High Speed Devices and Circuits

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Lecture – 5

Ternary Compound Semiconductors and their Applications (Contd)

Last time we discussed some aspects of ternary compound semiconductors and some applications. Today, we will continue with that because there are few more things that we want to touch up on.

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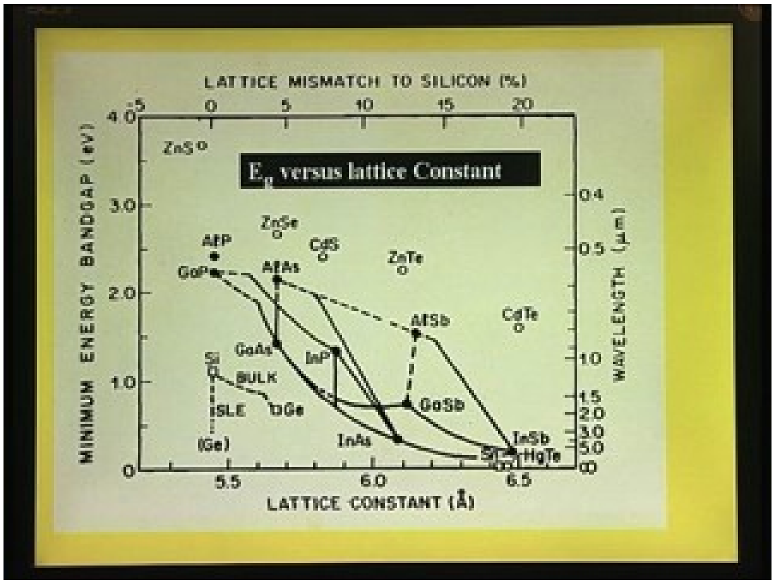

E_g versus lattice Constant

We are putting back this diagram from last lecture to refresh your memory. We have already discussed, y-axis is the energy bandgap and x-axis is the lattice constant and wavelength. We have also pointed out that the wavelength is related to the energy through a relation lambda is equal to 1.24 divided by energy. So, as the energy goes up lambda goes down. If you want shorter wavelength, you must have higher energy bandgap because shorter wavelength have higher energy (02:14). Now, what I just did not point out last time was this axis, that is, lattice mismatch with reference to silicon.

Everywhere it is in terms of silicon because silicon is the ruling king in the microelectronics today. If I want to see what the status with reference to silicon is, for example, silicon at 0 lattice mismatches, that is, lattice constant is 5.45 also 5.43 for other materials also.

For example, you can see, right on the top gallium phosphide is there, which means, I can arrange gallium phosphide on silicon. I can grow gallium phosphide without hurting or without having any defects. Epitaxial layers – the layer one over the other; epitaxial is the term used for arranged upon. You can arrange atoms; the same arrangement has the substrate provided the lattice constants are same. Now look at gallium arsenide, it is about 5.65 lattice constant, about 4% to 5% lattice mismatch is there. So, it makes it difficult to grow gallium arsenide on silicon.

You would be very fortunate if you were able to grow gallium arsenide on silicon because we can have silicon for many of the microelectronic devices. You can have gallium arsenide for high-speed part of it or up to-electronics part of it. It would have been very fortunate. Unfortunately, it is not so, but still there are lot of efforts put forward to grow gallium arsenide on silicon. People have done that not with great success but to some degree of success. One of the people who have been trying or with whom the work was going on was the legendary figure on compound semiconductors - Surab Gandhi (4.26). He was the one, way back from 1970's started working on growth of gallium arsenide. He was trying some of those works. Now he is retired of course, but still some work continues on that.

You can see some other material - gallium arsenide; we can grow aluminum arsenide on that or compounds of aluminum gallium arsenide, we saw yesterday - gallium phosphide and gallium arsenide. You can match and grow aluminum gallium arsenide compounds on gallium arsenide, because, as we vary add aluminum to gallium arsenide, it moves towards aluminum arsenide, but lattice constant is same. This is because tetra hetero radius of aluminum is same as the tetra hetero radius of gallium; arsenic is common, so the lattice constant is same; practically same. If you argue, some people may say, slight mismatch; still, it is almost same. We did not mention this last time, but if you want to grow on silicon, it is difficult.

You see indium phosphide mismatches much more; it is hopeless situation. If you want to grow indium phosphide on silicon, but if in case you need, you have another material, which is a composition of that is the ternary compound - gallium arsenide and indium arsenide. If you mix, it becomes gallium indium arsenide. We started on that yesterday, but rushed through it. Today, we will take a detail look into it. What happens is, if we adjust the gallium concentration and adjust some value, we can get gallium indium arsenide lattice match to indium phosphide. This is a very useful material. This is what we want to see today. We will also see mixing aluminum to gallium arsenide - aluminum gallium arsenide. These two are very powerful or useful ternary compounds. This is what we are trying to point out.

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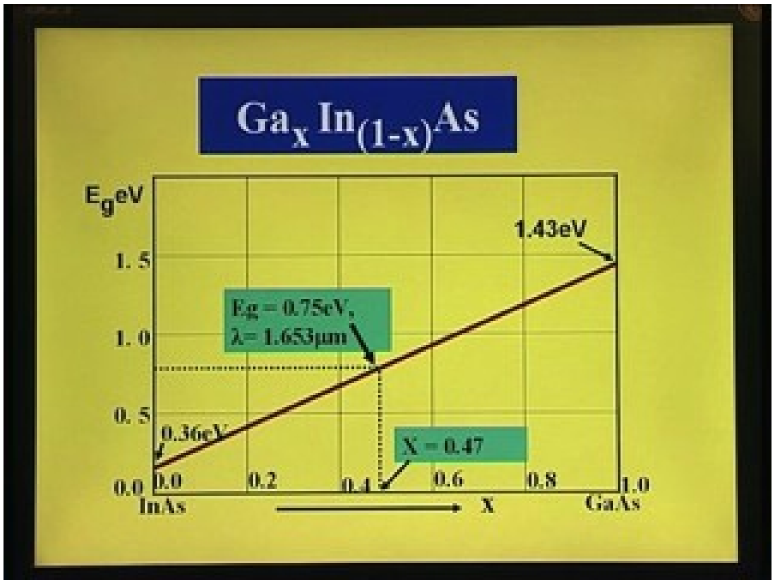

$Ga_x In_{(1-x)}As$

This is the energy gap on the y-axis versus x-axis. X is the gallium mole fraction. In gallium indium arsenide, if X is equal to 0, then gallium (Ga) is 0, you get indium arsenide. We are probably repeating some aspects, but since we went hurriedly in the previous lecture, we are going through it again. If, x is equal to 1, indium is 0; the total is gallium arsenide.

Both are direct bandgap, so we mix them together for whatever is the composition, you must get direct bandgap. You can use it for photonic applications or opto-electronic applications very easily, because the transition of electrons can be met with by emission of the photons light. Bandgap is 0.36 electrons volt for indium arsenide, but the bandgap for gallium arsenide 1.43 electrons volt. If you mix it, such that x is equal to 0.47, gallium is 0.47 and indium is 0.53, then we get gallium indium arsenide in that composition. That particular compound has got a bandgap of 0.75 electrons volt and it corresponds to 1.24 divided by 0.75, which is actually equal to 1.653 microns.

