Non-conventional Energy Resources

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Lecture - 18
Solar Energy: Solar cell construction

Hello, in the last class we looked at the IV characteristics of a solar cell. In particular we understood or we recognized the fact that the IV characteristic of a solar cell is a complex relationship it is not a simple relationship, in terms of what current and voltage is seen on the external circuit. And therefore, we recognize the fact that the simply looking at the open circuit potential and then you know looking at the open circuit voltage and making a judgment on a solar cell is a very incorrect way of going about it.

It is very likely that you are going to make a incorrect decision based on just the open circuit voltage. You can have a wide range of solar cells all of which have either the same or very nearly the same open circuit voltage, but their performance characteristic could be dramatically different. And as a result, a much more useful parameter to follow was the fill factor which recognized you know how much of the you know possible power that is available in the solar cell can be tapped from that particular solar cell given its specific iv characteristic. So, this is what we looked at.

In an earlier class, we also looked at how the solar the p-n junction is made, how it is you know put together, how do you start and you know create either a single crystalline or a polycrystalline or an amorphous material, how do you do the doping and how do you create this situation where you have a p-n junction which is you know perfect at an atomic level or near perfect at an atomic level. So, you can actually do some meaningful electronic characterization across it or you can see is a meaningful electronic characteristics across it.

We also saw that you know the a manner in which we make those single crystals essentially creates cylindrical structures from which we slice out the wafers and as a result if you actually look at solar panels, large solar panels you will see some hint of the circular shape in each of those cells. In fact, if you may even see the complete you know very distinctly circular shape except for some notches or even otherwise you will see a reasonable hint of that circular shape when you look at that panel based on how it has been made. So, these are these are some of the things that we have seen.

What we will see today, is over and beyond what we have already seen in terms of how you make those single crystals and slice them. Today you will actually see how you actually make the solar cell itself given that you have a single crystal let us say you have a wafer and then from there what would you do to create a solar cell after you have already done the doping.

So, we are now going to look at the doping, but beyond the doping, we will look at the solar cell construction.

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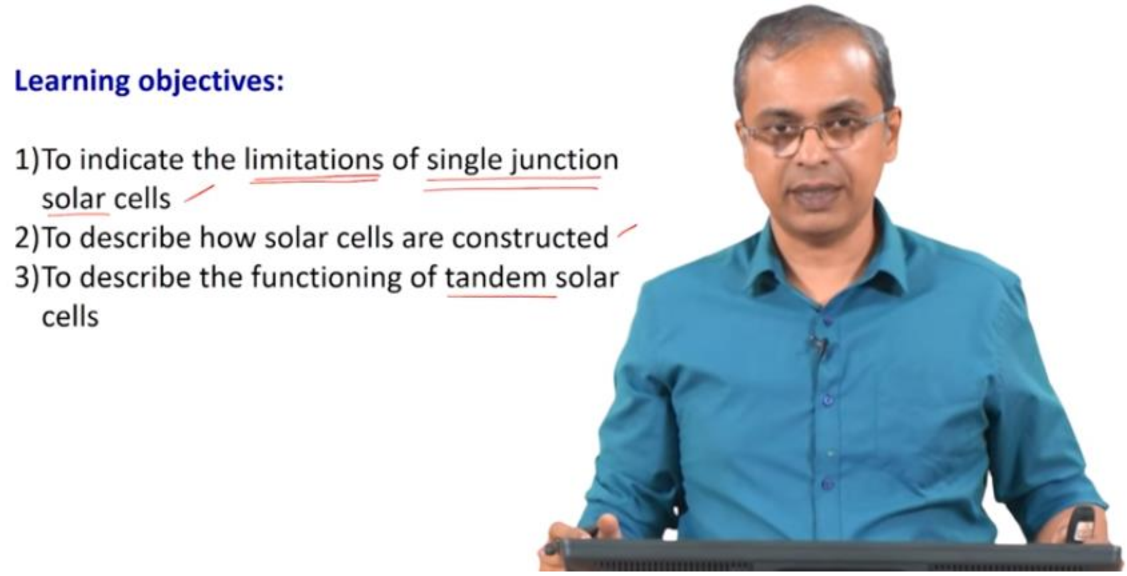

Learning objectives:

1)To indicate the limitations of single junction solar cells
2)To describe how solar cells are constructed
3)To describe the functioning of tandem solar cells

In this context, what our learning objectives for this class are the following. We will start actually by looking at the limitations, limitations of a single junction solar cell. So, single junction solar cells which is what we have, in fact, discussed for the most part of this class, course, as it relates to photo voltaic activity, is we have looked at single junction solar cells because which means there is a single p-n junction in that solar cell and that is how we are capturing a electricity. So, that is what we have, saw through these class.

But inherent to the idea that it is a single junction solar cell, it has some specific limitations. So, we will first start by actually looking at those limitations and then we will keep that in our mind, with that in our mind, we will actually describe how solar cells even if they are single cell a single junction solar cells how are they constructed, what are some things that we need to keep in mind as we construct that solar cell. So, that is the second thing that we will look at.

Then we will having done these two, we will see how we can overcome the limitation of a single junction solar cell, how we can overcome that limitation and the idea that we will be used is this idea called tandem solar cell and so that is something that we will look at towards the end of this class. So, those are the three things we will look at. What is the limitation of a single junction solar cell? How we put that single junction solar cell together. And then how do we overcome that limitation? So, these are the three things will come.

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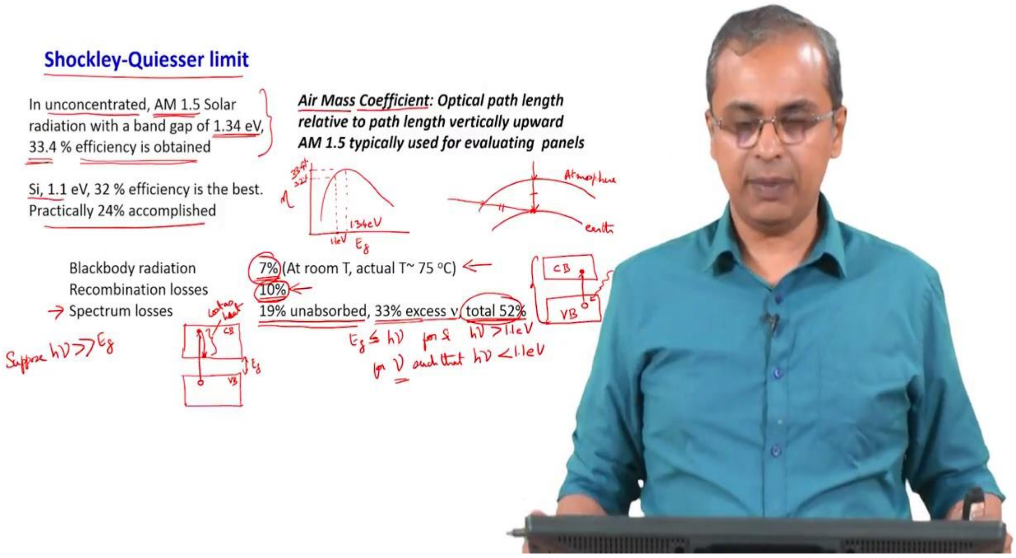

Shockley-Quiesser limit

In unconcentrated, AM 1.5 Solar radiation with a band gap of 1.34 eV, 33.4 % efficiency is obtained

Si, 1.1 eV, 32 % efficiency is the best. Practically 24% accomplished

Air Mass Coefficient: Optical path length relative to path length vertically upward
AM 1.5 typically used for evaluating panels

Blackbody radiation 7% (At room T, actual T~ 75 °C)
Recombination losses 10%
Spectrum losses 19% unabsorbed, 33% excess ν, total 52%

So, we will begin by looking at the first part. There is something referred to as the Shockley Queisser Limit. So, this is named after the people who studied this extensively and put this you know indicated this in a theoretical sense as to what sort of a limit is there for a single junction solar cell and that is what is referred to as a Shockley Queisser Limit. And most of the solar cells we tend to see commercially happen to be single junction solar cells at this point in time, most of them are and therefore, many of them do subscribe to this limit, I mean in the sense they are not really capable of doing better than this limit.

