Semiconductor Device Modelling and Simulation
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Lecture – 33
Problem Session-5

Hello, welcome to lecture number 33.

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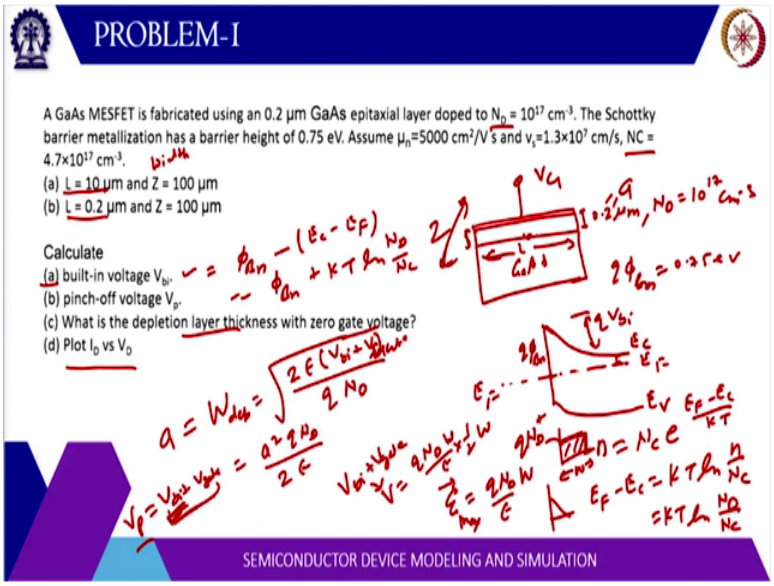

Today, we will discuss some problems, whatever concept on FET and the MESFET and MOS devices we have discussed. So, let us consider first problem, so, it says a gallium arsenide MESFET is fabricated on a 0.2 micrometre gallium arsenide epitaxial layer. So that is basically your structure here. And then so, this is semi insulating gallium arsenide then on top of that there is a gallium arsenide layer whose thickness is 0.2 micrometre.

Now, it is doping is 10 is to power 17 per cubic centimetre. Now, this is a Schottky context, so, there is a metal layer here. And it is barrier height is so that is q phi Bn is 0.75 electron volt. So, if you recall the band diagram, so, this is metal Fermi level and in equilibrium this Fermi level is constant throughout the metal and semiconductor and this is basically q phi Bn this is the barrier height.

And then this is the conduction band E c and then something happens here. This is E v the barrier height or the built-in voltage is this value this is qV bi. So, as you can see in the picture, qV bi is basically phi Bn minus this gap E c – E f. So, – E c – E F and E c – E F you can find from the doping because we know that here what is given is NC, NC is the effective density of a state for the conduction band.

And we know the relationship n = NC exponential E F – E C by KT. So, from this we can find out E F – E C = KT log of n by N C. Now, this is doped with N D, so, n can be replaced by N D so, this can be written as KT log of N D by N C. So, this is E f – E C. So, effectively this is E F – E C so, phi B n + KT log of N D by N C. So, this will be the built-in voltage. Then the pinch-off voltage, pinch-off voltage you can easily find.

Pinch-off voltage, the voltage required where the depletion region goes and touches this lower side. So, this depletion width is exactly equal to the width of this **(()) (03:49)** layer. So, we know what is the depletion layer thickness? The depletion layer thickness, so, W depletion is square root of 2 times epsilon V bi – V divided by q times doping N D. And the way to remember is basically because the charge consume, if you assume that the depletion region is uniform charge concentration is abrupt change in this:

So, the charge concentration is qN D plus so, this charge concentration will give or the fixed charge will give a linear change in potential electric field and that will be quadratic change in potential. So, you can find out that electric field will be linear so that will be qN D plus times the width this is the width here by epsilon. So, this will be the electric field.

And the potential will be the area of this thing so, half base into height, so, potential will be V is basically qN D W by epsilon times half W. So, this is E max. So, this is E max into half W because E looks like this, so, this is the barrier and now this barrier is actually V bi this barrier is equal to V bi minus forward applied voltage or if this is reverse voltage then it will come plus a basically. So, this is V for what you can say this is V forward.

