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 heterostructure and lattice matched layers, what are lattice matched layers and the continuation of that would be strained layers strained layers epitaxy which will take up in the next class.

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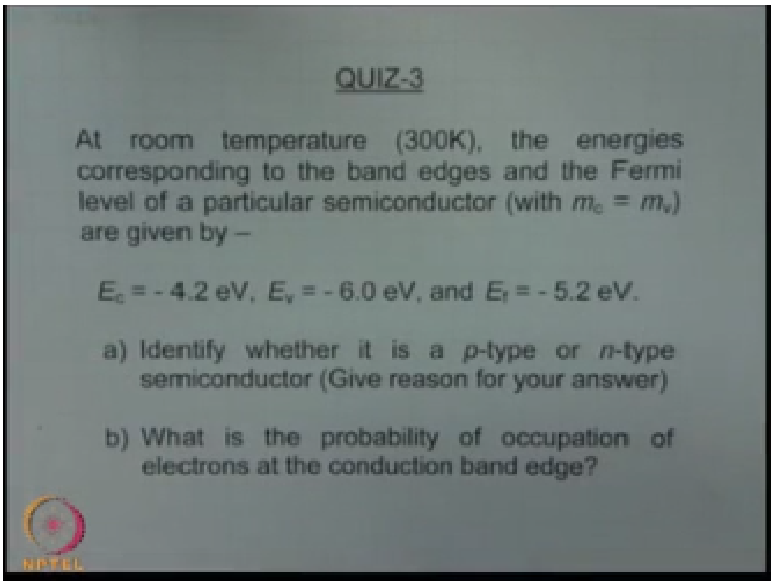

QUIZ-3

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 before I started briefly discussed the quiz that we had in the last class, so just recall the quiz at temperature the energies corresponding to the band edges and the Fermi level are given identify whether it is a t type or n type semiconductor, give reasons for your answer is a very straight forward that you just observe that the Fermi level is below half below the middle of the band gap.

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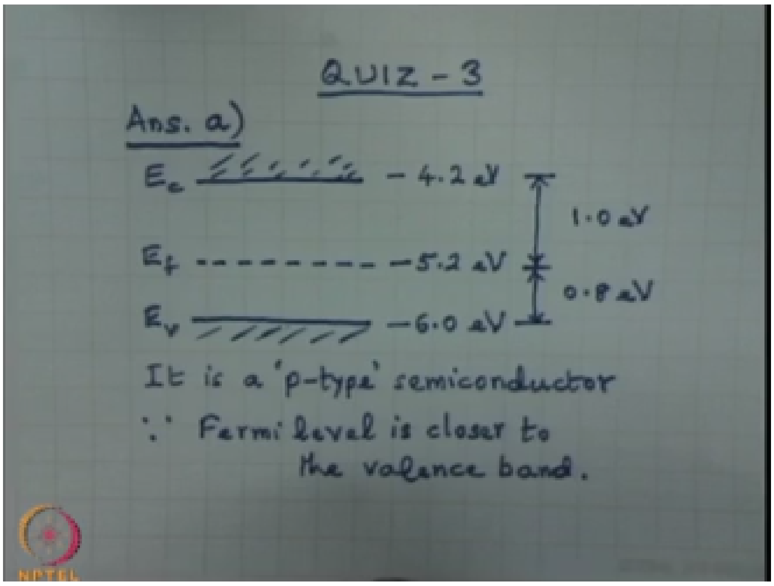

QUIZ - 3

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.

And because mc=mv if it is below the midpoint then definitely it is a p-type semiconductor, that was rather straight forward. So expected answer is here, so the given values are there. So you just show the band diagram and show that the Ef is closer to the valence band because the Fermi level is closer to the valence band is a p-type semiconductor or B of the question where you are asked to calculate.

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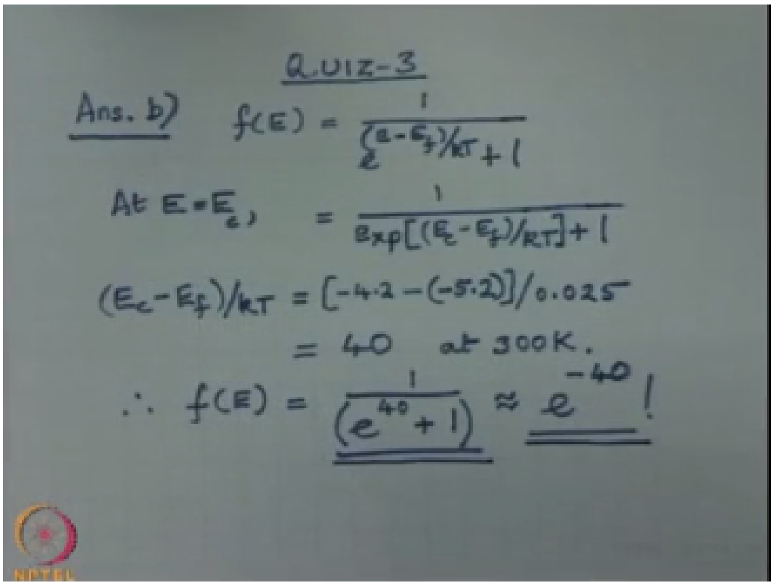

QUIZ-3

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

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

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

$= 40$ at 300K.

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

So this is a exercise to check whether you are familiar with the numbers, so to calculate the probability of occupation of electrons which is given by the Fermi function and E=Ec you simply substitute E=Ec in the Fermi function and substitute the numbers which are given and you get approximately E to the power -40. In a quiz question normally approximation are allowed to you do not need to use the calculator and get the exact values.

