Fiber - Optic Communication Systems and Techniques
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Lecture – 39
Double heterostructure lasers, Introduction to Quantum well lasers

Hello and welcome to NPTEL MOOC on Fiber Optic Communication Systems and Techniques. In this module we will look at good lasers. In the previous module we looked at a bad laser when I say bad and good, I mean when you measure its performance in terms of the current drive requirement, what is the gain that the laser can provide and what is the size of the laser and what additional property such as you know the compactness of the laser and so on and so forth.

Most importantly it is the current drive requirement, the controllability and the gain which are major requirements of what makes a good semiconductor laser. And in that regard homo junction lasers in which the p n junction acts as the mechanism to create a population inversion, but the p and the n type semiconductor materials are actually grown on the same substrate, same material.

For example, it could be a gallium arsenide. So, one side of the gallium arsenide can be doped with acceptor ion search to make it into a p type region and the other part of the gallium arsenide can be grown such that it can be made into a n type semiconductor. And when you forward bias it you are of course, creating certain carriers or in the conduction band that is electrons in the conduction band and holes in the valence band.

But that laser the width of that active medium where this kind of an inversion happens or the carriers are confined is not controllable because it depends on the diffusion and temperature. And moreover even when you could have some amount of control the width of that layer depends mainly on the diffusion and the width is typically very small. Does not match well with the optical mode and therefore, induces lot of problems when the light tries to come out of the laser facet. Because of small aperture, you will see that the light is mostly defracted out and therefore, it is not really a good laser.

In this module we want to look at a laser which overcomes all of the problems that have been mentioned in the previous few minutes. These lasers are called as double hetero structure lasers. The reason why it is double, because there are two hetero structures. So, the question now is, what is a hetero structure laser?

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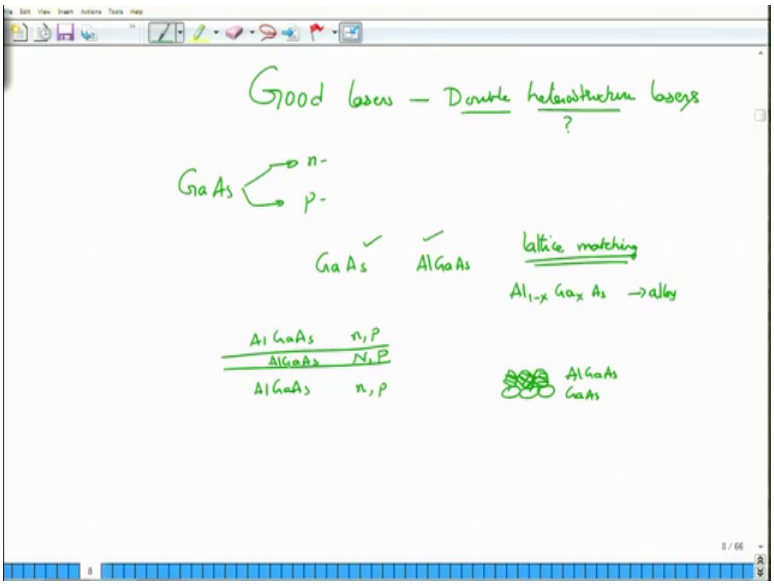

Now, we have said that you can take a gallium arsenide and then make that gallium arsenide into an n type and the p type, but these two are essentially made out of the same material, but it is also possible to take two different materials. For example, gallium arsenide and aluminum gallium arsenide, ok. You can take these two materials and then grow them on the same method or same machine on the same substrate. How is it possible that two different materials can be grown? The answer lies in what is called as lattice matching.

You are going to create an alloy; of course, the correct way to write this one would be al 1 minus x gallium arsenide x and arsenic because x depends on the amount of gallium present in this alloy and the amount of aluminum that is present in this alloy. This is an example of an alloy because as you vary the concentration of x, the material actually has its property which is slightly different at a particular value of x. The lattice constant that is, these are crystals right. So, these crystals have some sort of a periodicity, and these periodicity pattern matches that of the gallium arsenide in a direct matching

So, when you put the two together, when you try to combine them together they nicely combined with each other. Essentially you grow one on top of the other. They will have no problems in this particular growth because the lattice constant here of the gallium arsenide is the same as the you know lattice constant of the AlGaAs material on top of it.

