High Speed Devices and Circuits

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Lecture - 29

Self Aligned MESFET – SAINT

Threshold Voltage and Sub – Threshold Voltage

Today we continue to discuss about MESFET with particular reference to threshold voltage and sub-threshold current.

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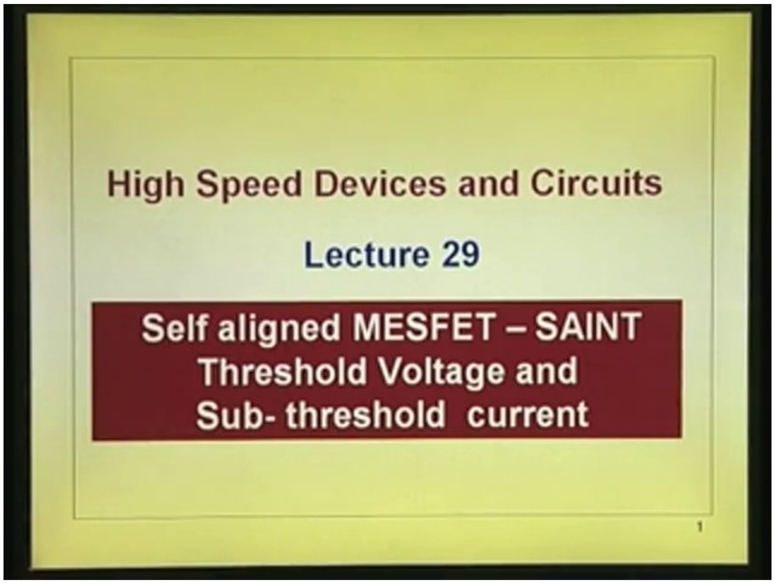

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Lecture 29

Self aligned MESFET – SAINT
Threshold Voltage and
Sub- threshold current

In fact, we have discussed the effect of the channel length and also the effect of the spacing between the n plus layer and the gate, that gap.

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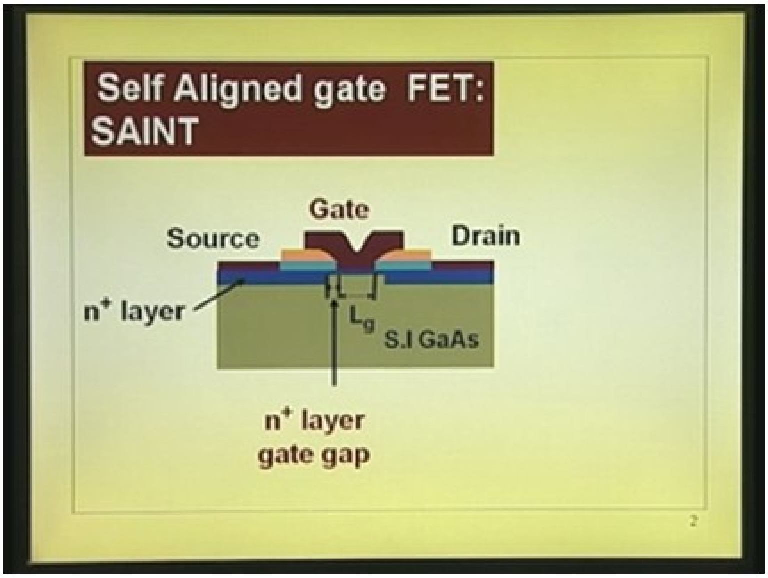

Self Aligned gate FET: SAINT

This is the self aligned implantation technology that is, SAINT (Refer Slide Time: 01:35), where this gap can be adjusted very precisely to the level of point 2, point 3 microns of that order. This is the gate length (Refer Slide Time: 01:50).

What we are seeing is the effect of the gate length and this gap on threshold voltage. I project it once more. This is what we saw and we have discussed in detail about this.

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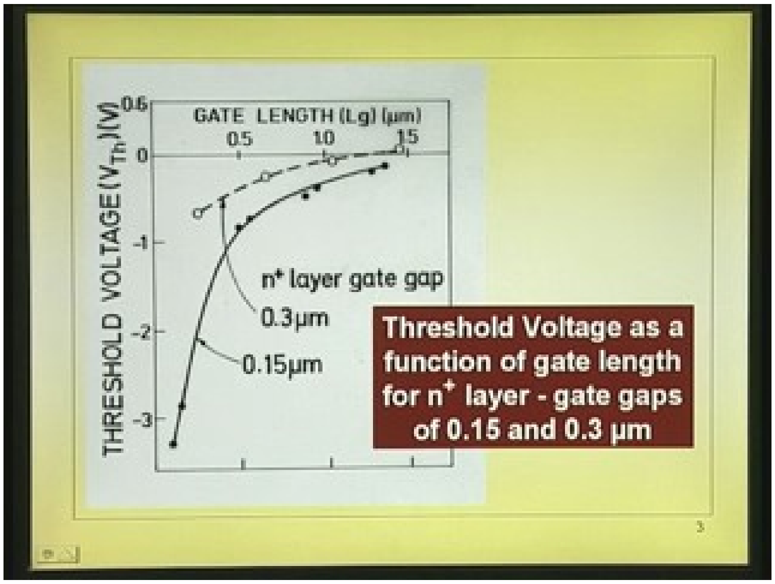

Threshold Voltage as a function of gate length for n⁺ layer - gate gaps of 0.15 and 0.3 μm

As we go to shorter gate lengths, threshold voltage gets shifted to the negative side because of the two dimensional effects which are coming in, in addition to the field in a particular direction you have got the field in lateral direction also along the channel. That prevents the channel being blocked completely with the particular gate voltage and you must apply more negative voltage. That becomes more and more predominant if the gap between the n plus layer and the gate is smaller, because then the channel length becomes smaller and fields become higher (Refer Slide Time: 02:36).

So the two dimensional effect becomes much more dominant and because of that the point 15 micron is rather dangerous to use and point 3 micron is more acceptable and you can overcome this problem further if you actually increase the field in the vertical direction compared to lateral field. You can increase the field in the vertical direction by increasing the doping accompanied by reduction in thickness so that pinch off voltage and threshold voltage is the same.

One more aspect which is a very popularly discussed in the case of MOSFET, which is common for all the field effect transistors, is the sub threshold current or sub threshold conduction.

