High Speed Devices and Circuits

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Lecture - 14
Metal Semiconductor contacts (contd.)

We have been discussing the metal semiconductor contacts. We started the whole thing because, it was necessary for MESFET in gallium arsenide FETs. Now, we have spent about couple of hours on this. We continue on this because, few things have to be sorted out which are very important for making rectifying contacts and also ohmic contacts particularly.

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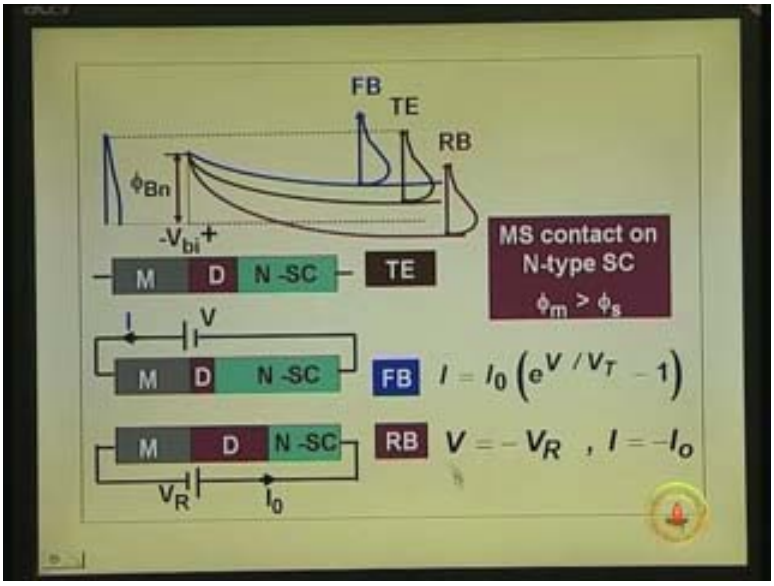

This is the diagram which is redrawn just showing only the conduction band. For example, here you have got three curves which are the conduction band represented for thermal equilibrium. TE refers to thermal equilibrium; RB refers to reverse bias and FB refers to forward bias. So, you can see that on the left-hand side of this which represents the metal have also given the density or distribution of electrons above the Fermi level. On the right-hand side with the reference to the conduction band, how the electron

distribution is there at thermal equilibrium is to be put here. The dotted line on the top tells you that the electrons on both sides are going up to a particular level. There is no net current flow, we have discussed it more than once but just putting in a different way, just showing only the conduction band, because after all now the interaction is, if it is N-type semiconductor the interaction is between the electrons and electrons. If it is P-type semiconductor, we need not look into conduction band at all. We will look into valence band, because interaction is between the holes and holes, plus charges and plus charges or absence of electrons and absence of electrons. That is more correct term because in metal people do not talk of holes as it is but we can talk absence of electrons, levels which are not occupied. So, that is finally what matters. So, here you can see that in thermal equilibrium situation, we have got the electrons transferred. We are talking of a case where, phi_m is greater than phi_S, now just going quickly through that. The electrons have got transferred from the semiconductor to the metal leaving plus charge on this side minus charge on that side. That is the built-in potential, in fact from this end right up to this barrier tip that is the built-in potential.

Now you can see the next diagram in the forward bias condition if you see, the polarity of this voltage is opposing the built-in potential. That means the total potential now, what was here, is reduced because that is lifted up now by an amount equal to the applied voltage. Now, the carriers also have the distribution with respect to that the whole this curve (Refer Slide Time: 04:13) what was brown has become blue now. So, that is having few electrons which have energies greater than energies of the electron in the metal. So, that is the one which gives rise to transport of electrons from the semiconductor to metal which gives rise to current from metal to semiconductor and that is what marked here. Metal to semiconductor there is current flow. Current flow is from metal to semiconductor due to transport of these extra electrons.

Now, when you reverse bias, the entire potential is plus here same polarity as a built-in potential. So, if that were the built-in potential there between this point and that point it has gone up now by an amount V_R. This is extra voltage that we applied additional to the built-in potential. So, the electron distribution of tip is at a much lower energy than that. So, these electrons are not able to climb up the barrier. The current is only due to these

electrons which are there from left to right or from the metal to the semiconductor. I am going through that in a slightly different way, but only looking into conduction band that is the one which gives rise to I_0. The transport of electrons from here to here, which is actually implies the current from semiconductor to the metal, reverse bias current. We also have seen… in fact derive this and show later that the I.V characteristics of this device is given by same equation as that of diode only the I_0 is different compared to pn junction. The mechanism of I_0 is different that we will discuss next in the I.V characteristic in the next couple of lectures. Now, reverse bias V equal to minus V_R that term goes off we will get minus I_0 telling you that polarity is reversed there.

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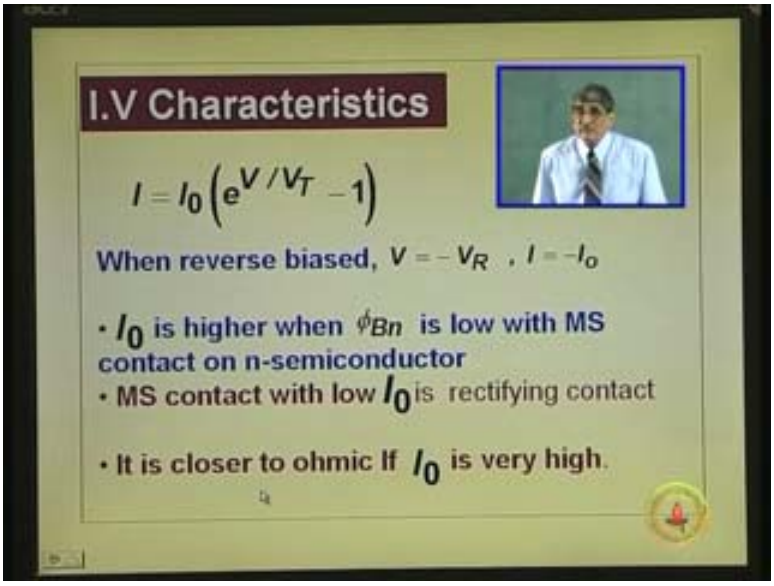

So, this is summing up the whole thing that same equations what you have written, but what we again reiterate is low I_0 will give a good rectifying contact; high I_0 will give a poor rectifying contact or a good ohmic contact or closer to ohmic contact.

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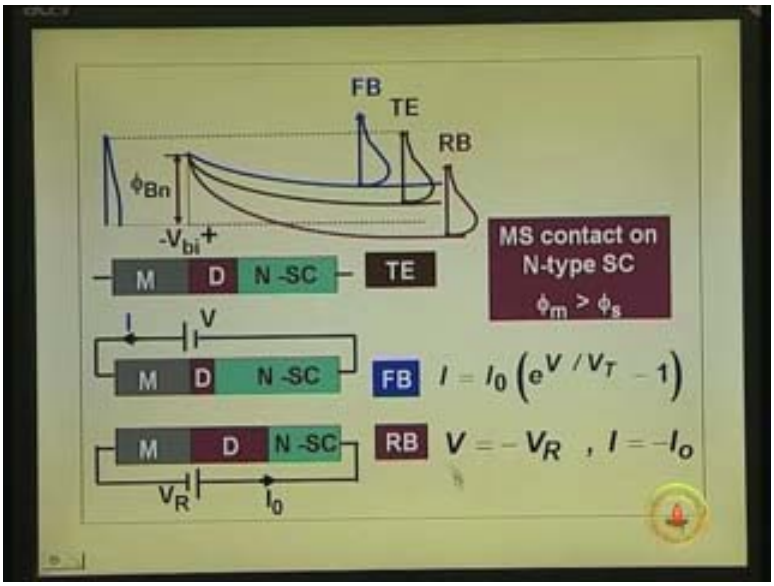

That again as we were telling depends upon this height (Refer Slide Time: 06:42). This height if it is lower more of these charges will be able to cross I_0 will be larger. This height is larger than the electrons which are above that barrier are less. So, less current I_0 is less. For a good rectifying contact phi$_{Bn}$ should be larger.

