Optoelectronic Materials and Devices
Prof. Dr. Deepak Gupta
Department of Materials Science and Engineering
Indian Institute of Technology, Kanpur

Module - 2
Lecture - 18
Semiconductor junctions in band-diagrams

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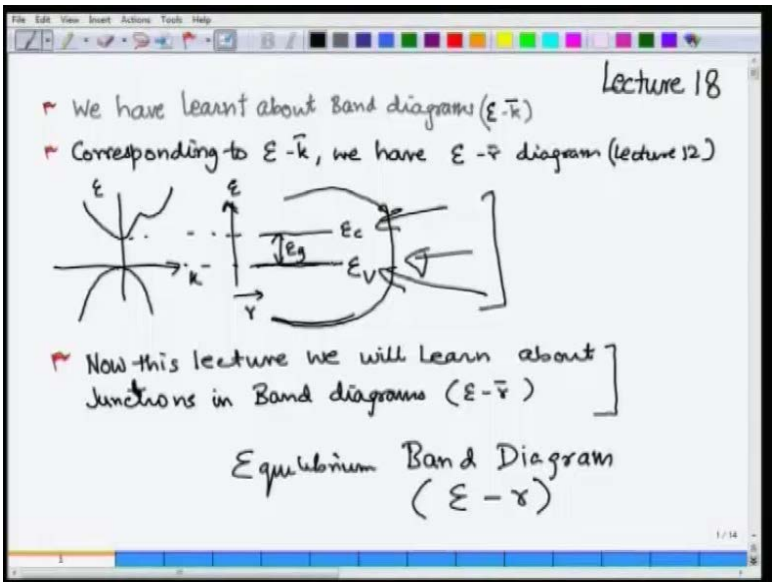

Welcome to lecture number eighteen. So, what I am going to do today, let us see. So, let us look at this; what we have done is, let us look at. We have learnt about band diagrams, we were learning about energy and k band diagrams, that is what we did. Then after that corresponding to e k diagram we examined that we could have e position diagram, and that we did in lecture number twelve.

If you recall what we have done was that we have drawn a band diagram, e k diagram. So, in that if this is k axis and this is energy axis then you know for some direct semiconductor the conduction band looks like this and a valence band looks like this. So, we could plot another diagram where we would have something like this as another semiconductor where you would say that this axis continues to be the energy axis, but axis is a position axis, and this was the e c, and this was e v which give us the, and this was the band gap, this was the e g which is the band gap in this material; and this is what we have done in lecture number twelve.

And, then from this point on once we started with this we started deriving then the carrier statistics, it will be a carrier statistics and we went upto carrier freeze out in our previous lecture. Now, we are moving on. We are, what we are going to do in this lecture is we are going to learn about junctions, junction band diagrams. What happens if you join two semiconductors together, and then how would the band diagram of this kind, of this kind e verses r type of band diagram look like, in that case if you join two materials.

Example would be, well, to best of my knowledge semiconductors by themselves are not really interesting- meaning thereby if I give you silicon, what you do with it? I mean by silicon alone, as such, probably it has not much utility. So, what is necessary, by that you know that silicon is a, is work horse, work horse of our electronics, micro electronics. So, how does that happen?

You also know the, you also know we can dope silicon with n type or we can also dope silicon p type; the thing is that silicon becomes useful, or we can make devices if you join this n type semiconductor and p type semiconductor together; and, we join them together, then something happens, then a junction forms. And, it is really action of this junction which allows us to make devices.

So, what is interesting is, now the semiconductor material by itself, but some modifications to it in different regions on realizing some regions. So, if we were to make, if we were to do this then we still need equilibrium band diagrams. If you join two materials then the question we ask is, what will be the equilibrium band diagram still it sticking to energy verses position. That means I join two different materials.

Question is how e c and e v, how should I draw e c, e v. In this case right here I have drawn e c as a straight line, e v as a straight line; that was done saying that if I have this material e c here and e v here, sorry e c here, e c and e v here, or e c and e v here, are at same position. So, if this is position axis then e c, I can draw e c as a one line and e v as another line in energy; in energy I can draw is, I have drawn a gap and that is what I am showing you down here as e c, where a gap between e c and e v, and it is a straight line, straight horizontal line because they do not change its position.

Now the question is if I join two materials what will happen, how would I draw this e c and e v, etcetera. So, now, this is what this, what we are going to learn in this lecture. To further refine what I am talking about, let us look at what we are going to do in this lecture.

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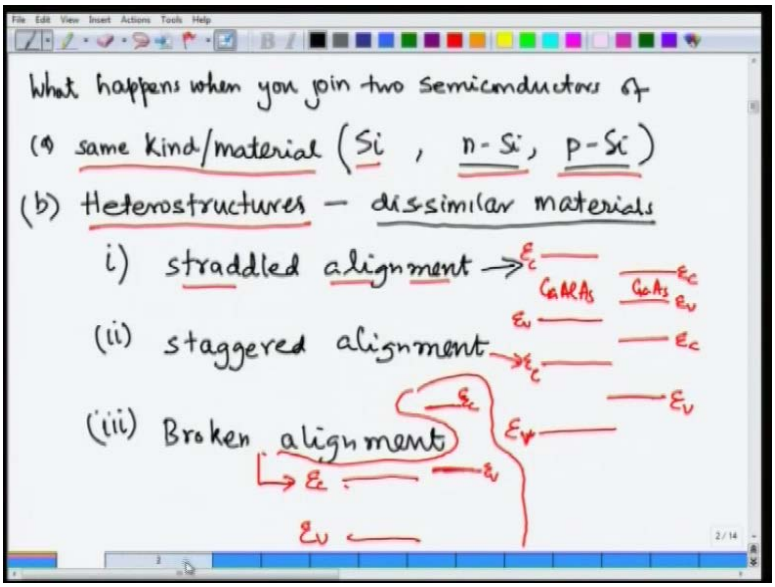

What happens, the questions you will answer is what happens when you join two semiconductors of same kind or materials. Example of this I have already spoken would be like silicon, except that- one is n type silicon, other one is p type silicon. But mentally as, material is the same; material is same that is silicon. Only difference is that one of them has a, n silicon has; for example, n type silicon has phosphorous doping and parts per million, very small amount. Similarly, p type silicon has go on doping, again parts per million, very small doping in it; otherwise, material remains the same; it is a same kind of material.

Alternative is, on that becomes very important which you will learn in optical properties when you make hetero structures. Hetero structures are made, for example, in quantum dots, quantum wires or led's or very high speed transistors, where we join dissimilar materials; we take two different semiconductors and join them. And, in that case the question is, how does the alignment or the band happen?

