Fundamentals of Semiconductor Devices
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Lecture – 20
Application of p-n junctions

Welcome back. So, if you recall in the last class, we had sort of wrapped up the p n junction details you know, we have studied about the diode current, ideal current of the diode equation and the generation recombination current that becomes important sometimes. We also discussed about how band gaps and other things play a role the minority carrier concentration and so on.

We understand that there are drift and diffusion currents in a p n junction, when you apply bias, the depletion width, the built in potential also change when you apply bias; all these things we have discussed I also told you that many of them devices the LEDs, BJTs, photo detectors and solar cells, they are all based on p n junction.

So, you know I would say that will pause for some time in this lecture and we will try to loγ back it with respect to the basics of p n junction that we have learnt how we can analyze or at least understand some of the devices in very brief.

Of course, there will be more discussions on all these devices in the later part of the course, but today we shall just you know look at the simple p n junction recalling from the last lecture and see how it can enable different kinds of devices, just the basic principles.

So, we will come to the whiteboard here and I will start with the p n junction band diagram again.

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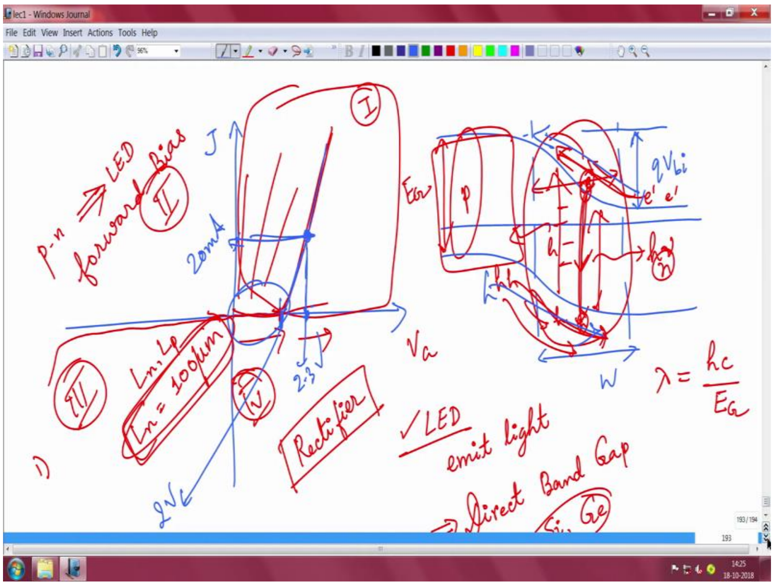

So, if you recall a p n junction in equilibrium you know has it's own depletion length depletion width you can say W and as I told you that if you apply forward or reverse bias, the depletion width can either increase or decrease. The built-in potential that you have here the voltage that you have dropping here, the built-in potential can also increase or decrease depending on whether you are applying forward or reverse bias right.

And if you recall you know the I V characteristics of this p n junction that is the current voltage characteristics look something like that and this is the applied voltage in the forward bias in the positive direction, it will stay like this very low and then it will increase we call this is the cutoff. The reverse bias side it is very small current eventually it breaks down right. So, that is why it is rectifier because it allows current to flow in one direction and does not allow current to flow in the other direction right that is why it is called rectifier.

Now, I had briefly mentioned that how this can be used as an LED which means, how can you emit light from this. Please recall that to emit light or semiconductor needs to be a direct band gap semiconductor which again we have discussed many times.

So, will not come to that again; for example, silicon is not a direct band gap semiconductor, germanium is not a direct band gap semiconductor so, they cannot emit light. And I told you that if this is the band gap of the semiconductor E_g, then the wavelength of light that you can emit is λ (lambda in nm) = hc/E_g. So, that is the wavelength of the light that will be emitted and an LED for a p n junction can behave as an LED a p n junction actually can behave as an LED when you forward bias it, when you forward bias it which means, when you apply a forward bias this is the regime, this is the forward bias regime right on the positive side of the x axis here and that y axis here.

So, when you applied forward bias which means you are injecting electrons from this side to that side, you are injecting holes from this side to that side, in such a case if it is a direct band gap of semiconductor it could emit light. So, what will happen is that when the electrons move here and the holes are moving here, there is a probability that they might recombine band to band and electron and a hole here could recombine band to band, that is called radiative recombination. So, that will emit light. If they are trap states here which recombined with the trap states help in a recombination of electrons and holes that are non-radiative, they do not emit light.

So, light could come out from here, but of course, this is not an efficient LED. Firstly, because number one, the problem done the problem number one if this kind of a simple p n junction is that the electrons and holes might move too fast here, may not get enough time to recombine because there is a time to be recombined you know. And secondly, of course, and that associated with that is that electrons and holes have diffusion length if you recall L_n and L_p. If L n is for example, 100 micron it means every 100-micron, one electron in one hole will be combined.