So, if of course, there were any mismatch here then what would it mean is that one of the materials must be present in larger concentration than the other otherwise they will not really mix with each other, but if you try and make such dissimilar crystals and then try to grow them they will not also grow very nicely, ok.; However, when you lattice match them, that is, you consider those materials whose lattices are actually matching then they can be grown one layer on the other layer very nicely.

So, for example, that may be an example of gallium arsenide layer, this can be the substrate or one layer on top of it you may grow another layer. I am just denoting some difference here, but essentially the lattices are same. So, therefore, there are as many number of AlGaAs materials. I mean, AlGaAs atoms as there are gallium arsenide and one can actually grow multiple layer thickness based on this particular lattice matching. So, this lattice matched fabrication or manufacturing makes it possible for us to grow a layer of gallium arsenide. On top of it, a thin layer of aluminum gallium arsenide and then follow it up with a gallium arsenide again.

But the properties in terms of. So, you can make this one either as n type or p type. You can make this as n type or p type. Similarly, you can make AlGaAs material also as n type or p type, but I am denoting this type by a slightly different letter, ok. You can see why I am denoting this one by a different letter is because they actually have different band gap ok. Of course, in many cases you can actually find aluminum gallium arsenide here and an aluminum gallium arsenide here and a gallium arsenide here the reason being the designations actually have a certain meaning. I will tell you in a minute now.

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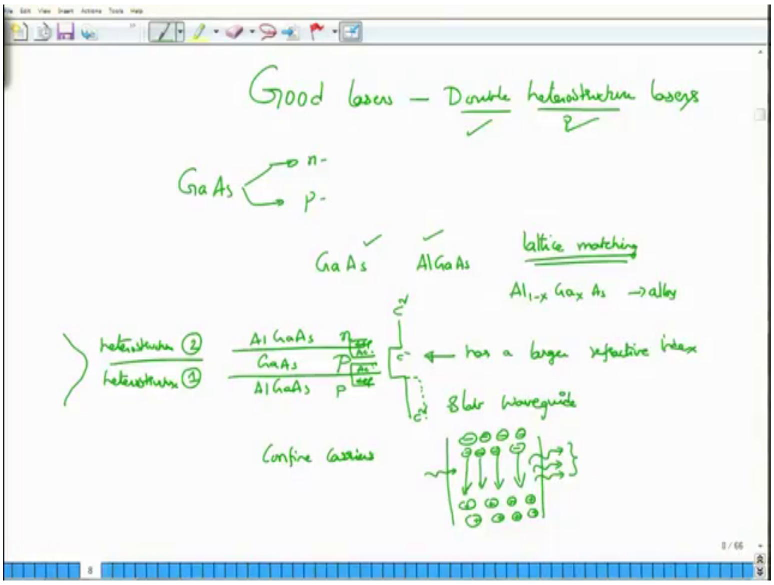

So, aluminum gallium arsenide layer, gallium arsenide in between because gallium arsenide has a larger band gap and aluminum gallium arsenide has a smaller band gap, but it is possible that both of them can be made into separately p and n type materials.

Now, suppose I make this as a p type material and this as a p type material ok. So, I am going to make this as p here, I have to distinguish between two types of p and two types of n. So, I am going to call this as P. You can see that this is a capital letter. I will use a small letter hopefully that is understood as a small case letter and then I have a n type material ok. These materials have a smaller band gap whereas; this material has a larger band gap ok.

What is the meaning of this and what is the implication of that? Before looking at that one, let us look at this. This layer one where a small p and a capital p meet corresponds to what is called as a hetero structure. This layer two again corresponds to a hetero structure because you have one capital P meeting a small n material ok. So, because these are two different type of band gaps ok, although they are lattice match, they are dissimilar materials, therefore, their properties are slightly different and this capital P small p capital P small n corresponds to two different hetero structure layers and therefore, together what you have is a double hetero structure laser. There are two layers and both of these layers are hetero structure lasers ok.

