

**Transducers For Instrumentation**  
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**Lecture - 19**  
**Optical Sensors: Heterojunctions and LASERS**

Hello, welcome to the course Transducers for Instrumentation. Last lecture we discussed some optical detectors just like PIN diode and avalanche photo diode and we discussed one type of optical source which is LED the light emitting diode which is very widely used for these optical power generation. The next important light source is the laser which we are going to discuss today. The laser is a short form of light amplification by stimulated emission of radiation. So, the word stimulated is a keyword here which we are going to discuss today how the light actually emission happening in laser which is different than the normal LED. Before discussing the lasers we need to understand a little bit about some device physics the properties of some material. So, we have some sort of homojunctions and heterojunctions when we make the junctions in the semiconductor device. So we have two types of junctions homojunction means when we form a junction and the material on both side of the junction is the same material then we call it homojunction and when the material is different on one side of junction is different than other side of junction then it is called heterojunction. For example when we make a silicon based diode we say it is a p-type material and we take n-type material join them together then a junction is formed which is called depletion region. If we see both the sides though it is p-type and n-type on the other side the material the fundamental material the base material is same which is silicon.

Silicon is p-type dope on one side and n-type dope on the other side, so it is called homojunction. However, if we take two different materials and we make a junction so one side it is let us say gallium arsenide and one side is aluminium gallium arsenide or some different materials some composition of the material is different then we call it a heterojunction and both these junctions have different properties. So, we are going to discuss today what is homojunction and heterojunction and then we will discuss the lasers which is the optical source. So, we have a homojunction both the p-type and the n-type regions are of the same semiconductor material. So, in homojunction both materials are same. In heterojunction the junction layers are made of different semiconductor materials. So, if we draw energy band diagram for these heterojunctions one side the band gap is larger for example we have let us say this kind of band where this band gap is  $E_{g1}$ . On the other side the band gap is smaller this is let us say  $E_{g2}$ . So now we have two different material one side is  $E_{g1}$  where we have high band gap and other side we have  $E_{g2}$  where this band gap is smaller. When we join these two materials now the band need to be continuous because these are energy bands energy distribution is continuous it

cannot be discrete. So if we join these bands they are going to join like this and this. So here now we see there is a sharp change in the energy bands and if we see here we are making some sort of a notch here or the well we call it. If we also draw the Fermi level for this p-type and n-type because Fermi level is close to p-type here this is the Fermi level or  $E_F$  this is p-side let us say we have positive charges here and we have electrons here. This is EC and this is EV. Now in this energy band diagram if we see carefully this Fermi level is flat and when we are joining these two different materials together in conduction band there is a notch this notch or the well we call it.

The tip of the lowest or the minima of this well is coming below the Fermi level the  $E_F$  this dotted blue line which is Fermi level. The minima of this conduction band or at this point at this well is coming below the Fermi level it means this region or this notch or this well will always be filled with the electrons because this is below the Fermi level so the probability of finding electrons here is very high. So all these this well will be always filled with the electrons and because these electrons are in the conduction band so this on the top this is a conduction band. These conduction band electrons are free to move so we always have some electrons in the device at this point this well quantum well we can call it. These electrons are always available for the conduction. So without doing anything without applying a bias we just added two different materials and because of the energy band the difference in the band gap we are creating a notch a well where electrons are freely available for conduction. So now if we apply a electric field in let us say perpendicular to direction of this board this board these electrons will be free to move as per the applied voltage. So this happens in case of heterojunctions because both the materials are different the different band gaps and we get these free electrons sometime we call it the 2D electron gas because these electrons are available there is like kind of liquid or you can say the gas they can move freely if we apply electric field. So these charge carriers are confined in a space away from the doping impurities. Hence improved mobility or the high electron mobility.

So the difference between these heterojunction where we are getting these electrons this is different process than how we create electrons or the mobile charge carriers in normal MOSFET. The difference is in MOSFET we do the doping in the channel so that we get these extra electron the charge carriers these are given by these impurities boron or phosphorus depending upon p-type or n-type. But the problem in doing that is when we put impurities the mobility of electron decreases because there is a kind of imperfection in the lattice when we put these impurities and these charge carriers need to travel in this channel so the mobility decreases. However in heterojunction we are not putting any impurity here we are not doping the material at exactly at this quantum well. These electrons are here because of this discontinue because of the difference in the band gap. So these electrons are created by that and these are away from the impurities so they are seeing a perfectly fine crystal and their mobility is very high and this is the basis of

something called HEMT or the high electron mobility transistors. These are very high devices used for high speed applications HEMTs. So this is the phenomena that give leads to the HEMT devices which is this two dimensional electron gas. So now we know that gallium arsenide is a direct band gap material. Let's say we have gallium arsenide this is a direct band gap material and it emits in infrared and for infrared typically the wavelength is 872 900 nanometer.