KT actually comes out to be around 0.4258, but I would ask all of you to use 0.425 in simple calculation because it easily cancel and get better simpler numbers. If you have to use a calculator in a quiz question calculator is not expected therefore use such number and that there is main point here is the objective of the quiz was to tell you what kind of energies one has for Ec, Ef, Ev.

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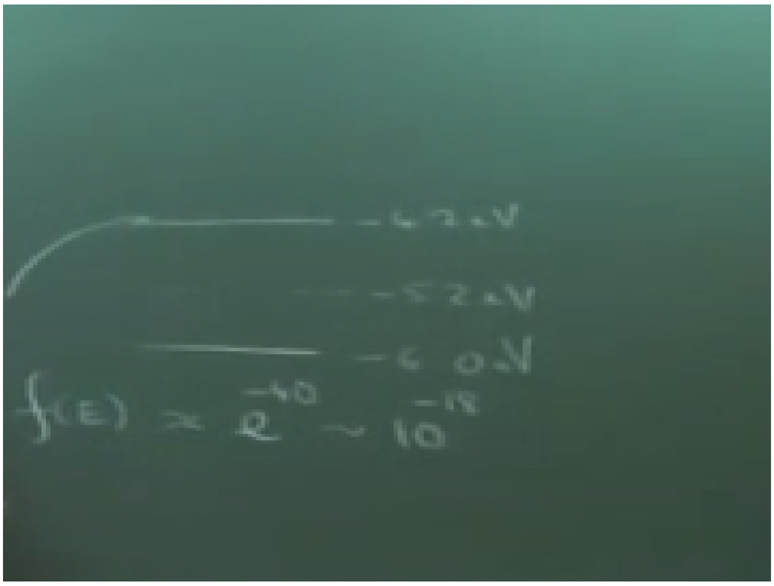

I am sure you all used the formula but how many of you have used actual value for energy for Ec, Ef, Ev, please note that the numbers are negative -4.2, -5.2 and so on, why did we give that number, so the numbers given were -4.2Ev, -6Ev, and -5.2Ev, why is this – and why is this 4 point why not 0.5 or why not 3, this is because all the states if we are considering here are bound states, bound states have negative potential energy.

You have to supply energy to free the electrons from the bond strain, potential energy is 0 is a free particle, and therefore these are all bound electrons to the semiconductor, so the typical numbers that you will encounter are these any of you knowing that the work function of materials is of the order of 4Ev, 5Ev, 3.5Ev what is work function, the 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 the text that f of E is extremely small and this came out to be of the order of a E power - 40 or of the order of 10 to the power of -17 or 18, it is extremely small but please remember it is not 0, if it is 0 then there will be no electrons.

There is no probability of having an electron, there is no electron occupying in the conduction band, note out 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 Mc or Mv 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.

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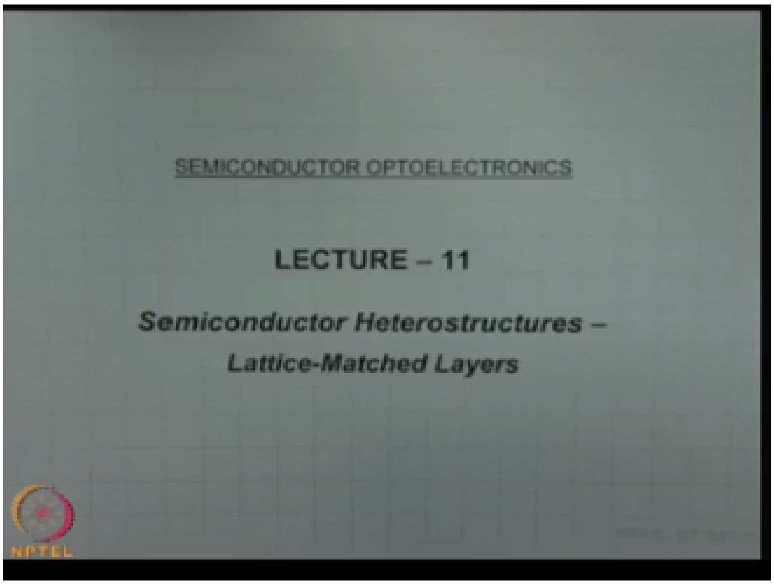

SEMICONDUCTOR OPTOELECTRONICS

LECTURE – 11

Semiconductor Heterostructures –
Lattice-Matched Layers

But you have to put real numbers to see what is really happened. So if you recall in the last class we discussed about semiconductor material and in particular we talk about ternary and quaternary compound, these are also called alloy semiconductor, what this alloy is different from doping we also have doped semiconductor, semiconductors are dropped.

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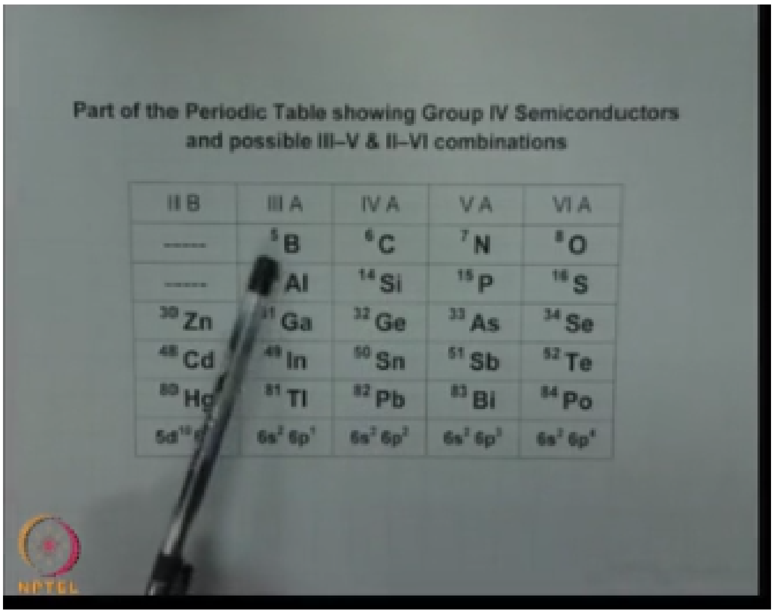

