Semiconductor Device Modeling
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Lecture - 32
Energy Band Diagrams

In the previous lecture, we have discussed the energy band diagrams of a uniform semiconductor under applied bias and then we began a discussion of band diagrams for spatially non-uniform semiconductors. We discussed the examples of non-uniformity doped semiconductors and compositionally graded semiconductors. We also laid out a procedure for drawing the band diagram of any general device under any bias condition.

In this lecture, we will be using this procedure to draw band diagrams for a number of situations.

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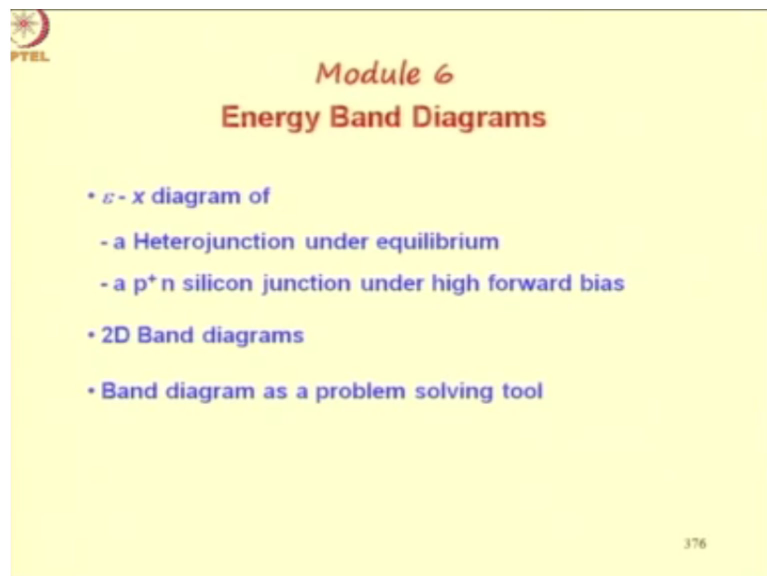

So we shall discuss the E-x diagram of a hetero-junction under equilibrium a p + n junction under high forward bias. Then, we shall be discussing 2 dimensional band diagrams and finally we shall look at band diagram as a problem solving tool. Let us begin with hetero-junctions.

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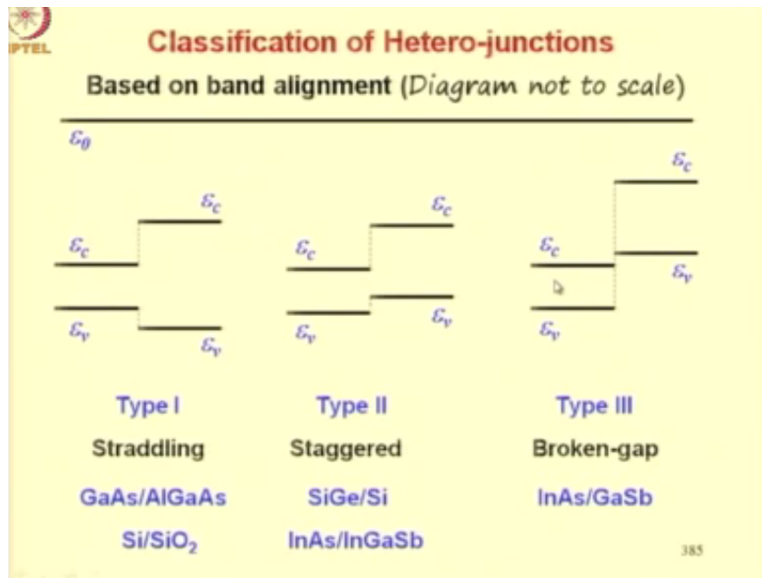

The hetero-junctions can be classified based on how the 2 sides of the junction, the bands of these 2 sides are aligned to each other and also based on the polarity of the doping on the 2 sides of the junction. First let us look at the classification based on band alignment. The diagrams that we shall draw here will not be to scale.

There are 3 types, when we draw the band diagrams for materials, which are isolated the band diagrams are reference to the vacuum level E naught that is why the first step will be to draw the vacuum level E naught. In type one, the conduction bandage on the higher band gap side is higher than the conduction bandage on the lower band gap side and the valence bandage on the higher band gap side is lower than the valence bandage on the lower band gap side.

Examples of this type of hetero-junctions are gallium arsenide, aluminium gallium arsenide. Left hand side is gallium arsenide, right hand side is aluminium gallium arsenide. Then left hand side or lower band gap side is silicon, right hand side or higher band gap side is silicon dioxide. The type 1 hetero-junction is called straddling type hetero-junction. Now let us look at type 2 and type 3.

In these 2 types of hetero-junctions, the conduction band and valence band adjust on one of the sides is moved up relative to the conduction bandage and valence bandage of the other side. So you can see that the same situation is present here also. The difference between type 2 and type 3 is that the valence bandage is aligned against the energy band gap of the other side of the hetero-junction.

Whereas in type 3, both the conduction bandage and valence bandage are above the conduction bandage of the other side. The type 2 hetero-junction is called staggered and type 3 is called broken gap hetero-junction. Examples type 2, so left hand side is silicon germanium and right hand side is silicon. Evidently, right hand side is higher band gap and left hand side is lower band gap in this case.

Similarly, left hand side indium arsenide, right hand side is indium gallium antimonide. Example of broken band gap or broken gap hetero-junction. So left hand side is indium arsenide, right hand side is gallium antimonide.

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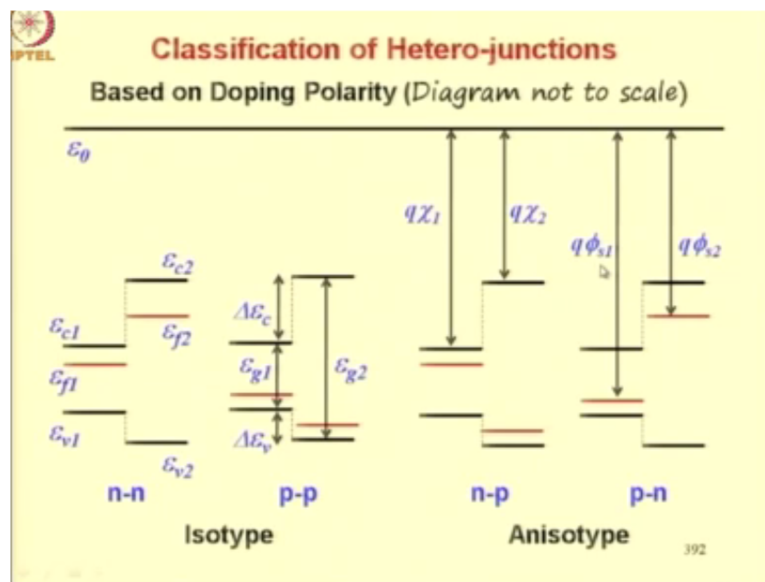

Let us look at classification based on doping polarity. In isotype hetero-junctions both sides of the junction are of the same polarity either n-n or p-p. In anisotype hetero-junctions, both sides are of opposite polarity. Let us look at the band diagrams as examples. We sketch the reference level E naught and then we sketch the band pictures of both sides of the hetero-junction.

The illustration we will take up will correspond to a type 1 hetero-junction, but the discussion will apply to type 2 and type 3 hetero-junctions also. So here you can see that the Fermi level on this side and the Fermi level on the other side both are close to the conduction bandages of the respective sides and therefore this an n-n hetero-junction. This is an example of a p-p hetero-junction.

You can see that the Fermi levels on both sides are closer to the valence bandages of the respective sides. The nomenclatures for various parameters of the hetero-junction are shown here. So you have Eg1 and Eg2 as energy gaps, Ec1 and Ec2, Ev1, Ev2 are the conduction and valence bandages and Ef1, Ef2 are the Fermi levels. Same nomenclatures would apply to all the cases though we have not shown these symbols on all the diagrams to avoid cluttering.