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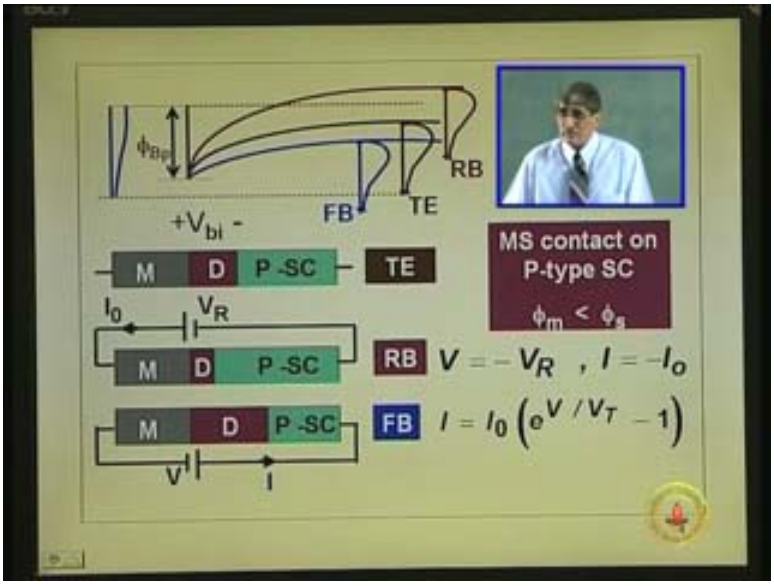

This is the P-type semiconductor which I just started discussing yesterday. Now, we do not put the entire band diagram. What we see whatever is showing for this conduction

band is like that is now shown for the valence band. So, this will be the valence band. Just If I go to the board I will show you the diagram once then you can see it.

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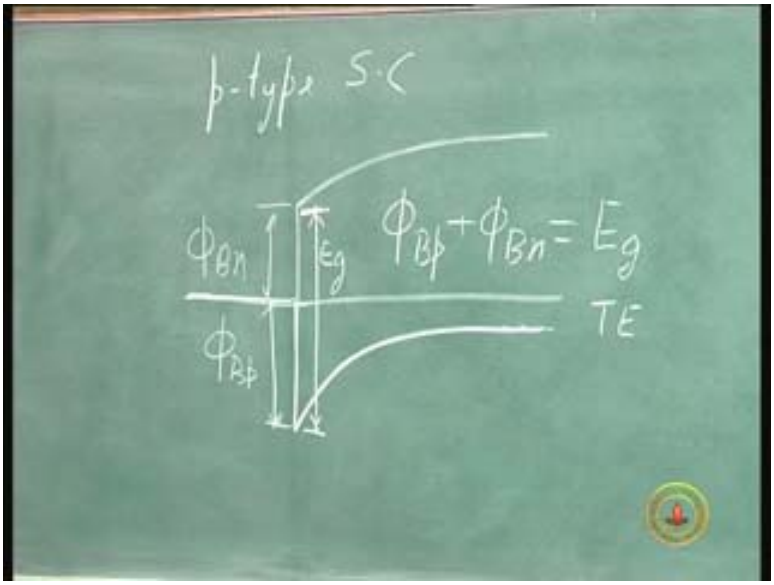

So, P-type semiconductor what we said is we are talking of a situation where phi_m is less than phi_S, that means, electron transfer from the metal to the semiconductor. What happens ultimately is you get a curve like that a P-type semiconductor electrons have got transferred from here to here; this has got negatively charged; field is in that direction, so energy band diagram is like that. This is the thermal equilibrium situation, how much is this bending depends upon the difference between phi_m and phi_S. The phi_m and phi_S difference is the difference between two Fermi levels they equalise that there is a built-in potential coming up which is equal to difference between the Fermi levels. It is same as the pn junction difference between the P-type material N-type Fermi levels that is the built-in potential. Solve what you have to keep track of Fermi level differences so phi_m minus phi_S or phi_S minus phi_m. The diagram what I have drawn there about the bottom here what we are drawing is only this portion (Refer Slide Time: 08:44) that portion. I have stopped here thermal equilibrium situation so that is the diagram which we have shown in this slide. If you look into the slide here, the brown curve is again the thermal equilibrium curve (Refer Slide Time: 09:10) that one. Now, the polarity of this built-in potential is plus here minus here because elect phi_m was less than phi_S the Fermi level in

the metal was at higher level. So, the difference is plus less compared to that so the Fermi level in the metal was at higher level. So, electrons have got transferred from the metal to the semiconductor you have got plus minus voltage there built-in potential. Exactly opposite to that of metal that of metal and layer so reverse. So, this is the V_{bi}. So, V_{bi} is exactly same similar to it. Here this portion is the phi_{Bp}. If you go back here this is the phi_{Bp} (Refer Slide Time: 10: 04) and this is actually phi_{Bn} sum of the two is equal to E_g, band gap. In all the cases the sum of phi_{Bp} plus phi_{Bn} is equal to E_g band gap. So, that is the situation in this particular case what I have shown is the phi_{Bp} here then, this thermal equilibrium by this curve and this distribution is the distribution of poles.

Just like we have holes in the conduction band up to certain level going up have electrons in conduction band above the conduction band that distribution, similar distribution is there for the holes in the valence band. I can talk of absence of electrons similarly, in the case of metal here. Though I do not like to talk of or people do not appreciate if you say holes in metals they are not real holes they are absence of electrons. So, vacancies are there. After all the electrons if they are moved from metal to the above the Fermi level there are vacancies left there and more number of vacancies here. Please notice for the vacancies the lower energy is up higher energy is down.

So, the vacancies tend to occupy the higher energy layer, more of the vacancies are there that shows here because, electrons tend to occupy lower levels. So, the vacancies are left at the top. Here, we can see the distribution of holes is more here less as you go down energy. Now, you can see these charge tips are matched one another here at thermal equilibrium. Now, if I reverse bias, the polarity of reverse bias means actually what do you mean by reverse bias and I increasing the barrier. So, the barrier here is just from this point right up to this point that is the barrier phi_{Bp} minus difference between the valence band and the Fermi level. In the case of phi_{Bn} N-type material the built-in the potential is phi_{Bn} minus E_C minus E_F Here phi_{Bp} minus E_V E_F minus E_V similar thing. So, I do not have to reiterate it. Now, here this polarity of this voltage is to be is the same thing what was like this here. The band bending there will increase. It will push the band energy band diagram valence band upwards. So, that is the reverse bias situation. Whatever built-in potential was there we add up this quantity that is the extra voltage that we are

adding up that extra voltage added up is V_R and we get reverse bias. There is a small problem here I have just shown the depletion layer here this depletion layer actually should be wider in fact I just copied from there. Here you see thermal equilibrium forward bias depletion layer decreases reverse bias increases. So, actually here if the same way, the reverse bias of the depletion layer should increase so this should have been there then, we have to correct it. So, the depletion layer is D is for depletion layer it will wider in the reverse bias case and in the forward bias case the depletion layer will be narrower. So, when the depletion layer is wider the barrier height is more. When you forward bias here the polarity of voltage is opposite to that. That means potentially you are reducing, that means the depletion layer actually here will be smaller. Once the depletion layer here is smaller barrier height will be smaller. So now you can see when you reverse bias the tip of these holes distribution is below that level barrier, none of them can cross the barrier. The current is due to only this holes which are above this crossing from this end to that end. That means current in the only due to the holes which are crossing this end to that end that is I_0. So, whatever left out current from the carrier transport from the metal to semiconductor whether it is holes or electrons has the case may be N-type or P-type that is gives rise I_0. Now, when you forward bias this is pulled down here.

So, you have more of these holes (Refer Slide Time: 15:05) which can cross from here to here compared to this. So, you have the hole current from when you forward bias you have got a hole current from here to here semiconductor to metal equation is same thing. So, in fact I think we should now get into detailed discussion on N-type and I gave a glimpse of the P-type you can actually sit down and work it out in detail. One thing you remember reverse bias depletion layer widens forward bias depletion layer narrows. That part you remember reverse bias barrier height increases on the semiconductor forward bias the barrier height falls. So, the current transport is there in the forward bias case in the N-type semiconductor the current transport is transport of electrons from semiconductor to the metal. In the case of P-type material forward bias barrier is reduced current transport is due to the transport of holes from the P-type to the metal. So, current directions are different current in the case of metals N-type semiconductor in the forward bias case is current is from metal to semiconductor just like pn junction p to n. In a case

of P-type semiconductor current is from p to metal, that makes a pn junction. These are the things to remember equations are same I_0 into e to power of V by V_t minus 1 forward bias case the reverse bias is I_0.