And, in this case is we are going to learn about three cases; we are going to learn about three cases in hetero structures- one which will be called as straddled alignment, other one would be staggered alignment, and the third one would be broken alignment. What you mean to say is, for example, take this case, guess you have a pen; for example, we were talking about something where we have a large band gap; one material has a band gap which is e c and e v like this, but the other one has smaller band gap, now at this similar material, this two different materials. So, the second material has a band gap which is much smaller; its e c is here and its e v is here; that is smaller band gap material.

For example, this may be, for example, this is, this could be gallium aluminium arsenide, whereas this may be gallium arsenide; this material will be gallium arsenide. So, this is the smaller band gap. And, the straddled alignment means that within the large band gap the second material has its alignment somewhere in the middle between its e c and e v is, as I have shown in this picture.

In contrast, you could have this staggered alignment, in which case if one material's band gap is like this- e c, e v; then other one has a, e c and e v, which looks like this. In this case notice, this is e c and this e v; maybe I will write bigger here- e v, this is e c and e v of two materials, you can see here in this particular case, where e c is, where e v is. This is the band gap of one material; this is the band gap of second material. But, the e c and e v alignment is such that the two materials are in the energies are there staggered. Example of this would be gallium; yes, I will give you another example little later.

Third one is, third case is this one where it is broken alignment meaning thereby is one e c and e v are like this; where in that case the other one is completely off, something like this- e v and e c is like this, and this is for this case itself here. So, let us make a line like this. So, for this case here, e c and e v are off completely from e c and e v of the other material.

So, these are the three different cases in case of hetero structures; in case of hetero structures we have three different cases. And then, the same kind of materials in which case it is only silicon often, any one material and in that case what is difference within those two materials, it is really the doping which is different between the two materials. So, these are the band diagrams you are going to study in this lecture.

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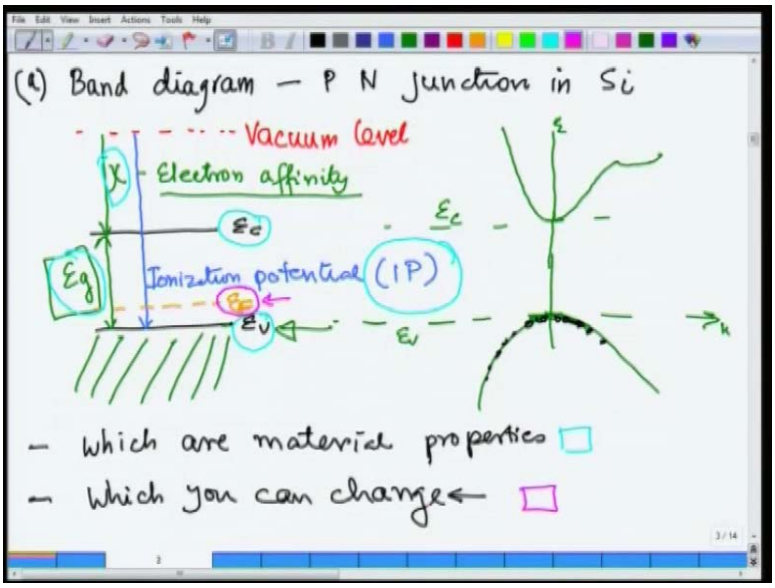

Now, let us start with this silicon band diagram, or for example, n type and p type silicon; it may not be silicon; the thing is, there it should be same material. So, let us look at this classic example where we have p type silicon and n type silicon, and we are going to make a junction of it. Let us start first with a material which is, let us start with a material which is silicon; let us say, let us take any silicon first of all.

Let us define some quantities here; let us use different colour pen. Let us say this is e c of silicon, this is e v of silicon. Now, we are going to choose a reference energy. In lecture number sixteen, you recall we have chosen different kinds of reference energies. In lecture number sixteen where I was talking about dopant levels and acceptor levels, I was saying that they all, because energies always appear in difference.

You will have seen some energy minus another energy, and hence what reference we choose trances out. And then there is all energies must be measured to a common reference. And, in that example I was saying, let us choose a reference, arbitrarily reference energy or some energy as 0; then I said let us move on and let us choose this point as 0 energy e, let us choose e v as the reference energy, etcetera, in this lecture number sixteen of what we have done.

Today what we want to do is something different; I will erase this. And today what we will do is we have to choose a vacuum level as our energy, reference energy; this is the vacuum level. So, this is the vacuum level. Let us choose this is a reference and measure all energies from here; what are the important energies with respect to this vacuum level.

Now one energy is this energy, which is defined as electron affinity; other energy, of course, you already know is the band gap. So, that sets another energy level which is like this one; this is called ionization potential.

Of course, typically what we do is we work with this electron affinity and band gap; these are the two quantities we work with; ionization potential then as automatically known. Now why the, why these names; you may just pay little attention to it and try to understand why it is called electron affinity. Remember, let us, let us assume temperature is 0 k; remember, upto this valance band level, electrons in this band are completely full; electrons are full upto this point to a top of the valence band.

If you want to make a e k diagram again, we can do so. We can do e k diagram; here is e v level. So, this is the valence band, and here is our conduction band, energy verses k. So, here is, this is the e v level and this is e c level. Remember, electrons are full upto here; upto here all the electrons of completely full. We have electrons all over here, completely full; this band is full with electrons. And, the conduction band is completely, this conduction band is completely empty.

So, now, if from vacuum level, from vacuum level if you want to put a electron into semiconductor, where you will put? You will put into this level- e c level. So, this energy therefore, this energy from the vacuum level to the conduction band, therefore represents affinity of this material to take electron. So, that is why, the name is called affinity, electron affinity.

On the other hand, if you want to take outer electron from the semiconductor, then where you take this electron out from. You have to take this electron out from the top of the valance band, that is one, that is the one which will have the highest energy, so is easiest to extract. So, if you take this electron out and make it completely free, take it away from the material; that means, you will have to take electron from the top of the valance band here, all the way to vacuum.

So, therefore, and therefore, that is how you ionize the material, and hence this is called as ionization potential. This label is therefore, represents ionization potential. What will of course, what will is, with is electron affinity and the band gap. We have two sufficient quantities from which we can derive all the things.

Now, in this, one more quantity you may be interested in is, but they would be a sub formue level also; they will be a formue level also. Let us say f formue level because the

formue energy is somewhere; it is a p type semiconductor, let us assume; that, that this is a p type semiconductor. Now, which ones are the material properties? So, the question is which are the material properties, meaning there are, once you say silicon, then they cannot be changed, then they therefore they are; another hand there are some properties some values, so much values I am showing you which you will be able to change. So, which are those?

