Semiconductor Devices and Circuits
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Lecture – 19
Junctions

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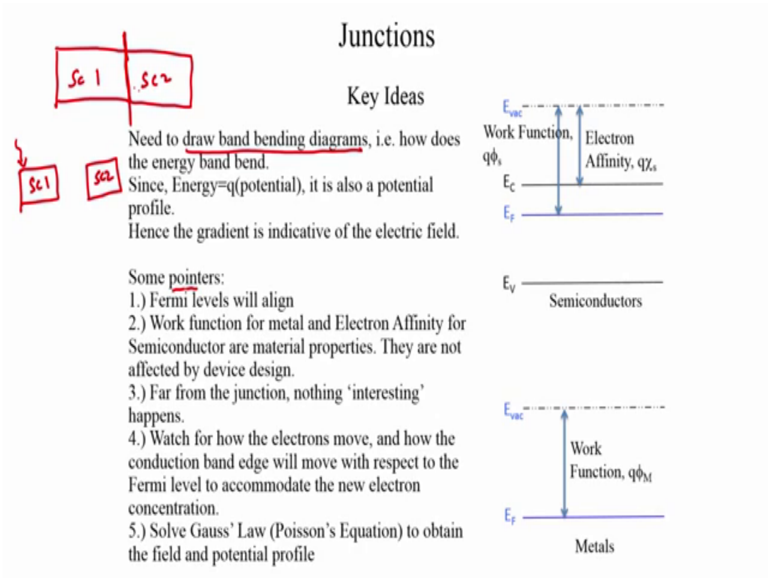

We will now look at the next unit as far as this course is concerned, and this unit is called Junctions ok. And by junctions we mean the merger of 2 different materials ok; which could be a semiconductor and a metal or a metal, and a metal or 2 different semiconductors ok. And, in particular we want to look at what happens; we will use all the concepts we have you know established so far in the fundamentals of semiconductors. And we will use those ideas to see how a material should behave when they are adjoined to another material ok. And it gives you a lot of interesting physics and some interesting ideas for engineering.

So, in high school I think several of you might have heard of p n junctions. So, p n junctions is one kind of a junction. But we will be looking at metal semiconductor junctions, p n junctions, junctions' calls to create the other devices or such as transistors etcetera etcetera. And the purpose of this lecture is to establish some very key ideas some very key concepts that we will be using time and again a when we want to analyze and understand how junctions behave ok.

So, the first concept has got to do with a drawing something called as a band bending diagram. Now this is a very useful idea ok, it is really not compulsory or necessary, but it is a very nice graphical representation of what happens near a junction ok. And how the semiconductors are the materials involved will be influenced by the creation of such a junction. Again, we will we will try to understand what band bending means, we will we will work out some examples and we will get those concepts clear, but before that let us try to look at some of the properties of different materials.

So, let us say we are trying to create a junction between say semiconductor one and semiconductor 2 ok. So, we have we have these 2 semiconductors separately initially ok. We know how the behavior thermal equilibrium, we know how they behave they throw if we throw light on it, we know how behave if you establish a current if you have establish a voltage across it etcetera.

So, you have studied all this with respect to a semiconductor and thermal equilibrium and in non-equilibrium. But now what we are trying to do is, see what happens when you bring these 2 semiconductors in contact with each other. And this is what is called as the junction between the 2 semiconductors. We want to see what happens with what is the physics in and around the junction.

So, before we establish all these concepts, let us look at some of the key properties ok. So, there are some pointers ok. So, I have just labeled these out as key pointers, and we will just go through these aspects one by one and be these aspects will get more and more you will familiarize yourself with these aspects as we go through this course as you solve what more examples.

So, the first thing is let us take semiconductor.

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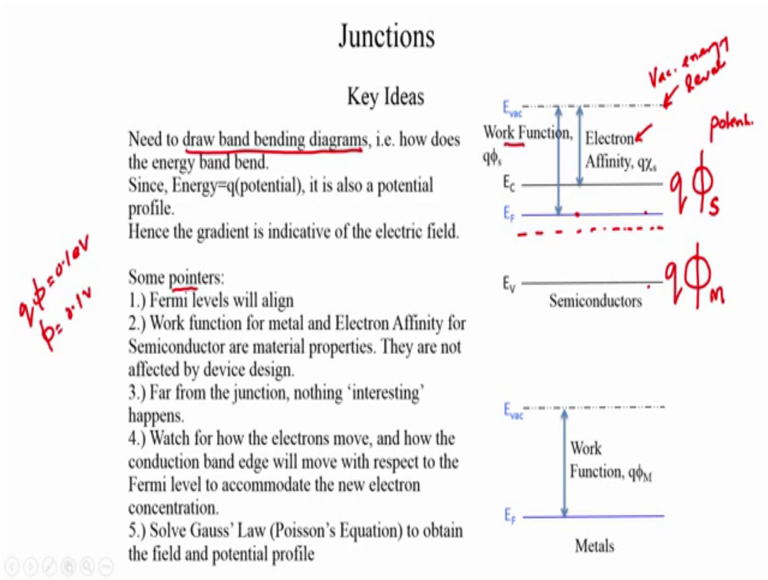

So, you are all familiar with you know the conduction band edge, the valence band edge and the location of a Fermi level. The semiconductor will also have an intrinsic Fermi level position which is the Fermi level when the semiconductors pure. But here as you can see the Fermi level is offset and it is closer to the conduction band which is indicative of the fact that the semiconductor has been doped n-type ok. So, nevertheless for any semiconductor you have your valence band, you have your Fermi level and you have your conduction band.

Now, we define a reference energy level called as E vacuum the vacuum energy level ok. It is just a reference energy level. And we establish 2 terms ok, the first is called as a work function which is the term which many of you might have heard in with respect to metals and with respect to the photoelectric effect. It is the same work function that we are talking about. And something called as the electron affinity ok, which I think students from chemistry might be more familiar with.

So, we have the work function as being the difference between the vacuum energy level and the Fermi level of the semiconductor ok. And we typically represent the work function by this symbol phi, the Greek alphabet phi, and for a semiconductor I will use the subscript S and for a metal I will use the subscript M. Now phi is the potential is the potential, and the energy is simply q times phi ok. So, if you know this potential as say so, if you know the energy in terms of let us say the q phi is equal to say 0.1 electron volt; it simply means phi is 0.1 volt ok. So, the energy and potential are easily related in any picture like this by simply multiplying the potential with the charge.

