Semiconductor Devices and Circuits
Prof. Sanjiv Sambandan
Department of Instrumentation and Applied Physics
Indian Institute of Science, Bangalore

Lecture - 46
MOSFET as a switch

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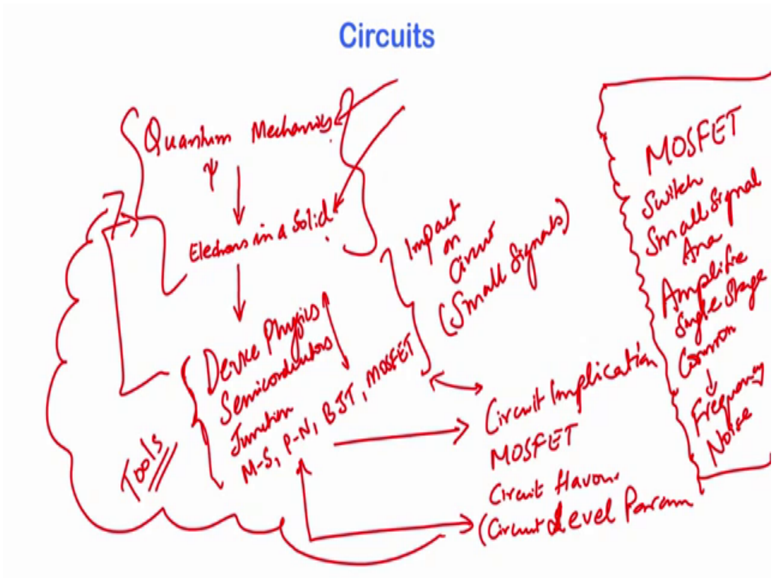

We have now approached the last unit of this course, which is the unit on the circuits aspects of all the devices that you have learned looked at so far, ok. So, if you just let us say summarize our journey ok, it is we started off with some ideas on quantum mechanics. And we looked at some interesting properties like the wave particle, the wave function etcetera. And we use those ideas to develop you know concepts on how carriers would behave in a solid, so electrons in a solid.

And we looked at that the formation of the band gap, what the valence band is, what the conduction band is very briefly. And we use those ideas to then develop a solid structure for device physics. And here we studied the basic properties of semiconductors. We looked at the formation of junctions, and we look at some of the devices you know particularly the metal semiconductor junction, the P-N junction; and in transistors, we particularly paid attention to the BJT and the MOSFET.

And here we developed huge set of tools ok, such as the Parson’s equation to study the behavior of all these devices. And throughout the study, they always tried to finish or wrap up every device or you know every concept with the impact on circuits, right. We looked at the small signal models of many of these devices.

And we now are ready to make use of all this knowledge to see the circuit implications ok. And what we will be doing in this unit is essentially is focusing on the MOSFET, we will not use any other device ok, because circuit design I mean circuit theory or analog circuits is an entire course in itself, and we are not here to completely explore every detailed of analog circuits. Although this is a course that I do teach at the graduate level, but at the senior undergrad level, but this is not the place for a exhaustive course on analog circuits.

But, instead the point here is to introduce all of you to circuits introduce all of you to you know, so that all of you at least get a flavor of what circuit design is all about. And most importantly try to see how different circuit parameters the circuit level circuit level parameters, how the circuit level parameters are connected to device physics, which in turn is connected to the behavior of electrons in a solid. So, every time we introduce a parameter, we will try to hunt or way back to some elementary concepts.

So, we will focus on the MOSFET, and we will explore some very basic circuits, particularly the use of the MOSFET as a switch, and small signal analysis with the MOSFET, and using the MOSFET to build an amplifier. And we will only look at a single stage amplifier, and particularly something that gives you gain, which is something called as a common source amplifier ok. And of course, once you understand the methods of using these techniques of small signal analysis for amplifiers, you can you can extend those techniques to other circuits.

And finally, we will look at two important properties very quickly the frequency response of MOSFETs, and secondly the noise in MOSFETs. And with that we will complete this course. So, I hope all of you find this last unit to be useful, because it completes the arc. It so this so, what we did is we briefly looked at many topics. So, this is this course is more wide than deep. It looked at many topics from quantum mechanics to solid state physics, through device physics and engineering. And finally it is going to terminate with the understanding of circuits.

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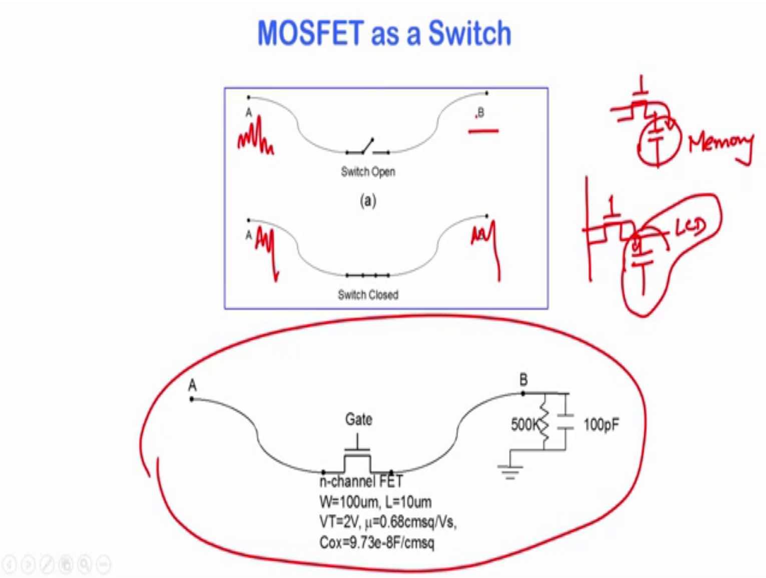

So, let us start off by looking at the MOSFET as a switch. Again, we are going to go back to a traditional example that we used to introduce transistors, which is I have point A and point B. And I want to send a message from point A to point B, and I need a switch in place. So, when the switch is closed, the message here gets to point B; and when the switch is open, nothing happens at point B. So, here is a more complete circuit.

Now, let us say we want to use the MOSFET as a switch a simple switch. And this kind of a circuit is extremely useful for memories. For examples, where you have a MOSFET is a switch and a capacitor, and you write information on the capacitor, you open the switch, and the information is retained on the capacitor. So, this is a very it is a form of a memory.

The other applications are your circuits and displays or any active matrix systems, wherein you have a MOSFET, and you have a capacitor again, and you store and then you have light emitting materials, for example say an LCD. And you store information on this capacitor, and you open this MOSFET, and you have the voltage here driving the LCD. So that you can see the color, the different levels of brightness on your display screen.

So, this use of the MOSFET is a switch is extremely important, even when it comes to analog circuit applications. And more than that the use of the MOSFET is a switch is the essence of digital circuit applications ok. So, let us study some of the important aspects of the MOSFET working as a switch.

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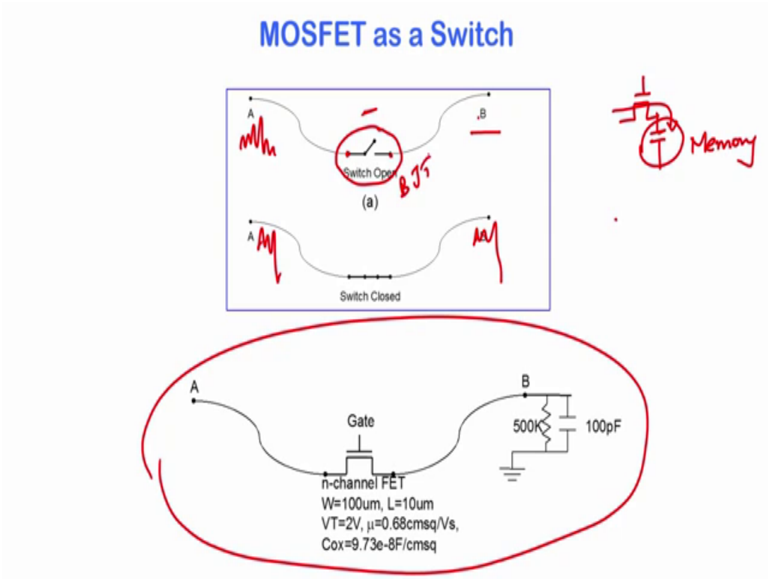

So, for a transistor could replace the switch, because you need a control signal, and you need these two terminals. So, you we have looked at BJTs, but we are not worried about BJTs in this section of the course. And instead, we will focus on using the MOSFET all right.

