Semiconductor Devices and Circuits
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Lecture - 22
Schottky Contact: Current-Voltage (IV) Characteristics

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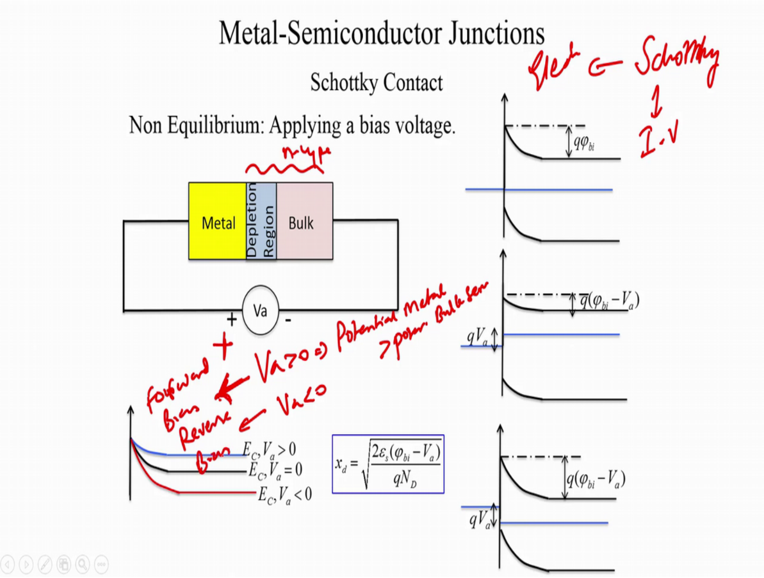

So, here you have a metal-semiconductor junction. This was my n-type semiconductor. And I have applied a voltage V a. And the voltage is applied such as you see the ground or the reference is kept at the semiconductor. The positive sign is sitting at the metal. So, when V a is greater than 0, it implies that the potential of the metal is greater than the potential in the bulk of the semiconductor, so that is what we mean by this circuit configuration right.

Now, we will call V a being greater than 0 as forward bias ok. Now, you might have all heard this contact this term in context of diodes, and in fact, the Schottky junction does behave like a diode, so that is why although we have not formally discussed diode some pretty. If the students have heard of diodes before, then you might have heard the term forward bias in the context of diodes, but nevertheless. Let us let us just go ahead and call this condition as forward bias ok. And when V a is less than 0, it is something called as reverse bias ok.

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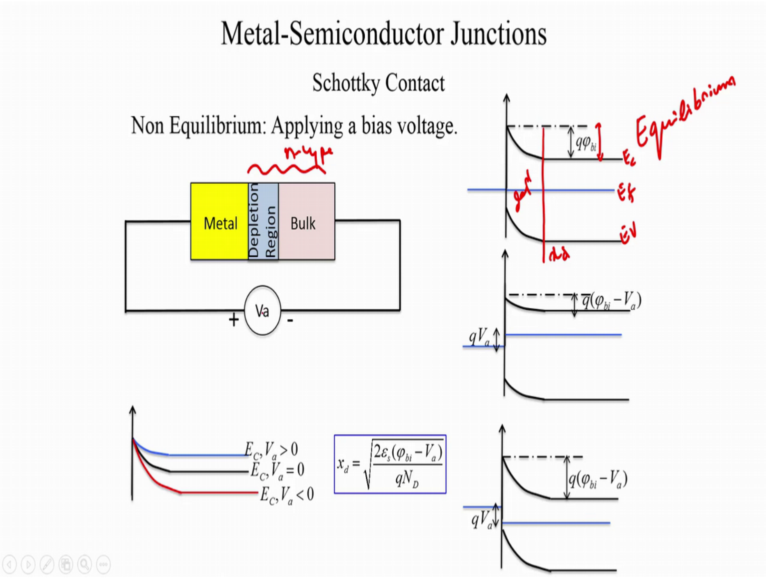

So, now what happens to the band diagram, when I apply a potential. So, let us look at these pictures here. So, this is the condition of equilibrium. So, this is the equilibrium condition, that we are very familiar with and on which we performed all the electrostatics analysis right, so that is my conduction band edge, that is the valence band edge, that is the Fermi level, that is the built in potential, that we calculated out, and that is the depletion region, which is got a depletion width of x d ok. And that was the relation between so x d turned out to be square root of 2 epsilon s phi bi by q N D ok, so there was the relation that we obtained.

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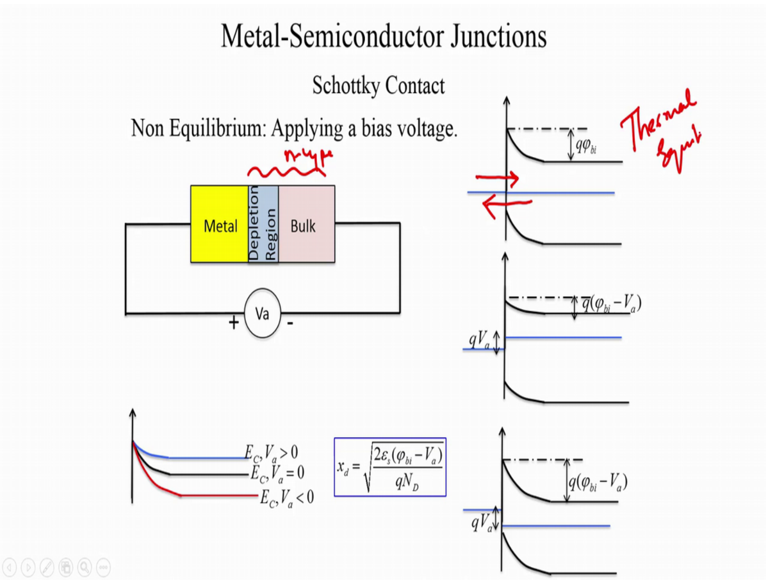

Now, the moment you take it out of equilibrium by applying a bias by applying a potential V a, what happens is you start the Fermi level need not be aligned anymore. You are now creating you are trying to change the flux, now why did the Fermi level aligned. So, if you remember the calculations, when we looked at the fundamental junctions. We said that the Fermi levels aligned, because the flux of carriers from the left to right across the junction was the same as the flux of carriers from right to left, and that is true only at thermal equilibrium right.

