Electronics Materials Devices and Fabrication
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Module - 01
Assignment- 06
Transistors

In today's assignment, we are going to look at transistors.

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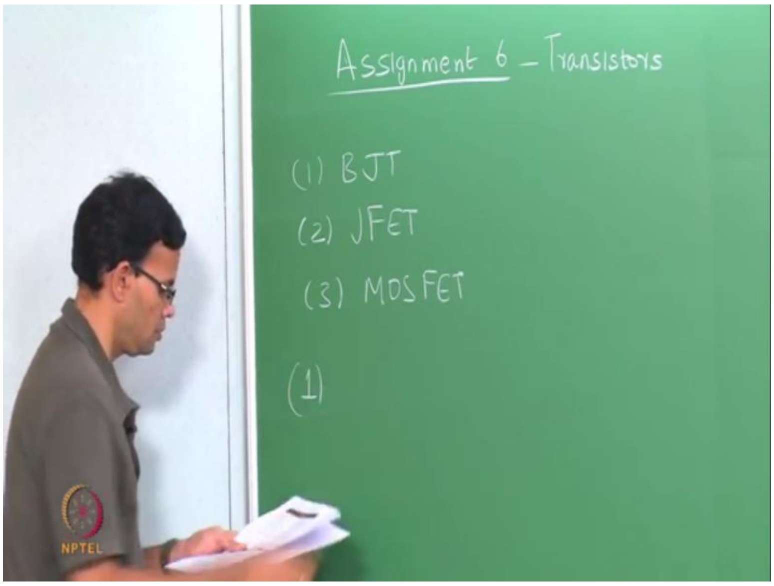

So, this is assignment number 6, we are going to look at numerical problems related to transistors. During the course of lecture we saw the theory behind the transistor action we saw that there were three main kinds of transistors that we discussed. One was the bipolar junction transistor or BJT, this essentially a current control device, it had an emitter base and the collector. Transistor action occurred when the minority carriers way inject through the base. Then, they moved on to the collector. The next kind of transistor that we saw was the junction field effect transistor in this particular type of transistor, there was an existing channel for carrier conduction.

So, this could be a channel for electrons, which will be an n channel or a channel for a holes should be a p channel and basically the width of the channel. Hence, the amount of current that could flow through it was controlled by an external feel, this was why it was called field effect transistors. Then finally, we discuss the MOSFET, which was the metal oxide semiconductor field effect transistor. In this particular case, the channel did not exist originally in the device, but was created by applying in electric field so that the channel was formed. We looked at the MOSFET slightly in more detail then the other two type of transistor and we did some numerical calculation for the MOSFET as part of the course.

So, in today's assignment we are going to look at some of the numerical problems related to all three type of transistors we already seen problem related to junctions. So, simple p n junctions and we can actually treat transistors as essentially having 2 p and junction. So, some of the concepts that will learn when we looked at p n junctions, we can apply here, so let me now go to problem 1.

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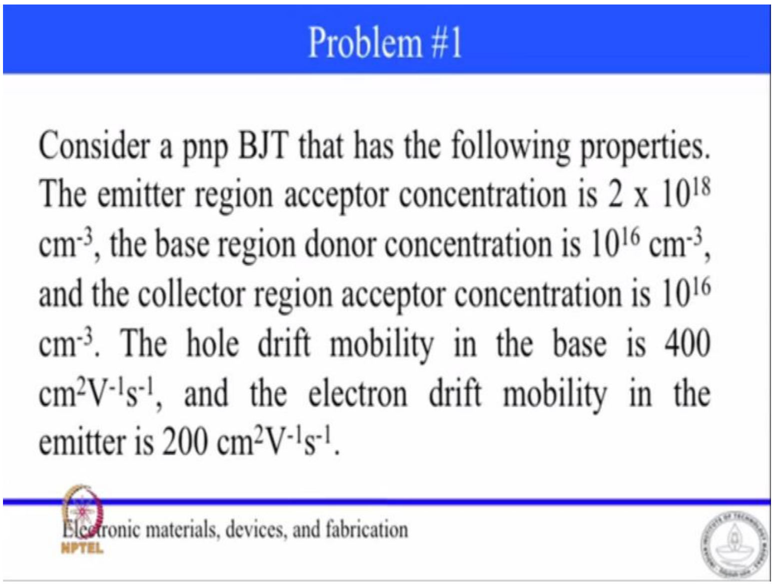

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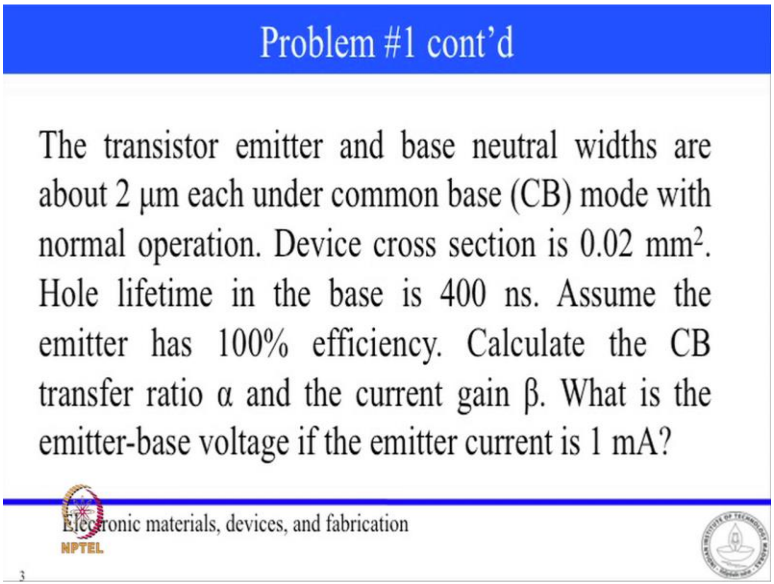