The discontinuity in the conduction bandage is represented using the symbol delta Ec and discontinuity in the valence bandage is indicated using the symbol delta Ev. So in this case for example, this is delta Ec and this is delta Ev. These are the band diagrams of anisotype hetero-junction. So left hand side is n Fermi level close to the conduction bandage, right hand side is p Fermi level close to the valence bandage. This is p-n.

Some of the other quantities of interest in hetero-junctions are the electron affinities on the 2 sides, which are in general different. Similarly, one can also talk of the work functions of the 2 sides q times phi s1 and q times phi s2.

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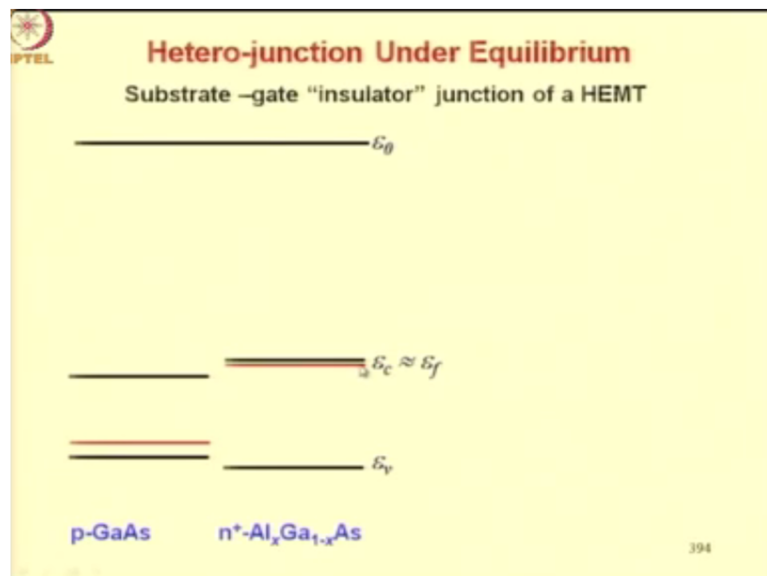

Now let us move on to drawing the band diagram of a hetero-junction under equilibrium. The specific example that we shall consider would correspond to the substrate gate insulator junction of a high electron mobility transistor. Now you may not know about the operation of the high electron mobility transistor. This is not important. All that you need to understand here is that the hetero-junction we are considering has a practical application and it is used in one of the modern devices namely high electron mobility transistor.

So first we sketch the band diagrams of both sides of the junction using E naught as a reference because we are considering the materials as isolated to begin with. So left hand side is p-type gallium arsenide and right hand side is heavily doped n-type aluminium gallium arsenide. The band gap of aluminium gallium arsenide depends on the mole fraction of aluminium.

We shall assume that the AlGaAs layer is so heavily doped that the Ec and Ef are very, very close to each other. Now the first step before drawing the band diagram when both sides are joined is to identify the direction of charge transfer when the 2 materials are joined. So we need to know how the electrons and holes will be transferred from which side to which side. This information is important to get an idea of the relative widths of the space-charge layer on the 2 sides.

If you know the direction of charge transfer, then you can figure out which side will be depleted of mobile carriers and in which side the mobile carrier concentration will be enhanced and this information gives you ideas about the relative widths of the space-charge region on either side of the junction.

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Electron Transfer During Junction Formation

Electrons are transferred from high E_f region to low E_f region

Misunderstanding	Counterexample to dispel the misunderstanding
Electrons are always transferred from high n region to low n region	In a M-S contact with $\phi_m > \phi_s$, electrons are transferred from S to M
Electrons are always transferred from high E_c region to low E_c region	In an anisotype hetero-junction between n-type low bandgap region and p-type high bandgap region, electrons are transferred from low bandgap region to high bandgap region

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So let us consider electron transfer during junction formation. The general rule is that electrons are transferred from high Ef region to low Ef region. Now students have a lot of misconception depending on their training of drawing band diagrams for homojunctions. For example, here is a misunderstanding you might think that electrons are always transferred from the high electron concentration region to low electron concentration region.

Let us give a counterexample to dispel this misunderstanding. In a metal semiconductor contact with phi M > phi S, electrons are transferred from semiconductor to metal.

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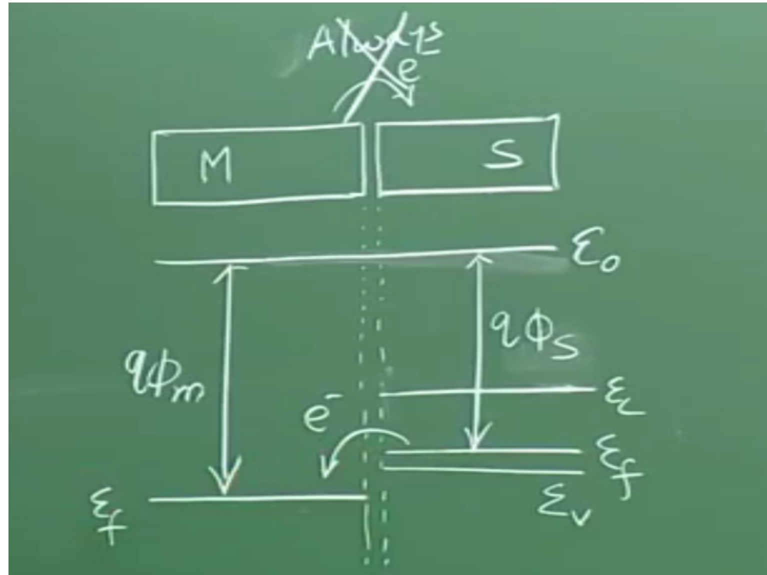

Now here is a metal semiconductor materials placed in close proximity, but not yet in contact so that you can draw the band diagrams using E naught as a reference. So here for example, the semiconductor side has its Fermi level above the Fermi level of the metal because after all the Fermi levels locations depend on the work functions. So this is the work function of the metal side and this is the work function of the semiconductor side.

So we are considering a situation, a combination of material such that phi M is more than phi S. Now suppose this side were to be even p-type, which means the valence bandage is close to the Fermi level on this side. So let us say this is the conduction bandage. Now if you were to go by the electron concentration argument, p-type has very little electrons, p-type semiconductor has very little electron concentration.

On the other hand, metal has a very high concentration of electrons. So you might then tend to think if you were to argue based on concentration that electrons will be transferred from metal to semiconductor, but this is incorrect because it is a Fermi level location that decide the electron transfer. So in this case electrons will be transferred from p-type semiconductor to metal even though the electron concentration here is small.

This is because the guiding principle is the energy even though the electron concentration is small on the semiconductor side, the energy of electrons is higher because the Fermi level is higher. So if you think that always electrons are transferred from metal to semiconductor because metal always has higher concentration of electrons than semiconductor. Then this understanding is not correct, you must go by the Fermi level locations.

Let us look at another misunderstanding. Electrons are always transferred from higher conduction bandage region to lower conduction bandage region. The counterexample in an anisotype hetero-junction between n-type low band gap region and p-type high band gap region, electrons are transferred from low band gap region to high band gap region. So here is an example of 2 semiconductors.

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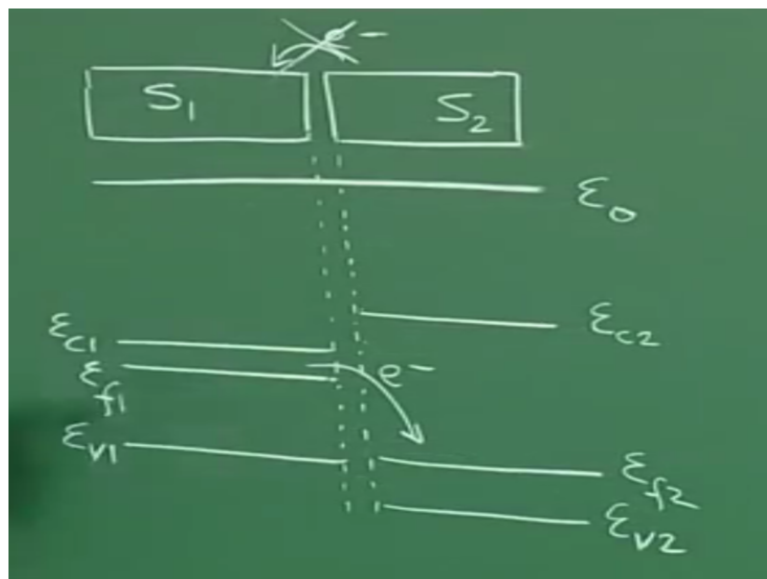

This side is low band gap and this side is higher band gap. Suppose this side is n-type so your Fermi level is here and this side is p-type so your Fermi level is closer to the valence bandage. Now the electrons will be transferred in this direction based on their Fermi level. If you were to think the conduction band of the right hand side is higher than conduction band of the left hand side therefore the energy of conduction electrons on the right hand side is more than energy of conduction electrons on the left hand side.