So, we will look briefly at that. In this context, there is a terminology we should become familiar with because in the solar energy context they use it a lot, that is what you see here am followed by a number am in this case it says AM 1.5, AM 1.5 is a technical you know specification that is indicated there. The AM stands for air mass. So, it stands for air mass and actually the full term, there is the air mass coefficient. So, what is this addressing or what is this conveying to us? What is it trying to refer to rather?

It is basically referring to the amount of distance or path that the sunlight has to travel through atmosphere before it reaches us in a relative sense in the sense that it assumes that if it is coming, the shortest path it can take is when the sun is directly above us right. So, shortest path that the sunlight can take to reach us is when the sun is directly above us which means it just goes through the thickness of the atmosphere just straight down the thickness of the atmosphere it comes to us. On the other hand, if we are obliquely situated. So, you basically have that is the atmosphere and this is the surface of the earth and that let us say that is the atmosphere.

So, sunlight that is coming straight down takes the shortest path down and comes here. So, we are here now. So, midday this is how it would be. So, in the same location, in the same location if you want to see the sunlight that some other point of time in the day sunlight would come obliquely and it would travel this distance before it reaches the same location. So, clearly if you compare you will find the this distance here is larger than this distance here. Ok, because it is coming at an angle it has to travel much longer distance through the atmosphere and therefore, sees much more, more of the atmosphere before it reaches that point.

So, this is captured by this idea of this air mass coefficient which simply talks of the optical path length relative to the path length vertically upward. Ok, So, optical path length relative to the path length vertically upward. So, AM1 refers to the idea that it is coming straight down on us. So, AM1 means the both the path lengths are the same it was straight coming down vertically from vertically upward and that is what we are comparing against. So, that is AM1. So 1.5 basically refers to some other point of time in the day where roughly one and a half times the you know distance you are traveling before you reach that point, relative to what you travel if you are coming vertically down.

Now, it turns out that in most places for much of the studies that are carried out where they are trying to figure out how well some particular solar cell will function, they typically prefer to use AM 1.5 solar radiation. So, they simulate or create AM 1.5 solar radiation which would refer to solar radiation which has travelled one and a half times the thickness of the atmosphere to reach the point. Primarily to a sort of average out for the fact that you are going to get AM 1 only during the middle of the day rest of the day you are not going to get this. So, you are going to get you know much less much higher numbers am, much higher numbers on either side of middle of the day. So, an average number of 1.5 is used to you know sort of capture the range that is possible.

Also it is all got to do with the fact that when you look at a you know latitudes that are significantly away from the equator, anyway they are not going to get direct overhead sunlight. So, with for them also using AM 1 it is not a very you know representative way of figuring out how much sunlight they are getting and figuring out how well this solar unit will function in their place right.

So, to figure out how much the; how the solar unit will function in their place you have to simulate the sunlight that is arriving at their place and therefore, usually AM1.5 use used as a generic number under which a lot of testing is done. So, that is stands for this air mass coefficient. It is, I mean, I thought we should we become aware of this term, but because when you read solar energy related literature you will see this term showing up here and there.

So, now, returning to our discussion on the Shockley Queisser Limit. Just to go over the sentence that is stated right at the beginning in un-concentrated AM1.5 solar radiation with a band gap of 1.34 electron volts, 33.4 efficiency is percent efficiency is obtained. So, this is just a statement, as we discuss this slight you will get a better sense of this statement. The statement simply says in un-concentrated AM 1.5 solar radiation with a band gap of 1.34 electron volts 33.4 percent efficiency is obtained.

So, what they are trying to convey here is that first of all we are using radiation as it is coming in we are not using reflectors to concentrate the radiation. So, we are setting some standard condition under which we are doing this measurement. So, the standard condition is there is no concentration, no reflection or a no lens, and no such thing is being used to concentrate the sunlight, just ambient sunlight as it comes down its being used and we are replicating the idea that it is one point coming through 1.5 times the thickness of the atmosphere and so AM1.5 is used.

And then this radiation is being captured by a material which has a band gap of 1.34 electron volts. So, 1.34 electron volts is the band gap that is being used. If you do that the efficiency you will get is 33.4 percent. So, 33.4 percent of the solar radiation that arrives will get converted to electricity and therefore, that is what we are talking off in terms of 33.4 percent efficiency.

So, 1000 watts of a solar energy 1000 watts per meter square of solar energy is arriving on the surface 334 watts is what you will capture as electricity as your usable electricity. So, that is what we are referring to as 33.4 percent efficiency is obtained. So, the point is this, basically there are a bunch of reasons why this happens and incidentally, this 33.4 percent is considered the best possible efficiency you can get theoretically, theoretically the best possible efficiency you can get with a single junction solar cell.

So, if you have a one p-n junction in it and you use that solar cell put it out in the sun under the under these conditions the best possible efficiency you can get is 33.4 percent. In fact, you typically get less than this. So, we typically get less than this. And this is some kind of a theoretical limit based on various phenomena that are occurring within the system. So, that is the point. So, therefore, we have to work with this as the being the upper limit.

And in fact, what this basically says is that you know if you plot the efficiency versus the band gap, so I just put a efficiency here as eta and this is the band gap E_g then you will see some curve which goes like that, something like that you will see a curve that looks like that and this maximum that you see will be at this you know 1.34 electron volts and the you know efficiency that will correspond to is this 33.4 percent. So, on either side of it you can have materials with band gap higher than that you can have materials with band gap lower than that. On either side of this you will have an efficiency that is less than this as per theoretical considerations. So, this is what the Shockley Queisser Limit is.

We will now briefly look at why this limit exists, what are all the phenomena that are creating the situation then you end up having this limit. So, we will look at that in just a moment. So, this by the way is a curve that is you know you can you know figure this there is a way in which they I mean do this across various materials, they do some calculation they arrive at this value of 1.34 electron volts. In fact, the material that we tend to use much of the material that we use in the commercial sense for the solar cells, as we have been discussing through this course the most commonly used material is silicon.

So, for silicon the band gap is actually not 1.34 electron volts, but it is exactly 1.1 electron volts. So, 1.1 electron volt is what you have. So, see somewhere here 1.1 electron volt. So, for 1.1, you will not even get, even the theoretical value will actually not be even be 33.4 percent you are actually looking at a only about 32 percent. So, you are only going to get about 32 percent efficiency there for the theoretically if you are using silicon as your material and which is what we are going to typically use. So, that is a limit.