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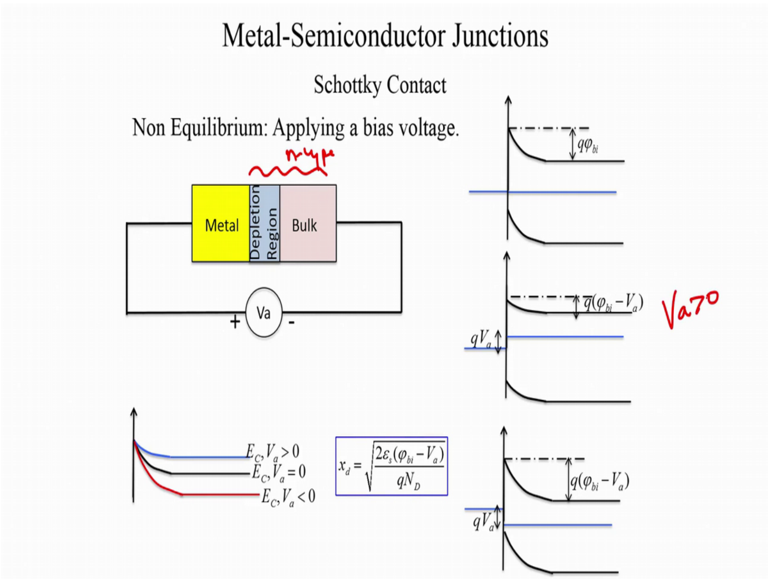

Now, the moment you take it out of thermal equilibrium, but the moment you apply a bias voltage. You are attempting to favour one direction as compared to the others. Now, when you apply a forward bias, when your V a is greater than 0.

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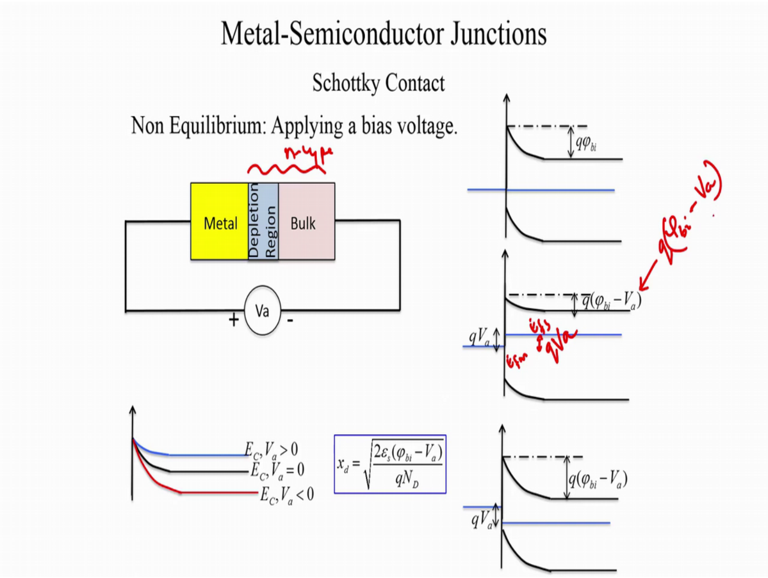

The Fermi level of this semiconductor is now split away from the familiar of the metal. The two Fermi levels are no longer aligned, and you have to split away by the amount of voltage you applied. And since, we are showing everything in terms of energy it is q into V a. Now, because of this the built in potential changes case, the built in potential is no longer q phi bi, the built in potential two is lowered by an amount of by the same amount that is V a.

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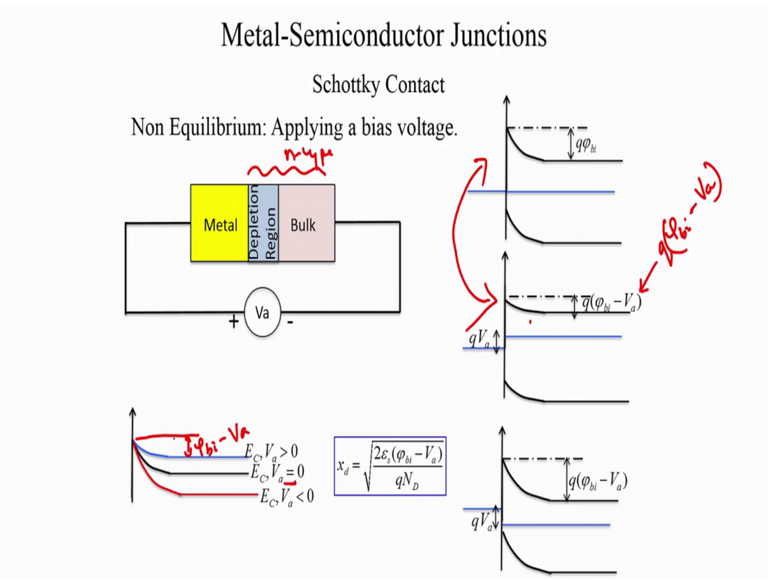

So, essentially what this means is that if you look at this picture here, on the left hand side that bottom left, so that is my equilibrium condition, when my V a was 0. So, we are looking at only the conduction band ok. So, you are trying to compare put these two plots on the same figure here, so that is my conduction band at V a equal to 0. The moment we apply V a to be greater than 0, the band bending becomes a little bit more gentle ok. So, this bending becomes a little bit more gentle. And the built in potential goes less than the built in potential and equilibrium ok, so that is what happens in forward bias.