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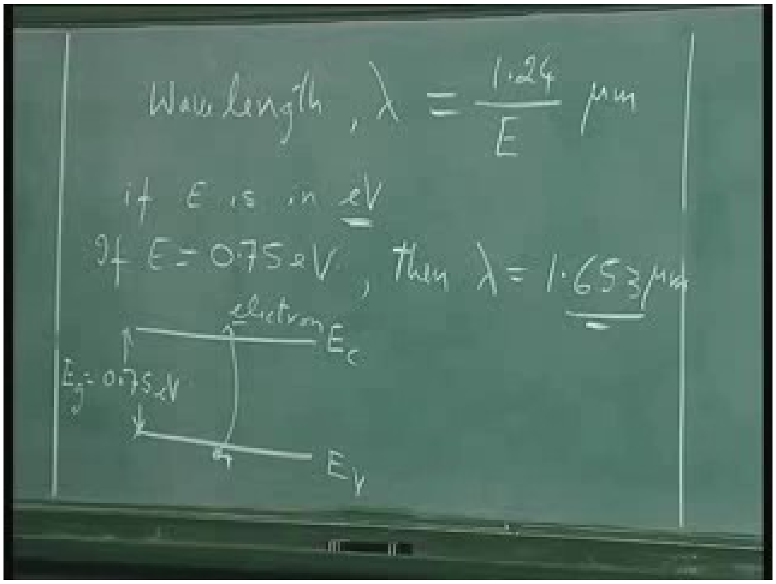

Wavelength, $\lambda = \frac{1.24}{E}$ μm

if E is in eV

If $E = 0.75$ eV, then $\lambda = 1.653$ μm

What are so great about 1.653 microns? Suppose, we are making a diode, it can be used as a detector for wavelengths up to that particular thing. Wavelength, lambda is equal to 1.24 divided by E – so many micrometres, provided E is in electron volt. This is the direct formula which comes out as a result of the relationship E is equal to h mu. If E is equal to 0.75 electron volt, then lambda is equal to the wavelength is equal to 1.653 micrometers. The question is what is the meaning of this? The meaning of this is – for example, if we have the bandgap, that is E_c minus E_v is 0.75 electron volt; then the photons having energy greater than 0.75 electron volt will be absorbed creating a hole electron pair, that is plus charge and an electron. The wavelength of these photons corresponding to this 0.75 electron volt is actually 1.653 micrometres.

If the energy of the photons is less than 0.75 electrons volt, it implies that the wavelength of the photons is actually more than energy that means, lambda is more than 1.653 microns. What we are saying is, if the photons have energy less than 0.75 electrons volt, it will not be able to raise the electrons from the valence band to conduction band. That means, the photons will not be absorbed. So, what we are telling again, if the wavelength is energy less than 0.75 electron volts and the wavelength is more than 1.653 microns and the photons will not be absorbed and it will just be transparent; it will go through the material completely.

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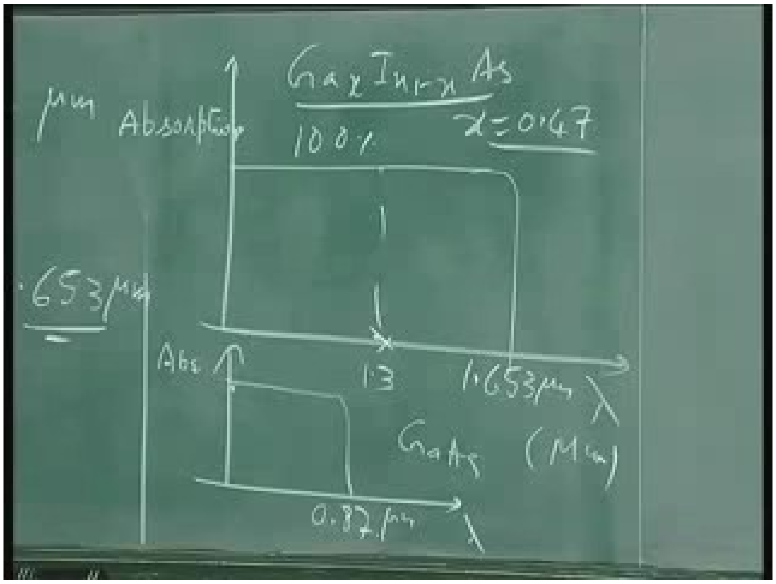

Therefore, if you say 1.653 is the wavelength beyond which it will not be absorbed, what we imply is the absorption coefficient versus lambda in micrometers, what happens is, the wavelength is equal to 1.653 will be absorbed 100% of the photons. It means it that, it will create hole electron pairs whether it give rise to current is a different matter. So, it will create hole electron pairs, till the wavelength is 1.653 micro ohms, for this situation. Therefore, longer wavelength will not be absorbed; it will be just transparent.

Why are we so much particular about this wavelength? What we are saying is the photons having wavelength within that particular value are used in the optical communication – fiber optics. There, the lambda that is used for communication purpose is 1.3 microns or

1.5 microns, because at 1.3 microns and 1.5 micron the (13:48) is minimum and dispersion is also minimum. Because of that they should be able to use a detector, which will actually absorb wavelength of about 1.3 microns or 1.5 microns. So, if the wavelength is 1.3 microns, somewhere here, absorption will be 100%.

This particular material – gallium indium arsenide with gallium x indium one minus x arsenic, that material can be used to realize the detector, provided x is equal to 0.47. That is, if the mole fraction of the gallium is 0.47, then it can be used for making the gallium indium arsenide diode, which will actually respond to the wavelength, which is within this particular value. In optical communication taking this wavelength particularly 1.3 microns and 1.5 microns, that is the two windows that they are using. This is a very useful material for making the diodes for the fiber optical applications. In gallium indium arsenide, if you use gallium arsenide, the cut off wavelength is much smaller than that, because the bandgap of gallium arsenide is 1.43. Therefore, the lambda corresponding to 1.43 electrons volt is 0.87 microns.

So, if you make a gallium arsenide diode and if you use it as detector that will actually stop absorbing – absorption versus lambda for gallium arsenide, if we plot, it will go like this, 0.87. So, if the incoming photons has wavelength 1.3, it will not absorb in that particular thing. The gallium indium arsenide diode should be made for realizing a detector for fiber optic applications. What we will see is how this can be made use of to absorb and generate current. We will see how diode can be fabricated, how a diode structures schematically make with gallium indium arsenide p-n junction.