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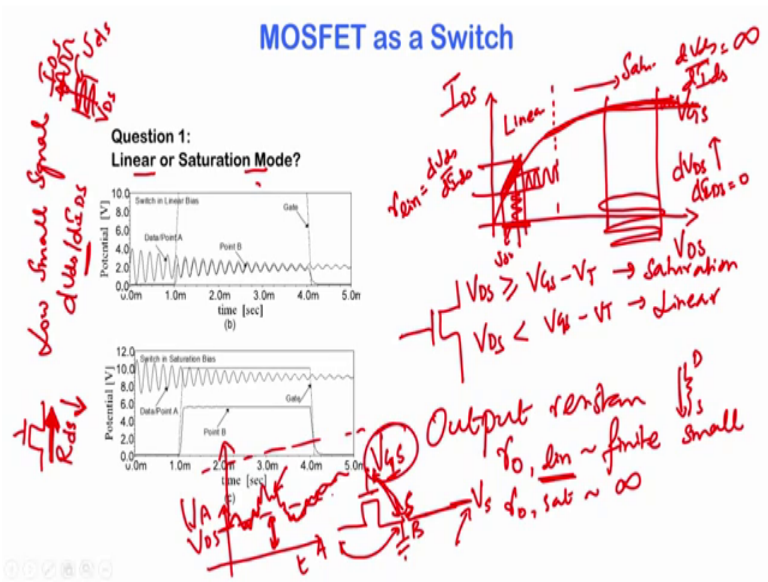

So, the first question ok. If I were to use the MOSFET as a switch and I want low I want low small signal resistance across the switch, do I bias the MOSFET a linear mode of operation or saturation mode of operation that is the first question. So, just to recollect what is the linear, what is the saturation mode of operation?

So, you have your current your output characteristics of the MOSFET, you have I DS versus V DS ok, and let us say it looks like that. And we know that for some particular V G. We know that when V DS is greater than or equal to V GS minus V T, the MOSFET is in saturation mode of operation. And when V DS is less than V GS minus V T, we say that the MOSFET is in linear mode of operation.

Now, what is the property of an ideal switch, the ideal switch should have a low resistance when it is turned on or when the switch is closed. So, this is the resistance of the switch ok. So, this is R ds let us say, and that it is desirable that this resistance be low.

And now, the question we are asking is do we biased a linear saturation mode operation, when for having a low small signal resistance small signal resistance. So, what do you mean by small signal resistance, it is dV ds by dI Ds that is you have fixed the drain voltage at some (Refer Time: 09:37) point, and we are having some current in response to the drain voltage. Now, if we fluctuate the drain voltage around this point that is we have a small signal, which we will represent with a small v ds. If we have a small fluctuation here, how does the current fluctuate, how much does the current fluctuate. So that is what you mean by, small signal analysis?

Now, where is the small signal resistance lower in saturation or a linear? So, if you were to draw demarcate the saturation region, and then you draw the linear region here, what is the small signal slope in the linear region. So, you may have set the V DS, and now we are going to fluctuate a small signal V DS around this, and we are going to see a fluctuation in the current in response to that. So, this slope is essentially the resistor. So, as we move the current voltage up and down, the current moves up and down ok, so the current changes by that level. And therefore, the resistance here is some values, which we recall as r linear which is your dV ds by dI ds.

Now, what about in saturation mode, if the MOSFET has got ideal characteristics, and this is perfect saturation that is there is no channel length modulation. A large fluctuation in the voltage does not fluctuate the current too much that is even if dV DS is very large, your dI Ds is this is almost 0. And what is dV ds by dI ds in saturation, it is going to be infinite. Therefore, the resistance the small signal resistance for a MOSFET in saturation is infinite. And this resistance is something called as the output resistance of the MOSFET ok, whether it is a linear or saturation. This resistance between source and drain that we are talking about is something called as the output resistance of the model.

So, r o for a MOSFET in linear is finite it is small, and r o for a MOSFET in saturation is infinite. Therefore, it is definitely preferable to bias the MOSFET in linear mode of operation, if you are using it as a switch, so which means that if I am going to have to send data from point A to point B, and I have a control. So, let us say point B is that our reference, so let us say that is the source. And we have a control signal, which is the gate to source voltage, so that DC is got a certain DC level here ok. And we have the data voltage the gate to source voltage, and we have a drain to source voltage.

So, let us say that with time, the information being sent at point A has got the certain DC value, so that is V DS. And on top of that, we have a small signal information that is being sent to B. So, it is this information that we want appearing at point B.

So, what is needed is that this DC level ok. So, this fluctuation is very small, so that is not going to be very large. So, this DC level is expected to be smaller than V GS minus V T. So, in that case the MOSFET will be linear. But, if this DC level is increased, and if this DC level is going to be larger than V GS minus V T, then we have the MOSFET in saturation.

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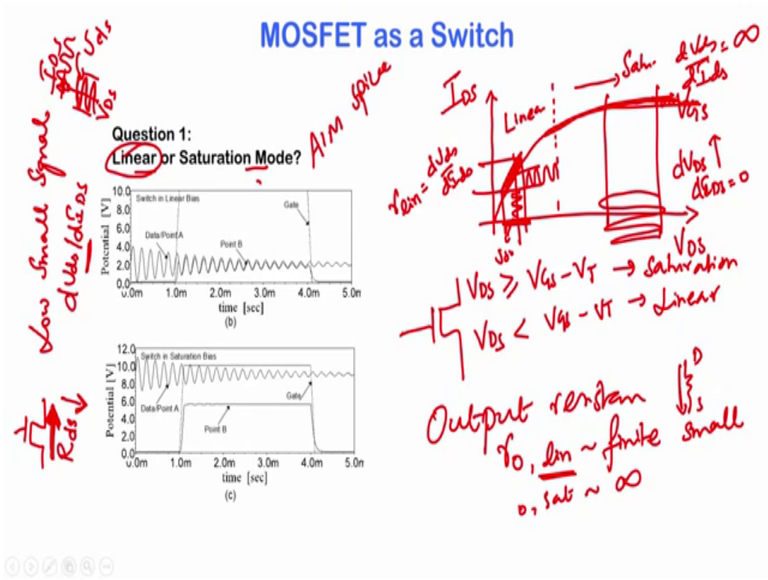

So, so here is the simulation ok, so the answer to this question is we want the MOSFET in linear. And to prove the point here is the simulation, which is done using AIM spice, so which is the software ok. And the simulator takes into account this circuit, so we are simulating this circuit here shown here.

So, the MOSFET we are considering has got a channel width of 100 micron, channel length of 10 micron, threshold voltage of 2 volts, the mobility that is very low. And we will; so, basically this is a thin film transistor MOSFET, which has got disordered semiconductors cox which is 9.73 e minus 8 farad per centimeter square. And we have point B here, which is got this terminal circuit. So, naturally if the MOSFET is open, point B is pulled to ground, it is kept at ground because of charge draining off through this resistor.

