Analog Electronic Circuits
Prof. Shouribrata Chatterjee
Department of Electrical Engineering
Indian Institute of Technology, Delhi

Lecture - 13
Introduction to current sources

Welcome to Analog Electronic Circuits. Today is the 13th lecture. And, we are going to continue from where we left off in the last class. And, then we are going to start with an Introduction to current sources in this lecture ok.

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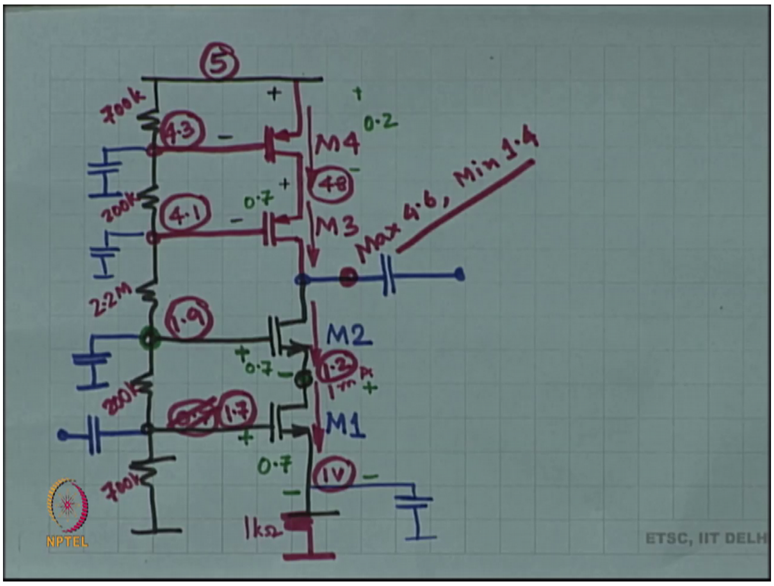

So, in the last class we had hypothesized or rather we had suggested, that maybe an amplifier that looks like this we will do a reasonably good job. This was the cascode amplifier all right. And the cascode amplifier has the first stage as common source the next stage as common gate the gate is grounded. So, it is common gate the first stage is common source. So, the input is applied at the gate of the common source amplifier right.

And then on one hand it is RDS of the bottom transistor on the other hand it says the impedance looking into the source of the top transistor, which happens to be low. So, the gm current chooses to go through the source and not through RDS right. So, therefore, the transconductance the short circuit transconductance of the structure is almost equal to GM. At the same time the output impedance looking in from the output node is very high, because this is a MOSFET terminated on the source side with RDS, from the source side there is RDS and on the here looking in from the drain.

So, the effective impedance looking in from the top is RDS 2 times gm 2 times RDS 1 plus RDS 2 plus RDS 1 gm 2 plus GMB 2 right. So, change that all right. So, this is the effective output impedance and this happens to be a large quantity. The output impedance times the same old transconductance gm gives you a reasonably large intrinsic gain, but to get this intrinsic gain as close to the actual gain as possible or rather to get the actual gain as close to the intrinsic gain; what do we need to do we need to make sure that the load is also a similar very large impedance ok. Just having a self-output impedance is not good enough the load also has to have a very high output impedance.

So, here we make a P mos structure and this is nothing, but the load ok. Once again common gate and the top 1 is nothing, but just an RDS, the top 1 is not even a MOSFET I mean effectively all it is doing is it is providing the required RDS, no it is actually a better idea to have a MOSFET over then not a resistor right. So, do not place a resistor MOSFET is what it is ok. So, this is the structure that we had. And these resistors give the required voltages at the gates of these individuals' devices and where is the output we can take the output from here, alright.

So, this is the overall plan of the circuit. So, this is what we had done in the last class this is the complete picture including both small and large small signal as well as dc biasing everything is in incorporated into this picture. And then we need to briefly talk about the swing limits or in other words, we need to talk about how to maintain saturation? That is how to maintain M 4 M 3 M 2 and M 1 in their respective flat regions of operation ok. Because, that is required that is absolutely required all right. So, we need to talk about that and how do we what do we do?

