavelength

↑ band gap

Basically, it is governed by  $1.24 \times E_g$  the band gap it is in electron volt and this gives you the  $\lambda$  or emission wavelength in micron, it comes from the relation  $E$  equals to  $h\nu$   $E$  equals to  $h\nu$  and  $\nu$  equals to  $c$  by  $\lambda$ . So, if you put the value of  $h$  equal to  $h$  the Planck's constant and  $c$  the velocity of light, you will arrive at this relation  $\lambda$  that is the emission wavelength it is it is equals to  $1.24 \times E_g$ , it is  $E_g$  is the band gap.

So, for the generation of electromagnetic radiation it is the light emission from the material and this is the relation which is the governing factor. So, more the band gap less will be the emission wavelength that means if we go for the nitride semiconductors that I shall discuss today itself. You will find that in nitride semiconductor basically because the band gap is higher than 2 electron volts. So, emission is obtained in the blue or ultraviolet region or if you take the example of says indium antimonide or indium arsenide which is the narrow band gap material. Then, if you put here the value of the narrow band gap material you will find that  $\lambda$  becomes the wavelength which is in the infrared region.


So, for detection and generation of the electromagnetic radiation these materials that means this 3, 5 compound semiconductors are very much essential and also in high speed devices. Now, if you look into the band gap of the material you find that say indium antimonide it has a band gap of point one seven electron volt. So, if you put 0.17 electron volt here in this relation you will find that it corresponds to the infrared and say if you take the example of

gallium nitride for which the band gap is 3.44 electron volt. You will find that if you put 3.44 here in this relation the lambda will be in the ultraviolet region.

So, we can say that in 3, 5 compound semiconductors, since the band gap varies from 0.17 electron volt as small as 0.17 electron volt to 3.44 electron volt for gallium nitride covering the wavelength range from about 7.29 to 0.36 micron. That is from infrared through visible to ultraviolet, the whole emission range, the whole electromagnetic spectrum is covered from 7.29 to 0.36 micron and this another important application of gallium arsenide or indium phosphide.

These are the two groups, three semiconductors that they are extensively used for substrates for a wide variety of electronic and optoelectronic applications because you know that in device technology what we do that we use a substrate. Then, epitaxial growth takes place by means of metal organic chemical vapor deposition or say molecular beam epitaxial method. So, for that the epitaxial layer must have the same type of lattice constant with the substrate so this case that gallium arsenide indium phosphide they are extensively used for making the substrates for wide variety of electronic and optoelectronic applications.

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**Compound semiconductor: some issues**

**Complex defect structures in GaAs that has two sublattices & deviation from stoichiometry in compound materials**

**The zincblende III-V compounds have no center of symmetry and their <111> direction is crystallographically polar. In such structure, the parallel {111} surfaces of a crystal segment may have different properties depending on whether they terminate with atoms from group III or V.**

**The deviation from stoichiometry (either Ga-rich or As-rich material) affects the formation of edge dislocations and may have different properties depending on whether a dislocation line consists of atoms from one group or another**

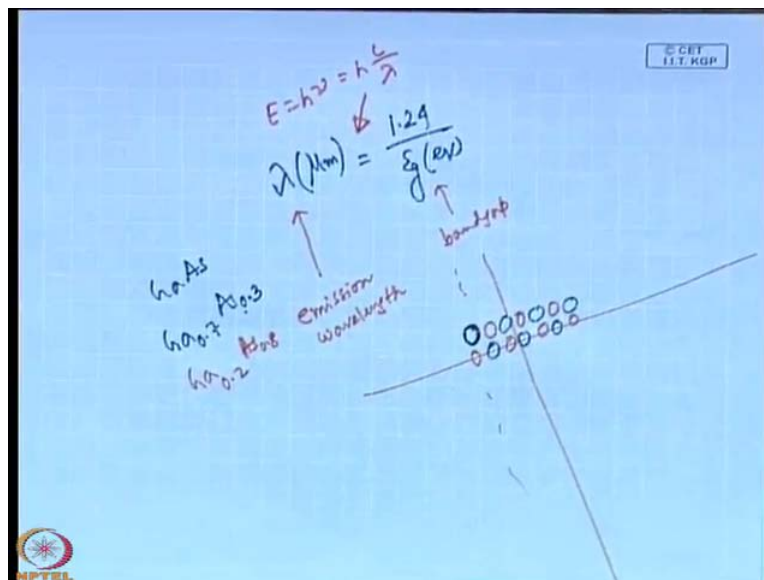
There are some issues also not that that the growth of gallium arsenide and indium phosphide is very easily. It is very simple not that there are certain issues and where in which areas the researchers. The investigators have been trying to sort out those issues particularly the

complex defect structures in gallium arsenide that has two sub lattices and deviation from stoichiometry in compound materials.

Now, these are two things one is the complex defect structures why it is complex defect structure because in gallium arsenide two sub lattices are present one sub lattice corresponds to gallium another sub lattice corresponds to arsenic. So, it is not like silicon or germanium the elemental semiconductor where only either silicon or germanium is there in the crystal lattice and another important thing is that. Since, two materials are involved; there may be deviation from the stoichiometry in the compound materials. That thing we shall discuss here itself, another issue is that the zinc blende 3, 5 compounds these are the zinc blende structures and have no centre of symmetry.

That we know and their 1, 1, 1 direction is crystallographically polar 1, 1, 1 direction is crystallographic polar. In such structures, the parallel 1, 1, 1 surfaces of a crystal segment may have different properties depending on whether they terminate with atoms from group 3 or group 5.

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Let me give an example to drive this point, suppose it is gallium arsenide the blue circles are gallium and red circles are arsenic. So, gallium arsenide and we will find that they are placed in this manner there are two sub lattices gallium arsenic gallium arsenic etcetera. Now, where the termination because it is the crystal so it will continue and if you terminate somewhere or

somewhere in this plane, so depending on the termination with the atom so which atoms are there is it group 3 or group 5.

