Fundamentals of Semiconductor Devices
Prof. Digbijoy N. Nath
Centre for Nano Science and Engineering
Indian Institute of Science, Bangalore

Lecture – 59
Summary

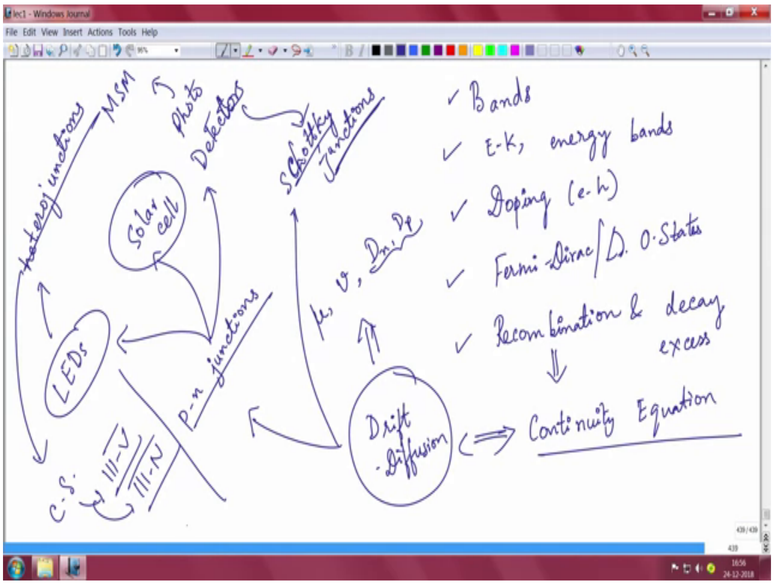
Welcome back. So, today will be the concluding lecture for this course, Fundamentals of Semiconductor Devices. Hope you have been able to understand the basics of semiconductors and semiconductor devices in this course. I tried to make this statement as unique as possible also one try to moderate the speed. For each of the topics that we have studied here we have only covered most of the basics.

There are far more you know things that are that can be learnt in very great details and depth in each of the topic whether it is transistor or LED or even just a p-n junction. There are many things which we did not covered because that will be an advanced course or we have to move very fast which will defeat the purpose of learning in this course right.

So, today we shall have a recap of whatever we have done very quickly and maybe try to see one or two you know unique type of questions are that are also probable in entrance exams what are you should be able to understand your concepts or test your concepts better and then we will conclude ok.

So, we will come to white board.

(Refer Slide Time: 01:31)



So, whatever we have studied in this course is that we have started with semiconductor bands that you now know right. We have studied the E-K diagram, the energy band diagram right energy band diagrams which are very basics, we studied about doping and carrier concentration like electrons and holes right.

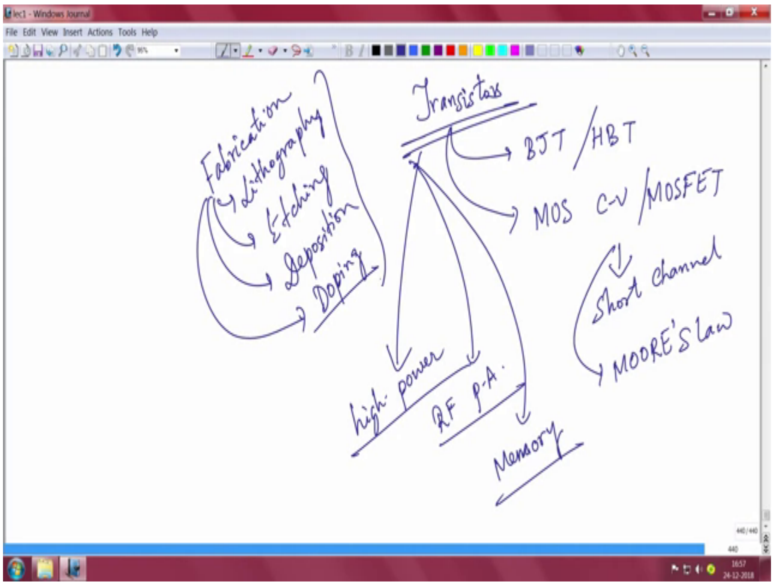
We studied about the Fermi-Dirac statistics to calculate electron hole calculate you know concentrations and a things like density of states density of states right of carriers right, we talked about recombination of carriers how traps might lead to recombination of carriers and decay of excess carriers when you inject excess carriers the decay right.