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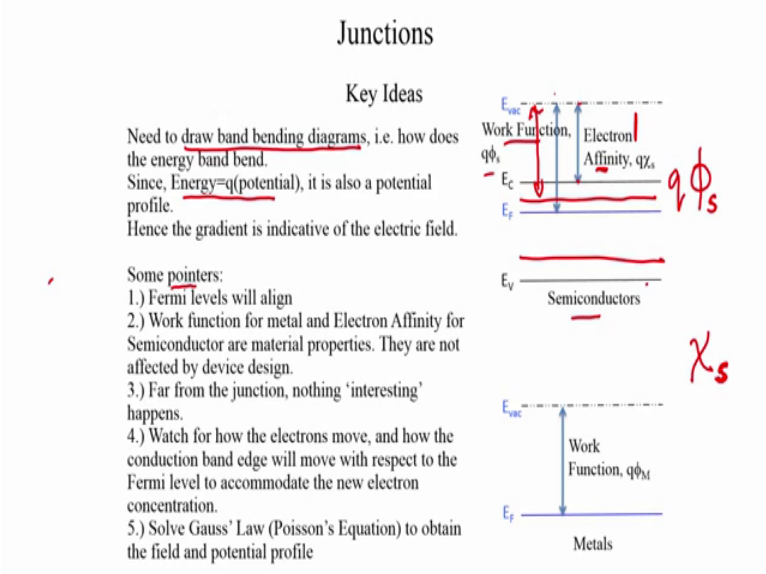

So, the energy level, the energy difference between the vacuum energy level and the Fermi level is essentially the work function of the semiconductor. And the difference between the vacuum level and the conduction band edge is the electron affinity of the semiconductor. And we will represent the electron affinity by this symbol, I think it is called chi and for a semiconductor we will say with a subscript S. So now, for a metal so, in the case of a semiconductor, you must always remember that the electron affinity is always a constant, it is a material property.

So, you can engineer the device in any manner you like you can apply whatever voltage you like, you can you can we can play around with the engineering as much as we want. But the electron affinity is always a constant. So, you cannot really change this energy difference between the vacuum energy level and the conduction bandage. So, that is a useful pointer to remember which is that the electron affinity for a semiconductor is fixed.

Now, in the case of a metal so just before we head to a metal; what about the work function of a semiconductor? Is that fixed; clearly the work function of a semiconductor is quite variable, because it depends upon the doping, right. If I dope it p-type, I have changed my work function. And if I dope it slightly more n-type I have moved the Fermi level closer to the conduction bandage and my work function has changed ok. So, the work function for a semiconductor really isn't a constant, whereas the electron affinity is a constant ok.

Now, for a metal, the metal does not have a conduction bandage and a valence bandage, instead a metal just has the Fermi level.

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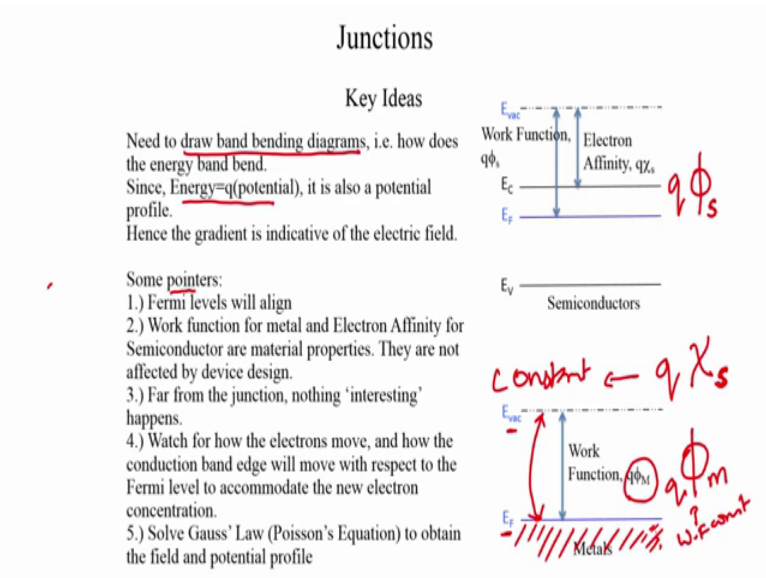

And the work function for a metal is the energy required to take the electron from the Fermi level and into vacuum ok. So, is again the difference between the vacuum energy level and the Fermi level of the metal, but for a metal the work function of a metal is a constant ok. So, in other words for a semiconductor the electron affinity is a constant. And for a metal the work function is a constant. The work function for the semiconductor depends upon the doping. So, these pictures are clear then you are one step closer to drawing a band diagram. Can I, and I will show you what a band diagram is and how we can draw it.

So, essentially what do you mean by band diagram? So, what we are trying to see is if you bring 2 different materials closer and create a junction between these 2 materials. So, you create a junction between these 2 materials it is very possible that you know you have carrier movement across the junction simply because the Fermi levels are not aligned ok. So, you can think of it this way. So, if you remember a while back had used the water bucket analogy ok and I told you the energies helpful, but it is not really going to take you all the way ok. But let us get back to that it is going to help us a bit here.

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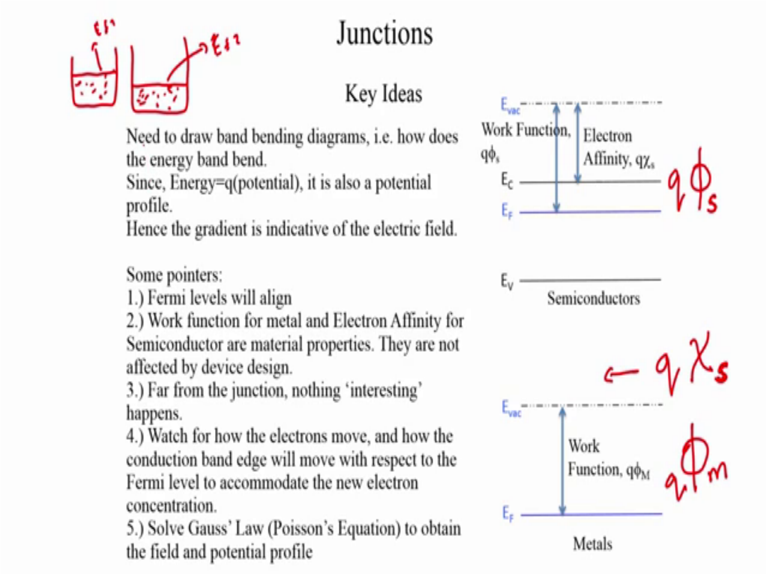

So, let us say you have 2 buckets ok. And you have water fill different levels in these 2 buckets. Now we had already discussed you know the water molecules above this level do have a Boltzmann's distribution. And therefore, we are quite you know we are quite close to what the Fermi level in a semiconductor is you know, they are using this little picture here.