So, the first thing is you are going to get a certain v GS for M 1 and that is very important this v GS is important, because this is what is creating the gm this v GS of M 1 is what is responsible for creating the gm v GS minus V T all right. Then if you have so, much v GS minus V T then this v DS has to be more than that at all times at all times it has to be more than that.

Now, let us understand one more thing. The impedance looking into this node is low right because on one hand you see M 1 the drain of M 1 on the other side you see source of M 2 and looking into the source of M 2 the impedance is low. Now, if the impedance is low then automatically. That means, that the amplitude of the signal at this node is not going to be very high do you agree with that. If you have a given current amplitude and the impedance is low then the voltage amplitude is going to be small, you apply a signal gm 1 times the signal is the amplitude in the current through M 1 signal current through M 1.

This signal current is seeing a certain impedance at this node right have an equivalent impedance of the rest of the circuit and that creates a voltage at this node right. So, that impedance happens to be low. Therefore, the voltage over here is also going to be low ok. So, this voltage is not really going to swing much no swinging right, it is a very low amplitude voltage, it is not really going to move much.

The voltage here is going to move not here all right. Now, what is this voltage going to be? This voltage is going to be the potential at the gate minus the requisite vgs, you see the potential at the gate is fixed minus the requisite v GS that is the approximate potential of this there is going to be some swing a little bit of oscillation around that, but it is not very significant it is a small signal, alright.

So, if I make sure that this v DS is sufficient to maintain M 1 in saturation, when that is good enough, this voltage is not going to swing, this is voltage is more or less more or less static ok. So, let us think about it let us say you know your vts 0.5 volts and let us say I want to maintain a gate over drive of 0.2 volts in which case the voltage here has to be 0.7 oh you wanted to do bias stabilization great that is a good idea we want to do bias stabilization.

So, this is wrong you add one more resistor over here to stabilize the dc operating point and you know put a capacitor across it. So, that it does not appear in the small signal that is not a bad idea that is actually fantastic ok. And let us say that you want net current of 1 milliampere and let us make this 1 k. So, you want 1 volt over here. So, 1.7 over here is that and we pick the device such that at 0.2 volts of overdrive V t point 5.2 volts of overdrive the current is 1 milliampere we pick such device.

Now notice this one milliampere is coming right through. So, all the devices now have 1 milliampere all right. And therefore, their respective vgss have to be created right. So, for example, M 4 let us say M 4 has the same k you pick up a p mos with exactly the same value of k right. We are going to discuss k today itself um, but let us say you pick a p mos with exactly the same value of k in that case this and let say the V T is also 0.2 volts in that case this voltage happens to be 0.7.

So, if I have 5 volts of power supply in this is 4.3 done ok. What about here this would also be something like 0.7 and what about here this is also something like 0.7 ok. So, this is the set. So, I clearly understand that I need 1.7 volts here. So, I make sure that this resistive divider is such that I get 1.7, I get 4.3 over there, what should the values over here be at these 2 nodes. First of all what should the value over here be this is 1 volt I have a gate overdrive of 0.2 which means v DS has to be more than v GS minus vt.

So, v DS has to be more than 0.2; that means, the source of M 2 should be at a voltage more than 1.2, but that is all that we are saying we are saying that any voltage more than 1.2 is good enough, it could be 1.2 it could be 1.3 1.4 whatever you want is that is that understood great. Because, this voltage is not swing in either it is pretty much static. So, 1.2 is actually fantastic, because that gives you the largest headroom across M 2.

So, 1.2 is fantastic I would like to place this node at 1.2, which automatically means that this node should be at 1.9. Now when I do the resistive divider and place this node at 1.9 then automatically this goes to 1.2. So, this voltage at the gate is what sets the dc operating point voltage at the source not vice versa; design wise we went backwards when I am thinking of designing, but when actually it is going to happen this is what is enforcing this potential divider will create 1.9 does not have a choice.

Now, that it has 1.9 over here it is going to enforce 1.2. So, that it conducts the same current right though is this all right, this is understood I think ok. So, I have got 1.9 volts here I need 1.9 about here. So, we will have this exactly the same story in the p mos right this is a low impedance node, you now understand what it means that is the impedance looking into this node is low.

