# HIGH SPEED DEVICES AND CIRCUITS

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## Lecture – 24

## MESFET: Drain Current Saturation $I_{DS}$ due to Velocity Saturation

We have been discussing the effect of velocity saturation infact what we have to see is, I will just quickly go through that, what we saw was that two cases. The two cases which we see in the diagram here: one of them the channel is pinching off at the drain end; the other one the channel is not pinching off. Both of them actually have current saturation and both of them have current saturation due to velocity saturation. The only difference is in the first case the long channel device and in such situation we have seen that the velocity saturation and the drain pinch off at the drain end coincide. That is actually the voltage drop here $V_{bi}$ minus $V_{GS}$ plus $V_{DS\ (sat)}$ turns out to be equal to $V_{p0}$; that is Shockley's condition.

Now in this case, it is all short channel devices or small pinch off voltages, both cases we have seen. Then the velocity saturation occurs much before the channel pinch off. That is what we have seen here.

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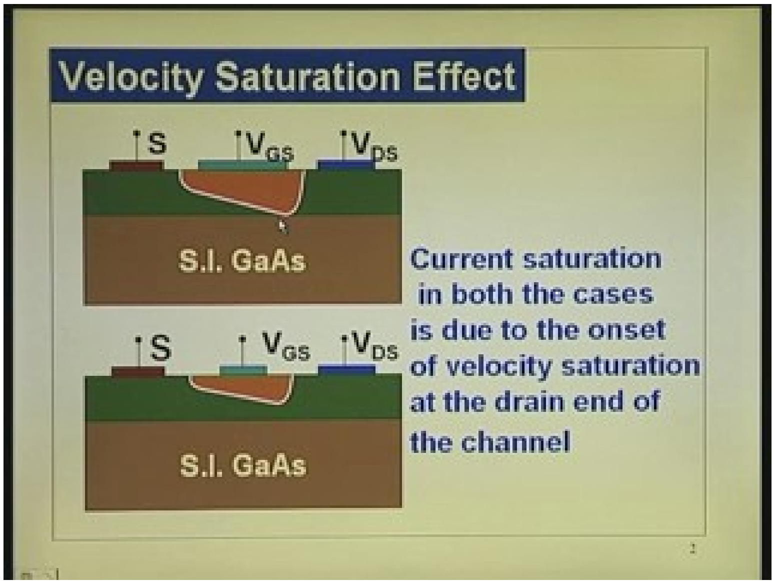

## Velocity Saturation Effect

Current saturation
in both the cases
is due to the onset
of velocity saturation
at the drain end of
the channel

Current saturation is due to onset of velocity saturation in both cases at the drain end, the velocity saturation at the drain end. In long channel devices it coincides with the channel pinch off. This equation is not valid, it cannot be used really or determining $V_{DS(sat)}$ in general case.

It can be used in long channel devices or in the devices where $V_{p0}$ is small, because our criterion was the parameter alpha which is actually equal to this. This is very much larger than 1, that is L is very large and $V_{p0}$ is being large small; even $V_{p0}$ is large if L is very large that must be greater than 1. Shockley’s condition and this is very much small. This is very small compared to 1, if that is small. Particularly, for small channel devices then you cannot apply the $V_{DS\ (sat)}$ criterion this particular one.

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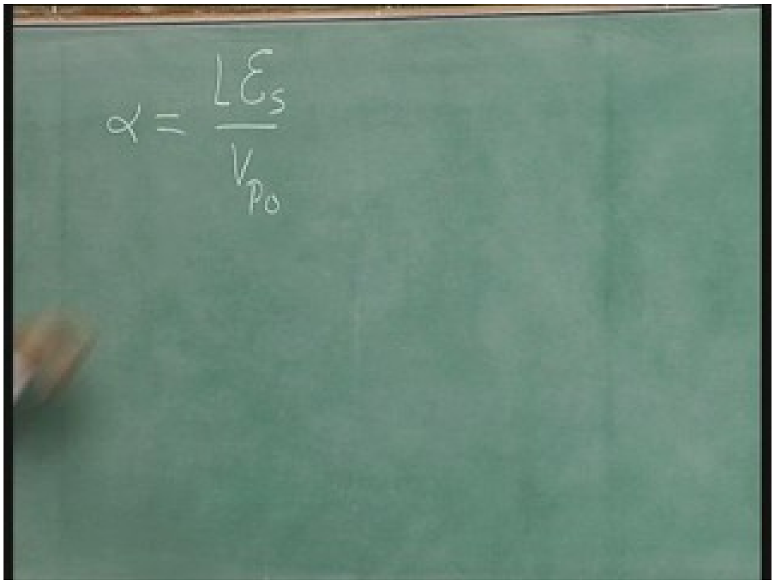

In general, what you do is, you approximate the velocity field characteristics, try piece wise linearization V is proportional to electric field, till the electric field is $E_{s,}$ saturation field and up to that point V is equal to mu$_n$ into E for E less than or equal to that. It is valid up to this point and beyond that point velocity is equal to saturation velocity. And saturation velocity is given also by this equation is valid try it up to that point.

Now what is the difficulty here? The difficulty is in Shockley's analysis, you assume the saturation occurs at a particular value of $V_{DS(sat)}$ which gives $V_{bi}$ minus $V_{GS}$ certainly is equal to $V_{p0.}$ Now if the saturation occurs at voltage less than that, you can notice that condition but you know that saturation will occur, in any general case, saturation will occur when the velocity saturates at the drain end.

That is why you have two unknowns now. In the previous case you were assuming this and finding out $I_{DS,}$ substituting it in the equation for ID.

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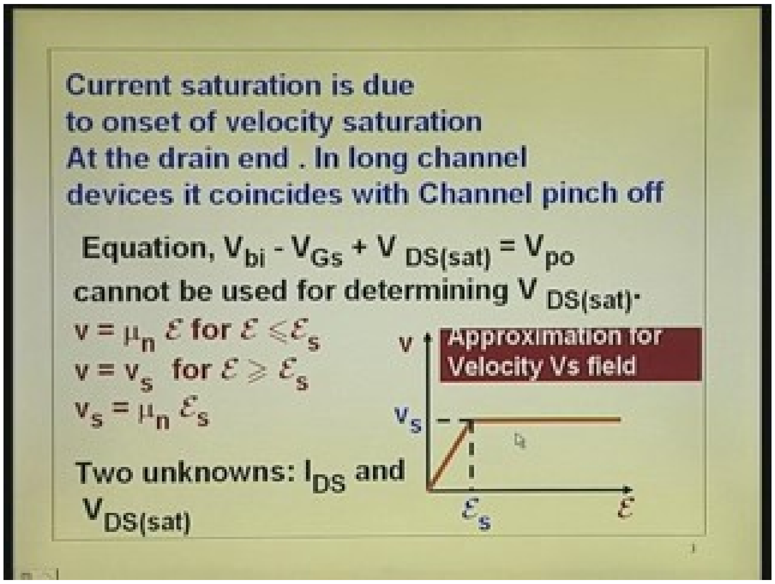

Current saturation is due
to onset of velocity saturation
At the drain end . In long channel
devices it coincides with Channel pinch off

Equation, $V_{bi} - V_{GS} + V_{DS(sat)} = V_{po}$
cannot be used for determining $V_{DS(sat)}$.

$v = \mu_n \mathcal{E}$ for $\mathcal{E} \leqslant \mathcal{E}_s$
$v = v_s$ for $\mathcal{E} \geqslant \mathcal{E}_s$
$v_s = \mu_n \mathcal{E}_s$

Two unknowns: $I_{DS}$ and $V_{DS(sat)}$

Approximation for Velocity Vs field

Now the two equations, I have just gone through it and quickly go through that, so for E less than E of s that is in this region that is from the source end close to the drain end of the channel, you can write that equation.

All that you have done is I am just quickly going through that because we have discussed in the last lecture. All that we have done is $V_{DS(sat)}$ by $V_{p0}$, I write it as $u_{ds}$, normalize and $I_{DS}$ is actually capital $I_{DS}$ divided by $t_0$ $V_{p0}$ normalized value of current, normalized values of voltages. So $u_{GS}$ is Vbi minus $V_{GS}$ by $V_{p0}$.

In fact it makes this equation look simpler, normalized values with respect to $V_{p0}$ and this quantity is $V_{DS(sat)}$ plus $V_{bi}$ minus $V_{GS}$ by $V_{p0}$. This is the standard equation we have derived from Shockley’s analysis which assumes velocity is equal to mu into E that is valid up to this point.

Now once you go to the drain end, we have seen that the current can be written as alpha into 1 minus this quantity. This I do not have to go through it once again. We have discussed that. All that we did was we wrote this equation J is equal to qn into v and E is equal V of s. And current is equal to qn into V of s into area and area is W into h minus that a.

You substituted for h and a in terms of $V_{p0}$, h in terms of $V_{DS\ (sat)}$. That is what you get here. This is just to recapitulate your memory into the last one. Now we have got equation one and equation two, $i_{ds}$, that is one unknown, $u_{ds}$ is another unknown and we are writing this equation for a particular gate voltages. In a given equation $u_{GS}$ is fixed.

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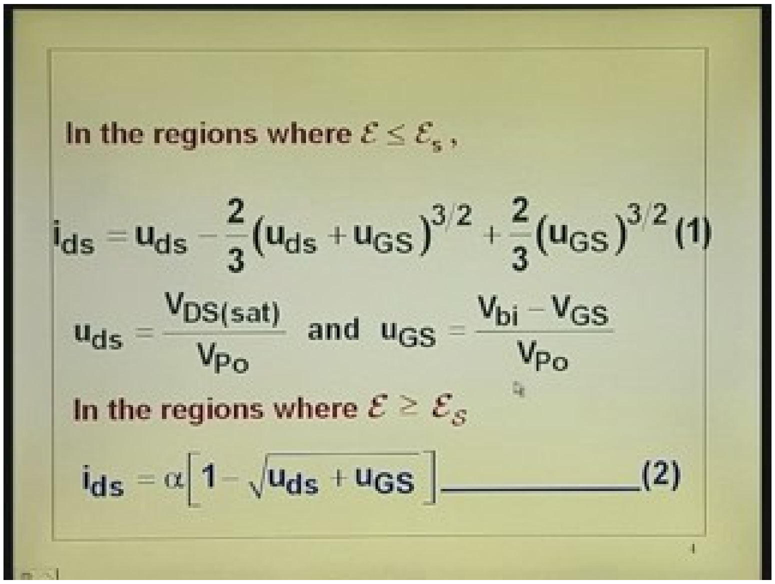

In the regions where $\mathcal{E} \le \mathcal{E}_s$ ,

$$i_{ds} = u_{ds} - \frac{2}{3}(u_{ds} + u_{GS})^{3/2} + \frac{2}{3}(u_{GS})^{3/2} \quad (1)$$

$$u_{ds} = \frac{V_{DS(sat)}}{V_{Po}} \quad \text{and} \quad u_{GS} = \frac{V_{bi} - V_{GS}}{V_{Po}}$$

In the regions where $\mathcal{E} \ge \mathcal{E}_S$

$$i_{ds} = \alpha\left[1 - \sqrt{u_{ds} + u_{GS}}\right] \underline{\qquad\qquad} (2)$$

What you are telling is in general $i_{ds}$ is given by these two equations. This is for E less than E of s, this is E equal to or greater than E of s, but what you have to understand is that this current and this current are the same because this is in the channel region up to the drain end, it is the current at the drain end. Whatever enters the channel goes through the channel and can the channel, so these two are equal.

In other words what you are telling is two unknowns are there $i_{ds}$ and $u_{ds}$ and two equations are there, equate the two, you are eliminating $i_{ds}$. Now you have got alpha is equal to $u_{ds}$ minus two thirds of $u_{ds}$ plus $u_{GS}$ power 3 by 2. That is this quantity divided by this quantity, alpha.

