Fundamentals of electronic materials, devices and fabrication
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Assignment – 6
Transistors

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

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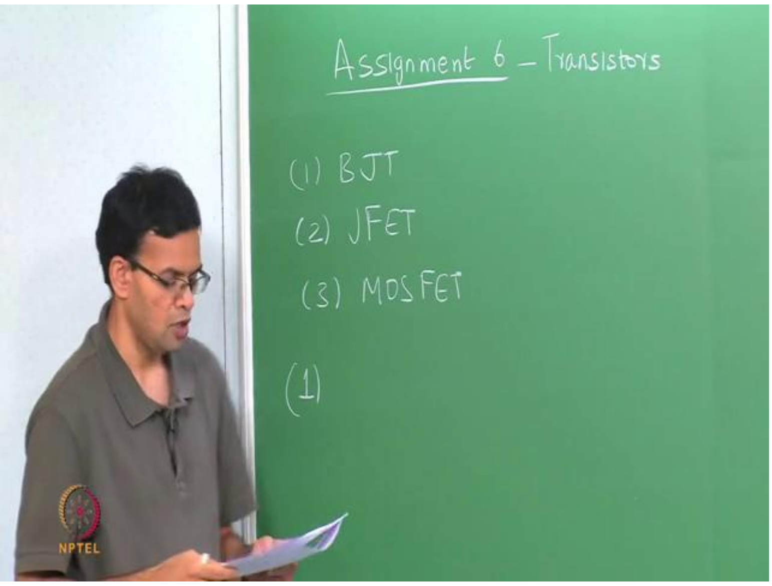

So, this is assignment number 6. We are going to look at numerical problems related to transistors during the course of the lecture, we saw the theory behind the transistor action; we saw that there were three main kinds of transistors that we discussed. One was the bipolar junction transistor or BJT - this is essentially a current control device, it had an emitter base and a collector and transistor action occurred when the minority carriers where injected through the base and 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 holes should be a p-channel and basically the width of a channel and hence, the amount of current that could flow through it was controlled by an external field this is why it was called a field effect transistor.

And then finally, we discussed the MOSFET which was the metal oxide semi conductor field effect transistor. In this particular case, the channel did not exist originally in the device, but was created by applying an electric field so that the channel was found. We looked at the MOSFET slightly in more detail then the other 2 types of transistors, and we did some numerical calculations for the MOSFET as part of the course. So, in today's assignment, we are going look at some of the numerical problems related to all three types of transistors; we have already seen problems related to junctions. So, simple p-n junctions and we can actually treat transistors has essentially having 2 p-n junctions. So, some of the concepts that we learned when we looked at p n junctions we can apply here.

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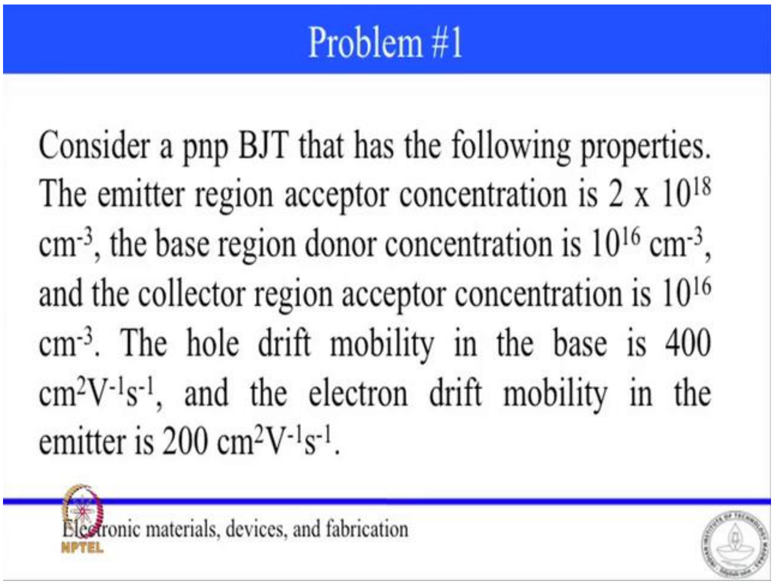

So, let me now go to problem 1.

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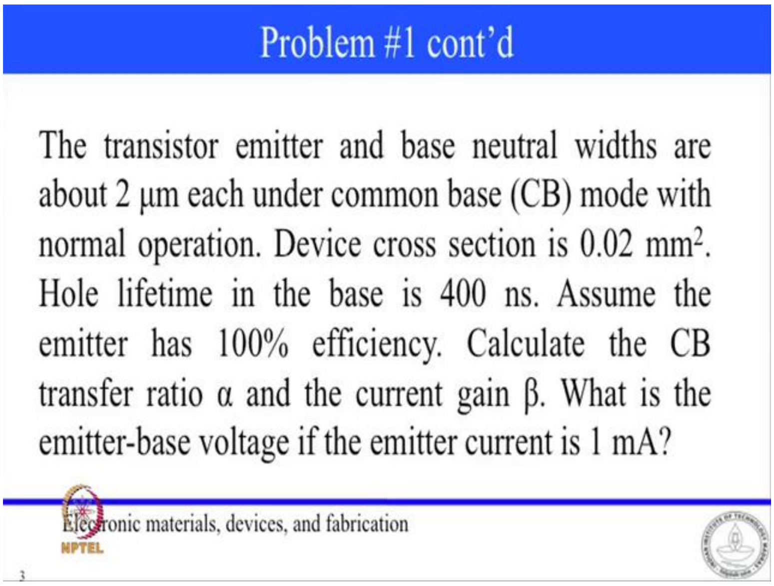

So, in problem 1, we have a pnp BJT. So, we have a pnp Bipolar Junction Transistor.

