Non-conventional Energy Resources
Prof. Prathap Haridoss
Department of Metallurgical and Materials Engineering
Indian Institute of Technology, Madras

Lecture – 17
Solar Energy: Solar cell characteristics and usage

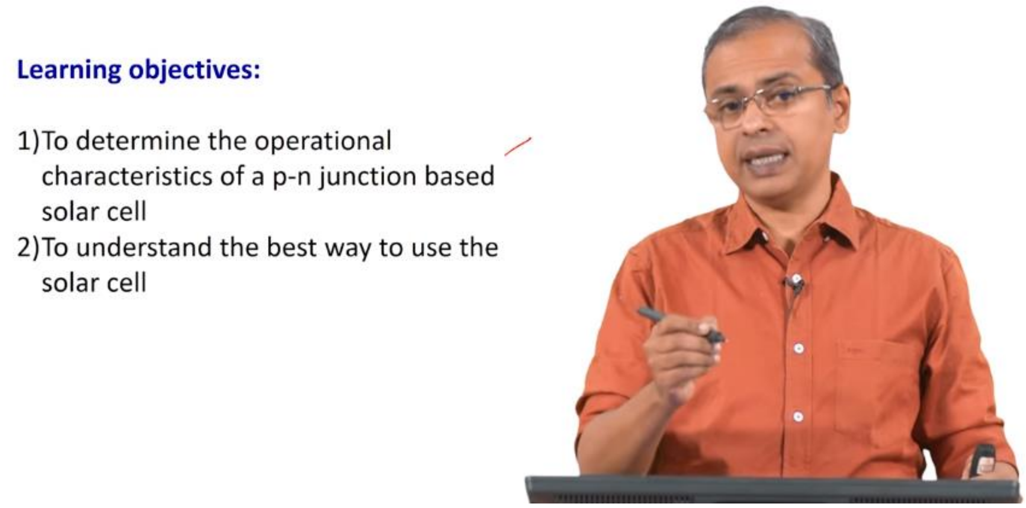
Hello, in the last class we looked at how the p-n junction interacts with incoming radiation. So, we have a p-n junction based solar cell, which is our typical photovoltaic solar cell and then you have incoming radiation, we looked at what happens across the boundary, we looked at you know how the charges are, charge carriers are created on each side of the boundary and the fact that because there is a boundary, because there is a depletion region or a space charge region, and because there is band bending; the negative charges accumulate to one side, the positive charges accumulate to the other side and that is how we have the charge separation and therefore, you have some stabilization of the charges and then you are in a position to tap it for electricity outside.

We also understood the fact that, this is you know p-n junction, it is functioning as a diode and so, you know if you have the charges appropriately positioned, you have excess positive charges on the p side and excess negative charges on the n side, then you have automatically no forward bias the diode and this does not have to be necessarily using a battery in an external circuit, even internally due to incoming solar radiation when you do that, you create a forward biased p-n junction and therefore, that has some characteristics associated with it.

So, in this context we also looked at you know circuit elements that describe what is happening with respect to p-n junction, when you attach a load to it, p-n junction based solar cell when you attach a load to it, what are all the various components that sort of show up in that circuit, and what are they representing, you know how the current flows etcetera we had some diagrams that we put up. So, from there we will take it a little forward here, in this class we are going to look at the solar cell characteristics and usage; sort of from an external circuit perspective we looked at it only as a p-n junction previously. Now, we will take that I mean fundamentally it is a p-n junction. So, those characteristics are going to be there.

So, we are going to try and see what we can understand; in terms of you know given that these are the characteristics of the inherent junction, what are you likely to see in the external circuit and what are some you know ideas associated with that. So, that is the point that we are going to see and that is what I mean by saying solar cell characteristics and usage, in terms of usage also how those characteristics, because that is what the external circuit says. So, we have to understand in terms of usage what are the implications.

(Refer Slide Time: 02:44)



So, our learning objectives are to determine the operational characteristics of a p-n junction based solar cell, which is what as I said is how the solar cell will behave with respect to an external circuit. So, once an external circuit is hooked up to it, what is the behavior that the cell will display towards it, what can the external circuit expect out of it. So, that is one important thing that we are going to look at.

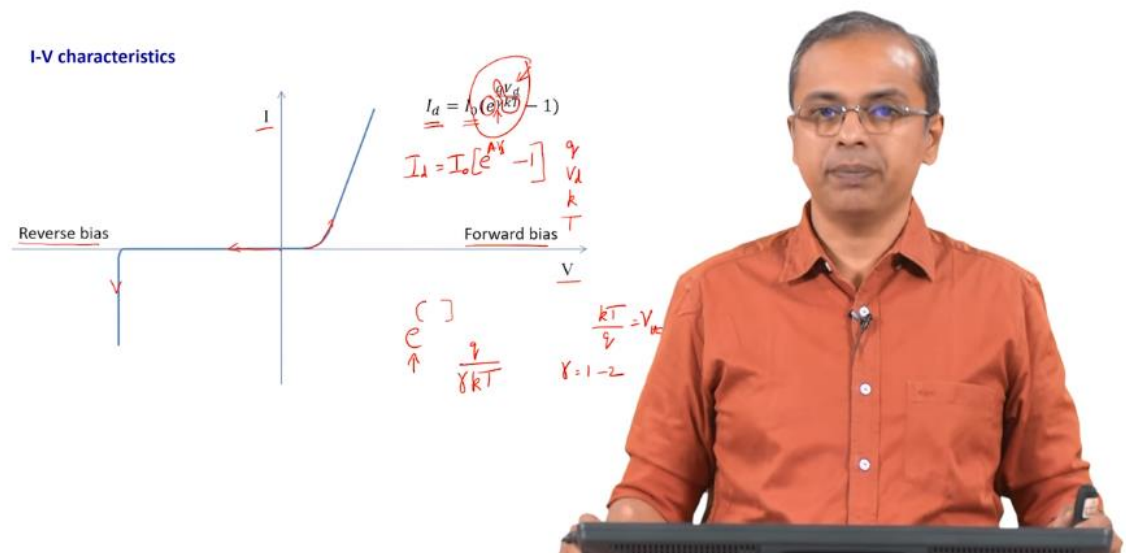
And once you understand that, we are also going to look at, using that information using that understanding, we are going to see what is the best way to use the solar cell. We are going to look at what is the best way to use the solar cell, because the solar cell has some characteristics and as you are going to see in this class, if you ignore those characteristics you could use the cell in a very poor way, very ineffective way, and as a result you will not get the full benefit of the solar cell.