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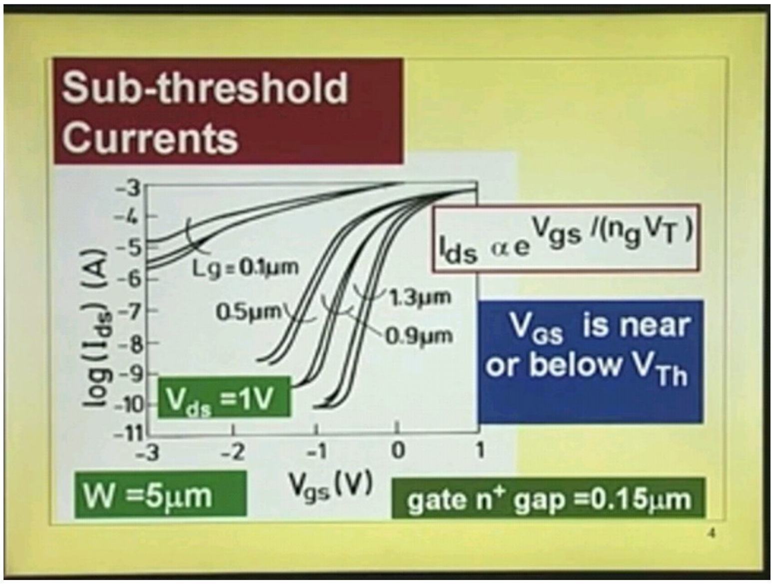

Sub-threshold Currents

$I_{ds} \alpha e^{V_{gs}/(n_g V_T)}$

V_{GS} is near or below V_{Th}

V_{ds} =1V

W =5µm

gate n^+ gap =0.15µm

We can just keep this slide here.

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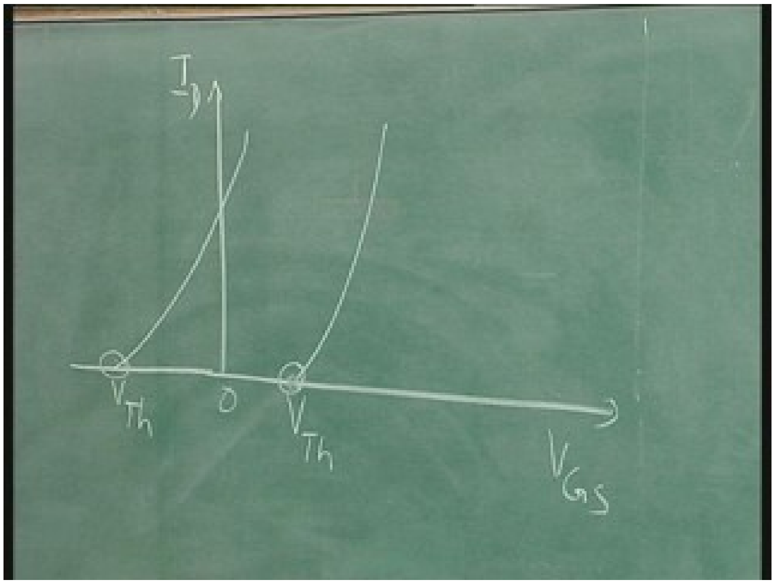

What I am pointing out here is, normally when we do V_{GS} verses $I_{D,}$ you have got 0 and then that is the characteristic, which we call threshold voltage. This is an enhancement mode type of device where threshold voltage is positive. Gate voltage you must apply positive voltage so that the device just turns off. Now we call this as the square law right from the threshold voltage, just when the channel is pinched off (Refer Slide Time: 04:08).

What happens in reality is, when you go right up to threshold voltage, it is still not completely off. So what we are thinking is, look at this region, around threshold voltage, particularly, voltage that goes below that, how is it turning off? For example, what you understand from this curve initially is, when you take a casual look at this curve, what we see is, when you go to threshold current is 0. But current cannot turn off to 0.

There is a certain finite current flowing. It may have come down to microamperes or several microamperes. You must reduce the voltage further down so that current is reduced down to at least one or two orders of magnitude. Now if you take a depletion type of device that is the characteristic. You have got the threshold voltage here (Refer Slide Time: 05:05); this is negative. Now I apply voltage which is below the threshold. How will the characteristic be around this point? In fact we can have one short discussion for both - enhancement type and depletion type. Only difference is threshold voltage is positive here and negative here.

So if I want to go below threshold voltage here, I must have V_{GS} which is less than threshold voltage, but positive (Refer Slide Time: 05:38). If I want to go below threshold voltage, I must have V_{GS} more negative compared to threshold voltage. That is the whole thing that we are discussing.

What you can see here in this plot is, which is actually an experimental result which people have reported in the papers for SAINT effect, self aligned structures (Refer Slide Time: 05:58). There are different curves you can see; quite frightening to see because you can see on the x-axis you have got the V_{GS}, the same curve that you are putting; and on the y-axis you have logarithm of I_{ds}. It is not I_{ds}, it is not a linear region that we are seeing.

If you see in the log scale, I come down below threshold voltage. It is almost linear. Linearly falling the log scale actually means the characteristics are exponentially falling. Once you reduce the voltage below the gate voltage, you would expect it to fall down very steeply; that means you could turn off. But you can see there is a curve here (Refer Slide Time: 06:45) from a threshold voltage falling very gradually. That means if you want to reduce the current by at least two to three orders of magnitude, you have to reduce the voltage from 0 right up to minus 3 volts, very large voltage. It is not a good sign. So these things have been observed for the plots given here for different gate lengths. The gate length varied from 1 point 3 micron, this curve (Refer Slide Time: 07:15); point 9 micron, second curve; point 5 micron here and point 1 micron. This is about the range that they have got that. They have put some number of curves with the range, but we can take it as one curve if you are putting an average value. So you have got 1 point 3 micron here. The gap between the gate and n plus region is point 17 micron. You are cutting it very short. For both devices, it is like this. In fact you are talking of really short channel effect.

On the first hand, before we understand why it is not steeply falling as it reduces the channel length or gate length, before that what we must understand, is this like this when the long channel device is present? How will it fall? I keep this curve. We will go through this analysis and then you can understand this. So these devices were for channel width is equal to 5 micron and spacing between the n plus and the gate layer is point 17 micron.

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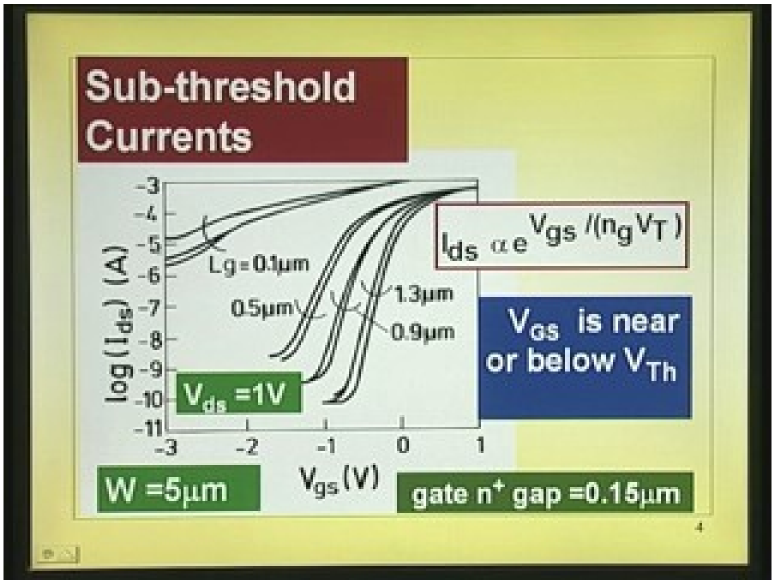


Sub-threshold Currents

$I_{ds} \alpha e^{V_{gs}/(n_g V_T)}$

V_{GS} is near or below V_{Th}

V_{ds} =1V

W =5μm

gate n^+ gap =0.15μm

These devices were for this type; just put it like this (Refer Slide Time: 08: 30); this is n plus. I am just augmenting the whole curve for the same effect. Then n plus and then you have got n layer. I have a metal here - drain and I have metal here - source and I have this gate here; that is the gate (Refer Slide Time: 08:59). All that is done in the plot and this is varied, that is, keeps on reducing, by keeping this width the same; which would mean, this is shrunk and this is also shrunk, so that the gap is same. To find out how this V_{GS} verses I_{DS}, I_{DS} is there, this is n layer, for voltages below the threshold voltage and this is semi insulator (Refer Slide Time: 09:40). Let me keep that figure there so that we can take a look at it whenever we need.

