High Speed Devices and Circuits

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Lecture - 34

HEMT – Off Voltage, I – V Characteristics and Transconductance

We have been discussing the high electron mobility transistor. We have just gone through how it operates – the general idea. Today, we will discuss some more aspects of the device, things like off voltage, that is, equivalent of the threshold voltage of the MOSFET. Here, we call it as off voltage, the voltage that is required to turn off the device. In MOSFET, it is actually also considered as off voltage required to turn off in a depletion mode type of device. We will also see the I-V characteristics and transconductance.

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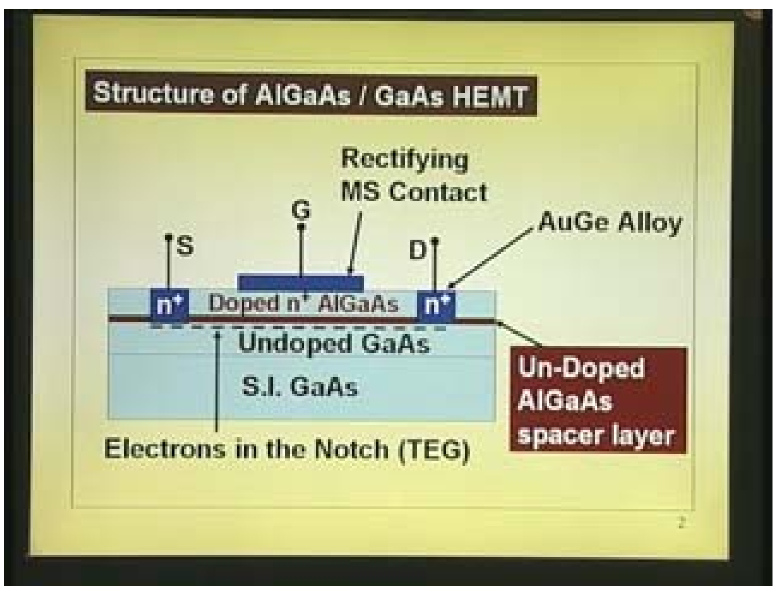

The structure of this device, just to recapitulate, the generic HEMT, the first type of HEMT that was used was aluminum gallium arsenide, heavily doped and undoped gallium arsenide. Semi-insulating gallium arsenide, undoped gallium arsenide, undoped AlGaAs and then, doped aluminum gallium arsenide (heavily doped, n plus). This is the two-dimensional electron gaAs region where electrons are confined into the notch. Also, on the top of this, we have got a metal semiconductor contact, which is a Schottky barrier, which is actually the gate region.

Just like in the case of MESFET, we have got source and the drain, both as in the case of MESFET and MOSFET. we have got the gate. In the case of MESFET, we have got the doped region between the gate and the substrate. In the case of MOSFET, we have an insulating layer between the metal and the substrate – MOS, but in this case, you have a doped layer and that doped layer actually should not be conducting. It should be depleted totally; otherwise, current will flow through this. (Refer Slide Time: 03:14) more like a combination of MESFET as far as the top layer is concerned and a MOSFET as far as the interaction between the gate and the channel is concerned, because between the gate and the channel, in the MOSFET, you have got the oxide. In the case of high electron mobility transistor, you have got a depleted region that acts as the insulator.

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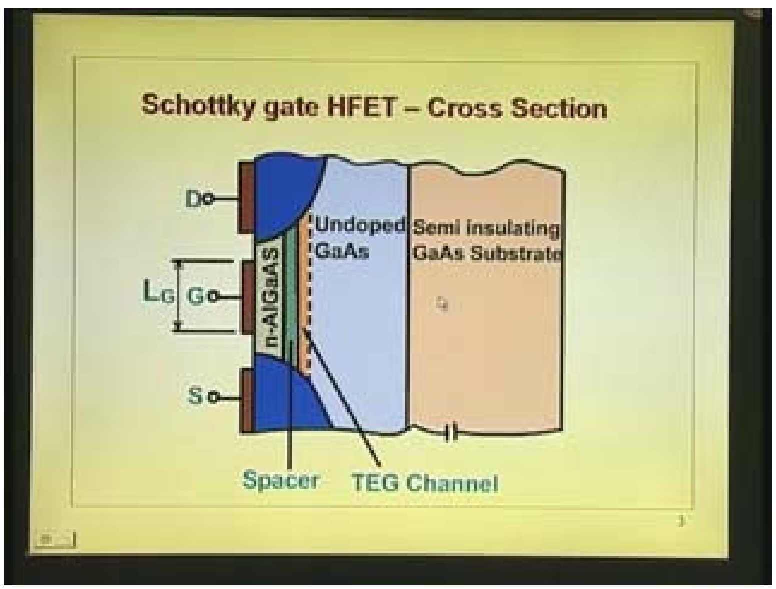

This is actually the same diagram (Refer Slide Time: 03:40) and shown: gate, drain, source, aluminum gallium arsenide, spacer. Spacer is undoped aluminum gallium arsenide; it is also called as set-back layer. Then this is the two-dimensional electron gaAs undoped gallium arsenide, then semi-insulating gallium arsenide. Usually, we show it in this fashion because that is the way we grow it (Refer Slide Time: 04:06). (Refer Slide Time: 04:07) easy for us to draw all the diagrams. We move from the gate towards the drain like this if I take as the axis and plot things in that. This also suits us to draw the equivalent representation of this HEMT, where each device has got its own representation.

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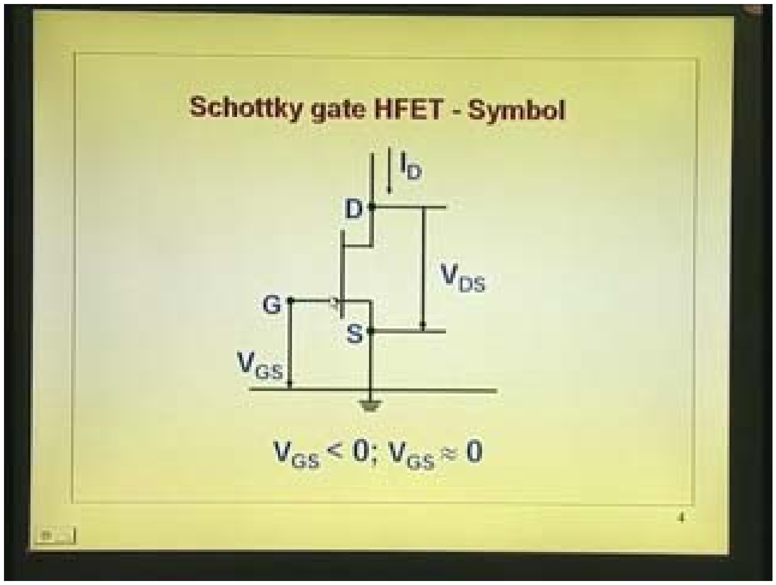

This is the representation symbol. A circuit engineer cannot put in the entire device structure there and so he will put the symbol. You can see it is almost like the case of the MESFET or the JFET, except that this arrow (Refer Slide Time: 04:43) is not at the center, but shifted to the edge, indicating that you have the injection starting at the source end. Just to distinguish from JFET and MESFET, this is there, the arrow. The arrow indicates that the channel is n-type. (Refer Slide Time: 05:06) p–n junction p type and n type, arrow is from p to n, so this arrow indicates this is an n-channel HEMT.

