Introduction to Semiconductor Devices

Dr Naresh Kumar Emani
Department of Electrical Engineering
Indian Institute of Technology – Hyderabad

Lecture - 6.7
Inversion in a MOSCAP

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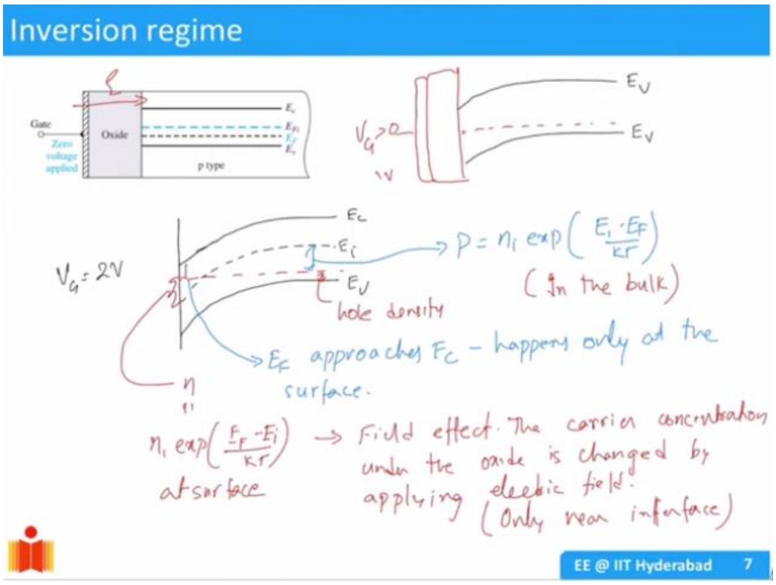

Inversion regime

$p = n_i \exp\left(\frac{E_i - E_F}{kT}\right)$ (In the bulk)

E_F approaches E_C – happens only at the surface.

$n = n_i \exp\left(\frac{E_F - E_i}{kT}\right)$ at surface

→ Field effect. The carrier concentration under the oxide is changed by applying electric field. (Only near interface)

Welcome back. So, in the last video, we were talking about various biasing modes for a NMOS capacitor. So, we have started with the p type substrate. And then when there is no applied voltage, the bands will be flat. Right now, we are only looking at the bands in the semiconductor. We will worry about oxide in the metal in the next week. For now, I just want you to focus on semiconductor.

And if you apply a positive voltage, so, I will not draw the bands in the oxide. Let us say this is you know V_G. There is a oxide and then there is a metal and then I apply a V_G greater than 0. So, we saw that the positive voltage will actually repel the holes in a p-type substrate and then cause a depletion region. This is what we saw so far. So, you can put a Fermi level.

And then we showed depletion by actually drawing the E_V away from the E_F. So, this is a MOSCAP in a depletion mode. Now, what happens if I further increase my voltage? I increased my you know let us say this was just some numbers. Let us say this was 1 volt. I increased it to now 2 volts. What do we think will happen? Well, it should repel the holes further because essentially this is a capacitor like structure.

So, whatever charge you put on the metal plate positive plate the opposite equal and opposite amount of charge should be there in a semiconductor. So, I should have more bending. You know we call this as band bending. We will define that later on. Right now, what should happen is if you let us say put V_G equal to let us say 2 volts just V_G greater than V_{G1}. So, in that case, what would happen?

So, you can have a situation like this wherein my, is here, E_F is here. And let us say my E_i could be something like this. So, this is E_V. This is E_C and E_i. So, in principle, I can deplete it so much that actually my bands bend in such a way that E_F goes closer to E_C. So, notice here, this is the charge density. This is my hole charge density by applying a larger amount of voltage.

And just I keep increasing my positive voltage. So, once I start increasing, the semiconductor starts depleting. And it will keep depleting to let us say you know it can actually the E_F can actually cross E_i and then go towards the E_C. It happens only at the surface remember. So, here E_F approaches E_C. And this happens only at the surface. This is referred to as field effect.

So, we are applying a voltage and because of the electric field we are changing the carrier concentration in the semiconductor. So, that is called as a field effect. We know that there is a field. When you apply here, there is a field electric field here. So, this is my electric field. So, now, what does it mean E_F is closer to E_C? It means that there are some electrons there. How many electrons?

That will be defined by the distance of E_C from E_i, E_F or you could also define it as this, this distance. This will give you the number of electrons. So, this is essentially equal to $n_i exp\left(\frac{E_F - E_i}{kT}\right)$. That is the number of electrons at the surface. If you go in the bulk this is going to be

$$P = n_i exp\left(\frac{E_i - E_F}{kT}\right).$$

This phenomenon is called as field effect. This is field effect. So, the carrier concentration under the oxide is changed by applying electric field. So, only surface phenomena only interface only happens only near interface. In the bulk, it is still the same P type substrate. So, it has holes. But only at the substrate, you have electrons. So, well, let me show you the band diagram now.