So, you have to be conscious of those characteristics and only then you can make the best use of the solar cell and you have to keep that in mind both in terms of you know when you buy the solar cell, what to expect from it when you use the solar cell, what to expect from it, how do you compare solar cells that are available all those things are intricately related to this idea that it has some characteristics and you need to know those characteristics to; characteristics meanings it is behavior, when how much current it will give at what voltage it will give that that is what I am referring to as it is characteristic.

So, as the voltage changes, the current changes and so, there is some graph that comes out of it. So, you have to know that, only then using that plot for you know different solar cells you can compare them, you can compare this as a you know function of time as the solar cell ages, and also what is going to happen to that characteristic as the sun moves. So, let us say you have bright sunny day, you are going to see some behavior, cloud goes on top of it some period of time, on top of the solar cell and therefore, blocks the sunlight a little bit. So, is going to be a drop in intensity of the sunlight. So, then naturally the behavior of the solar cell is going to change.

So, how do you understand that behavior and therefore, how do you keep that also in mind when you operate the solar cell. So, these are the kinds of things that we are going to look at when I say; what is the best way to use the solar cell? So, these are the operational parameters that we are going to look at in this class.

(Refer Slide Time: 04:58)



Okay, so, as we already plotted once in one of our earlier classes we looked at this plot, this is the current voltage characteristic for diode and so, you can see that, this is the forward bias and this is the reverse bias. As we discussed in the forward bias we reduce the space charge region or the depletion region and then pretty soon the current starts flowing.

So, for up to some voltage you are fighting the you know a voltage that was in inbuilt in the system, and then eventually you overcome it and then you start flowing current and so, after some point you see a steady increase in current. So, this is what you see. In the reverse direction, you have a very small reverse saturation current which is almost negligible in the scale, you do not see it here and then from there on you basically have know you keep building potential in the negative direction, it keeps growing the space charge region and therefore, becoming more and more of I mean resistor or more and more of a blockage to the flow of current, and then eventually this material breaks down and then you have this sort of you know breakdown voltage after which you see very high current, but that is not really the mode in which we want to typically operate this diode.

So, if you want to; for the purpose of this class, we are going to look at some equations and the main thing that we need to look at here is this equation that you see up here, which relates the diode current I_d to the diode voltage that is shown here. So, diode current to the diode voltage is the relationship. So, this may look a little complicated, but actually we are not going to derive this, if you actually look at semiconductor textbooks they derive this. Primarily to derive this they are looking at you know how the charge carriers are created, how the charge carriers move from one side to the other and from the other side to this side, the majority charge carriers, minority charge carriers, what role are they playing all of that is looked at and based on that you come up with this idea of what is the current when you have some amount of voltage.

Now, you will see here there is an I_0, this is the reverse saturation current, the small value that you will see somewhere out here, it's the reverse saturation current and you see here some parameter. So, you have q that is the charge on the electron, the V_d is the voltage on the diode. So, that is what we have there and k of course, is Boltzmann’s constant, T is the absolute temperature. So in fact, we even talk of this you see this kT by q or q by kT, that is listed here, but if you write it as kT by q that is referred to as a thermal voltage ok.

So, you have a parameter like that, which we will, we are not really deeply interested in that and one constant here gamma, in different books they call it gamma, eta, n and so on, which deals with ideality or non ideality of the system. Usually gamma has values between 1 and 2, 1 to 2. So, that is sort of the number that we are looking at for gamma, it is something representing how ideal or non ideal the system is, in fact, it relates to all at the discussion that we had on direct band gap semiconductors, indirect band gap semiconductors and so on.

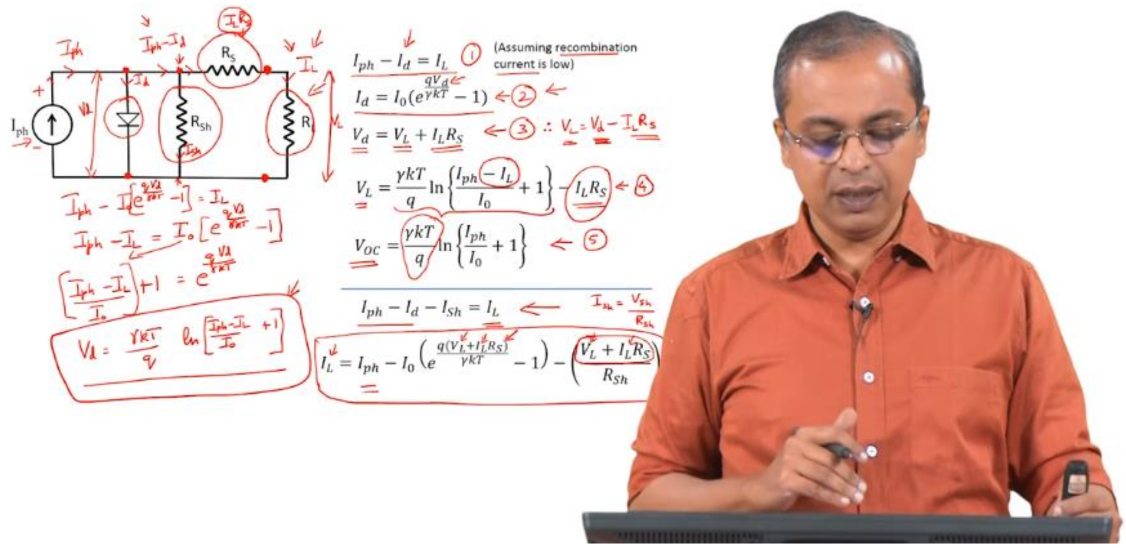
So, there are some terms out here and actually this whole exponential part, this is the fact that you have an e power something. So, e power some you know e power something you are having right. So, this e power something comes from the equation for the charge carrier concentration. So, the behavior of the charge carrier concentration is what results in this e; e power something and that is how we know eventually when you and you have to you need these charge carriers to do the current to you know carry the current so, to speak. And therefore, in the current equation the sum term corresponding to the charge carriers is going to show up and therefore, you end up having this exponential term that you see out here. So, that is how that exponential term ends up arriving.

So, we find that I_d is related to, the current in the diode is related to the voltage of this diode using this equation that you have here, where you have an e power some constant. So, you can call you know q by gamma kT is all constant. All these are constant once you set the temperature, once you set the temperature to be something then q by gamma kT is a constant. So, you essentially have, you can even write this as I_d equals I_0, e power some constant let us say A V_d minus 1. ok, minus 1.