So, you have a lot of water molecules here, you have plenty of water molecules below the Fermi level here, and this was the Fermi level for this bucket and this is the Fermi level for the other bucket. Now while creating a junction what we do is we bring these 2 buckets close to each other and we simply remove the edge between them ok.

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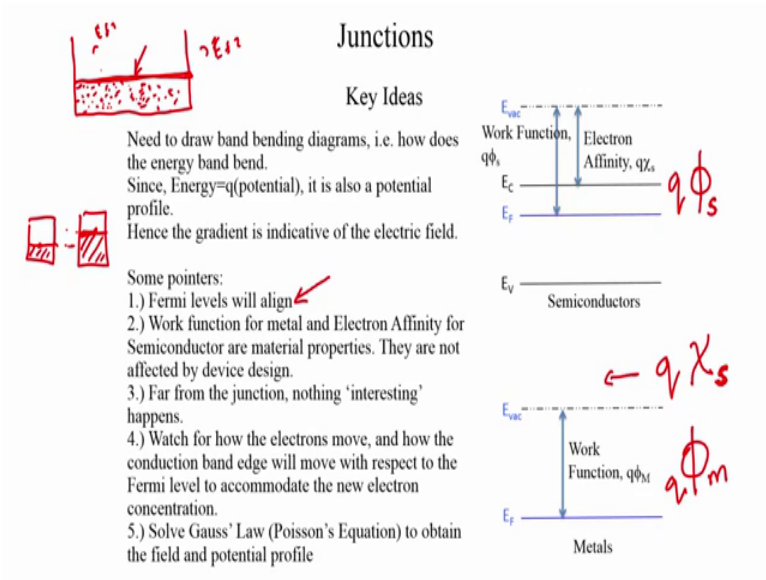

There is no wall between these 2 buckets. So, what is what is going to happen? So, what will happen is the water molecules will not like to see these 2 different levels that is clearly a concentration gradient here. And therefore, you will establish a diffusion of electrons, or in this case water molecules from the bucket that is got a higher water level to the bucket that is got a lower water level. So, the electrons or the water molecules are flow out till the water level is the same in both buckets ok.

So, in this case water molecules have transferred from there to here in order to align, or in order to make the water level the same. You will not end up in equilibrium; you will not end up in a situation where there is a difference in the water level within space ok.

So, the water will flow and it will ensure that the level which was equivalent to a Fermi level is constant throughout this region ok. A similar thing happens here ok. So, here too we will have a Fermi level alignment. And if you create a junction between 2 different materials, the Fermi level tells you is an indicator of the energy at which the probability of you finding an electron is half; electron occupying a state is half ok.

So, that probability is half at this point for this material and that probability is half for that point in that material, which is which in some sense implies that there are larger number of electrons sitting here as compared to this material. And just like in the case of a bucket with water, if you bring these 2 materials together and you create a good junction; which means, very nicely getting rid of any edge between them ok.

So, do not take do not take that will previous statement extremely literally. So, what the way junctions are created is through a very different process, and it is not equivalent to you removing the wall between 2 bucket. So, please do not take that statement too literally. So, we were to create a good junction, then the electrons will flow from the material having a higher Fermi level to the material having a lower Fermi level which means the material having a lower work function to a material having a higher work function. So, what do you mean by band bending diagram?

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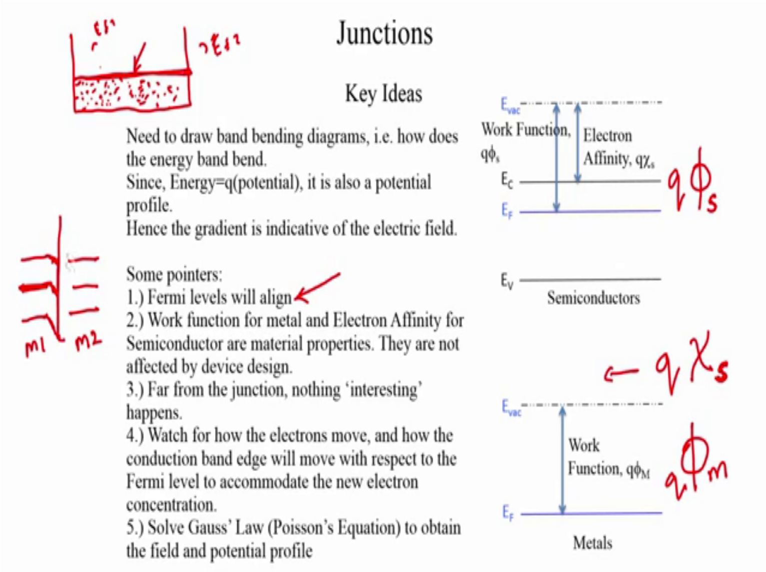

It is that we want to see what happens to the conduction band, valence band and Fermi levels of the 2 materials when you create a junction.

So, when I create a junction we will have electrons moving back and forth and you know electrons moving from one material to another, and you know these bands might change their location ok. They may not want to be where they are right now ok. And that is what we wanted that is what we want to look at in a more quantitative manner. So, that is what we mean by band bending. And I will soon bring up an example. So, those things will become clear. So, the first point in order to understand what happens to the conduction band edge valence band edge and the Fermi level, is to note that the Fermi levels will align the moment you create a junction. That is the first point. The second point is something that we have already discussed which is the work function for a metal will always be a constant.