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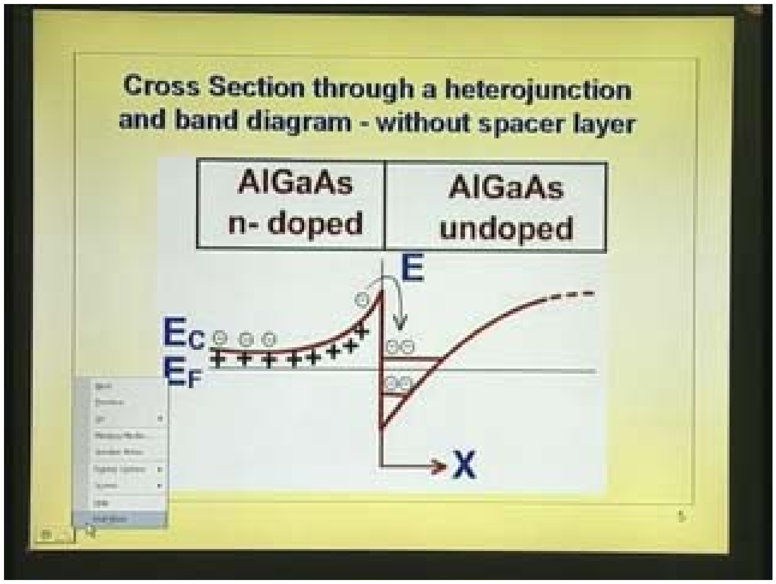

This is actually when we draw the cross section through the heterojunction and band diagram. If the spacer layer is not present, we have aluminum gallium arsenide and then you have actually got… This is actually the undoped. Let me just go back to this. This is actually undoped gallium arsenide. In between, there is undoped aluminum gallium arsenide, but more accurately, we can see this.

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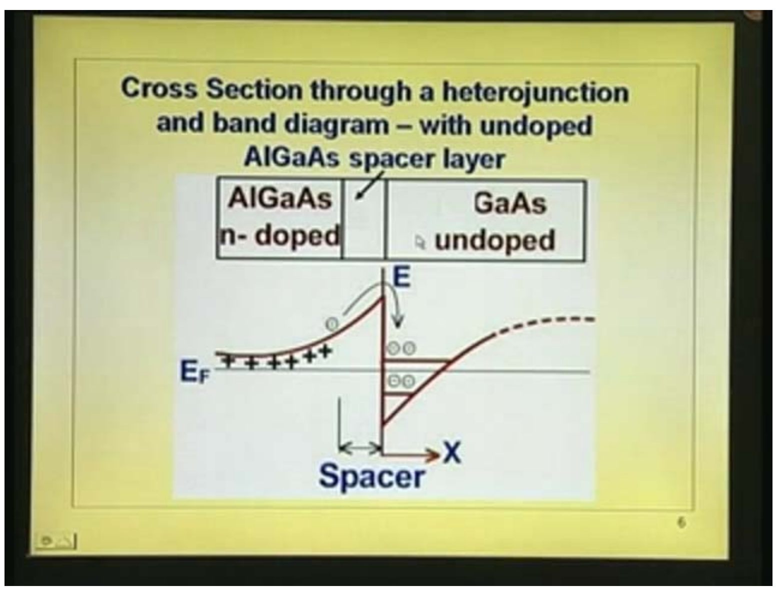

The real structure is this. We have aluminum gallium arsenide doped, undoped aluminum gallium arsenide and then, gallium arsenide undoped. This is the spacer layer. Now, we can see the energy band diagram, flat, a depletion layer coming up. These are the donors and this is the notch. From this edge (Refer Slide Time: 06:16), right up to this edge, there is a depletion layer. This region contains actually the ionized acceptors, because it is a lightly doped p-type, undoped actually, and also the charges at the notch, that will contain the charges.

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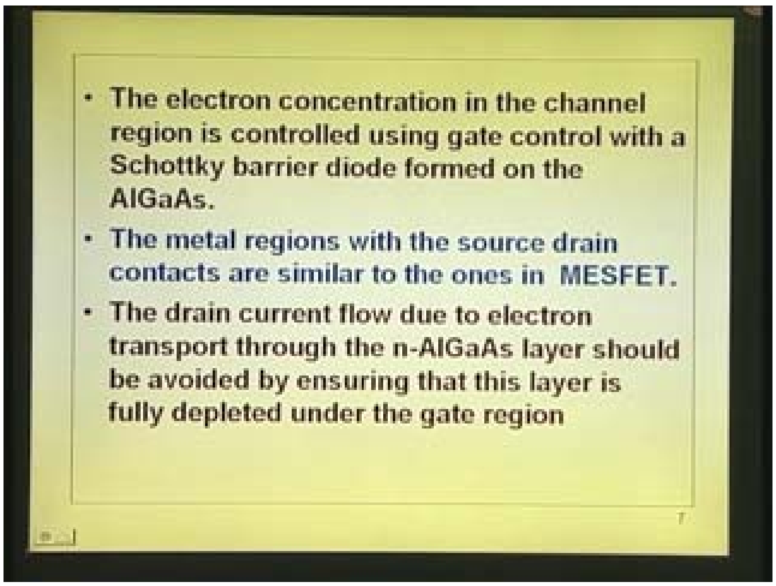

If we see further, whatever we have been telling, we put in words here. The electron concentration in the channel region is controlled using the gate control with the Schottky barrier. For example, if you take it here (Refer Slide Time: 06:54), there are electrons here and there is no gate control. We have n-type material doped, undoped layer that is almost p, so there are charges collected here, there is no control. To control that, we must put a gate here (Refer Slide Time: 07:09). That is what is said here (Refer Slide Time: 07:12): Schottky barrier that is acting as a gate.

The metal regions with the source and drain contacts are similar to ones in MESFET or MOSFET for that matter. The drain current flow due to electron transport through the n aluminum gallium arsenide should be avoided right at the (Refer Slide Time: 07:35). We will just quickly go to that. (Refer Slide Time: 07:40) The current flow from the source to the drain should take place only through electrons in the notch because they are the high mobility electrons. There are electrons in plenty here, but the mobility of these electrons are low because doping is high. What is said in that sentence is the current transfer from the source to the drain should not take place through this layer (Refer Slide Time: 08:14) but should take place only through this layer. That is possible by depleting this particular layer and that can be depleted using this gate. The gate will serve the purpose of depleting this gallium arsenide layer. The gallium arsenide layer will be depleted due to two reasons. One is due to the gate depletion layer and the other is due to charge transfer from the AlGaAs to gallium arsenide. The depletion layer here is the result of two junctions playing on that AlGaAs layer. One is this p–n junction and the other is Schottky the junction. What we say here now (Refer Slide Time: 08:58) is that the drain current flow due to electron transport through the AlGaAs layer should be avoided by ensuring that this layer is fully depleted under the gate region.

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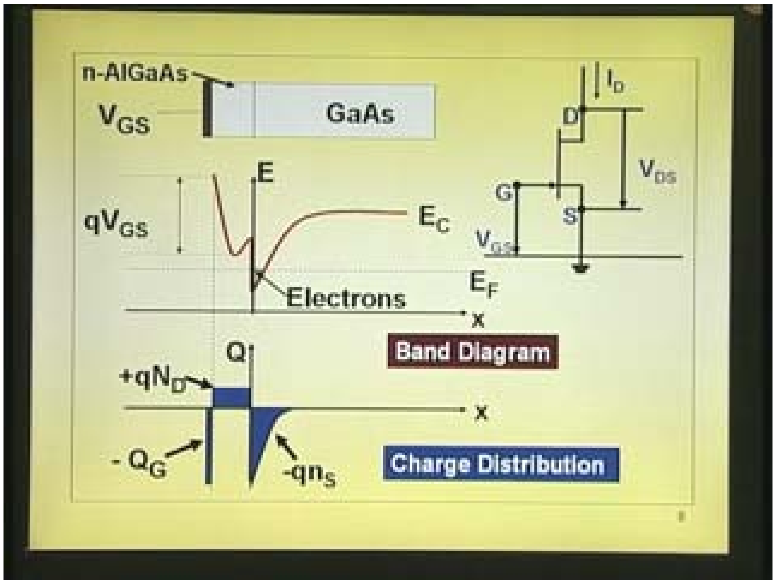

How that is achieved? In fact, what I have shown here is AlGaAs, n type, undoped gallium arsenide; I have not shown the spacer layer, it is understood that it is present there; it is a very thin layer. This is the doped layer and undoped layer. Now, you can see the gallium arsenide layer is fully depleted and V_{GS}… I am not able to show it here because it is just through the gate layer the cross section is drawn; V_{GS} is between the gate and the source.

