Introduction to Semiconductor Devices
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Lecture – 7.6
Nanohub Demo - MOSCAP Tool

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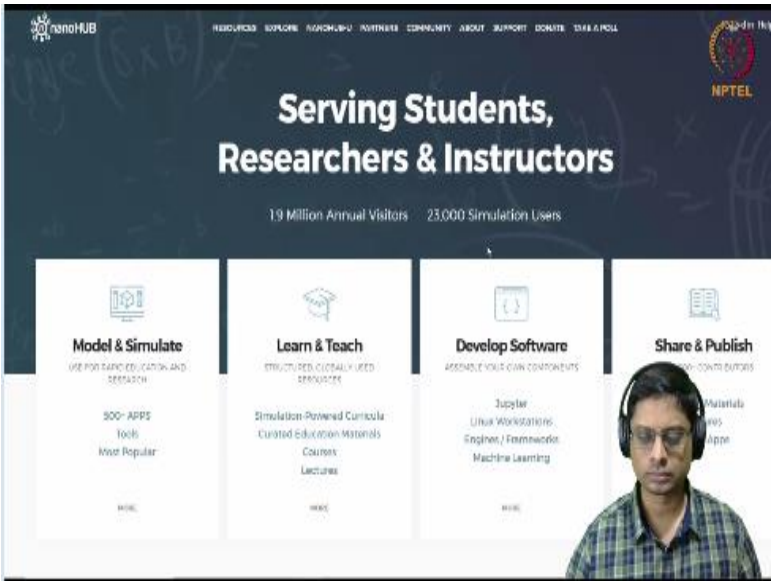

Welcome back. So, we have understood the theoretical aspects of MOS capacitor by now. So, in this video, I would like to briefly show you the use of Nanohub, there is a tool called MOSCAP in Nanohub and it is very, very useful to analyse MOS capacitors. So, you could try various scenarios and then study. So, we will use the basic part of it today. In the next week, we will analyse CVs using the same tool.

So, to get started, so, this is Nanohub. I already introduced to you for PN junctions. So, log into Nanohub and then go to resources and find tools. And within the tools, you will find a tool by name MOSCAP so, that should be somewhat here, so, MOSCAP, which is a one. I will go here. So, this is a capacitance of a MOS device it says.

So, now, let us launch tool, taking minute of time. So, here we go. So, this is the front end of the tool when it opens for you and let me kind of, this should be good. So, there are a lot of features in this. Before we know, we get into that so, basically, we could use, right now, we will just use single gate. There is something called as double gate which will not study in this course essentially almost.

And then the gate insulator thickness is 0.1 microns so, leave at this, this means 100 nanometres of insulator. So, this is the basic structure of the device. So, you have the metal blue, insulator which is right and that semiconductor which is in green. So, the semiconductor doping is shown as $1*10^{15}$ here. If you want to change it, you know, you click it and then 16, 15 whatever.

Right now, we will leave it as 15. So, gate oxides thickness is 100 nanometres which is good. This is essentially telling you how many discrete points are there in the gate insulator, we will leave it 100. Gate insulators dielectric constant is 3.9. So, right now, this is silicon dioxide dielectric constant as we have seen. In the next week, we will see a little bit about what how you can change this. And semiconductor thickness is 5 microns.

Well, you know we could actually simulate for larger because, if you look at the actual wafer, I told you it expanded micrometre thick. It is not really necessary for us to simulate that long semiconductor because most of the essential physics is happening within the first few microns. So, we will simulate for 5 microns actually sufficient. The number of nodes in the semiconductor are 200 which is okay.

So, p type semiconductor uniform doping, I could actually change the doping concentrations to some other I mean, in principle, you could specify some functions. I do not know if this is allowing, but at least on my screen, it does not seem to be allowing any options. So, and gate electrode, we will choose it to be aluminium for now. We change this. Default was I think, n plus volume, but we will talk about this next week.

So, for now, we will choose gate electrode aluminium. And then there are some parameters which are fixed oxide trap density and this, which you do not need to worry about right now. And then there is an environment tab which tells you, what is the range of simulations. You can run it from you know, some initial voltage to the final voltage and then number of voltage

steps is fine. Rest of the parameters are fine, you can leave it and this tool, you do not need to worry about. So, that is it.