And, along with that we have studied the continuity equation which we studied which you know gives you sort of the transport equation for carriers in conjunction with things like drift and diffusion. We studied this disc carrier transport equations of drift and diffusion when it happens which of course, depends on things like mobility, carrier velocity, diffusion coefficient and so on right we have discuss that.

And, from there of course, we have the Einstein relation also. We move to basics of p-n junctions; forward bias of p-n junction, reverse bias p-n junction, breakdown and so on, capacitance voltage of p-n junctions work. We also have studied Schottky junctions sorry Schottky junctions that is metal semiconductor contacts how they can form Schottky and Ohmic barriers the I-V relation they also have capacitance and so on. p-n junctions can be also used as LEDs that we have studied in some details; can be also used as solar cells which also we had touch base and also can be used as photodetectors there could be also sorry photodetectors.

Photodetectors can also be from Schottky junctions we have studied; of course, photodetectors can be also in lateral MSM devices and solar cell can be from different other kinds of architectures and materials also. LEDs also depend at a performance depend on heterojunctions. So, there we introduced the concept of compound semiconductors and heterostructures. Compound Semiconductors - CS where I said group III compounds like arsenide phosphide and group III nitrites semiconductor polarization and things like that and transistor. These are some of the things that we have studied.

(Refer Slide Time: 04:03)



We also have studied about transistors. In some details, if you recall we have studied about BJTs and of course, in heterojunctions we have HBT, the advantages that they give, how BJTs work, what is gain. We have studied about MOS capacitance, MOS C-V and MOSFET.

In that MOSFET we had also studied about things like a short channel effects short channel effects and then Moore's law right, how devices are being scale down right and then transistors are used in different applications. I also talked about like the generic cases of high power switching or maybe RF power amplifier right maybe memory devices right.

This may not be in the syllabus of entrance exams, but these are something you should be generally aware of like what are the things needed in a material or in a device to qualify it as a high power switching, transistor or an RF amplifier, what are the figures of merit, what is the you know how do the transistors work as a memory devices and so on.

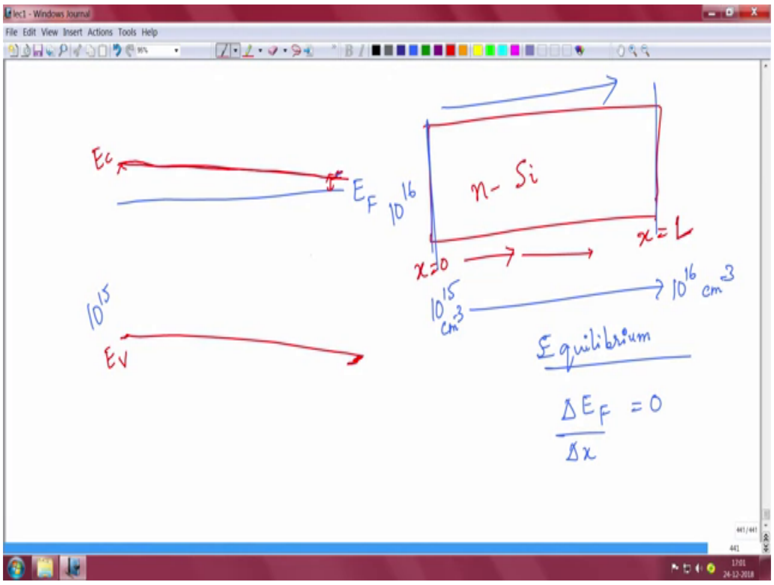
And, finally, I had also talked about little bit on the fabrication of many of these devices in the clean room things like lithography right lithography, etching to make the patterns and decide you know structures in the devices also it talked about deposition like metal deposition, CVD Chemical Vapour Deposition, EV evaporation. Also we talked about things like you know doping like diffusion and ion implantation and so on right.