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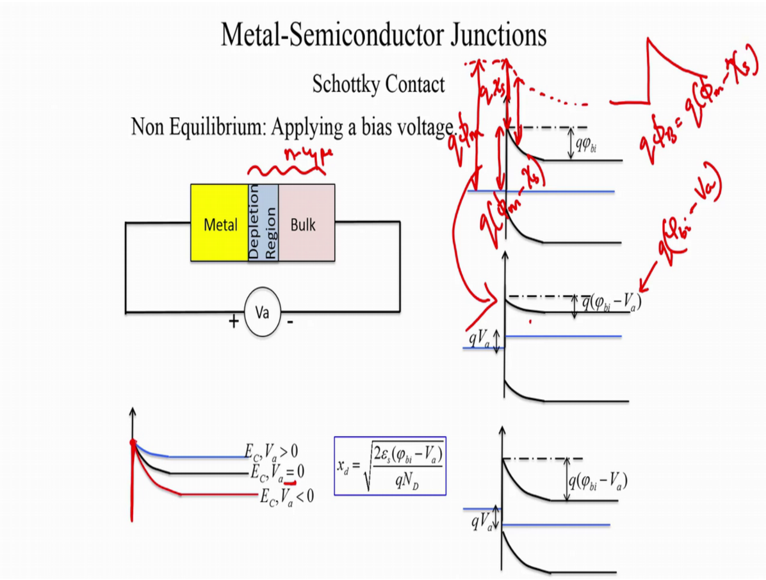

But note, what has happened to the barrier height, the barrier height remains unchanged. And why is it, because the barrier height ok. If you think about it, let us say there is the vacuum level there ok, that is the vacuum level. This is the electron affinity. So, as we if you mark it from the semiconductor side, that is the electron affinity of the semiconductor. .

And from the metal side just if you just slip it down to the metal side, that is the work function of the metal. And both these are material properties that are constant. And therefore this barrier height is essentially q times phi m minus chi s ok. And therefore that the barrier height remains unchanged ok. So, you are not you do not influencing the barrier height in any manner. So, the barrier height remains the same, it is only the bending of the bands that becomes more shallow.

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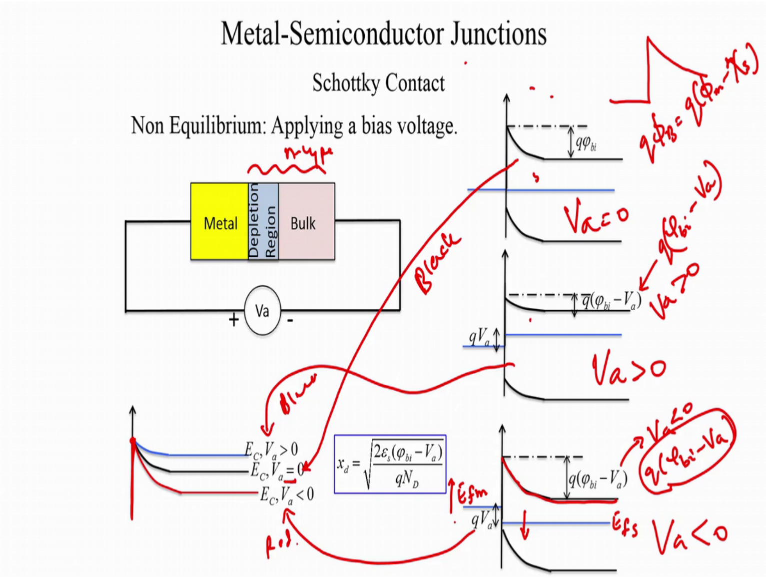

Now, when you apply reverse bias, the opposite happens. The work function of the I am sorry the Fermi level of the semiconductor, now lies below the Fermi level of the metal. So, by applying a positive voltage by applying a negative voltage to the metal we have in fact made the metal Fermi level go higher as compared to the Fermi level of the semiconductor.

And therefore, the bands now bend a little bit more steeper ok. And you should remember that V a is negative, so that is why q into phi bi minus V a is actually going to be greater in reverse bias as compared to equilibrium ok. So, V a is less than 0 in this case. In this case V a was greater than 0, sorry should have label that, I just realized that these labels are missing, so that is the case of V a greater than 0. This is the case of V a less than 0. And that is the case of V a equal to 0. So, this case corresponds to this drawing here that is in black. This case corresponds to this drawing here that is in blue. And this case corresponds to this drawing here that is in red.

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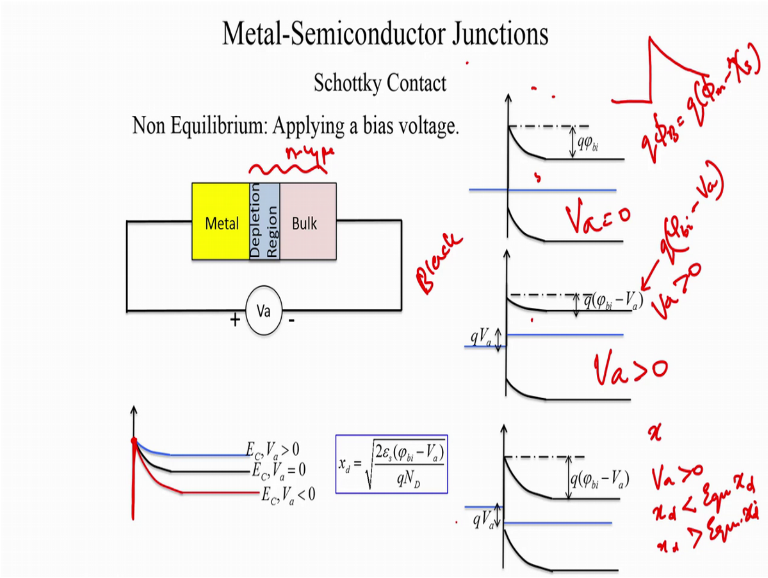

So, now let us look at, what happens to the depletion width. At equilibrium, the depletion width was simply given by this term, but V a being equal to 0. There was no V a, so that was the depletion width. This is what we had calculated from the solution of Poisson's equation. Now, after we apply a bias, the depletion width changes to having a term of phi b i minus V a inside. When V a is greater than 0 that is when you are in forward bias, the depletion width goes smaller, because phi b i minus V a is going to be smaller as compared to phi b i. And the depletion width is now less than the equilibrium depletion width.

And when the device is reverse biased, phi b i minus V a is now greater than phi b i. And the depletion width goes to be greater than the equilibrium depletion width ok. So, therefore, the depletion width of the device in forward bias is smaller than the depletion width of the device in reverse bias, but the depletion width an equilibrium lying in between these two conditions ok.