Part of the Periodic Table showing Group IV Semiconductors
and possible III–V & II–VI combinations

II B	III A	IV A	V A	VI A
-----	^{5}B	^{6}C	^{7}N	^{8}O
-----	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
$5d^{10}6$	$6s^2\,6p^1$	$6s^2\,6p^2$	$6s^2\,6p^3$	$6s^2\,6p^4$

These are doping and alloying doping versus alloying, what are the differences between doping and allowing. If you to see carefully let us look at the table which we had in the last class that table are let me put the table here. So when we want to dope silicon b type silicon then silicon is doped by boron. If you want to make it and type then you doped with arsenic normal or prosperous.

So what is the point that we see that for doping you dope the material that is you add and infinity which is from the adjacent group, this is group IV semiconductor. If you add impurity from group III it become t type semiconductor and if you add an impurity from group V it becomes n type semiconductor. The first point to know is that you add material the dopant or the substitutional element.

The substitutional element is from the adjacent group these are first point from the adjacent group adjusant, what about in the case of alloying it was from the same group aluminium gallium arsenide extraction of gallium is replaced by aluminium extraction of gallium from the same group to the first differences that substitutional element here in a alloying is from the same group.

You dope from the adjacent group second point why do you dope this to change the conductivity, you make it more conductive the conductivity is increased by doping either you dope by either case the carrier concentration increases and conductivity increases and why do we do alloying so the first point here is from the same group, what do we achieve by **by** replacing we get band gap modification.

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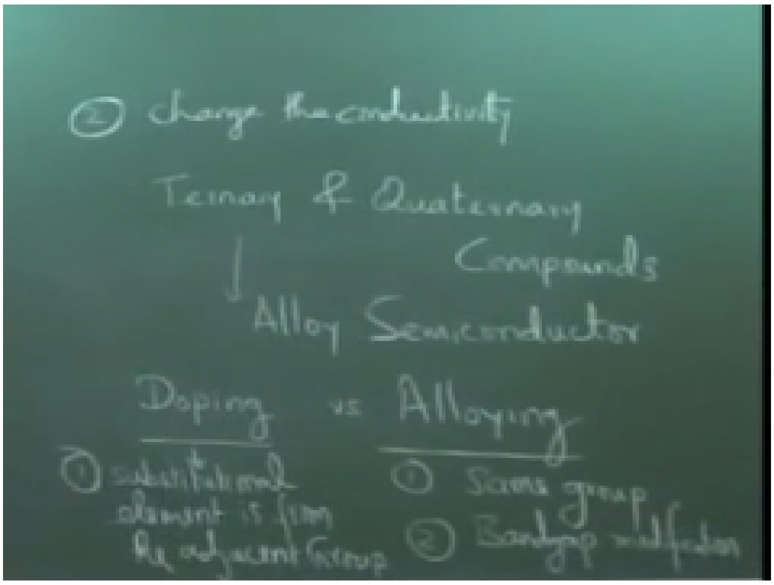

② change the conductivity

Ternary & Quaternary Compounds

↓

Alloy Semiconductor

Doping vs Alloying

① substitutional element is from the adjacent Group

① Same group

② Bandgap modification

This is for changing conductivity, this is for band gap modification, very little changes in terms of conductivity but band gap model, any other differences, what about the doping concentration, doping concentration are typically 10 to the power of 12 to 10 to the power of 19/cc. In other words the number of atoms to 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 X1 a fraction that is a 0.3 means 30% and typically semiconductors have 10 to the power of 22 atoms/cc. So 30% is also the same order. So here in this case it is of the order of 10 to the power of 22/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.

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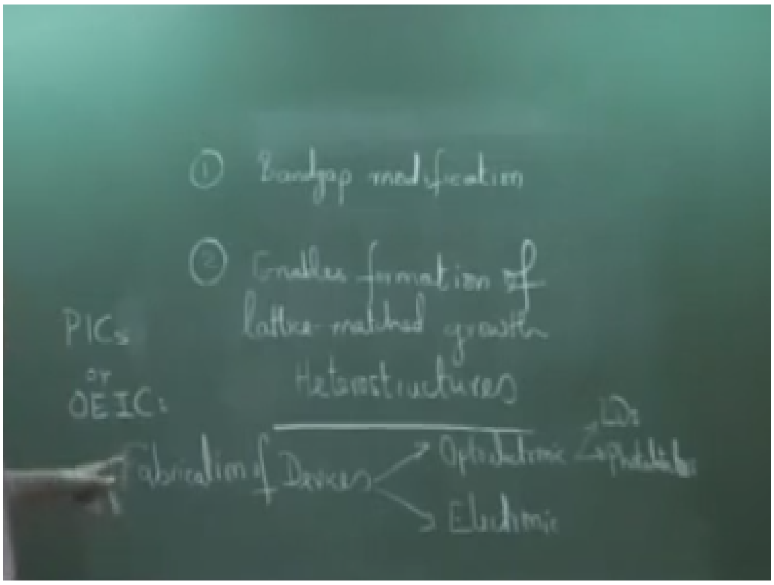

I have answering the question why do we go for alloy semiconductor, why ternary and quaternary compound, I have given 2 reasons the first reason was of course band gap modification. So we go for why go for ternary and quaternary compound. So there are 2 reasons 2 primary reasons, there are many other reasons actually from fabrication point of view there are certain design flexibilities which are provide by using additional degrees of freedom that you get.