You can see this portion of the energy band diagram (Refer Slide Time: 09:45). The conduction band here dips down because of depletion and also, there are (Refer Slide Time: 09:53) of electrons, that is, the notch. On this side, you can see that there is a depletion layer. Just notice that the energy band diagram here dips down. It means the field is in that direction, whereas the energy band diagram here has a minimum and that means, the potential is minimum there, which means, the electric field is 0. (Refer Slide Time: 10:16) is 0 and phi is minimum. d phi by dx is actually the electric field, but throughout the region, there is electric field. We say that because the energy band diagram is bending throughout. Now, I will just go to the board and show how that is possible.

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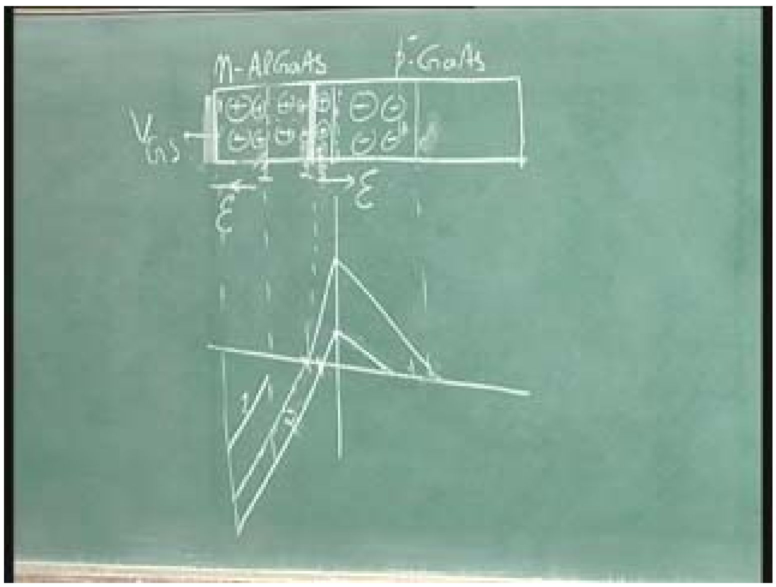


If I take the n–aluminum gallium arsenide, let me just put it on the outside and this is gallium arsenide p minus, very lightly doped. Now, what we say is we have a gate here on to which we apply a voltage with respect to source. The source is connected to the channel, the n plus layer goes all the way up to the two-dimensional electron gas you have seen in all the diagrams. We have got electrons here, we have got the depletion layer here, we have got a depletion layer here (Refer Slide Time: 12:02), which I represented by this plus. I just put 2 plus there, but there are a number of charges present there, because this is very heavily doped. This part (Refer Slide Time: 12:19) of the depletion layer is part of the p–n junction. The electric field is in this direction here. All the field lines originating here terminate on that side.

The Schottky barrier, if I apply a negative voltage to the gate, to the built-in potential itself, there will be a depletion layer. This is the built-in potential, plus here, minus here

(Refer Slide Time: 12:54). There will be an electric field from this side to this side. As I keep on increasing the gate to source voltage, this depletion keeps on moving and at a particular voltage, the entire layer will be depleted. This keeps on moving, so let us just plot the electric field.

The electric field is 0 here and so the electric field is steeply going up like this because it is heavily doped and from there onwards, falling down like this. That is the electric field distribution in a p–n junction and all of us know it. On this side, how will the electric field be? If the depletion layer is only up to this point, the electric field will be in this direction (Refer Slide Time: 14:01): minus, plus. The built-in potential here is plus here, minus here and the electric field has to be in that direction. You will have the electric field direction like this. The slope of this electric field will be parallel to that; the electric field depends upon the doping concentration; it is the same. So we will actually have a line like this, at this point (Refer Slide Time: 14:28).

Suppose the depletion layer moves further. When it will move? I keep on increasing the voltage negatively, more and more. (Refer Slide Time: 14:37). If you do not apply voltage, it is like this. If I increase this V_{GS}, the depletion will keep on moving. At a particular voltage, what will happen will be that both the depletion layers merge, that is, this is 1. Corresponding to this one, this is a curve. This depletion layer merges here and we are drawing it again on this. This will go like this and this is 2 (Refer Slide Time: 15:15).

Line 1 corresponds to the case when the depletion layer is at position 1. Line 2 corresponds to the situation when the depletion layer is at 2. Both the depletion layers have merged now. We can see that at a particular voltage V_{GS}, the total depletion, total AlGaAs layer is depleted, but the charges are present here, because we have not disturbed that part so far. All that was happening was (Refer Slide Time: 15:58) minus charge that we put here, plus charge was coming from here. Now, what will happen if I increase this voltage negatively further?

At this point, we have not disturbed the p–n junction additions, because the interaction was between the aluminum gate and this n plus layer. Hereafter if I increase the voltage, we will encroach into this p–n junction, because when I change the voltage further, it will look forward to the plus charges. Where will the plus charges come from? It can come if this moves further down. Up to this point (Refer Slide Time: 16:56), all these are plus; all these charges belong to the Schottky; these charges beyond this point 2 belong to this p–n junction.

If this Schottky barrier needs more positive charges, the only way it can happen is by the depletion layer of the Schottky barrier encroaching into this region. It moves into this region. That means some of the positive charges from here participate in the Schottky barrier. What happens to the depletion layer here then? (Refer Slide Time: 17:35) This is the point at which the electric field is 0, because from here, it is in this direction and from here, it is towards the right side.

If the depletion layer moves further down, what happens is this point moves there to 0.3; it will move to 0.3. What about this (Refer Slide Time: 18:03)? If this moves to 0.3, the additional charges from here belong to the Schottky. That means the plus charges that belong to the p–n junction have been reduced and it has been taken care of by this. This is the minimum point in the depletion layer. Now from there, it goes up like that; I just over amplified it. It goes up like this and then, what about the electric field here? Like that, parallel.

Physically what happened is… we argued it out by pushing this depletion layer towards that side, so that the depletion layer belonging to the Schottky barrier has widened, the depletion layer on this side belonging to the p–n junction has reduced because of that; if it has been reduced on this side, the charge on the depletion layer of the p–n junction has been reduced – plus charge and that means the minus charge on this side has got reduced, so the depletion layer has (Refer Slide Time: 19:05). The potential variation from here to here was the area under this curve.

The new situation from here to here is the area under this curve. That means the notch that is there from the… or the potential variation from here to here and from here to here has got reduced. What is the meaning of that? The ultimate result is the potential from here to here has been reduced – potential change. When we draw a diagram, we will see it further. Now, we can view it in different way. What we have seen now is this is getting pushed to this side, telling that the minimum point or the 0 potential or 0 electric field point has shifted to the right or the minimum potential point is shifted down to the right.

But what happens actually is that when we put minus charges here (Refer Slide Time: 20:10), if the whole thing is depleted at this point, at this point, the whole thing is depleted (Refer Slide Time: 20:17). If you put a minus charge here extra, that is, if we increase V_{GS}, where will the plus charge come from? From the other end, because it is as if there is an insulating layer; when I put a minus charge, the plus charge should come from here.

How can the plus charge come from here? By uncovering the depletion layer, because this has got plus charges like this. It moves in this direction (Refer Slide Time: 20:47). What does plus charge appearing here mean? The depletion layer width has got reduced by movement of the positive charges towards that side. That is exactly what has happened here. This has moved, the depletion layer width has reduced because the plus charges from here due to the holes has come up here. This is another way of looking at it.

Ultimately, what has happened is the depletion layer on this side has reduced. As a result of that, what does it reflect upon? Let us go back to the diagram and see. I hope the explanations are clear.