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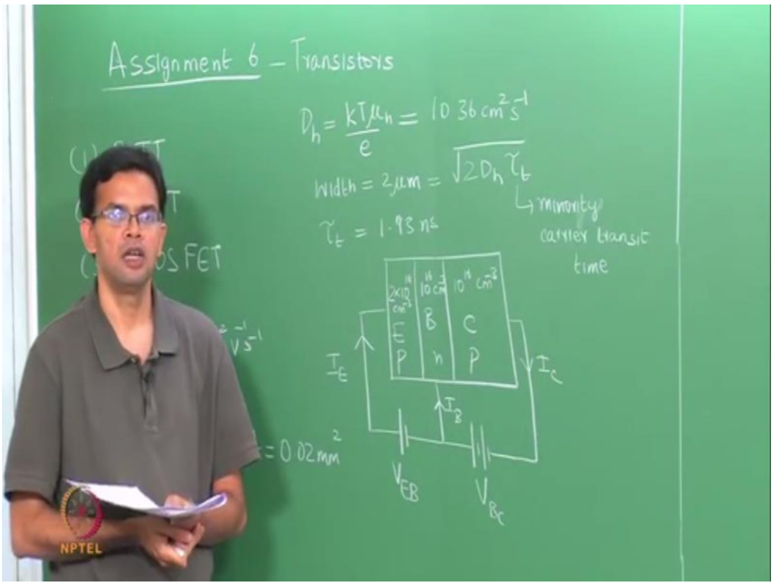

So, in problem 1 we have a p n p BJT, so we have a p n p bipolar junction transistor. So, let me just draw this schematic of that a transistor essentially three regions an emitter region a base and a collector in a case of a p n p transistor you have the emitter and the collector to be p type the base is n type. So, the concentration of the different regions is given.

So, the emitter region has a concentration of 2 times 10 to the power 18 per centimeter cube the base is 10 to the power 16 per centimeter cube and the collector is also 10 to the

16 per centimeter cube. So, there are different configurations in which a transistor is connected. So, here we are going to look and a connection were we have a common base mode in this particular case the emitter base junction is forward biased EB and collector base junction is reverse biased. So, in this particular case, holes are injected from the emitter to the base so that there is an emitter current I e.

These holes are essentially minority carriers in the base they will recombine with some of the electrons in the base, but most of the holes will essentially move from the base to the collector and that forms your collector current. Some of the holes which move into the base and get recombined are essentially replants by the external circuit and that forms the base current.

So, this is just a simple schematic of how a p n p or how a bipolar junction transistor works in a common base mode. So, some of the numbers there are given here says that the hole drifts mobility. So, m u h in the base is 400 centimeter square per volt per second, so this is in the base. So, this is the mobility of the minority carriers in the base the width of the neutral base region is also given. So, the width w of the base region is 2 micrometers and the device cross section is also given, so a is 0.02 millimeter square. The whole life time in the base is 400 nanoseconds, there is stove h is 400 nanoseconds.

We want to calculate the common base mode transfer ratio alpha, which means the amount of current that goes from the emitter to the collector and also the current game beta. We also want to know what the emitter base voltage is if the emitter current is 1 mille. So, we look at the mobility of the holes in the base from the mobility we can essentially calculate diffusion coefficient. So, d h is k t mu h over e, so this we have seen before in the context of both of extrinsic semiconductors, so d h comes out to be 10.36 centimeter square per second.

So, once we know the diffusion co efficient we also know the width of the base. So, the width is 2 micro meters from which we can calculate the minority transit time or the time it takes for the electrons to go from the base for the holes go through the base and to go from the emitter to the collector. So, this is assuming simple two dimensional diffusion.

So, this width is equal to square rout of 2 times the diffusion coefficient d h times the transit time. So, this is the minority carrier, so the width is known the value of d h we just calculated. So, we only need to value of t tau for the transit time is essentially 1.93

nanoseconds. So, within 1.93 nanoseconds your holes essentially sweep through the base and move from the emitter to the collector. Some of these holes will recombine in the base along with the electrons and this recombination depends upon the transit time and it also depends upon the whole life time.

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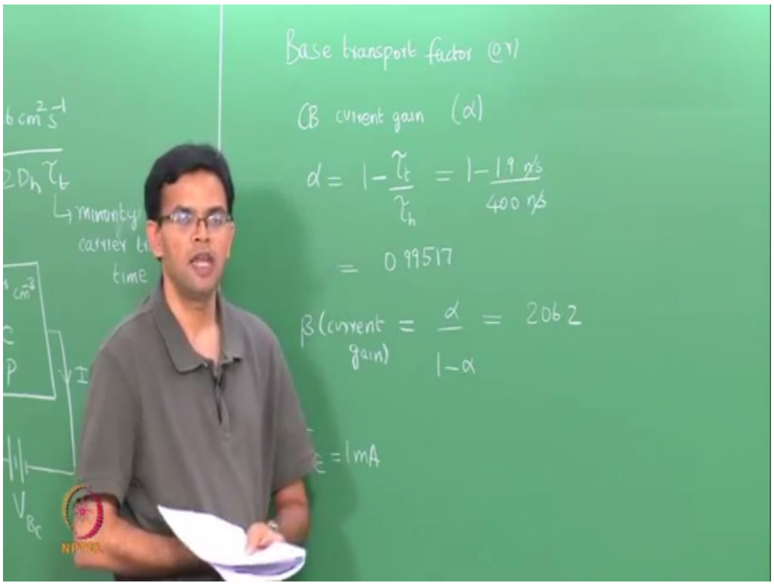

So, based upon this we can define a base transport factor this is also the common base current gain or alpha other name for this common base this is alpha and alpha is nothing but 1 minus tau t over tau h. So, all the values are given tau t is 1.9 nanoseconds tau s is 400 nanoseconds so that alpha comes out to be 0.99517. So, higher the value of alpha then greater is a current transfer from the emitter to the collector. So, one way to do that is to reduce the transit time, this you can do by making the base thinner.

Another way to do that is to have a higher value of tau h which is the higher value of you minority carrier life time this again you can do by reducing the doping concentration in the base. So, alpha is 0.99517, we also want calculate the current gain that is beta and this is a again given by a formula beta is defined as alpha over 1 minus alpha.

