Semiconductor Optoelectronics
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Lecture - 11
Semiconductor Heterostructures - Lattice-Matched Layers

We continue with our discussion of semiconductor materials and today we will discuss about semiconductor Heterostructures and Lattice-matched layers, what are Lattice-matched layers and a continuation of that would be strained layers, strained layer epitaxy, which we will take up in the next class. So, before I start I will briefly discuss the quiz that we had in the last class.

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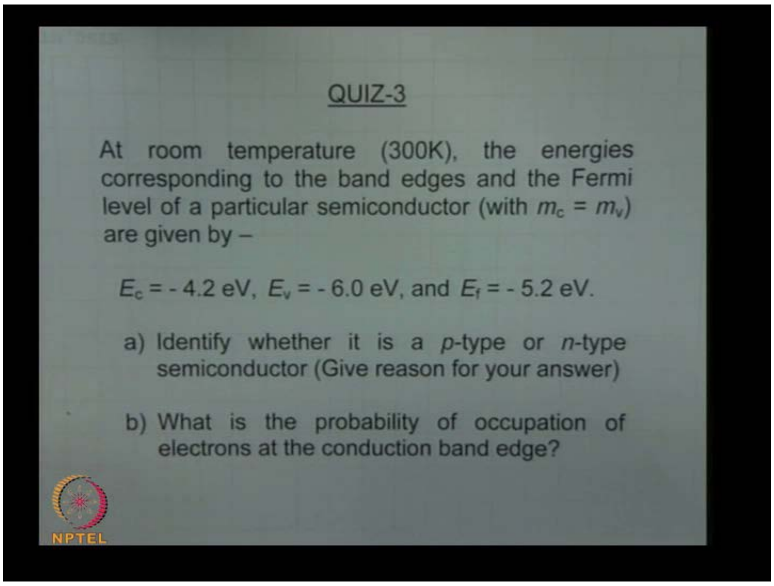

QUIZ-3

At room temperature (300K), the energies corresponding to the band edges and the Fermi level of a particular semiconductor (with $m_c = m_v$) are given by –

$E_c = -4.2$ eV, $E_v = -6.0$ eV, and $E_f = -5.2$ eV.

a) Identify whether it is a *p*-type or *n*-type semiconductor (Give reason for your answer)

b) What is the probability of occupation of electrons at the conduction band edge?

So, just recall the quiz, at room temperature the energies corresponding to the band edges and the Fermi level are given. Identify whether it is a p-type or n-type semiconductor, give reasons for your answer. It is a very straight forward that you just observe that the Fermi level is below half, below the middle of the band gap. And because m c is equal to m v, if it is below the midpoint, then definitely it is a p-type semiconductor; that was rather straight forward.

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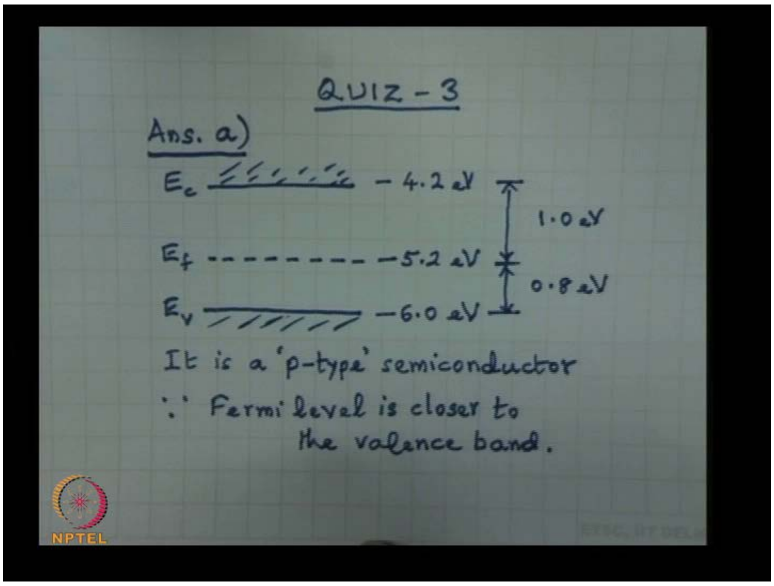

QUIZ - 3

Ans. a)

E_c — -4.2 eV

E_f - - - - - - - - -5.2 eV

E_v — -6.0 eV

1.0 eV

0.8 eV

It is a 'p-type' semiconductor

∵ Fermi level is closer to the valence band.

So, the expected answer is here. So, the given values are there. So, you just show the band diagram and show that the E f is closer to the valence band. Because the Fermi level is closer to the valence band, it is a p-type semiconductor. Part b of the question where you are asked to calculate, so this is an exercise to check whether you are familiar with the numbers.

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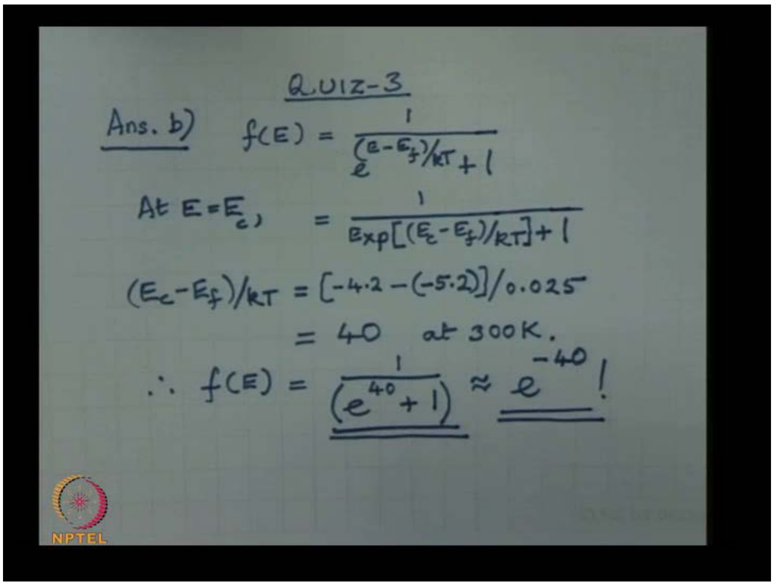

QUIZ-3

Ans. b) $f(E) = \dfrac{1}{e^{(E-E_f)/kT}+1}$

At $E=E_c$, $= \dfrac{1}{\exp[(E_c-E_f)/kT]+1}$

$(E_c-E_f)/kT = [-4.2-(-5.2)]/0.025$

$= 40$ at 300K.