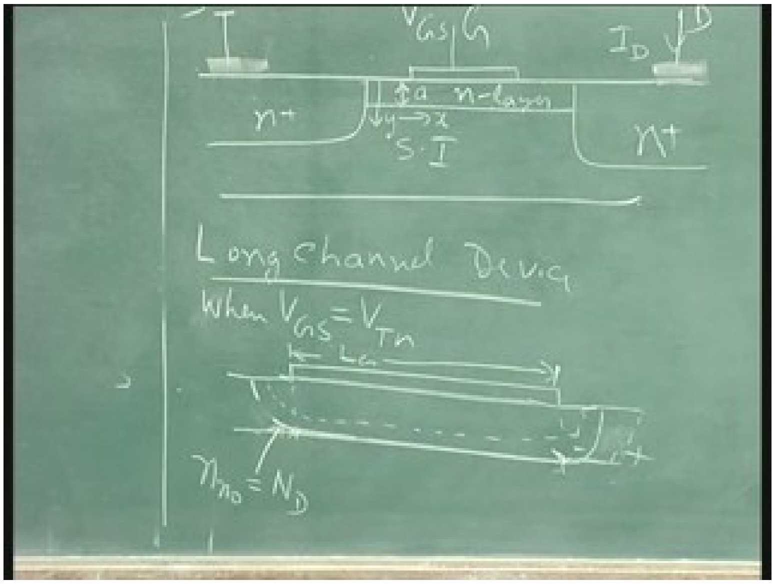
First, what we are trying to do is, let us not worry about short channel 1 micron 2 micron but a long channel that is the gate, which is very long. In that situation, how will be the behavior of the device below threshold voltage? What we see is a long channel device; that is what we see first. Then if I plot the potential, I call this as y and call this as x and I will just put this back here (Refer Slide Time: 10:40). This is ‘a’; it is getting a bit crowded, but still I think they can figure out and see those things - channel thickness, y direction and x direction. What we want to do is, at pinch off or when V_{GS} is equal to V_{Tn}, in both cases, whether enhancement or depletion type, if you take V_{GS} is equal to V_{Tn}, how will the depletion layer be? Let me just plot to write here (Refer Slide Time: 11:30). I will take a long channel device. When you take V_{GS} is equal to V_{Tn} what is the meaning of that? The meaning is that depletion layer has closed at the source end. Depletion layer is actually like this: this is an n layer (Refer Slide Time: 11:58). Depletion layer is actually closed here and V_{DS} is equal to 0; it will be like that.

Depletion layer actually will be almost like that if it moves like that. That is the depletion layer edge (Refer Slide Time: 12:18). Now the potential actually is negative with respect to that, a total drop. So the applied voltage between this and this is V_{Tn}. What is the potential variation from here to here? If I plot the potential lines, this is the maxim, edge of the depletion layer (Refer Slide Time: 12:45). If I plot another depletion layer at a lower voltage, it will be coming like this. I can have all the depletion layers like this starting from 0 position. This is in fact the solution to Poisson's equation. Equi-potential lines will be going like this and here it will be like this; this not a very difficult concept. What I am telling now is if I move along this line from the source end to drain end, there is no potential variation. If you move at the edge of this depletion layer, there is no potential variation. Please understand this very carefully. If there is no potential variation that is, where we will take current to be 0. If there was potential variation, current would have been there, some charge is there. But, when you go to the edge of the depletion layer, what is the charge concentration? We take it as 0, but you can see from here to here there is no potential variation.

What is the carrier concentration here? The carrier concentration here (Refer Slide Time: 13:54) is n_0 equal to N_D. The carrier concentration at this edge here is n_{n0} that is if I want to call it, that is equal to doping. What is the carrier concentration here? If I do not apply any voltage here, definitely there is no current - neither concentration gradient, nor electric field. But if I apply voltage here, when I apply voltage here if it is a long channel device, there is no potential variation here. There is one-dimensional effect. If there is applied voltage, it may go from here to this side like this, depletion layer move that side. But between this point and this point (Refer Slide Time: 14:55), there is no potential variation. But when I apply a potential like this, this is plus and this is minus. I am making the drain positive. The entire voltage appears across that. There is no potential change here because whole thing is depleted there. If it were a short channel it would have extended but because it is a long channel, all that is happening is depletion layer widens here. What happens to carrier concentration here – plus and minus? Whatever carrier concentration is here will be brought down to 0, like a reverse bias p-n junction. Electrons are actually collected completely by that. If there is a potential drop from here to here, carrier concentration will be much lower than carrier concentration here. Here the carrier concentration corresponding to one doping is there. Here the carrier concentration is low (Refer Slide Time: 15:52). Now of course, area for cross section will be very small.

There is a small layer, which is conducting there. Here carrier concentration is equal to doping and here it is. What we will say? There is no field here, there is no potential drop, but there is a concentration gradient. N_D here, 0 there, so between these two there will be a concentration gradient, there is a current flow.

(Refer Slide Time: 16:45)



So what will happen now will be: at 0, x is equal to L_G. This is almost similar to MOSFET, but the mechanism is different here where the pinch off taking place. This is zero carrier concentration. I plot n as a function of x - electron concentration. That is falling from there (Refer Slide Time: 17:00). At V_{GS} is equal to V_{Tn}, there is a concentration gradient. How much is the current would depend upon how much is the area of cross section. Area of cross section is very small. That is a very thin layer; may be a couple of divided lines corresponding to KT by 2 into 2 or something like that, thickness is very small. Density may be there but current will be small.

I_D in this case will be J_D will be equal to minus qD_n dn by dx. dn by dx is same everywhere. There is no change is slope, there is no recombination. So whatever is the slope, it is linear. It is just equal to this concentration by 0. The current actually at threshold will be equal to J_D will be equal to qD_n N_D divided by L_G. Why? This quantity is N_D is equal to n_0; just put it separately. Take all this as n(0). Then I will put it here again once more this is n(0), divided by that length. That is, dn by dx; the minus sign gets cancelled with this because the slope is negative. This will be equal to qD_n N_D by L_G.