That argument will make you think that the electrons are transferred like this, but this is not correct okay. So you should not look at the conduction bandages, but you should look at the Fermi level. Now you might think why do I look at the Fermi level? The argument is very

simple. The electrons are transferred from regions of higher probability to lower probability okay.

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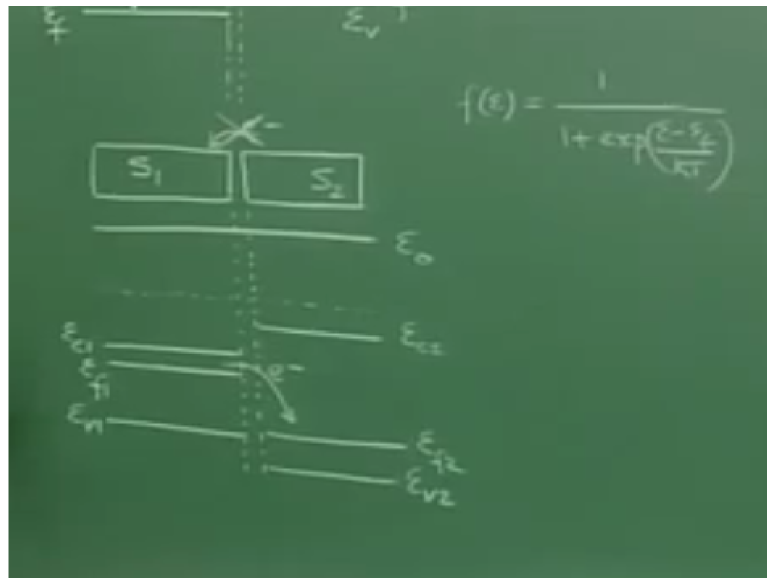

Let us look at the energy level here for example. Since this energy level is located closer to Ef1 than to Ef2 so I move to this side at the same energy. The probability occupancy of this energy level by electrons on this side will be higher than the probability occupancy of this energy level on this side because the energy level occupancy depends on the difference between the energy level and Ef2.

It follows the rule the fraction of occupied states at any energy = 1/1 + exponential of E - Ef/kT. So if E-Ef is more f of E will be less is the probability occupancy. So here E-Ef is more therefore probability occupancy is less here E-Ef is less therefore probability occupancy is more. Therefore, at these energy electrons will be transferred from left hand side to right hand side and this will be applicable at all energies.

Take energy, the same argument would apply. Therefore, electrons are transferred from regions of higher Fermi level to lower Fermi level. You can apply this argument in case of this diagram also.

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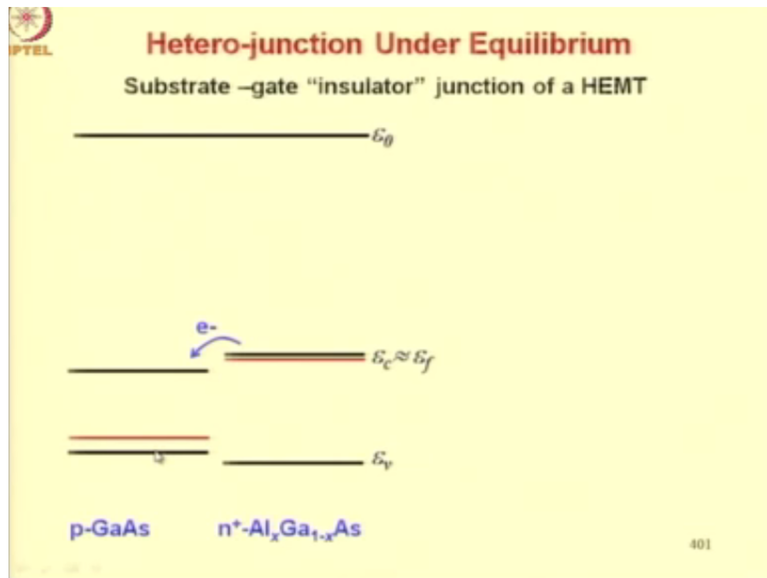

Now let us move on to drawing the band diagram of the hetero-junction of the HEMT. So from the Fermi level locations, we argue that electrons will be transferred from AlGaAs region to GaAs region okay. What does this mean? When you join the AlGaAs region to GaAs region, the AlGaAs region, which is n-type will be depleted of electrons so right hand side will be depletion region.

The left hand side, the gallium arsenide side on the other hand the electron concentration will increase, this is a p-type region so here electrons will increase and they can really become very high in concentration as we shall shortly see.

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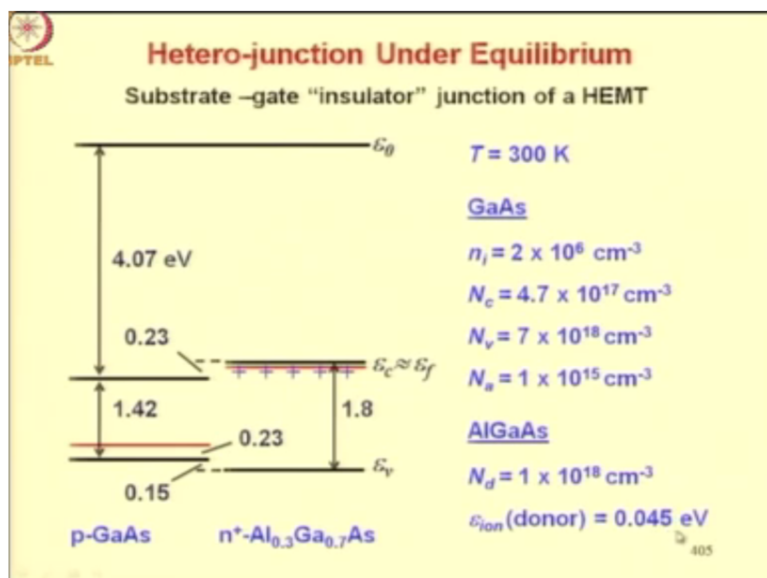

P-type gallium arsenide, the band gap is 1.42 electron volts and electron affinity is 4.07 electron volts. The AlGaAs side if the mole fraction of aluminium is 30% or 0.3, the

corresponding gallium arsenide mole fraction is 0.7. For this case, the energy gap happens to be 1.8 electron volts. So the difference between 1.8 and 1.42 is distributed between the conduction band discontinuity and valence band discontinuity as given here.

So the conduction band discontinuity is 0.23 electron volts and valence band discontinuity is 0.15 electron volts. We have to accept these values, which are based on the practical experiments done to measure these quantities. Let us look at the gallium arsenide side Fermi level. The Ef-Ev on the p-type gallium arsenide side can be calculated to be 0.23 electron volts based on the data given here.

We are considering the temperature to be 300 K so doping level on the gallium arsenide side is 1 into 10 power 15 per centimeter cube and these are the values of Nc and Nv. On the AlGaAs side, the doping level is heavy 1 into 10 power 18 per centimeter cm cube, it is n-type and the ionization energy of the donor is 0.045 electron volts. You need both these values to locate the Fermi level because this is heavily doped region, the ionization energy becomes important.

So you will have to use the Joyce-Dixon approximation and the partial ionization term right in the charge balance equation to determine the location of the Fermi level on the heavily doped n-side. On the lightly doped p-side, we do not need the value of the ionization energy of the acceptor because this is a lightly doped side and the Fermi level will be above the acceptor level and partial ionization therefore need not be considered, the ionization will be complete.