All that you did is, equated the two, and so left hand side goes off, alpha becomes equal to that right hand side of this divided by this quantity. In fact initially, we wrote this equation also last time but we deviated from this point that is it. Let us take alpha is very much larger than 1, that is alpha is very much low. That told us that alpha is equal to very much larger than 1, satisfies the Shockley's condition, that is why we did that.

Now let us take a look at the general equation, so at the general equation is derived from Michael soo of transfer technique right now.

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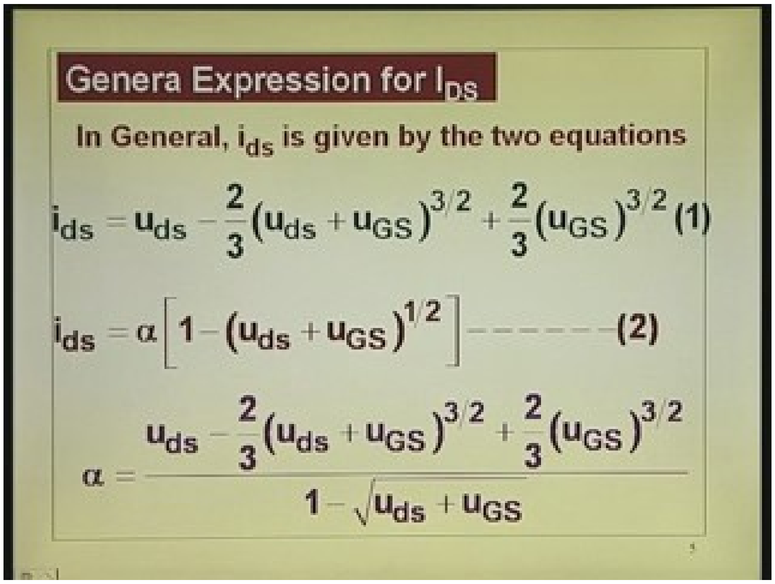

Genera Expression for $I_{DS}$

In General, $i_{ds}$ is given by the two equations

$$i_{ds} = u_{ds} - \frac{2}{3}(u_{ds} + u_{GS})^{3/2} + \frac{2}{3}(u_{GS})^{3/2} \quad (1)$$

$$i_{ds} = \alpha\left[1 - (u_{ds} + u_{GS})^{1/2}\right] ------(2)$$

$$\alpha = \frac{u_{ds} - \frac{2}{3}(u_{ds} + u_{GS})^{3/2} + \frac{2}{3}(u_{GS})^{3/2}}{1 - \sqrt{u_{ds} + u_{GS}}}$$

What he did in it, what we have done there is, for a particular $u_{ds}$ rewrite $i_{ds}$ versus $u_{ds}$ characteristics, now what we did here is we assumed a particular value of alpha and find out the $u_{ds}$ or alternatively plot $u_{ds}$ as a function of alpha. For a given $u_{GS}$, $u_{GS}$ is $V_{bi}$ minus $V_{GS}$ by $V_{p0}$ is less than 1. For any given $u_{GS}$ what you do is alpha versus $u_{ds}$ is plotted analytically when I say analytical, the meaning is I have got that from this. This equation is regress.

Substitute, give values for $u_{ds}$, $u_{ds}$ here $u_{ds}$ here everything for a given $u_{GS}$. Find out what alpha is. The correct way to point out is put alpha and what is $u_{ds}$ is, that means we have got numerical but we can get around it with a simple calculator, that is analytical. Now what was done in the literature way back by Michaela shore was, you get $u_{ds}$ versus alpha, which you obtain regressively for a particular $u_{GS}$.

I can approximate it, I am sorry this is numerical, this is not analytical, this is numerical value but what he did was what I mentioned just now is, you take $u_{ds}$ value and find alpha. But we can numerically also you can do or regressively you can do, find out alpha versus $u_{ds}$. This matches this thing.

You plot alpha versus $u_{ds}$ in this equation. Now you get an analytical expression which fits in very close to that. What they did is this is in not a very good language but we can say that is adjusting it, adjust those equations, that is called interpolation and we can say that, what they found is this equation can be fitted by an analytical expression with this. That is $u_{ds}$ as a function of alpha for a given $u_{GS}$ can be obtained by this.

They plotted a number of curves like this for different $u_{GS}$. As you know the one curve for one $u_{GS}$ they have plotted number of curves with different $u_{GS}$ and then said I can fit in $u_{ds}$ versus $u_{GS}$ through alpha by this equation. This you can take it in fact you can substitute it and see. That holds good for different $u_{GS}$ numerical and analytical. Analytically is this expression.

Now once you have got this, see ultimately what do you want? You want to get $i_{ds}$ versus $u_{ds}$.

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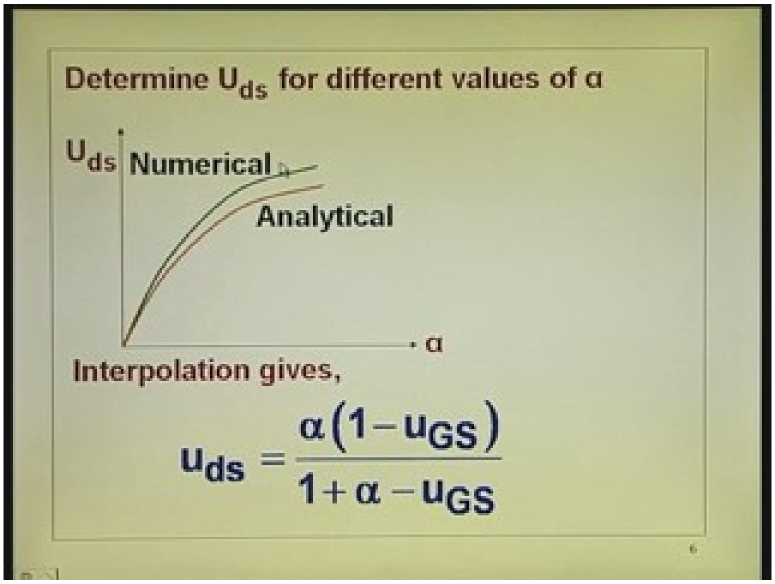

Determine $U_{ds}$ for different values of $\alpha$

Interpolation gives,

$$u_{ds} = \frac{\alpha(1-u_{GS})}{1+\alpha-u_{GS}}$$

You have got $u_{ds}$ as saturation voltage as a function of $u_{GS.}$ In the Shockley's analysis what did you get? You got saturation voltage into $u_{GS.}$ See if you recall, Shockley's assumption that is alpha very much greater than 1, $V_{bi}$ minus $V_{GS}$ plus $V_{DS(sat)}$ is equal to $V_{p0.}$ So $V_{DS(sat)}$ is obtained from $V_{GS}$ and alpha is of course hidden, here it is not coming in to picture here.

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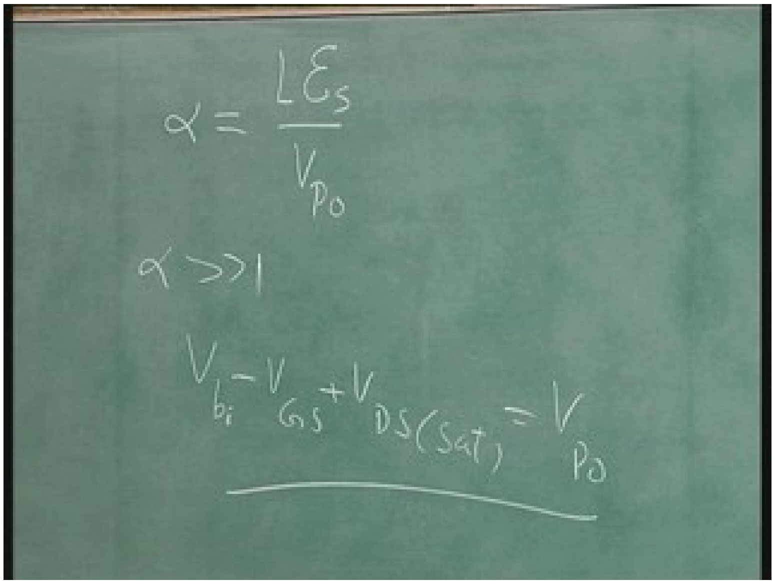

But here we are obtaining $V_{DS(sat)}$ in terms of $u_{GS.}$ But we get a more involved equation because it is a general in this expression, which fits in closely to the numerical thing. Now use this equation in this equation. We have got an analytical expression for $u_{ds.}$

Let me go back to that. You have got an analytical expression for $u_{ds,}$ now what you do is substitute $i_{ds}$ equals alpha into 1 minus root of this. All that you do is you substitute for this analytical expression that you have got just now.

This sum amount of interpolation or extrapolation, whatever you want to call it, from the newly retrieved thing, it is the best fit curve that they have obtained and they found that whole square root part is depending upon $u_{GS.}$ Substitute for that then you get $i_{ds}$ in terms of, now you got $u_{ds}$ in terms of $u_{GS,}$ that means you removed $u_{ds}$ and replace it in terms of alpha and $u_{GS.}$ Right hand side contains only alpha and $u_{GS.}$

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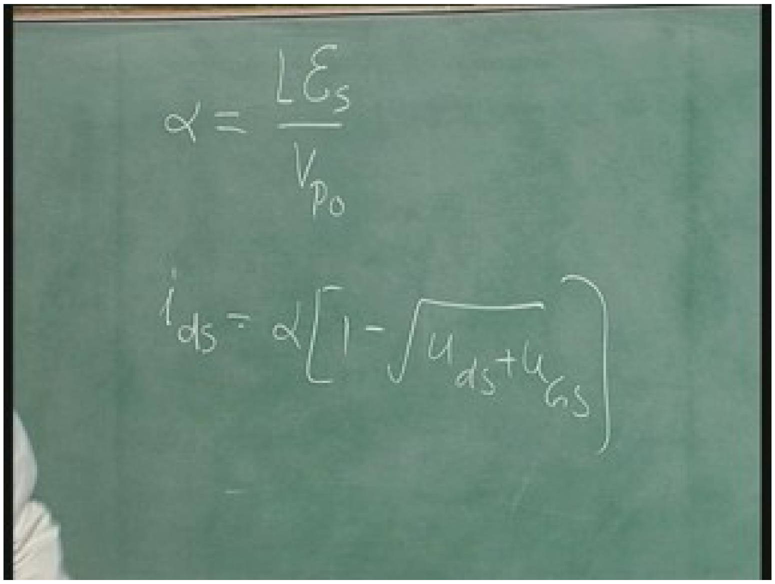

$$\alpha = \frac{L\mathcal{E}_s}{V_{p0}}$$

$$i_{ds} = \alpha\left[1 - \sqrt{u_{ds} + u_{GS}}\right]$$

You do that then again little bit of curve fitting they did, they have got that expression. So you can see that it is not a straight forward thing that we have done but on about that way and shown this gives the best fit. The power of getting this particular analytical expression is you can see it, see what happens when alpha changes. Because after all let us see what is this expression? If this expression is correct and alpha is very much greater than 1, you must get mu$_n$ C$_s$ W by 2L V$_{GS}$ minus u$_{GS}$ to the whole squared.

Let us see what it is? What I do now is or remove those normalizing parameters. i$_{ds}$ is capital I$_{DS}$ by G$_0$ V$_{p0.}$ So I just substituted for that and alpha divided by 1 plus 4alpha is retained and this quantity is V$_{bi}$ minus V$_{GS}$ by V$_{p0,}$ you have come out of the normalizing parameters, writing the actual currents.

Now what we do is remove this V$_{p0}$ square outside, so you get G$_0$ by V$_{p0.}$ V$_{p0}$ divided by V$_{p0}$ square, that is that, alpha by 1 plus 4alpha there within bracket of course, V$_{p0}$ minus V$_{bi}$ plus V$_{GS}$ whole squared. Now what we do is we do remember that G$_0$ by 4V$_{p0}$ is term that is mu$_{Cs}$ W by 2L.