So, if I have some signal current then the voltage over here is going to be signal voltage over here is going to be low ok. If I maintain 0.2 volts across vsd then that is good enough; that means, if this node is at 4.8 it is good enough ok, because it is not really going to move much that is 4.8 then a voltage over here a 4.1 would be fantastic all right.

So, you organize this resistive divider you know pick something like 700 k over here, 200 k, 200 k, 700 k, and 2.2 mega ohms fine. So, this is the basic idea all right we are going to look at all of this in a lot more detail very soon I am just trying to give you a flavor for what is coming? This is this is actually I am trying to set the pace over here you might not have understood everything. For example, you might not have understood why this node is not swinging much all right it is ok. Just accepted move on right you might not have understood exactly the idea behind the setting of all these voltages. Finally, what is the swing the possible swing over here the maximum voltage it can go to is 4.6, the minimum voltage it can go to is 1.4, alright.

So, this is just to set the pace you might not have understood everything there going to be a lot of questions I hope and, but let us move on from here and start something fresh, because what is going to come is finally, going to add back, alright. So, we are going to move on to something new we are going to start discussing current sources and mirrors.

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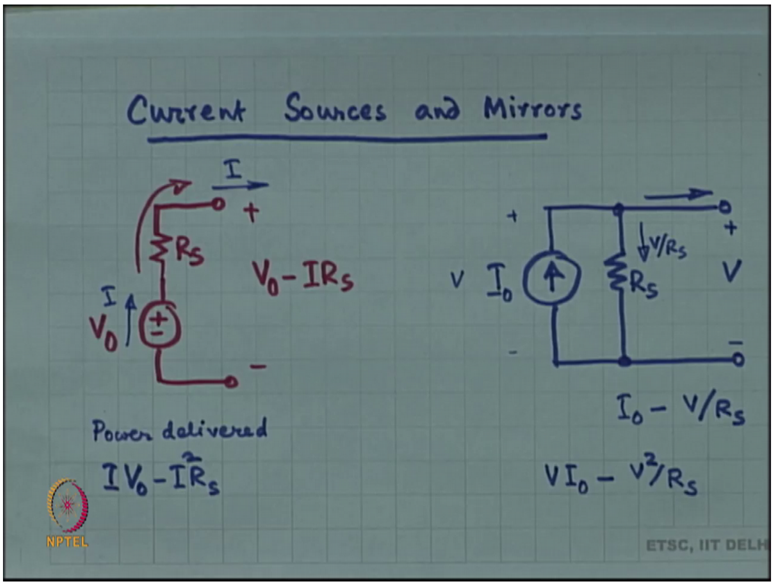

So, this is a very important topic and this topic is one of the cornerstones of analog electronics modern analog electronics ok. So, make sure you understand it very well. So, you all know voltage sources right and the dual of a voltage source is a current source. In a current source the current is constant and any voltage can appear across the current source. In the voltage source the voltage is constant and the voltage source can supply any current with that constant voltage.

However, for a voltage source things can become things are usually not ideal in which case a voltage source when it tries to supply current the voltage actually dips. So, this is modeled as a resistor. When, it tries to push current the voltage dips right this voltage is no longer V 0 it is V 0 minus IR s where this is the source resistance fine.

So, this is a non-ideal voltage source, just like a non-ideal voltage source when you actually try to make a current source there is no such thing as a current source by the way, voltage source can be made with a chemical reaction, but a current source cannot be made with a chemical reaction right there are other ways to do current sources. For example, a photodiode could possibly behave like a current source in some in a in a in a in some modes of operation, if you use it right a photodiode could behave like a current source.

But, anyway by the way we had discussed this earlier it is all relative it is all subjective weather of voltage source is at all a voltage source or a current source is a subjective matter, why because it all depends on the quality of the output impedance ok. In general it is a power source it is a source of power whether it appears like a constant voltage or appears like a constant current it is for you to decide.