So, let me just draw this schematic of that. A transistor has essentially three regions; an emitter region, a base and a collector. In the case of a pnp transistor, you have the emitter and the collector to be p-type the base is n-type. So, the concentrations of the different regions are given. So, the emitter region has a concentration of 2×10^{18} cm^{-3}; the base is $10^{16} cm^{-3}$ and the collector is also $10^{16} cm^{-3}$. So, there are different configurations in which a transistor is connected. So, here we are going to look at a connection where we have a common base mode. In this particular case, the emitter base junction is forward biased V_{EB}, and the collector based junction is reversed bias.

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 replenished by the external circuit and that forms the base current. So, this is just a simple schematic of how a pnp or how a bipolar junction transistor works in your common base mode.

So, some of the numbers that are given here says that the whole drift mobility. So, μ_h in the base is $400\ cm^2\ V^{-1}\ s^{-1}$. 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 μm; and the device cross section is also given, so A is 0.02 mm^2. The whole lifetime in the base is 400 nanoseconds that is τ_h is 400 nanoseconds. We want to calculate the common base mode transfer ratio α, which means the amount of current that goes from the emitter to the collector, and also the current gain β. We also want to know what the emitter base voltage is if the emitter current is 1 mA.

So, we look at the mobility of the holes in the base; from the mobility, we can essentially calculate the diffusion coefficient. So, $D_h = \frac{kT\mu_h}{e}$. So, these we have seen before in the context of both of extinguish semiconductors. So, D_h comes out to be 10.36 $cm^2\ s^{-1}$. So, once we know the diffusion coefficient, we also know the width of the base. So, the width is 2 micrometers 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 to go through the base and to go from the emitter to the collector. So, this is assuming simple 2 dimensional diffusion. So, this width is equal to square root 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, you only need the value of t tau. So, 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 in this recombination depends upon the transit time and it also depends upon the whole life time. So, based upon this, we can define a base transport factor.

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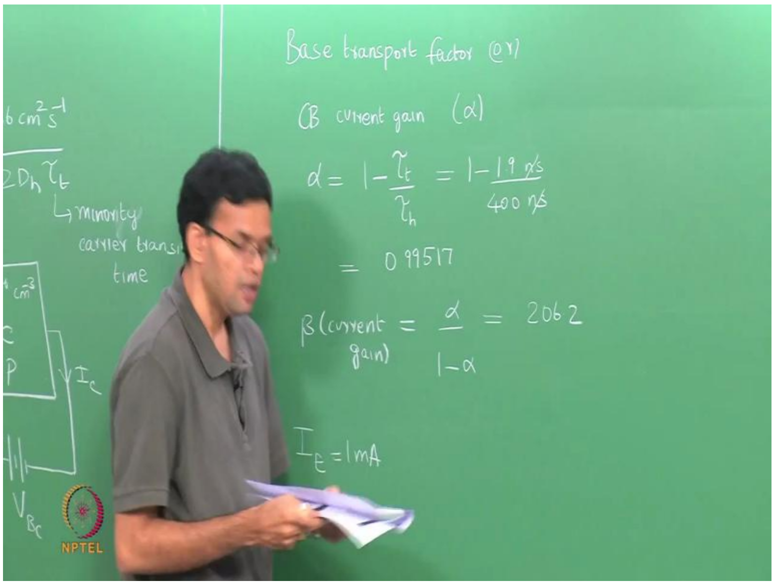

This is also the common base current gain or alpha; the other name for this is the common base, that is alpha and alpha is nothing but 1 minus tau t over tau h. So, all the values are given τ_t is 1.9 nanoseconds τ_h is 400 nanoseconds, so that α comes out to be 0.99517. So, higher the value of α then greater is the 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 τ_h, which is the higher value of your minority carrier lifetime; this again you can do by reducing the doping concentration in the base. So, α is 0.99517.

We also want to calculate the current gain that is beta and this is again given by a formula, beta is defined as $\frac{\alpha}{1-\alpha}$. So, we can substitute in the values, so that β comes out to be 206.2. So, again higher the value of α, we will essentially find for the current gain is also higher. In the last part of the question, we have to calculate the emitter based voltage given that the emitter current is 1 mA. So, I_E is 1 mA. So, if you look in the case of an emitter current, your emitter current is generated because you now have a p-n junction between the emitter and the base, and you basically have minority carriers that are injected across the junction.