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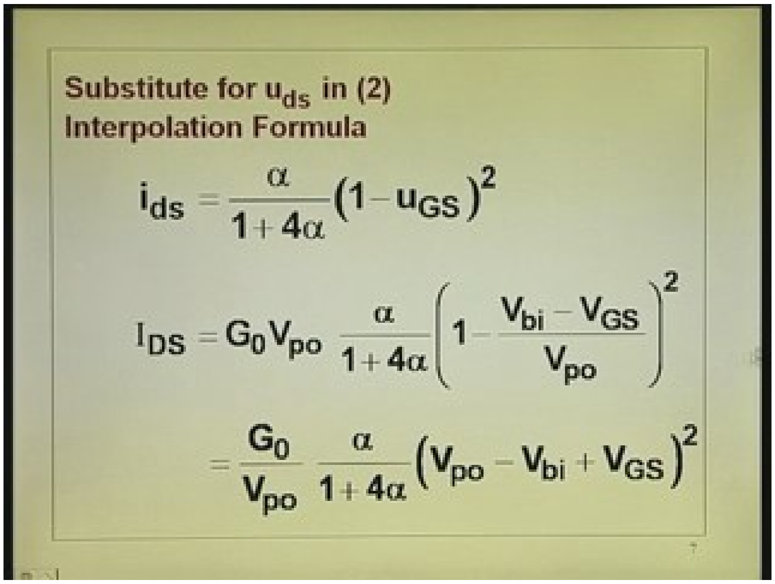

Substitute for $u_{ds}$ in (2)

Interpolation Formula

$$i_{ds} = \frac{\alpha}{1+4\alpha}(1-u_{GS})^2$$

$$I_{DS} = G_0 V_{po}\,\frac{\alpha}{1+4\alpha}\left(1-\frac{V_{bi}-V_{GS}}{V_{po}}\right)^2$$

$$= \frac{G_0}{V_{po}}\,\frac{\alpha}{1+4\alpha}\left(V_{po}-V_{bi}+V_{GS}\right)^2$$

I multiply it by 4 divide it by 4, not yet. I have rewritten of that equation, multiply this by 4 divide it by 4, same equation I rewritten four, four and also what we have done is substituted for this quantity, $V_{GS}$ minus $V_{threshold}$ because $V_{bi}$ minus $V_{p0}$ is $V_{threshold}$ voltage. That is what we have done.

First, what I have done is substituted for this quantity and then what I did is multiplied by 4 divided 4. What is this quantity now?

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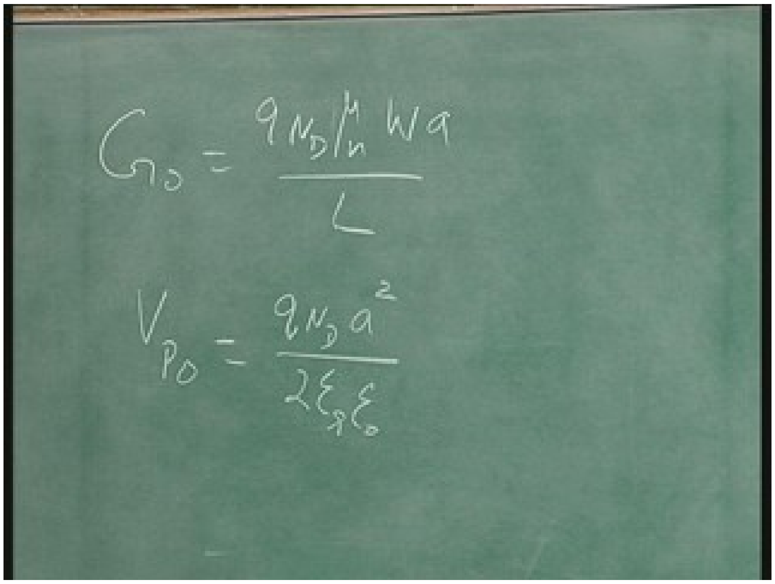

$$G_0 = \frac{q N_D \mu_n W a}{L}$$

$$V_{P0} = \frac{q N_D a^2}{2 \epsilon_s \epsilon_0}$$

$G_0$ by $4V_{p0}$, if you recall $G_0$ is actually equal to $qN_D$ $mu_n$ that is sigma into Wa divided by L, and $V_{p0}$ is $qN_D$ a squared divided by, so divide it by that and therefore you get this in fact $qN_D$ is cancelled and you get, you have seen this earlier, so it is actually this quantity. Now you can see, I again rewrite it and this quantity is nothing but beta that we are calling, $beta_0$ I call it. This quantity I call it $beta_0$ and 4 alpha by 1 plus 4 alpha into that. The whole thing we call it as beta, let me go back to this now.

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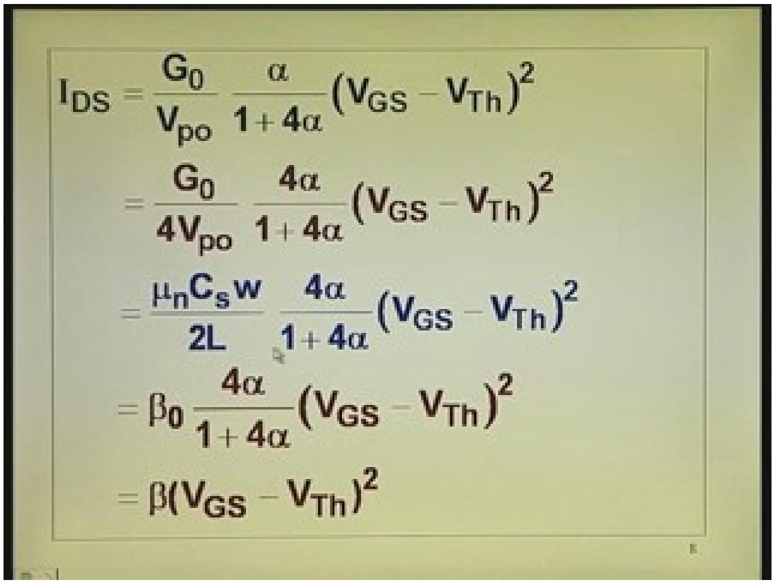

$$\begin{aligned}
I_{DS} &= \frac{G_0}{V_{po}} \frac{\alpha}{1+4\alpha}(V_{GS} - V_{Th})^2 \\
&= \frac{G_0}{4V_{po}} \frac{4\alpha}{1+4\alpha}(V_{GS} - V_{Th})^2 \\
&= \frac{\mu_n C_s w}{2L} \frac{4\alpha}{1+4\alpha}(V_{GS} - V_{Th})^2 \\
&= \beta_0 \frac{4\alpha}{1+4\alpha}(V_{GS} - V_{Th})^2 \\
&= \beta(V_{GS} - V_{Th})^2
\end{aligned}$$

Last time we saw Shockley's model, what does it give you? $I_{DS}$ which is equal to VGS minus $V_{threshold}$ whole squared. This is what we saw from Shockley's model.

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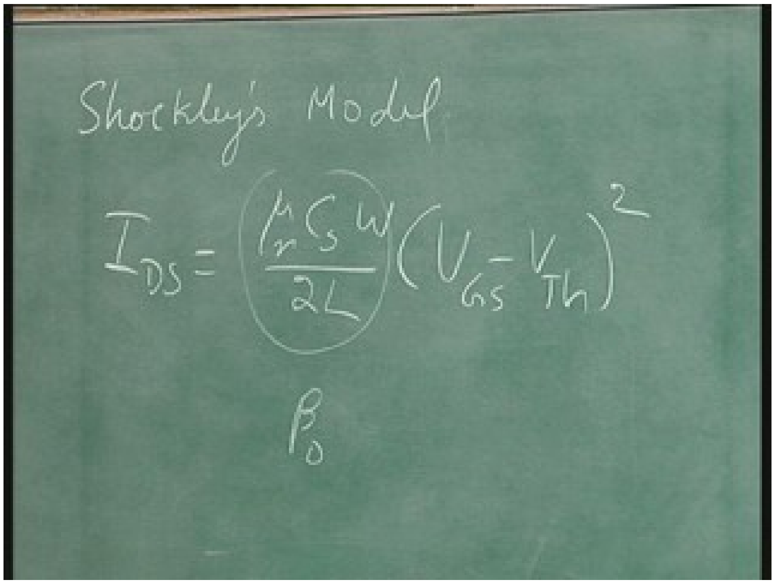

Shockley's Model

$$I_{DS} = \boxed{\frac{\mu_n C_s W}{2L}} (V_{GS} - V_{Th})^2$$

$$\beta_0$$

And this I call it as beta$_0$. Just beta$_0$ because to distinguish from what we are going to call later, so in this case what we have got is, now what we got is, that quantity, see this is same as Shockley's equations, except you got a multiple factor 4 alpha by 1 plus 4 alpha. That is all what you have got.

I retained this term as beta$_0$; beta$_0$ into 4 alpha by 1 plus 4 alpha $V_{GS}$ minus $V_{threshold}$ squared. The total thing we can call it as beta. In fact beta will be the factor which decides what is your current, saturation current is for a given $V_{GS}$ and it is also a factor which determines what the value of transconductance is.

I just deliberately did this analysis because it gives lot of insight into what is happening when keep on reducing the channel length.

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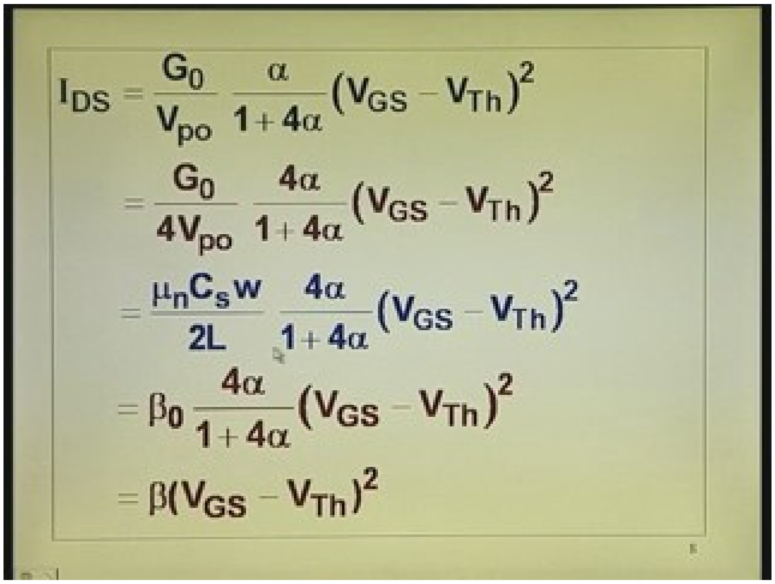

$$I_{DS} = \frac{G_0}{V_{po}} \frac{\alpha}{1+4\alpha}(V_{GS}-V_{Th})^2$$

$$= \frac{G_0}{4V_{po}} \frac{4\alpha}{1+4\alpha}(V_{GS}-V_{Th})^2$$

$$= \frac{\mu_n C_s w}{2L} \frac{4\alpha}{1+4\alpha}(V_{GS}-V_{Th})^2$$

$$= \beta_0 \frac{4\alpha}{1+4\alpha}(V_{GS}-V_{Th})^2$$

$$= \beta(V_{GS}-V_{Th})^2$$

Let us see what happens so here if alpha is very much large compared to 1, what is this quantity? 1, then you get that expression beta$_0$ into $V_{GS}$ minus $V_{threshold}$ just Shockley's analysis. alpha is very much larger than 1 is actually the channel length is long. So Shockley's analysis holds good there, transconductance current everything is same as Shockley's analysis.