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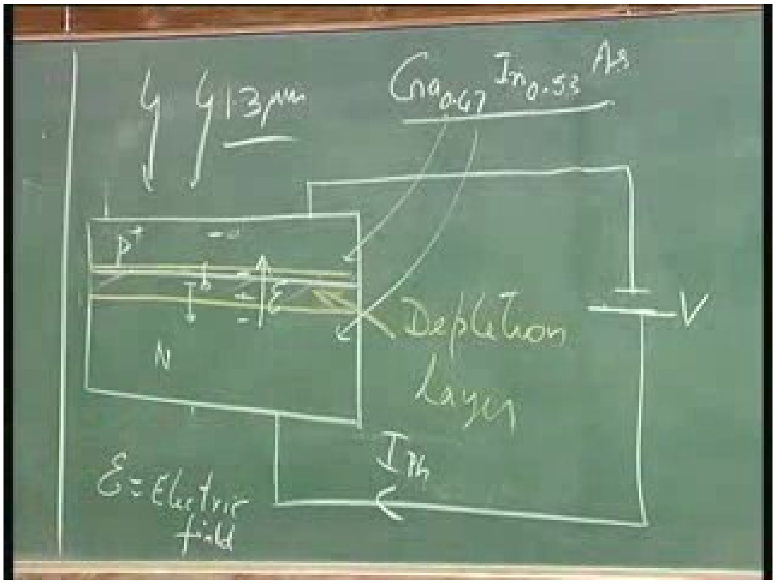

We make a diode, you make a p plus n diode and both made up of this material both. We are just showing a schematic diagram, which actually is that 1.3 wavelength. If you are connecting a fiber on to that which is about 10 micron uncladded, including cladding is about 120 microns and align it to this junction. You also have to bias this, reverse bias it. The whole idea is the hole electron pairs which are generated should be separated. When we separate them the current flow will be in the external path like the solar cells. Suppose, this falls here, from there we know, if this is 1.3 microns wavelength; definitely hole electrons pair will be created. When it is created, they are in the vicinity of the each other; if nothing separates them, they will recombine. What we should do is, the hole electrons pair should be generated in a region where there is an electric field that is the depletion layer. If you take a look at this particular region, we will just put a light colour here that is the depletion layer. If this falls on the depletion layer, what is the fate of the hole electrons pairs are created? Where is the electric field? Plus here, minus there; so the polarity of voltage is like this. The electric field is in this direction. E is the electric field. This is the voltage we are applying reverse bias. This electric field is, plus here minus there. So, the hole electron pairs which are generated here, they have no time to recombine, because before they decide to recombine, the electric field pushes it in this direction, this pushes in this direction.

If you take any cross section, if you take this cross section there, it is only the hole which is giving rise to current. If you take on this side, it is only the electron. It is only one charge either hole or electron plus q or minus q, either way, the current flow direction is the same. Hole move in this in that direction gives rise to current in that direction. Electron moving in this direction also gives current in that direction. In the external circuit, current is in this direction I photon – current due the photons. If 100 photons for impinging, you will get 100 hole electron pairs, giving rise to current, provided all of them are generated within that. If they generated outside here, the chance of being collected on the external circuit is zero or small.

If out of 100 photons, if 50 of them fall here within this region, the other 50 of them will not be giving rise to current because they will recombine. The quantum efficiency, which is the number of hole electron pairs which are available for current flow divided by number of photons; but there is a quantum efficiency, hole electron pair not generated hole electron pairs which are available for current flow, if they recombine, there is no point; so that is the quantum efficiency. It is a jargon term used by physics people. It is how much current flows for so many photons which (21:18). That is the ratio it is a figure of merit.

The problem in this type of structure is if this layer is thicker, what will happen? Most of them will fall here, most of them will recombine, and the current will be very small. The sensitivity of this detector will be small. You have to optimize this thickness. You have to reduce it. We must have a finite thickness, no doubt. You have to have at least 0.1 or 0.2 micron within which quite a bit will be absorbed. You cannot say you will make it 0; it means no reaction. The key thing to do is to use your ingenuity, come up with another semiconductor at the back side and inject light from the back side. This will be a very powerful technique. That is what we were trying to mention.

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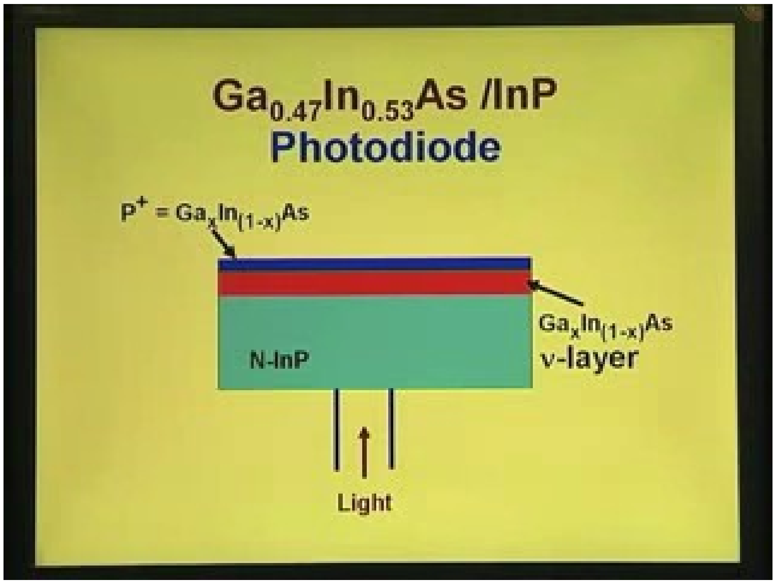

$Ga_{0.47}In_{0.53}As$ /InP

Photodiode

To avoid recombination this layer, what we do is you change the entire structure now. The above diagram is the diagram of the detector. Instead of making the entire p-n junction with gallium indium arsenide, we use the substrate, which is indium phosphide – n type; use the p type region gallium indium arsenide. Instead of making a p-n junction both of gallium indium arsenide, you make a p-n junction, consisting of gallium indium arsenide and indium phosphide. Let us see what the indium phosphide will do.

Notice here, instead of shining light from top, in this case you have connected on the back side the fiber – the blue things is the fiber; you have connected that on back side, light is connected to that. We have shown it small, because the fiber is just about 9 to 10 microns uncladded but when we clad them it may be 120 microns. What happens to the light, which is coming here on the back side? The junction now is here; this is a p-type and this we marked it as new layer. What is new layer? New layer is n layer, very lightly doped. In the previous lecture, we wrote it as intrinsic deliberately, because we did not want to confuse the issue at that time. It is actually very lightly doped region.

If you have very lightly doped region, what happens? This is P plus; this is N layer. The depletion layer will be occupying completely this layer. Take this N layer doping, something like 10 to the power of 17; does not matter and take this as 10 to the power of

19 or so; this is very lightly doped. If we reverse bias that, make this region negative and this region positive. Here, we have got from bottom side indium phosphide and on the top side, it is the p layer, we have P plus and a new layer and the new layer is very lightly doped. That layer can be a micron. Now, what happens when a wave length comes into this? Let us see.