So, the properties will be different so that is one important thing that must be taken care of which is not the case in for silicon or germanium and the deviation from stoichiometry. Either gallium rich or arsenic rich material because it can be gallium rich, it can be arsenic rich when we talk about gallium arsenide.

So, suppose if the crystal becomes gallium 0.7 arsenic 0.3 that means arsenic has less amount in this crystal. So, it is the arsenic deficiency or the gallium rich or in the other case if we consider that gallium is 0.2 and arsenic is 0.8 also it is the non stoichiometry because it has arsenic rich material. It is arsenic rich material since the gallium is only twenty percent and arsenic is eighty percent so the deviation from stoichiometry. It can be either gallium rich or arsenic rich material; it affects the formation of h dislocations and may have different properties depending on whether a dislocation line consists of atoms from one group or another.

Here, it is the where the where is the dislocation line it consists of atoms from one group or another one group means from group 3 that means gallium or another means group 5 or arsenic. So, it is very important that the deviation of stoichiometry affects the formation of h dislocation and also some of the properties may be deviated from the original or the intrinsic one also it can have many native defects.


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**Many native defects and their complexes are responsible for both shallow and deep levels in these compounds.**

**GaAs: As vacancies act as shallow donors whereas Ga vacancies act as deep acceptors.**

**An intrinsic defect ( $\text{As}_{\text{Ga}}$  antisite defect) acting as EL2 centre and gives rise to deep level responsible for semi-insulating property of undoped material.**

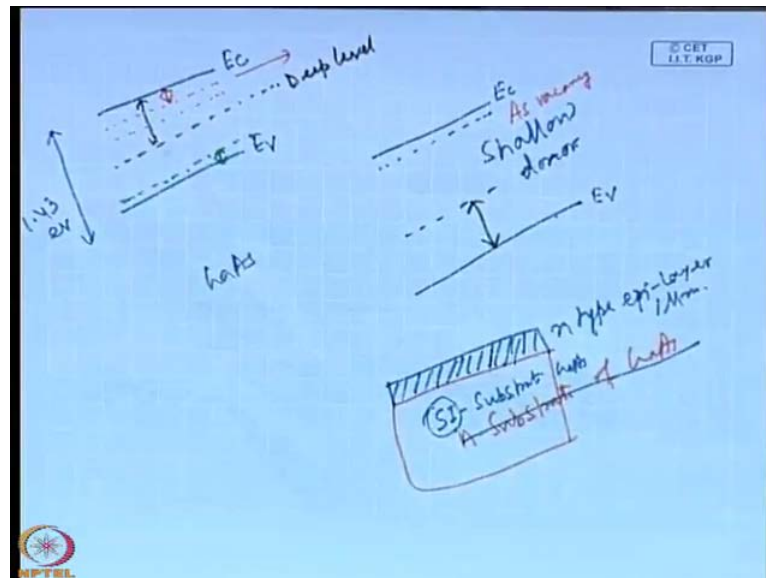
Epitaxial layers of these compounds are grown at much lower temperatures than their melting point





There complexes are responsible for both shallow and deep levels in this compound, now we have also discussed deep level and what shallow level is and let me discuss this thing again to refresh your memory.

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Suppose, it is the band structure diagram it is the conduction band edge it is the valence band edge and say it is gallium arsenide whose gallium arsenide whose band gap is 1.43 electron volt. Now, ideally there should not be any impurity states inside the band gap because of the presence of various types of defects or impurity there are many levels that can have inside the band gap.

If these impurity levels or the defect levels these levels means it is an energy somewhere inside the band gap and this level is very near to the bottom of conduction band or say it can have very near to the top of the valence band for say acceptor state etcetera. So, these are the shallow levels a few milli electron volt, otherwise in some cases you will find that this defect level is actually deep inside the band gap.

That means several milli volt either from the top of the valence band or from the bottom of the conduction band and in this case this is known as the deep level and this deep levels are not very fruitful in electronic industry. Basically, these levels act as the killers for the optoelectronic materials in the sense that it gives rise to non radiative recombination. So, that is why this deep level is not we do not invite this level to be there inside the band gap and this is detrimental for the operation of the optoelectronic device. So, this shallow or shallow or

deep levels that can be due to the native defects or their complexes. It is there for 3, 5 semiconductor and suppose there are there is a arsenic vacancies that act as shallow donor, whereas gallium vacancies act as deep acceptors.

So, shallow donors and deep acceptors means shallow donors it is very near to the conduction band it is very near to the bottom of the conduction band. This is the conduction band edge this is very near to the bottom of the conduction band that is shallow this is known as the shallow donor if it is arsenic vacancy if it is arsenic vacancy or if it is gallium vacancy then deep acceptor. So, it is the bottom of the conduction band and so the deep acceptor must be this type of thing which is some milli volts or some milli electron volts away from the top of the valence band. Another defect is there which is known as the intrinsic defects which is basically the antisite defect.

That means arsenic in gallium side in the crystal lattice structure gallium and arsenic are there. If we find that arsenic is there in the gallium side it is known as the antisite defect and it act as E 1 2 centres and gives rise to deep level responsible for semi-insulating property of undoped material. This semi insulating property of gallium arsenide is very interesting one in the sense that because of this E 1 two defect it act as semi insulating that means either the substrate of gallium arsenide can be p type. It can be n type or it can be semi insulating type, these type three types of conductivity is not available in case of silicon or germanium or most of the semiconductor.

The essential feature of this deep level E 1 2 type of defect that there is a semi insulating property it is very important for characterizing the epitaxial layer grown on it so far as the electrical characteristics are involved. Suppose, we take a n type substrate suppose it is n type substrate n substrate of gallium arsenide and you make a n type layer on it epitaxial layer. This is also n type this is also n type epitaxial layer and say its thickness is say a few micron say 1 micron.

