High Speed Devices and Circuits

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Lecture - 30

Hetero Junctions

Today we start our discussion on Hetero Junctions. The need for Hetero Junctions comes about due to various reasons. We see, in the case of MESFET, the threshold voltage shifts in the negative direction. We have seen this when the channel becomes short. Sub-threshold slope becomes larger, that is, it becomes difficult to turn off the device that is guided by a number called the ideality factor n_g that is I_{D0} e to the power of VGS minus V_T by V_T by n ng times V_T. That is slower; it turns out slowly.

Now all these are due to 2D effect in the channel direction, in the direction along the channel. The way to do that is to increase the field in a particular direction so that it is large compared to the field in an x direction along the channel.

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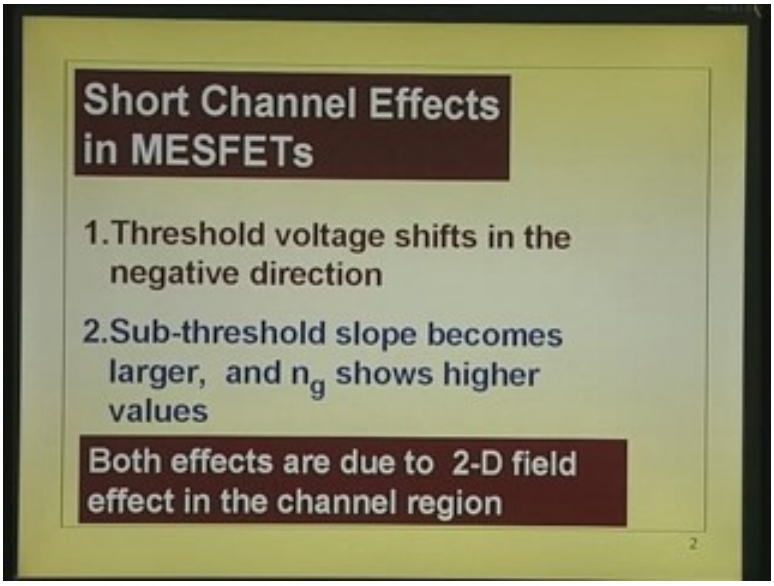

That you can do by increasing the doping. Short channel effects are reduced by increasing the channel doping density and by reduction in the channel thickness. Both are possible. But increasing the doping in the channel adversely affects mobility and velocity overshoot effect. In fact, this problem of mobility getting affected by doping is common for all the devices. To talk of MOSFET, you need to reduce the channel length. When we reduce, we increase the doping.

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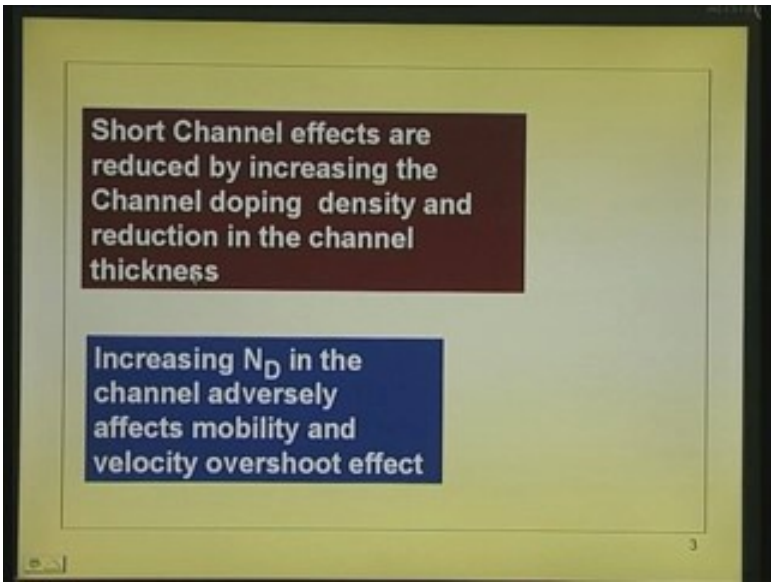

The reason I am putting this across is one might be wondering why we should restrict to MOSFET at all. If you see MESFET, we see that increase in doping is required. What about MOSFET? MOSFET structure is like this (Refer Slide Time: 03:22). All of you know that this is the heart of the present VLSI p-type substrate and then you have the gate and the field oxide. That is the gate and I put a metal here and source. This is a schematic diagram (Refer Slide Time: 03:52). What we do here is, when you reduce the channel length, your worry will be the depletion layer from here will encroach into this region (Refer Slide Time: 04:07). As we go to say, a depletion layer can reach through a channel thickness of point one micron.

To prevent that, you want to reduce the depletion layer width and you can reduce the depletion layer width by increases the doping. What you do here is, in a short channel

MOSFET, to reduce the channel length, increase the doping and when you increase the doping, threshold voltage goes up. To keep the threshold voltage down, you reduce the oxide thickness. This is the oxide and then this is the metal (Refer Slide Time: 04:44). Let me put it clearer, you have the oxide and then the metal, so you reduce the thickness of oxide. That is why today people talk of oxide thicknesses of 100 Angstroms, 50 Angstroms. Ultimately, everything goes down to 0. If this goes down to 0, what happens? It becomes MESFET; that is ultimate. But then you can use this N-type. MESFET is a version of MOSFET. That is, oxide thickness is small or 0 and this is of course N-type. In either case, doping increase is inventible. Ultimately, what you are doing is you are actually providing provision for a finite channel length, which is having a large concentration of electrons. See dope is high here (Refer Slide Time: 05:35) and when inverted, you will have as much electrons as holes were there. You will have a high electron concentration. Once you have high electron concentration, you can have the same current density for the lower field because current density is proportional to electron concentration and the field. Any size field can be low for the same current density. So you get all those things like increasing the doping.

By increasing doping you are increasing p. But when you invert, N is actually equal to p; that is where it begins (Refer Slide Time: 06:21). So it is high electron concentration. More than anything else, here you are eliminating or overcoming the problem of punch through.

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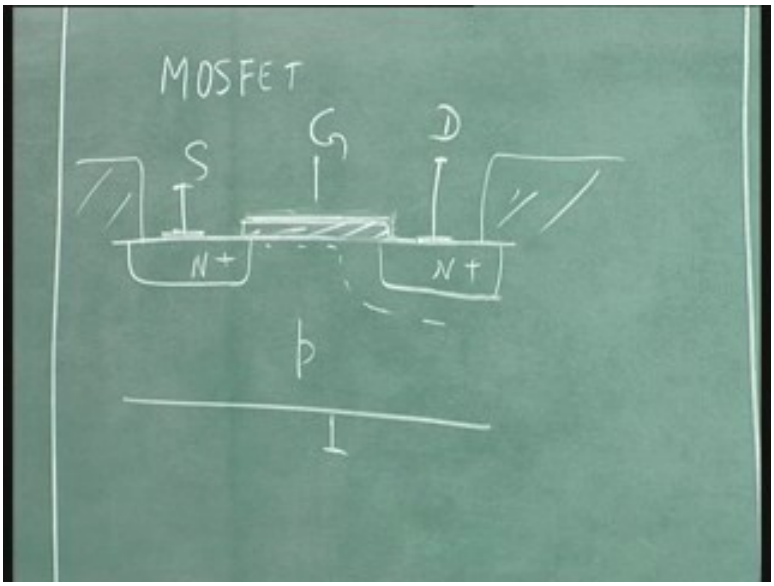

In the case of MESFET, we have said these are the reasons. Solutions are those that would be known. What is the solution? You have to change the device structure such that high electron concentration can be achieved using some different type of transistors called hetero junction transistors and with these transistors you will see that it is possible to ensure that the transport of electrons takes place in the regions where doping is low. For example, if you take MOSFET, unfortunately, the transport of these electrons takes place in the region where the doping is high.