Let us mark; then in, let us say two different colours; let us use this colour kind of box for this quantities and this colour box for this kind of quantities. So, let us use this and see. You see electron affinity is a material property. Once silicon is specified then its conduction band is specified, this edge is specified, and hence electron affinity is specified. The band gap of silicon is fixed, you cannot change that. Once you say silicon then it has a band gap; valance band edge is specified. Ionization potential therefore, all these quantities are material properties. Once you say silicon they all set; already set.

But this, some other quantities you can change and that is this quantity's formue level. That we have learnt in several, several previous lectures where we have derived carrier statistics. You know that you can put a donor- phosphorous and silicon or boron do, or a acceptor, in boron like acceptor in silicon, and you can move from energy. And we start calling this as a p type semiconductor just because it has been doped by boron, and therefore, formue level have moved towards to, this formue level have moved towards to valance band.

And you know that if you dope n type, like phosphorous you put in silicon in that case formue energy moves up and it goes closer to conduction bandage, and then it is called n type silicon. But you see e f, you can manipulate, move it up and down in this band diagram, based on what doping you do; that is under your control. So, this is a quantity which you can change. So, with these things in mind, let us move on and start drawing the band diagram.

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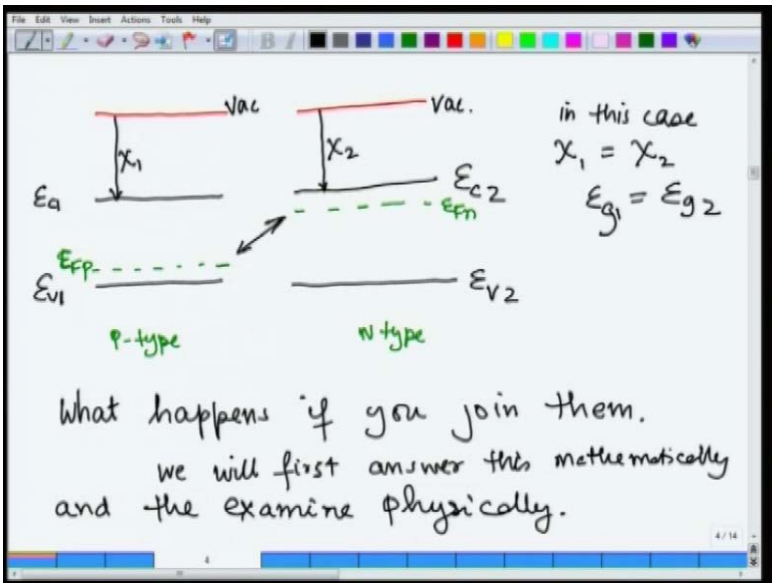

So, what I am going do is, then let us take two materials- one is right here, this is our vacuum level and this is other material. Let us draw conduction band, valance band; conduction band, valance band, for the other material. So, this is e c, this is e v; and let us call it 1, let us call it 1, material 1; this is e c 2, conduction band of material 2, this is conduction, valance band of material 2, and this is vacuum level, this is the vacuum level. So, this is affinity of electron, call it 1; and this is affinity of electron, call it 2.

And, in this case, in this case, is equal to the same electron affinity; and similarly, e c 1, e c, e g, I should say, e g 1 is equal to e g 2; the band gap of the two materials same because the same materials silicon we are talking about. And hence, the band I e c and e v levels align with each other, unlike the hetero structures where they were straggled type or staggered type or broken type. So, in this case these two are aligned well together.

Only difference is, let us say one of these materials is p doped. So, here is the formue energy, and here the formue energy for this particular material, all right. Now, since this is different, so we give it a name. This material of course is n type, what is called formue energy n on n side; this is p type, e f p; this is on the p type, formue energy on p type. So, that is what this material is, and you can join them; these two materials aligned. So, n type material and p type material align next to each other, but we are not so far joined them. So, question is what will happen if you join them?

We will first answer this mathematically and then examine physically. So, that is what we do. First we will examine this question, what happens if you join them; what way I am taking you is, I am going to prove that these two energies must become the same, then they must become equal, that is what I am trying to take you to, and we will see why, would this happens. So, first we will answer this question mathematically, and then we will examine it physically why has to, why this should happen. So, let us do that.

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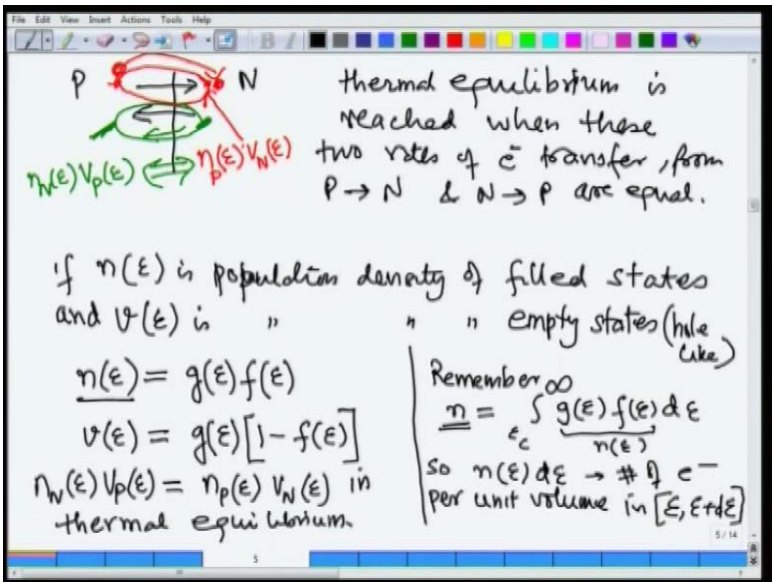

Let us consider this, that on this side I have p type material, on this side I have n type material, like in this page. On this side, on the left I have p type material, on the right I have n type material; some continues with this. So, what will happen?

Electrons are going to go from this direction to this direction and then you join them. When you join them, electrons are going to try to flow from p to n type, and they will try to flow from n to p type. Thermal equilibrium is reached when these two rates of electron transfer, from p to N, and N to p, are equal. So, let us look at this condition as to what will happen.

So, if n (e) is population density of filled states, and v (e) is population density of empty states meaning hole like, meaning hole, hole like. If this is the case then what is n? What is n? What is this function? We have already learnt this before that this quantity will be equal to g of e, which is the density of states, times, from the function the probability of finding electron at energy e. Recall if you already forgotten. Then, remember we had done this; we have calculated n as equal to n integrated from e c to infinity; and what we

have been indicate, integrated? We have integrated g function f (e) d e, this is what we had integrated to calculate n, when you are calculating equilibrium carrier statistics. So, that is what we had done.