So, we made one change. We made change the gate electrode to aluminium and when it simulate, let me do this, this is clear. So, the first the result that shows up is what is known as CV characteristics. We will discuss this in next week. So right now, I want you to go to, let us say, the other things. The CV characteristic may drop. So, we can look at surface potential as a function of gate bias.

You see, as you change the gate voltage, the surface potential change. This is exactly what we have discussed in the last lecture. So, we said that you know, it is surface potential from 0 to $2\phi_F$, will be in that expression that we derived and after that, it is going to be not very so much. So, this sort of shape we saw in the classes. So, energy band diagram, so, this is V_G equal to 0 so, more applied bias.

This work function difference, I have to talk about. It tells you that basically there is a Fermi energy here and there is already depletion of semiconductor because bands are bending downwards. So, here, there is certain doping density and then there is already some depletion happening. Why it is? We have to actually, you know, it is an advanced, you will study it in the next week.

So, we could look at, let us say electric field, at applied gate voltage of 0 volts. So, in 0, actually, it turns out, it is already depleted. So, we can look at the field here. So, actually click the x axis and then move it to actually zoom it out. Then I will just zoom in this part which is of interest. So, what you see is; the electric field is linear function in the depletion region and there is a small region here, I think the interface is now 0.

So, this is the gate; left of 0 is gate. So, there is 1 micron thickness and then there is this field difference here and then there is linear change. So, here, the peak electric field is turning out to be about 12741 volts per centimetre. And if you look at the field in the oxide, it turns out to be 38,000.

So, this is how the you know, we explain this jump, why this jump should come about because of boundary conditions cross for it and you can also look at the hole density. So, it is a p type

semiconductor. So, the hole density was supposed to be 10^{15}, but it turns out that; from 0, there 0.1 micron is flat. So, basically this completely depleted here and then the holes are increasing in this fashion.

So, we saw this, we defined a delta depletion this way, we made a square here, a rectangle sorry, but essentially, so, – 10^{15} what we were showing. So, it is completely depleted. And you can also look at electron density. Is there any electron density? Well, it turns out that it already is inverted at this point. So, I will have to look at slightly change this to; you go back.

So, since we are running at – 3 final voltage. This is electron; electron is at last applied gate voltage. At last applied means, I have applied 5 volts. So, when I look at this, this is also a hole density at the last applied bias. So, it is at 5 volts gate voltage. It is fully depleted and I look at electron density. It is having 10^{15}. So, this is the background doping but we have electron density close to 10^{18}.

So, 3 orders of magnitude higher. So, you see 1000 times higher electron density at the interface and if you look at the net charge density. We will see that. This is the hole density part which is what you would expect. You know, holes are depleted and this is electron density part. And this is a space charge that is the net charge. This is removed and this is electrons come in so, net charge total is this.

So, there is a huge accumulation here of electrons in the interface. So, in this fashion, you could study electrostatic potential. So, well, electric field at the last applied gate bias, this is interesting. So, we are looking at. So, this is your linear part of this curve. You should check this out. So, here is the electric field is 0 in the bulk of the semiconductor. As you are going, there is a depletion region.

So, there is linear change something around 16,000 volts per centimetre, but then at interface, it is 52,000. So, you will see that this is actually slightly higher than actually the ratio of $\varepsilon_{si}/\varepsilon_{ox}$. You should think about why that is so. So, we showed this Gauss law saying that epsilon oxide into electric field in the oxide should be equal to epsilon silicon into electrical in the silicon. That is true when you do not have any sheet charge.

Here, the inversion charge itself acts like a you know, boundary condition. So, you have to account for the inversion charge also, because of that, if you look at the electric field here, it is about 52. At the edge of the depletion region it is 14 so, 14 more than 3 times. It is getting to more than 3 times. So, you can compute and check it out. So, this difference is coming because if you look at the electron density in the same curve, same thing but so, electron density is very substantial.