$\therefore f(E) = \dfrac{1}{(e^{40}+1)} \approx e^{-40}$!

So, to calculate the probability of occupation of electrons which is given by the Fermi function and at E is equal to E c, you simply substitute E equal to E c in the Fermi function and substitute the numbers which are given and you get approximately E to the power minus 40.

In a quiz question, normally approximations are allowed. So, you do not need to use the calculator and get the exact values. k t actually comes out to be around 0.4258, but I would ask all of you to use 0.025 in simple calculations because it easily cancels and get singular numbers. If you have to use a calculator, in a quiz question calculator is not expected. Therefore, use such numbers and there it is. The main point here is the objective of the quiz was to tell you what kind of energies one has for E c, E f, E v. I am sure you have all used the formulae, but how many of you have used actual value of the energy for E c, E f, E v. Please note that the numbers are negative; minus 4.2, minus 5.2 and so on.

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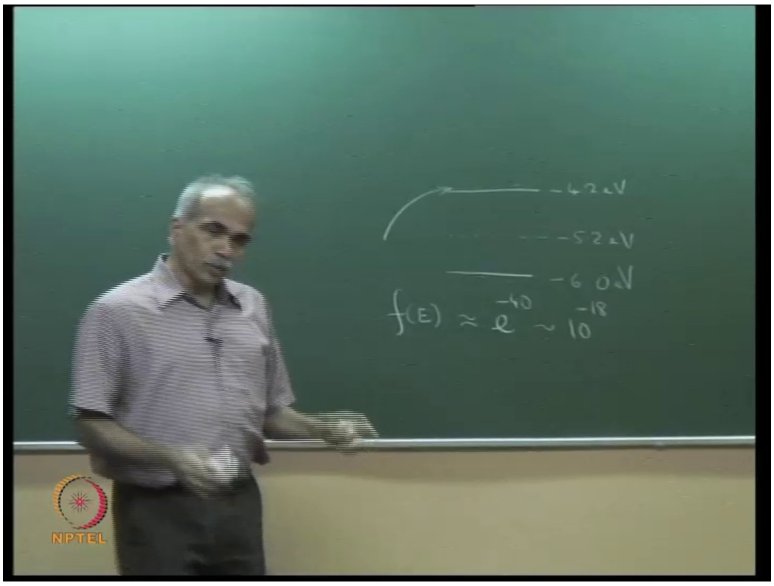

Why did we give that number? So, the numbers given where minus 4.2 E v, minus 6 E v and minus 5.2 E v. Why is this minus and why is this 4.2? Why not 0.5 or why not 3? This is because all the states which we are considering here are bound states. Bound states have negative potential energy. You have to supply energy to free the electrons from the bound state. Potential energy 0 is the free particle and therefore, these are all bound electrons to the semiconductor. So, the typical numbers that you will encounter are these. Many of you may be knowing that the work function of materials is of the order of 4 E v, 5 E v, 3.5 E v. What is work function? Minimum energy required to free an electron from the surface of the material. So, these are the kind of actual numbers which we have for this.

The second point is, when you calculated the probability of occupation of electron here, I briefly mentioned this in the class in the text that f of E is extremely small and this came out to be of the order of E power minus 40 or of the order of 10 to the power minus 17 or 18. It is extremely small, but please remember it is not 0. If it is 0, then there will be no electron. There is no probability of having an electron. There is no electron occupying the conduction band. No doubt this is extremely small. You cannot write that the probability is 0. It is extremely small, but you remember that this will be multiplied by n c or n v which is very large; 10 to the power of 17, 10 to the power of 18, and therefore, there are electrons here. So, this is the primary reason that we have to put some numbers to get the real feel for qualitative is something, but you have to put real numbers to see what is really happening.

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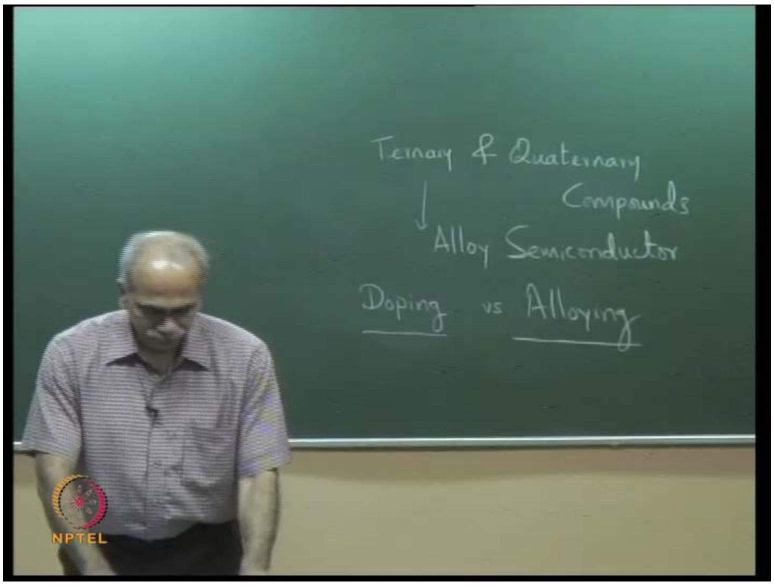

So, if you recall, the last class we discussed about semiconductor materials and in particular, in particular, we talked about ternary and quaternary compounds; ternary and quaternary compounds. These are also called alloy semiconductors; alloy semiconductors. How are these alloys different from dope, doping? You also have doped semiconductor; semiconductors are doped, these are… So, doping and alloying; doping verses alloying. What are the differences between doping and alloying?