So, what is, so, really this quantity n (e) is really equal, is this quantity. This quantity is n (e), what we talking about. So, n(e)de therefore, represents number of electrons per unit volume in n, in this interval, in this energy interval. So, that is what this quantity n really represents. So, that is what its population density is. Similarly, v (e), we write as same density of states multiplied by probability of not finding electron which will be f of, since f(e) is probability of finding electrons, f 1 minus f (e) is probability finding holes or not finding electrons. So, this is what these two quantities would be.

Now, let us look at, now let us look at what would happen. So, what would this transfer depend on? What would this quantity depend on? Let us make it a red colour; what would this depend on? Transfer a electron from p to n side. Clearly, this rate would depend on, this particular rate would depend on two factors- one is number of the filled states on the p side; and the second quantity, it will depend on is number of; let me write this properly. So, this would depend on number of filled states, but this side on the p side.

So, I am going to use the subscript p to indicate the side, and so, it should transferring from p side; and it will depend on number of vacant sides here because electrons have to go from here over to here. So, whatever the number of electrons here are, they must and they must see vacancy here to take the electrons in this side. So, they will depend on n on the p, on p side, and v on the n side, the vacant state on this side.

Whereas, as for as this transfer is concerned it will be exactly the reverse. It will depend on the filled states on n side, on n side filled states it will depend on. So, we are going to use n here. And, it will depend on the vacant state on this side because electrons have to go from here to here. So, if vacant of on the p side this will be; in formal equilibrium these two quantities then must become equal, these two quantities must become equal then only we will have equilibrium. So, let us see what will happen in this case. So, let us go to, I want to write this here, a little bit more nicely n N of energy, v on p side should become equal to n of p, then in thermal equilibrium.

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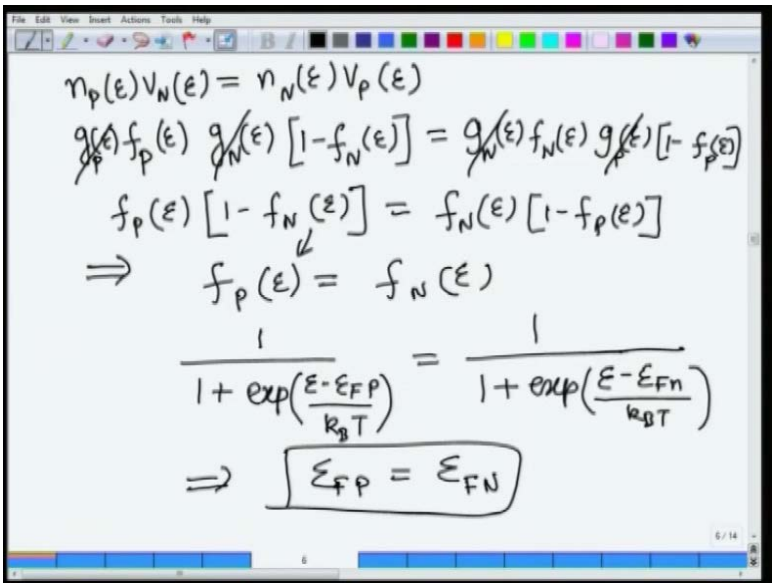

So, let us do that again, next page, let us write this out; maybe I write it one more time, so, just to for continuation sake. I just copied the same line. And, let us write down what this n is. Remember, n is g on the p side, g on the p side times, f on the p side; what is v? V is equal to g density of states on n side, times, 1 minus formue function on n side; and, this should be equal to likewise g on n side, f on n side, g on p side, times, 1 minus f on p side.

If that is the case, now you can see I can cancel this out, this out, with this and this. So, I have, f of p; this implies clearly f on p side, formue function on p side should be equal to formue function on the n side; from this you can derive this. What is that mean? And, we know how, how we can write this formue in direct function is written as 1 plus e x p, you will write this as e minus e f p by k B T, should be equal to 1 by, e x p, f on the n side by k B T.

Remember what this quantity is, what these quantities are. Remember these quantities are fromue levels- on the p side and on the n side; and for this you will have to go back here. Remember, this is a quantity I am talking about; formue function, formue level on the p side, formue level on the n side and that is the question you are trying to answer where what will happen when you join them, whenever I sight saying that I prove to you that these two were become equal when you join them. And, that is what we heading towards.

Now you can see, from this relationship which you see this implies that E f p energy on the p side should become, formue level energy on the p side should become equal to N side. So, this we have, we able to prove that these two formue energies should become the same, and that you should be able to see from here itself. This formue energy at 0 k represents chemical potential of electrons. And, even at slightly higher temperatures, the kind of temperatures we are dealing with, even that point this formue energies still represents very closely what the chemical potential of electrons are.

So, we have these two materials and we are trying to join them. Clearly, the energy of electrons on average on this side, on the n side of material is much larger than this side. So clearly, that electron would like to move from this side to this side. And when they do so, what will happen? This level, formue level will start going up a little bit; remember whenever you add electrons to the system that means, you add for example, donors or electrons this thermal energy will start moving the up; and, you take out electrons and add holes then this thermal energy start moving down.

So, when you add electrons from here to here, and anyway this side has lot more electrons and this side has lot more holes. So, holes will like to flow from here to here, and electrons will like to flow from here to here. So, consequence will be that this formue level will start going up a little bit; and since electrons are moving out of here, so this electrons, this formue level will start moving a down, until the two formue levels become equal and then the chemical potential is the same and this process is stop, and you would reach thermal equilibrium. So, this is the basis on which we make this band diagrams. So, since we require this, then let us see how we can make the band diagram.