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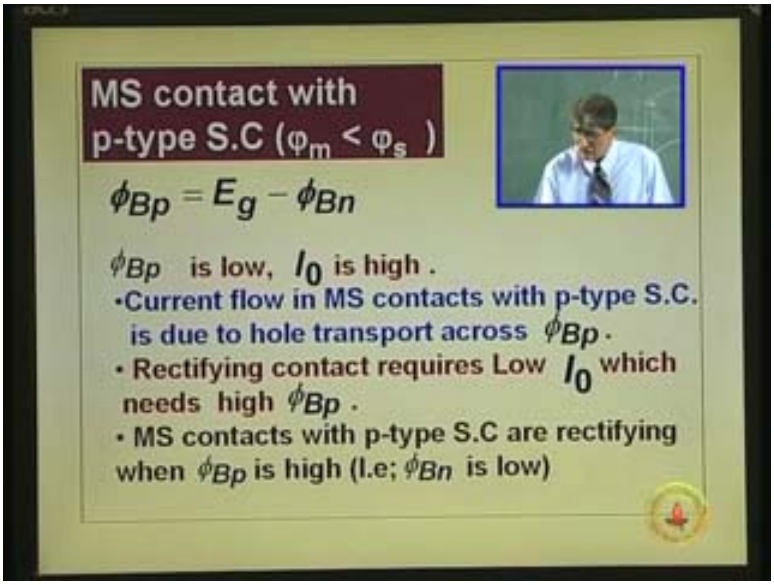

So, with those things what we see is of course this is what I have said already that phi_{Bp} is phi_{Bp} plus phi_{Bn} is E_g and in this case also whether it is rectifying or ohmic also depends upon the barrier height. If phi_{Bp} is small I_0 is large it slows at ohmic contact phi_{Bp} is large closer to rectifying contact.

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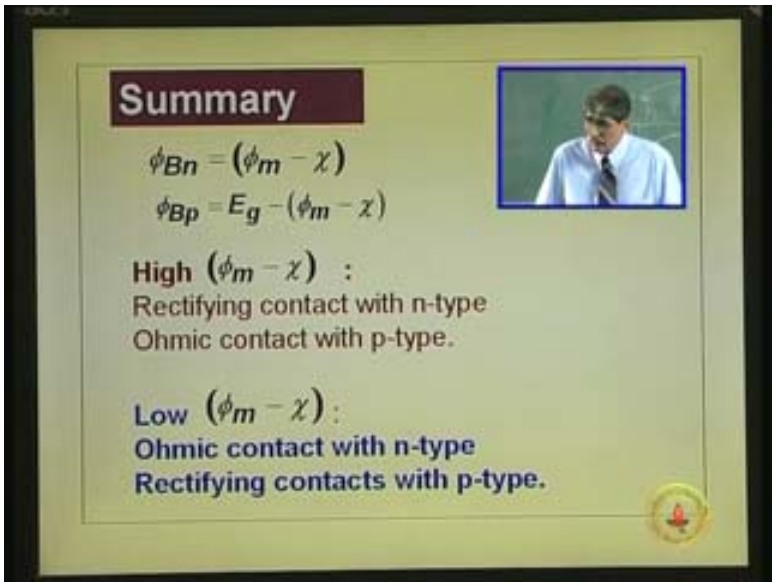

So, in summary about all types of rectifying contacts phi_{Bn} what we have derived is phi_m minus chi that we have said right at the first of our theory, phi_{Bp} is actually equal to… because sum of phi_{Bn} phi_{Bp} must be equal to E_g so phi_{Bp} is E_g minus phi_m minus chi. So, what our thinking is once your phi_m is fixed phi_{Bn} is fixed and phi_{Bp} is fixed. So, that will tell us phi_{Bn} should be large for rectifying contact in the N-type material. That is straight away tells us that means phi_m minus chi should be larger. If phi_m minus chi is high E_g minus that is low that is phi_{Bp} is low that is ohmic. So, if phi_m minus chi is large that is rectifying N-type P-type is ohmic reverse is true in other cases. So, people generally say phi_m is larger than phi_S we get rectifying in N-type and ohmic in P-type and other condition is exactly opposite. Now, the hard reality is all these are idealistic theories. When you make the device there are several other problems that come up.

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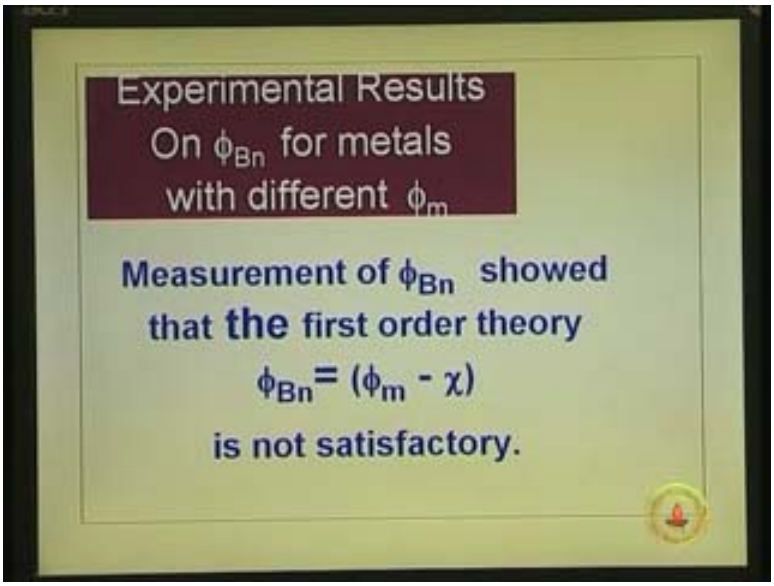

Measurement of phi_{Bn} that is ultimate truth is it phi_m minus chi, if it is phi_m minus chi phi_{Bn} must be dependent on phi_m. That is if I choose different metals I must get different phi_m that will be there. If I choose different metals therefore I must get different phi_{Bn}, it is not satisfactory experiment.

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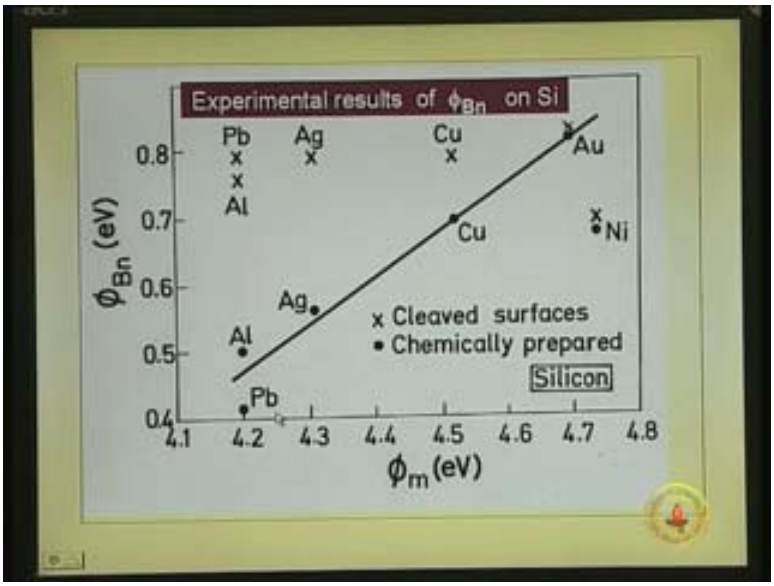

See that curve there; these are the real measured values. I really wonder the amount of time and effort that has been put for this measurements here you see only four points but, the amount of time that must have been spent for this is enormous this report in literature is way back. On the x-axis you have phi_m made for key barriers on N-type substrate silicon. I just coated silicon straight away and then the phi_{Bn} actually in that case what we should have expected is phi_m minus chi. If it is 4.2 the phi_{Bn} that you must have got would have been for silicon, chi is 4.05. So what you should have got would have been 0.15. Now, you see here there are two values for that aluminum one is black one is that, here points at 0.75 electron volts and for same material the black dot says it is 0.5 both of them are away from your theory. So, it shatters your theory totally. Now take this black cross curves. Now before you keep wandering what this cross is cross is made on a surface which is freshly cleaved. You cleave silicon you get all those dangling bonds hungry for grabbing electrons, surface states that if you make a metal semiconductor contact you get a barrier height which is practically independent of phi_m. Where does our theory stand now? phi_m minus chi phi_m we varied from 4.2 right up to 4.8.