And if you see practically what is normally being accomplished is only about 24 percent, 24 percent efficiency is what is being accomplished. So, it means about three quarter of the energy that falls on the solar cell is lost. It is not really being converted to electricity, only a quarter is being converted to a if electricity a in a single junction solar cell. So, this is the situation that we face. However, I mean, it may on the one hand it may look you know not so impressive you know which means you are only capturing 24 percent of a whatever is following and in fact, yes from know from a research perspective from a technology perspective people are constantly working on finding ways to increase this efficiency.

So, they obviously, you are putting something out there you would like to get as much you know power captured by that unit as you can for the same meter square of that unit that you put out there. So, clearly that efficiency should be as high as possible and people will work towards it. But at the same time we keep in mind the fact that you know every hour we are receiving enough energy from the sun that covers the entire energy requirements of the planet for a full year right. So, for a full year whatever humanity needs is being received by us every hour.

So, even if let us say you have only 24 percent efficiency. So, or even let us say 20 percent efficiency, I will not even say 24, let us say 20 percent efficiency, we have 20 percent efficiency, it simply means in 5 hours time you will get all the energy that you require to serve the entire you know words needs, if you are capturing all the solar energy that is falling on the planet right. So, that is just to give you a sense of perspective. I mean even there are lot of things that you have to keep in mind because for example, all the energy that comes to the planet is not falling on the land, quite a bit of it is falling in the sea.

So, we have to do many other corrective factors in it, but just to give you a some sense of you know what are we dealing with. So, what is you know, what we spoke of as a 1 hour for the whole year may become 5 hours. If you account for the fact that you know maybe even much more than half is oceans. So, instead of 5 hours let us say it will take 15 hours, 15 hours to get all the energy we require for the entire year. So, still you put in all that maybe you are instead looking at a day, in a day you can capture on all the energy that you require for the entire year, if you would, if it is set up that way. So, that is just a thought to keep in mind. I mean there may be other factors that you and you need to throw in, but you can see the room available for error where in you still have the ability to serve the needs of the entire planet.

So, now, this is some general information that I have given you up here on the idea that you take this, there is this upper limit. So, now, we will just briefly see why this limit comes about. So, we need to see where is it that the solar cell is losing energy once you have incident energy why is it getting lost why it is not all of it being captured. So, to start, to consider that the first thing that you have to keep in mind is that the solar cell is not sitting at absolute 0, it is sitting at room temperature. In fact, it is not even sitting at room temperature because sunlight is falling on it typically the solar cell may actually heat up. So, and there are various processes is happening inside it, it will tend to heat up. So, you are actually looking at a solar cell which is typically sitting maybe closer to say 60, 70 degrees centigrade. So, that is the kind of temperature its sitting at, which means it will lose a heat by radiation, as a blackbody it will lose heat by radiation.

So, somehow, where is that heat coming from? The heat is coming from whatever came into it right. So, it is not the magically generating this heat and putting it out. It is the heat, part of the heat and energy that reached it is being rereleased by it in the form of radiation corresponding to its temperature being that of a black body right.

So, it turns out that about 7 percent given the temperature it is a 10 what not, even at room temperature it is giving out about 7 percent. So, at least about 7 percent of the energy that is coming in is lost by the system simply as you know blackbody radiation leaving the system. So, that is the first source of loss. So, which basically means already you will not capture a 100 percent, only 93 percent of what is coming to the cell can now be captured that is the first loss.

Second loss is recombination loss, which means off the energy that falls on the solar cell which ends up creating the electron hole pairs, some of the electron hole pairs recombine. So, we discussed this earlier, so we have the conduction band and we have the valence band and then you have this incoming solar radiation then that takes an electron from here and pushes it up. So, you end up having an electron up there and here you have the hole right. So, this is what you end up creating. So, you take the electron push it up into the conduction band you create a hole in the valence band.

So, if you give it some chance these two can recombine, the electron can fall right back into the hole and you know you will no longer have a charge carrier available you have you know that is called recombination.

It has recombined with the hole and no longer it is possible for you to tap it as electricity. So, this recombination is a statistical process it will happen some amount of recombination will keep happening although you are put in a p-n junction and you are try to stabilize the electrons and holes were moving them away and doing all that still some amount of recombination will occur, that recombination has been estimated theoretically to be at around 10 percent. So, 10 percent of whatever falls on it will undergo recombination. So, now what was, you know maximum possible was 93 percent just now we saw after you accounted for blackbody radiation, after you account for recombination the maximum that is possible is 83 percent. So, this is what we have.

But a very significant amount of the loss that happens in a in a semiconductor device is associated with this loss referred to as the spectrum loss, spectrum loss. So, what is the spectrum loss? So, we need to have a idea of what is the spectrum loss. Again it has got to do with this band diagram. So, this band diagram is what decides spectrum loss.

Let me just put that up here. So, we have a conduction band we have valence band and we have this band gap E_g. So, this is, sorry, this is conduction band, this is valence band.

Now, a single junction device, single junction p-n junction device has a single band gap which is this E_g that we have. So, clearly this E_g you can link up with a particular frequency. So, we have E_g equals h υ. So, this is an equation of the possible energy that an incoming photon has and the frequency corresponding to that photon and how that matches up with the band gap.

So, the way this system works is, as long as E_g is greater than or equal to, I am sorry as long as the E_g is less than or equal to the h υ, then that frequency is absorbed, right. So, if you have a single junction semiconductor being used as your p-n junction, single p-n junction material being used as your solar cell. Let us say it is a silicon based cell of band gap 1.1 electron volts. As long as h υ is greater than 1.1 electron volt, so for silicon if h υ is greater than 1.1 electron volt that a photon is going to get absorbed, but in our solar spectrum we have wide range of a wavelengths right. So, we have a full range of wavelengths. So, any frequency that is less than the frequency required for h υ to be greater than 1.1. So, any frequency that is less than this does not have sufficient energy. So, the therefore, h υ is not less than 1.1 right. So, if you have h υ less than 1.1 for υ such that h υ is less than 1.1 electron volt, the radiation is not going to get absorbed it will just go through, right.

So, if you look at the spectrum, the solar spectrum and how much energy is available at frequencies which correspond to this such υ that range of frequencies which are all less than the a value required for h υ equal to 1.1 that entire range of frequencies if you take into account, it turns the turns out that 19 percent of the incoming radiation cannot will not be in a position to get a be absorbed by the silicon semiconductor. 19 percent of that radiation will not have a enough energy to enable the transition between the valence band in the conduction band and therefore, it will sort of the material will sort of be transparent to it, it will just not participate in the process it will be lost. So, therefore, that you have lost that by having that, by specifying the band gap you have completely lost that.

Now, look at the other extreme. So, that is not even going to participate in the process. So, it is left. Now, let us look at all values of a υ where E_g is, where h υ is greater than E_g. So, so supposing h υ is greater than E_g. So, supposing h υ is such that it is much greater than E_g let us just say it is much greater than E_g. We will consider a case where h υ is much much greater than E_g. Then what happens is the electron that leaves goes to a much higher level. So, you have done a transition, but you have pushed the electron to a much higher level above the lowest available energy level in the conduction band, it has gone to much much higher level.

So, normally once you do that, that is not going to be a stable situation because there are lot of energy levels below this position which are all sitting vacant right, which are all sitting vacant because that is by definition how the conduction band is being set up most of it is sitting vacant. So, you are pushed an electron very high up because you had that much energy available in the incoming photon. So, what normally happens is it will just come straight down and it will land here. So, it will come back to the, you know sort of the edge of that band it will just come straight down will come to that location of that a bottom of that conduction band and so that is sort of where it will eventually settle down.

