Non-conventional Energy Resources
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Lecture – 16
Solar Energy: Interaction of p-n junction with radiation

Hello, in the past few classes, we have been looking at the semiconductor the p-n junction, various characteristics of the kinds of you know materials that are involved, what happens when you put them together? What parameters we have to be cautious about and so on and we also looked at how the material is even you know manufactured; how do you start off with essentially sand and arrive at something that is single crystal silicon or polycrystalline silicon or even amorphous silicon and then the idea that you know you take this and then you make your p-n junction and so that is something that we seem to think was necessary.

So, what we would like to do today is to look at this p-n junction a bit more and to see how this junction you know responds to the arrival of radiation. So, in the end, we are going to use a p-n junction as a solar cell. So, what we will see today is how does it function in the context of solar radiation incident on it and therefore, you know how why is it that you know you need that p-n junction for it to work as a solar cell ok.

So so, that's the idea that we will pursue through this class.

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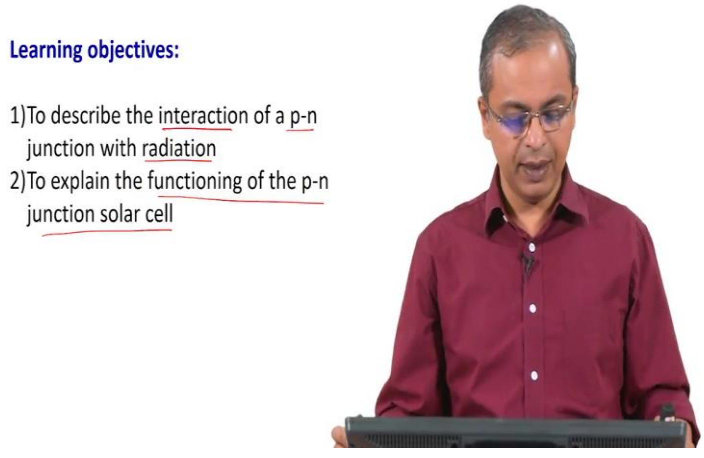

So, we are going to look at the learning in terms of learning objectives we are going to describe the interaction of a p-n junction with radiation. So, a p-n junction how does it interact with radiation once radiation is incident on it what are the phenomena that are occurring in it and what's the consequence of that phenomenon and in that context we would like to explain the functioning of a p-n junction solar cell. So, that's the basic idea that we would like to pursue through this class ok.

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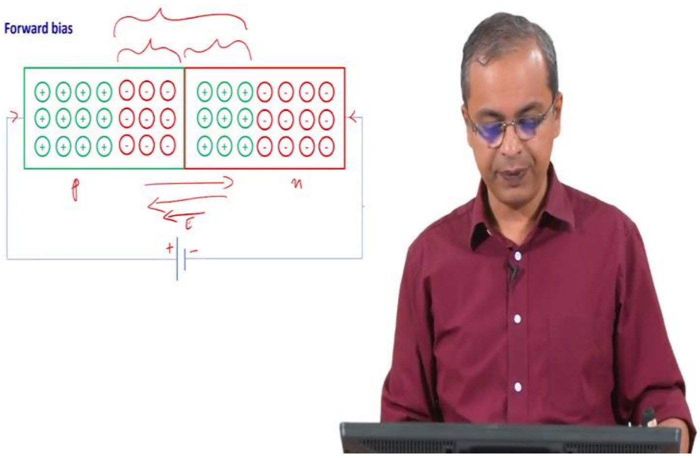

So, we actually did some work on this a p-n junction understanding how it behaves, I will just highlight 1 or 2 key aspects of it specific aspects of it because that is how we will be able to continue with the description we will see in this class. So, we spoke about the idea that once you make the p-n junction, there is a transfer of charge from one side to the other and from the other side to this side and you end up creating this depletion region or the space charge region and then that you can actually do a forward bias of it. So, so once you create this p-n junction, it has certain characteristics in terms when I say characteristics, it in terms of how its current and voltage will change depending on what conditions it is placed in.

This is you can think of it as you know information that you can learn independently, but and in often that is how it is taught often that is how you see the p-n junction and its IV characteristics, etcetera, but it is not just an independent you know scientific curiosity kind of thing on what a p-n junction will do, but really those characteristics are critical in explaining how it functions as a solar cell and that is why we are you know spending some time trying to understand those characteristics so. In fact, you do have this exchange of charges because of the way in which the energy is line up and and you create this space charge region or depletion region which primarily means that on each side of the junction whatever was the majority carrier is missing for a small distance ok.

So, it is exaggerated here as a little larger distance here and similarly a larger distance here, but you are really looking at a very thin region across the junction where the majority carrier. So, in this in this case we have the n side here and we have the p side here in keeping with the p-n named p-n junction, I am most of my diagrams are with I am I have been trying to keep it consistent with p on our left side and n on the right side. So, that it is easier for you to follow.

So, on the n side, the majority carrier would have been an electron on the p side, the majority carrier would have been a hole when you create this junction because the holes don’t see enough holes on the n side, they drift into the; I mean, they diffuse into the n side and the electrons do not see enough electrons on the p side. So, they diffuse into the p side. So, that’s basically what you are seeing and in fact, as I said once in one of our idea classes, when we looked at the metal the electron can actually roam all over the metal because you have the same you know ionic core everywhere and therefore, it can roam everywhere, without any restriction.

Whereas, in this kind of a situation where you have a p-n junction the electrons as they roam into the p side are seeing a different you know background condition. The holes which are moving to the n side are seeing a different background condition. So, they cannot indefinitely move they are charged. So, the the region they move into, it is no longer charge neutral they are creating they are building up a charge in that area, it’s no longer charge neutral it was charge neutral to begin with, but since they are arriving at that region with the with a different charge.

They are actually changing the charge neutrality of the region and that is why, this is actually called the space a space charge region. This entire region is called a space charge region because it is building up a charge there and that’s the reason why you know the holes don’t diffuse all the way across into the n side and the electrons don’t diffuse all the way across to the p side and that is how this differs from; you know; this being a metallic sample or even a junction between 2 metals.

So, even there you will have some buildup, but that's maybe that's not the that also has some aspects associated with it, but let's say 2 you know 2 pieces of the same metal which are put together then you can actually have you know essentially the electrons free be roaming around.

So, this is how the buildup is there and having put this together you can attach a battery to it. So, now, clearly because we have put charge on either side of it I mean not put it has automatically redistributed, it's charge and charged and created this space charge region. So, there is an inbuilt potential that has been created you can put a potential outside of the sample which can you know counteract this potential or built on this potential okay. So, this potential that builds inside this sample or the field which would actually be from the positive to the negative. So, the e field would be this way.

So, this potential is preventing further flow of charge right. So, you can put external potential to this sample which either assists this potential in which case, it makes it even more difficult for charge to get transferred across this junction or it counteracts this potential and makes this potential essentially ineffective or less effective and then eventually charge can go across it.