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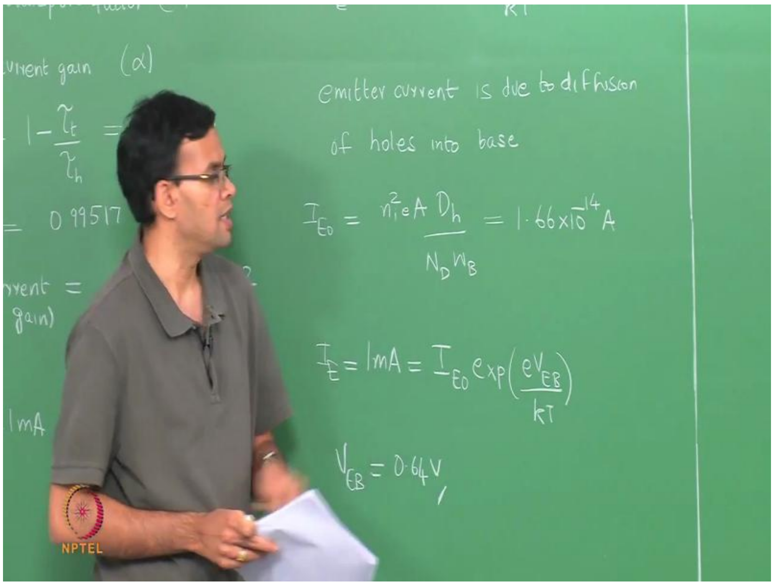

So, I_E is nothing but the current that is generated when a p-n junction is essentially forward biased. So, I_E is $I_{Eo} exp\left(\frac{eV}{kT}\right)$, so that your emitter current is due to diffusion of minority carries. In this particular case, these are holes diffusing into the base, so I_{Eo}. 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 $I_o exp\left(\frac{eV}{kT}\right)$, where is a -1 term, but usually that can be neglected. So, in this particular case, $I_{Eo} = n_i^2 eA \frac{D_h}{N_D W_B}$. So, here N_D which is the concentration of electrons in the base; it is much smaller than N_A, which is the concentration of holes in the emitter. So, since it is one 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 micrometers, so that this is equal to 1.66×10^{-14} A. So, we have the cross sectional area A here, so that the final answer is in amperes; if we did not have A, this will be a current density; so typically A cm^{-2} or A m^{-2}. So, I_{Eb} is known. So, I_E is given to be 1 mA which is equal to I_{EO} $exp(eV_{EB})$ which is the emitter based voltage divided by k T. So, all the terms here are known, except V_{EB}. So, you can rearrange and then V_{EB} is 0.64 volts. So, we essentially looked at p n p bipolar junction in forward biased; we tried to calculate the current gain and also the transfer ratio, and how you can calculate the emitter based voltage for a given value of the current. So, we essentially treat a bipolar junction transistor has made up of two kinds of p-n junctions; one forward biased, the other reversed bias and then we go through this calculations. So, this will be more clear when we look at problem 2.

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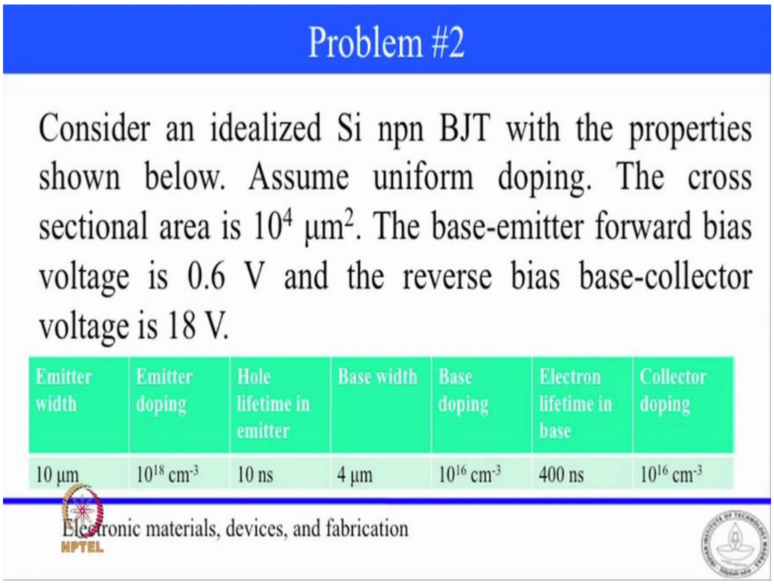

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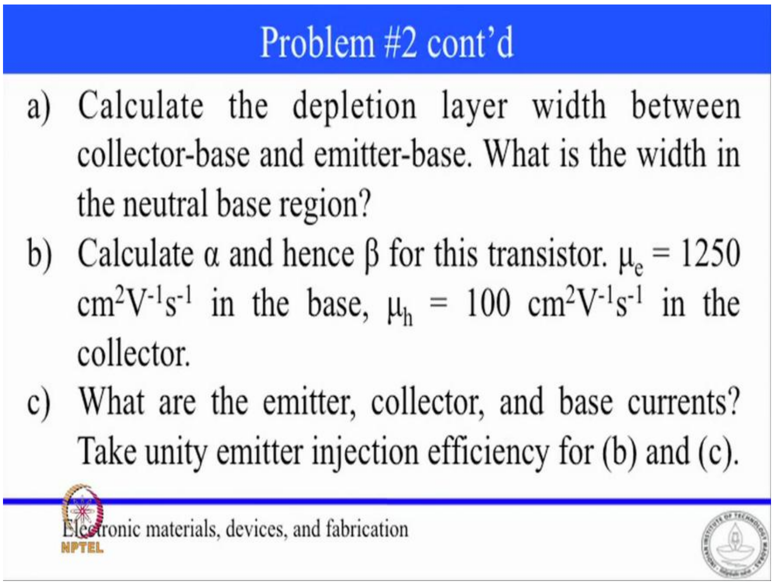