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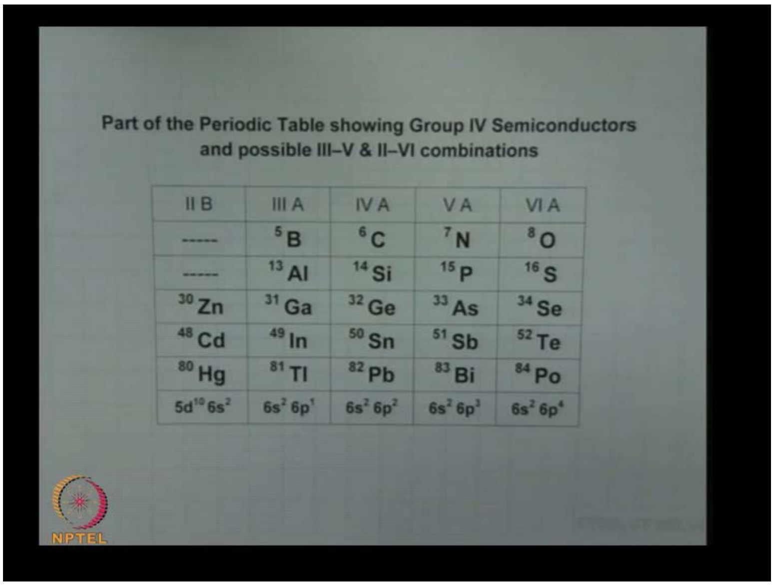

Part of the Periodic Table showing Group IV Semiconductors and possible III–V & II–VI combinations

II B	III A	IV A	V A	VI A
-----	^{5}B	^{6}C	^{7}N	^{8}O
-----	^{13}Al	^{14}Si	^{15}P	^{16}S
^{30}Zn	^{31}Ga	^{32}Ge	^{33}As	^{34}Se
^{48}Cd	^{49}In	^{50}Sn	^{51}Sb	^{52}Te
^{80}Hg	^{81}Tl	^{82}Pb	^{83}Bi	^{84}Po
$5d^{10}6s^{2}$	$6s^{2}6p^{1}$	$6s^{2}6p^{2}$	$6s^{2}6p^{3}$	$6s^{2}6p^{4}$

If you see carefully, let as look at the table which we had in the last class; the table, let me put the table here. When we want to dope the Silicon p-type Silicon then Silicon is doped by Boron to make it p-type. If you want to make it n-type, then you dope it with Arsenic normally or Phosphorous. So, what is the point that we see, that for doping you dope the material that you add an impurity which is from the adjacent group. This is group four semiconductor; if you add impurity from group three, it becomes p-type semiconductor and if you add impurity from group five, it becomes n-type semiconductor.

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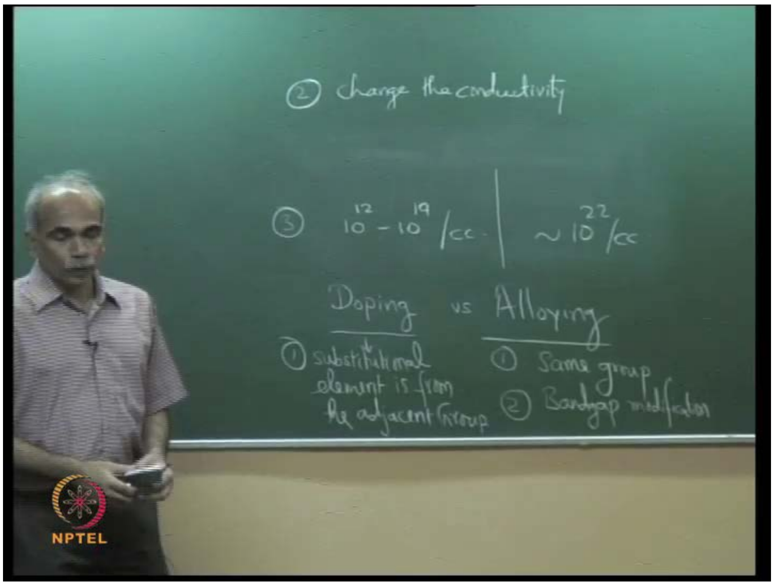

② change the conductivity

③ $10^{12} - 10^{19}$ /cc. | $\sim 10^{22}$ /cc

Doping vs Alloying

① substitutional element is from the adjacent Group

① Same group

② Bandgap modification

So, the first point to note is that you add material, the dopant or the substitutional element. The substitutional element is from the adjacent group. So, this is the first point; from the adjacent group, adjacent group. What about in the case of alloying? It was from the same group; Aluminum Gallium Arsenate. X fraction of Gallium is replaced by Aluminum; A fraction of Gallium is replaced by Aluminum from the same group. So, the first different is the substitutional element here in alloying is from the same group. You dope from the adjacent group. Second point, why do you dope is to change the conductivity. You make it more conductive. The conductivity is increased by doping; either you can dope p or n. In either case, the carrier concentration increases and the conductivity increases. And why do we do allying? So, the first point is here. It is from the same group.

What do we achieve? By replacing we get band gap modification. This is for changing conductivity. This is for band gap modification. Very little changes in terms of conductivity, but band gap modification, any other differences. Third, what about the doping concentration? Doping concentrations are typically 10 to the power of 2 to 10 to the power of 19 per cc. In other words, the number of atoms with which you dope is much smaller compared to the total number of atoms. So, the dopants are very small in number. Whereas, here you are replacing x one fraction; let us say, 0.3 means 30 percent and typically semiconductors have 10 to the power of 22 atoms per cc. So, 30 percent is also of the same order. So, here, in this case, it is of the order of 10 to the power of 22 per cc. So, the concentration of the substitutional atoms is much higher in alloying. These are the three basic differences which we see straight forward between alloying and semiconductor and doping.

I was answering the question - why do we go for alloy semiconductors? Why ternary and quaternary compound? I had given two reasons: The first reason was, of course, band gap modification. So, we go for, why go for ternary and quaternary compound? There were two reasons, two primary reasons. There are many other reasons actually. From fabrication point of view, there are certain design flexibilities which are provided by using additional degrees of freedom that you get, but the most important two points are band gap modification.