So, we can substitute in the values so that beta comes out to be 0200 and 6.2. So, again higher the value of alpha will essentially fine for the current gain is also higher. In the last part of the question, we have to calculate the emitter base voltage given that the emitter current is 1 mile amplifier I e is 1 mile amplifiers. So, if you look in the case of an emitter current your emitter current is generator because you now have p n junction between the emitter and the base and you basically have minority carriers, then the injected across the junction.

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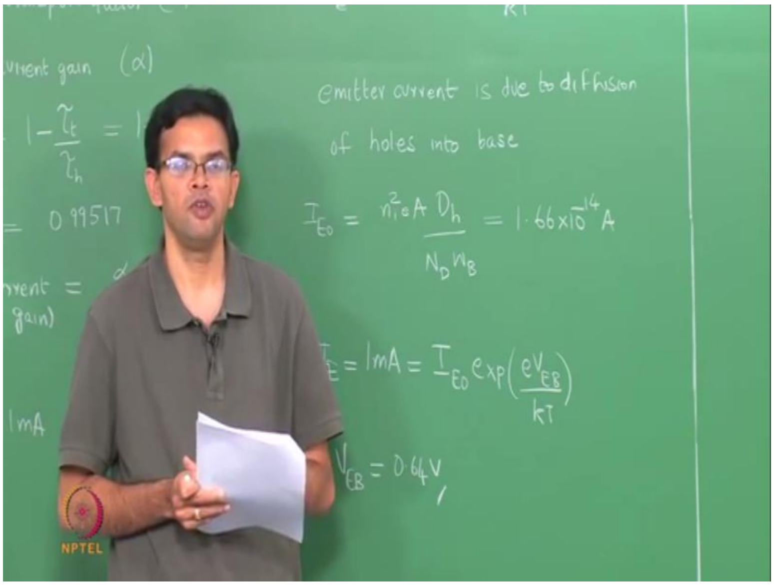

So, I e is nothing but the current that is generated when a p n junction is essentially forward by us. So, I e is I e not exponential e v over k t so that your emitter current is due to diffusion of minority carriers in this particular case these are holes diffusing into the base, so I e naught. So, if you look at this expression, this is very similar to the expression that we got for a p n junction under forward biased. In that particular case, I was I naught exponential e v over k t, where is a minus 1 term for usually that can be neglected. So, in this particular case I e naught is equal to n I square e times the cross sectional area a times d h over n d times w b. So, here n d which is the concentration of electrons in the base it is much smaller than n which is the concentration of holes in the emitter.

So, since it is 1 over n d this particular term will dominate, so all of the values here are known w b is the width of the base which is 2 micro meters so that this is equal to 1.66 times 10 to the minus 14 amplifiers. So, we have the cross sectional area A here so that the final answer is an amplifiers if did not have this will be a current density. So, typically amplifiers per centimeter square or amplifiers per meter square, so I e b is known. So, I e is given to be 1 mile amplifiers just equal to I e not exponential eV, EB, which is the emitter base voltage divided by k t.

So, all the terms here are known expect v e b, so you can re arrange and then V EB is 0.64 volts. So, essentially looked at a p n p bipolar junction in forward bias try to calculate the current gain and also the transfer ratio and how you can calculate the emitter base voltage for given value of the current. So, we essentially treat a bipolar junction transistor as made up of 2 kinds of p n junctions, one forward bias the other reverse bias and then we go through these calculations, so this will be more clear when we look at problem 2.

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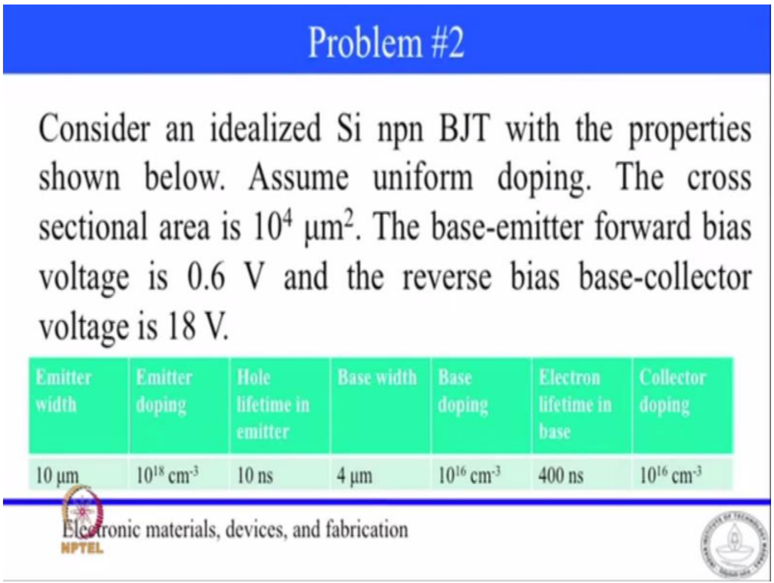

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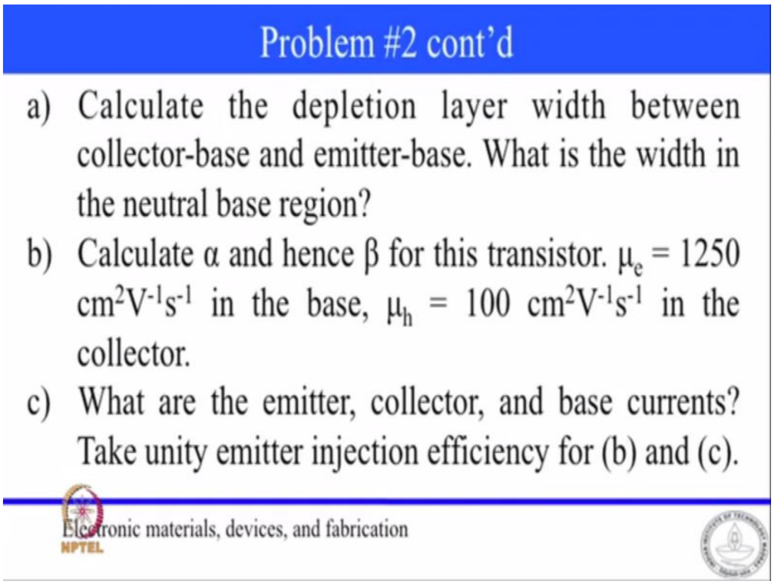