So, what did we do here actually in case of MESFET, this gate voltage is always reverse bias, so, this will become basically plus v gate. So, V bi plus V gate is equal to this. And you can find from here that W = epsilon by qN d times this. So, this is the depletion layer thickness at 0 bias we will just use V bi so, V bi we have calculated already from expression 1. Then pinch-off voltage is when this W depletion is equal to let us say this is a when this is equal to a.

So, you can find out V bi + V gate = a square times qN D divided by 2 epsilon. So, this is basically the pinch-off voltage generally what we do? We ignore this V bi then we say this is pinch-off voltage. So but this is small but not insignificant so, actually we should include it and that will give you the pinch-off voltage. So, what I have done here basically, I have written a Matlab code to calculate all these parameters.

And then use the expression that we drive for ID VD to calculate the I-V curve. Now, here the concept that I wanted to introduce we have to compare this input two cases one this is the length so, in one case length is 10 micrometre. In other case, the length is 0.2 micrometre and Z is basically the width into the paper. So, this is into the paper that is a Z so that will be the cross action area so W times the a.

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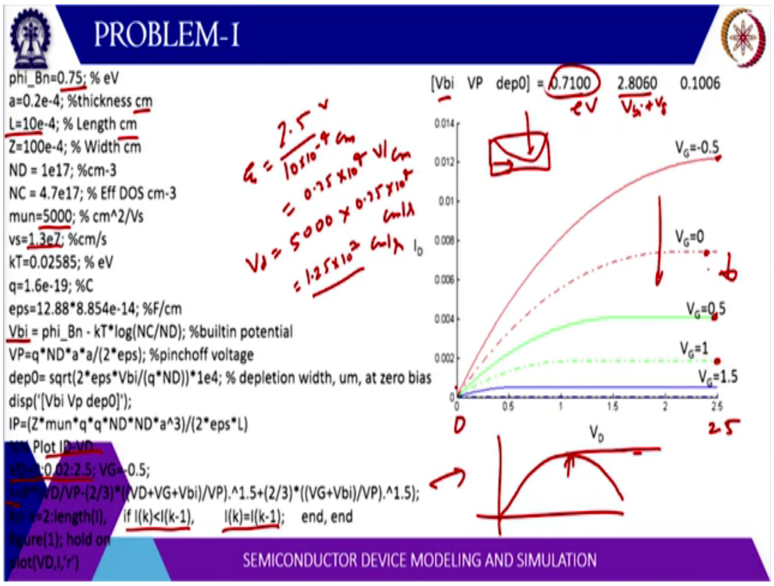

So, this I have written here the phi Bn is 0.75. The unit is electron volt then a is 0.2 micron here I have used centimetre for all this values expressed in centimetre because our carrier concentration all those parameters are in terms of centimetre. So, they will effectively manage out and ND is a doping NC is the effective density of a state for conduction vent. Then mu n is the mobility centimetre square per volt second.

And then this is the expression for V bi so, this phi Bn – KT and the value we get around 0.71 electron volt. Then VP is q ND a square by 2 epsilon so that is around 2.8. So, this is basically V bi + V gate. So, V gate will say 2.1 basically, you subtract 0.7 from here. So, the corresponding to V gate of 2.1 you will get the pinch-off. Then to calculate ID VD what we do? We select some range of voltage VD from 0 to let us say 5 volt.

So, 2.5 volt so, this is 0 to 2.5 volt then use that expression that I P times VD by VP – 2 by 3 VD + VG + V bi power 3 by 2 + 2 by 3 VG + V bi by VP to the power 3 by 2. So, this expression then what we do here? VD is a vector and therefore, this I is also a vector. Then because the curve, actually if you use this equation, the curve you will get, will be something like this like MOSFET, you know very similar.

So, what we do here? Up to this region where there is a peak there is a linear region and then this goes to saturation. So, beyond this value, where it start to degrees, we maintain a constant value. So that is what is done here. So, if I k is less than I k – 1 then we set I k to I k – 1 and so on. So, this way for remaining values we make it constant and we get this curve, so, this is ID versus VD curve.