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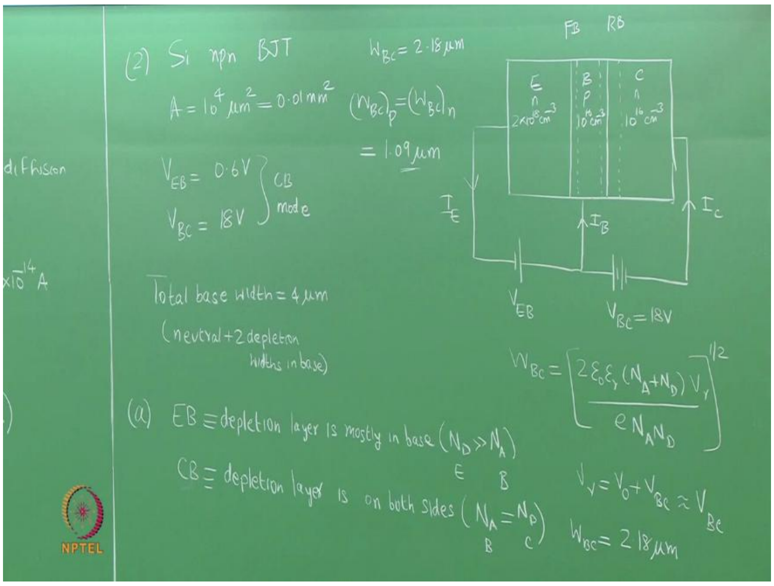

So, in problem-2, we have an idealized silicon n-p-n bipolar junction transistor. So, you have a silicon n-p-n. So, problem-1 was a p-n-p bipolar junction transistor. Now we have an n-p-n. The cross sectional area is given; so A is 10^4 μm^2 . So, micrometers is nothing but 10^{-3} mm^2. So, another way of writing is just 0.01 mm^2. The base emitter forward biased voltage, so V_{EB} is given to be 0.6 volts; and the reversed 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 this schematic for this bipolar junction transistor as well.

So, we have 3 regions and 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 x 10^{18} cm^{-3}; this is a majority carrier concentration then you have 10^{16} cm^{-3}, this is also 10^{16} cm^{-3}. So, this is in your common based mode, so that this is V_{EB}; this is V_{BC}. You can compare this with problem-1, you will essentially see that the polarities are reversed, because now we have an n-p-n, but once again your emitter based junction is forward biased, 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 one p-n junction that is forward biased; this is your forward biased p-n junction. You have another p-n junction that is reversed bias. We can also mark the depletion regions. So, for the emitter based junction, the base is lightly doped while the emitter is heavily doped. So, most of the depletion region will essentially lie in the base. 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 micrometers. 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 2 depletion region widths, and we also want to calculate the width of the neutral base region. So, let us look at the emitter base E_B. 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 we can use the formula; this is the emitter base region; for the collected 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 reversed bias. So, reversed bias tensed to increase the depletion width, so that W_{BC} is given by $\left[\frac{2\varepsilon_o\varepsilon_r(N_A+N_o)V_r}{N_AN_D}\right]^{1/2}$ 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 V_r is not the contact potential, but it is the contact potential + the externally applied reversed bias voltage. So, V_r is nothing but V_o which is your contact potential plus the reversed 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_o. 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_{BC} 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. We can use a similar argument to calculate the depletion width for the emitter-based region.

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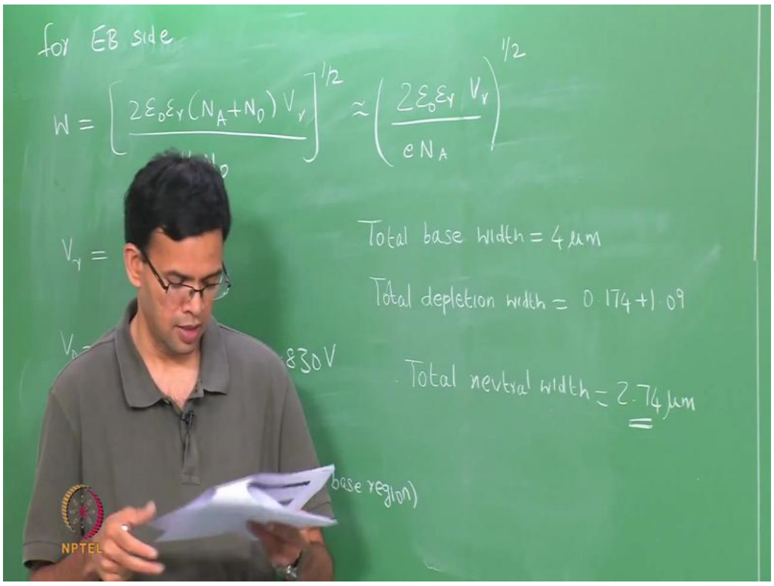

So, for the emitter-base region, so for the E_B side, we can calculate the width. So, once again W is $\left[\frac{2\varepsilon_o\varepsilon_r(N_A+N_o)V_r}{N_A N_D}\right]^{1/2}$. For the base and the collector region, we said that there is reversed bias, so that V_r is nothing but the reversed bias potential plus the built-in potential V_o. Now we have V_r to be equal to the built-in potential V_o - 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 $V_o = \frac{kT}{e}\ln\frac{N_A N_D}{n_i^2}$, 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 $\left[\frac{2\varepsilon_o\varepsilon_r V_r}{N_A e}\right]^{1/2}$ 2 epsilon naught epsilon r V r divided by N A e whole to the half. So, everything else we know V_o is V_o - V_{EB}, 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 0.174 micrometers. So, this is mostly in the base region.