So, this extra energy that you have is actually lost right. So, that a extra energy that you pushed into the a conduction band is lost, it just is it is no longer useful for us because it just picked it up and then just dropped right back that extra energy it actually loses its heat. So, this comes off as heat. So, it is lost as heat. So, you end up seeing a situation that even though you have kept a band gap such that everything with energy greater than the band gap can be absorbed by the material and it does get absorbed by the material. It turns out that only energy close to the band gap value is usably available all the extra energy that we have got over and above the band gap is getting lost as head.

And again if you look at the you know a range of a wavelengths available in the solar spectrum if you take whatever corresponds to 1.1 electron volt and then look at all the energies that are available higher than that for all those energies the extra energy is lost. So, essentially you are capturing mostly close to that 1.1 electron volt that is really what you are capturing most of the rest of it you are losing right.

And if you look at the spectrum and you analyze the spectrum of how much energy is available in all those wavelengths that is higher, how much extra energy is available and the fact that all that extra energy is lost you find the 33 percent of excess, a 33 percent is lost by using a frequencies which are higher than what is required for that a band gap. So, for all frequencies corresponding to a values that are greater than that of the band, band gap required frequency all that energy is lost and that corresponds to a 33 percent that is lost.

So, if you simply look at the 19 percent that is unabsorbed and 33 percent excess that is lost because only the close to the band gap value is going to get used to be captured between the two of them you already have lost 52 percent. So, the spectrum losses itself just the spectrum losses just the fact that you have one band gap and it cannot absorb wavelengths of no lower energy and wavelengths of higher energy it will waste some of that energy if you just take that into account 52 percent of the incoming energy is lost ok.

So, now you do the total you have lost 52 percent due to spectrum, spectrum losses, you lost another ten percent due to the recombination losses because of the electron hole pair recombining and another seven percent you have lost due to blackbody radiation. So, this is 52, this is a 62 and if you add all that that comes to 69. So, something like that. So, you are just less than seventy percent you can I mean based on the exact details that you take into account exact numbers will be slightly different.

But if you do, you find that approaching about 70 percent somewhere between 65 and 70 percent is the number you will arrive at which represents the total loss that is that is there from the system simply because of the various phenomena that are occurring based on, you take the exact you know details of what is the temperature what is the material all those things you work on for you get somewhere between 65 and 70. So, that is the loss that you will have.

So, therefore, the and that therefore, what you are actually capturing is just over 30 percent, so 33. So, that is how they came this they arrived at this number 33.4 percent is the more you know more precise calculation you arrive at that number, 33.4 percent is what is usably capture. So, you have about you know 66.6 percent that is lost. So, 33.4 percent is all you can capture. So, that is what the Shockley Queisser Limit is about.

It conveys to us the idea that basically even though solar energy is incident on the solar cell there is an upper limit to what can be captured. So, this is a basic limit. It is there inherent to most of the solar cells that you see around if you go see a solar panel anywhere around in your city chances are it is subject to this limit. So, that is something that you can keep in mind, all right.

So, now, that we know that there is a limit and it is not a very impressive limit we are sitting at 33.4 percent let us see how a cell is constructed.

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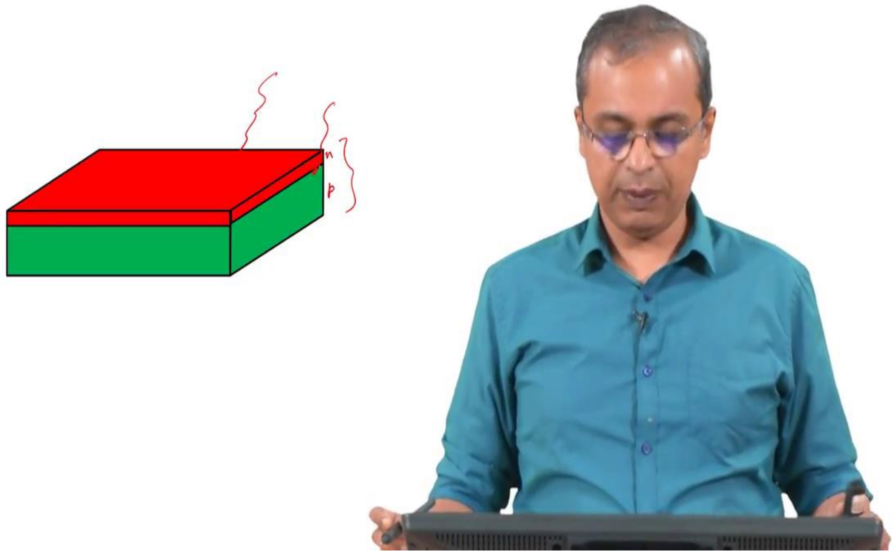

So, the starting point is the p-n junction. So, I will say this is the p material and that is the n material that is there. So, this is p and that is n. So, that is what we have. So, clearly you have all, you know you have a, you have solar radiation that is coming in and it penetrates this material comes arrives at the junction and then at the at the junction you have the electricity, I mean you have the charges getting distributed and then you have the buildup of charges you have electrons getting built up in the n side, holes being built up in the p side and then you can tap, tap it to the external circuit.

So, what do we need to tap? So, first thing we what we need is we need a contact we need to make electrical contact to this material right. So, that is how we will be in a position to tap the electricity.

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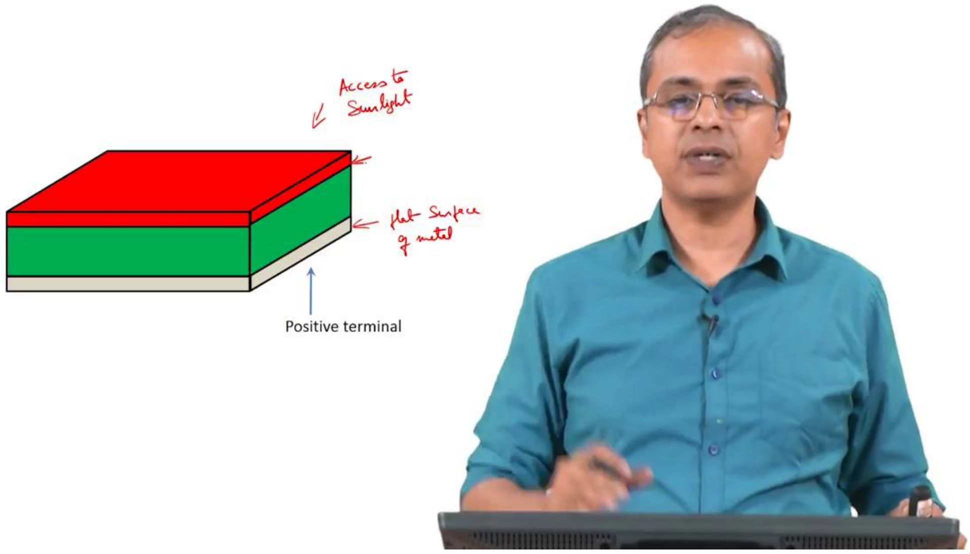

So, first thing we need is a contact and in this case I have pointed out that we have put a material at the bottom which I should call the positive contact. So, some metal I mean you could put say a aluminum for example, a layer of aluminum at the bottom or anything else you which is a high conducting material and then make a contact to it, make an electrical contact which takes us out to the external circuit.

