Digital IC Design
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Lecture – 03
MOS Capacitor Threshold Voltage

So, last class we studied some of the essential concepts that we need from semiconductor device physics in order to develop the theory of the transistor right.

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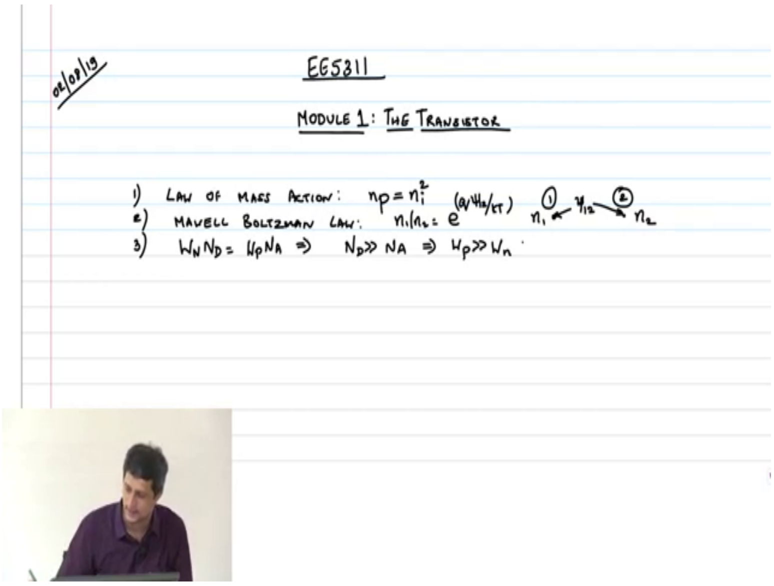

So, we did three things: one is law of mass action right which basically says that product of electron and whole concentration is always a constant. And, since at intrinsic for an intrinsic semiconductor n n i equal to p i right number of electron free electrons is equal to number of free volts it is just equal to n i square.

Second thing that we studied was the Maxwell-Boltzmann law which basically says that if you have two points in a semiconductor which has a electron concentration, free electron concentration of n 1 at one point; point 1 and at point 2 it has a concentration of n 2.

Then there has to be a potential difference between these two points called psi 1 2 right and the relation is given by n 1 by n 2 is equal to e power q psi 1 2 by k T ok. This was the second thing and was there any other law that we needed from there I believe not right, just with these two and when I put the p n junction together right. W the depletion width in the N region into the donor concentration is equal to the depletion width in the p region into acceptor concentration ok. What is this imply? If N D is much much greater than N A it implies that W p will be much much greater than W n.

The depletion region will sort of go deep into the other side right which makes sense because you have a high concentration of charges on one side, in a small distance you can get a lot of charge. Whereas, on the other side to get the same charge number of charges you need to go a much larger distance inside that because the concentration is much lesser ok. These are the three key concepts that we needed and this is all we will use in developing the entire theory of the MOS transistor.

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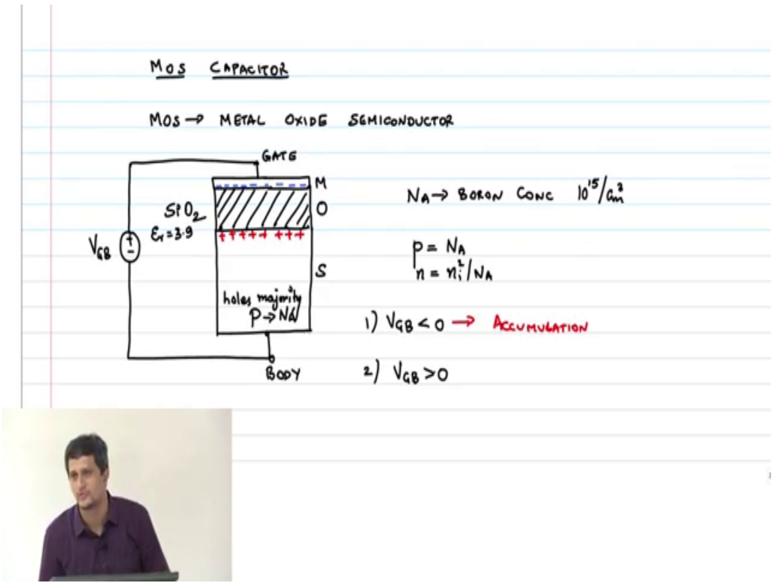