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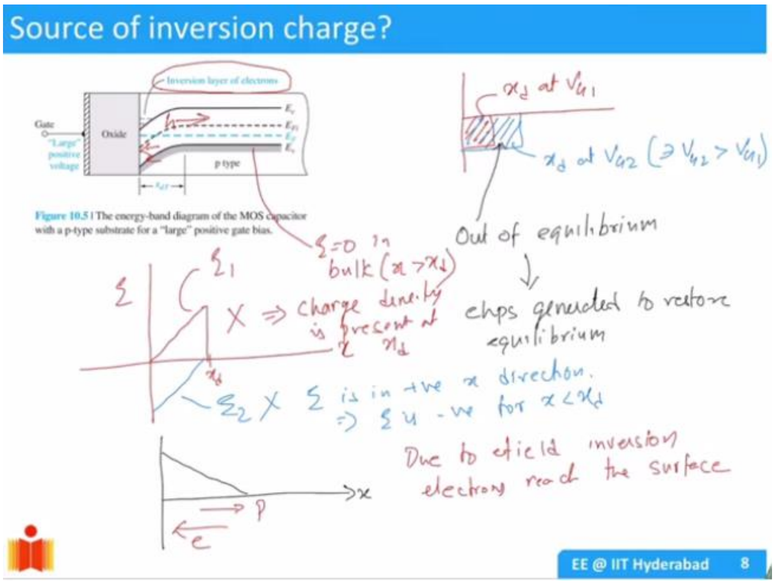

Source of inversion charge?

Figure 10.5 | The energy-band diagram of the MOS capacitor with a p-type substrate for a "large" positive gate bias.

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So, here is another picture. So, same picture it is much neater than what I have drawn. So, this is basically surface inversion layer of electrons we created here at the surface. What is the source of this inversion, electrons? Think about it. So, what happens? When let us draw the depletion region for a moment. So, initially, let us say, I have my depletion region in this way. So, this is some x_d. x_d at let us say V_{G1}.

I increase my voltage, what happens? If I increase my positive voltage on the gate, then I get to a point where it becomes like this. This is x_d at V_{G2} such that V_{G2} is greater than V_{G1}. This is what happens. Now, this is obviously out of equilibrium. We have depleted the semiconductor of the free charges. So, what happens? Well, the semiconductor tries to come back to equilibrium. The system always tries to restore the equilibrium.

If you have excess carriers, they will recombine. If you have fewer carriers, then the system tries to generate the electron hole pairs. So, basically, ehps generated to restore equilibrium. What does it mean if ehps are generated? Well, the bonds in the lattice are going to break and then there are going to be more electrons and then correspondingly there is going to be a hole also.

That is the electron hole pair generation process we will see. So, what? What happens to electron hole pairs when they get generated? Well, for that you need to look at what is the field in the semiconductor. So, if I want to draw the field E, how does it look like? As a function of x, let us say, I want to plot this as a function of x. How does the field like look like? We already know enough answers.

We have studied how the field affects the bands. We saw that sorry if you apply a voltage there is going to be a field and that will be reflected in the gradient in the energy band. So, in this case, there is a certain gradient. So, there is a positive electric field. And the direction, can it be this? This is Option 1. Let us say and we also know that as you cross the x_d. This is x_d. As you cross x_d, the field has to go to 0, E equal to 0 in bulk, essentially x greater than x_d.

That is bulk for us. So, is this correct? Let us call it E1. Is it a valid solution for our problem? If you think about it, it turns out that, no, this is not correct. The reason is there is surface charge or there is a charge. Let us say charge density is present at x_d. And that is not possible because we there is no physical reason for a charged density to be present at the edge of the boundary sorry edge of the depletion region.

So, then can this be a correct field E2? Well, this also is not going to be correct. The reason is we know that E is in positive x direction. Electric field is in positive x direction. So, we do not and this means that it is below 0. For x less than x_d, E field is negative. This blue implies E is negative for x less than x_d which is also not correct. So, the only logical way to have the field is this. So, what does it mean? There is a positive field.

When a positive field is there, your electron hole pair will be generated. In that electron hole pair, holes will move into the bulk, electrons will move towards the interface. So, here holes will move in this h. Let us call it P rather h. Holes will move into the bulk. And the electrons will move towards the surface. And hence, you have due to E field, electrons in some sense inversion electrons.

E field inversion electrons reach the surface. So, that is why we call it inversion. Essentially, we are having a p-type substrate and now we are flipping it. We are making it have electrons. So, we are inverting the substrate. That is why this regime is called inversion. And in a MOS capacitor, the source of this inversion charges is the electron hole pair generation. In a MOSCAP, it is electron hole pair generation.

In a MOSFET, it is going to be something else. We will see that. So, well that is it. Essentially, this is the process. And we will discuss this in greater detail in the next lectures.