So, A V subscript d. So, A V d is subscript, V subscript d minus 1. So, this is basically what we have, in our subsequent equations, I will still keep the you know q by gamma k T available, but you just have to keep in mind that it is simply it does not, it is not as complicated as it looks on the, when once you write all the terms, but because it is all several of them clubbed together as a constant and so, that is just something that you have to keep in mind. So, this is the relationship of I_d to the V_d.

So, this relationship we will use to understand how the solar cell behaves as you attach some kind of an external circuit to it.

(Refer Slide Time: 10:53)



So, if you go here, in this page we have a bunch of equations, I will walk you through them. So, there is nothing to worry about. The primary equation is what you saw here. So, let me just clear some of this. So, it is clear to you. So, the primary equation is what you see out here, which is how the I_d relates to V_d. So, just keep that in mind and I am going to show that again the next slide and so, even though there are several terms, in fact, it is just some simplification of a set of terms, which includes this particular term of I_d which is the diode current ok.

So, now we saw in our previous class the equivalent circuit. So, I will just walk you through the equivalent circuit and then go through these equations. So, that we understand what is the various parameters and how they relate to this equivalent circuit. So, on the equivalent circuit you see this; this is where your solar cell is sitting and that is creating this photo current. So, there is lot of light falling on it photo current is being created.

So, this is the direction of conventional current. So, you have positive charges heading off that way and this is the, so, this is the same diode in. So, you have positive this side and you have negative this side, and clearly this the internally it is a diode internally as I said it is a diode and so, when you build up more positive charges on the p side, and more negative charges on the n side, you have internally forward bias the diode. So, this is that diode that we are talking of internal; internal to the solar cell. So, this is not a external circuit this is internal to the solar cell right. So, this is a forward biased diode.

And so, some amount of current will flow through the forward bias diode, and internally get consumed. We do not want that to happen, but that is what is going happen. So, some will always happen that way. So, that is going to happen, then we also saw that you know if you generate all these charge carriers, there is always going to be some recombination that is a occurring. So, that is internally again you know sort of an internal shunt resistor that we are putting here, which basically means this you are getting a opportunity for those electrons and holes to recombine within the solar cell. And when it recombines that is again some current that you cannot get in the external circuit because you have lost the charge carrier, you created the charge carrier and so, it shows up as part of a photo current that you generated, but you lose it before you get to the external circuit it is consumed internally.

And then you come to the finally, you manage once you get past these two processes; you get some current out into the external system. So, when you get the current out through the external system it has to anyway go through the entire internal processes and arrive out of the circuit. So, the current flows through a solid you know some solid region, physical region through which the current flows right.

So, corresponding to that there is some resistance. So, even within the cell there is some internal resistance that it has to flow through and then come up. So, that is this resistance in series. So, in essence that is also internal to the cell. So, internal to the cell may you can also include contact resistance whatever, all that is included in that. So, when you get past this point only, you are actually reaching the external circuit. So, you get past that point you reach the external circuit. So, essentially you can say the external circuit is here, between here and here. So, this side is your external circuit.

So, this is how the; So, and we are saying you know there is some load resistor out here and that is your external circuit. So, this is how the various parts of the solar cell internally operating in their own natural ways, contribute various components to the circuit which then is operational within the solar cell, and then after you cross this internal circuit you arrive at the external circuit which is your R_L, load resistor right. So, that is why this is called like an equivalent circuit, what of, whatever the solar cell is.

Solar cell you look at it you do not immediately see physically a resistor there, you do not physically see you know diodes separately sitting there. If you put all of them together you will sort of see this, but you recognize that there internally all these things are happening and then you can put the circuit together. So, that is what it is. So, this is how you get this circuit to work.

So, now let us look at a few parameters here, let us look at the first equation. So, as I said in fact, most of the equations even though you have a page full of equations here as I walk you through you will find most of them are actually quite straightforward, the only equation that may not immediately you know is something that you have to look at a little bit more is the actual relationship between I_d and V_d which we saw in the previous slide. So, beyond that most of it will be fairly straightforward, but we will still walk you through I will walk you through of the process that is happening here.

So, you have I photo current that is coming here, and then we will we have some. So, this is I_{ph} that is what we have here. So, coming out here is I_{ph}. So, that is what has come of the solar cell as a result of the; you know charges sunlight falling on it. Now, from there some current goes into this I diode. So, some current goes there right. So, what is the remaining current? The remaining current that is coming here is simply I_{ph} minus I diode, right; simple, straightforward. So, you had I_{ph} start of I diode went off into the, through the diode, which is internal to the solar cell and then the remaining current headed out in the in the external circuit I mean towards the external circuit which is I_{ph} minus I diode.

Let us assume we have a very good solar cell and so at least to some degree to simplify our calculation, we can take it into account, but we will at this moment we will you know neglect it. We will assume that the recombination current is very low or in other words this shunt resistor is very high and a new cell it may, you can may be assume that is reasonable assumption, temporarily we will assume that is the case. We would in fact, include it later, but for the moment we will ignore it.

So, we will ignore that there is any shunt resistor here. So, this is the current that starts moving this way right. So, now, if you look at your load resistor here, the current that comes here, we are calling as I_L the current that is going through the load resistor. So, the first equation is simply that. This I_L is basically this I_{ph} minus I_d. So, this I_L is whatever is coming from the solar cell and that what is coming from the solar cell is the photo current minus the diode current. So, that is your first equation, I_L equals I_{ph} minus I_d or I_{ph} minus I_d equals I_L, way I have written.

The second equation we have here is what I showed you in the previous slide. It is simply an equation, which relates the diode voltage to the diode current. So, that is all that equation is. It relates diode voltage diode current, as I told you that comes from the basic behavior of the charge carriers inside the you know inside the semi conductors, and how they move across the junction, what is the flux going one way, what is the flux going the other way etcetera and then once you do all that calculation will arrive at that equation. So, that is that equation which we are not deriving which as I said you can look up in a book associated with semiconductors, but that is the one equation you have to look at.

So, now if you look at it, what we can do is, we can substitute this equation into this here. Okay, so, I have an expression for I_d, I am going to substitute it in equation 1 which is, let, let me call this equation 1. So, I am basically going to substitute equation 2 in equation 1 and do a little bit of rearrangement. So, little bit of rearrangement. So, so that we can you know put something together. So, let just substitute it there and then we will take a look. So, if I want to write it in terms of say, let us say I_L, I_d is we are put this equation now. So, I just put that down there I_{ph} minus I_0 e power q V_d by gamma k T minus 1 equals I_L ok.