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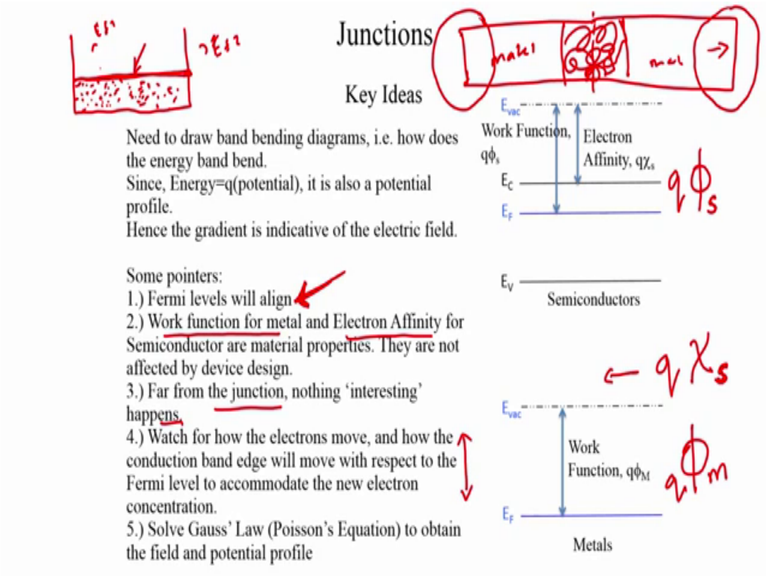

And the electron affinity for a semiconductor will always be a constant ok. So, these 2 will not change so, remember that. And the next thing is very far away from the junction.

So, let us say you have a very long piece of material 1 and you have another long piece of material 2, and you created a junction ok. So, these are long and we can soon define the length scales you know more accurately, but we create a junction between these 2 materials. Now you have a lot of interesting things happening in and around the junction ok, you have the bands moving shifting away from where they were, you have electrons moving across it stretched.

But very far away from the junction ok, the material really does not see any of these any of these phenomena. And very far away from the junction the material could be said to live in it is own world, and you know retain the properties, that it had if it were to be in equilibrium. If the entire system is in equilibrium that the material really does not see any change ok. And very far from the junction nothing interesting happens.

So, then while drawing a band bending diagram, we watch for how the electrons move about. So, this is exactly what I described with the water bucket analogy ok; which is to see you know which material transfers electrons ok. And that will help us gauge the bending of the bands in a semiconductor. Finally, in order to analyze you know the degree of bending and the shape of bending, and you know what the electric fields are and what the potentials are inside the junction, we solve Gauss's law.

And you know we solve the differential form of Gauss's law which is something called as the Poisson's equation ok. So, these are several pointers that we have I have thrown out quite early ok. Any is a things to remember and we will discuss each of these in the next few minutes. And we will soon see how to you know how these can be used to draw a band diagram ok.

So, let us go to the very first point, which was the alignment of the Fermi level ok.

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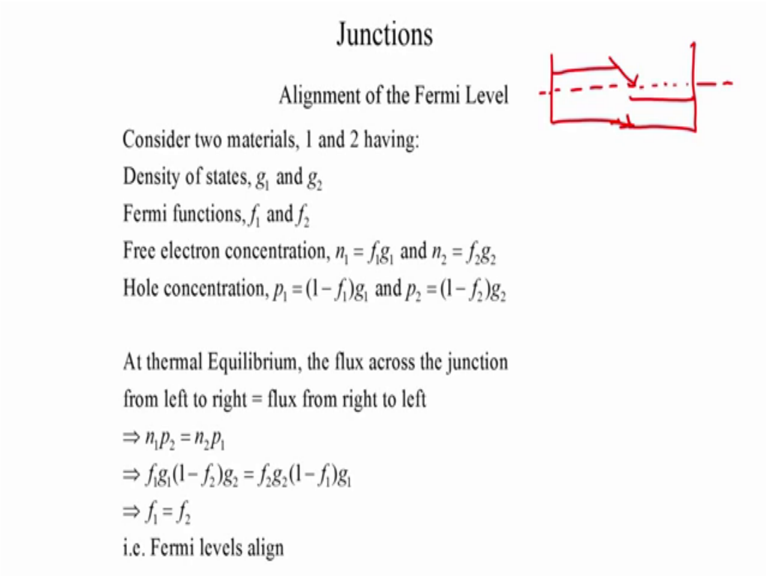

So, I stated that you know I gave this analogy of the water bucket ok, the bucket carrying water. So, one bucket had a different level the other bucket had a had water at a much shallower level ok. And when we created a junction we just removed the wall separating these 2, and we said that the level of the water would align. And this was sort of they sort of built upon the use of this analogy a while back when we were discussing you know the Fermi function and the Boltzmann's distribution etcetera. But now let us try to mathematically prove this, the alignment of the Fermi level ok.

So, let us take 2 different materials.

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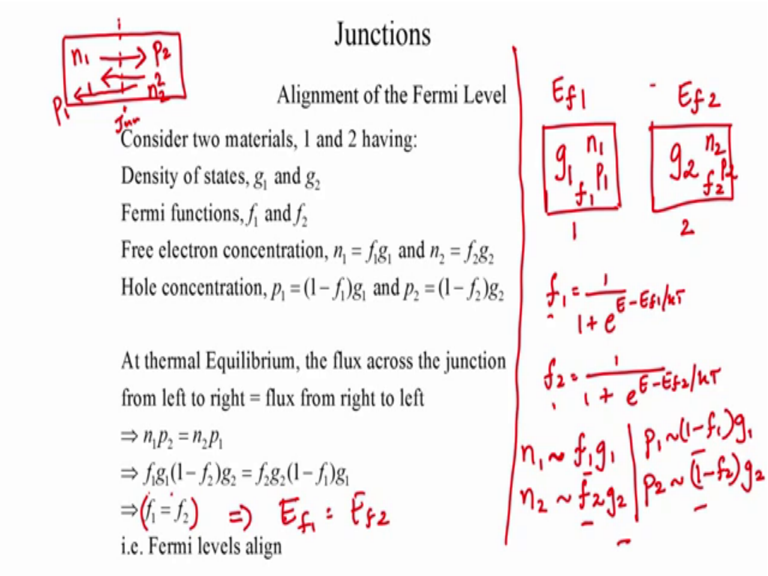

Let us say there is material 1 and that is material 2, and let us say material 1 has got some density of states which is given by g 1 and material 2 is got a density of states given by g 2, and depending upon the location of the Fermi level ok. So, this material 1 has got a Fermi level located at E f 1 and material 2 is got a Fermi level located at E f 2. And depending upon the location of this Fermi level, material 1 could have a Fermi function called f 1, and material 2 will have a Fermi function f 2.