So, this is the model for a non-ideal voltage source. And a current source would like to produce a constant current no matter what the voltage across it is. So, it does not matter what voltage it has right it would like to produce a constant current push a constant current. However, current source is also going to become non ideal in which case when I increase the voltage across this the current pushed out is no longer I 0 a portion of the current is used up ok.

So, for example, if this voltage is V then the current going out is I 0 minus V by R s this correct is V by R s ok. So, the model is very similar a non-ideal voltage source is a voltage source in series with the resistance. Non ideal current source is a current source in shunt with the resistance. The model is very similar in one case V 0 minus I times R s in the other can I 0 minus V times g s ok.

So, you convert you go from voltage to current all the all the elements changeover. So, the resistance becomes a conductance. So, an ideal voltage source will have R s equal to 0 and ideal current source will have g s equal to 0 or R s tending to infinity fine great. This is the basic understanding ok. As a source of power how much power is the voltage source producing, if this if this voltage is something right how much is it generating?.

And how much is it pushing in how much is delivering to so, this is I and this is V 0 minus IR s right this is also I. So, the power that it try to generate was V 0 times I and the power that it delivered was V 0 times I minus I squared R s fine ok. How about in case of the current source? It try to generate V times I 0 right, but what it pushed finally, into the load is I 0 minus V by R s the whole thing times V. So, V times I 0 minus V squared by R s, which is last in the source impedance ok. In both cases whatever voltage is there over here and whatever current goes into the load right the product of the 2 gives you the power delivered.

So, it does not matter at the end of the day it does not matter whether you model the source of power as a voltage source or as a current source this is just a model. Ok. This is perception is convenience right sometimes when the output impedance is large you say that the source of power looks like a current source. When the output impedance is low you say that the source of power looks like a voltage source.

For example, chemical reaction is taking place right, you say right by zinc and acid lead acid battery or zinc and acid battery. In such case you say that it happens to look like a voltage source it is a source of power right, it is chemical energy being converted into electrical energy. So, source of power it just happens to behave like a voltage source. Whereas, in a photodiode right you can have both situations, at times it will look like a current source, at times it will look like a voltage source all that it matters is where are you on that curve right

So, we are not discussing the photo diode over here, but in general I am trying to establish that a source of power it is at the end of the day a source of power ok. Whether you qualified as a voltage source or a current source is subjective all right. Now, we want to make a current source ok. For reasons that are not very obvious to you, but let us say I want to make sure that in the circuit, let us say that I want to make sure that in the circuit

I want a fixed bias current 1 milliampere I would instead of having this resistor over here, I would place a current source pulling 1 milliampere down this entire circuit ok.

So, that is probably my objective actually that is one of the most important things that I will be doing using this current source ok. So, this 1 k resistor is going to be replaced by a current source to make sure that everywhere I get 1 milliampere, this is the plan. How do I make a current source?

Now, the easiest thing is to recollect that the MOSFET.

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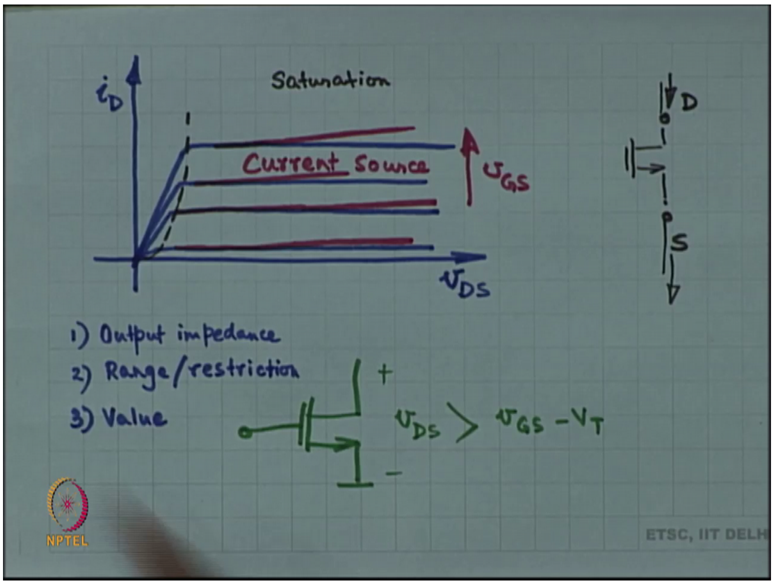