So, we basically can put what is we what we would call as the forward bias which means we are putting the positive side of the battery external battery in contact with the p side of the sample and the negative side of the battery in contact with the n side of the sample right.

So, we are pushing more electrons into the n side and we are drawing away electrons from the p side which means effectively like we are pushing more holes into the p side. So, as we discussed what this does is that.

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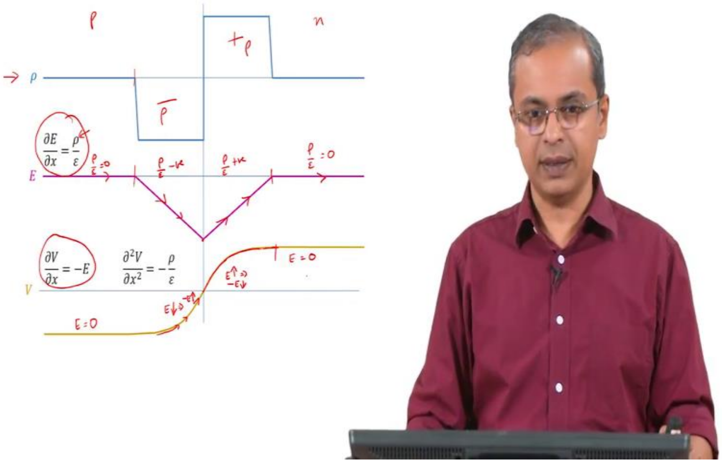

It basically reduces the space charge region.

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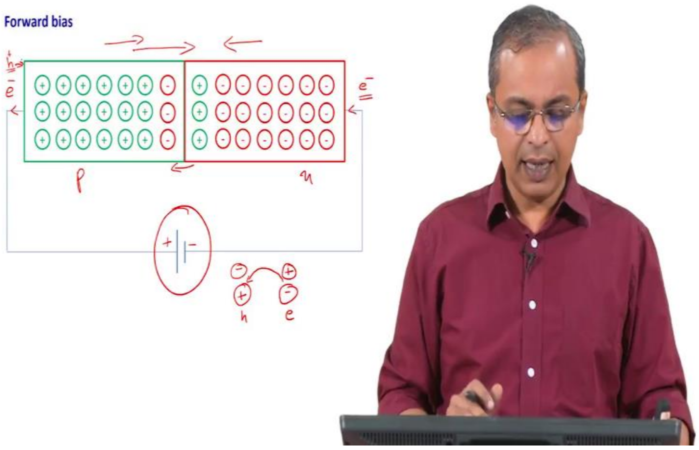

So, it starts pushing more holes this way it starts pushing more electrons this way. So, that therefore, the space charge region begins to decrease and once you cross the potential that corresponds to this space charge region, essentially, you will have current steadily flowing through this p-n junction and in the context that the we traditionally associate current the conventional current is associated with positive charge, this is the direction of flow of current of conventional current the direction of the flow of the holes is the kind of direction of the flow of the conventional current electrons are flowing the opposite way.

So, you can think of it this way; electrons are coming this side and they are getting consumed by the holes coming from the other side and hole essentially means it means this sample is charge neutral, but the bonds can actually accept one additional electron right. So, that is what we mean by saying that there is a hole there and so, this electron that is coming from the n side as it crosses across the boundary and goes into the p side it is actually going into that location where that you know one additional bonding electron was not available. So, it's readily accepting that electron.

So, the electrons are actually steadily flowing from your right to left and and and and because there are as ; it sits in that location one more hole arrives one more electron arrives and it keeps occupying a with locations and therefore, you can think of it as a current that is flowing okay. So, one way they describe it is that they are all coming and getting annihilated at the junction the other ways you can think that there is a steady flow of electrons and which is being compensated by electrons being drawn away there and therefore, being replaced by holes again and again.

So, every time you put an electron into the p side, you are also removing an electron from this side, right. So, electron is entering from the right side and it is exiting out on the left side of our sample you can think of it that way. So, if you remove an electron it is the same as having added a hole there. So, you were short of you know one one bonding electron was missing there and one electron crossed over from the n side and occupied that site and then you took that electron all the way to the left hand and took it off the circuit and therefore, you have essentially reintroduced that hole that place.

So, that's why that's the description you keep hearing of holes coming from the left electrons coming from the right and they are basically; you know annihilating each other in the junction, it does not mean matter is being destroyed or some you know some energies some nuclear activity is going on there that's not what is happening it is just that this is the description that captures the activities that are happening there, but you can also think of it you know, if you really want to not to confuse yourself you can think of it as an electron that is going through and through and through as it crosses the junction it occupies the location that was available where there was a hole which means that hole now disappeared that's basically what we mean. So, that hole is no longer there because an electron is now sitting there.

But you slowly draw the electron away to your left and there you removed that electron from that region you have again brought back that hole that missing bonding electron is still there. So, you have brought a hole. So, each time the electron hops from one hole to the other hole it is the same as that hole having hopped this way. So, you have a one hole; one electron; electron goes this way, it has cleared this location on your right hand side. So, you have let's say one hole here which I put us a positive h and I put an electron here e minus. So, if this, switches here then this location now has the electron and this region which it left goes back to being a hole. So, that's essentially what it means. So, every time an electron moves from left to right it is the same as the hole moving from right to I am sorry from every time an electron moves from our right to left it is the same as the hole moving from our left to right.

So, so that's what we mean and. So, you can think of this circuit that way and also understand what is going on. So, anyway; so, this is what is happening if you forward bias the sample and so, this junction will disappear and you will have steady flow of current. So, that's the idea of this p-n junction in forward bias, please note that when I said forward bias to show that as an experiment we put this battery here. So, we put this battery in this external circuit and we know deliberately connected the positive to the p side then negative to the n side. So, this is what we did to demonstrate this process to demonstrate this you know characteristic of this p-n junction.

But in reality what has happened, in reality what has happened is, we have pushed electrons to one side of the a p-n junction and we have pushed holes to the other side of the. So, if you want to call it h plus as the hole with that charge and we have pushed that on the the p side of the sample. So, or we are drawing electrons out that side. So, therefore, you are pushing holes into this side. So, you can put it that way.

So, the point that I am trying to make is that when we say something is in forward bias when we say p-n junction is in forward bias it basically means we have electrons additional electrons from an external circuit or from anywhere additional electrons appearing on the n side additional holes appearing on the p side okay. So, so anytime you create a situation where you know initially you have a p-n junction which is sitting there and there and because it this is the junction is formed you had the space charge region being developed you had this depletion region being developed and that happened as soon as you made your p-n junction right. So, that is your starting point from this starting point if you do anything to this sample which creates more electrons on the n side and more holes on the p side you have essentially created a situation which is similar to what you are seeing on your screen which is you have created a forward bias okay.

So, that's the point I wanted to keep in mind. So, it doesn't have to be through a battery in this case we are showing this example by putting a battery outside and doing the connection, but that is not necessary you create a situation where there are more electrons sitting on the n side and more holes sitting on the p side, then I say more with respect to what we are present when you initially found the junction when you do more you have created a situation which is similar to a forward bias and therefore, at that point the p-n junction will show you this behavior that you just saw of what it it is going to do during a forward bias okay. So, that is something you keep in mind and we will get back to it.