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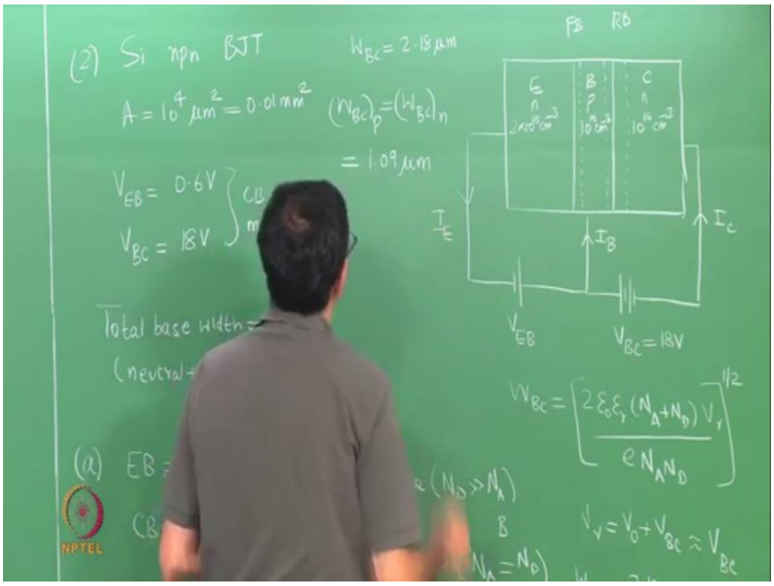

So, in problem 2, we have an idealized silicon n p n bipolar junction transistor. So, you have a silicon n p n, so problem 1 was a p n p bipolar junction transistor. Now, we have an n p n the cross sectional area is given. So, a is 10 to the 4 micro meter square, so micro meters is nothing but 10 to the minus 3 millimeter square. So, another way of writing is just 0.01 millimeter square, the base emitter forward bias voltage.

So, V EB is given to be 0.6 volts and the reverse bias base collector voltage is 18 volts, so once again this is in a common base mode. So, CB mode we can go ahead and draw the schematic for this bipolar junction transistor as well. So, we have 3 regions, an emitter a base and a collector this is an n p n, so we have n p and n the concentrations are also given. So, 2 times 10 to the power 18 per centimeter cube this is your majority carrier concentration, then you have 10 to the power 16 per centimeter cube. This is also 10 to the 16 per centimeter cube, so this is in your common base mode so that this is V EB, this is V BC.

We can compare this problem 1, you will essentially see the polarities are reversed because now we have an n p n, but once again your emitter base junction is forward bias so that electrons from the emitter basically move to the base. This gives you your emitter current I e, these electrons are minority carriers, some of them will recombine with the holes in the base, but most of the electrons essentially move through the base and go to the collector this gives you the collector current I c. So, those electrons that essentially recombine in the base have to be replenished so that you also have a base current I b.

So, if you look at it we have 1 p n junction that is forward biased p n junction, you have another p n junction that is reverse biased, we can also mark the depletion regions. So, for the emitter base junction the base is likely doped, well the emitter is heavily doped, so most of the depletion region will essentially lie in the base. On the other hand, for the base collector junction, we will have the depletion region both in the base and the collector and since the concentrations are the same the depletion regions are essentially of the same width. So, the total width of the base is given, so the total width of the base is 4 micro meters, so this includes the neutral region at the same time it also includes the depletion region.

So, this is the neutral plus the two depletion widths in the base, so the first part of the question we want to calculate the depletion layer width between the collector base and the emitter base we also want to calculate the width of the neutral base region. So, in part a, we want to calculate the two depletion region widths and you also want to calculate the width of the neutral base region. So, let us look at the emitter base EB, so here the depletion width is fully in the base and this is because n d in the emitter is much greater than n a in the base, so then you can use the formula.

So, this is the emitter base region for the collector base region the depletion layer or the depletion layer or depletion width is on both sides. This is because n a in the base is equal to n d in the collector side, so let us look at the base and the collector region, this is essentially a region that is in reverse bias. So, reverse bias tens to increase the depletion width so that w b c is given by 2 epsilon not epsilon r n a plus n d times total voltage V r divided by e n a n d and this is the square root of the whole thing. So, this is the same formula that we have used when calculating the depletion width of a p n junction.

We are just using that formula, the only difference here is that we are is not the contact potential, but it is the contact potential plus externally applied reverse bias voltage. So, V r is nothing but V naught, which is your contact potential plus the reverse bias voltage. So, this value is given in this particular problem V BC is equal to 18 volts so that this number is usually much higher than V naught. So, this I can approximate as V BC, so we can plug this in the formula, all the numbers are essentially known from which we can calculate W BC to be equal to 2.18 micrometers.

So, W BC, let me just write it here is the total width of the depletion region between the base and the collector and this is equally shared between the base region and the collector region. Therefore, w b c on the p side which is your base is equal to W BC on the n side, which is your collector is equal to half of 2.18 or 1.09 micrometers. So, this represents the depletion width on the base side for the base collector junction you can use a similar argument, calculate the depletion width for the emitter base region.