The barrier height was about 0.8, 0.8, 0.8 and 0.8. So, this is where we have to work out this is where the difficulty is making ohmic contact and rectifying contact; you have problem because of this. Now that is freshly cleaved surface you prepare a metal semiconductor contact on slightly differently on the same substrate. Instead of cleave ng what you do is chemically prepare it clean the surface chemically HnO_3 Hf clean up to give. Now, the barrier height is lower but getting closer to what you think it is. You think it is phi_m minus chi 0.15 but, still about 0.5 and you also see that there is a variation with phi_m, so what you say is partly true. So, if you take a look at this curve we will feel bit closer to theory. Take a look at this curve you will be heartbroken because totally new theory to work out but, we do not have to work out that from new theory. We have to see what we have neglected. Let us see other curve I hope this portion is clear enough freshly cleaved surface lot of dangling bonds are there. Chemically treated surface there will be some sort of layer will be there which satisfies some of those dangling bonds. when it satisfies it gets closer to the ideal surface. In the theory that we have derived what you said is that good surface metal is in very good contact with semiconductor no surface states, no interface states then, phi_m minus chi. So, you reduce if you have the high

interface state density that is very high. If I have reduced the interface state density then behaves some sort of behavior what we have seen but not exactly the same value.

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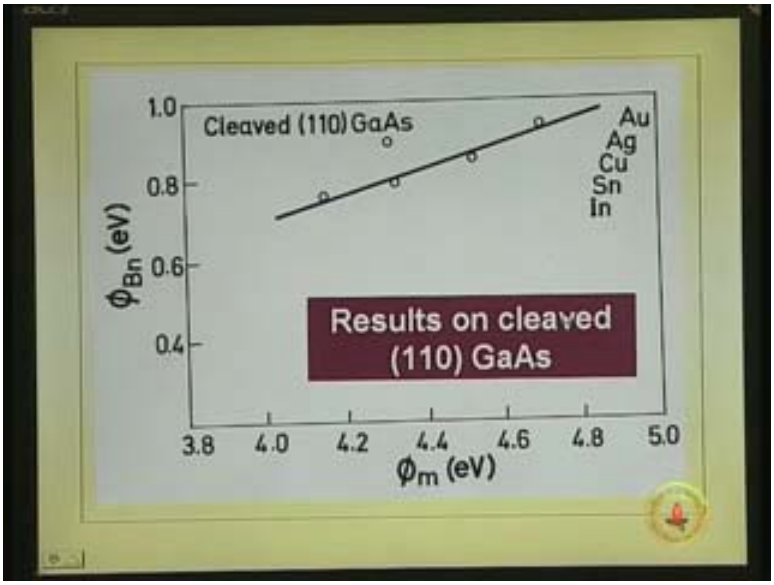

This is on gallium arsenide. I just put that down first for silicon it is remarkably seen their gallium arsenide on (1 1 0) oriented gallium arsenide cleaved surface is not all that flat but it is still again you see phi_m is 4 or some 4.2 or so. We get again about 0.8, something like that and if you take gold see these are the curves: indium, tin, copper, silver and gold. Now, I think one more curve is here copper and silver here gold is that point these things which are put here refer to those points, these are going up like that in this these are going up there that is the indication. Instead of putting on x axis just put like that it is taken from literature straight away. So straight away copy it on to without to resist on a change now what is reported in literature. Here we say this is also too far from the theory there is slight variation you take a look at chemically prepared slightly better variation is there. Same indium, we can fix about 0.6 which was showing earlier close to 0.8 has shown now 0.6.

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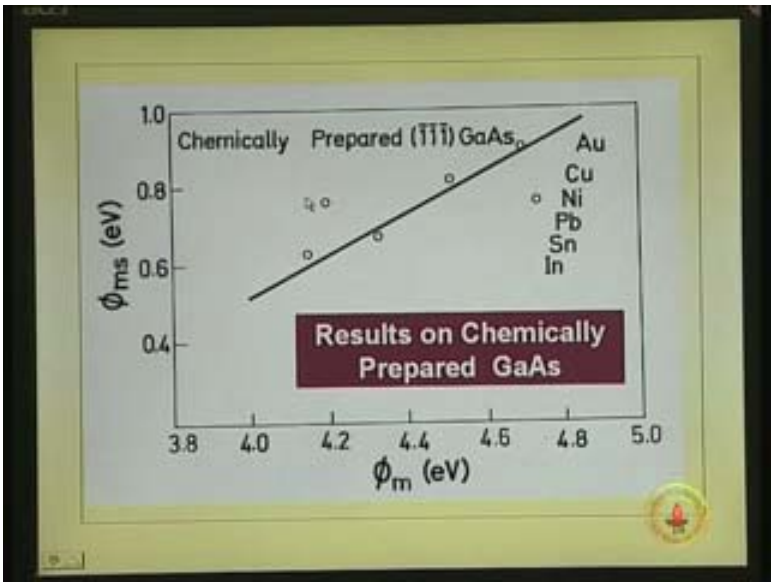

So, there must be some method in all this things there is some law which follows this. In fact if you examine the law what follows is that.

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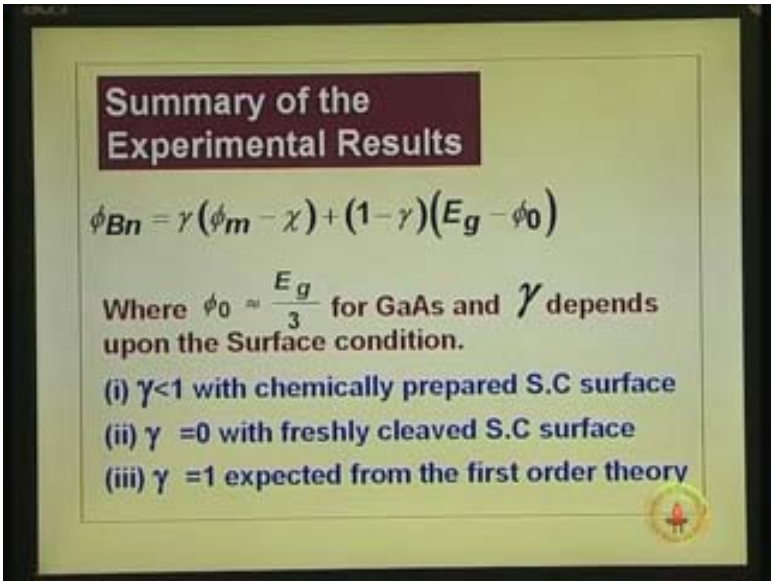

We will see it very shortly how it comes up. If for example we said phi_{Bn} is equal to phi_m minus chi but, it is much more complicated than that. It is an equation well accepted, way back it has been derived but, if you include the effects of the surface states you get this

equation. If gamma is equal to 1 see then phi_{Bn} is equal to gamma what gamma is we will see afterwards. We will derive this equation very simple in four steps if you know the theory. Gamma if it is 1 phi_{Bn} becomes equal to phi_m minus chi that is our theory that first order theory. In fact that would correspond to interface state densities 0 ideal and if gamma is equal to 0 that is freshly cleaved surface gamma is 0. With the ideal surface gamma equal to 1 freshly cleaved surface high density of interface states gamma is equal to 0. So, if gamma equal to 0 that term is gone and this is 1, 1 minus gamma is 1. So, phi_{Bn} becomes equal to E_g minus phi_0 and E_g is fixed for a given semiconductor that number phi_0, we will see soon what it is. That also is fixed. Once you fix a semiconductor the phi_0 which is actually a particular level within a forbidden gap that turns out to be for E_g by 3 for gallium arsenide and silicon. For indium phosphide it is slightly different it makes your life much more miserable for making MESFETs there, we will see that later on. Today, we will focus on gallium arsenide and a silicon where this is the E_g by 3. Now, let us see what is the cause of this; apparently or evidently gamma is related to the interface state density state density D_{it} and some other terms. Gamma is between 0 and 1 it can be only between 0 and 1, ideal 1 and worst 0. So how that comes up we will just see them

