Introduction to Semiconductor Devices
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Lecture – 7.2
NMOSCAP in Depletion Mode

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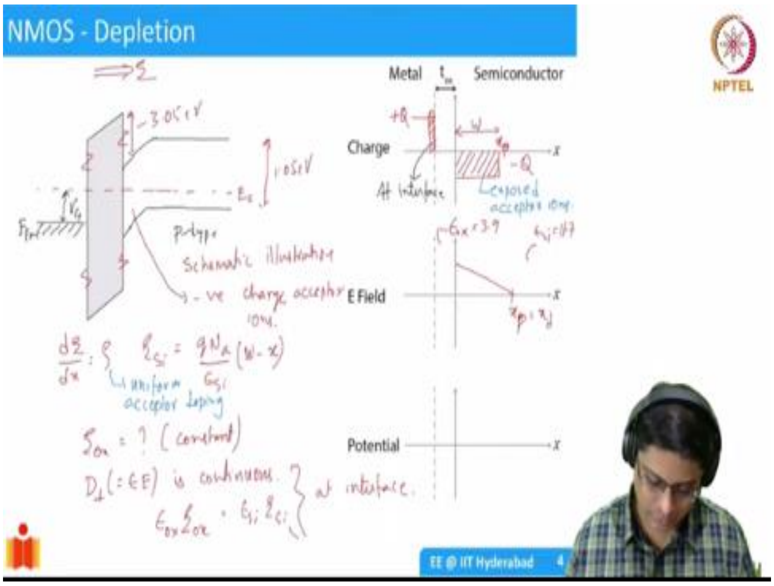
NMOS - Depletion

$\frac{d\mathcal{E}}{dx} = \rho$ ↳ uniform acceptor doping

$\mathcal{E}_{Si} = \frac{qN_A}{\epsilon_{Si}}(W-x)$

$\mathcal{E}_{ox} = ?$ (constant)

$D_\perp (=\epsilon E)$ is continuous $\epsilon_{ox}\mathcal{E}_{ox} = \epsilon_{Si}\mathcal{E}_{Si}$ } at interface.

Welcome back. So, now did not like to look at NMOS in the depletion region and we have seen in the last week that NMOS in depletion will have bands which are bent downwards. So, for example, if I take this to be my equilibrium Fermi energy, E_F, I am depleting the MOSFET so, p type semiconductor. So, I am going to have bands which are bending downwards like this.

So, now, even E_i will bend in the similar fashion. What will happen to the bands in the oxide and metal? So, to analyse that, we have to think about what kind of voltage, do we have to apply to cause depletion. So, p type semiconductor, it is p type so, it has holes and you want to deplete the hole. So, you want to push the hole away, we have to apply positive voltage. And when we apply a positive voltage, the metal Fermi level shifts down relative to the bulk.

This is my V_G. I am applying a positive voltage so, it is moving down. This is E_F of metal. So, essentially, what we are having is we have pushed the holes away, so there is a negative charge in the semiconductor. So, we can draw the block charge diagram by introducing let us say here, a block charge like this. This is my, I could call it x_n or this x_n, I could call it or I could call this as the width of the depletion region.

So, I am pushing my holes away, so I am creating a depletion region that is a depletion approximation, we had seen this already. So, because it is acceptor ions which are pushed away, so this is basically exposed acceptor ions and what happens when you have these exposed acceptor ions in a capacitor kind of texture? There has to be an opposite charge in the other side. So, if this was – Q, there should be a + Q.

And where will that + Q be? As in the previous case, it has to be right at the interface. This is your balancing charge. So, this is going to be + Q. So, if you have a + Q and – Q in this fashion in the block charge, what will the direction of the field? The direction of the field has to be in the positive direction. So, I will just mark it here. Let us say that this is my direction of the electric field. It should increase in the; sorry, it should point in a positive x direction.