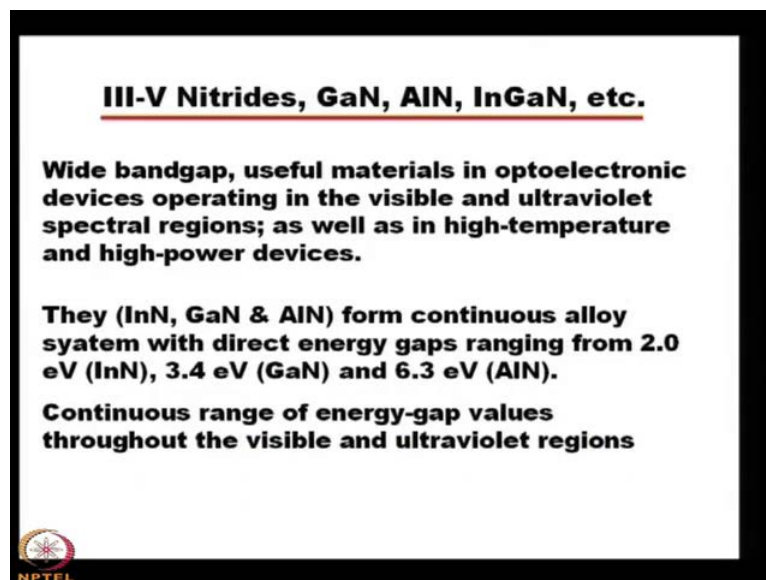
Then, if you want to make the electrical characterization of this player of one micron n type grown on n type substrate of gallium arsenide. Then, the problem will be you are you will not be able to decouple the effect of the substrate in the electrical conductivity of the epitaxial layer. So, now what to do because either you can grow this thing on a on a insulating substrate, but in that case the lattice matching will not be there. So, there will be many defects at the boundary so better use any semi-insulating type of substrate. Now, if you use this semi-

insulating type of substrate semi insulating substrate Si substrate of gallium arsenide and on the substrate of semi insulating.

You grow the n type epitaxial layer of 1 micron, you will find that because of substrate is semi-insulating the contribution of the substrate will not be there on the epitaxial layer which you have grown on the substrate. So, that is very good feature of the semi insulating substrate and one can when the epitaxial layer characterization particularly the electrical characterization of the epitaxial layers are involved. These epitaxial layers of these compounds are grown at much lower temperatures than their melting point that is also very important consideration of this 3, 5 semiconductor say gallium arsenide.

The melting point is above 1200 degree centigrade, but the epitaxial layers are grown at say 650 degree centigrade. So, that is applicable for indium for indium phosphide also and we know we know that the epitaxial layers are the most important layers for the devised fabrication. All the devices particularly the devices of related to the IC technology, it is made on the epitaxial layer and for epitaxial layers the substrate is essential for growing the layers. Then, another important group of semiconductors which we can discuss is the 3, 5 nitrides.

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**III-V Nitrides, GaN, AlN, InGaN, etc.**

**Wide bandgap, useful materials in optoelectronic devices operating in the visible and ultraviolet spectral regions; as well as in high-temperature and high-power devices.**

**They (InN, GaN & AlN) form continuous alloy system with direct energy gaps ranging from 2.0 eV (InN), 3.4 eV (GaN) and 6.3 eV (AlN).**

**Continuous range of energy-gap values throughout the visible and ultraviolet regions**

  
NPTEL

So, you see that we have already talked about silicon we have talked about germanium then we have talked about gallium arsenide indium phosphide. That means 3, 5 five arsenic arsenide phosphide, now we shall discuss the 3, 5 nitrides that means the gallium nitride aluminum nitride indium nitride aluminum gallium nitride both the binary nitrides and the

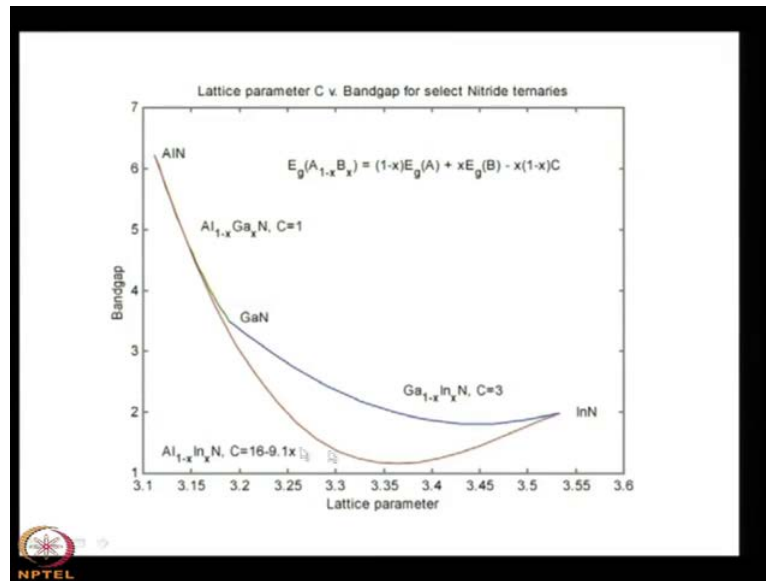
ternary nitrides. So, that we shall discuss, now these are wide band gap material, wide band gap means band gap is greater than 2 electron volt. Since, the band gap is very wide these are useful materials in optoelectronic devices operating in the visible and ultraviolet spectral region.

There is very important that it is available in the visible region, if we talk about the gallium arsenide or the indium phosphide or other 3, 5 arsenide phosphide. We will find that the visible spectrum emission in the visible region is not available if you use that material for fabricating the light emitting diodes, but in 3, 5 nitrides there are visible. It is visible because if we if we can show you the relation of  $1.24 \text{ by } E_g$ , you will find that this  $E_g$  this is the band gap this band gap is void in case of the nitride semiconductor greater than 2.