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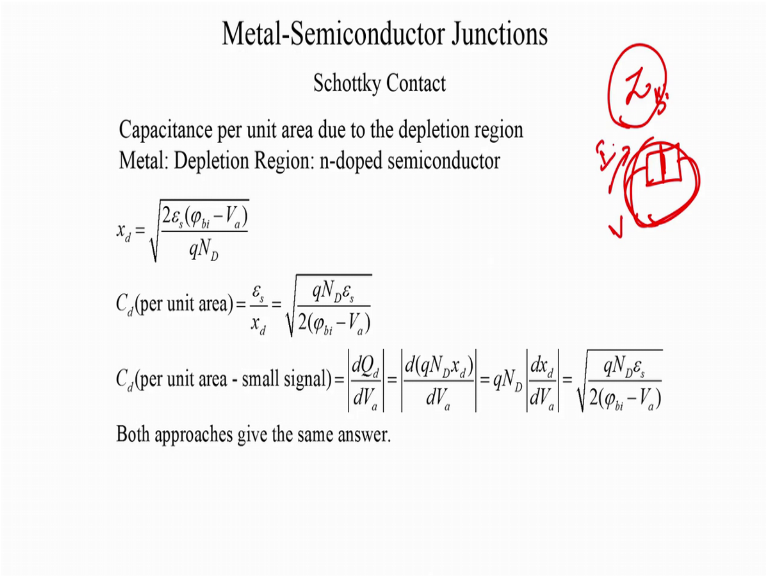

So, now let us look at the capacitance of this junction ok. So, we are trying to we are trying to head towards the calculation of the effective small signal impedance right. So, we want to know, what happens you know what if I have a Schottky junction, what the impedance does it offer, when I apply a voltage across this. And what is the kind of current I would get across, yes I capacitance is one of the aspects of the impedance calculations, so what is the capacitance.

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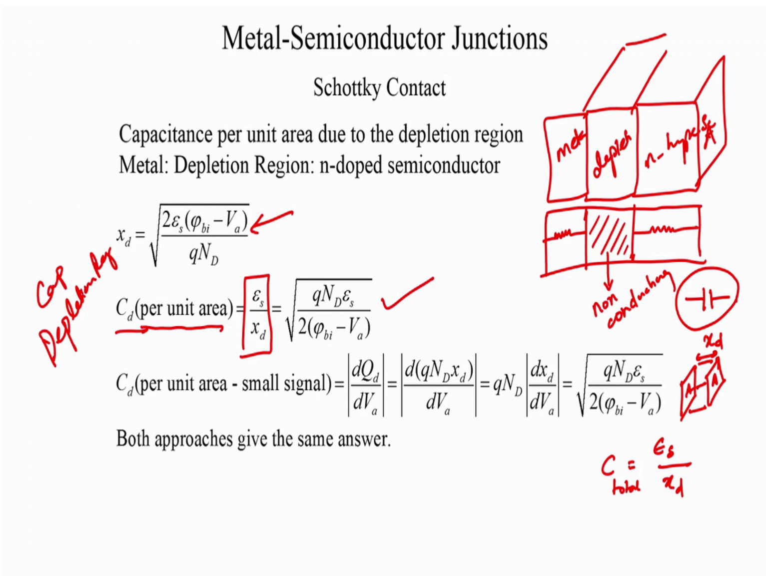

So, if you think about the Schottky junction, you have metal on one side. Then you have a depletion region here. And you have a n-type semiconductor. So, the n-type semiconductor the bulk can be thought of as a resistor, which is what we have looked at, when we study the mobility of carriers n-types, the metal also is a very low resistance resistor.

The depletion region of however, has got space charge right. It is gone just these fixed ions. It is got no mobile carriers, there are no electrons. I should not say no mobile carriers got very few mobile carriers ok. So, these two are negligible. So, it is as though you have these two resistors. And there is some kind of a depleted or you know non-conducting insulator in the middle. So, you one can imagine it to be that way. So, therefore, this is like a capacitor in some sense. And what we would like to do now is to calculate the capacitance of this capacitor.

Now, if you think about it this in this manner, the capacitance of a what we need to calculate is the capacitance of the parallel plate capacitor right. So, the device had some cross section area A ok. This is equivalent to having a capacitor, which is got two plates with cross section area A with a insulator in the middle, which has got a thickness of x d, which is a depletion width. So, what is the capacitance, it is going to be epsilon s A by x d that is going to be the total capacitance of this junction.

But if we want to the per unit area capacitance ok, so we are interested in finding the per unit area depletion capacitance, capacitance of the depletion region. So, per unit area implies I will just remove the A term there, and just have epsilon s by x d. Now, I know my x d is this, and I divide epsilon s by x d in order to get, this to be the capacitance of the depletion region.

Now, this may not be the most general method of thinking of capacitance ok. So, it worked out very nicely here, because we could draw a nice analogy to a parallel plate capacitor. But, from henceforth it would be good to think of the capacitance across two terminals in a slightly different manner, let me describe that ok. So, what we want to calculate is something called as the small signal capacitance ok. Now, what do what do we mean by that.

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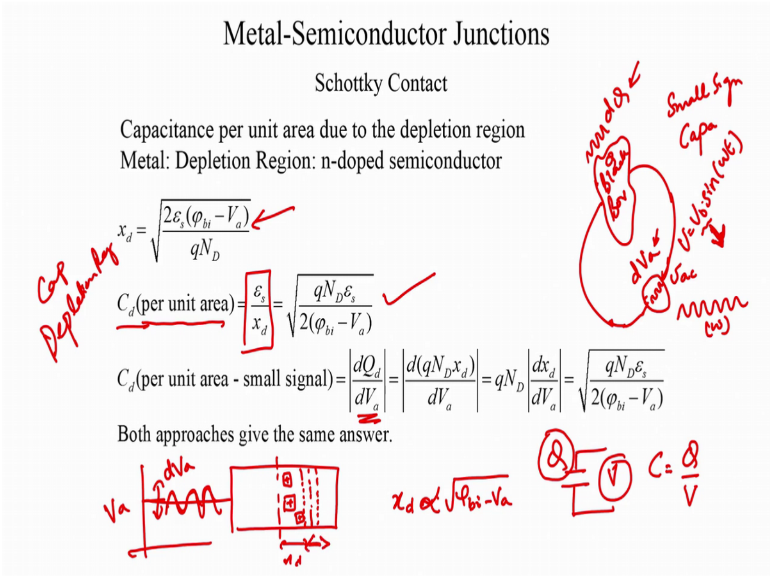

So, let us say there is some device; it is sitting inside a black box ok. And you have these two terminals across ok. And we want to measure the small signal capacitance small signal capacitance. Now, what is a capacitance, how do you define capacitance, capacitances so suppose you had your familiar parallel plate capacitor. And you were to apply a voltage V across this capacitor, you will store a charge Q on this capacitor, and your capacitance of this capacitor is Q by V. So, it is the amount of charge stored on the capacitor for a given voltage V.