The total base width is 4 micrometers, the total depletion layer width; total depletion width is nothing but 0.174 + 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 micrometers. So, we can essentially calculate the total the width of the depletion regions and also the neutral width on the base side.

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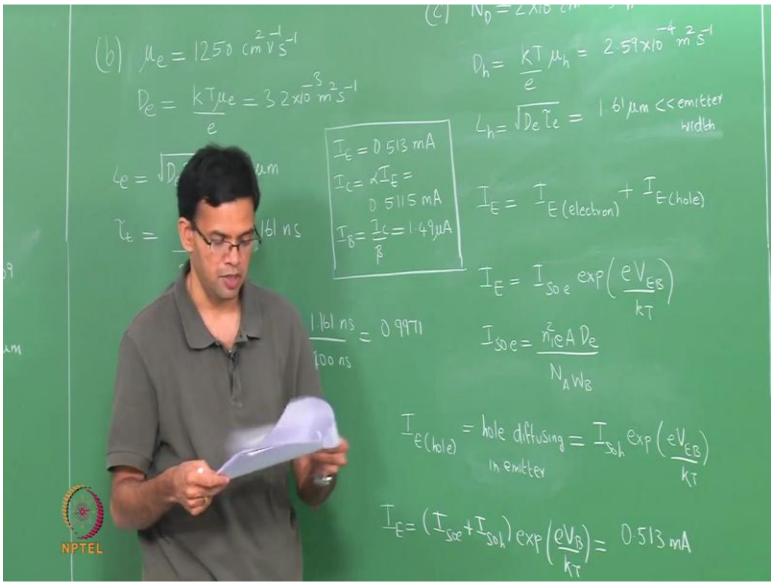

Let us now go to part-b; in part-b, we want to calculate the values of alpha and beta so, the current injection ratio and also the current efficiency β. We going to take unity emitter injection efficiency, so that is something we looked at in problem-1. So, we will follow a similar argument. So, electrons are the minority carriers, so μ_e is 1250 $cm^2\ V^{-1}s^{-1}$. So, the first thing is to calculate $\frac{D_e k T \mu_e}{e}$, this is $3.2 \times 10^{-3} m^2\ s^{-1}$. You can also write this in cm^2; from which, you could calculate a diffusion length $D_e\ \tau_e$. So, it is equal to 36 micrometers. So, from this, we can also calculate the transit time; the transit time is the time it takes for the electron to move through the neutral base region. So, τ_t and we saw the expression last time is nothing but $\frac{W_B^2}{2D_e}$. So, last time we wrote it as $W_B = \sqrt{2D\tau}$, just writing in the other way. So, this is the transit time and this has a value 1.161 nanoseconds.

α is then $\frac{1-\tau_t}{\tau_e}$. So, tau t is the transit time; tau e is the lifetime of the electron in the base region. So, this is nothing but 1.161 nanoseconds by 400 nanoseconds. So, it is equal to 0.9971. So, β which is your current gain is nothing but $\frac{\alpha}{1-\alpha} = 343$. 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 2×10^{28} cm^{-3} that is your doping concentration; mu h which is the mobility of the holes is 100 cm^2 V^{-1} s^{-1}. So, the first thing to do is to calculate D_h. So, $D_h = \frac{kT}{e\mu_h} = 2.59$ and 10^{-4} m^2 s^{-1}. So, we can calculate the length, and this length works out to be 1.61 micrometers. So, this is much smaller than the emitter width. So, you can basically treat it as a simple p-n junction that is essentially in forward biased, 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 hole which is because of recombination.

So, I_E which is the electrons that are defusing from the emitter to the base is just given by I_{SO} for the electrons $exp\frac{eV_{EB}}{kT}$. So, this is similar to the equation for a p-n junction in forward bias. I_{SO} is nothing, but $\frac{n_i^2 eN_De}{N_AW_B}$. So, again all the numbers are essentially known. So, we can calculate the value for I_E. So, I_E the whole component is basically the holes that are defusing into the emitter. So, we can write a similar expression $I_{SOh}exp\left(\frac{eV_{EB}}{kT}\right)$. In this particular case, I_{SOh} will have a similar value except this will have N_D and it will have D_h. So, we can take these components and add them together, so that your I_E which is the emitter current is $(I_{SOe} + I_{SOh})exp\left(\frac{eV_{EB}}{kT}\right)$. So, we can substitute all the values, all the different components are essentially known. So, we will not do the substitution here, but just write the final answer. So, the emitter current is 0.513 mA.