So, the visible spectrum is obtained and particularly the blue or the ultraviolet because the  $E_g$  that kind of a value which will give you  $\lambda$  equals to 400 micron, 380 micron, 420 micron the blue or the ultraviolet region. Now, apart from these, they can emit in the visible and the ultraviolet region high temperature and high power devices are also important which can be grown on the 3, 5 nitrides. They form the indium nitride gallium nitride and aluminum nitride, they form continuous alloy system with direct energy gaps ranging from 2 electron volt indium nitride 3.4 electron volt gallium nitride, that is 6.3 electron volt aluminum nitride.

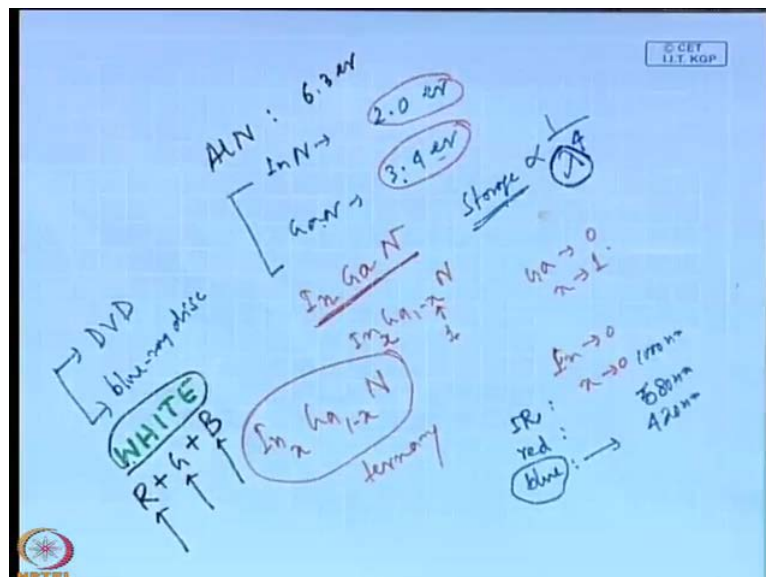
So, what are these are basically 3 nitrides with 3 different band gaps, it is indium nitride its band gap is 2 electron volt gallium nitride is 3.4 electron volt and aluminum nitride is 6.3 electron volt. So, one can continuously vary the energy gap values of the alloys made from all this three or any two of them throughout the visible and ultraviolet region that will be apparent from this diagram.

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This is aluminum nitride what is its band gap you see that the aluminum nitride band gap is 6.3 it is 6.3 then gallium nitride its band gap is 3.4 its band gap is 3.4 electron volt. Then, indium nitride it is 2 electron volt, so that means you can tune the band gap from 2 to 6.3, 2 to 6.3 that means it is throughout the visible and ultraviolet region.

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So, let me describe this point in detail that suppose this is a indium nitride its band gap is 2 electron volt and then gallium nitride it is 3.4 electron volt. That means if you make an alloy of this two material to binary material, suppose the alloy I can write in this manner that it is

indium. Then, gallium nitride and this gallium, indium, gallium nitride, you find that when it is indium when gallium is 0 that means when  $x$  is 1 when  $x$  is 1 this  $x$  is 1. So, it becomes indium nitride and when  $x$  is 0, then it becomes gallium nitride. So, by changing the value of  $x$  from 0 to 1 indium  $x$  gallium  $1 - x$  nitride, so if you change the value of  $x$  from 0 to 1 you can vary.

So, when  $x$  is 0, it is gallium nitride and the band gap is 3.4 electron volt and when  $x$  is 1 it is indium nitride the value is 2 electron volt, so continuously you can change the value from 2 electron volt to 3.4 electron volt by changing  $x$  from 1 to 0. So, that means it is a ternary compound it is a ternary compound whose band gap is between 2 electron volt and 3 electron volt. So, you can tune band gap also and if you can tune the band gap, then you can see that the emission can be blue or ultraviolet or violet that you can think. Similarly, if you take the case of aluminum nitride, suppose aluminum nitride band gap is 6.3 electron volt.

So, continuously you can vary say gallium aluminum nitride you can vary from 3.4 to 6.3 or indium aluminum nitride you can vary from 2 electron volt to 6.3 electron volt. So, this is band gap engineering that we can discuss separately, but one point that we can see that the nitride semiconductors are essential for the visible spectral region and why it is essential because of the fact that it is directly related to the storage device. If we talk about the DVD or say high power blue ray device blue ray disc, then what we find that there storage capacity is very high. It is due to the availability of the blue light emitting diode which is required for reading or writing the data on either DVD or blue ray disc, present generation people use a red LED earlier people used infrared LED.

So, the storage capacity was almost the storage capacity in a disc it is almost proportional to  $1/\lambda^4$ . So, the  $\lambda$  if it becomes very small, the storage capacity will be increased and with very high storage will be there if  $\lambda$  is small. So, now present day red is used earlier infrared was used and then blue was used this can be used, these days if you find the wavelength say red is 720 nanometer, sorry 680 nanometer and blue is 420 nanometer and infrared is say 1,000 nanometer.

So, if you put the value here you will find that there will be many fold increase of the storage in DVD or blue ray disc because of the advent of the blue LED for writing or reading the data on the disc. So, in that case the blue is very much important for as the storage device and nitrides are the most promising candidates using which you can grow this blue light emitting

diode. Also, this blue is very important for white light because the white light consists of we know that it consists of RGB red plus green plus blue RGB. Now, red LED or green LED is available in the market with their costing is very very less, now if one can add the blue then the white light can be obtained just by mixing the three lights.

Then, what will happen the important application of the white light will be in our domestic applications or in the street light where the consumption of power will be very less. If you consider with the incandescent lamp or even the lamp which is used these days, so that is important consideration. So, in that respect the nitrides are the important candidates or the contenders then you see that if you vary this indium nitride gallium nitride or aluminum nitride this is on the x axis. It is the lattice parameter because I have mentioned that lattice constant is one of the most important consideration in epitaxy.