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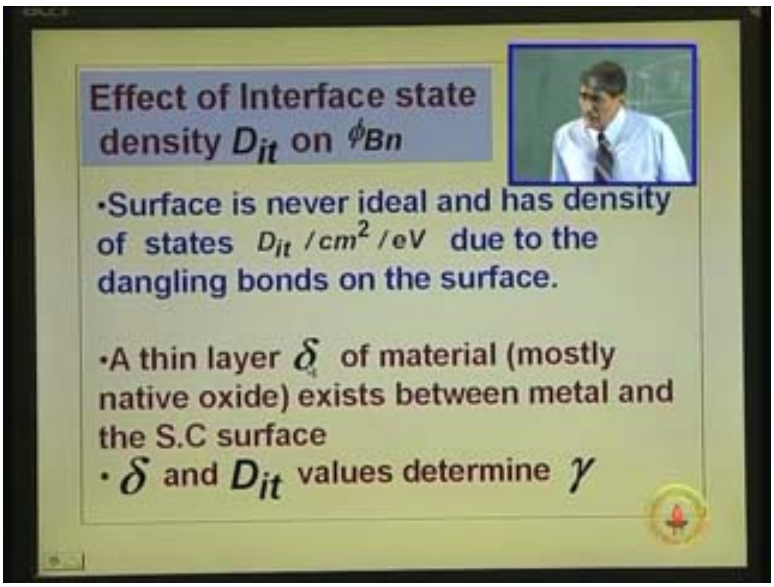

Let us take a look at little bit more of physics of this one. Effect of interface state on the density D_{it} and phi_{Bn} because, you have seen here phi_{Bn} and gamma so, here what we are seeing is the effect of interface state on phi_{Bn} through gamma, so gamma is related to phi_{Bn}. So, what we said here now I have summed up whatever is to be said the surface is never ideal and has density of states which is called D_{it} and is the accepted symbol for interface state. Whether you talk of MESFET MOSFET or Schottky D_{it} and that tells you how many number of states are there per unit area of surface within energy gap of 1 electron volt. So, if there are 10 to the power of 12 D_{it} per centimeter square per electron volt. If I take an energy gap of 0.1 10 to the power of 12 per centimeter square per electron volt. If it is 0.1 electron volts there is one tenth of that.

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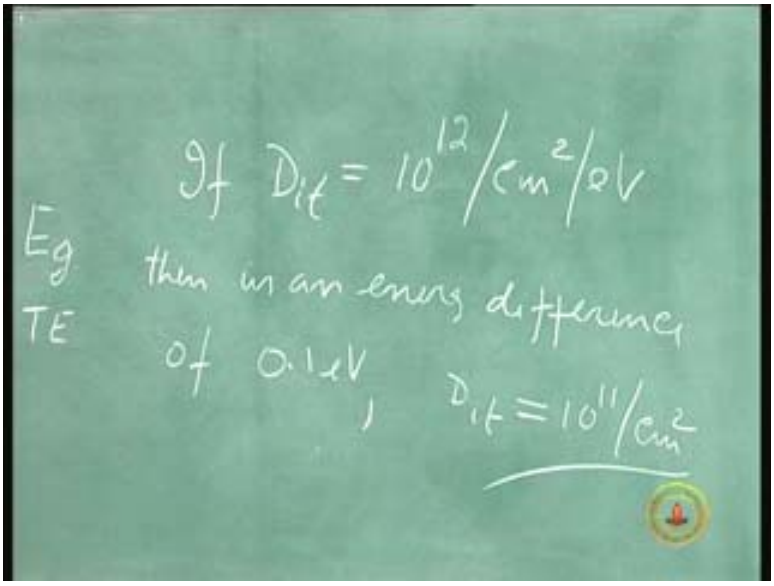

If I say D_{it} equals 10 to the power of 12, this is the number I am tossing out per centimeter square per electron volt. Then in an energy difference of 0.1 electron volt, you will have D_{it} equal to total D_{it} will be this is per centimeter square per electron volt into 0.1 will be equal to 10 to power 11 per centimeter square. If it is not charged you do not have to worry, if it is charged negatively there will be 10 to power of minus 11 into 1.6 into 10 to power minus19q. If it is charged positively it is plus charge multiplied by q, q into D_{it} is a charge and it can take one state can take one charge only. So, due to dangling bonds on the surface this interface state density is due to the dangling bonds on surface.

That is one deviation from the ideality other deviation is however much you struggle there will always be thin layer. A very thin layer 5 Armstrong 10 Armstrong, it could be a gap that is present when you put the metal it could be a dielectric material which has resulted in due to the native oxide that is present. So, whatever you do there will be thin layer unless you force in and try to remove quickly put the metal. In vacuum itself you remove the oxide, put the metal then there is chance that delta is 0. Otherwise you always would have a thin layer delta of material mostly native oxide exist between metal and the semiconductor surface S is standing for semiconductor, I used the short form here SC. Delta and the delta thickness of that layer and that D_{it} that we are talking of interface state density values determine the value of gamma. So, if delta is 0, gamma effect is not there. We get phi_m 0 or D_{it} is 0 ideal conditions you get phi_m minus phi_S. Let us go into some of those.

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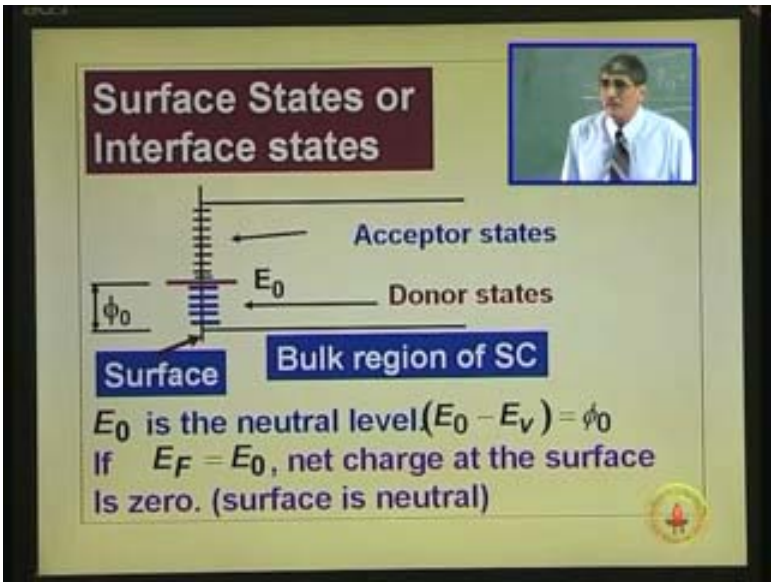

This is the diagram which you must see and understand. Once you understand this everything will seem clear. The energy band diagram is that in fact you can see that difference between phi_S and the color that I put here to distinguish between that, therefore phi is in that dangling bond. Dangling bond is dangling bond. So what I put here is there is one line here called E_0 if this is the conduction band I just forgot to put there. There is a conduction band but it is understood that when you put the energy band

diagram conduction band valence band. So, what we have drawn is this portion this right is bulk region of the semiconductor and this on this line that I drawn is a surface of semiconductor. Here, you have taken the semiconductor layer surface then going to the bulk. So, on the surface also we are putting how will be the energy steps levels will be if you take the bulk, if there are no dopants, no imperfection we do not see any levels. So, you will see only conduction band and valence band. I will deliberately suppress all other levels you may have dopants N-type then there will be a level which goes here. We will discuss that when we discuss the metal semiconductor contact. So, these each one of them represents the distribution. So, the surface states are represented by continuous distribution of energy levels it is not separate, it is like energy levels in a conduction band virtually. So, you have got one after another going. What is the reason is in fathat we can just spend couple of minutes on that why you call a dangling bond as a level which is distributed level and which are distributed all over the band. One Why you call there is a level here all the levels above that you call them as acceptor states? Some dangling bond behaves like an acceptor state same dangling bond behaves like a donor state it is not a same it belongs to a different atom each. There are so many atoms 10 power 15 atoms per centimeter square some of them behave like the acceptors some of them behave like donors.

So, these levels below this are behaving like donors, we will see soon the reason for it. But the moment you say the levels above this E_0 are acceptors and the levels below that are donors. Notice I put here that this level between E_0 and E_V is called phi_0. In the equation that you wrote, go back to that there is a phi_0 there that phi_0 is this one this is phi_0, phi_0 is the difference in energy between the level E_0 we will see what E_0 is and the valence band edge. What is E_0? It is a level which separates acceptors and donor levels. More precisely suppose the Fermi level is matching with that E_0 if the Fermi level is coinciding with the E_0 what will be the charge state of this donors what will be the charge state of acceptors? Please understand all the levels below the Fermi level are occupied. Let me remove this now.