What is the advantage of this? It turns out that if you were to look at the optical properties of this layer, let us write down the optical properties here ok. So, let me write down the optical property here. The optical property that I am interested is force in the refractive index. It turns out that the refractive index here in the central region is actually larger which I have denoted by n 1 and the region outside I have denoted by n 2. Of course, I am assuming that the layer on the n and p type regions are essentially the same ok.

Therefore, their refractive indexes are almost same. In practice they are not exactly same. There is a slight mismatch because one of them is p dope, the other one is n doped, the refractive indexes are not exactly quite the same, but most importantly even if this is not exactly same, it is important to note that the central region has a larger refractive index ok. What is the implication of having a larger refractive index? Well, the implication of this central region having a larger refractive index is very obvious that you can actually put a mod into it. This corresponds to a nice slab waveguide and therefore, can support an optical mode which would then propagate along this active layer, ok.

So, this mode is confined by the central layer and this is useful because it can be used to confine optical modes and therefore, optical modes actually can see the population inversion or the inversion that is created by the injection of the current and that when you couple it with the feedback mechanism can actually lead to a very good laser. Of course, there is another point that you need to appreciate about this double hetero structure laser. You will appreciate it slightly you know in 1 or 2 minutes, but I will give you the basic idea first. The idea is that the different values of P and small p actually serve to confine carriers as well, ok.

Carriers can also be confined. Here there will be a depletion region, here there will be an accumulation region and here again there will be a depletion region and here there will be a sorry here there will be a depletion region and here there will be an accumulation region. I got them wrong in the other time also. Let me get it correct here. So, I have these three layers correct. So, I have a depletion region here and an accumulation region here. Similarly, I will have an accumulation region here and a depletion region here ok.

What is interesting is that as the optical mode propagates through this active layer. It is actually seeing the accumulation layer. When we say accumulation layer, it means that more electrons are to be found in the conduction band and similarly holes are to be found in the valence band in the central region and because there is large number of electrons. Then it is possible for us to employ this large number of electrons and corresponding holes in order to make them recombine band to band recombination so that they can give off nicely a large number of photons ok.

With one noise photon that goes in at the beginning you may actually start to get large number of photons and when this optical mode is reflected further back and back and back we will see that this mode continuously goes through the active layer depleting the or rather causing the electrons from the conduction band to transition into the valence band and thereby giving off more and more photons. So, what you have created is a very very good laser which provides optical confinement because the central gallium arsenide region has a higher refractive index and therefore, forms a slab waveguide. It is also a layer because of the property of the double hetero structure or the hetero structure materials or hetero structure junctions you have accumulated region in between which leads to lot of electrons and holes being available for the recombination process.

And this is the major reason why double hetero structures can provide high gain, good optical confinement, an extremely good carrier confinement compared to homo junction lasers and when you couple it with suitable wavelength selective feedback then you can actually make extremely good lasers. It is also fortunate that these materials that we have been talking about gallium arsenide or aluminum gallium arsenide they are transparent at the right kind of wavelengths where fiber optics is dominant. That is, in the range of say 1300 to 1600 nanometers where optical communication takes place especially in the 1550 region where the attenuation of the fiber is lowest and 1300 nanometer where the dispersion of the fiber is actually 0 or at that particular wavelength it is 0. Attenuation is reasonably higher, but it is not so bad that you cannot use it for communication.

But most of the communication today happens at 1550 nanometer region in which these double hetero structures are a nice match with the properties. And this marriage of double hetero structure lasers on one hand and optical fibers low loss silica optical fibers on the other hand is what kick started this entire optical network revolution in the 1970s ok.

Now, it is time for us to just look at very briefly the band structure ok. I say briefly because this is a rather complicated theory behind this one, but unfortunately we will not be able to look at that entire theory. So, we will not be looking at that one ok.