Now, this can be a flat piece, this is a flat surface of say some of metal, some metal basically metallic surface which is flat and then therefore, you can get electricity out of it. Now, there is a problem in the sense that you cannot put the same flat surface on top. If you put the frame flat surface on top, you will block access to sunlight. So, this junction needs to receive sunlight. So, sunlight should arrive at this material, it should penetrate through the top layer and reach that junction. So, therefore, your top layer should first of all be very thin. So, that it you know permits the sunlight to go through and then thin and transparent it should actually arrive at that junction.

On top of that if you are going to put you know electrode on top which is going to capture the electricity and take it out to the external circuit, that electrode should have a design which still enables the sunlight to go through right. So, therefore, you cannot just take a flat surface and put it on top the way you did for the bottom electrode.

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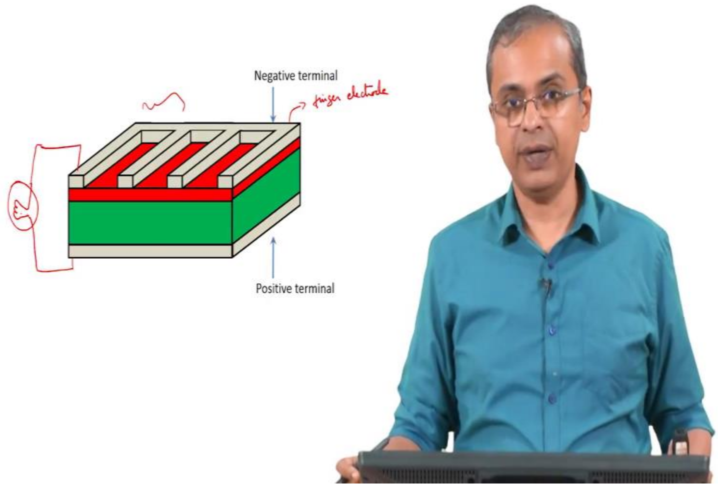

So, what is typically done is to use something called a finger electrode. So, it say, as you can see here it is a shape like fingers. So, this is called a finger electrode and all we have done is you have now put a metallic contact on top so that, but there is a lot of gap in the middle. So, there is a lot of gap in the middle where the sunlight can fall ok.

So in fact, it is because of practical considerations like this the fact that you have you know, but you still see that you know even though you have put a finger electrode you have lost, you have masked a little bit of the area, right, some of the area has been masked. You are not you know hundred percent opening the area. So, because of practical considerations like this only you do not even reach the Shockley Queisser Limit. Even though Shockley Queisser Limit says thirty odd percent you will get what you practically get is more like 21 percent, 24 percent something that is what you are getting.

This is one of the contributing factors to it, it is not the only factor, but it is a one of the contributing factors. But essentially you have to put this finger electrode which basically means that some areas are masked, but you have a plenty of area at various locations where it is open to sunlight where the sunlight can come through. So, that is how the system works. So, you have sunlight coming through, past the finger electrodes goes through the let us say in this case the n material, n layer which is thin reaches the p-n junction and that generates the electricity and then creates the charge I mean electron hole pair, the electrons get tapped through the top electrode which then is the negative electrode and the holes get tapped to the bottom electrode which is the positive electrode.

So, this is your circuit this is basically the structure, this is the basic structure that you use. So, if you basically tap this, you put a wire here and you put a wire here you can essentially have a bulb. So, some bulb you can have. So, you can light up a bulb by doing this. So, this is how you would set it up right. So, that is the structure that we basically create which is the simple p-n junction based single terminal, I mean, sorry, single p-n junction based structure of a solar cell with a finger electrode on top and a continuous electrode at the bottom.

So, this is a something we will keep in mind, we will make some variations on this some modifications on this and we will try to understand what is possible.

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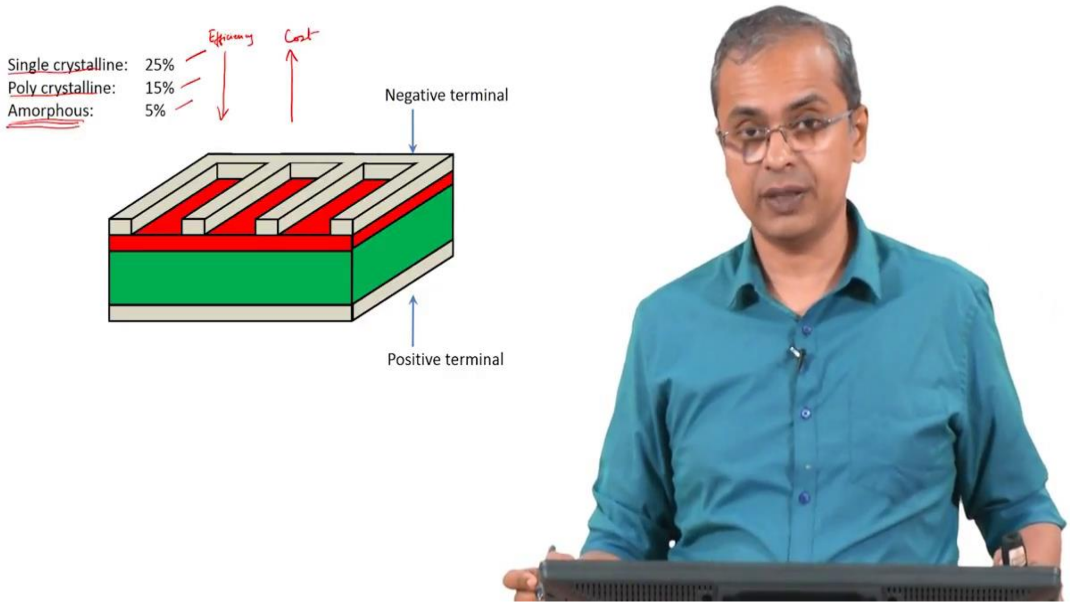

Single crystalline: 25%
Poly crystalline: 15%
Amorphous: 5%

Incidentally in the same context, you know this can be made out of a single crystal. So, a single crystalline material could have been used, a polycrystalline material could have been used or amorphous material could have been used. We discussed these when we discussed you know how the p-n junction can be made and what are the possibilities that we have there.

So, when you do this single junction based solar cell, if that happens to be also single crystalline a silicon then the kind of efficiencies that are reported in literature is of the order of about 25 percent, that is a range there, but sort of the better ones are at 25 percent that is what we are looking at. If it is a polycrystalline material, we are looking at value of around 15 percent as the efficiency and if it is an amorphous material you are looking at 5 percent efficiency. So, this is what we are looking at.

So, efficiency is coming down this way. So, efficiency is, but cost is the other way, cost goes up. So, that is the trade off. You want more efficiency you pay more because you have to create a single crystal if you do not care much for efficiency pay less and then you get a less I mean efficient system. So, if you look at the commercial, I mean the locations where you see this commercial fuel cells, sorry, the commercial solar cells those are for example, on your calculators on the calculators that we tend to buy you know in a shop or any small solar cell that is there on toy they are all in fact, typically amorphous silicon that is what has been used there and the on that basis you have they have created a solar cell that works just fine for the requirements of a calculator because the power requirements are so small that that small sized solar panel a beautifully works for the calculator. So, that is how it works.

But if you want anything more serious, If you want a performance oriented you know a solar panel which will be used you know with the less area, you get a high you know power, let us say to power and electric vehicle or something like that then clearly you have to go for something which is more concentrated in its ability more capable in its ability to capture sunlight and therefore, you will typically go for single crystalline silicon. So, this is the, you know set of things that we have to keep in mind.