So, if then this depletion width is typically in the range of 500 nanometer micron. So, if every 100 micron which means it is a very large distance, one electron and one hole recombined; that means, one photon will come out that is not I mean that there is no light from there right, you need the large number of electrons and holes to combine like 10^{15}, 10^{16}, it is not going to happen in this. So, you know this is a limitation of the depletion of length problem. So, you want the electrons and holes to sort of be confined in this area. So, stay more time there so that they can get more time to recombine and emit light.

So, how you do that, we shall discuss when you come up with LED chapter you know hetero junction and compounds semiconductor. But in general, it is possible that electrons and holes that are crossing here in a direct band gap semiconductor would be able to recombine radiatively and emit some light. Another problem, this is not a good

LED is that when the light is emitted from here you see the band gap of this side and n p side or n side is the same as band gap of this region where you are emitting light. So, this region will be essentially absorbing the photons.

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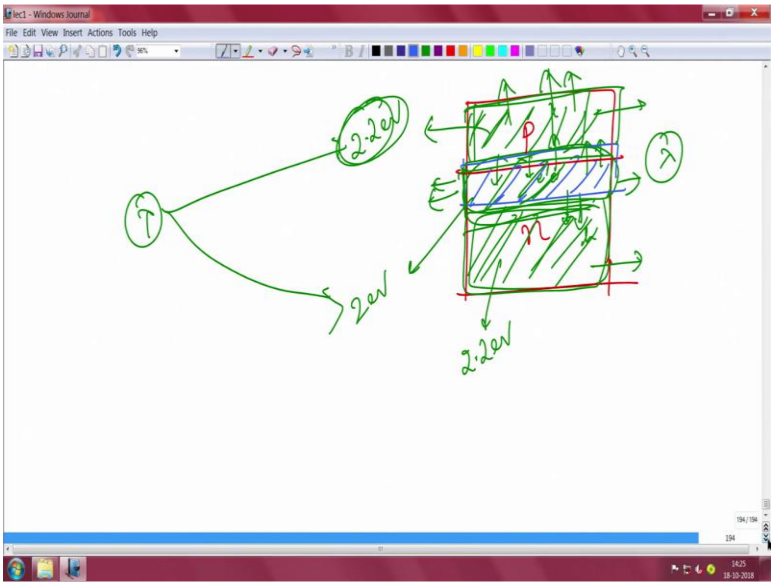

So, what I mean is that, because they have the same band gap no, so what I mean is that if I take you know structure like this. So, for example, I have a p type layer and then I have a n type layer, in between I have a depletion layer, in between I have a depletion layer, this is the depletion layer, but the band gap is everywhere same. So, when electrons and holes recombine in depletion region here, you know they emit light, they emit light; emitted light cannot come out here I mean they will all get absorbed here actually. This area has the same band gap as this area. So, the wavelength of light that is emitted will be corresponding to the band gap here also right.

So, then this will absorb the photon, this will also absorb the photon top down. So, the photons will get absorbed and will very small fraction could come out. Of course, it can come out to the side, but that is a very tiny, you know fraction that might come out here. So, essentially it will not be efficient LED because this will absorb it out. So, the solution of course, you know is to have this region and this region of slightly wider band gap, then this region.

Because if your band gap of this, you know depletion region suppose this region. Depletion region has a band gap of say 2 eV; the photon that is emitted will be absorbed here if the p and n region also have 2 eV. But if I make the p region 2.2 eV for example, and n region 2.2 eV slightly larger, than the photon will not be absorbed because a photon that corresponds to 2 eV will have a lower energy than 2.2 eV. So, it will not be absorbed by 2.2 eV it will come out very nicely.

So, that is a solution we shall discuss all this when we discuss the chapter of LED later. But please be advised that you know p n junction can behave like an LED and it is operated at the forward bias which means that you have your turn on volt is very important. So, you are your p n junction is operated in this regime this regime in the, it is called the first quadrant, this is called a second quadrant, this is called a third quadrant, and this is called a fourth quadrant of a p n junction I V.

So, p LED is operating in the first quadrant here because and in this regime, in this regime you will not get any light because the current is very low you will get light here you know here. So, you want to operate on the LED to operate here. So, for example, if the turn on voltage is 2 V, you want to operate maybe at 2.2 or 2.3 V slightly above the operation the turn on voltage so that you will get some current. So, you get 20 milli Amp of current.

So, you want that current to flow electrons will go to the p side holes will come to the n side. So, that current is flowing here and is giving some light. So, it will emit, and it will be some brightness. So, that is how LED is operated in the forward bias junction. The same concept of a p n junction this is the same p n concept of a p n junction.