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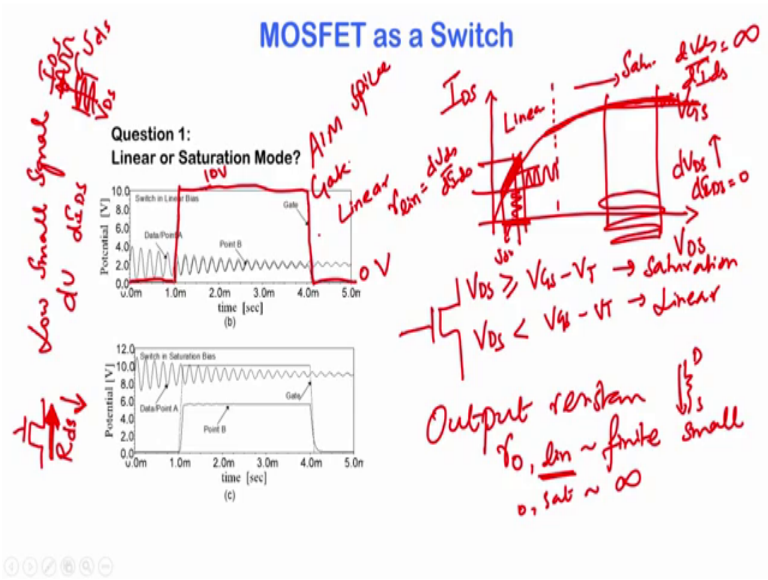

Now, what happens, so let us say we bias the MOSFET in linear mode? How do we know that? So, this diagram corresponds to linear mode. How do we know that this is linear mode? This signal that you see here, the square response is the gate of this MOSFET ok, so it is the gate voltage of this MOSFET. And the gate voltage is going from 0, it climbs to 10 volts, and stays at 10 volts for some time, and comes back down to 0, so that is the gate of the MOSFET. The source is generally at ground, because that is my point B. So, this line you see here is point B.

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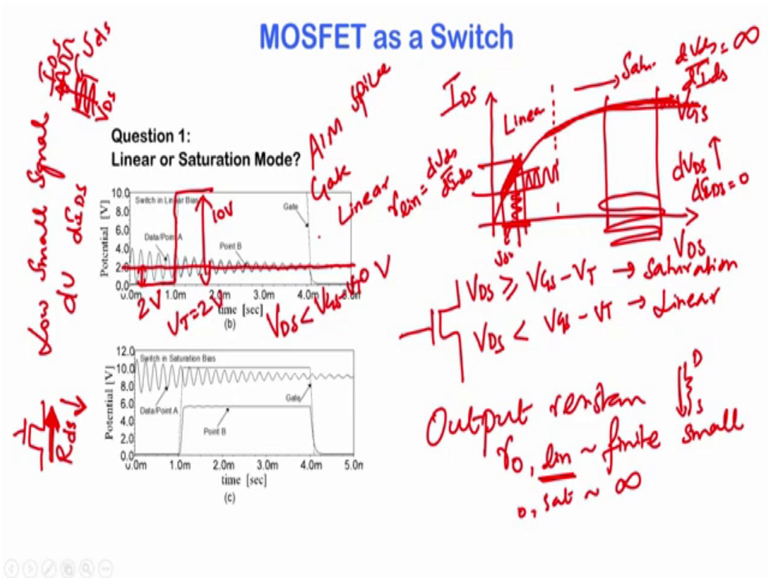

And this is the voltage fluctuation at point A. So, you can see a small signal that is trying to get across ok, it is a dying out sin wave. But, what is the average value of the signal, what is the DC value of the signal, the DC value of the signal is around at this point, so which is about 2 volts. And what does the DC value of V GS that is about 10 volts. And the threshold voltage is 2 volts. So, definitely V DS is less than V GS minus V T, which means that the MOSFET is in linear mode operation. So, when it is in linear mode operation let us look at what happens at point B ok.

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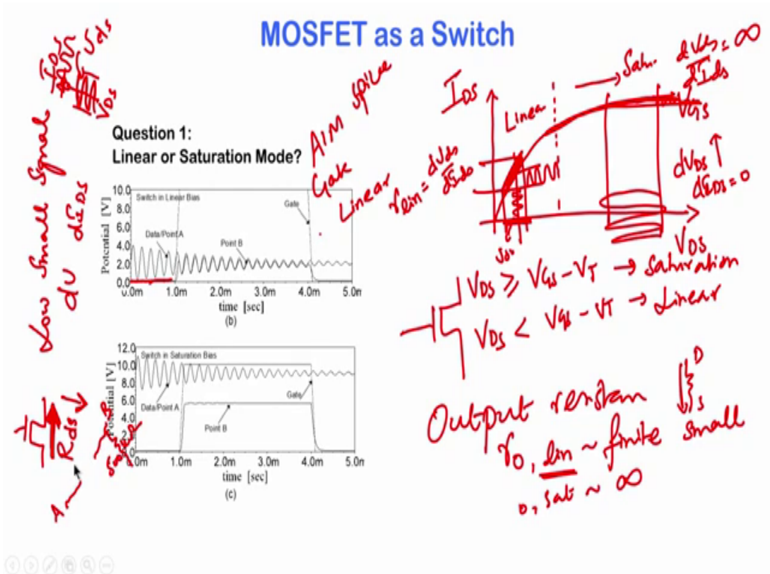

So, point B is seeing a signal like this. When the MOSFET is got 0 gate to source voltage, the MOSFET the switch is open, so point B sees nothing, because you have A that is fluctuating, and then the circuit is open, and B that is connected to ground with the 500 kilo ohm resistor ok. So, point B sees none of this fluctuation that is what is expected. But, the moment the MOSFET turns on, you can see point B climbing up, and almost following point A except for a small delay, it is almost following point A, and the moment the switch closes again point B loses connection with point A, and it goes back to 0. So, you can see that the signal from A is successfully transferred to B, if you keep the MOSFET in linear mode of operation.

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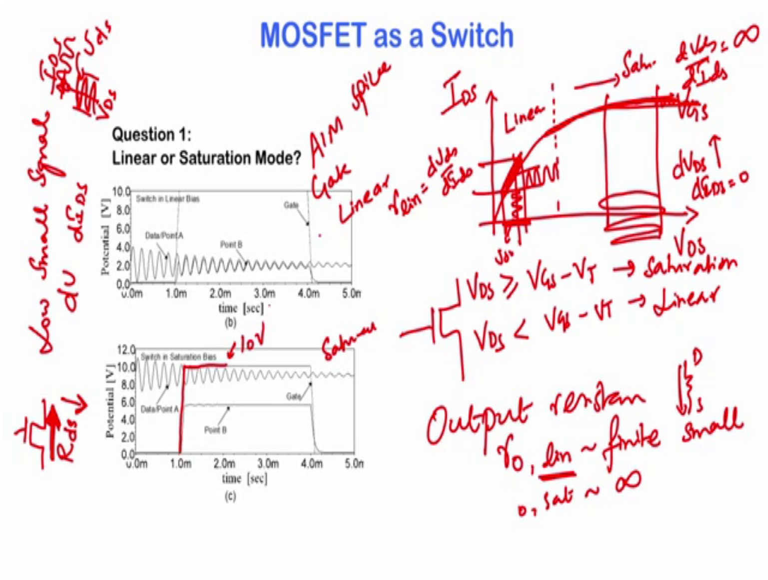

Now, what about keeping the MOSFET in saturation mode of operation ok? Now, this is the case, where the MOSFET is in saturation mode. How do we know it is in saturation mode? So, the gate voltage is still the same; when it is on, it is still 10 volts.