So, that is the thing we want to do. So, let me do some rearrangement here, if I want an expression for the diode voltage. So, in terms of the currents that are out here. Supposing I want an expression for the diode voltage in terms of the currents that are present here, what would I have to do? I will rearrange this. So, we have I_{ph} minus I_L. So, I am just moving the I_L to this side and moving the other current to the other side equals I_0 to the power q V_d by k T, gamma k T minus 1. So, I have just rearranged. So, now, I will move the I_0 this side and I will move the 1 also to the other. So, I will basically do that here, I_{ph} minus I_L by I_0 and then I can, so, this is now one term and then I can move the 1 to this side. So, that will become a plus 1, equals e power q V_d by gamma k T, ok.

So, now if we take natural logarithm on both sides, so, you basically and then do a little bit of rearrangement, you will get V_d equals, so, I will take the natural log here. So, I will put here lon of I ph minus I_L by I_0 plus 1. And this is q and this would have been a q by gamma k T would have been that next to this. So, here you would have had this q by gamma k T sitting here. So, I will shift that to the other side. So, I will have gamma k T by q. So, I have just. So, therefore, we have got an expression for the diode voltage, in terms of the currents that are present ok.

So, that is the other one equation that we have arrived at, simply by looking at how, by simply substituting equation 2 in equation 1 which is simply the expression for how the diode current varies as a function of diode voltage into expression one, which talks of how the current is distributing as it comes off the solar cell into either the load circuit or into the diode that is internally present within the circuit. So, once you do that in terms of the current. So, now, we only have the load current the photo current and I_0 that are present there and with respect to that we have an expression for V_d. So, this is what we have put together.

Now, let us look at equation 3. So, what is equation 3? We are simply saying that there is a voltage across this diode. So, that voltage is this voltage V_d. So, that voltage is this from here to here, what voltage you see, is the voltage V_d. The voltage that you see here across the load resistor, the voltage that you see here is Vload V subscript L, that is the load resistor right and so, the voltage across the load resistor is V_L. So, how do V_d and V_L relate. We just had a relationship between you know I_d and I_L right, we came up with this equation 1 which is a relationship between I_d and I_L, which says that you have so much photo current something went into the diode remaining current goes into the load.

Similarly, we can think of a relationship between the voltage across the diode and the voltage across the load. What is the relationship? Whatever is there across the diode will be equal to load because that is the source from where the, we know that is where the current is generating, that will be equal to whatever is there across the load plus the IR drop across this resistor R_S right. This resistance, series resistor, resistor due to all the internal resistance is present in the diode and the contact resistances. So, if you include all that that is the resistor there. So, the IR drop across it is a voltage drop. So, you have generated a diode voltage, but some of the due to the current going through this series resistor there is an IR drop, the remaining voltage goes to the load ok.

So, what is this I? This I is the same I that is coming here, this is the same as in this circuit you only have I_L, once you cross this point you only have I_L. So, this is actually I_L, I subscript L is the current, it is not just some I, it is I subscript L, it is a current that is going into the load, it is also the current that is going into the series resistor, I subscript L and the resistance there is this series resistor R_S. So, therefore, the voltage of the on the load plus the I_L R_S together will equal the voltage across the diode. So, that is what we have here, the voltage across the diode is equal to the voltage across the load plus the IR drop that was there on that series resistor. So, V_d equals V_L plus I_L R_S.

So, now what we are simply going to do is, we are going to rearrange this. So, we are simply going to say therefore, V_L equals V_d minus I_L R_S. So, this is what we are going to, we are simply rearranging that equation, and for V_d we have an expression here, right. We have an expression here for V_d. So, that V_d I am going to substitute there. So, that is exactly what we have done in this equation here, which is the equation four if you want. So, what have we done, V_L is still here, as you can see whatever this V_L is the same V_L that shows up here. For V_d, I have put in this expression out here. you can see the same thing here gamma k T, gamma k T and then q the denominator, natural log and then I_{ph}, I_L, I_0 which is exactly what you see in the equation that we have derived below plus 1. So, that is the, so, we have basically got all the terms there right. So, so that is V_d the diode voltage and this is the IR drop which is the same as this term here fine.

So, now this is the equation which relates the load voltage to the parameters that you see which is the load current for example, and most of the other things basically being constants. So, that is essentially what we do. Now, in many of the, you know sources that we buy, we are interested in knowing what is the open circuit voltage right. Open circuit voltage is something that we typically associate as a parameter that we should check. So, I am going to caution you here that in a solar cell there is an open circuit voltage, but as you are going to see, as we go forward that that is not the best parameter to follow. So, keep that in mind, that it is not going to be the best parameter to follow, but at the same time there is an open circuit voltage and we need to know what it is. So, and it is of interest to know what it is.

So, in this equation, equation 4, basically if you want to find out what is the open circuit voltage, the main thing that you have to do is to set the load current to 0. It means there is no load right. So, you remove this entire R_L you remove R_L. So, it is open. So, therefore, since it is open there is no R_L there the circuit is not complete there. So, there is no question of an I_L going into that circuit right because there is nothing there it is just open. So, if you set I_L equal to 0 whatever voltage you get, as the voltage across the load will then essentially be the open circuit voltage. So, whatever voltage becomes available at that point is the open circuit voltage. So, if you set I_L equal to 0, then this term drops to 0, I_L R_S drops to 0, and this I_L also drops to 0, right.

So, if you just do those two things, you will arrive at equation 5. This is exactly the same thing, this is open circuit voltage here, you see this gamma k T by q sitting here the natural log of I_{ph} by I_0 because I_L has dropped to 0 plus 1 and that is all there is there is no other term here. So, this is the open circuit voltage. Similarly, we can also see that you can write similar equation for the currents.

So, now, let us say we also assume that there is a shunt current, there is a small amount of current that goes through the shunt. So, we have what? We have actually the load current whatever comes off as the load current will be, we previously looked at only I_{ph} minus I_d, we can also consider this I_{sh} the shunt current. So, if you subtract the diode current as well as the shunt current from the photo current you will arrive at I_L right.