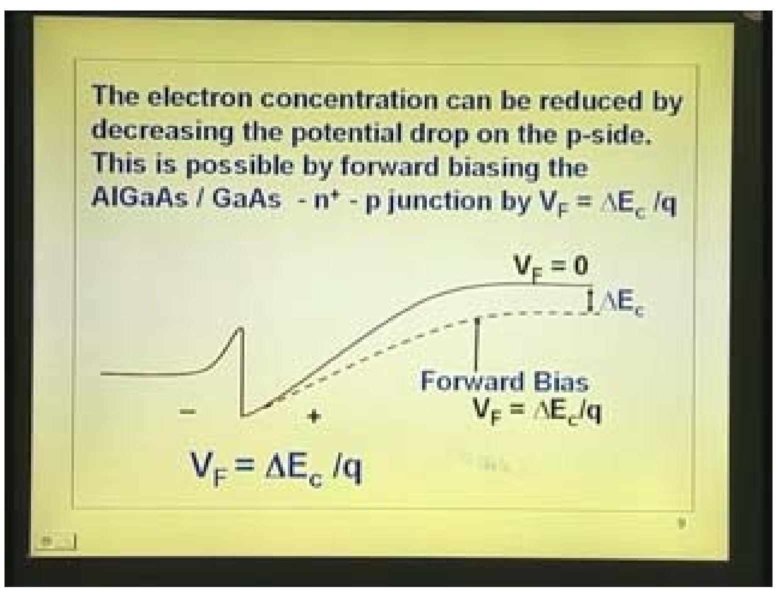
The gate now gains control, the gate gain control over this region (Refer Slide Time: 21:29), because once the entire layer is depleted, it gains control over this and when it gains control over this, the depletion layer collapses. What happens? Let us just draw the diagram. In fact, let me just go back to this and show you. This is the diagram that we have been seeing (Refer Slide Time: 21:54). From the left-hand side, we can see that the conduction band drops down like this. That is because this is the region where the field lines are from the semiconductor to metal – plus here, minus here. This is the region where the electric field is from here to here – plus to minus. Wherever the potential is positive, the conduction band goes down. The potential is just here with respect to this point. That is why the energy band diagram is dipping down; minimum potential is the situation that is shown there – minimum potential corresponding to 0 field (Refer Slide Time: 22:43) and from there to left-hand side, the field is from right to left; from here, it is left to right.

Now, see the charges that are present on this side. Below this (Refer Slide Time: 22:58), we have got all the charges plotted. The entire region is depleted – that is the q N_D plus, the plus charges of the depleted layer and this is the negative charge in the gate.

Corresponding to the negative charge of the gate now, we have got plus charges here and corresponding to some plus charges from here, we have the negative charges here, due to this charge in the notch and also depletion layer charge; all this is negative; part of plus charges interact with this, part of plus charges interact with this negative charge.

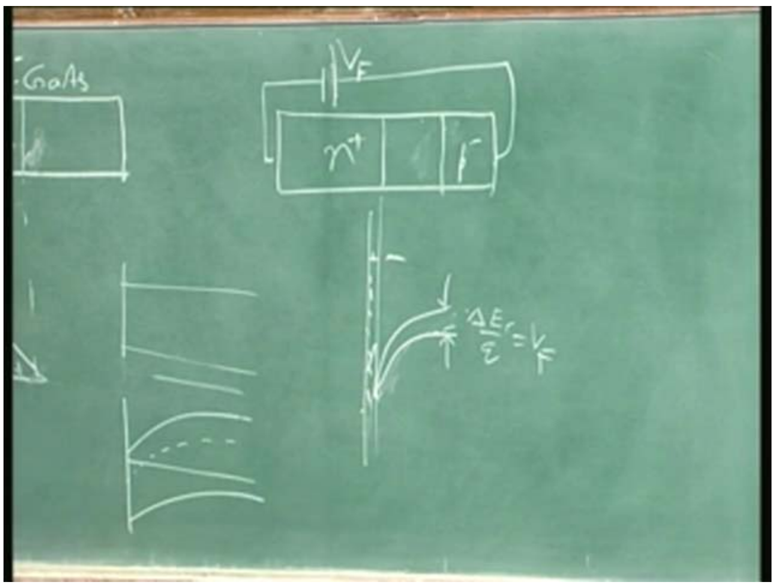
At this point, if I increase the negative charge here, what happens is as we have just now discussed, this potential barrier reduces. If this potential barrier reduces, the surface potential here reduces. What happens to the charge here (Refer Slide Time: 23:52)? It becomes less n–type, less band bending; it is like an inversion layer. If the band bending is more, more electrons will be in the inversion layer; if the band bending is less, less electrons. By increasing this voltage more negatively, we actually have a reduction in the surface potential, reduction in the potential change here, which will reduce these electrons here. The depletion layer also collapses because the potential is reduced. What I am telling now is if I increase the voltage beyond a certain point, you will have control over this negative charge through the gate. Let us go further down.

(Refer Slide Time 24:32)



This diagram makes it further clear. Under thermal equilibrium conditions, I have drawn the energy band diagram for this portion alone (Refer Slide Time: 24:47), p–n junction alone. Under thermal equilibrium condition, there is no depletion layer here in the aluminum gallium arsenide, whereas the depletion layer is present here (Refer Slide Time: 25:02), the depletion layer is present here and there are electrons here. If you recall when we discussed the heterojunction, we said that the band bending here is more than the homojunction by an amount equal to this delta E_c. E_c is equal to that. That is not to scale. Whatever is discontinued in the conduction band is here, that extra potential hill will be there in the heterojunction compared to the homojunction. Now, if I apply a forward bias into this plus minus…. What is the polarity of this potential? Plus here, minus here. If I apply a forward bias equal to delta E_c by q, the total potential will be reduced by that amount.

(Refer Slide Time: 26:05)



It is just like this. If I have a p–n junction with p minus and n plus, the depletion layer is almost here (Refer Slide Time: 26:13). We have got this. It is true even in the case of homojunction. We have the depletion layer here and slightly small width there. Since that is what we have shown there, I am showing only that portion; that is the potential. Here, there is practically nothing. In fact, what we will have will be further down in this homojunction, but in this case, you have got like this – delta E_c. Now when I forward bias this and the polarity here is plus here minus there, built-in potential, which is delta E_c by q was higher in the case of a heterojunction.

If I forward bias, you superimpose on that, the voltage is opposing that and that actually comes down. That comes down in the same fashion that I have shown there and that quantity is actually delta E_c by q. What about here (Refer Slide Time: 27:40)? That will also slightly fall down. It will fall down slightly because the charge is very high there.

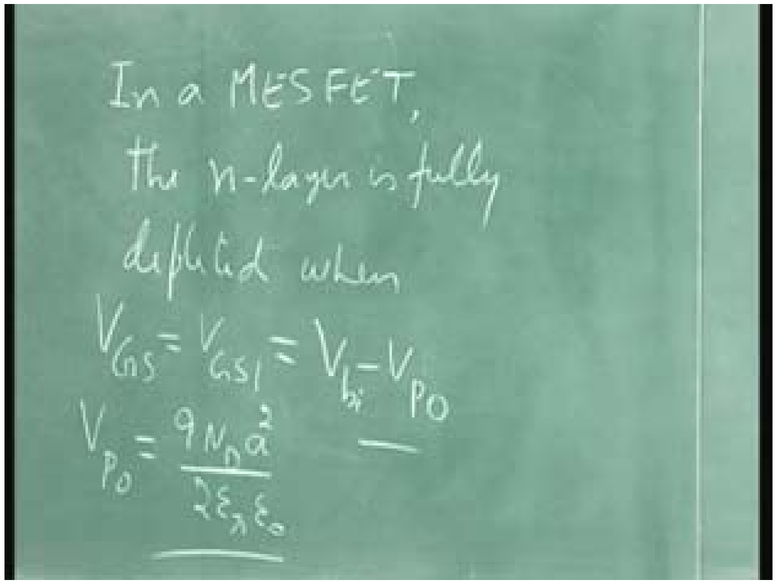
We would not notice the changes in the (Refer Slide Time: 27:52) so much. The entire effect is felt on this in an (Refer Slide Time: 27:57) diode. What we are trying to point out is by applying forward bias like this, I am reducing this potential radiation, potential change. Therefore, the band bending is reduced and therefore, charge here is reduced.

For example, if we take a p-type semiconductor. (Refer Slide Time: 28:26) semiconductor. The Fermi level is there. Under thermal equilibrium conditions, there is no depletion layer, but when the depletion layer comes up, what happens? You have to visualize all that happens. How much it is n–type depends upon how much it is bent. If it bends less, it means less n–type. In this case, actually, it is a similar argument (Refer Slide Time: 29:06). If it bends less by forward bias, the numbers of electrons in the notch are less. What we are telling is that if we apply voltage equal to delta E_c by q across the junction, you will be able to reduce the charge particle to 0, because in a homojunction, when V_{bi} N_D which is logarithm of N_D N_A by N_i squared, the charge there is minimum, but that extra charge is present at the notch corresponding to delta E_c by q, potential change. I reduce that potential by applying forward bias and the charge is brought down to a very small value.