So, f 1 would be something like 1 by 1 plus e to the power E minus E f 1 by k T. And f 2 would be of the form 1 by 1 plus e to the power E minus E f 2 by k T. And to continue on, let us say there are n 1 free electrons and material 1, and n 2 free electrons and material 2, and p 1 vacancies in material 1 and p 2 vacancies in material 2. And now what we do is we are trying to bring these 2 we try to bring these 2 materials together and form a junction.

So, before we do that let us try to get a gauge on what are n 1 and p 1. So, what is n 1? N 1 is calculated from the probability of occupancy of all these states in material 1 so, it is f 1 g 1, and n 2 is f 2 g 2. And what is the probability of non-occupancy? That is the probability of finding holes it is, 1 minus f 1 g 1 and in p in material 2 it is 1 minus f 2 g 2. So, these are the parameters that we have in material 1 and material 2. So now, let us say that we try to create a junction between these 2. Now we bring material 1 and material 2 together and we have established a junction.

Now, at thermal equilibrium so, we created this junction and we left it in dark, we did not apply a voltage, we did not apply light. We left these 2 material and these 2 materials with the junction in the dark ok. And what would happen? In the dark there cannot be any current ok, you cannot have current. If you have a current you can establish, you can do work and you have probably solved the energy crisis; so in the dark, any flux from any flux across the junctions. So, let us call that the junction ok. So, between these 2 materials that is one that is 2. Any flux from left to right across this junction should be matched by a flux of carriers from right to left across this junction ok. These 2 should be the same otherwise you will have an effective current.

So, what does the flux from left to right depend on? It depends upon the number of electrons I have a material 1, and the number of vacancies I have in material 2, because if there are no electrons in material 1, there is no current from material 1 to material 2. And even though there are electrons material 1, if there are no vacancies in material 2, the electrons cannot fill any states in material 2. And therefore, there will not be any current ok. So, the current from 1 to 2 depends upon n 1 and n 2 in fact, it is the product.

So, if I want to match the flux, the flux from left to right depends upon this product n 1 p 2. And the flux from right to left depends upon the product n 2 p 1. So, you need to have electrons from the second material trying to occupy the vacancies in the first material. So, at thermal equilibrium, they cannot be a current and therefore, these 2 flux, flux is must balance each other, and n 1 p 2 must be equal to n 2 p 1.

So, let us write out n 1 and p 2 in terms of the density of states and the Fermi functions using these terms that we described here. So, n 1 is f 1 g 1 and p 2 is 1 minus f 2 g 2 and so on so forth. And if you were to solve this equation out you will find that it says that f 1 is equal to f 2. And f 1 equals to f 2 automatically implies that at thermal equilibrium E f 1 will be equal to E f 2. So, in other words, if you were to create a junction between these 2 materials, and keep this system at thermal equilibrium, the Fermi levels will align and E f 1 will have to be equal to E f 2 ok. So, this is the little hand wavy proof that the Fermi levels of these 2 materials will align when you create a junction.

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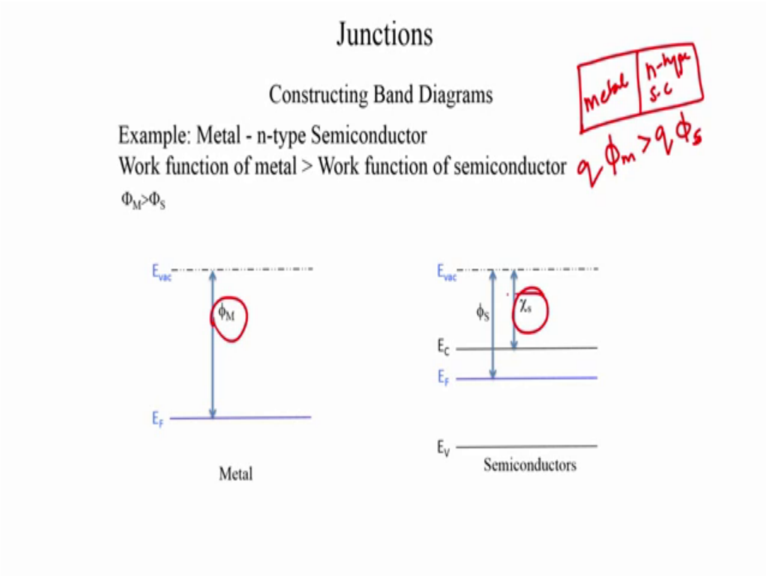

So now let us start creating a band bending diagram ok. So, this is a very useful concept as I told you. And I think it is best done we take help of an example. And I will create a band diagram for 2 material 2 I will consider 2 examples, because we will very soon be using these examples. So, you might as well just take this opportunity to consider these 2 cases ok.

So, the first band bending diagram will be between will be for a junction created with a metal and an n-type semiconductor. So, you have a metal that is going to form a junction with an n-type semiconductor ok. And we will choose this particular condition, that the work function of the metal, so q phi m. So, it is all if you consider everything in terms of energy. So, it is all got a q there and phi M is simply the potential. So, q phi M is the work function of the metal is greater than q phi S. What does that mean? It means that the Fermi level of the metal is lying further away from the vacuum energy level as compared to the Fermi level of the semiconductor.

So, the Fermi level of the semiconductor is closer to the vacuum energy as compared to the Fermi level of metal. Or in other words, the semiconductor has got a Fermi level that will lies above the Fermi level of the metal ok. And it is a semiconductor that is going to donate electrons to the metal, if we create a junction because that is what we looked at in the water analogy ok. So, this is the condition.

So, the first thing we need to make sure is if we create a junction the Fermi levels will align. And the second thing to make sure is that the work function of the metal does not change and the electron affinity of the semiconductor does not change ok.