We are confining the electrons here (Refer Slide Time: 07:15). How are we confining the electrons here? We are confining them because of a notch which is present here. Let me put that diagram which I put yesterday in the previous lecture. For example, if I take MOSFET, that is, I draw the energy band diagram here in the direction y (Refer Slide Time: 07:40). If I draw the energy band diagram there, oxide band gap, conduction band gap valance band, then p-type material comes down like this. That becomes N-type inversion.

And here it actually comes down like this (Refer Slide Time: 08:07). It becomes N-type. Intrinsic level will be something like this. Here also you will have a voltage drop in the oxide, conduction band in oxide and this one. What I am trying to point out is, we are

confining the electrons into this region. How are we confining it? We are confining that because there is a barrier for electrons from here. Once you invert, they stay there. Even in thermal equilibrium conditions they will illustrate the electron concentration. It is because of the jump there. This is the notch (Refer Slide Time: 08:50). I am focusing on to this particular notch because that notch is encountered in the case of Hetero Junction also. At this height, it is quite large. Something like 3 point 3 electron volts. It is so large here that it is very difficult for the electrons to surmount this.

We will have problems of course, if the thickness becomes small. Then they can travel through that. That is when people get large leakage currents. In fact in the case of the integrated circuits of Intel chip where the oxide thickness is the order of 40 or 30 Angstroms, that is the inside story they talk of that. Then you will see channeling of electrons from here to here. Even in off state you have got heavy current which is channeling through this (Refer Slide Time: 09:37). That is why you get problems like gate leakage current and dissipation in the gate power itself. Those are the problems that are faced there. If I talk of a different type of device where you can confine this, where you do not have to worry of such channeling, that is just a ….

Now I want to point out a related thing. You have this type of bending in the case of p-n junction also (Refer Slide Time: 10:04).

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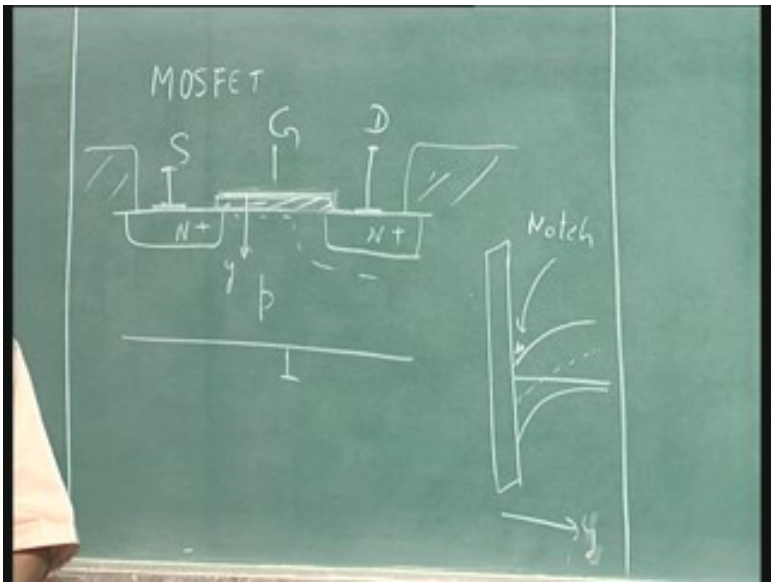

But you do not have this notch. You do not have confinement of electrons there. We may draw the p-n junction, a p-n junction in which both sides have same type of material. That is the Fermi level. And if I have p-type material here, it is like that, this is N and this is P (Refer Slide Time: 10:45). You can see this. Band bending is there, similar to this junction. But there is no accumulation of electrons there because they all roll down here. Equilibrium is reached so that transfer of electrons from here to here and here to here are same.

Whereas here (Refer Slide Time: 11:05) there is no transfer of electrons from here to there and electrons come here and accumulate. With that background, I would like to take a look at the Hetero Junctions. Ultimately you would like to have a structure like this where this channeling problem will not be there and you will still have a barrier for electrons to prevent them from going from this material to that region. And what are you doing here? These electrons are here. These are those electrons (Refer Slide Time: 11:33).

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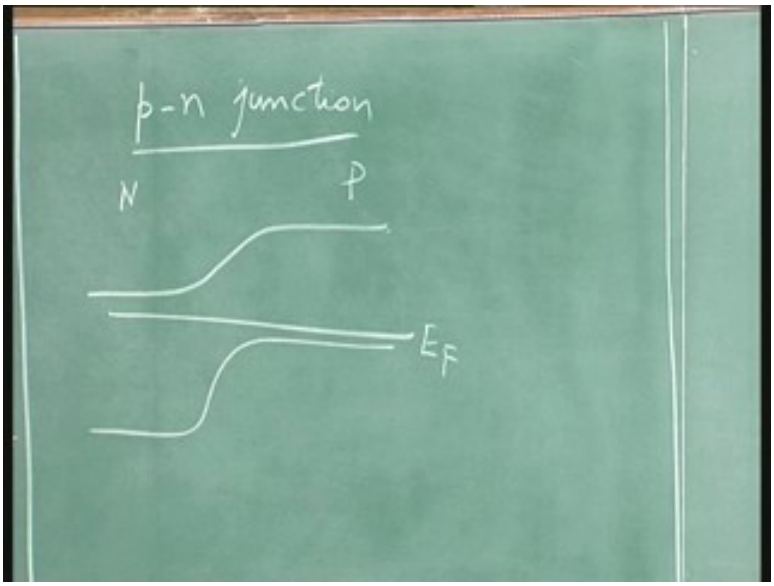

How are you collecting them? Applying voltage between the two. That means here you go perpendicular to the board. Apply voltage between the two and electrons can flow like that.

When you invert, this is in the conduction band that is there. Let us take a look at the Hetero Junctions, where you can get a structure? You achieve this notch etcetera with this region lightly doped. If this region is lightly doped and if you confine the electrons into this region, we are in business. That is because, these electrons will not get scattered by the ionizing impurities. That is the sort of thing that we are talking of there. Isolate the electrons from the doped regions. Doped region will be this type of region, which is separated from that (Refer Slide Time: 12:22). We can also see here, this is a narrow band gap material. This is a wide band gap material but it is too much wide. It is not a semiconductor, but it is an insulator.

The clue is therefore to use a substrate which is of slightly narrow band gap and another region with a wider band gap and then you will get a notch. That is the clue. The clue is taken from the MOSFET itself - oxide 8 point 8 electron volts and this is 1 point 1 electron volt. If I replace this with Gallium Arsenide, I will have the electrons experiencing all the velocity overshoot effect, high mobility and every thing, provided the

doping is low here (Refer Slide Time: 13:10). That I can do if I have undoped region here, with a doped region adjacent, but with wider band gap material so that the dopants are in this region.

Then how do we get these electrons? We will see soon. This itself is a hetero structure (Refer Slide Time: 13:28). Only thing this is not single crystal. Oxide is amorphous. It is not even poly crystalline. We are looking for a structure like this with wide band gap material narrow band gap material.

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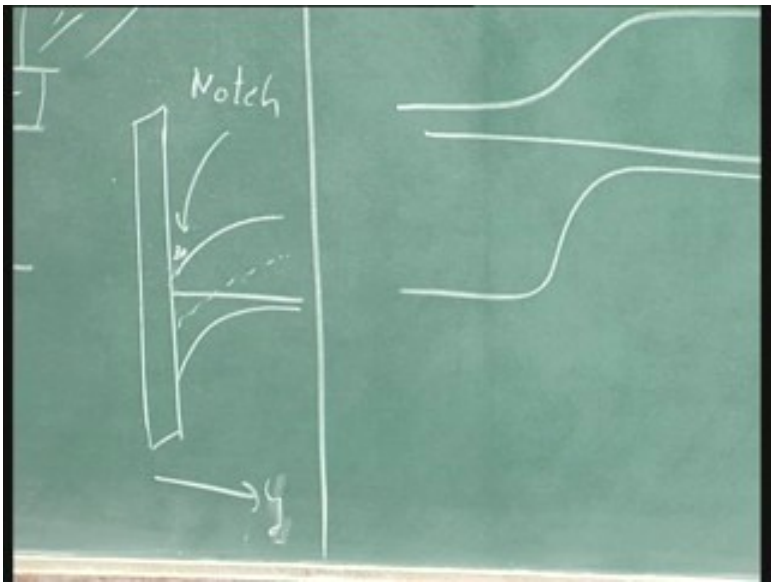

Let us take a look at that now. Going to this discussion that is extending it too much and saying oxide semiconductor is a Hetero Structure. It is a Hetero Structure; it is not a junction, but it is a Hetero Structure all right.

