Introduction to Semiconductor Devices
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Lecture – 4.4
Depletion Width and Peak Electric Field

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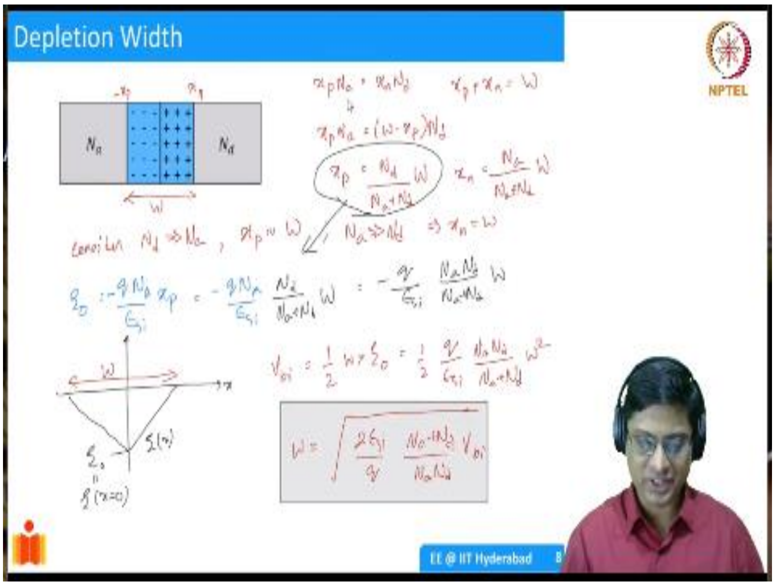

Depletion Width

$x_pN_a = x_nN_d$ $\quad$ $x_p + x_n = W$

$x_pN_a = (W - x_p)N_d$

$x_p = \frac{N_d}{N_a+N_d}W$ $\quad$ $x_n = \frac{N_a}{N_a+N_d}W$

Consider $N_d \gg N_a$, $x_p \approx W$ $\quad$ $N_a \gg N_d \Rightarrow x_n = W$

$\mathcal{E}_0 = -\frac{qN_a}{\epsilon_{si}}x_p = -\frac{qN_a}{\epsilon_{si}}\frac{N_d}{N_a+N_d}W = -\frac{q}{\epsilon_{si}}\frac{N_aN_d}{N_a+N_d}W$

$V_{bi} = \frac{1}{2}W \times \mathcal{E}_0 = \frac{1}{2}\frac{q}{\epsilon_{si}}\frac{N_aN_d}{N_a+N_d}W^2$

$W = \sqrt{\frac{2\epsilon_{si}}{q}\frac{N_a+N_d}{N_aN_d}V_{bi}}$

So, we will see how to calculate built in potentials. And now, we would like to calculate the depletion width, you will see that depletion, which is going to play a critical role in the operation of semiconductor devices. So, what is it? So, to calculate that let us just refresh these definitions for x n, this is going to be minus x p, this is going to be 0. So, I will call the entire region between x p and x n; – xp and xn as width.

And we have already seen that:

$$x_pN_a = x_nN_d$$

$$W = x_p + x_n$$

So, now, we would like to get an estimate for W or calculate the expression for W.

$$x_pN_a = (W - x_p)N_d$$

$$x_p = \frac{N_d}{N_a + N_d} W$$

$$x_n = \frac{N_a}{N_a + N_d} W$$

$$x_p = \sim W; consider\ N_d \gg N_a$$

$$x_n = \sim W; consider\ N_a \gg N_d$$

Let me see, what is the electric field? We derive expression for electric field, the peak electric field, I will call it as E0. E0 is going to be 1. So, remember dE by dx is going to be qNa by epsilon silicon.

$$E0 = -qN_a/\epsilon_{si}$$

So, q N a divided by epsilon silicon and then there is a term which is containing x. In the entire semiconductor, it has to go to 0. So, it was basically xn – x; it was. Now anyway, x = 0, so, it is going to be xn.

$$E0 = -\frac{qN_a}{\epsilon_{si}} x_p$$

$$= -\frac{\frac{qN_a}{\epsilon_{si}} N_d}{N_a + N_d} W$$

And once we know the electric field, we said, we could also derive the built-in potential.

So, if you have x this way and let us say this is V you are plotting. So, this is going to be your electric field correct. So, this is your E of x and we know what this quantity is E 0. This is E 0; this is equal to E at x = 0. And we know by definition, this is your width. So, the area under the electric field was the built-in potential. So, now, what is Vbi(built-in potential) is going to be simply half base into height, area of the triangle.

$$V_{bi} = \frac{1}{2} W E0 = \frac{qN_a N_d}{\epsilon_{si}\ N_a + N_d} W^2$$

$$W = \sqrt{\frac{2\epsilon_{si} N_a + N_d}{q\ N_a N_d}}$$

So, this is; so far we have not applied any voltage, but this expression is going to change when you apply voltage. We will use that to analyse PN junctions. So, this is your depletion width. And I could actually calculate this.