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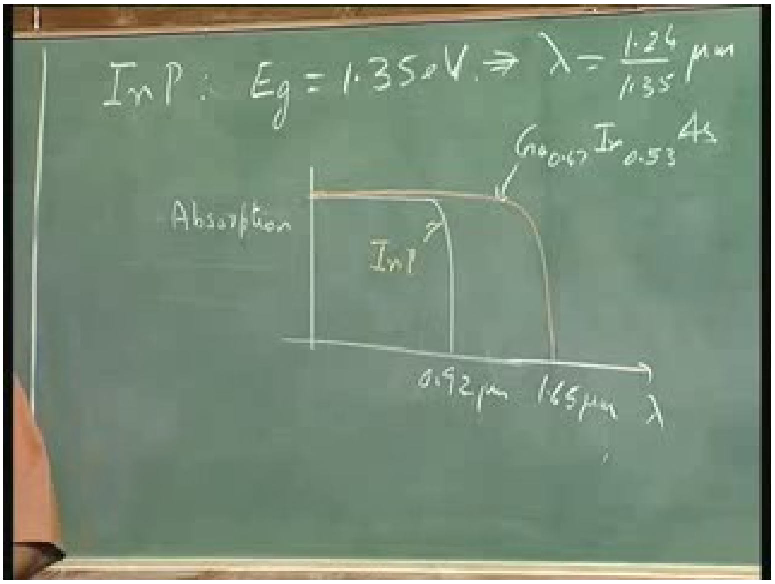

In indium phosphide, what is the bandgap? It is 1.35 electrons volt. What is the cut off wavelength? Lambda corresponding to that is 1.24 divided by 1.35 micrometer, which is actually equal to 0.92 micrometer. What does it mean? If we have lambda versus absorption, up to the wavelength of 0.92, energy is greater than that – smaller wave length larger energy. Therefore, it will go like that. At lambda equal to 0.92 microns beyond that point, if we have light falling wavelength, it will not absorb. It is transparent for wavelength greater than 0.92 microns. Now, this wavelength is of no interest for us. If you use indium phosphide, on this side and if a light of whatever wavelength comes in, until the wavelength is about 0.92, it will be absorb. It is because the energy is greater than 1.25 electron volts; it will be absorbed by, on this layer. If it is thick layer of 200 micron, if it is absorbed there, it is lost by recombination.

If you do not care about this, in fact this is very good, because some other light coming, it is suppressed there. So, up to 0.92 microns, this is absorbed. Beyond that point, if a wavelength is more than that, indium phosphide is transparent. It means, this layer is empty layer, as if the layer is absent. When the wave length is more than 0.92 microns, the light goes through all the way and picks this lightly doped new layer. The lightly doped new layer is depleted. Why it is depleted? Doping very low concentration depletes layer of 1 micron very easily. The entire red colour portion is depleted. The electric field is actually in this direction, from bottom to top. Wavelengths, which are greater than 0.29 micron, will regenerate this. Once it hits it, it generates hole electron pairs because that can be absorbed. This is for indium phosphide.

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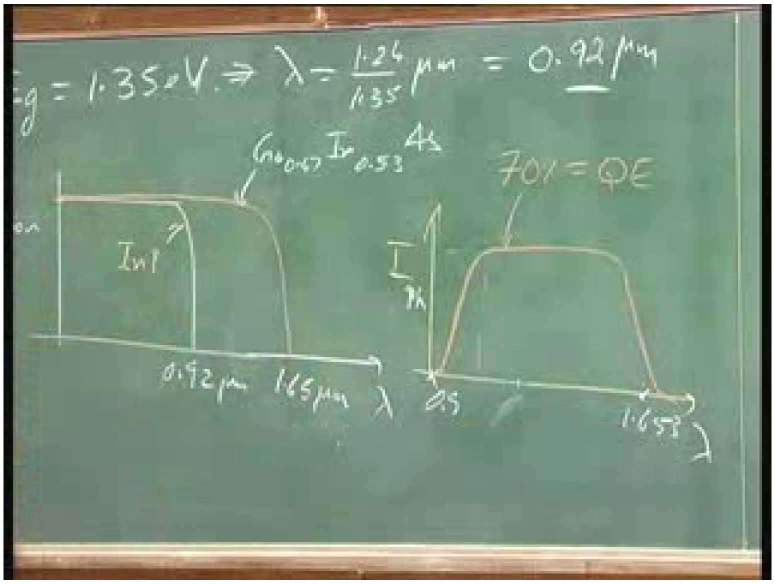

For indium arsenide, we saw what it was like; we will put it like this that is the cut off. This is 1.65 microns; it is the cut off point for the indium phosphide; gallium 0.47 indium 0.53 arsenide. Now, can you tell, if we have bottom layer consisting of indium phosphide and the top layer consisting of gallium indium arsenide; if the light comes in from bottom up to this wavelength, it will not reach that. It is not reaching that because it absorbs right here. However, beyond that 0.92, it will be absorbed here. You actually have a window current, so whatever is generated here will give rise to current, though it is electric field. So, till that point, till lambda equal to I photon for this diode, but we are sure a detector will be till lambda equal to 0.9, up to that there is no current. We have put it out as 1.65;

up to 0.92, it is absorbed by indium phosphide, no current. Beyond that point, it starts coming up like this; gradually goes up there steeply and becomes like that. The I photon, in fact this will be about 70% quantum efficiency. QE is the quantum efficiency current generated due to one photon, hundred photons are generated in that layer. Some of them escape, because they are just generated near the edge, so you get about 70%. That is, 70 hole electron pairs are created and all of them gives rise to current.

This is actually a window. If we have a window, right from our 0.92 to 1.6 microns, where you will get the current – it will be sensitive to that. This is very powerful technique for using device or used in fiber optic application, where you need some air filling that region. If you want 1.3 or 1.5, this can be used. In fact, we are happy to say that, in the EE department in the microelectronics laboratory, a device has been made like that with gallium indium arsenide on indium phosphide. You need to actually do lot of passivantion (31:38) work etc., which may come up, when we discuss in the later stage. In this, when we talk about little bit of technology, that sought of device has been made.

Including connecting this fiber on the backside, you etch on the back side so that the fiber is connected on that. In fact, we were trying to get one device today, but somehow were not able to, because they handed over it to the company in Hyderabad. We just made prototype, just few of them and handed them over. They were very happy. The signal output that you get there, the current through the diode that will be quiet large, but still if we want amplification, we can put amplifier. Therefore, what people like to do is, the detector and the ftp amplifier can be put together. That is something, which we are looking into now.

The idea of putting the indium phosphide layer on the substrate is what is the benefit you get? You do not have to worry about this particular junction type, because you choose this about 1 micron; when it comes from this end right up to this, almost everything is absorbed. If it is not absorbed, little bit loss will be there. That is a small loss you will get. That is the key; you do not have to worry about the thickness of the junction there. This presence of indium phosphide layer, automatically decides, the moment the wavelength is more than 0.92, it is available for hole electron pairs. This is very powerful technique.

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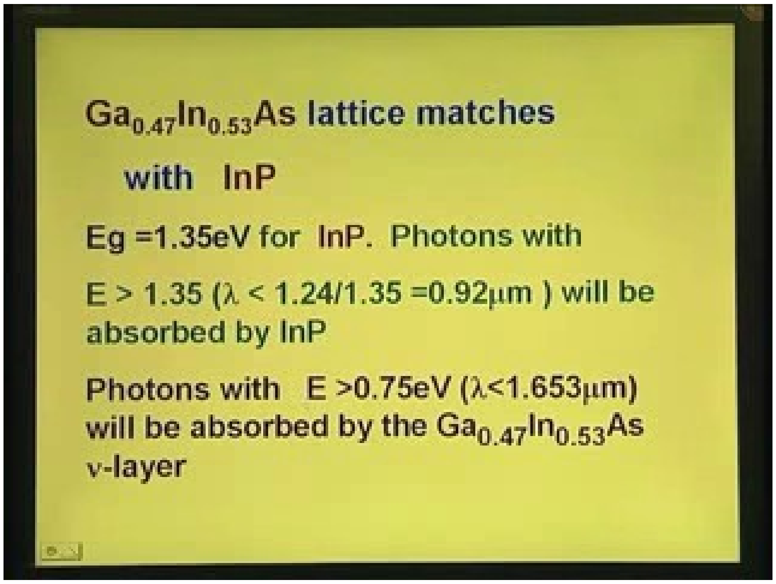

$Ga_{0.47}In_{0.53}As$ lattice matches with InP

Eg =1.35eV for InP. Photons with

E > 1.35 (λ < 1.24/1.35 =0.92μm) will be absorbed by InP

Photons with E >0.75eV (λ<1.653μm) will be absorbed by the $Ga_{0.47}In_{0.53}As$ ν-layer

This is all we have said today. We have written those things about the bandgap, lambda 0.92 micron; photons with energy greater than 0.75, which will be absorbed by the high layer; that is lambda in this region, below that it will be absorbed, we will get that thing. Without the slide, I have just mentioned that with the help of the board there.