So, please remember that this is at interface, because it is a metal. But now, in the semiconductor, we have pushed away the majority carriers. So, what we are left with exposed acceptor ion? This is important. So, since we have a field which is positive x direction, how should the bands in the oxide be? Well, that is fairly simple. What we have to do is; they should be band bending in this sort of a fashion.

So, always remember, this is a crude way of representing, it is not exact, because this is we know, that this distance is 3.05 eV and this distance is 1.05. So, it is only a schematic illustration. The band diagram is not to the scale. Sometimes in some textbooks, you will see that they will put a small mark here that this. So, that is indicating that it is extending, you know, there is a jump in the energy there. Similarly, there could be a jump in energy.

So, that you can you know, we do not need to show it exactly to scale. So, now, so this region here is basically negative charge acceptor ions. So, once we know this, what is the electric field? We have played this game before multiple times. So, whenever you have a charge, E field is basically going to be dE by dx equal to ρ, so in the semiconductor I will call it, E_{si} is going to be what.

$$\frac{dE}{dx} = \rho$$

I will assume that the field is 0 inside the bulk of the semiconductor and as you approach the interface, there is a positive field because E is positive because we have seen. The direction is positive; the E has to be positive. So, without actually solving it, I will write it and I hope that by now, you are also able to write this. This is electric field. So, what is this ensuring?

$$E_{si} = \frac{qN_A}{\varepsilon_{si}}(W - x)$$

I know that because you know this is a uniform doping, ρ is uniform, the uniform acceptor doping in semiconductor at least. So, there should be a linear field and the field has to go to 0 at x = W. So, that is why I will draw my electric field in this fashion. So, this is my x_n. Sorry, I should actually call it x_p. Even in the previous case, I think I call it x_n so, let us call it x_p because it is a p type semiconductor. Please do not get confused. So, make that correction in the previous video as well.

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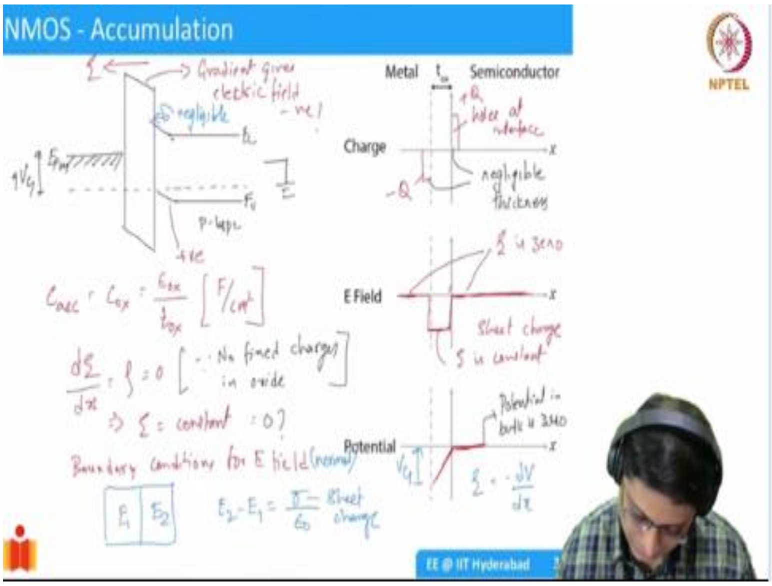

NMOS - Accumulation

I did not mention this, fine so, right now, x_p. Sometimes, we also call it as x_d, x depletion that is also another notation that we use. So, now, what should happen to the electric field in the oxide? If I call this as electric field in oxide, how much? Because there are no charges, no charges in the oxide we know that it should be constant. But what is that constant? That is what we need to determine.

So, to determine this, we need to remember that we are talking of 2 different materials. So, this is oxide. So, epsilon of oxide is going to be 3.9. Here, it is silicon, epsilon of silicon is going to be 11.7 or 11.9. I am not very, 11.7, I guess, it should be. So, please verify that number one, I will do that in the next lecture. So, we have these 2 different dielectric materials.