Now that is the thing. When alpha is very much less than 1, go back to that equation and alpha is very much less than 1 or 4 alpha is very much less than 1, it becomes beta$_0$ into 4 alpha. They can neglect that, beta$_0$ into 4 alpha, that is beta$_0$ into 4 $L_{Es}$ by $V_{p0,}$ if we recall alpha is this quantity $L_{Es}$ by Es is electric field saturation field by $V_{p0.}$

Now what is this beta? Because after all what you got now is, in general what we got is a general expression $I_{D(sat)}$ equals beta$_0$ into 4 alpha divided by 1 plus 4 alpha, that is equal to beta times $V_{GS}$ minus $V_{threshold.}$

What I am trying to get that is beta this quantity. So this is the thing, alpha very much larger than this becomes beta$_0$ itself and then alpha is very small that becomes beta$_0$ into 4 alpha and alpha is actually equal to alpha is equal to $L_{Es}$ by $V_{p0.}$

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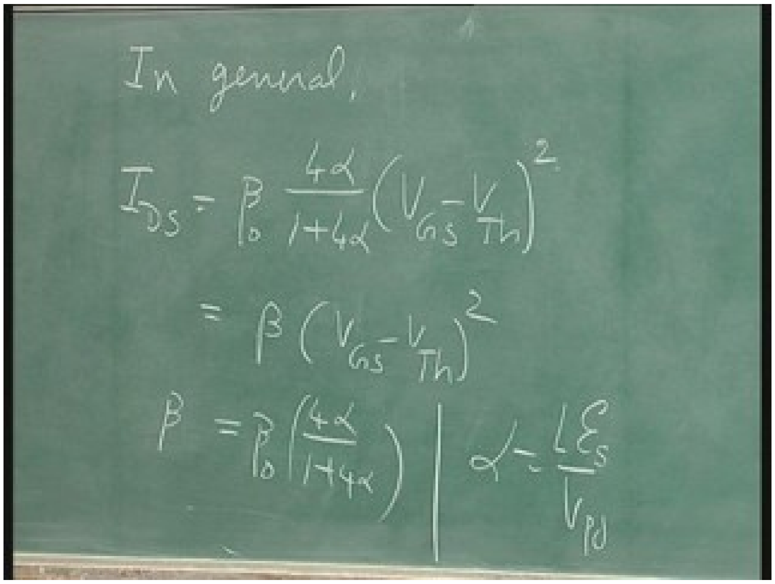

In general,

$$I_{DS} = \beta_0 \frac{4\alpha}{1+4\alpha}\left(V_{GS} - V_{Th}\right)^2$$

$$= \beta\left(V_{GS} - V_{Th}\right)^2$$

$$\beta = \beta_0\left(\frac{4\alpha}{1+4\alpha}\right) \Bigg| \; \alpha = \frac{L\mathcal{E}_s}{V_{P0}}$$

It is very clear about long channel, short channel and the channel thing, but what you want see now is that beta by beta$_{0,}$ beta is actually a factor which will decide what is transconductances or a current is for a given $V_{GS}$ minus $V_{\text{threshold}}$ what is the current? Current is larger if beta is larger.

Now you keep on reducing alpha that means you keep on reducing channel length for a given pinch off voltage beta by beta$_0$ keeps on solid.

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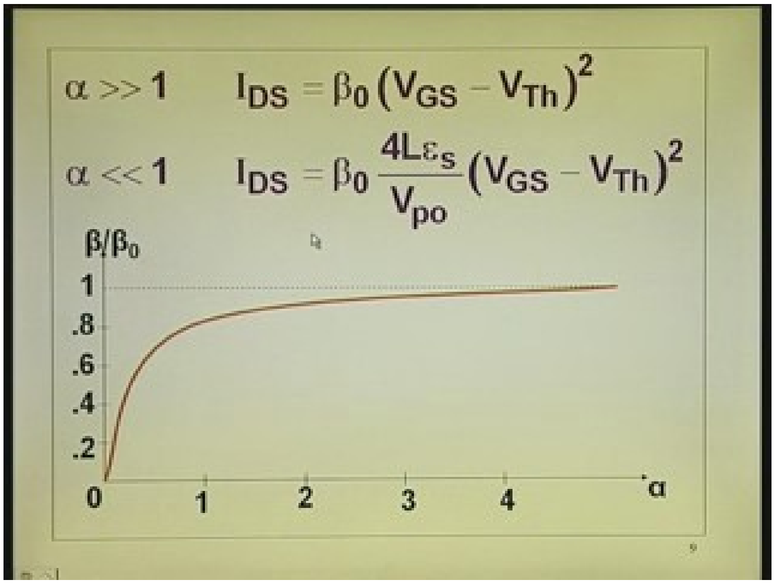

$\alpha >> 1 \qquad I_{DS} = \beta_0 (V_{GS} - V_{Th})^2$

$\alpha << 1 \qquad I_{DS} = \beta_0 \frac{4L\varepsilon_s}{V_{po}} (V_{GS} - V_{Th})^2$

What is the effect of that? This is the numbers chart. I just put the number you can see once alpha is about 2 or 3 then beta becomes beta into beta$_{0,}$ almost the same. You have to worry about this factor coming to picture then alpha is less than about 3, 3 or its 2 also fine, you can say it is Shockley’s alright but when alpha is less than 2 drastically false. So number just for quantitative comparison output beta by beta$_0$ becomes that, .88 when alpha is equal to 2.

When alpha is equal to 2, 2.5 for alpha is equal to 3, there only 8% of that, .92. That is why we put this table. When alpha is 3 almost you can say Shockley is right. That is why he got everything right, most of the time, compared to rest of the experimental results.

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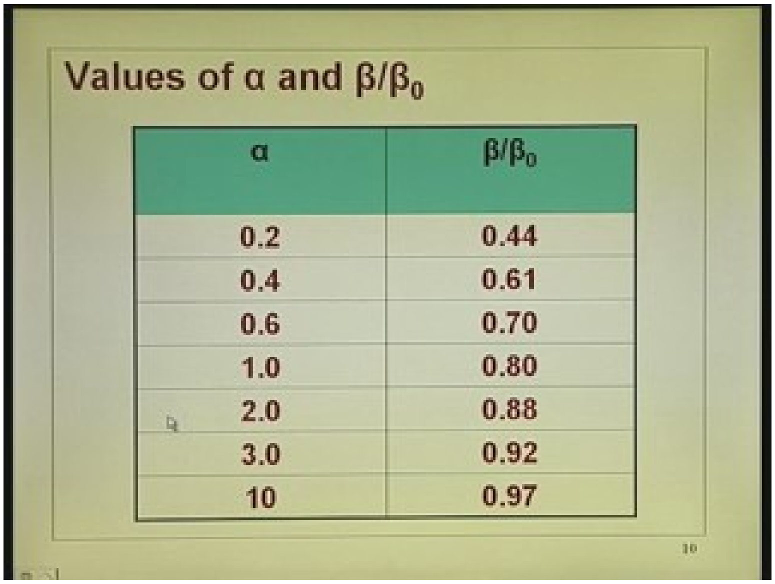

Values of $\alpha$ and $\beta/\beta_0$

| $\alpha$ | $\beta/\beta_0$ |
|---|---|
| 0.2 | 0.44 |
| 0.4 | 0.61 |
| 0.6 | 0.70 |
| 1.0 | 0.80 |
| 2.0 | 0.88 |
| 3.0 | 0.92 |
| 10 | 0.97 |

Now let us put this thing, beta is equal to 4 alpha divided by 1 plus alpha that is what you have got from here.

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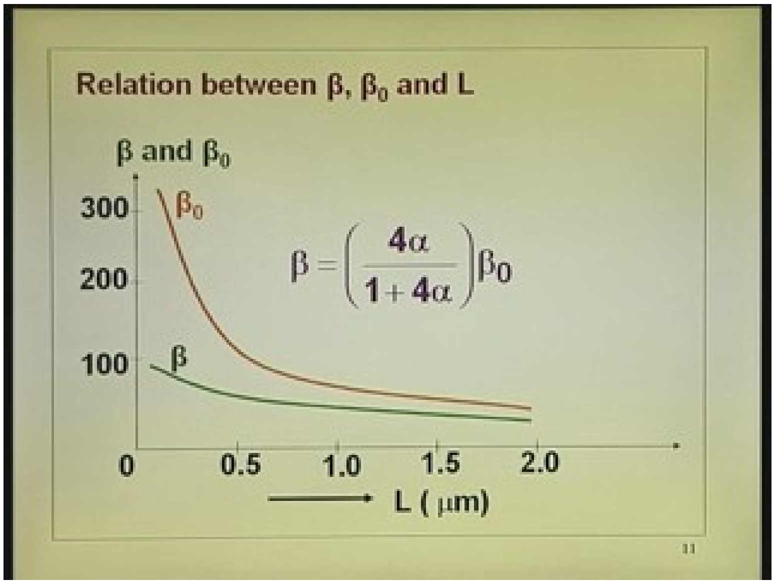
Relation between $\beta$, $\beta_0$ and L



$$\beta = \left(\frac{4\alpha}{1+4\alpha}\right)\beta_0$$

This is the factor. Finally, this term is what $I_{DS}$ is and this is the factor which determines what transconductance is. Transconductance is delta $I_{DS}$ by delta $V_{GS,}$ which is nothing but twice beta into $V_{GS}$ minus $V_{threshold.}$ So you want beta to be high, if beta is high only your transconductance is good. What do we think usually from this expression is from long channel analysis what you think is, what is beta$_0$ even $C_s$ W by 2L.

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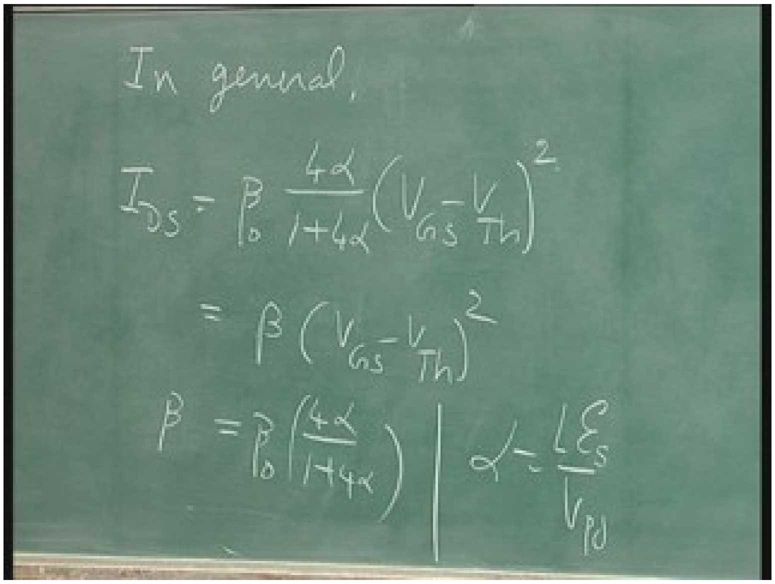

In general,

$$I_{DS} = \beta_0 \frac{4\alpha}{1+4\alpha}\left(V_{GS}-V_{Th}\right)^2$$

$$= \beta\left(V_{GS}-V_{Th}\right)^2$$

$$\beta = \beta_0\left(\frac{4\alpha}{1+4\alpha}\right) \quad \Big| \quad \alpha = \frac{L\mathcal{E}_s}{V_{pd}}$$

What we think is the value is reduced beta will keep on increasing. That is what I have plotted here. This quantity beta$_0$ if mu$_n$ $C_s$ W by 2L that you keep on increasing. For example when L is equal to 2 it may have something like 49 or so it is basic some numbers, but when L is about .5 if you go up to about 100 or if you reduce to .25 if it is 100 here it will become 200.

So beta$_0$ goes up exactly by the same factor as L is reduced. If L is reduced by the factor of 4 beta$_0$ becomes four times. What do you think then, it is your current goes up for a given change in voltage, the changing current is large by same factor, the factor you have reduced L. That is $G_m$ goes up quite a bit but what happens is that beta, actual thing that comes into the equation is not beta$_0$, beta as I keep on reducing L that keeps on falling.

You are from long channel devices you are moving to short channel devices, beta which is nothing but beta$_0$ into that factor, even though beta$_0$ increases this factor pulls it down. The result is the beta of the device does not increase as much as thing it will be. See here, channel length is equal to 2, channel length is equal to 1, in this point actually it would have doubled, channel length 2 to 1, beta$_0$ would have doubled, but beta wouldnot have doubled, it almost flat.