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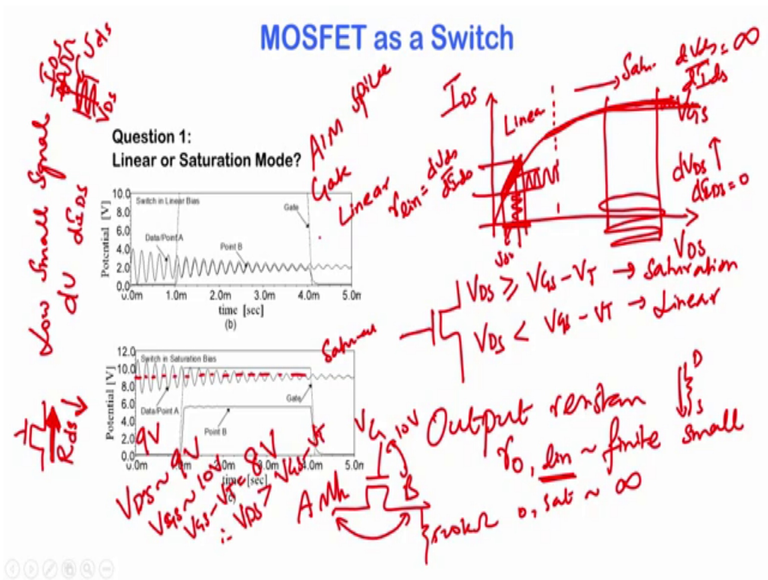

But, let us look at the voltage at point A ok. The voltage at point A is the this is 500 kilo ohm that is point B, and this is point A, this is where the signal is coming in, so that is 10 volts that is V GS. What is V DS? So point A has got a signal that looks like this right. And what is the DC value of that signal that somewhere here and that is about 9 volts.

So, V DS is about 9 volts, V GS is about 10 volts. And what is V GS minus V T, it is about 8 volts. Therefore, V DS is greater than V GS minus V T, which means the MOSFET is in saturation.

So, now let us look at what happens to point B, is it able to capture the signal. So, this is point B. You can see that when say MOSFET is turned on, its voltage increases, but it is not able to so well, I mean so clearly track the message coming in from point A. You can see there is some very light movements, but generally it is a constant, and then it dies out ok. So, point B in this case is not able to track the signal from point A, because the MOSFET is in saturation, and it has got a very high output impedance. So, this is a very illustrative example, where you say that we need the MOSFET to be in linear mode operation, and because it is going to have a low output impedance in linear mode operation. So, this is the summary.

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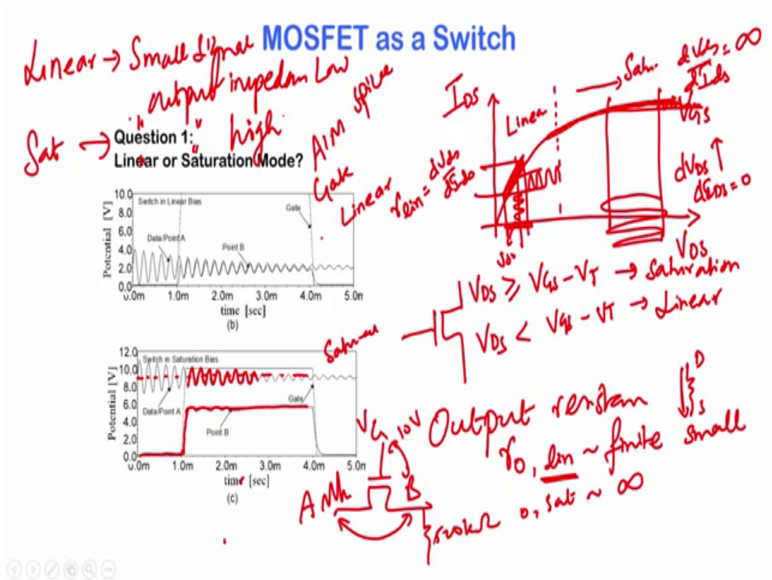

So, in linear mode operation, the MOSFET has the small signal output impedance of the MOSFET is very low. And in saturation mode operation, the small signal output impedance of the MOSFET is very high. And therefore, we want the MOSFET biased in linear mode operation for use as a switch ok. So, we have decided it is linear mode operation.

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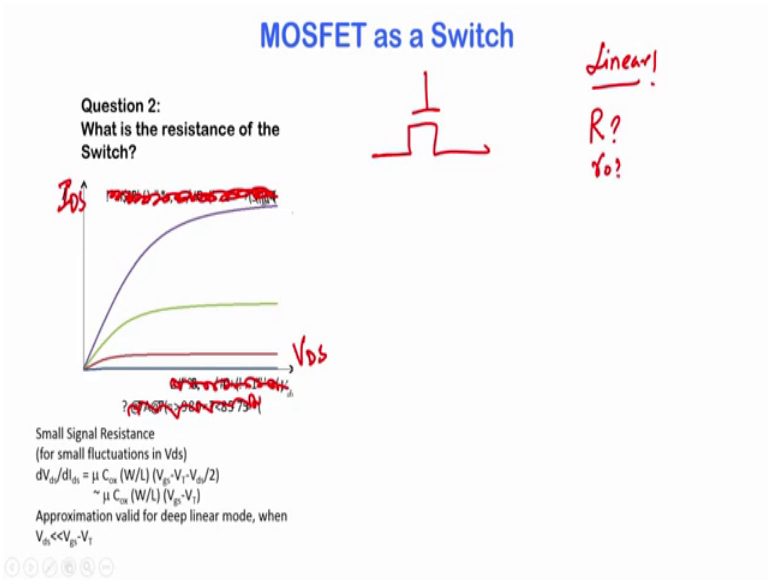

Now, what is the resistance of the switch ok? So, what do you mean by the resistor, what is the resistance of the MOSFET switch? So, do forgive this plot having all these scripts, because this is the image that is transferred from a Mac to a PC, and it generally happens to have these kinds of errors.

So, what we are trying to show here is the output characteristics, it is V DS versus I DS or the rest of the details are not important ok. So, the point of this is going to be in the previous slide, we realize that we should bias the MOSFET in linear ok. Now, the question is what is the value of the resistance, what is the output resistance of the MOSFET. So, we are talking about the small signal resistance of the MOSFET.

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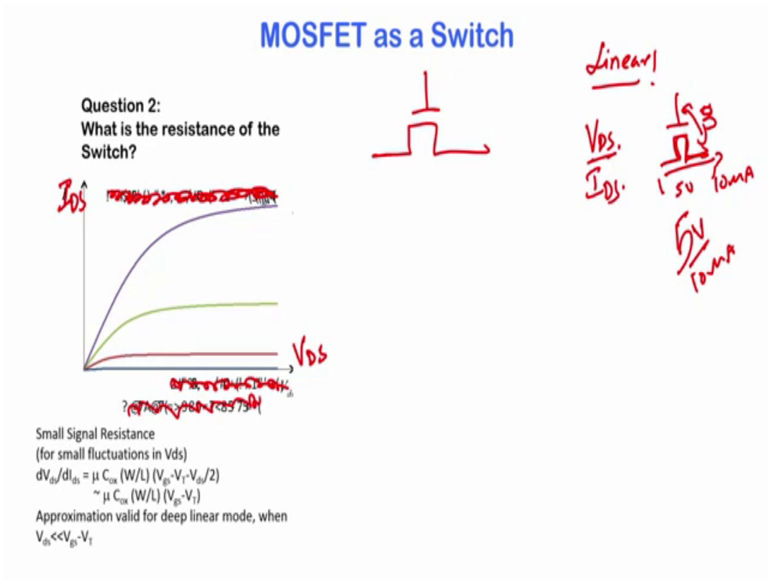

We are not talking about resistance measured as V DS by I DS, no because if it is V DS by I DS, even the saturation mode in the saturation mode, the MOSFET does have a finite resistance ok. You have let us say a V DS of 5 volts. And let us say the V GS is whatever 3 volts, and therefore the MOSFET is in saturation.