So, now let us get started with the a two terminal device called a MOS capacitor ok. MOS capacitor is what is MOS? It’s Metal Oxide and Semiconductor that is what MOS stands for. So, the way just the structure of the device is the following, you have a metal which is called the gate, then you have a thick oxide ok. By thick I mean maybe a nanometer at most I mean at least maybe a 3 to 4 nanometers at most ok. This is metal oxide and then you have the semiconductor which goes pretty deep into this, this terminal the second terminal is called the body.

So, what is this oxide? It is basically silicon dioxide that has a relative permittivity epsilon r of 3.9. So, silicon dioxide is the advantages like I told you last time is that it’s you just have to you just take a silicon substrate and you oxidize it and you get silicon dioxide. So, the interface is going to be very clean right between the oxide and the semiconductor. If you do not have a clean interface as you will see later that will lead to alterations in the threshold voltage ok. Therefore, you have to ensure that interface is as clean as possible right.

Now, this and this is semiconductor MOS ok. The semiconductor can either be p type or n type right. If I dope it boron I get a p type semiconductor if I dope it with phosphorous I get an n type semiconductor right. So, let us consider the case of a p type semiconductor which means I have an acceptor concentration of N A ok; N A is a boron concentration. What is a typical number again? It is about maybe 10 power 15 per centimeter cubed, this is like not very heavily doped; you can go up to 10 power 17 10 power 18. And, that becomes a very heavily doped semiconductor which we will come to a little later ok.

So, now I can do, I can start applying a potential across this gate and body and we will see what happens right. So, what I do is I basically apply a plus minus V GB ok. So, first of all in this semiconductor which one which is in access, holes or electrons? Holes so, basically holes are majority. And if the holes are in majority what is the number of holes available free at room temperature? N A and therefore, what is the number of electrons in this? n i squared by N A law of mass action ok.

So, now what do I do? I apply a first I will apply a negative voltage on this V GB, I am going to consider three cases V GB is less than 0 ok; so 1. So, what will happen here? So, you have negative charges on this metal here right you will have negative charges sitting here because its negative gate is negative with respect to the body. And, that has to attract holes to the it needs positive charges across the oxide for the electric field to terminate right.

Therefore, you are going to now you have lot of holes sitting in the semiconductor right free holes and therefore, those holes will get attracted to this point right. So, effectively there is a charge available for termination and really there is nothing that is very special about this because what we have done is we have taken a p type semiconductor and we have made it even more p type. If you look at this surface, the surface concentration of holes will be greater than the surface the concentration of holes in the deep in the bulk or the body ok.

This silicon sub substrate is also called a body or a bulk ok, bulk terminal. So therefore, this is not very useful and this region of operation is called accumulation. You are just accumulating more holes there and you cannot do much with that. So therefore, what you do is you start applying a positive voltage. So now, what happens? You start attracting positive charges on that on that metal gate because V GB is greater than 0 which means now that I need to attract negative charges ok.

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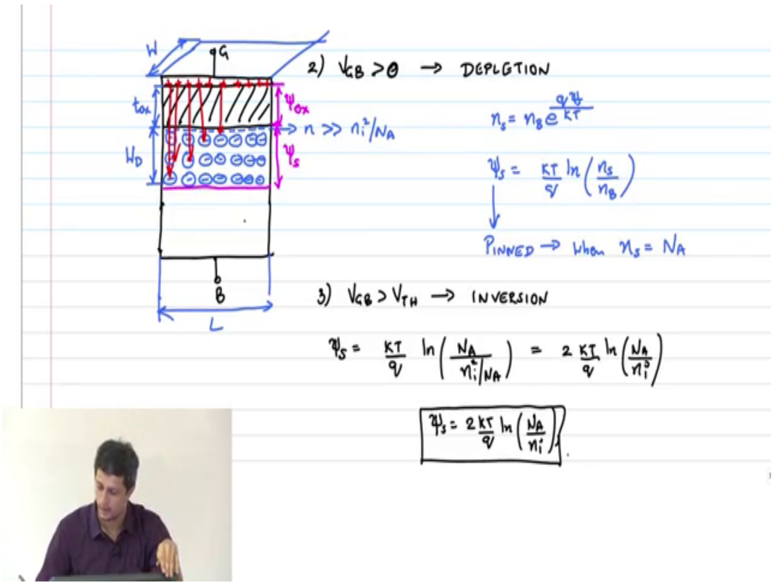