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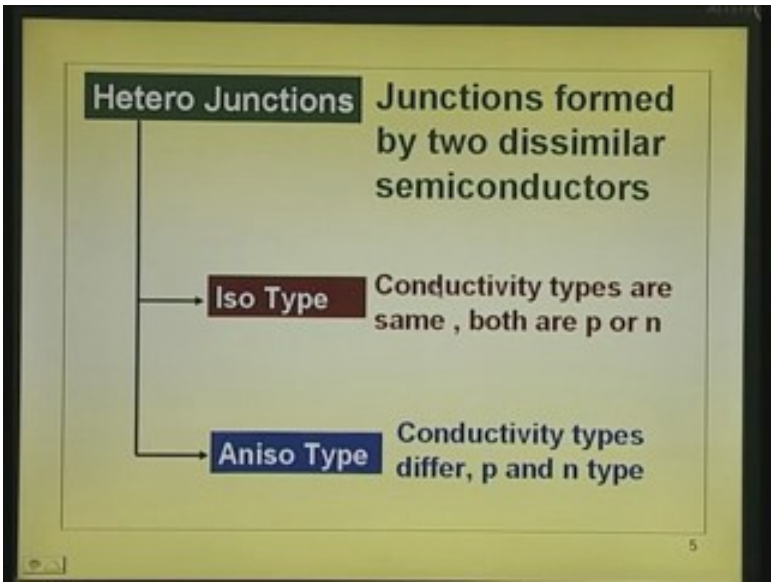

A Hetero Junction is formed by two dissimilar semiconductors. A Hetero Structure is formed by two dissimilar materials, like the oxide semiconductor. The nice thing is all these have some common features like what you see for the MOSFET. Hetero Junctions can be of two types.

We can just name, there is nothing in that. We have Iso type and Aniso type (Refer Slide Time: 14:37). Iso type is not a p-n junction it is p and p. One is wide band gap p-type material and the other one is less wide or narrower band gap p-type material. Only difference is the material. For that itself you can call it as an Iso type junction. Or, both are n-type. Now if you take Aniso type, which are the ones we usually come across, conductivity types are different. n-type may be wide band gap and p-type may be narrower band gap. So there are two things, one is p-type and the other one is n-type, one is narrower band gap and one is wider band gap; that is Aniso type. Junctions are formed with single crystal. But Hetero Structure can be formed with anything like what you see in oxide semiconductor.

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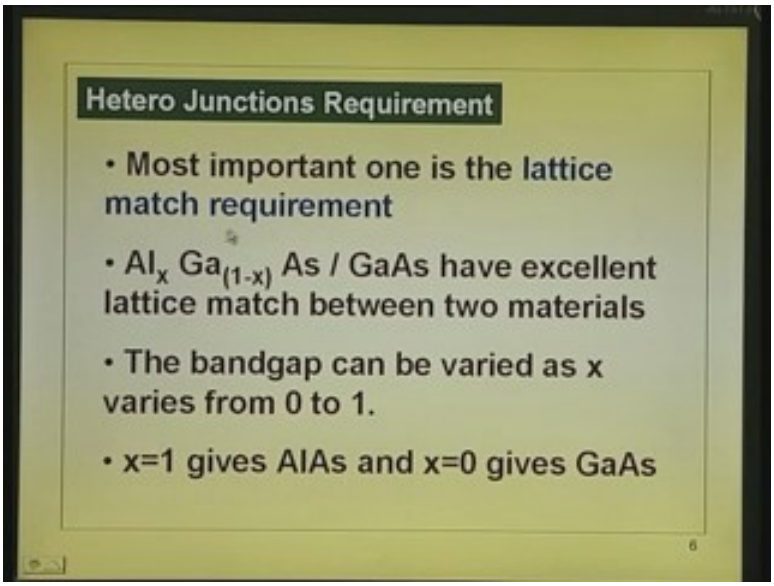

To make a junction, the most important property is there should be lattice match. If you want to make a structure, all that you have to see is a good thermal match. When deposited one over other there is no feeling of cracking up, etcetera. Whereas, if you want to make a junction, the most important property is there should be some lattice match. If you do not have lattice match there will be a defective region, because after all, if there is lattice constant 5 point 6, then if you go to 5, there will be a change and adjustment of the atoms to get the single crystal structure and there will be a region which is defective. Ultimately, when they grow on top you may have a layer, which is good, but when you talk about thinner layers like 1 micron, 1/2 micron or even less, you will have problems. Those layers would be defective. In fact, these are the problems people faced way back in Silicon on Sapphire; that is SOS. That was Saving the Soul when we wanted high speed in those days. Sapphire is single crystal and at a particular orientation, lattice match is good. It is not a perfect lattice match, but it is better than other orientations. So they were able to grow Silicon on Sapphire, single crystal, but the interface used to be very highly defective. The transition used to be very highly defective. That is the problem they faced with Silicon on Sapphire and when the layer is defective, what can you expect? Which property will be deteriorating if the layer itself is defective? Mobility. The moment you deviate from single crystal, perfect periodicity, you have the mobility getting affected.

That is why when you dope it very heavily, 10 to the power 17, 10 to the power 18, etcetera, that layer is having stress. Because you have some atoms of a different size sitting there, that is, the dopants. You have defects generated because of that. That is why the mobility gets reduced in addition to ionizing of this scattering. When you have the defects generated, you have the mobility reduced. That is how the problem came up with Silicon on Sapphire. That is why, if you want good mobility, good Hetero Junction, you need a prefect lattice match.

If you get perfect, that is the best. We have already seen and let me go through quickly, Aluminum Gallium Arsenide on Gallium Arsenide - these two junctions have excellent lattice match, because Aluminum tetrahedral radius is almost the same as that of Gallium. You replace some percentage of Gallium atoms with Aluminum and you get Aluminum Gallium Arsenide. So Aluminum is sitting very quietly where Gallium is supposed to be sitting, without getting noticed in the lattice side. That is where perfect lattice match is there. When you grow on Gallium Arsenide, Algas, we call it as Gas and Algas, when you want to grow Algas on Gas, you can very easily grow. If you are going by MOCVD, when you grow Gallium Arsenide, you have Arsine and Trimethyl Gallium.

After a certain thickness of the Gallium Arsenide, add on trimethyl Gallium and trimethyl Aluminum together, that is, you adjust the fluorides properly and you can adjust this x. And if you want dope, add a dopant also to the gas. Hydrogen sulphide gas or sulfur mono chloride you get sulfur doping, or if you use saline, you get Silicon doped Aluminum Gallium Arsenide. How much dopants you add will decide the doping concentration here. You can have undoped Gallium Arsenide. On that, you can grow this layer – Aluminum Gallium Arsenide and that layer can be doped. So you have a layer, which is undoped and a layer which is doped. But when you say undoped, it is unintentional, that is, it is not doped intentionally. But unintentional doping is always present. It generally turns out to be p-type. It has come up due to some of the impurities. You do not get an n-type at a lower temperature. But if you grow by MV, definitely it is going to be p-type due to carbon contamination. Similarly, if there is carbon contamination of some of the gases, you get the p-type. This transfer to the p-type may be 10 to the power 13 per centimeter cube, very lightly doped.

We know that we can vary x (Refer Slide Time: 20:50). x is equal to 1, this is again recapitulating what we have been discussing earlier, where we talked about technology, x is equal to 1 makes Gallium 0 and Aluminum equal to 1. It is Aluminum Arsenide; it is a wide band gap material. It is an indirect band gap material, 2 point 17 electron volts band gap. Whereas, when x is equal to 0 and there is no Aluminum, you get Gallium Arsenide with band gap of 1 point 43 electron volts, direct band gap.