Now, I also said that you know amorphous materials are, I mean amorphous silicon is used, there the build this made slightly different. So, I will just briefly I mean alert you to it or you know indicate the way it is put together for an amorphous silicon cell.

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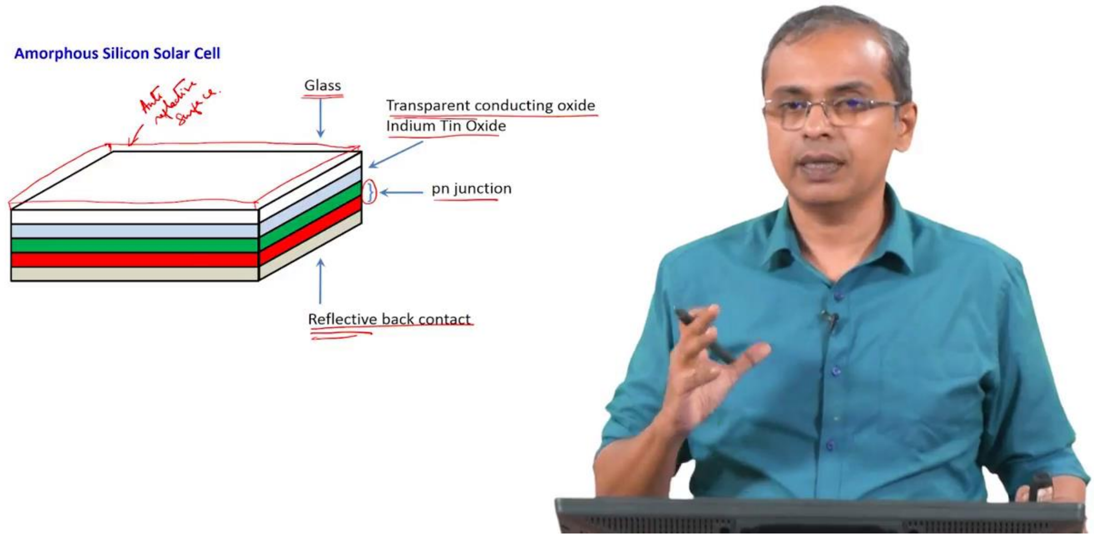
Amorphous Silicon Solar Cell

So, in an amorphous silicon cell, you first need a substrate because by definition it is a film, it is a film that forms. The nice thing about it is, because it is a film you can actually use it in you know in almost any surface. So, therefore, that is an advantage. But in any case, if you want to make it as a cell which we want to sell somewhere, you know as a product then you need a substrate. So, for that typically the substrate is some glass. So, this is actually being built sort of an in inverted way, the glass is the front facing surface and then all these things are happening below it. So, below the glass, they put a transparent conducting oxide. So, these days there is a lot of work on this material the transparent conducting oxide typically it is indium tin oxide. So, it is a transparent material which also has a reasonable electronic conductivity so that acts as your collector for electrons, but at the same time it allows sunlight to go through which is necessary for the p-n junction to function.

So, the p-n junction comes below that which is what you see here, comes below it the p-n junction and that is where the you know charge separation occurs and your electricity generation happens. And in the back, you again have a contact through which you can pick up electricity which is your reflective back contact, but one other, I mean it is a back contact which has conductivity, but you additionally also add the idea that it is reflective.

So, why do we do this? The back contact is made specifically reflective. So, that the sunlight that goes through has sometimes will not you know participate in the electron hole generation process it may just miss the junction interacting in the junction it just go through. So, now, by reflecting it back you are giving an additional chance for the sunlight to get captured therefore, you are sort of increasing the efficiency with which the sunlight will be captured by simply putting a reflective surface at the bottom.

So, the bottom you have a reflective surface, at the top you have a transparent surface. So, those two are things that you do and in the process you create a cell which is still a single junction p, single p-n junction cell, but it is made out of amorphous silicon. So, structure is slightly different from what we just saw, because the other things that we just saw did not require a substrate, but for support here we need a substrate for support. So, that is the primary difference.

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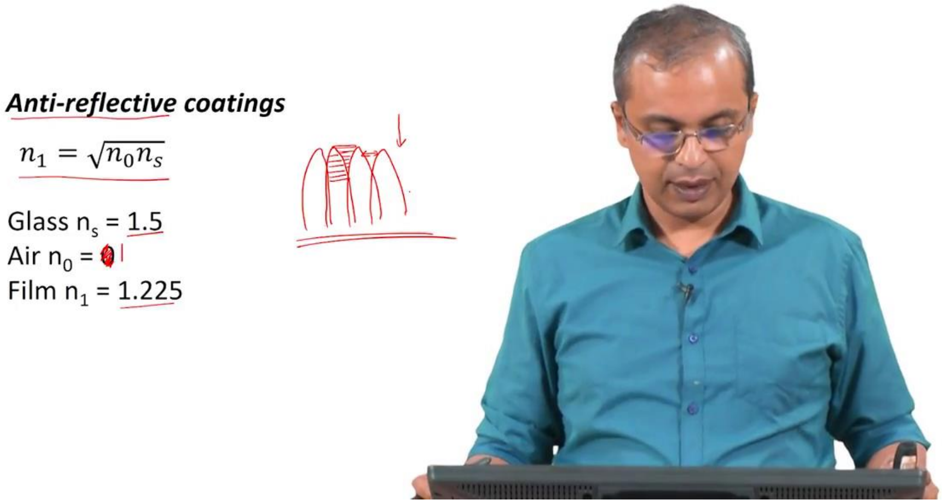

Anti-reflective coatings

$$n_1 = \sqrt{n_0 n_s}$$

Glass n_s = 1.5
Air n_0 = 1
Film n_1 = 1.225

In the context of these kinds of cells, one important parameter you have to keep in mind is that the top surface should be anti reflective. So, if it is reflective then the some of the sunlight that comes to the solar cell is lost simply because it is reflected back right.

So, the top surface needs to be anti reflective. So, for example, on top of this glass, on top of this glass you should actually have a thin anti reflective surface sitting on top of this glass. So, on top of the glass this is an anti reflective surface or coating anti reflective surface or coating. So, this is an area of work that is you know looked at in great detail with respect to solar cells and so basically the idea is this, you have a refractive index for air and you have a refractive index for whatever surface is there a present and the you know with which you are trying to study.

So, the greater the refractive difference in refractive index between the air and whatever that material is the greater the capability of that material to reflect light. So, that is how it ends up. So, you want do the opposite, you want to make the transition from air to the material more gradual rather than abrupt. So, therefore, you put in a layer in the middle which has a refractive index which is in between that of glass and that of air. So, glass typically has refractive index of about 1.5, air has the refractive index of 1 actually and the. So, this is not 0, this is 1.

So, the film refractive index is actually the geometric mean, geometric mean of the two refractive indices that are present n_0 and n_s. So, you will get a, you know the square root of 1.5 in this case and therefore, that is roughly about 1.225. So, if you have a refractive index of a 1.225, it is significantly anti reflective with respect to sun sunlight coming through the air and entering the glass surface. So, these kinds of anti reflective coatings are worked on and in fact, in this context a there are lot of work is done even with respect to say a bio mimicry. So, for example, people look at the eyes of moths and those are considered very non reflective and there it is done with respect to structure.