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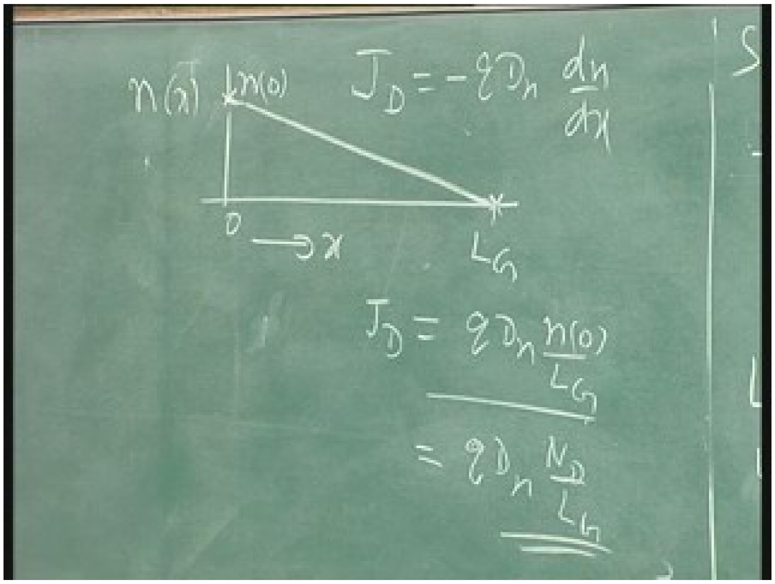

What we are telling is there is some amount of current density giving rise to current at threshold. In fact people talk of threshold – ok, it is at 5 micro amperes, it is at threshold; the drain current drops out 5 micron ampere, that is the threshold. That is one way of identifying. That means 5-micron ampere is there. Now from 5-micron amperes, how will it fall down if it comes below the VT_n? That is what we are trying to see.

Here I have got some of the terms, for example, what we talk of now is sub-threshold. That is, a voltage that you applied to the gate which is below threshold voltage. So let us see what happens. I will remove some of these things so that we can see better. All these are long channel devices that we are talking of and I will put it once again. So V_{GS} is equal to VT_n minus V; that is the second case. First case was V_{GS} is equal to VT_n. That is what we got. Second case is when V_{GS} is equal to less than VT_n. Now you can see it works out fine for you for both enhancement and depletion mode because V_{GS} is less than VT_n. If VT_n is 1 volt, V_{GS} is 1 volt minus whatever we apply. V that we talk of here are not in volts. 100 milli volts, 200 milli volts or V may sometimes chalk-up even higher voltages. So this is 1 volt and if this is point 5 volts, then I am talking of point 5 volts. In other words, just put the diagram here (Refer Slide Time: 20:48). If it is positive there, that is VT_n. If that is VT_n, we are talking of the point here – whatever is the current there.

We estimated what current is this one (Refer Slide Time: 21:05), doping concentration decides that. I want to go down up to this point in a depletion mode type of device. How does it work out? VT_n is negative, negative minus 1 volt let us say, minus 1 volt further again. Say this is minus 1 threshold voltage (Refer Slide Time: 21:30). I have been using for some time VT_h actually. If this is minus 1 point 5 volts minus 1 point 4 volts, we are going down here. Please understand the same formula, same discussion how its good for both enhancement type and depletion type.

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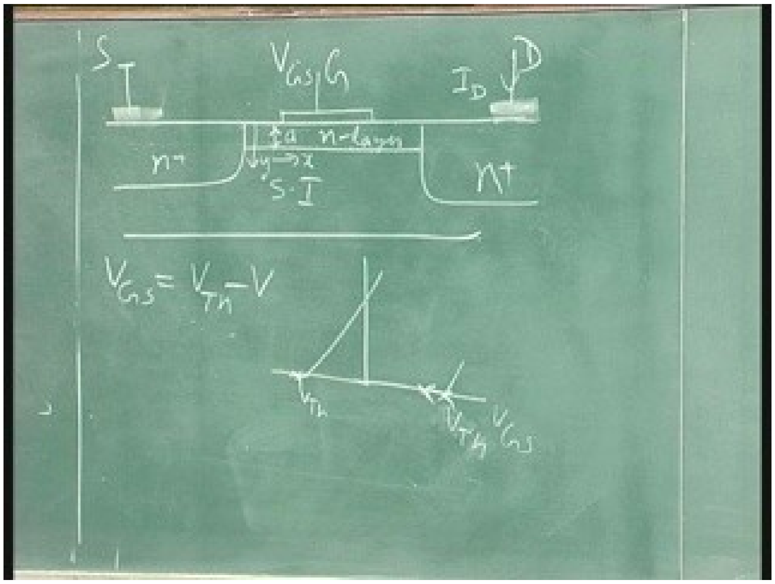


Let us plot the depletion layer for one particular case. The same thing holds good. You can understand from here that the equation that we have used is similar to the equation of a bipolar transistor. In the base region in the n-p-n transistor, you have got electron concentration raised up, electron concentration 0, and whole thing by diffusion. Same thing is written here. Now all that we have to find is if I reduce the voltage V_{GS} below V_{Tn}, what will be the concentration at this edge? That is what we want to see. Let us see what happens. Let us plot only the potential variation.

What we have now is, we are talking of a long channel device (Refer Slide Time: 23:10); it is like this and we have got the source, we have got the drain and we have got the V_{GS} and we applied some V_{DS}. At threshold we had this behavior. Corresponding to that it has pinched off; that is, V_{DS} is equal to 0. What we are seeing is, between this point L_G and this point 0, that is x (Refer Slide Time: 23:54). That is what we wrote. Now if I apply V_{GS} equal to V_{Tn} minus V, let us talk about depletion mode because argument holds good for both. What happens if more negative voltage is applied to the gate? What happens to this depletion layer? It expands that way. So this will be like this (Refer Slide Time: 24:20). This is for this situation; like that depletion layer. What will be the concentration here? Here it is N_D. What we want to see is, what is the concentration here? That concentration has fallen down because there is a drop from here to here by an amount equal to V because V_{GS} is V_{Tn} here corresponding to the depletion layer. Now if I have V_{GS} minus V, more reverse bias, depletion layer has moved here; so change in the voltage between this point and this point is equal to that (Refer Slide Time: 25:00).

Now what will happen will be, if you do that, (just a few things I had sorted out because there is lot of confusion on this) I can plot this particular potential now x is equal to 0 and x is equal to L. If I take this as 0 potential here, how does the potential vary along this line? We are talking along this line only (Refer Slide Time: 25:35), because there is no current here, charges are very small there. As you move from here to here, see this is the edge of the depletion layer. As you move from the edge deeper into the depletion layer, what happens to the carrier concentration? It goes down to 0.