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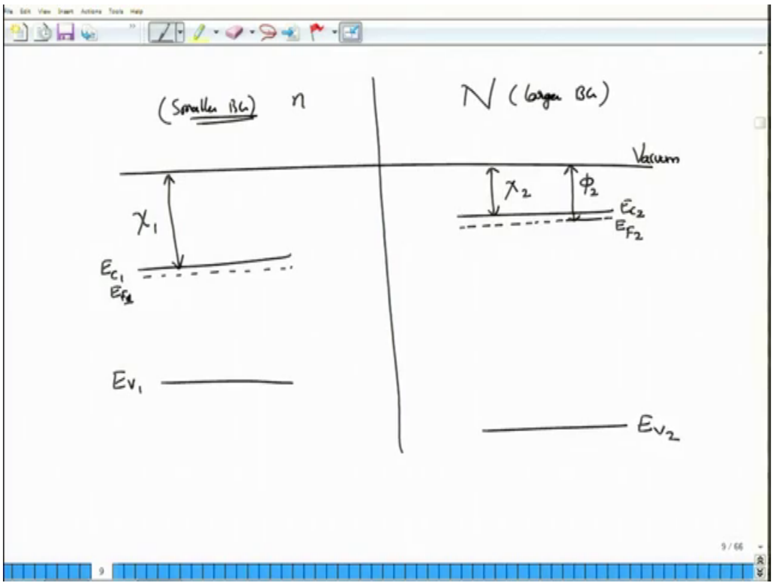


Let us start by considering the idea between an n type junction and a capital N type junction. Remember capital N will have a larger band gap whereas, small n will have a smaller band gap. But we will also assume that corresponding to the vacuum level ok. So, the electron affinity which is where we had located the conduction band over here would be so, I should not write it very close to the junction because the property will change. So, I am going to write here and this would be my conduction band which I would call as E c 2. Of course, this distance between the vacuum level and the top of the conduction band is the affinity chi 2 ok. The smaller the affinity the smaller the energy required for the electrons to be removed from that particular material. Please keep that in mind; that is very important.

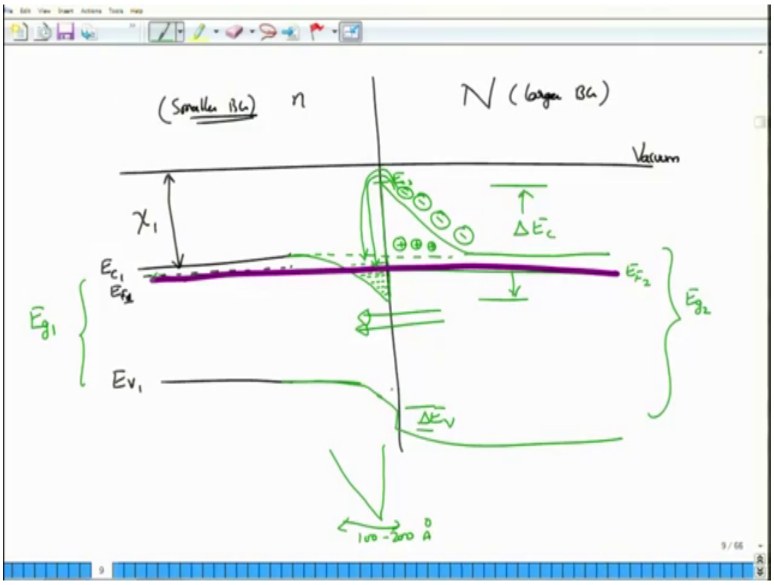
Of course, because this is n type material there has to be a fermi level which is very close to this n type material. So, we will call this as E F 2 and measured with respect to the fermi level is the work function phi 2 which is the kind of amount of energy that is required to remove an electron completely from the material and we are going to assume that phi 2 is also small compared to the corresponding value of phi 1.

Now, we have located the conduction band, we have to locate the valence band. So, let us locate the valence band here and call this as E v 2 ok. Similarly, on the other side I need to locate E c 1. So, I am going to call this as my E c 1. Of course, as you can clearly see the affinity chi 1 for this region is actually quite larger, which means there is you know you require more energy to remove an electron from the smaller n type material than the corresponding capital N type material. So, but please remember when I say smaller band gap I refer to the difference between the conduction and the valence band. So, for example, this would be my valence band E v 1 here as before the Fermi level has to be found near the conduction band. Therefore, this is located close to the conduction band as it is

So, this is the junction far far away from whatever is the you know whatever that is happening. So, but at the junction itself sometimes also called as metallurgical junction, what really happens? What happens is that this is an N type material capital N, but it is still nevertheless an n type material therefore, even when you merge these two materials together, overall characteristics should be still an N type material characteristic ok. That is very crucial when you merge a small n and a capital N, the overall characteristics should still be an n type material and when the when the junction is not biased or it is not you know in the dynamic process then there has to be an equilibrium and in equilibrium the Fermi level must be constant throughout the region.