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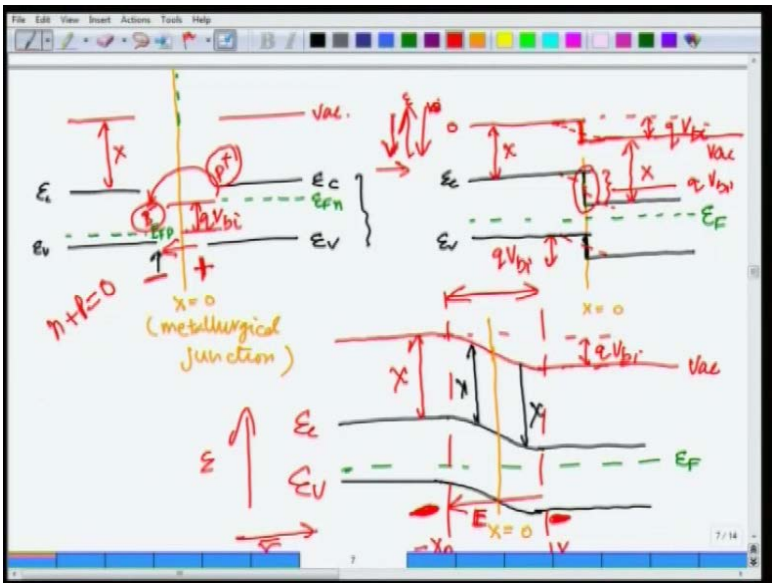

So, let us again do this. So, what we going to do? Let us draw the band diagrams from number six again. That, we had said that here is the vacuum level, here is the vacuum level; and here is e c and e v of one material, e c, e v of other material and they are same. So, this silicon only one has a formue level here, other has a formue level here, and we have not joined them; we intend to join them right here, we intend to join them right here.

This is the, let us call it x equal to 0, or let us call it metallurgy, metallurgical junction. This is that you want to form a metallurgical junction, you were not joined them. So, let us do that, let us join them. And, this is the vacuum level of course. If you join them, then let us take the steps.

What you want to do is, first thing is that the formue level must be same that is what you have learnt. If this is there, this metallurgical junction lies; this is x is equal to 0, this metallurgical junction. Then we know that formue energy should; this is e f on the n side and this was e f on the p side. Now when you join them there should be common formue energy. Formue energy cannot be different; if there is a gradient to formue energies carriers will flow from one ever the energy higher to the other side until they become, they become an equilibrium.

So, now, what we are going to do is let us join them. So, once formue energy becomes equal; so, I would imagine as if, otherwise I will draw it is, then I will say n type semiconductor; look at this semiconductor, once I will draw this semiconductor this as

this. When I look at this semiconductor, this particular semiconductor, and I join them also; this is p type semiconductor, so, I keep its p type corrector like this.

And, when I have to draw the vacuum level, what I will do is, I will draw the vacuum level with the same gap; whatever the gap here was I will draw this; same electron affinity whatever this electronic affinity was. And, what I am going to do is draw vacuum level here, and this is electron affinity. Now what is, what does happen? So, this is e c, this is e v continuing; so, e c and e v if I draw I should draw, more than I join them I should draw it like this. And, when I say vacuum level, then vacuum level must be going something like this, they must be following like this.

So that everywhere; the problem is right here, problem is right here. What is the electron affinity? What is the potential? What is the potential? Where is the vacuum level? Where is the potential here? On this potential, this is discontinuity. Now, the potential, why should the potential have discontinuity? It comes you require continuity or potential here in this particular case. It is possible for, to have discontinuity potential also, if there were some dipoles present here. If there was some dipoles at this inter phase then it is possible. Why we neglecting that?

We note as, we assume it is a same material, homogenous material- both are silicon pieces. So, we; and this n type and p type doping alone cannot produce dipoles. So, we respect this vacuum to be, this vacuum level to be continuous. If that is the case then I would be able to draw a, this vacuum level is a continuous level; if I instead of doing it like this, let me erase this and clean this of little bit. If I instead of drawing it like this, if I had drawn it little bit smoother namely something like this, something aggrading inbetween; and similarly, aggrading in here, aggrading in here. Let us see what will happen here. Let us try to do this one more time.

What we will do is, now we will be able to draw band diagram with lot more easily with this understanding that we say, now I redraw this diagram. I will say this, here is a anometrological junction, x equal to 0. This time what I am going to do is, again draw the formue level; here is a formue level, e f. And, what I am going to do is now, I am going to draw this semiconductor, p type. But I will not go all the way to junction, I will stay away from it little bit, for little bit. I will draw this n type junction, and I will draw this vacuum levels, and this vacuum level is higher, and we stop here.

Then I will say that look. What I have needed was, what I needed was that vacuum level should have been continuous. I will therefore, very smoothly join them; instead of roughly I join them smoothly. If I do that, if I do that then in that case; will, how fast, how slow, what you, what is the value here, that you will learn quantitatibly also. I am just qualitatively showing you that this should be smoothly joined so that it is continuous. So, that is why I have shown you qualitatively later in some other lectures; in future lectures you will quantitatively derive also this, this portion of the curve also.

And now, similarly because every place it should be electron affinity; it is a material property. So, we can say that the same value, same scope I should be able to join these, sothat everywhere this remains, everywhere this remains electron affinity, and this remains the vacuum level. And now I have got my band diagram, e c and here e v and the formue level is common.

What has happened is, semiconductor, something happened to the semiconductor, here between this regions, this is minus x p let us call it, let us call it x n. In this region, in this region, but when we join two semiconductors they were affected and the band diagram changed. Whereas, far away from this these junction semiconductor remain as it was before. And hence, only place where the change was in the interface; and how the change was, along like this; and this is the easiest way to visualize this band diagram. So, this is your e verses r diagram; this is e, and this x is its position r and this becomes a combined band diagram of two materials together.

So, one point you have to remember that if I take say this as a 0, 0 reference of energy then I have changed this n a semiconductor by amount, this much amount; this typical is called as q v; let me remove this vacuum level right here. So, this is right here, this is the vacuum level, and I am talking about this energy, is written often as q times v b i, the builten voltage; remember, voltage multiplied by q is energy. So, that is a q v b i.

And notice, that this n will be at higher, this n, this n to the semiconductor would be at higher potential, potential not energy; q times potential is energy; this we will learn little bit later and for the detail, but q times charge times potential. So, this n would be at higher potential. Remember, electron energy increases in this direction. So, hole energy increases in this direction which means potential also increases in this direction. So, this is the electron energy, this is the hole energy; the hole energy increasing in this direction,

and therefore, potential also increase in this direction. So, since this n is lower therefore; so, this n would be at higher potential and this would be at a lower potential.

What will that will do is; and I, the same builden field I have shown here also because after all it is the same thing, same quantity. This is q times v b i; and remember, this quantity is also, this quantity is also q times v b i; remember, this quantity is also q times v b i; and remember, this quantity is also, between these band diagram this quantity is also q times v b i. Remember, it has happened because we have tried to move the two formue levels together. So, the amount of shifting that we have done is the difference of e f n and e f p. And that is the, by that much amount all the levels have moved. And hence that is the builten voltage; that is the voltage which have been builten.