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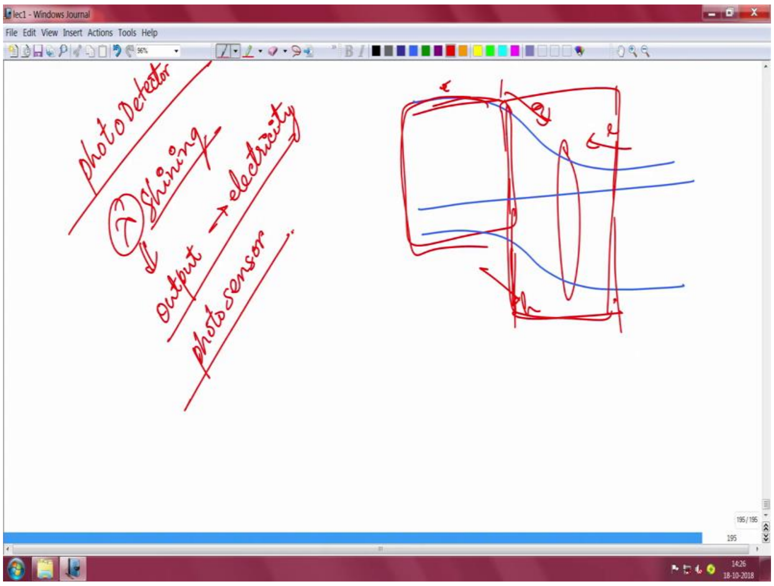

See the p n junction everything you know the most important things happen in the depletion region, only I told you the electrons and holes must recombine here. If they recombine here, they cannot I mean they are crossing over this point no, the electrons are going here and holes are going here, so they recombine here.

They will not recombine here, I mean they will all diffuse and they will get absorbed here their recombination is only important in the depletion region, the recombination is important only in the depletion region here you will emit light. Now, the same structure can be used also as a photo detector. What happens in a photo detector? A photo detector basically detects light. So, you are shining a light of a wavelength on a sample and you expect that there should be current, you are shining the light of a is the reverse of LED.

So, you are shining a light of a wavelength and you expect the output to be electricity or output to be a very small current. So, essentially by shining light you are getting current. So, it is a sense it is a sensor, it is like a photo sensor that is called photo detector. So, in a semiconductor-based photo sensor photo detector what will happen is that, you know if I lo into same structure again here is the same thing.

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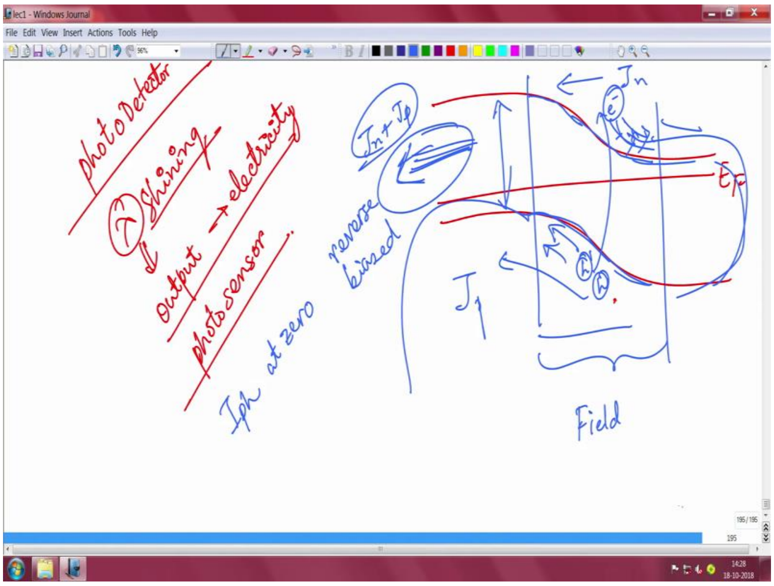

So, if we have the Fermi level and then you have this p n junction here, you are shining light suppose in this region, the depletion region there is a field here you know that there is a field here because the I have been telling you that many times that there is a slope in the conduction band.

So, it means that there is a field here that is slope in the valence band, there is a field here. If you shine light in this region, but photons that are absorbed will be able to excite electron from the valence band to the conduction band, leaving behind a hole here right, so that one photon will basically release one electron hole pair. So, if you have many photons, you will also generate a large number of electron hole pair, large number of electron hole pair will be generated. So, it depends on the intensity of the light if you have a very high intensity of course, you will have many photons that are bombarding this here.