So, if the Fermi level has to be constant and the conduction bands have to be closer together right it cannot be possible that you know I just pull down this E c 2 and E v 2 to align them to E c 1 and E v 1 and E v 2 right. I cannot really do that, but it is essentially the same thing that I have to do if I have to make the final E c 1 and E c 2 to lie together.

So, I am going to write down the band diagram, do not worry if you do not really understand how these band diagrams are made because they have a complicated theory behind all that to understand, but the basic idea is this E c 1, as you gradually go towards the junction would fall somewhat ok.



It would fall somewhat creating a well here in the middle and then there is a spike right away. And what does the spike do? At the spike it will actually reach E c 2 here where the previous E c 2 was there right and then gradually drops off eventually being almost equal to E c 1 far away from the junction ok.

So, this is the change that has actually happened ok. What about the Fermi level, well to the Fermi level. We draw the Fermi level here. So, this is the Fermi level that I am drawing. So, this is my Fermi level overall ok. As you can clearly see E F 1, E F 2 are the same and they are constant

Now, look at this very interesting thing. The Fermi level is lying above this well. What does it mean? The Fermi level actually tells you that this is the region where you know, 50 percent of the probability happens, but because there is a well here what is really happened is that the electrons which are having a smaller affinity have actually moved and then fallen into this accumulation region ok. So, when they move and fall this would be the depletion region right and this would be the immobile ions and an electric field will be set up along this direction which of course, eventually forces everything to go into the equilibrium situation.

But it is important to note that there are many many electrons which have now accumulated and they are all in the form of this well or not in the form. They are actually in the well itself. You can show that when it is properly you know, all theoretical things are considered and then you calculate the parameters. This will actually be a triangular well whose width is about 100 to 200 angstrom not at all a large width. Just about nanometers you know few tens of nanometers, but the important point about this one is that there are lot of electrons in the conduction band.

What about the valence band? Well for the valence band, what happens is that the valence band would essentially also start to go down, but then exhibits a sharp discontinuity and then further goes down here. Of course, the energy gap that you would see E g 2 will still be much larger than the energy gap E g 1 that you are going to see. And this jump is what we would call as delta E v and this change in the electric field is what we would call as delta E c. And remember our density of states idea that if you have electrons, their effective mass is lower. Therefore, there are many electrons inside to create a larger energy gap; however, to create the same energy gap, the number of holes will be smaller. So, even when delta e v is smaller, it is possible because of the larger density of states that the amount of holes will be kind of matching the amount of electrons ok.

So, that when the junction is forward bias or when the junction there is a certain potential applied, you know, then these electrons can actually drop down and then go to valence band just creating the lazing action or the recombination action. Now this was between N and P.

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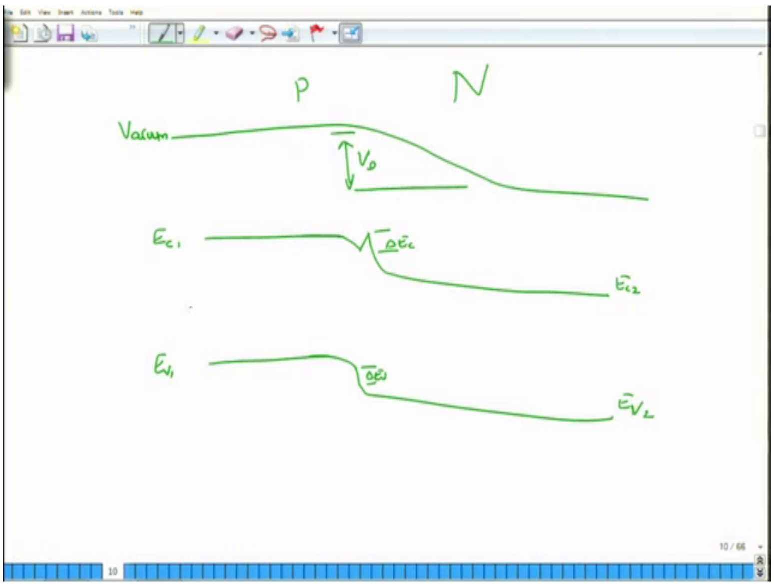