So, that is really all you have to do, and to do that the I_{ph} is whatever it is right and for the I diode we look at equation 2. Equation 2 has the I diode except that for the V diode I am just elaborating the V diode in terms of the load versus the, we are going to use equation 3 in fact, for the V diode. Instead of just putting V diode here for V diode I am going to put equation 3. So, that is why you see that here instead of q V_d by gamma k T I have q times V_L plus I_L R_S by gamma k T. So, that is the additional detail that is there and then minus 1 which is the same as in equation 2, and then the shunt current is simply whatever is there on the load. So, basically for the shunt current we simply want I R_{sh}. So, we will simply say that you know the shunt current I R_{sh}, I mean sorry I_{sh} is simply the V on the shunt, on the shunt by the R of the shunt right that is all you need to know that you have a voltage across a shunt, you have a resistor corresponding to the shunt. So, V by R is the your shunt resistor.

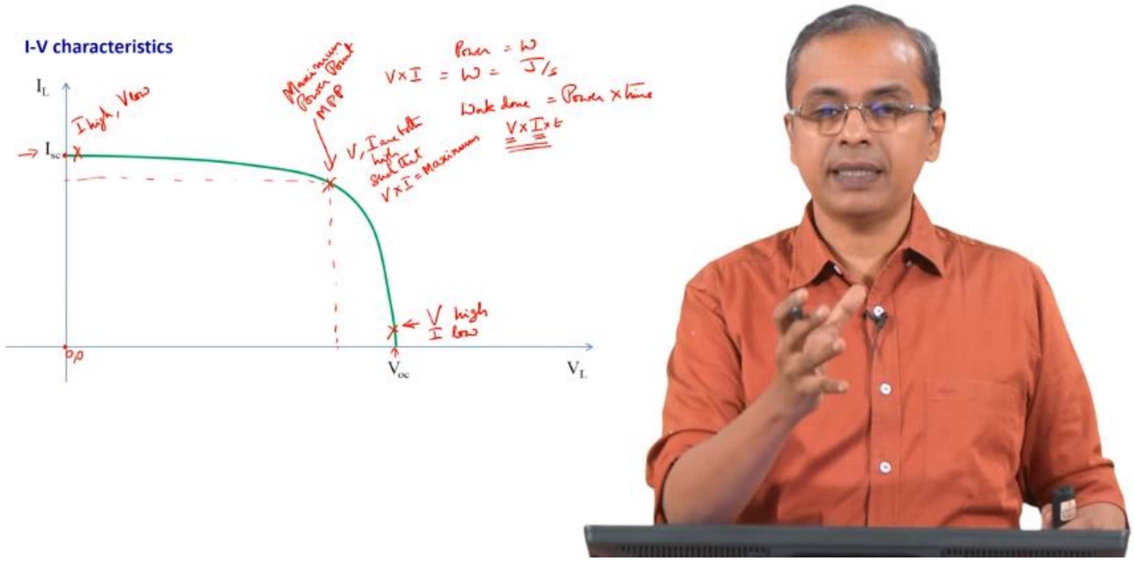
So, the what is the voltage across the shunt? It is simply the voltage that is there between this point and this point right that is the voltage across the shunt. So, what is that voltage that is simply the voltage across the load plus this I_L R_S, that is the same as a shunt. So, that is what you see in the numerator here V_L plus I_L Rs. So, this is the relationship. So, now, what we see here is that you have an equation at the bottom, which relates the, in which you see this I_L and you also see the V_L. So, the and only issue is that you see I_L in multiple places. So, you see I_L here also, you see I_L here also, you see the V_L also in multiple places you I already showed you one place you see it here also.

So, in other words it is a kind of a complicated relationship between the load across the voltage and the current that is going, sorry the load across the voltage across the load I am sorry, the voltage across the load and the current going through the load. So, it is a complicated relationship between these two, and that is what is being shown by this equation. It will fairly straightforward derivation we simply looked at various parts the current takes, and we have arrived at this expression. But this expression shows that the relationship is kind of complicated, it is not a simple straight line of some constant times current is not some constant times voltage or voltage is not some constant times current.

So, it is nothing like a resistor, you see here some complicated relationship, where the current has in the equation for the current, you also have the current value, you also have the voltage value etcetera. So, it is a complicated equation you have to use some mathematical methods to actually you know plot this out, if you want look at various values, you can also do this experimentally and then you can experimentally you know measure current at a various load currents, at various load voltages and make a plot. But any case you can take this equation, this is the equation that now describes what is if you attach some load to the solar cell, what is the current you will see, and what will be the voltage that the load will face. So, and that is what typically any external unit that you are attaching to the solar cell needs to know right.

So, you are attaching some external unit to the solar cell that external unit needs to know that this is the behavior that is going to come from the solar cell and therefore, you have to make sure that that external unit that you are attaching which could be a bulb, it could be a motor, it could be a fan whatever it is that you are attaching to the solar cell, can work properly given that this is the current voltage relationship, that is going to come from the solar cell. So, therefore, it is important to know how this plot looks.

(Refer Slide Time: 32:50)



So, if you plot this equation, you will get a behavior that looks like this.

So, if you see here this is origin 0,0. So, if you look at it when the voltage is 0, when you set the voltage equal to 0 then basically you have short circuited the diode right. So, so that is the short circuit current. So, that is what is called I_{sc}, and then when you basically set the current to 0. So, which means there is no current coming out of that cell, then you get the open circuit voltage V open circuit. So, that is I short circuit and this is V open circuit.

And we you can see that this curve that you see here, it is not linear in any sense, but it is corresponding to that last equation that we had down here. So, let me just call this equation 6 for example. So, I just did this that here is equation 6. So, sort of a plot of this equation 6 is what you are seeing here, which could also be obtained experimentally. You simply have to put it together and measure all these things and do it. So, there are some experiments which should do that. So, you get this thing.

So, now please remember. So, this is what the external circuit can see from the solar cell. Now you should also keep in mind that anytime you are trying to use some power supply to do some work, I mean to get something done what do we have power is given to us and watts right. So, power is in watts and watts is simply joules per second. So, and this is V into I, in joules per second. So, if you want to look at the work done, work done, of course, power into time. So, I will just say V into I into t. So, V into I into time so, that is the work that is done.

So, anytime you are using some power source to get some work done, you basically want to do as much work as possible right. So, you want to do as much work as possible because that is the whole point, you have some power source, you have some something coming out of it, you want to use the capability of that power source to do as much work as possible and that is when you have you know utilized it properly, used, utilized it efficiently and you are not you know wasting resources so, to speak.