Now, if this n is at higher voltage then at this end, then an electric field will setup and this electric field direction would be like this; this is the electric field direction. Why? With this is higher voltage on this side, this is the lower voltage on this side, so electric field that a setup in this direction. And, that you can see because when electrons go from here to here, then what do have, what happens? Then leave behind p plus charge here, phosphorous atom, and it remains ionized; this is a donor atom which is ionized; and the fifth electron is gone, it is gone on this side. And, what happened?

This electron which went on this side they have lot of holes here. This electron and, this electron and hole recombine and enhalated each other. So, what happened? That let to on this side some boron minus, over left; that means, acceptor ionize. Remember, boron minus and the hole are neutral; the electron which came from the other side and highlighted the hole. So, what was left was b minus, boron minus. So, now, I have charged, negative charges lying here and positive charges lying here, then clearly electric field will setup in this direction, that is what we have seen also in this case right here.

So, that is how; but this is the part, since we have learning about p n junction lot more I thought that I tell you about the band diagram right now, and later on the device is done p n junction; this whole story will be repeated; at that point of time this band diagram will be immediately drawn.

But, we will do quantitively at that point of time and derive all these whatever the curvatures you see here, whatever this, what, what the, how much amount this will fall apart, fall down; how much what will the builden voltage, etcetera, will be carefully

calculated, and that time we will have another posititive learn. But now let us move on to hetero structure which we may not cover in much more, in that much detail later.

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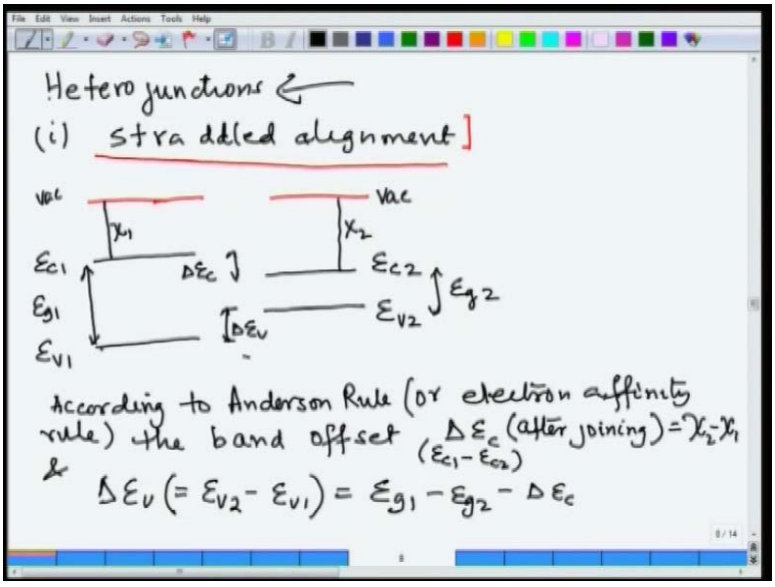

So, now, so, this is something where band diagram, making band diagram gets little bit more deify tricky, but I think now that you have learnt some concepts it will be fairly easy. So, now we are going to talk about this hetero junctions. And, first case let us take this straddled type; let us take this straddled type alignment. Remember, what is straddled type alignment? In that case, the way we have shown this picture here, right here. As we are showing this is the vacuum level for one material. And, in this material we will, which has a electron affinity psi 1, that I am showing here; its conduction band level is e c 1, its variance band level is e v 1, and band gap is e g 1, it have larger band gap.

And, the other band gap is straddled; e g 2 band gap is small band gap, and it is straddled between these two. So, when it is a straddled here, e c 2, that means, it is here, and e v 2 is here; that means, e v level, e v 2 level is higher than e v 1 level; whereas e c 2 level is lower than e c 1 level, and hence the word straddled has been used, which is also means that the electron affinity will be higher.

Now, what do we do here, in this case? How we make band diagrams? In this case also remember the formue energy which I have not drawn yet, here I have not drawn the formue energy, but that formue energy will have to become equal, that we all put there in a minute, but just wait for a second. But the question is what would be the, when you

join them; remember, e c 1 minus e c 2, there is, that is the band offset in the conduction band that is this point of time, when vacuum levels are aligned. When vacuum levels are aligned, when vacuum levels are right here, at that time there is a conduction band; and e c 1 minus e c 2 is some number delta e c 2, that delta e c.

Question is, when you join them together then what will be that e c? That is the question we want to ask. So, what we do here? So, how do we find, answer this question? And that is the trick how, we need to know that in order to able to make band diagram. So, according to, so this according to this, what we going to use is what is called is Anderson rule or electron affinity rule which was works well in most cases, and the end I will point out when it may break down. But, and then based on these we will able to find out band oxide.

What do this rule say? This set of band oxide will be delta e c that is after the join them, then this band oxide will be equal to psi 2 minus psi 1. That means, when you join them, as if you look at right now what is the band oxide; that is, what is value of e c 1 minus e c 2, clearly that is psi 2 minus psi 1, when they are not joined yet. And what point been made is that after we join them it remains the same. And, by the same token you should be able to see, you should be able to see this that if, so, this value is delta e c and this value is delta e v; and delta e c you can clearly see is psi 2 minus psi 1, which is written right here. And then, after joining also it remains the same.

And, what is this value now? This value now is equal to, delta e v is equal to e g 1 minus e g 2 minus delta e c; you subtract this and subtract this quantity and you will get this. If you subtract out of e g 1, subtract this amount, and you subtract this amount, and you will get this. So, that is what this quantity is, and the point is after joining also it remains the same. That is what this Anderson rule or electron affinity rule says. Once you know that let us see how this band diagram is to be drawn, and now it is fairly easy to draw this band diagram.

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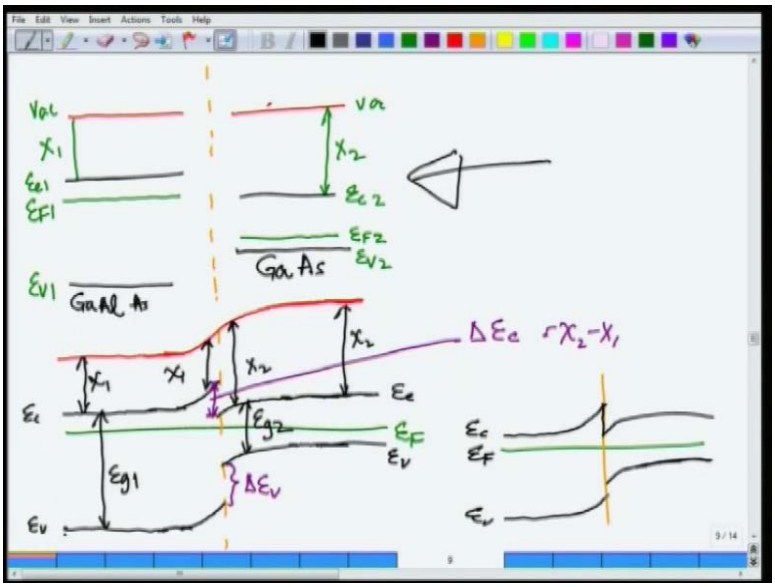

So, let us do that. I will have to make it one more time. Vacuum level, we have to be very careful about. So, we can do that. And then we want to make a straggled e c and e v, like this it will be get, so that picture remains little cleaner. And, in this case, let us choose the formue energy also. Let us say this material has a formue energy of, this one is n type material, let us say this one is p type material, this is a p type material.