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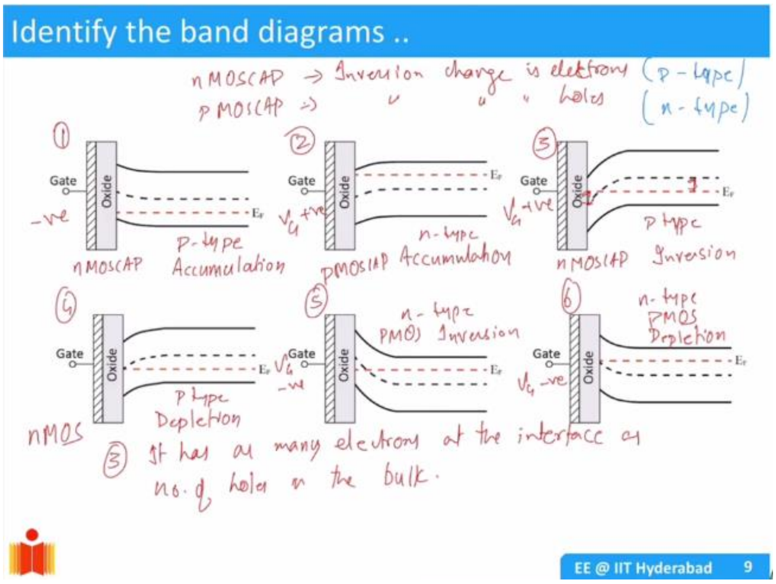

Identify the band diagrams ..

nMOSCAP → Inversion charge is electrons (p-type)
pMOSCAP → " " " holes (n-type)

③ It has as many electrons at the interface as no. of holes in the bulk.

So, before I stop, I just wanted to help you identify you know a few scenarios. We have discussed accumulation, depletion and inversion, 3 scenarios. We have discussed all of them for NMOS. Why did we call it NMOS? Basically, NMOSCAP means inversion charge is electrons. If I say PMOSCAP, this implies inversion charge is holes. So, we are inverting the substrate.

That is why we start with P type substrate for NMOSCAP. And we will start with n type substrate for a PMOS. Please you know make sure that you remember this. Many times, students you know mix up these two. So, now, I have 6 band diagrams here. And we want to identify, what are the different regimes? So, they are mixed up. They are not in a sequence. Let us see this one first one.

This is a, first identify the substrate. So, this is the P-type substrate. We know that E_F is closer to E_V. And then at the surface, if you see, you are having excess of holes. If you are not able to see this, you have to go back and review how the Fermi level position is impacted by the density of carriers. So, this is P-type semiconductor. And it is in accumulation. So, this is obviously a NMOS device, NMOSCAP.

And the voltage in this case is negative. And that is why you are having more holes at the interface in accumulation regime. So, now let us look at this. Let us go to the second one here on the right. So, here, what is this substrate? Well, this is a n-type substrate, n type. And we are having excess electrons in the n type. So, this is in accumulation again accumulation. And when will this happen?

When you have V_G to be greater than 0, V_G is positive. If V_G is positive, then it will collect electrons on the other side of the capacitor. So, you have n type this is of course then that means it is a PMOSCAP. PMOSCAP in accumulation. What about the third picture? Now, we are back to P-type. And what is happening to the surface? Well, you have to exactly I mean this is not exact here.

But let us say this is some distance. You have similar distance here. So, basically it has as many electrons if you look at number 3 has as many electrons at the surface or at the interface as number of holes in the bulk. This is a definition of threshold actually. When we cross this we say that you know we have we reached a threshold. We will discuss this again. So, this is a P-type substrate.

So, it is an NMOSCAP, and the regime is inversion. If you want to have an inversion that means if you want to have lot of electrons, you need to apply a gate voltage which is positive. V_G is positive actually large positive not just positive large positive to reach inversion. What about the figure here 4? In this case, we have again P-type substrate. And so, this is NMOS device. And this is in depletion.

So, since E_F is at E_i here E_F is at E_i, so, we have simply depleted the substrate of all the holes. But there are not, really not many electrons present. That is why we call it depletion. And then this it is a n-type substrate. So, it is a PMOS device, and we are having inversion. So, if you want to have a PMOS device in inversion, you need to have negative voltage here, V_G negative.

That is one you can have holes in the surface. The last one, again a n-type substrate, so, PMOS and depletion. So, if you are pushing away electrons, so, you need to have V_G to be negative. So, this is how you can analyse. So, I want you to really spend some time. Review this. I want you to be comfortable with just looking at the bands and then deciding whether the MOSCAP is in accumulation, inversion or depletion.

In the next lecture, we will actually draw the full band diagram. We will include the bands of oxide and even the gate. And then it will be a slightly more complex. But then we can actually understand the full electrostatics of what is happening. The next couple of lectures will be on the electrostatics of the MOS capacitor. So, this week, I would like to stop here. And then please take your time. You know we have covered a lot of material.

It is new probably. So, I would like to give you more time. And then you please review it. And if you have any questions, we can discuss. Thank you so much, we will see you in the next week, bye.