Now, what we mean by small signal capacitance is this. We now apply a small fluctuating signal ok. We will apply a small ac signal. So, let us say, it is a tiny fluctuating sine wave, if you like at some frequency omega. So, essentially it is going to be the input, that we are going to give to the circuit is going to be say some V naught sin of we just write it a little bigger. It is going to be V is equal to V naught sin of omega t ok.

So, let us say we giving a small, this is a very small signal. You know, and what you mean by small is a great question, it simply means that we have it is small enough that the device can be considered to be linear ok. And we will understand these concepts a little better as we go down. So, now if I were to apply a small voltage fluctuation here, this device has got some charge ok. It is all we cannot see it, but we can sort of measure it ok.

And this charge is going to fluctuate in response to this applied voltage, so because of this applied voltage. You going to see an effect of fluctuation in the charge inside the device ok, so that is d V applied, and that is the d Q the fluctuation in the charge. And we know, what we are applying here, and we can measure this fluctuation. And therefore, the small signal capacitance is simply d Q by d V. And in our case and so the depletion capacitance is d Q d by d V a.

So, if you were to perform the same experiment on your Schottky junction. So, you have that to be the junction, this is the depletion region, and that was x d all right. And we already know that x d is a function of the applied voltage. It varies its proportional to square root of phi bi minus V a. And this region has got all the positively charged donors right. It is got some charge that is balancing any charge that is applied on the other side.

Now, if I were to fluctuate V a, so let us say I set a certain bias value for V a. And then, on top of that dc bias we are going to fluctuate V a, a little ok. We are going to have a small fluctuation in V a. So, how would the depletion region respond, the depletion region [res/respond] will respond by changing the position of x d right. So, this position the x d is going to fluctuate, it is going to move up and down.

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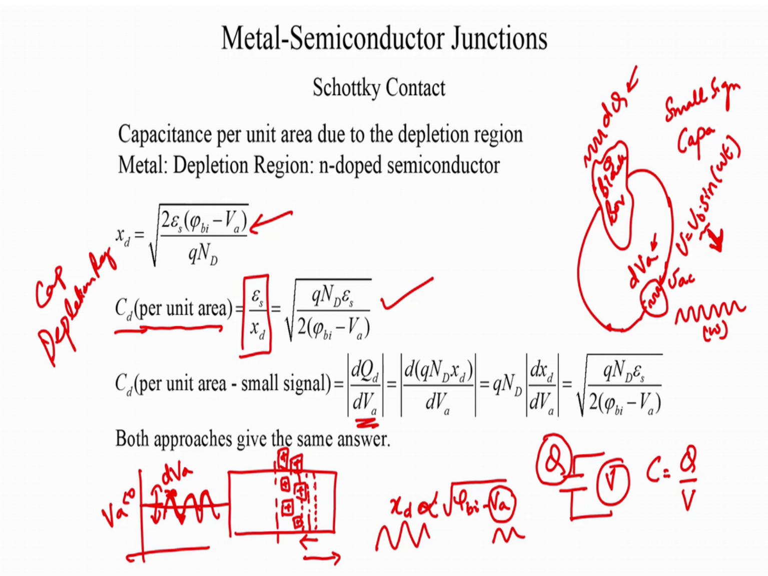

Let us say, we are doing these measurements into reverse bias, so V a is less than 0. And then, you are having the small signal fluctuation here. So, as V a goes a little higher x d reduces a bit. And a V a goes a little lower x d increases a bit ok. So, therefore as V a fluctuates your x d fluctuates. So, essentially it covers and uncovers either more or less, it exposes more doughnut charges fixed ions, when V a goes up. And it covers up some of the doughnut charges, when V a goes down.

So, by fluctuating x d you expose and cover up these doughnut charges. And therefore, it is a response of charge to the applied voltage, so that is how your Schottky diode behaves in the Schottky contact behaves in response to the a small signal variation in the applied voltage. So, your d Q d by d V a is essentially your capacitance. And you will find that, if you were to perform this calculation, you have x d in as a function of V a, you take it differentiate this with respect to V a. You will find that, you end up with the same expression as our little picture of a parallel plate capacitor.

Henceforth, it is more useful to use this approach to calculate capacitance, because it is a more generic approach, it is a approach that is compatible with performing an experimental measurement ok. So, we will keep this in mind. And whenever, we discuss the other devices let us say a p n junction diode or any transistor, we will use this approach to calculate or measure what the capacitances.

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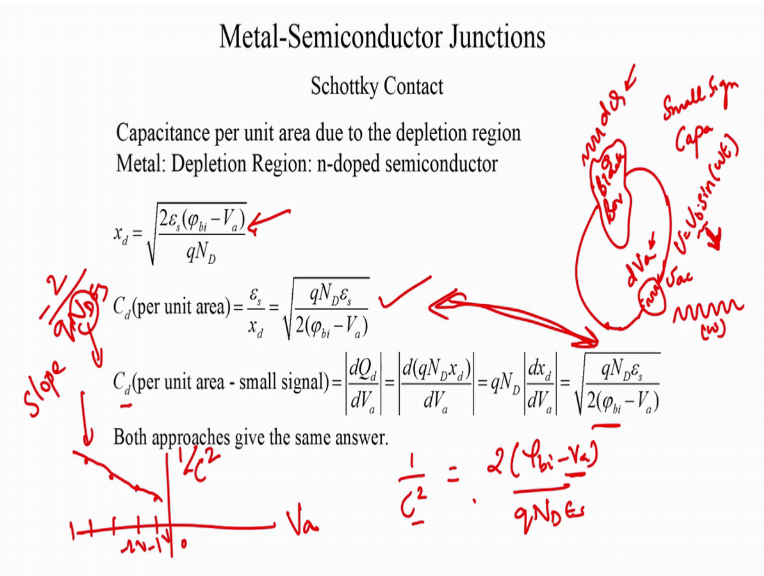