Now, if you see here, the potential is 2.5 maximum that VD are applying and the length is 10 micrometre. So that is 10 into 10 is to power –4 centimetre. So, the electric field that comes out to be around 0.25 into 10 is to power 4 volt per centimetre. And correspond drift velocity will be mu times mu is 5000, so, 5000 centimetres of a volt second times 0.25 into 10 is to power 4 volt per centimetre.

So that will be basically centimetre per second, so that is around 1.25 into 10 is to the power 7 centimetre per second. And if you compare this thing with the saturation velocity is around 1.3 10 is to power 7. So, it is below saturation velocity. So, therefore, we can use this expression with V = mu e because this expression was derived with the substitution that V = mu time C.

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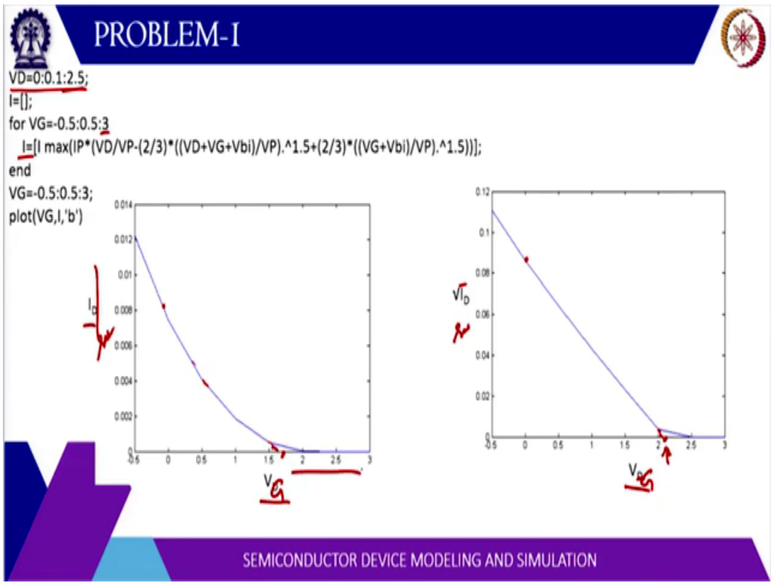

And for the same case, we can also calculate I D versus V D. This should be V G. This is V D and this is V G so, this should be V G actually this should be V G. So, this is I D, this is square root of I D versus the technique is same. What we do basically? For different V G we find out what is the maximum value? So, this is basically what we have plotted here is the maximum value or I saturation.

This is I saturation, so, maximum value of I for a given V G from the range of 0 to 2.5 value of V D. So, what we have done here? Let us say if you see the previous figure, this is the maximum value, this is the maximum value, this is the maximum value, this is a maximum value. So, V G = 1.5 the I D is around is pretty small for V G = 1. It is around 0.002, V = 0 at around 0.008 you can also notice a trend here, as the V G is increasing and the current is decreasing.

Because this is reverse biasing, basically, reverse biasing means your channel is getting narrowed basically. So, this is your channel region and this is getting narrowed basically. So, the current that is flowing through this channel is getting reduced basically. So, we cannot go below –0.71 because beyond this it will come forward bias. So, we go to 0.05 although this is also not a region of operation, we typically operate it below 0 volt.

So, this for 0 volt this is around 0.008. So, you can hear for 0 voltage around 0.008 and then square root of 0.008 will be around 0.08. And then you can identify here, especially with square root of I D if you extend this linear line, it will enter somewhere here. So, this is the basically intersection of root I D versus V G and same thing if you extend somewhere here, this is the voltage you will get.

So, this is how concept of the threshold voltage that should we beyond this voltage basically, current will not flow because depletion region will cover the whole of the channel layer.