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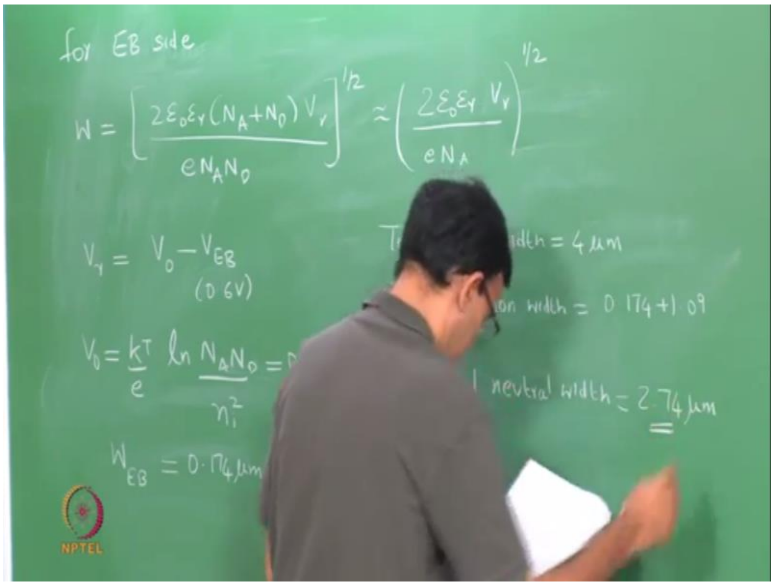

So, for the emitter base region, the EB side we can calculate the width. So, once again W is 2 times epsilon naught epsilon r n a plus n d times v r over e n a n d in a whole square root. For the base and the collector region, we said that it is reverse biased so that V r is nothing but the reverse biased potential plus in the built in potential v naught.

Now, we have v r to be equal to the built in potential v not minus V EB and V EB is given as 0.6 volts. The built in potential we can calculate by simply taking this to be a p n junction so that V naught is k t over e l, one of n a n d over n I square. This works out to be 0.830 volts, so in this particular case n d is much greater than n a so that W can be approximated as 2 epsilon naught epsilon r v r divided by n a e whole to the half. So, everything else we know V r is v not minus V BE n a is known, so we can calculate W between the emitter and the base region and this mostly lies in the base and this comes out to be 0 point 174 micro meters.

So, this is mostly in the base region the total base width is 4 micro meters, the total depletion layer width total depletion width is nothing but 0.174 plus 1.09. So, one on the emitter and base side, one on the base and the collector side, therefore the total neutral width is this minus this which comes out to be 2.74 micro meters. So, we can essentially calculate the total the width of the depletion regions and also the neutral width on the base side, let us now go to part b.

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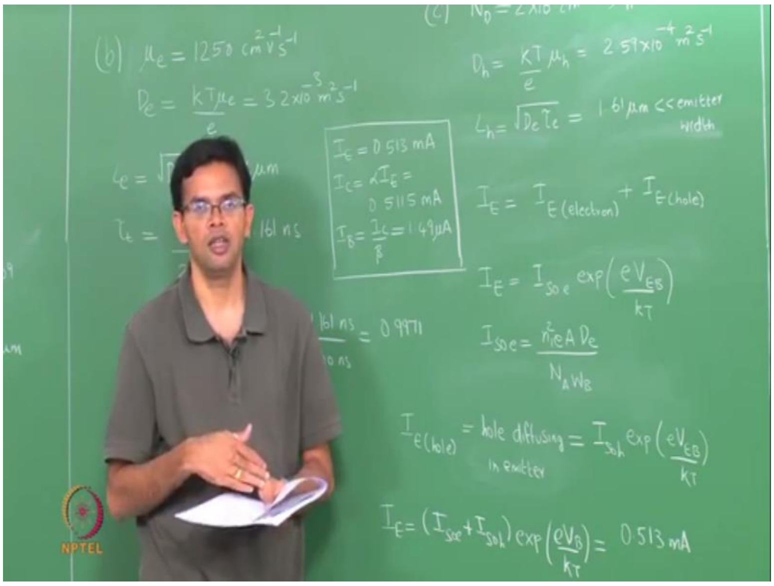

In part b, we want calculate the values of alpha and beta, so the current injection ratio and also the k a current efficiency beta, we going to take unity emitter injection efficiency so that something we looked at in problem 1. So, we follow a similar argument, so electrons are the minority carries, so mew e is 1250 centimeter square volts per second. So, the first thing is to calculate d e k t mew e over e this is 3.2 times 10 to the minus 3 meter square per second.

We can also write this in centimeter square from, which we can calculate a diffusion length d e tau e. So, it is equal to 36 micro meters, so from this we can also calculate the transit time, the transit time is a time it takes for the electron to move through the neutral base region. So, tau t when you saw the expression last time is nothing but w b square over 2 d e.

So, last we wrote it as w b equal to square rout of 2 d times tau just writing in the other way. So, this is the transit time and this has a value 1.161 nanoseconds alpha is then 1 minus tau t over tau e. So, tau t is a transit time tau e is the life time of the electron in the minority a in the base region. So, this is nothing but 1 point 161 nanoseconds by 400 nanoseconds which is equal to 0 point 9971.

So, beta which is your current gain is nothing, but alpha over 1 minus alpha which is equal to 343. In part c, we want to calculate the emitter collector and base currents, so we want to know the values of I e, I b, which is your base current and then I c. So, once again in the case of an emitter region you have n d to be 2 times 10 to the power 28 per centimeter cube that is here doping concentration mu h, which is the mobility of the holes is 100 centimeter square per volts per second. So, the first thing to do is to calculate d h, so d h is k t over e mu h is equal to 2.59 times 10 to the power minus 4 meter square per second.

So, we can calculate the length and this length works out to be 1 point 61 micrometers, so this is much smaller than the emitter width. So, you can basically treat it as a simple p n junction there is essentially in forward bias so that I e which is the emitter current is I e due to the electron flow. So, the electron flow is due to recombination, so the electron flow is due to the carrier injection plus I e, which is the contribution to the whole, which is because of recombination. So, I e which is the electrons that are diffusing from the emitter to the base is just given by I s not for the electrons exponential e v e b over k t.

So, this is similar to the equation for a p n junction in forward bias I s not is nothing but n I square e over a d e over n a w b. So, again all the numbers are essentially known, so we can calculate the value for I e, so I e though whole component is basically the holes that are diffusing into the emitter. So, we can write a similar expression I s naught h exponential e v e b over k t.