So, we are going to label this now. This is e f on second side, and this is e v on the second side, this e c on the second side, this is the vacuum level, this is electron affinity on the second side; this is the vacuum level, this is electron affinity on first side, this is e c 1, this is e f 1, this is e v 1, these are the quantities. Now we again know that we want to draw the band diagram; it is very easy. What we have to do is first make common formue energy. If you join them, you going to join them right here; right here you going to join them.

You are going to join them. So, first introduce next common formue energy. Formue energy must be common. If you make formue energy common then what happens, that is what we need to look at. Let us draw it far away. Again, look for, away from, far away from interface. Far away from interface we assume in the semiconductors of very long. In this, this one in this direction, and this one in this direction. So, far away interface they remain unaffected. If that is the case, then with respect to the formue energy, e c level will remain the same; that means n type behaviour will remain the same; we are going to draw that.

So, right here I am drawing the same band diagram as which is on up here. I am drawing this. And, same thing will happen here also. Then far away it will remain unaffected with respect to this band diagram e v level p type behaviour, it maintain its p type behaviour in the same way, and here would be the and the other level e c 2 level whatever this distance was, approximately same distance we have to draw this. Now, if you want to draw the vacuum level then we have to do the vacuum, do the vacuum level; that is the most important part to draw. So, I am going to distance about this much distance, psi 1. I am going to draw this vacuum level. So, this is the vacuum level I have drawn.

And from here psi 2; remember, psi 2 is bigger than sigh 1. What we have done is we have imagined that we have lifted this part of the curve higher up to this formue energy will be lifted up to here. So, by this amount this level is also lifted, by this amount this level is also lifted, by the same amount this level is also lifted. So, what are the difference here was. Since, I am lifting this formue energy and aligning it. So, we have to lift this vacuum level also higher by same amount that of the difference in formue energy was. So, let us say that vacuum level becomes, goes here, right here. This is the vacuum level for this one and this one. This is the vacuum level here, right here and this is the vacuum level here.

And, I have not drawn, have; so, this is the; now let us label them. So, this is e v and e c, and remember this is e c and e v. And remember, now I am not writing e c 1, e c 2, because now it will be continuous. I have joined them. So, there will be one valence band level and one conduction band level. It may change from place to place, but I have to join them together. So, therefore, now what I am going to do is, again we smoothly join this vacuum level because we cannot have discontinuity, that is why.

We cannot have discontinuity in vacuum level, unless they are dipoles. Assuming these are dipoles then this is ok. So, if that is the case then I am going to draw in a way where this material, say this is the material property. So, i 1 is a material property; everywhere, every point in this material, this particular material this must remain psi 1. In fact, let me give you example and then only it will make, you will appreciate, and benefit from it better.

Let me give you some material names also. Let us assume that this is, let us take this material as, I just write down here. This is gallium aluminium arsenide and this material is gallium arsenide, this one is gallium arsenide. Alright, we had our two materials here.

This is aluminium arsenide. So, this material which is psi 1 is known. So as long as left to this line, this psi 1 is always, must remain psi 1. It must also lift, this must be psi 1. What happens on this side? On this side also this curve must be same with as it has here, and this side the vacuum level is curving down, and this distance will always beside to, that means remains this region would be done like this, so that this is psi 2. This is psi 2, silicon affinity. And, in this case what you see, what is this quantity?

I mark it far away; this is delta e c which is equal to psi 2 minus psi 1. And now, similarly I am going to adjust this part of the band diagram, this must also therefore exactly follow that because everywhere it should be e g, e g infact. It should be e g 1 everywhere. And, this must follow exactly like this because everywhere it should be e g 2. And, what is this quantity? This is delta e v. That is the delta e v.

Now, if you look at it then if I draw only the black lines then this band diagrams therefore looks something like this. I am just copying this for your convenience for clarity, little bit clarity. It looks something like this. So this is e c, this is e v, and this is e f, and this is what you get the band diagram as. This is very important. Now you will see in making high mobility transmitters you can lock in electrons in this region. And these are the things which help in making, controlling device statistics. These junctions are very important, and which is why I made some for you.

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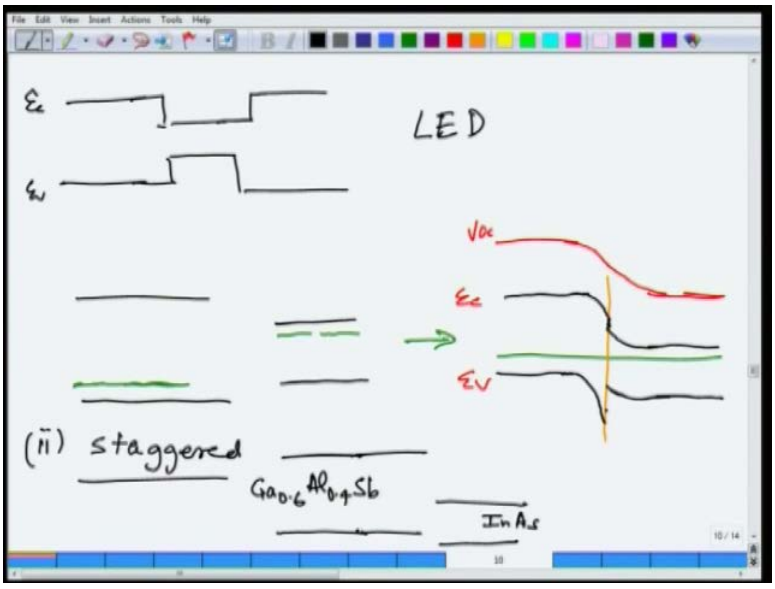

For example also in LED's you will see we have semiconductors are like this. We take another semi conductor which is in the middle, and then we take another semi conductor

which has a bigger band gap. Three semiconductors we take something like this. And, you will have LED's that this is e c and this is e v before joining. If you join this nature will change as you have seen. This is what I am trying to teach you how this junction area will change in the behaviour like here. When you join them like this then the change, change to this behaviour. Same thing will happen here. And this you will see when you use as an LED. And hence these types of diagrams are very important.