And let us say there is a current of 10 micro amps, so the MOSFET has got the V DS by I DS of 5 volts by 10 micro amps. So, you could say that effectively that is the resistance of the MOSFET, no but that is not what we are talking about, because that is the large signal behavior of the MOSFET, and that is the non-linear behavior. So, it is really not appropriate to define a resistance there.

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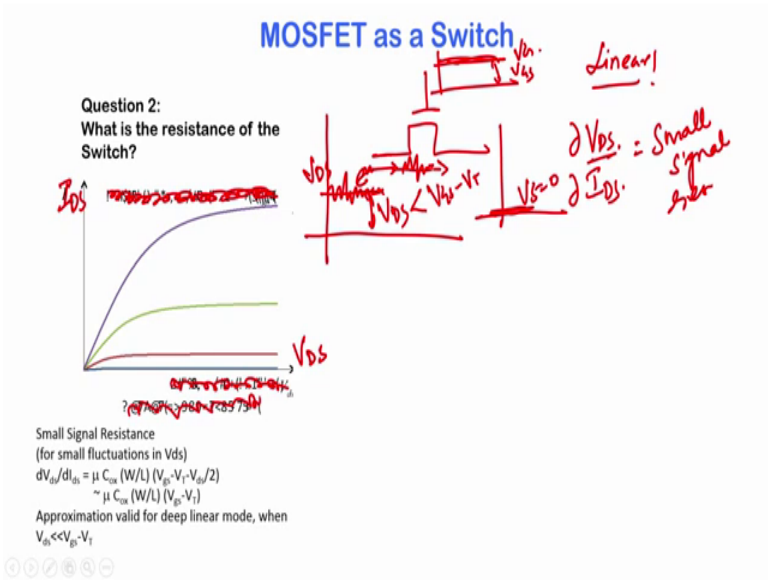

What we are interested in is the small signal resistance ok. So, I am reiterating this point small signal resistance of the MOSFET, which is for a small fluctuation, after you have set all the DC voltages, you set all the DC voltages. Sources at ground, the gate is at some voltage, so that you know with respect to ground you have a certain V GS, and the drain is at some voltage, and with respect to ground you have a certain V DS. And this V DS is less than V GS minus V T. So, this is smaller than that.

And now, on top of that you have a little fluctuation. And therefore, you have a little current that is DC, and then you have a fluctuation in the current. And this fluctuation is defined by the small signal resistance of the MOSFET, so that is the resistance we are after. So, what is the value of that?

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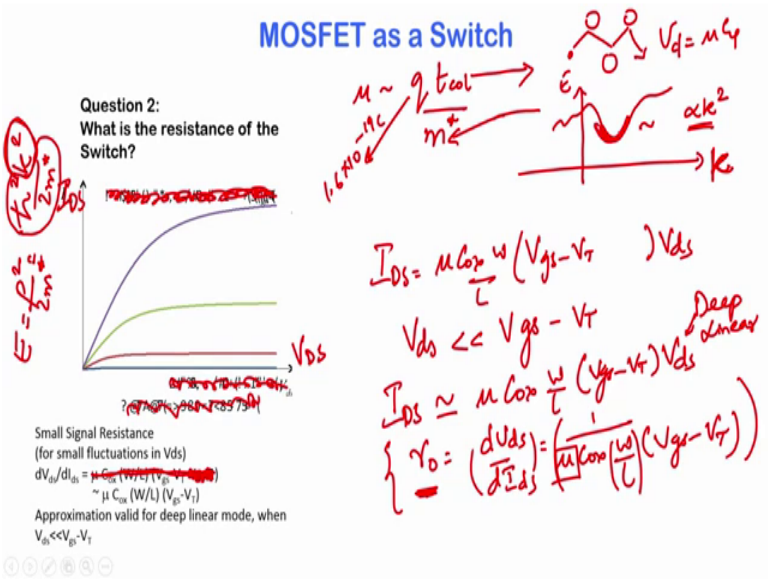

So, the value of that, since we have biased the MOSFET in linear mode operation, what is I DS, I DS is mu Cox W over L into V gs minus V T minus V ds by 2 into V ds. And if my V ds is much much smaller than V gs minus V T, we could say that we are going to ignore this term. And therefore, I DS is approximately mu Cox W over L into V gs minus V T into V ds ok. So, this is something called as a deep linear, I mean it is a very very linear operation. V ds is much much smaller than V gs minus V T.

So, now what is the small signal output impedance, what is the output impedance of the MOSFET, it is dV ds by dI ds, which is what 1 by mu Cox W over L into V gs minus V T. This is nothing but the slope of the i d v g characteristics in the linear region.

So, since it is deep linear, they are going to set the V ds to be very low, and we are looking talking about a slope in this region here. So, this slope is given by that is inverse of that slope if you wish, because that is an I DS versus V ds characteristics the inverse of the slope, which is dV ds by dI ds is given by 1 by mu Cox W over L into V gs minus V T. So, this is the quantitative estimate of the small signal resistance of the MOSFET.

So, here there should not be a V ds by 2 term existing, so that part is probably not very accurate that is a typo on that slide (Refer Time: 25:06). So, let us now you know play this game of connecting all these properties to our understanding of the device physics. So, let us see whether we can use this is the refresher for your device physics.

Now, as a circuit designer, you have identified that this is the small signal output impedance of the MOSFET, when it is in linear mode operation. So, first it does not make sense. When the mobility goes up, should the resistance increase or decrease. And the mobility goes up, the carriers move faster, the current increases. Therefore the resistance should decrease that makes a lot of sense. If Cox goes up, the field effect improves, the current increases, and the resistance decreases that also makes a lot of sense.

If the MOSFET has got a large channel width over channel length large aspect ratio, the resistance should definitely go down, so that makes sense. And if the V T is very small or V gs minus V T is very large, definitely you have larger inversion charge, and you have a lower resistance, so that also makes a lot of sense. But, let us now go ahead and start defining each one each one of these terms.

What is mobility? You can say we are talking about the output resistance of the MOSFET. Now, what is the mobility, the mobility is connected to the mean collision time, it is q t collision by the effective mass of the carrier. What is q; q is your 1.6 into 10 power minus 19 coulombs. What is mean collision time, mean collision time is the time for the is the mean time between the scattering events of the carrier that is scattering through the lattice and through the defects etcetera, thereby giving you a definition of mu, which is your v d is equal to mu times electric field.

What is the effective mass, the effective mass is dependent on the shape of your E K diagram, you have an energy, you have a momentum or the K space. And let us say you have your E K diagram say that is let us say that is the conduction bandage, we saw that this the valley of this conduction bandage can be approximated as a parabola ok.

And why can it be approximate as a parabola, because you are in a classical sense your energy is P square by 2 m, and this P is nothing but the momentum, which is also h bar K, so is h bar K square by 2 m. And this m is nothing but m star, where m star is the effective mass. And therefore, this is a coefficient attached to the K square dependence or a parabolic dependence, so it is an approximation here.