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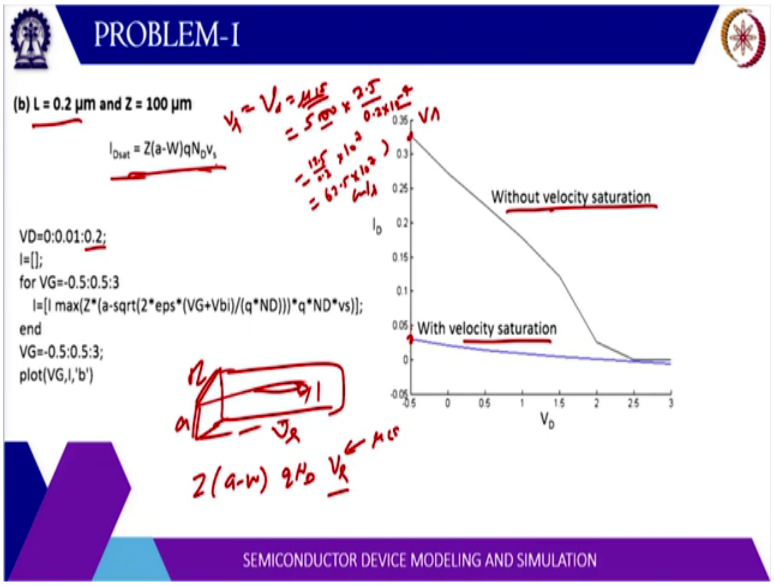

Then for a smaller length, where length is 0.2 micron here, if you use Vd = mu E. What you will get, basically mu is 5000 times electric field is let us say we apply 2.5 volt V d divided by 0.2 micron so, 0.2 into 10 is to the power –4 centimetre. So, the value will be around 0.2 so that will be 10 is to power 7 3 + 4 is 7 then that is 12.5 divided by 0.2. So that will be around 62.5 into 10 is to power 7 centimetre per second.

Now which is actually much larger than the saturation velocity so that means we cannot use this expression Vd = mu E. So, in this case, we will assume that throughout this channel region, the velocity is V s because now electric field is pretty high. And you can also find out at what point this is equal to V s? So, you can find the corresponding voltage that will be pretty small, so, here we go up to 0.2 volt only so that is also in the saturation only.

So, when the field is high enough, electron move with the saturation velocity. So then current equation will be so, the width of this Z so, this is a width and then this is the height, let us say a and that the depletion width is W. So, the area of cross, section Z times a – w times charge that is qN D times the velocity. So, here we are not using mu E. We are using saturation velocity because length is small.

And therefore, the field will be high here and the velocity value saturation velocity. So, with this expression, if we calculate then you will get this blue curve with velocity saturation. And if you do not include velocity saturation without velocity saturation, so, using the previous these equations, this equal this code with this equation, only changing the length equal to 0.2 micron you will get this black curve.

So, you see, this basically kind of over estimating by a large amount. If you see here that it is around say 0.05 here, this is around 0.3 something so, it is pretty large, basically. So, at high field, basically we have to modify the expression and same thing applies to MOSFET, also. So, in MOSFET also, we have to use the similar expression when there is a velocity saturation scenario.

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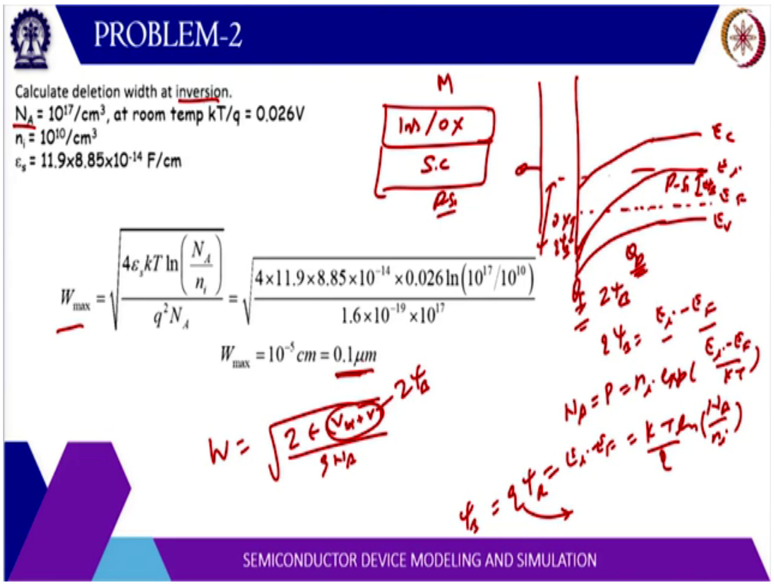

Now, a problem 2 is basically we have to calculate the depletion width at the inversion. So, this is basically a MOS structure, so, there is a metal then there is a oxide here or insulator here and then there is a semiconductor here. Now, if you draw the band diagram, let us say this is oxide and this is N A so, this is p-type semiconductor. So, let us say this is p-type silicon.