So, how does the electrostatics you know work when you have such large electron density at the surface? Well, there has to be a discrete jump in the electric field. So, one part of it is because of Gauss law because of the dissimilarities in the dielectric constant, they should be jumping the electric field. The other part of it is because of the sheet charge presented the interface, further jump so, that is why.

If you look at this, unfortunately here, you cannot look at any particular voltage. So, let me take – 1, where I know that I think they should be in depletion or even 1.5. I know that it will be in depletion mode. Unfortunately, you know if I could I can only see the last applied bias so, I was seeing only 5 volts. So, now, I will run it only to – 1.5 and if I do that, this is a lot of background calculations that go on.

So, this is something that you do not see it but. So, It just started depleting. Let us see how do I know that. Well, I can, no applied gate, no gate bias, is already some depletion. But if I look at the last applied voltage, let me look at the bands. Well, no, I am wrong. So, at – 0.5. you see, I am actually still accumulating since, that is why it is interesting. You can correct yourself.

I was thinking that it is going to be depletion but it turns out that is still in accumulation. So, now, E_F is closer to E_V. So, it is accumulation actually. So, let us see, it is an interesting thing. So, now, let us look at the electron density that is excess hole density is automatically the electron density has fallen here. But if you look at the hole density, you see, this is 10^{15} which is a background.

But the moment you come to the surface, you saw the sharp spike that I showed you the exact solution. That was analytical calculation, but this is actual numerically you can try to compute the different doping concentrations and check. You know, this is background 10^{15}. So, already hole density is about 10^{16}, $4*10^{16}$. So, one order of magnitude higher.

If I want to see depletion, what should I do? I should choose a slightly smaller voltage. Maybe I will say 0.5. I hope that it is still depleting there. Well, you might wonder you know why is how can depression be there at – 0.5. You told us that gate voltage will be positive for depletion. The difference is coming because of metal. I will talk about it in the next lecture.

We have so far discuss what is known as ideal MOS capacitor. But you know, the real case always, there is a metal work function which is never going to be equal to the semiconductor work function. There is going to be a work function difference because of which you have to consider something. We have to do some changes; we will do that in the next week. Let us look at the band diagram at the last applied voltage, energy band diagram here.

Now, we have depleted; we have just depleted. So, you should be comfortable doing all these things. So, look at electric field there, electric field at last applied voltage. So, now, we have electric field. Yes, this is a linear part. We have not really depleted much. That is why the depletion width only going up 0.6 maybe or 0.7 and look at this number. This is 7800 and this is 23,000. So, 7800. So, 24,550 showing you.

It is very close to the exact number what we like. But in the last previous simulation where you had you know simulation 2, I think it was, go back or you can plot all of it, you see here So, this was I think one of the simulations where electric field. The first one was already depleted and the second one, I think we had inversion, you see this now. This is wonderful. When you have inversion, there is a much, much bigger jump.

Each of these things, you can export and check the data. So, there is a much bigger jump here. So, it is here and then from here to here, you have to check and from this to this. So, essentially whenever you have inversion charge, there is an additional jumping electric field. So, that is one. We will look at the potential electrostatic potential well. This is surface potential I call it. In the semiconductor, there is a surface potential and then there is a linear function. Is not it?

So, we see this. We see the quadratic potential and then there is a linear variation in oxide but this is at high inversion. We already inverted this in the simulation too. One of this was actually accumulate, depleting. So this is one depletion right now. Currently, we are depleting them significantly and this is low amount of inversion.

So, for various situations, you will see surface potentials you can calculate everything that we have discussed in the last, you see, we look at surface potential as a function of the inverse. So we have run different simulations. So, now if you want to, essentially in the next week, we will see how to design these things. So far, you are only learning physics, but when you are using MOSFET, we will have to design them. How to design them?

You will see that the next week. This is your first step in designing a MOSFET. Let us go back now. I cleared all the simulations. Let us try to look at an n type semiconductor doping. If I do that, I just kept aluminium again. Let us see what we get. So, now we have started to invert. So, let us look at. Let us change it. I want to go to – 1. I do not want to do till – 3.

I will explain later why it is clear the simulation. I want to run it one more time. Let us look at last applied bias at this 0.5. Charge density now is this positive number. Hole density, there is a large hole 10^5 or so this, not so much actually. And this was n substrate, n type and you are having less. Let us look at the net charge. So, this is your hole but that electron.