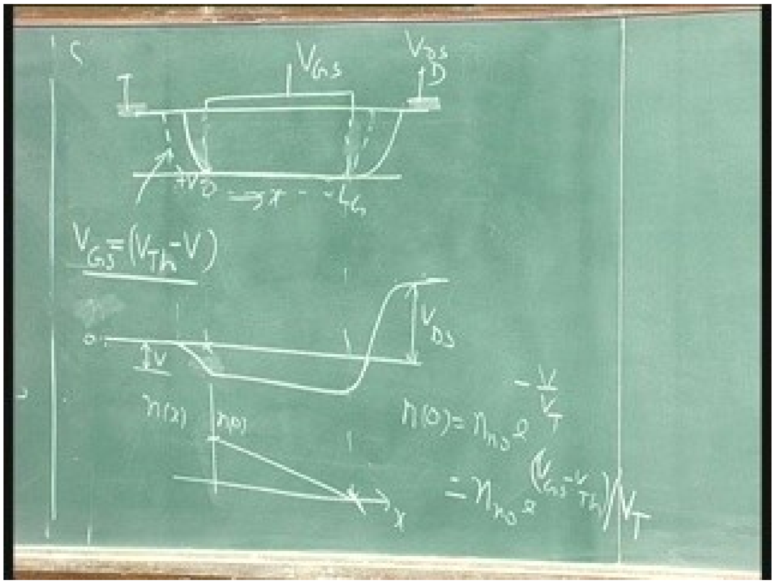
What we are talking of is a very thin layer. Given the length there, how much is the charge? And we have to worry about that because we will still be having micro-amperes of current. You may not worry about what device is there, let us say micro ampere 1 micro ampere 1/2, why should I worry? In integrated circuits, if there are hundreds of such devices which you believe is off, all those currents add up and there is power dissipation. That is why you want them to turn off. When they turn off, they really turn off; there is very low voltage difference. Now what will be the potential difference? - 0. At this point it is negative, that is, at x is equal to 0 (Refer Slide Time: 26:36). From here onwards, I have a drop like this; that is V.

This quantity is V; this is very simple but one has to really follow carefully. From here onwards, up to this point, what is happening? No potential change. That is corresponding to this potential (Refer Slide Time: 27:00). This one will actually come - depletion layer like this. But I am plotting from here to here and I am finding what the carrier concentration on the channel is and from there to drain there is no potential change. So you get that thing like this (Refer Slide Time: 27:18). In the previous case this barrier was not there. Carrier concentration was here and that was 0 there. So from this point onwards how does it go? If drain voltage was 0, that would have come down to plus minus, minus plus. But because drain voltage is 0, there is a drop here plus to minus and when we come down to this point, if this is not there, depletion layer would have been here, what will be the potential here? Plus minus, minus plus, 0. It would have come down like this. But you have got additional drop V_{DS}. So the whole thing will be like this. You do not have to worry about this at all. This quantity is V_{DS} and this quantity is V. Total drop here from here to this point is V_{DS} plus V, which actually makes it further 0. It may move slightly into that, into this channel region, but we are not taking the movement at all because we are talking of a long channel.

So whatever movement is there, it is small compared to this gate length. If the channel length becomes smaller then you will have to see how much it will move. I will do only qualitatively; you can get this quantitatively. What is the carrier concentration here? If I plot, n of x verses x that is 0 there. And here it is some n(0) (Refer Slide Time: 29:14). Same expression, drain current is there. Only difference is, n(0) in this case is smaller compared to what it was. n(0) is smaller because there is a depletion layer from here to here. So carrier concentration here will be the carrier concentration here multiplied by e to the power minus V by V_T. The potential difference is V.

In this situation therefore, we can write n_0 will be equal to n_{n0} e to the power of minus V by V_T. When you move from positive to the negative or 0 to negative potential, it is the potential barrier to the electrons. In this I am plotting electro-static potential. If you take the potential for the electrons, it finds it difficult to move towards the negative charge, negative portion. That is why the carrier concentration is lower by that amount. Amount is equal to voltage. So now what is this quantity V? V is that. This is so straight-forward now. This is actually equal to minus V is equal to V_{GS} minus $V_{Tn..}$ This is n_{n0} into e to the power of V_{GS} minus V_{Th} divided by V_T. You have got this particular term now. I hope this is clear. We have obtained that from here because we started off with that, if you recall (Refer Slide Time: 31:15). Let me put it once again here; V_{GS} is equal to, we are seeing just below the threshold voltage, by an amount equal to V. So V is equal to V_{GS} minus V threshold, whether V_{Tn} or $V_{Th.}$ I call it V_{Tn} sometimes because this is n channel. V_{Th} is just straight away threshold voltage. What is n_{n0}? Doping. n_{n0} is carrier concentration here, that is, doping.

(Refer Slide Time: 31:30)



What you will get is, when V_{GS} is equal to V_{Tn} minus V, n_0 is equal to N_D e to the power of V_{GS} minus V_{Th} divided by V_T. I have rewritten that by just putting n_{n0} as $N_{D.}$ Therefore, current I_D will be equal to qD_n n(0) minus n(L) divided by L_G. N_L is equal to there (Refer Slide Time: 32:40); it is collecting all the electrons, which are reaching there like the collector of junction. N_L is equal to 0. So that is equal to area into qD_n n(0) by $L_{G.}$ I can write this as into area; I have left out area everywhere. Whatever I wrote was current density; multiply it by the area (Refer Slide Time: 33:05). When I say current density is $qD_{n,}$ it will be per unit. So multiply by the area; this is equal to area into (we are substituting for this quantity) this one (Refer Slide Time: 33:35).

This is equal to A into $qD_n N_D$ divided by L_G into e to the power of V_{GS} minus V_{Th} divided by $V_{T.}$ I hope you now understand and the ideal is clear. The entire idea is that there is a current flow from the source to the drain, which is by diffusion in the small thickness here (Refer Slide Time: 34:32) there is a current. And how much current flow depends upon what is the carrier concentration is here. How much is the carrier concentration depends how much the drop is here from here to here. More the drop here, lesser the carrier concentration (Refer Slide Time: 34:43). Ideally what will you say from this equation? Ideally the first quantity here, what is that? Not ideally, the quantity that you have written here, that is, A into $qD_n N_D$ divided by $L_{G.}$ That is what we wrote initially at threshold voltage; this was equal to V threshold. So that is I_1, current at threshold voltage, which you may take as 5 micro to 10 micro amperes. From here what you can see is the drain current keeps on falling exponentially; makes V_{GS} more and more negative. What we are talking of is, this is a negative quantity - minus V. Keep on increasing V_{GS} negatively, there is more less, this becomes less and less.

So when you go down, negative voltage of threshold voltage, below the threshold voltage you have exponential fall in current. That is what you have seen here. That is what you see here. (Refer Slide Time: 36:00). Now, there are several curves which are put depending upon the channel length. One thing, your threshold voltage itself changes as you reduce the channel length. That we have seen: the two-dimensional effect and change in threshold voltage. Why should this slope change? You can see that. The slope here is something, it becomes less, it becomes flatter and flatter as you go to shorter and shorter channel length. The only way it can happen is in this equation (Refer Slide Time: 36:48) this concentration here is changing. The concentration here is not falling as much you think this should be. From here, what is the change in voltage for one decade change in current? Ultimately what we have got is I_D is I_{D0} e to the power of V_{GS} minus V_{Th} divided by $V_{T.}$ So if you plot in a log scale, logarithm of power 10 I_D log to the power of I_{D0} plus V_{GS} minus V_{Th} divided by $V_{T,}$ 2 point 3; 2 point 3 times V_T is 60 milli volts.