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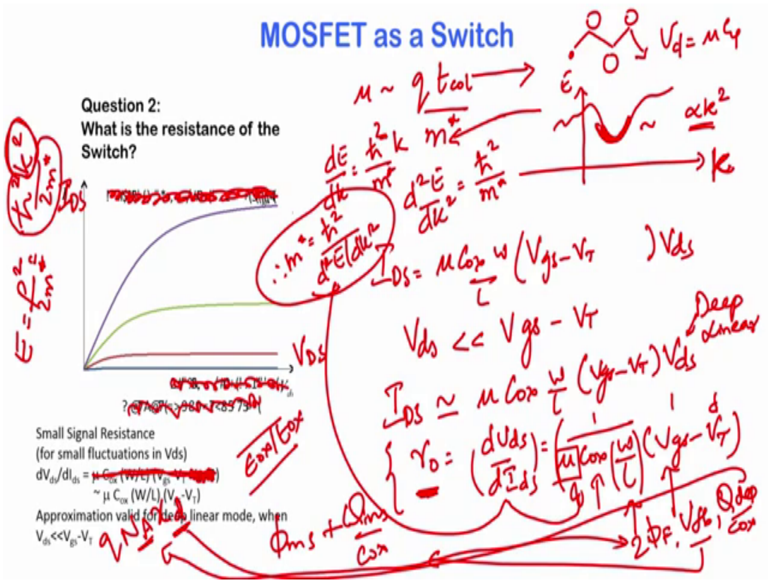

And what is the effective mass, we identified it from the second derivative of E, so dE by dK is h square by m into K, and d square E by dK square is h square h bar square by m star. And therefore, your m star was nothing but h bar square by d square E by dK square. So, for therefore, the shape of the E K diagram is directly going to impact the output impedance of your MOSFET, so that is your mu right.

What is Cox? Cox is nothing but the capacitance the gate capacitance or the insulator capacitance per unit area of your capacitance voltage characteristics or your MOSFET sorry, and that is nothing but epsilon ox by t ox, it depends on the thickness of the oxide. Aspect ratio is the geometry with which you have designed the MOSFET. V gs is the applied gate to source voltage. And what is V T, V T is the threshold voltage, it depends on the flat band voltage, it depends on it depends on the depletion charge divided by Cox, it depends on 2 phi F, the surface potential reaching 2 phi F.

And what is V fb, V fb is the flat band voltage, which depends upon the metal semiconductor work function for the gate metal and the semiconductor, it depends on any trapped charges in the insulator divided by Cox. And what does q depletion depend on, q depletion depends on q N A x d, sorry it is a very crowded slide here. So, q depletion depends on q let me just mark it somewhere else, it depends on q N A into x d.

And what does what does N A, N A is nothing but your dopant ion concentration in your P type or N type doped body of the MOSFET. And x d is the depletion width, which in turn depends on the surface potential, and which should be 2 phi F at the time of turn on of the MOSFET. And 2 phi F again depends on the dopant concentration. So, here is a complete breakdown of the output impedance of the MOSFET a linear mode with respect to all the device physics that we have learned so far.

So, this connection is the is the value or the message of all these lectures ok. So, it is the value of talking about circuits, so that you understand not only how to design the circuit or what the circuit the implication of the circuit design is in terms of circuit performance ok, but also what to do and where these parameters came from, so that it helps you debug at a very fine level. Of course, this is a very it is an introductory course in some sense, but nevertheless it is got a lot of valuable messages in this in the in this content. So, now let us move on. We have answered this question, which is what is the resistance of the switch.

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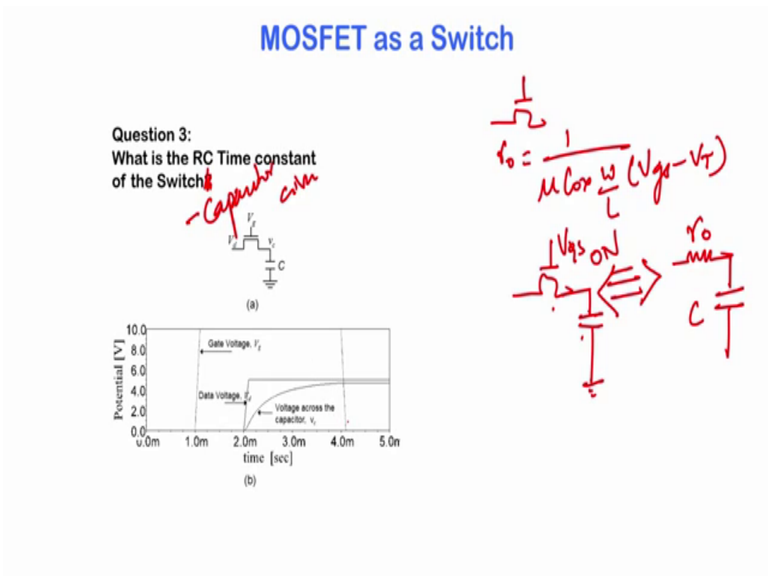

So, we know that we are going to use the MOSFET as a switch, and we know that it has got a resistance of 1 by mu Cox W over L into V gs minus V T. Now, here is the next question. So, suppose we use this MOSFET as a switch in a switch capacitor circuit, which is the switch in series with the capacitor, and let us say the MOSFET is on, so the now MOSFET is on. And the small signal circuit or the equivalent small signal circuit can be written as replacing this MOSFET with a small signal resistor, and here is the capacitor.

So, what is the time constant of the switch capacitor circuit, what is the RC time constant of the switch capacitor circuit. So, what do you mean by RC time constant ok? (Refer Time: 32:56) people are not I hope all of you are familiar with RC circuits, but just in case you have forgotten what RC circuits are what an RC circuit is let us just go down the track for a in a minute.

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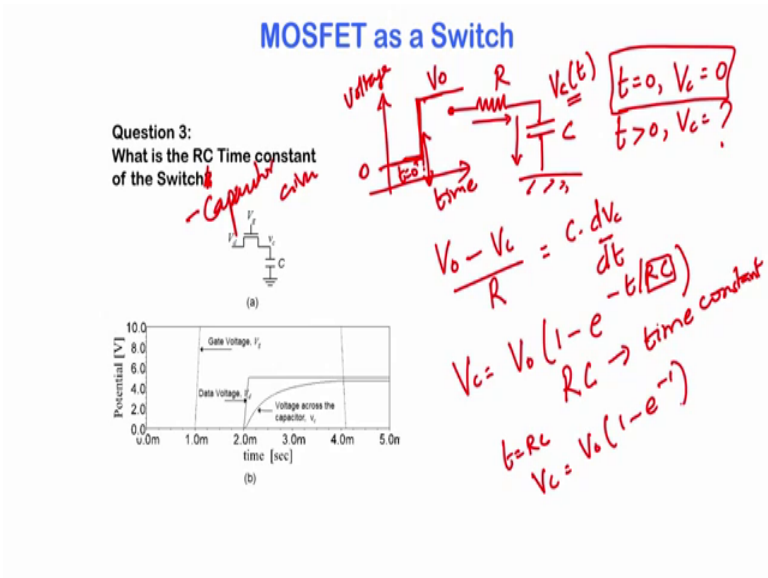

So, let us see you have a series resistor and a capacitor circuit. You have a capacitor, it is connect and series the resistor. And let us say you have an input voltage here, which is appearing as a step. So, you have a voltage versus time, and it is a step input voltage, it goes from 0 volts to say some voltage V naught. And the question is what happens to the voltage on the capacitor. So, at time t equal to 0, the capacitor had a voltage of 0. But, as t greater than 0, what is the voltage on the capacitor, so that is the question we want to answer ok, how do we solve this.

So, since the current through the resistor and the current through the capacitor should be the same, we say that the current through the resistor is the movement this is turned on at this point just after a turn on. So, let us say at t equal to 0 plus, the current through the resistors V naught minus V c which is the voltage drop across the resistor divided by R, and the current through the capacitor c dV c by dt ok, which is basically the dq by dt through the capacitor. And solving this differential equation, you will see that your V c is and you apply this boundary condition of t equal to 0, V c is 0, we will find that V c is equal to V naught into 1 minus e to the power minus t by RC, you will end up with this answer.