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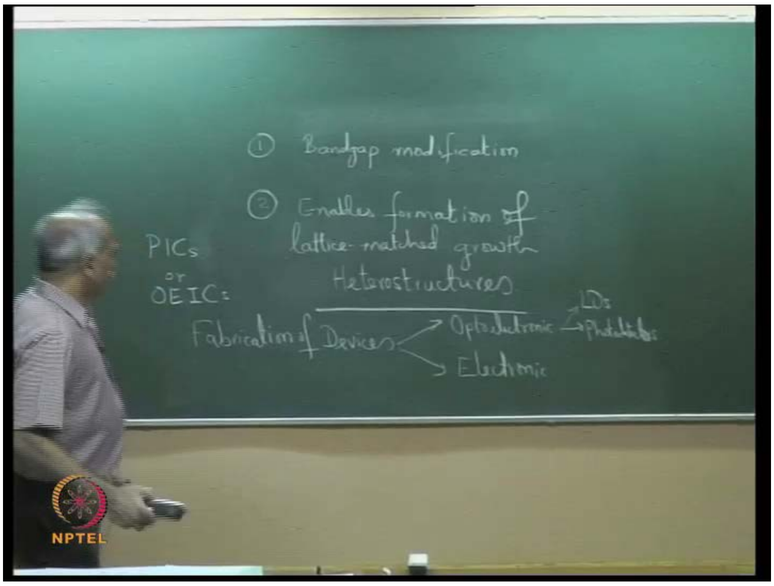

So, the first point was why go for ternary and quaternary compounds. First point was band gap modification. This we discussed in the last class. The second point I had written was - it enables formation of enables formation of lattice-matched Heterostructures. Lattice-matched growth of Heterostructures; enables formation of lattice-matched growth; enables Lattice-matched. I do not need to write formation of lattice-matched growth of Heterostructure.

So, we discuss today, this second point - what are Heterostructures? Heterostructures are structures where you grow a semiconductor of different type on a substrate. If you look at the fabrication - fabrication of devices, in electronic devices and optoelectronic devices, so optoelectronic and electronic very briefly and electronic devices, in general, optoelectronic devices are much bigger in size compared to electronic devices. You know that in integrated circuits with very large scale integration, on a small chip you can have a million electronic compounds; components, a million components; very large number of components on a single chip, but usually in the optoelectronic devices such as laser diodes, LD’s, photo detectors, these are much larger in size. And typically on an optoelectronic chip are what are called as photonic integrated circuits.

Now they are called as PICS PICS PICS - Photonic Integrated Circuits. Earlier, they were also called O EIC’s PICS or OEIC’s optoelectronic integrated circuits. IC- we are familiar with the IC; integrated circuits in electronics. Exactly like that, optoelectronic integrated circuits or photonic integrated circuits. The number of components on a chip are generally very few; 3,4,5,6,8, small number because each component the dimensions are typically tens of micron to hundreds of micron, whereas, in microelectronics, we have components which go to sub-micron. So, the dimensions are extremely small or the sizes of optoelectronic components are very large.

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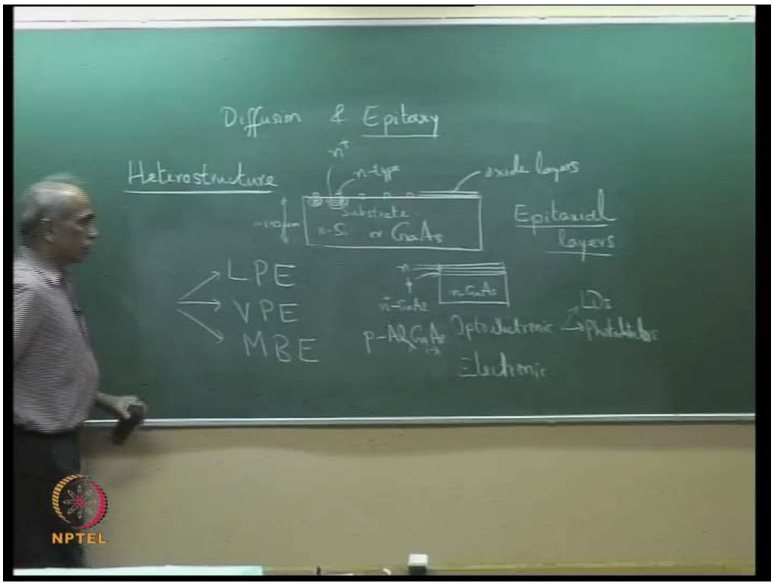

What is the reason? Why does why is this situation? Normally, in fabrication of components, you start with the substrate. You start with the substrate say Silicon or Gallium Arsenide substrate, typically about 60 to 100 micron thickness; dimensions depends typically and on this you grow large number of components. Most of the electronic components which involved in the p n junction, you can deposit the required p-type or n-type dopant and diffuse. So, the material is diffused here and you have. If this is the p-type dopant, then the diffused region is p. You start with the n Silicon; low doped n Silicon; diffused region is p-type. You deposit an n-type material here; n-type dopant and diffuse it. So, you have a strong, let us say, n plus; so this diffused region is n plus. You can have any number on the substrate; on the surface you deposit and diffuse. So, you already have a p-type n-type. So, you can make NPN transistors or whatever. Similarly, for most devices you also have to deposit oxide layers. So, they are deposited in terms of layers; oxide layer. So, normally a chip involves multi processes, many processes.

Finally, when the chip comes it has passed through several stages, several processes of diffusion and deposition. So, these layers are the layers which are deposited on top, are called epitaxial layers. Basically, there are two processes: one is diffusion and other is epitaxy growth on top. Most of the electronic chips used both these processes and finally you come up with very large number of devices. Most of the optoelectronic devices are fabricated by epitaxy which means you start with the substrate and then deposit layer by layer; so epitaxy - various types of layers.

We will discuss a certain device structure at a later stage, but you deposit different layers: p-doped layer, n-doped layer and so on; you deposit layered structures. So, the growth is mostly epitaxy. It is epitaxial layers. There are three commonly used processes for epitaxy. So, you use Liquid Phase Epitaxy LPE - Liquid Phase Epitaxy, Vapor Phase Epitaxy also called CVD - Chemical Vapor Deposition; so Vapor Phase Epitaxy and MBE - Molecular Beam Epitaxy, Molecular Beam Epitaxy. We will not go into the discussion of fabrication here because as I mentioned, it would be different course. So, Liquid Phase Epitaxy, Vapor Phase Epitaxy, and Molecular Beam Epitaxy MBE; CVD, mocvd these are all variants of VPE.