So, this was in a way in the nutshell the course is all about. As I told you we have touched on the very basics each of doing things can be many you know it can we studied in many details, semiconductor bands and energy band diagram with Kronig-Penney model or you know other things. Many of these things have got an multiple Nobel Prizes where they are very intense actually. Doping is very important.

Even new semiconductors are being synthesized and discovered everyday you know and many layer 2D materials their coming up and up and doping is very important in many of these new materials like if you get a new material how will you what will be they could dopant for it. So, you have to depend on you know material scientists and chemists to tell you that.

So, all these things we have studied in this course and in many of these parts are very important for your gate or net exams many of this parts are important for understanding and to just get an interest for higher studies for doing research or you know sort of thing. So, for example, some of the questions that people give which we have not solved many of the numericals here. But, one of the questions that you know you should be able to think based on the concept that you have learnt.

(Refer Slide Time: 06:37)



Suppose, I tell you that for example and these are these are the questions that might be asked ok. Suppose I take you tell you that I have a piece of silicon which is n-doped and from this is the left side.

So, this is x equal to 0 and this x is equal to L. It is the some piece of semiconductor. I said that I am gradually increasing the doping from 10 to the power 15 to 10 to the power 16 per centimeter cube ok. I am increasing the doping gradually from the left side to the right side I am gradually increasing the doping gradually increasing the doping and it is in equilibrium which means when I say it is in equilibrium, it means there is no current is flowing and that the Fermi level is constant there is no change in Fermi level ok. The Fermi level is constant. The change of Fermi level with respect to distance is constant.

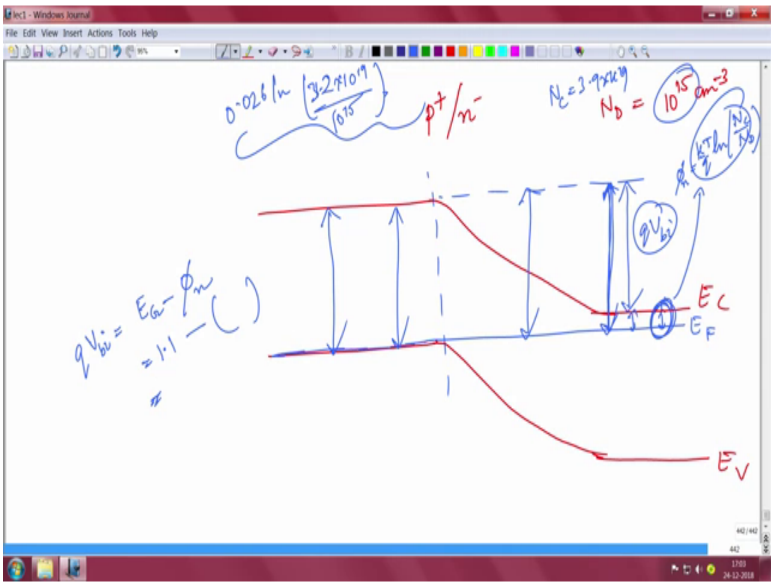
So, how will you draw the band diagram? So, one thing is that the Fermi level has to be constant right. The Fermi level cannot have a slope. How will you draw the energy band diagram of this? So, the Fermi level is constant. So, assume this is Fermi level and this is constant I know that at left side the doping is 10 to the power 15. So, there will be some distance of the conduction band and then this is valence band for example.

Now, on the right side the doping is 10 to the power 16 which means the conduction and Fermi level will become closer. So, conduction band will be here valence band will be probably here right. This spacing this conduction band and Fermi level spacing will become lower because the doping has increased if the doping is lower, then this spacing of conduction and Fermi level will be more you remember that.

But, this is because equilibrium Fermi level cannot change, so, the conduction band has to band essentially ok. Conduction band has to sorry conduction band has to band like this and the valence band also has to band. The band gap of course, is the same everywhere.

