Semiconductor Devices and Circuits
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Lecture – 34
MOSCAP: CV Characteristics

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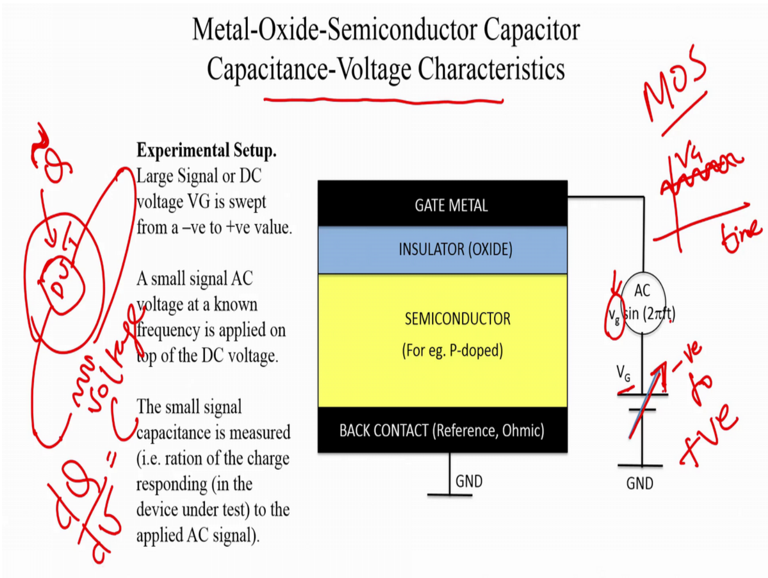

So now let us look at the MOS capacitor, but start looking at the capacitance voltage characteristics of the MOS capacitor. The essential idea of this experiment is to see how does; see measure the capacitance of the small signal capacitance of the MOS capacitor. And see how the MOS capacity the capacitance varies when the V G or the gate voltage varies.

So, we have already done these kinds of exercises before. You know, if you look at if you remember the metal semiconductor junction, we built an equivalent circuit. We said that the metal semiconductor junction, you know it had rectifying nature, if it was a Schottky junction it had a depletion capacitance, etcetera. In the case of a diode we said yes, in reverse bias it had a depletion capacitance and in forward bias it had a depletion and diffusion capacitance.

So, this is another such exercise, but with the metal oxide semiconductor capacitance ok. So, we have been calling it a capacitor. So, let us start measuring the capacitance, what is the capacitance of this capacitor. So, here is the experimental setup ok. So, how do you measure capacitance? In order to measure capacitance essentially you need to give an AC signal, and measure the current through the AC current due to this AC signals.

Because a capacitor would have an equivalent impedance of about one by j omega c, if C is the capacitance the impedance is about 1 by j omega c; where omega is the frequency which is angular frequency which is 2 pi f, with f being the frequency in hertz, C being the capacitance and j the complex number square root of minus 1 ok.

And if you apply a sinusoidal or a time varying voltage, it is only a time varying voltage that is going to create a current in the capacitor. And therefore, the time varying voltage is going to create a current of V by this impedance; which is going to be the voltage applied into j omega c. And by measuring this current and by knowing this voltage and knowing the frequency, you can extract the capacitance.

So, there are many equipments or instruments that will measure the capacitance for you in a very accurate manner. And our investigation here is not the development of the instrumentation to measure the capacitance, but let us assume that we have an accurate estimate of the capacitance. And we are trying to see or guess what the capacitance will be based on our understanding of the MOS capacitor.

So, this is our experimental setup ok. So, we have our gate voltage, but the gate voltage is now variable can varied from say a very negative voltage to positive voltage. So, we have a variable gate voltage. And on top of this gate voltage, so we are going to apply a gate voltage. And on top of this gate voltage we are having a small signal that is our capacitance measurement signal, that is applied a small signal AC that is applied along the large signal gate voltage. The gate voltage determines the DC value and the small signal determines the AC value, ok.

So, it is an AC signal, and all operations are linearized around this AC measurement right. And using these 2 in combination, we are going to estimate what the capacitances, we are going to see what the behavior of the devices. But as before you know, what is small signal capacitance? So, let us say you have a device sitting in a black box and, let us say it is got 2 terminals outside. The way we want to define capacitance is we will met we will apply this small signal fluctuation, the voltage fluctuation. And we are going to estimate what the charge fluctuation because of this small signal is ok.