So, what is done is, you have a series of, so to mimic that you will have a series of a structures that look like this which are very closely spaced and then the closely spaced in the sense that this spacing should be of the order of the wavelength of the of the radiation that you are looking at. So, there is some a specific calculations that you have to look at, but it is in that order, so wavelength of the radiation. So, what is happening is as you go down you start by seeing more of air, you see less of air, less of air, less of air, less of air, less of air you see start seeing more of this material.

So, therefore, the refractive index gradually changes from that of air to that of the material and that is a much more smooth change of refractive index, and so a lot better anti reflective properties are there. So, these kinds of structures are also being examined of course, I have drawn it in large scale, but this is as I said you know we are looking at structures which have dimensions in the wavelength of a light. So, there are few micron or you know a few you know fractions of microns that is what you are looking at to get you the structure. So, that is also being a looked out it creates these anti reflective coatings.

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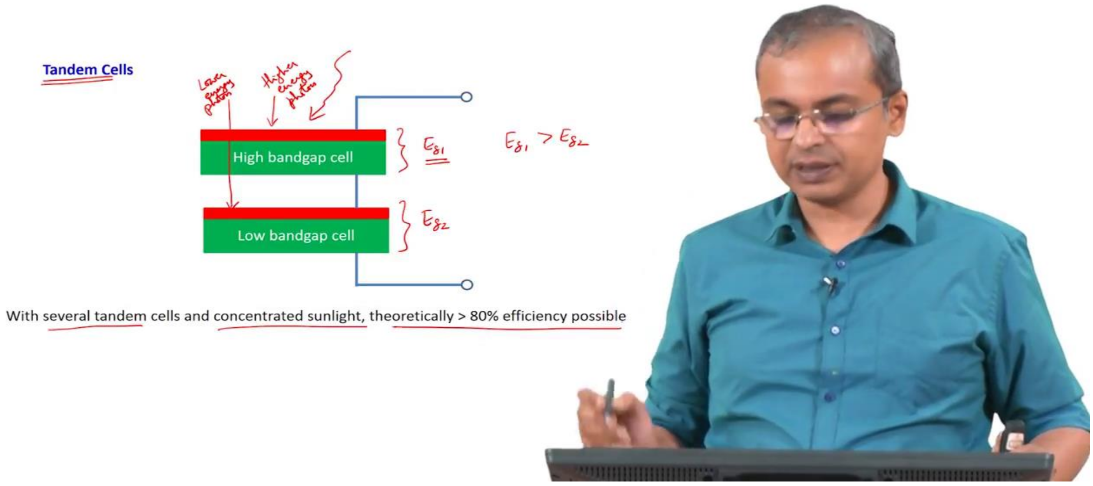

Tandem Cells

With several tandem cells and concentrated sunlight, theoretically > 80% efficiency possible

So, we looked at how the; we looked at a limitation of the traditional solar cell, traditional single junction solar cell and we also looked at a how the solar cell is constructed, you looked at a various parts of it, looked various parts of the graphitic I mean I am sorry the amorphous silicon solar cell and we also looked at the anti reflective coatings. So, we looked at all of them.

Now, given that we are stuck with this 33.4 percent efficiency is there anything we can do to make it better is the question that we would like to address. So in fact, there is a very nice solution to it using you know just plain incoming sunlight which is to use something create something called a tandem cell, but it is a bit tricky people have shown it, it can be done and therefore, it is a road worth traveling, but it is not an easy thing to do. So, what we are actually doing is we are putting two solar cells in series. So, you have E_{g1} and E_{g2} and the idea is that E_{g1} is greater than E_{g2}.

So, what happens? You have a radiation coming in, you have a solar radiation coming in which has a range of frequencies. So, if the frequency is less than that required to be captured by the first material that frequency will go through. So, that frequency the, so the lower energy photons, lower energy photons will go straight through and arrive at the lower material the higher energy photons will get absorbed. So, lower energy photon and this is the higher energy photon. So, the higher energy photon gets absorbed by that top cell. So, all the photons are arriving at the top cell, but only the higher energy photons which are which have energy greater than the band gap of that top cell get absorbed by the top cell. The rest of the photons which have energy less than the band gap of the top cell go through the top cell they go to the cell below it and they get captured by the cell below because that has a lower band gap.

So, this is a nice way in which you now have got two band gaps and therefore, the first one can capture some number of photons effectively, the second one will capture some of the remaining photons more effectively. So, overall you have captured even more photons, so, than you would have done if you are used either one of them separately right. So, you can see it is a very simple way in which you can increase, I mean effectiveness with which the same surface area can be used to capture solar radiation.

So, in fact, that is how they are constructed there, these are solar cells where they have shown you know two layer, three layer, etcetera, where you have to create these layered structures such that there is also enough transparency that you know the a light is able to go through. So, that is how these cells are created.

So, with several tandem cells and using concentrated sunlight, if this does not really require concentrated sunlight, but supposing you also add that as a factor theoretically greater than 80 percent efficiency is also possible, so 33.4 percent is one end of this you know of the possibility, but if you actually do tandem cells, you do other things to help you know the improve the capability of the cell to capture sunlight then you can actually end up with the numbers which are much more impressive, 80 percent of what is falling on that location can be captured.

So, clearly there is a way in which you can go around the limitation that the you know single junction solar cell presents to us and therefore, it is of very good interest to of all. So, in this context you know it is nice to know that you should be, your, you can do this, but how do you get you know materials with all sorts of a band gaps right. So, of course, you can look at the literature for every material there is some band gap and therefore, we can pick band gaps that you want, but those are some numbers that you do not have control on, you pick a material that has some band gap and then you can look at a table you will find them it another material which is say 0.3 electron volts away from it and that may be the nearest band gap material available you have to just take that and go.

So, the gradation of band gaps is, at first glance appears something that you do not have much control on.

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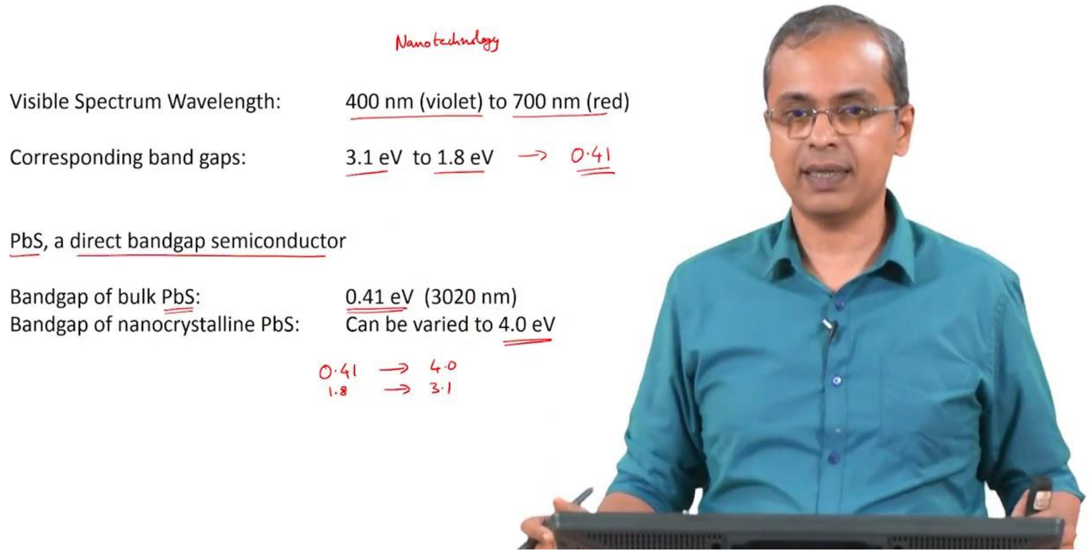

Nanotechnology

Visible Spectrum Wavelength: 400 nm (violet) to 700 nm (red)

Corresponding band gaps: 3.1 eV to 1.8 eV → 0·41

PbS, a direct bandgap semiconductor

Bandgap of bulk PbS: 0.41 eV (3020 nm)

Bandgap of nanocrystalline PbS: Can be varied to 4.0 eV

0·41 → 4·0

1·8 → 3·1

But we have some interesting solution to that what is the interesting solution, solution is the word that is very popular in material science these days which is nanotechnology. It turns out that when you take a material and let us say it has a bulk band gap some bulk band gap value and you keep making the a size of that material smaller and smaller and smaller. So, you take crystals of the material large crystals and then you start making them smaller and smaller and smaller, when you go when the crystal size goes into the nanometer scale of sizes, it turns out that the band gap begins to change.