This is one material and the other material is let's say gallium phosphide which we know is around 2.2 electron volt. So here we have now two material one is gallium arsenide which is a direct band gap material and the band gap is such that it emits in the infrared region and another material is gallium phosphide which is a indirect band gap. So these materials are also the mixture for example gallium arsenide material is nothing but gallium when it is mixed with arsenic then it is gallium arsenide and which is a direct band gap and when we mix gallium with phosphide or the phosphorous then it becomes gallium phosphide which is a indirect band gap material and band gap is 2.2 electron volt. Now this arsenic and phosphorous both are in the group 3 so they belong to the same group in the periodic table. So this arsenic and phosphorous they can also be mixed together. For example we can have something called gallium arsenide phosphide where we mix gallium with certain amount of arsenic and certain amount of phosphorous. So when all these three materials are mixed together we call it gallium arsenium phosphide GAASP with certain fraction of arsenic and remaining fraction of phosphorous. Then the effective band gap of this material which is now the newer material made up of these three material. The effective band gap is determined by how much is the ratio of arsenic and phosphide in this complete material. So for example we have both these arsenic and phosphide belong to same group in periodic table it is possible to make alloy. Having composition of gallium arsenic the component of arsenic is  $1 - x$ .  $x$  and phosphorous is so we are taking  $x$  part of phosphorous and  $1 - x$  part of arsenic and mixing it with gallium so that we are making a new component which is gallium arsenide phosphide. Now the lattice constant of these gallium arsenide and gallium phosphide are quite comparable or almost equal so we can mix them effectively.

So the lattice constants of gallium arsenide and gallium phosphide are nearly equal for  $x$  value less than 0.5 and 0.45. Radiation in red and infrared, red and infrared range. However if we increase the composition of phosphorous means  $x$  is greater than 0.45 and alloy becomes indirect band gap. So this is a process of even converting a material or making a different material and tuning the band gap of this new material. For example gallium arsenide has a fixed band gap of that is a direct band gap and which is fixed. Gallium phosphide is again a different material with a fixed band gap of 2.2 electron volt. Now we can play around with the composition of phosphorous and arsenic and we can tune this band gap depending upon how much phosphorous we have in this material and how much arsenic we have. So depending upon that we can tune the band gap of

materials and as we saw for the composition of phosphorous if it is less than 45 percent the alloy remains a band direct band gap material it emits in red and infrared range. If we increase the amount of phosphorous more than 45 percent or  $x$  value is more than 0.45 the alloy becomes an indirect material. So we can see even how continuously this kind of proportion changes the band diagram.

So let us say we have this graph where on the  $x$  axis we have mole fraction which is  $x$  value. This is 0 and this is 1 and in between we have let us say this is 0.5, 0.2, 0.4, 0.6, this is 0.8 and 1 and on the  $y$  axis we have energy band for the band gap starts from typically let us say 1.4 to 2.6 and it is a linear graph. So now we have two graph one is for the direct band gap which starts from let us say 1.4 and it goes like this. This is for the direct band gap and the other graph is for indirect band gap which comes like this. This is indirect band gap. So here we have two graphs with one is for the direct band gap, one is for the indirect band gap. These are the values of the conduction band and this is the difference between the value of conduction band and the top peak of the valence band. So we see as the mole fraction is changing from 0 to 1 these both of these graphs are changing and whatever is the minimum value that will be the band gap of the material overall. So we see below 0.45 the red curve is below the green curve it means the material will remain a direct band gap material for  $x$  less than 0.45 and higher than 0.45 the green curve is below the red curve it means that material will become an indirect band gap material. So depending upon the mole fraction of how much phosphorous we add in the mixture the band gap of material changes. So even if we reduce the mole fraction to 0.

2 we can see the band gap is actually reducing compared to the band gap at 0.45 mole fraction. So this is how we can tune the band gap of material within a limit. So this is how we change the material and changing the material band gap means that the light the kind of which light it will emit that also changes. So these indirect band gap materials are generally inefficient as light emitting diodes.

So now let us discuss the optical source which is laser. Laser is an acronym so the full form of this is light amplification by stimulated emission of radiation. So laser is a device and that laser is an acronym actually so the full form of laser is light amplification by stimulated emission of radiation. So we are producing a light we are amplifying certain photons the photon energy by stimulated emission of radiation. Stimulated is a keyword here we are stimulating the emitted photons and they are generating further photons by stimulation.