But most junctions actually involve a small p and a capital N region or a small p and a capital P region. I am going to just write down for the small p and the capital N ok. The difference here now, is that the vacuum level actually starts to bend and the amount of bend that the vacuum level undergoes. Well, it is not really a star bend its a gradual transition, but nevertheless, the small amount of bend is the one that actually sets up the corresponding built in potential or the junction potential between this small p and a capital N junction material.

So, the vacuum level actually undergoes change and, but it is a continuous change. So, if the levels continuously change from the small p region to the capital P region; however, that is not. So, the case for the conduction band, because in the conduction band case right, what happens is initially it will go like this, if it was a small n it would have continued and dropped right, but this is not a small n this is a capital N. So, it cannot continue forever, but it does go down and then goes back up. It will never reach the level beyond here. So, it goes back up here and then goes down and then becomes E c 2 to on the other side of the region. Whereas, delta E v would go down, have a sharp transition delta E v here and this of course, is your delta E c. The spike and then again falls down to become E v 2. This of course, is E v 1 again in the equilibrium position. You have your let me move it because in the equilibrium position the Fermi level has to be closer to n.

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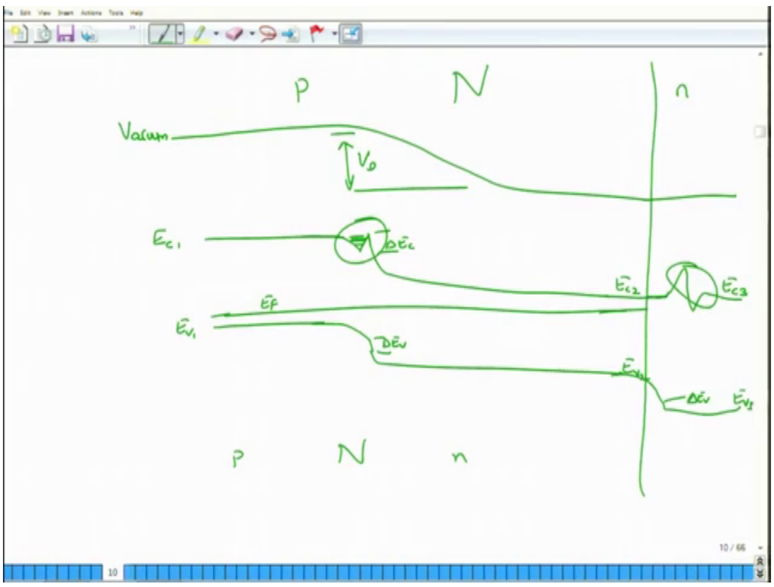

But it has to be closer to this material also right. So, it you will actually have E v 1 here. So, this is the Fermi level which is constant under equilibrium drops down. There is a sudden drop of delta E v and then drops down to E v 2 here ok.

So, this is what the band diagram of a small p and a capital N region would look like, but now if you put a p N and an n right. So, you had created a p and an N and an n. So, there was a spike here and you now know that if you were to follow it up with an N junction. So, let us see if we can follow it up with an n junction there have to be a spike right. So, from the small n region has to go down initially then rise up and then fall down and exactly not. So, this is the falling down. So, this is a triangular well that is created. This is the well that is created over here ok. So, these are the two wells created eventually the region here on the n type material would actually have the same value of E c.

So, we will call this as E c 3. This one would simply drop have a sudden transition and then move back to the ev3 ok. The Fermi level of course, I did not write it correctly, but the Fermi level has to be constant. So, I should have written down the first the Fermi level and then made these bends as such. So, this is the levels which I was talking about. This is the accumulation layer that I am talking about.

So, this is precisely. So, the accumulation layer would actually be on the other side right. So, it should be as you go accumulation layer has to be in this particular side. So, yes so, this would be depleted region as you can clearly see. So, as you go from the small n, first it will encounter a well and then it goes back up. So, this is actually correct sorry for multiple reasons. So, this is how this layer would go.