So, let me just write the down here; separate a small section make it easier. So, I_E is 0.513 mA. So, we want to also calculate the collector current that is given by alpha. So, I_C is nothing but $\alpha \times I_E$; here α 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 your current gain beta which is 1.49 micrometers. So, by again just treating your bipolar junction transistor as a series of two p-n junctions - one in forward, one in reverse can essentially go ahead and calculate all the current and the voltage parameters.

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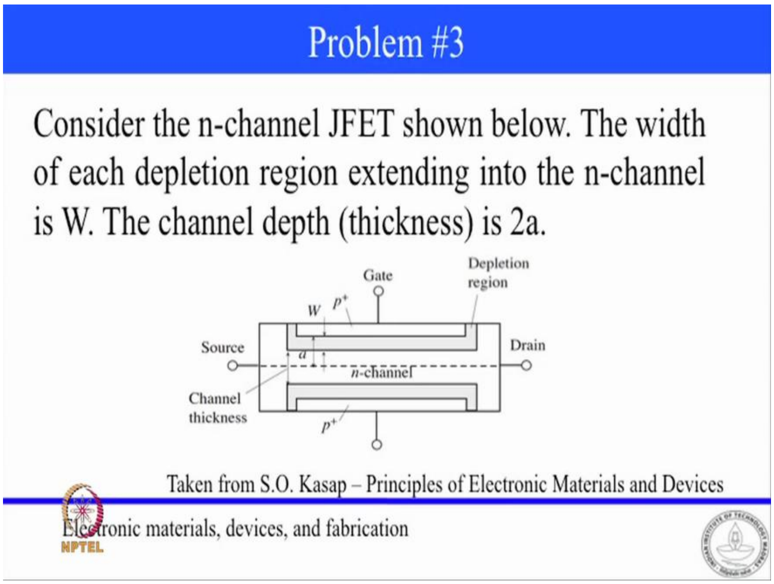

Let me now move to problem-3.

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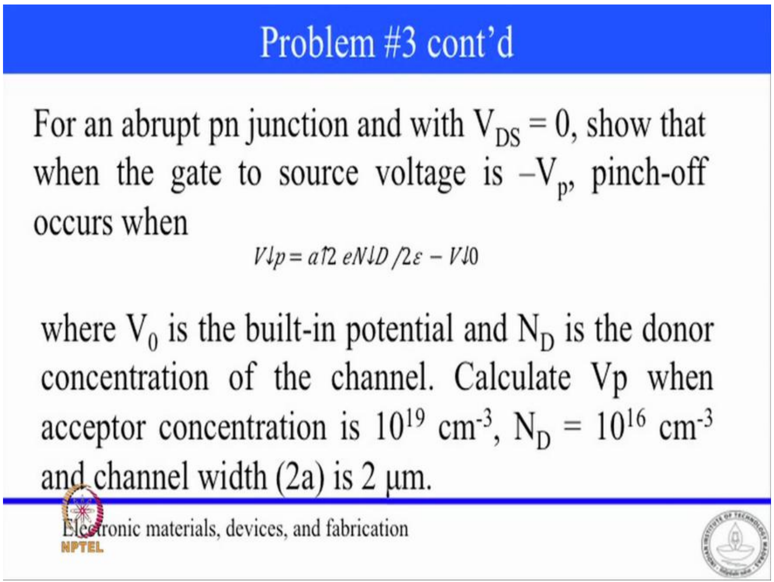

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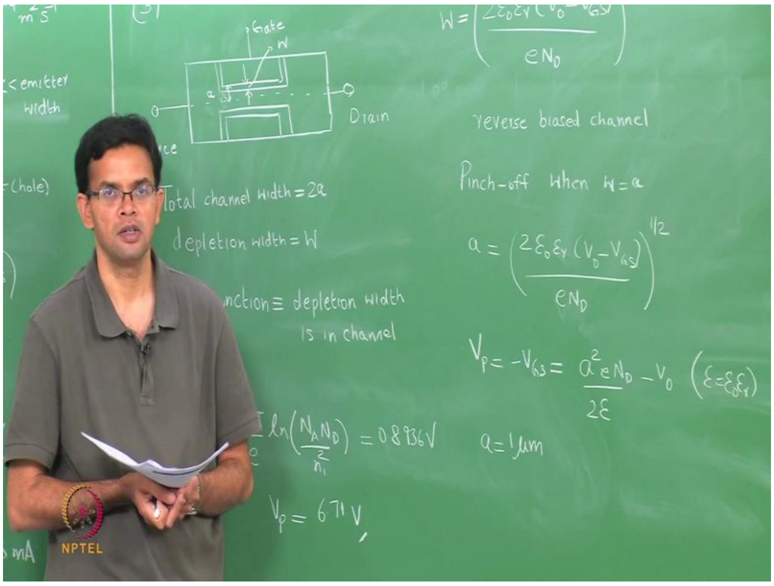

In problem-3, you essentially have a junction field effect transistor. So, you have an n channel JFET. So, let me draw this schematic. So, you have a source, and you have a drain. So, this is the drain that is my source; this is the gate the source. The total width of the channel is essentially a, so 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 just redraw this. So, the channel width goes from here to here and that is a to the total channel width is 2 a. So, half the channel width 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 concentrations.