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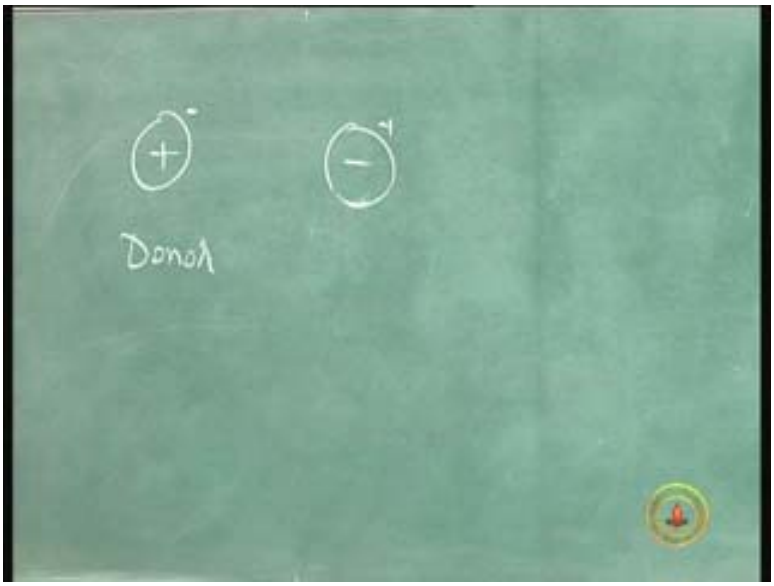

What I am trying to point out is if there is a donor level if the electron is occupying that, it is neutral. If the donor level is below the Fermi level that level is occupied there. If it is occupied it is neutral An acceptor level is the donor. Acceptor level can be represented like that if the hole is removed from their plus charge is removed, it is ionized minus charge. Here if electrons are removed it is ionized, it is plus charge. But otherwise if the Fermi level is below this whatever level is there it will be occupied. Now, let us see what happens is if you take the donor level you have to wave very carefully if the Fermi level is aligned with respect to that then, the levels below that are occupied they are neutral. The acceptor levels are above that the acceptor levels are not occupied. It is just the reverse if the donor level electron is occupying, it is neutral. If the acceptor level if the electron is not occupying it is the neutral. If it is not occupying the level is not occupied, it is neutral. If the level is occupying here, it is neutral. So, if the Fermi level what we said here now a very simple to understand electron occupying not occupying. So, if it is occupying below this donor level the neutral the acceptor level is not occupied by electrons it is neutral. In the sense this is neutral. If I remove that (Refer Slide Time: 37:00) it is occupying negative. So, if it is occupying it is negative, if it is not occupying it is neutral that is the understanding. So, it is simpler to visualize with a donors because that is a physical thing.

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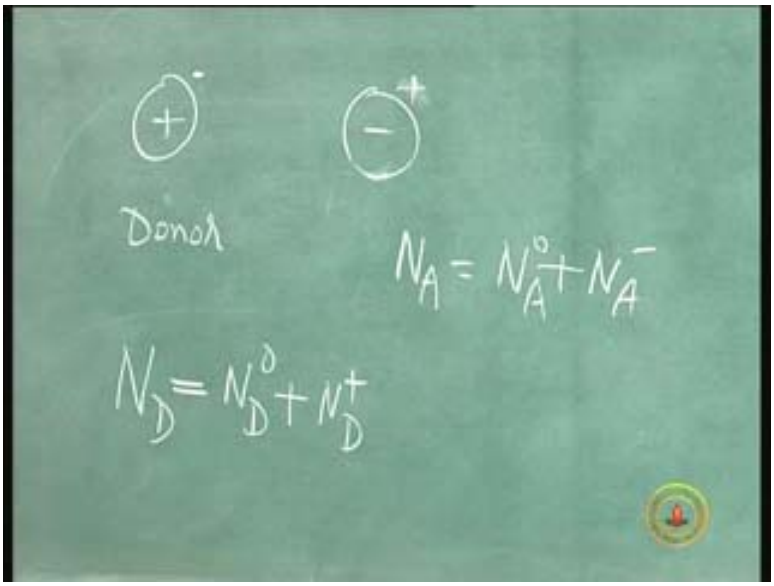

Electron not occupying it is positively charged electron occupying it is neutral. So, you have the donor states that can exist as neutral and N_D plus this is 0 charge occupied not occupied, occupied, not occupied that is removed. And Acceptor states can be written as neutral and if it is occupied minus that is the understanding. When you say it is ionized, what has happened at acceptor level electron has gone from valence band and occupied that position that is the meaning of it. Where in the hole is pushed down to valence band that is why you get N_A 0 and N_A minus. Not occupied is plus charge occupied is neutral this is un occupied neutral like that you remove from there to there means what electron you have brought in there; you bring in one electron that becomes negatively charged. That is why when you occupy it, it becomes negatively charged unoccupied is neutral. With that understanding, we have to spend more time thinking about it but simple thing to remember is levels below the Fermi level are occupied and if donor level is below the Fermi level is occupied and when it is occupied it is neutral. Acceptor level above the Fermi level is not occupied and when it is not occupied it is neutral that is simple thing. So, this E_0 is called the neutral level that means if the Fermi level is occupying into that parallel to that level. If the Fermi level is occupying the neutral level, what is the total charge at this surface?

I have interfaced state density uniform everywhere D_{it} per centimeter square per electron volt. What is the charge? If the Fermi level is parallel I am not saying it is occupying if it is like this, what will be the charge? There is nothing much to think. Suppose in a Fermi level is occupying with the neutral level that is E_0 if I draw a line there that is the Fermi level if I say that means the very name tells you neutral level. If the Fermi level is occupying to the neutral level charge in the surface is neutral 0 why because all these states below this neutral level are occupied which are donors, total charge there is 0 when it is occupied. And All these states above that are acceptors they are not occupied with the electrons that is neutral. So, when the Fermi level is aligning with respect to aligning with the E_0, charge in the entire surface is 0. You may have 10 to power of 15 charges per centimeter square but charging will become equal to 0. So, the final thing with Fermi level the role it should play will be occupying such a position that the charge becomes minimum that is the whole trick. So, if E_F is equal to E_0 net charge at the surface is 0, surface is neutral. So, with that background about the surface states or interface states both are same. We will move on to analyzing a Schottky barrier.

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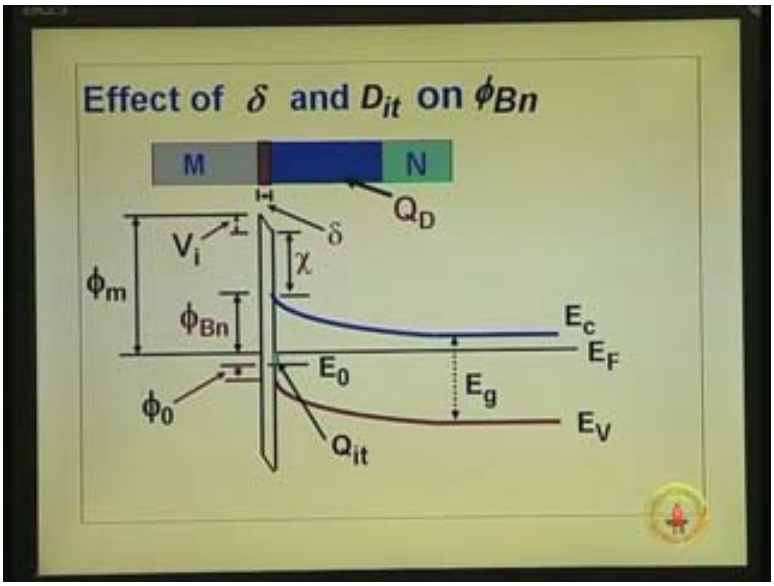

This is the new diagram, fresh appearance for this metal semiconductor contact. We saw the situation right in the first lecture on ms, metal semiconductor contacts, as we keep on reducing the thickness of delta, ultimately we saw this or this. So, we have put back the

delta there metal that thin delta layer of insulator which is always present. You cannot make it 0 this is the depletion layer Q_D charge in the depletion layer plus and this is the neutral region. This is the conduction band after all if this layer were not present also you would have got that transfer of electrons because phi_m is larger than phi_S we are talking of electrons have transferred from here to here. So, you have got a depletion layer here. We have got the deletion layer here and you get this entire band bending. Now what difference is in the absence of this delta and in the absence of interface states, you have to deal with only two charges charge in the semiconductor depletion layer charge Q_D which is actually equal to charge in depletion layer doping concentration into depletion layer width into cube. That is the charge that is present there but in this situation just notice what has happened. I have drawn the diagram after all this band bending suppose the neutral level is here I just drawn that a hypothetically E_0 I put there phi_0 at this point. There is a gap and I have put just slight shading there in this portion. Now, let us take a look at it, identify all the things there is plus charge here minus charge here and that is why the conduction band or the vacuum level. If I call it as vaccum level if I do not take delta as vaccum itself then also I can put that diagram I cap delta. So,that field is in that direction from right to left, so the conduction band will be sloping up like that. Whenever plus is up energy band diagram will take tip down so that is there constant electric field so slope is linear for that. So, that is the 0 level so from here to here you have got phi_m I am going bit slow because you are to identify each one of those terms there. When the band bending is there; if this layer is very thin, there can be tunneling. So, the actual barrier height is actually this one (Refer Slide Time: 44:22) this point that is the phi_{Bn}. If delta becomes equal to 0 then the whole thing merges so that is the phi_{Bn}. If delta is small the electrons do not care they can tunnel through that, 10 Armstrong hardly it matters. So, it is of that order that we are talking of it can turn so that is phi_{Bn}. Now you see because of this field across this oxide there is a voltage drop and that voltage drop is given by V_I V interfacial drop. This is the vacuum level will change exactly the same way asyour potential changes. I have not shown the vacuum level beyond this point so it comes down like this. Between this point and this point the difference is chi that is between the vacuum level and the conduction band edge.