So, the electron concentration which is very steeply falling. n type semiconductor, we have depleted but not a lot. Actually, there is a very, very small depletion. So, the easiest way to identify what mode we are running on is basically looking at band diagram. So you see here, this is n type semiconductor. So, this distance should give you the doping density of 10^{50} and then slightly depleted if you are not really applied gate voltage enough to invert it.

So, if you want to invert it, we will have to go to large negative voltages inside. Instead of this, I will go to – 3 here just for. Check it out. Let us see if it inverts the band diagram. So, PMOS has to go to negative voltages to invert. That is NMOS will go to positive voltages. There is a small correction term that will come about. I leave you to analyse what happens. Well, I managed to – 2 or – 3.

Let us see energy band diagram at last applied gate voltage. Well, so n type but now, this has come very, very; this has come relative to close. Definitely closer than this distance E_F and E_I; E_F and E_C this was distance. It is definitely closer. So, basically we have more holes than there are electrons in substrate. Let us verify that. So, hole density is 10^{17} whereas electron density would be 10^{15} that is a substrate.

Actually, in fact, we have removed electrons from. We have pushed away electrons and we have created a space charge and then we have created an inversion layer of holes. So, if you look at this, you should combine this. This is electron density. So, electrons are not present in the hole. This is a depletion region and then the net charge hole density is only at the interface, you have holes.

The total density will be basically holes electrons and then this will also introduce space charge that is why there is a flat here. And then there is coming down. The total is coming down. So, what else can we do? We can look at electrostatic potential. Interesting. See, I showed you that they should be minus you know, the linear electric field should be like this, decreasing function.

It is linear here and then there is a sharp change here. So, sorry, electric field is linear. Yes. And then in the oxide, it should be constant. Let us check it out. Well, it is too close here. We are not able to distinguish. It is too close potential. So, let us go back and try to, we need to do it at normal voltages because we have inverted with some because of the charge, there is some strong changes here.

So, we should actually mean depletion. So, if you want to be depletion, I would say let us just do the previous simulation. Let us see. Well, we are not reaching also, when there is a gate voltage that should be linear. So, here it is quadratic and then it is linear. So, this is how the voltage? This is applied voltage of about I would say, I take this to be 0. The reference, it is taking a simulator slightly differently 0.3 as a reference.

So, with respect to that, we have 0.14. So, there is this electrostatic potential that we will see. So, well, I mean, this will be similar again. So, there are a whole lot of things, you can study based on this energy band diagram without any applied any gate voltage, there is an accumulation now. This is interesting. In the last case, we saw the depletion. But in case of aluminium, we are seeing accumulation. So, we will explain this in the next class.

So, you can play around with many, many things here. It is just your interest and how much you want to check. So, as a small take home assignment or you just can do it or do not do it, up to you. But I would encourage you to think about what are the various ways of changing

V_T. Just change some parameters and try to see if you know, V_T is changed that means the point at which inversion happens changes.

What is the various parameters that we can tweak? Because I said V_T is one of the most important parameter when it comes to design of semiconductor devices. So, what are the ways to control V_T? Increase, decrease, play around. Let us say what happens if you change the oxide thickness or if you change the permittivity, what happens? Each of these parameters, you could kind of, it will not help you if you change the thickness of semiconductor much. But definitely if you change the gate, it will change.

So, you see some of these things and see if you can analyse. So, you will have a lot of questions. I am sure you will not be able to understand a lot of it, but it is good to have those questions. So, as I keep saying, you know, the best way to learn is to explore, look at what does not make sense, ask questions about why it does not make sense, analyse, then that is how you will learn deeply.

So, that is why I like these sort of software tools, which will help you play around. If you have to do it by calculations, it will be very tiresome. All you have to do is simply click. I know this interface is not the best interface. But I think it does a really wonderful job in capturing the essential physics. So, please take some time and analyse these things. We will give you a few problems in the assignment which will make you run this once and then extract some numbers and then just put it in the assignment.

Thank you so much. I will see you in the next week. Have a great week. Thank you.