In this particular case, I s naught h will have a similar value expect this will have n d and will have d h. So, we can take these 2 components and add them together so that your I e, which is the emitter current I s not e plus I s not h exponential e v b over k t. So, we can substitute all the values all the different components are essentially known. So, I will not do the substitution here, but just write the final answer, so the emitter current is 0.513 milliamps, so let me just write that down here, so else spate a small section make it easier.

So, I e is 0.513 milli amps, so we want to calculate the collector current that is given by alpha. So, I c is nothing but alpha times I e your alpha is value of 0.9971 so that this is 0.5115 milliamps. So, almost all the emitter current is nearly transferred to the collector, small portion of the current is essentially lost in the base due to recombination so that I b is nothing but I c over you current gain beta which is 1.49 micrometers. So, then again just treating your bipolar junction transistor as a series of 2 p junctions, one in forward, one in reverse can essentially go head and calculate all the current and the voltage parameters, let me now move to problem 3.

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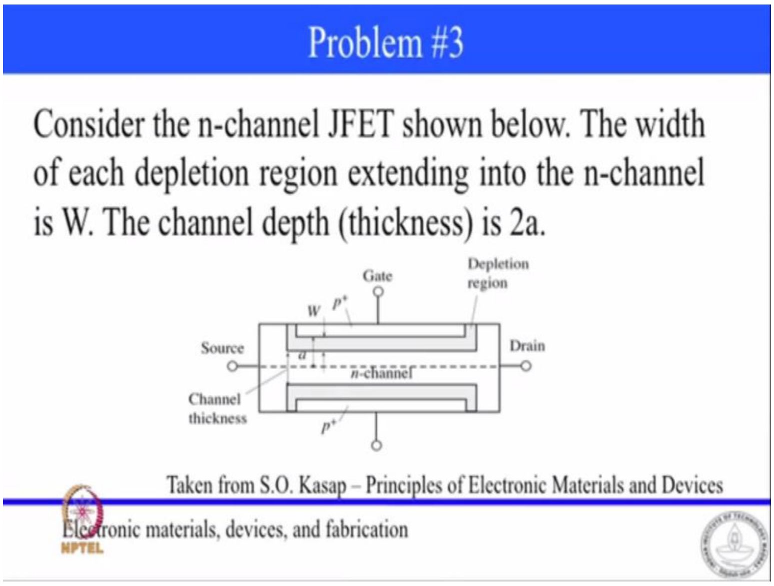

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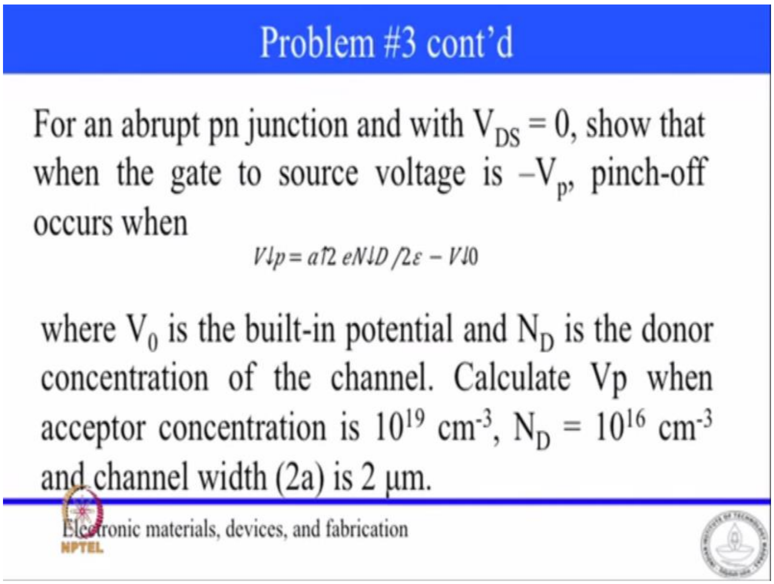

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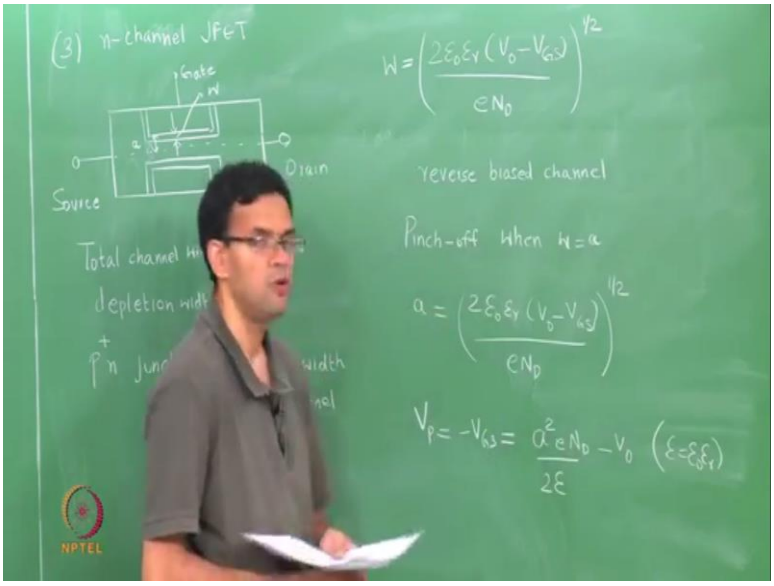

In problem 3 you essentially have a junction field effect transistor. So, you have an n channel JFET. So, let me draw the schematic, so you have a source and you have a drain this is the drain that is my source this is the gate this source the total width of the channel is essentially a.

So, this is a and you also have a certain width of the depletion region so that this is W, so the channel depth is 2 a. So, let me write it, redraw this, so the channel width goes from here to here that is a to the total channel width is 2 a. So, half the channel width is way is a and the depletion width is W, so we want to calculate basically the potential at which pinch of occurs and how this is related to the built in potential and also the doping concentration.