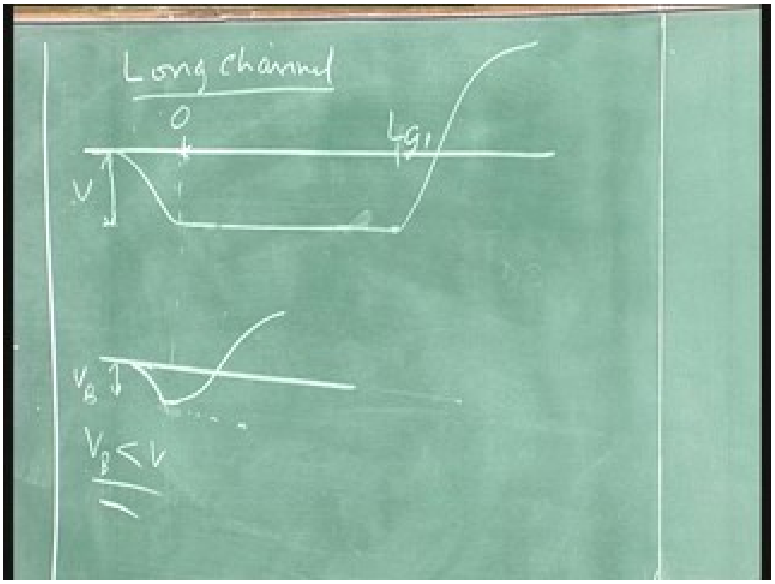
You should ideally get the sub threshold slope, whether you talk of MOSFET or this MESFET, is that 60 milli volts per decade. For example, if my threshold voltage is 0, I can reduce the current by 1 decade by just reducing the voltage by 60 milli volts. I can reduce the current by 5 decades down, it was 10 micro amperes, I want go to pico amperes, 10 to the power of minus 12, minus 6 into minus 12, that I can do by reducing the voltage 60 into 6, 360 milli volts, point 36 volts. Now notice what is happening here (Refer Slide Time: 38:46).

Here we are talking of channels which are very short and as I move from right to left it gets shorter and shorter. They are not falling by 60 milli volts. How many decades here? This is about six orders of magnitude down from here to here, 6 decades. These are all decades, 4 10 to the power minus 4, minus 5, minus 6, minus 7, minus 8, minus 9 (Refer

Slide Time: 39:00). If you take 10 here, 10 minus 6 is 4. So that is falling by six orders of magnitude. We expect an ideal case point 36 volts. That is about 0 there and this is about more than point 5. It is not point 36 or so, it is about point 7 volts. But still it is exponential, because it is almost linear. The entire equation now gets modified with short channel devices. This is the long channel device, sub threshold current. Conduction in sub-threshold region, there is gate voltage slightly below the threshold voltage. Here in closed devices, I_D is equal to I_{D0} e to the power of V_{GS} minus V_{Th} divided by some constant n_g times $V_{T.,}$ where n_g is greater than 1. It is like a diode idea into factor where n is equal to 1 it is 60 milli volts per decade. Now here n is equal to 1, 2, 3, 4 depending upon how short the channel. In the long channel n_g is equal to 1, short channel is equal to 1, 2, 3, 4.

You can see these curves are given here it could be a very high. Even when I went from 0 volts to 3 volts negative, the current has fallen just about two orders of magnitude. That is, you can see that n may be a factor of even 10, a very large number. You are not able to turn off at all. What is the cause? The cause is this barrier is not remaining constant (Refer Slide Time: 41:20). As you go to shorter channel lengths, for the same voltage, let us plot and qualitatively discuss what is happening.

(Refer Slide Time: 41:30)



This is the potential that I am plotting and I am having that x is equal to 0 and x is equal to $L_{G1,}$ long channel. Then I will have the potential coming down like this at a particular V_{GS}. Plot like this up to a point that is positive. 0, negative and positive, source and drain end.

With the same voltage if I reduce the channel length, how will that be? If I reduce the channel length, this keeps on encroaching to this region (Refer Slide Time: 42:15) and in very short channel devices what would happen? In fact we are talking of very short channel devices - 1 micron, 1 point 3 micron. What would happen? That is there, this is long channel and this is V, that is, the voltage which is there below the threshold voltage. The barrier height here is totally controlled by V. There is no other factor which is affecting the barrier height. That means the carrier concentration here is totally controlled by the V. Now if I move this at short channel, what happens at very short channel? I put it here, 0 and L_{G2}. How will that be? L_{G2} is very much short compared to L_{G1}, 1 micron, 1/2 a micron, of that order. The potential ideally what would be expected would be, start from here whatever way it falls, then come like this and then go up like that (Refer Slide Time: 43:45). But what is happening is, from the drain end the field lines terminate on to this because this is so small, we are talking of point 3, point 4 microns. Instead of starting from here, the entire thing comes like this. Let me just augment it and show you. The potential varying like this instead of varying like that (Refer Slide Time: 44:13). The drain end also that potential we are talking of, that comes like this. It is actually a one-dimensional effect here, whereas, the field length is coming from this side when it is very short they are encroaching to that and the potential actually becomes like this. So this V_B the barrier is less than V. I am going to very qualitatively show you that it will no longer remain flat there. The current due to collection due to not only diffusion, but also by drift is one thing.

Other thing is the electron concentration here is actually more because the barrier is small compared to that because, after all, the electron concentration at this end is equal to (initially take that diffusion equation) doping concentration into e to the power of V_B by V_T minus. That V_B is smaller because of the two-dimensional effect. So put together, it becomes less and less exponential ideal and you can see finally when you go to very short channel devices, all that we are talking of will never hold good.

The barrier will be reduced quite a bit and there will be a direct path from region source to that particular end. That is almost quite happening here. Whatever we are talking of will not apply there but at least if this is not so much, encroachment is not too much, then still what you talk of holds good with N_g greater than one. What we are telling is, ultimately you have got, when you go to shorter channel length, the potential barrier at the source end to the transport of electrons towards the drain end keeps on reducing or it is controlled by the drain also. So for a given drain voltage, you will have that factor n_g greater than 1.

When you increase Vd that barrier will be further reduced. You would have another factor come into the Vd. I am not talking about that. I just want to point out that two-dimensional effect harms the performance of the device. As you go to shorter and shorter channel devices, one thing that happens is the threshold voltage changes. You may say I do not mind that much, but you will have to mind when you talk about integrated circuits.

Other thing is you are not able to turn off your device so easily. You cannot turn off the device so easily meaning you must apply much more voltage to turn off here compared to this device. So in shorter channel devices you get the two-dimensional effect. In fact this is what the n_g that is plotted here. If you have taken this slope of lines exponential, how much is n_g?