On the right hand side on the other hand, you can see that if the Fermi level is moving closer to the conduction bandage then it goes above the donor level and therefore ionization will be partial. Now with these values, let us draw the band diagram under equilibrium. I am going to follow the same procedure that I have outlined in the previous lecture. The first step is to determine the concentration of electrons, holes, current densities, Jn, Jp, E and psi from the drift-diffusion model.

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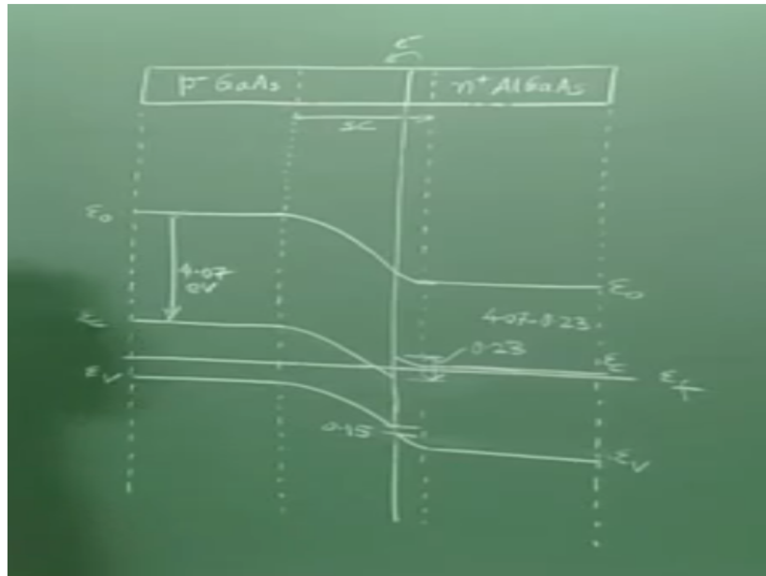

The next step is to divide the device into junction, space-charge and neutral regions. So we locate the junction as shown here. Then near the junction, we locate the space charge region part of it on the right hand side and part of it on the left hand side and the remaining region is the neutral region. For example, here is a neutral region on n+ AlGaAs side and here is the neutral region for the p- gallium arsenide side and this is the space-charge region here.

So SC means space charge. Now why is it that we have drawn the space charge width on the n+ side smaller than the space charge width on the p side? It can be shown that the potential drop in the heavily doped side is very, very small compared to the potential drop in the lightly doped side and therefore there is another reason why their space-charge region here tends to be thin.

Most of the potential drop occurs on the lightly doped side, therefore this side the space-charge region is wider okay. So now we have identified the junction, space-charge region and neutral regions. The next step is to draw the various levels in the following sequence. The first we draw the Fermi level everywhere. Since this is an equilibrium condition, quasi Fermi level for electrons and holes are the same as the Fermi level.

So we draw the Fermi level as a constant line because it is equilibrium. The next step is to draw Ec and Ev in a neutral regions conduction bandage and valence bandages. So this side is heavily doped n-type so this conduction bandage very close to the Fermi level and let us say this is the valence bandage. Let us draw the valence bandage and conduction bandage on the left hand side.

So the doping on the left hand side is lower so the difference between Ef and Ev here will be more than the difference between Ec and Ef here. So let us say this is Ev. Now when we draw the diagram, we must have an idea of the relative scale of various energy differences. For example, we know that this is 1.8 electron volts and the band gap here has to be 1.4 so this has to be smaller band gap than this and we must remember that the band gaps are in the ratio of 1.4 to 1.8.

So here it has to be less than this so let us say about this much. If you do not draw the diagram to scale then the information that you infer from the diagram may not be accurate. So this is Ec, so this is 1.4 and this is 1.8. The next step is to draw the E naught or vacuum level everywhere. Now vacuum level is at a distance of 4.07 from the conduction bandage, this is 1.4 so 4.07 so multiply 1.4/3 and then a little less than that.

So let us say here so this is E naught so this distance is 4.07 electron volts. Now E naught on this side first do it in the neutral region. Here the electron affinity is 4.07-0.23 so here this height should be less than this by 0.23. So if this is the height here and a little less so this is your E naught. Now the E naught should be drawn as a continuous line in between, the exact shape of this is obtained from the solution of the Gauss's law of Poisson's equation.

So we have taken care of the fact that the potential drop on the gallium arsenide side is much more than the potential drop on the aluminium gallium arsenide side. Now we sketch Ec and Ev in the space charge region following the E naught. So the electron affinity remains constant throughout the material so I draw the Ec as a line parallel to E naught at a distance 4.07 on the gallium arsenide side.

Something like this and similarly I draw a line here parallel to this at a distance 4.07-0.23 on the aluminium gallium arsenide side, something like this. So you see you have a discontinuity here and this discontinuity = 0.23 electron volts so all quantity is here are in the electron volts. So I should have a discontinuity of 0.15 electron volts here, the valence band discontinuity.

So this line is parallel to this line, this line is parallel to this line because the energy gaps are constant in the respective materials. So this is how one can complete the energy band

diagram. So you can see from here that the Fermi level on the p-side has gone into the conduction bandage, which means a very high concentration of electrons. Now this is the advantage of the hetero-junction that it has provided you a very, very high concentration of electrons on the p-type gallium arsenide side.

If this were a homojunction, right hand side heavily doped n-type, left hand side lightly doped p-type even in that case you would have had a large amount of electron transfer from right to left. The amount of electron transfer in the hetero-junction is much more than that okay because of the conduction band discontinuity.

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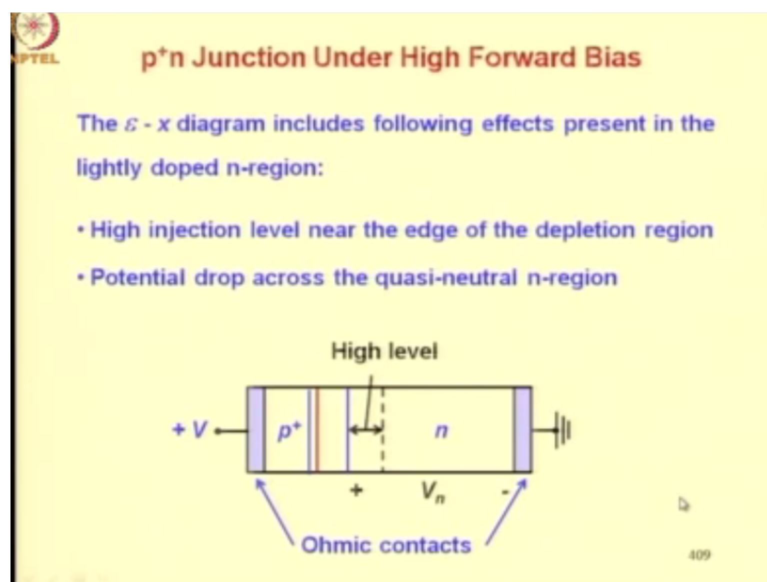

Now let us discuss the p + n junction under high forward bias. So this is the diagram of the junction, you have ohmic contacts at the 2 ends and this is the space-charge region width the drown line here is the junction. The E-x diagram includes the following effects present in the lightly doped region. First high injection level near the edge of the depletion region in the lightly doped side.

And then you have a potential drop across the quasi neutral n-region. So when the applied bias is large, these 2 effects have to be taken into account.