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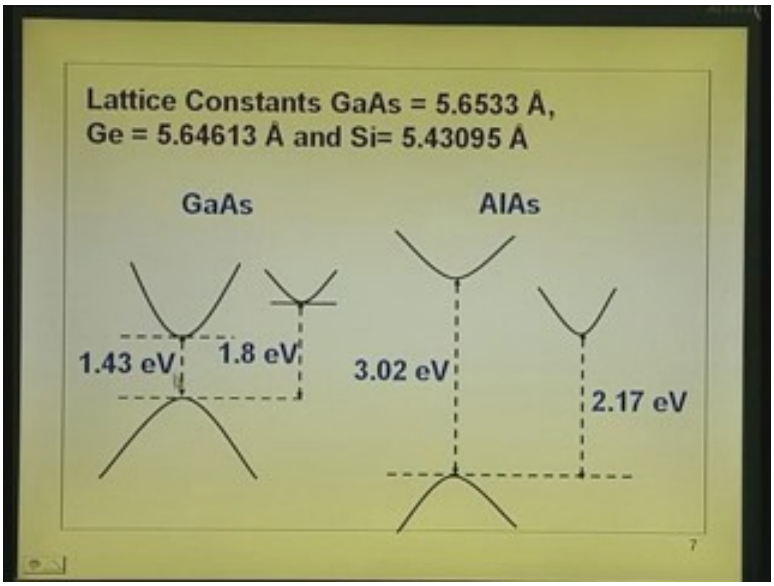

This diagram is very familiar to you now, but still I flash it across to you so that you can recollect that Gallium Arsenide direct band gap 1 point 43, there is indirect band gap region here. There can be indirect transitions, if possible, at 1 point 8 electron volts. Aluminum Arsenide - direct is 3 point 02, indirect 2 point 17. The actual band gap is, whichever is minimum because electrons here tend to occupy the lower level. This is the conduction band edge.

The actual band gap is two point one seven. If you are varying x is equal to 0 in this, you get 1 point 43. As you keep on increasing x, 1 point 43 increases linearly, almost practically not exactly linear, matches with 3 point 02 and 1 point 8 latches on to this. So you get this type of arrangement (Refer Slide Time: 22:17).

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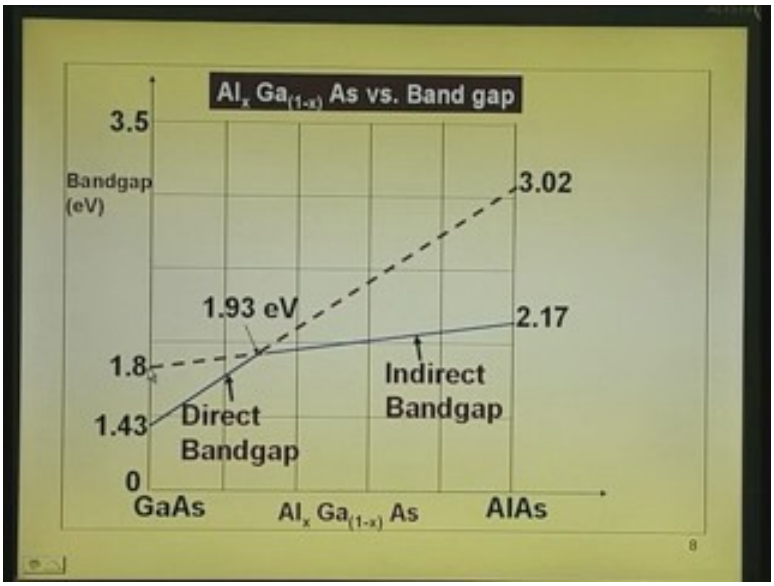

I am flashing this once more to you for you to recollect. 1 point 43 direct band gap goes through 3 point 02, almost linearly, not exactly linear. Similarly, the indirect 1 point 8 changes linearly with respect to that. So you can see till x is equal to about something like point 3 or something like that, you get direct band gap smaller than indirect band gap. (Refer Slide Time: 22:49) If you move from here to here, till some level it is direct band gap, beyond that it becomes indirect. It is very clear, x is equal to 0 is direct and x is equal to 1 is indirect. In between there is some point where transition is direct to indirect (Refer Slide Time: 22:17). This is the structure and all through this composition lattice matches Gallium Arsenide. Even here there is lattice match; you can put anything. You may have other technological problems.

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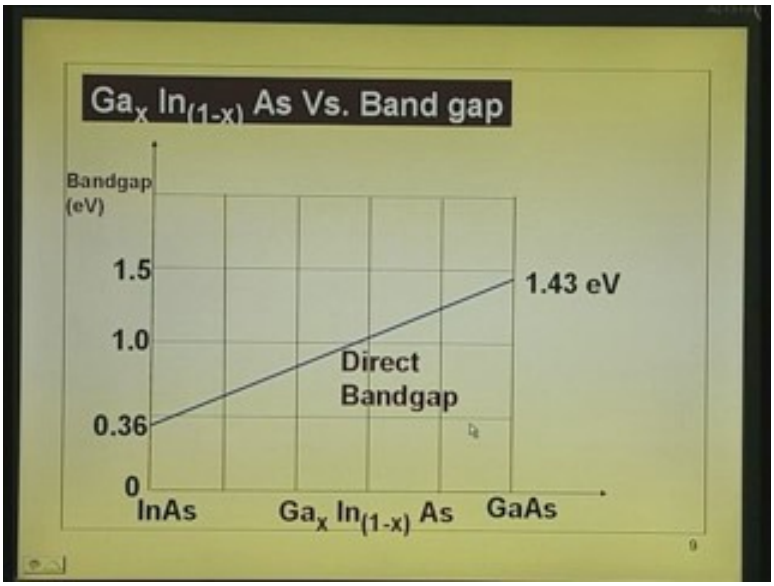

Let us take a look at this - Gallium Indium Arsenide. If x is equal to 0 it is indium Arsenide and if x is equal to 1 it is Gallium Arsenide. Both are direct band gap. So there is no question of indirect, point 36 and the other, 1 point 43.

I have drawn this as linear, but it is not exactly linear. It goes through slightly less sloping like this in this fashion. Now the key thing here is, on what substrate can I grow Gallium Indium Arsenide?

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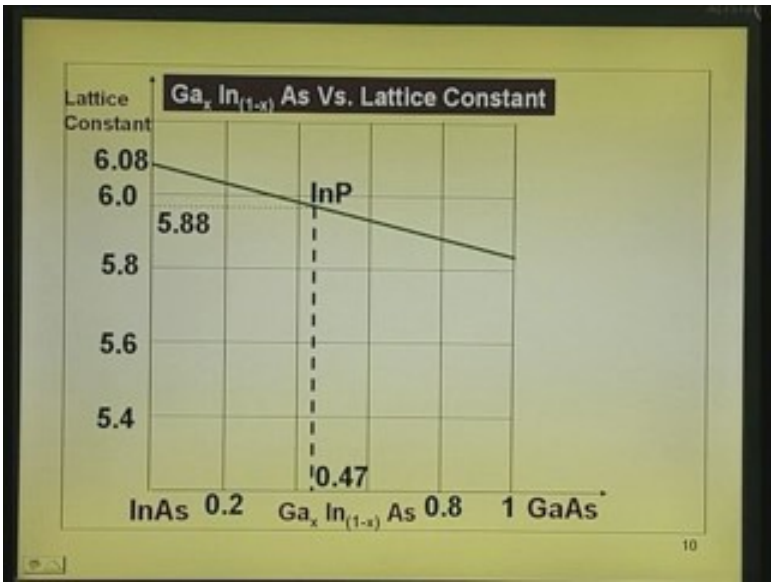

This is the lattice constant (Refer Slide Time: 24:05). Indium Arsenide lattice constant is 6 point 08 Angstroms. The left out one here is Angstroms. And Gallium Arsenide constant is some where around this. What happens is when you mix Indium Arsenide and Gallium Arsenide you get a band gap, which actually matches within a phosphide. Let us take a look at this diagram.