But the most important 2 points are band gap modification, 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 have written was it enables formation of enables formation of lattice matched lattice matched growth of heterostructure enable formation of lattice match growth, enable lattice matched.

I do not need to write formation of lattice matched growth of heterostructure, so this discuss to be a second point what are heterostructure structures. Heterostructure structures are structures where you grow a semiconductor of a different type on a substrate. If you look at the fabrication of devices in electronic devices and optoelectronic devices. So optoelectronics and electronic very briefly an electronic devices.

In general optoelectronic devices are much bigger in size compared to electronic devices. You know that in integrated circuits is very large scale integration on a small chip you can have a million electronic components very large number of components on a single chip. But usually the optoelectronics devices such as laser diode, LEDs, photo detectors. These are much larger in size and typically on an optoelectronics chip or what are called as photonic integrated circuits.

Now they are called as PIC photonic integrated circuits. They are also called OEIC optoelectronic integrated circuit. I see we are familiar with IC integrated circuits in electronics exactly like that optoelectronics 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 tense of microns to hundreds of micron.

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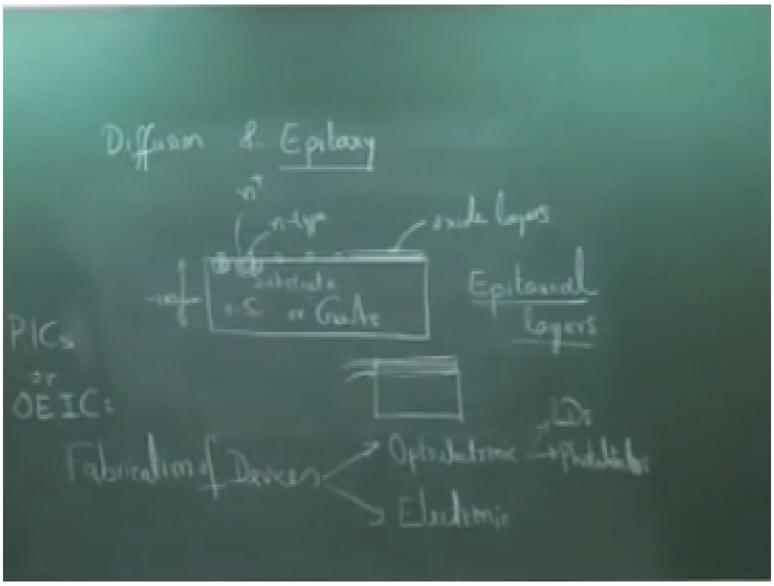

Whereas in microelectronics we have components which go to submicron. So the dimensions are extremely small of the size of optoelectronics components are very large, what is the reason, why does why is this situation. Normally in fabrication of components you start with a substrate, silicon or gallium arsenide substrate typically about 60-100 micron thickness dimensions depend typically.

And on this you grow large number of compounds, most of the electronic components which involve PN junction you can deposit the required P type and n type doping and refused to the material is diffused here and you have it is a p type dopant then the diffused region is P, you start with n silicon low dope n silicon diffuse region is beta. You deposit an n type material here n type dopant.

And diffuse it so you have a strong let us say n+, so this diffuse region is n+, you can have any number on the substrate on the surface you deposit and diffuse. So you already have a p type and n type. You can make NPN transistors or whatever. Similarly for most devices you also have to deposit oxide layer. So they are deposited in terms of layers oxide layers. So normally a chip involves in multiprocessor, many processes.

Finally when the chip comes it as pass through several stages several processes of diffusion and deposition. So these players are the layers which are deposited on top are called epitaxial layers. So basically there are two process one is diffusion and other is epitaxy, both on top, most of the electronic chips use both these processes and finally you come up with a 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 ways, we will discuss a certain device structures at a later stage, but you deposit different layers p-doped layers and n doped layer and so on. We deposit layered structure, so the probe is mostly epitaxy, epitaxially. There are 3 commonly used processes for epitaxy.

So you use liquid phase epitaxy LPE liquid phase epitaxy, vapour phase epitaxy also called CVD chemical vapour deposition, so vapour phase epitaxy and Mb molecular beam epitaxy, it will not go into the discussion of fabrication here because as I mentioned it would be a different course. So liquid phase epitaxy vapour phase epitaxy and molecular beam epitaxy MB, CD, MOCVD. These are all variants of PP.

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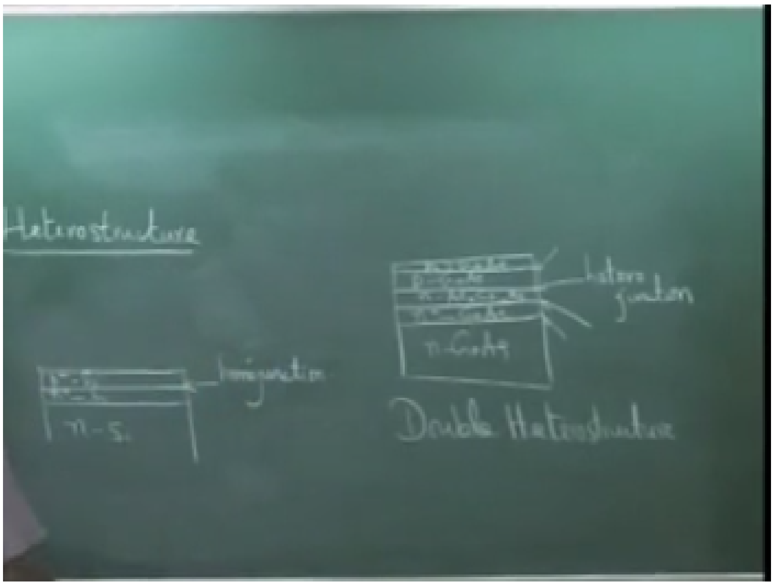

Basically epitaxy means growing layer on top layer by layer growth, so you deposit p dope layer, n dope layer and so on, you can also deposit material with different composition that is you can have you start with n gallium arsenide here n gallium arsenide and the first layer could be n+ gallium arsenide, the second layer could be P type aluminium gallium arsenide Alx gallium 1-x arsenide and so on.