If you recollect the MOSFET characteristics, what do you recollect over here why did I draw this again; because, in the flat region in the saturation region of the MOSFET, the current does not change no matter what v DS is right the drain current. So, I have got the drain I have got the source in between I have got something right in between I have got the MOSFET ok, but let us not draw this is as a MOSFET right now. I have got the drain I have got the source. I can change the drain source voltage, but the current is not changing the current this drain current is fixed. So, this is the job of a current source. So, this MOSFET is behaving like a current source ok.

So, naturally the MOSFET is a current source that is the basic premise. It happens to be controlled by the voltage v GS, right for different values of v GS I get different values of the current, but otherwise fundamentally it is a current source because I can change drain to source voltage it does not change the current does not change ok.

So, this is the ideal MOSFET of course then you say that the device manufacturer cannot make an ideal MOSFET and invariably he is going to give me some slope to this curve, some slope to this curve and so on. So, it is not going to be an ideal current source the current will change slightly all right. So, this is the general idea ok.

So, generally speaking if I just have a MOSFET success all I have to do is make sure that v DS is greater than v GS minus V T and this MOSFET behaves like a current source ok. Now, if this things were so, simple then I would not be spending this, I would not be talking about this as the chapter things are not as simple as this you are not really very happy with the this kind of a these restrictions. So, you have got 2 restrictions; 1 restriction is the voltage it has to have some minimum and the second a bigger problem is the slope on this line and the slope is not really you know, sometimes your boss might say that give me a better current source and this current source is no good can you design a better current source.

So, these are the 2 problems; one is the output impedance of the current source. So, what is the slope 1 by RDS right that is the slope 1 by RDS is the slope RDS is the output impedance of this particular current source. And so, slope output impedance is one problem, a second problem is the range of voltages, and the third problem is the value it is a current source, but what is it is how do you have any control over the value of this current source ok.

These are my 3 fundamental things that I have to work on. So, the first thing that I am going to work on is the value all right. And we change the problem of the value into a problem that is like this that, suppose I show you current source suppose I show you a current source of value 1 milliamperes or suppose I give you a current of 1 milliamper.

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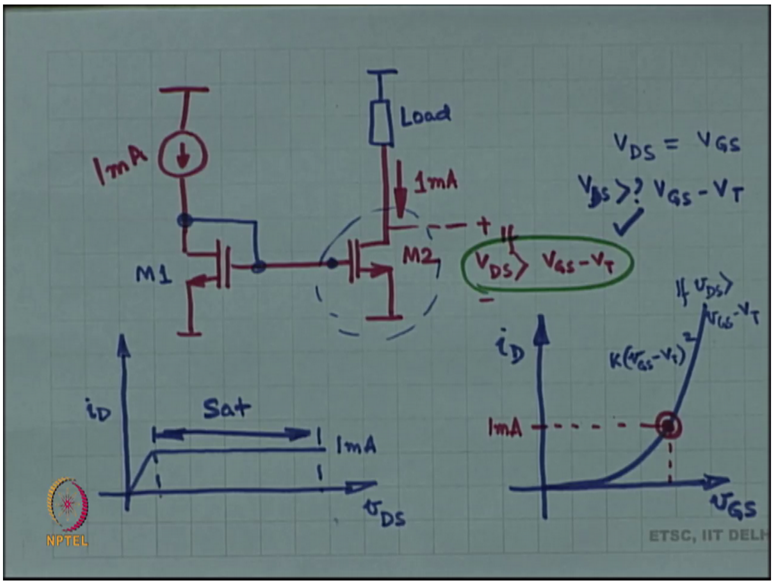

Can you make another current source of value 1 milliamper ok, if I tell you what 1 milliampere is can you tell can you make a current source another current source of 1 milliampere or can you make 2 milliamperes A 1. If you can make 1 milliampere may be you can make yet another one milliampere can you combine them and make 2 milliamperes, can you give me 10 milliampers. If I tell you the value of 1 milliampere can you give me anything else and this is called a current mirror ok.