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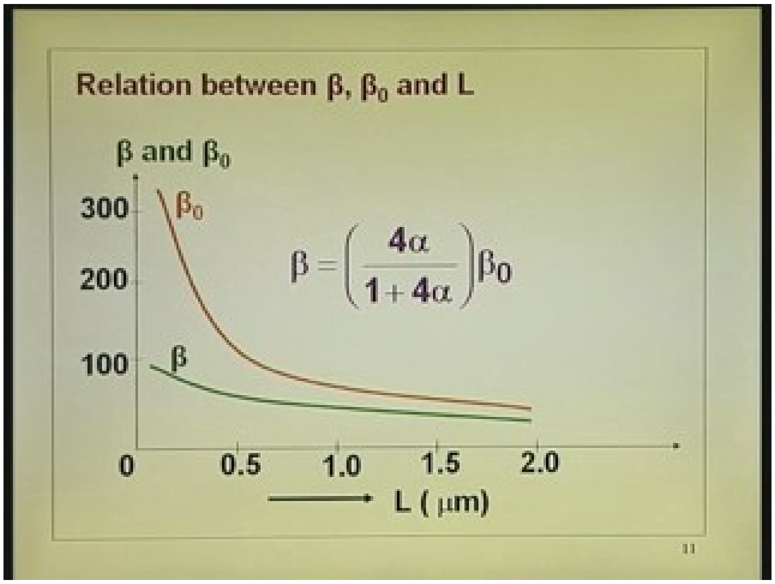

Relation between β, $\beta_0$ and L

$$\beta = \left(\frac{4\alpha}{1+4\alpha}\right)\beta_0$$

Just to get the idea of numbers as you know what values you get, in these devices I put those calculation here example, what you are trying to find out what beta$_0$ is first and you can see beta$_0$ is inversely dependent on channel length.  That is why we just took it that way, all these are constants. Notice that taken mu$_n$ is 4000; I have not taken 8,500 approximate value. Particularly, when you go to doping concentration of 10 to the power 16 and above here the mobility is lower than that, so I just to put 4000 in the L factor better than that.

Now let us go to that, compute this number, for the situation where the channel thickness is .25 micron, this is typical number that you see in MESFET and W is equal to 1 millimeter. Usually these values are expressed as per millimeter width of the channel, because I always cheat, by saying I get better beta, what I do is increase W. To prevent for comparison purposes, you choose a standard either W as 1 millimeter or W as a micron for comparison purpose. You do not take micron because that is not a real number, millimeter also may be a larger size but for analog devices it may be alternative.

So for that you substitute this quantities W and a, then I get this quantity, 9.12 into 10 to the power minus 6 by L. Now all that we have seen is taking L, if I take L equal to 2 microns, 2 into 10 to the power minus 4, that is 2 microns, that is 4.5 into 10 to the power minus 4, that is 45 into 10 to the power minus 3.

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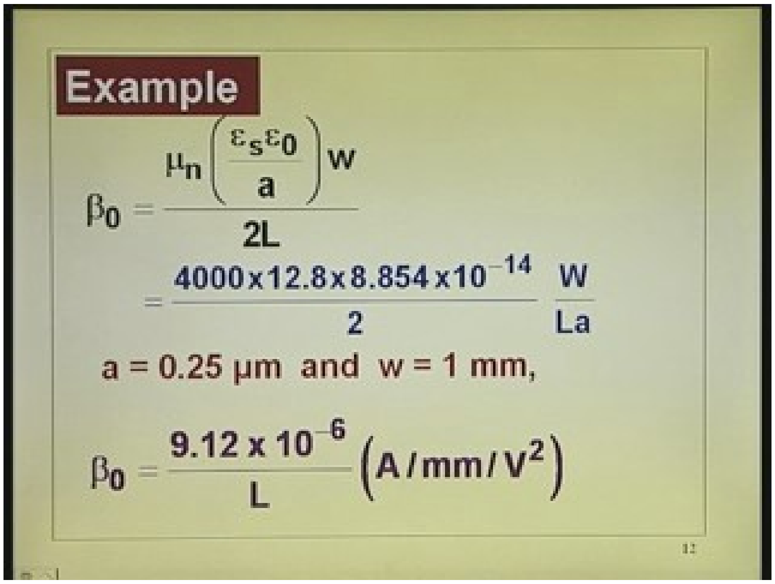

**Example**

$$\beta_0 = \frac{\mu_n \left(\frac{\varepsilon_s \varepsilon_0}{a}\right) W}{2L}$$

$$= \frac{4000 \times 12.8 \times 8.854 \times 10^{-14}}{2} \frac{W}{La}$$

$a = 0.25\ \mu m$ and $w = 1\ mm$,

$$\beta_0 = \frac{9.12 \times 10^{-6}}{L} \left(A/mm/V^2\right)$$

45.6 milli ampere per millimeter per volts square, all we get is when L is equal to 2, what is that beta$_0$, for a channel thickness of .25 micron and W is equal to 1 millimeter. That is why so many milli amperes per milli meter channel width per volt square. This is how you will see, many milli amperes per voltage square, milli ampere per millimeter.

Now what we do again is, a we have taken as .25, what you would like to see is what is alpha now. Because you have got the beta$_0$, what is beta? For that we must find what is V$_{p0}$ is, because after all alpha is decided by not only channel length and the saturation field, if you go to 3 kb per centimeter, by V$_{p0}$, see what this is.

See you have got a good criterion to decide whether alpha is whether it is a long channel or short channel because that is alpha. When you take this substitute all this value V$_{p0}$ is about 1 volt 1.05 took at 1 volt.

Now what is $E_s$ is if we take 3 into 10 to the power 3 volts per centimeter that is missing here, it is so many volts per centimeter. Then L is equal to 2 microns, we have calculated that for 2 microns, L is equal to 2 microns I will take 3 kb per centimeter which is good for Gallium Arsenide devices.

L into E of s, because this 2 into 10 to the power minus 4 into 3 into 10 power 3 this is .6. So 4 alpha by 1 plus four alpha is .7. See alpha is less than 1, in this case .6 its actually short channel device, you know its 2 microns.

Now beta is equal to $beta_0$ into .7, $beta_0$ is 45.6 this we saw just now, so this is 31.98.

What we said is if alpha were not coming to picture, as both are long channel devices and reduced, if I reduce channel length from 2 to 1 micron that would go from 45.6 to 91.2.

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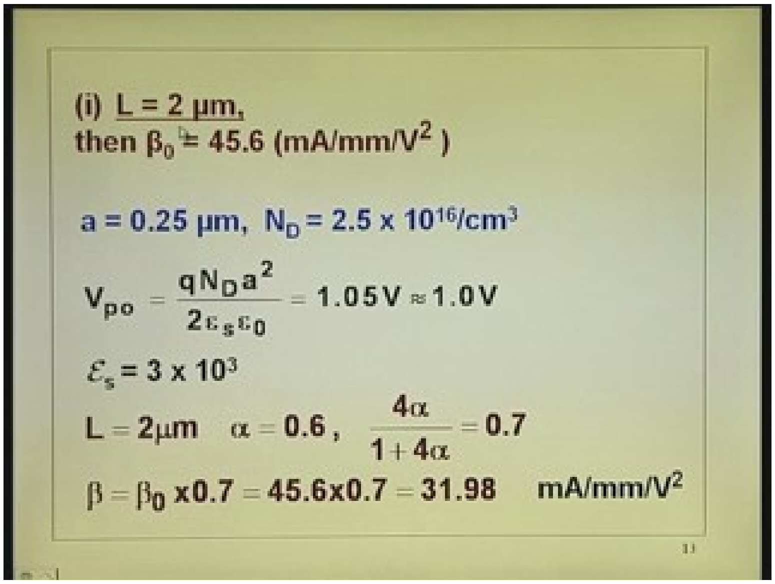

(i) L = 2 μm,
then $\beta_0$ = 45.6 (mA/mm/$V^2$ )

a = 0.25 μm, $N_D = 2.5 \times 10^{16}/cm^3$

$$V_{po} = \frac{qN_D a^2}{2\varepsilon_s \varepsilon_0} = 1.05V \approx 1.0V$$

$\mathcal{E}_s = 3 \times 10^3$

$L = 2\mu m \quad \alpha = 0.6, \quad \frac{4\alpha}{1+4\alpha} = 0.7$

$\beta = \beta_0 \times 0.7 = 45.6 \times 0.7 = 31.98$ mA/mm/$V^2$

But now even for 2 microns it is 31.98, if nothing else happens it would have been 62 when you make L is equal to 1. I will just plug in those numbers just go through that same calculations, you will get beta is equal to instead of 91.2 you get 49.7.

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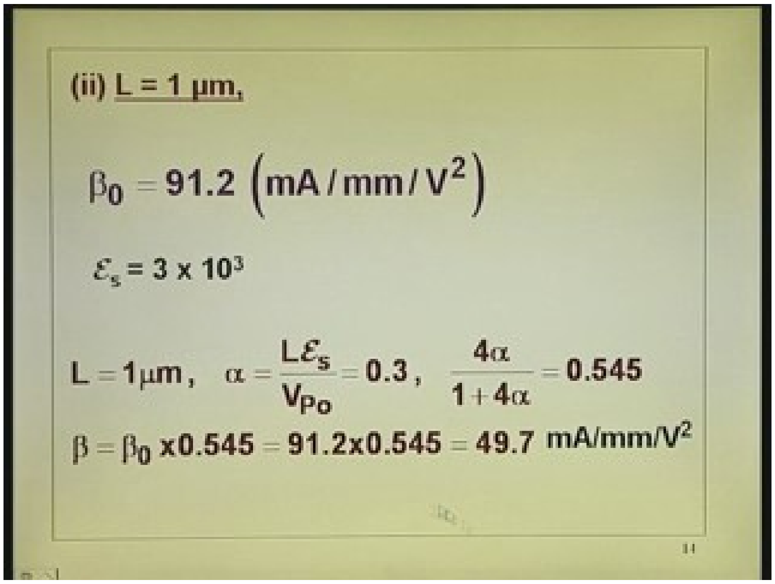

**(ii) L = 1 μm,**

$$\beta_0 = 91.2\ \left(\text{mA/mm/V}^2\right)$$

$\mathcal{E}_s = 3 \times 10^3$

$$L = 1\mu\text{m},\quad \alpha = \frac{L\mathcal{E}_s}{V_{Po}} = 0.3,\quad \frac{4\alpha}{1+4\alpha} = 0.545$$

$$\beta = \beta_0\ \text{x}0.545 = 91.2\text{x}0.545 = 49.7\ \text{mA/mm/V}^2$$

So what you are telling is you get L is equal to 2 microns you get beta is equal to how much is there 3.98 milli ampere per millimeter volts squared. You reduce the channel length by the factor of 2, beta does not increase double; it does not double if it is just 49.7.

So what we are telling is going back to that diagram, this diagram.

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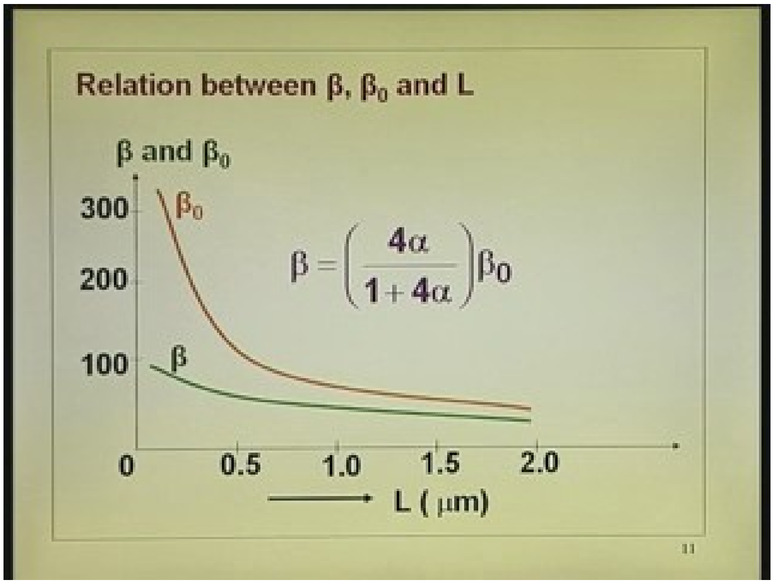

**Relation between β, $\beta_0$ and L**

$$\beta = \left(\frac{4\alpha}{1+4\alpha}\right)\beta_0$$

I illustrated the numbers, I have quickly gone through that but as this equation itself it tells that transconductance does not improve if you reduce the channel length, if you are in the region of short channel devices. Let us see that. Dream what happens? What we saw is this is the channel equation, beta$_0$ into 4 alpha by 1 plus 4 alpha, alpha very much less than 1 that is equal to 4 alpha the factor.