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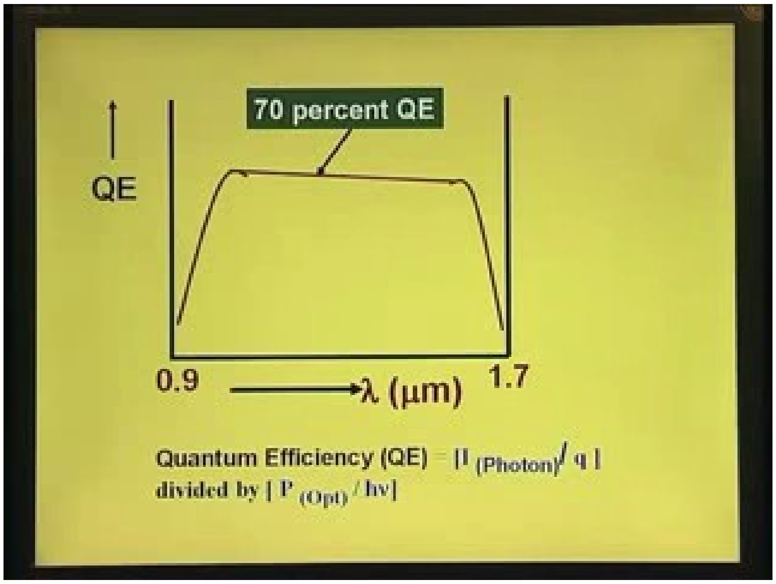

Quantum Efficiency (QE) = $[I_{(Photon)}/q]$ divided by $[P_{(Opt)}/h\nu]$

This is the plot, where lambda micron 0.9 and that is about 70% quantum efficiency. The quantum efficiency definition is put there. Photon current divided by q; I photon – current that you get on the external circuit divided by q gives you number of hole electron pairs. Please note it is pair. Because the hole electrons are separated. Therefore, it is only one particle, which gives rise to current in any cross section. So, that is why you have got, the current divided by q gives number of pairs, which are made available –divided by the optical power divided by h mu (34:38), that gives you number of photons. Total power divided by total energy or power divided by the energy of one particle gives you number of photons. Therefore, that is the quantum efficiency of a detector. In a LED, it will be other way. You talk of how much current flows and how many photons are emitted. That is called as quantum efficiency. So quantum efficiency means, whether you talk of the emission or deduction.

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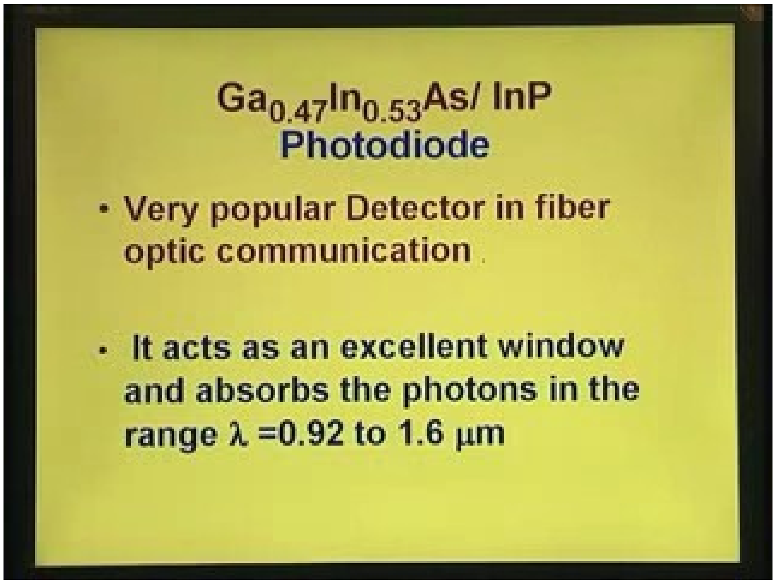

$Ga_{0.47}In_{0.53}As$/ InP

Photodiode

- Very popular Detector in fiber optic communication
- It acts as an excellent window and absorbs the photons in the range λ =0.92 to 1.6 μm

This is the summary of very popular detector in fiber optic communication, because you are looking for detectors in that particular wavelength. The window, where it is about 1.3 microns wavelength, it acts as an excellent window and absorbs the photons in the range 0.92 to 1.6 microns. That is about that particular compound which we have been discussing. We will go back to this original slide here.

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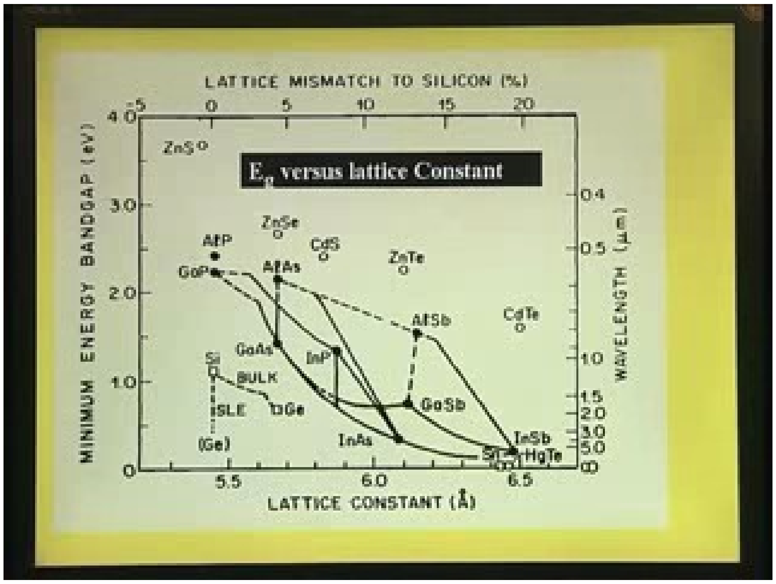

This is the one which you know, when there was lot of work, picking up on compound semiconductor, whichever conference you go, this slide was projected and at least 5 minutes was spent on that. We have spent actually more than 5 minutes because we want to get it a greater look into the thing rather than splashing it and taking it off. We have first set this material yesterday gallium arsenide phosphide for light emitting diodes. We have seen this portion, where you have gallium indium arsenide, lattice match to indium phosphide. Therefore, we can grow gallium indium arsenide by epitaxial technique arranging atoms of gallium indium arsenide on indium phosphide, it is perfectly matched. You can make the detector. Such wafers are available commercially. If you want, you can buy. p plus (36:47) made up of gallium indium arsenide on indium phosphide, we can buy that. In fact, when we made the device, we bought that and etched and made all contacts etc.