This RC has the dimensions of time right. And therefore, RC is called as the time constant of the circuit. So, what is the time constant mean. So, technically when t is equal to RC, the voltage in the capacitor is V naught into 1 minus e to the power minus 1 ok, but I mean that is only the accurate quantitative definition.

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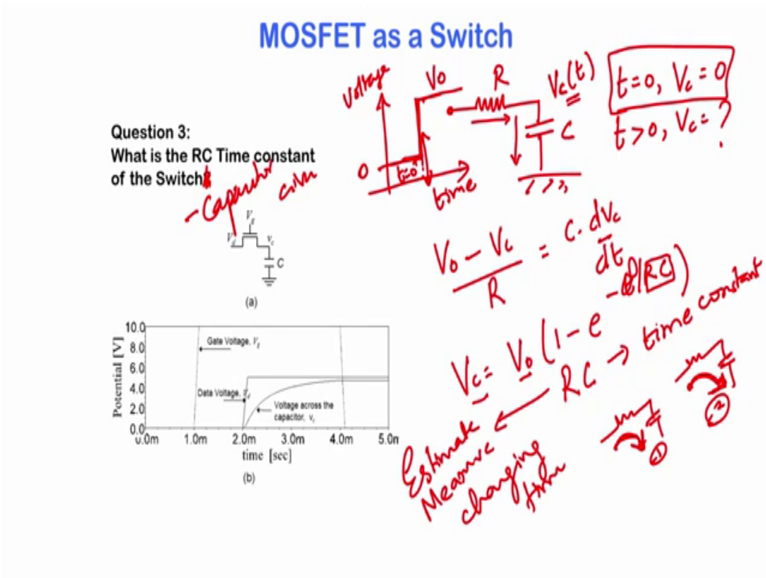

But, essentially the time constant is a useful parameter that gives you an estimate; it is an estimate or a measure of the charging time of the circuit you know. If you want to compare two RC circuits you compare two RC circuits, and you say that this one has got a smaller time constant than that one, which means to say that this circuit will charge faster as compared to circuit 2 ok, which means to say that circuit 1 is faster compared to circuit 2.

So, time constant is a good measure, it is not the total time taken to charge the capacitor ok. The total time taken to the charge the capacitor is the time taken to bring V c to equal to V naught, and that is technically infinite, it means infinite time to charge the capacitor that is not so, RC the time constant is not the total time taken to measure charge the capacitor is just a measure or an estimate of the delay or the time taken during charging. Is the capacitor charging fast or slow compared to another capacitor that is the answer it gives you.

So, we need to find the RC time constant. What is the time constant of the switch capacitor circuit with the MOSFET, so that is the purpose of this slide. So, now after this discussion, the answer is quite simple. It is simply the output impedance of the MOSFET multiplied by the capacitance, and that gives you a good enough answer.

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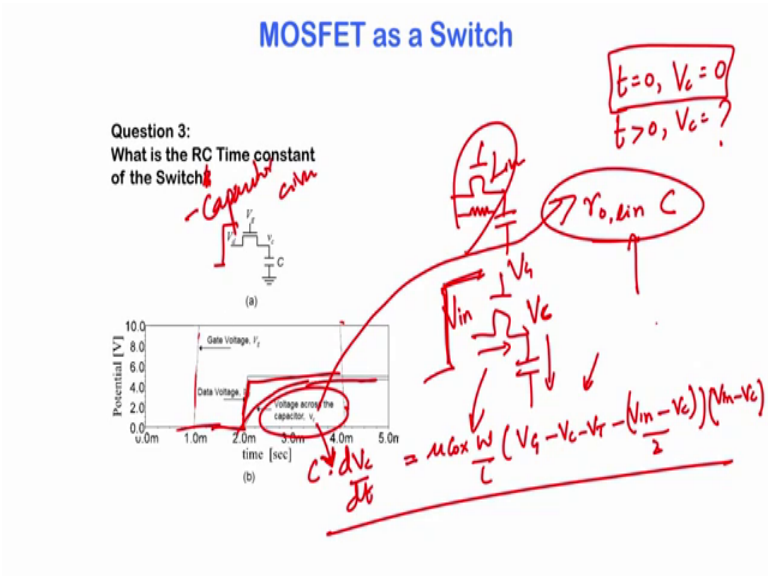

So, if you have a MOSFET operating in linear mode operation, and somebody I asks you is to what is the small signal capacitance a small signal time constant of the MOSFET, it is simply r o linear into the capacitance of the capacitor, it is an approximate model. And what is the approximation, we have linearized the MOSFET.

Now, if somebody asks us to what is the exact charging dynamics ok, so do not linearize it, how do we go about it. We simply equate the current through the MOSFET into the to the current in the capacitor, which is we have taken into account the non-linearities of the MOSFET. So, let us say that is the V C that is the input.

So, what is the current through the MOSFET, it is going to be mu Cox W over L into vg V gs, which is V G minus V c minus V T minus V ds, which is V in minus V c by 2 into V ds, which is V in minus V c. This must be equal to the current through the capacitor, so it is c dV c by dt. You solve this equation, and you will end up with the exact charging dynamics, which also takes into account the nonlinearities in the MOSFET.

So, if the voltage is concerned, if the input voltage is all very large, if the step input is very large, this is the more appropriate equations (Refer Time: 38:38). But, you will find that for most cases, this is not very far. The time constant, you will get in this case will not be very far from the time constant you get by simply linearizing the MOSFET and to using that value ok.

So, here is the simulation, and it shows you the charging of the MOSFET, so the gate voltage goes up, the MOSFET is on. And then when the drain voltage takes up a step like response, you can see that the capacitor starts charging. And this charging time constant although it is the simulators using the exact model, you could easily model it using a much simpler linearized model instead of worrying about solving this differential equation, so that is the strength of having these kind of small signal models. Of course, it is going to be very useful, when we study amplifiers etcetera. So, it talks about the linearization of the non-linear device around a certain operating point ok.

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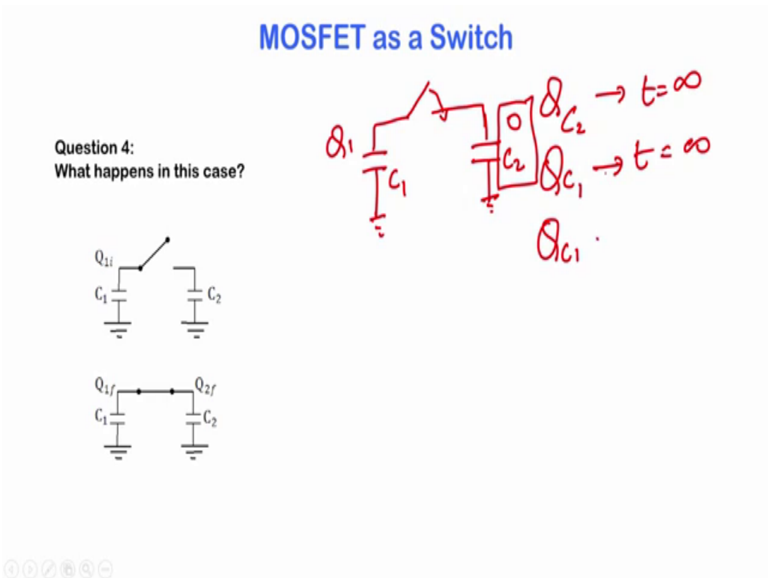

Now, here is another useful circuit, but although this really does not connect us to our device physics, nevertheless it is a useful circuit for all of you to know ok, which is basically you have a capacitor that is charged with some charge Q 1. And you have another capacitor say C 2, which does not have any charge in it. And you use a MOSFET or any switch for the matter. So, although we are talking about MOSFETs as a switch, you could use a MOSFET, but it really does not matter, you use a switch of any kind ok, and you close the switch.