Then, you can consider if it is a say a is one material and b is another material, so the band gap of the material suppose if you want to make aluminum gallium nitride out of aluminum nitride and gallium nitride. Then, you can use this formula which is known as the Vegard's law  $1 - x E_g$  that means the  $1 - x$  into band gap of material a. Suppose, material a is aluminum nitride, so aluminum nitride band gap must be put here and another is  $x$  into  $E_g$  b.

That means the band gap of material b which in our case is the gallium nitride and so  $x$  you can choose for particular band gap and this  $c$  is a constant in this case it is 1. So, that means since in this case it is 1, so you can calculate the value of the band gap of the ternary material out of aluminum nitride and gallium nitride and suppose you if you go for the gallium indium nitride.

So, indium nitride is here and gallium nitride is here, so if you go for the ternary preparation, then you find that the same thing is applicable. Suppose, the material a is gallium nitride so put the band gap of gallium nitride here and material b is say indium nitride put the band gap of indium nitride here and  $c$  is a constant. In this case, it is 3, so very easily one can calculate the band gap of the material particularly the ternary materials.

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Other III-V materials

**$\text{Al}_x\text{Ga}_{1-x}\text{As}$ ,  $\text{GaAs}_{1-x}\text{P}_x$ ,  $\text{Ga}_x\text{In}_{1-x}\text{As}_y\text{P}_{1-y}$ : substrates, etc.; highly desirable to match the lattice structure and lattice constant of the epitaxial layer and the substrate.**

**GaAs (5.65 Å) on Ge (5.65 Å)**

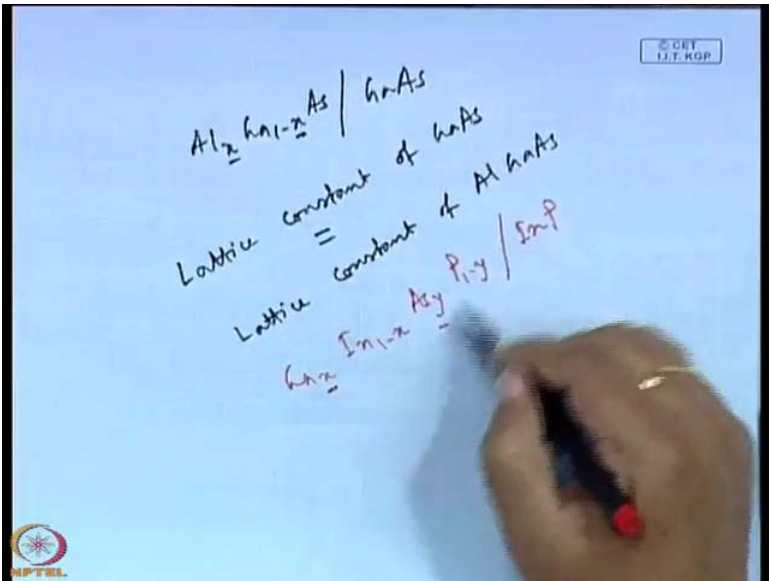
**GaAs on Si: attractive for the integration of optoelectronic devices based on GaAs with Si circuitry on a monolithic chip.**

**Lattice constant mismatch: Si (5.43 Å), GaAs (5.65 Å): resulting in generation of high dislocation densities in the epi-layer**



Then, apart from the nitride materials there are other 3, 5 materials as well say aluminum, gallium arsenide, gallium arsenide phosphide, gallium indium arsenide phosphide. So, they are mostly used in fiber optic communication and proper substrates are important and I can give you one example that proper substrates means if you want to grow this aluminum gallium arsenide.

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If you want to go this aluminum gallium arsenide, this aluminum gallium arsenide it has to be grown on gallium arsenide. This is because the lattice constant because the lattice constant of

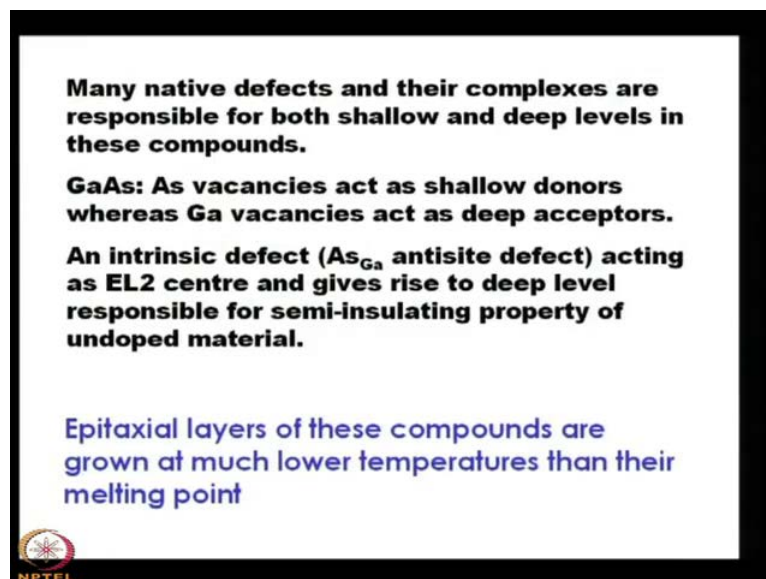


gallium arsenide is equal to the lattice constant of aluminum gallium arsenide. So, that is the very important consideration that for all values of  $x$  whatever be the value of  $x$  it is lattice next to gallium arsenide and this gas system is used for making the first generation sources for fiber optic communication in the 800 nanometer region. You see that other material which is gallium arsenide phosphide, it is also lattice next to gallium arsenide. Then, gallium indium arsenide phosphide, it is lattice next to indium this gallium  $x$  indium  $1 - x$  arsenic and phosphorous.