And send each photon will basically excite if it is 100 percent efficient it will excite one electron hole pair. So, one electron hole pair we created. So, what will happen is that because there is already an in-built field here the electron will be quickly swept here to this side and the hole will be quickly swept here to this side because the field will assist in that movement and because of that there will be current here. The electrons will come out here; the holes will come out here; electrons going this side means the current is flowing this side because of electron holes going this side means the current is flowing this side in the electron in the device.

So, effectively, all the current is actually because of hole in electron when light is shining will go to the left side here and this is the reverse direction of the ideal diode current in forward bias equation. This is the direction of the current when this device is reverse biased is the same direction if you recall in a negative side right. So, essentially in a p n junction you do not even have to bias the device.

If you just keep it like this and you shine light of any wavelength, not any wavelength the wavelength has to correspond to the band gap of the material, then you are going to get some light a current out and that current is the photo current I call it I_{photo}. At 0 bias, you will not get any you know any current otherwise, but here if you shine light you might get some current, it is called the photo current at 0 bias, but typically photo detectors are operated in the third quadrant which is if you recall again the IV here.

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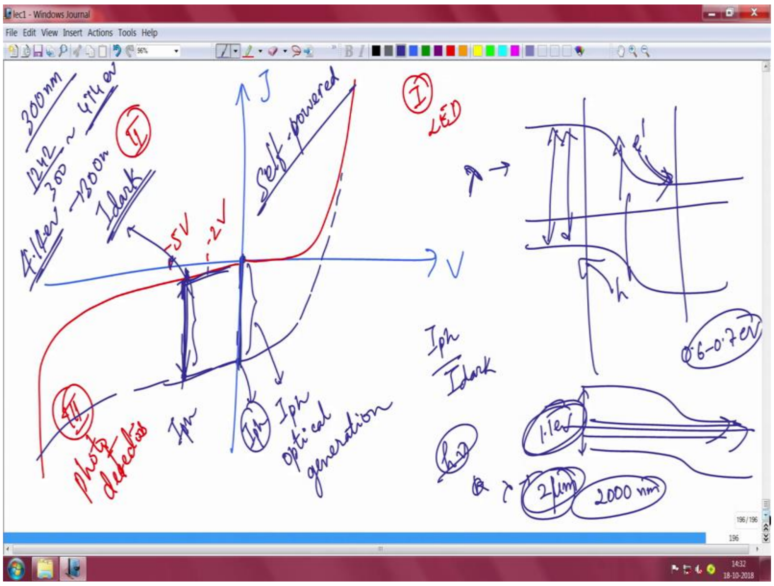

You know if I recall this is the p n junction IV, so that is why I am saying p n junction, I Vs are so important.

Because many of the devices can be analyzed here, this is your forward bias, this is your reverse bias. So, this is the first quadrant were LED is operated, second quadrant nothing happens, there is no characteristics. This is the third quadrant for a photo detector are operated, photo detectors are operated. Essentially, although you can you do not have to apply any voltage, but you people typically apply very small voltage like say -5 to -2 V and then you basically shine light.

So, even if you do not apply any voltage, this is 0 V right. When you shine light, what will happen is that when you shine light, what will happen is that this curve will shift like this. This extra current that is coming here no this is called photo current; this comes because of optical generation of carrier this comes because of optical generation of carriers in the depletion region right. So, I keep telling you.

So, in this depletion region you are shining light your electrons will come this side, holes that are produced electricity it will produce electron hole pairs; electron will come this side, holes will come that side. There is a electricity, there is a small current even at 0 bias, this is 0 bias, this point is 0 bias.

And still there you will get some current; this current value is called the photo current. This is the photo current that you are getting and you, but you slightly bias it negative. So, of course, you are operating in the third quadrant here, so essentially you are going to get this is the current that is at minus 5 V you are getting. This is I photon photo current and this is the current that you are getting without shining light at minus 5 volt. For example, this is minus 5 V, that is called dark current, that is called dark current and the dark current is basically that the current of the diode when you are not shinning any light.

So, at minus 5 V typically you will have a very less current no because that is a diode reverse saturation current plus the generation current when you shine light you have a lot of optical generation of carriers that are swept away the field. So, the current increases right. So, that is why this is called dark current this is the photo current. You want this ratio of the photo current to dark current to be very large right so that, there is a lot of you know light, there is a lot of sensitivity to light. If it is not large; that means, that it is not a very sensitive detector right.

So, essentially p n junction can behave as a detector that is what it means right. And of course, the light that you are shining you know it must be absorbed for it has to be for it to be absorbed the band gap of the semiconductor has to be the same as the energy of the photon. So, for example, in a even a silicon can be detected for example, if am using a silicon photo detector and silicon band gap is 1.11 eV, if am shining a light whose photons you know, whose photons are said 2 micron then 2 micron actually or 2000 nanometer, that is the wavelength of the photon.