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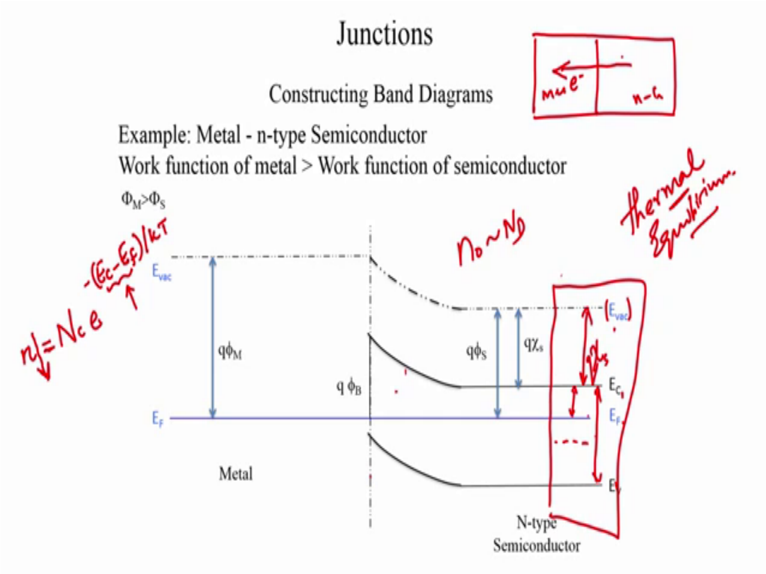

So, let us say we create a junction between these 2 materials. So, the first thing we do is let us align the Fermi level, we keep the Fermi level flat ok. So, you can see that the metal and the semiconductor now have the same Fermi levels. So, we are all at thermal equilibrium so, all at thermal equilibrium. So, if we go out of equilibrium the Fermi levels need not be aligned. Because then there is no reason for the flux from the left to the right to be matching the flux from the right to the left. So, is all at thermal equilibrium.

So, the moment you have a metal n-type semiconductor junction with phi M greater than phi S, the Fermi level line, the vacuum level will adjust itself; so as to ensure that the electron affinity in the semiconductor and the work function of the metal is always a constant. So, you can see the work function of the metal has never changed the work function is the same ok. The difference between the Fermi level in the metal and the vacuum level has is constant throughout. But since the semiconductor had a higher Fermi level as compared to the metal, the semiconductor will now donate electrons to the metal ok.

So, you will have in the metal semiconductor junction with phi M greater than phi S ok. So, you had an n-type semiconductor you have a metal here, and you have an n-type semiconductor, and it had a Fermi level that was located higher as compared to that of the that of the metal, and electrons will effectively flow from the semiconductor to the metal upon the creation of a junction. So, what do you mean by electrons are going to flow from the semiconductor to the metal?

So, let us look at close to the junction, let us look at this region close to the junction. So, the semiconductor has now lost electrons, in the case of this it initially had the equilibrium electron concentration, you know, it had some n o which was approximately N D, and now the semiconductor has lost electrons because it is donated it to the metal in order to align the Fermi levels. So, if you have to if the semiconductors lost electrons, it implies that the conduction band has moved away from the Fermi level position, because what is the electron count the electron the electron concentration is n c e to the power minus E c minus E f by k T.

So now, as this electron concentration goes down, the E c minus E f must increase ok. Therefore, since this region has got fewer electrons as compared to the bulk ok; so this is the bulk region, very far away from the interface, the conduction band edge will move away from the Fermi level ok. So, it is no longer going to retain it is position here. Close to this is going to move far away and then just a little after that it is going to be located there and there and then therefore, you have a gradual bending of the conduction band edge with respect to this Fermi level.

Now, the energy gap in the semiconductor hasn’t changed ok. So, therefore, the valence band edge will also move in accordance. Now very far from the junction; so, let us look at this region, there is no change here. It is as though you had a pristine semiconductor right it you look at this condition here. And this condition here you still have an n-type semiconductor. So, this is the E c minus E f, it is n doped because the E f is lying above mid gap, that is your band gap, that is your E v E c E f and that is your E vacuum with the electron affinity being constant. So, nothing has happened. This region far away from this junction hasn’t really seen anything interesting, but it is only close to the junction that we have lost some electrons.

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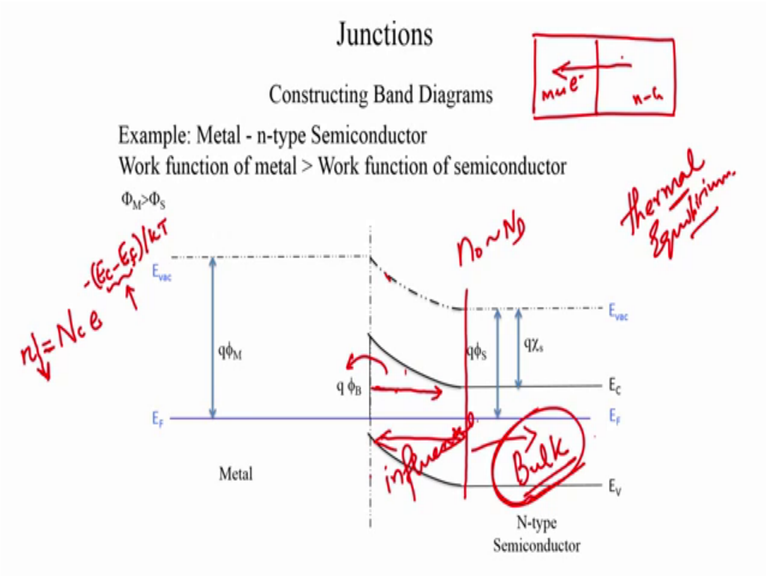

And as you move deeper, as you start walking from the junction and into the semiconductor, as you get deeper and deeper, you will find that the movement of the conduction band away from the Fermi level is sort of gradually decreased, till you reach a point where you are in the bulk ok. So, this region here is called as the bulk, it is a region that is not seen anything interesting, because it is too far away from the junction. And it is only this region here that is influenced by the creation the formation of a junction.

So, there are some simple ideas we will again come back to drawing a band bending diagram when we talk about metal semiconductor junctions. And throughout the vacuum level, I know as I mentioned it adjusts itself ok. So, as to keep the electron affinity constant and the work function of the metal constant, but note here that the work function of the semiconductor need not be constant, again it is not required ok.

So, this is the way you construct a band bending diagram. So, essentially what we do? Is you first align the Fermi levels and you just mark out which of the materials is going to donate electrons, where is electron going to flow from? Is it from the right to the left or left to the right?