If you look at the capacitance, the expression for the capacitance ok, so C is given by, this term here. So, if I were to plot, if I will take 1 by C square ok. What is that 1 by C square is nothing but 2 into phi bi minus V a by q N D epsilon s. So, if I were to plot, 1 by C square as a function of V a, when V a is negative ok. So, there is a reason, why I am picking reverse bias, because in forward bias, we are going to see soon that we are going to have other aspects of the impedance coming up, because you are going to have currents significant currents.

If you were to perform a measurement, where you plot 1 by C square versus V a, so you measure you take an experimental setup. And you go ahead put your device through the setup, measure out the capacitance for different negative biases ok. You are going to set V a as minus 1 volt apply a small signal measure the capacitance, and mark a point. Set V a as minus 2 volts perform a measurement mark another point. And do this for several negative biases. And you will end up with the, you should end up with a straight line, because 1 by C square is linearly related to V a, so this is a straight line. And the slope of the straight line has to be minus 2 by q N D epsilon s.

So, therefore if I know my if I have my capacitance measurement, if I have this measurement, if I have this experimental result, I can extract what my N D is ok. So, even though ND was decided at the time of fabricating your device, we can measure out what ND is, so it is a useful point remember.

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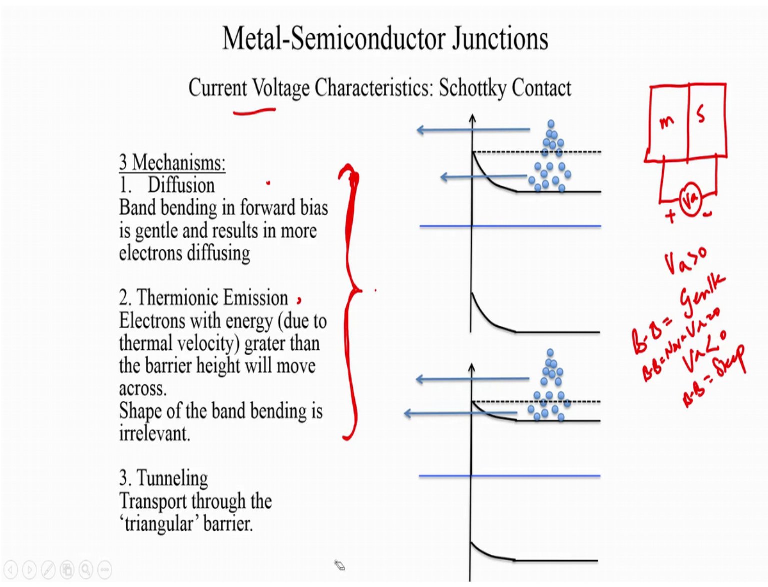

So, now let us look at the current voltage characteristics through a Schottky contact. So, we have seen that by applying a bias voltage to the metal-semiconductor junction. We can change, we can alter the band bending by varying your applied voltage V a. So, when V a is greater than 0, the band bending becomes more gentle ok, so the band bending is gentle. And V a is less than 0, the band bending gets more steep as compared to the equilibrium value.

So, equilibrium lies on band the middle, you just call it as band bending is normal, so because of this change in the bands. I mean the band structure; we are going to see some mechanics you are going to see things move out of equilibrium ok. And this essentially is going to lead to the effective change in the change in the effective flux of carriers across the junction, which implies that we are going to start seeing charge moving in one particular direction as compared you know more charge moving in one particular direction as compared to the other. And therefore, we are going to see currents across the junction. .

So, we are interested in looking at the current voltage characteristics in a Schottky contact, we are still talking about Schottky contacts ok. So, metallic semiconductor contacts had two kinds, they were Schottky contacts, Ohmic contacts. We are still talking about Schottky contacts. We looked at the electrostatics, and we looked at the non-equilibrium case, we have looked at the measurement of capacitance. And now, we are looking at the current voltage characteristics. .

So, there are three general mechanisms for current that lead to currents in our Schottky contact ok. Now, the first two mechanisms are in some sense, you know the general behaviour is quite similar, but although they imply a slightly different physics ok. And they are called as diffusion and thermionic emission ok. And they are both represented by this arrow here ok, so this arrow represents both these ideas. Again, I will I will explain what those are.

And the third mechanism is something that we have looked at, when we studied quantum mechanics, and it is called try it is called tunnelling ok. So, what are diffusion and thermionic emission ok. Now this is what happens ok, so you have you have your you know some electron population yeah. So, let us say this region is all depleted. .

Now, these electrons are at equilibrium, these electrons are trying to diffuse over to the other side. And what do you mean by diffusion, you have a barrier ok. There is a concentration gradient here and this concentration gradient is driving this current across this junction, but that current is balanced at equilibrium that columns current was balanced by carriers that are moving across from the metal to the semiconductor ok. You have an equal an opposite flux from the metal to the semiconductor.