When you have electric field normal to those directions on the interface, then we know that D normal, D perpendicular which is essentially equal to epsilon times E is continuous. What does this tell us? It tells us that epsilon of oxide into electric field at oxide should be equal to epsilon of silicon into electric field of silicon at the interface and this is essentially you know this case at interface. So, let us see what happens. So, we have to find out what is the electric field, the constant electric field in the oxide.

$$D_{\perp} = \varepsilon E \ \ is\ continuous$$

$$\epsilon_{ox} E_{ox} = \epsilon_{si} E_{si}$$

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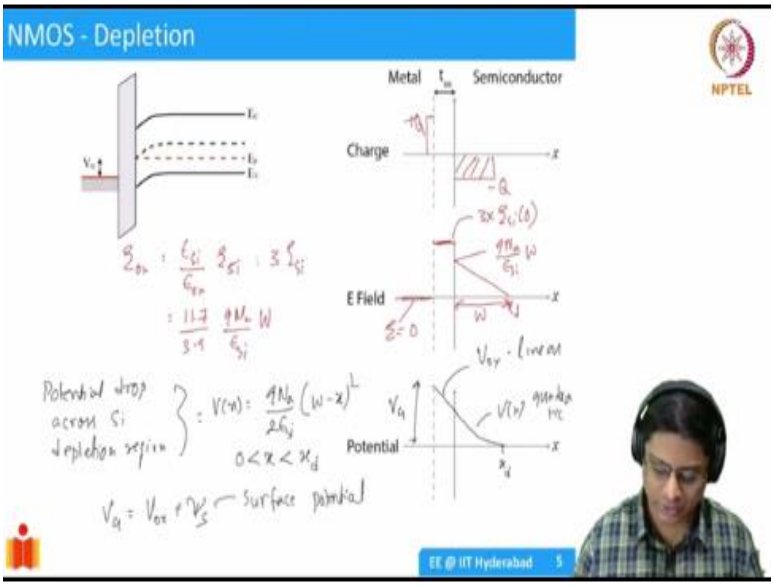

NMOS - Depletion

$\mathcal{E}_{ox} = \frac{\epsilon_{si}}{\epsilon_{ox}} \mathcal{E}_{si} = 3\,\mathcal{E}_{si}$

$= \frac{11.7}{3.9} \frac{qN_a}{\epsilon_{si}} W$

Potential drop across Si depletion region $\Big\} : V(x) = \frac{qN_a}{2\epsilon_{si}} (W-x)^2$

$0 < x < x_d$

$V_G = V_{ox} + V_s$ ← surface potential

And so, I have a much better looking band diagram here. Just for completeness, I just put this here, the same – Q and then there is a + Q here. And we already seen that they should be let us say, D and this is your W.

$$E_{ox} = \frac{\epsilon_{si}}{\epsilon_{ox}} E_{si}$$

And this is again coming from Gauss law itself.

$$= \frac{11.7}{3.9}\frac{qN_A}{\epsilon_{si}}W$$

So, this is simply going to be Q N a divided by epsilon times width, this is going to be 3 times peak electric field in silicon or other, you can call it this. So, there is a jump in the electric field because it is 2 different dielectrics. So, that jump has to be there. Please remember that. And then what is the electric field in the metal? Well, metal is 0. So, now, how will the potential look like?

To determine that, we will just consider first let us say, potential drop across silicon or rather silicon depletion region. What is this equal to? We know the answer.

$$V(x) = \frac{qN_A}{2\epsilon_{si}}(W - x)^2 \quad for\ (0 < x < x_d)$$

In the depletion region, this is going to be the form. You convince yourself that this is correct.

If you are not comfortable, just make sure that you revise. So, now, the potential is going to be quadratically decreasing here. This is my V(x) and at $x = x_d$, it becomes 0 and rest of it is all 0. Now, what happens to the potential in outside? Well, it is a constant and that potential has to be continuous. So, this is going to be a linear function. So, whatever gate voltage we applied now V_G, this is falling part of its V_{ox}, which is linear across oxide, and this is V_x which is quadratic.