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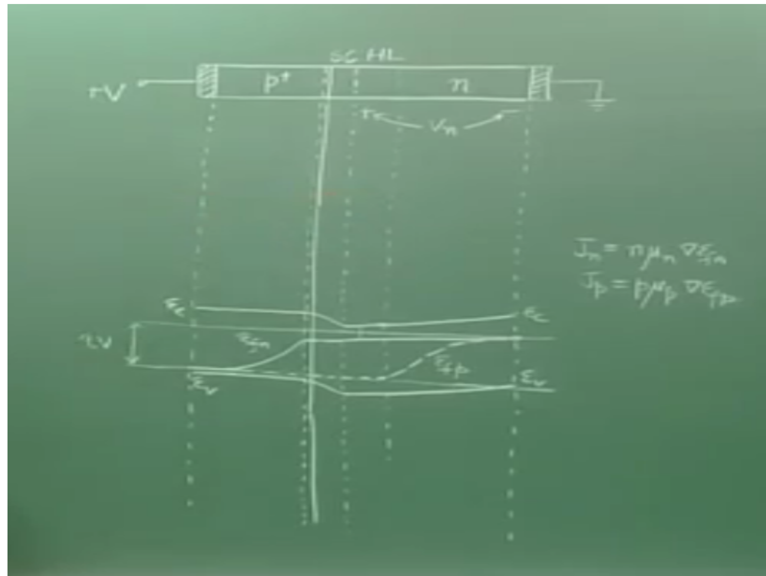

Now let us see how do we draw the band diagram taking into account these effects? So again we use a same procedure so we assume that we have information about n, p, Jn, Jp, E and psi solved from the drift diffusion model at least in the qualitative form. Then we divide the device region into space-charge, which is this much and neutral regions, these 2 are the ohmic contacts.

Then we also identified the high injection level region. The junction is here. Now we will start sketching the band diagram. So first we show the difference in quasi Fermi levels on the 2 sides. In the applied bias case, the quasi Fermi level for electrons and holes will not be the same, there will be a separation between the 2 and we know from our previous lecture that if I take the Fermi level variation from one contact to the other contact, the total variation of the Fermi level would be = q times applied voltage for both Efn and Efp.

Since left hand side is positive, right hand side is negative, quasi Fermi level for electrons will be higher on the right hand side than on the left hand side okay. So let us start by first identifying the voltage drop that is q times V. So the total variation Fermi level from this point to this point would be q times V. Now let us take Efn, the relevant equation is Jn = n mu n gradient of Efn.

At high forward bias, Jn is high therefore gradient of Efn becomes significant and the current is from left to right so which means gradient of Efn is positive so we start from let us say this is the location of Efn at the contact then I must have a small positive slope in the neutral

region. The exact shape of the quasi Fermi level will not bother right now we know that it is decreasing.

Now in the space-charge region, we can assume close to quasi equilibrium condition. So we can extend this through with a small slope in fact if quasi equilibrium is perfectly valid this region this Fermi level should be flat, but at high injection level or rather high forward bias the quasi equilibrium condition may not be exactly satisfied. So therefore there is a small slope.

Then the Efn falls to Efp because at the contact, you have equilibrium condition Efn and Efp should be same. So this is your Efn. Now let us draw Efp. You again use a formula like this except that n is replaced by p since the doping here is very heavy, the hole concentration is high so if I write the formula Jp = p mu p gradient of Efp since p is high even for high Jp gradient of Efp small.

So we will assume that quasi Fermi level for holes is almost flat. So this is how it looks here and in the space-charge region also it remains approximately flat. Now Efp in the neutral n-region, now this is where one has to take care of the fact that there is high injection level. If you recall the band diagram of an illuminated semiconductor under high injection level Ec-Efn=Efp-Ev so Efn and Efp should be parallel in the high injection level region.

So therefore here the quasi Fermi level for holes is parallel to the quasi Fermi level for electrons and then it merges with Efn at this end. Now this is how we have completed Efn and Efp so this is Efp. Now next is to draw Ec and Ev in the neutral regions. So Ec, in the high injection level region Ec should be parallel to Efn at some distance and then the distance between Ec and Efn should be slightly more when you go out of the high injection level region right because the injection level is becoming low so something like this.

Diagram is not exactly to scale so this is your Ec. Now your Ev, this distance should be same as the distance between Efp and Ev and the Ev should be parallel to Efp. It is parallel to Ec also because energy gap should be the same. So something like this. So this is your Ev. This point need not be the same as this line okay. It is just a coincidence that this line which tells you the voltage drop Qv happens to be close to Ev.

Now let us do the Ec and Ev exercise on this side. This is a heavily doped side so your valence band edge will be close to the hole quasi Fermi level and conduction bandage you can draw at taking the same energy gap. We draw this as a flat line because Ev is also almost flat because no voltage drop on the p-side and then we can join Ec as a continuous line and Ev as a continuous line.

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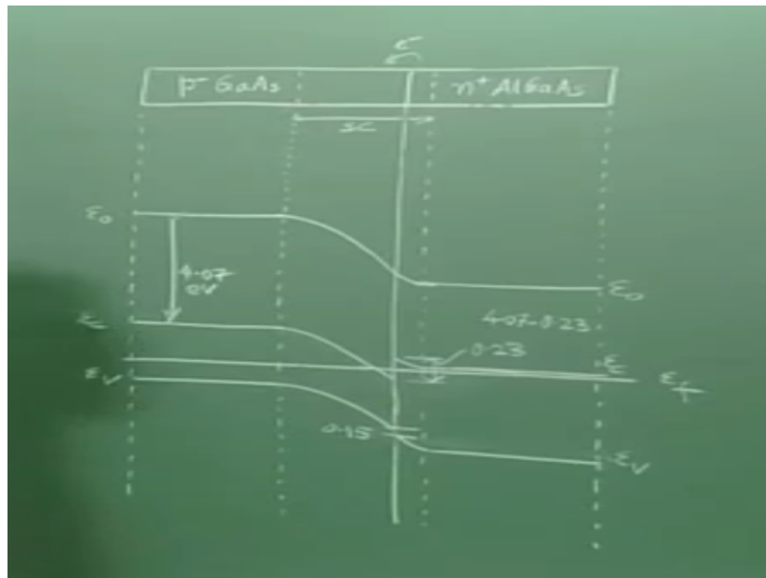

We need not draw E naught in the hetero-junction in this case while drawing these lines we have sketched E naught first. This was important because the electron affinity was not same on both sides so only E naught is continuous, Ec is not continuous so we should first draw the continuous line and then with reference to that we should sketch the Ec on both sides. However, this is a homojunction electron affinity is same on both sides so continuity of E naught automatically implies continuity of Ec and Ev.

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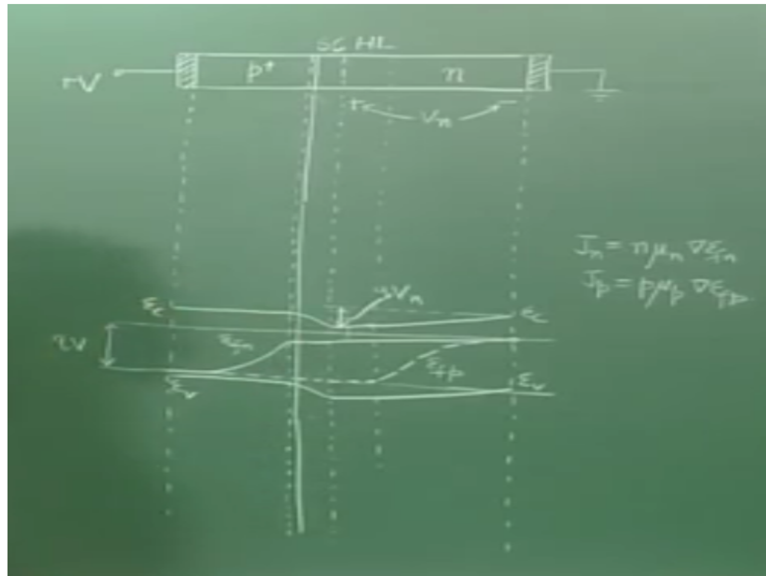

So for homojunctions drawing of E naught is not important. Now this is Vn is the potential drop on the lightly doped side so that is indicated here on the diagram as follows. So this difference is q times Vn. So total variation in Ec over the neutral region. So high injection level conditions are represented by maintaining Efn as close to Ec as Efp is close to Ev and Ec, Efn, Efp and Ev are all parallel to each other.

And the total variation in Ec or the neutral region represents the q times Vn. If this voltage drop is negligible this Ec would have been flat as Ec is in the p-type region here there is no voltage drop so it is flat.

