Introduction to Semiconductor Devices
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Lecture – 4.6
Demo of PN Junction Lab on Nanohub

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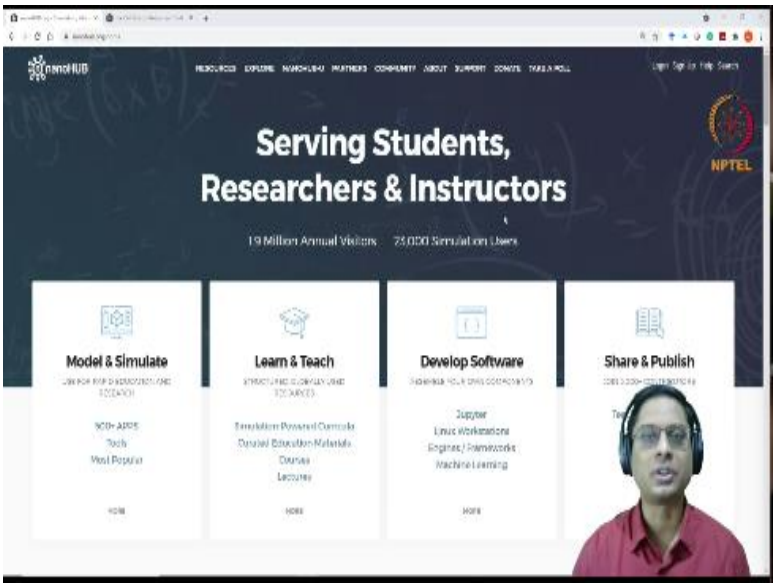

Hello everyone, welcome back. As promised, I would like to give a brief demo of a tool on Nanohub. So, you can go to Nanohub by visiting Nanohub.org. And this is a tool based out of Purdue University in the United States. And it is an excellent platform for learning about semiconductor devices. So, if you go into this website, this is a free website, you can log in, you can sign up using your Google account.

And then you will be able to access a lot of resources. For example, there are like many, many courses and tools. So, it is one of the most extensive collections of resources for nanotechnology and semiconductors and even photonics. So, I wanted to expose you to that.

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And I also wanted to, I know that many of you are really fascinated by computer science and you like programming. And some of you might think that you know, what you are learning in, let us say electromagnetic or semiconductors is not that exciting. But you know, what we are learning in the course is essentially the fundamentals. For example, when we are solving for PN junctions, we simply assume that it is a one dimensional structure.

But you know, what happens if you have a 3 dimensional junction, you know, you will definitely have a 2 dimensional regenerate, it is a 3D N type and 3D P type material. So, the junction will be a 2D interface. So, what happens there? What happens if you have various combinations of doping profiles and things like that? So, the actual physics is going to be very, very complicated.

And that cannot be done by analytical tools that we are developing in the course. The course is essentially intended to give you the fundamentals. After that, you will be able to apply computational resources and then analyse real life problems. So, I just wanted to give you a glimpse of you know, how these things are, of course, we are not going to talk about how to solve them computationally that is the entire subject by itself.

But I will just give you an exposure to what we can do. So, when you log into it, I would like you to locate, as I said, there are many courses and all that you can check it out, especially for people doing research or an advanced graduate students in semiconductors, this would be a good, great resource. But for this course, I would like you to go and locate a tool, you know, go to the tool sections.

When you do that, I want you to locate a tool by name PN junction lab. So, go to P, PN junction. So, here it is. So, there is a PN junction lab. And then there is a new interactive front end, I would still prefer to go with PN junction lab. So, once you go here, so basically, it tells you that this tool enables users to explore and teach basic concepts of PN junctions. So, launch this tool.