So, for p-type silicon Fermi level is close to the conduction band balance band so, this is Fermi level. Now, just applying the voltage to metal gate here it does not allow any current to flow, so, your Fermi level will be constant. But when you apply the potential, these bands will actually bend here and they will bend down. And that say this is the intrinsic level in between so, this will also bend.

Now, at inversion this bending is such that if this is psi B or q psi B this will also be q psi B so that means total, so, the total band bending is 2 psi B. So and psi B is what psi B is q psi B is E i – E F and for semiconductor now here is E i and E F so, we will write expression p = n i exponential E i – E F by KT. So now, this is doping is N A so, p we can equate to N A and we can find E i – E F = KT log of N A over n i.

So, this is your psi B q psi B so, 2 times q psi B and again for depletion region you know the expression W is equal to square root 2 epsilon V bi + V divided by q. Here we have N A instead of N d. So, you can write q n here. Now, the band bending here, so, this potential here will be replaced on the band bending and that is 2 psi B. So, 2 psi B will be 2 KT log N A by n i. Now, this is psi B so, this is q psi B so, Q will go here in the denominator.

So, it will come create E by q that will be psi B. So, you will get this expression for the maximum width of the depletion region. Now, why this width is the maximum? Because once it reaches this level where the band bending is such that from psi B it becomes minus psi B. So, beyond this, small change in the band, this potential energy will result in large change in the inversion charge. So, Q I here and Q depletion charge here.

So, if you change it slightly, most of the charge will appear as inversion region here instead as depletion region here. So, the depletion with width effective does not change beyond this voltage, so, this width can be said as the maximum depletion width. However, having said this, if you do fast sweeping so that means, if you quickly drop the voltage to a large, lower value.

In that case, we can get a depletion with larger than this that is possible. But that is basically testing procedure and normally that is not used in device operation. But if you suddenly change the voltage to high voltage, we can get a depletion width bigger than this and because this inversion charge will take some time to get created there. So, in first sweeping it is possible but in normal operation this is the maximum depletion width.

Now, from this we go to third problem and we calculate the C-V relationship for this MOS structure.

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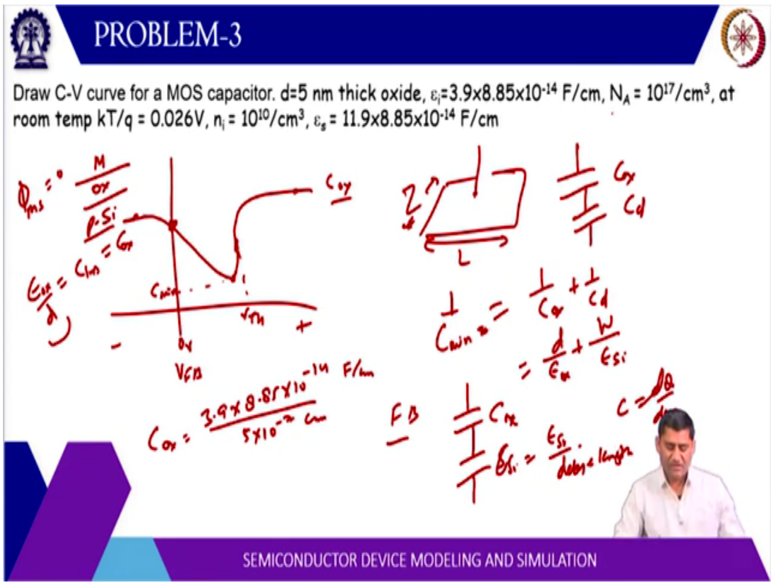

So, this is a metal, this is oxide, this is a p-type silicon, so, for this C-V and we know that this is p-type. So, for negative voltage the capacitance will be same as oxide capacitance because this will lead to the accumulation of these holes negative voltage. So, your C will be C oxide or C insulator and that will be epsilon oxide by d the thickness of the oxide. Then at flat band voltage so, here we are assuming ideal oxide and we have no information is given or the phi ms.