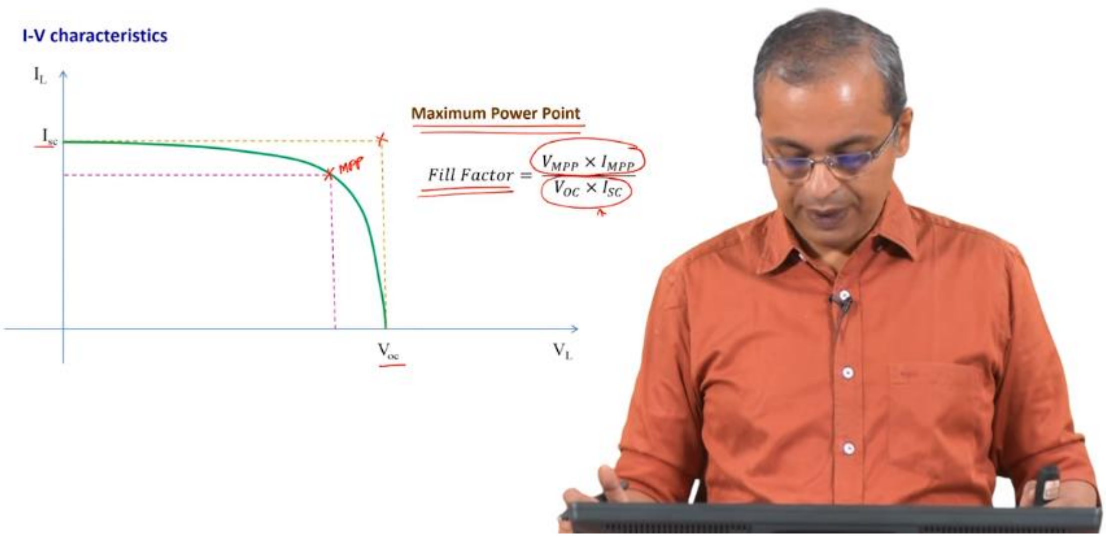
So, therefore, it does not help if you are taking a power source and using it under conditions where volt, where it is voltage is high, but current is extremely low or current is high voltage is extremely low things like that. When you do all that, given that the power source has a variation in voltage current characteristic, you can select different operating points on that system.

So, even here for example, I can select this as an operating point, I can select this as an operating point. If I select this point is an operating point the voltage is high. So, V is high, I is low here I is high V is low, right. So, with the same you know behavior same cell, I can select two operating points, I can select multiple operating points, I am just giving you examples of two of them. In one case voltage is high current is low, the other case current is high voltage is low. In both these cases the work that, that I am going to do is going to be less than the maximum amount of work that this unit can do. So, when I select these kinds of operating points, when I attach some device to the solar cell that that is actually at these operating points, then I am not making the best use of the solar cell, I am using a very ineffectively.

So in fact, you want to keep change, you want to pick a voltage and current location, which maximizes the power that you can pick out of the cell and therefore, maximizes the amount of work that you can do with the cell, at any given point in time. So, if you just do all the calculation, you will find that there will be some point here, if you do at all the different possible ways of getting your V and I, you will find some point there based on you have just optimize it, and you will get one particular point here where your V and high, V as well as I are both high, such that V into I is a maximum, ok.

So, this point is called maximum power point or it is called, in short it is called MPP. So, this is the maximum power point and it is important to know that such a thing exists for a solar cell and therefore, we have used the solar cell such that we operate as close to this point as possible. So, that we get the best out of the solar cell, best of whatever the solar cell is delivering to us right. So, this is what we would like to do. So, we have to match the, end use to the solar cell so that we are actually able to do this.

(Refer Slide Time: 38:15)



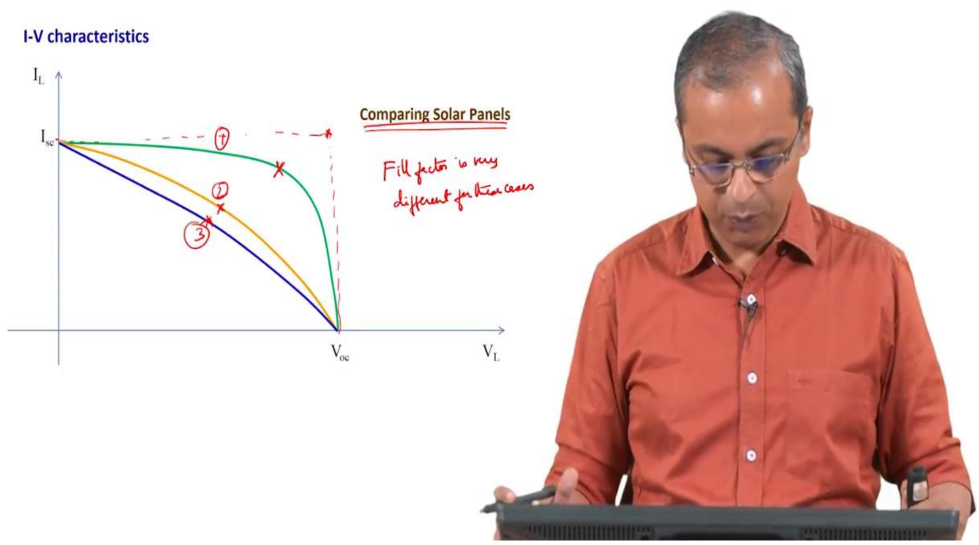
So, just to highlight some of the, I mean ideas associated with this plot itself, if you just look at the same this maximum power point thing, I am just indicating that here. So, you have something called the maximum power point which is in this case I have indicated here and we can relate that to the hypothetical product of the maximum current you are getting there which is the short circuit current, and the maximum voltage you are getting there which is the open circuit voltage.

So, that is what is there in the denominator. So, then a maximum you know current that you can possibly get out of the system, maximum voltage you can possibly get out of the system that is in the denominator whereas, what you actually operationally get as your best operating point is this MPP that I have that is listed here.

So, maximum voltage the voltage, corresponding to the maximum power point and the current corresponding to the maximum power point. So, if you do this you know ratio of the maximum power that you will get from this cell in the actual operational condition, versus this you know sort of the theoretical limit that you can consider for it. So, to speak we are referring to that as the fill factor. So, the fill factor is simply the ratio of V_{MPP} into a I_{MPP} to the product of V_{OC} times I short circuit current. So, this is a very important characteristic of a solar cell, when you try to put it to some end use. So, therefore, it is very important to be aware of it and to actually utilize it.

So, I am also going to show you how you utilize it or how we you know keep in mind that this is something that needs to be addressed or even how it impacts us as you look at it.

(Refer Slide Time: 39:48)



So, for example, if you keep this in mind and we now look at let us say different solar panels. So, for different solar panels, this I V characteristic could be totally different.