So, how does the charge in the device under test respond to our small signal fluctuation? That is the measurement of this small signal capacitance. So, it is dQ by d applied voltage. So, that is the small signal capacitance ok; so that is. So, we are going to what we are going to do in this experiment? Is you are going to have this AC signal we are going to set the frequency of the AC signal we have a knob to set the frequency. The magnitude is typically kept very low we will not worry about the magnitude of the AC signal; we will keep that constant. But we are very interested in the frequency of the AC signal and we are interested in varying the gate voltage; and also the rate at which we vary the gate voltage. And I will let you know about nodded at some point ok.

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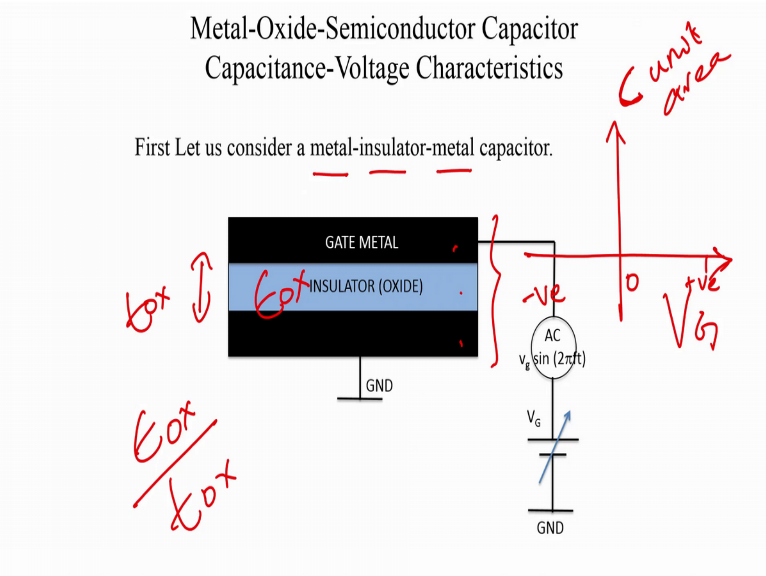

So, first let us say let us run our first experiment ok. So, let us not worry about the MOS capacitor to start with. Let us start with a very traditional metal insulator metal parallel plate capacitor, that all of you are very familiar with. So, let us say we were trying to build the mosque capacitor, but we forgot to put the semi conductor ok.

So unfortunate, but we ended up with this structure here. So, you have the gate metal, you have the insulator and you have a rather back contact. And the experiment we are going to run is we are going to vary the gate voltage. We are going to vary V G from a very negative value through 0 to a very positive value or let us say through flat band, but here flat band does not make any sense; so from negative to 0 through positive value.

And we are going to see what the capacitance per unit area is, what is the capacitance I am recording from this measurement. So, what do you expect for a metal insulator metal? So, let us say the thickness of the insulator is t ox and it is got a permittivity of epsilon ox ok. So, what is the capacitance per unit area of this capacitor? It is simply it is parallel plate capacitor; so therefore, epsilon ox by t ox ok. So, do you do we expect the epsilon ox by t ox to vary with the applied voltage? The answer is no, because the insulator is ideal, there are no trap charges in the insulator and we do not expect any variation, ok.

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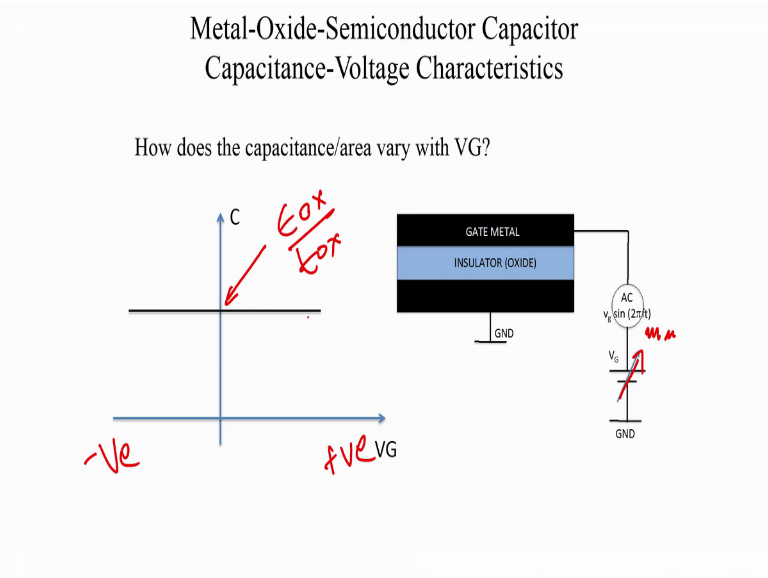

So therefore, there is all that we expect to see is this. So, if you were to sweep V G as you go from negative values to positive values, this capacitance will be constant ideally, and the value of this is going to be epsilon ox by t ox. So, that is the value it is going to take ok

Now, we can also try to vary the frequency of the AC signal, we can try to vary the speed at which we sweep etcetera. But ideally, for an ideal capacitor all this should not make any difference, you can measure the capacitance at any frequency and you should see the same behavior. But of course, in reality it is not going to be. So, because that every capacitors also got a say a resistor in parallel etcetera. So, there are many leakage mechanisms instead of it is not going to allow you to see this response. But let us just talk about the ideal case for now ok.