The point is we deposit layers why we go for different layers we will see when we come to the devices, but we have to deposit layers of different composition and band gaps. So the structure where in you grow layers of different composition and band gaps is called heterostructure, heterostructure. If you start with n silicon, if you deposit n+ silicon and then you could deposit P+ silicon, this is a junction.

This is a PN junction but of the same material a junction between p-type and n-type material the same material p-type and n-type and this is called a homojunction in contrast if you use layers of different materials and different band gaps it is p type silicon n type silicon band gap is the same because the material is the same, but if I start with let us say n gallium arsenide.

Why this n+ we will discuss at a later stage, so n+ gallium arsenide and on top of this if I define deposit n aluminium gallium arsenide Alx Ga1-x arsenide, and then I deposited again p or p+ gallium arsenide and then deposit another layer of p+ gallium arsenide, then I have seen this junction, if you see this junction it is a junction between gallium arsenide and aluminium gallium arsenide it is a p-n junction between gallium arsenide and aluminium gallium arsenide.

This is the junction between aluminium gallium arsenide and gallium arsenide, the band gaps are different. So these are 2 heterojunctions and there are 2 junctions in this 2 heterojunctions, these are homojunction, this is p gallium arsenide, p+ gallium arsenide. So this is a homojunction, but these two are heterojunctions and this structure is called a double heterostructure.

So this is a double heterostructure, you will see that almost all the laser diodes are double heterostructure, in fact they also called double heterostructure, so what is a double heterostructure. The heterostructure where which has 2 heterojunctions, a heterostructure that has 2 heterojunction is called a double heterostructure. We will discuss why such a structure is required and what are the benefits of this and the structure was proposed by Alpharho in 1970 who got Nobel Prize in few years back.

We will discuss more details a little later which is very simple proposition at a very beautiful proposition and see you will see the advantages of hostel discuss this in detail but the point is when you want to grow heterostructure these are two materials with two different band gaps, if the junction should be free of defect then have to be lattice matched.

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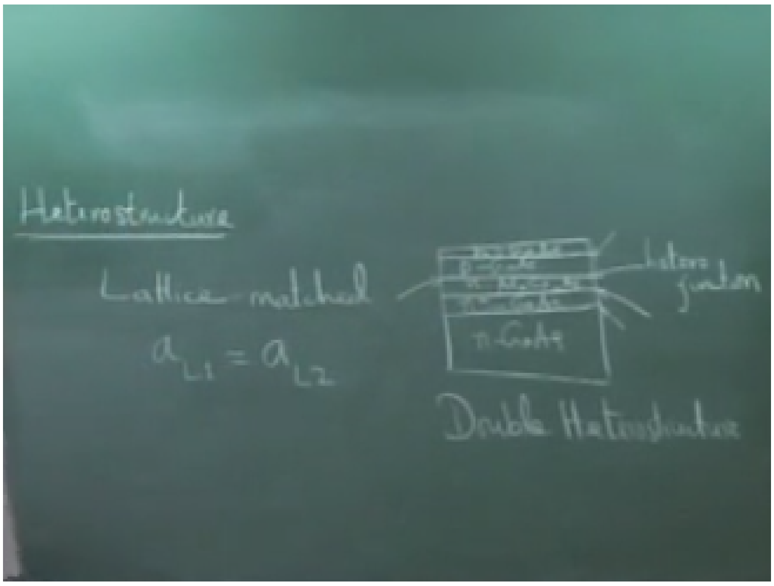

Latest match is the junction is to be free of any defects then have to be latticed matched. Lattice match means the lattice constant of the layer which is being grow lattice constant of layer one must be equal to lattice constant of layer to L1 and L2 I am just using for layer 1 and layer 2 maybe let me write it as a substrate please correct Al1=Al lattice constant of the two layers if they are equal then it is latest matched.

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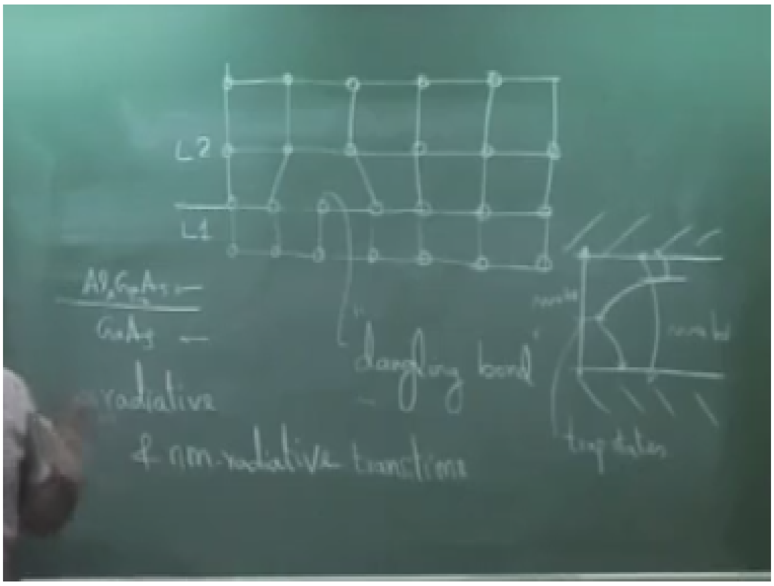

And that minimizes the possibility of defects at the junction, defects are very very detrimental to the optoelectronic devices, how do we have lattice matched and why it is important just have a simple picture, if I draw a one dimensional lattice for a two dimensional lattice let us say 1 material which has a lattice constant I am showing identical atoms if it is gallium arsenide gallium arsenide which are alternate.