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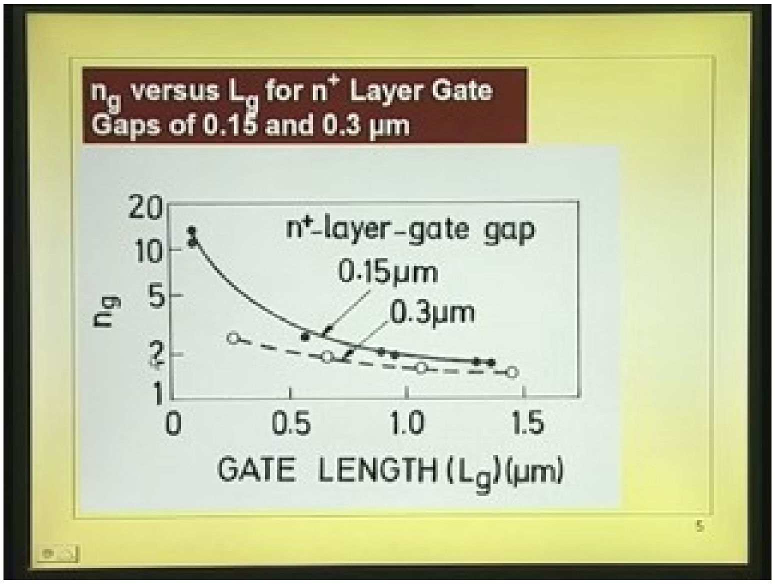

n_g versus L_g for n^+ Layer Gate Gaps of 0.15 and 0.3 μm

You can see when L_g is 1 point 2 microns and the gap is point 3 microns, now you can see the two effects are there. On the gap is point 3 that is a bit larger, you have a short channel effect coming up and you have got that factor is equal to 2. What you have plotted here is for point 1, point 15 micron gap. It is the worst situation. See what happens.

Go to shorter gate lengths. The factor of the device that we were talking on the other side is 10. That is a large number that you get. So you get n_g larger and larger with short channel devices, which are more and more difficult to turn out. Why this difference between the two? Between this device and this device (Refer Slide Time: 48:17) it is almost the same gate length that we are talking of. But the channel length is smaller in this particular case. The two-dimensional field in this direction and the gap is smaller.

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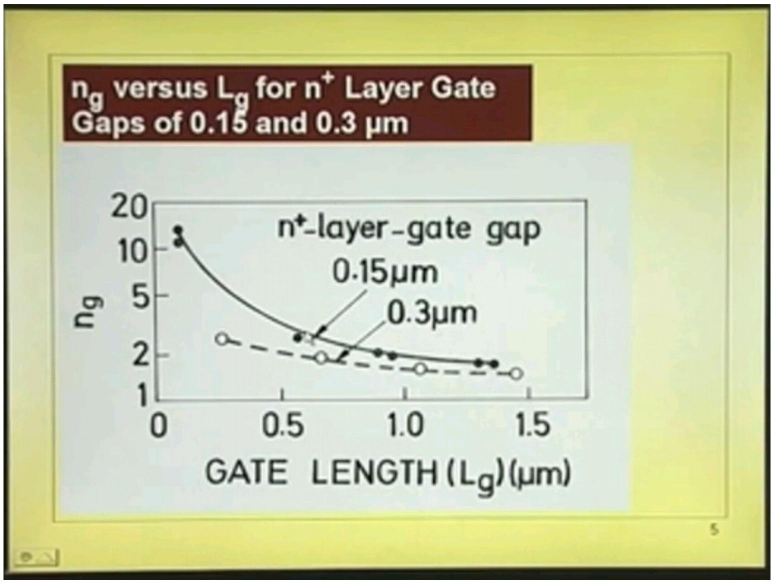

n_g versus L_g for n^+ Layer Gate Gaps of 0.15 and 0.3 μm

If I plot it like this - n plus n plus n, source and drain gate (Refer Slide Time: 48:50). For the same channel length, if you reduce the width, then that is closer. When I apply voltage here, the field in this direction is more. The gap between the gate and n plus region is reduced, the two-dimensional effects give much more and as a result you have got n_g more, you have got threshold voltage mode more negative and all sorts of things are there. How do you overcome that?

This is summing up what I said now: threshold voltage shifts in the negative direction in short channel effects. Sub threshold slope at I_D verses log I_D verses V_{GS} becomes larger and ng shows higher values that coefficient because it falls less deeply and it takes more voltage to turn off. Both effects are due to the 2-D field effect. How can we overcome that? How can we reduce the short channel effect?

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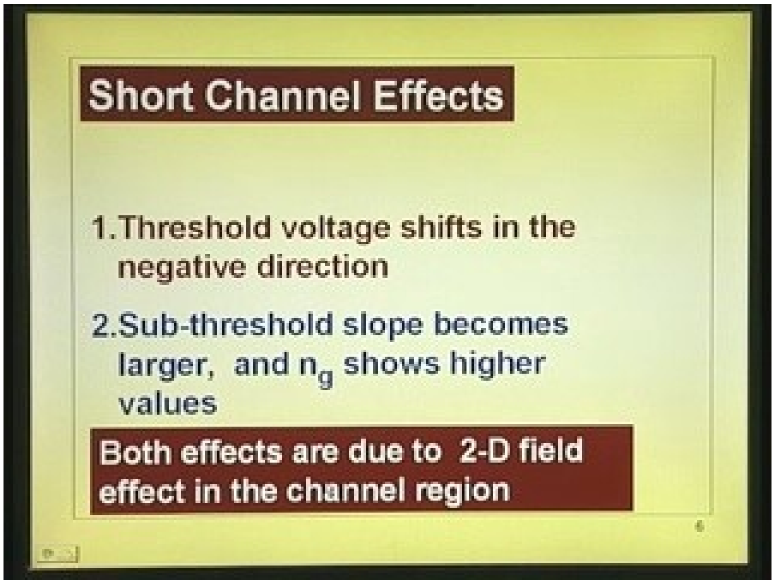

Short Channel Effects

1. Threshold voltage shifts in the negative direction
2. Sub-threshold slope becomes larger, and n_g shows higher values

Both effects are due to 2-D field effect in the channel region

The entire cause is the field in the vertical direction that is one-D, then it is completely under our control. The moment the other field also comes in, then the control of gate is reduced, it does not have as much control as it had earlier. That is why that ng factor comes, that is why the threshold voltage becomes more negative and you must apply more voltage. You must cut down the field in that direction for a given current. How can you cut down the field? You can cut down the field or increase the other field - both are same. You can increase the vertical field by increasing the doping and of course follow it up with reduction of thickness; this is the thumb rule.