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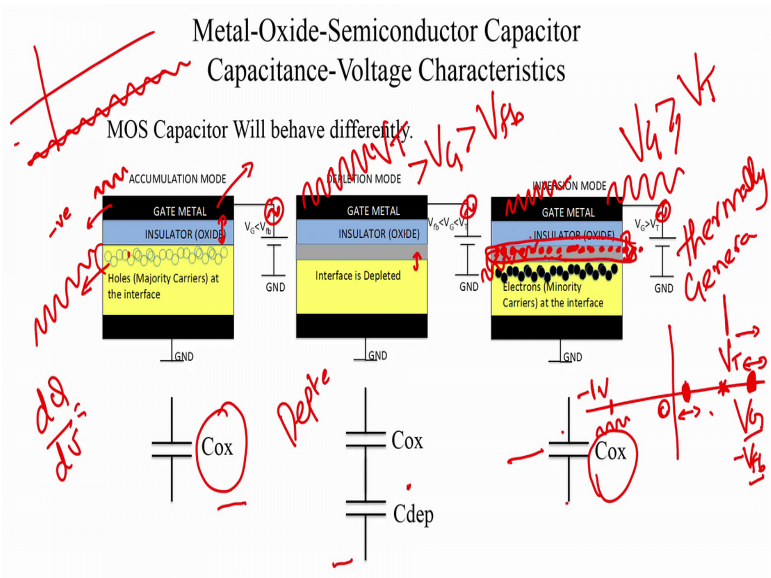

So now let us say we went back and we constructed our MOS capacitor more correctly ok. We now a brought in our semiconductor, and we are going to do the same experiment, but with the metal insulator semiconductor metal structure. So, what is going to happen? So now, as you vary the V G our semiconductor is going to react to it, and the structure is going to behave very differently, and why is it different?

So, let us say we are in accumulation mode; that is, V G is less than V fb we are in accumulation mode. And what happens in accumulation mode? All the majority carriers appear at the interface. And in this case the majority carriers in the holes; and you find that all the holes have appeared at the interface. The band bending is now like that, and you have all the holes appearing at the interface. So, for V G less than V fb if I were to provide a small signal fluctuation; I have now set my gate DC voltage right. So, let me pin my DC voltage further.

So, we have now set V G equal to minus V G minus V fb equal to minus 1 volt and left it that ok. So, the DC point is set. And now we are going to apply the small signal AC ok. So, I have forgotten to add the AC source everywhere. So, we apply the small signal AC and we are now going to measure the response of the carriers in the MOS capacitor. So, what is going to happen if the gate metal fluctuates a little? You will find that since though there is a charge fluctuation on the gate, since the negative charge and the gate is fluctuating a little.

So, you have some negative charge on the gate, because of the DC voltage, but now because the AC signal this negative charge is fluctuating. This small fluctuation has to be reflected by the whole population. And the holes are all the number of holes is also going to fluctuate, in response to the fluctuation here, ok.

So, it is as though you now have a capacitor which is got a gate metal, you have the insulator and this fluctuating whole population, there are plenty of holes in the semiconductor there is no dearth of holes. It is a p-type semiconductor, the majority carriers. This fluctuation of the holes is like equal to another metal plate if you imagine. So, you can imagine a metal plate an imaginary metal plate here and therefore, it is like, you know, you have carriers fluctuating ok.

If you want to imagine it that way, but more properly what we are looking at is the charge fluctuation in the device under test in response to the applied signal. And what does the charge response? It is the hole fluctuation in the semiconductor insulate interface.

And therefore, our dQ by d applied the small signal applied voltage is simply going to be, what is the whole population going to what is the fluctuation there? It is simply C ox into V ox right; so C ox into v, so that is the voltage difference. And therefore, our capacitance is going to end up being just C ox, but now let us say we increase the gate voltage, we reach the point where V G is greater than V fb, but it is still less than V T. We have still not reach threshold voltage, but we are greater than the flat band voltage.