So, this is how a band diagram will look like ok. There will an inbuilt feel inside the there will be an inbuilt feel inside it of course, the way in which the bands will band will depend on how is how are you changing the doping; are you changing the doping linearly? Are you changing the doping exponentially, logarithmically and so on? In this case you see conduction band E C is changing linearly which means your doping is changing exponentially. You have to prove that yourself I will not tell you that. So, this is one way. So, this is one you know something that you have to think on your own for example.

(Refer Slide Time: 08:47)



Suppose, you are given a very highly doped ps p plus semiconductor and its junction is n minus lightly doped. For example, p-side is very highly doped extremely highly doped and the doping level is not given. When you say extremely highly doped it means on your p-side, suppose this is your p-side your Fermi level is almost at the valence band. It is very highly doped, that is why it is almost there and n minus is lightly doped.

So, all your depletion will fall only on the n minus side. The depletion will not be under p-side which means if this is your Fermi level it has to be equilibrium everywhere know and then your n minus is very lightly doped. So, it will be like this; conduction band this is valence band. So, all the depletion will drop across this only ok. All the depletion will drop across the all the depletion will drop across the n-type n minus only. It will not drop across the p-side because it is very highly doped.

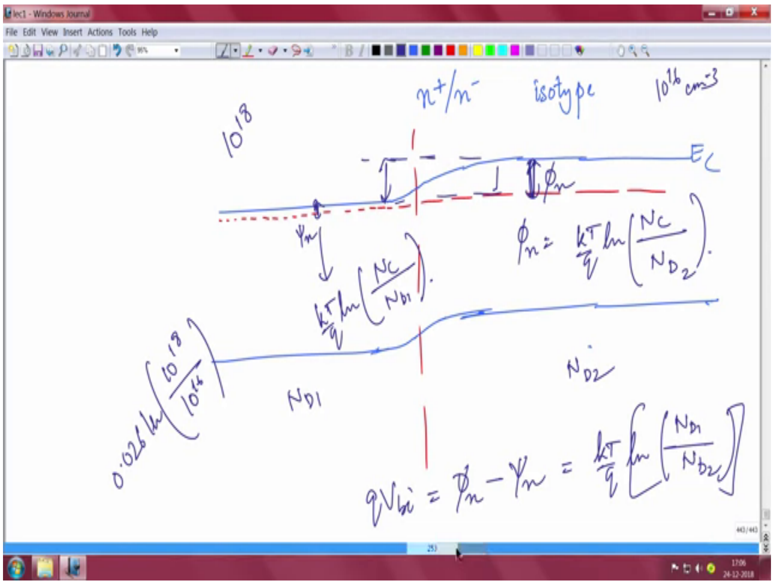
Now, the n-type doping on the n side; suppose, it is given to be 10 to the power 15 per centimeter cube, silicon. How will you find out the built-in potential? So, the built-in potential is this value. So, that value is built-in potential how will you find out that value is nothing, but that is equal to this quantity, if you see very carefully minus this E C minus E F.

So, E C minus E F this quantity if I call that phi n that quantity is nothing, but kT by q ln of N C by N D, do you agree? N C is that conduction band density of states, N D is the doping that is given. So, that value you can find out because this is given and N C for silicon will be given that will be around 3.10 into 9 to the power 19. So, some value will come out here may be 0.2, 0.3 whatever right. So, that value is phi n.

So, your built-in potential this quantity is actually this amount minus the phi n. Now, what is this amount? If you look carefully that amount which is this is actually this which is the band gap of silicon right. So, your built-in potential band gap silicon right. So, built-in potential is equal to actually the band gap of silicon minus phi n. So, band gap of silicon is 1.1 minus whatever this value. You get these value know that is k 0.026 ln of 3.2 into 10 to the power 19 that is your N C divided by 10 to the power 15. Whatever value you get whatever value you get that you subtract here and you will get the built-in potential.

Of course, here I am assuming that because of high doping on the p-side the band gap of silicon has not shrunk because that very high doping the band gap will become slightly lowered that I have not considered ok, but that is [FL]. So, this is how will you find out the build in potential of this very highly doped and p plus n junctions for example.