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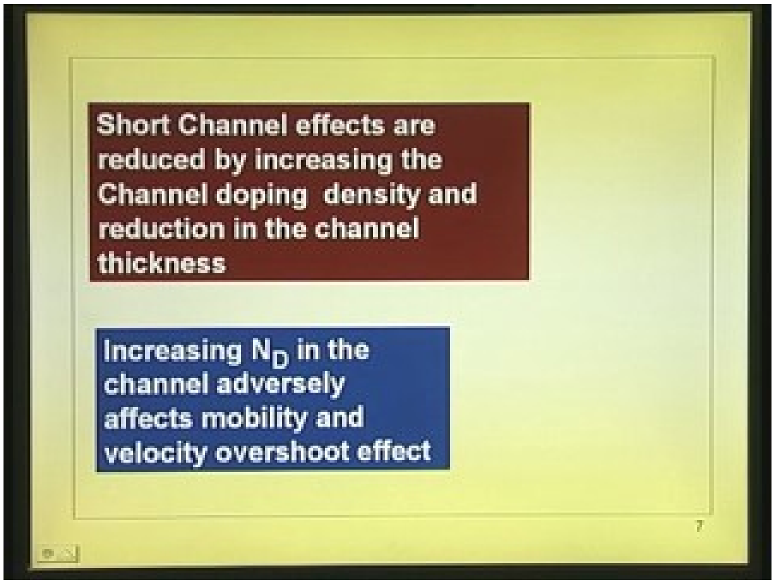

Short Channel effects are reduced by increasing the Channel doping density and reduction in the channel thickness

Increasing N_D in the channel adversely affects mobility and velocity overshoot effect

Scaling - you have to scale down the thickness of the channel and increase the doping. Increasing N_D in the channel adversely affects the mobility. You prefer to increase the doping to reduce the short channel effect. But that affects mobility and also affects the velocity overshoot effect because after all it rises slowly. So in a given time the peak velocity up to which go will be not as much as you expect; what is the solution?

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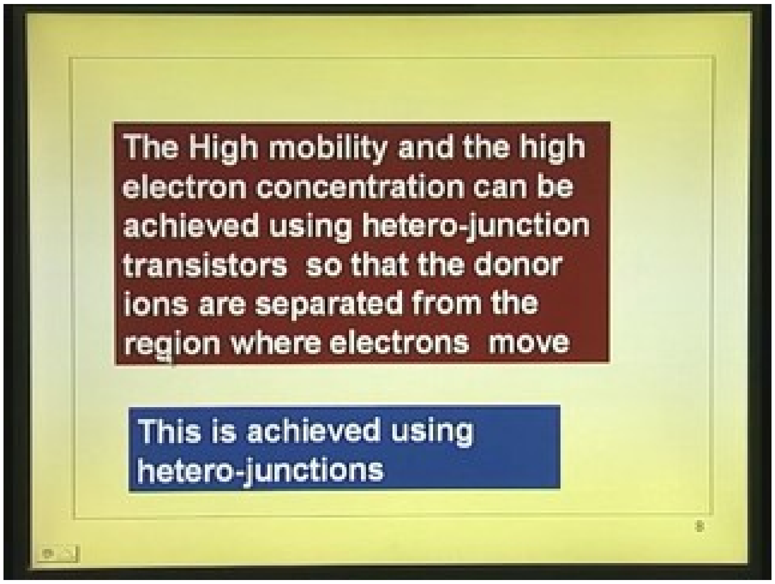

The High mobility and the high electron concentration can be achieved using hetero-junction transistors so that the donor ions are separated from the region where electrons move

This is achieved using hetero-junctions

The high mobility and high electron concentration can be achieved using hetero structures. Now you can see we are moving from the MESFET. At this point we will stop discussing about the MESFET, the structure that we are discussing, but we move on to a device called high electron mobility transistors. Here it affects mobility because you want high doping. What you require ultimately is high carrier concentration. For a given current flow, the field will be smaller if the carrier concentration is made high. J is equal to mobility into n into electric field into q. If you increase n, the field will be smaller. In a MESFET, to increase n, doping must be increased; so that is the thing. To use hetero junction transistor, what you do there is, you actually cheat the donors. In the sense, you have a device where the ionized donors are located in one place and the electrons are located in a different portion of the device where the doping is not high. This is achieved by using hetero junction.

Since there is not much time, I will just briefly mention what we are trying to do. We will go ahead with the hetero junction etcetera tomorrow or in the next lecture. I do not want take it now. But I want to mention a few things - what we mean, where the dopants are, where the electrons are, etc. How it done we will understand in the next couple of lectures; it is like this.

We are now on to the nineteen eighties or nineties or current which are going on in this device, real high-speed devices. What you do is you have n layer or p layer whatever it is; you have a layer here (Refer Slide Time: 53:40). I put it as i layer, undoped. Now you put a layer here which has the dopants; layer, doped layer N_D or the dopants. Now if you make a hetero junction, what we mean by hetero junction is, the band gap here is E_{g1} and band gap here is E_{g2} (Refer Slide Time: 54:15).

If you do that, which we will illustrate, if you do that, supposing it is i or p very lightly doped, you want it very lightly doped because when the electrons are here, they do not to experience ionizing between scattering. If you do that what happens is the donors here will supply the electrons to this layer. How it is done we will see in the next lecture, but this is exactly the same thing you do in case of MOSFET. In a MOSFET, what do you have? You have an oxide, you have a gate. Here also you can put a gate if you want to control this charge (Refer Slide Time: 55:04). What do you do in the case of MOSFET? What is the energy band diagram incase of MOSFET? Three types of substrates if you take; MOS capacitance if you take, what is the energy band diagram?

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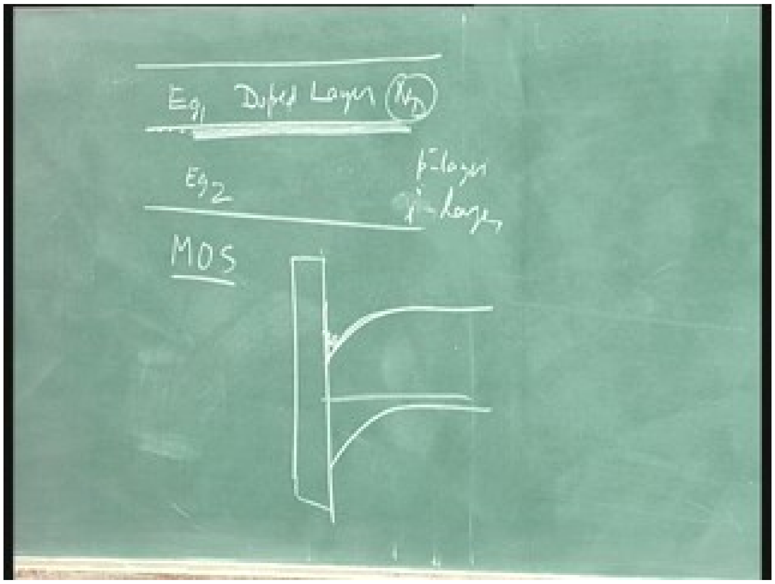

That is the conduction band of the oxide, valance band of oxide. So you will have energy band diagram like this - inverted region (Refer Slide Time: 55:35). You can see the electrons are locked here. You have a notch here. That is the inversion layer. Electrons somehow come here due to applied gate voltage and they are locked here because they cannot climb up to here. That is oxide. If you make a hetero junction, you will get a similar notch here. When you go from here to here, you will have a notch. It will actually collect the electrons here and those electrons from the donor level. This is heavily doped donor (Refer Slide Time: 56:10). This is lightly doped - these electrons experiences only lateral scattering. I will discuss details of this hetero structure in the next lecture; it is quite interesting actually.