It is lattice next to indium phosphide by properly choosing the value of  $x$  and  $y$  not that for all values of  $x$  and  $y$  it will be lattice next to indium phosphide not that, but for certain values of  $x$  and  $y$  this is lattice next to indium phosphide. The important consideration of epitaxial growth is its substrate and you must choose a proper substrate for making the epitaxial layer free from all types of defects dislocation etcetera.

Here, it is written over here you see that highly desirable it is highly desirable to match the lattice structure and lattice constant of the epitaxial layer are and the substrate. So, it is also important thing that lattice constant and lattice structure is the basic parameter which one must maintain for making the epitaxial growth and in that case we have mentioned earlier that this.

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**Many native defects and their complexes are responsible for both shallow and deep levels in these compounds.**

**GaAs: As vacancies act as shallow donors whereas Ga vacancies act as deep acceptors.**

**An intrinsic defect ( $\text{As}_{\text{Ga}}$  antisite defect) acting as EL2 centre and gives rise to deep level responsible for semi-insulating property of undoped material.**

Epitaxial layers of these compounds are grown at much lower temperatures than their melting point

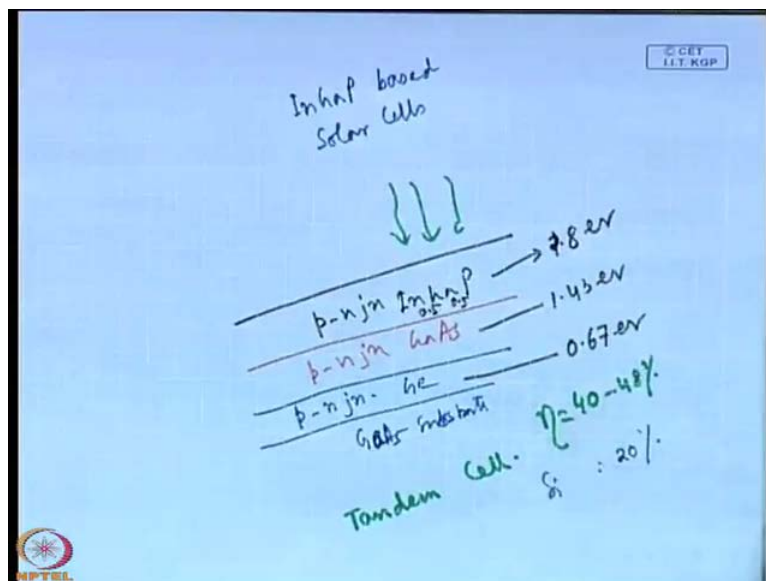


Gallium arsenide and indium phosphide, they are extensively used for a substrate for a wide variety of electronic and optoelectronic material most of the materials by choosing proper

values of the x and y or the proper value of x or say the proper values of y. You can grow on either gallium arsenide or indium phosphide substrate, so in that sense we can say that lattice matching is important and gallium arsenide. You see that the lattice constant of gallium arsenide it is 5.65, this 5.65 is the lattice constant of gallium arsenide and germanium its lattice constant is 5.65 angstrom and both the lattice constant is same.

So, gallium arsenide is grown on germanium, so that is very important thing that germanium is a group 4 elemental semiconductor and its lattice constant is equal to almost equal to gallium arsenide. So, we can very easily grow gallium arsenide on germanium so that there will not be any lattice mismatch between the substrate and the epilayer grown on it because of the same lattice constant. This is very important material particularly I can tell you that if you take the example of the 3, 5 solar cell indium gallium phosphide based solar cells.

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The structure is essentially it is first you take a germanium substrate or a gallium arsenide substrate on gallium arsenide substrate you grow a p n junction after the upper layer. You grow a p n junction of germanium because it is lattice match to gallium arsenide very easily you can grow without any free from any defect the p n junction of germanium. Then, on the p n junction of germanium above it, you grown the p n junction of gallium arsenide and finally above p n junction of gallium arsenide. You grow p n junction of indium gallium phosphide with indium 0.5 gallium 0.5, actually indium is 0.49 and gallium is 0.51.

Then, you will find that there are three junctions p n junction one is indium gallium phosphide its band gap is almost 1.8 electron volt, then gallium arsenide its band gap is 1.43 electron volt. Finally, the germanium its band gap is 0.67 electron volt and you see that it can harness a substantial amount of the solar radiation on it and it can convert the electricity from the solar radiation. This type of a cell is known as the tandem cell, tandem cell because there are three types of junctions and I have simplified the structure. Basically, the structure must involve the tunneling layer so that there will be addition of the current without any substantial load.

So, the output will be better and in this case you see that germanium has lower band gap and gallium arsenide is somehow higher than the germanium and indium gallium phosphide the highest in this series. We have to place the top layer with the highest band gap and the bottom layer with the lowest band gap so that it will be the window for the solar radiation which will be absorbed in the germanium layer. If you do not use germanium then what will happen that substantial portion of the solar radiation and will not be absorbed by this will not be absorbed.