But let me just show a simple picture, so we have this are the bonds, the circles are atoms on this you want to grow another material which has a larger lattice constant, let us say so when this material is grown on this, if you grow this material on this atom form bond with this, this atom bond is already created, 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 so this was one material to up this it is material one that is L1 and this was materials L2, so when we draw the second layer on top of this is a substrate let say then you have there are certain atoms whose bond is not complete. So such bonds are called dangling bonds, they are free, there is no bond, the dangling bonds the electrons which correspond to dangling bonds have energy different from those electrons which are formed bonds.

Two electrons sharing have formed a bond, the electron the energy of these electrons is different from this free electron with this here which has not been able to form a bond, and when you see the band diagrams 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 trap states.

So these behave like that like trap, trap states occur due to various reason this is not the only reason that could be due to improve dopants substitutional impurities and interstitial impurities. Interstitial impurities also need to practice, so there are various reasons but even if you are the two materials are very pure, no impurity but with the lattice does not match then the dangling bonds will have energy which is different from the rest of the electron which are forming the box.

And if the energy corresponding to these happened to be in this gap then they are like trap states. Trap states increase non radiative recombination. So there are radiative and non radiative. We will discuss this in more details shortly non radiative transition, optoelectronics we are always interested in radiative transition generally we are interested in radiative transition which means what is radiative transition.

A transition which involves emission or absorption of a photon and electron from the conduction band can come down to the valence band giving out a photon. The electron can also make a transition to the intermediate trap states and come down through phone on transmission without emission of a photon. The optoelectronic we are interested you pass a current view like that every electron recombining with a hole ideally.

You would like that emits photon because our interest is to make at source optical source. Therefore we would like recombination takes place like this giving out emission of a photon. But if it starts coming through these trap states then the probability of emission of a photon decrease or the rate of radiative transition decrease which is detrimental to the performance of the device.

So particularly in optoelectronics most of the times in electronics we have to pass current, does not matter whether it is going through nonradiative or radiative. There are we combinations taking place which means current is flowing through the device, but in optical device optoelectronics devices is very important that non radiative transition are minimised. Primarily the transitions take place radiatively.

So that an emission or absorption of a photon is involved. If you have absorption and electron if it makes an awkward transitions by absorption of photon that would be idea emission or absorption in combination I am referring to transition. Transition means it could be a emission or absorption. Radiative means a transition with involved emission or absorption of a photon.

Nonradiative as the name indicates does not involve emission and absorption of a photon and generally these transactions take place by phone on, the phone on carry away the difference in energy. So the trap 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 are many account devices new query deliberately introduced trap states, but in optoelectronics it was very rare and you would not like any trap states coming which means you would like to have growth where the lattice constant of the second material here is the same as lattice constant of this. So that such thing does not happen. So every atom finds a corresponding atoms to form all completed bonds which means the second material that you are growing.

So if I am now going and heterostructure which means on gallium arsenide and growing a layer of alluminum gallium arsenide then we would like that the lattice constant of this must be the same as lattice constant of this have taken an example of this but that would be different material. In other words what kind of materials can we grow on a given substrate maybe gallium arsenide, maybe indium phosphide.

What are the materials which we can grow, we want materials with different band gaps, because we would like different emission wavelength. So we would required materials with different band gap for our explication but when we take materials of different band gap what is the substrate that we should choose for what is the composition that we should use and is there lattice matching or not.

This is the concern when you talk of lattice matched growth of layers. If you take simply the binary compound, binary semiconductors I had given a list of binary semiconductor you see that although that band gaps are different for those different materials but the lattice constant are also different and therefore we generally cannot grow a binary compound semiconductor on another binary semiconductor because of lattice mismatch.

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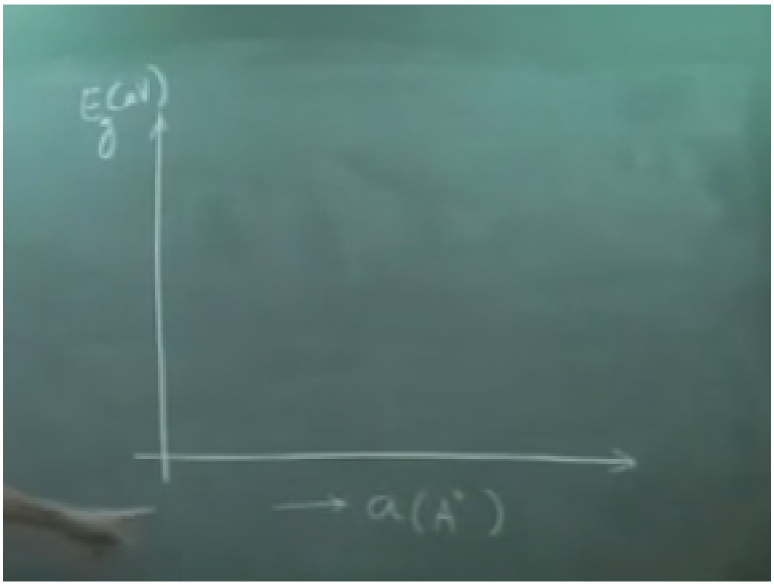

Now how to ensure that a particular composition is lattice matched to the substrate that is an important graph which is lattice constant versus energy, you will find this almost in all books which discuss heterostructure and growth of heterostructure, this is an important graph for engineers to determine which are the materials that are latest matched, here is a list of so let me show you a list of some common optoelectronic materials particularly in the emphasis in the range of optical communication materials which are very relevant to optical communication.