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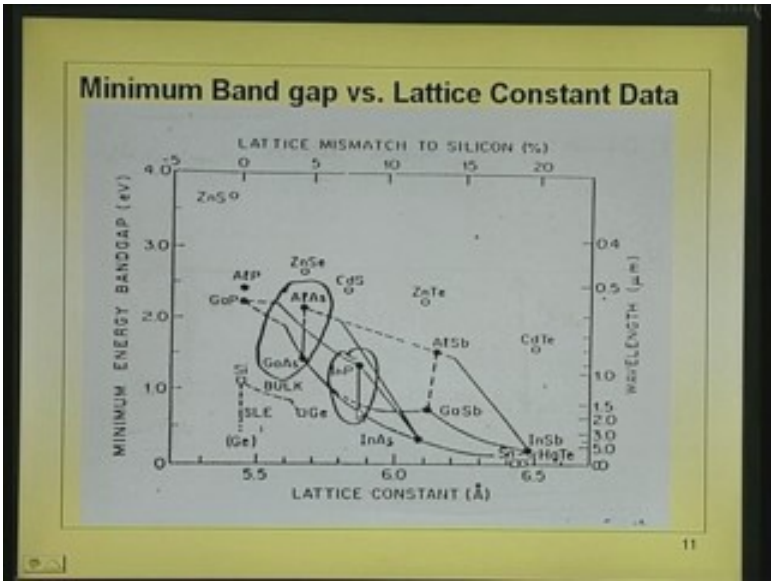

You can see Gallium Arsenide here (Refer Slide Time: 24:40), x axis is lattice constant and it is about 5 point 65. In the previous diagram you must note that it is 5 point 65. Indium Arsenide lattice constant is something like close to 6 point 1. I vary the composition and change some Gallium Arsenide to Indium Arsenide. That is, I vary x. x is equal to 1, you get Gallium arsenide and x is equal to 0 you get Indium Arsenide. When you move from Indium Arsenide to Gallium Arsenide, lattice constant keeps on falling from 6 point 1 or so to about 5 point 65. But somewhere in between it is something like about 5 point 88. That matches Indium phosphide.

What I am trying to point out ultimately is, you can mix with Indium Arsenide and Gallium Arsenide. You can keep on adding Gallium to Indium Arsenide. Two things will happen. One is, the lattice constant keeps on falling from this value to that value. Simultaneously, the band gap which has point 36 here, corresponding to that, keeps on increasing to about point 75 or so. You get band gap increase from point 36 you get lattice constant falling and ultimately matching with Indium phosphide.

To sum up, if I am using Gallium Arsenide based devices you will make a Hetero Junction with Aluminum Gallium Arsenide on Gallium Arsenide. If I am using Indium phosphate based substrate, I will make Gallium Indium Arsenide on Indium phosphate. That has a good lattice match with Gallium equal to point 47.

What I am trying to point out now is: $Ga_x In_{(1-x)} As$ (Refer Slide Time: 27:05). This lattice matches with Indium phosphide, InP when x is equal to point 47. Indium is point 53 and Gallium is point 47. That is, 47 percentage of Gallium and 53 percent of Indium. So if I want to grow, with good lattice match, this on Indium Phosphide, I can do that by adjusting that point 47; that is what I am trying to tell. Whereas, if I want to grow Aluminum Arsenide on Gallium Arsenide, I can choose any x, Aluminum 0 to 1, that is a perfect lattice match. In fact that is seen here (Refer Slide Time: 24:34 or 28:00). You can see Gallium Arsenide about 1 point 43 Aluminum Arsenide is 2 point 17. I can get it anywhere in the band gap. This is the key to that thing. Whenever people talk of Indium Phosphide based devices, they make Hetero Junction with Gallium Indium Arsenide and

with Gallium Arsenide we invariably make Aluminum Gallium Arsenide. Let us take a look at the hetero structure itself.

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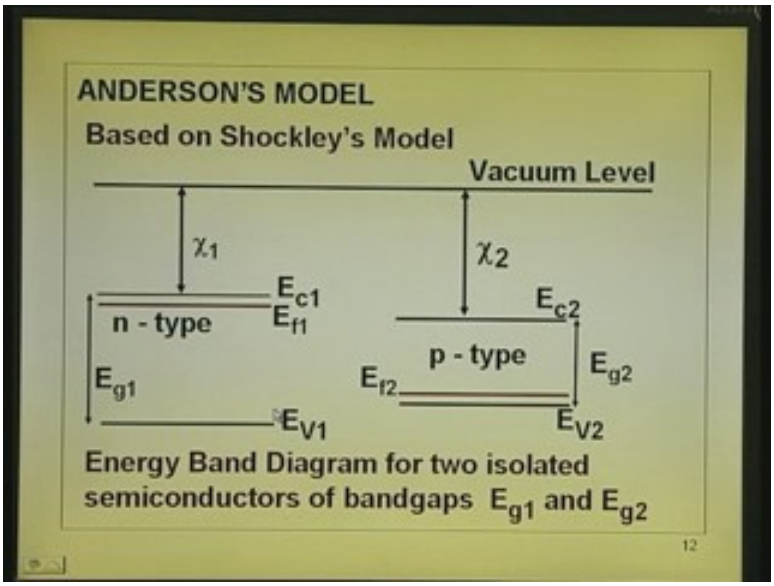

How to make a Hetero Junction? We now know that you can take Aluminum Gallium Arsenide, n-type and wide band gap material. Band gap of Aluminum Gallium Arsenide is more than that of Gallium Arsenide. I hope you now understand that. I can have Aluminum Gallium Arsenide n-type and that is the first device that is seen in the high electron mobility transistors mostly. I put this as p-type Gallium Arsenide, but to keep the discussion general, I just put n-type material with wide band gap material E_{g1} and another material with p-type with the band gap material E_{g2}.

Now when you put them together, hold your breath, (how it is got - we will get that down on the board), you get it with the band structure like this.

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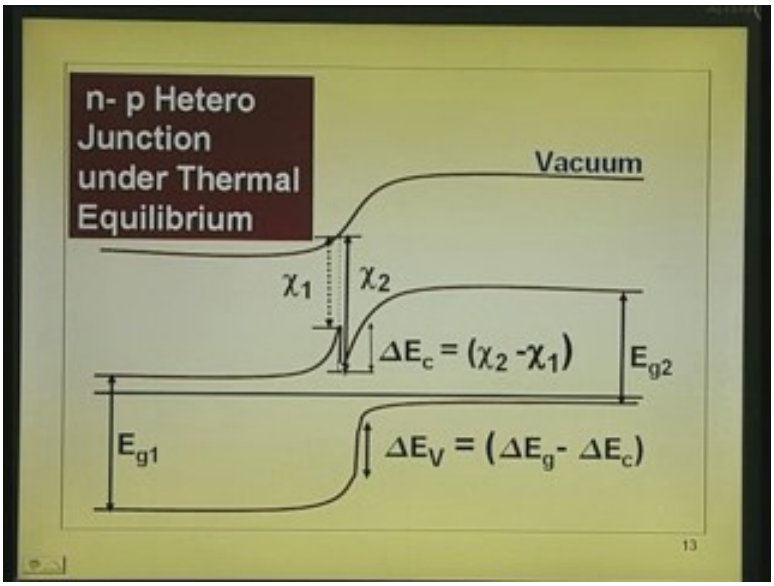

Conduction band going like this, you get the notch that you are looking for and you can confine the electrons. This is the wide band gap material and this is the narrower band gap, $E_{g2.}$ Now this is under thermal equilibrium conditions. Let us go back and see how to construct this. We will have to develop it step by step. Instead of putting it on the slide, I better develop it on the board.

First, let us see what is happening in a material like this. Homo junction, both are of the same material. How do you draw it? If it is equal doping, you have the depletion layer there and you have the Fermi level like this. I am deliberately drawing like this because only then you can generate the other one – EF. And then get this n-type like this - depletion layer.