If you lo at the energy, the energy of the photon will be very less. It might be 0.6 or 0.7 maybe eV (electron volts) which is less than the silicon band gap. So, they will pass through it, they will not get absorbed. So, to get absorbed you need to shine a light whose band whose photon wavelength is such that the energy of the photon is equal to a more than the band gap of the semiconductor.

So, it depends on the semiconductor that you are trying to see. For example, if you want to detect an ultraviolet light of say at 300 nanometer which is an ultra violet light, you need to have a band gap of the material as 1 2 4 2 I have given you this formula 3 hundred roughly 4.14 eV basically right. So, you need a material a band gap around 4.14 eV to essentially absorb a light of 300 nanometer.

So, photo detectors are typically operated at slight reverse bias although they can operate at 0 bias. If they operate at 0 bias, it is called self-powered. It is called self-powered for the detector because you are not applying any voltage it is a self-powered voltage detector, but it is a p n junction eventually right. Now, actual photo detectors will have more design rules and more of the sophistications coming which, but essentially a p n junction can be a photo detector and it is very important to know. Similarly, a photo a p n junction can also behave like a solar cell. Now, you know all over the world solar energy is becoming very cheap.

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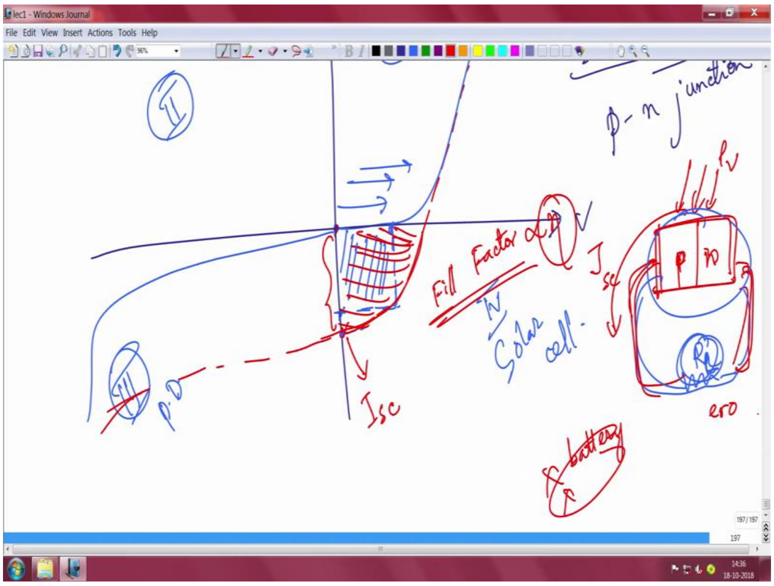

And solar energy and solar cells are becoming you know the latest trend, I mean everywhere the government is trying to have solar cell, you know how a solar cell works a solar cell also a sort of a p n junction only. Although there could be more you know design variations like it could be p plus n junction or n plus p junction. Those are there to increase the efficiency and other things but typically it is a solar cell is a p n junction only. And remember and again, I will talk about the I V characteristics of p n junction diode, it is so important that every time it keeps coming here and here.

So, this is your I V characteristics right and this is the first quadrant where LED by work again for LED, it must be direct band gap material. So, silicon cannot be an LED; nothing happens in second quadrant, then the third quadrant you have, you use it as a photo detector P D. Of course, you can use it as a 0 voltage also and a solar cell is used at the fourth quadrant, this is a solar cell quadrant. In solar cell, what happens is that, when you shine light of course, I told you your curve shifts like this.

So, at even at 0 bias, you have a finite current here, which I call photo current in a photo detector, but the same thing same thing exactly is called the short circuit current. In a solar cell context, it is called short circuit because the voltage is 0. So, if you are taking a solar cell, if you are taking a solar cell essentially it is 0 voltage. So, it is short both p n side are short. So, that is called short circuit current, you are not applying any voltage, but the moment you are shining light if you do not shine light and you have connect a p n junction like this it over you are not going to get any current it will be giving you a 0 current.

Because there is no voltage nothing and it is there is no bias that you are applying right. The moment you shine light here, the moment you shine light here, same thing will happen you know if you recall the if you recall the diagram here, you know electron hole pairs will be generated if you shine light if you shine light this electron. Of course, it has to be absorbed, so the band gap materials has to be such that you know it is absorbed and then it will be electron will drift this side holes will drift this side that will give you a current even at 0 voltage, that is what is happening here.

So, even if you apply, do not apply the voltage. Once you shine light electrons and holes will travel and there will be net current that is flowing and that is current is called the short circuit current here, that is the current you are getting here.