So, basically in the case of a JFET, you have a heavily doped p + region when you 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 reversed bias, so that W is nothing $\left(\frac{2\varepsilon_o \varepsilon_r (V_o - V_{GS})}{eN_D}\right)^{1/2}$. So, V_{GS} is actually a negative number, so that when we do V_o - V_{GS}, you are essentially adding this is basically a case of a reversed bias channel. So, pinch-off occurs, when this depletion width starts to increase and essentially reaches the center of the channel. So, we have pinch-off, when W is equal to a, so that a is nothing but $2\varepsilon_o \varepsilon_r$ you can just write it as $\varepsilon\sqrt{\left(\frac{V_o - V_{GS}}{eN_D}\right)}$. So, this we can basically rearrange, so that V_p which is $-V_{GS}$ is your pinch-off voltage.

So, all I am doing is taking this expression and rearranging, this equal to a^2 e N_D where 2ε-V_o where ε is nothing but ε_o and ε_r. So, we can do a simple calculation that relates your pinch-off voltage to both the width of the channel and also the concentration of the dopants in the n channel. So, for this particular numerical problem N_A and N_D are given. So, we can essentially calculate V_o; V_o is $\frac{kT}{e}\ln\frac{N_A N_D}{n_i^2}$. So, the material is silicon. So, V_o is 0.8936 volts. We need to calculate the pinch-off voltage; a is 1 micrometer. So, everything else is known; V_o is known, a is known from which we can calculate V_p to be equal to 6.71 volts. So, this represents the pinch-off voltage to essentially close the n channel, and basically stop conduction in your JFET.

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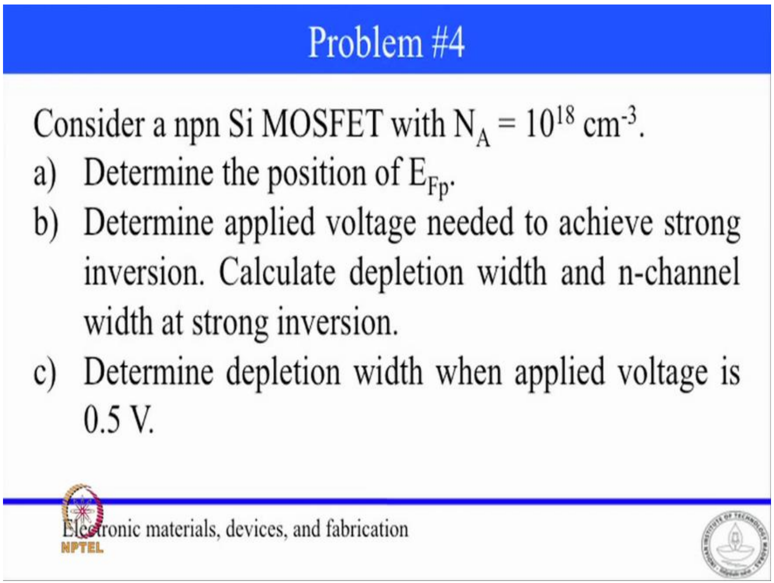

So, let us now go to the last problem.

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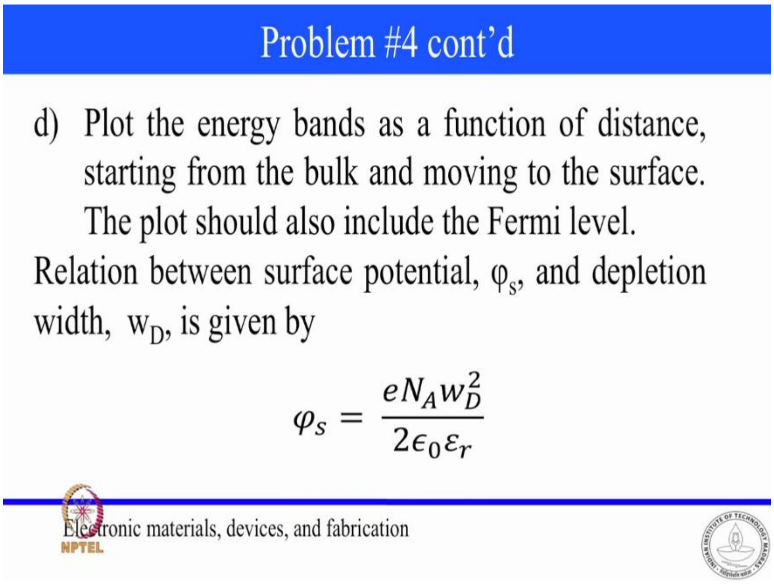