And I will give you an example of external type diagram. And now may be you could draw another diagram as you inclined during the; let me quickly do it for you on the screen one more type of diagram. For example if you were to take a material and give it to you two diagrams and you try it out and find out whether it is true or not. While trying it out suppose one material is like this, other material, it is the same material we are talking about which we have drawn in the previous page, once you continue to use this to.

These are the examples let us say the change are formidable, well, I have this green lines are. I have to change the location and draw everything, and then ask the question what happens here. In this case let us say we make this one p doped and this one n doped. Then what happens? In this case, the band diagram we want to get is a common energy far away from thing like this. I could join them here, right here. And, these are the conduction band; and now I take this material, then it is far away as this.

And now if you join this what is going to happen in this case? I am just going to draw it for you. And, you should be able to practice it. In this case we are going to see something like this, and we see something like this. It should be e g 2 all the time.

And this time whatever happened in the previous diagram you got this feature in the conduction band and this type feature which was, this was delta e v of course, we will write here. Anyway, in this case it will be y axis, it got its feature in the bottom. We should be able to try this exactly as in the same level, and the vacuum level of course will be in this case would be something like this; vacuum level will look something like this. This is the vacuum level. And, this will be the e c, and this will be the e v. So you should be able to practice this diagram.

Let me try one more, and there is it will end. If you look at this another material means type two, the second one we are looking at was; this was the straggled type. The

straggerd type is really easy also to draw the same way and this will be given in; I will give you this example; this one in as an simon may be.

So, in this case this is the standard type of diagram where you have a something like this for example in gallium at 0.6, alluminum 0.4, antimonium; this was semi conductor, and another semi conductor which is Indium gas, this is indium arsenide. This is the material, and this is the staggered type. And, I will ask you to try, draw the band diagrams in such cases.

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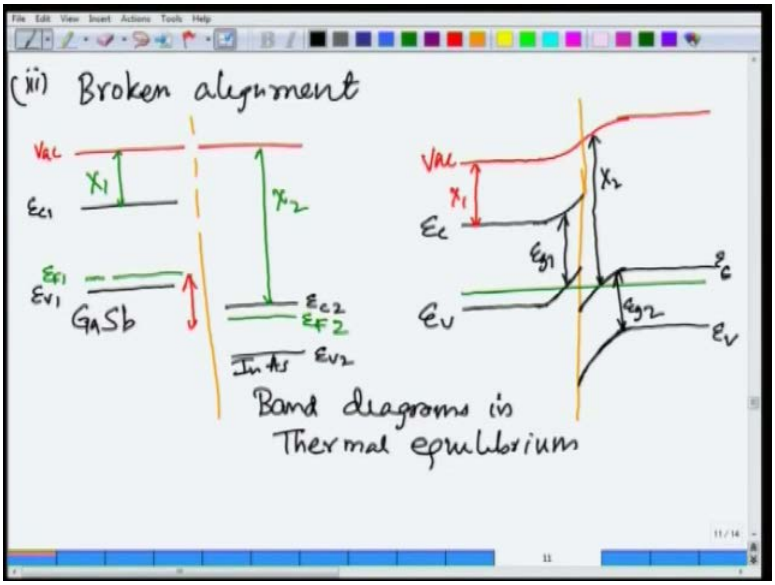

Where I will do is one more attempt for the third one which is the broken type, and this will be my last example. Broken alignment. Let us look at this one. This diagram as to what will happen in the particular case. So let us look at it as follows. In this case you can take the vaccum level. We can put a breakin here. And, in this case it is the broken type. So let us take, let us say, we take this as one semi conductor and the other semiconductor is actually seen below this. So, this is e c 2, this is e v 2; this is e v 1 and this is e c 1. And, I am going to do is I am going to join them here; from here we are going to join them.

Unfortunately, in this case there are, e c 2 level is even below e v 1 level; and hence it has been called as broken alignment. Let us assume, let us look at this formue energy to be here p type ; this is e f 1; and let us take this n type, this is e f 2. And, deliberately I am doing that otherwise the line would be too much off the screen and hence it will be

difficult. And this is psi 1 and this is psi 2. This is electron affinity of the second material. What happens if we join them?

Again, same way the way to do it is imagine material in the right you lift it up so that the formue energy becomes equal; here I do. The formue energy got the junction. What we do is always one material; on the left material let us draw completely. So here it is; and you just stay away from the interface; far away you have gone; materials do not change. It remains as it is. And, I am going to do the vacuum level also. Vacuum level this was psi 1. This was psi 1, and I am drawing the same diagram as it was before. Now, what we will do is then in right hand side we lift it up, so the formue energy comes equal, becomes equal.

So, the amount you have to lift up is this much. So, let us do that. In that the vacuum level will be lifted up by this much amount. And, we do that. Then we have conduction e c 2 level would have come here; and this level would have in this case comes from the here, this is the second one. And then what happens? The other one happens again smoothly going this vacuum level, smoothly join it. And now use this exercise for the material they must remain the same.

The material should go exactly the same way; right here it should go up. So this material should also go up, same following that this band gap remains the same e g 1; and what happens to this material? This material would be something like this, and something like this. It should be something like this. We should follow this psi 2 and this everywhere should remain e g 2. And therefore this black is e c and e v, this e v and e c; this is e c.

Thermal equilibrium diagrams, it is in thermal equilibrium band diagrams, thermal equilibriums; this is the last part of my lecture. But when you do that how to make this band diagrams, how do you meet junctions, how do you join two materials together and draw the band diagrams; before I told you, in semiconductors it is really junctions which are very important to electronic devices it will have junction we have got devices over here. If we do that in doing electronic devices you must know how to make these band diagrams at junction points if you learn because this is the thermal equilibrium.

After that you apply it, after you apply voltages of current and the devices start behaving. But in order to understand how behavior verses current and voltage, how it work, you first have to understand what the thermal equilibrium picture is; and that thermal equilibrium picture I have shown in different case how this diagrams can be drawn. And,

maybe I will try to let me give you the example for this material also which we are talking about here like this could be gallium antemony. And this material could be antieum arsenide. This is the broken type band diagram which I just try to show you. So with this let me end the lecture.

Thank you.