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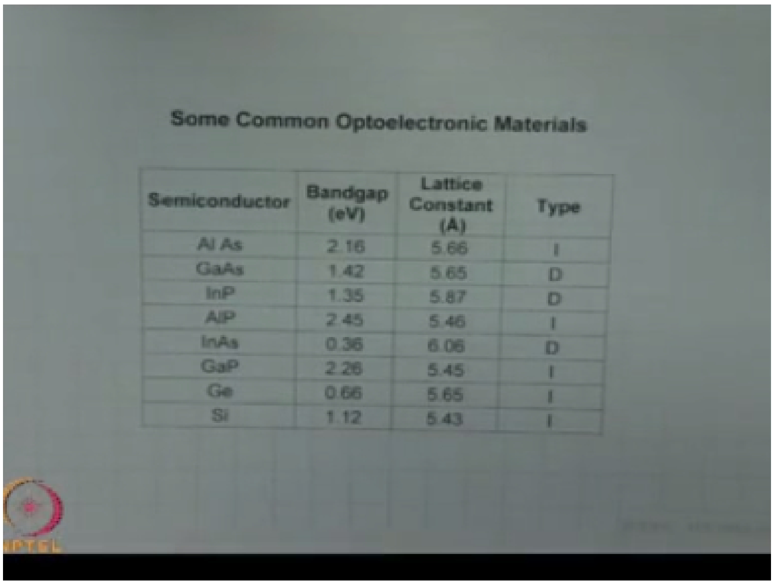

Some Common Optoelectronic Materials

Semiconductor	Bandgap (eV)	Lattice Constant (A)	Type
Al As	2.16	5.66	I
GaAs	1.42	5.65	D
InP	1.35	5.87	D
AlP	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 aluminium arsenide, gallium arsenide, indium phosphide, indium oxide, gallium phosphide, germanium and silicon. What I also given here is the band gap energy and the lattice constant and the last column indicates the type that is direct band gap or indirect band. Now a particular graph where you plot energy band gap energy Eg Ev verses lattice constant k.

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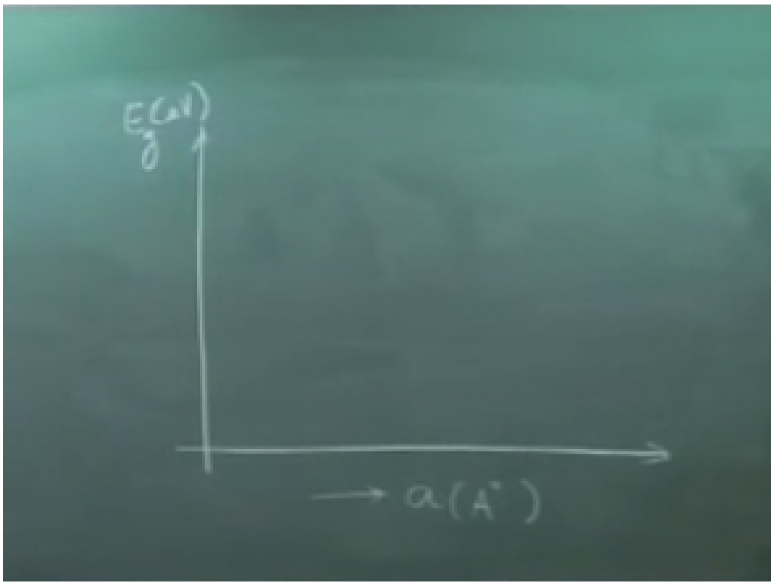

For every material that I have listed here you see the band gap energy and lattice constant is here, so here I am plotting the lattice constant versus the band gap energy, there are 6 materials here. So if you pick gallium arsenide or let me pick one by one and every pick here is plot which I have made already, so let me show you the plot, so what I have done is simply plotted this lattice constant versus band gap.

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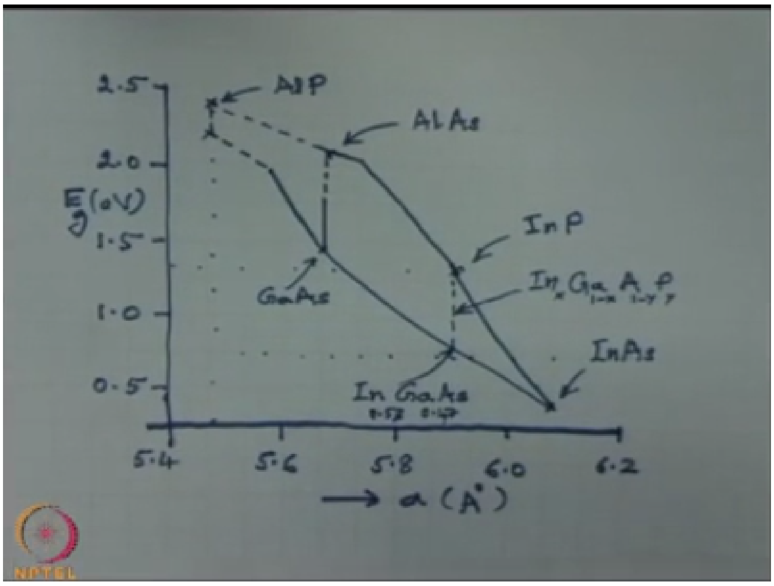

So see the plot lattice constant verses gallium arsenide is here, gallium arsenide band gap energy is 1.42 EV you can see 1.42 gallium arsenide 1.42 and lattice constant is 5.65, if you go down here you can see 5.65, the plot is simply you have X and Y packs of X and Y in simply plot the points first and then it is a link gallium arsenide from here is linked to indium arsenide. This is not a theoretical plot these are experimental plots.