The question is what is the charge and the capacitor C 2 ok, what is Q C 2 at time t equal to infinity. And what is Q C 1, when t is equal to infinite. We already know that Q one C 1, when t equal to 0 is Q 1 ok.

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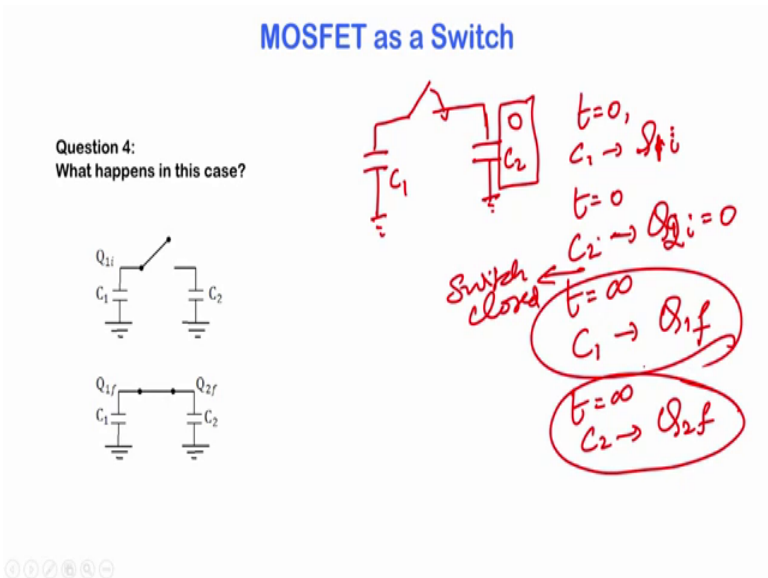

So, I think in this diagram, I have used let us just use the variables, I have used here, which is at time t equal to 0 q I mean C 1 has a charge of Q initial 1 Q 1 initial. And at time t equal to 0, C 2 has a charge of Q 2 initial, which is 0. At time t equal to infinite, C 1 will have a charge of Q 1 final. And at time t equal to infinite, C 2 will have a charge of Q 2 final. And what has happened here is that the switch has been closed. The question is what is the charge on the capacitors at time t equal to infinite; so how do we go about solving this? So, we simply use charge conservation right.

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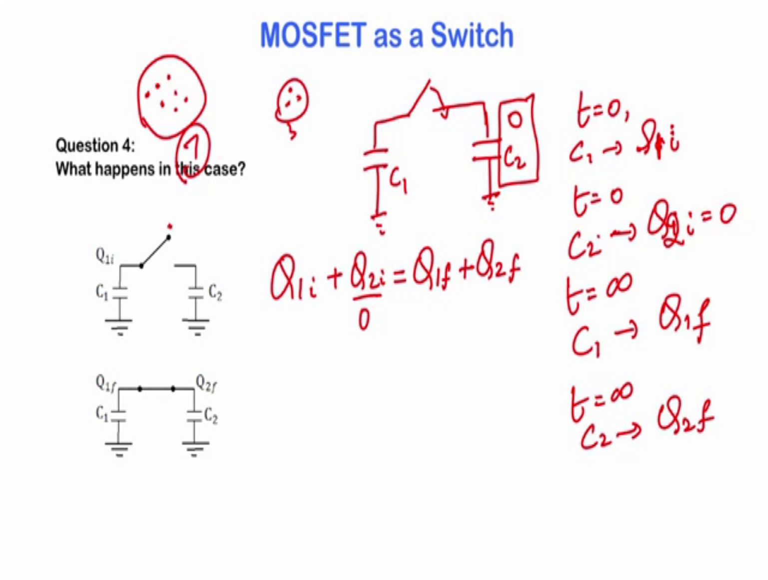

So, if you use charge conservation what is the total charge, so the total charge is Q 1 initial that was the entire charge in the system, because Q 2 initial was 0. So, this is simply, so this is nothing but 0, and that must equal the final charge in the system.

So, what is charge conservation? So, suppose you have 10 electrons, and you had to take 3 electrons away, and keep them here. How many electrons do you have left here, the answer is 7. And how did we get that number, because charge is conserved. So, you took 3 away, and you have 7 and you had and you had 10 in the beginning. And therefore you have 7 remaining.

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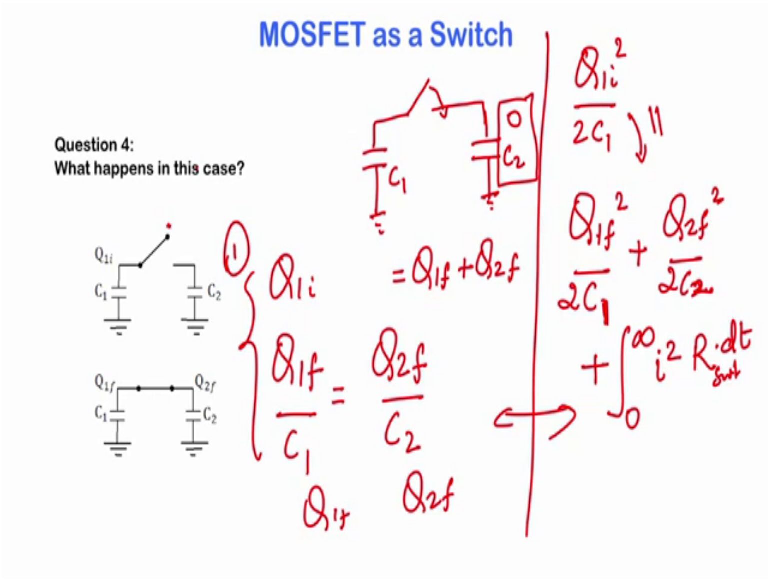

So, so according to charge conservation, you had up get one equation, which is basically this. And after at t equal to infinite, after you have short circuited this at t equal to infinite, these two points must have the same voltage ok, they cannot have different voltages, they are short circuited. And at t equal to infinite, they must have the same voltage.

So, therefore, the voltage on C 1, at t equal to infinite is Q 1 final by C 1, I must equal the voltage on C 2 at t equal to infinite, which is Q 2 final by C 2. And using these two relations, we can identify what Q 1 final and Q 2 final are so. We will leave that to us as an exercise.

But, here is another interesting detour. So, let us say we said charge conservation is what we need to use here. So, let us say we use energy conservation. So, what is that initial energy in the system? So it is Q 1 initial square by 2 C 1. What is the final energy in the system? It is Q 1 final whole square by 2 C 1 plus Q 2 final whole square by 2 C 2.

Now, is it for me to equate the initial energy in the system to the final energy in the system, can we say charge energy conservation energy is conserved. And therefore the initial energy in the system is equal to the final energy in the system. If we define the final energy in the system in this manner, the answer is this equation will not hold. And why will it not hold, because what we have ignored to consider here is any loss due to joule heating in the resistor that we used.

No matter what the switch and what the resistance of the switch, there will be some amount of joule heating ok. And in fact, it turns out that that heating or the energy loss becomes independent of the resistor used ok, which is an interesting offshoot from this. So, we will look at that also in some assignment.

So, therefore this these two can be equated, the initial energy of the system and this can be equated, only if we consider the loss due to joule heating in the resistor of the switch resistance. So, this equation will hold true. And if you actually solve this out, you should get the same answer as you get for charge conservation ok. So that is a message from this slide.