So, basically in the case of a JFET, you have a heavily dope people as a region when we have an n channel so that the width or the depletion width is almost entirely in the channel. So, you have a p plus n junction so that the depletion width is in the channel this again depends upon the reverse bias so that W is nothing but 2 epsilon not epsilon r V naught minus V g s over e times n d whole to the half. So, V g s is actually negative number so that when you do V naught minus V g s are essentially. Adding this is basically a case of a reverse biased channel, so pinch of occurs when this depletion width starts to increase an essentially reaches the center of the channel, so we have pinch of when w is equal to a.

So, a is nothing but 2 epsilon not epsilon r can rest write it as epsilon times v not minus v g s divided by e n d whole to the half. So, this we can basically rearrange so that V p which is minus vg s pinch of voltage, so all I am doing a staking this expression and rearranging is equal to a square e n d by 2 epsilon minus v naught, where epsilon is nothing but epsilon not and epsilon r. So, we can do a simple calculation that relates your pinch of voltage to both the width of the channel and also to concentration of the dopants in the n channel.

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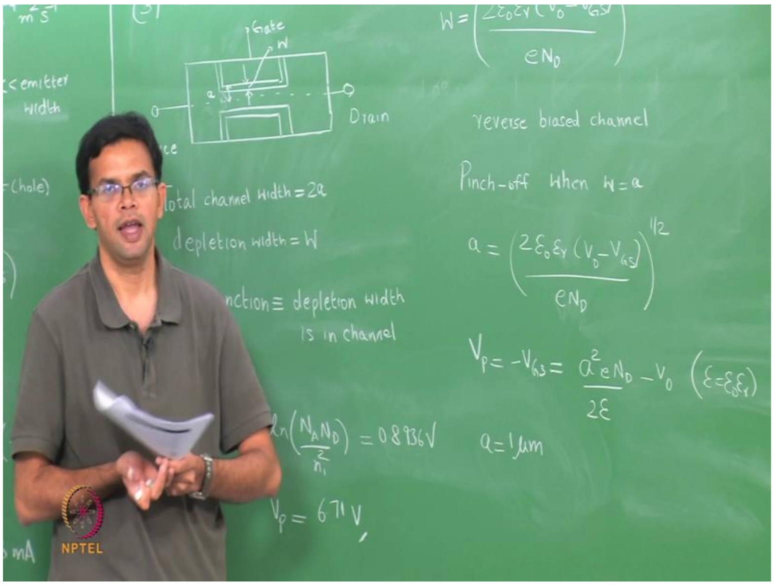

So, for this particular numerical problem, n a and n d are given, so we can essentially calculate v naught V naught is k t over e lone of n a n d over n i square. So, the material silicon, so v naught is 0.8936 volts we need to calculate the pinch of voltage, a is 1 micro meter. So, everything else is known v not is known, a is known from which we can calculate V p to be equal to 6.71 volts. So, this represents the pinch of voltage to essentially close the n channel and basically stop conduction in your JFET, so let us now go to the last problem.

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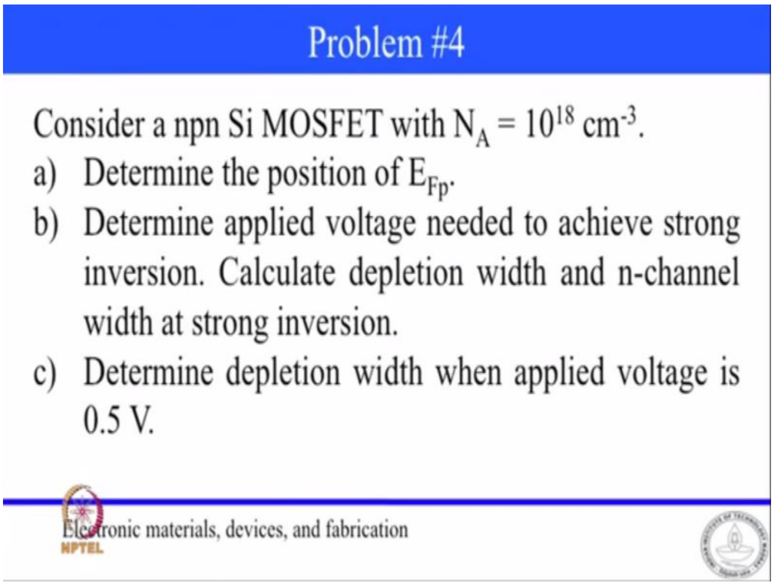

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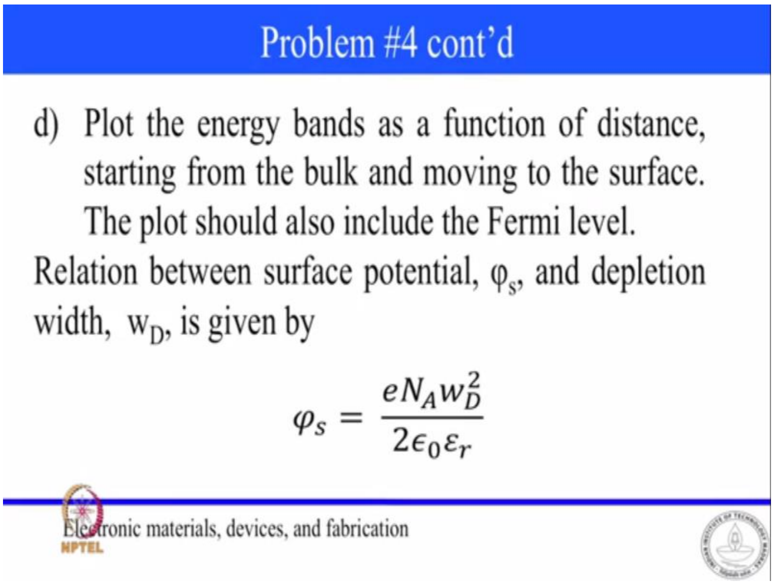