So, we can assume it to be 0 so then flat 1 voltage will be here at the 0 volt. This is negative, this is positive so, this will go down here. And then at threshold voltage so, this is some threshold voltage. So, this is the flat band voltage, V FB and this will be the minimum. And again it will be if it is low frequency, it will be again the C ox or C insulator. Now, if we find the key voltages the key capacitances here then we can basically draw the curve.

So, this is the C in accumulation, C at flat band, C at beyond inversion and this is C minimum. So, C oxide is basically epsilon oxide divided by the thickness and we know that epsilon oxide is 3.9. That is the dielectric constant times 8.85 into 10 is to power –14 farad per centimetre then this 5 into 10 is to power –7 centimetre. So, capacitance will be farad for centimetre square.

So, this term this epsilon by D is actually capacitance per unit area. So, what will be the area? So, if you consider let us say, this is your gate. So, this is the width Z times the length so, Z times L multiplied by C ox will be the overall capacitance of the gate. So that we can find C x and psi s at that point we already know. So, we can find the minimum capacitance also so, C minimum will be when the depletion width is maximum.

So, there will be two capacitance in parallel oxide capacitance and the depletion capacitance. So, 1 over C minimum will be you can write 1 over C oxide plus 1 over C depletion and C oxide is epsilon oxide by d oxide plus C depletion will be epsilon silicon by W. And W we have calculated around 0.1 micrometre. So, C minimum can be obtained from here that will be C minimum and then this is the inversion region here.

So, once you go to inversion region C oxide, only and flat band will come from the debye length. So that will be so, for the flat band this is C ox the flat band occurs at 0 volt here. So, the bands are actually flat there. So but if you change the voltage slightly then there will be some change in the depletion width. So because C is dQ by dV, so that can be found from the debye length.

So that will be C silicon that will be epsilon silicon by the debye length for in silicon for a given doping.

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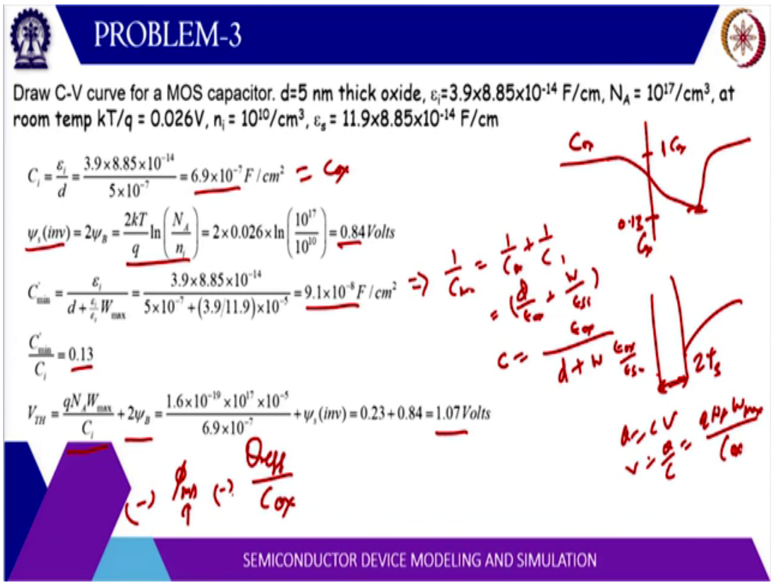

So, if we substitute this and we do the calculation then the oxide capacitance we get around 6.9 into 10 is to power – 7 fard per centimetre square. Then of course inversion surface potential for inversion region that is 2 times kT by q lon N A by n I, so that is around 0.84 volt. And C minimum this is basically arranged like this 1 over C minimum is equal to 1 over C ox + 1 over C silicon.