This is my metal, I have my oxide and then I have my semiconductor, this is gate body ok. So, this is so now, I am going to attract some get some positive charges on this metal gate here and now I want to get some negative charges on the other side of the oxide. So, that I can terminate this electric field because of the positive charges there. So, what we will it do? No, no so, why not why cannot electrons get attracted? Ok.

But so, let us do a thought experiment suppose, suppose I attract electrons free electrons here forget about holes getting repelled let us say ok. Then you agree that as I keep increasing my V GB this will start becoming more and more and more and more right which means at the surface I am going to have an electron concentration which is different from that of my bulk. So, here electron concentration will be greater than n i squared by N A; if V GB is greater than 0; V GB greater than 0.

Now, we know that by the Maxwell Boltzmann law the ratio of those concentrations has to have some potential, I mean e is equal to e power cube put some potential by k T which means that there has to be a potential difference that develops across this point and somewhere in the bulk right. So, it is not possible to directly attract the electrons to the surface ok, you need to have you need to as you attract electrons to that surface you need to start developing a potential difference with respect to the bulk right. And therefore, as he said the other way to look at its easier to repel the holes initially right.

So, what do you mean by repelling the holes? It means that I am going to create the immobile negative charges in the p substrate. So, what happens is if the boron gives away a hole then the boron atom becomes negative and it will becomes an immobile charge. So therefore, I start creating negative immobile charges first does not mean there are no free electrons, free electrons.

So, as it depletes now there is going to be a potential difference between the surface and the bulk, some potential difference. And therefore, the concentration of free electrons has to go up by some small amount, but that is negligible compared to the number of immobile charge carriers that are available initially.

As I continue to do this you will see that this will keep going on and all and all and this will go on until a time when the width or the depth of this depletion region becomes some W D and simultaneously I have also attracted some free electrons on this at this point. So, the electric field it does not terminate only at the free electrons, it actually terminates across all of them. You see this, this is how it happens; something will terminate at the free electron also.

It is a combination of both free electrons and immobile negative charges which are in the form of dopant atoms.

So, it turns out that as I start attracting electrons to the surface beyond a point this surface potential will get pinned ok. So, I have shown on the left hand side a distance, I will show on right hand side in magenta here the potential. So, this is the surface potential psi s that develops between the surface and the deep in the body and of course, there is a oxide potential also which is here psi ox ok. On the left hand side I am showing distance, on the right hand side I am showing potential; this is t ox ok. And, I am going to call this distance here as the length into the plane of the paper is the width ok. So, if I draw this like this then this width is what I will call W

So, now what do you do is you have attracted free electrons, you have created some surface potential. So, the question is will the surface potential keep increasing? Well, it turns out that because it is an exponential relation right, if you look at the surface charge concentration related to the concentration of electrons deep in the bulk right n B, it has to be e power q psi s by k T. So, beyond a certain point a small increase right in the surface concentration is like a lon the surface potential has to go only a lon of that and therefore, it will stop increasing. So, if I want to derive the surface potential psi s it will be k T by q lon of n s by n B ok.

So, if this is very large, if there is enough number of surface charges already available any further delta change right, any further change in the surface charges can happen with very little change in the surface potential. So therefore, at some point we say the surface potential gets pinned, it does not get altered after that; the reasonable approximation. When does that happen? So, it turns out that this happens when this surface electron concentration is as much as the hole concentration in the bulk.

So, when it gets pinned when n s is equal to N A. So, what does this mean? It basically means that I have made my surface as n type as the bulk is p type. So, I have really reversed or inverted this surface region and therefore, this region the third region when V GB is greater than some threshold potential right, it enters the region of inversion. When V GB is just greater than 0, it is in the region of depletion; it is just depleting this the bulk. So, that it can develop that surface potential in order to invert the channel; so, this region is called depletion.