In other words, I can reduce this charge (Refer Slide Time: 29:48) practically to a very small value by reducing this barrier by an amount equal to delta E_c by q. Whatever extra delta E_c was there in the conduction band, I remove that by applying forward bias across this and this charge will be reduced to 0. If the charge is reduced to 0, what happens to the drain current? Go back to this diagram. Unfortunately, I have to keep on going back to that (Refer Slide Time: 30:19).

The charge here is reduced if the potential drop across the forward bias is delta E_c by q and the entire layer is depleted. When I apply a voltage between the drain and the source, there are no electrons, no electrons in the depletion layer and in this charge layer is a very small layer; it is just like saying just about to invert. (Refer Slide Time: 30:43) We have minimum electrons there and current is 0. What we are telling is we can turn off this device by applying voltage across the gate and the source such that there is a forward bias voltage across the junction, which is equal to delta E_c by q. What should be the voltage across this aluminum gallium arsenide layer such that the entire thing is depleted? In a MESFET, we saw a term called as pinch-off voltage. Pinch-off voltage is actually the total potential across the channel region in the MESFET. That is V_{P0}, which will actually deplete the channel completely. Let me just go back to that now. I hope these points are clear.

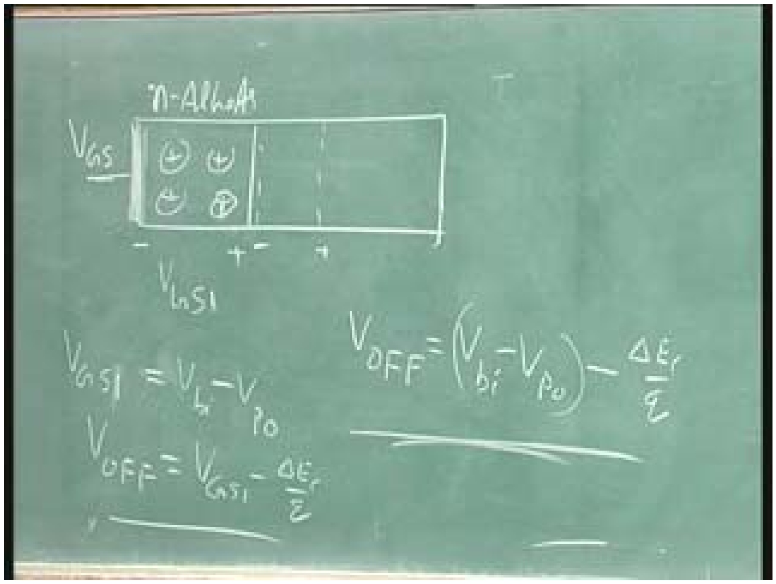
(Refer Slide Time 31:43)



In a MESFET, the n–layer is fully depleted when V_{GS} is equal to V_{GS1} equal to threshold voltage V_{bi} minus V_{P0}; when it is equal to V_{bi} minus V_{P0}, the channel is fully depleted. What is V_{P0}? V_{P0} is this (Refer Slide Time: 32:50). Now, what we have got is a situation where we must have voltage across this entire layer (Refer Slide Time: 33:02). Let us neglect the drop across the spacer layer because it is very thin and it is an undoped layer. The total thickness is 'a' here. Let us forget for the moment that this layer is present. The entire layer will be depleted and V_{GS} is equal to the threshold voltage of the MESFET. That is V_{bi} minus V_{P0}.

What we are looking for is what should be the gate voltage that I must apply so that not merely is this layer depleted fully… electrons are absent here or it is just about to conduct. What will be the total potential of this point and this point? The total potential is the voltage that we must apply to the gate to deplete the n–layer completely plus the potential that must appear across the junction. Let us put it down like this.

(Refer Slide Time 34:23)



We can draw it like this here because you are clearer. If I have that is n–AlGaAs, what we are looking for is what should be the voltage that I must apply to the gate so that this entire layer is depleted. We know that the voltage required to deplete the entire layer is equal to V_{bi} minus V_{P0}. V_{P0} is the total potential barrier from here (Refer Slide Time: 35:03), but if there is already V_{bi}, the voltage required is V_{bi} minus V_{P0}. I think we have just forgotten the formula that is used for the MESFET. This portion is equivalent of a MESFET. What is the potential that we must apply here? This is minus, plus, so V_{GS1} to deplete that.

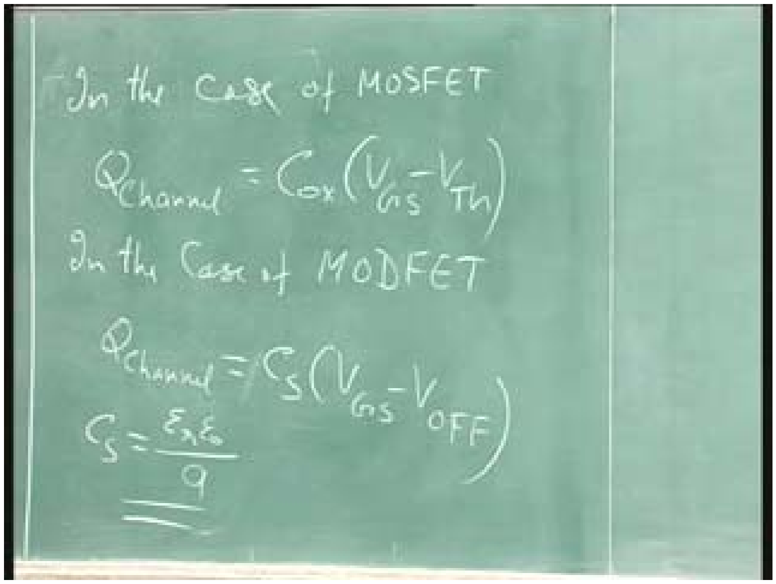
Now, over here, the applied voltage appears across this plus that – forward bias. This voltage is V_{bi} minus $V_{P0} - V_{GS}$. V_{OFF} is V_{GS1} minus delta E_c by q, because this is plus, minus here.. Though V_{GS1} has this polarity (Refer Slide Time: 36:30), we have put here, but we are putting it as a plus voltage. V_{GS1}, threshold voltage of the MESFET portion, is V_{bi} minus V_{P0}. You must apply extra voltage with negative polarity here. That means minus, plus; minus, plus (Refer Slide Time: 36:49) and minus, plus here.

If I apply V_{OFF} is equal to V_{GS1}, that is, V_{OFF} is V_{bi} minus V_{P0}, it is the threshold voltage of the MESFET portion – the voltage that we must apply to the gate so that the entire AlGaAs is depleted. To remove the charges from here (Refer Slide Time: 37:19), we must apply a negative voltage with respect to the substrate (Refer Slide Time: 37:24) subtracting minus delta E_c by q. That is actually the voltage we must apply to the gate to turn off the HEMT to ensure that electrons are just barely minimum. There will still be some electrons, but minimum – not sufficient for conduction. It is just like the MOSFET. In a MOSFET, we say the threshold voltage is the voltage at which MOSFET is turned off. You actually take that voltage as the voltage at which surface potential is twice (Refer Slide Time: 38:07). It is equivalent of that. There are some electrons, but beyond that point, if we increase the voltage positively, we will have more electrons coming up. V of this is very small; it is the equivalent of threshold voltage. Now, if I increase the gate voltage with respect to (Refer Slide Time: 38:33) positively… let us give some numbers: let us say V_{bi} minus V_{P0} is equal to 0 (V_{bi} minus V_{P0} is 0 is possible), Kirchhoff voltage is equal to 0.8 volts, V_{bi} is 0.8 volts, that is 0 – just to give an idea and delta E_c is 0.3 electron volts.

What is the off voltage? 0 minus 0.3 volts. The threshold voltage of this, which we call as off voltage, is —0.3 V. Now, if I bring it from negative to positive, what happens? If we bring it from negative to positive, it will appear across this straightaway (Refer Slide Time: 39:27) or we can say that if I bring it from negative to positive, the coupling will be between this gate and the channel, because there is an inversion layer. Like in the case of MOSFET, I can increase the charge from here onwards, just on the verge of inversion in the case of MOSFET by applying voltage at the gate over and above the V_{OFF}. The charge here now can be calculated as gate voltage minus V_{OFF}.