This becomes now beta$_0$ into 4 alpha into that quantity, that is beta$_0$ into 4 alpha into $V_{GS}$ minus $V_{threshold}$ whole squared, which now becomes, I substitute for that alpha which is L E of s by $V_{p0}$. Now look at what happens, extreme case of alpha is very much less than 1 you get this.

What do you see from here? What is see is that numerator L and this L will get cancelled and this whole term is independent of L. That means you will not get any improvement in the current or any improvement in transconductance, once you hit the short channel, L short channel devices.

I just substitute here, cancel these two and mu$_n$ into E of s is nothing but velocity saturation V of s.

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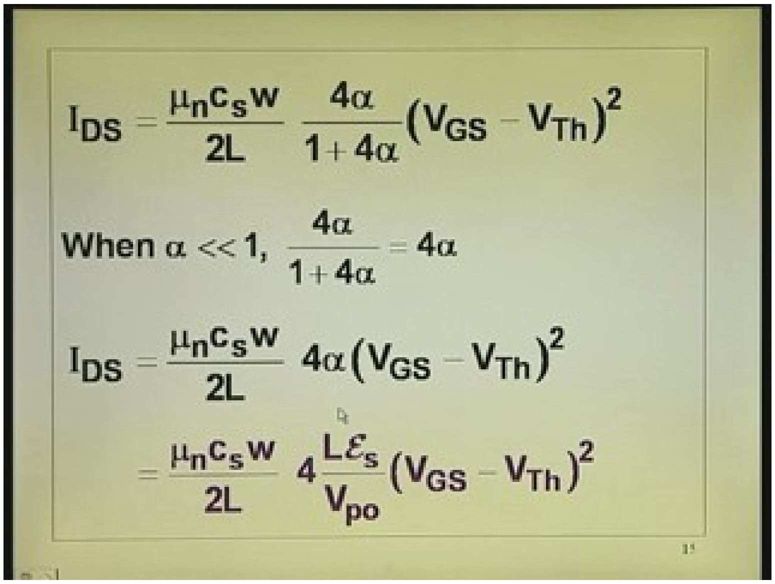

$$I_{DS} = \frac{\mu_n c_s w}{2L}\,\frac{4\alpha}{1+4\alpha}(V_{GS} - V_{Th})^2$$

When $\alpha << 1$, $\frac{4\alpha}{1+4\alpha} = 4\alpha$

$$I_{DS} = \frac{\mu_n c_s w}{2L}\,4\alpha(V_{GS} - V_{Th})^2$$

$$= \frac{\mu_n c_s w}{2L}\,4\frac{L\mathcal{E}_s}{V_{po}}(V_{GS} - V_{Th})^2$$

I have just removed that alpha if its etcetera $C_s$ W into $mu_n$ into V of s, Cs W into $mu_n$ into V of s divided by $V_{p0}$. Just go back to that in the denominator only you have $V_{p0}$ numerator you have got $mu_n$ into V of s and $C_s$ W. That is what you have got. And this quantity $mu_n$ into V of s is nothing but saturation velocity because you have taken in piece wise.

Thus when alpha is very much less than 1, you have got entire thing depending upon the saturation velocity of the, effective saturation velocity if you want to call it, we will see why we talk so, if saturation velocity is or the effective velocity in the channel is constant, that is constant, all that will effect $I_{DS}$ and $g_m$ will be C of s $V_{p0}$ W of course is the quantity which we do not want to talk of because that takes more space.

When we increase W, we increase the transconductance and $I_{DS}$ but that takes more space that is may not be on low like unless you suppose to do so and also of course how much is the $V_{GS}$ over and all threshold voltage.

What we are trying to point out is let us say remove all those things.

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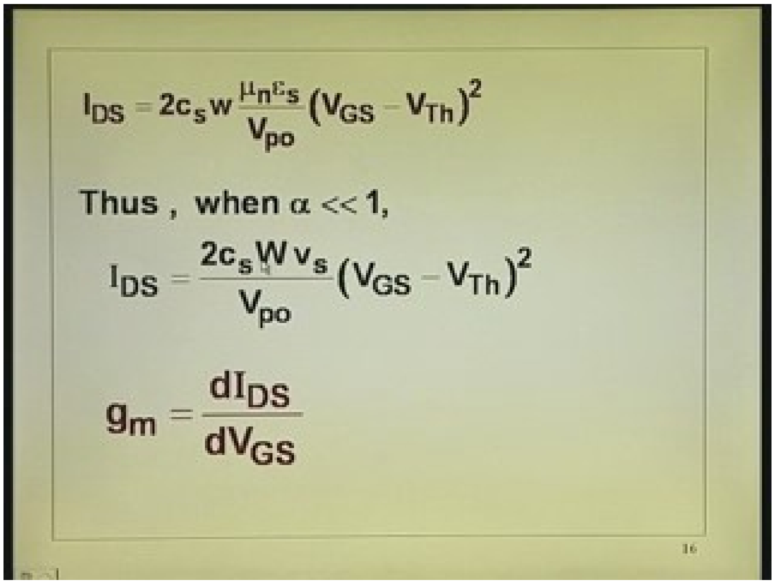

$$I_{DS} = 2c_s w \frac{\mu_n \varepsilon_s}{V_{po}} (V_{GS} - V_{Th})^2$$

Thus , when $\alpha << 1$,

$$I_{DS} = \frac{2c_s W v_s}{V_{po}} (V_{GS} - V_{Th})^2$$

$$g_m = \frac{dI_{DS}}{dV_{GS}}$$

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Ultimately what we arrived at is alpha very much less than 1 goes to .6, .4etcetera if you go then $I_{DS}$ is equal to $C_s$ W, $C_s$ W twice into V of s divided by $V_{p0,}$ that is what we are telling.

Now $g_m$ is $dI_{DS}$ divided by $dV_{GS}$ is actually equal to four times C of s W V of s divided by $V_{p0}$ into $V_{GS}$ minus $V_{threshold,}$ I am sorry twice, differential of that twice that becomes 4 $V_{GS}$ minus $V_{threshold}$ linear. So that is what we are saying.

Our given tells you this is the thing. Now let us take look at some of both $I_{DS}$ and $g_m$ are independent of the channel length L for the situation alpha very much less than 1.

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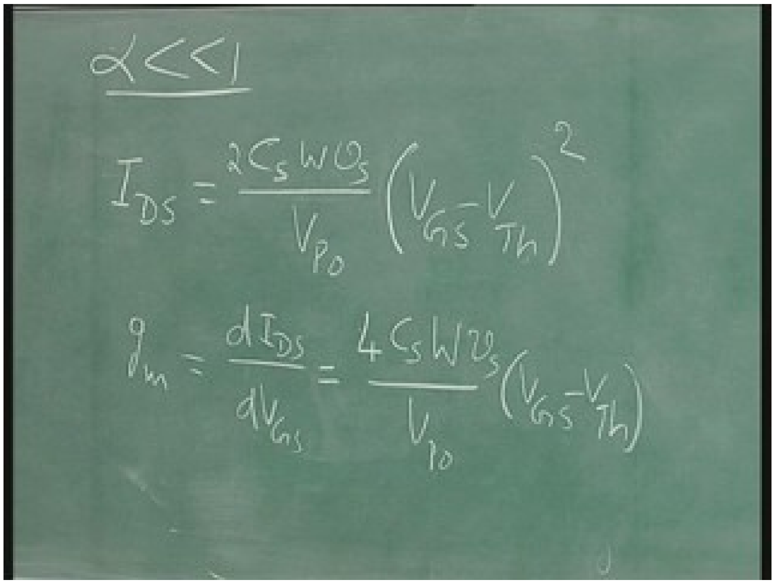

$\alpha << 1$

$$I_{DS} = \frac{2 C_s W \upsilon_s}{V_{P0}} \left(V_{GS} - V_{Th}\right)^2$$

$$g_m = \frac{dI_{DS}}{dV_{GS}} = \frac{4 C_s W \upsilon_s}{V_{P0}} \left(V_{GS} - V_{Th}\right)$$

Now let us taken look at this. It is not enough if you get an analytical expression for the current and transconductance, what we have to see is experimentally we need to see the same effect that is what you want to see.

People have seen experiments. They have fabricated two devices, two types of devices where one of them has got the channel length is equal to 1.2 microns, doping is 2.5 into 10 to the power 17, quite high doping they do, which will give you the mobility which is not very high but may be something like 4000 of that order.

Notice this diagram this edge has a spacing of that much, some D, here also they could have the same D, perfectly aligned but all that they did is this length, channel length is .2 micron that is 1.2 micron.

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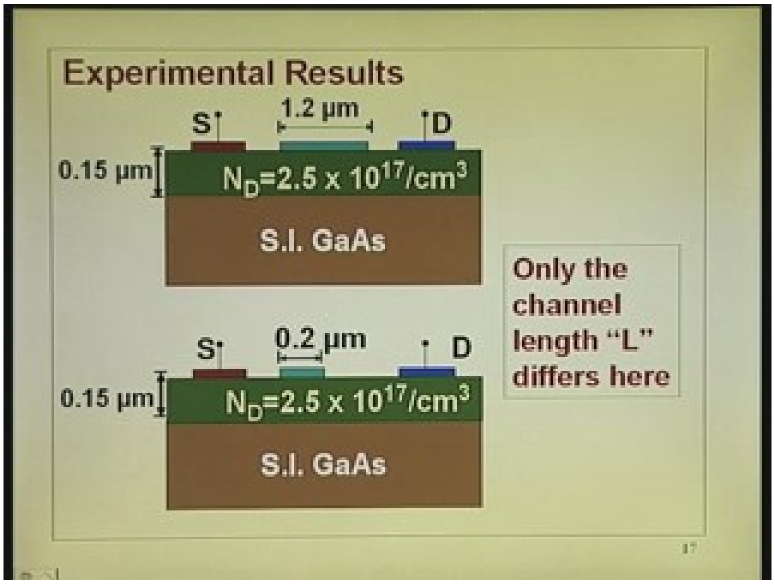

Experimental Results

Only the channel length "L" differs here

Now I just want to go through the process that is done here because it is very interesting. It is interesting for different three cases different reasons: one is they could prove whatever the C whether what is arrived it correct or not; number two using the conventional lithography, where optical lithography using, they could get .2 microns channel length. So the way, the devices are made the MESFET are meant infact this sort of MESFET have been fabricated in the laboratory in IIT our micro laboratory also by using this approach.

The way it is made is like this, first take this as semi insulating Gallium Arsenide, take semi insulating Gallium Arsenide on which they have this repetition layer, I will put it down here because there is some space I will put it down here semi insulating, I have not shown this in the slides but we can see it here now, that is the n Gallium Arsenide, n type of doping concentration which is about 2.5 into 10 to the power 17, that is what they have taken.

How do you make MESFET? It is very simple.

First you make ohmic contact like that, how do you make? You operate Gold Germanium alloy it at 400 for one minute that is to get a good ohmic contact. This is the source contact and the drain contact. Evaporate Gold Germanium, you can edge from these portions and alloy or you can ensure that it is evaporated only this portion the other portions that is photo resist left off. We will see what it is. You can do that.