So, what we have to see is the value of phi_{Bn} in the absence the voltage drop in that layer what was phi_{Bn} it was phi_m minus chi. Now the difference between the old theory and now present theory is that, phi_{Bn} is actually equal to phi_{Bn} minus chi minus the extra drop that is present. So we can see that there that drop V_I. So, (Refer Slide Time: 46:05) phi_m minus V_I minus chi leads to this phi_{Bn}. So, if you want phi_{Bn} that is all, what you want to find out is the drop. Subtract it from chi it may be plus or minus I have with the way I have drawn I have put it like that. Now, how to find out this V_I you find outwhat is the charge within this side Q is equal to C into V, simple law of high school. Charge is equal to capacitance into voltage, so voltage difference is charge at one plate divided by capacitance between the two plates. So I can find out this drop V_I as charge that is present at this side of this oxide or dielectric divided by capacitance of that layer. What is the charge? Initially if there is no interface state density charge is only due to Q_D depletion layer. There will be charge corresponding to the interface state. Let us see here that this derivation straight forward and simple. I put the E_0 here is what we derived that holds good for wherever that E_0 is. So, this is for convenience I put it here somewhere. Actually we have seen that is about that the difference phi_0 is E_g by 3 for gallium arsenide. So, if it is here and if the Fermi level is occupying, this position now as it is strong. What is the charge in the interfaced state density?

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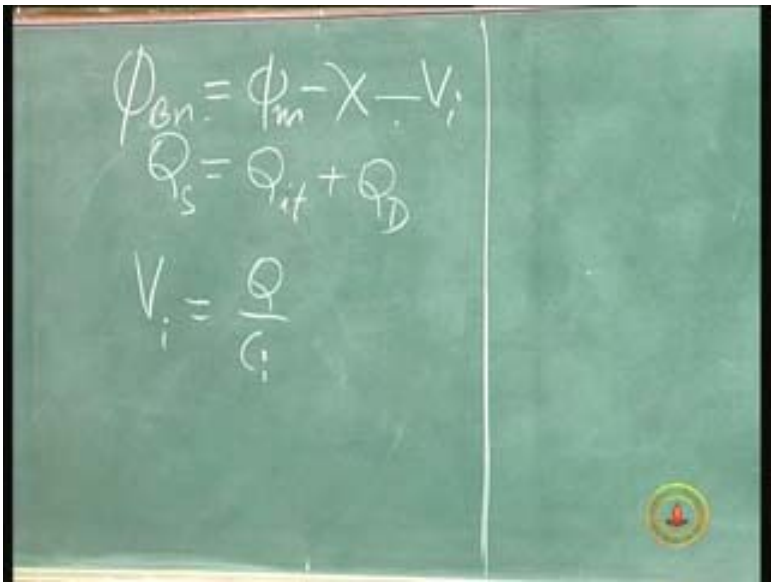

So, Q is equal to Q_{it} plus Q_D that is the Q silicon in the silicon that is the Q. So V_I is Q divided by C_i that is all. If I find that I am in business phi_{Bn} is equal to phi_m minus chi is the original value. I have addition drop here. So, I have to determine this V_I that is all what I have to do. So, now what is Q_{it} it is related to D_{it} what we have assumed is D_{it} is there uniformly from across the band gap with the density D_{it} per centimeter square per electron volt. Now, how much is the chargethe depends upon whether it is acceptor or donor. The way we have put it here this is a neutral level Fermi level is above that please remember this holds good if it is up or down. Now, if it is here what is the charge here charge is D_{it} is the density per centimeter square per electron volt, multiplied by the energy difference the levels below the Fermi level are occupied. The levels above the Fermi level are not occupied E_0 above E_0 all are acceptor below E_0 all are donors Fermi level is at E_0. What will you say about the charges below E_0? I repeat below E_0 all are donors and Fermi level is above E_0 that means all the donor levels are below the Fermi levels means all the donor levels are occupied that means the charge in donor level is 0.

Above E_0 all the levels are acceptors and from here up to that point. Part of them between E_F and E_0 are those acceptors at with the D_{it} number present in per electron volt. They are acceptors which are occupied and when they are occupied they are negative when they are not occupied they are neutral. The acceptor levels are occupied with electron that is the hole has been evolved into the valence band. Let me show that to you how much is the charge .

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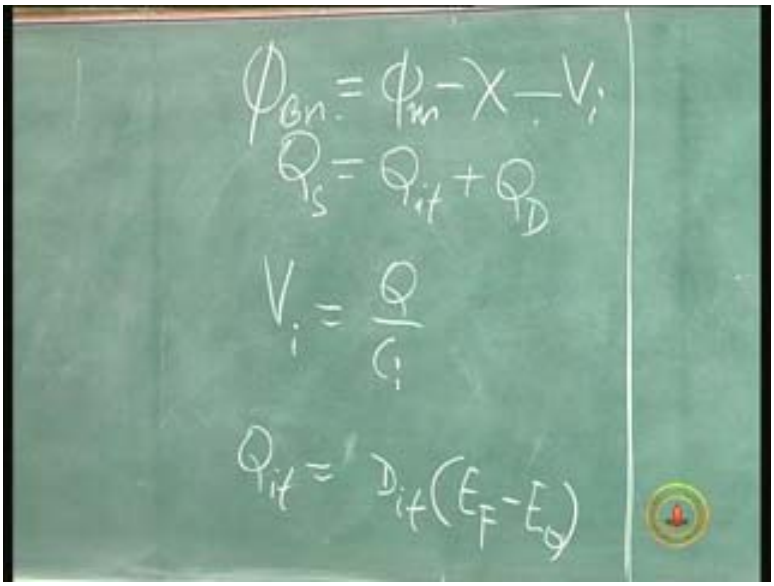

D_{it} is per centimeter square per electron volt you have to multiply it by differences between E_F and E_0. If I multiply see the difference between these two levels is E_F minus E_0 that multiplied by D_{it} gives me total number of dangling bonds total number of states multiplied by q.

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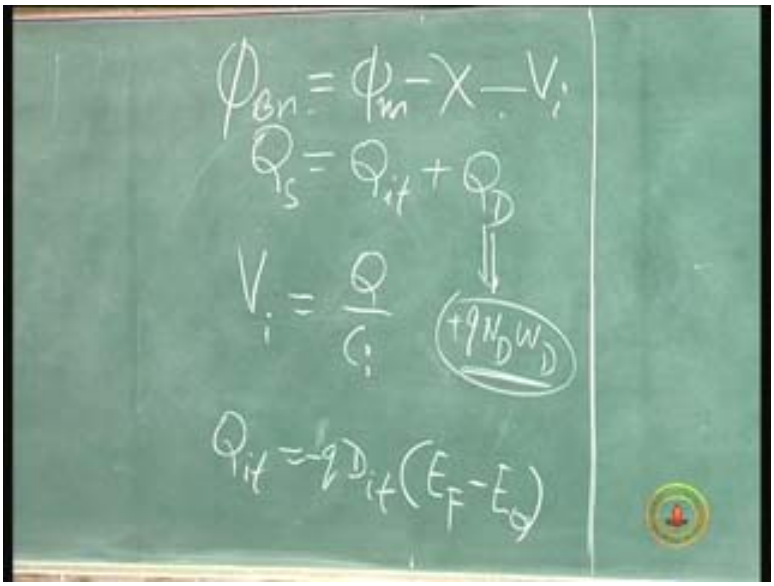

Is it plus q or minus q? It is minus q because these are acceptors. So, this is that, that is it. Now you are in business, so all that you do is use this equation use this Q_D which you know once you know the depletion layer width. Q_D is actually equal to how much q that is plus N_D into W_D where, W_D is the depletion layer width and Q_{it} is how to find out.