So, as we saw that you know because of the space charge region you will get this negative charge here you will get this positive charge on the I mean the n side of the sample, this is the p side as we said this is charge neutral here. So, charge neutral. So, negative and positive and because of this relationship we find that e has you know linearly decreasing characteristic from where this region begins and goes to a fairly low value here some appropriately low value here and then since the slope suddenly becomes positive here the rho becomes positive here this is rho this is rho.

So, negative rho becomes suddenly positive rho and therefore, in your equation the slope is now suddenly positive. This slope is now suddenly positive and therefore, from this lower value the slope keeps increasing and then you arrive at this neutral value where suddenly again the rho is 0 because then once the rho is 0, the slope rho by e rho by epsilon becomes 0. So, here rho by epsilon is positive, rho by epsilon negative rho by epsilon 0 ok.

So, because it is 0 you have a flat line here it is negative, so, you have a negative slope it is positive. So, you have a positive slope it says its 0. So, again you have a flat line here. So, this is basically the behavior we see and then a correspondingly if you look at the potential as you go from left to right you find that know the if you look at this relationship here then you see that the slope is essentially related to minus e and e itself is 0 here. So, e is 0 here and then e is decreasing ok.

So, if e is decreasing minus e is increasing and minus e is increasing means the slope dou v by dou x is increasing okay. So, it is continuously increasing that’s what you see the slope is steadily increasing right. So, the slope is continuing to increase and then you cross this origin. So, you suddenly see here e is basically increasing implies minus e is decreasing okay. So, minus e is decreasing because minus e is decreasing the slope having reached some value now starts decreasing. So, the slope starts decreasing. So, it starts decreasing like this and then once you reach this region again once you reach this flat region corresponding to this point here e has become 0 okay and so, once e is equal to 0 the slope is 0 and you again get a flat line.

So, this is the you know behavior of this junction in its static state as soon as it is being built or once it is in that kind of a stable situation. So, this is the characteristic and we saw what would happen if you stake this and then you put you know forward bias to it.

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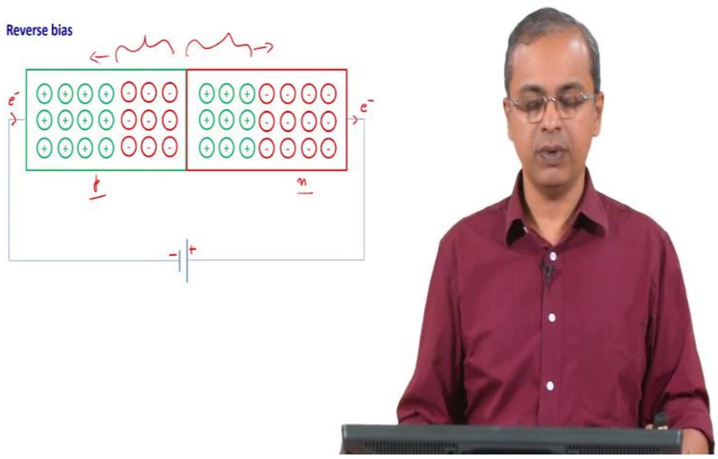

And again if you take the same thing and you do a reverse bias which means you are now taking the negative side and I am sorry the positive side and connecting that to the n side and you are taking the negative potential here and connecting that to the p side okay as supposed to the opposite that you saw here we are doing the opposite here we are taking the positive and connecting to the n side whereas, previously, you had the positive connecting to the p side and here you are taking the and previously, you had negative connecting to the n side you now have the negative connecting to the p side.

So, what is happening, you are pushing more electrons in here and you are pulling out electrons from here. So, when you pull out an electron you leave behind a bond that is unsaturated okay. So, if I essentially you have added a hole. So, that’s would basically what happens.

So, you are increasing the number of holes in the n side of the sample you are decreasing the number of holes on the p side of the sample because you pushing electrons in you are pushing electrons in it will go it will travel through and through and through and it will reach a point where it till it hits some other electron and it is not able to go forward it will go it will continue to go there and it will because you are pushing it and it will go there and it will occupy that site which was a hole.

So, you are increasing the number of electrons on the p side and you are increasing the number of holes on the n side naturally you can expect that the number of you know this region which was positive will now increase a little bit and the region that was negative here will increase a little bit. So, that is called reverse bias and. So, that’s essentially what you see here.

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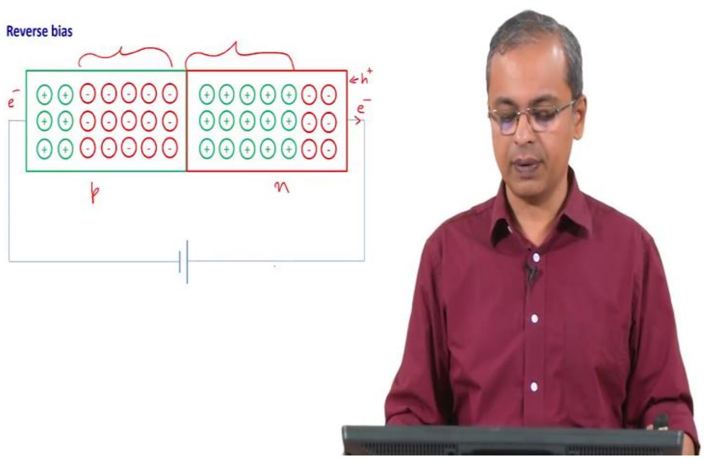

So, this region has now increased because you pushed more electrons in and you pulled away more electrons from here essentially pushing holes in and therefore, this region also enter and clearly this; this is acting as a barrier it is you know it is opposite to the flow of the electron. So, it is resisting this process.

So, this is called reverse bias and it basically means that it is going to prevent flow of electrons as much as possible you can continue this till you close up all the you know holes that are remaining on your p side and all the electrons that are remaining on your n side and then you will you will be able to force a current through this sample right. So, you can force a current through the sample if you do that and at, but that point you are actually sort of broken down this material at some fundamental level and you are you know pushing this electrons through that sample.