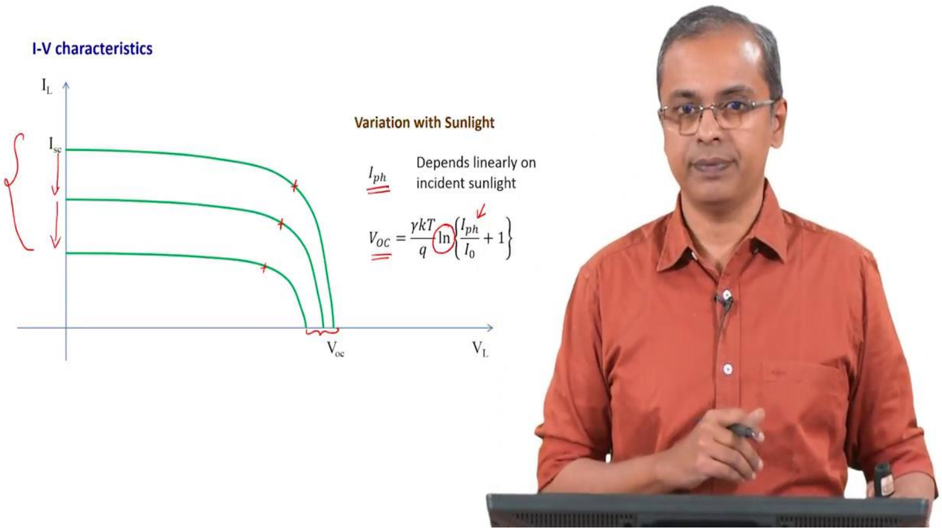
So, for example, I am showing you three different panels this is panel 1, this is panel 2 and this is panel 3. So, it is very important to remember that the fill factor for these three panels is dramatically different. So, whereas, for one your maximum power point is somewhere here, for the second one is probably somewhere here, for the third one it is probably somewhere there something like that. For each of them that fill factor which will be the ratio, in all of them in all these cases your denominator for the fill factor is this.

So, in all these cases denominator is starting off with a product corresponding to the coordinates of this point, numerator is here for this, numerator is here for this, numerator is here for this. So, numerator can be dramatically less as you go from 1 to 2 to 3 denominator is the same. So, the fill factor is totally different. So, the fill factor is very different for these cases and therefore, if you simply you know do this thing that this idea you stick to this idea that you go to a shop and you see or you go to some online location and you want to buy this solar panel, you simply look at open circuit potential saying oh what is the open circuit voltage I want a 5 volt solar panel, and there are like half a dozen manufacturers giving you a 5 volt solar; let us say some panel with multiple cells in it is some 5 volts, and you want a 5 volt panel and there are multiple people selling a 5 volt panel and you simply go buy the cheapest one right.

So, when you do that you have to bear in mind that you are missing this point, that the each of those 5 panels potentially could have different fill factors maybe they are the same we do not know. Maybe it is the same thing being sold more expensively in one place and less expensively in another place that is also possible, but the point is there is a good chance that these fill factors may be different, and it is important for you to know what is that fill factor. So, you need this curve or you need at least this data from them saying what is the fill factor, and then on that basis only you should make your judgment.

So, the closer it is to one, that is the value that you should be more interested in and just a couple more points related to this with which will help us you know sort of get a more complete picture on this.

(Refer Slide Time: 42:17)



Is that, we can also look at the idea, that you know what is given that you have this equation, relationship between load current and know the load voltage. What happens to this solar panel as let us say a cloud passes by or there is some change in the amount of sunlight that is falling on the solar panel, how is the solar panel's behavior changing right.

So, when you want to do that, when you look at that carefully. What we see is that the photo current depends pretty much on the sunlight because that is the source of the current. So, how much sunlight falls if twice as much sunlight falls you can expect twice as much current to come sort of you know then only you can expect that it will depend linearly on the amount of sunlight that is coming. So, if you know let us say you decrease by some percentage, this will keep decreasing correspondingly the amount of photo current.

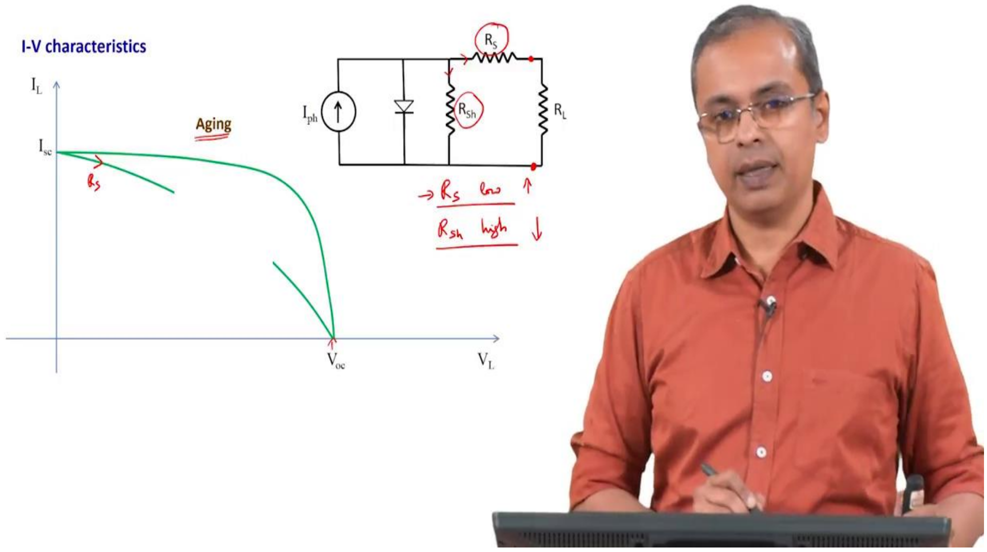
But if you look at the open circuit voltage, and you look at its relationship to the photo current; if you look at this relationship, it is a logarithmic relationship there is a lon there. So, if you take again 2.303 log let us say 2.303 logs. So, let us convert that from natural log to you know log to the base 10 if you keep that in mind. So, then and let us say for a moment just for understanding sake let us ignore the 1, ignore the 1 for the moment, what this means is if you if the current drops from say by a factor of 100 something that was say just to given as some 100 amps it drops to one amp, because you have taken a log that is basically a change of a factor of two orders of magnitude right. So, 2 its so, something current changes by 100 voltage changes by 2 that factor that impacts the voltage changes by 2.