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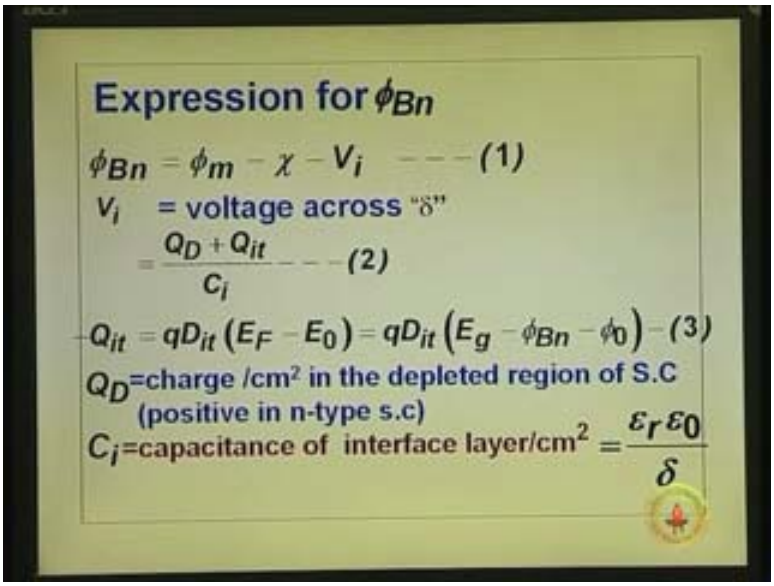

Let us go back to this equation and see, so with those things all that you do is just a bit of mathematical (52:09). We evaluated that V_I so that is what I have written here phi_{Bn} is that, I can quickly go through V_I is Q_D plus Q_{it} by C_i total charge and Q_{it} I put as minus q because I do not have place that Q_{it} on other side. So, Q_{it} is minus q D_{it} E_F minus E_0. That term within the bracket E_F minus E_0 I can put it as E_g minus q phi_{Bn} minus phi_0 is that, this particular term is E_F minus E_0 we can go back and see what you are writing is this that is we are rewriting E_F minus E_0 as total E_g minus this phi_0 minus phi_{Bn}. This portion is I think it is clear enough there. This portion is E_g minus phi_{Bn} minus phi_0 subtract this phi_{Bn} and phi_0 from E_g you get that point that is what is there, so this is second equation. Q_D is of course charge per centimeter square in the depletion layer which you have put down there. Now, C_i is the capacitance of interface layer $epsilon_r$ into $epsilon_0$ divide by delta where, delta is the thickness per unit area, all these are per unit area. So, this is the capacitance, now we have got one, two and three all that you do

is put those things together that is you substitute for this V_I. So, you will have here phi_m minus chi minus Q_D by C_i minus this quantity by C_i that is what is put there.

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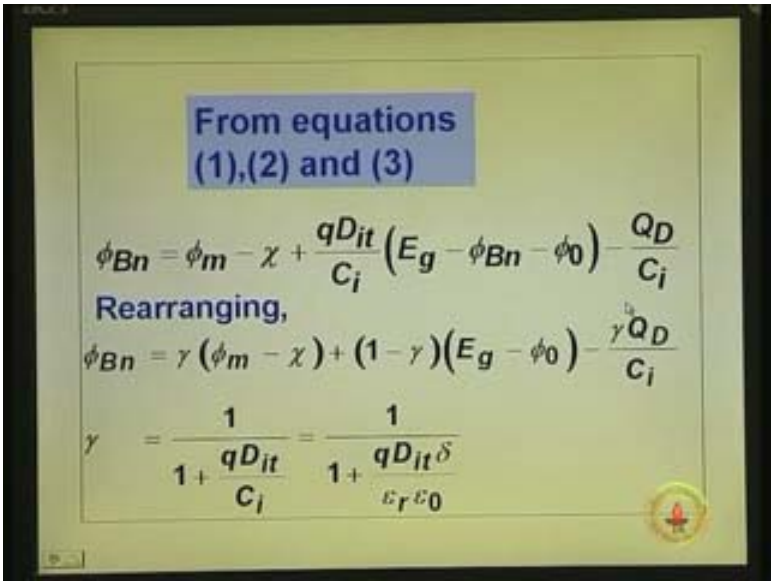

phi_m minus chi plus q D_{it} therefore minus minus cancels plus q D_{it} E_g minus phi_{Bn} minus phi_0 minus Q_D by C_i simple mathematics just we have rearranged this. You can just sit down and see we have got phi_{Bn} here phi_{Bn} here you get this equation that is what is you are looking for. We have got phi_m minus chi into gamma where gamma is this quantity. The concept is simple phi_m minus chi minus V_I, V_I we have estimated and put it here when you rearrange everything you get this equation. You have got extra term gamma into Q_D by C_i now gamma is this quantity q D_{it} into C_i and we have substitute for C_i you get this. Now, you can see D_{it} 0 what is gamma if D_{it} is 0 you can just go through the derivation yourself now because, it is all straight forward concept is that V_I determination adding to that. So, D_{it} is equal to 0, you get gamma equal to 1 and you get phi_m minus chi. If D_{it} equal to infinite gamma equal to 0 and gamma equal to 0 phi_{Bn} becomes equal to E_g minus phi_0. So, infinite D_{it} the phi_{Bn} is independent of phi_m flat that is freshly cleaved surface. In fact, D_{it} equal to 0, gamma becomes equal to 1 ideal case phi_m minus chi that is what I have put down here

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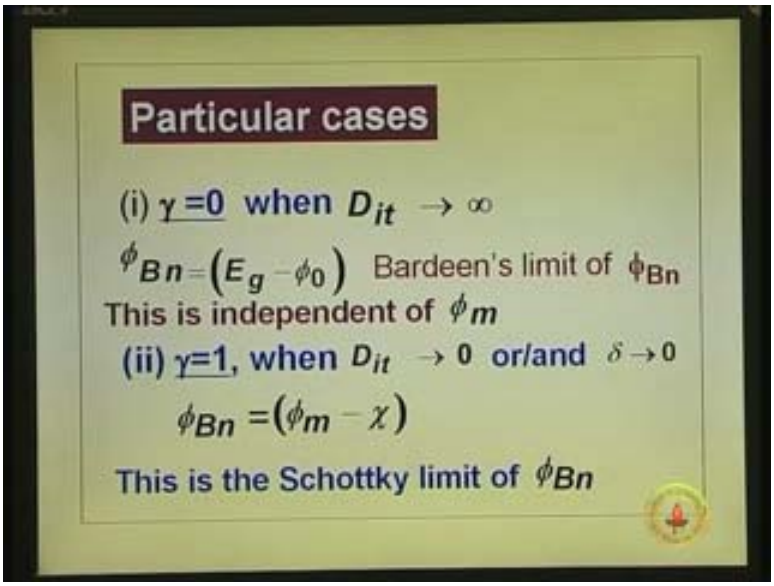

There are two limits: one is D_{it} infinite you get phi_{Bn} is equal to E_g minus phi_0 that is Bardeen's limit that is what Bardeen said whole thing is controlled by surface states. Schottky limit, he said that ideal surface phi_m minus chi is the barrier rate phi_{Bn} that is the Schottky limit. Everywhere I am it is within the two limits now the impact of this we will see, when you go on seeing your life becomes horrible because the phi_{Bn} now what you think it is phi_m you choose large value you get such as value. If D_{it} is large you are stuck with phi_{Bn} equal to E_g minus phi_0. Invariably, you get large density of states invariably you get E_g minus phi_0 as phi_{Bn} you put aluminum, you get phi_{Bn} gallium arsenide equal to two-third of E_g which was quite high. You get gold you get two thirds of E_g high you get rectifying contact where you put gold aluminum everything. You thought aluminum phi_m is very small it makes ohmic. It is not going to make. How to sort it out that sort of thing We will see in next lecture, . , we will see how to do this particular thing and also I.V characteristics. Today, we will close down with this particular thing.