Let me give some other example. Supposing V_{bi} minus V_{P0} is +0.4 Volts, this is 0.3, V_{OFF} is +0.1 Volts. Now if I apply 0.3 Volts here, 0.3 Volts minus 0.1 Volts, 0.2 Volts appears across this (Refer Slide Time: 40:20) and the interaction is between these two straightaway, negative charge. When I change this voltage, negative charges (Refer Slide Time: 40:27) here, because there is a direct connection between the gate and this point (Refer Slide Time: 40:32). We are applying the voltage between the gate and the inversion layer in the case of MOSFET. Similarly, the (Refer Slide Time: 40:38) voltage is above the off voltage or threshold voltage, whatever we apply will appear into this layer. What was the relationship between the charges? Let us just go back to that now (Refer Slide Time: 40:53).

(Refer Slide Time 41:03)



It is always easy to compare with MOSFET, because it is almost like a MOSFET. The notch in the case of MOSFET is obtained by means of the oxide. Here, notch is obtained by the means of heterojunction. The Q channel is actually equal to C_{oxide} into V_{GS} minus $V_{threshold}$ if there is no drain current. Drain current means actually we subtract the drop in the channel from there. This is because whatever voltage is there over and above threshold voltage, it interacts between the gate and the channel. C_{oxide} into that extra voltage is extra charge in the channel. In the same way here, instead of C_{oxide}, you have got the capacitance of this AlGaAs layer (Refer Slide Time: 42:15), which we can call as C_s, like in the case of MESFET.

In MODFET, the only difference is S and D, one is MOSFET, the other is MODFET, because it is modulation doped. $Q_{channel}$ is instead of C_{oxide}, you will have.… In the case of MOSFET, you have metal, oxide, and semiconductor. In this case, we have got metal, aluminum gallium arsenide (which is fully depleted), and the semiconductor. (Refer Slide Time: 43:00) the inversion, you have got the notch charge, so coupling is between these two. I am bringing these analogy (Refer Slide Time: 43:07) is exactly same as MOSFET hereafter. All that we have to know is that if I apply the voltage V_{OFF}, it could be V_{bi} minus V_{P0} minus delta E_c by q, that is my threshold voltage. We will turn off the channel. Whatever extra voltage we apply above that will couple between the gate and the channel. That is what we have seen.

This will be C_S into V_{GS} minus V_{OFF}. Just notice the difference – we call it as threshold voltage there, we do not want to call it as threshold voltage, actual threshold voltage, we call it the off voltage, the voltage that we must apply to turn off the channel, because there will always be a channel there because of the AlGaAs layer. What is C_S? epsilon_r epsilon_0 divided by a. I will call this as a, the entire layer is a (Refer Slide Time: 44:15). It is per centimeter square (Refer Slide Time: 44:20). The charge is per centimeter square for all that we are talking about here.

From what we have seen, it is clear that this entire device would behave like a MESFET if this is conducting (Refer Slide Time: 44:39). That is not we are looking for. We are trying to solve the problem of heavy doping here. If the entire layer is depleted now and when the charge is present here due to the gate voltage, the charge is present (Refer Slide Time: 44:59) control by means of gate voltage, we have a current through this, this entire shaded region here. The yellow color here is the two-dimensional electron gas. That is actually controlled by the gate voltage, exactly the same way as the MOSFET.

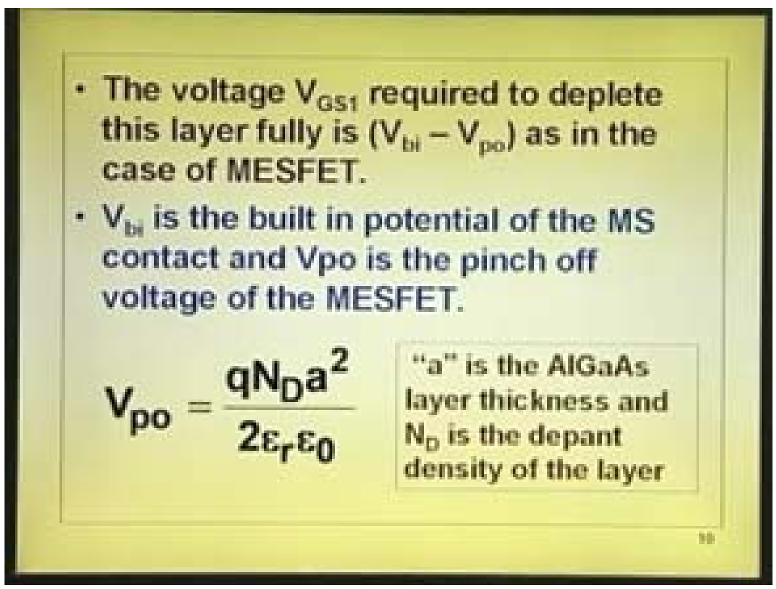
All that we write is the charge here is gate voltage minus the V_{OFF} into the capacitance of this layer, where that would include capacitance of doped layer and this undoped layer. What we are telling is that this layer must be kept small, as small as possible, but this layer is (Refer Slide Time: 45:41) so that the electrons here do not see the dopants. The electrons are not in the vicinity of the dopants and so, the Coulumbic scattering is removed by putting the undoped layer here, but we can see if we put the undoped layer here (Refer Slide Time: 46:00), immediately what happens?

The thickness of the layer slightly goes up. If the thickness of the layer slightly goes up, the C_S layer slightly falls down. For a given gate voltage, the charge falls down. We immediately see that if a goes up, C_S falls down and if C_S falls down, the charge falls down. For a given change in voltage, the charge is less if C_S is smaller. That means for a given change in voltage, the change in current is small and it means that GM will fall. What we are telling is that putting this layer here is good (Refer Slide Time: 46:43). Introducing the spacer layer is good to improve the mobility of these electrons here, but you cannot make the layer thicker and thicker. If we make it too thick, the entire a that decides the capacitance, which couples the gate to the channel will actually go down. It will affect the current and it will affect the transconductance.

We are looking for devices that have high (Refer Slide Time: 47:13) and high transconductance. That is why this layer is invariably chosen as about 20 angstroms or 40 angstroms at the most. I think I have been discussing most of the things and everything has been put in the form of diagrams. I will just flip through these diagrams now. Everything is explained on the board.

This is where we just stopped and went to explain everything in the board (Refer Slide Time: 47:40). Now, you can see that the charge here (Refer Slide Time: 47:43) can be reduced by applying more negative voltage here. This is the situation where the entire thing is just depleted here. If we increase the voltage by an amount equal to minus delta E_c by q, the charge will go down to minimum and that is the off voltage. This is what we have drawn here (Refer Slide Time: 48:02). We apply a forward voltage across that layer to bring the charge to 0.

(Refer Slide Time 48:09)



We have gone through all this. The voltage V_{GS1} required or the threshold voltage of the MESFET is V_{bi} minus $V_{P0,}$ where V_{bi} is the built-in potential of the MS contact, metal semiconductor contact. Please do not confuse between V_{bi} of the p–n junction and the metal semiconductor – they are two different things. The built-in potential of the Schottky barrier is V_{bi}, which will be about two-thirds of the E_G, if that is (Refer Slide Time: 48:40) and V_{P0} is the pinch-off voltage, which we have written down there equal to q N_D a squared by (Refer Slide Time: 48:47) epsilon$_r$ epsilon$_0$. That is V_{P0} which we are very familiar with, doping in the n plus layer, a is the thickness of layer – a is the AlGaAs layer thickness, and N_D is the dopant density of the layer.