Basically, epitaxy means growing layers on top; layer by layer growth. So, you deposit p-doped layer, n-doped layer and so on. You can also deposit material with different composition; that is you can have, you start with n Gallium Arsenide here; n Gallium Arsenide and the first layer could be n plus Gallium Arsenide; the second layer could be p-type Aluminum Gallium Arsenide Al x Gallium 1 minus x Arsenide and so on. The point is we deposit layers. Why we will go for different layers? We will see when we come to the devices, but we have to deposit layers of different compositions and band gaps. So, a structure wherein you grow layers of different composition and band gaps is called heterostructure; heterostructure.

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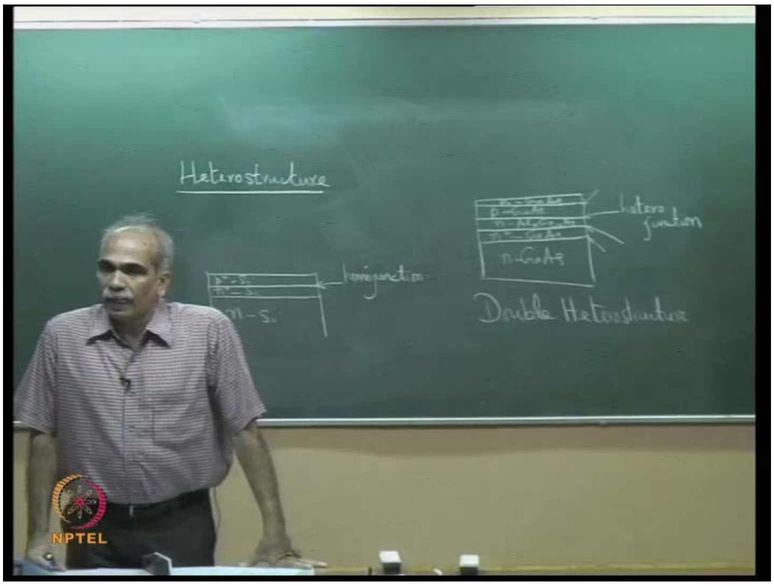

If you start with n Silicon, if you deposit n plus Silicon and then you deposit p plus Silicon, this is the junction; this is a p n junction, but of the same material a junction between p-type and n-type material, the same material p-type and n-type. So, this is called a homojunction homojunction. In contrast, if you use layers of different material and different band gaps, please see it is a p-type Silicon n-type Silicon; band gap is the same because this material is same. But if I start with let us say n Gallium Arsenide, why this n n plus? We will discuss at a later stage. n plus Gallium Arsenide and on top of this if I deposit n Aluminum Gallium Arsenide Al x Ga 1 minus x Arsenide and then I deposit again p or p plus Gallium Arsenide and then deposit another layer of p plus Gallium Arsenide, then I have, see this junction; if you see this junction, it is a junction between Gallium Arsenide and Aluminum Gallium Arsenide. It is a p n junction between Gallium Arsenide and Aluminum Gallium Arsenide.

This junction, it is a junction between Gallium Arsenide and Aluminum Gallium Arsenide. The band gaps are different. So, these are two hetero junctions hetero junction and there are two junctions in these two hetero junctions. These are homo junctions, this p Gallium Arsenide p plus Gallium Arsenide. So, this is a homo junction; this is a homo junction, but these two are hetero junctions and this structure is called a double hetero structure. So, this is a double hetero structure.

We will see that almost all the laser diodes are double hetero structures. In fact, they are also called double hetero structure lasers. So, double hetero structure. So, what is a double hetero structure? A hetero structure, where which has two hetero junctions; a hetero structure that has two hetero junctions is called a double hetero structure. We will discuss why such a structure is required and what are the benefits of this. The structure was proposed by Alphorn in 1970 who got Nobel Prize in a few years back. We will discuss more details a little later. It is a very simple proposition and a very beautiful proposition and we will see the advantages of a double hetero structure. We will discuss this in detail.

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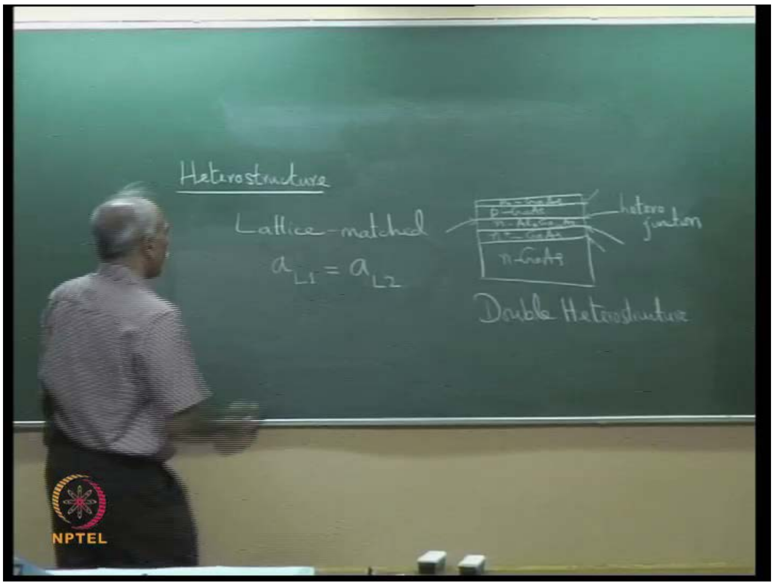

The point is when you want to grow a hetero structure, when you want to grow a hetero structure, these are two materials with two different band gaps. If the junction should free of defects, then they have to be Lattice-matched lattice- matched. If the junction is to be free of any defects, then they have to be Lattice-matched. Lattice-matched means that the lattice constant of the layer which is being grown, lattice constant of layer 1 must be equal to lattice constant of layer 2; L 1 and L 2 have just using for layer 1 and layer 2; may be let me write it as a subscript; please correct it. a L 1 is equal to a L 2 lattice constant of two layer. If they are equal, then it is Lattice-matched and that minimizes the possibility of defects at the junction. Defects are very, very detrimental to the two optoelectronic devices. How do we have a Lattice-matched growth and why it is important? We can just have a simple picture.