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NPTEL

ε - X Diagrams of Various Junctions

Assignment-6.7

Sketch the ε - x diagrams for

a) Isotype hetero-junction with type II band alignment under equilibrium

b) Illuminated p^+n junction in open circuit condition

c) p^+n^+ tunnel diode in forward and reverse bias

d) Metal / n-silicon schottky junction ($\phi_m > \phi_s$) under forward bias

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So let us look at an assignment, sketch the E-x diagrams for isotype hetero-junction with type 2 band alignment under equilibrium, illuminated p+ n junction in open circuit condition, p+

n+ tunnel diode in forward and reverse bias. Metal n-silicon schottky junction with phi M > phi S under forward bias.

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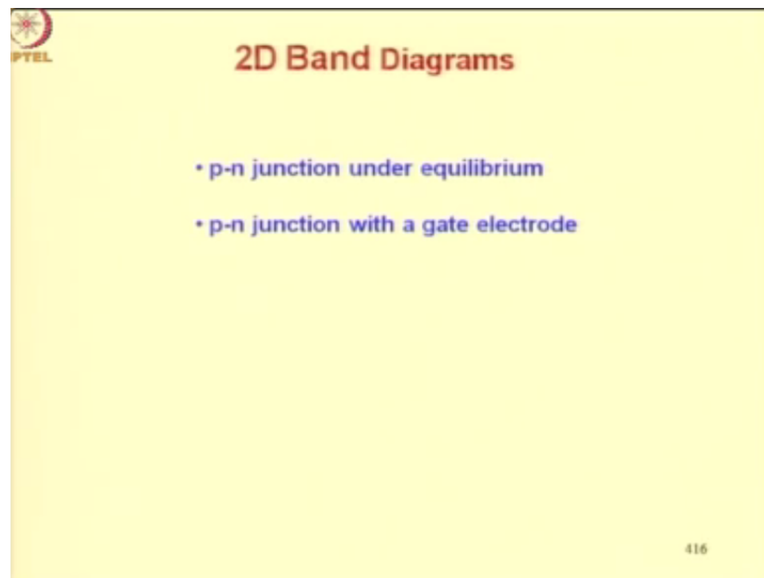

Now let us move on to the 2 dimensional band diagrams. So here we shall sketch the electron energy as a function of x and y. So far we have sketched electron energy as a function of x. You can see that all these diagrams electron energy is the function of x so these are one dimensional band diagrams.

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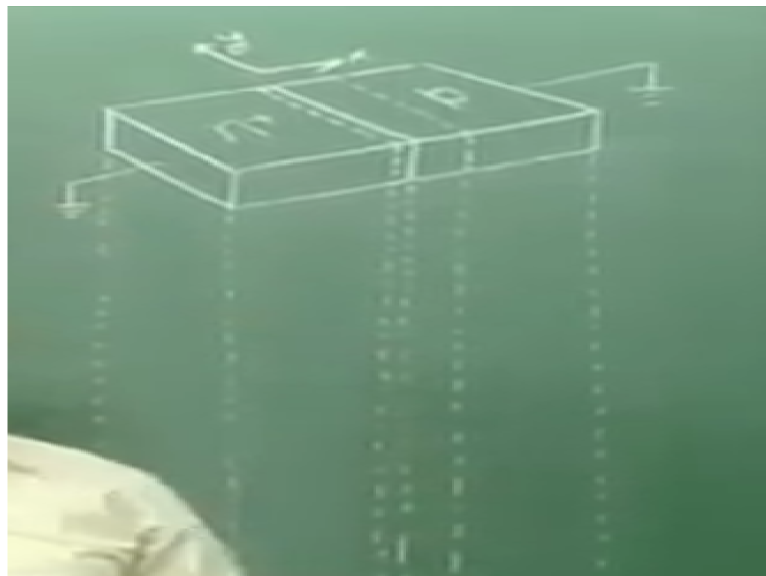

Here we are plotting electron energy as a function of x and y in a 2 dimensional band diagram so the vertical axis is electron energy and the 2 horizontal axis are x and y. In a 2 dimensional band diagram, every level of the one dimensional band diagram will become a surface. In one dimensional band diagram, every level is a line.

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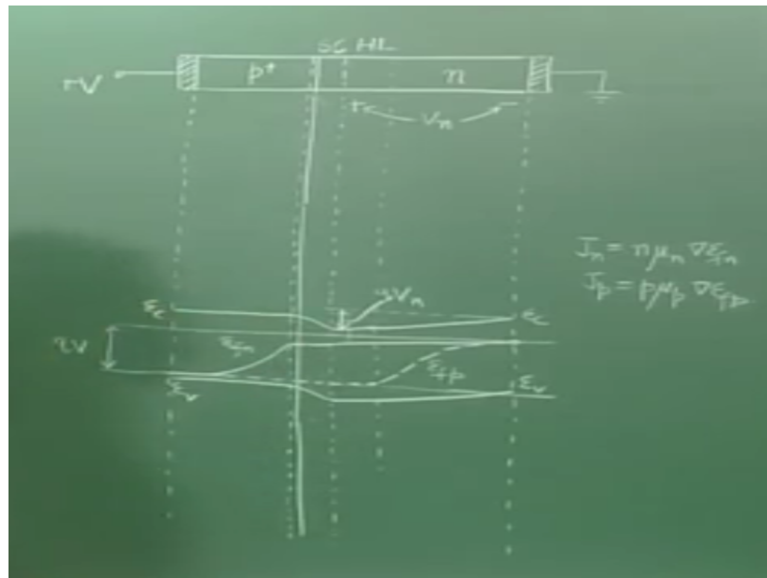

So here you can see Ec is a line, Ev is a line, Efn and Efp are also lines. These will become surfaces in 2 dimensional band diagram. So by way of example, let us illustrate 2 dimensional band diagrams of p-n junction under equilibrium and p-n junction with the gate electrode.

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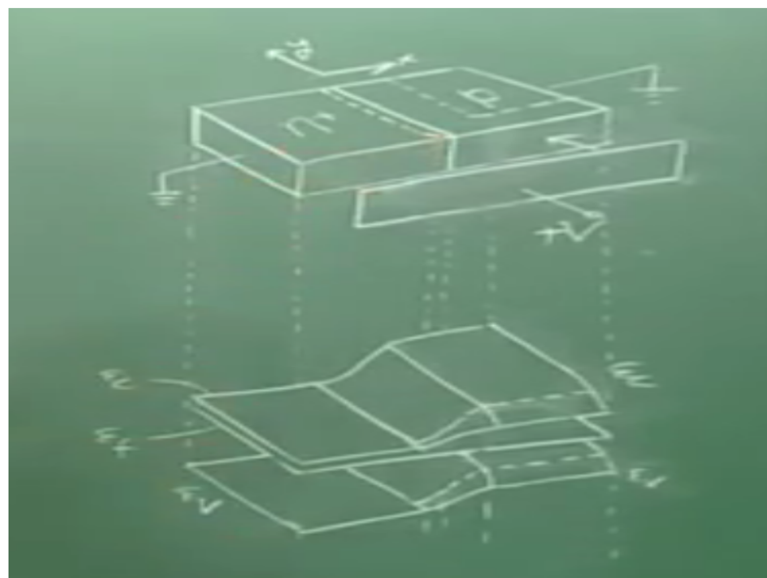

So this is our p-n junction, left hand side is heavily doped n-type, right hand side is p-type. We are assuming the junction is under equilibrium so the starting point would be Fermi surface. We have already identified the space-charge in neutral regions okay. So the Fermi level is now the Fermi surface. So we draw a horizontal Fermi surface under equilibrium conditions equivalent to horizontal Fermi level of the one dimensional case.

So let us say this is our Fermi surface. Now let us sketch Ec and Ev surfaces, let us start with the Ec surface on the end side so Ec is above the Fermi level. So this is Ec in the neutral n-side, Ev on the neutral p-side. Now Ec on the neutral p-side, so energy gap so this length should be equal to this length so this is the Ec and this is Ev. Let us sketch Ev on this side so I should use the same energy gap here.