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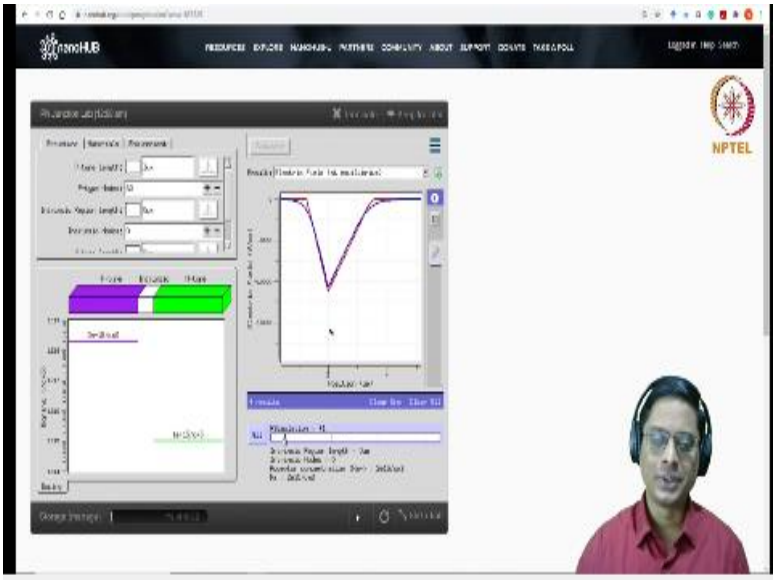

So, to access this, all you need is an internet connection and a desktop. There is nothing else required for this. So, this is how a tool would look like, I will try to zoom it a little bit more. So, this is how the interface looks like. It looks a little clumsy, of course, is not a commercial tool; it is developed by academics in the university. So, you should accept that. And here, you will see that you know, this is a basic interface.

So, you have the structure of the device and the materials tab and then there is environment tab. And there are some instructions about you know what this can do and what these things mean. So, essentially, what is happening is: if you go to structures tab, there is a P type region. So, you can specify a PN junction this way. So, there is a P type region of some length.

Of course, when you solve it numerical, you cannot assume in in finite structure. So, some finite micrometre structure and then there is this entry called as P type nodes. So, essentially, you know, when we are solving differential equations, when we do it on pen and paper, we have analytic functions we can solve. But when we do it numerically, we cannot use that. We have to discretize the differential equation.

For example, the derivative that we have in the basic definition of a derivative is limit of delta x tends to 0 divided by dx. So, essentially you take series of points, numbers, take the difference in the f(x) or f(y) and difference divided by delta x that is how you compute derivative. The same thing is done for all differential equations. So, for that you need to have what is called as a grid and the number of points in the grid is 60.

So, essentially, this P type region is divided into 60 points. And then there is an intrinsic region that you can specify, right now a specify intrinsic length is 0. So, we just want to analyse PN junction. And of course that is my number of intrinsic nodes is also 0. And then you can specify the length of N type as somewhat limited default; right now I will not change much. And then the number of nodes is this much.

So, you see here that the doping of P type region is 2×10^{15} and N type regions, 1×10^{15}. So, the rest of the tabs are essentially, you know, this, you do not need to really worry, I think it is taking time for me to load this today. So, my internet connection is slower I guess. So, you do not need to worry about the life stance for now, leave it. And then the environment also, you can leave it right now.

(Video Starts: 05:49) So, just you leave all the parameters at the default numbers and hit simulate, it takes some time to run a simulation. And here you have the energy band diagram for a PN junction. This is exactly similar to what we have seen. So, here in the diagram, they are taking E_F to be 0 at 0 energy E_V, 0 E_V. And then if you look here, this particular, this is a P type region you know, corresponding to p type, so, 3 microns, you have the distance. So, this is your 3 microns; below 3 microns is all P type region.

So, here you see that distance of E_F from E_V or you could also measure it respect to E_i. So, E_i is at a distance of 0.315. So, 0.32eV from E_F. And similarly in the N type region, you could measure the E_F is basically going to be 0.3eV from E_i. So, essentially the same; we have studied this in the class, so essentially the same band diagram you are getting and you can explore what is the; I mean, there are various parameters that you can check.

But right now, I want you to take a look at let us say, this density of carriers. So, in the P type, you have 2×10^{15} holes. And then as you go across the semiconductor, the hole density is reducing. And here it should be 1×10^{15} for N type region. So, whatever we have seen in the course. And then similarly, for holes, sorry for electrons starting at 10^{15} and then coming down to some number here.