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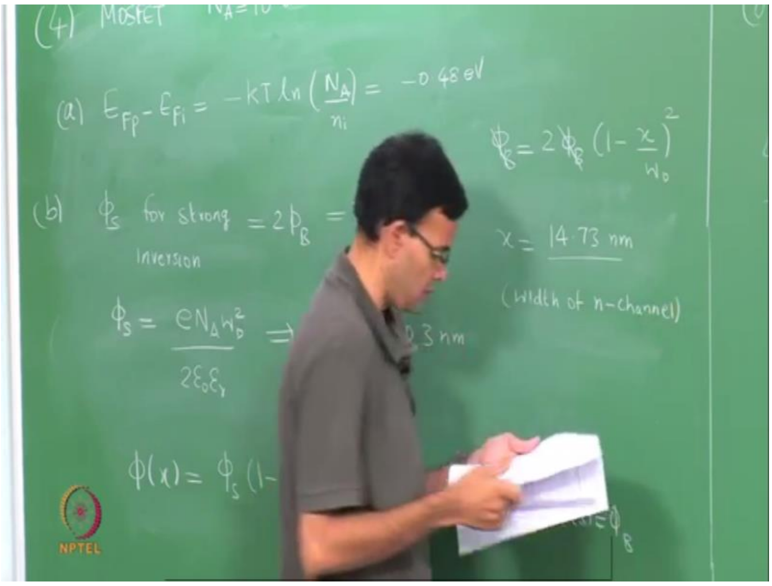

So, problem 4 you have an n p n silicon MOSFET. So, now, you have a MOSFET, so you have trying to create a n channel in a p type material n a is 10 to the power 18 per centimeter cube. We are again take the material to be silicon, so you can use all the silicon parameters, so part a, we need to determine the position of the Fermi level. So, Fermi level position we can just calculate it is a p type dope material, so e f p minus e f i is minus k t lone of n a over n i. So, for silicon n I is 10 to the power 10 n a is known so that e f p minus e f I is essentially minus 0.48 electron volts to the Fermi level is located 0.48 volts below the intrinsic Fermi level, next is part b.

We need to calculate the applied voltage to achieve strong inversion, we also want calculates the width of the depletion region and the width of the n channel a strong inversion. So, strong inversion is defined as basically the voltage at which the channel is as much n type as it is originally p type. So, this occurs when the Fermi energy is 0.48 electron volts above the intrinsic level since originally it was 0.48 electron volts below the intrinsic level.

So, phi s for strong inversion is essentially 2 times phi b, phi b is the bulk potential which is the difference in the Fermi levels in the bulk. So, phi s is 0.96 volts, this width is essentially related to the depletion width and it is given by the formula phi s is equal to e times n a w d square by 2 epsilon not epsilon r.

So, phi s is a surface potential that is equal to 2 times phi b n a is known, everything else is known only thing we do not know is w d which is the depletion width a strong inversion. So, you can substitute all the values an essentially calculate w d w d works out to be 50.3 nanometers. So, the next thing we want to calculate is the width of the n channel to know the width of the n channel we need to know how the potential varies as we go from the surface to the depth. So, in this particular case, this is given by the expression phi of x is equal to phi s which is your surface potential minus 1 over x by w d the whole square. So, w d is the total width of the depletion region in phi of x is the potential at some depth x from the surface.

So, we define the n channel to be in the region where the potential where the potential goes from 2 times 5 b which is the surface potential to 1 times phi b so that now you have a channel which has a higher value of electrons, then holes. If you go deeper, you have a higher concentration of holes than electrons, so we basically calculate x when 5 of s is equal to phi b. So, we can use expression phi b a surface potential 2 times phi b this is something you seen in class 1 minus x over w d the whole square. So, w d is known, so you can calculate the value of x in x is essentially 14.73 nanometers, so this is the width of the n channel.

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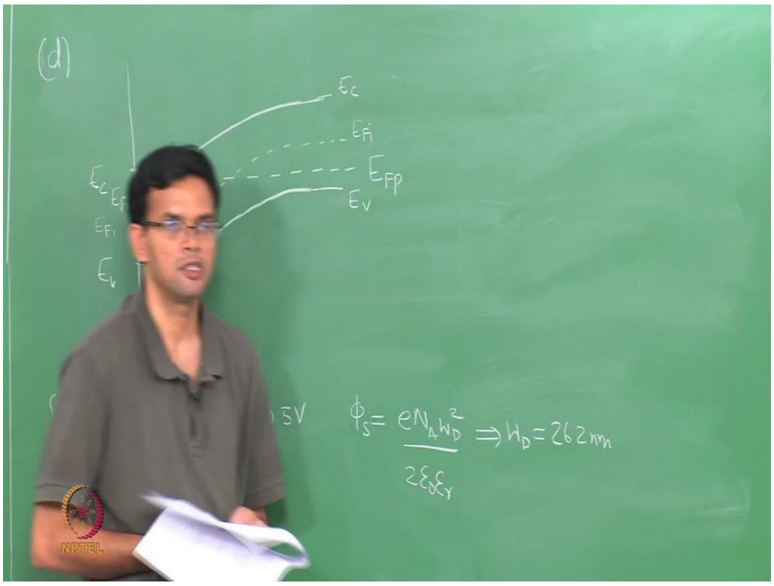

In the last part c, we need to plot the energy bands as a function of distance starting from the bulk and then moving on to the surface. Let me just draw the section corresponding to part d it is the surface at the surface you have an n type material. So, e c e v e f n the Fermi levels should essentially be constant, so within the bulk where we have a p type material, this is essentially e f p this is e v, this is e c can also draw e f I e f I should be at the center e f I.

So, this represents how your band diagram changes as you go from the bulk to the center from the bulk to the surface part c something. So, part c wants to calculate the depletion width when phi 0.5 volts, so once again you have to just use the formula. So, phi s is equal to e n a w d square by 2 epsilon not epsilon r. So, all the numbers are essentially known he only want to calculate the w d, so W d is 26.2 nanometers.