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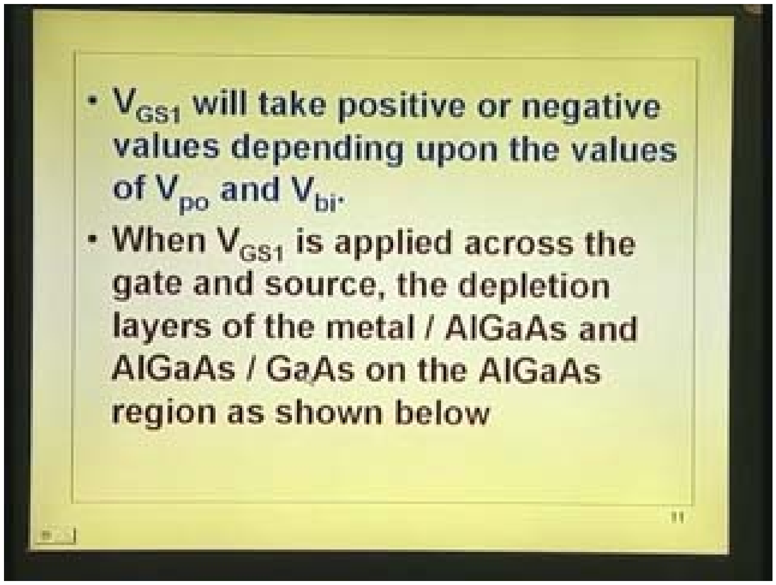

All that has been explained is written here in words, that is, V_{GS1} will deplete the entire layer and so, any extra voltage that you apply across the gate source, the depletion layers of the metal, the region as shown below.

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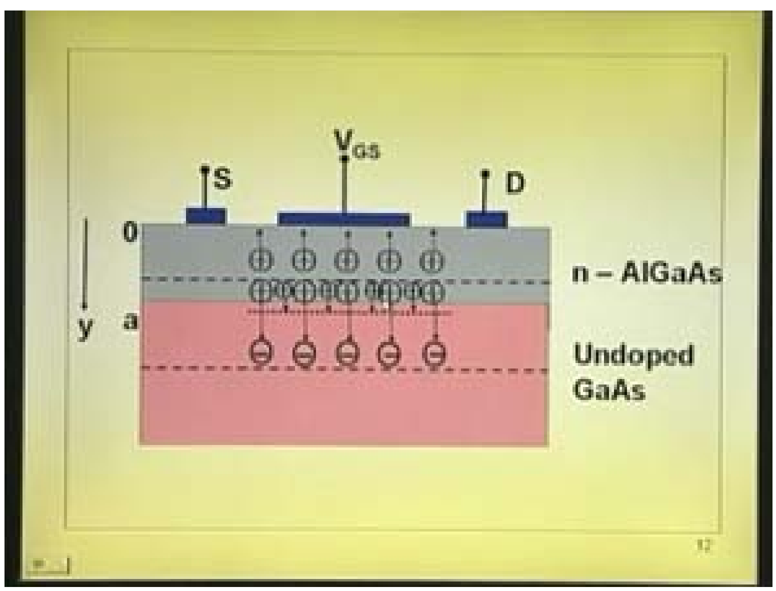
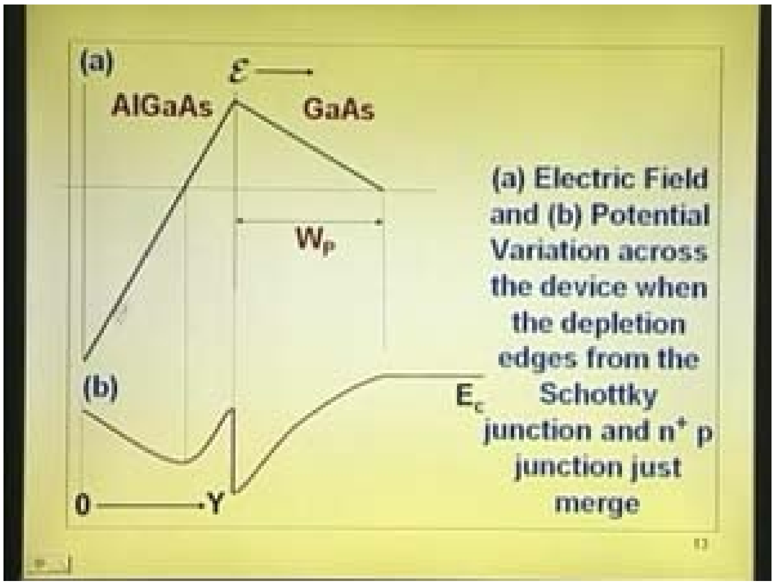


I have drawn all the diagrams on the board. This is just summarizing the whole thing. This portion of the depletion layer belongs to the gate (Refer Slide Time: 49:55). This portion of the depletion layer belongs to the p–n junction. If we apply extra voltage, this depletion layer will move down and this (Refer Slide Time: 50:05) will collapse and the charge here will reduce. That is what we have been telling right through, redrawing it in a neat fashion here.

(Refer Slide Time 50:13)



This is actually the electric field just when the depletion layer is merged. If we increase the voltage further negatively, this point is moved to the right (Refer Slide Time: 50:22) and this point is moved to the left. This potential is reduced.

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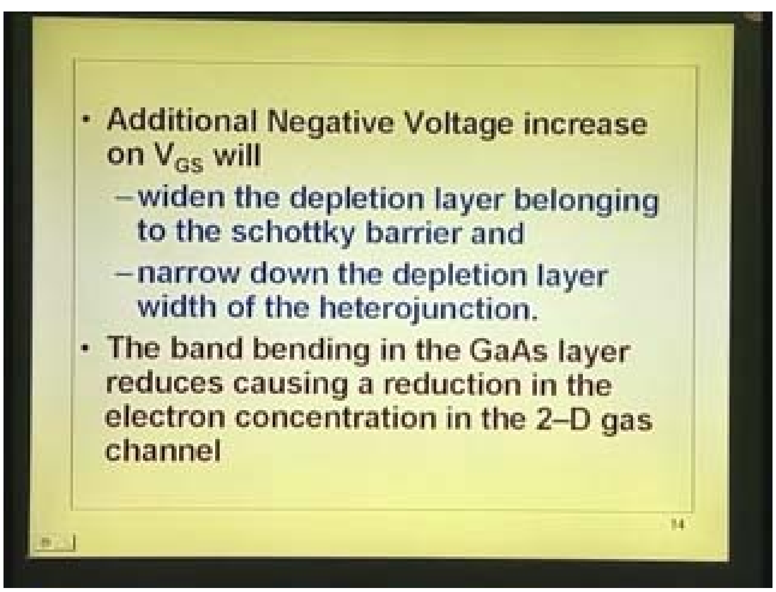
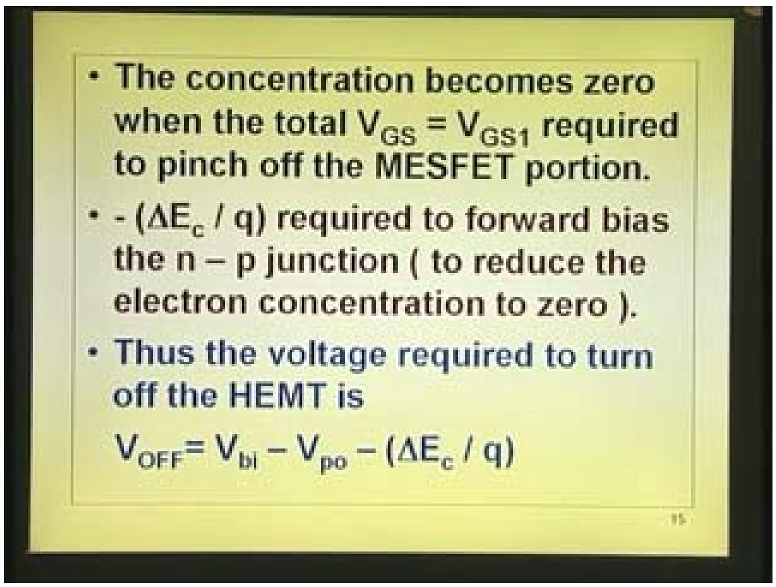