And now I should join Ec as a continuous line and Ev as a continuous line. So Ec as a continuous line taking into account the fact that most of the potential will drop across p-region and similarly here. We have not drawn the E naught line or E naught surface because it is a homojunction continuity of E naught implies continuity of Ec and Ev as we discussed for the case of p-n junction here, here also we did not draw the E naught line because it is a homojunction.

Now let me clear up some of the things that are cluttering the diagram so that you can see the 2 dimensional band diagram clearly. Now let us apply a gate electrode, will apply electric field from this side to the surface. So this is an electrode that is applying an electric field. So it sets up in the electric field like this. So this electric field will attract electrons and drive away holes so it will create a depletion region here and will create an accumulation in the n-side it will attract electrons, so this depletion region will become thin.

So this is your new picture, this will have its effect on the band diagram how? As you move over the surface from this end, you will have constant or horizontal energy levels until this point and as you enter this depletion region, the conduction bandage should fall down because electron concentration increasing and holes are being driven away right so conduction bandage will fall down, valence bandage will fall down.

So let us show that here so the conduction bandage falling down can be shown like this similarly the valence bandage also falls down. So here this is sloping down and here this is sloping down okay. The Fermi surface on the other hand remains constant so it remains horizontal okay. So this is the band diagram under the condition that a gate electrode has been placed against this surface.

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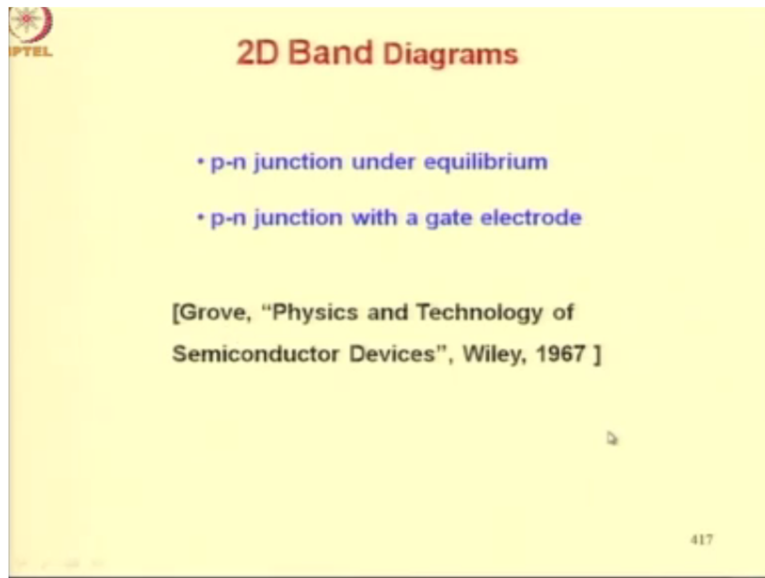

So this is how you can draw 2 dimensional band diagrams okay. It is a challenging exercise. The band diagrams that we have just now drawn on the board is taken from this book Physics And Technology of Semiconductor Devices by Grove.

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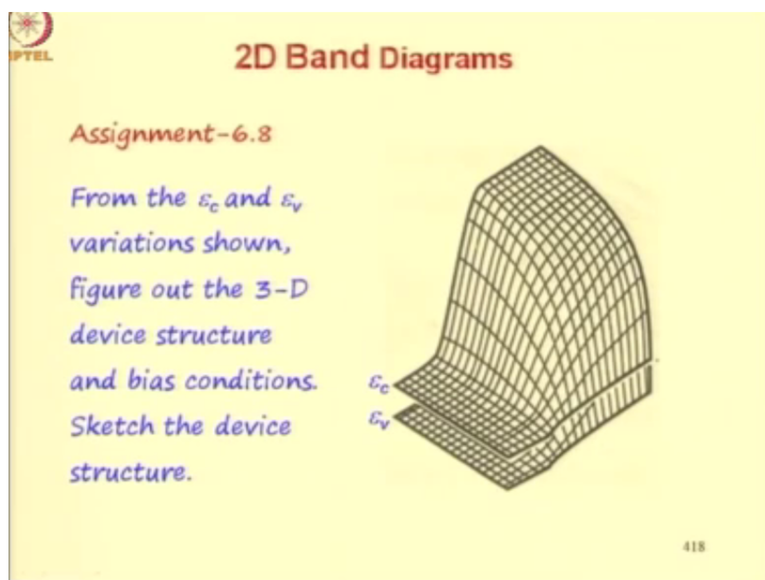

The assignment is from the Ec and Ev variation shown figure out the 3D device structure and bias conditions, sketch the device structure. So far what we have done is we have been given a device structure and we have been given bias conditions and we have been asked to draw the band diagram that is what we have done. In the assignment, you are being given the band diagram and you are being asked to figure out the device structure and bias conditions.

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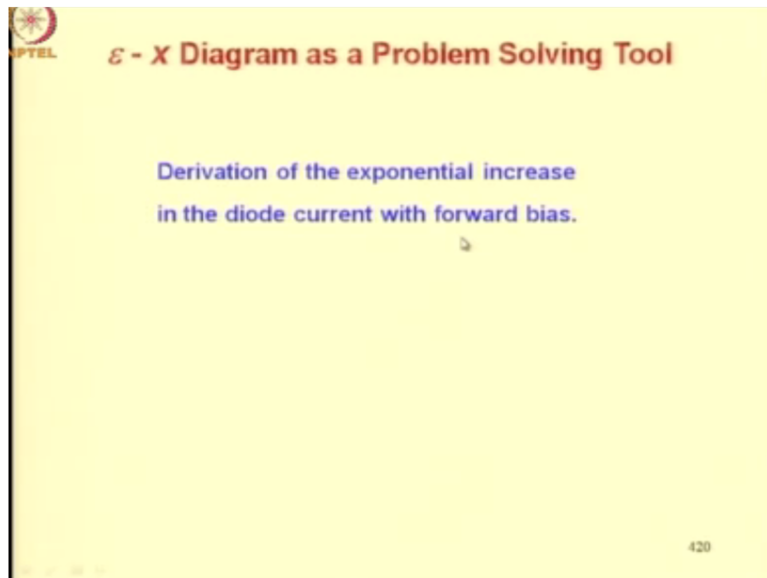

Towards end of the lecture let us discuss E-x diagram as a problem solving tool. The energy band diagram is nothing but a form a graph. Now you might know that graphs can be used to represent equations, graphs can also be used as a tool for solving equations.

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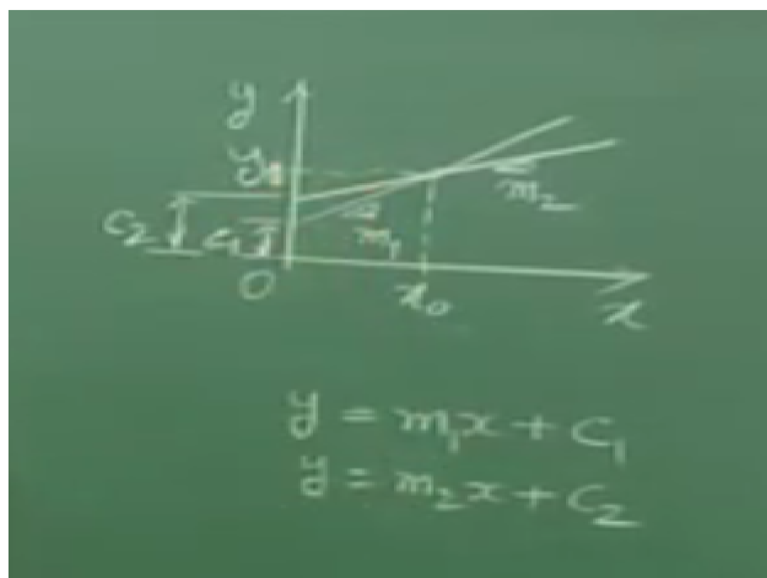

Take this example this is a graphical representation of a straight line, which has the equation y=mx+c so the slope is m, and this intercept is c. Here I have used the graph to represent this equation. How do I use the graph to solve equations? Well supposing I have 2 equations, y=m1x+c1 and y=m2x+c2. I want to get the values of x and y which satisfy both these equations.