So, you can verify your whatever you calculated. And then net charge density, you could check. So, remember what I said. So, we were using a depletion approximation, by which we mean that; let me go back. I am trying to zoom in here. I do not want all the details. So, we had a depletion approximation, wherein we said that it is rectangular form. We have assumed the charge density to be rectangular.

But I said the real charge density is going to be some sort of a curve like this, this is what I have shown in the class. So, you are having this approximation, depletion approximate and the exact solution. So, how will the charge density look like? How will the electric field look like? If you solve for that, you see, this is the difference. So, the red line is the numerical approximation that we did, the blue light is exact field and you see that the peak is nearly close.

There is not much of difference here, you know, it is 10,500 to 11,000 volt per centimetre. So, it is very, very close to what we expect and then of course, there is some smearing of electric field at the edges because the potential is not sharp, there is some smearing here. That is to be expected. And look at even for potential, electrostatic potential, you see how close it is.

So, the total potential that you have, is supposed to be 0.613. So, you can compute or this was what 1×10^{15}, 2×10^{15}. So, essentially, it will be like 10 times 60 milli-volts roughly. So, 60 milli-volt, 0.6 volts roughly. So, you can cross check these numbers by computing the exact numbers and then see what happens. The point to note is: the potential is exactly equal, there is no change.

So, the depletion approximation is a very good approximation. We do not need to worry about the exact thing if you can ignore; if your physics is not going to; I mean, if you are exactly the interface, the edge of the depletion region is not very important for your device performance,

then depletion approximation is a very good approximation. This is something that you are analyse.

Of course, there are many more things that we can analyse here. I leave it to you and your curiosity and right now what I want to show you is another example that we discussed. We talked about the intrinsic PIN diode. So, you could put the intrinsic region as, let us say, 0.3 microns. So, 300 nanometres intrinsic region, I will put and I also need to increase, let us say, I will put the nodes to be 60. If I put 0, it will not take it. I mean, even though you mentioned 0.3, there are no nodes.

So, you have to split this intrinsic region into discrete values. So, the number of them is 60. I just randomly chose that. So, solve for that. So, that is it. The solution is done. So, let us look at the charge density, net charge density, you see here. So, we have taken the space charge profile as 2 rectangles separated by no charge in between it. So, the intrinsic region, there is no charge.

But in the N type region and P type region, you have similar charges. So, you have a space charge profile like this. And I mean, right now, it is not shown, you could also put the; you can calculate your approximation and then put it here; it will be quite close to this. It will be somewhere here; so, like this and this is here. So, this is interesting. And how about the field? We have calculated the field as well.

So, that was you know, this sort of a function, a flat, there is a linear, flat and then linear. So, I mean, this will become much more apparent if you increase the intrinsic region length. But if you do that, the space charge will come very, very small and it will be difficult to see you, could try it out, you can increase 0.5 and see what happens. And what do you expect with electrostatic potential? This is a built in potential.

So, you see the built in potential now is the same as what you saw in the first case. I can go back to the earlier simulation by taking this arrow. So, this was the first simulation where I had only PN junction, intrinsic region length was 0. And then I see that the electrostatic potential is 0.613. Even if I go for the second simulation, where I have introduced a 0.3 micron intrinsic region, it is still the same. This was what I mentioned to you in the class.

So, think about why it is say. You could, in a way, understand it from the energy band diagrams, draw energy band diagrams for both situations; think about what happens for the; you do not need to worry about the intrinsic when you are trying to band diagrams. So, essentially, what happens is only the Fermi energy in the N and P type region matter; in the intrinsic, it does not really matter.

This, you could also verify by let us say, changing the intrinsic lengths to let us say 0.5, let us explore what happens. I am not sure if it will work. I mean, the field will be fine, the potential will be fine, but the net charge might be too weak for us to see clearly. You see in the background, there is a simulator running; somebody has written a code on how to do it numerically.