So, now let us calculate this surface potential that is going to get pinned right; what is this psi s is this k T by q lon of we said that the surface charge concentration should be N A. And what is the this bulk electron concentration? n i squared by N A, it is a hole concentration that is N A. So, this is n i squared by N A and therefore, you can write this as 2 k T by q lon of N A by n i bringing the square out of the lon. So, this is a very important surface potential term 2 k T by q lon of N A by n i ok. So now, let us try to first develop an expression for this threshold voltage. What is the threshold voltage?

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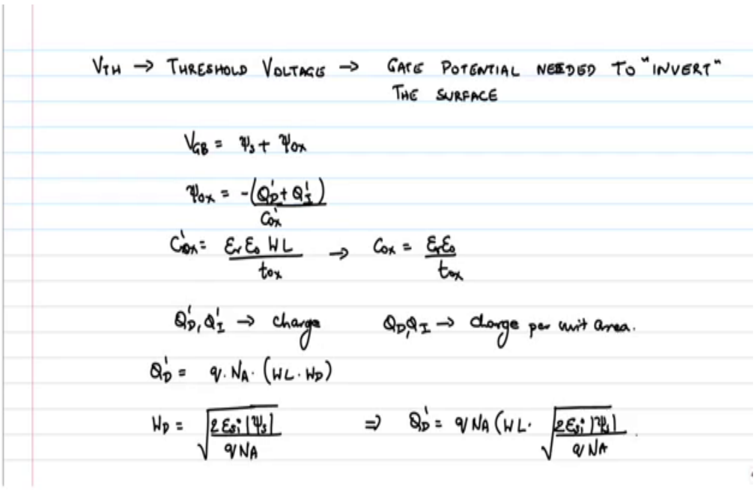

So, V TH is the threshold voltage and what is the definition? It is the gate potential necessary to gate potential needed, needed to invert ok; I will put this in quotes invert it has a very specific meaning what we discussed earlier invert the surface ok. So, now what we are going to do is we will write out this expression right and just write the k v l around that loop V GB is basically psi ox plus psi s, potential across the oxide plus surface potential plus psi ox. Now, what is the oxide potential? It is just charge by the capacitance right.

So, because the charge in the sir at the surface is negative, I am going to write it as minus Q D right Q D prime I will call it by C ox prime; I will tell why I am calling this prime. It is a net charge of course, this is not true because it I also have some inversion charge right; Q D refers to the depletion charge, I also have some inversion charge sir. So, it is only fair to write that this is Q I prime by C ox prime. Now, what is the capacitance of the oxide? What is the capacitance of the oxide? Epsilon yeah epsilon r epsilon naught a by d a is W into L by t ox ok.

So, I am also going to write the equivalent term which is normalizing it to the area, C ox is going to be defined as epsilon r epsilon naught by t ox. Similarly, Q D and Q I prime are basically charge, but Q D and Q I are charge per unit area ok. So, now how do I evaluate Q D prime? What is Q D prime? Q D prime is basically the total depletion charge that is available, Q I is the total inversion charge that is available. What is Q D prime? It is so, it is basically every dopant atom that has got ionized is basically the contributing to one Q D. Therefore, it’s just the concentration into that total volume of the depletion region right. And what is that volume? It’s basically its basically the charge into the concentration which is N A into the volume. What is the volume? W L into W L into W D.

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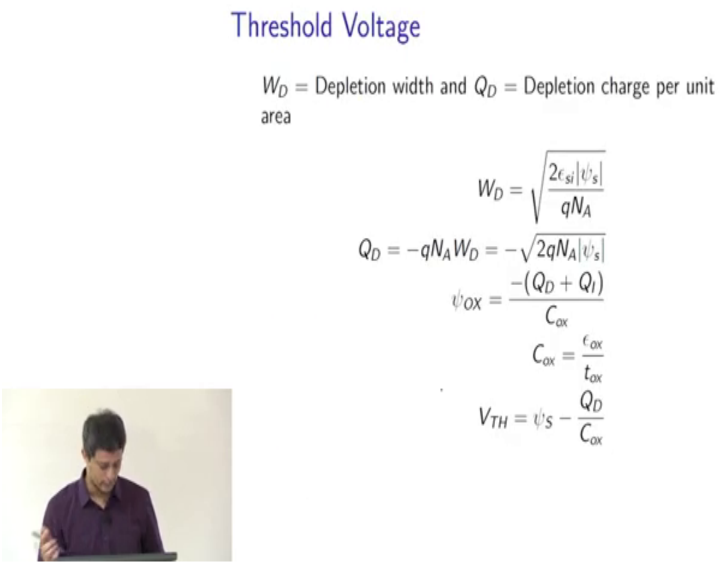