So, the basic circuit for the current mirror looks like this ok. So, somebody has given me this one milliampere and I have to create another 1 milliampere. So, the MOSFET itself is the current source. So, this is the source and I have to decide what is the right gate voltage remember this current source is a controlled current source, it is a voltage controlled current source controlled by the voltage at the gate ok.

So, I have to decide what is the right value of voltage at the gate such that I get 1 milliampere? Now, what I am going to do is I am going to take yet another MOSFET which is an identical copy of this MOSFET. So, these 2 are identical to each other what does identical mean identical means that they have the same value of k, they have the same value of V t and everything else there at the same temperature they are co-located and so on. They are in the same region there in the same area they are subject to the same environmental conditions ok.

So, that is what identical means. So, these 2 MOSFETs are otherwise identical then I push 1 milliampere through this MOSFET though M 1 I push 1 milliampere this was the reference current. The reference current was given to me I use the reference current pushed 1 milliampere push the reference current through M 1.

Now, when I push the reference current through M 1 it creates. So, certain v GS it requires the certain v GS all right, this v GS happens to be just right to place M 1 in saturation v DS of M 1 is equal to v GS of M 1 v DS is equal to v GS. This automatically means that this device M 1 right this automatically means V DS is greater than V GS minus V T. The answer is yes, because V T is some positive voltage. If V DS is equal to V GS then you are done, alright.

So, this MOSFET M 1 happens to be M it is plat region. So, this gate voltage that I have created over here is just right such that M 1 remains in saturation M 1 milliampere comes through. So, if I apply the same gate voltage to M 2, then hopefully the current here will also be equal to 1 milliampere; if the drain voltage is greater than V GS minus V T all right.

So, this is the basic premise of the current (Refer Time: 37:49) let us go over it once again. You remember this characteristic id as a function of v GS this characteristics is valid when v GS is such that v DS is greater than v GS minus V T v DS has to be greater than v GS minus V T. Then this curve is valid some k times v GS minus V T the whole squared fine that is this curve parabola ok.

Now, this curve is valid in saturation I push 1 milliampere through the device and I make sure that v GS is equal to v DS, which means the device is in saturation right the device is guaranteed to be in saturation whatever value it is because v DS is always equal to v GS for M 1 guaranteed to be in saturation then I push 1 milliampere through it. So, I look up 1 milliampere and this happens to be the required v GS.

So, that v GS is created across the device or rather across the gate source all right. And then the same v GS is applied to M 2 and as far as M 2 is concerned, you look at the other curve M 2 also has the same set of curves right the same set of curves it will. So, for this v GS it will have 1 milliampere of current if the device is in saturation, or rather if the device is in saturation then it is going to pick this particular curve which happens to be a 1 milliampere curve right. And if the device is in saturation then this does not change right the current does not change when I change v DS.

So, this is the basic premise in one case you are using this curve to create the operating point, in the other case you are using the flat region of the curve to show that this is actually a current source all right. Now of course, there is going to be some restriction on what this load can be right for this one milliampere of current the voltage over here should not drop to below V GS minus V T ok. So, the load has to be such that right it can not be any arbitrary resistance for example, right.

If it is you know 100 mega ohms for example, then you try to push 1 milli pull 1 milliampere through 100 mega ohms you get a huge voltage drop it would not be able to sustain that voltage drop, because this is v DD right an automatically this device is going to have v DS equal to 0 which means that you are going to end up at this point not in saturation at all right. So, that is not going to help the load can be arbitrary large right there is some maximum to what the load can be and that maximum is dictated by this condition fine.

So, this is the basic premise of the current mirror this is your first current mirror right, it is just a 2 MOSFET circuit in one you push the reference current in the other you mirror it you create another one all right is this understood. Now we are going to slightly extend things right if I had 1 milliampere can I create 2 milliamperes instead of 1 and the answer is yes.