So we discussed earlier LEDs and photo detectors so this is the difference between the photo detector for example if we when we discussed photo detector we had their energy band diagram such that this is the conduction band and this is the valence band AC EV and in photo detector we receive a photon from outside. The photon comes in  $h\nu$  and it

excites an electron from the valence band to the conduction band. So this is what happens in photo detectors. In LEDs or the light emitting diodes we discussed we have conduction band and valence band AC EV and there is a hopping of electron from conduction band to valence band and in this process this electron is actually losing energy and this energy comes out in terms of a photon  $h\nu$ . So this is a photon which is being generated by this the hopping of this electron from conduction to valence band.

So this is kind of a reverse process happening in photo detector so this is what LED. Now let us discuss the third case which is lasers what we have in laser is a conduction band and valence band. In laser we have so many electrons available here to jump down the primary requirement here is we have so many electrons here which are ready to jump to some conduction to valence band. So when they will jump from conduction to valence band they are going to lose energy in terms of photon. Now we have a photon which is there which is generated elsewhere now this photon is travelling in the lattice and there are so many more electrons available which are about to jump from conduction to valence means they are about to generate these photons.

So our original photons actually stimulates or affects these further photons so that the emitted photon the new photon which is generated from hopping this photon is coherent with the originally available photon so this is what it is called stimulated emission. So we in this process we have a photon which comes in  $h\nu$  and at the same time one electron is jumping from conduction to valence this is about to lose energy in terms of photon. Now this photon is actually reacting with this electron such that in the process it generates two photons now this is the newly generated photon and this is the original one which is on the left now it generates two photons they are coherent means the all their properties are same. So this process is called stimulated emission this is very particular to the lasers. The main or the necessary condition for this to happen is there should be so many electrons available in the conduction band so that when a photon comes in at the approximately that the same time one electron is there which is jumping from conduction to valence band.

So it means we need to have lot of electrons available in conduction band ready to jump in it means we need to have a very high concentration of electrons in conduction band or we can say the population inversion. So we need to have a population inversion which is the necessary condition for lasers to work. So this is the difference between LED and lasers. So this is the process happens in lasers. Now we saw that there is a something called population inversion which is a necessary condition for lasing action.

So let us discuss what this population inversion is. So in a semiconductor population inversion can be obtained by means of high carrier injection which results in electrons and holes in the same special region. So now if we look at the band diagram for this material we have let us say the conduction band and we have the valence band. For

example this is our conduction band this is the valence band. Now in normal case we have so many electrons available in the valence band.

So this is the normal case where we have conduction band which is completely empty and the valence band which is completely filled now. Now we inject a high current so that many electrons has energy high enough so that they can jump to the conduction band. So remember in the first case in the earlier case some of the electrons only have energy to jump to conduction band and they were giving rise to conduction. Here in this case we have a very high carrier concentration which are jumping to conduction band or this called a population inversion where the complete layer a top layer of valence band completely all the electrons jump to the conduction band and remains in the conduction band. It means the conduction band is completely filled on the top however a valence band is empty in the bottom. So if we apply a population inversion here after population inversion the bands look something like this. This is valence band conduction band and this layer all the electrons jump to the top and leaving behind a completely empty layer in the valence band. So if we can see whole of this area this whole population actually have migrated to the top which is here. So this is called the population inversion where all the electrons in the valence band they have jumped to the conduction band leaving behind a complete layer of empty states and all the states in the conduction band are now filled with electrons. So we see here now we have so many electrons in the conduction band and these conduction band electrons they can lose this extra energy anytime and they can jump back into the valence band anytime and give rise to the photon.

So this is called the population inversion. Now the incident photon which is coming from the left if the incident photon with energy  $h\nu$  this is the energy of photon if this energy is greater than  $E_g$  the band gap of material but it is lesser than  $E_c$  minus  $E_v$  the difference between conduction and valence band. If the photon energy is such that is between  $E_g$  and  $E_c$  minus  $E_v$  this cannot be So to understand this let us draw this diagram again we have a conduction band and we have valence band and we have population inversion it means we have many electrons in the conduction band all these states are filled and in the valence band all the top layer is empty this whole layer is actually empty there is no electron in the valence band the top layer of valence band this is no electron. Now when photon is coming from the left now this photon it cannot be absorbed if the energy of this photon is higher than  $E_g$  but lesser than  $E_c$  minus  $E_v$  because to absorb this photon a electron need to be present here somewhere so that it can jump from the valence band to conduction band and absorb this photon this is not possible because there is no electron available here electrons are further down in the valence band so they cannot absorb they need more energy compared to what energy photon has to jump to valence band. So this photon will not be absorbed by the material however at the same time so many electrons are there which are ready to jump to jump down to valence band emitting a photon. So in this process this photon actually interferes with the energy emission of electrons and

generate to one more photon because of this hopping these both the photons are coherent or the same in all the characteristic how they interact it to each other that is beyond the scope of this course but this photon actually reacts or interfere with the hopping of electron and generate another photon.