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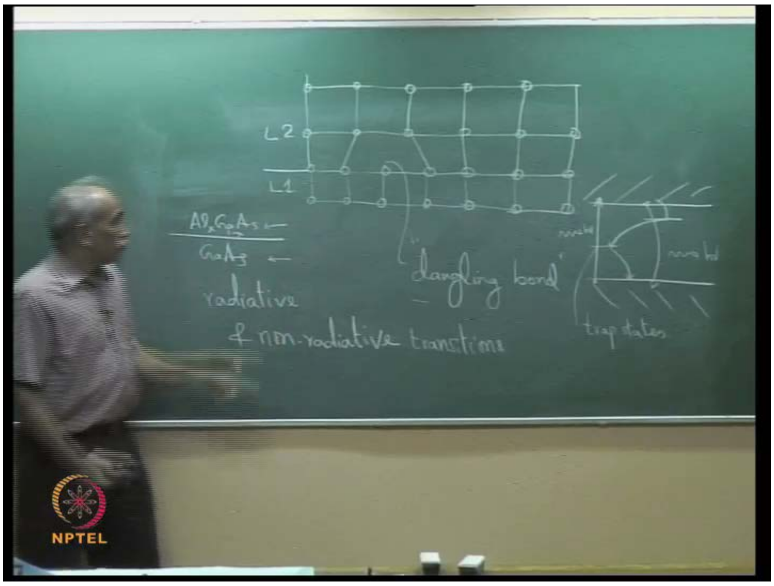

If I draw a one dimensional lattice or a two dimensional lattice, let us say, one material which has a lattice constant. I am showing you identical atoms. If it is Gallium Arsenide then Gallium Arsenide are alternate, but let me show a simple picture. So, we have, these are the bonds, the circles are atoms and on this you want to grow another material which has a larger lattice constant, let us say. So, this material should grow on this. If you grow this material on this, atom forms bond with this atom, bond is already tilted. This atom does not know whether it will form bond here or here; let us say it is forming bond here. This is forming a bond here. So, what do we see? This was one material. So, up to this, it is material one that is L 1 and this was material L 2. When we grow that to second layer on the top of this, this is a substrate let us say, then you have there are certain atoms whose bond is not complete. So, such bonds are called dangling bonds. They are hanging. They are free. There is no bond.

The dangling bonds, the electrons which correspond to these dangling bonds have energy different from those electrons which have formed bonds. Two electrons sharing have formed a bond. The electron, the energy of these electrons is different from this free electron which is here, which has not been able to form a bond. And when you see the band diagram, these states have energy different; all others have energy within the band these states may have energy somewhere in the band gap and these we call as traps; trap states. So, these behave like trap; like trap state. Trap states occur due to various reasons. This is not the only reason. There could be due to impurity dopends, substitutional impurities and interstitial impurities; interstitial impurities also lead to trap states. So, there are various reasons, but even if your, the two materials are very pure, no impurity, but if the lattice does not match, then the dangling bonds will have energy which is different from the rest of the electrons which are forming the bonds. And if the energy corresponding to these happen to be in this gap, then they are like trap states. Trap states increase non-radiative recombinations.

So, there are radiative and non- radiative transitions, radiative and non-radiative transitions. We will discuss these in more detail shortly; non radiative transitions. In optoelectronic we are always interested in radiative transition. Generally we are interested in radiative transitions, which means what is radiative transition? A transition which involves emission or absorption of a photon, an electron from the conduction band can come down to the valance band giving out a photon. An electron can also make a transition to the intermediate trap state and come down through photon transitions without emission of a photon.

In optoelectronics, we are interested, you pass a current we would like that every electron recombining with a hole; ideally you would like that emit photon because our interest is to make a source; optical source. Therefore, we would like the recombination takes place like this, giving out emission of a photon, but if it starts coming through the trap states, then the probability of emission of a photon decreases or the rate of radiative transitions decrease which is detrimental to the performance of a device; so particularly in optoelectronics.

Most of the times in electronics, we have to pass current; does not matter whether it is going through non-radiative or radiative. There are recombinations taking place which means current is flowing through the device, but in optical devices, optoelectronic devices, it is very important that non-radiative transitions are minimized. Primarily, the transitions take place radiatively, so that an emission or absorption of a photon is involved. If you have absorption an electron, if it makes an upward transition by absorption of a photon, that would be ideal emission or absorption in combination. I am referring to transition. Transition means it could be emission or absorption. Radiative means a transition which involves emission or absorption of a photon. Non-radiative, as the name indicates, does not involve emission or absorption of a photon and generally these transitions take place by phonons. So, phonons carry away the difference in energy.

So, the traps and the defects in a material reduce the radiative transition probability and therefore, we would like to keep as minimum as possible.

There are many devices where you deliberately introduce trap states. There many electron devices where you deliberately introduce trap states, but in optoelectronics it is very rare and you would not like any trap states to come in which means you would like growth where the lattice constant of the second material here is the same as the lattice constant of this so that such thing does not happen

. So, every atom finds a corresponding atom to form all completed bonds, which means the second material that you are growing. So, if I am now growing a hetero structure, which means a Gallium Arsenide and growing a layer of Aluminum Gallium Arsenide, then we would like that the lattice constant of this must be the same as lattice constant of this. I have taken an example of this, but there could be different materials.

In other words, what kind of materials can we grow on a given substrate? May be Gallium Arsenide or may be Indium Phosphide. What are the materials which we can grow? We want materials with different band gaps because we would like emission in different wave lengths. So, we would require a material with different band gaps for our application. But when we take material of different band gaps, what is the substrate that we should choose or what is the composition that we should choose and is there lattice matching or not? This is the concern when you top of Lattice-matched growth of layers. If you take simply the binary compounds, binary semiconductors, I have given a list of binary semiconductors. You see that although the band gaps are different for those different materials, but the lattice constant are also different. Therefore, we generally cannot grow a binary semiconductor on another binary semiconductor because of lattice mismatch

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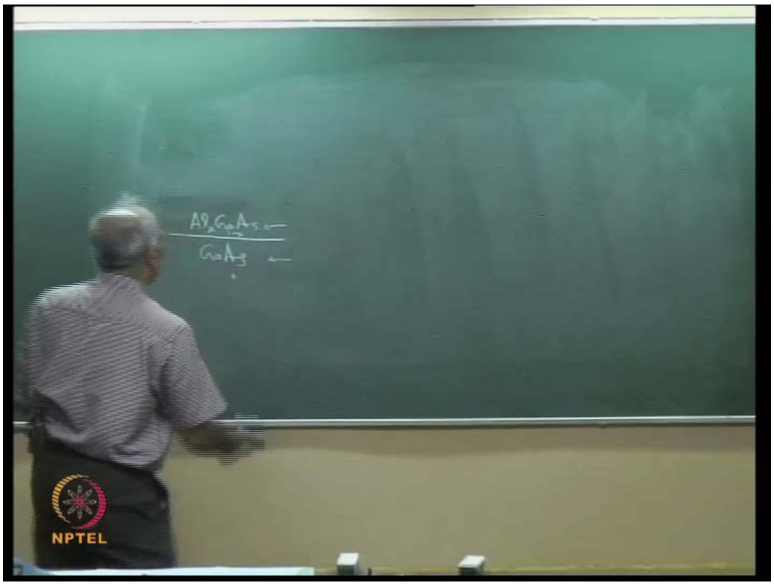