And remember a solar cell you know you cannot have a battery or an external power source in a solar cell because the solar cell has to behave like a battery a solar cell has to give electricity to the remote areas to anybody, you know you cannot expect if you distribute solar cells among in remote areas. You cannot ask the people to also get a battery and then apply voltage to the solar cell that is not that is meaningless right. The solar cell has itself has to be like a power source, it must behave like a battery only.

So, when you shine light it generates electricity without any voltage without any requirement of any voltage or anything and it gives you this current right. That is your short circuit current here. Now, you might ask that that is almost the same thing as a photo detector that is true, but we do not go into the reverse bias we just keep it without only bias, but you know you want to deliver power to something. So, for example, if you have a solar cell like this, you want it to deliver power somewhere right.

So, you know it is solar cell like this, then you want to deliver power to some load ;I am putting as a load resistor, this could be a electric fan, this could be a TV or you know a bulb or whatever this is the load to which you are delivering the power. The moment you deliver power to the load, I mean there is the electricity that is going to the load, this will be self-bias automatically. So, it will basically come in this side of the x axis or y axis. So, it will be self-biased and then because it is here. So, it will be self-biased somewhere here.

So, basically you are going to get this much current in real operation, this is the real current, this is the real voltage it is self-biased. And this area will be divided by this whole area of this red curve here , it is sort of the something called a fill factor will not discuss it right now, but this is very important because that corresponds to the efficiency of the solar cell , how efficient the solar cell is right, but anyways the essential idea is that there is a solar cell is also actually basically a p n junction only .

It is a p n junction only, there can be variations like the p side doping can be high n side doping can be less and so on p plus n the many things are there, but essentially a solar cell could be a p n junction only. And one important thing is here of course, is that in a solar cell, in a photo detector, you know in a photo detector you can detect, you can choose to detect any light.

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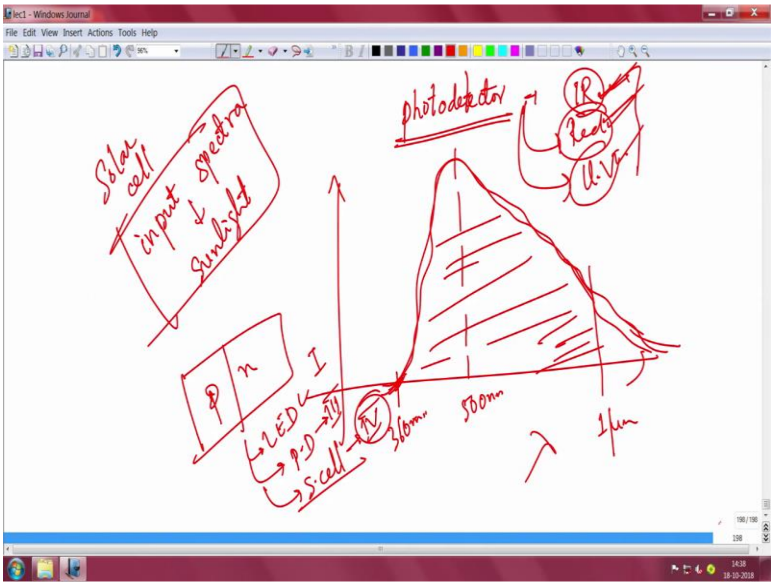

A photo detector one important thing is that you might want to have a photo detector that detects only say infrared or that detects say red or that detects a ultra violet so on so forth.

So, the band gap of the photo detector can be made such that it will only correspond to I R or it will only correspond to U V only correspond to red and so on because the input the input light. whether it is U V or I R or near blue or blue whatever that depends you know, it can change. But in a solar cells, it cannot change, in solar cell the input spectra is fixed, why the input spectra is fixed because the sunlight is the input spectra and the sunlight has a particular wavelength distribution and that is corresponding to the blackbody radiation of the sun and that is not going to change.

So, no matter what material you take you cannot change the input spectra and so your material choice must be dictated by these input spectra. So, the if you plot the energy of the sun, you know per unit area. For example, and over wavelength, it is λ, then it will have something like this you know. It is a black body basically, it peaks at around 500 nanometer or 550 nanometers, cuts off around 360 nanometer or so, there is no very little light below 360 nm.

So, and UR rays nothing like most of the light is invisible and then here I think it is like 1 or 1.5 micron and so on, less light is then I R. So, most of the light is here invisible and near I R, near I R. Of course, so you want the solar cell such that this spectrum is absorbed that are maximum essentially, that is what you want. So, those are the things we will discuss when you come to solar cell photo detector LED chapters, we will discuss that in the course. Here we are not concerned with the, we just wanted to show that are simple p n junction, a simple p n junction can behave as an LED can behave as a photo detector, can behave as a solar cell.

And they operate this is in the first quadrant, this in the third quadrant, this in the fourth quadrant of the of the p n junction.