So, in this case the interface is not depleted. So, we are in the depletion mode of operation. So, what is this capacitor like? You know, you can now imagine this back metal with an ohmic contact and is doped semiconductor width which is basically like a resistor ok, and you now have a gate metal here. And in between you have 2 capacitors sandwiched in series. You have the insulated capacitor and then you have the depletion capacitance ok. And we all know how to calculate the depletion capacitance by solving Possion's equation.

So, this region is depleted does not have free carriers, you can imagine it to be an insulator another insulator ok, if you wish. So, you have a series combination of these 2 insulator; so the capacitance now decreases. It becomes a series combination of not only it no it is not only C ox, but it is a series combination of C ox and C depletion in depletion mode operation. So, that is the capacitance that you see. And if you want to imagine the response to the charge, how is the charge responding?

So, let us say you have applied your AC signal; there is a small fluctuation on the gate ok. So, we have now set V G is equal to is greater than V fb, but it is less than V T. So, let us say that is our V T point so, that is V T. And this we are plotting V G minus V fb. So, we have somewhere there. Just slightly above V fb. So, you have depleted the semiconductor and now you are fluctuating this voltage. So, there is a fluctuation in this voltage right.

So, we are moving this voltage back and forth with a small signal AC. So, how does the semi conductor respond? It responds by increasing or decreasing the depletion width.

So, the x d increases or decreases in response to the applied voltage. And by increasing or decreasing the depletion width, you are either covering or uncovering all the fixed ions. So, if the depletion boundary is there you have uncovered all these and if the voltage on the gate increases the little, you need to add more negative charge and therefore, that goes away and the x d increases a little bit more. You have more negative charge being uncovered. So, that is the response of the semiconductor to the applied AC signal in depletion mode operation. And therefore, it is a series combination of C ox and C depletion ok.

And what about the inversion mode: inversion mode operation; so, if my V G becomes greater than V T ok, greater than or equal to V T you have a lot of electrons in the interface ok. So, electrons have appeared at the interface. So, I have still shown the depletion region here, but the electrons are now sitting there. They are probably I should have redrawn this picture, but this picture is not entirely accurate.

Because you can still see the depletion region, the depletion region does exist, but they I am I am worried about the way I have located the electrons. So, these electrons must be located at the semi conductor insulator interface. So, the electrons are located there, not on the other side of the depletion region. So, this is a mistake so, do I apologize and it is a mistake. So, it is actually quite a serious mistake, I would say me because it changes the situation of it.

So, the electrons are at the semi conductor insulator interface, you still do have depletion regions, but the electrons are between the depletion region and the insulator ok. So, they are at the interface ok. So, please do make this correction. And since the electrons are at the interface, any increase or in any fluctuation of charge for V G greater than V T. So, we are now operating there. So, we have crossed V T, we are now operating here, and any fluctuation in the gate voltage is going to respond to the electron population increasing or decreasing ok. So, this situation is exactly like, you know if you think of it as a met if you want to imagine things as a metal insulator metal plate, this electron sheet is acting like your pseudo metal plate.

So, it is like exactly like what the holes were doing, the electrons are doing the same thing now. Or in other words, all the response to the applied charge in the gate is being met by the fluctuation in the electron charge at the semi conductor insulator interface. The depletion width need not increase or decrease anymore. So, the depletion width is more or less static now.

So, that is not the response anymore ok. So, here it was a depletion width that was responding, here it is not, here it is the electron count that is responding. And therefore, our capacitance once again becomes same as C ox ok. So, the capacitance is C ox, then it decreases, then it again increases and comes back to C. But this is all under a specific condition and we will explain that conditions. And the condition has got to do with the frequency of the AC signal that we are using to make this measurement, ok.

So, if so, here in the accumulation mode we had holes appearing at the interface. And there are plenty of holes in the semiconductor absolutely no problem, they can you have enough holes present for you for them to respond to your applied gate voltage. In the depletion mode, if the frequency changes, the frequency of AC signal changes, will the covering and uncovering of the ions respond to an increase in frequency? The answer is yes, because it is a response of an electric field, right it is the electric field whether the bands are bending fast enough. So, of course, they can respond.

What about the appearance of electrons? The minority carriers they interface. So, these electrons are very few in the bulk material. So, where are these electrons coming from? These electrons are coming from these are thermally generated electrons in the depletion region, we are thermally generated, they there is a certain rate of thermal generation ok.

So, there is a certain rate at which they are being generated. And if the AC signal frequency is much higher than this rate, then the electrons cannot respond to that AC signal frequency. And if they elect AC signal frequency is much lower than this rate, then no problem, the electrons will respond in the manner which we described ok. Therefore, the signal frequency becomes very important when we look at the response, the capacitance of the MOS capacitor in inversion mode, when the minority carriers come into the interface.