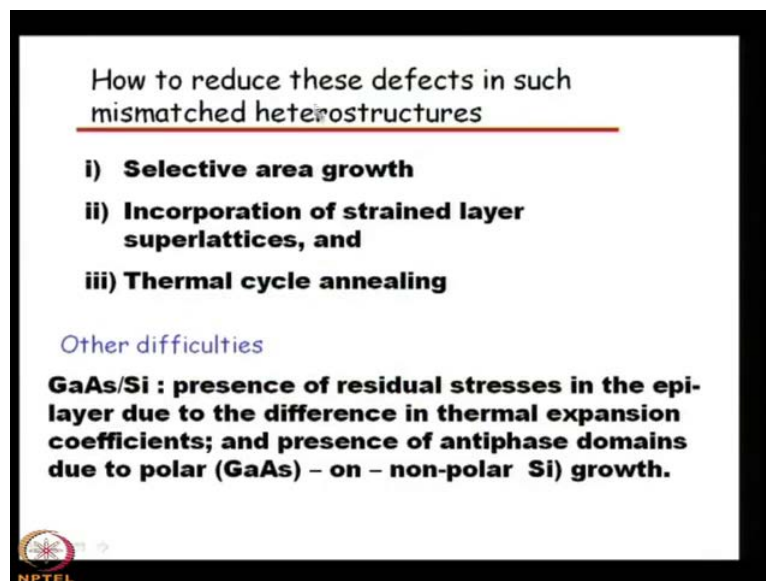
So, harnessing the solar radiation will be difficult and the efficiency of the solar cell will be reduced and with this tandem solar cell one can make the efficiency as high as 42, 48 percent. If you compare this efficiency with silicon solar cell silicon solar cell and you will see that the efficiency is almost 20 percent, so it is double. So, in that sense we can say that this germanium is very important material because of its lattice constant which is equal to the gallium arsenide. Then, one attractive point of investigation is the gallium arsenide on silicon why it is very attractive because of the integration that it is attractive for the integration of optoelectronic devices based on gallium arsenide with silicon circuitry on a monolithic chip.

These all the chips are made of silicon and those chips are essentially the integrated circuits based on the integrated circuits where there is no scope of integration of the optoelectronic devices. That means a light emitting diode or say detector or laser and that is possible if one can make gallium arsenide on silicon because silicon will give you the better electrical characteristics for integrated circuit IC. Already, the process technology and a the mature process because of the mature process technology it as the most important material for IC technology and gallium arsenide it is the most important material for optoelectronic that we have discussed.

So, gallium arsenide on silicon is very important in is very important for the investigators, but the problem is lattice constant mismatch and silicon has a lattice constant of 5.43 angstrom and gallium arsenide has a lattice constant of 5.65 angstrom. So, essentially we find that there is a difference of 0.22 angstrom and this 0.22 angstrom is very high for the growth of gallium arsenide epitaxial layer on silicon why because there will be lattice mismatch. Because of the mismatch how dislocation density will be there in the epitaxial layer and if there is high dislocation density on the epitaxial layer.

Then, what will happen that the epitaxial layer or dislocation sites will act as recombination centre for the electrons and coming down from the coming down in the excited state from the say the conduction band. They will act as the dislocation centers will act as the killer centers, they will the electrons will be trapped in the dislocation centre and instead of making the radiative recombination non-radiative recombination will be there, so you will not get any light. Now, this dislocation density you can reduce if you can match but, for silicon and gallium arsenide it is not possible, but there are some ways people have been trying.

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How to reduce these defects in such mismatched heterostructures

- i) **Selective area growth**
- ii) **Incorporation of strained layer superlattices, and**
- iii) **Thermal cycle annealing**

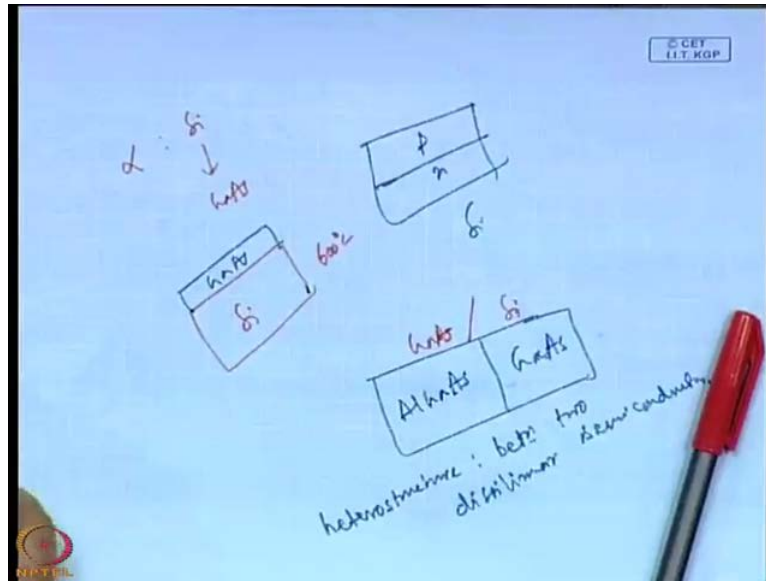
Other difficulties

**GaAs/Si : presence of residual stresses in the epi-layer due to the difference in thermal expansion coefficients; and presence of antiphase domains due to polar (GaAs) – on – non-polar (Si) growth.**

 NPTEL

How to reduce these defects in such mismatch hetero structures? Why they are hetero structures? Because, when we talk about the silicon p n junction which is silicon.

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It is silicon p n junction, so it is not hetero structure is there homo junction because p and n are of the same material, but if we consider that gas cell gas system that means this aluminum gallium arsenide is made on gallium arsenide. Then, it is a hetero structure because two different two dissimilar it is a junction between two dissimilar semiconductors. So, hetero structures are nothing but a structure or the junction between two dissimilar semiconductors between two dissimilar semiconductors.

Now, this hetero structure and also it is mismatched hetero structure because silicon is involved and gallium arsenide is involved. We are talking about the growth of gallium arsenide epitaxial layer on silicon substrate and how to reduce this defects that people have been trying for a long time and they have come out with the solutions.

The selective area growth another step can be the incorporation of strained layer super lattices and thermal cycle annealing. So, one can try those steps or the pseudo morphic buffer on silicon and can grow the gallium arsenide on silicon. This is very important material for integrating that we are discussed earlier that integration of optoelectronic devices with silicon circuitry on a monolithic chip. Then, apart from these difficulties of dislocation density how dislocation density originating from the lattice mismatch, there is other difficulties and in silicon gallium arsenide case that presence of residual stresses in the epi layer. Due to difference in thermal expansion coefficients, we know that the thermal expansion coefficients or alpha of silicon is different than gallium arsenide.