So, this is basically, if you rearrange it then this is d by epsilon ox + W by epsilon silicon and this is 1 over C. So, C can be written as 1 over this thing. So, 1 over this thing, what we can do? We can take epsilon outside. So, this is d + W times epsilon ox by epsilon silicon. So that is what done here and then you get around C minimum 9.1 into 10 – 8 farad per centimetre square. So, the ratio of C minimum C oxide is around 0.13.

So that means this is your C ox here in accumulation region it goes then similar, so, this is 1 here this will be 0.13. So, let us say this is 1 times C ox this will be 0.13 times C ox. And then threshold voltage is basically the dope across the silicon region plus oxide region. So, dope across silicon region is 2 psi B and the dope x across oxide is C oxide times Q = CV. So, voltage is basically Q by C.

So, Q is the charge here so that you can write q D, now q D will is what? Q times N A times W max divided by C oxide. So, add these two you will get the threshold voltage that is around 1.07 volt. Please remember here we have ignored any charges in the oxide and phi ms. If there is a phi ms charge in the oxide then this threshold voltage will be added with phi ms and this will term due to the Fermi level difference between the metal and semiconductor.

And as well as this charge in the oxide so, Q effective in the oxide divided by C oxide. So, these two term will come. These are usually negative, as we have discussed earlier, for both whether it is silicon is n-type or p-type. The value comes out to be negative for these two.

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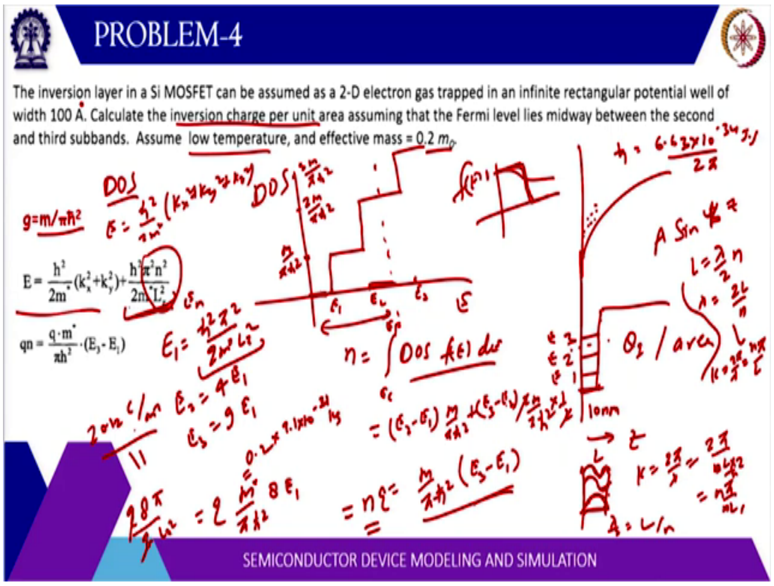

Now, last problem for this session here it is said that inversion layer in a silicon MOSFET it can be assumed as a 2D electron gas because if you see the diagram here so, this is the band diagram and this region can be filled with electrons. So, it is basically 2D electron gas. Now, this is can be assumed, although it is basically triangular but let us assume that it is a rectangular quantum band.

And it is width is 100 armstrong so that is 100 armstrong is 10 nanometre. Now, we have to calculate inversion charge, so, Q I per unit area, as you mean that Fermi level lies midway between the second and third sub band, so because this is a quantum band, so, there will be bends here let us say bend 1, bend 2, bend 3. So, energy levels E 1, E 2 this is E 3. This is E 3 so, in the middle of these two bends bend 2 and 3.

Now, if you recall, for 2D band structure, please revisit the discussion on the density of a state lecture DOS lecture there we have mentioned or we have drive basically, the density of a state for 2D is constant and given by m by pi h bar square. So, how it look like? If you cut so, this is a DOS versus energy. So, it will look something like this, so, this is m by pi h bar square. Then this let us say this is E 1, this is E 2 so, E 2 again this jump here.