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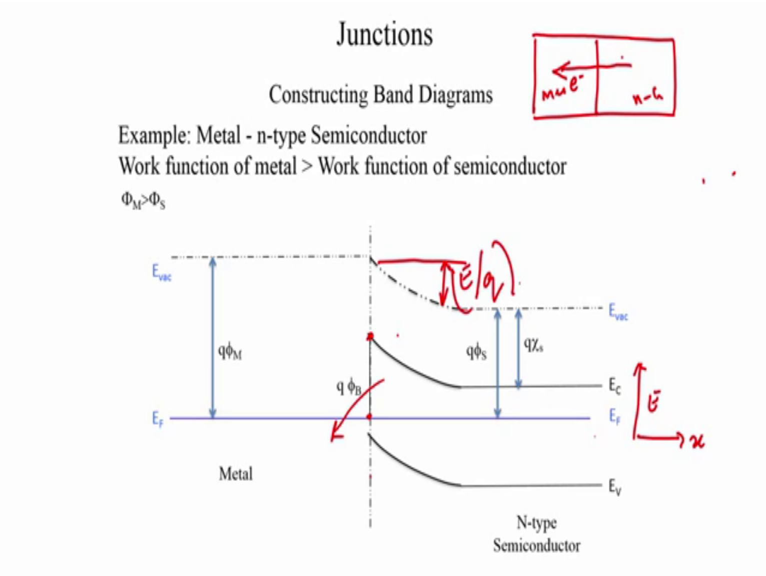

And depending upon which material is lost electrons and which material is gained electrons, we adjust the band position the E c minus E f location in these 2 materials ok. And therefore, you get a bending of the bands in space. So, this is a energy distance diagram. So, the x axis is distance the y axis is energy, and it is also indicative of potential. So, if you want to locate the potential difference between these 2 points, it is simply the energy difference between those 2 points divided by q. So, that is the potential difference ok.

Now, several other points, you know the band bending diagram is always drawn with respect to electrons ok. And what I mean by that? Is if you see a slope here. So, for example, if you see for example, let us take this region here ok, you see this bending of the bands. You see the bending of the conduction band. Essentially, what this means is that the region that is lower located at lower energies have got a higher potential ok, as compared to the regions located at higher energies.

So, if I have a Fermi level and I increase the potential of that so, let us say there is a metal and it is a Fermi level here. And I increase the potential of the metal, I increase the voltage the Fermi level will start moving downward. And therefore, since this is the case if I have an electron and a hole ok, the electrons would like to run down the hill, when you see a bending and the holes would like to run up the hill ok. So, this gives you a very intuitive feel for what the electrons will do and what the holes would do ok.

Now, since it is an n-type semiconductor there are not many holes, there is quite a very, very few, and whatever majority electrons whether I have all moved in here into the metal and essentially any electron coming in here will try to run down the hill and away from the junction. So, they are going to be very few electrons here and very few holes here. And therefore, in some sense this junction can be said to be sort of depleted of free carriers ok. So, we will come back to these points later. So, these are the this is the way you draw a band bending diagram, that is the way you look at the different aspects of it.

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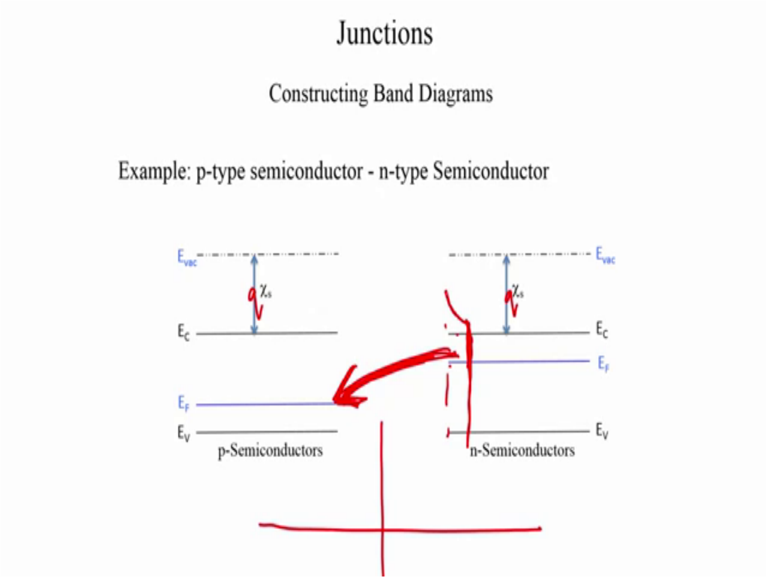

So, just to complete this let us go to another example.

So, let us take a p-type semiconductor and an n-type semiconductor. Now let us try to create a junction. So, this is your very well-known p n junction ok, it is the same semiconductor. So, here that is my electron affinity that has to be constant. Again if you want the energies it is q times chi, and the Fermi level for a p-type semiconductor is located closer to the valence band edge. And the Fermi level for an n-type semiconductor is located close to the conduction band edge, and here you have your 2 different semiconductors. And now we try to create a junction.

So, let us try to think about what will happen before, we actually see we see the next figure. The first thing is the Fermi levels will align ok. So, let us align the Fermi levels. Now which material do you think will donate the electrons to the other? So, the Fermi level here is higher than the Fermi level in a p-type ok. So, it is very likely that the electrons will flow from the n-type into the p-type once we create a junction.

So, the electrons flow from the n-type and into the p-type, what do you think will happen to the conduction band edge, and the with respect to the Fermi level in the n-type material. So, since the region near the junction will lose electrons, the conduction band will have to move away from the Fermi level position ok.

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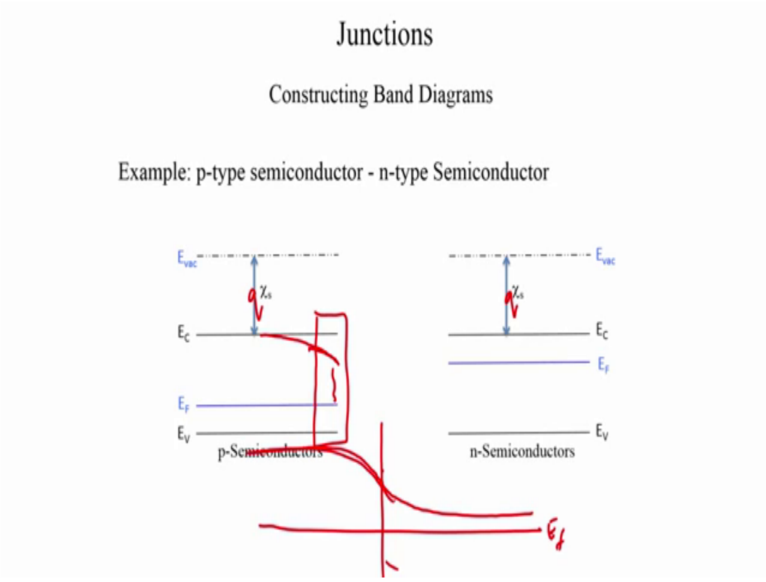

So, in the n-type material: so, this is the Fermi level that is the junction it is expected that the conduction band edge move away from the Fermi level position. And in the p-type material, the p-type material has now received electrons ok. It had any a small number of electrons initially, but now it is received a lot of electrons from the n-type material.