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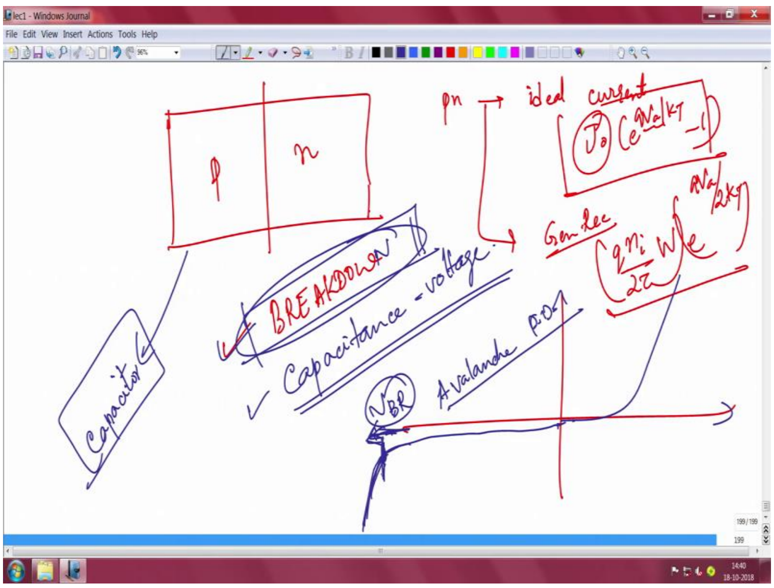

So, if p n junction is a very powerful concept and just because we do not forget everything that we are studying till now a p n junction has an ideal diode equation, an ideal diode current. An ideal diode current which goes as J_0*e($^{qVa/kT}$-1) that is what we had studied this the reverse situation kind, this the voltage we are applying.

But it also has a generation recombination current, the generation recombination current arises because of trap assisted recombination and other things in the depletion region. It goes as ($qn_i/2\tau$) *W e($^{qVa/2kT}$), this is the generation current and the recombination current will be this by this 2kT minus.

So, this is your generation recombination current this is the ideal diode current. So, both must be added together, and you know there is a diff diffusion component is happening, that is why we could not get this current, we had solved the equation. Now, most of the things of p n junction have now been covered. So, what remains now in p n junction before we go to more you know further topics is that a p n junction can break down, it is something called breakdown I have been referring to it every now and then, that you know if you have a p n junction.

For example, have a p n junction here and then in a forward bias current rises in the reverse bias the current is very low and eventually it breaks down I say. So, what is this breakdown it is happening at some breakdown voltage here right V_{BR} I call it. So, some breakdown happens here and break down, what is this breakdown and when does it happen? So, that is an important thing that we need to understand, there is one thing that is remaining. And the second thing that is remaining is capacitance voltage profiling, capacitance voltage profiling.

So, a p n junction is like a capacitor also actually, it is like a capacitor only. So, from the capacitor behavior of the p n junction a lot of information about the doping and other things can be extracted. So, capacitance voltage is a powerful tool to measure you know the properties of a p n junction and breakdown is a process or a phenomenon where device or diode breaks down.

So, what happens at breakdown why does breakdown happen, all these things some are something that we should be aware of because real devices like you know photo detectors are the things they can break down. And sometimes, you take advantage of the breakdown you want to operate photo detector near the breakdown point and in that case, it is called avalanche photo detector for example, avalanche photo detector. So, people can try to take advantage of the breakdown also, a breakdown in generally is not a good thing.

Because breakdown means that your device is now essentially not going to work beyond the breakdown beyond the breakdown point, your device is not going to work. So, that is what it means.

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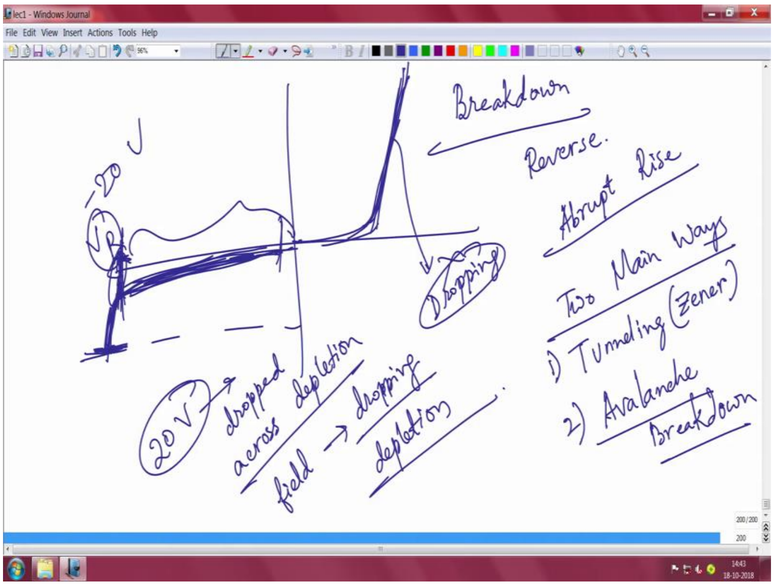