(Refer Slide Time: 11:27)



Few years back there was a question on gate I think there was an n plus n minus junction these are called isotype junction, homo junction isotype junction because they are the same type. So, you have for example, a very highly doped n plus. So, the Fermi level is very close here and then you have suppose another same material. So, silicon so, same band gap for example,, but you have same band gap, but your Fermi level is little below because you know it is lightly doped.

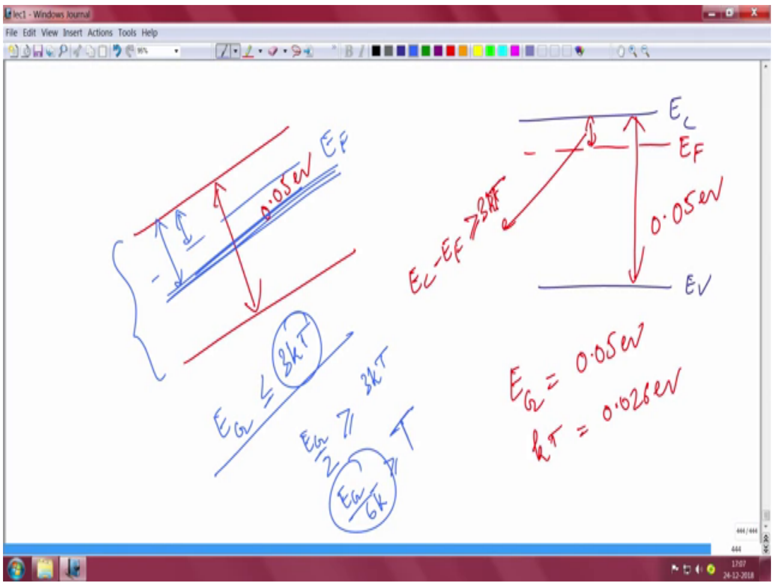
If you join them what will if you join them what will happen? If you join them essentially what will happen is that your band depletion will primarily fall across the lower dope side know. So, what will happen is that, if you join them then your there is a Fermi level right um. So, this is your conduction band, this is your valance band. So, there will be a slight left and then like that right slight most of the depletion will be on n-side.

We cannot call it exactly depletion because you know there is carriers here, it is not depleted per se. It is high it is n-type dope only, but the built-in potential is built-in potential corresponds to this quantity which is nothing, but this quantity minus this quantity. This quantity if I call it phi n and this small quantity if I call it says psi n that if you see my point right this minus this is the built-in potential. So, phi n is nothing, but kT by q ln of sorry N C divided by N D I call it this is N D 2 and this is N D 1. Both are n-typed dope know. One is suppose 10 to the power 18, one is suppose 10 to the power

16 per centimeter cube. So, N D 2 similarly psi n will be equal to kT by q ln of N C by N D 1.

So, the built-in potential is equal to phi of n minus sorry psi of n minus psi of n you see my point right this minus this quantity will give you the built-in potential. So, that will be equal to kT by q right ln of N D 1 by N D 2. So, the doping the ration of the doping on both sides basically will give you that ok. So, that will be you know 0.026 ln of 10 to the power 18 by 10 to the power 16 or whatever that will give you the built-in potential for example. So, these are some mock examples I have told you for you know for example, your p-n junction. Similar questions can be asked in each of the other topics you know.

(Refer Slide Time: 14:05)