Now, how to ensure that a particular composition is Lattice-matched to a substrate? There is an important graph which is lattice constant verses energy. We will find this almost in all books which discuss hetero structures and growth of hetero structures. This is an important graph for engineers to determine which are the materials? That are Lattice-matched. Here is a list of let me show you a list of some common optoelectronic materials, particularly with emphasis in the range of optical communication, the material which are relevant to optical communication.

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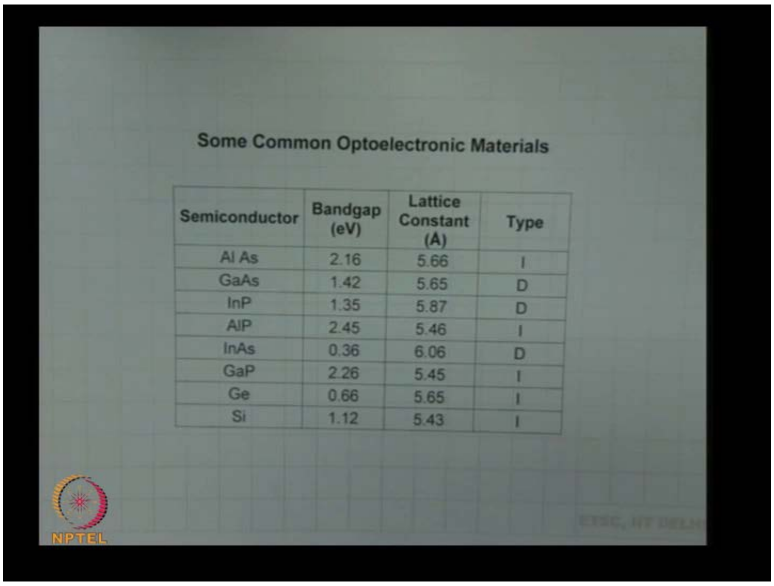

Some Common Optoelectronic Materials

Semiconductor	Bandgap (eV)	Lattice Constant (Å)	Type
Al As	2.16	5.66	I
GaAs	1.42	5.65	D
InP	1.35	5.87	D
AIP	2.45	5.46	I
InAs	0.36	6.06	D
GaP	2.26	5.45	I
Ge	0.66	5.65	I
Si	1.12	5.43	I

So, you can see Aluminum Arsenide, Gallium Arsenide, Indium Phosphide, Indium Arsenide, Gallium Phosphide, Germanium and Silicon. What I have also given here is the band gap energy and the lattice constant, and the last column indicates the type - whether it is the direct band gap or indirect band gap.

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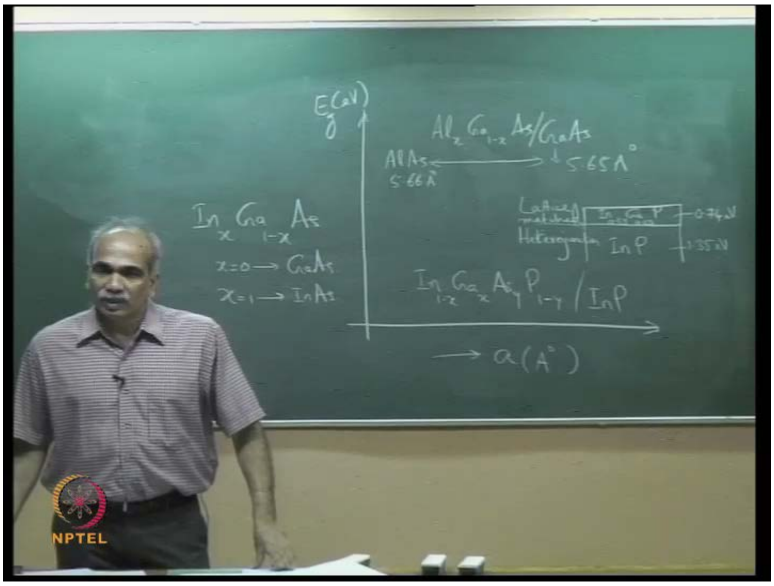

Now, a particular graph where you plot energy, band gap energy Eg in ev verses lattice constant a in angstrom. For every material that have listed here, you see the band gap energy and the lattice constant is given. So, here I am plotting the lattice constant verses the band gap energy. There are 6 materials here. So, if you pick Gallium Arsenide or let me pick one by one, and a very quick here is a plot which I have made already. So, let me show you the plot.

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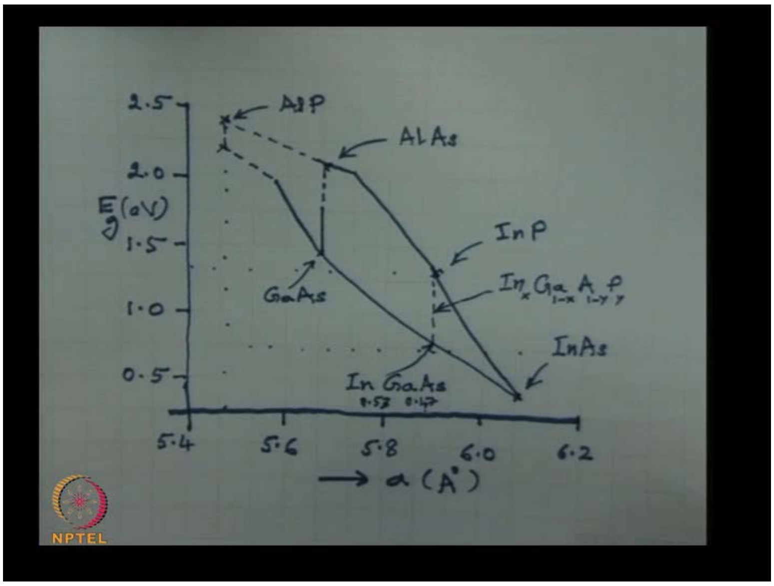

So, what I have done is simply plotted this lattice constant verses band gap. So, see the plot. Lattice constant verses Gallium Arsenide is here. Gallium Arsenide band gap energy is 1.42 ev. You can see this here 1.42; Gallium Arsenide is here 1.42 and lattice constant is 5.65. If you go down here, you can see it is 5.65; 5.65. So, the plot is simply you have x and y; pairs of x and y. Simply plot the points first and then it is linked Gallium Arsenide from here is linked to Indium Arsenide. It is not a theoretical plot; these are experimental plots.