So, the total potential, the applied gate voltage potential now in the depletion is falling across the oxide plus actually the potential in the silicon, we will introduce a term which is called a surface potential in a moment. So, this is surface potential. We will define that. So, this is how the potentially drop whatever applied gate voltage. So, what is this? This is the surface potential.

$$V_G = V_{ox} + \psi_s$$

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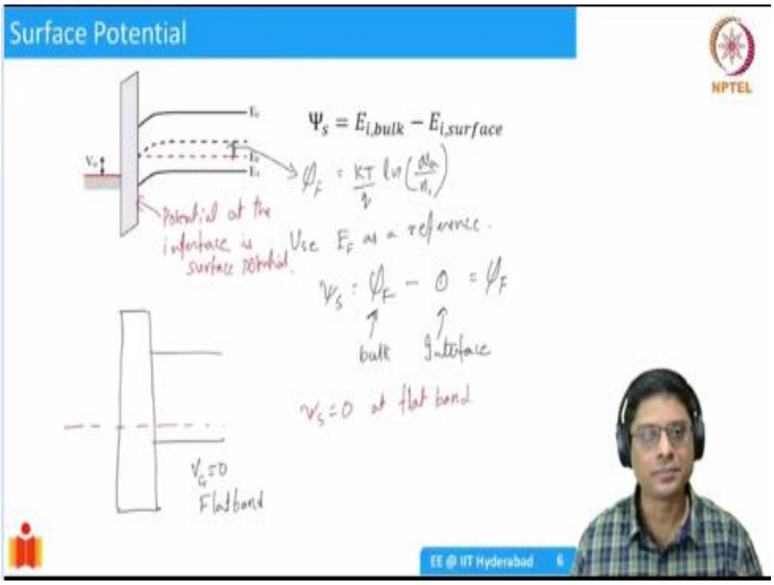

Surface Potential

$\Psi_s = E_{i,bulk} - E_{i,surface}$

And the way, you define surface potential is this. Let us say the same band diagram of p type semiconductor in depletion. And what you see is definition ψ_s, a surface potential; it is defined as simply the E_i in the bulk minus the E_i in the surface. This is the definition of calculate and I will explain it is a logical thing.

$$\psi_s = E_{i,bulk} - E_{i,surface}$$

This is ϕ_F, which is simply the distance of the Fermi energy E_F from E_i.

$$\phi_F = \frac{kT}{q} ln\left(\frac{N_A}{n_i}\right)$$

So, now if you look at it, we can take E_F and say, use E_F as a reference. So, if you use E_F as a reference, ψ_s is going to be ϕ_F in the bulk, this is bulk minus 0 at the interface. So, this is going to be ϕ_F in this case. Surface potential is ϕ_F.

$$\psi_s = \phi_F$$

So, I mean, essentially in a way, you can think of it like, you know, you have this surface potential is this potential at this point, potential at the interface. You can call it, it is surface potential. So, essentially you have a positive surface potential and then 0 in the bulk potential, electric field is positive. So, your bands are nicely bending upwards, which is consistent. And once you have this, the bands in the oxide are also going to be the positive direction.

Remember always these are consistent, same direction unless there is an interface charge which is actually changing this. So, let us try to analyse you know if you have this, you know, we have seen the initial case where the no applied gate voltage when we had and then there is a

V_{G0}. So, basically the bands were all flat. This is a condition at $V_G = 0$. So, I will call this a flat band condition.

What is the surface potential at flat band? ψ_s is equal to 0 that is flat band. Why is 0? Because there is no band bending. So, E_i is same at the bulk of the surface, so it is 0. So, this is a useful term that we keep using that is why I wanted to introduce this. And with that, I can also introduce the concept of inversion. So, we will introduce inversion in the next video. So, I will meet you there. Thank you so much.