What as happened is, the n-type layer has got depleted because of transport of electrons from here to here. Correct? Less of n-type. The gap between the Fermi level and the conduction band increases. So that is E_c and this is E_v. Notice this has bent up because it is depleting and that has bent down because that has depleted. Now where is the 0 level? Somewhere here; same nature, that is 0 level or vacuum level. That is vacuum level or 0 energy level. Wherever there is potential variation, there is a band bending. All the energy levels bend here like that. If there is a sudden jump in the energy band diagram

that will not show up there. It is only where there is a potential variation. In fact you saw it in the case of Shockley barrier.

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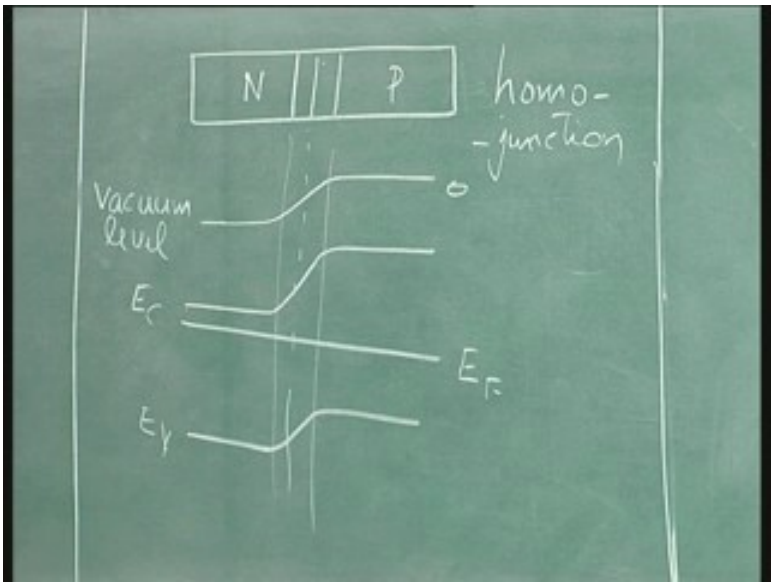

Let us take the Hetero Junction. What we have put there is a 0 level here and 0 level there. It is the same level, 0. When two different materials are separated, that is 0 level. Now I have taken a material whose electron affinity is a model that is given for Hetero Junction by Anderson way back on how the junctions are formed. That is what we are discussing.

And there they correlated everything to kai_1 and kai_2. If you see, kai_1 is actually taken as smaller than kai_2 and that is the band gap E_{g1}. It is n-type so Fermi level is there. You are talking of a junction being formed between that material and another material whose band gap is actually smaller and also kai_2 is larger than kai_1.

See the first model said everything is tied down to this (Refer Slide Time: 34:33). Now you bring them together. If I bring those two things together, what happens? Exactly what is happening here must happen. Because when you bring them together, join them, you will have transfer of electrons from here to here, so this layer will get depleted and of course this also will get depleted. Holes are neutralized by electrons. You can talk of

electron transfer which means, depleting the layer here and electron neutralizing the holes there.

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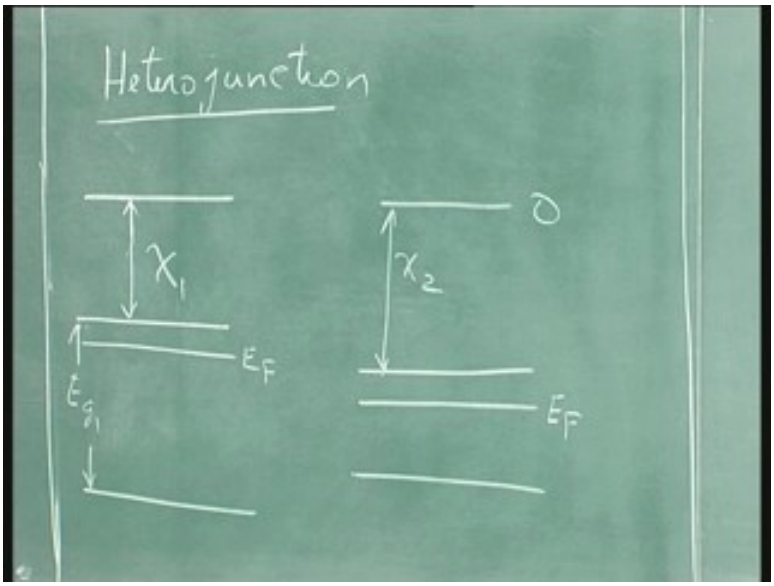

In fact you have both of them taking place, but I am talking of one to understand. So holes will get neutralized here. You have depleted layer here, this will go up. And similar to this junction, this will go up here. Up to this it is n-type. That will go up and that will come down. So how will the diagram be now? Let us construct that. You will have the n layer like this, going up. The first thing to be drawn in thermal equilibrium is to draw the Fermi level. That is flat; same barrier thermal equilibrium condition. We are going to see how that is generated. Draw the Fermi level, the n layer will get depleted near the surface and will go up. Let us put it a bit more dominantly so that I can see it clearly. It will go up.

What will happen to the 0 level? That also follows the same path. Here this also will follow the same path. That is the edge of the region. What is this gap? This is kai_1 and that is kai_1. Now exactly what is happened here in the p-n junction is happening. From the other side there will be a depletion layer. That means this potential actually will be what will happen to the potential?

Just go back to this (Refer Slide Time: 32:10) From here it is continuously flowing. That is, depletion layer here and depletion layer here. Less n-type and lesser p-type here. So both of them come down like this smoothly. As far as potential variation is concerned, it is plus charges here and minus charges here and continuously going up. Same thing should happen there also. In case of zero energy level there is no problem because zero energy level follows the potential variation totally. All the energy level follows that. So from here I will have a layer going up like that, flat. Wherever the depletion layer is present, up to that point there will be bending. That is kai_1.

Let me draw one curve like that. That is actually the kai_1 point. This is because we know there is a depletion layer on both sides. That is the potential variation. Where will you place the conduction band edge on the other side? On this side the conduction band edge is at a level kai_1 below the 0 level. When you cross from here to here, kai_2 is larger than kai_1. Where will the energy band diagram be?

That actually will be at a level equal to kai_2; that is delta E_c. This can come even below that. For this diagram I will just put one diagram like this. You have got delta E_c. A sudden jump in the energy and from there what will happen? Follow that. Potential variations are followed by energy band diagrams. But there is a sudden jump here to satisfy that kai_1 and kai_2 are different. So you will have discontinuity in the conduction band and it goes up like that. I will put it all the way up like this.

What we are trying to point out is you have ultimately ended up, (let me just redraw that and mark these things together) you will have this going up like this. Similarly, that will go up and this quantity is delta E_c because it is a discontinuity in the conduction band. Now as far as this is concerned, that comes up like this, up to this point parallel and from that point onwards it will come down parallel to that. It will reach here till it comes to the end of that material. And from that point onwards there is again a discontinuity delta E_V. In the final analysis, that is, E_{g1} and that is E_{g2}. This is delta E_v. If you leave out those discontinuities in the conduction band and valance band edges, the energy band diagram is same as the homo junction. The key thing to note is that the potential variation is described by the zero energy level. There is no discontinuity there. The discontinuity is in

this material here. There was a time when people used to say when you talk of some of the material or Shockley barrier for example, that will have some discontinuity like that. It will not be there. In the MOS device also you do not talk of the notch in the 0 level. You talk of the smooth transition to the 0 level. There is energy required to transfer the electrons from here to there. That is all. So what we are telling is: we have created a p-n junction with the notch present here. We are not discussing more than that right now.