So, this is 2m by pi h bar square plus this is E 3 so, again jump here. So, this is 3m by pi h bar square so, this is a DOS. Now, Fermi level is somewhere here in the middle of E 2 and E 3. So, from this we can calculate number of electron. So, n will be integral DOS times probability of occupation, dE. So, an integral will be from, let us say E c to Fermi level E F. Now, here a condition is given low temperature.

So that basically, simplifies our calculation because the Fermi level, basically, if you plot F E the Fermi level distribution, it looks something like this. So, as this is low of temperature at high temperature, it becomes more sloppy. So then of course, integration become more complicated but at low temperature, if we assume it is close to 0, it will be rectangular. So that means it is basically1. So, this F is 1 in this region.

So then this can be simply written as E 2 – E 1 because below E 1 this is 0, so, E 2 – E 1 times the density of a state so which is m by pi h bar square times1 because this F is 1 + E 3 – E 2 now E 3 – E 2 only half of this we have to consider. So and the value is 2m by pi h bar square times half because only half is filled, other half is empty. So that if you simplify what you will get here, this 2, 2 will cancel.

So, this is m by pi h bar square times E 2 – E 1 + E 3 – E 2 so that is E 3 – E 1. So, this will be the n so that is a density of carriers in the quantum band. Now, what does this E 1, E 2, E 3? That also we can calculate we know E = h bar square K square by 2 m now, K square written as K x square + K y square + K z square. If this is the Z direction, so, in Z direction, it will be quantized but in x and y it is free so, it can take any value.

So, now K z can be written as now, this length is, let us say L. So, the wave function, if you think like this wave function, can have this type of curve or this. So, it is K is basically you can write 2 pi by lambda and lambda can be L by 2 or L like that so, n times L by 2. So, this will be written as 2 pi divided by n times L by L times 2 because this will be this is lambda by half. So, lambda by half is equal to L. So, lambda is 2L. So, n times 2L.

So, this will be pi by nL so, h bar is square by 2m times n pi by L square. This should be L by n L by n so, this is n pi by L so, K is n pi by L. This requires some background information about the quantum mechanics. So, let me just give a brief overview let us say, the wave function generally, these electrons are described by the wave function. So, this wave function lets here some form A sin psi or K times Z.

So, this K is basically the wave vector. So, if you compare this type of situation, where this length is basically equal to this length is L but this is half wavelength, for the second this is 1 wavelength, for third one it will be 3 by 2 wavelength and so on. So, your L = lambda by 2 times n, n lambda by 2. So, lambda by 2, lambda by 3, lambda by 2. So, from this we can say, lambda = 2L by n.

And then K is 2 pi by lambda, so that is then you will get n pi by L here, if you substitute this here so, this is how we are writing this one. So, the energies will be E 1 these energies are E n basically. So, these are the energies E n because in other 2-dimension there is no restriction. So, E 1 will be h bar square pi square by 2m L square, E 2 will be n is 2 so that will be 4 times E 1, E 3 will be 3 square, so that will be 9 times E 1, so, E 3 – E 1 will be 8 times E 1.

So that is m by pi h bar square times 8 times E 1 and E 1 is this value. So, we substitute here this n what you have to calculate charge per unit area? So, this is the n is the density per unit area. So, you multiply this thing by Q will be charged per unit area and when you substitute the value, this m is m effective, so that is 0.2 into 9.1 into 10 is to power –31 kg. And then E 1 of course you can substitute here, h bar you can substitute is h over 2 pi and the h is 6.63 into 10 is to power –34 few second divided by 2 pi.

So, we substitute this one then m by h bar this you can put here and then substitute even here. So, what you will get here? Q times E 1 is h bar is square by 2m. So that is 8 times h bar square will cancel m will cancel so, pi 1 pi will remain here. So, pi by q L z square, so, this q will also cancel out. So, the value will get will be around 20.12 coulomb per metre square. So, you can do the calculation. So, this is a charge density.

So, here the concept that we have discussed the quantization of the energy levels then corresponding density of states to calculate the carrier, concentration that is DOS times F and that simplifies to DOS times E 3 – E 1. Then we substitute the value you will get this around 20 coulomb percent metre square as a inverse and charge per unit area. Thank you very much.