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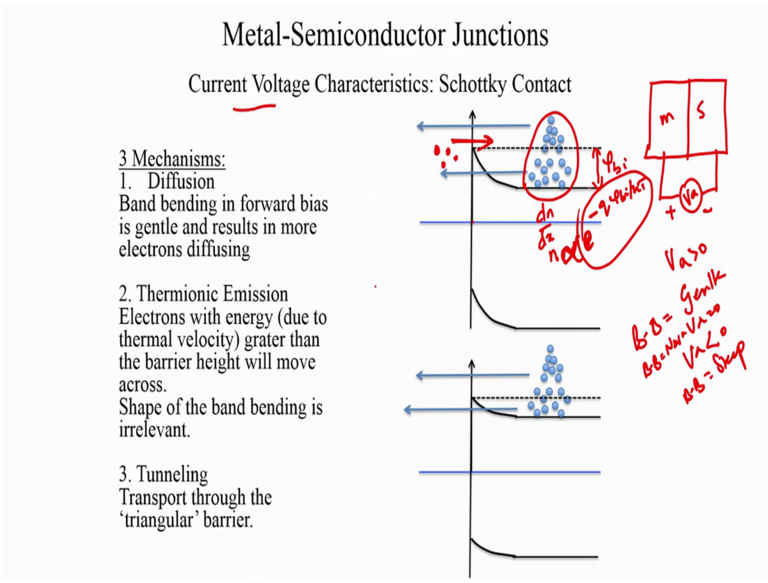

Now, this concentration gradient ok, this d n by d x is very dependent upon the built in potential. And why is that, it is because the electrons all have a Boltzmann distribution. So, though all vary as you know they are all proportional to your e to the power minus q b i by KT ok. So, as the built in potential changes your electron concentration would be affected ok.

And in case you are wondering, how this came about you can you know you go back to the general study. I am just going to go back a few slides ok. So, you can see that you know in this expression here ok. Here this is where we you know sort of wrote out all the quantities for your exact solution of Poisson's equation. So, I am going back a few slides, because it is illustrative. And you can see that the carrier count depends upon all these potentials ok. So, the built in potential plays a role in the carrier counter.

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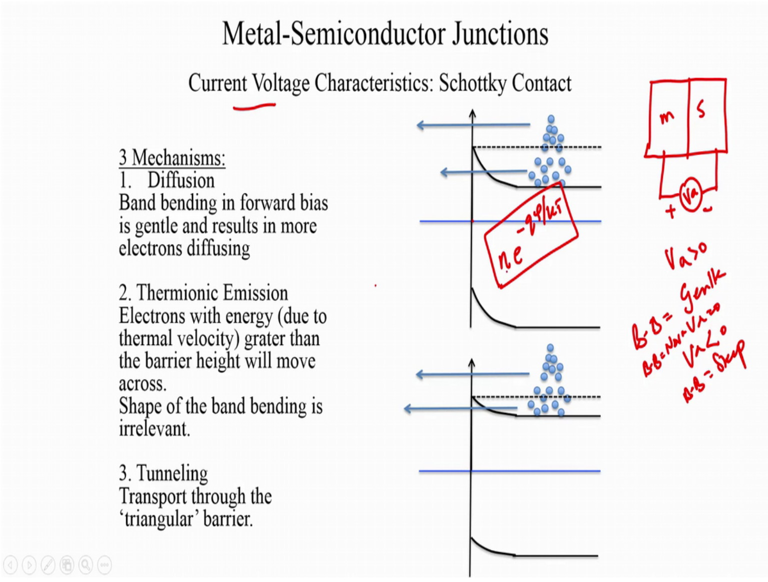

So, now if I change the built in potential, I therefore can influence the carrier count ok. And I can therefore influence the carrier concentration and that can lead to an effective diffusion current, so that is the diffusion current mechanism ok. And we will look at it in more detail. So, essentially it is the diffusion of the carriers that have got a count of e to the power minus q phi by KT. So, it is this effective number that is going to have create the concentration gradient that is diffusion.

So, diffusion is very strongly it depends upon the nature of the band bending. And you know what the built in potential is and you know what the shape of this bending is etcetera. So, it is very dependent upon all these features ok, so that is that is diffusion. Now, thermionic emission is quite is a little different ok. So, what thermionic emission says is that irrespective of what this band bending looks like ok, you know we really do not care about the band bending.

We only know that the barrier, that have we need to cross from the semiconductor to the metal side; we have to cross this barrier. And for the metal-semiconductor side, we have to cross that barrier. And we only look at those electrons that have got a large enough energy and large enough velocity ok. Basically if you think about it, the electrons sitting here let us take an electron at the conduction band edge, it has just climbed and climbed up from the valence band to the conduction band, and it is called 0 velocity ok.

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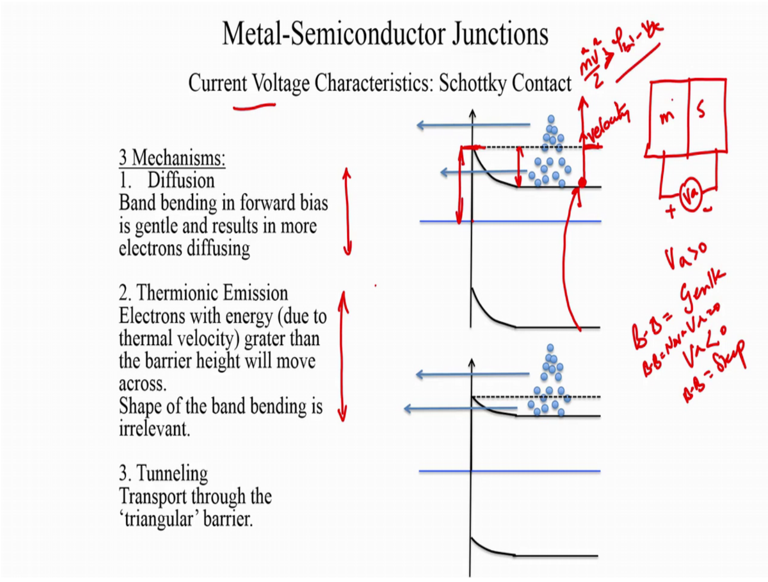

Now, as the electron climbs in energy, its velocity increases ok. And be after it crosses this particular line here, its velocity is increased to such an extent that its kinetic energy ok. The kinetic energy of the electron is now greater than say phi b i of phi b i minus V a. If you are talking about, this in a very general science so, these electrons have got enough energy, they are sitting here ok. They have got large enough velocity, these electrons are located there. They really do not worry about the barrier ok. They do not really worry about the band bending.

Now, this electron is got so much of energy. And if you just measure the effective flux and one direction, it is the current it is the current contribution of that electron ok. So, thermionic emission takes a look at all the electrons that have got a velocity large enough that is got a high enough energy, that can simply you know walk past the barrier like as though there was no barrier and existing there ok.