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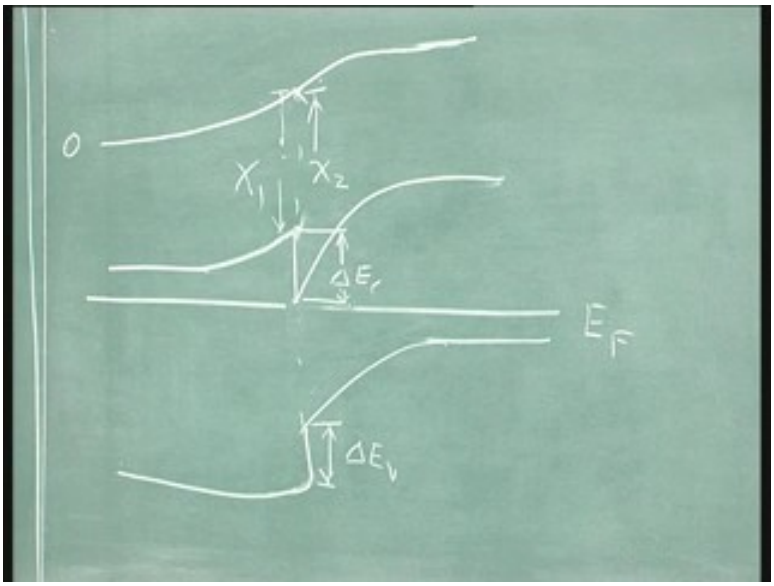

We have chosen a material with kai_2 greater than kai_1 and E_{g2} less than E_{g1}. That is the type we have chosen. It suits us very well: this could be Aluminum Gallium Arsenide and the other one could be Gallium Arsenide. Or, this could be Indium Phosphate that could be Indium Gallium Arsenide. So now what is delta E_c? In this model delta E_c will be equal to kai_2 minus kai_1. Kai_2 minus kai_1 is delta E_c. This kai_2 is actually from here to there - conduction band edge in this material and kai_1 is in this material. They are all merged together when the junction is formed.

What is delta E_v? That is E_{g1} and that is E_{g2}. I am sorry, this is E_{g1} and this is E_{g2} (Refer Slide Time: 44:10) E_{g1} minus E_{g2} is equal to delta E_c plus delta E_v; this is E_{g1}. E_{g1} minus E_{g2} is these two.

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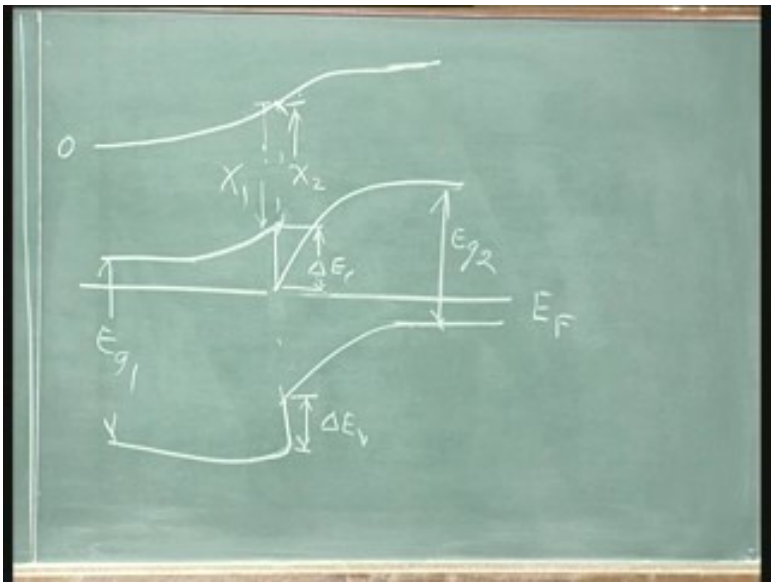

So, E_{g1} minus E_{g2} is equal to delta E_g, difference in the band gaps. Delta E_g is difference in the band gap. That is equal to delta E_v plus delta E_c. So if you know one of them you know the other one immediately. And delta E_c is related to this - kai_2 minus kai_1.

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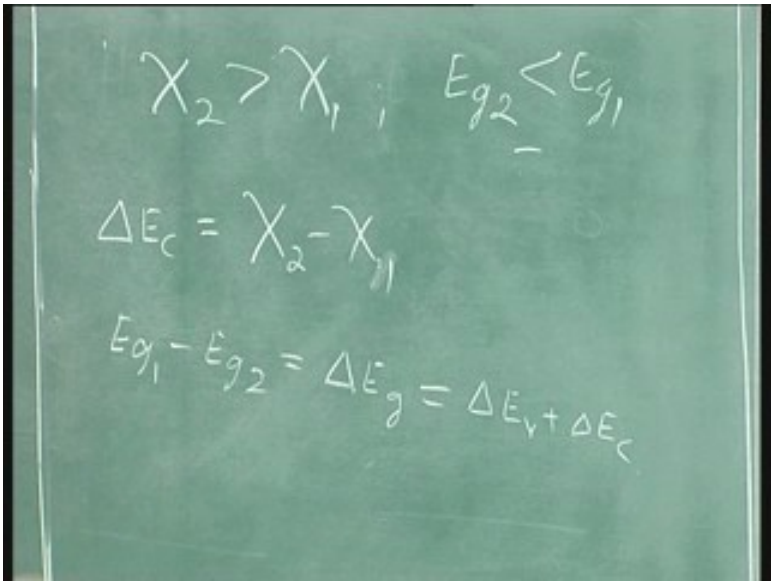

In fact, from this principle you should be able to generate any other type of Hetero Junction energy band diagram. For example, if I make this p-type, you can try to work

out and see how the energy band diagram will be. Look out yourself and draw the energy band diagram. It is a sort of exercise, you can workout for yourself and see the following: p-type, E_{g1} and kai_1. In the thing that we worked out, it is N-type, E_{g1} and kai_1. Let me just put it as usual, P-type; N-type, Eg2 and kai2. Same example, E_{g1} is greater than E_{g2} and kai_2 is greater than kai_1. I can give a clue for people who want to work it out sitting at home, that the notch will be shifted on to the bottom side. You see the notch there on the top, that notch will be shifted down like that. It will be an inverted diagram of that. You can work it out by following the same rule. If prepared we can work it out in our next lecture, but today I just leave it for people who wants to get a feel for that. You have to follow this particular rule that one will be depleted and the other will benefit on the other side.

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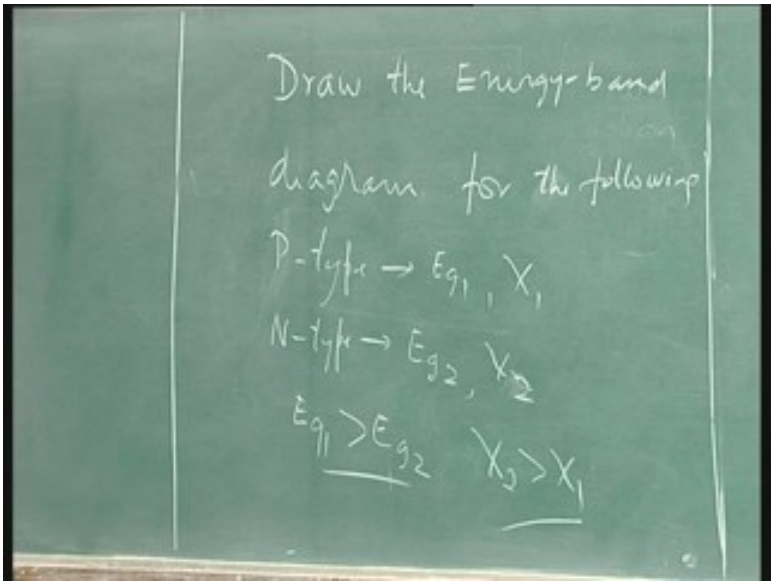

And keep this in track. Now let us go back further and see is it really true? See this is the problem. You give the idealistic model, you saw in the case of Shockley barrier, what happened? You had the barrier height is equal to 5 minus kai. Ultimately, you found out that it is not 5 minus kai, but it depends upon 5 minus kai to some extent. So we will see whether that is true in this case also. So that is ultimately the energy band diagram, which we have drawn - kai_1 here and kai_2 here. Kai_2 is larger than kai_1.