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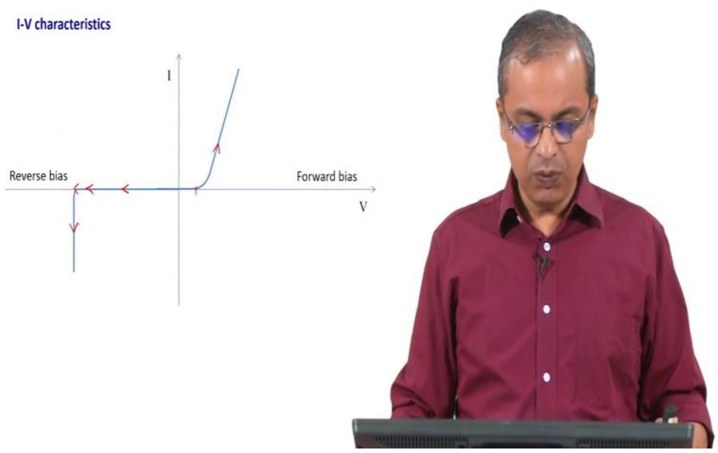

So, that’s the reason why we get this characteristic when we go in forward bias, we quickly run out of the with small increase in potential we you know counteract that built in potential that is there due to the presence of that space charge region and then you start having a steady increase in current with increase in voltage, in the your reverse bias as you keep increasing the voltage the sample keeps on resisting the it also increases its resistance to the voltage that you are applying and then. So, steadily that. So, it does not really prevent does not really allow much current into through the sample it takes whatever little charge you put in it; it just holds the charge there and you know resist further charge coming in.

Till eventually you know max out that junction and with sample and then it breaks down and then you have this high current flowing through that sample okay. So, so this is the forward bias and reverse bias characteristic the only thing I will again alert you to before we move forward is the fact that although in the description we gave we used an external battery to enable this that is just for our understanding of the process the key idea is whereas, if given that you have a p-n junction where are you adding where are you forcing in or creating more electrons where are you creating more holes.

So, depending on where you are creating more holes and more electrons correspondingly you can think of the junction being forward biased or reverse biased okay. So, that is the idea that we I would like you to keep in mind ok.

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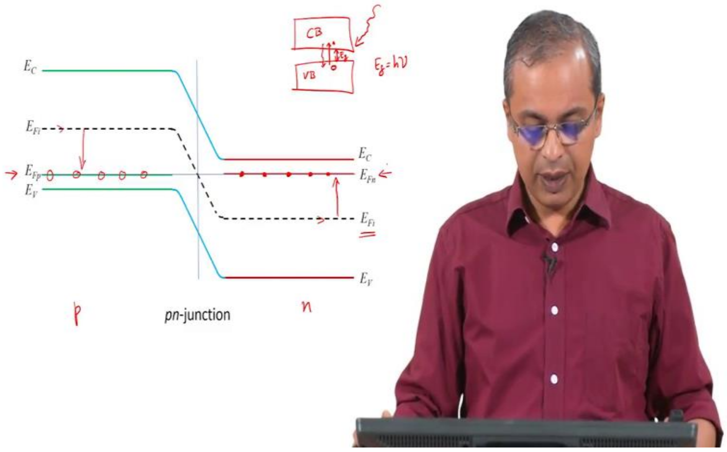

So, with this in mind we will now look at the characteristics associated with the energy band diagrams of that p-n junction because this is where we will have to understand what happens as the radiation comes in.

So, if you look at this we discussed this earlier that you know when you have when you simply have a conduction band and valence band. So, this is valence band and that is conduction band and you have a band gap E g okay. So, that’s a fixed band gap across the sample E g. So, when you have E g equals h nu you have some incoming radiation E g equals h nu when you have E g equals h nu you can have an electron transition and you will have an electron sitting here you will have a hole sitting here.

So, this is what will happen when you have incoming radiation at that point I indicated to you that when you do this you are creating a situation where the electron and hole are in physical proximity. So, in the in the sense that this hole in the electron are essentially physically in the same location they are just the electron is simply moved up in energy to a value across the band gap. So, if you give it enough time the electron will simply decade on and it will come back down and it will occupy that spot that it vacated and it will the material will go back to being its old self before the radiation came to it.

So, therefore, when you simply take a semiconductor even though we say you know semiconductor has a band gap and then therefore, it can absorb some radiation and all that stuff even though we say that if you simply take a sample of a semiconductor and keep it out in the sun you are not really going to be able to capture any electricity out of it the it will do the transitions, but the transitions will simply reverse and at the end of it, you will not really be able to capture any electricity.

So, we have to do something about you know ensuring that you are decreasing the chances that the electron can fall back into this hole that it created okay and to do that we essentially have to move the electron to some other location move the hole away to some other location and in that process you know physically it is not no longer that easy for them to just like that collapse into each other; we doesn’t drop that to 0 percentage, but it decreases it dramatically.

So, this is called charge separation you have to chop a separate the charge and stabilize it. So, it has to get just separated from these locations and only then, it will get stabilized. So, that’s the point we would like to understand with the perspective of this diagram. So, we looked at it as you know again the pain same thing p-n junction. So, this is p side this is n side.

So, for the n side; for both these samples assuming that we started with the same semiconducting material their original intrinsic Fermi energy EFi. So, that is what I am calling as E subscript F for Fermi energy and subscript I saying that it is the intrinsic Fermi energy is that is the energy Fermi energy of that material if it had got no dopants was this particular value. So, that is the value that you see here. So, that is the Fermi energy value that you have.

Now, because the on the p side you put in some dopants, you created some acceptor levels which were here. So, those acceptor levels were available here which made it easy for electrons to go to those acceptor levels and similarly on the n side, you put in some donor levels. So, donor levels showed up here and. So, that again became easy for the material to you know perform I mean put gate charge carriers into the system.

So, now given the way the Fermi energy is defined essentially the Fermi energy of the n side of the sample moves to this donor level and the Fermi energy on the p side of the sample moves to this acceptor okay and so they. So, on the p side the Fermi energy came down on the n side the Fermi energy went up and when you put these samples in I mean we will connect the 2 samples because of equilibrium requirements for equilibrium these 2 energy levels line up they line up with each other okay because there and that becomes the defining you know parameter for that sample the fact that the Fermi energy now lines up across that sample you took an n sample and a p sample and you join them together and the 2 of them now understand that they are you know in contact with each other their Fermi energies level off.

So, that that’s how the energy remains constant. So, it’s just basically got to do with energy minimization. So, it minimizes the energy and this is how they end up minimizing the energy the Fermi energy and the fact that the chemical potential on either side should be the same and this is how it ends up being in contact okay. So, this is the situation we will have.

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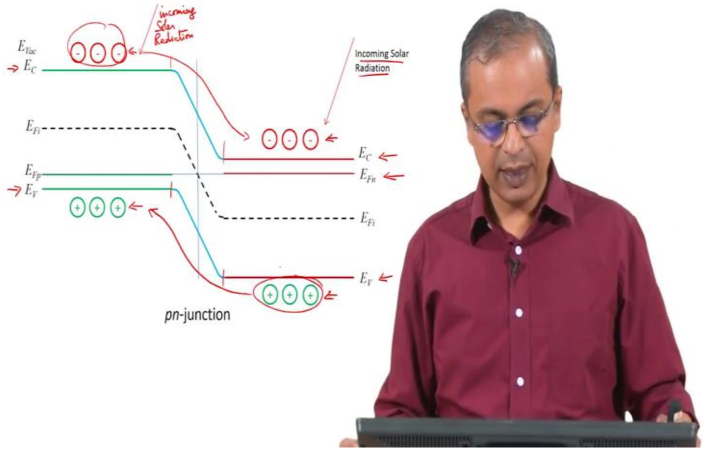

And on this sample; let’s say we have incoming solar radiation. So, we have incoming solar radiation. So, in in some ways you can still think of it as you know a transition occurs you create holes and electrons holes on the; you know valence band and electrons on the conduction band. So, that’s basically what I am showing you here there is incoming solar radiation this radiation. So, this is also incoming solar radiation right. So, incoming solar radiation on both sides of this of this junction and you create these holes down here you create these electrons appear holes down here electrons appear ok.