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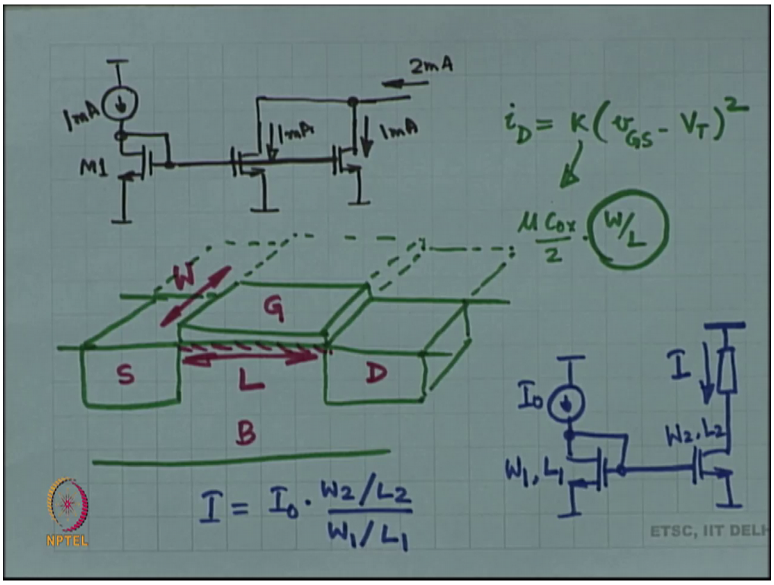

So, this is your reference current you push it through 1 device and you generate just the right voltage such that, if I have another MOSFET it will create the same current ok. And guess what you can have yet another MOSFET and get the same current. So, this is 1 milliampere and this is also 1 milliampere, because all these devices are identical ok.

Then you combine them and now this is 2 milliampere any questions. So, if I have a 1 milliampere reference. Therefore, I can create 1 milliampere 2 milliampere 3 milliampere and so on and so forth ok. So, the way we do this we do not really actually at the end of the day you could implement it in this fashion, but we have some shortcuts; so the mos device equation that you studied.

So, what we projected over here was id equal to k times v GS minus V T whole square where k is some constant. Now what I am going to do is I am going to expand this constant this constant k is nothing, but mu cox by 2 times W over L all right mu happens to be the mobility of either electrons or holes whatever is the majority charge carrier, Cox is the oxide capacitance of the gate alright; Cox is the area of the gate times epsilon of the gate of the gate insulator divided by the thickness of the gate, right; A epsilon by D, that is cox and W and L what are these W and L are the width and the length of the MOSFET gate.

So, if I have a gate. So, this is the gate source drain right I have drawn a 3 D kind of a projection image body, alright. This dimension is the width of the gate and this dimension is the length of the gate right. The length of the gate is the length of the channel that is formed between that is induced between the source and the drain when the gate voltage is above V T ok.

So, L is the length of the channel width is the width of the gate right. So, you can think of it has something like a resistor right this channel is like a somewhat like a resistor, in which case if I increase L the current is going to decrease right. If I increase L the current is going to decrease. And likewise you can think of this width as the width of the channel right of the channel resistance, in which case if I increase W the current is going proportionally increase all right.

If you place two such devices in parallel then effectively like this right two devices in parallel then effectively you have got double the width, you can place another 1 over here right next to it right, you have got double the width in such a case right the width doubles. So, the current doubles right or you could draw it as 2 different MOSFETs all right.

So, the current is proportional to W by L, where W is the width of the channel L is the length of the channel width and the length of the gate of the MOSFET fine. So, effectively what you could do is you could make. So, if this is I 0 and this has W 1 and L 1 and if the second device has W 2 and L 2, then this current is going to be proportional to W 2 by W 1 all right that is how it is going?

To work out you are going to get a v GS. So, here you got W 1 l 1 that is going to create a v GS and then you apply that v GS here now you have W 2 l 2 you get a certain I ok. So, I 0 times W 2 by L 2 divided by W 1 by L 1 that is going to be your final current. And now you choose your W 2 W 1 according to. However, you what ratio of current you want between the reference and the final result and you get the desired current all right is this fine is this so, far great.