What is this curve this curve represents here we see this curve represents indium gallium arsenide why this end is if I write indium gallium arsenide indium Inx gallium 1-x arsenide x=0 which is gallium arsenide x=0 is gallium arsenide and x=1 is helium arsenide which means as you travel from here to here along this curve this is 0.x=0 and this is the 0.x=1 by varying the fraction x.

If you are somewhere on this line this 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 is 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 2 compounds on the same vertical line which means they have the same lattice constant, so this particular composition which I have showed is 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 as a lattice constant of 5.8z and that means this particular material composition is lattice matched to indium phosphide.

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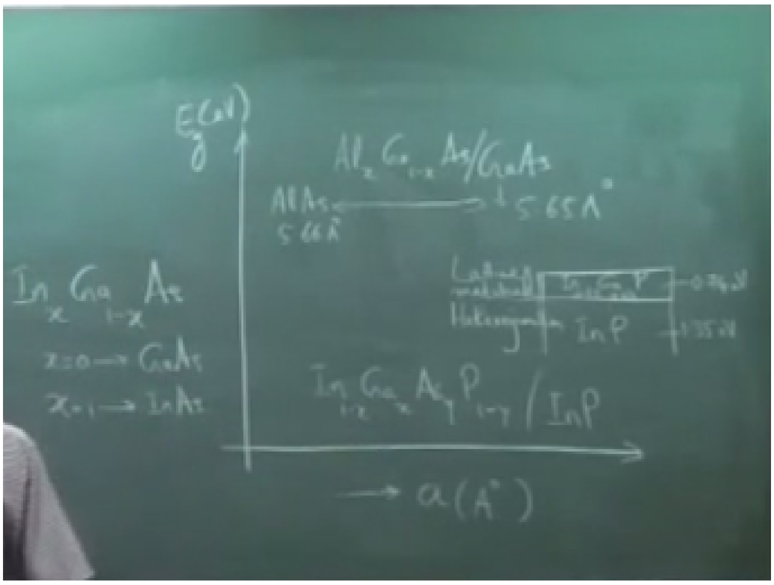

That means if I start the substrate as indium phosphide and if I grow a layer of indium 0.53, gallium 0.47 that is x 1-x and phosphide then this si lattice matched**.** But the band gap are different indium phosphide has a band gap here 1.35 and the material indium gallium arsenide as a band gap 0.74, 0.74 Ev, so band gaps are different but lattice constant is the same which means it is lattice smashed heterojunction.

Why I have picked up this material is this is the material which is used for photodetectors in optical communication very high speed and extremely good detect or indium gallium arsenide detectors, indium gallium and we will discuss about the photodetectors little later but this is the material which is used. This particular composition is matched to indium phosphide.

And the band gap of this is 0.74 EV and this is 1.35 Ev, in the last class I mentioned about alluminum Alx gallium 1-x arsenide, aluminium gallium arsenide I mentioned that most of the commercial devices use this you can see why I changing x it is here see this gallium arsenide is this point, aluminium arsenide is this point x=0 is gallium arsenide x=1 is a aluminium arsenide.

And it so happened that the lattice constant of gallium arsenide is almost the same as lattice constant of gallium arsenide. The correct numbers are gallium arsenide is 5.65 Armstrong and this is aluminium arsenide is 5.66 Armstrong, therefore this line which is here is almost vertical, simply vertical line linking gallium arsenide to aluminium gallium arsenide and any composition which is remaining on the vertical line indicates that it is lattice match to the substrate.

But as you move along the vertical line Eg is changing y-axis is Eg, so the band gap is changed. Band gap is changing with composition but lattice constant is not changing. So by choosing different values of x you can have emitters is laser for LED which emit the different wave length, but you can grow lattice matched heterostructure. You see some dotted lines and solid lines here.

Solid lines indicate the region where the material is direct band gap indicate the region where it is indirect gap. In the last class we discuss that up to X=0.4 aluminium gallium arsenide is direct band gap and beyond that it is indirect band gap. This is an important curve I have taken a small portion of this graph has a small portion of lattice constant. If you go for gallium nitride, aluminium nitride the lattice constant are very small 3.3, 3.4, 3.1 Armstrong

So they are not lattice match here, you can go to another portion for materials which are relevant to UV or infrared the different materials if you go to 2, 6 compounds like mercury cadmium telluride then you have a different range of Armstrong here and this one, I have just expand to receive the entire access this 5.4 to 6.2, I have taken only a small portion because our interest are these materials which correspond to optical communication which are used in optoelectronics and optical communication.

In particular there is a line here because of very interest I said indium gallium arsenide is this point and indium phosphide is this point, when you move along this point this line then you the material that you have is indium gallium arsenide phosphide, in fact why inside this correspond to quaternary compounds because the lines are ternary compounds please see the corners ends are binary compounds.

Aluminium arsenate, indium phosphide, aluminium arsenate, 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 compound and this particular line here represent indium gallium arsenide phosphide which is lattice match to indium phosphide.

So indium gallium arsenide indium 1-x, gallium x I could write x gallium in other way gallium arsenide white phosphide 1-y. This tells me that indium phosphide is a substrate and this material is lattice matched to indium gallium arsenide, indium gallium phosphide is the substrate binary compound, you start with the substrate which is usually binary compound in optoelectronics.

In electronics you normally start with silicon, so you start with the binary compound like a gallium arsenide or indium phosphide and deposit these alloy semiconductors on top to make it restart. So this is the material which gives you all the laser diode for optical communication indium gallium arsenide phosphide all lasers in the 1.3 to 1.55 range can be made by different compositions of X and Y lattice matched to indium phosphide full stop here.