So, this situation we have created. Now we see an interesting situation the interesting situation we see is that we have holes sitting a 2 different levels the Fermi energy is what leveled out Fermi energy is flat, but the band structure is not flat the band structure is not flat Fermi energy is flat across the sample band structure is not flat the conduction energy I mean the conduction band the lowest energy level of the conduction band of the n side is sitting here the lowest energy of the conduction band or the p side is sitting there.

So, the lowest energy level of the conduction band is not the same if you go from left to right okay. So, the conduction energy band lowest available energy level is high on the left side it is low on the right side okay. So, that is the idea we have. So, this is called band bending the idea that in the middle you have this is situation where the band is actually bending from one level to another level right. So, this is a band bending that has happened.

So, these 2 are not in the same level similarly you look at the no valence band energy level. So, the valence band energy level on these. So, this is the highest occupied energy level on the I mean if it I set aside you know the impurity levels a with respect to the intrinsic material this is the highest occupied energy level on the n side of the sample and this is the highest occupied energy level on the p side of the sample of the valence band.

So, clearly they are they are also not at the same level the highest occupied energy level on the valence band on the p side is high the highest occupied energy level on the way of the valence band on the n side is low and. So, it has to bend down and go it starts off bends down and goes. So, so that is basically what we have now given the nature of the electrons and the holes the electrons basically are negatively charged and in the context of this energy diagram will tend to go to the lowest negative value lowest energy level that they can find. So, they will naturally slide towards the lowest energy level they can find.

So, this they tend to slide down and the holes on the other hand given that they are positive charge and essentially they represent an absence of electrons will try to move to a high level so that the electrons can go to a lower level okay. So, the electrons will like in this diagram is set up with respect to electrons fundamentally. So, as the an electron and a hole moving up in energy level is essentially equivalent of an electron moving down in energy level right. So, if all the electrons are moving down you can think of the holes as moving up.

So, therefore, in this situation when you have created electrons at 2 different energy levels and you also created holes at 2 different energy levels the holes try to consolidate. So, they all the holes try to gether and consolidate such that they are holding the highest position possible all the electrons tend to consolidate get together and consolidate such that they are holding the lowest position possible.

So, what this basically means is the electrons that are out here will try to come this side and the elect holes that are out here will tend to try to go that side essentially trying to minimize their energy this is basically what they are trying to do to minimize the energy electrons on which were holding a higher energy level will slide downwards and to join electrons which are holding a lower energy level and holes which were holding this lower energy level here they are not necessarily going to a higher energy level, but they are you know analogues to electrons sliding down. So, holes going upwards are the same as electrons coming downwards.

So, these electrons will bubble up. So, to speak they will bubble upwards whereas, the holes will bubble upwards electrons will slide downwards. So, this is basically what you are going to see and that is how the sample now behaves okay. So, you initially formed p-n junction and you already had a transfer of charge okay from one side to the other and that is what created your space charge region etcetera now over and above that you put solar radiation on it and you created more electrons and more holes transition occurring on all sides and then these electrons gather together in one location the holes gather together in another location driven by the ideas that I have shown you in this slide.

So, once this happens these diagram will evolve. So, if you want to look at it step by step once this is this is the step of the radiation just having come and having created this electron holes pair hole pairs. So, once they consolidate these electrons here would have gone down to this location and the holes here would have gone up. So, once you do that you will have a situation which looks like this.

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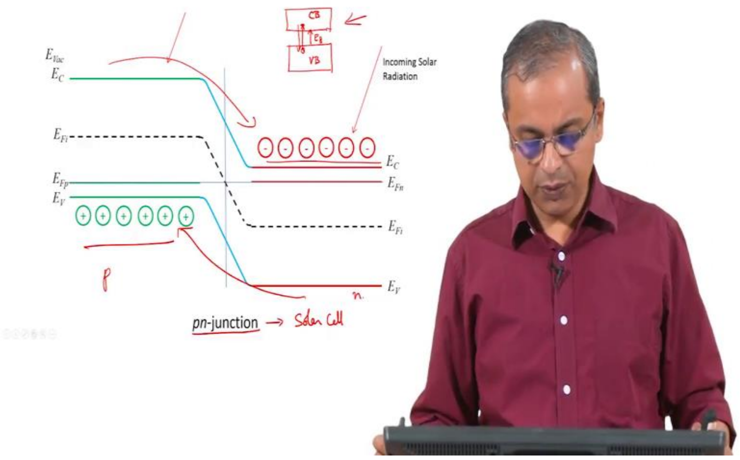

Those electrons which were sitting here moved down and the holes that were sitting here moved up.

So, we have this situation where the electrons have gone one side and the holes have gone the other side. So, now, what do we have we have an interesting situation again as I said if you look go back to what we had previously just put down we had one semiconductor and we had this transition. So, you had a hole here and you had an electron there, right, a hole here and an electron there and this transition occurred electron in the conduction band this is the valence band at that time I told you that you know if you do this there is a equal chance that the hole I mean the electron drop right back because the hole and the electron are sitting right there and they can recombine fine.

Now, what do we have we have a situation where you did the transition you created a bunch of electrons in the conduction band and created a bunch of holes in the valence band, but they are no longer in a same location the holes all slid off to this side the electrons all slid off to this side. So, you have greatly dramatically reduced the possibility that these electrons which are now on the n side of the sample will be able to combine with the holes that are sitting on the p side of the sample and annihilate each other okay. So, you are greatly reduced this chance or at least it is not an immediate activity, it is not like immediately this is going to happen you have given them a chance to stabilize okay and so, that is the key function that the p-n junction accomplishes ok.

So, that that is the key step that the p-n junction accomplishes which an independent semiconductor such as what you see here is not able to accomplish okay. So, a single individual you know separate semiconductor is not able to accomplish this stabilization of the charges which this p-n junction is able to accomplish because of the band bending that it has created which has created a situation where all the holes know agglomerate or accumulate on one side of the sample all the electrons accumulate on the other side of the sample and therefore, suddenly you now have a stable situation it doesn’t immediately collapse on itself and that is how we are able to tap this for electricity outside ok.

So, therefore, a p-n junction is a very essential part of the solar cell structure. So, a p-n junction is very essential to the; solar cell structure and so, therefore, they use this this you know device to create this situation. So, we have now got this. So, this is again the p side and this is the n side okay. So, this is what we have accomplished.