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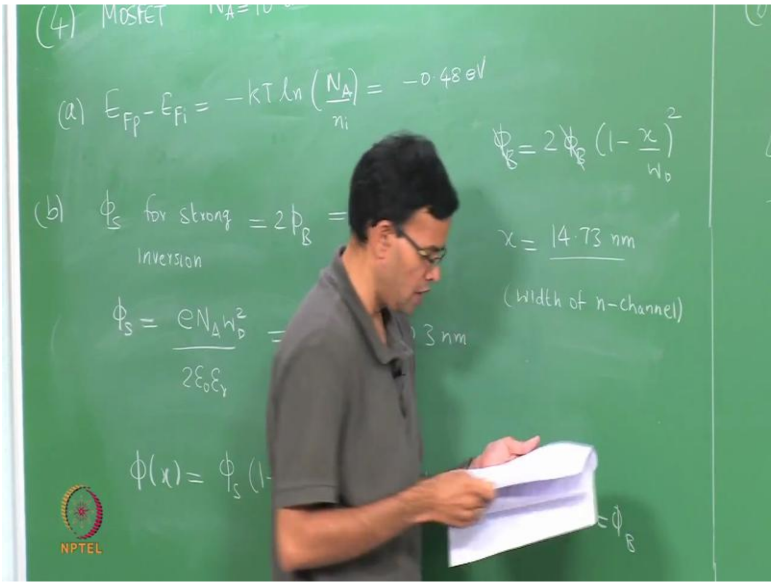

So, problem-4, you have an n-p-n silicon MOSFET. So, now you have a MOSFET. So, you are trying to create an n-channel in a p-type material; N_A is 10^{18} cm^{-3}. We will again take the material to be silicon, so you can use all the silicon parameters. So, part-a, we need to determine the position of the Fermi level. So, Fermi level position, we can just calculate it is a p type dope material. So, E_{Fp} - E_{Fi} is $-kT \ln \frac{N_A}{n_i}$. So, for silicon n_i is 10^{10}, N_A is known, so that E_{Fp} - E_{Fi} is essentially -0.48 electron volts. So, the Fermi 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 to calculate the width of the depletion region, and the width of the n-channel that is strong inversion. So, strong inversion is defined as basically the voltage at which the channel is as much n-type as it does 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, φ_s for strong inversion is essentially two times φ_b φ_b is the bulk potential which is the difference in the Fermi levels in the bulk. So, φ_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 $\frac{eN_A W_D^2}{2\varepsilon_o \varepsilon_r}$. So, φ_s is a surface potential that is equal to $2\varphi_b$; N_A is known, everything else is known. The only thing we do not know is W_D, which is the depletion width at strong inversion. So, you can substitute all the values and essentially calculate W_D; W_D works out to be 50.3 nanometers.

So, the next thing you 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 $\varphi(x) = \varphi_s$ this is your surface potential -1 over x by W_D the whole square. So, W_D is the total width of the depletion region and $\varphi(x)$ is the potential at some depth x from the surface. So, we define the n-channel to be in a region, where the potential goes from two times φ_b which is the surface potential to $1x\varphi_b$, so that now you have a channel which has a higher value of electrons than holes and if we go deeper you have a higher concentration of holes than electrons.

So, we basically calculate x when $\varphi(s) = \varphi_b$. So, we can use expression φ_b, a surface potential is $2\varphi_b$; this is something you have seen in class $\frac{1-x}{W_D}$ the whole square. So, W_D is known. So, you can calculate the value of x, and x is essentially 14.73 nanometers. So, this is the width of the n-channel.

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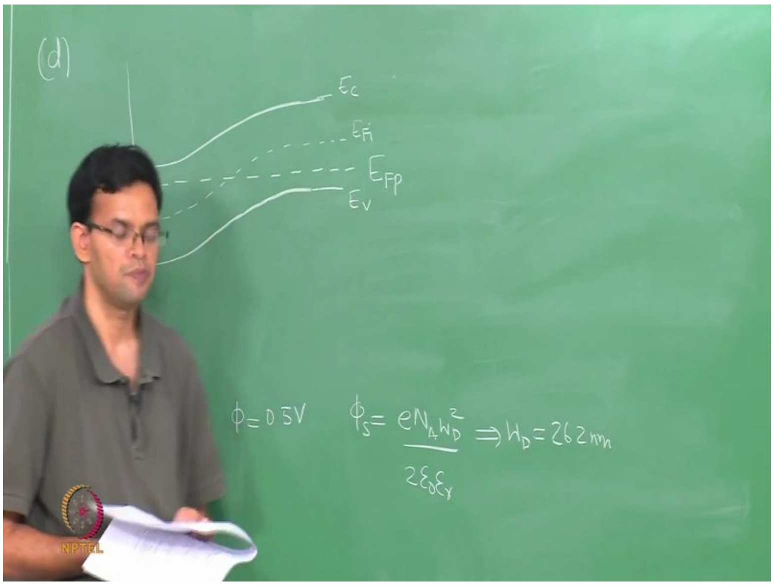

In the last part c, we need to plot the energy bands as a function of distance starting from the bulk and then moving on to the surface. Let me just draw the section corresponding to part-d. This is the surface; at the surface, you have an n-type material, so E_C, E_V, E_{Fn}. The Fermi levels should essentially be constant. So, within the bulk, where you have a p type material this is essentially E_{Fp}, this is E_V, this is E_C. You can also draw E_{Fi}; E_{Fi} should be at the center.

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 is something that I missed. So, part-c wants to calculate the depletion width when φ is 0.5 volts. So, once again, you have to just use the formula. So, $\varphi_s = \frac{eN_A W_D^2}{2\varepsilon_o\varepsilon_r}$. So, all the numbers are essentially known; you only want to calculate W_D. So, W_D is 26.2 nanometers.