These electrons have all diffused in from the n-type material. And therefore, this region near the junction has now got excess electrons and therefore, the conduction band would like to move closer to the Fermi level in order to reduce the E c minus E f gap. And therefore, the p-type material will see a band bending that looks like that; where the Fermi level sorts of bends downward where the where the conduction band bends downward to meet the Fermi level in the p-type material.

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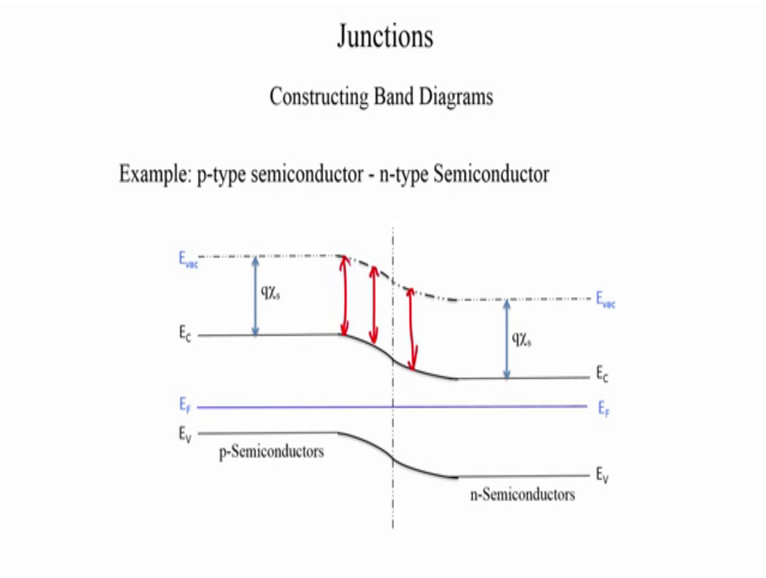

Therefore, we can construct a band diagram that looks like this.

So, you can see that the conduction band edges moved away from the Fermi level in the n-type and it has moved towards the Fermi level in the p-type. Therefore, giving you a band bending that looks like what is shown. So, this is the method to construct the band diagram. So, throughout you will find that you know the electron affinity is always constant.

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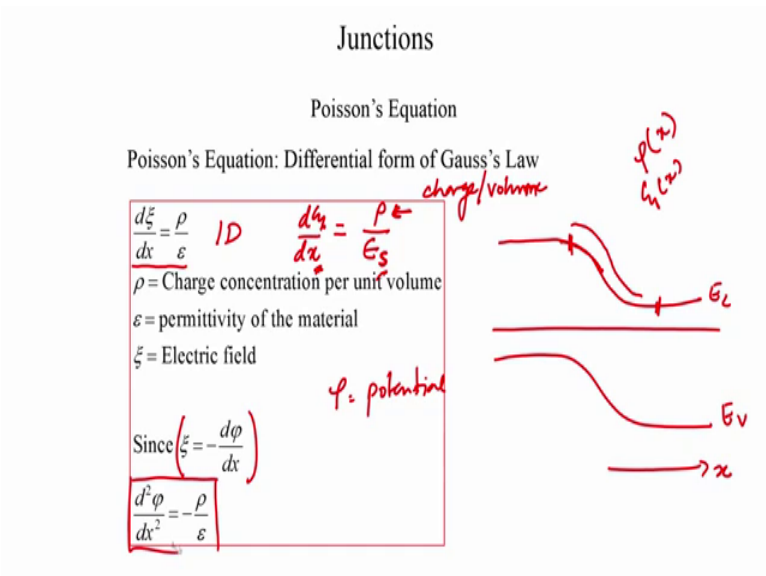

So, the final point you know before we you know stop this study of this overview of junctions, and actually start looking at some certain very specific junctions; is to understand something called as a Poisson's equation ok. Now we did draw all this band bending. So, let us say it was a p-type and n-type semiconductor we said that you know the band bending would look like it would look like that. The question now is how do we exactly and you know very quantitatively determine the shape of this bending you know, what is this ok. So, that is x so, what is the relation between the potential and the electric field etcetera with respect to as a function of x.

So, you want to establish this quantitatively. We want to know the exact shape of this bending, because these quantitative results can help us estimate many things such as currents and charge concentrations etcetera in a more accurate manner. So, in order to establish this, get this quantitative estimate of the amount of bending. We need to solve Gauss's law ok. And we want to particularly solve the differential form of Gauss's law ok, where we use the differential form of Gauss's law which something called as a Poisson's equation.

And here is a very brief understanding of that. So, Poisson's equation simply says that the change of the electric field in space. So, this is the one dimensional Poisson's equation. It is simply equal to the charge concentration per unit volume ok. So, this is the charge per unit volume ok. It is not per unit area; it is not the total charge the charge per unit volume divided by the permittivity of the material in which we are doing all this analysis.

So, in our case it is mostly going to be the permittivity of the semiconductor. So, that is the electric field that is the distance that is the spatial coordinate x, rho is the charge concentration per unit volume and epsilon is the permittivity. And since the electric field is minus d phi by d x which is; where phi is the potential ok; we can also rewrite Poisson's equation as d square phi by d x square is equal to minus rho by epsilon. And this is a relation that we will use and we will look at some examples soon on in order to establish the correct nature of the bending of bands ok.

With that we will close our overview on you know how to create you know what a junction does, and how to create a band bending diagram, and you know, you know what the Poisson's equation is. And we will now start looking at very specific junctions and of interest are the metal semiconductor junction and the p n junction. And we will start looking at these junctions in order to establish our understanding of the different semiconductor devices.