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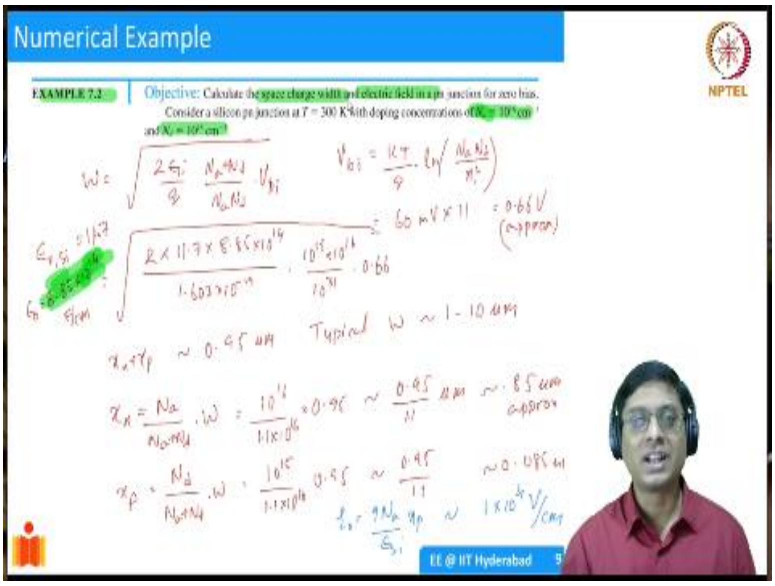

Numerical Example

EXAMPLE 7.2 Objective: Calculate the space charge width and electric field in a pn junction for zero bias.

Consider a silicon pn junction at $T = 300$ K with doping concentrations of $N_a = 10^{[illegible]}$ cm^{-3} and $N_d = 10^{[illegible]}$ cm^{-3}.

$W = \sqrt{\frac{2\epsilon_{si}}{q} \frac{N_a+N_d}{N_aN_d} V_{bi}}$

$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_aN_d}{n_i^2}\right) = 60\,mV \times 11 = 0.66\,V$ (approx)

$\epsilon_{r,Si} = 11.7$

$\epsilon_0 = 8.85 \times 10^{-14}$ F/cm

$= \sqrt{\frac{2 \times 11.7 \times 8.85 \times 10^{-14}}{1.602 \times 10^{-19}} \cdot \frac{10^{15}+10^{16}}{10^{31}} \cdot 0.66}$

$x_n + x_p \sim 0.95\,\mu m$ Typical $W \sim 1-10\,\mu m$

$x_n = \frac{N_a}{N_a+N_d} \cdot W = \frac{10^{16}}{1.1 \times 10^{16}} \times 0.95 \sim \frac{0.95}{11}\,\mu m \sim .85\,\mu m$ approx

$x_p = \frac{N_d}{N_a+N_d} \cdot W = \frac{10^{15}}{1.1 \times 10^{16}}\,0.95 \sim \frac{0.95}{11} \sim 0.085\,\mu m$

$\mathcal{E}_0 = \frac{qN_a}{\epsilon_{si}} x_p \sim 1 \times 10^{4}\,V/cm$

So, I have taken another example from 7.2 that there is a solution in the textbook. You can verify if you have any doubts. So, essentially, you are given basically a semiconductor width Nd Na and asked to calculate the space charge which is essentially W in the electric field. My width of the depletion region:

$$W = \sqrt{\frac{2\epsilon_{si}N_a + N_d}{q\ N_aN_d} V_{bi}}$$

What is V bi?

$$V_{bi} = \frac{kT}{q} \ln\left(\frac{N_aN_d}{n_i^2}\right)$$
$$= \sim 60mV * 11V$$

So, now we got built in voltage, so, we can easily compute. So, I mean, I could leave it to you, but I just want you to note one small thing here. A couple of small things:

- Epsilon silicon is going to be permittivity of silicon that is 11.7
- $\epsilon_o = 8.85 * 10^{14} F/cm^2$

$$W = \sqrt{\frac{2 * 11.7 * 8.85 * 10^{14}.}{1.602 * 10^{-19}} \frac{(10^{15} + 10^{16})}{10^{31}} 0.66}$$
$$= \sim 0.95um$$

Typical w in the range of 1 to 10 micrometres. If you go to high doping, that depletion region will reduce.

And just one final point before I stop, what is; this is the total width of the depletion region. So, this was xn + xp. How much is xn?

$$
\begin{aligned}
x_n &= \frac{N_a}{N_a + N_d} W \\
&= \frac{10^{16}}{1.1 * 10^{16}} * 0.95 \\
&= \sim \frac{0.95}{1.1} um \\
&= \sim 0.85 um
\end{aligned}
$$

E0 simply going to be:

$$
\begin{aligned}
E0 &= \frac{qN_a x_p}{\epsilon_{si}} x_p \\
&= \sim 10^4 V/cm
\end{aligned}
$$

It is not a small electric field. So, because it is only confined to this 1-micron region. Even one volt is going to give you a large field in the depletion region.

So, with that, I think you know, I hope you have got a glimpse of how to analyse PN junctions, the basic electrostatics and how to calculate these quantities, the width of the depletion region, the electric field, the built-in potential for various scenarios. So, please take some time to review this. In the next lecture, I would still continue with the electrostatics PN junction.

And I will take some special type of junctions. I will deal with PN junctions or one-sided rejections, I just briefly explained what they are. And then I talk about PIN junctions. And then I will take a couple of interesting problems. So, that will clarify your concepts. And then finally, I will also take a short demo in the next lecture, wherein I will use a tool on Nanohub to show you how the exact calculations compare with the depletion approximation that we have used in the class.

I also use this you know as a homework and post some problems you have to calculate manually and also compare with the exact answers. So, with that I would like to stop. Thank you very much for your attention and I look forward to seeing you in the next lecture.