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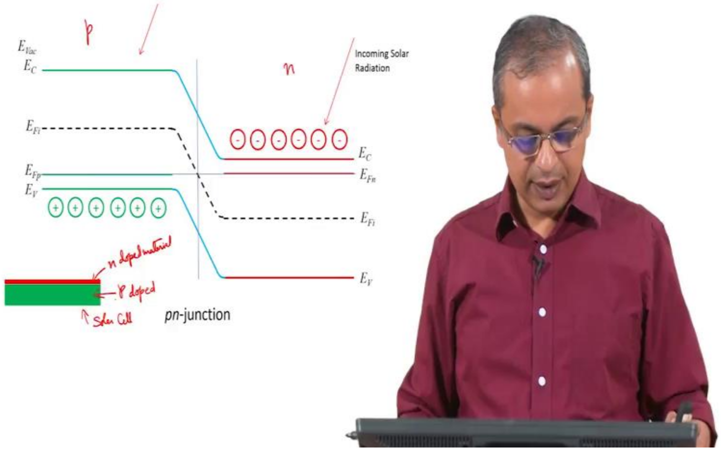

So, now I would also like to take a moment to tell you something about the orientation of the band diagram because I think just the way you saw here what is happening with respect to the charges what charges are going where and how they are stabilizing it is good to also have a physical picture of what this is a in terms of a solar cell that is that you are likely to see somewhere.

So, when we look at a solar cell we actually saw in our previous class as we manufacture the solar cell you essentially have a disc thin wafer that is created thin circular disc that is created which is maybe let’s say it is doped with p p dopant in it and then you do maybe ion implantation or you do surface diffusion or something and you add an thin layer of n dopant on the top. So, it’s a single crystal let’s assume we are talking of a crystal in a single crystal solar cell. So, you have a solar cell where you have a top layer which is n doped and bottom layer which is p doped.

So, this is what you see here would then be that the solar cell and this would be your p; p doped material and on top we have this n doped material we saw how it is manufactured how the wafer is manufactured and the idea that you can do no either no diffusion or ion implement implantation or a pit or epitaxial growth and end up getting this n n doped material sitting on top of the p a doped material with a very good interface that is that is the most critical part of it okay.

So, we have this structure and you have this band diagram. So, this band diagram corresponds to this structure. So, so that is how you need to associate these 2, but one important point I want to draw your attention to it may be a trivial point, but I think it is necessary for you to get a physical sense of this. So, that you know you can understand these diagrams better at least in your mind please note that the band diagram that we have drawn is from left to right. So, on your left we have the p type material and on the right we have the n type material.

Whereas the solar cell that I have drawn is bottom up right we have p at the bottom we have n at the top. So, the orientation of this band diagram is different from is ninety degrees away from the orientation of this solar cell the way we see it. So, that is just something that you have to keep in mind. So, in reality what is happening is this is the orientation that you have to associate with this diagram.

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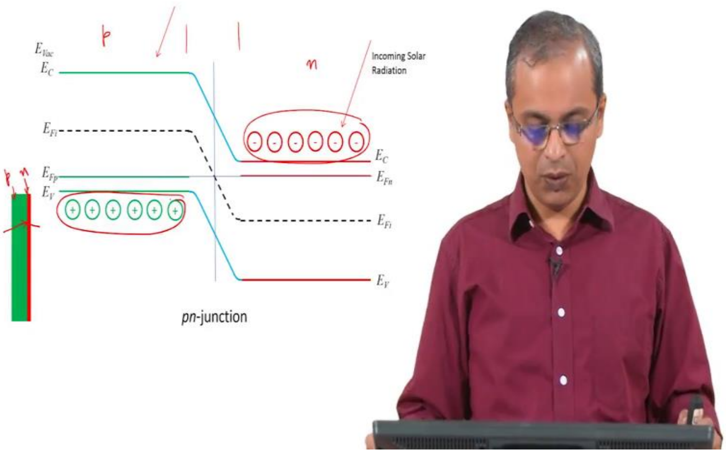

You can use it any which way you want, but this is the orientation of the solar cell that you should associate as supposed to this horizontal orientation you should associate this vertical orientation with this band diagram.

So, then you have it all lined up correctly this is your p side and this is your n side similarly you have the p; p side here and you have the n side here n side here right. So, p and n are there and that lines up with the band diagram that you are seening here also in terms of scale this is a very expanded band diagram that I am showing you from left to right for sake of clarity clearly this is all going to I mean from p to n is of course, going to be that extent of that sample that you have we spoke about that being you know just about 0.2 millimeter or 0.5 millimeter or even less those are all those are there wafers that you start with you can even make it much smaller and also this zone in the middle the depletion zone is going to be an extremely tiny zone centered along this the interface that you see here right.

So, this interface that you see here at that interface is where the depletion layer is going to exist. So, so you are thinking of looking at a very narrow region. So, please understand keep in mind the orientation of the cell relative to the orientation of this band diagram and the fact that you know dimensions are all exaggerated okay. So, for sake of clarity that's the reason why it is being exaggerated. So, this is something that you should keep in mind. So, that it doesn't confuse you that you know; why is it in one way in the other way. So, solar radiation falling on this has created the situation that you have more holes on the n side of the sample and more I am sorry more electrons on the n side of the sample and more holes on the p side of the sample.

Now, as I mentioned right at the beginning when I when we spoke about the forward bias of the sample okay forward bias of a p-n junction I told you that we basically put a battery there to create more electrons on the n side of the sample and more holes on the p side of the sample and that created a forward bias for that p-n junction, but I also told you that that is not the only way you can do that in any manner if you create more electrons on the n side of the sample and more holes on the p side of the sample more relative to what was there before that you know shortly after the junction was formed in in in all those cases you have created a forward bias.

So, if you look at a diagram that you have here you have actually created a situation where the p-n junction is now in forward bias. So, all that we discussed about the forward bias and reverse bias was not in vain there was a purpose for it. So, this is the purpose, the purpose is that when you actually use the p-n junction and you subject it to solar radiation it's it's natural position that it arrives at a natural position that it settles into which is what you see on the diagram in front of you is a position which is which corresponds to this junction being in forward bias.

So, that is something that you have to keep in mind.

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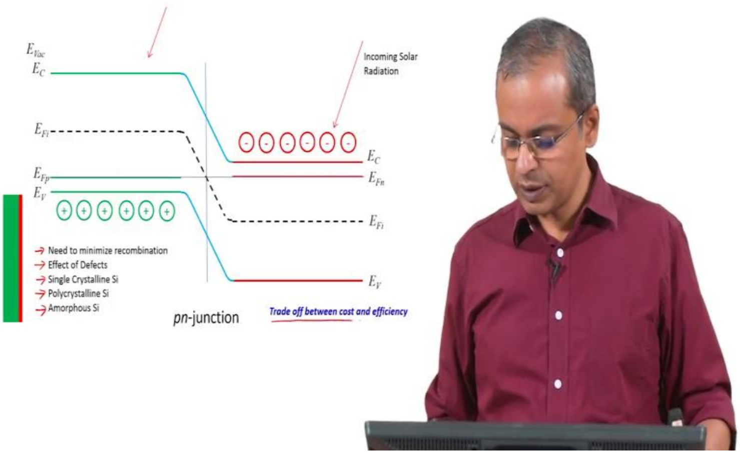

So, when you use this sample as a p-n junction what as I mentioned there are a few things that we have to keep in mind one is that we would like to minimize the recombination okay. So, recombination as I said will more easily happen when you have only a single semiconductor it is much less likely to happen when you have a p-n junction, but it is not 0. So, recombination will happen. In fact, it does happen even in a p-n junction.