So, if some of your interested, I mean down the line of course, not in your under graduation, but later on, you could, this is an interesting direction of study. So, net charge density, net charge is still good. So, you have the positive charge, negative charge separated by depletion by an intensive signature here. And the electric field is the flat top that we mentioned like this linear, flat, linear and then the potential is still the same 0.613.

So, essentially, the intrinsic region is not really changing your electrostatic potential, the built in potential, I mean, we call the built in potential in the course. So, what is interesting here is that even though the built in potential is not changing, the electric field is significantly different. You see here, the shape is one; you also see the magnitude of the electric field, you see that the peak electric field is only 6000 volt per centimetre.

Whereas in the first situation, we had a peak electric 10,000 volt per centimetre. And the second one was 8000 you see. So, as I am increasing my intrinsic region length, I am seeing that the electric field in the intrinsic region is reducing. And it is also sort of expected I would say, but try to convince yourself why it is expected. And it has a lot of implications.

This large intrinsic region with a small electric field is going to have some useful effects when we come to photo detectors. So, before I stop, I would also like you to like to show you what about one side. One side junction was when you have, let us say, one side doping, let us make the P type doping to be. Let us make it 17 or even 18, I do not mind. And you will see if you run the simulation, I am sorry, I should remove the intrinsic but I left for the simulation.

I take my intrinsic region length to be 0. And I am just a pure one sided PN junction. And then I will simulate that. So, this was intrinsic region 1,0, intrinsic 0, acceptor concentration is increased. In the previous case, add my acceptor concentration to be is N_A. So, now increased it. So, let us see what happens. Let us look into the charge density. Well, this is where you know, it becomes difficult, because you see, this is 10^{18}.

And this is 1×10^{15}. So, 3 orders of magnitude becomes very difficult to see in the charge plot. You have to zoom in and try; you could try I mean, I will not try to do it and there are some issues, you have to identify what are the differences, but let us just look at an electric field here. You see, the electric field is now confined to; see the electric field is like this. And the peak is now getting close to 10^{15} here; so, sorry 1500 into, so, 15,000 volt per centimetre.

And on the P side, the electric field is sharply reducing. And there is this sharp spike here. We do not want to get into the details of why this is happening. Because the charge is quite high, there is some interesting things that will happen anyway. Let us not worry about that. Let us focus on this part. This is linear and this is very sharp, because it is a one sided junction.

And if you look at the potential, the built in potential, we do expect it to be larger or smaller. In the previous case, the built in potential was 0.613. Now, you definitely expect it to be larger because the doping has increased on the P side. So, it is now $1 \times 10^{18} \times 10^{15}$. So, this is about 10^{33} divided by 10^{20} so,30×60 milli-volts, roughly that should be it will come out to be 0.719.

So yes, this is what I wanted you to check out. So, we will put a few assignment questions, just asking you to just put in some numbers and read what is the number, you know. For example, if I take an intrinsic semiconductor, PIN diode, what is my electric field? So, you would see that the PIN electric field is this much 8 into we just, you know, something close enough is good. I want you to notice this.

And let us see, if you look at this, of course, it is going to be much larger 10,000. So, nearly difference of 1 by 2 or something. So, we will give you a few questions just to make sure that you, you know, look at this, some very simple ones, you do not have to; it is enough, if you

follow the demo here, the idea is not to teach you this, how to solve this, but just to expose you what is possible? **(Video Ends: 18:44)**

Because now we are still seeing one dimension, but you could also immediately see what happens in you know, 2 dimensions and all that, the same thing will apply. So, if this is something that is interesting to you, you can always take a course on numerical techniques to solve differential equations. And that is a very, very general thing, you know, you will use that in mechanical engineering, I mean, physics everywhere, you know, anytime you say differential equation and you have to use the same techniques.

So, that will be something very useful to you. So, you can try that. So, that will combine your, I mean, if somebody is interested in computer programming. So, it will combine your local programming and also physics. So, I hope you liked it. We will try to come back next week with a few more things about PN junction and a forward bias. We will try to show a demo that as well.

And then, in the mos cap section, also, we will use this tool; at this particular tool, but Nanohub tools will use. Thank you very much. Good luck.