Now, the other one that is very popular, the first of those compounds, which we were looking into, was gallium arsenide lattice match to aluminum arsenide. You can see, gallium arsenide is direct bandgap material. If you keep on adding aluminum at that point onwards, from that arrow point, you see the dotted line, saying that it is indirect bandgap. Therefore, you have got direct bandgap switching over to indirect bandgap beyond certain point. The nice thing is, any composition of aluminum gallium arsenide is lattice matched with gallium arsenide because the worst case is gallium is zero that is matched. Therefore, any other combination is matching with the thing. Mismatches are practically zero. Now, let us see that compound consisting of this and bandgap we can vary from 1.43 right up to 0.26, but changing from direct to indirect.

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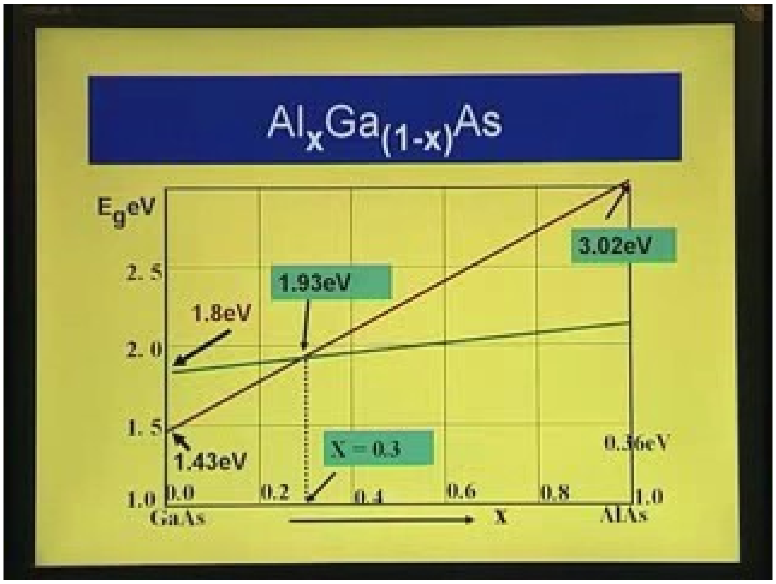

$Al_xGa_{(1-x)}As$

The next slide, if you see is the aluminum gallium arsenide – AlGaAs. This is another term which we can use, because it takes lot of time saying aluminum gallium arsenide. We will say AlGaAs, do not stop with the alga, it is AlGaAs. Now, the red colour or if you take gallium arsenide, it has a direct bandgap at 1.43 electrons volt. It has the indirect bandgap at 1.8 electrons volt. We hope you are able to recall that if you see the energy band diagram.

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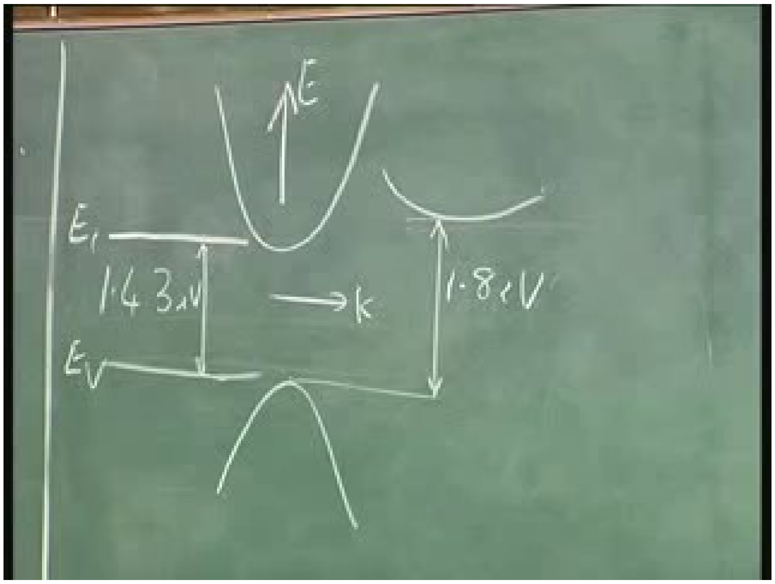

(39:09) putting those to all just to recapitulate your memory, electron volt one point eight electron, that is the energy versus momentum. That is the conduction band and valence band. So, that is what we projected there – 1.43, where the red colour is the direct bandgap and the green is 1.8. If you take gallium arsenide, that is x is equal to 0 gives gallium arsenide; x equal to 1 gives you aluminum arsenide. You have got 3.02 electrons volt there. This is gallium arsenide. Aluminum arsenide has got a direct bandgap of 3.02 electrons volt.

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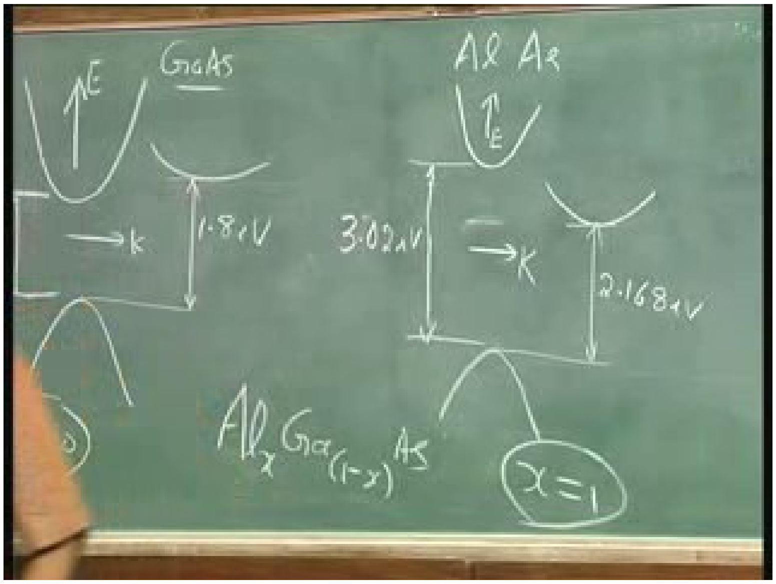

It has also an indirect bandgap; we just did not put it down there, which is actually equal to 2.168 electron volt. This point here shows 2.168 electrons volt. As we pointed out yesterday, when you vary, where the change, what we are looking for now is, aluminum gallium($_{\text{1 minus x)}}$ As – AlGaAs. This quantity is actually x equal to 0; this quantity is, x equals to 1. When you vary x is equal to 0 to 1, this which is 1.43 keeps on increasing to 3.02 that is what is plotted there. The indirect bandgap, which is 1.8 electron volts, keeps on changing, coming to 2.168 electron volts.

This is linearly varying. At x is equal to 0.3, both of them become equal. That is, from x is equal to 0 that is from gallium arsenide to gallium aluminum arsenide, with x is equal to 0.3, up to that point, that is indirect; this is direct. The material in this region, this is smaller than that, so that is direct band here. Here, this is smaller than this, which is indirect band here. So, if you grow, as you keep on increasing x, this becomes wider and this also becomes wider. (43:49) they finally become almost equal. So, up to this point on red, that is a direct band here is smaller than the indirect band here, which means, it is a direct bandgap material here, till x is equal to 0.3.