This has got to do with how the electron hole pair is confined within that system etcetera. So, we will not go into the physics of it in great detail, it is called the exciton, how it is confined in the system. But we will not go into the that part of it in great detail, there is a something called a excite on bohr radius and that when this size approaches that radius this effect begins to appear. For us it is sufficient to note that when you go to the nanometer size scale then the same material exact, same material begins to demonstrate at different band gap same chemically its exactly, the same crystal structure is exactly the same, you are not making any difference to those, but the band gap begins to change simply because the crystal sizes become very small.

So, for example, we already saw this that you know visible spectrum has 400 to 700 nanometers range of wavelengths that corresponds to band gap of 3.1 to 1.8 electron volts and silicon is you know 1.1 electron volt band gap. So, you have lead sulfide as a material which is a direct band gap semiconductor, we spoke about direct versus indirect. So, this is a direct band gap semiconductor. The bulk band gap of lead sulfide is 0.4 electron volts. So, that is well below this. So, it is well below this. So, it is well into the infrared part of the spectrum, significantly into the infrared part of the spectrum right. So, so that is where 0.41 will show up. But if you start going to the nano-crystalline size, same lead sulfide, you start creating nano-crystalline version of it, it turns out that you can start changing this band gap, you can keep changing it, you can, this is called band gap engineering or tuning the band gap.

So, you can change the band gap from 0.41 electron volts all the way up to 4 electron volts. So, 0.41 to 4 and your visible spectrum is bang in the middle 1.8 to 3.1. So, suddenly you have a material, same material available such that it has a band gap which can pick up infrared, it can it has a band gap that can pick up red, it can pick up the visible spectrum, it can pick up violet, it can pick up ultraviolet. So, the entire spectrum can be captured by the same material by creating layer after layer after layer after material each one having a different band gap. For example, I mean that is just a example there may be other issues that we have to keep in mind, but that possibility shows up.

So, now you do not have to go and you know leaf through your you know pages of data and find out which material is the next material you should use, what is the other material you should use, you have 1.3, can you get a 1.4, can you get a 1.5. So, you do not have to do all that. By just doing this you know change to the material you are now got the a material with a different band gap and therefore, potentially you have a continuous range of band gaps available to you which you can use to create tandem cells of a any type that you wish.

So, of course, these are like I said you know these have all been shown experimentally, I mean ability to change these band gaps and create all these materials, but to make a solar cell that really utilizes all this and then shows you that dramatically improved efficiency is always going to be a technical challenge and it is still a technical challenge to do that. So, we are still not quite out there in terms of the kinds of efficiencies that people would like to see in a solar cells or solar panels.

So, that sort of the state of a affairs right now with respect to solar energy, but this shows you the possibility it shows you where the research is right.

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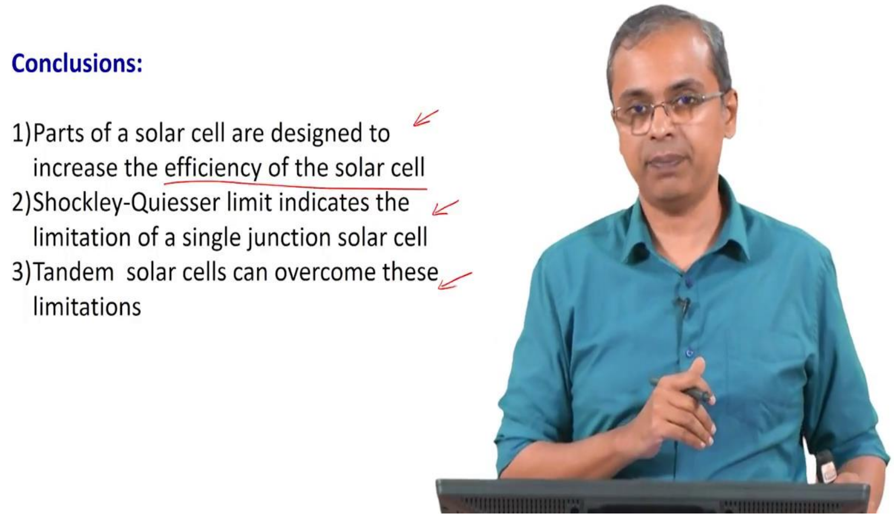

Conclusions:

1) Parts of a solar cell are designed to increase the efficiency of the solar cell
2) Shockley-Quiesser limit indicates the limitation of a single junction solar cell
3) Tandem solar cells can overcome these limitations

So, in conclusion, we saw that there are various parts to a solar cell and these parts are designed as you may expect to increase the efficiency of the solar cell. So, that includes everything from you know having an anti reflective coating, having a finger electrodes, having a backing layer and if it is a thin film based amorphous film based solar cell, then you have the backing layer also being a reflective layer to reflect back some of the sunlight so that you can improve the efficiency with which the sunlight is captured.

We also saw the Shockley Queisser Limit and it shows us that just because of you know blackbody radiation related losses, radiation related losses, then recombination related losses where the electron hole pairs simply recombine and are lost and also due to spectrum losses. Simply because a single junction solar cell will not be in a position to capture all wavelengths effectively it only captures wavelengths very close to that just marginally above the band gap that is what it captures most effectively and even other wavelengths it captures it effectively is gives you only energy corresponding to that.

Given all that taking all that into account the Shockley Queisser Limit shows us that only about you know one-third of solar incoming solar radiation can really be meaningfully captured using a single junction solar cell.

We also saw that tandem cells, which you know keep one cell of one band gap on of a higher band gap over and above a cell of lower band gap, actually overcome, that is one way in which you can overcome this Shockley Queisser Limit, such that in the same region you suddenly have more wavelengths being captured effectively when compared to a system where you have only one band gap material being used.

So, there are interesting ways to work around it and therefore, there is a lot of promise in solar energy and a lot of companies that work on, a lot of a governments push hard for it, mainly because of you know in principle it is quite clean and there is a potential that there is enough energy available for us to capture. But there is still a lot of research to be done and therefore, it still remains in area for active research and development and I expect that it will remain so for some period of time.

So, with that I would like to conclude this class.

Thank you.

Introduction: In this lecture, the efficiency aspects of a solar cell are discussed. The construction of different types of solar cell and the concept of tandem solar cells to increase the overall efficiency are discussed.

Keywords: Efficiency of solar cell, Techniques to improve solar cell efficiency, solar cell construction, tandem solar cells.