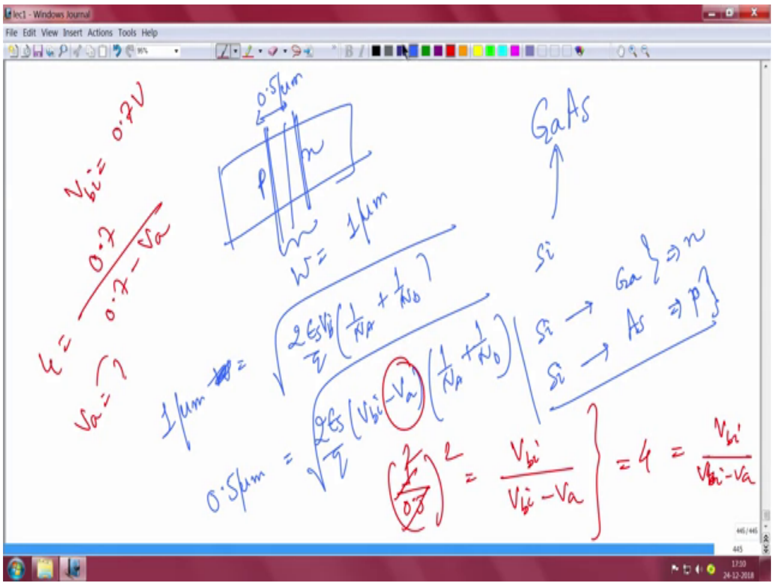
For example, you have learned Maxwell-Boltzmann equation; when you have conduction band, we have valence band and then there is this Fermi level. I told you that Maxwell-Boltzmann holds true when this gap E C minus E F has to be greater than equal to 3 times kT right. So, if I have a band gap of a semiconductor is very small. Suppose, the band gap is 0.05 eV; suppose, the band gap of a material is very small 0.05 eV and the room temperature energy kT is 0.026 eV.

Now, you know if you have a semiconductor whose band gap is 0.05 eV, then does not matter where you have the Fermi level. This will always be less than 3 kT because band gap is itself the band gap is itself less than 3 kT. Now, will Maxwell-Boltzmann distribution equation hold true? No, it will not hold true. At what temperature will it hold true?

At that temperature only when such that 3 kT will become low enough such that a Fermi level can be in a middle of the gap so that you know E G by 2 has to be greater than equal to 3 kT because Fermi level can be at max mid gap away from the conduction of valence band. So, the band gap by 6 k less than equal to temperature. So, from this value we can find out the temperature maybe 50 Kelvin or 40 Kelvin whatever you will get. Below the temperature only you will be able to apply Maxwell-Boltzmann rule.

So, there are many conceptual questions that might come up right. Similar questions might come up in BJT or MOSFET and all that routine questions that come in many entrance exams are not very difficult you know.

(Refer Slide Time: 15:35)



They might give you some very similar questions like for example; in gallium arsenide one of the questions in entrance exam also like gallium arsenide if I dope with silicon. So, what will happened if silicon occupies group 3 sides which is gallium, then it will be n-type ok. If silicon occupies the arsenic sides, which is group 5 side, then it will be p-type. So, those things you should remember for example. Those are simple questions that are given right.

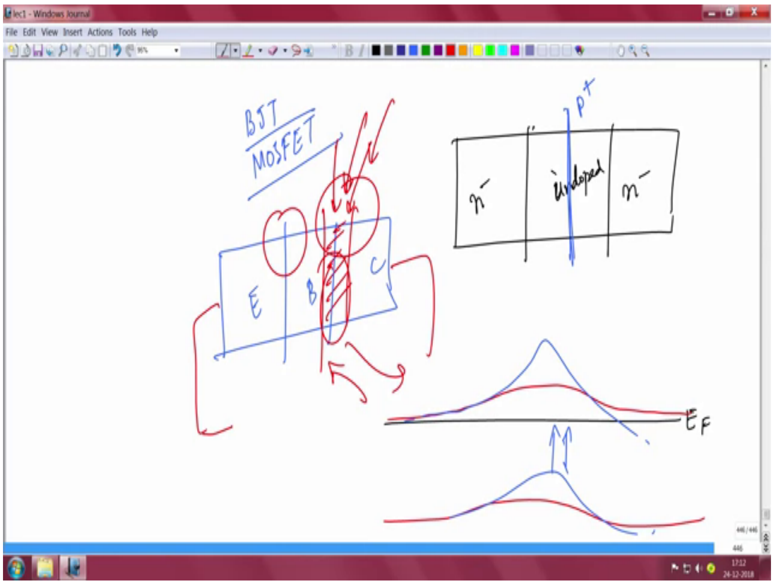
Sometimes they might give you questions k you know I have a p-n junction normal p-n junction I have a normal p-n junction and at zero-bias the depletion width suppose is you know 1 micron; suppose at zero-bias depletion is 1 micron. So, when I say zero-bias then you know I will say that W equal to if you recall 2 epsilon by q V b i built-in potential 1 by N A plus 1 by N B equal to this right. Now, this is 1 micron ok.