So, unfortunately I will not have time to go through all how to get this W D. So, we will just take that for granted here ok. I hope yeah we will just take this expression for granted W D is root of 2 epsilon s i into let us write that down; W D is root of 2 epsilon s i into mod psi s. I will tell you what why we writing mod psi s by q into N A ok. This is going to be you can derive this by solving Poisson’s equation, del squared phi equal to the charge density minus q into N A.

And, then you solve the differential equation by putting the boundary conditions you will get this expression, but that you can do in a device physics course ok. So, the whole point is that W D goes as root of psi s and is inversely proportional to N A ok. So now, what is Q D therefore, Q D prime is q N A into W into L into root of 2 epsilon s i mods psi s by q N A.

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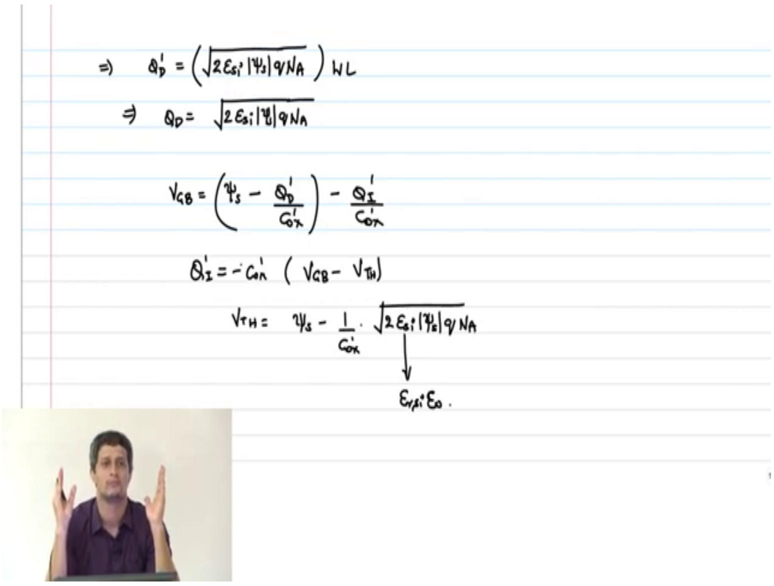

This implies Q D prime is that q N A will go and you will basically get 2 epsilon s i into mod psi s into q into N A whole thing into the area W into L. So, which implies the charge per unit area is just root of 2 epsilon s i mod psi s into q into N A right. So, now what do I do? I can write my V GB as psi s minus Q D by C ox right and minus Q I by C ox. I am just splitting that this term here where is that yeah, I am splitting this term right of course, let be clear 2 D prime because these are all absolute charges.

So, what is my inversion charge that is available? It is basically C ox prime into V GB minus the threshold voltage. So therefore, V T H is defined as psi s minus 1 by C ox prime into root of 2 epsilon s i mod psi s into 2 N A. Note that this is epsilon r of silicon, not silicon dioxide because this is in the substrate, it is in the silicon substrate. Therefore, you are solving Poisson's equation there, the epsilon will come from silicon not silicon dioxide right into epsilon naught. So, effectively what is happening of course, there is a minus sign here because it is a negative this thing.

Effectively what is happening is in order to create some inversion charge right which is going to be useful for current flow right, in the form of free electrons I need to first invert the channel right or invert the surface; in order to do that I first need to deplete part of my body or part of the substrate. And, that voltage or that work that the gate voltage has to do in order to invert the channel is basically called a threshold voltage.

So, even if you apply a large potential it is only V GS minus the threshold voltage that is actually going to be available for you in order to create more inversion charge and thereby increase the current from there on right. Below the threshold voltage it’s like saying that the inversion charge is sort of negligible and you cannot do any useful thing with that ok.