So, what it means is, even though you may have dramatic changes in current the open circuit potential is much less affected by it. So, the effect of the incoming sunlight which affects the photo currents very significantly, affects the open circuit voltage much more mildly and therefore, for the same variation in the sunlight, the voltage change is much more narrow; current change is large voltage changes narrow. So, voltage change is just this much so that whereas, the current changes this much.

So, that is again something that you have to keep in mind. So, a solar cell behaves very differently. So, I mean or differently from what we intuitively think it might do. So, so what is this thing or what is we may be unaware that it is doing all these things; this is what it is doing. So, again you have to look at the fact that there are peak power points. So, you will have some a peak power point here, corresponding to this, some other peak power point here, some other peak power point here. So, you have to keep track of this peak power point and accordingly use it ok.

So in fact, they even have maximum power point, maximum power point trackers. They have circuits which keep track of this maximum power point and try to optimize the you know the way the external circuit is working with respect to this solar panel, to track this maximum power point and use the best use of it. So, therefore, this is. So, this is important stuff. So, we cannot ignore it this that is my point. So, you have to and people who manufacture these kinds of things or trying to make the best use of the solar panels are looking into all these issues. So, that is how this is used.

(Refer Slide Time: 45:19)



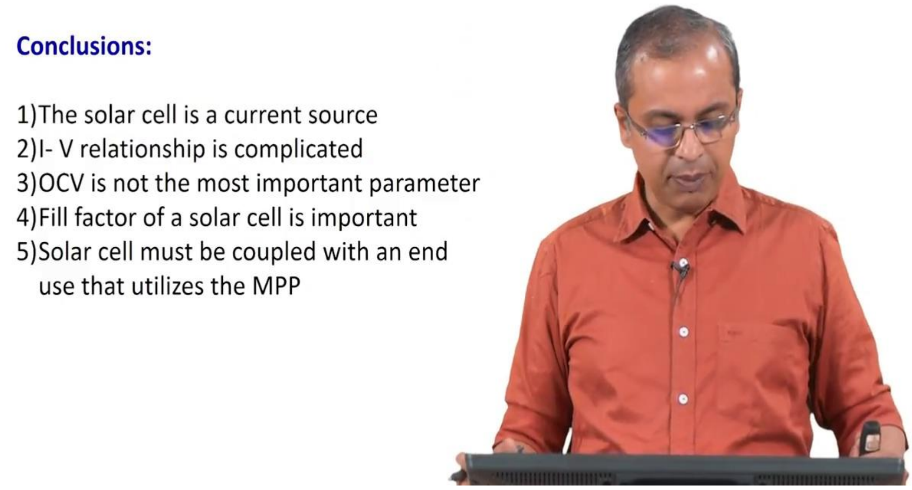
So, I would just like to finish off with a couple of comments here, one is and that is first got to do with the aging. So, you put a solar panel out then again you look at the open circuit. So, you put it brand new, it will have some open circuit after many years of operation it will have some open circuit, you will find that does not change much. So, again this is again a instance where you have to understand that the open circuit does not, open circuit voltage, does not fully capture the complexity of the operation of the solar panel right.

So, what is happening? In general for the solar panel to operate well you want the shunt resistor to be as high as possible, the series resistor to be as low as possible. So, R_S should be low, R_{sh} should be high. If you do that the current going down this path will be very low, the current going down this path will be higher and therefore, and if R_S is low the voltage across your load will be high. So, therefore, you want this to be true, you want this to be true, you want this to be true. Generally, what happens is over a period of time, impurities will diffuse into the solar panel and as a result R_{sh} R_{sh} will start decreasing. So, this will start decreasing and R_S will start increasing.

So, how does that affect us? When you go to very high currents in the circuit, then your R_S impact of R_S starts showing up more. So, R_S starts impacting us here. So, this is where the R S impact is beginning to impact us. So, increase in R_S starts impacting us because higher currents in the higher current region, you are adding more I_L drop. So, correspondingly what you get out of the panel becomes less. On the other hand the shunt resistor starts impacting us in the high voltage region and so, the in the high voltage region again you are you know ability to get power out of the solar panel decreases dramatically, as your shunt resistor starts becoming lower and lower in value because you know you are now giving an alternate path for the current.

So, you can see here the characteristic is going to change dramatically and therefore, it is also going to affect your maximum power point. So, even though open circuit voltage you look relatively undisturbed. So, this is again an important information to keep in mind that this is how the character of the solar panel is changing with time, and you have to keep that in mind when you use that panel. So, these are all the major parameters associated.

(Refer Slide Time: 47:50)



So, just to sum up the a solar cell is a current source. So, that is one point that we would like to remember. The I-V relationship is complicated, incidentally in this context I will also point out that in the I-V relationship we did not see the band gap E G. E G did not show up in that relationship and that is primarily for two reasons because the E G sort of, the band gap sort of sets the upper limit for what you can get us the open circuit voltage, but since you have all these other events going on like recombination etcetera, it is not directly you know impacting your voltage and also we are looking at the characters, characteristic of this cell from an external perspective of load voltage diode voltage etcetera.

So, our approach also puts us in a situation, where we are not necessarily directly tapping into the exact value of the band gap into that equation itself. But basically it sets a sort of an upper limit, but it does not show up in the equation. So, that is the point we have to remember so, but also I have highlighted, the I-V relationship is complicated. So, most importantly the OCV is not the most important parameter that you have to that reflects the capability of the solar panel, that is not the most important parameter.

Although because we are used to this idea from various other you know buying batteries etcetera, we tend to go there and ask for voltage with respect to the voltage. Rather the fill factor of the solar cell is the most important parameter that is what decides how well the solar cell can function. And not just that if you know the fill factor and you know the I-V characteristic you should try your best to operate at the maximum power point and as I said there are people who set up circuits called the maximum power point tracker, to keep track of the maximum power point and you know keep the load on that a solar panel corresponding to that.

So, that you are fully benefitting from that solar panel and so, that is what I have said here the solar cell must be coupled with an end use that uses the maximum power point. So, those are the important ideas that we discussed today, which where we basically took all the learning that we have had so far, and tried to put together the thoughts and the ideas and the equations that relate to how the solar panel actually gets used, and also try to understand how it is characteristics impact the end use, what care we must take and the end use to fully benefit from the solar cell, ok.

Thank you.

Introduction: In this lecture, the VI characteristics of a PN junction based solar cell are determined, the usage and importance of these VI characteristics with respect to an external load connected to the solar cell are discussed.

Keywords: VI Characteristics of Solar cell, Fill factor, Open circuit voltage, Short

circuitcurrent.