So, the question is at what voltage will this depletion becomes smaller and become like say 0.5 micron? At some forward bias forward bias voltage it will become smaller know. So, it will become 0.5 micron at some forward bias voltage, so, 2 epsilon by q V b i minus the forward bias voltage 1 by N A plus 1 by N D. So, if you divide what voltage? You want to find out the question what voltage you have to apply. So, you divide one by the other. So, it will be 1 by 0.5 whole square will be equal to, everything will go cancel out V b i by V b i minus V a.

Now, the built-in potential might be given to you in the question, but if the doping is given you will find out the built-in potential. So, this will be equal to 1 by this is 2; so, 2 square is 4. So, 4 equal to V b i .V b i minus V a. So, if V b i is known say this is given to be 0.7 volt then 4 equal to 0.7, 0.7 minus V a. So, this will come out you can find out V a right you can find solve and find out V a. So, that kind of power voltage is needed. So, these are simple questions based on equations and formula.

But, there can be more conceptual questions you know as I told you something that are not you know generally taught for example, something that is like the grading like if you gradually dope the semiconductor what will happen for example, right. So, those kind of questions are not covered in many of the textbooks. Many of the thinking problems also you know you have to think hard about the situation what will happen if that is the case.

(Refer Slide Time: 17:49)



For example, you know if I have a if I have an n if I have an n minus semiconductor an n minus semiconductor in between is undoped then how will it look like? It slightly doped on both sides. So, the Fermi level if you draw the Fermi level E F then you know it will be like n minus and then there is undoped and then again it will n minus right like that it will be like that.

Suppose, I have a sheet of very highly very very highly doped p plus here how will it look like and that will pull the band up. So, it will pull like that it will pull the band up because the p-type will try to make it the Fermi level come closer to conduction valence band right.

So, those kind of things are conceptual dependent and you should be able to do that ok. So, these in an essence are sort of the things that one should be prepared of and again in the transistors in sort of BJT and MOSFET and so on. There are many equations that I have given you. You can use those equations and solve most of the simple straight forward numericals, but you know many of the questions might need to think for example, you have to think harder in terms of for example, if I have a BJT I told you that I have a ammeter, I have a base and then collector and then base emitter has junction here.

You know the operations of the BJT in a conventional forward active mode. But, there other modes also like reverse mode, there is a saturation mode, there is a cut off mode any kind of textbooks will tell you what it is. We have only discussed about mostly forward active mode which means the emitter base these junction is forward biased and these junction is reverse biased. Both of them can be forward bias, both of them can be reverse bias they have different modes.

But, suppose I shine light on the base emitter junction base collector junction what will happen? There will be photo carriers generated in the base junction. Electrons will go to one side; holes will go to another side what will happen now? What will happen to the base current? What will happen to the collector current? So, that kind of things you have to think and also you know ask questions about it right. So, there are many questions that you can think about and always ask questions. So, the idea is to keep asking questions and trying to see from the basics of semiconductor point of view the device point of view how it will work basically ok, that is in a nutshell the question is.

So, that is all about. So, let us end the last class here. We have given you a summary of whatever we have learnt and the topics that we have discussed in this course. We have also discussed about you know many of the devices and you will see that in the course as we go ahead there will be assignments, there will be also n time exams. Many questions will be slightly different from the questions that you find in many of the entrance exams. Whatever we have learnt in this course you know although not at very advanced level, but hopefully it will be enough to create an interest in you and it will be enough to make you think in the exam, in the assignments ok.

So, so, this was the end of the lecture and also the end of the course we will look forward to interacting with you over the live sessions and assignments exams and so on. Please feel free to e-mail me or e-mail my TAs. There will be three teaching assistants in this course and they will be also very actively involved in answering your questions and clearing your doubts. We are always reachable on e-mail, so, please feel free to do that.

And, so, with that I will end this course as well as also end this particular the last lecture. Although the lectures have ended as I told you I will always be in touch over e-mail and live discussions ok. So, thank you for the time and with that, I will conclude the course ok.

Thank you.