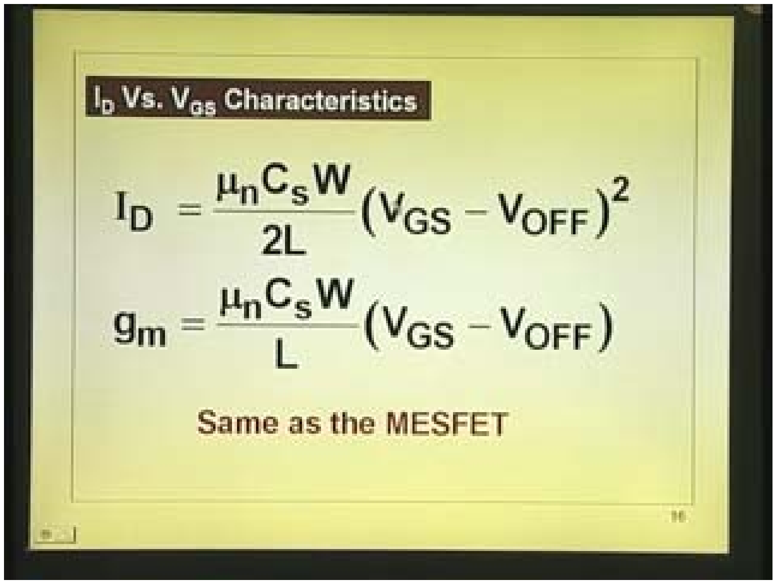
Additional negative voltage increases V_{GS} and this will widen the depletion layer belonging to the Schottky barrier. What I mean is this is the depletion belonging to the Schottky barrier (Refer Slide Time: 50:40). Any more negative voltage actually will widen this layer, which belongs to that Schottky barrier and it will reduce the depletion layer width here. That is what is said there. Narrow down the depletion layer width of the heterojunction. The band bending reduces; this means the electron concentration in the channel gets reduced.

(Refer Slide Time 51:01)



(Refer Slide Time: 51:04) As a result, we have got V_{OFF} equal to V_{bi} minus V_{P0} minus delta E_c by q. Please note now that V_{bi} is the built-in potential of the Schottky barrier, V_{P0} is the pinch-off voltage of the n plus layer and this is the forward voltage that appears across the junction (Refer Slide Time: 51:27), because that is the voltage that is required to forward bias the junction to bring the electron concentration not actually to 0 but a very small value.

(Refer Slide Time 51:36)



Now, what do we say about the I-V characteristics of this device? Exactly like a MOSFET. Once you say that the charges in the inversion layer is that in the case of MOSFET and V_{GS} is equal to 0, the charge in the channel of the MODFET is this (Refer Slide Time: 51:57), the equations governing the MODFET and the MOSFET will be the same except replace C_{ox} with C_S. If we get a square law in the MOSFET, we get a square law in the case of MODFET also, provided, of course, there is no velocity saturation and we get this equation.

Notice that we have replaced C_{oxide} by C_S (Refer Slide Time: 52:20). In the case of MOSFET, we have the oxide that is actually coupling the gate with the channel, whereas in the case of MODFET, we have the depletion layer whose capacitance is C_S, which couples the gate to the channel. Transconductance is delta I_D by delta V_{GS}. So, 2 and 2 cancel and we get this. We get better and better transconductance if you have got better mobility. Since gallium arsenide layer is undoped, there is no scattering due to impurity scattering and so, at room temperature itself, we will get a voltage 1500 centimeter square per volt second here (Refer Slide Time: 53:07) and we would prefer to keep C_S large and keep g_m large. Compared to MOSFET, C_S will be large compared to C_{oxide} for the same thickness, because C_{oxide} is (Refer Slide Time: 53:19) same as this, except this is $Epsilon_{oxide}$. In the case of MOSFET, this quantity is 4 (Refer Slide Time: 53:26) and in the case of AlGaAs, this quantity is almost 12.8 to 13, above 12.8, so about 3 times more in the case of HEMT; this is about 3 times larger than that of the MOSFET C_{oxide}, epsilon 0 is the same thing and we are taking a the same. Comparing for the same situation, this will have C_S that is about 3 times larger.

We go to the HEMT (Refer Slide Time: 54:03). You get transconductances that are larger due to higher mu_n. In the case of silicon, how much is mu_n? The surface scattering is dominant, about 1000 centimeter square per volt second. In this case, it is about room temperature, about 8500 – 8.5 times larger and C_S is 3 times larger for the same a, same thickness. Transconductance is at least about 25 times larger. If transconductance is 25 times larger, the cut-off frequency will larger by the same factor or same capacitance, so cut-off frequency is g_m by c. That is the figure of merit for all these FETs. So you will have much higher frequency of operation for these devices.

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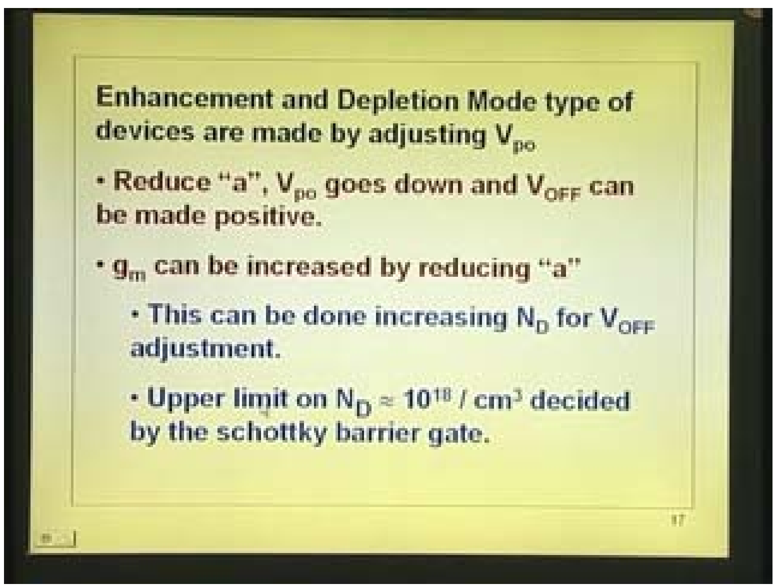
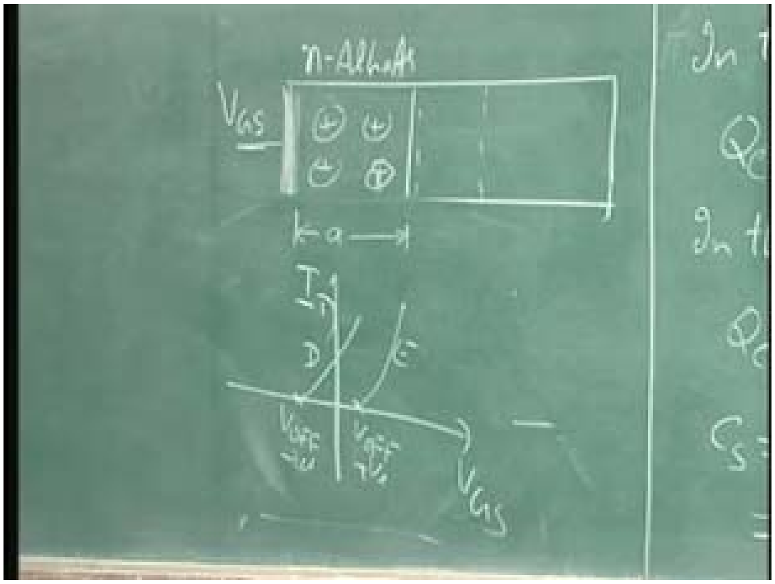


You can get enhancement type or depletion type of MODFET. How do you do that?

(Refer Slide Time 55:17)



I_D versus V_{GS}. This is depletion type, enhancement type. This is V_{OFF} positive, this is V_{OFF} negative, this is enhancement mode, and this is depletion mode. By adjusting what can you adjust V_{OFF}? V_{OFF} is a combination of…. I think I will discuss this in the next lecture. V_{OFF} is determined by V_{bi} minus V_{P0} minus delta E_c by q. The only parameter that you can control there is V_{P0}. So doping and thickness have to be adjusted. I will take on from here in the next class, but we can see that the most important thing to note is that you can control the V_{P0} and you can control the doping and thickness.

In fact, (Refer Slide Time: 56:19) two things should be done. You must keep C_S as large as possible. So you must reduce the thickness. To change the V_{OFF}, we must change the doping. There is some sort of optimization involved in these devices. I think I will discuss some of these aspects in the next lecture, because optimization parameters are there.