So, if we say, GaAs, E_g is 1.43 electron volt, direct bandgap. X is equal to 0.3, which is actually aluminum 0.3 mole factions, gallium 0.7, arsenide – AlGaAs, for this E_g is equal to 1.93 electron volts. This is direct. Up to that point 1.43 to 1.93 electron volt, you get a direct bandgap semiconductor. If you want to choose, you can choose for opto-electronic applications. Beyond, that point, if you increase the aluminum mole faction, more than 0.3, the bandgap will go up from 1.93 right up to 2.168 electron volt. It will go right up to that point. The whole thing is green colour here. Green is indirect; red is direct. So, this will become an indirect semiconductor. This is actually a very popular semiconductor, which has been tried out for years together. Professor Herbert Kroemer got Nobel Prize related to this hetero-junction etc. This is just to illustrate, you can get the bandgap varying. You can engineer the bandgap. You can make from direct to indirect. You can do all those things.

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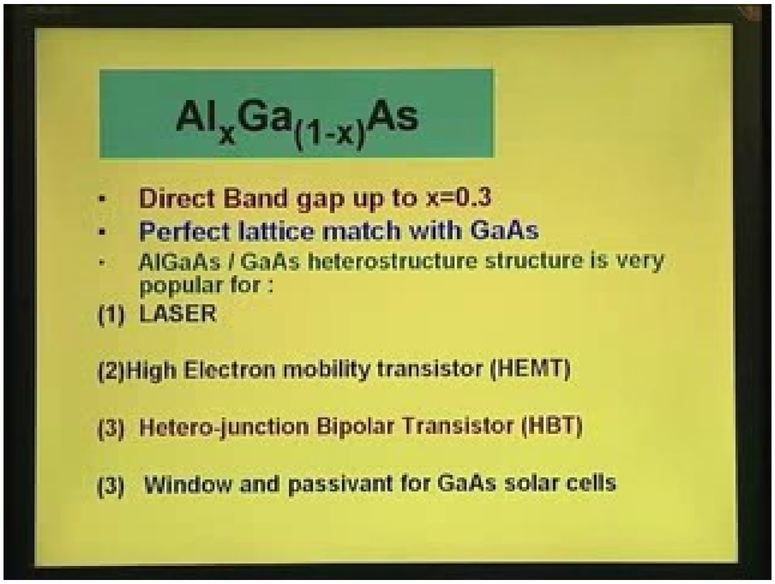

$Al_xGa_{(1-x)}As$

- Direct Band gap up to x=0.3
- Perfect lattice match with GaAs
- AlGaAs / GaAs heterostructure structure is very popular for :

(1) LASER

(2)High Electron mobility transistor (HEMT)

(3) Hetero-junction Bipolar Transistor (HBT)

(3) Window and passivant for GaAs solar cells

What are the different applications? Why are we looking at this aluminum gallium arsenide? If you can vary the bandgap, what is the consequence of that? Where is the more powerful application? One of the application is of course is in opto-electrical application. For a direct bandgap up to x equal to 0.3, you can use it for opto-electronic application. Mostly this material is used for x is equal 0.3, because beyond x is equal to 0.3, the aluminum concentration becomes more and more and the material becomes unstable. We are not touching that point now. Up to the 0.3, if people are using it, it is a manageable material. You can not only do bandgap engineering, but also manage the material. Growing and see the whether the material is stable or not.

Therefore, up to 0.3 is direct bandgap – very stable material and a perfect lattice match on to gallium arsenide. The vertical line you saw. It means, you can grow aluminum gallium arsenide layers on gallium arsenide. That means, you can make hetero-junctions using AlGaAs on GaAs. If you remember, in indium phosphide, if you want to make hetero-junction, what material you will use? Gallium indium arsenide, because the lattice match of indium phosphide is with gallium indium arsenide. That is where the hetero-junction is made. One application you saw. Here you can use AlGaAs. The nice thing about this is, the bandgap of AlGaAs is more than that of gallium arsenide 1.43 there. That is right up to 1.93. Therefore, you have no worry about leakage current. Bandgap is larger in the case of AlGaAs.

So, with a perfect lattice match these hetero-structures are very popular for different applications. One of them is for laser. In laser, it is a p-n junction again. You make a p-type material with aluminum gallium arsenide and n-type region with gallium arsenide, like this. Not exactly n-type material with gallium arsenide, it is like this. It is a very popular structure with laser. (49:28) is also diode only. The diode is so powerful that it will haunt everybody, in microelectronic, optoelectronic, and everywhere.

So, you have got, this material you can use as gallium arsenide p-type; this material you can use as aluminum gallium arsenide within x is equal to 0.3 p-types; this material you can use as aluminum gallium arsenide n-type. Now, what happens is, this material is a wider bandgap material, this material is a wider bandgap material, and this is like this. This is E_c and E_v. We are just giving you an idea of this. Here, there is a notch, if you forward bias this device, pump in current, then of course it will bend. You will have the electrons injected from here; they will be trapped there. They can be forced on to recombine. Therefore, you have got a notch, in which it will capture those electrons and those electron injected from n-region to p-region, forward bias p-n junction will inject electrons. That will be trapped here. It will not go to the p-region; it will be available. Once it is available there, it will lose its energy to this side there and you will get the laser wavelength corresponding to gallium arsenide. That is 0.87. This is one of the applications hetero junction, aluminum gallium arsenide, and gallium arsenide. Another application on which we are going to spend lot of time is high electron mobility transistor.

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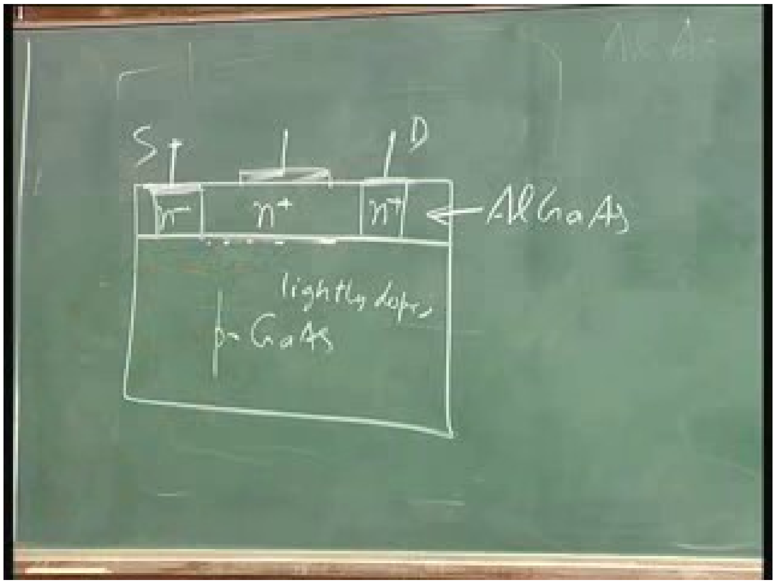

The high electron mobility transistor (HEMT) - we are just showing the application that is all. This is p gallium arsenide, on the top of that you will have AlGaAs. You will have contact made here; please do not worry, if you do not understand the whole thing, because we will have lot of discussions on this. Source drain, this is aluminum gallium arsenide and you will have a gate region put here, which will actually create a channel below this. In fact, you will have n plus. What we are trying to point out is, in a high electron mobility transistor, aluminum gallium arsenide there, gallium arsenide here, the aluminum gallium arsenide will be heavily doped and gallium arsenide will be very lightly doped. In the case of MOSFET, if you recall, this is a oxide layer and this region will be inverted. In this case, this whole region will be depleted, because it is made very thin, and instead of oxide, you will have this layer.