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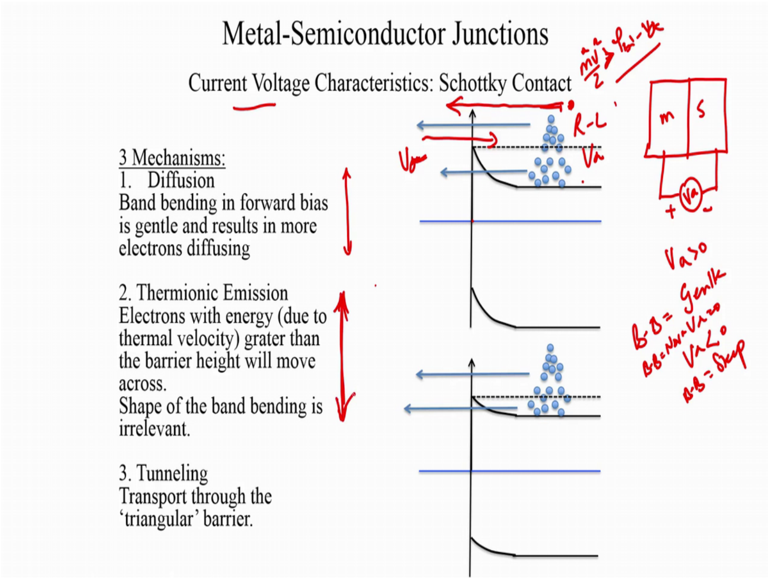

So, we just see how the flux from right to the left is affected by the applied voltage, and how the flux from left to right is affected by the applied voltage. And the effective flux is the difference of these two. And if not effective flux is [def]- effected by the applied voltage, then definitely you will have a current, and that current is something called as thermionic emission ok.

Finally, tunnelling is quite different. So, in the case of tunnelling even though there is a barrier ok despite the presence of a barrier, you have electrons sitting here. They do not have enough energy to you know you know walk over the barrier, but they can definitely tunnel through this barrier ok. So, the electrons actually the wave function the probability of finding the electron on the other side of the barrier is non-zero ok.

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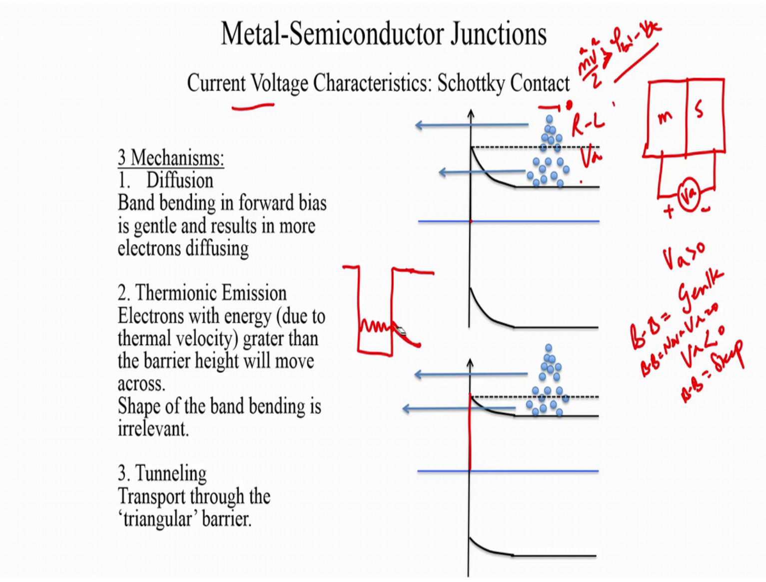

So, we have we are familiar with looking at rectangular barrier. So, when we look at quantum mechanics we you know, when we said the particle in a box, we said the it was really a box. So, we drew diagrams like this the potential energy diagram looked like this with the electron having a you know a sinusoidal wave function here. And there an exponential decay in the wave function outside the box, and that was the barrier we always discussed.

But here, the barrier if you think, about this band diagram the barrier is not the rectangle ok. It is got this little it is got a straight edge on one side and this quadratic appearance on the other side ok. So, these are the three mechanisms that we will discuss the diffusion, the thermionic emission, and the tunnelling ok.

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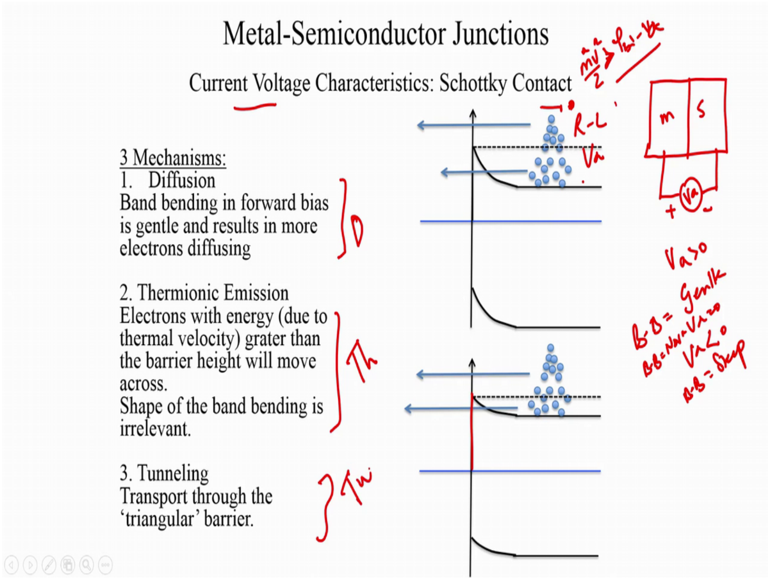

And what we are going to do now is go through a lot of mathematics ok. And calculate out, what the current due to diffusion is, what the current due to thermionic emission is, and what the current due to tunnelling is ok. So, once again please do bear with me, I understand that lecturing on a lot of equations may not be the most interesting thing to do, but, nevertheless it is important that you know how to calculate, and see where all these you know how to put down, this physics and this concept, and you know choke out the equations required for calculating these currents ok.

But, as I mentioned, I know you will not be quizzed on nobody is going to ask you to derive these different aspects in your tests and exams ok, the exam should be purely based on your understanding and concepts.