That is delta E_c. This quantity is kai_2 minus kai_1. It is very clear in this diagram and delta E_v is equal to delta E_g that is difference between the two band gaps, minus delta E_c. E_{g2} minus E_{g1} is sum of these two quantities. Delta E_g is sum of delta E_v plus delta E_c.

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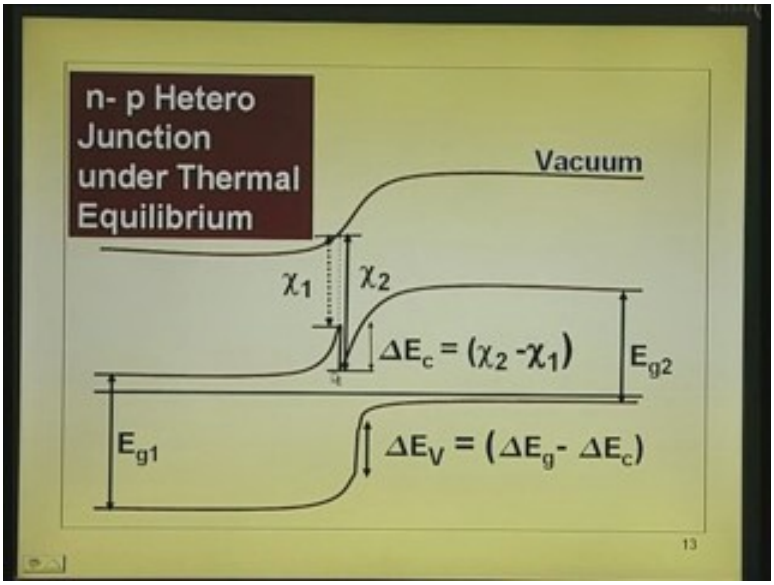

Finally, the experimentalist has an upper hand on whatever you predict. But the first order theory given by Anderson was good enough for people to understand and energy band diagram remains like that, whatever the thing. Now the question is whether delta E_c is kai_2 minus kai_1, or is it different or is it independent of kai_2 minus kai_1 at all.

For example, when we make a Shockley barrier diode, we said kai_{pm} is kai_m minus kai. But when the interface state is large, you found that it is independent of that kai at all. It is dependent only on the band gap and the neutral level. Similar thing happens here; because after all when you bring the two regions together, dissimilar materials, there is an interface between them. When you talk of oxide semiconductor, you talk of that interface. When you talk of metal semi conductor, you talk of that interface and several things are controlled by that interface. If you talk of Aluminum Gallium Arsenide Gallium Arsenide, you will have concerned about what happens there.

Now it so turns out that delta E_c by delta E_g is given by that factor practically for Aluminum Gallium Arsenide. For Aluminum Gallium Arsenide Gallium Arsenide system, it is given by this factor. No doubt it depends upon what material you are using. But for this system, delta E_c by delta E_g is decided by that factor. And delta E_v is related to that concentration. But it is enough if you hold on to one. Because if you know what delta E_c is then you know what delta E_v is, because, delta E_v is the difference in the band gap minus delta E_c.

Now let us take this number. At x is equal to some particular value, delta E_g is point 5 electron volts, where x is actually that quantity. So delta E_g is point 5 electron volts. If it is point 5 electron volts, delta E_c is actually point 64 multiplied by delta E_g and so point 64 times delta E_g.

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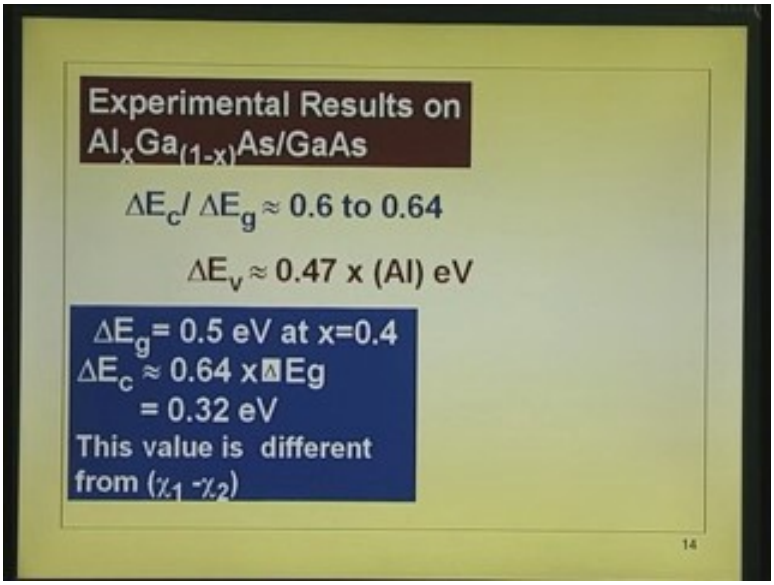

E_g for Aluminum Gallium Arsenide is equal to 1 point 93 electron volts, when x is around point 4. Eg for Aluminum x Gallium 1 minus x Arsenide is equal to 1 point 93 for x is equal to that. E_g is 1 point 43 electron volt for Gallium Arsenide.

Which should be delta E_g is about point 5 electron volts. Delta E_c is point 64 times delta E_g. Notice that this is delta E_g and that is actually equal to point 32. That is what I tell you

it is not exactly the same as kai_1 minus kai_2, it is far from that. Now you work out what is the cause for that.

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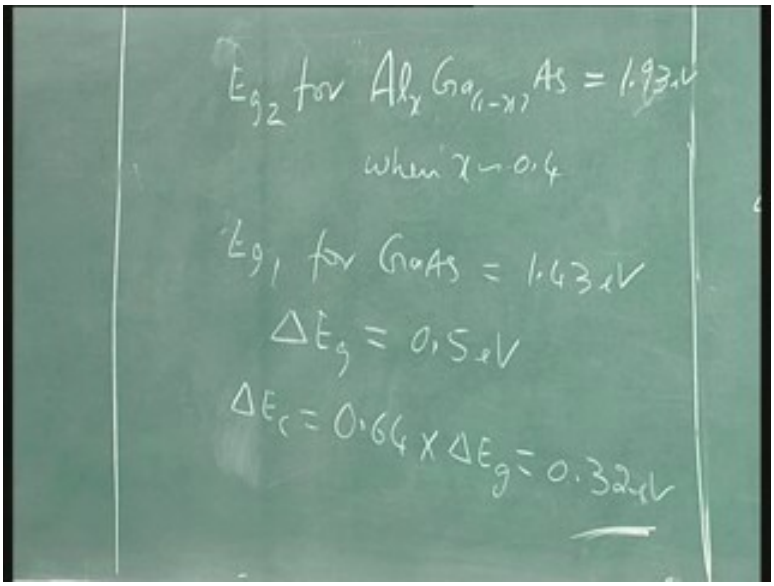

I will come back to other discussions afterwards. But here the reason for this is, how much that notch there depends upon a factor point 64. Now if you recall a neutral level, what is point 66? It is two-thirds. You can very easily correlate this to the neutral level. In the case of Shockley barrier diode, ultimately everything is around the neutral level. So the charges are 0. When you bring the two materials together, you do not want any net charge on this interface.

It so turns out that the leveling is such that the neutral levels match with each other. In fact, a lot of theories to came up with this and the moment they said it is not kai_2 minus kai_1, every physicist jumped up into that analysis. So much analysis went up and finally what is accepted today seems to match with the experiment is that it is related to the alignment of the neutral levels. That is, this number is obtained close to, if I take the level here, the neutral level for Gallium Arsenide is there - two thirds on the conduction band. Neutral level for Aluminum Gallium Arsenide is also almost about two thirds when this notch takes place such that these levels match with each other. When that happens, you can see acceptors here on both sides are the same thing as far as this energy band diagram

is concerned and this energy band diagram is concerned. So whatever negative charges are there they are same for both. Interface cannot have different charges. If there is a different charge then there will be a dipole layer. That gives rise to violations of energy minimum conditions. We will see more details about this in the next lecture; it so turns out that when the neutral levels align, this point 66 into the picture. We will see the details in the next lecture.