So, what does actually break down mean? So, what does break down mean? A breakdown happens typically in reverse bias. So, when you apply a large reverse bias, when you apply a large reverse bias suddenly there can be a spike of current, you know a sudden rise or abrupt rise of current and abrupt rise of current can be there any it typically would not be destructive which means the device can still be operating later on unless you allow a lot of current to flow.

So, what happens is that if you increase am only plotting the reverse voltage here, on the negative side if you keep increasing the current in a voltage the current slowly keeps increasing, increasing at one-point current will start to rise sharply. If you do not limit the current, a large current will flow, and that large current will burn the device or destroy the device also the voltage is larger.

So, a lot of power will be dissipated, and this device will be destructively broken down, but if you want to set a compliant. So, that you do not let the current in you know that the current is spiking increasing here, but you click the current. So, do not let the current increase, you know that this is a breakdown that is happening now. If this is the case, you can again come back and operate the device in this region there is not a problem, the device has not burned because the current is low.

But if you do not let it if you just go it like that and the device will current is very high and a device is burned forever. So, typically people measure the breakdown by keeping the limit low. So, that you know you will see that is breaking down, but the current is not high. And so, you can work the device around again. So, when breakdown happens that are suddenly, many current increases there is very small area here range here the current that has suddenly it has increased in the reverse bias not in forward biased.

Why because in reverse bias when you are increasing the content from here to here, suppose the breakdown voltage is - 20 V. So, over 20 V the current is very low. So, current is very low the film is depleted, the depletion region is very good. So, 20 V essentially is dropped across the depletion region right is dropped across the depletion region or in other words you can say that depletion region of the p n junction is blocking 20 V.

So, the entire field is existing there right, all the field is dropping across, all the potential is dropping there. So, all the field is dropping across the depletion region. So, all the field is deplete dropping across the across the depletion region, that is why eventually it will break down here.

On the forward bias side, it will not break down because there is no voltage blocking the current is increasing very fast. So, there is nothing like dropping the field or blocking the voltage, there is nothing like that. In forward bias because the current is very high think of it like a say metal not exactly metal, but in a metal, you cannot drop field you can block voltage, right.

So, in the forward bias when the current is high, you are not going to drop any, you are not going to have blocked the, you cannot block the voltage you can drop a field right. So, only the reverse bias the current is very low you are going to block a voltage and drop a field. So, that is how breakdown happens in the forward bias. Now, there are two main ways in which breakdown can happen, there are two main ways in which breakdown can happen one of the ways in which breakdown is happen can is called Tunneling that I will come to that and if this is the case, it is called as Zener breakdown.

And you know the current associated diode, we call Zener diode, you might have heard about it and the second is Avalanche, it is called avalanche breakdown, and this is a very important breakdown. Many of most of the practical devices are limited to the avalanche breakdown only; they are limited by avalanche breakdown only.

So, let us wrap up the class here today. So, we will end the class. So, what did we learn today? We had learned about the in the context of p n junction how it can be used as a solar cell, LED, photo detector that we had touched a very basics many things are remained here we will discuss that in a later in the course when we come to this optical devices.

I also told you that you know now a p n junction has two important things that are remaining to be covered; one is breakdown, one is capacitance profiling. We are starting at breakdown, I told you a breakdown is you know it occurs when you have a large reverse bias. So, suddenly the reverse leakage current which is very low suddenly increases and if you let it increase, then it will burn the device, but if you clip that you put a compliant sort of thing, then it will not burn the device you can still use the device again, but you know where the breakdown occurs it is a very rapid rise of current.

And breakdown occurs in the reverse bias only because until breakdown happens, say 20 V or 30 V is the breakdown, until that volt is reached, you are actually reverse current is very low which means the depletion region is really depleted it is blocking the voltage the field is dropping there.

In the forward bias current is very high when very high current flows like any metal, you cannot block a voltage, you cannot drop a field. So, breakdown happens only in reverse bias. The two main mechanisms of breakdown one is tunneling based breakdown, it is called Zener breakdown associated Zener diodes you might have heard about it.

And other breakdown is called avalanche breakdown and that is very common breakdown and most of the devices you know are limited by avalanche breakdown. So, in the next class, we will discuss what is Zener breakdown and avalanche break down mean and what you know how we understand what is which breakdown and so on. So, that will discuss in the next class. So, thank you for your time today.