In the final analysis, this contact returns first because you do not want to form the short key barrier first, see you should do the other way, first make the short key barrier and then put this one, what happens you are subjecting into four hundred degree centigrade. So there is a danger that the short key also can form some sort of alloy with the substrate. That is why you put it afterwards.

Now what they did was they deposited, they have put photo resist everywhere, spin photo resist I should not say spin photo resist, spin positive photo resist and then develop it. Develop it like that. This is the photo resist, so let us write slightly better there, that is the photo resist.

Notice there is orang on that, because this is photo resist called AZ 1350 positive photo resist, positive PR for photo resist positive photo resist this Shipley Mack company which gives that number. Now you give some chemical treatment like solutions like Benzene or Tolven it gives slightly tougher on top.

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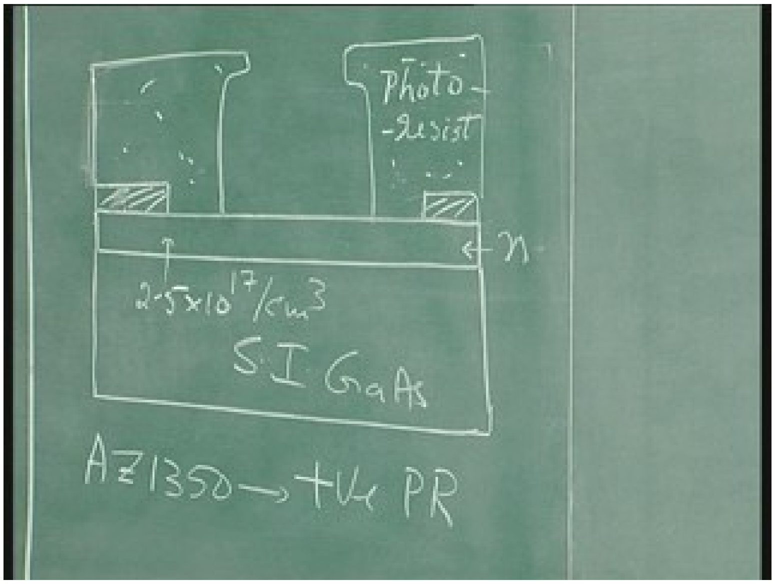

Now if I just have a mask with which I expose the photo resist in this portion. The lithography process you know that have a mask for example if this is the pattern that is there and everywhere it is dark and if this is not dark in the glass plate, you have pattern glass plate on which everywhere it is dark, it is transparent here and enormously present that is the mask making process. First you must generate that pattern so if you have it like that, now if I am sending light through this, light will go through that and it will be exposed to the photo resist in this region.

Now you are putting the developer if it is positive photo resist wherever it is exposed it will get development that means it will dissolve in the developer, other portions will remain. That means wherever pattern was present photo resist will remain, this is the positive resist. Now what I have put there in that particular diagram is when I have the chemical treatment done on the top, the top layer of the photo resist becomes a bit tougher.

If this is the window opening, if this is the size, I develop oval develop it. If I oval develop it slightly, what happens is this does not get attacked, but it slightly under cuts below that. The top surface is chemically treated slight under getting it. If I do not expose it to some chemical treatment like Benzene or Tolven you will get everywhere reduction.

See you will get everywhere like this if you have oval developed but you do not want that, that you have done by toughening that. This is the technology that they have used. Now 1.2 micron window if there is an open, the window opening is 1.2 micron. This extension that you get it here is marginal. What they adjusted that is there is 1.2 micron this is more than that.

Now you operate the gate metal that is Titanium, Platinum, gold. There are three combinations, multi layer metals, you operate what happens? You have photo resist there evaporate vertically down, evaporate gate metal. I think that color need not come out, sorry just one minute, evaporate gate metal or gate metals what so ever. Usually, Titanium, Platinum, gold, three layers are put. Ultimate goal for that you can bond very easily. So now, when you operate what happens? That is here where the metal comes true.

This portion is trying to masking it. So metal you go through this and this will be 1.2 microns. That is chosen to be 1.2 microns, that portion you have chosen that length to be 1.2 microns.

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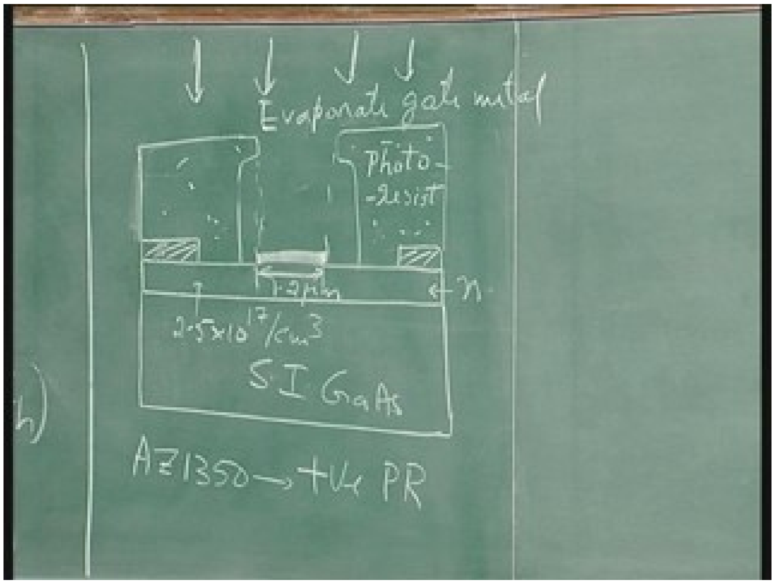

Now with the same pattern generated, what they have done is they would have realized the next one that is channel length which is .2 micron. That is where by ingenuity was present in the entire thing. So what I will do is I will remove this particular diagram now, modify it only you for evaporation. See they have two wafers. In one waffer they have done the operation vertically down; in another wafer, up to this point they have done the same thing and all this channel length like this, instead of drawing the whole thing to illustrate that they used the same process for realizing the two channel length that is retained as it is.

How do I get a short channel length? Rather short gate length? What you are looking for is a short gate length, what they did was it is very interesting, they evaporated like this. Evaporate at an angle. Now this is what I am asking of, this is preventing its going from in this direction. This is the nice thing about this technology. So it goes like this, now what you have got metal landing right up to that point only.

You have that metal, testing by this all over here, when it goes, it rests here like this. You have got metal like this beyond that point, it does not because this is masking. That is all, it is line of sight. It is line of sight communication it is metal and wafer. Metal is at rest only in the place where it can go, so this is the shadowing it, you get that and this is much smaller compared to that and that is actually .2 microns.

I forgot to tell you one thing after this is evaporated; the photo resist must be removed, in the previous case also. How do you remove that? When you do this the metal go here, here, here all through there will be metal; previous case also there will be a metal all through but now what to do is you do not want this photo resist afterwards, do not want metal here, you want only this metal. In previous case also you do not want the metal on the photo resist that has gone through semiconductor in the some portion, all that you do is put this wafer into a chemical Acetone.

Acetone I will put it here on the top. Acetone dissolves positive photo resist that is this, positive photo resist PPR that is the shortcut term used by people who work on technology.

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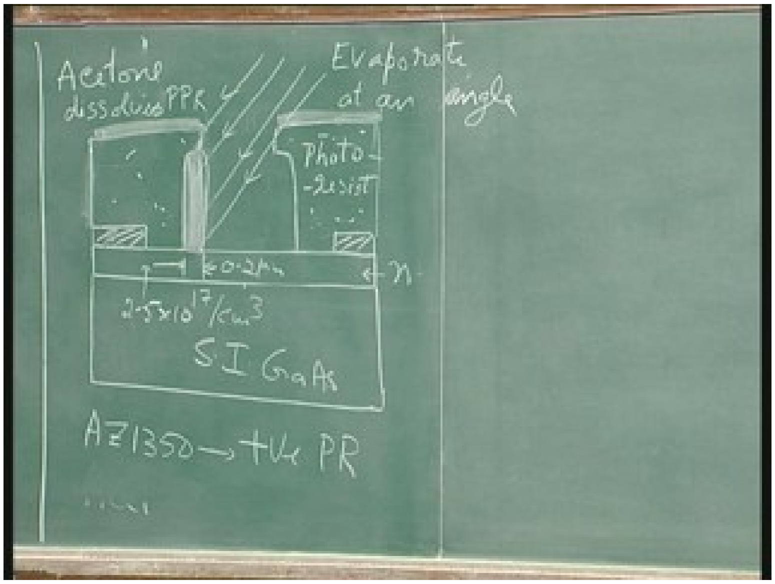

Once that is removed what happens? If it is dissolved in the photo resist whatever metal is on the top over that, goes off. It is called lift off. Shall I do that? When I do lift off, of course after the operation is over this is what we will see; this is what we see at the end of your operation. Now if you do lift off that is gone whatever along that metal on the top has gone, now this will go, along with that metal on top will go. So this is anchored on to substrate that remains. You have got this gate which is .2 microns. In the previous case all the metal goes so we get .2 microns. That is how they get.

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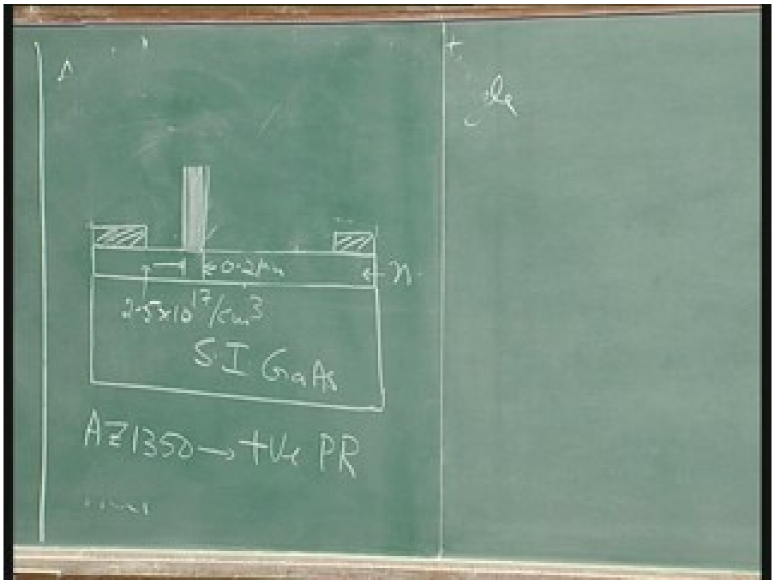

I just went through this technology because I thought it is very interesting for us to see, can be made in terms of some technology wherever required and I hope you understand the meaning of lift off.

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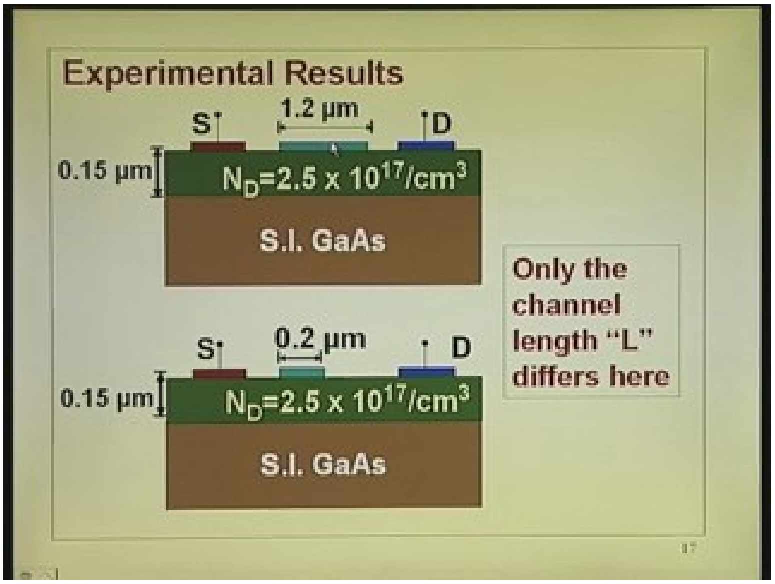

Experimental Results

S
1.2 µm
D
0.15 µm
$N_D = 2.5 \times 10^{17}/cm^3$
S.I. GaAs

S
0.2 µm
D
0.15 µm
$N_D = 2.5 \times 10^{17}/cm^3$
S.I. GaAs

Only the channel length "L" differs here

Lift off is the technique that is used here. That is the metal is on the photo resist, dissolve the photo resist, the metal on the photo resist is lifted off. That is called lift off to remove the metal from over the PPR. You remove the metal from over the PPR by removing the PPR itself.