So, if the thermal expansion coefficients of silicon are different than gallium arsenide what we do that is you grow gallium arsenide with silicon say at a temperature of 600 degree centigrade is an example not the actual temperature. So, 600 degree centigrade what will happen the expansion of silicon and the expansion of gallium arsenide will be different because of the difference in the alpha or the thermal expansion coefficient and then what will happen that there will be residual stresses.

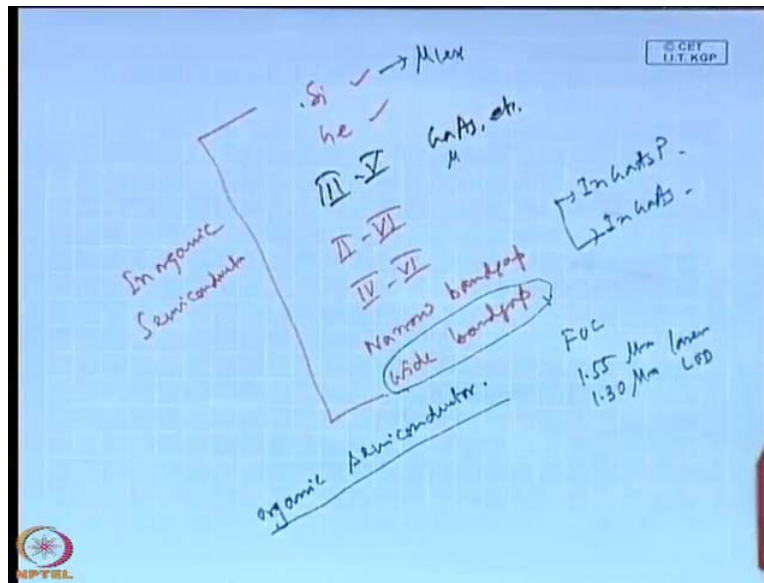
So, because of the stress it can be compressive or it can be other type of stresses or say there are presence of anti phase domains because this is a polar semiconductor which one is polar the gallium arsenide is polar and silicon is non polar. Now, we are growing a polar material on a non polar material so we will find that there will be anti phase domains presence in the epitaxial layer.

So, if there are anti phase domains, so those will be detrimental for the application of the optoelectronics with that gallium arsenide epitaxial layer. So, these are the essential three things that we can discuss on the 3, 5 semiconductors and till now apart from silicon or germanium we have discussed the arsenide the phosphides the 3, 5 nitrides. Then, the some of the band gap engineering type of layered structures like say gallium arsenide phosphide indium gallium arsenide phosphide aluminum gallium arsenide. Then, one can think of the then one can think of the nitrides and then gallium arsenide on silicon gallium arsenide on germanium it has its own application.

So, as the gallium arsenide on germanium is concerned, I have given you the example of tandem solar cell with very high efficiency. Those are used in the satellite communication not in the domestic application or the terrestrial application.

That is for the space application and even when a satellite is there on its orbital space the power that is it takes from the solar cell which is made by the indium gallium phosphide tandem solar cell on gallium arsenide. Below that, there is germanium and also we talked about the silicon integration with the gallium arsenide because the present day all the chips are made of silicon. One can make some very good integration with the silicon for making optoelectronics with the silicon integration. Now, we can say that with this knowledge in this type of semiconductors, we can proceed further and there are many other materials also that we can discuss in due course.

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If we start with silicon germanium that we have done and the gallium arsenide and indium phosphide or 3, 5 semiconductors 3, 5 that means gallium arsenide etcetera that we have discussed today. Then, we can start with discussing say a 2, 6 semiconductors then 4, 6 semiconductors, then say narrow band gap then wide band gap. So, these are the conventional semiconductor which is mostly the inorganic nature inorganic semiconductors. When we shall complete the discussion of all the semiconductors we shall come across a new type of material which is the organic semiconductors.

This is also known as the polymeric semiconductor if the organic is polymeric one, so all such materials will be discussed in due course and it each category has its own advantage has own disadvantage. In silicon, the mobility is less compared to the mobility of gallium arsenide and is the band gap is less compared to the band gap of gallium arsenide. Also, it is indirect it is direct, so it is used for the optoelectronic application, then we talked about the indium gallium arsenide phosphide or indium gallium arsenide. Those are also 3, 5 base semiconductors where this is ternary, quaternary, these are used for the present day fiber optic communication for making 1.55 or 1.3 micron laser for fiber optic communication laser or LED.

So, every category of materials have its own application and in wide band gap semiconductors. We shall see that these materials are very important for high power or devices high temperature devices with very high saturation drift velocity etcetera and organic

semiconductor. Those are mostly important and in case of the large area deposition and coating of the large area for some particular application in the semiconducting area because the coverage is very high and solution process ability. Another important thing is the cost which is very less, so those things we shall discuss in detail in the next class.

One thing I must mention at the end of this class is that this semiconductor is the important in device application that we all know suppose it is a p n junction or the most primitive that is a rectifier diode or says it is a light emitting diode. Let us say it is a solar cell or any kind of device says it is FET the MOSFET, so all types of devices different semiconductors are used and depending on its particular is application or the characteristics it has. So, for optoelectronics we do not use silicon because it is we have discussed that it is the indirect band gap material and also in case of I C technology we do not use silicon for microwave sources we use gallium arsenide we do not use silicon.

So, because of the high mobility in gallium arsenide, so those things one must take into account for the application in a particular or device area and different types of material. We shall use some of the material we will find that they are very good in thermoelectric applications some in the memory type of thing. Then, there are oxide materials also zinc oxide aluminum oxide, so those oxides titanium oxide, copper oxide, those are also show some semiconducting property which is unique. Though, those are not widely used in all the cases like silicon in IC technology, even then those are very important materials for our application and in different fields.

Thank you.