So, recombination simply means you brought in this energy you created some electrons on the n side you created some holes on the p side, hopefully, you can tap this as a external electricity, but before you can tap it as a external electricity internally itself the p and n are you know canceling each other out or the or rather the hole and the electron are cancelling each other out. So, that is recombination this recombination occurs much more when you have defects okay. So, when you have defects you have dangling bonds when you have dangling bonds it traps all these electrons and holes and then it creates a situation where they more easily annihilate each other.

So, presence of defects is a bad thing in a semiconductor and that’s the specific reason why there is such interest in using a single crystalline silicon as the best possible you know if you think within the silicon system single crystal silicon is your; is distinctly better sample for you to work with for creating a solar cell, but as I mentioned in our earlier class that you know when you will do single crystalline silicon simply because of the process involved in creating it is expensive okay.

So, your next bet is your polycrystalline silicon, but clearly that has grain boundaries and that’s the reason why it is called polycrystalline sample and that has many more defects than single crystalline silicon naturally many more of the electrons are annihilated within this electron hole pairs are annihiliated in that sample and therefore, its effectiveness is less and finally, you have amorphous silicon which is distinctly cheaper than the single crystal or polycrystalline silicon to make and more than that it is also very flexible in the sense you can put it on any surface of any kind of contour and use it and therefore, there is lot of interest in working with amorphous silica, but by nature again amorphous means those atoms have a lot of dangling bonds and. So, on and clearly there are more defects of course, we saw how hydrogen can be used to stabilize those defects.

But nevertheless it off the three the single crystalline sample the polycrystalline sample and the amorphous sample the amorphous is the least effective in capturing the solar radiation in a manner that you can continue to use as a external you know power source. So, it is basically a tradeoff between cost and efficiency okay and with the idea being that you would like to minimize recombination you will never eliminate it, but you would simply want to minimize it okay. So, this is something that we would like to keep in mind ok.

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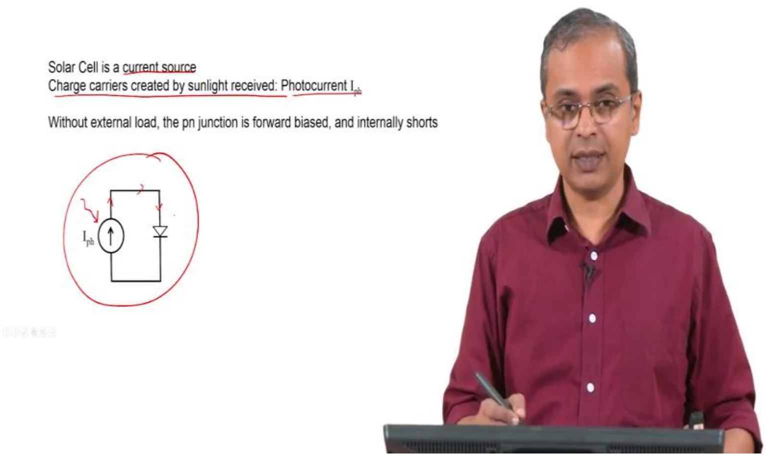

So, if you look at this now that you have created this the p-n junction and you have seen how you can you know separate out the charges you can actually generate electricity I mean you can tap this that now that you have separated the charges that's basically what it is even in a battery that is what you have got you have got a source of electrons and those electrons will come through the external circuit and it will come to the other side. So, anode cathode you have and then you have some process by which you you know utilize the thing in the external circuit.

So, similarly with the with the solar cell you have a now created situation by putting this p-n junction that you have separated the charges and this charges can flow in the external circuit the one important aspect of a solar cell that we have to keep in mind which we will discuss in greater detail in one of our immediately succeeding classes is the fact that a solar cell is a current source okay as opposed to most of the units that we get for any from any other purpose which happened to be voltage sources.

So, when you buy a cell a battery a battery from a shop which is an electrochemical device that's typically a voltage source whereas, this is typically a current source meaning that you are first generating the current and then the voltage is whatever happens because of the current okay. So, the current is what drives the behavior of this sample and this is because the charge carriers are being created by the sunlight that is received and. So, essentially you first generate this thing called the photocurrent okay because of the incoming solar radiation.

So, when you don't have any external load. So, you have just put the solar cell out there you just buy the solar cell you put it out in the sun you don't connect anything to it you just put it out in the sun when you put it out in the sun you have created done exactly what I said which is put more electrons on the n side more holes on the p side which basically means when you just take a p-n junction or solar cell and put it out in the sun without even putting any external load you have created a forward biased solar cell okay.

You have not connected a battery and then the forward bias you just left it out in the sun you left it out in the sun it became forward biased because there is more holes sitting on the p side more electrons sitting on the n side not just more holes and electrons sitting there in there is solar radiation coming in and; that means, it is creating even more it is just continue to create more holes and more electrons and both on both sides of the sample and they are and the electrons are continuing to slide one way the holes are just continuing to slide the other way.

So, you are building this up as you build this up clearly you have now got this sample sitting in this is junction sitting in forward bias as long as it is in forward bias you will have a current going through it corresponding to the characteristic that we just saw here you are now in forward bias. So, you will have a current going through that sample this is a current going internally through the sample please keep that in mind we have not connected anything external to the circuit it is internal to that sample you have current going through the sample and it is an internal short circuit okay. So, it says you can think of it that way it is an internal short circuit internally this current is going and that is how the electrons and holes are getting consumed ok.

So, so and it is behaving as a forward bias diode. So, when you simply take the solar cell and put it out in the sun then this is the circuit that you are dealing with the circuit that you are dealing with this that solar energy is coming in and creating this photo current that you see the photo current is flowing through the circuit internally. So, this is not an external circuit this diode that you see here is sitting internal it is it’s an internal diode inside that sample and through that the electron holes are getting consumed ok.

So, it is itself powering its own self. So, it is itself powering an forward bias within itself as opposed to an external battery powering the forward bias. So, this is what happens when you put it out in the sun.