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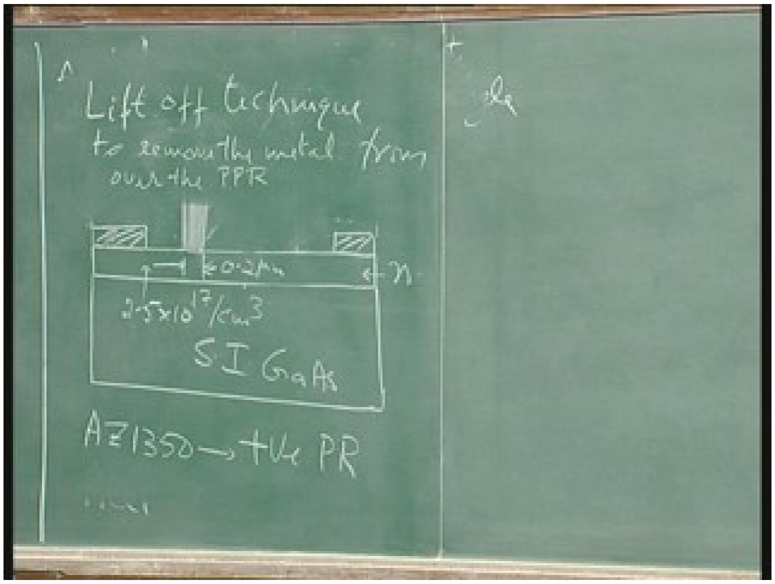

Lift off technique to remove the metal from over the PPR

AZ1350 → +ve PR

That is the trick now. This is a device, device-1 long channel, device-2 0.6 microns, not long channel 1.2 micron .6 microns.

Now what would we expect for this situation?

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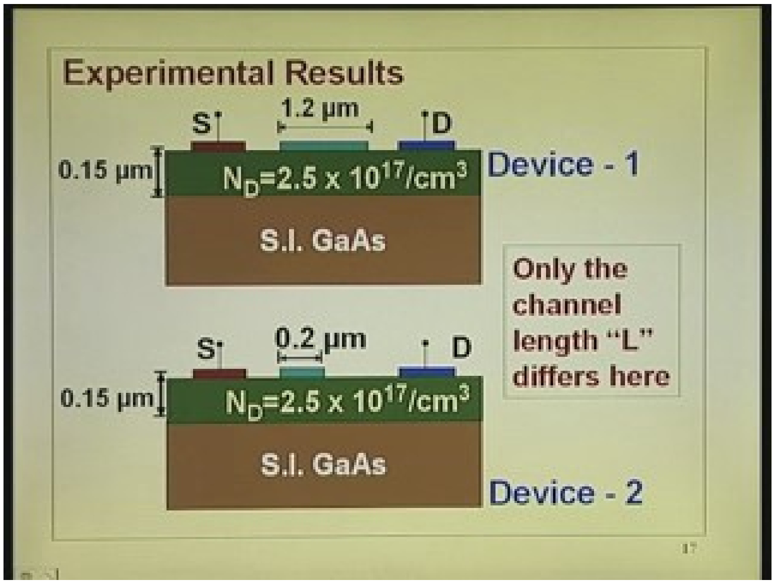

## Experimental Results

Device - 1

Device - 2

Only the channel length "L" differs here

For this device the pinch off voltage for the doping and the thickness is to estimate substitute for q $N_D$ 2.5 into 10 to the power 17 and a is .15 into 10 to the power minus 4, thickness is .15 the channel thickness in this case and putting all these things it is 3.9 volts quite large pinch off voltage, so your doping is high.

What is this L $E_s$? What you want to see is how much is alpha for this case. Alpha decides whether it will obey Shockley's equation or not? $L_1$ into E of s is 3 into 10 to the power 3 into 1.2 into 10 to the power minus 4, that is .36, alpha is very much less than 1.

If 1.2 micron channel length is alpha is very much less than 1, for the next device 2 which is .2 microns channel length is even smaller .06. What you are telling is we have got devices in which alpha is very much smaller than 1, what we should respect is this equation.

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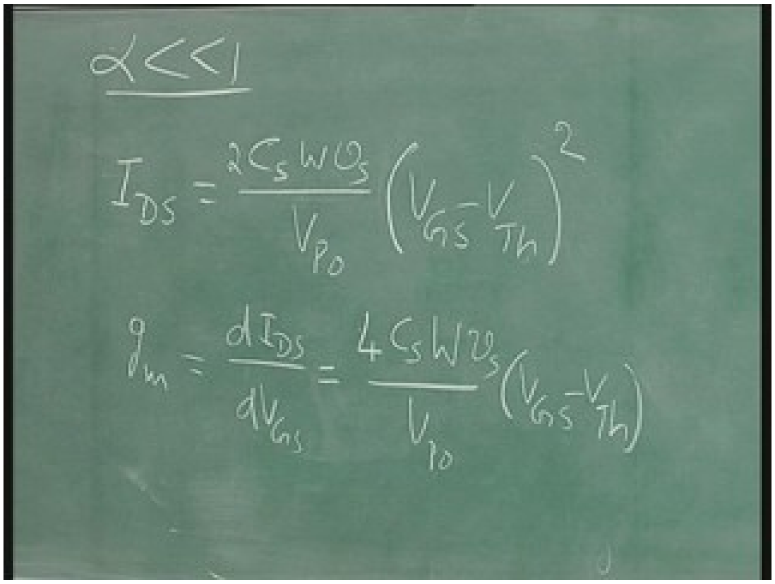

$$\underline{\alpha << 1}$$

$$I_{DS} = \frac{2 C_s W v_s}{V_{po}} \left(V_{GS} - V_{Th}\right)^2$$

$$g_m = \frac{dI_{DS}}{dV_{GS}} = \frac{4 C_s W v_s}{V_{po}} \left(V_{GS} - V_{Th}\right)$$

This is correct there is nothing wrong in that. What we can expect is $I_{DS}$ should be now independent of channel length, whether alpha is .36 and .06; alpha is very much less than 1. Therefore you must get that and $g_m$ also should be independent of channel length. But now what they observed when we made this experiment is, in both the cases alpha is less than 1. We expect that $I_{DS}$ and $g_m$ will be independent of channel length.

For the two devices you must get same $I_{DS}$ same $g_{m}$. Measurements at $V_{GS}$ is equal to 0 because after all $V_{p0}$ is 3.9volts. Is it enhancement or depletion type? Threshold voltage negative means it is depletion type, threshold voltage positive means it is enhancement type. Because the $V_{bi}$ minus $V_{p0}$ is threshold voltage $V_{p0}$ is 3.9 negative of course, depletion because $V_{bi}$ it will be .8, .9 volts not more than that. So it is a depletion type.

$V_{GS}$ is equal to 0 then the current flowing through that. Because after all this device current in flowing through that. What they observed in this case $I_{DS}$ in the device 2 where channel length is .2 microns, it is three times $I_{DS}$ of the $I_{DS1}$, it should be here, 3 times $I_{DS1}$ and $g_{m2}$ it is almost equal to $g_{m1}$.

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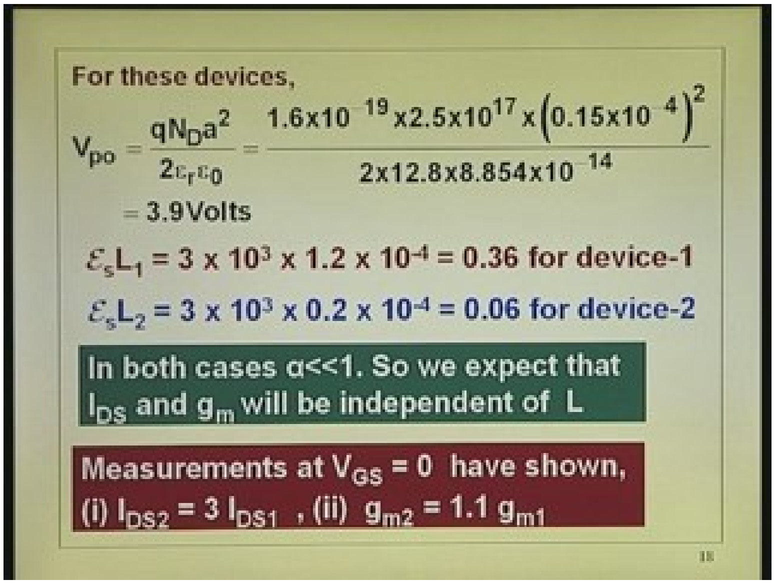


For these devices,

$$V_{po} = \frac{qN_D a^2}{2\varepsilon_r \varepsilon_0} = \frac{1.6\text{x}10^{-19}\text{x}2.5\text{x}10^{17}\text{x}\left(0.15\text{x}10^{-4}\right)^2}{2\text{x}12.8\text{x}8.854\text{x}10^{-14}}$$

$= 3.9\text{Volts}$

$\mathcal{E}_s L_1 = 3 \times 10^3 \times 1.2 \times 10^{-4} = 0.36$ for device-1

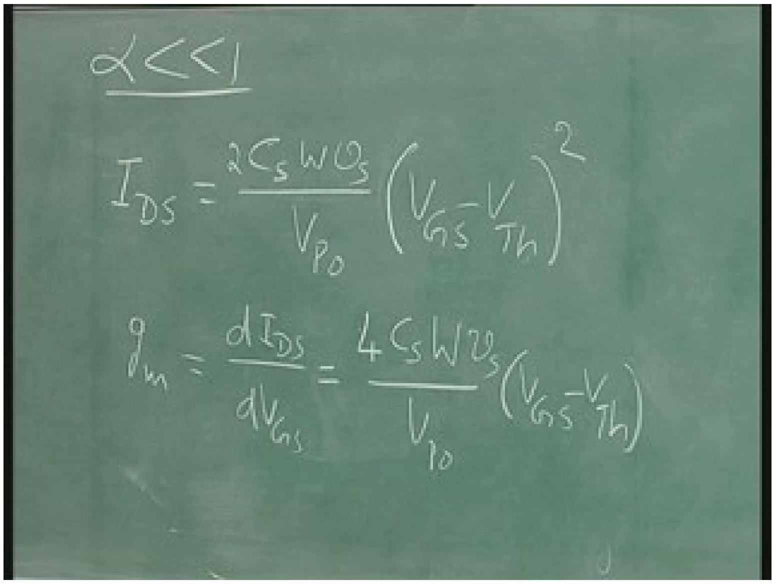
$\mathcal{E}_s L_2 = 3 \times 10^3 \times 0.2 \times 10^{-4} = 0.06$ for device-2

In both cases $\alpha \ll 1$. So we expect that $I_{DS}$ and $g_m$ will be independent of L

Measurements at $V_{GS} = 0$ have shown, (i) $I_{DS2} = 3\ I_{DS1}$ , (ii) $g_{m2} = 1.1\ g_{m1}$

This is 3 times in the short channel device .2 microns channel device. This is almost constant. There is something wrong some where or some parameter is changing, so what it is actually we should have to analyze and see, in fact what parameter that getting affected will be the threshold voltage itself.

(Refer Slide Time: 36:50)



$\alpha << 1$

$$I_{DS} = \frac{2 C_s W v_s}{V_{p0}} \left(V_{GS} - V_{Th}\right)^2$$

$$g_m = \frac{dI_{DS}}{dV_{GS}} = \frac{4 C_s W v_s}{V_{p0}} \left(V_{GS} - V_{Th}\right)$$

And threshold voltage changes we will see what are the causes, etc., in the next lecture.