Of course these spikes are not going to be constant when you bias it, when you actually apply bias the junction. So, this was p N and a small n junction this is not normally used, but we will come back to the actual one that is used in practice, but this is the idea. So, you will have three different materials. One of the material will happen to be having a larger band gap than the other materials. The other two materials will be of the same type and the overall effect is that the energy levels are actually changing and the middle layer has to act like an accumulation layer. So, clearly I cannot put a small n on this side. I should have put the small n on the I mean something else on the other side right.

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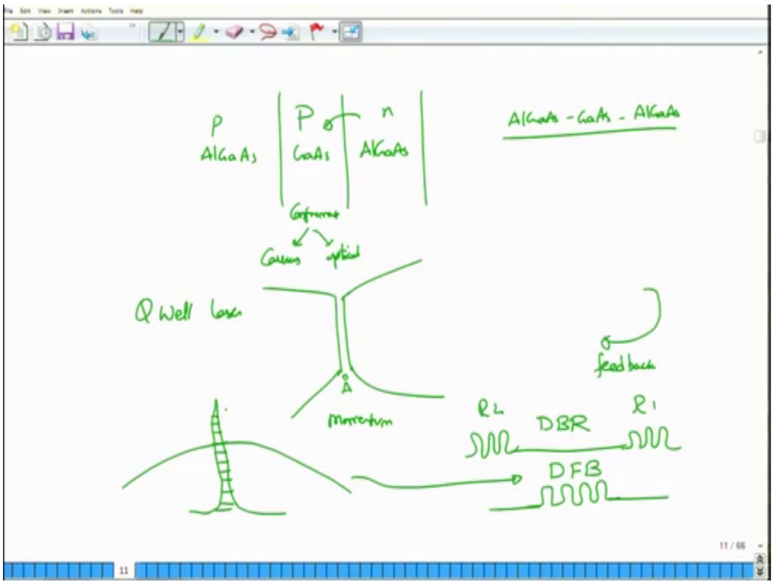

So, in practice what do we do in practice you have. a p type AlGaAs material and N type gallium arsenide material and a small n type AlGaAs material. So, or rather you can actually have instead of an N type material you will have a P type material itself. So, this is also perfectly fine. In fact, this is because electrons can easily move compared to the holes that would actually move and this region will be the confinement region ok

So, these AlGaAs gallium arsenide AlGaAs materials or the combination is actually widely used as a double hetero structure laser which of course, provides both confinement to the carriers as well as to the optical modes in the same material structure. Of course, in an actual material there will be many different layers. It is also possible to get an even better laser which is called as a quantum well laser in which the thickness of the central region is made very small. This is in the range of just about an angstrom instead of about 100 to 200 angstrom. This is just about an angstrom. What it does make is that the because of the extremely small region the momentum of these states will be very high and therefore, they are capable of giving extremely large gains even though the central region is actually very small.

So, you are trading off the smaller region higher momentum and therefore, you get a higher gain because of the extreme confinement. This is called as quantum well laser and quantum confinement of the carriers and there have been many you know different types of this quantum well lasers that people have worked on. And the state of the art includes multiple quantum well lasers in which the quantum wells are also slightly strained because of the an isotope in the materials

So, this is all about how you make a good laser. Of course, the only thing that we have left out is how to make a feedback into the lasers. The traditional way of making a feedback would be to actually put two reflectors on the other side. This is called as a distributed drag layer ok. So, you have one reflector here, another reflector alternatively you can make the active material itself undergo this grating structure. So, this corresponds to what is called as a distributed feedback laser. Whereas, this one corresponds to what is called as a DBR laser ok. So, you have a DBR and a DFB laser.

Most practical lasers that we use today are DFB quantum well lasers and this provide of course, both the wavelength selectivity and wavelength selectivity is important and feedback. Wavelength selectivity is important because as you know, the radiation spectrum of an laser or a of a semiconductor material is quite wide, but by incorporating the feedback in the form of a DFB or a DBR laser it is possible to have an extremely narrow line width laser that can come out of this one. So, this is what you would actually have in the output when you put a wavelength selective feedback mechanism into the system. So, this is all about lasers.

Thank you very much.