What is this curve? This curve represents here, please see, this curve represents indium Gallium Arsenide. Why? This end is, if I write indium Gallium Arsenide indium I n x, Gallium 1 minus x, Arsenide; x equal to 0, it is Gallium Arsenide; x equal to 0 is Gallium Arsenide and x equal to 1 is indium Arsenide which means as you travel from here to here along this curve this is point x equal to 0 and this is the point x equal to 1. By varying the fraction x, if you are somewhere on this line the entire line from here to here represents various compositions of indium Gallium Arsenide. I have indicated one particular composition here of indium Gallium Arsenide.

I hope you can read the number; Indium - 0.53, Gallium - 0.47 Arsenide. This is Lattice-matched to Indium Phosphide. If you see Indium Phosphide, any compound which is remaining on the vertical line, if there are two compounds on the same vertical line which means they have the same lattice constant. So, this particular composition which has shown has the same lattice constant as Indium Phosphide. Indium Phosphide as a band gap of 1.35 ev and a lattice constant which is Indium Phosphide has a lattice constant of 5.58. That means, this particular material composition is Lattice-matched to Indium Phosphide. That means, if I start the substrate as Indium Phosphide and if I grow a layer of Indium - 0.53, Gallium - 0.47, that is x 1 minus x and Phosphide, then this is Lattice-matched Lattice-matched, but the band gaps are different.

Indium Phosphide has a band gap here 1.35 and the material Indium Gallium Arsenide has a band gap 0.74, 0.74 e v. So, band gaps are different, but lattice constant is the same which means it is Lattice-matched hetero junction. Why I have picked up this material is this is the material which is used for photo detectors in optical communication. Very high speed and extremely good detectors are Indium Gallium Arsenide detectors; Indium Gallium Arsenide. We will discuss about the photo detectors little later, but this is the material which is used. This particular composition is Lattice-matched to Indium Phosphide and the band gap of this is 0.74 e v and this is 1.35 e v.

In the last class, I mentioned about Aluminum A l x, Gallium 1 minus x Arsenide, Aluminum Gallium Arsenide, Aluminum Gallium Arsenide, Gallium Arsenide. I mentioned that most of the commercial devices use this. You can see why. By changing x, it is here, see this Gallium Arsenide is this point; Aluminum Arsenide is this point. x equal to 0 is Gallium Arsenide; x equal to 1 is Aluminum Arsenide and it so happens that the lattice constant of Aluminum Arsenide is almost same as the lattice constant Gallium Arsenide. The correct numbers are Gallium Arsenide is 5.65 angstrom and this is Aluminum Arsenide is 5.6 angstrom. Therefore, the line which you see here is almost vertical; simply vertical line linking Gallium Arsenide to Aluminum Gallium Arsenide.

Any composition remaining on the vertical line indicates that it is Lattice-matched to the substrate, but as you move along the vertical line E g is changing; y axis is E g. So, the band gap is changing. Band gap is changing with the composition, but lattice constant is not changing. So, by choosing different values of x you can have emitters that is lasers or LEDs which emits a different wave length, but you can grow Lattice-matched hetero structures. You see some dotted lines or solid lines here. Solid lines indicate the region where the material is direct band gap and dotted line indicates the region where it is indirect band gap.

In the last class, we discussed that up to x equal to 0.4. Aluminum Gallium Arsenide is direct band gap; beyond that it is indirect band gap. So, this is an important curve. I have taken a small portion of this graph as a small portion of lattice constants. If you go for Gallium Nitride Aluminum Nitride, the lattice constants are small; 3.3, 3.4, 3.1 angstroms. So, they are not Lattice-matched. Here you can do another portion for materials which are relevant to uv or infrared, they are different materials. If you go to 26 compounds like Mercury, Cadmium, Telluride then you have different range of angstroms here and this one I have just expanded. You have, see the entire x axis is 5.4 to 6.2. I have taken only a small portion because our interests are these materials which correspond to optical communication which are used in optoelectronics in optical communication.

In particular, there is a line here which is of every interest. I said that Indium Gallium Arsenide is this point and Indium Phosphide is this point. When you move along this point this line then you the material you have is indium Gallium Arsenide Phosphide. In fact, point inside this polygon corresponds to quaternary compounds because the lines are ternary compounds. Please see that corner ends are binary compounds; Aluminum Arsenide, Indium Phosphide, Aluminum Arsenide Gallium Arsenide and so on.

Corners are binary compounds. The lines which are linking are ternary compounds because binary to ternary. Lines linking are ternary compounds and inside the polygon if you go here inside, it is quaternary compounds. And this particular line here indicates Indium Gallium Arsenide Phosphide which is Lattice-matched to Indium Phosphide. So, Indium Gallium Arsenide, Indium 1 minus x Gallium x, I could write x and y in other way, Gallium Arsenic y Phosphide 1 minus y. This tells me that Indium Phosphide is the substrate and this material is Lattice-matched to Indium Gallium Arsenide. Indium Phosphide is a substrate binary compound.

You start with the substrate which is usually binary compounds in optoelectronics. In electronics, you normally start with Silicon. So, you start with the binary compound like Gallium Arsenide or Indium Phosphide and deposit these alloy semiconductors on top to make hetero structures. So, this is the material which gives you all the laser diodes for optical communication; Indium Gallium Arsenide Phosphide. All lasers in the 1.3 to the 1.55 range can be made by different compositions of x and y Lattice-matched to Indium Phosphide. We will stop here for today.