This n plus layer will donate electrons into this region. So, the electrons are here, when you invert, when you supply this, into this region. Those electrons are in the very lightly doped region. In a MOSFET, if you recall, it will go to smaller and smaller scaling, doping in that region goes up and mobility goes down. Here, you do not touch the doping on this layer. Increase the doping here which supplies electrons on to that. So, the electrons are in a region, which are not scattered by the doping very lightly doped. What you get is, the electrons in this region do not suffer from ionised impurity scattering, no doubt, they will experience lattice scattering.

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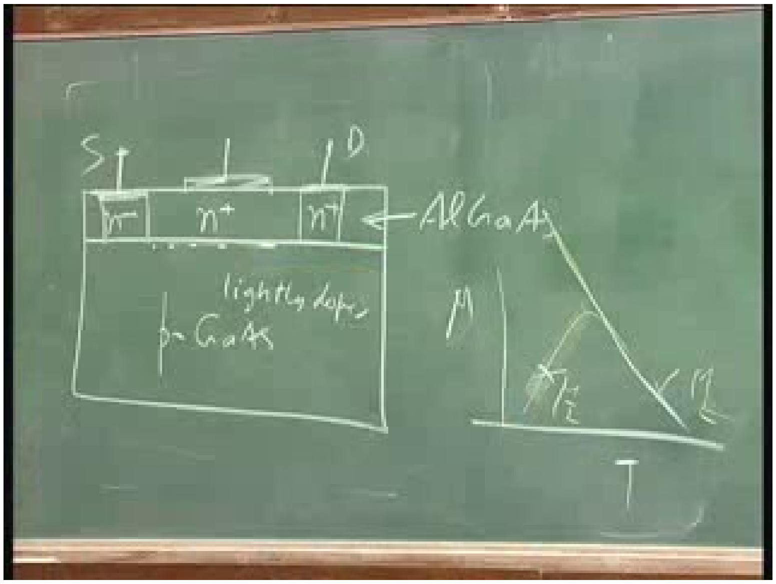

If they experience lattice scattering, what is the consequences? Mobility versus temperature was like that, if you remember. But, we cut this out, because this is (54:08) and this is ______, lattice scattering. We will have only one curve; this is removed. So, we can go to lower temperatures. We can go to 100,000 centimeter square per volt second mobility. That is a powerful technique.

The other application which we can mention is a hetero-junction bipolar transistor. If you make a n-p-n transistor; the n-region made up of aluminum gallium arsenide and p-region made up of gallium arsenide; and again collector made up to gallium arsenide or AlGaAs, whatever it is, it does not matter.

This is HEMT – high electron mobility transistor. We will have at least few lectures discussing on this. This is a very important device for high speed operations. We will also see its circuit applications.

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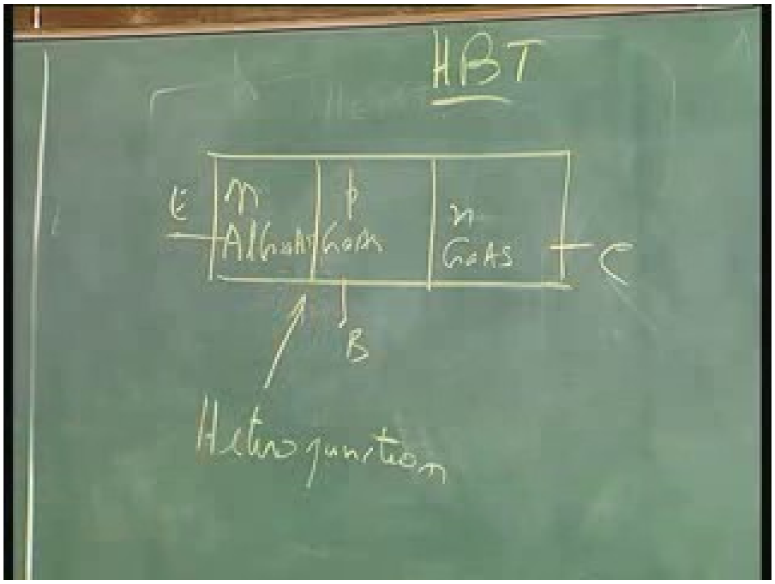

HBT – hetero-junction bipolar transistor n-type aluminum gallium arsenide; p-type gallium arsenide; n-type either gallium arsenide or aluminum gallium arsenide. This is emitter, base, and collector. This junction is hetero-junction. In fact, what we have done is, we have replaced the emitter instead of making that gallium arsenide. We have made a wider bandgap material AlGaAs. We are just giving you the result; the consequence of that is – the beta of the transistor will be very high and it will allow you to reduce the doping here. If you get high beta, you do not have to make this n plus. It will allow you to reduce the doping. If you reduce the doping, depletion layer will be wider and the device will become faster. I will discuss this later in full detail.

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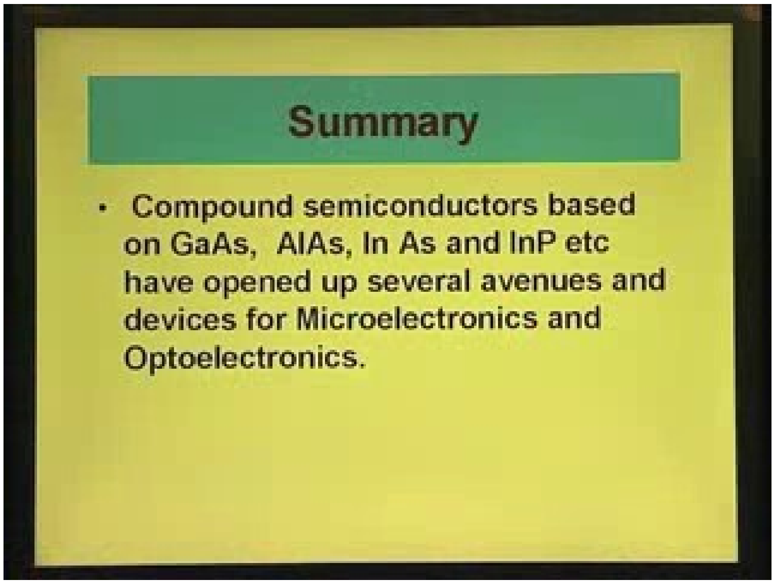

Summary

- Compound semiconductors based on GaAs, AlAs, In As and InP etc have opened up several avenues and devices for Microelectronics and Optoelectronics.

To sum up today, compound semiconductor based on gallium arsenide and aluminum arsenide, indium arsenide and indium phosphide etc., have opened up several avenues and devices for microelectronics and optoelectronics. With that, we will stop today. We will take a closer look into the crystal structure etc., for these materials in the next lecture.