So let us say we have now this electron which is jumping down to empty state here and in this process we are generating two photons this is  $h\nu$  and this is another photon which is  $h\nu$ . When these two photons are generated again they are propagating in the same channel now other electrons are ready to jump for example these electron this electron is also ready to jump from top to bottom to this empty state and this also reacts with these incoming photons so let us say these two electrons are jumping down emitting a photon and two photons are coming from the left which interferes with this emission of photon and at the end we get four photons of exactly same characteristics. So this process is called amplification by stimulated emission and the necessary condition for this to occur is the condition for stimulated emission another population inversion is the energy of incoming photon should be greater than eg the band gap of material but it should be lesser than the difference between  $e_c - e_v$ . This is the necessary condition for laser action. So this is how the laser device works in this we have a population inversion where all the electrons in the valence band they jump to the conduction band because of the very high current flowing or very high and very high charge is provided to this lattice.

Now these electrons on the conduction band they are ready to jump at any time they are continuously jumping now if a photon comes in where the photon energy is higher than the band gap so it can be absorbed but it will not be absorbed because there is no electron available right on top of valence band which can take this amount of energy and jump to conduction band because there is no electron available in the valence band and there is no empty state in the conduction band where it can jump. So this photon will not be absorbed on in fact this photon will not be absorbed but at the same time if electron is jumping down emitting a photon this incoming photon will react with interfere with this release of energy and that resulting photons are identical in nature. So this one photon give rise to two photons which is a amplification one photon becomes two and both are same and these two photons further react with two jumping down electrons and create four electrons which are again of the same properties and there is further amplification from two to four. So this is called the amplification by stimulated emission because here the photon is interacting with a jumping down electron and releasing the same kind of photons so we call it amplification by stimulated emission. So this is how a laser device works and the condition for stimulated emission is  $h\nu$  then the energy of photon should be higher than the band gap but it should be lower than the band gap.

So this is the difference between the conduction band and the valence band and at this point this is  $E_{fc}$  and let us say we call it this  $E_{fv}$  so this is in fact  $E_{fc}$  minus  $E_{fv}$ . How many electrons are jumping from top to bottom that dictates what is the value of  $E_{fc}$  and

Efv. So this is the condition for stimulated emission. Next we discuss a little bit about the wave guides we can make these wave guides where light can travel in those wave guides on chip and light will travel through total internal reflection and these are these can be made using micro electronics processes. So we can make something called wave guides to carry photons from one place to other and making of this is very simple.

If we have a p-n junction this side is let us say p-type this is n side and this is the junction or depletion region. Now we see this region which is depletion region this is this does not have any moving charge carrier available here it means the property of this material is different than p side and n side. So if we measure the refractive index of this material along this direction if we measure the refractive index the refractive index will come out like this. So this is refractive index in this region the refractive index will be different because this material is does not have any charge particles. In this region this refractive index is different. So if there is a change in the refractive index it means we can compare it with the optical fiber where we have core which is of different refractive index and we have cladding which is of different refractive index and now if we shine a light in this structure along this direction more of the photons will be confined in the center region. We shine a light in this structure many of these photons will be confined in this region. These are the photons confined in this depletion region and this can act as a waveguide all these photons will be travelling from one side to another within this structure itself. So we can say the electron hole concentration in the depletion layer modifies the refractive index.

Creating a waveguide which helps to confine the photons. So here we have a structure where we have PNN type material when we join them together they form a depletion layer and because this depletion layer is different than both of the materials because it does not have free charged particles. So there is a slight change in the refractive index of this depletion region compared to both the sides which is very similar to our optical fiber where we have a core which has different refractive index and on the cladding which is surrounding this which has different refractive index. So just like our optical fiber carries these photons or confined all the photons in the core itself the same structure if we shine the light here the photons will be confined in the depletion region because of this difference in the refractive index. So today we discussed the lasers and before that we discussed homojunction and heterojunctions and we saw for the lasing action we need a population inversion and we saw the necessary condition for lasing action and then we saw the waveguides where we can confine these photons instead of optical fiber we can use waveguides which is easy to make on chip when you are making these using microelectronics fabrication process it is easy to make waveguides on the wafer.

So, this is all for today.

Thank you.