Now the way I can use the graph is as follows. I will plot the second line also on the graph, which may be say something like this where if this is c1 then this is c2, this is m1 and this is

m2 and then the point of intersection here gives me the solution of these 2. So I could get the solution by actually algebraic manipulation. Alternately, I can get the solution using this graph x naught y naught that is the solution.

So earlier we knew n, p, Jn, Jp, E and psi and we drew the band diagram okay. Now we are going to use the band diagram to get information about n or p, Jn or Jp or E or psi. How do we do that? In fact, Shockley used it. Shockley used it to derive exponential increase in the diode current with forward bias. So let us discuss this situation. Now you know that the current is related to carrier concentration.

So if I can somehow show that the carrier concentration within the device is increasing exponentially with voltage then I can explain how the current can increase exponentially with voltage so let us explain how we can get information about carrier concentration as a function of voltage.

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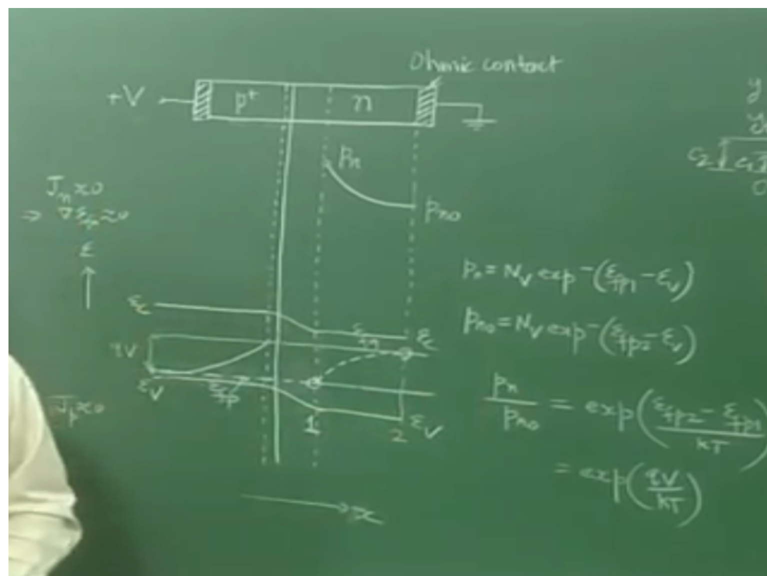

Now qualitatively we know that if you apply a forward bias to the p-region then the p-region will inject holes into n-region so at the depletion edge the hole concentration will increase. Let us call that concentration as p suffix n. Now at the contact since this is an ohmic contact, this is also an ohmic contact. So at the ohmic contact the carrier concentration should be = equilibrium value pn0. We want to know how pn is related to the voltage.

We shall derive this information from the band diagram. So let us draw the band diagram. We first mark the applied voltage as 2 horizontal lines the difference between which is q times V.

so this is energy and this is distance. We have already separated the space-charge and neutral regions and now we start with the quasi Fermi level for electrons and holes. So quasi Fermi level for electrons, let us assume that the applied voltage is very small so that our diagram is simple and you can quickly derive information about p suffix n.

So when applied bias is small, the currents are also small and therefore the gradients in Efn and Efp would also be small. So therefore we can assume Efn and Efp to be approximately constant in the neutral regions. So let us say this line therefore shows the Efn as a constant line because current is small. Now we move into the space-charge region. We shall assume quasi equilibrium in the space-charge region that is Jn=0 approximately.

So drift and diffusion are very large compared to the difference between them which is Jn. This is the meaning of quasi equilibrium. So this means the gradient of Efn would also be small. So I can pull this quasi Fermi level as a constant line here to this end. I can do the same thing for quasi Fermi level for holes so quasi Fermi level for holes is again a constant line because currents are small and I can pull this constant line into the space-charge region.

Because I will assume quasi equilibrium Jp approximately = 0 and I have come up to this point. Now beyond that the quasi Fermi level for holes will rise and merge with Efn at this contact because equilibrium conditions have to be there at ohmic contact and same thing we can say about Efn, it will fall and then merge with the Efp at this point because there should be equilibrium because this contact is ohmic.

Now once we have got this information how do we get information about p suffix n? Let us complete the diagram drawing Ec and Ev. So here this p+ so your Ev will be close to the Fermi level, here Efn is at a distance from Ec, this distance is more than this distance because this is lightly doped region. Then I can plot Ev here and Ec here. Then I can complete the picture because again it is a homojunction I do not plot E naught, Ec and Ev have to be continuous lines.

Now using the band diagrams let us see how I can get p suffix n. I can write p suffix n as Nv into exponential of - of Efp - Ev at which point so you take this point that is here so here this is your Efp. So let us call this point as point number one for our case this edge of the depletion region. So therefore location of Efp at this point one I will indicate as Efp one. Now

what about pn0, I can write this as Nv into exponential of - of Efp at the contact let us call that point 2 - Ev.

So at the contact that is this is point 2, this Efp is merging with this Efn okay. Now I can take the ratio pn/pn0. Nv will cancel out and you will get this as exponential of Efp2-Efp1/kT. Now what is Efp2-Efp1? Efp2 is this, Efp1 is this and the difference between these 2 is q times V okay. So difference between Efp here and here this q times V therefore this = exponential of q times V upon kT.

So this is how you can infer that the hole concentration p suffix n in exponential related to the applied voltage. Now this is how the energy band diagram helps you to derive information about the variation of the hole concentration with applied voltage. Note that there has been a slip in writing the expressions for pn and pn0. The exponent in the exponential terms should be divided by kT in both the expressions for pn and pn0.

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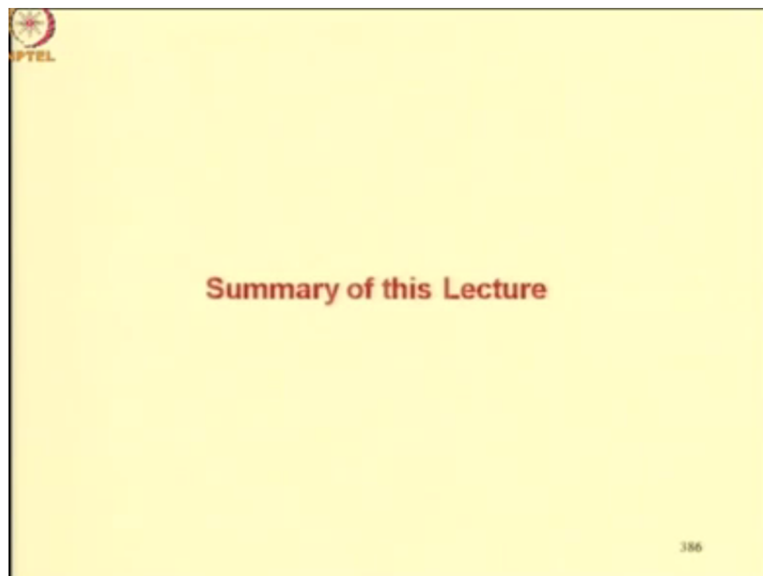

Let us make a summary of the important points. In this lecture, we have applied the procedure we outlined in the last class for drawing energy band diagrams to various situations. So first we discussed how to sketch the energy band diagram of a hetero-junction under equilibrium. Then we considered the energy band diagram of a p-n junction under high forward bias.

Wherein we represented features such as high level injection near the depletion edge in the lightly doped side and a potential drop across the lightly doped region. Then we discussed how to draw 2 dimensional band diagrams where every energy level becomes a surface. We

considered the 2 dimensional band diagram of a p-n junction under equilibrium and under the application of a gate electrode.

Even in the presence of gate electrode, the equilibrium condition prevailed in the p-n junction. Finally, we discussed a very important point how to use the energy band diagram as a problem solving tool to derive information about n p, or Jn Jp or E and psi given the device structure and bias conditions. In the next lecture, we shall consider the correspondence between E-x and E-k diagrams and summarize the entire module.