So, next what we are going to do is. So, we have kind of solved this problem right in what tense. In the sense that if you give me a reference current I can produce another current of equal value or a value proportional to the reference current ok. So, if you give me a 1 milliampere current then I can create any other current source right, depending on W width and length I can create any other current source ok.

So, this value problem is done next what we are going to do is we are going to look at output impedance. So, let us first think of the output impedance of the basic current mirror.

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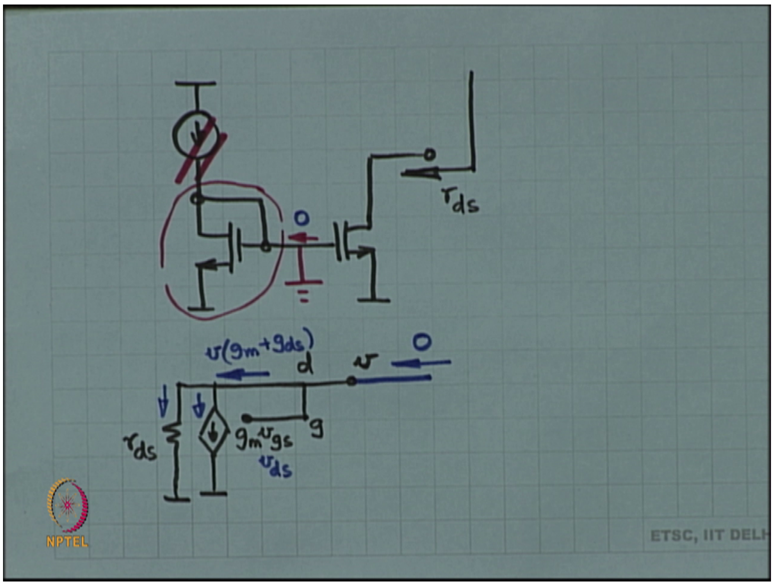

So, I am going to looking from outside what is the impedance that I am go to see small signal impedance that I am going to see. When you are going to do small signal analysis, what will you do with this reference current source you are going to null the current source right you are going to make it stat this is static.

So, there is no incremental current going through this reference current source, which means that this current source is going to be treated as a current source of value 0, which automatically means that it is an open circuit. Unlike the voltage source case a current source becomes an open circuit right a voltage source becomes a short circuit because it is value is 0.

So, here the value is 0 it becomes an open circuit ok. And then what are you going to do was this current gate current is 0 perfectly 0, which means the current going into this drain is 0 right, gm times v GS is 0; all of this is 0 ok. So, effectively this entire node is like a ground 0 volts, you do not understand think of the small signal model of this gmb is not required, because both body and source are at ground gate and drain are connected together which means v GS is equal to v DS ok.

So, if I apply a voltage v over here what is going to be the current I apply v v times g DS is the current through this path and the current through this path is going to be v times gm. So, the net current is going to be V times gm plus gds ok.

Now, I am telling you that this net current is 0, because there is a gate over here no current can come through a gate. So, what does it mean what does what does we have to be then this current is if this is V then the current is V times gm plus gds all right. Now, I am saying that the current is 0. So, what is v v has therefore, got to be equal to 0 fine ok.

So, what is the impedance looking in from outside the gate is at 0 volts, the source is at 0 volts, the body is at 0 volts. So, g M times v GS is nothing gate and source are 0 body source are also at 0. So, gmb is also gmb times vbs is also nothing all you have is r ds between drain and source and therefore, the output impedance looking in is just r ds nothing else is this ok. So, this is the output impedance of the structure.

Let us stop here. And we are going to carry on in the next class we will start from here. So, today what we did was first we looked at the cascode amplifier and then be started on with current sources and mirrors, where we discussed the properties of ideal and non-ideal current sources and voltage sources then we showed how a MOSFET is a nice current source right away right in front of us. And then we made a current mirror with which we can generate any current if I know the value of the reference right, be recalibrated or MOSFET equation right k has been elicited over here. And, then now we are working on the output impedance the output impedance of the current mirror is nothing, but r ds ok.

Thank you.