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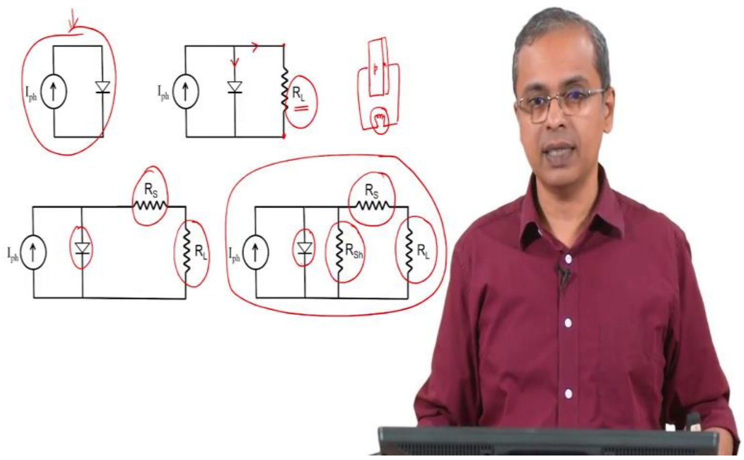

Now, on this slide I would like to show you what happens when you try to take this solar cell which is what you see on your left hand top corner and then use it to actually do something useful externally. So, to do that given that you know in ten intent I mean by itself this is the situation it is going to face you when you put it out in the sun over and above this we now try to attach a external load. So, RL is your road load resistor. Okay so, you put this load resistor.

So, now what do you have you have a situation where you are generating more electrons and more holes more holes on the p side more electrons on the n side they have 2 options they can internally do the you know short circuit. So, internal diode they can go and you know complete this short circuit they can also go in the external circuit. So, this is what they can do so. In fact, they do both. So, that's the point they. In fact, they end up doing both you have some electrons going through the external load which does the job that you want to do and you have some electrons going through your electrons and holes going through the diode in the forward bias and they are also lost there.

So, ideally you want to minimize what goes through that diode maximize what goes through your external rule that's basically the idea that you want to do, but there are some you know restrictions which is what this diagram is about which shows you progressively what are all the different parameters that are involved in this process okay. So, this is what is going on now in addition to this external load even though we have put this external load here by nature of you know just the electronics of what is happening there you are not going to have only the external load okay.

So, the current has to flow, it has to flow through that sample and come out. So, there is an internal resistance and that internal resistances exist in any you know even in a battery there is an internal resistance. There is always an internal resistance because it is not that there is because the battery is in the current path the solar cell is also in the current path. So, if you complete the circuit; there is a physical dimension to the solar cell the current has to physically flow through that dimension right.

So, there is a resistance associated with that. So, that is your internal resistance. So, to speak and that resistance is in series; so, you will always have a series resistance which will add to your load resistance; so, this is something that you cannot escape in this sample; so, in addition to the diode that is sitting here you know you have all these additional parameters which is this series resistance associated load resistance.

The one other aspect that we have not accounted for here is that recombination that I spoke to you about earlier okay. So, that recombination is even without any without this forward bias aspect of it that does not involve any biasing aspect of it; it simply means you created electron and hole even before they let's say even before the electron could go off to the you know n side and the hole could go off to the p side it might get annihilated in internally itself.

On the p side itself they may get annihilated on the n side itself they may get annihilated, but it's all got to do with the same solar energy that came in. So, say solar energy created all this thing it created the possibility that you could have all this current, but some of the current basically got lost within itself right. So, that photo current some of it got lost internally because of the internal short circuit or internal recombination. So, to speak and. So, that is what this is ok.

So, this is like a shunt resistor. So, it adds to the internal aspect of you know recombination that is going on. So, this is from the forward bias this is from the recombination this is the series resistance that you have and this is the load resistor okay. So, this is how the circuit looks. So, you basically buy a solar cell and you connect an external load to it. So, you buy a solar cell and you connect a bulb to it, let's say you connect an led to it. So, then what you have done is you have taken essentially a solar cell and you. So, you only are aware of the solar cell being present here okay. So, so you have a p and you have an n and then you have taken this and connected it to a bulb right.

So, I am just notionally showing that here. So, you have some bulb here. So, this is what you have done internally this is what is happening if you take the whole thing into account this is what is happening. So, you are you have lot of processes going on you have the photo current that is generated you have the diode operating internally itself the diode is there it is operating in forward bias you have a shunt resistor which is representing the recombination events that are happening you have a resistor in series which represents the idea that there is current going through that solar cell before it even comes out of the circuit and then and then finally, you have your load resistor. So, this is your overall circuit okay.

So, these are all the various parameters of how the solar cell behaves when you have incoming radiation. So, the purpose of this class was to look at how the p-n junction and therefore, the solar cell based on the p-n junction how does it behave with respect to the incoming solar radiation. So, in conclusion what the main points that we see here are that the p-n junction stabilizes the electron hole pair okay.

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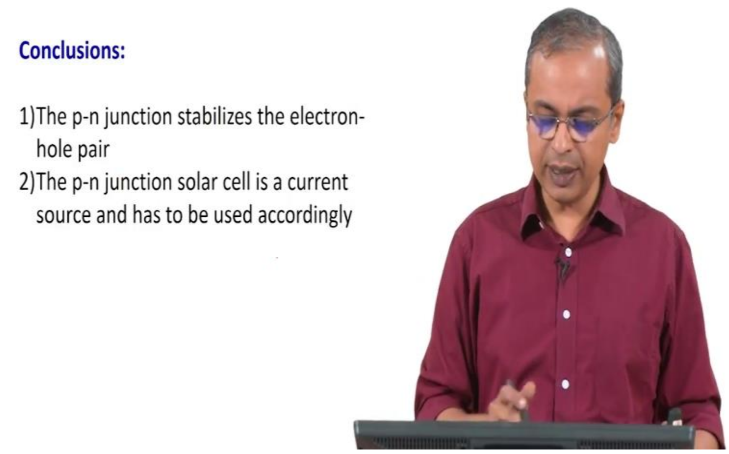

So, this is very critical and that is why it is preferred over simply having a semiconductor and then it the p-n junction is as I mean p-n junction solar cell is a current source because the photo current is being generated and therefore, it has to be used accordingly and what that accordingly is we will see how do you maximize the potential know how do you maximize the ability of the solar cell to function for a particular induce or how do you match the induced to function to the characteristics of the solar cell.

It’s a little bit tricky. So, we have to understand some parameters associated, then we will understand how that matching is done or even why that matching is required; how how do you match some endues to a solar panel it is a bit different from what you would do with respect to a battery and that is why it’s of interest. So, so in summary that’s what it is we wanted to see how it functions in the in the presence of radiation and that is the detail that we looked in considerable detail through this class going forward we will see something more on how it can be utilized what other parameters come into place when you put that solar cell plus end use together okay. So, with that we will conclude today’s class.

Thank you.

KEYWORDS:

p-n Junction; p-n junction interaction with Radiation; Space Charge Region; Electron; Holes; Forward Bias; Charge Neutral; Behavior of p-n junction in static state; Reverse Bias; Charge Separation; Band Bending; Internal Circuit; External Load; Shunt Resistor

LECTURE:

This lecture focuses on p-n junction in detail and therefore, the solar cell based on the p-n junction how does it behave with respect to the incoming solar radiation and how a p-n junction stabilizes the electron hole pair with illustrations.